



LHC

High- p_T Physics and Detectors

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Lecture Themes

1. Setting the Stage ... Motivation for a Huge Machine

- Is the Standard Model the final particle physics theory ?
- New Physics ?
 - SUSY
 - Extra Dimensions
 - Little Higgs

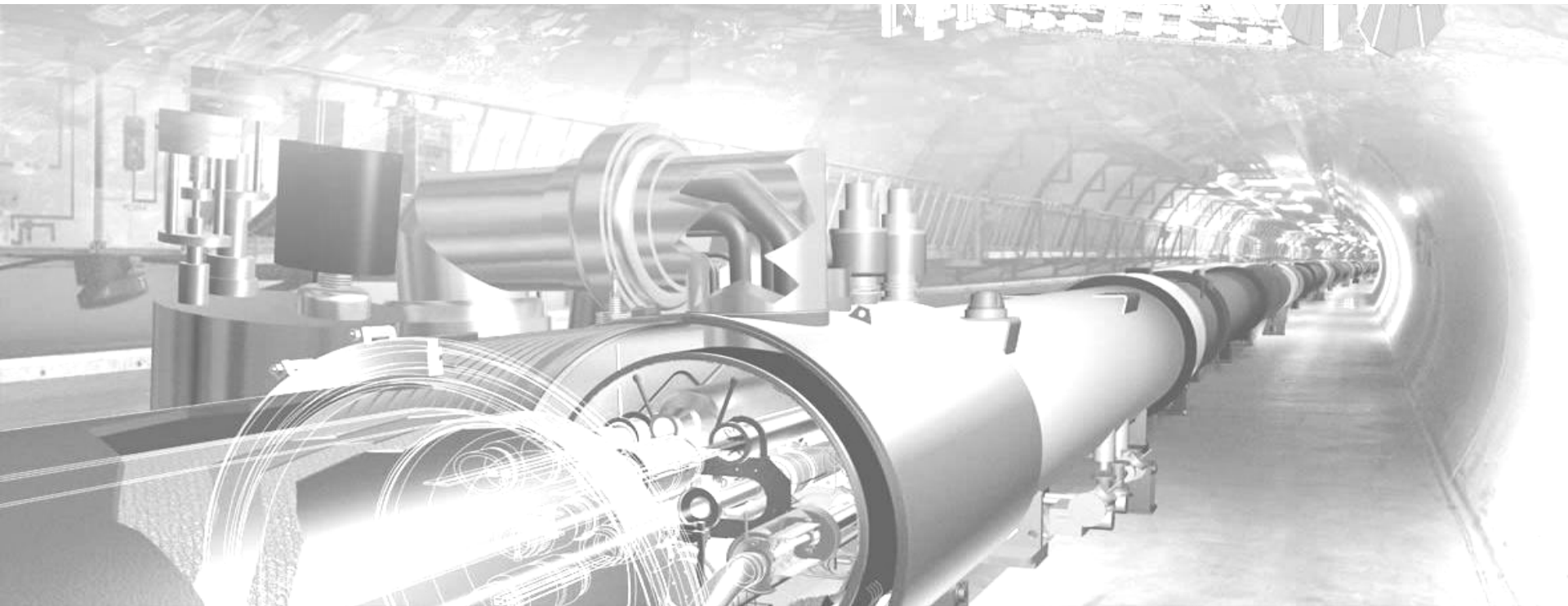
2–3. CERN and the Large Hadron Collider (LHC)

- ATLAS Movie (*Episode 2 – The particles strike back*)
- The LHC
- The ATLAS Experiment
 - Detector challenges and concept
 - Specific systems

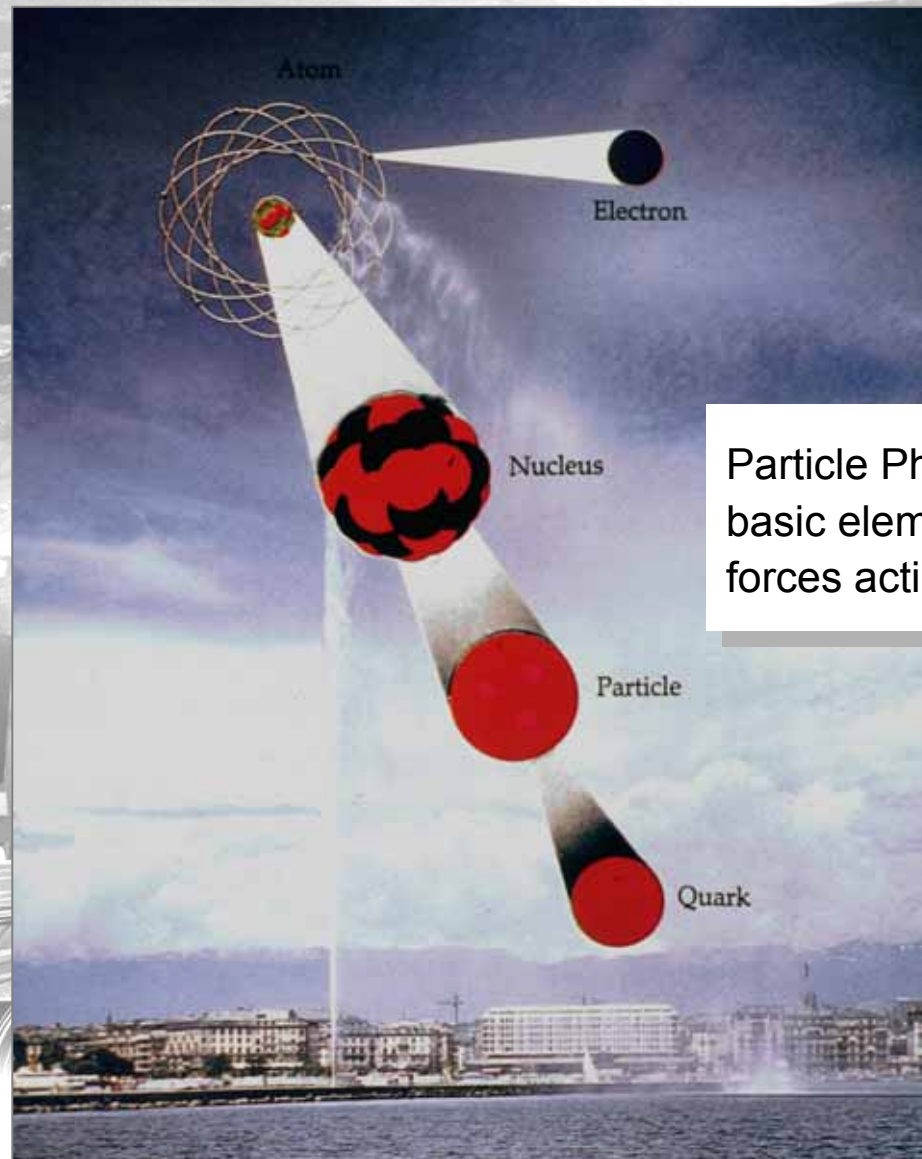
4. Searches for New Phenomena at ATLAS and CMS



Setting the Stage

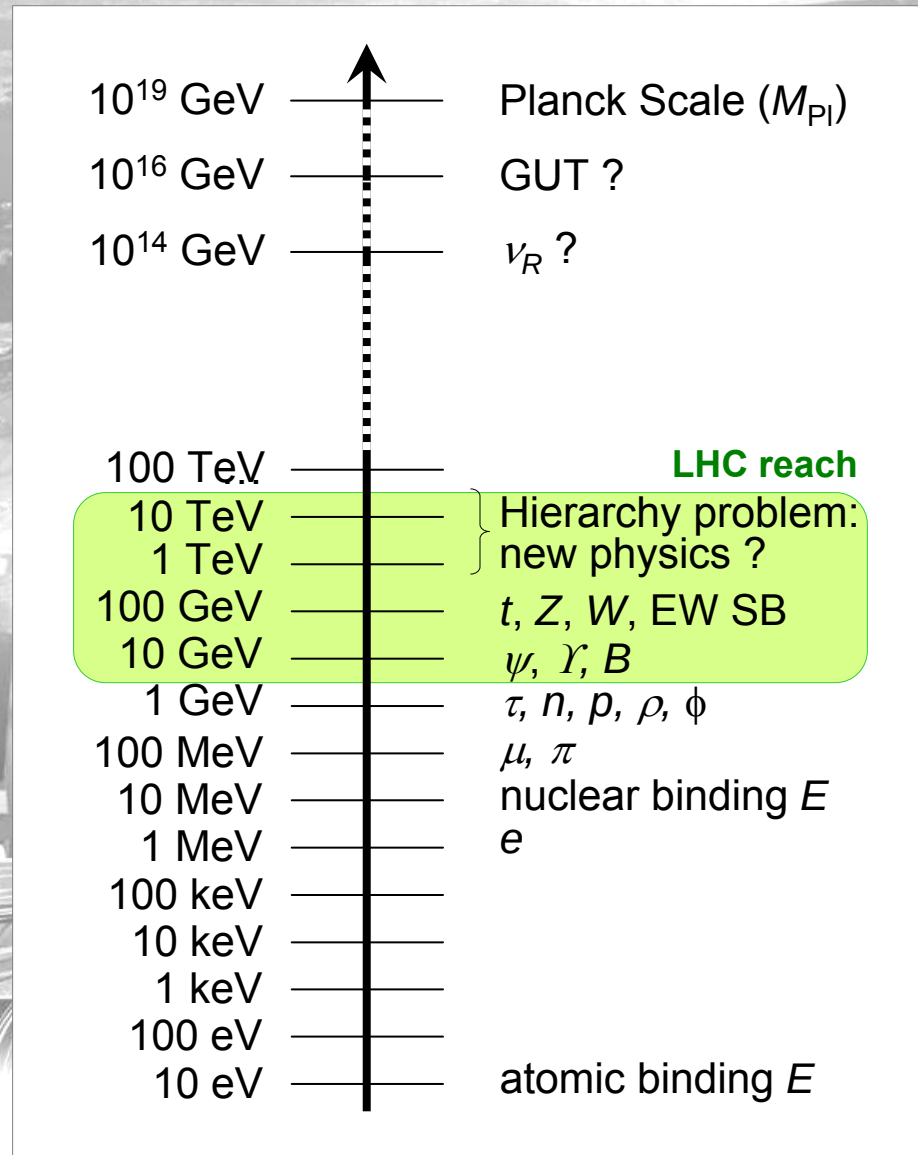


A Postcard from Geneva



Particle Physics is the study of the basic elements of matter, and the forces acting among them.

A Postcard from Geneva



The Standard Model (SM)

The SM describes all observed phenomena using 21 (24) matter particles and 4 forces

Fermions

Matter particles

Organised in 3 generations

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

6 Leptons



6 Quarks



$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Bosons

Force particles

Distinguishing 3 forces

Photon

Electro-magnetic force



3 Weak bosons

Weak force



8 Gluons

Strong force



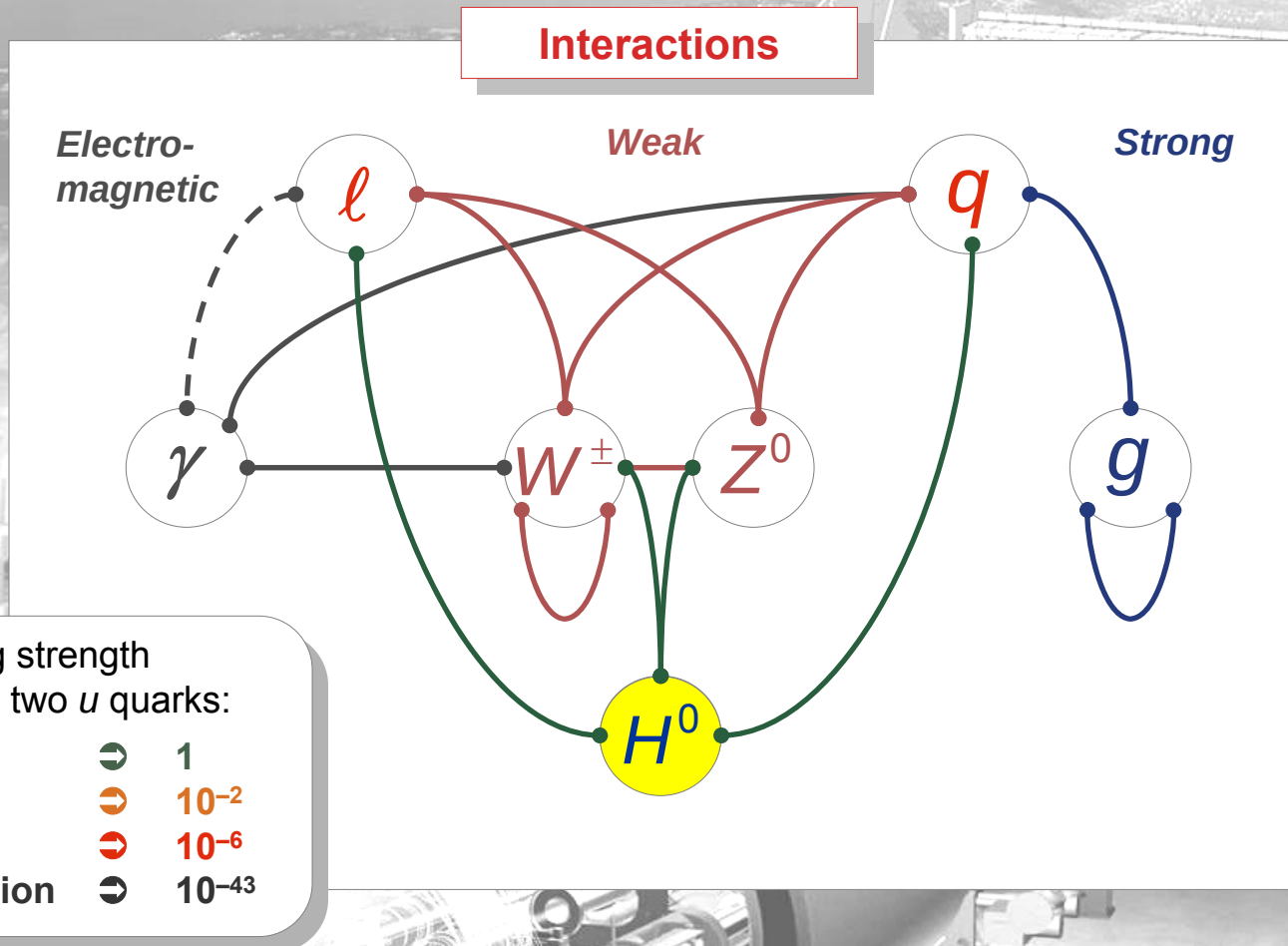
Higgs boson



*Breaks electro-weak unification
Generates particle masses*

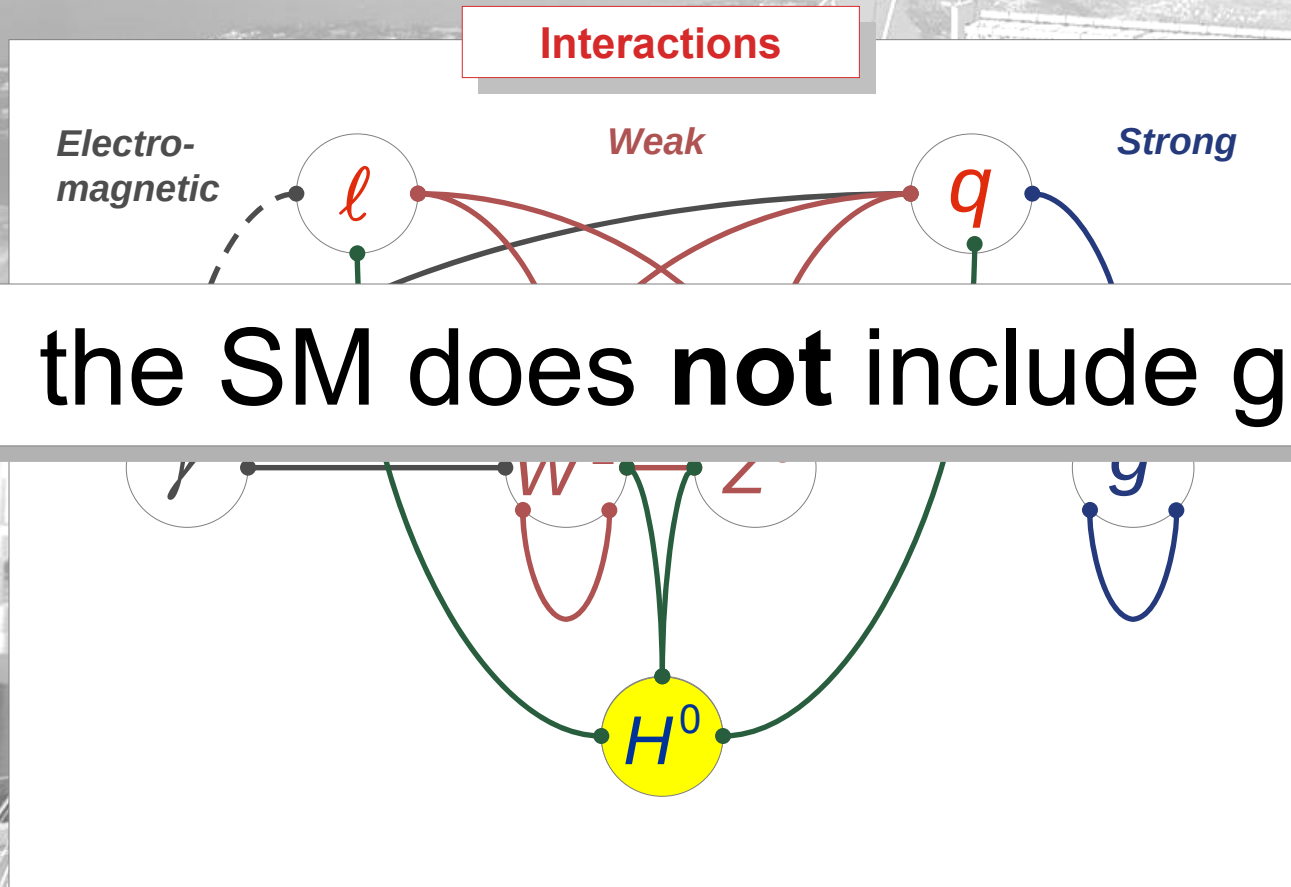
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The Standard Model (SM)

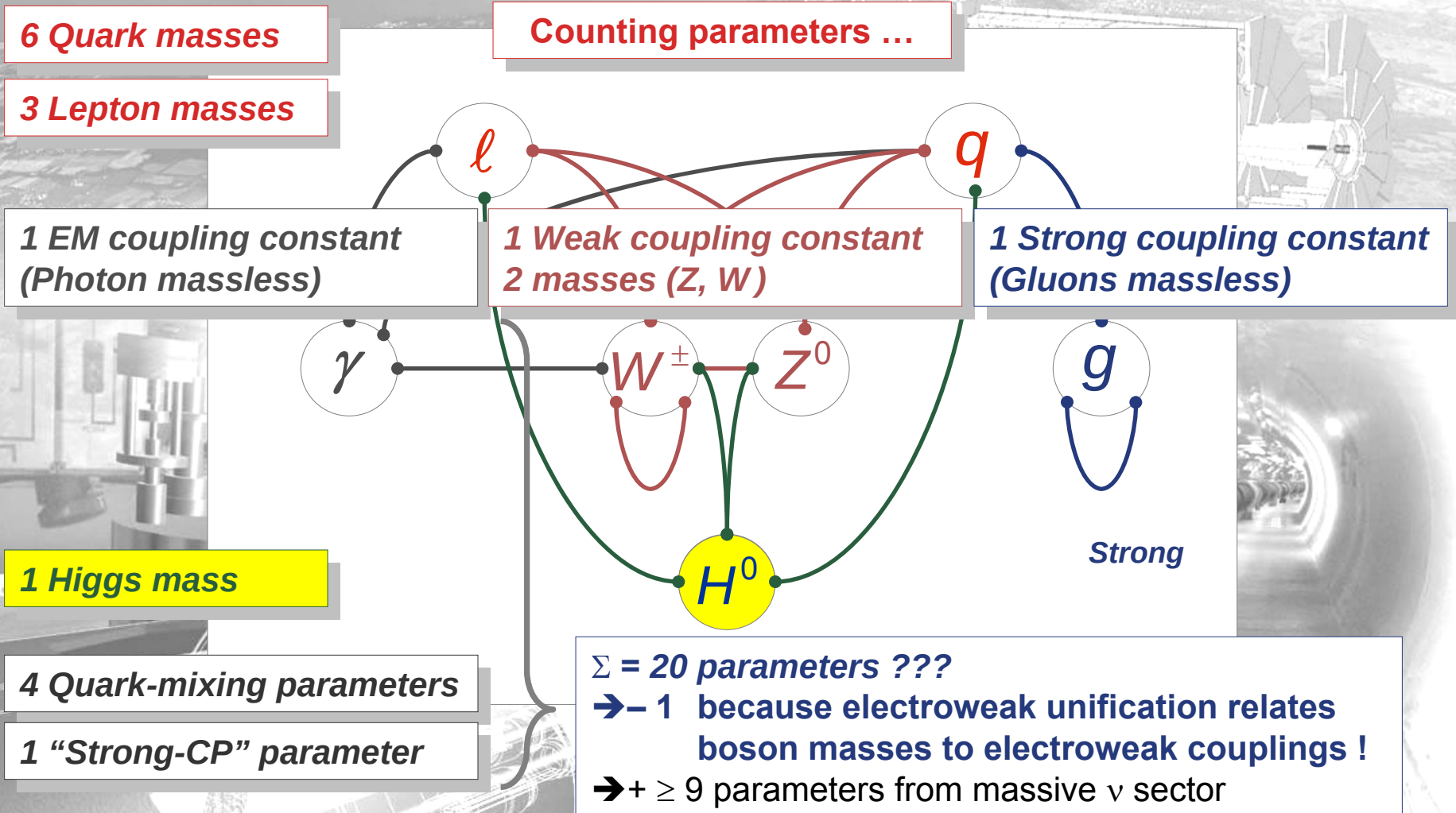
The SM describes all observed phenomena using 21 (24) matter particles and 4 forces



Note: the SM does **not** include gravity!

The Standard Model (SM)

The SM describes all observed phenomena using 19 parameters



The Standard Model (SM)

During the last 35 years, the SM has been experimentally verified to extreme precisions

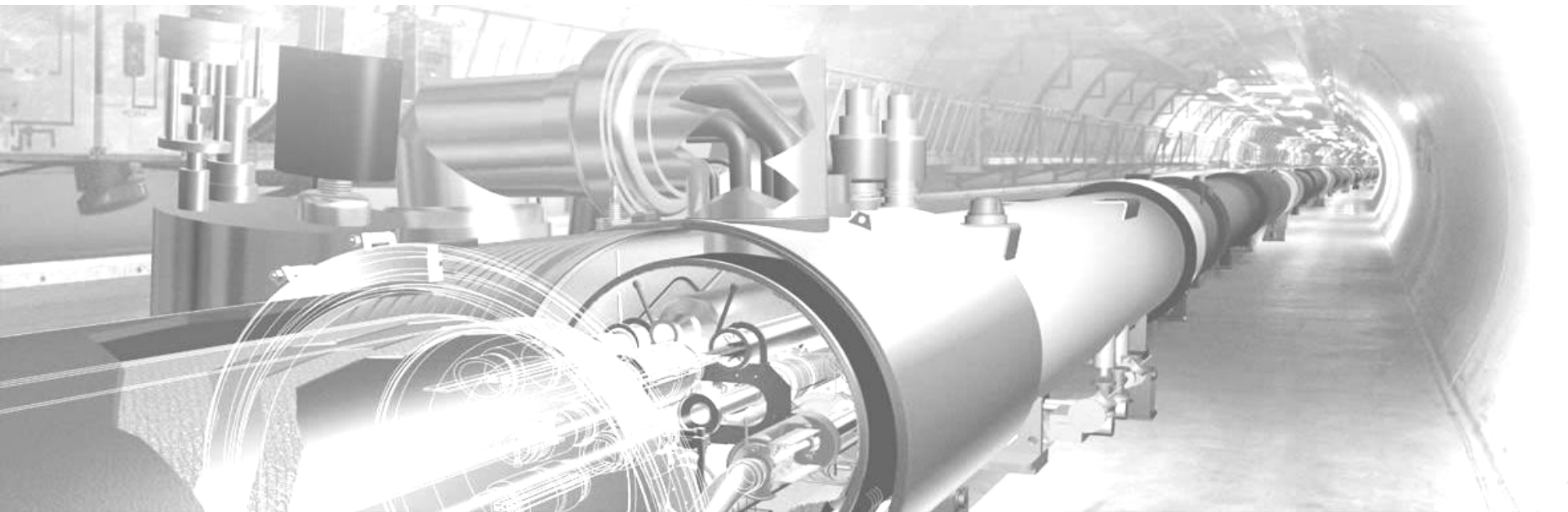
- Cross sections of lepton and hadron (pair) production up to $M \sim \text{TeV}$
- Electroweak unification (relations between masses and couplings)
- “Asymptotic freedom” property of QCD coupling at % level
- “Universality” of weak interaction at 0.3% level
- $V-A$ structure of charged weak current
- Matter-antimatter symmetry (CP) violation through CKM mechanism
- Absence of electric dipole moments (and $CP-V$) at particle level
- QED via e and μ anomalous magnetic moments at ppm level
- ... many more tests

The Standard Model (SM)

soooo... **What's the Problem ?**



Motivation for a Huge Machine



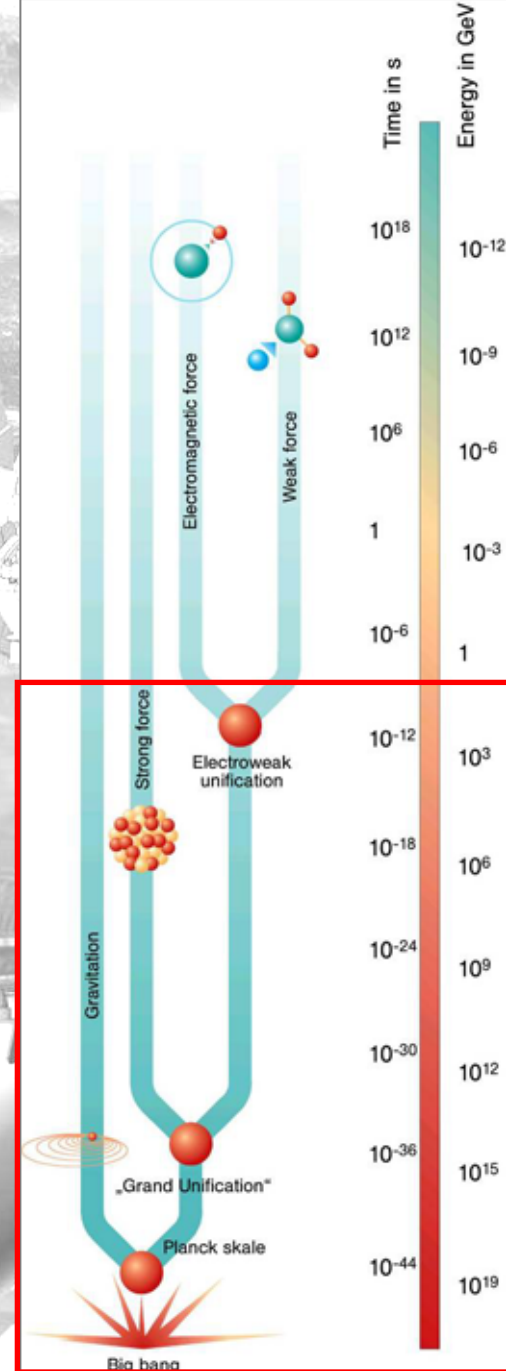
The Problem is ...

- **The Higgs is not yet discovered !**
- **The Higgs is the only fundamental scalar (☹)**
- **What is the origin of the huge mass hierarchy between matter particles ?**

... and :

- **Dark matter (and, perhaps, “dark energy”)**
- **Baryogenesis and Leptogenesis (Matter-Antimatter asymmetry)**
- **Grand Unification of the gauge couplings**
- **The gauge hierarchy Problem**
- **The strong CP Problem (why is $\theta \sim 0$?)**
- **Neutrino masses**
- **Gravitation**
- **New Physics: why not ? [D.E. Kaplan]**

Most of these
problems are
related to the
earliest
moments of
our Universe

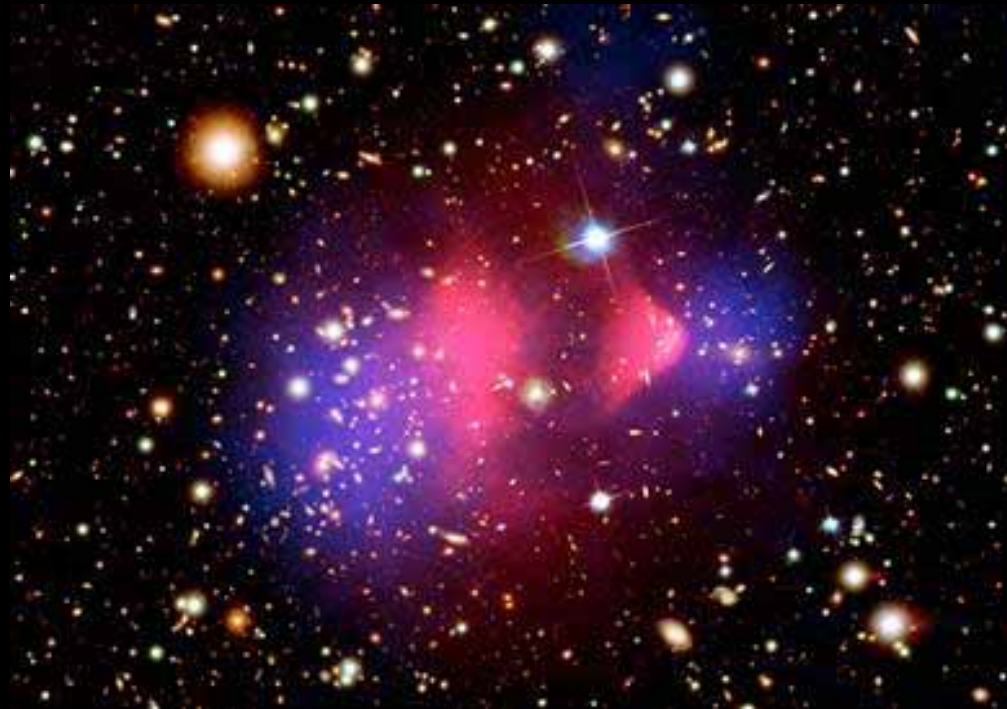


A few examples

Dark Matter

- *Dark matter* does not emit or reflect sufficient electromagnetic radiation to be detected
- Evidence for dark matter stems from:
 - **Gravitational lensing obs.**
 - Rotation curves galaxies
 - Anisotropy of cosmic microwave background radiation

Bullet cluster: Collision of galaxy clusters: baryonic matter, stars (blue in picture) – weakly affected by collisions – and strongly affected (x-ray) gas (pink)

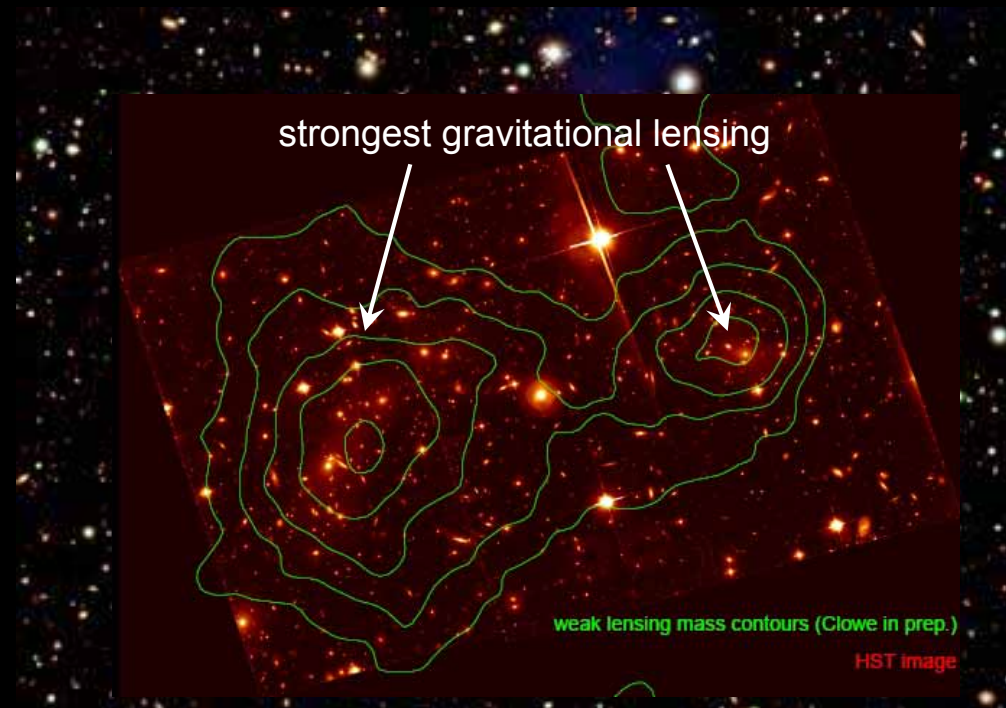


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Interesting side effect: the observed pattern allows to derive limits on cross sections of self-interacting dark matter !

Bullet cluster: Collision of galaxy clusters: baryonic matter, stars (blue in picture) – weakly affected by collisions – and strongly affected gas (pink)

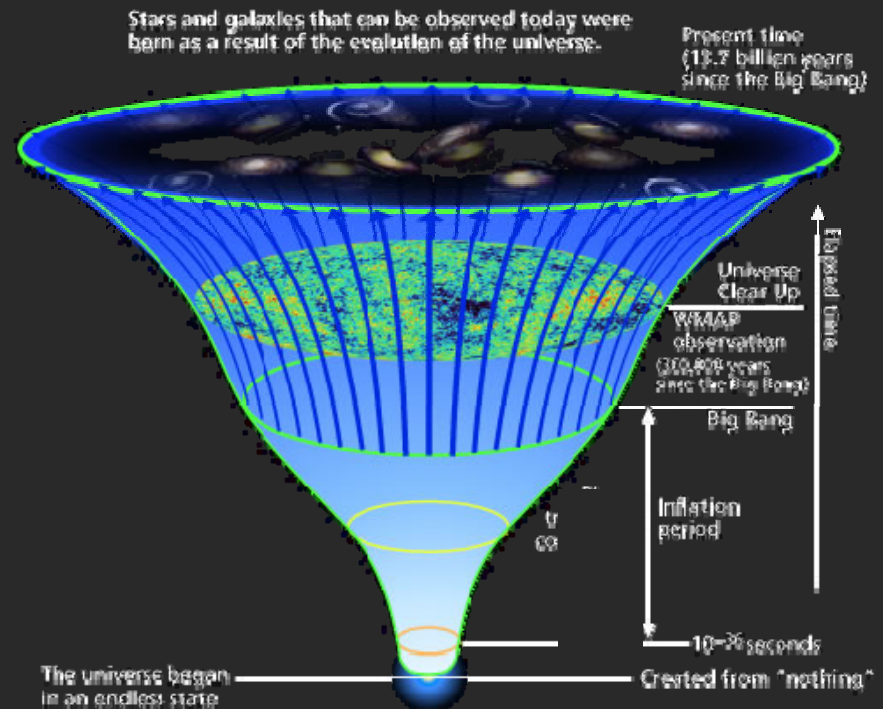


Mass density contours superimposed over photograph taken with Hubble Space Telescope

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→ 2006 Nobel Price in Physics:
John C. Mather, and George F. Smoot
(COBE satellite)



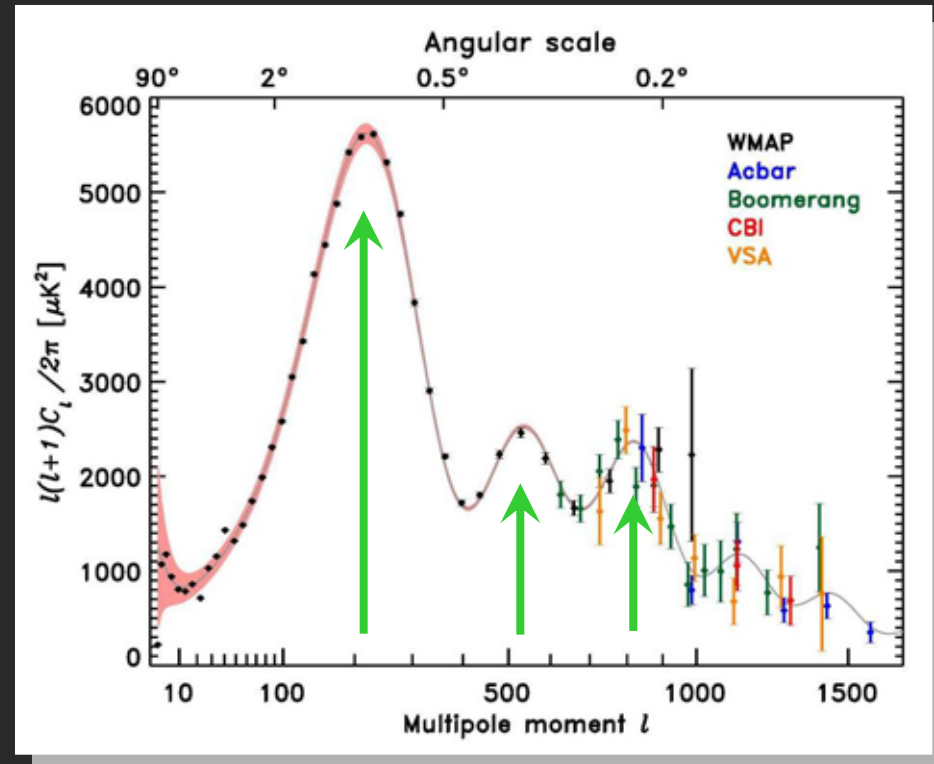
Source: NASA/WMAP Science Team, 2007

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arXiv:astro-ph/0603451

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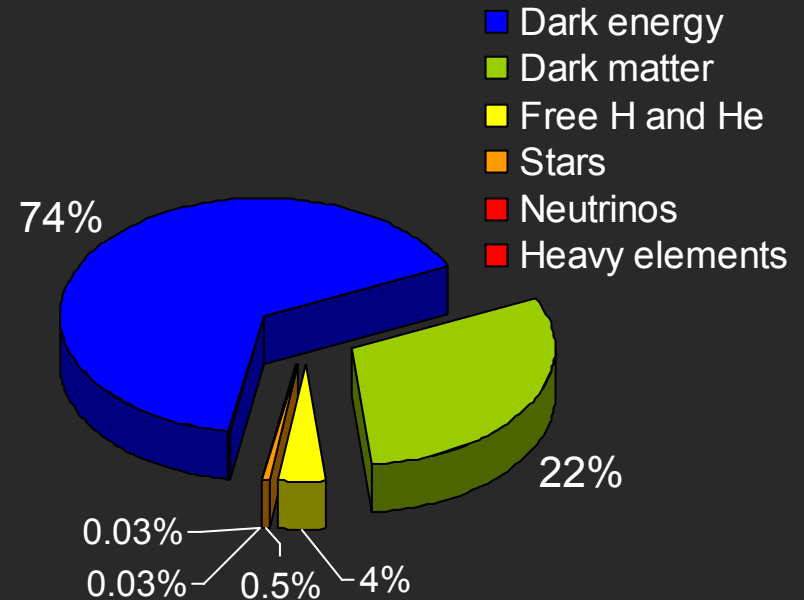


- First peak determines curvature of universe
- Second peak (ratio of odd-to-even peaks) determines reduced baryon density
- Third peak is related to dark matter density !
- ◆ **Data analysis reveals a flat universe and lots of unknown matter and energy !**

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Dark Matter – The “WIMP Miracle”

- Consider Some new particle χ

- During an early *soup*, its annihilation reaction is in thermal equilibrium

$$\chi\chi \leftrightarrow f\bar{f}$$

- As the *soup* expands it cools down, so that (assuming here: $m(\chi) \gg m(f)$, still remaining in thermal equilibrium)

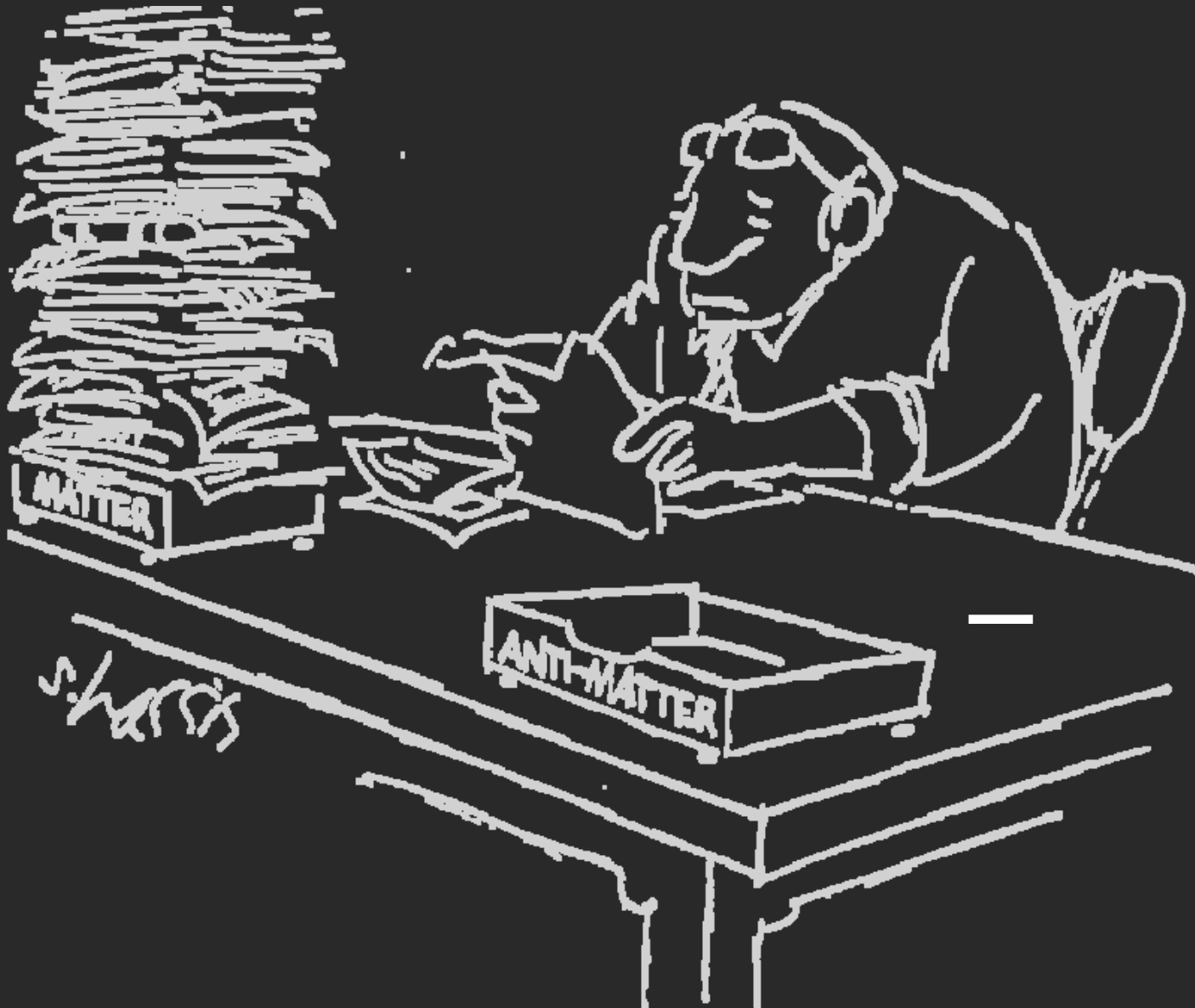
$$\chi\chi \rightarrow f\bar{f}$$

- When $\sigma_A \ll H(T)$, some χ freeze out and create weakly interacting **dark matter** Ω_{DM}
- The abundance of the dark matter inverse proportional to the annihilation cross section

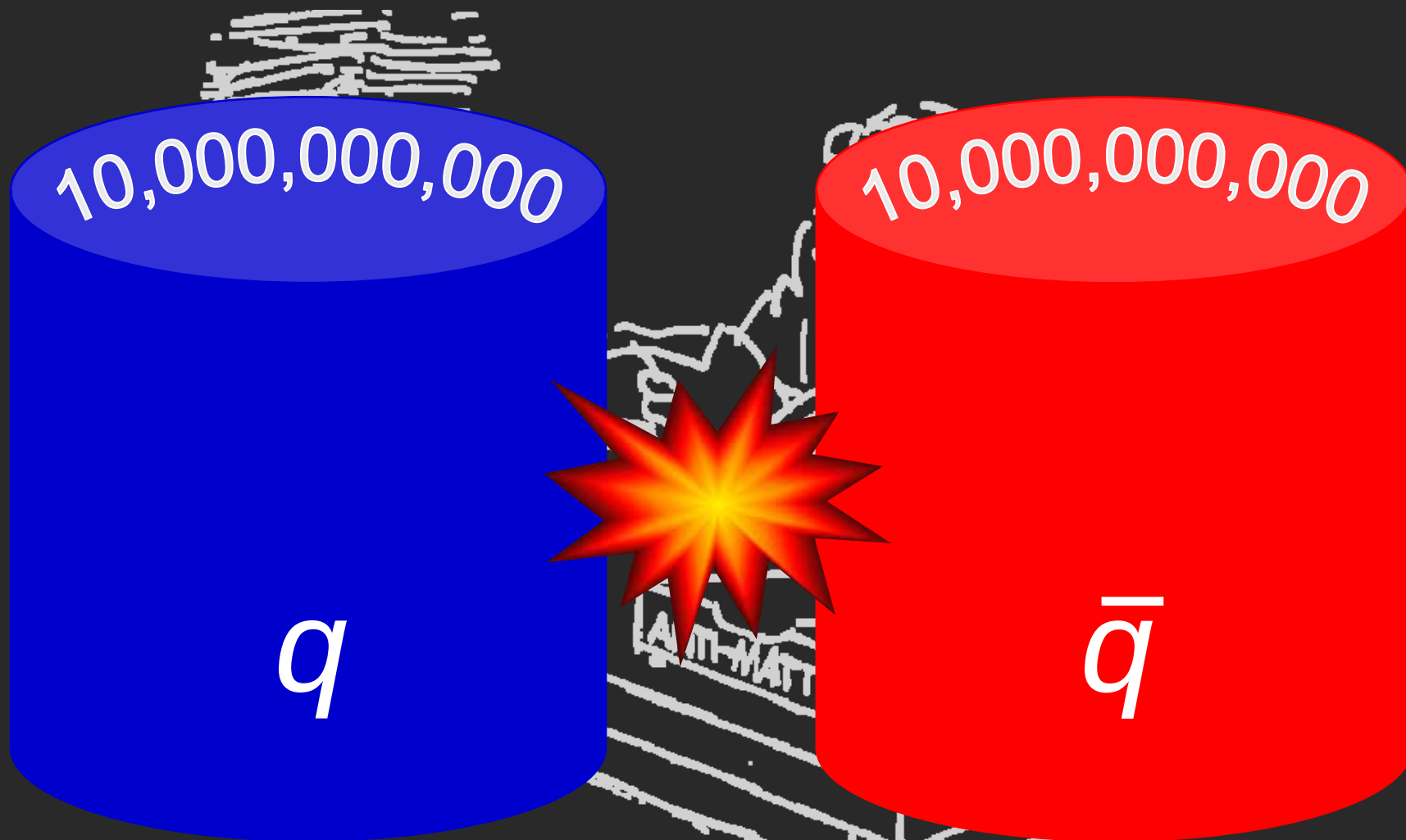
$$\Omega_{\text{DM}} \propto \frac{1}{\langle v\sigma_A \rangle} \propto m_\chi^2 \quad \Rightarrow \quad \Omega_{\text{DM}} \approx 0.1 \quad \rightarrow \quad m_\chi \sim 0.1 - 1 \text{ TeV}$$

COINCIDENCE ?

Matter-Antimatter Asymmetry

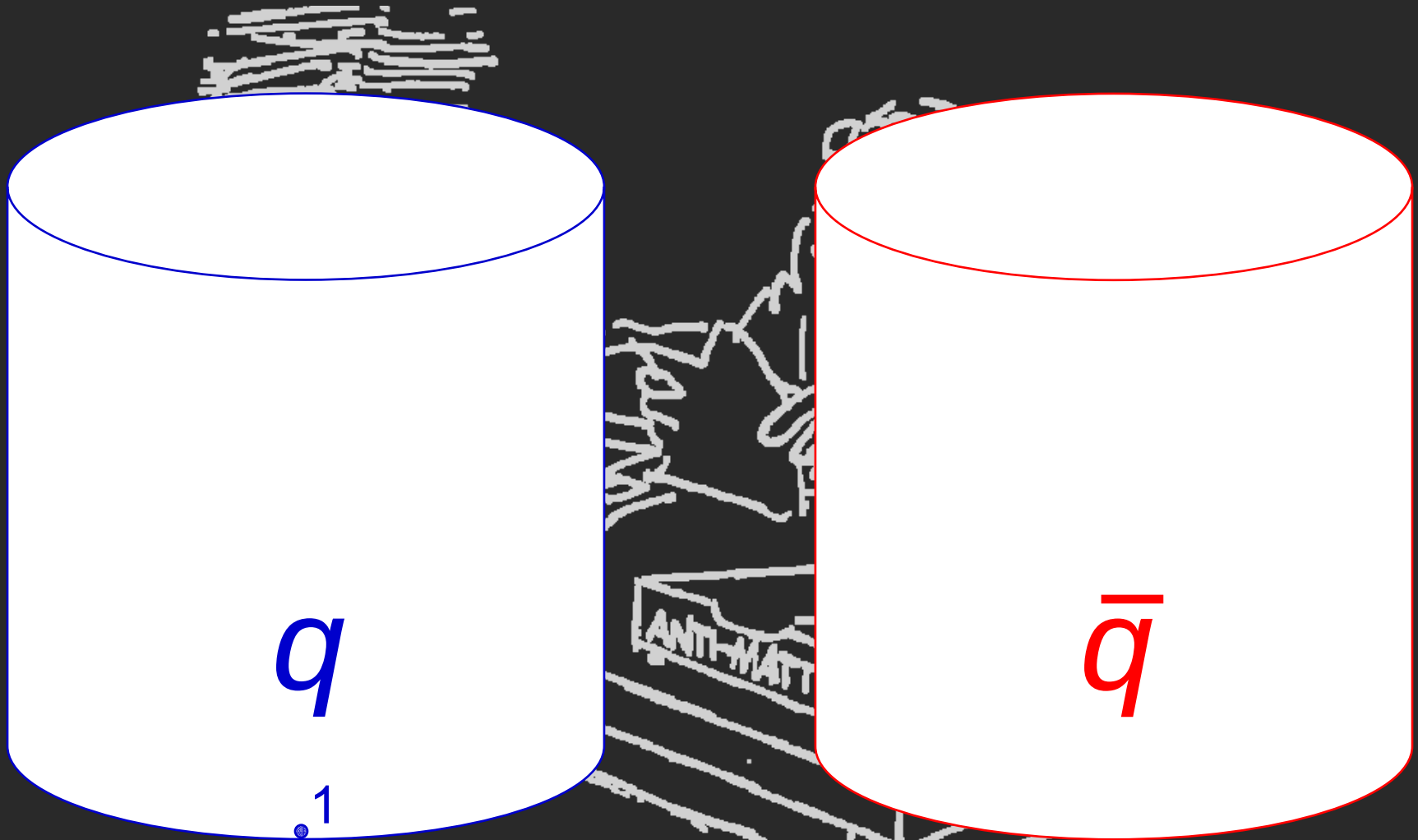


Matter-Antimatter Asymmetry



Early universe ?

Matter-Antimatter Asymmetry



Current universe

Sakharov Conditions

- Is baryon asymmetry initial condition ? Would that be Possible ?
- Dynamically generated ?

Sakharov conditions (1967) for Baryogenesis

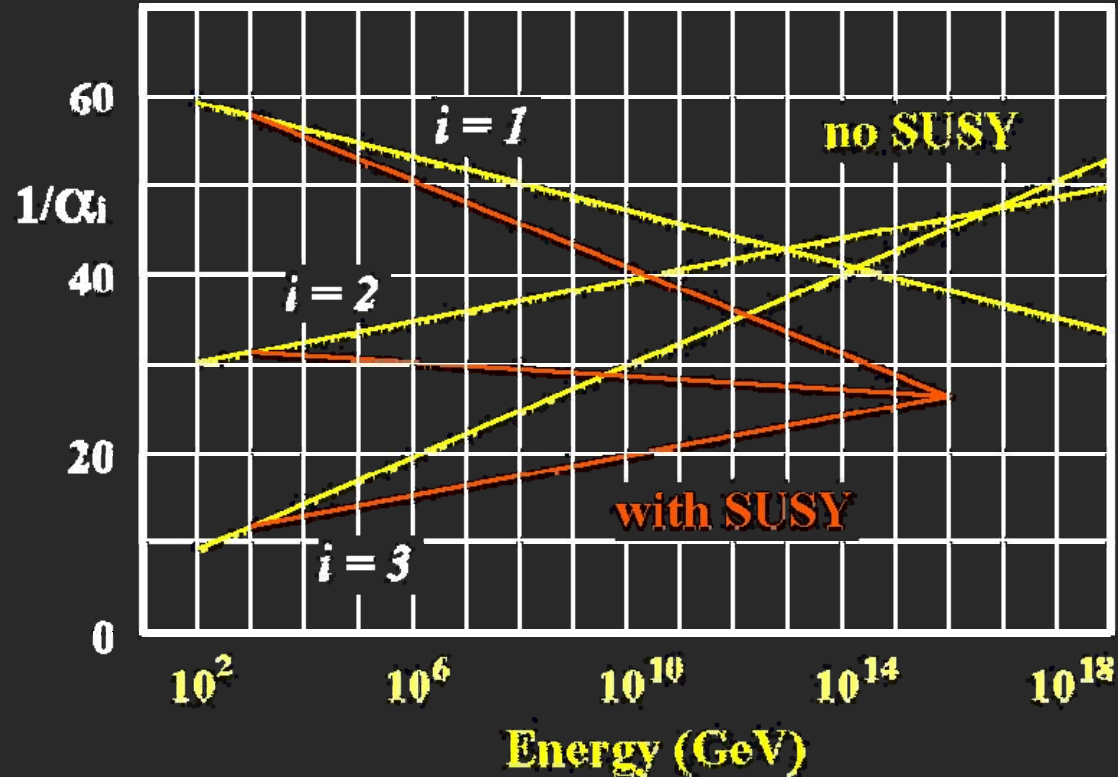
1. Baryon number violation → new physics !
2. C and CP violation → (probably) new physics !
3. Departure from thermodynamic equilibrium (non-stationary system)



Grand Unification of the Gauge Couplings (GUT)

T. Kondo (KEK)

- Electromagnetic and weak couplings unify at $E \sim 100$ GeV
- The evolution of the couplings α_1 (EM/hypercharge) α_2 (weak), and α_3 (strong), **almost** coincides at $E \sim 10^{15}$ GeV
- SM extensions such as SUSY with a characteristic mass scale of ~ 1 TeV can have the right properties to adjust the running and allow for GUT at $E \sim 10^{16}$ GeV



➡ **Exact unification does not need to occur, but wouldn't it be very appealing if it did ?**

It would be consistent with the speculation that the three couplings (forces) are in effect different manifestations of a single overarching gauge symmetry

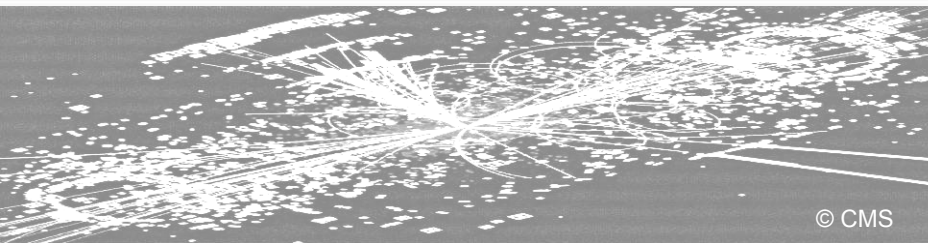
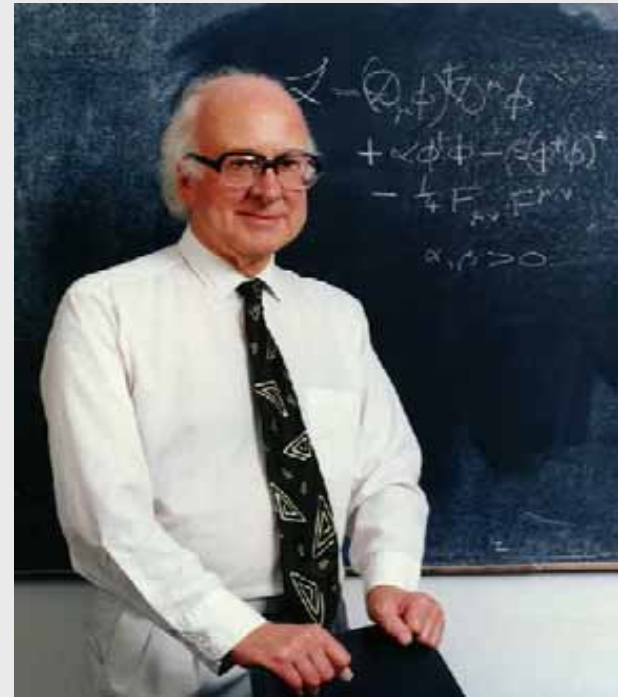
The Higgs Boson (correct: *the Brout-Englert-Higgs Boson*)

Daniel Froidevaux (CERN):

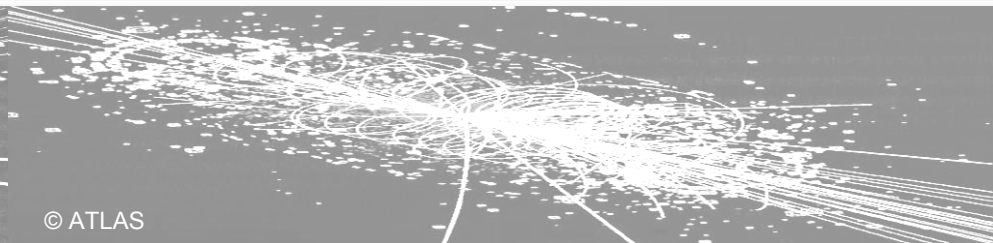
The Higgs has been with us for four decades as ...

- A theoretical concept to generate masses
- An incarnation of the “Communist Party since it controls the *Masses*”
[L. Alvarez-Gaumé at CERN summer school in Alushta]
- A painful part of the first chapter in our PhD thesis ...

P.W. Higgs, Phys. Lett. 12 (1964) 132



© CMS



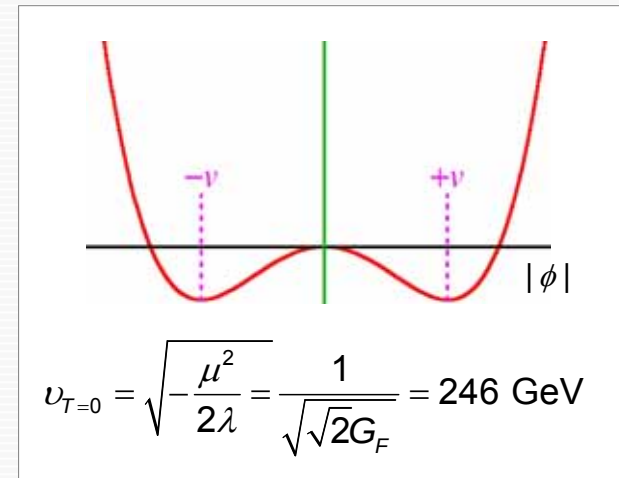
© ATLAS

The Higgs Mechanism

- The fermion and gauge-boson masses of the SM are dynamically generated via the **Higgs mechanism** when spontaneously breaking electroweak symmetry
- Recall the **Higgs** “Mexican hat” potential at **$T \approx 0$** :

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4, \quad \mu^2 < 0$$

with vacuum expectation value: $\langle 0 | \phi | 0 \rangle_{T=0} = v_{T=0} / \sqrt{2}$



- At $T < T_{EW}$, the massless fermion fields interact with the non-vanishing Higgs “condensates”:

$$\text{fermion line} = \text{propagator: } 1/q + \frac{(g_f v_T / \sqrt{2})}{1/q \text{ --- } \text{Higgs loop} \text{ --- } 1/q} + \frac{(g_f v_T / \sqrt{2})^2}{1/q \text{ --- } \text{Higgs loop} \text{ --- } 1/q \text{ --- } \text{Higgs loop} \text{ --- } 1/q} + \dots$$

- Geometric series yields massive propagator creating effective mass for fermion:

$$\frac{1}{q} + \frac{1}{q} \left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} + \frac{1}{q} \left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} \left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} + \dots = \frac{1}{q} \sum_{n=0}^{\infty} \left(\left(\frac{g_f v_T}{\sqrt{2}} \right) \frac{1}{q} \right)^n = \frac{1}{q - m_f}$$

similar
for gauge
bosons

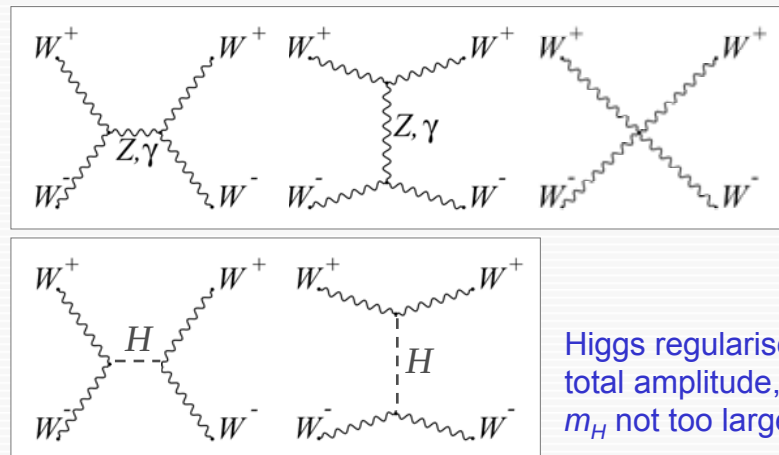
Theoretical Arguments for a light (but not too light) Higgs

- **Unitarity:** if only Z and γ are exchanged, the amplitude of (longitudinal) W^+W^- scattering is:

$$A_{Z,\gamma}(W^+W^- \rightarrow W^+W^-) \propto \frac{1}{v^2}(s+t)$$

violating unitarity. The Higgs contributes with:

$$A_H(W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$

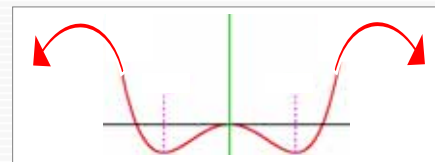


- **Landau Pole:** Higgs self-coupling in potential is UV divergent ($\rightarrow$ only good solution is “trivial”: $\lambda(M_W) \rightarrow 0$):

Coupling λ increases with mass μ : $\frac{d\lambda(\mu)}{d\ln\mu^2} \propto \lambda^2 \Rightarrow \lambda(\mu) = \frac{\lambda(\mu_0)}{1 - C\lambda(\mu_0)\ln(\mu/\mu_0)}$ denominator can be =0 $\rightarrow$ Landau pole!

Landau pole leads to upper limit: $m_H^2 \propto \lambda(v) < 53 \cdot v^2 \ln^{-1}(\Lambda/v) \approx 300 \text{ (1500) GeV} \left\{ \Lambda = 10^{19} \text{ (10}^3 \text{) GeV} \right\}$

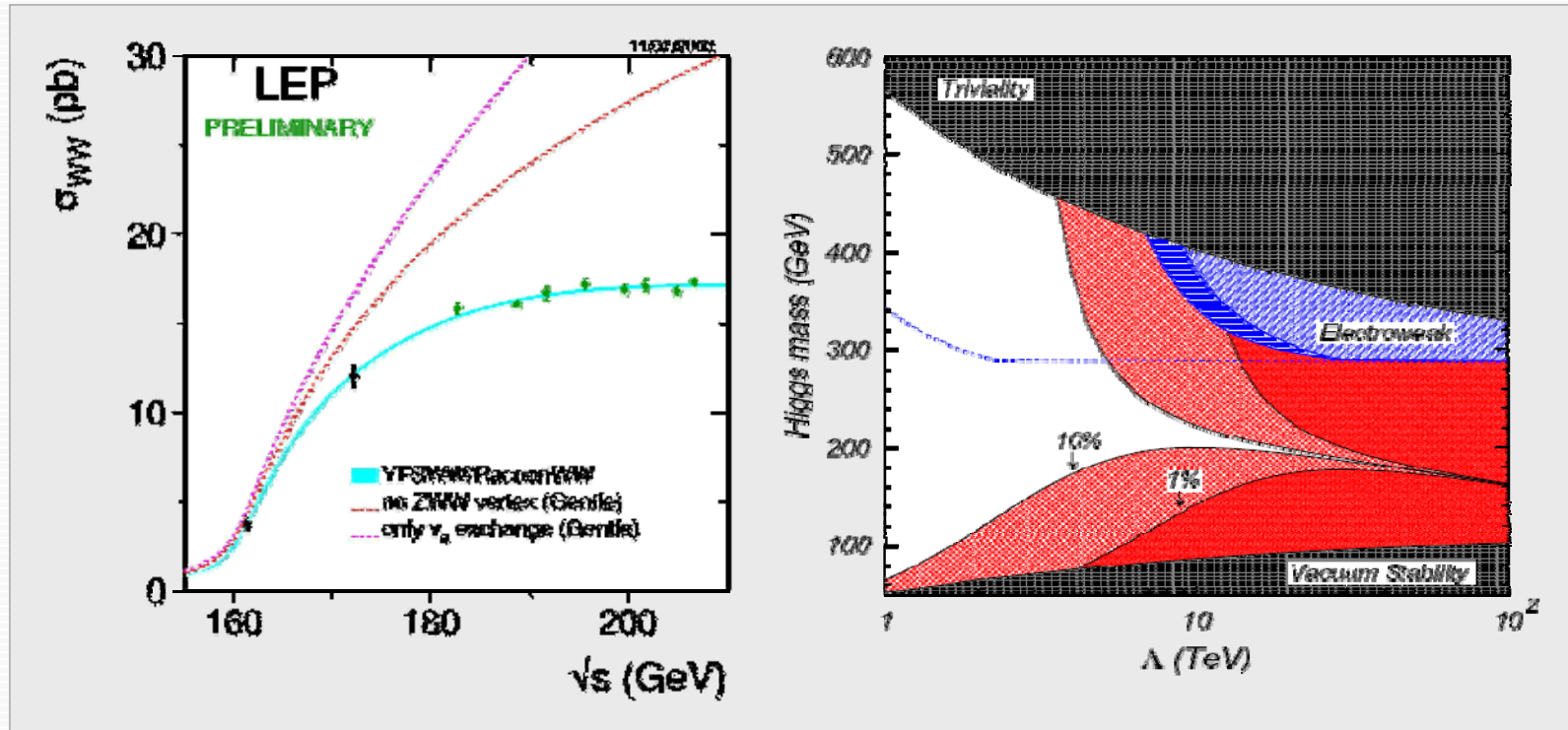
- **Stability:** for light Higgs (small λ), top quark contributions can decrease λ and make it negative; stability requirement leads to lower limit on m_H



Stability criterion:

$$\lambda(\mu) > 0, \forall \mu < \Lambda_{\text{cut-off}}$$

A Light Standard Model Higgs Boson

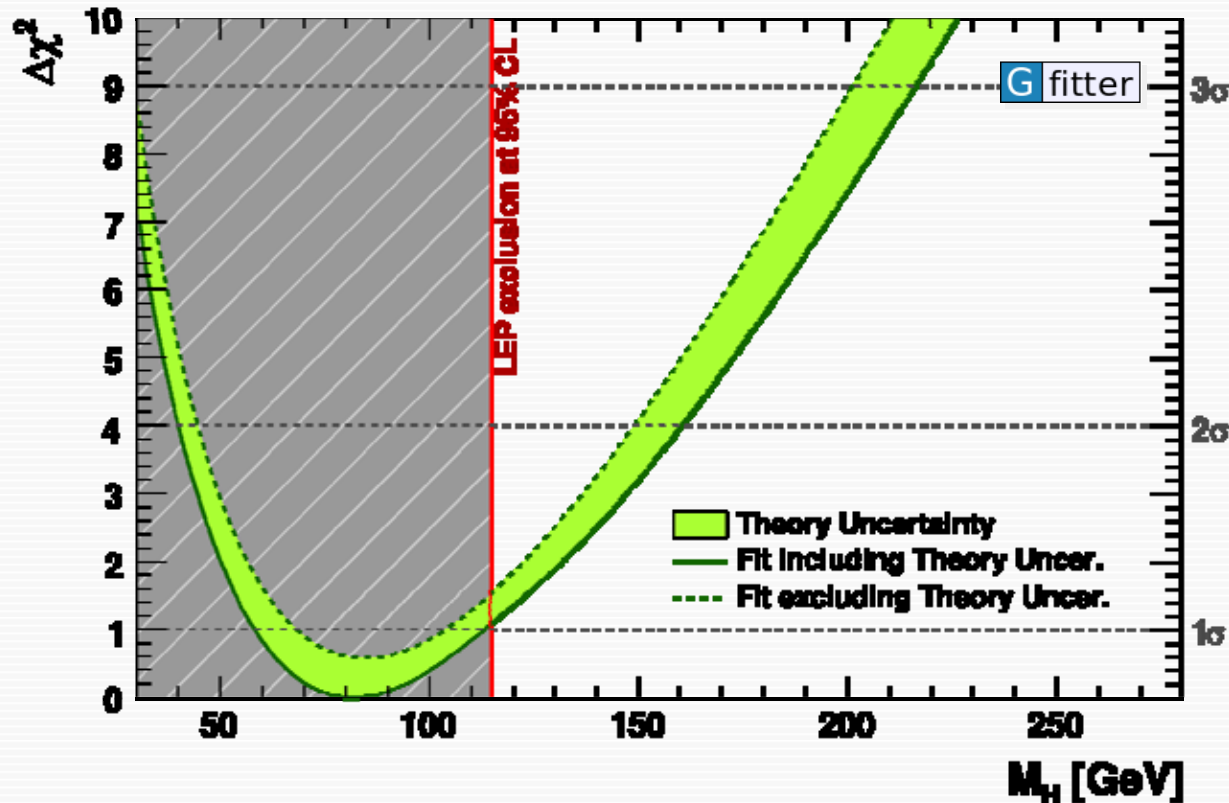


Experimental result: $e^+e^- \rightarrow W^+W^-$ cross section measured at LEP2. Contribution which grows like $s \cdot m_e^2$ is cancelled by Higgs amplitude

Higgs mass as a function of cut-off scale Λ

A Light Standard Model Higgs Boson

- The global fit of all the electroweak precision data from experiments at LEP, SLC, Tevatron accelerators constraints the Higgs to be light !



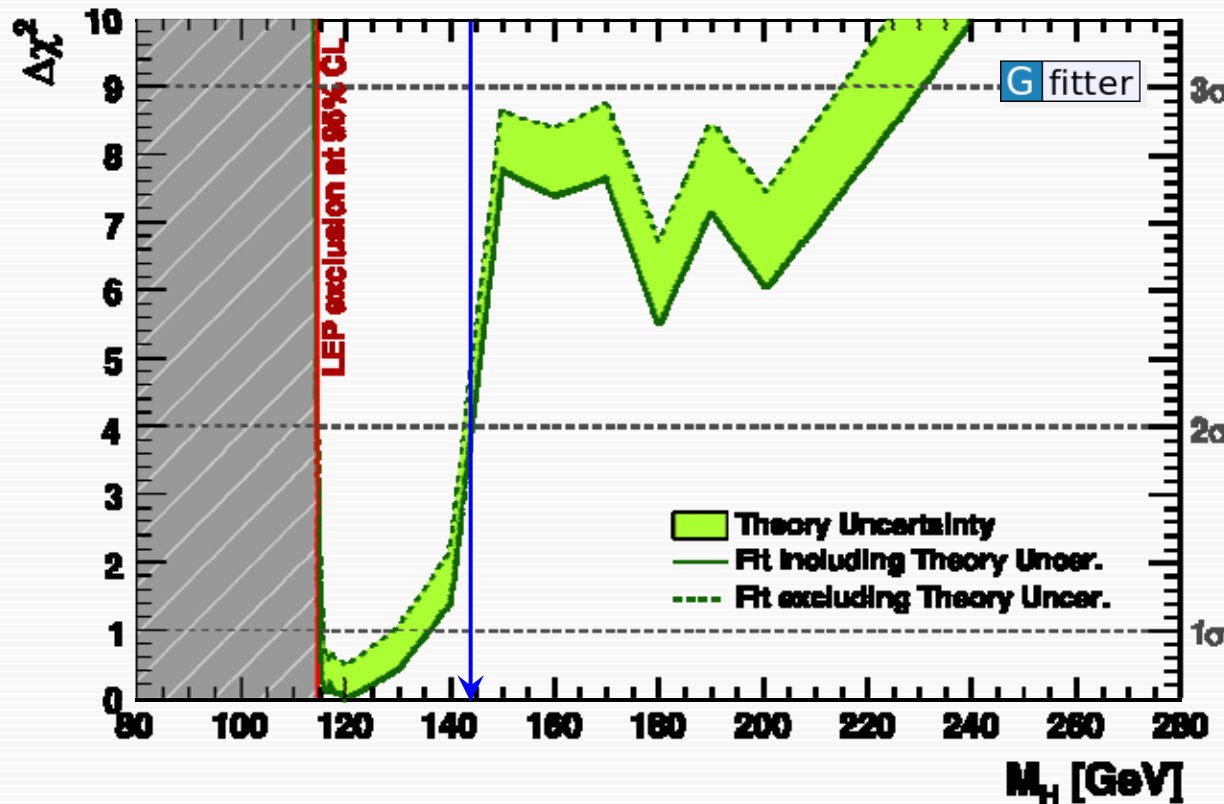
*Higgs mass
from fit to
electroweak
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$$\Delta\rho_{(\text{Higgs})} = \frac{11G_F m_Z^2 \cos^2 \theta_W}{24\sqrt{2}\pi^2} \log \left(\frac{m_H^2}{m_W^2} \right)$$

A Light Standard Model Higgs Boson

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Higgs mass from fit to electroweak precision data

Fit including constraint from direct searches at LEP and Tevatron



$$\Delta\rho_{(\text{Higgs})} = \frac{11G_F m_Z^2 \cos^2 \theta_W}{24\sqrt{2}\pi^2} \log \left(\frac{m_H^2}{m_W^2} \right)$$

The Mass of the Scalar is Unprotected !

- If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:



$$m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \underbrace{\int_0^\infty d^4k \frac{k^2 + m_f^2}{(k^2 + m_f^2)^2}}_{\text{Integral quadratically divergent}} + \dots$$

- The cut-off sets the scale where new particles and physical laws must come in
- Above the EW scale we only know of two scales: GUT ($\sim 10^{16}$ GeV) and Planck ($\sim 10^{19}$ GeV)
- Such a cut-off would require an incredible amount of finetuning to keep m_H light and stable

top loop largest contributor to δm_H . For $< 10\%$ finetuning need $\Lambda_{\text{cut-off}} < 2$ TeV

$$m_H^2 \stackrel{?}{=} (120 \text{ GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

The natural Higgs mass seems to be M_{Pl} rather than the experimentally favoured value...

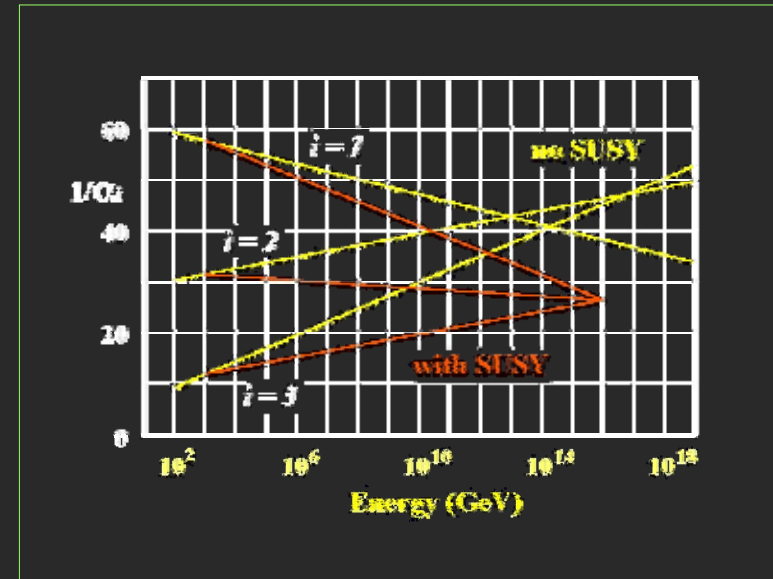
The “Hierarchy Problem”

The Gauge Hierarchy Problem...

- ...denotes this finetuning of parameters, and the strong dependence of physics at the weak scale on the physics at (presumably) much higher scale.
- If the loops are cut off at the scale of gravity, why is the scale of electroweak symmetry breaking so different from the scale of gravity? Why is $m_W \ll M_{\text{Pl}}$?
- Equivalently, why is gravity so weak? $G_F = \frac{g^2}{4\sqrt{2}m_W^2} \gg G_N = \frac{1}{M_{\text{Pl}}^2}$

The “Hierarchy Problem”

The Gauge Hierarchy Problem...

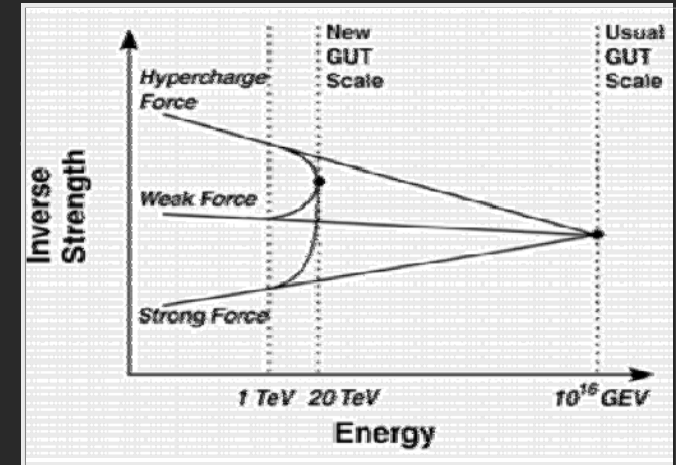


Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences.

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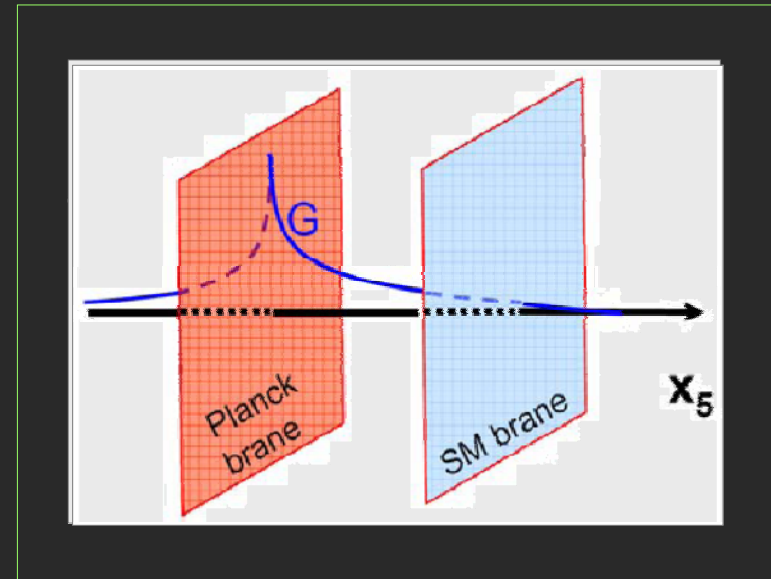


Possible solutions to the hierarchy problem:

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- New physics modifies the running of the couplings, approaching GUT to the EW scale.

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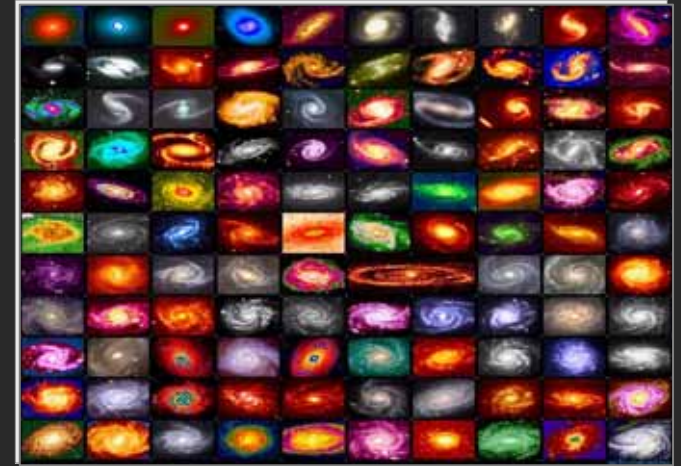


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- Gravity is not as weak as we think, it's only diluted in our 4D world but it is as strong as EW interactions in, e.g., 5 or more dimensions, $(M_{Pl})^{5D} \sim O(\text{TeV})$

The “Hierarchy Problem”

The Gauge Hierarchy Problem...



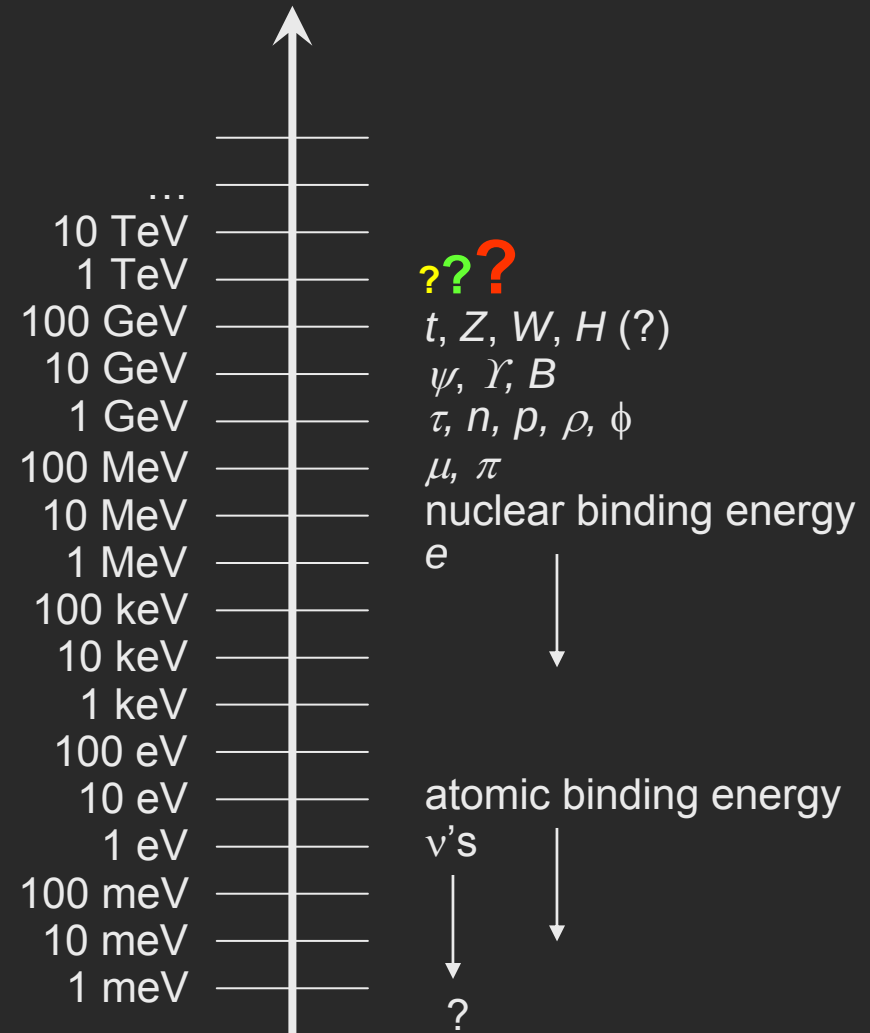
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- Anthropic principle: the theory is finetuned. Explanation for parameter values is statistical rather than dynamic.

New Physics: Why Not ?

© David E. Kaplan, HCP
Summer School, CERN 2007

Why should there be a
desert in the logarithmic
energy scale ?



New Physics: Yes, but How ?

There are also strong arguments against new physics at the TeV scale

- ➡ Electroweak precision data
- ➡ Flavour changing neutral currents
- ➡ Matter-antimatter symmetry violation in flavour and non-flavour sector
- ➡ Baryon and lepton number violation

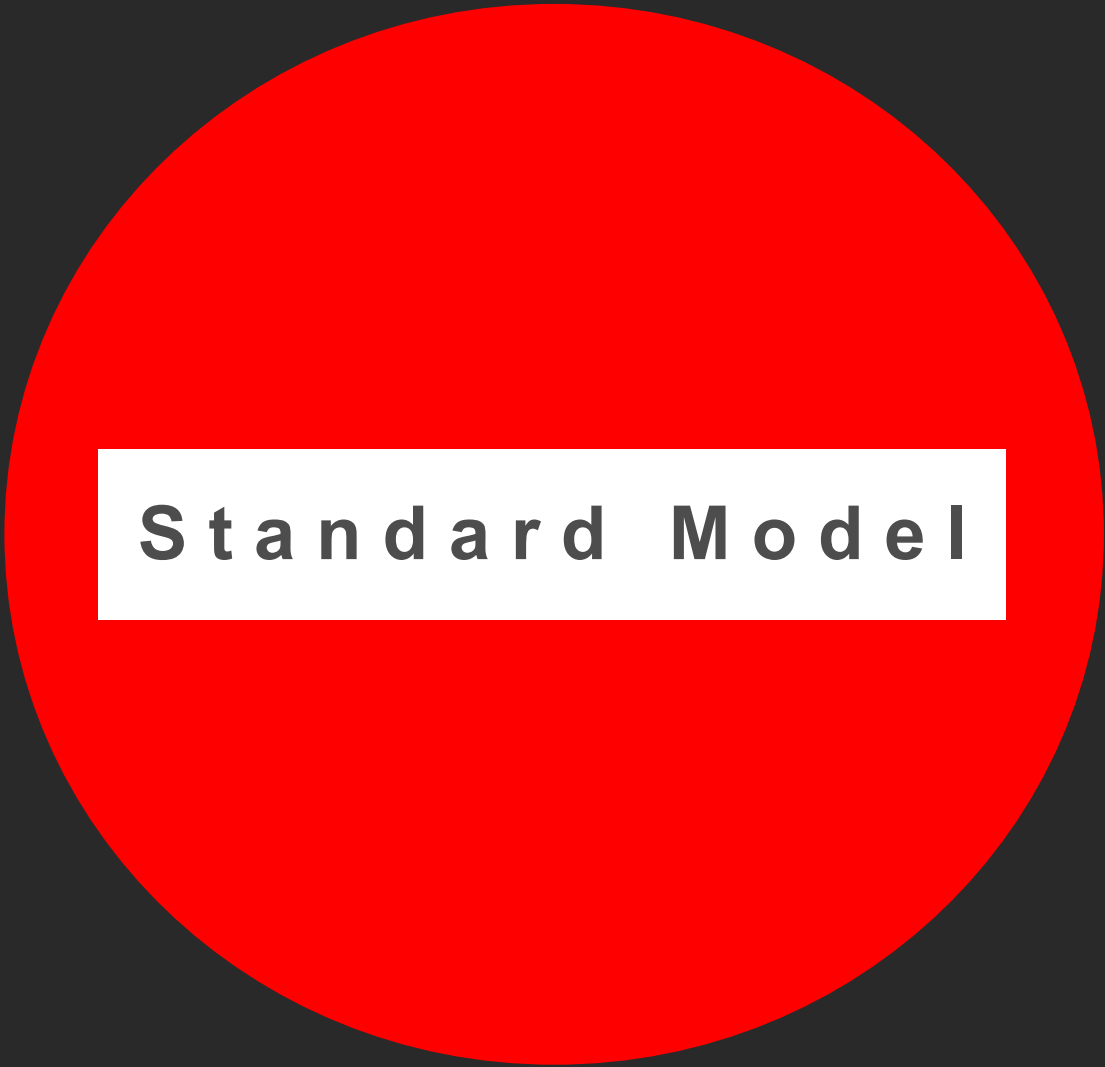
- The non-discovery of effects in precision measurements translates into strong constraints on the new physics properties
- How to stabilize the light Higgs without violating these constraints ?
- No trivial answer ... some finetuning seems to be always involved ?!

What the New Physics Should Be ...

Three diagrams give the largest contributions to the Higgs radiative corrections...

Top loop	$-(3/8\pi^2)\lambda_t^2\Lambda^2$	$\sim (2 \text{ TeV})^2$	Contributions of diagrams, assuming $\Lambda_{\text{cut-off}} \sim 10 \text{ TeV}$
Gauge boson loop	$(9/64\pi^2)g^2\Lambda^2$	$\sim (700 \text{ GeV})^2$	
Higgs loop	$-(1/16\pi^2)\lambda^2\Lambda^2$	$\sim (500 \text{ GeV})^2$	

- The total mass-squared of the Higgs is the sum of these contributions and the tree-level
- What would be the cut-off (= new physics) scales if only small ($\sim 10\%$) finetuning existed
 $\rightarrow \Lambda_{\text{top}} < 2 \text{ TeV}, \quad \Lambda_{\text{gauge}} < 5 \text{ TeV}, \quad \Lambda_{\text{Higgs}} < 10 \text{ TeV}$
- Hence... with a new physics sensitivity of $\sim 3 \text{ TeV}$, the LHC could discover the new physics !
- To naturally cancel these divergences, the new physics should **couple to the Higgs** and should **be related to the particles in the loop (top, gauge, Higgs) by some symmetry**



Standard Model

Extending the Standard Model

Models for new physics focus on curing the hierarchy problem and providing dark matter candidates

- ➡ **Supersymmetry**
- ➡ **Extra Dimensions**
- ➡ **Little Higgs**
- ➡ **Composite Higgs models with extra dimensions**

Some Observations Beforehand (II)

- The hierarchy problem (among others) of the SM Higgs sector can be turned into a prediction that **new physics** is expected at the TeV scale
- Since precision data do not give hints for new physics, we can use the data to constrain “**effective models**” that have the particle content of the SM, and where new physics is parameterized by loop operators suppressed by the new physics scale $\Lambda > O(\text{TeV})$.
- The operators can be categorized by the **symmetries they break**, for example:

Broken symmetry	Operators	$O(\Lambda)$
Baryon number	$(QQQL)/\Lambda^2$	10^{12} TeV
Flavour (1 st ,2 nd family), CP	$(dsds)/\Lambda^2$	10^4 TeV
Flavour (1 st ,3 rd family), CP	$(dbdb)/\Lambda^2$	10^3 TeV
Flavour (2 nd ,3 rd family), CP	$m_b(s\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50 TeV

example only... many more indirect constraints

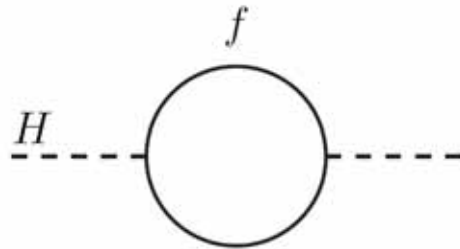
- The question is: **how to stabilize the light Higgs without violating the above bounds ?**
- The answer to this is by no means trivial, and the SM extensions discussed in the following only partially succeed in doing so ... some apparent finetuning seems to be always involved

Supersymmetry (SUSY)

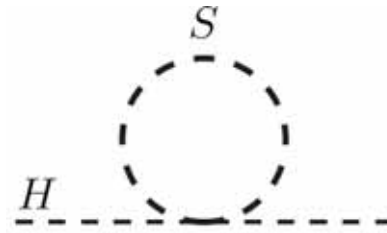
The light scalar **Higgs** boson is **unprotected at GUT/Planck scales**

Fermion and **boson** loops contribute with **different signs** to the Higgs radiative corrections: if there existed a **symmetry** relating these two, this could protect the masses of the scalar !

Fermion loop



Boson loop



Supersymmetry (SUSY)

The light scalar **Higgs** boson is **unprotected at GUT/Planck scales**

Fermion and **boson** loops contribute with **different signs** to the Higgs radiative corrections: if there existed a **symmetry** relating these two, this could protect the masses of the scalar !

Supersymmetry realises this by transforming **bosons** $\leftrightarrow$ **fermions**

- SUSY transforms for example a scalar boson into a spin- $\frac{1}{2}$ fermion, whose mass is protected
- Hence, the scalar mass is also protected (precisely through SUSY)
- ➡ This solves the **naturalness** and the **hierarchy problems** of the SM (at least technically)

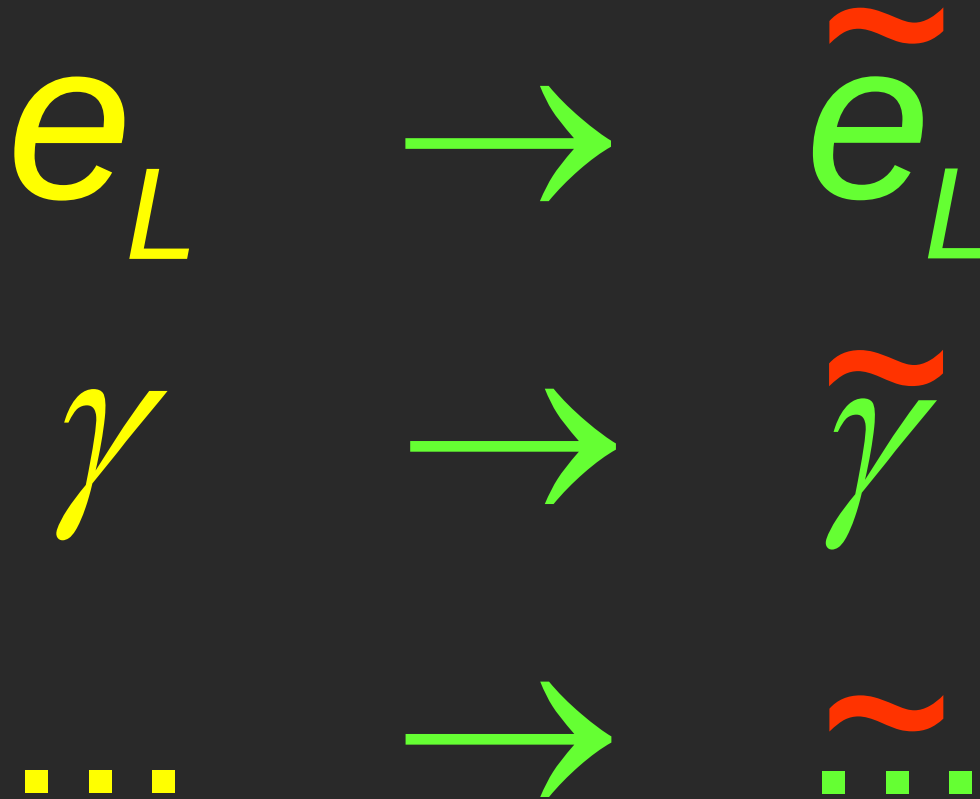
“Local gauge invariance” of SUSY requires existence of spin- $\frac{3}{2}$ and spin-2 particles

- This naturally introduces the **spin-2 graviton**, assumed to mediate the gravitational force

TeV-scale SUSY also achieves **Grand Unification** of the forces at $\sim 10^{16}$ GeV

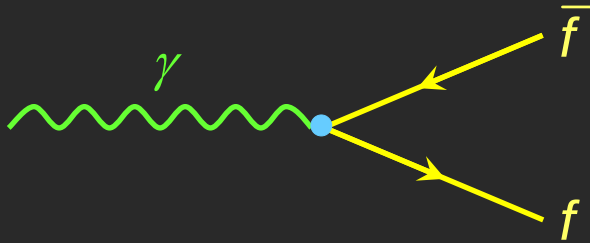
Since the “Super-partners” have not been seen yet, they must be (not too!) **heavy**

(SM $\rightarrow$ SUSY)

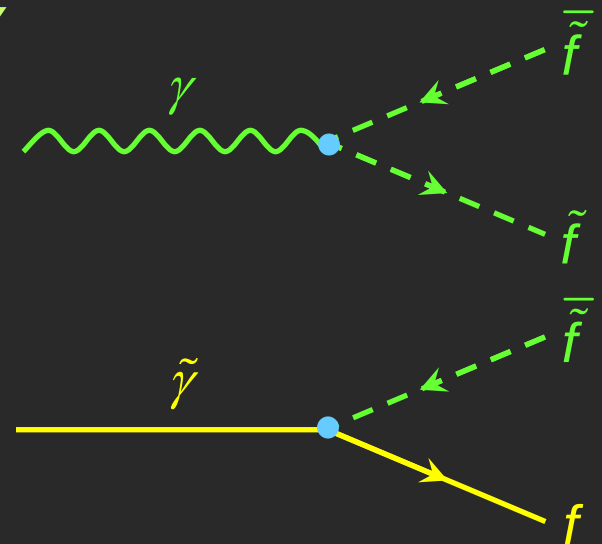


Interactions of SUSY Particles

SM



SUSY



Take any SM diagram and switch the spin of two lines

Minimal Supersymmetric Standard Model – MSSM

- SUSY has: $N_{\text{dof}}(\text{bosons}) = N_{\text{dof}}(\text{fermions})$ [cf. SM: $N_{\text{dof}}(\text{bosons}) \ll N_{\text{dof}}(\text{fermions})$]
 - ➡ To create **supermultiplets**, we need to add one **superpartner** to each SM particle
 - ➡ Superpartners have **opposite spin statistics** but otherwise **equal quantum numbers**
 - ➡ Need to introduce an **additional Higgs doublet** to the non-SUSY side

Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sLepton	Lepton		Gravitino	Graviton
sQuark	Quark			
Higgs	Higgsino			
	Photino	Photon		
	Zino	Z		
	Wino	W		
	Gluino	Gluon		
				SM
				SUSY

The MSSM Supermultiplets

Eigenstates of gauge	Superfield	Spin 0	Spin 1/2	Spin 1	SU(3)×SU(2)×U(1)	
	Q	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	—	$(3, 2, \frac{1}{3})$	
	U^c	$\tilde{u}_R^*$	$\bar{u}_R$	—	$(\bar{3}, 1, -\frac{4}{3})$	
	D^c	$\tilde{d}_R^*$	$\bar{d}_R$	—	$(\bar{3}, 1, \frac{2}{3})$	
	L	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_L$	$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	—	$(1, 2, -1)$	
	E^c	$\tilde{e}_R^*$	e_R	—	$(1, 1, 2)$	
	H_1	$\begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}_L$	$\begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_1^- \end{pmatrix}_L$	—	$(1, 2, -1)$	
	H_2	$\begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}_L$	$\begin{pmatrix} \tilde{H}_2^+ \\ \tilde{H}_2^0 \end{pmatrix}_L$	—	$(1, 2, 1)$	
	B	—	$\tilde{B}^0$	B^0	$(1, 1, 0)$	
	W	—	$\tilde{W}^{\pm,0}$	$W^{\pm,0}$	$(1, 3, 0)$	
	G	—	$\tilde{g}_a$	g_a	$(8, 1, 0)$	

Chiral
Super-
multiplets

Gauge
Super-
multiplets

The full particle content of the MSSM: each SM helicity state has a corresponding “spartner” (the indices indicate the helicities of the SM partner)

The MSSM Supermultiplets

Eigenstates of mass	Spin 0	Spin 1/2	Spin 1
	$\tilde{l}_1, \tilde{l}_2$	ℓ	SM
	$\tilde{q}_1, \tilde{q}_2$	q	SUSY
	$h^0, H^0, A^0, H^\pm$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	
		$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\gamma, Z^0, W^\pm$
		$\tilde{g}_a$	g_a

The gauge-mixed physical states that propagate in space and time and that can be observed.

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

Charginos : mass eigenstates of winos and charged higgsinos

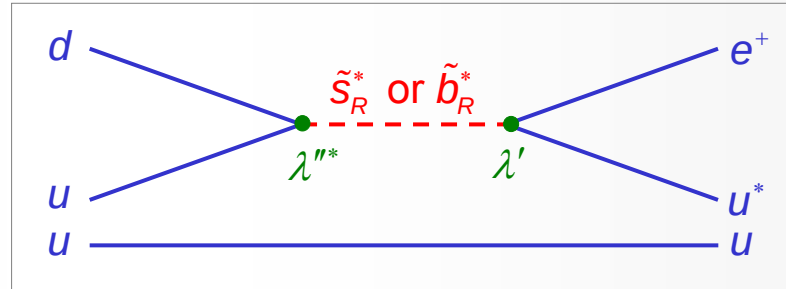
Note: all scalar particles with same e-charge, colour and parity quantum numbers can mix !

R-Parity

- The *superpotential* contains new lepton- or baryon number violating couplings

$$\left[\frac{1}{2} \lambda \cdot L L E^c + \lambda' \cdot L Q D^c + \mu' \cdot L H_2 \right]_{\Delta L=1}$$

$$\left[\frac{1}{2} \lambda'' \cdot U^c D^c D^c \right]_{\Delta B=1}$$



Proton decay
 $p \rightarrow e^+ \pi^0$
 Unless couplings
 very small – or
 sfermions very
 heavy

- Avoid proton decay by introducing discrete *R*-parity (or matter-parity):

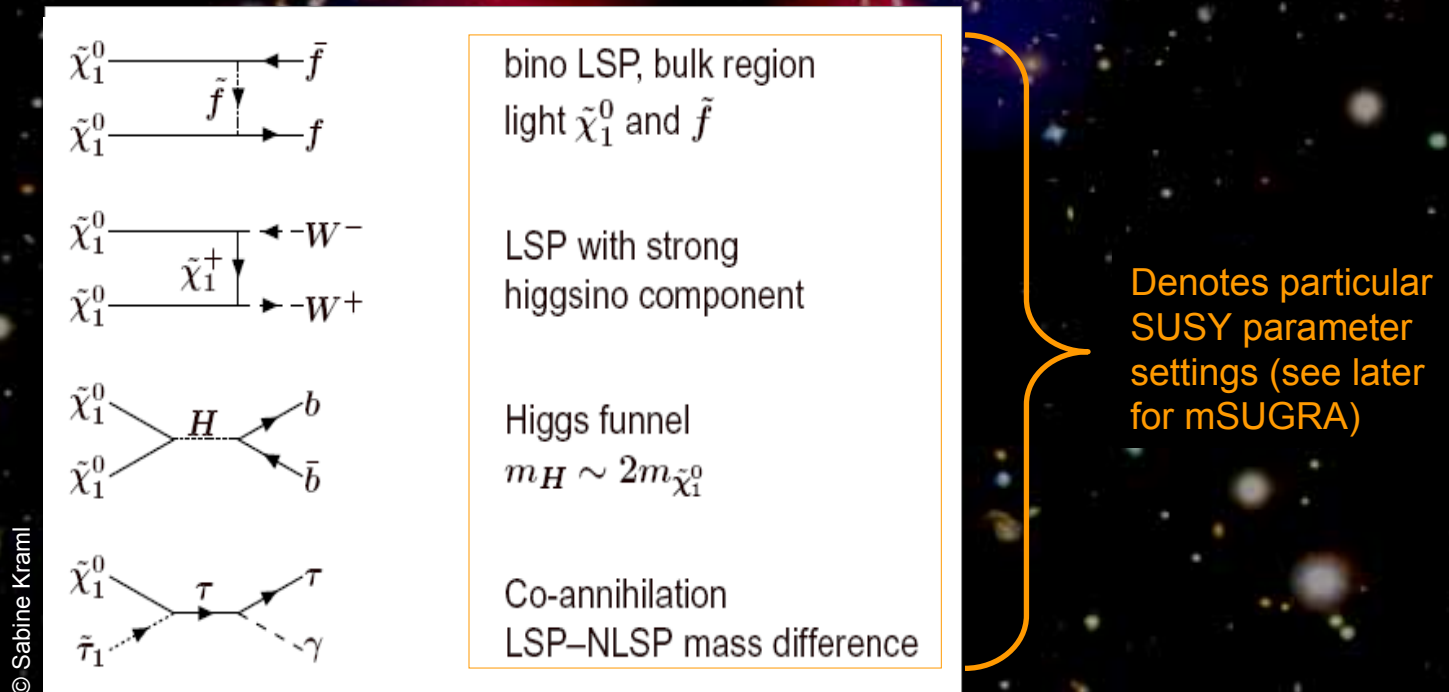
$$R = (-1)^{3B+L+2S} = \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for SUSY partners} \end{cases}$$

- ➡ All interactions with odd numbers of SUSY particles are forbidden (SUSY production in pairs !)
- ➡ The lightest SUSY particle (LSP) is stable; if LSP neutral $\rightarrow$ missing energy in detector
- ➡ SUSY naturally provides a dark matter candidate (should be neutral (WIMP) $\rightarrow \tilde{\chi}_1^0$ LSP candidate)

- *R*-parity has important phenomenological and experimental consequences (see later)

SUSY and Dark Matter

- R -parity provides **dark matter candidates**: sneutrino (ruled out?), gravitino and **neutralino**
 - The χ^0 **LSP** as **thermal relic**: relic density computed as thermally averaged cross section of all χ^0 annihilation channels $\rightarrow$ **Cold dark matter density**: $\Omega_{\text{DM}} h^2 \sim \langle \sigma v \rangle^{-1} \sim 1 \text{ pb}^{-1}$
 - ➡ **CMB measurement**: $0.094 < \Omega_{\text{DM}} h^2 < 0.129$ strongly bounds SUSY parameter space
 $\rightarrow$ **Need to annihilate the LSPs to avoid over-abundance !**
- [However, bounds are model-dependent: MSSM parameters, R -parity, other DM candidates, ...]



SUSY Breaking

SUSY – if it exists – must be broken to create (heavy) masses of the Superpartners

- Spontaneous SUSY breaking is much more complicated than the EWSB in the SM
- Masses are added by hand to the SUSY Lagrangian (“soft” symmetry breaking)
 - Unlike massive fermions, massive sfermions do not break gauge symmetry of the Lagrangian
 - **Masses should not be $\gg$ TeV to not reintroduce the hierarchy problem !**

$\tilde{A}^\dagger \mathbf{m}_A^2 \tilde{A}$, where: $\tilde{A} = \tilde{Q}, \tilde{L}, \tilde{U}^c, \tilde{D}^c, \tilde{E}^c$

$m_{H_1}^2 H_1^* H_1 + m_{H_2}^2 H_2^* H_2 + (\mu B \cdot H_1 H_2 + \text{h.c.})$

$\tilde{U}^c \mathbf{A}_u \tilde{Q} H_2 + \tilde{D}^c \mathbf{A}_d \tilde{Q} H_1 + \tilde{E}^c \mathbf{A}_e \tilde{L} H_1 + \text{h.c.}$

$M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g}_a \tilde{g}_a + \text{c.c.}$

Squark and slepton terms ($\mathbf{m}_A^2$: 3×3 matrix)

Higgs boson mass terms

Trilinear Yukawa couplings ($\mathbf{A}_i$: 3×3 matrices)

Gaugino mass terms

The MSSM has 124 Parameters of which 44 are *CP*-violating phases → why not seen yet ?

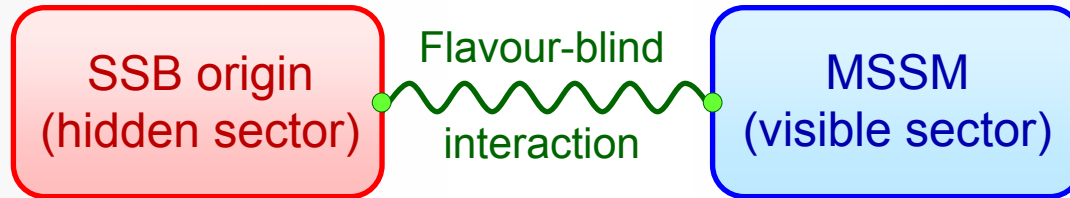
Gaugino Mass Hierarchies

Hierarchy	Phenomenological Consequences
$M_3 > M_2 > M_1$	mSUGRA – Jets, leptons & missing energy
$M_3 > M_1 > M_2$	Lepton cascades, lightest slepton charged
$M_2 > M_3 > M_1$	Only jets & missing energy
$M_1 > M_3 > M_2$	Jets & missing energy and/or lightest slepton charged
$M_2 > M_1 > M_3$	Gluino may be long lived, at least 4-body decay

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C(onstrained)MSSMs: Modeling SUSY Breaking

- One can assume that SSB is hidden, and the various models then differ in how the SSB is transmitted through flavour-blind interactions to the observables



- Through **gravitational interaction (SUGRA)**: the minimum model **mSUGRA** has only 5 parameters:

At GUT scale $\Rightarrow$

$$\begin{aligned}
 m_0^2 &= M_{\tilde{Q}}^2 = M_{\tilde{U}}^2 = M_{\tilde{D}}^2 = M_{\tilde{L}}^2 = M_{\tilde{E}}^2 = m_{H_1}^2 = m_{H_2}^2 \\
 m_{1/2} &= M_1 = M_2 = M_3 \\
 A_0 &= A_u = A_d = A_e \\
 \tan \beta &= v_2/v_1 \\
 \text{sgn}(\mu) &
 \end{aligned}$$

The renormalisation group equations govern the running to the EW scale

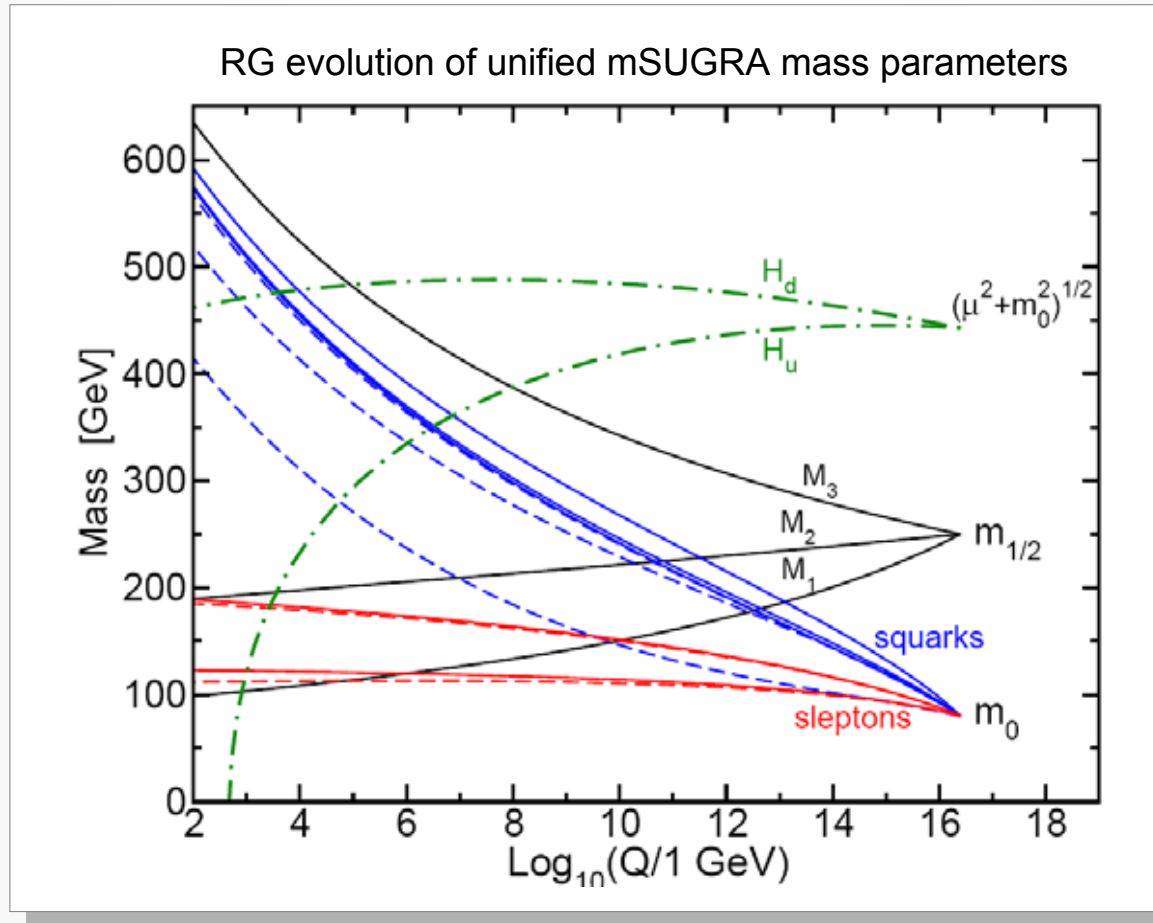
At one loop all M_i/α_i are equal, so that:

$$m_{\tilde{q}} \gg m_{\tilde{\ell}_L} \approx m_{\tilde{\nu}} < m_{\tilde{\ell}_R}$$

Lightest neutralino is LSP

- Through **gauge interaction (GMSB)**: “messenger fields” transmit the SSB to the MSSM
 - The SSB scale is much smaller than in SUGRA
 - Very light gravitino is LSP, different experimental signature than SUGRA (where $m_{3/2} \sim m_{\text{soft}}$)

C(onstrained)MSSMs: Modeling SUSY Breaking



The Supersymmetric Higgs Sector

- At least 2 Higgs doublets with opposite hypercharge (Y_H) are necessary to realise EWSB

$$H_1^{Y_{H_1}=-1} = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2^{Y_{H_2}=+1} = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

Theoretical reasons:

1. Require $\sum_{f \in \text{Gen.}} Y_f = 0$ to cancel chiral anomalies
2. In SM, masses of weak isospin fermions created by ϕ and $i\tau_2\phi^*$, but conjugated superfields not allowed in superpotential

- VEVs $v_{1(2)}$ and $v_{1(2)}$ give masses to fermions with weak isospin $I_z = -1/2$ [d_i, e_i] and $+1/2$ [u_i, ν_i]
- Their ratio determines the mixing parameter: $\tan\beta = v_2 / v_1$

- After EWSB, 5 out of 8 degrees of freedom (dof) become the physical Higgs fields

$$h_{\text{CP-even}}^{(\text{light})}, H_{\text{CP-even}}^{(\text{heavy})}, A_{\text{CP-odd}}, H^+, H^-$$

- As in the SM, the remaining 3 dof become the longitudinal modes of W^+ , W^- and Z^0

- The masses of the physical fields are obtained by minimising the Higgs potential; at tree level:

$$m_h = \frac{1}{\sqrt{2}} \left(m_A^2 + m_Z^2 - \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos 2\beta} \right)^{1/2} < m_Z \quad \rightarrow \text{Upper limit !!!}$$

- ➡ If there weren't higher order corrections ($m_h < 128$ GeV) it would have been excluded already !

The Supersymmetric Higgs Sector

Higgs radiative corrections

$$\delta m_h^2 = \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \dots$$



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- ➡ If there weren't higher order corrections ($m_h < 128$ GeV) it would have been excluded already !

SUSY – Résumé and Comments



- The MSSM naturally responds to a number of SM problems:
 - The quadratic divergence of the Higgs radiative corrections becomes logarithmic
 - SUSY “naturalises” the Higgs and cures the hierarchy problem by introducing new fields at $O(\text{TeV})$
 - Grand unification of the forces at high scale is achieved
 - A spin-2 graviton (and a spin-3/2 gravitino) is naturally embedded in SUSY
 - SUSY provides a cold dark matter candidate $\rightarrow$ LSP
- BUT: no experimental evidence for SUSY yet $\rightarrow$ the MSSM requires finetuning (“little hierarchy problem”)
- Other SUSY models exist, which attempt to improve on these problems:
 - Split SUSY
 - Next-to-MSSM
 - ...



Extending the Standard Model

- ▶ Supersymmetry
- ▶ **Extra dimensions**
- ▶ Little Higgs

Perhaps the problem
with the hierarchy is that
we use the wrong M_{Pl} ?

Could there be strong
gravity at the TeV scale ?

Indeed, if there were
extra spatial dimensions
into which gravity
propagates, it could only
appear weak to us in 4D

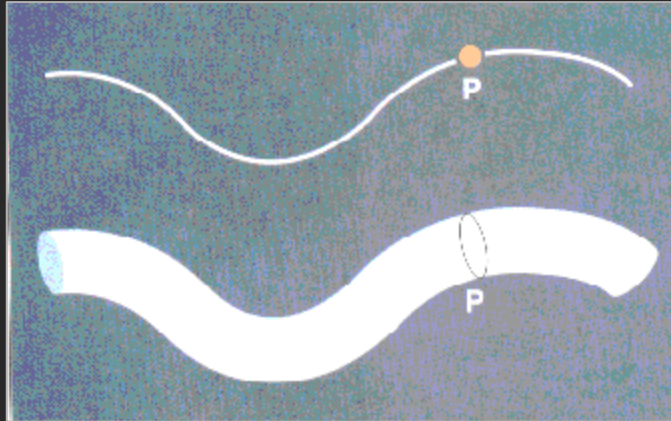
Quantity	Value
Planck Mass	$1.2 \times 10^{19} \text{ GeV}/c^2$
Planck Length	$1.6 \times 10^{-33} \text{ cm}$
Planck Time	$5.4 \times 10^{-44} \text{ s}$
Planck Temperature	$1.4 \times 10^{32} \text{ K}$

Extra Dimensions (EDs) ?

- Since the very end of the last century, an old theory (~1920), invented to unify gravitation and EM interaction was rediscovered to solve the hierarchy problem... the **Kaluza-Klein theory**
- ED theories associate “Kaluza-Klein towers” with the particles propagating in (compact) EDs
- String theory requires 10–11 space-time dimensions → **≤ 7 extra spatial dimensions (ED) ?**
- String theory acts at scale $M_{\text{string}} \sim M_{\text{Pl}} \sim 10^{19} \text{ GeV} \sim 1.6 \cdot 10^{-33} \text{ cm} \rightarrow$ **not observable at LHC**
- Up to $M_{\text{EW}} \sim 10^2 \text{ GeV} \sim 1.6 \cdot 10^{-16} \text{ cm}$ **[SM], and 10^{-2} cm [Gravitation] EDs can be excluded**
- Relatively large EDs in which gravitons propagate are thus not excluded; the SM particles could be confined in a smaller sub-space: a “**brane**”
- Gravity would allow us to probe the EDs
- Unfortunately, since gravity is a very weak force, and the EDs are small, we can hardly see the effects of them in a laboratory... **unless gravitation could be amplified making extra dimensions of up to a mm possible ?**

**If there are extra (spatial) dimensions,
why did we only observe 3 spatial dimensions so far ?**

Extra Dimensions are Compactified ...



Extra space dimensions are hidden from view because they are "compactified", *i.e.*, tightly rolled up. In this demonstration, a 2D surface is rolled up in a tube (bottom), becoming so tightly rolled that it looks like a 1D line (top).
[Graphics by Mark McLellan].

If the size of the compact ED is much smaller than the wavelength of the particles we are observing, then the ED could remain hidden

Extra Dimensions and Newton's Gravitation

■ Let us consider d EDs with some size R , the distance r_{12} between two masses m_1 and m_2

■ If $r_{12} \gg R$, we approximately live in a 4D world with gravitational force:

$$F^{(4)}(r_{12}) = \frac{G^{(4)} m_1 m_2}{r_{12}^2} = \frac{m_1 m_2}{\left(M_{\text{Pl}}^{(4)}\right)^2 \cdot r_{12}^2}$$

■ If $r_{12} \ll R$, we live in a $(4+d)$ D world with the modified Newton force:

$$F^{(4+d)}(r_{12}) = \frac{G^{(4+d)} m_1 m_2}{r_{12}^{d+2}} = \frac{m_1 m_2}{\left(M_{\text{Pl}}^{(4+d)}\right)^{d+2} \cdot r_{12}^{d+2}}$$

■ From continuity at $r_{12} = R$, one finds:

$$\left(M_{\text{Pl}}^{(4)}\right)^2 = \left(M_{\text{Pl}}^{(4+d)}\right)^{d+2} \cdot R^d$$

➡ At the LHC scale of $M_D \equiv M_{\text{Pl}}^{(4+d)} \sim 1 \text{ TeV}$, one finds:

4D gravity is diluted by the extra dimension !

The Planck scale is no longer fundamental !

$G^{(4)}$ is only a reflection of the real gravitational constant $G^{(5)}$, reduced by the extra dimension !

$d=1$: $R \sim 10^{14} \text{ cm}$ (excluded from large scale gravitation tests, e.g., planetary orbits)

$d=2$: $R \sim 10^{-2} \text{ cm}$ (limit from gravitation tests) → only probes energy scale $R^{-1} \sim 2 \cdot 10^{-3} \text{ eV}$!

$d=3$: $R \sim 10^{-7} \text{ cm}$ (allowed)

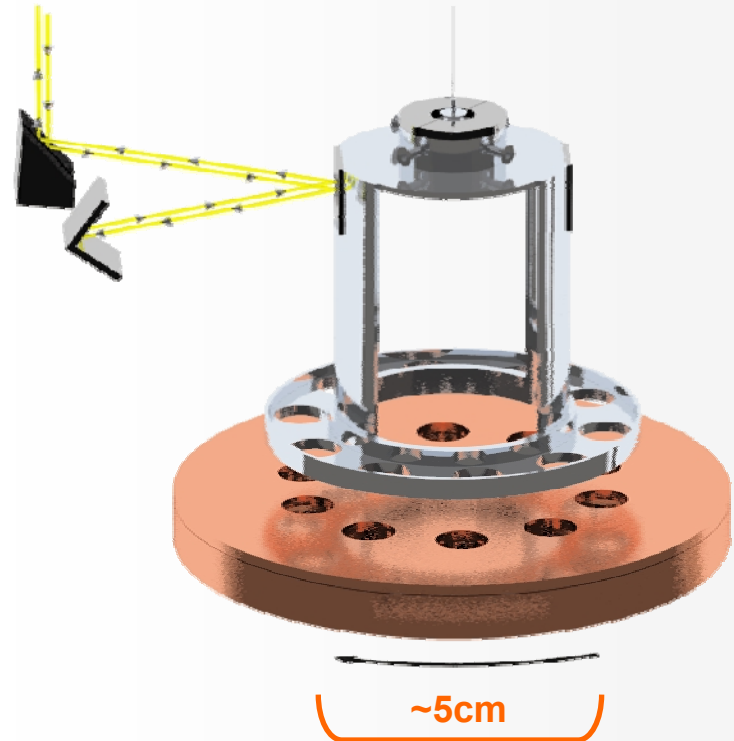
Measuring Gravity at Short Distances

- Parametrise break-down of $1/r^2$ law by:
$$V(r_{12}) = \frac{Gm_1m_2}{r_{12}} \left[1 + \alpha \cdot e^{-r_{12}/\lambda} \right]$$

Hoyle *et al.*
hep-ph/0405262

- **Eöt-Wash Torsion pendulum experiments:**

- *Missing* masses are 10 holes in Al ring
- 2 Cu rotating attractor disks with 10 holes
- Upper disk: holes as Al ring
- Lower (thicker) disk: holes displaced
- If $G = \text{Newton}$, twists from both disks cancel
- Twist measured by reflecting laser light
- Surfaces gold-coated to shield EM forces



- Newtonian fits agree with observed twist patterns (2006 results)

- ➔ 1 dominant ED: $R < 44 \mu\text{m}$
- ➔ 2 equal sized EDs: $M_D > 3.2 \text{ TeV}$

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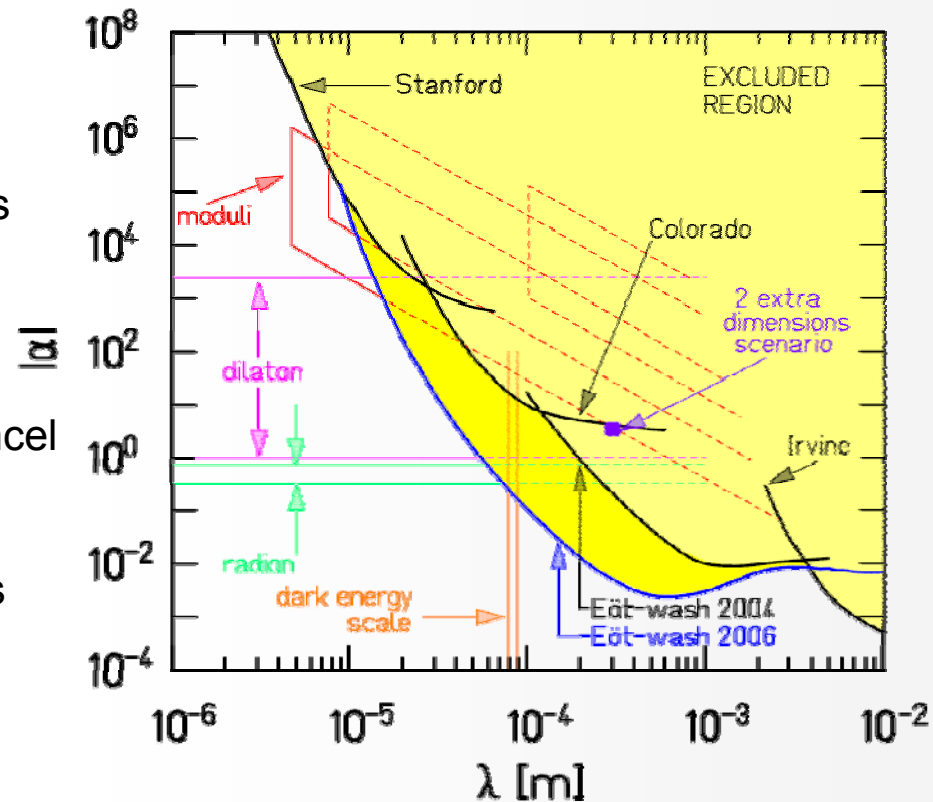
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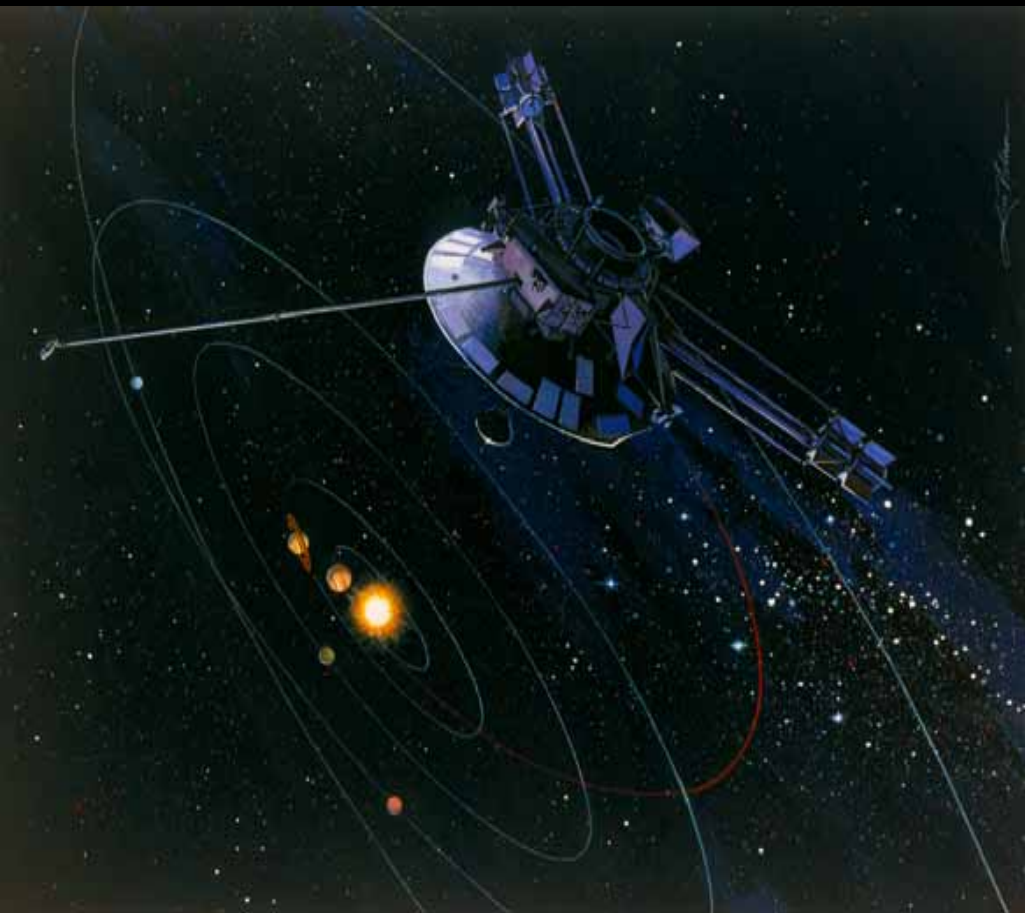
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- ➔ 2 equal sized EDs: $M_D > 3.2 \text{ TeV}$



The Pioneer 10 /11 Anomaly

Pioneer 10: launched in March 2, 1972; it left the solar system 1983;
now heading towards Aldebaran (Taurus constellation)



- Anomaly consists of (blue-shifted) Doppler frequency drift, that can be interpreted as acceleration of $\sim 10^{-9}$ g towards Sun
- ➡ Known systematic effects $\sim 15\%$ (incl. computation accuracy and internal and external spacecraft systems)
- ➡ Unknown systematics ?
 - Gas leaks [would be sufficient, but why both spacecrafts, and why directed]
 - Heat [much available from PI source; however, wouldn't be constant over all times]
- ➡ **Modified gravity ?**

see, e.g., Anderson *et al.*
gr- qc/0104064

Kaluza-Klein Towers

Suppose a massless scalar ϕ in 5D space. 1D, y , is compactified on a circle with radius R

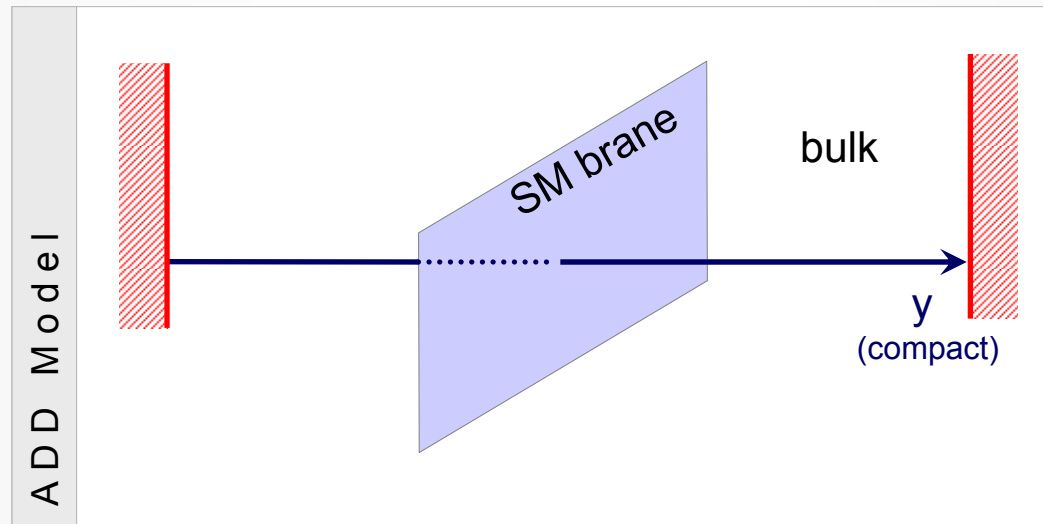
- This requires periodic boundary conditions: $\phi(x^{(4)}, y) = \phi(x^{(4)}, y + n \cdot 2\pi R)$, $n \in \mathbb{Z}$
which translate into a quantification of the momentum in this dimension: $p = n/R$
- Developing ϕ into a Fourier series of y ,

$$\phi(x^{(4)}, y) = \sum_n \phi_n = \sum_n \phi(x^{(4)}) e^{iny}$$

one finds that the ensemble of ϕ_n represents a **Kaluza-Klein (KK) tower** of momentum eigenstates (**KK-modes**) and the mass-squared of the mode ϕ_n in 4D (solution of Klein-Gordon equation) is given by:

$$m_n^2 = m_0^2 + \left(\frac{n}{R}\right)^2 \Rightarrow \Delta m = \frac{1}{R} \overset{R \sim 2 \times 10^{-17} \text{ cm}}{\sim} 1 \text{ TeV} \quad (n^{\text{th}} \text{ excitations of ground state})$$

Large Extra Dimensions: The ADD Model



Arkani-Hamed, Dimopoulos,
Dvali, hep-ph/9803315
3272 citations to date !

- The SM fields are trapped on 4D SM brane; only gravitons see the ED y and have KK states
- The small 4D coupling of the graviton to the SM particles is compensated at large enough energy by the large number of accessible KK states that is summed over
- No momentum conservation per ED, *i.e.*, gravitons are emitted into ED by SM fields
- Main ADD ED signatures at the LHC:
 1. $pp \rightarrow \text{jet} + \text{missing energy}$ (from undetected sum of accessible KK graviton towers)
 2. gravitons can modify SM cross sections through loops (here: all KK towers are virtually accessible)

Small Universal Extra Dimensions

ADD Model

Universal Extra Dimensions

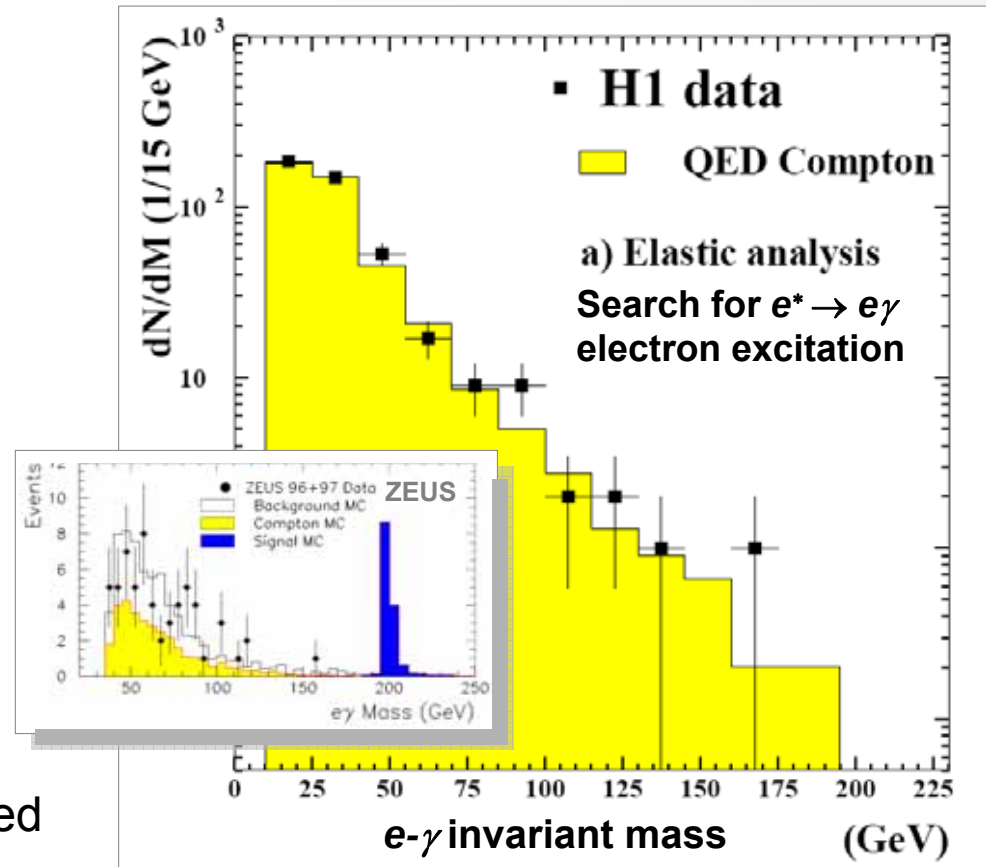
Variation of this model for **small EDs**: let SM propagate into the bulk. Translation invariance along ED provides conservation of KK number in 4D theory $\rightarrow$ “**LKP**” for **odd number of EDs** (“KK parity” $(-1)^n$). SUSY-like phenomenology.

$\rightarrow$ **KK states of SM particles: heavy Z' , γ'**

[Appelquist-Cheng-Dobrescu , 2001]

Gauge Forces in the Bulk ?

- Interactions between SM fields measured to very high accuracy $\sim 10^{-16}$ cm
- If gauge forces acted in the bulk, deviations to SM should be measurable
- Indeed, the boundary conditions in the compactified ED would create KK towers ($\rightarrow Z', \gamma', \dots$ excitations) for SM fields
- For large EDs, the KK mass splitting would be small enough to be observable
- Lepton excitations also occur for compositeness models parametrised by contact interaction terms



Unfortunately, there is a little secret in the ADD model.

The original purpose of it to eliminate the hierarchy problem is missed: although the true $(4+d)$ Planck scale is indeed of $O(EW)$, one finds that $R \cdot M_D = (M_{Pl}/M_D)^{2/d}$ is a very large number (due to the large EDs).

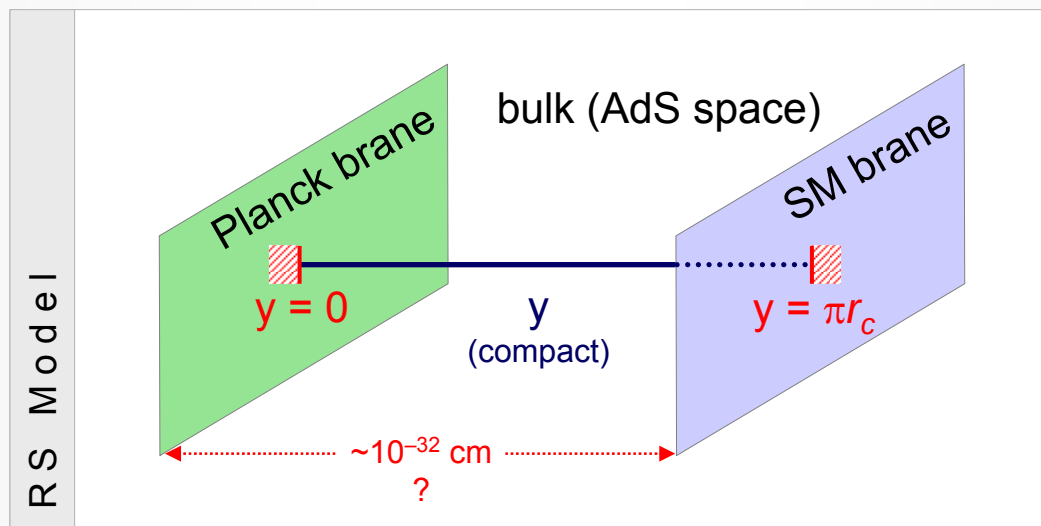
→ ADD trades one hierarchy problem for another one !

Until now it was assumed that the extra dimensions are flat, or only weakly curved, and that they factorise with the other spatial dimensions

But the extra dimension could also be strongly curved (or "warped") by a large negative cosmological constant.

This has surprising consequences...

Warped Extra Dimensions



Randal-Sundrum,
hep-ph/9905221
3526 citations to date !

- As ADD, but special metric: $ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 \rightarrow$ 4D subspace depends on y
- Parameter k has dimension; basic assumption of RS: no mass hierarchies $\rightarrow k \sim M_D \sim M_{\text{Pl}}$
- Solving Einstein's equations and integrating out y , one finds for 4D: $M_{\text{Pl}} = \frac{M_D^2}{k} \left(1 - \underbrace{e^{-2\pi k r_c}} \right)$
- For a mass $m_0 \sim M_{\text{Pl}}$, we – on the SM brane – see the red-shifted: $m = m_0 e^{-\pi k r_c}$! “warp factor” $O(10^{-15})$ for $k r_c \sim 11 \rightarrow$ large hierarchy is naturally explained by exponential factor !
- Signature at the LHC: the KK gravitons-to-SM couplings are enhanced by warp factor
 - ➡ Weak scale graviton KKs with weak scale couplings should produce universal spin-2 resonances !

Warped Extra Dimensions

Randal-Sundrum,
hep-ph/9905221
3526 citations to date !

bulk (AdS space)

If discovered, to truly identify these spin-2 resonances as gravitons, one needs to demonstrate:

1. That it is indeed spin-2 (“easy” from angular distribution)
2. That couplings are universal (general relativity)
→ measure branching ratios

- Parameter k has dimension; basic assumption of RS: no mass hierarchies → $k \sim M_D \sim M_{\text{Pl}}$
- Solving Einstein’s equations and integrating out y , one finds for 4D: $M_{\text{Pl}} = \frac{M_D^2}{k} \left(1 - \underbrace{e^{-2\pi k r_c}} \right)$
- For a mass $m_0 \sim M_{\text{Pl}}$, we – on the SM brane – see the red-shifted: $m = m_0 e^{-\pi k r_c}$! “warp factor” $O(10^{-15})$ for $k r_c \sim 11$ → large hierarchy is naturally explained by exponential factor !
- Signature at the LHC: the KK gravitons-to-SM couplings are enhanced by warp factor
➡ Weak scale graviton KKs with weak scale couplings should produce universal spin-2 resonances !

EDs in Astrophysics and Cosmology



- Large EDs would act only after the inflation period; they could influence:
 - Primordial nucleosynthesis
 - Cosmic microwave background – if the gravitons decay into photons by interacting with the SM brane
- A priori, nothing is known about cosmology when we enter the domain of strong gravitation. For example: non-perturbative effects could occur
- EDs could modify the ν -nucleon scattering cross section of ultra-high energetic cosmic ν 's
- EDs could modify deflection angle of gravitational lensing [limit: for $d=2$, $M_D > 4$ TeV]
- EDs could influence the maximum allowed mass for neutron stars, and contribute to cooling of stars: limit on ED scale from super nova (SN1987A) [$d=2$, $M_D > 50$ TeV, $d=4$, $M_D > 1$ TeV]



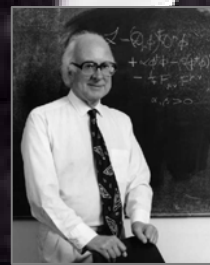
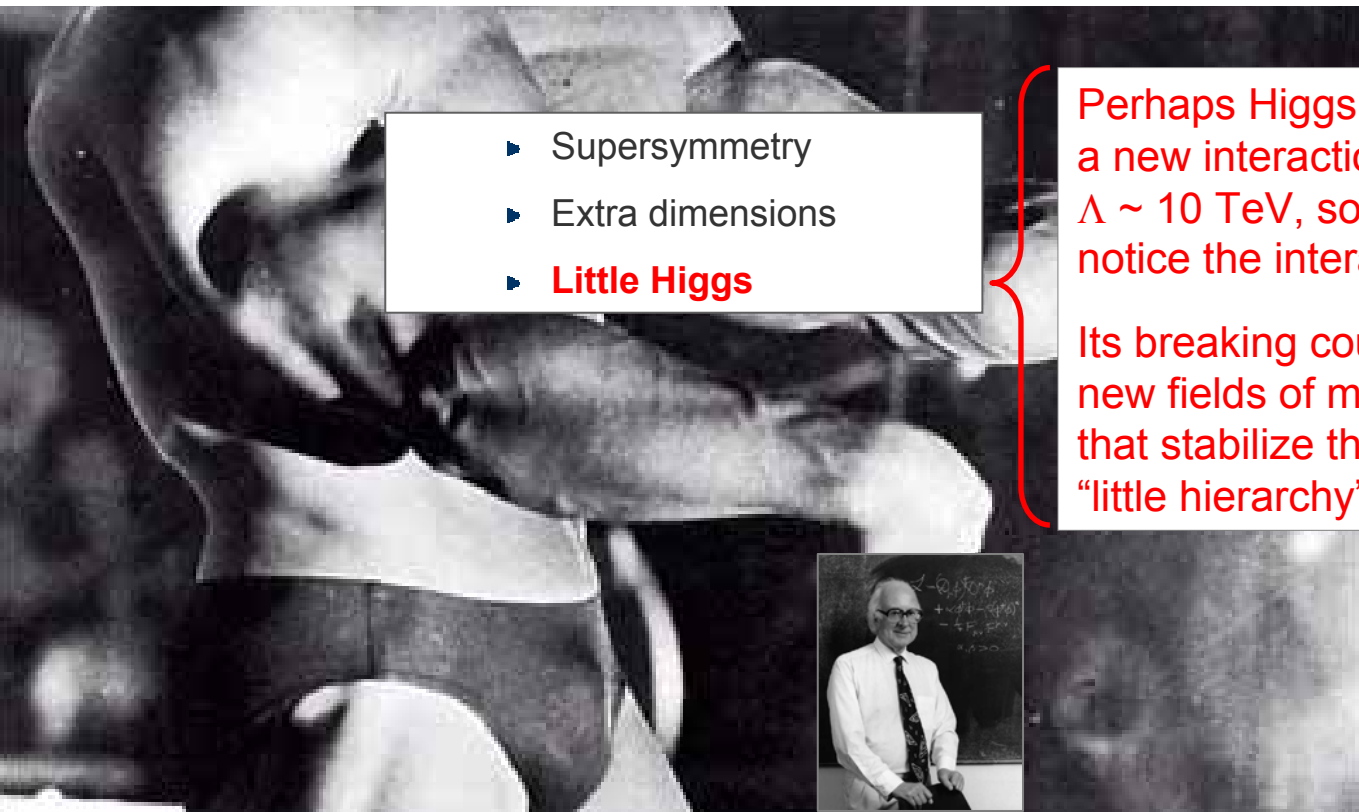


Extending the Standard Model

- ▶ Supersymmetry
- ▶ Extra dimensions
- ▶ **Little Higgs**

Perhaps Higgs results from a new interaction at scale $\Lambda \sim 10$ TeV, so we didn't notice the interaction yet ?

Its breaking could lead to new fields of mass ~ 1 TeV that stabilize the SM for the "little hierarchy": $EW \rightarrow \Lambda$



OK, enough ...

let's find our way back to
what we believe to know ...



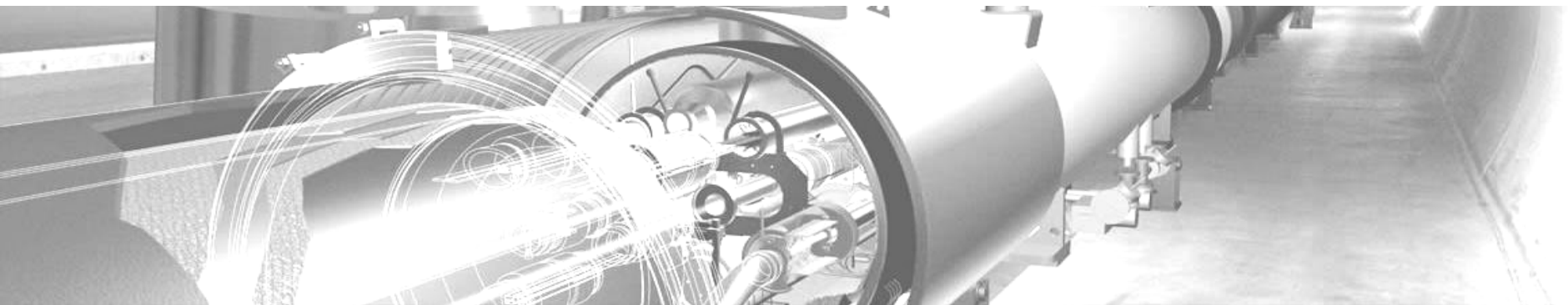
We asked for the ...

Motivation for a Huge Machine



All SM extensions have in common that they solve the hierarchy problem by introducing new particles at the **TeV scale**.

To find these, we need a new, huge collider providing hard parton collisions with centre-of-mass energy well above 1 TeV



and **tomorrow** ...

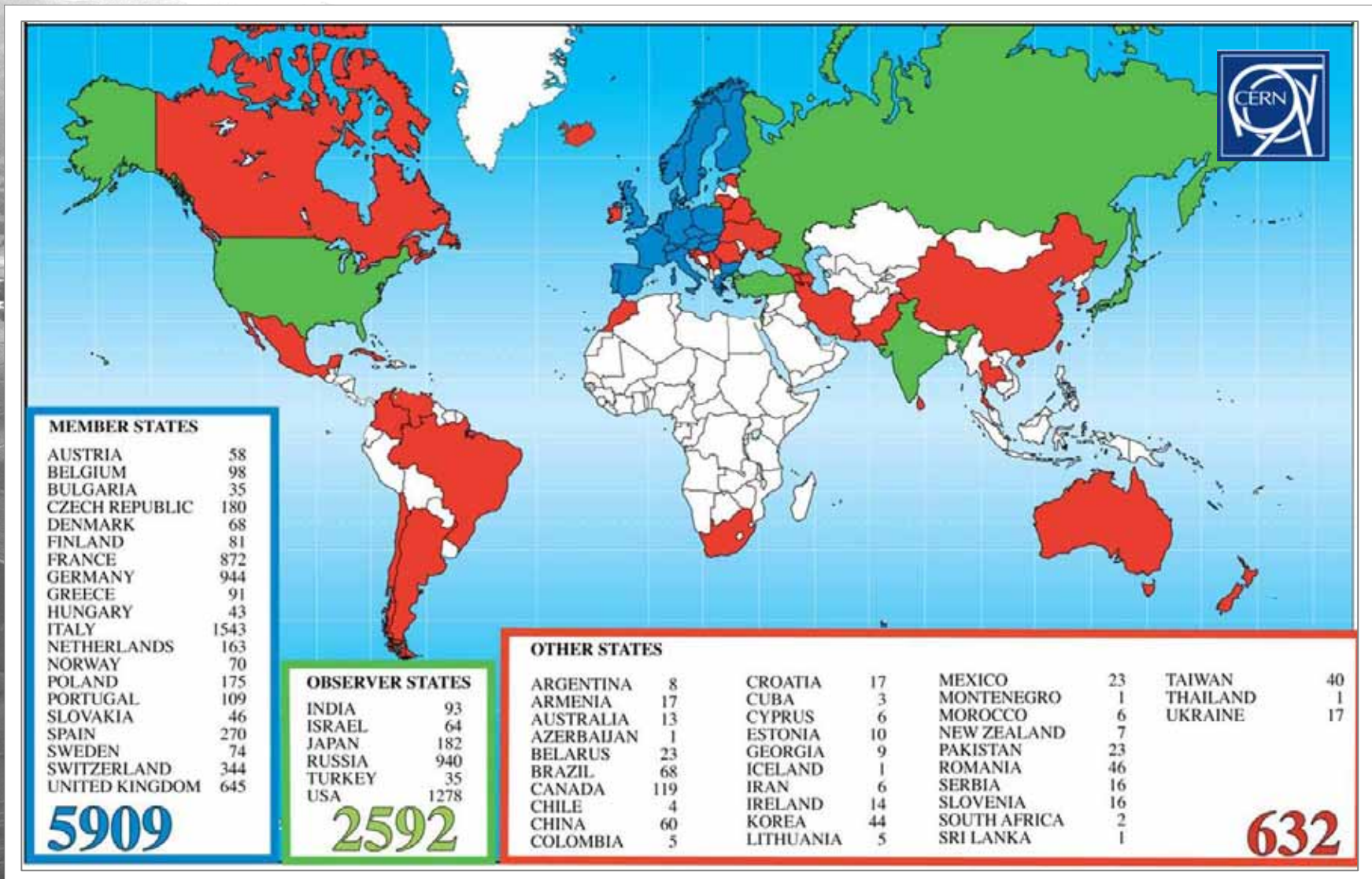
CERN, the LHC and ATLAS

Experimental Challenges



CERN AC/DI/MM 3324-07 07-1998

Distribution of all CERN Users by Nation of Institutes on 5 Feb 2008



CERN AC



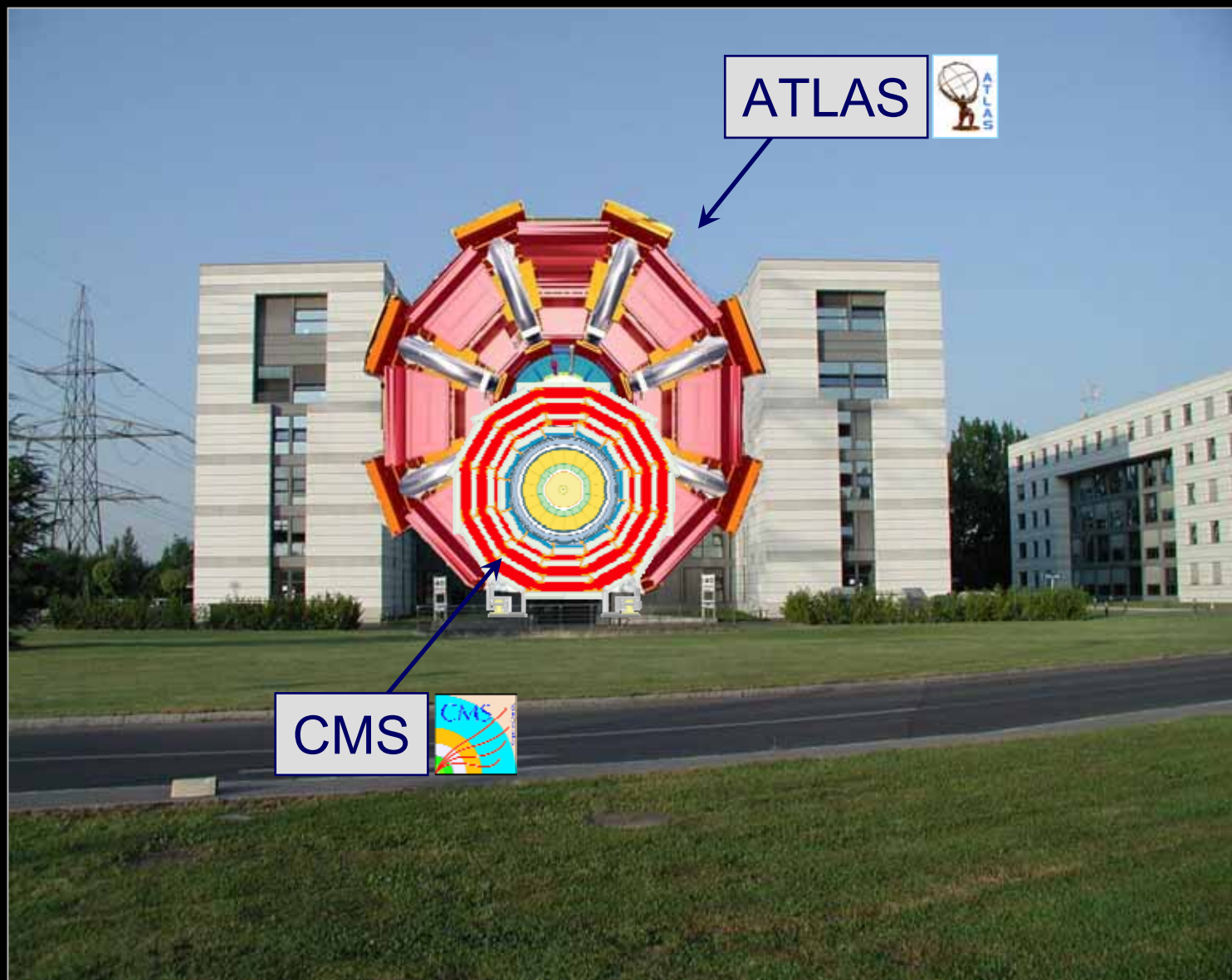
Founded in 1954 by 12 European countries
Budget: 1075 MCHF = 664 MEuros
Personnel: 2500 Staff, O(700) Fellows and Associates, 9100 users
Nobel prizes: 3 (Charpak, Ting, Rubbia)

CERN & THE LHC



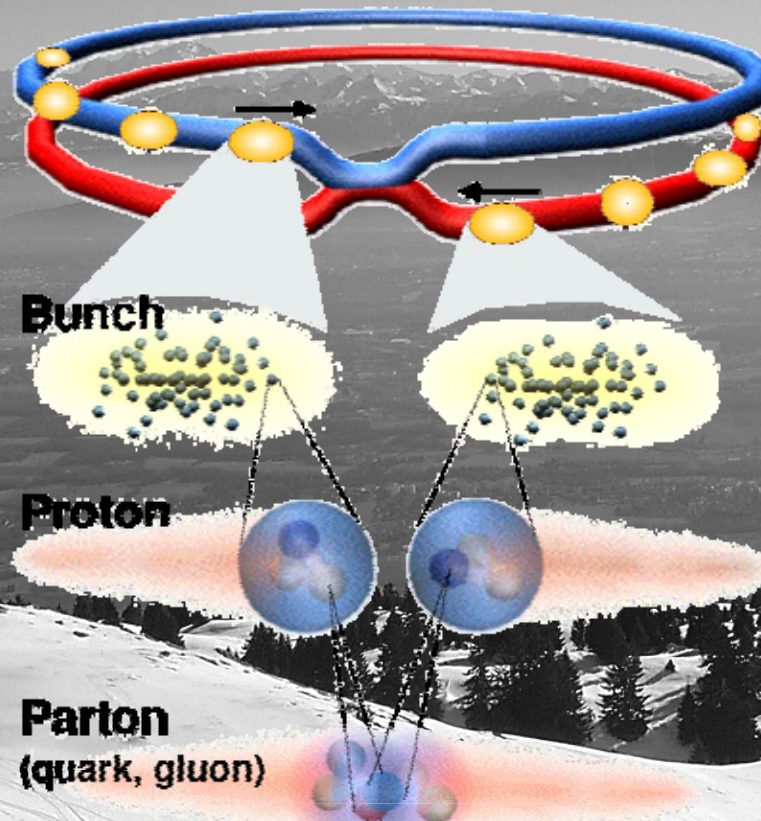






LHC: The Accelerator Challenge

- The search for new phenomena exploits **ever smaller distances** → **ever larger energies**
- The LHC collides protons at $E_{\text{CM}} = 14 \text{ TeV}$ → probing a distance of $1.4 \cdot 10^{-20} \text{ m}$?
... not quite, since protons are composites: the energy is distributed among its partons



LHC: The Accelerator Challenge

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... not quite, since protons are composites: the energy is distributed among its partons
- Want to produce **rare new particles** → **need high intensity beams**
- **Proton energy is limited by magnets that guide the circular beams**
- $E_{\text{proton}} \sim 0.3 \cdot B \cdot r$: since radius is fixed (27 km), use as strong fields as possible ($> 8 \text{ T}$), and fill all free LHC sections with magnets ($\sim 2/3$)

ATLAS



CMS



LHCb

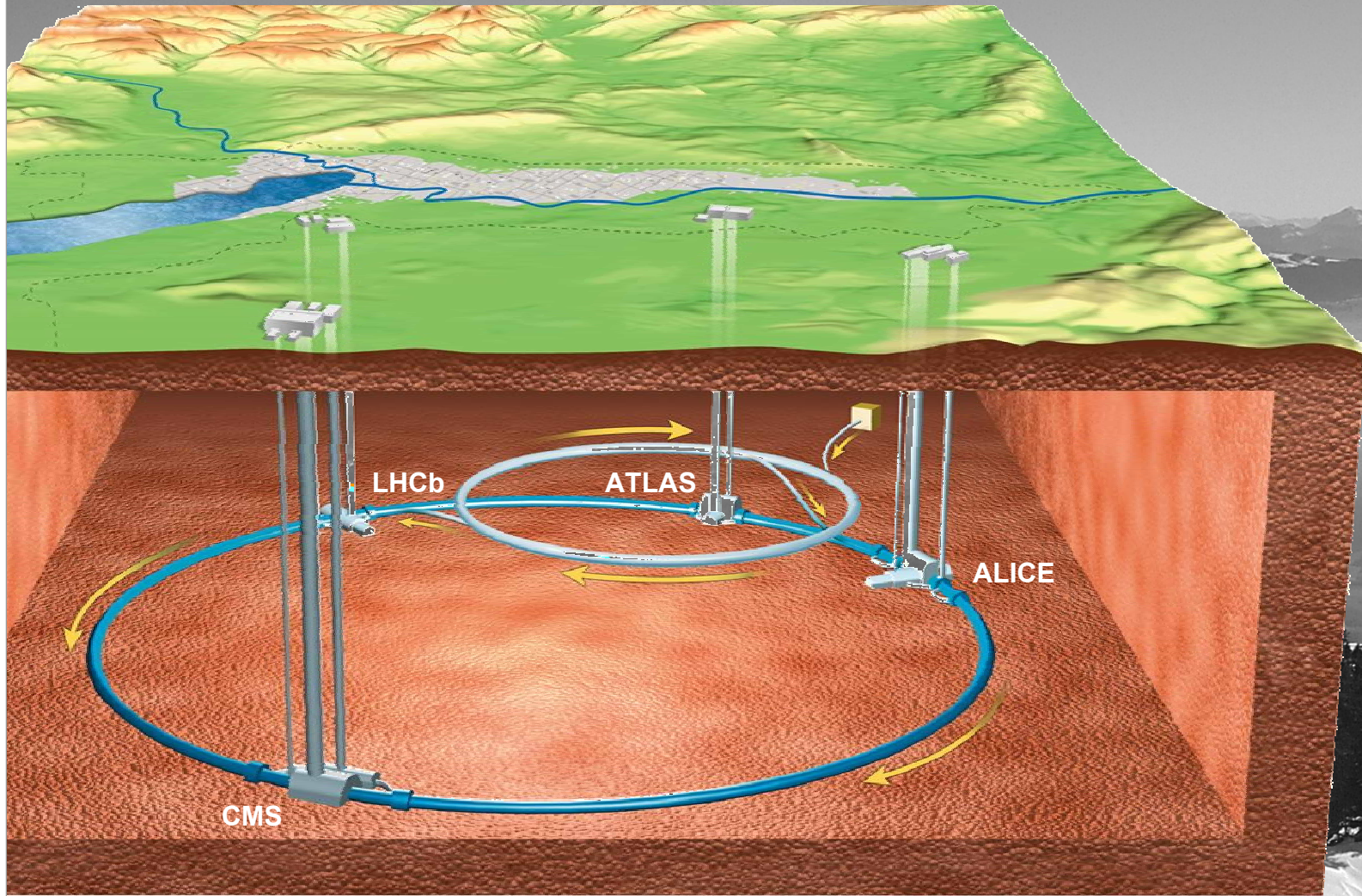


... and also ALICE !

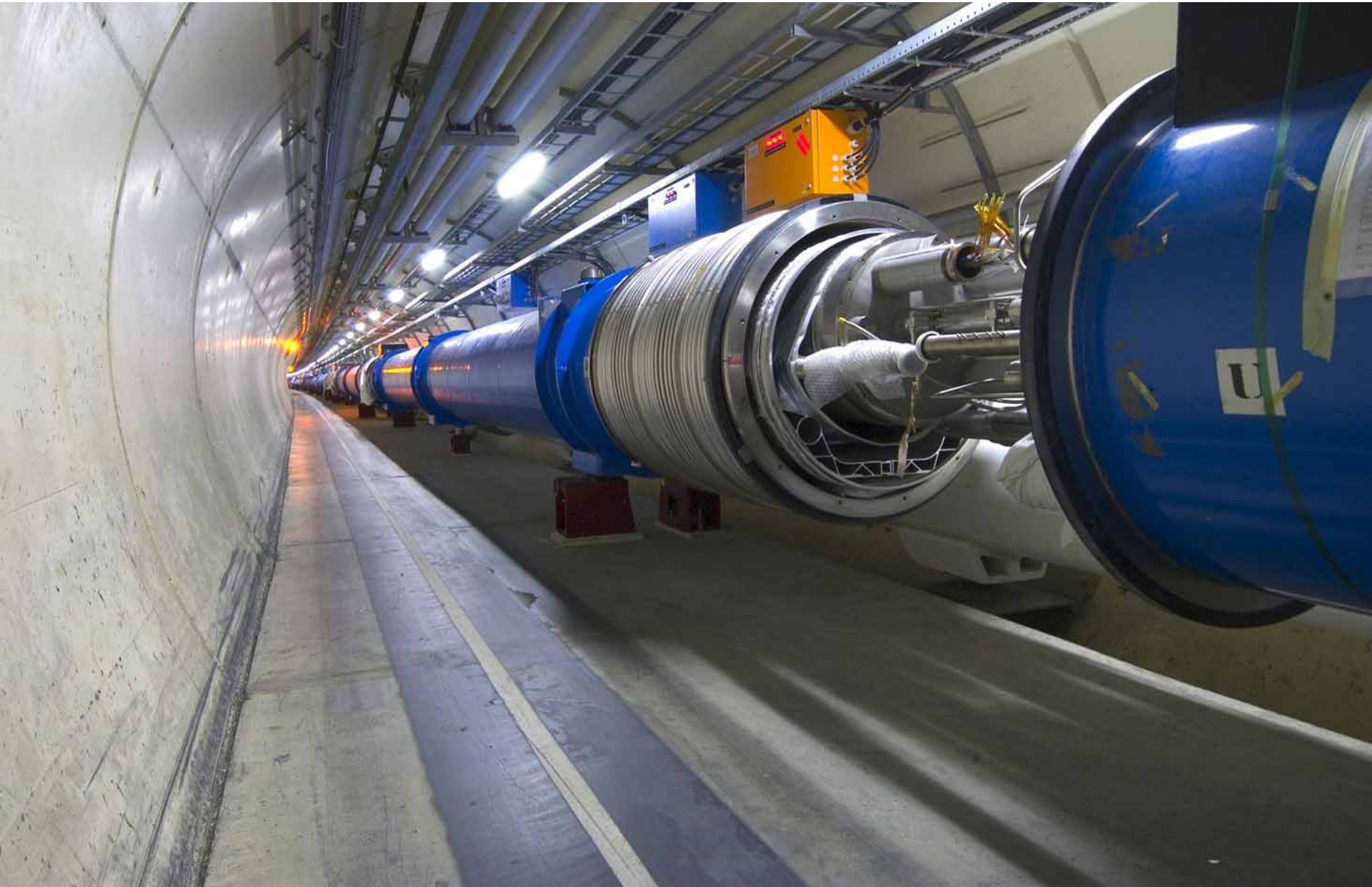
Accelerators for the LHC

The LHC has 4 large experiments: ATLAS, CMS, LHCb, ALICE

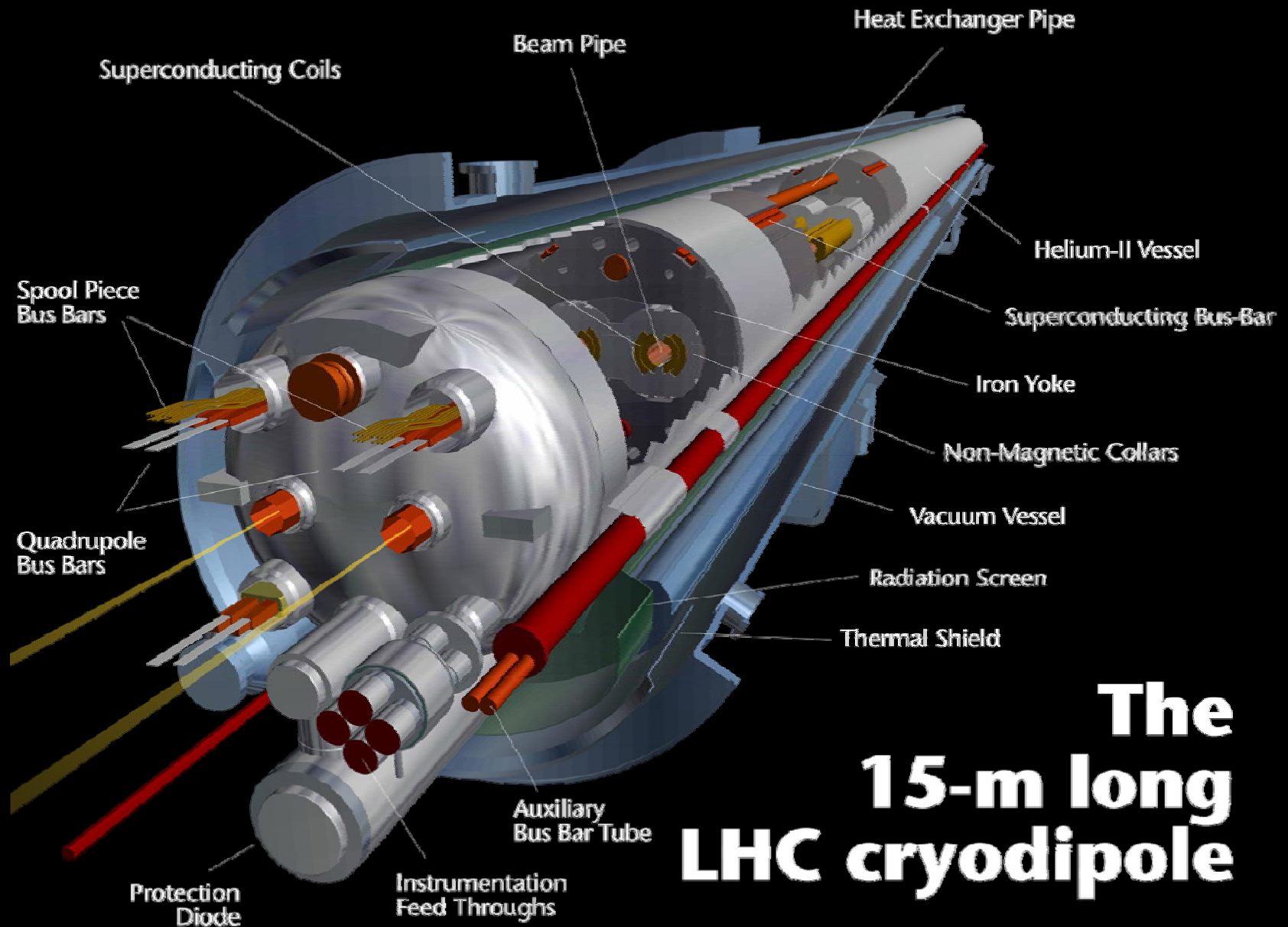
7 TeV
↑
LHC
450 GeV
↑
SPS
26 GeV
↑
PS
1.4 GeV
↑
BOO-
STER
50 MeV
↑
LIN-
AC2



The LHC — Dipole Section



The LHC — Dipole Section



The LHC

The LHC surpasses existing accelerators in 2 main aspects:

- 7 TeV beam energy in 26.7 km (LEP) tunnel (Tevatron: 0.98 TeV in 6.3 km)
 - ➡ LHC dipole field strength: 8.3 T
 - ➡ HERA / Tevatron: ~ 4 T
- Unprecedented peak luminosity for hadron machine
(note: no. of events = luminosity $\times$ cross section)
 - ➡ LHC (pp): $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [requires: *many bunches* + *many protons* + *small beam size*]
 - ➡ Tevatron/SppbarS: $2.5 \times 10^{32} / 6 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$

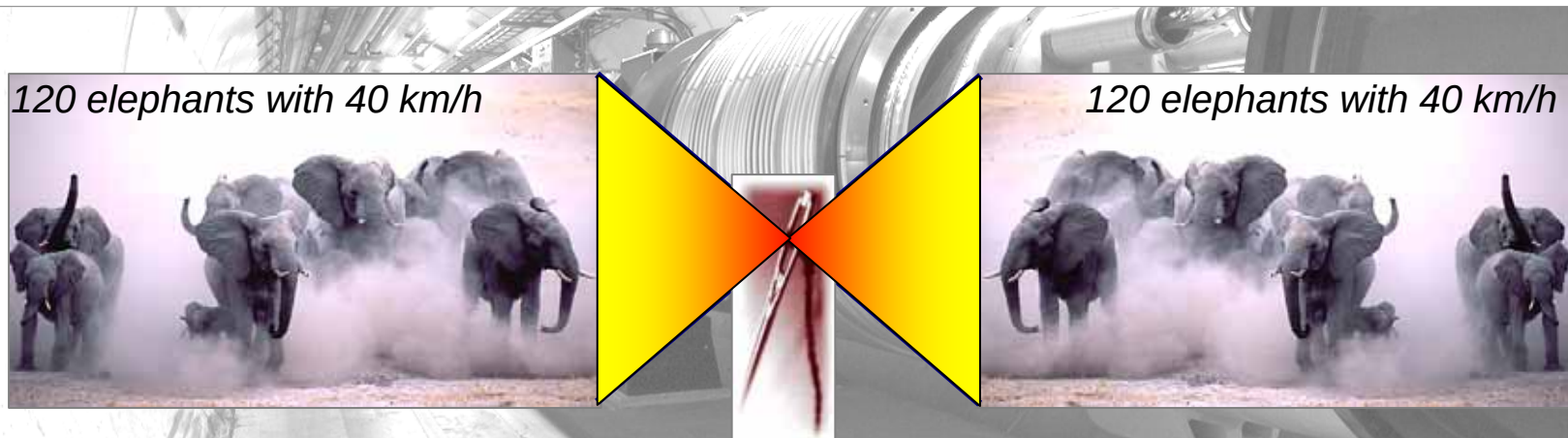
The combination of very high field magnets and very high beam intensities required to reach luminosity targets makes LHC operation a great challenge

The LHC — Stored Energy

2808 bunches filled with 10^{11} protons à 7 TeV per bunch

➡ 360 MJ stored energy per proton beam

Equivalent to Colliding 2×120 Elephants



Energy of a single 7 TeV proton equivalent to flying mosquito ($1 \mu\text{J}$)

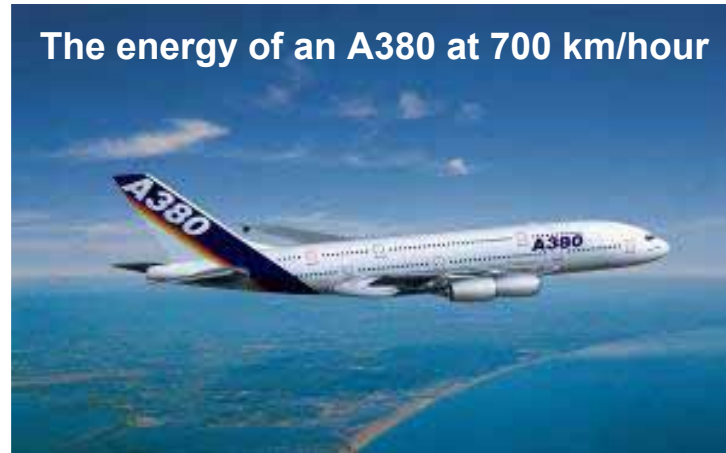
Eye of a needle: 0.3 mm diameter

Proton beams at interaction point are 20 x smaller: **$16 \mu\text{m}$ diameter**

Big challenge to control (and dump) the stored energy and to avoid damage

The LHC — Stored Energy

The energy stored in one LHC beam corresponds approximately to:



The LHC — Pictures



Dipole storage on car-parks all over CERN

The LHC — Pictures



Lowering through an elliptical shaft

The LHC — Pictures



Quality Control

The LHC — Pictures



Transport with optically guided vehicle

The LHC — Pictures



Interconnection welding

The LHC — Pictures



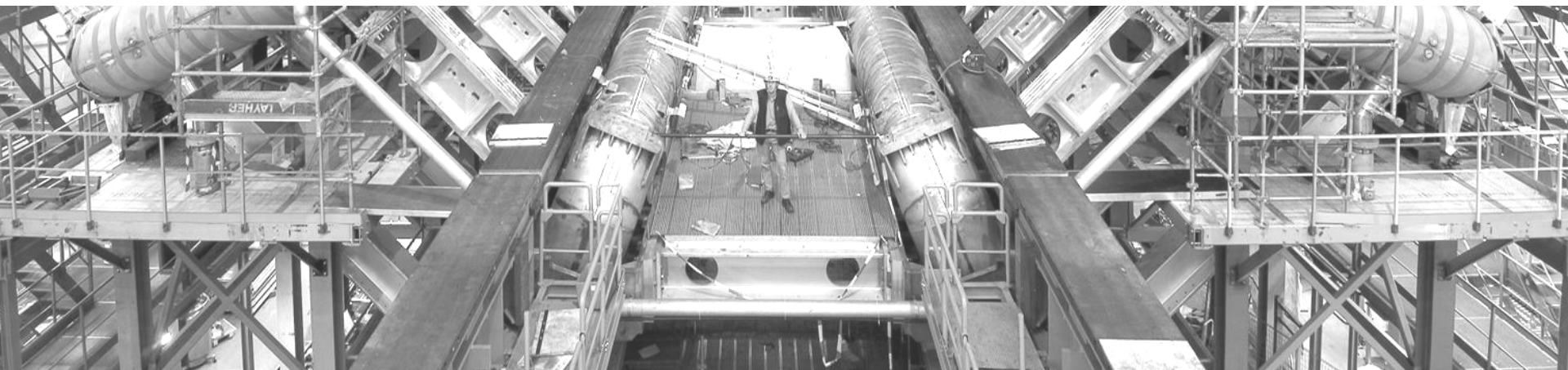


The High- p_T LHC Detectors

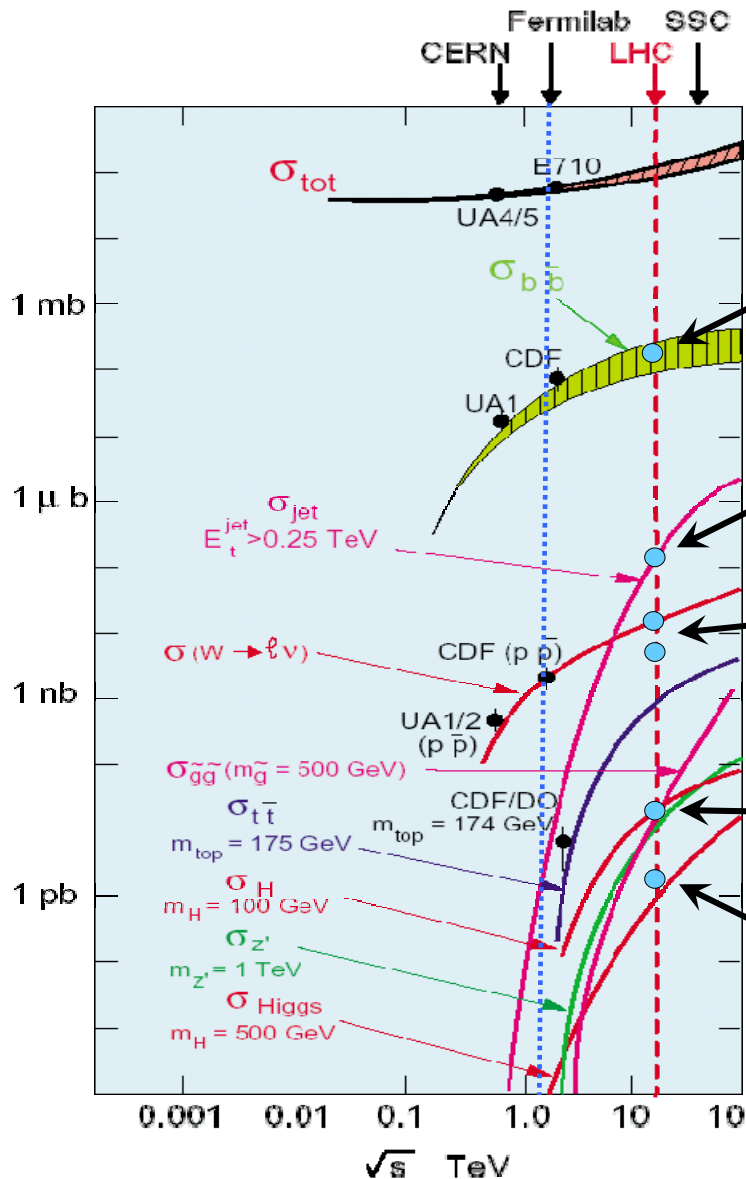


ATLAS and CMS are “general purpose detectors”, capable of adequately covering the entire physics programme reachable with high-luminosity 14 TeV pp collisions

- ➡ From charm and beauty physics at lowest transverse momenta (~ 3 GeV) ...
- ➡ ... to New Physics searches up to the highest reachable scales (~ 4 TeV)



Cross Sections



$$g \rightarrow q \bar{q}$$

Quark-flavour production

$$g \rightarrow \text{jet}$$

High- p_T QCD jets

$$q \bar{q} \rightarrow W, Z$$

W, Z production

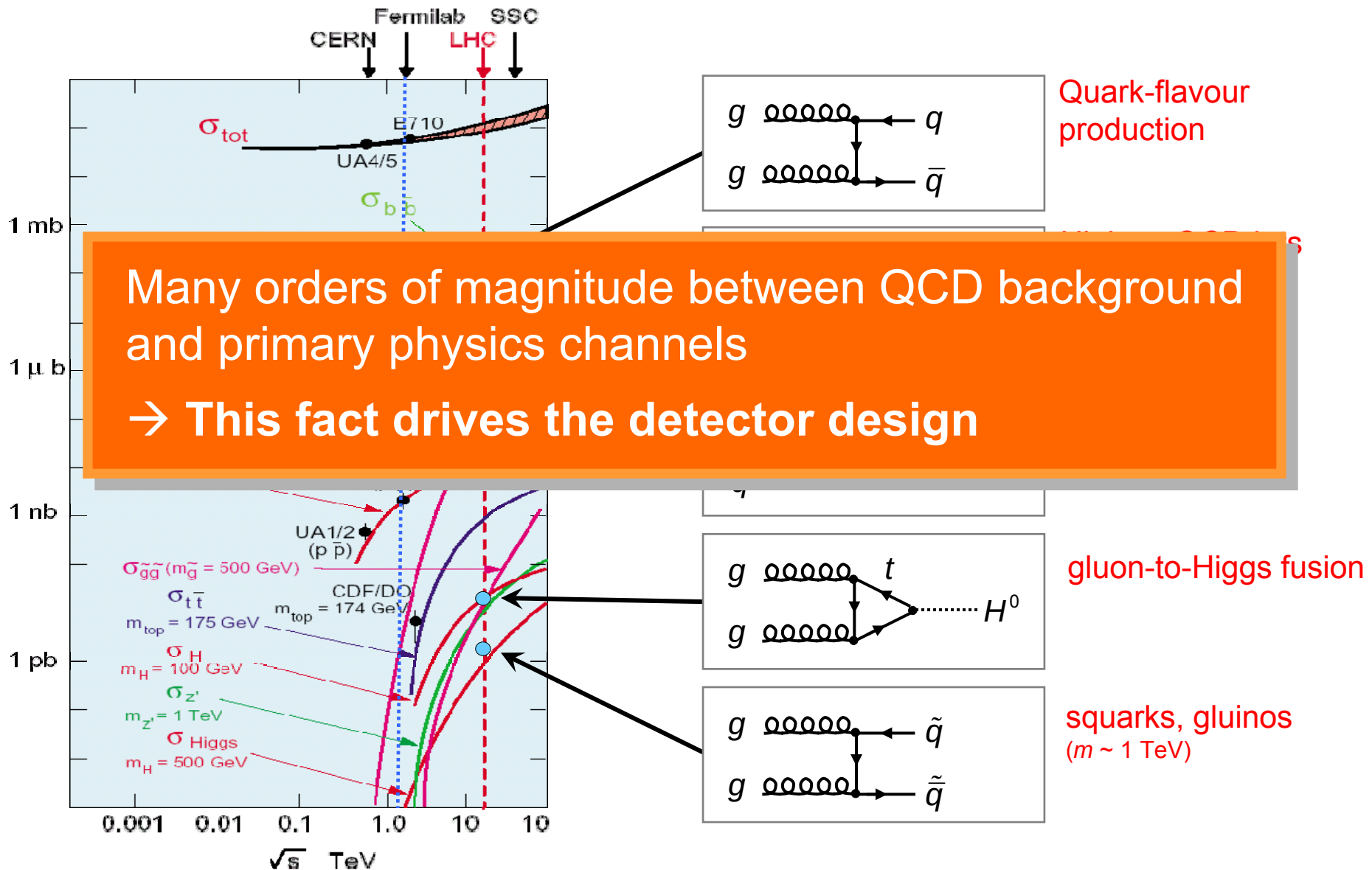
$$g g \rightarrow t \bar{t} \rightarrow H^0$$

gluon-to-Higgs fusion

$$g \rightarrow \tilde{q} \bar{\tilde{q}}$$

squarks, gluinos
($m \sim 1 \text{ TeV}$)

Cross Sections

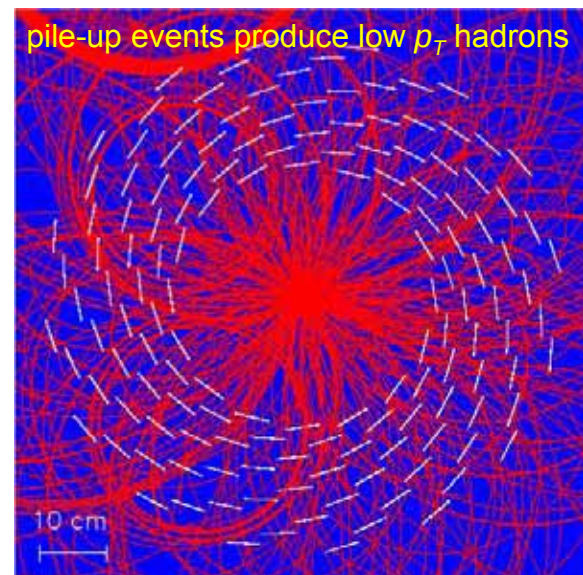


Principles of Event Reconstruction

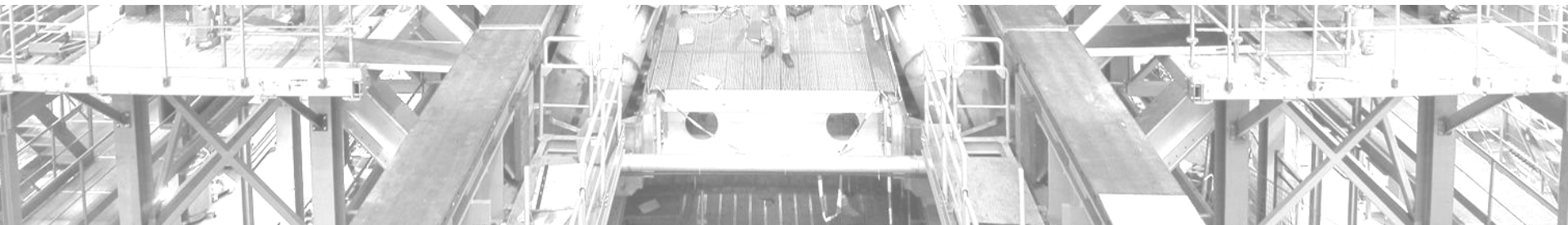


■ Event reconstruction:

- “Trigger” on an interesting event → read out detector
- Reconstruction starts with detector signals:
 - ▶ Space points from ionization by charged particles in tracking systems
 - ▶ Energies from showers in calorimeter cells/crystals
 - ▶ Signals from particle-identification detectors
- “Fit” track helices to space points
- “Cluster” adjacent calorimeter energy deposits
 - ▶ Form electromagnetic objects (electrons, photons)
 - ▶ Form hadronic jets



18 superimposed pp collisions in CMS tracker
(there are also 4 muons from Higgs decay...)



LHC Physics Programme and Challenges

■ Some benchmark analyses:

➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

➡ W mass

➡ top mass

➡ $H \rightarrow \gamma\gamma, 4e, 4\mu, \tau\tau$ (VBF)

➡ SUSY with R -parity, SUSY Higgs

➡ RS KK modes

■ Design challenges:

Trigger efficiency ($p_T(\mu) > 3$ GeV) and purity
(HLT tracking reconstructs charge, vertex and B mass)

Excellent **tracking alignment**, calorimeter **uniformity**, **resolution and low noise**

Excellent **jet & missing transverse energy resolution** and **uniformity**, excellent **b -tagging**

Excellent **PID**, **resolution & uniformity**, **efficient high-lumi tracking**, **forward jets**

Excellent **jet & $E_{T,miss}$ resolution**, **low noise**, **τ identification**, **maximum acceptance**

Good **tracking (incl.charge ID)** and calorimeter **resolution at $O(\text{TeV})$** , **little calo saturation**

Requirements from LHC Conditions

LHC and data conditions:

- ➡ **40 MHz bunch crossing rate**
(25ns = 7.5m bunch spacing)
- ➡ **~1 GHz interaction rate at $L = 10^{34}$ cm⁻²s⁻¹** (~20 ias. per bunch crossing)
- ➡ **~300 Mbytes/seconds data rate**
(200 Hz × $O(1.5$ MB/event))
- ➡ **Irradiation rate / 10 LHC years:**
 5×10^{14} n_{eq}/cm² (300 kGray [= J/kg])
- ➡ **High charged multiplicity**
($O(1000)$ tracks per event, 10^{11} / sec)
- ➡ **High background rates** (beam halo muons, neutrons, beam-gas collisions)

Design challenges:

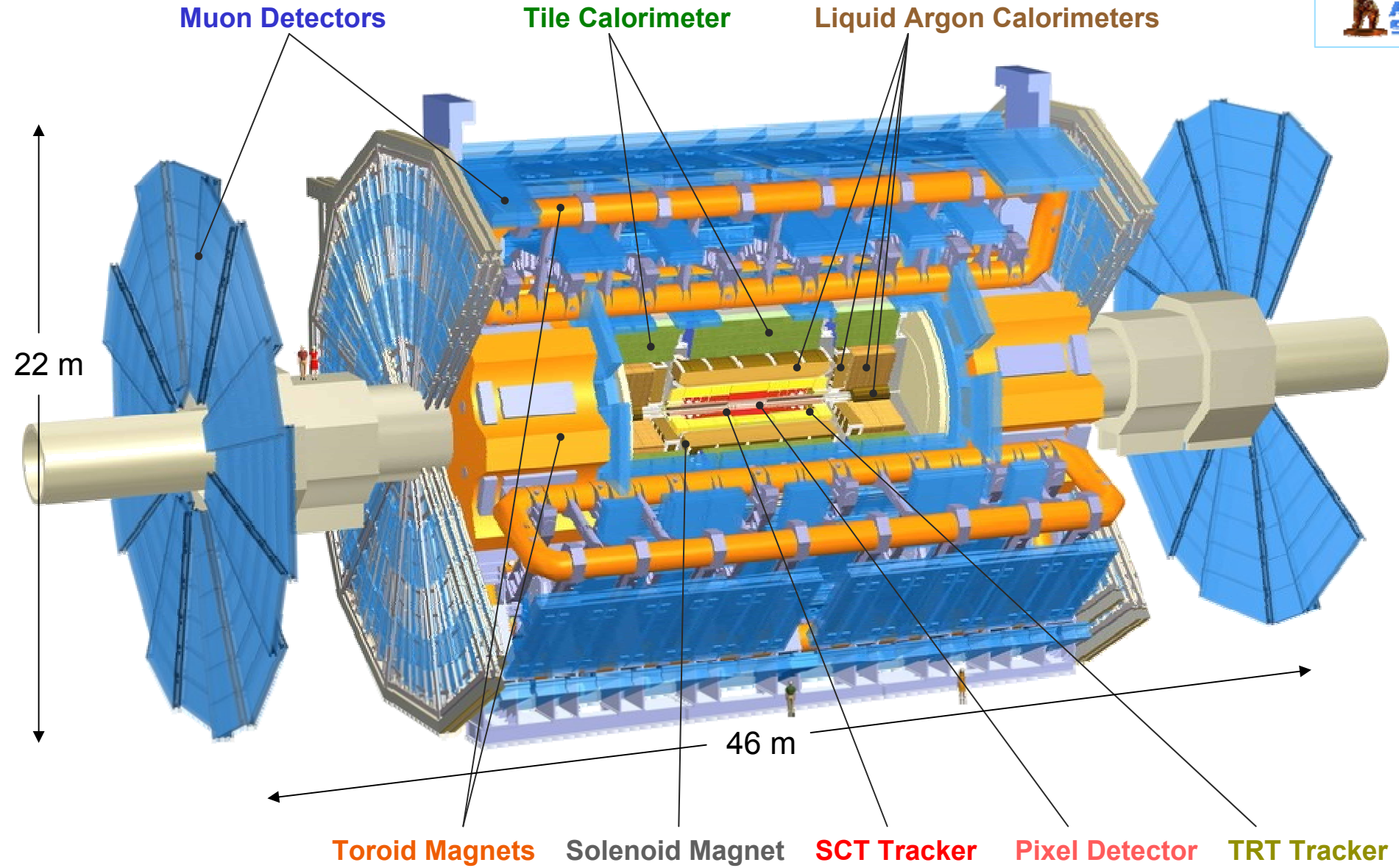
- Fast trigger, precise timing and “pipeline” electronics: Level-1 latency < 2.5μs**
- Efficient pattern recognition to reduce:**
GHz → L1 → 75 kHz → HLT → 200 Hz → Disk
- Powerful data processing farms:** distribute data analysis among many computing centres
- Radiation hard inner tracker** (pixel with large S/B) **and forward calorimeter technology**
- High-granular pixel/silicon or fine-grained straw tracker technologies**
- Precise muon timing, redundant pattern recognition, radiation hardness**

Trading the Requirements

ATLAS & CMS

- ▶ Detector Schemas
- ▶ Reconstruction of Physics Objects
- ▶ Design Guidelines and Performance Characteristics

Hidden valley Z' decay in CMS



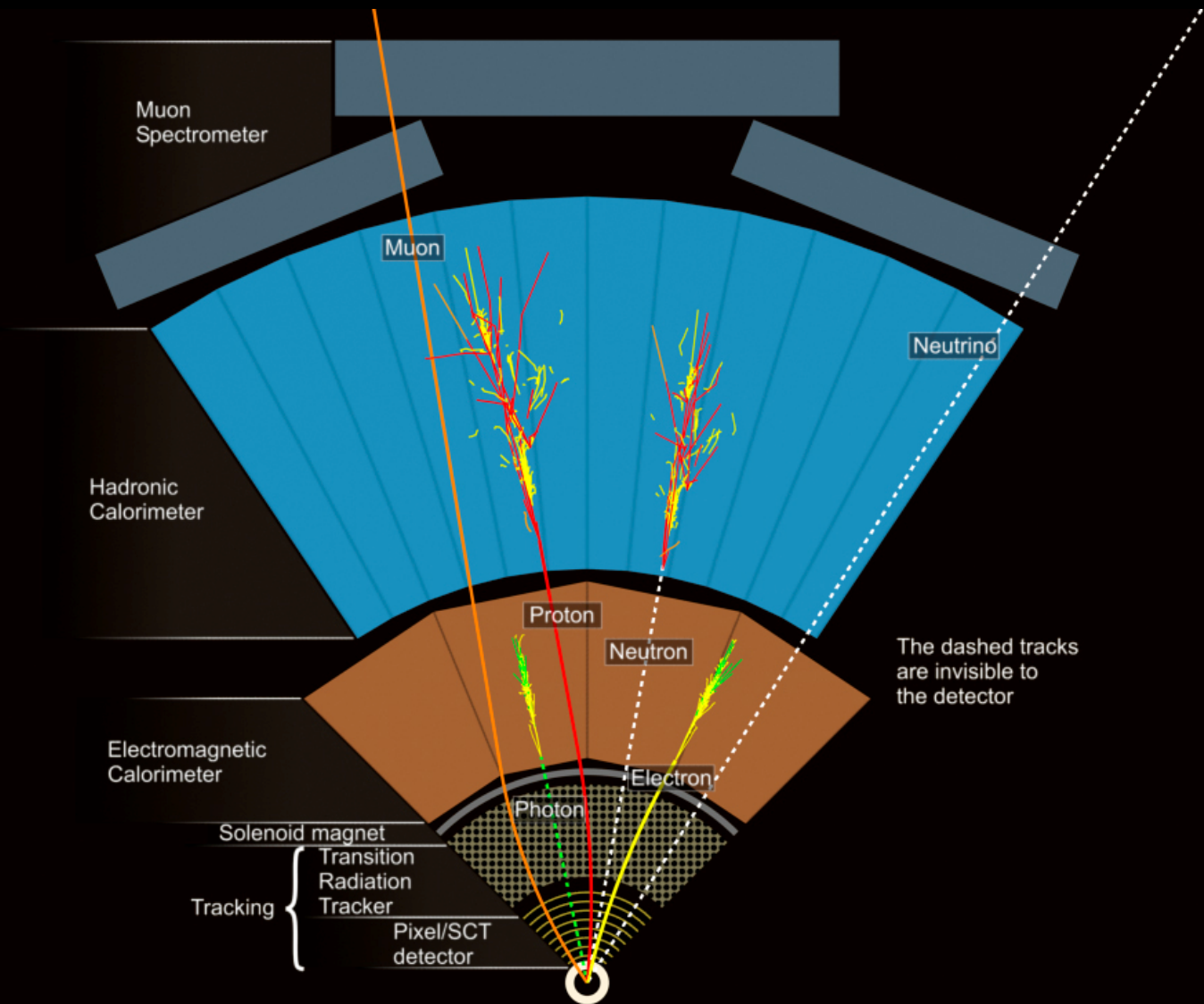
ATLAS Detector Layers

Particles are detected through their interaction with the active detector materials

Charged particles	Photons	Hadrons
Excitation Ionisation Bremsstrahlung Cherenkov radiation Transition radiation	Photo effect Compton scattering Pair creation	Strong interaction creates showers with → charged particles → photons → neutral hadrons

ATLAS Detector Layers

Particles are detected through their interaction with the active detector materials

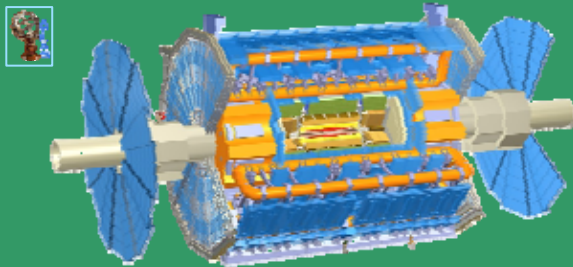


ATLAS & CMS: Design & Performance Overview

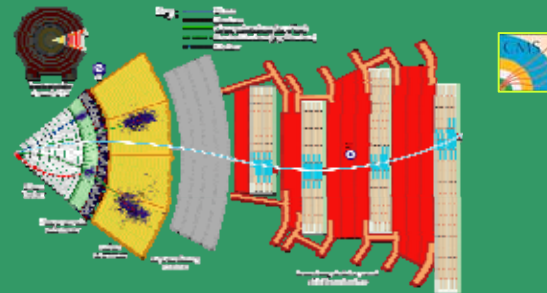
	ATLAS (7 ktons) 	CMS (12.5 ktons) 
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • $B = 2\text{T}$ • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • $B = 4\text{T}$ • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
MAGNETS	• 4 Magnets • Solenoid + Air-core muon toroids • Calorimeters outside solenoid field	• 1 Magnet • Solenoid • Calorimeters inside field
EM CALORIMETER	• Pb / Liquid Ar sampling accordion • $\sigma(E) \sim 10\text{--}12\% / \sqrt{E} \oplus 0.2\text{--}0.35\%$ • Longitudinal segmentation • Saturation at $\sim 3\text{ TeV}$	• PbWO_4 scintillation crystals • $\sigma(E) \sim 3\text{--}5.5\% / \sqrt{E} \oplus 0.5\%$ • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. tiles (EC: Cu-liquid Ar) • $\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%$ (Barrel)	• Cu (EC: brass) / Scint. tiles • Tail catchers outside solenoid • $\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%$ (Barrel)
MUON	• Drift tubes & CSC (fwd) + RPC/TGC • $\sigma(p_T) \sim 10.5\% / 10.4\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)	• Drift tubes & CSC (EC) + RPC • $\sigma(p_T) \sim 13\% / 4.5\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)

Source: Froidevaux-Sphicas, Ann Rev 56, 375 (2006)

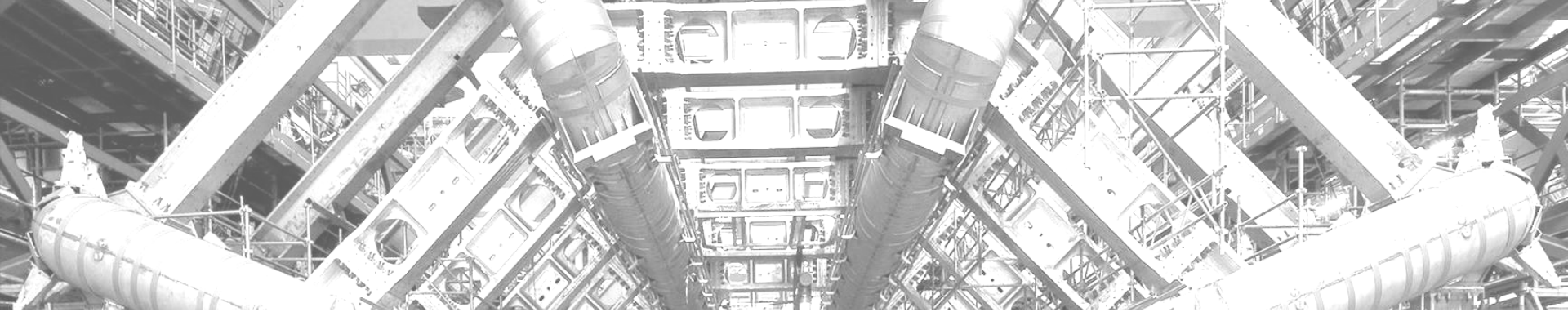
ATLAS & CMS: Design & Performance Overview



ATLAS: emphasis on excellent jet and missing- E_T resolution, and on particle identification



CMS: emphasis on excellent electron/photon and muon resolution



The ATLAS Movie

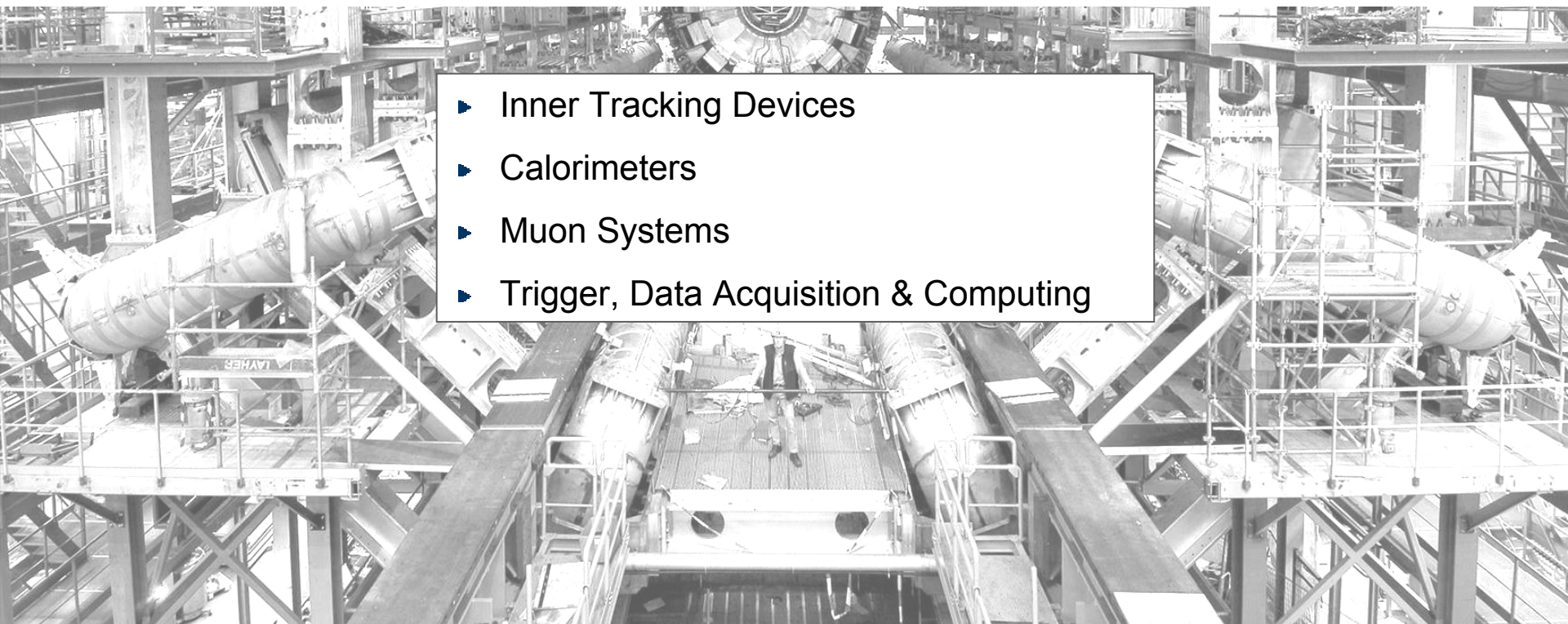


► Episode 2 – The Particles Strike Back

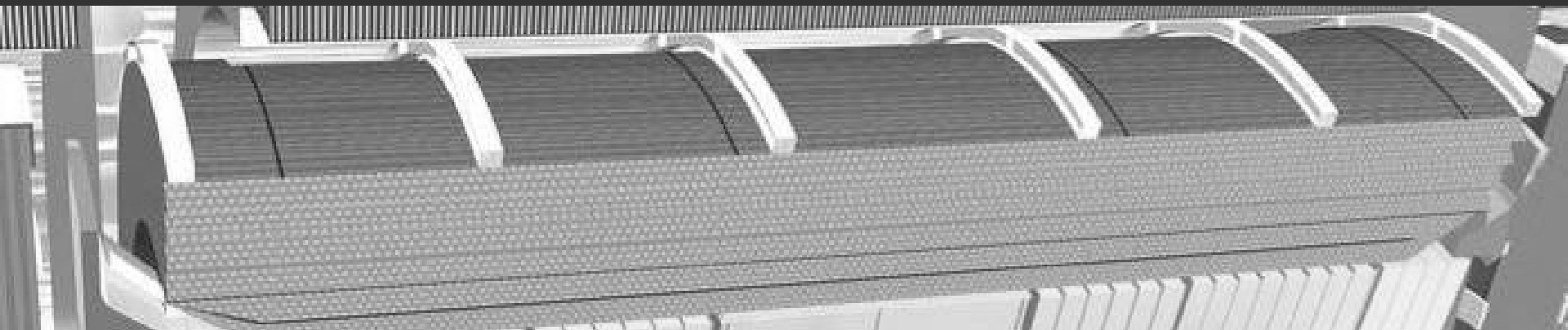
and **tomorrow** ...



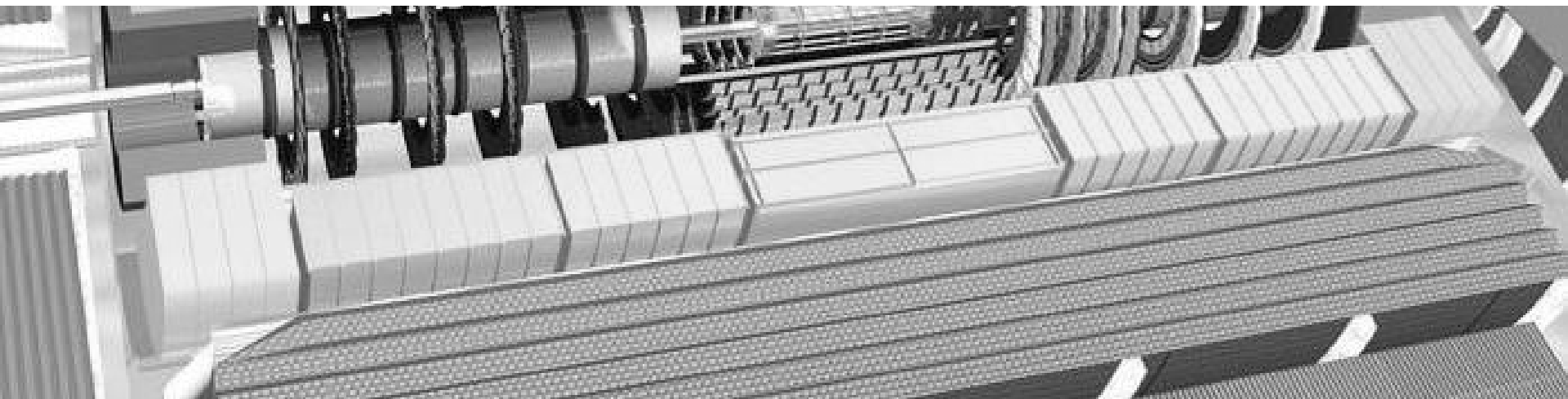
Specific Detector Systems



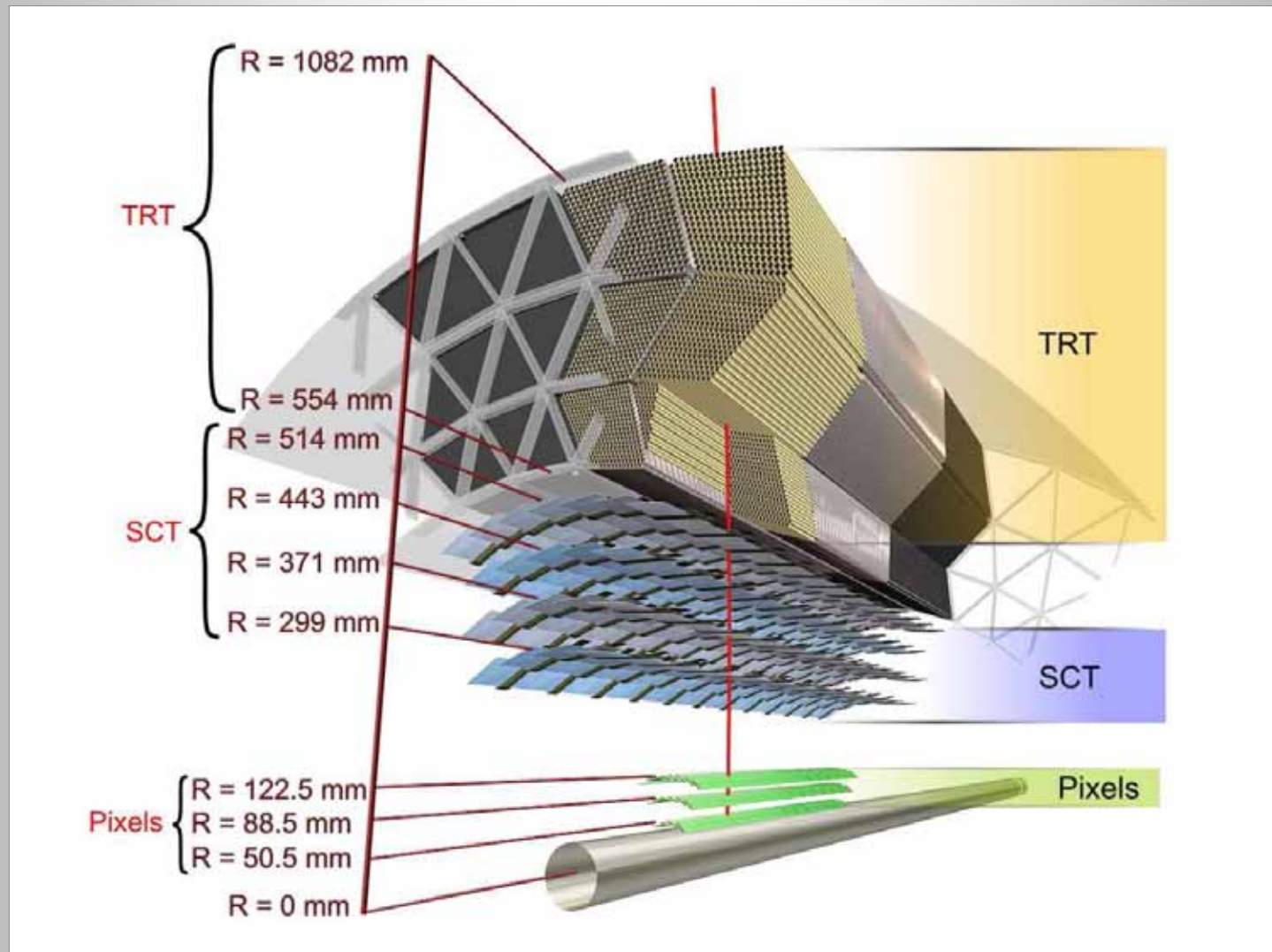
- ▶ Inner Tracking Devices
- ▶ Calorimeters
- ▶ Muon Systems
- ▶ Trigger, Data Acquisition & Computing



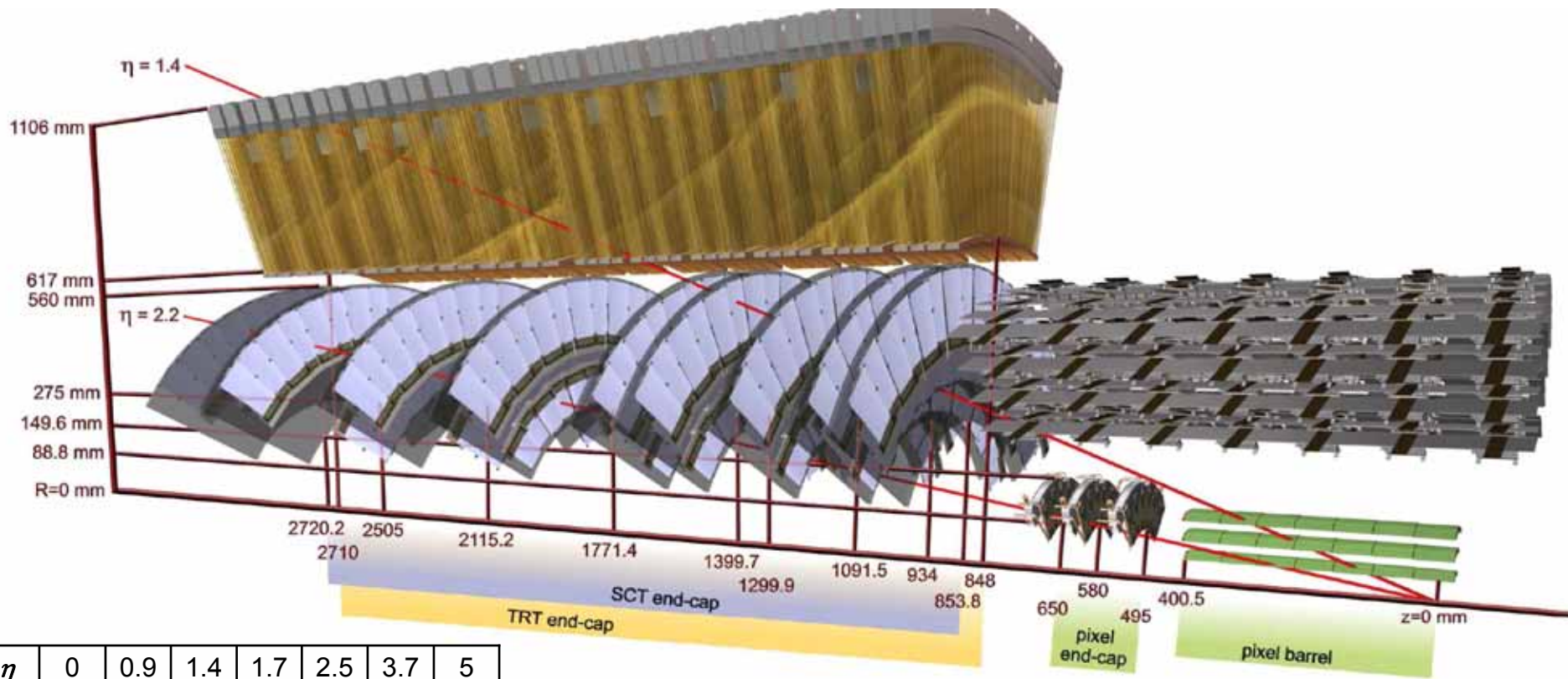
Inner Tracking Devices



The ATLAS Inner Tracker (Barrel)

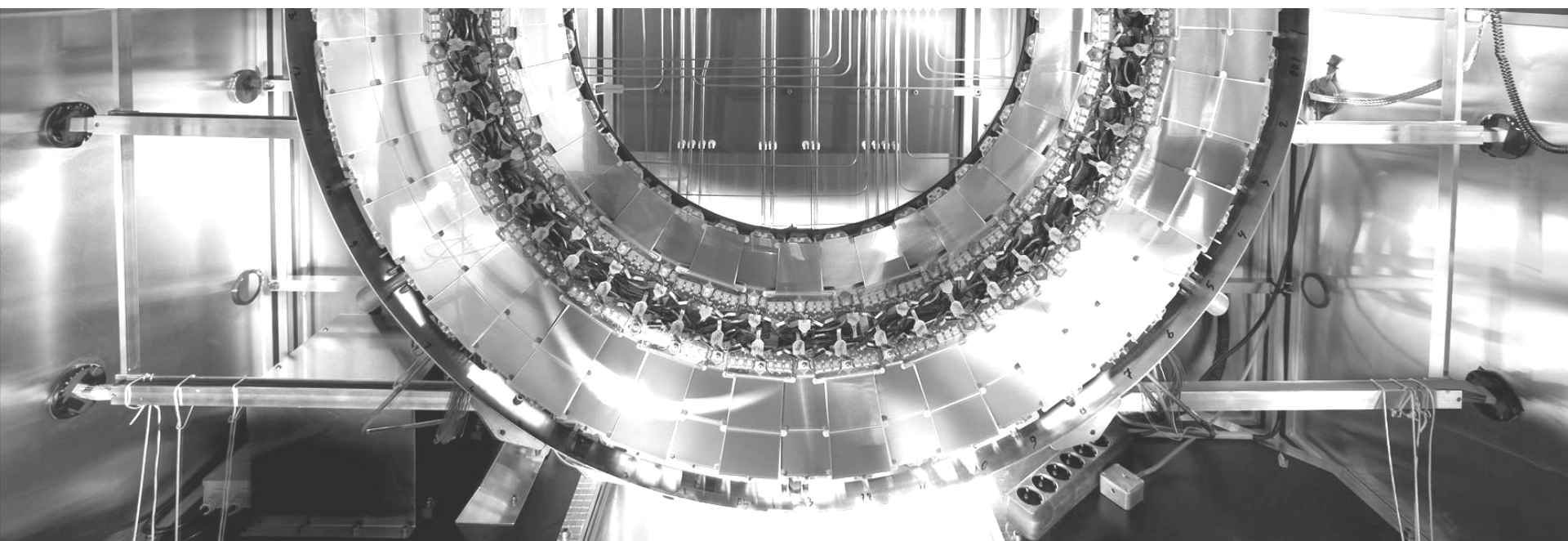


The ATLAS Inner Tracker (Endcap)



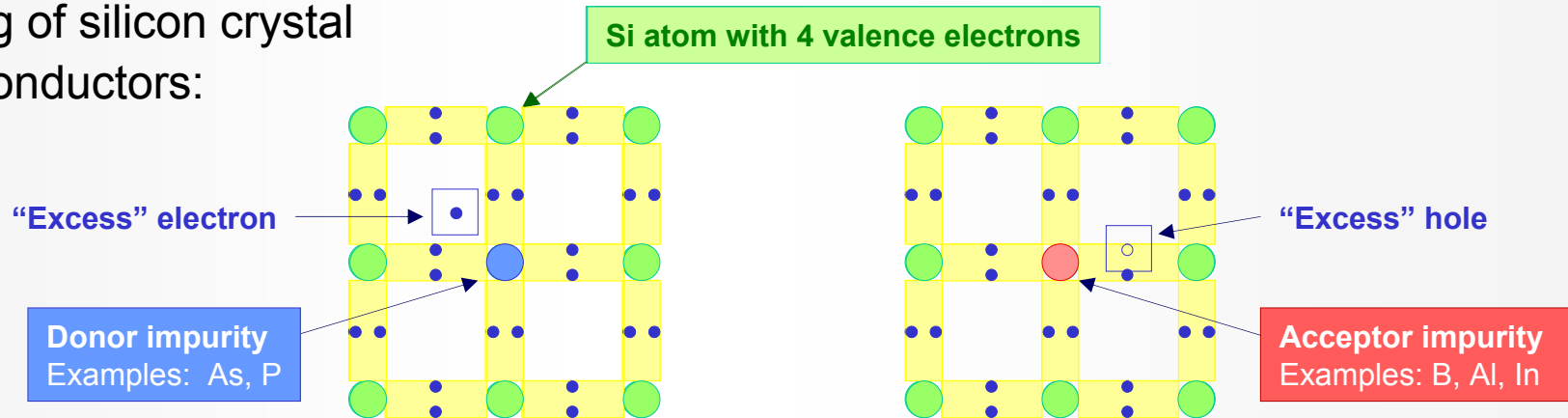


Semiconductor Trackers

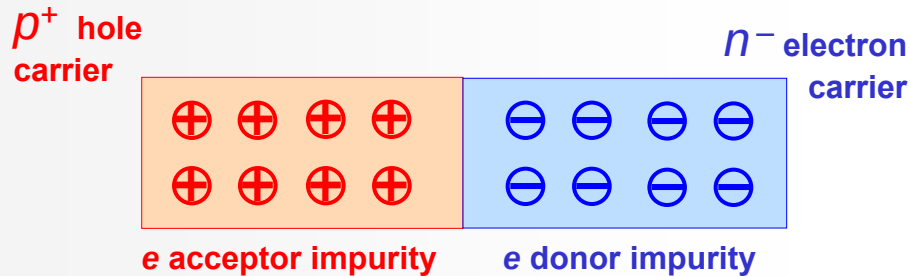


Semiconductors

Doping of silicon crystal semiconductors:



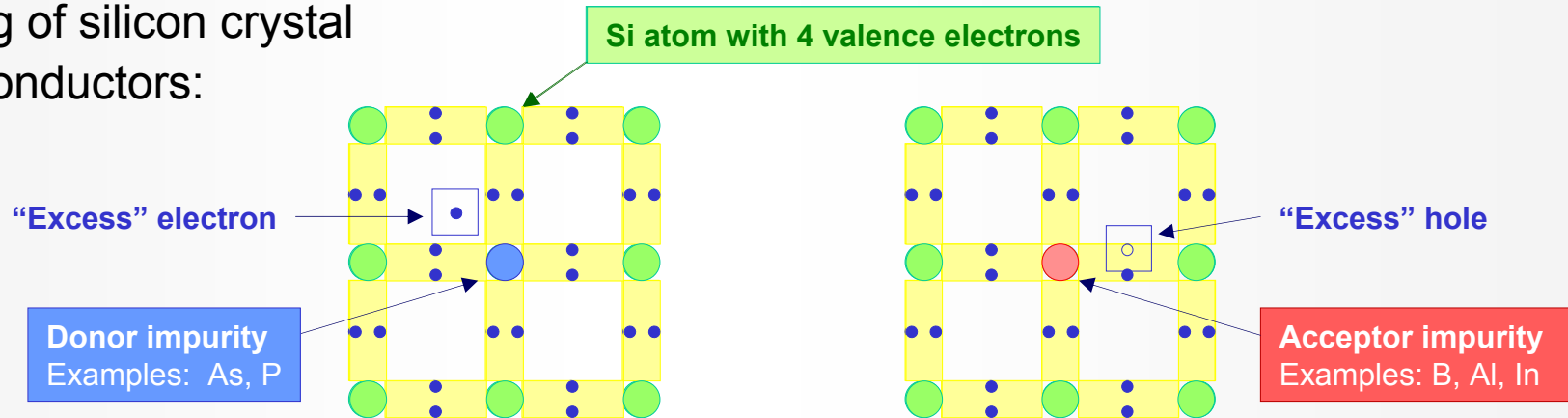
$p-n$ junction



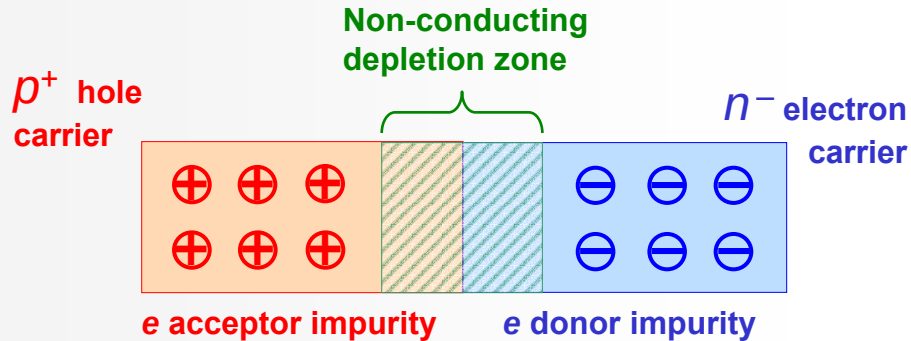
- p doping adds electro-phile atoms
- n doping adds electro-phobe atoms

Semiconductors

Doping of silicon crystal semiconductors:



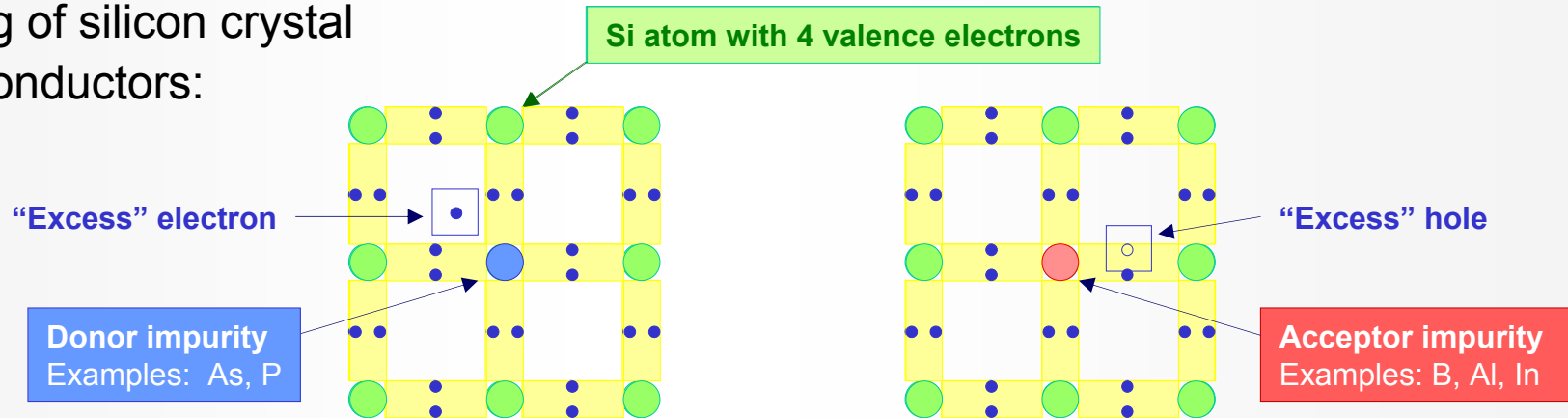
$p-n$ junction



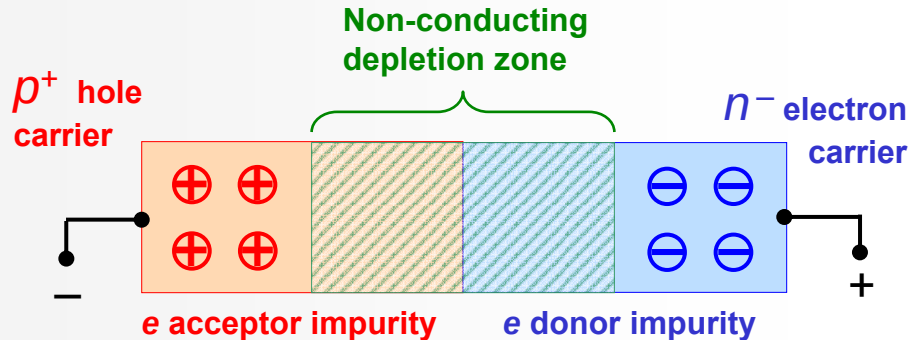
- In the junction zone, electron-hole pairs recombine creating depletion
- The potential barrier in the junction counterweighs the doping potential

Semiconductors

Doping of silicon crystal semiconductors:



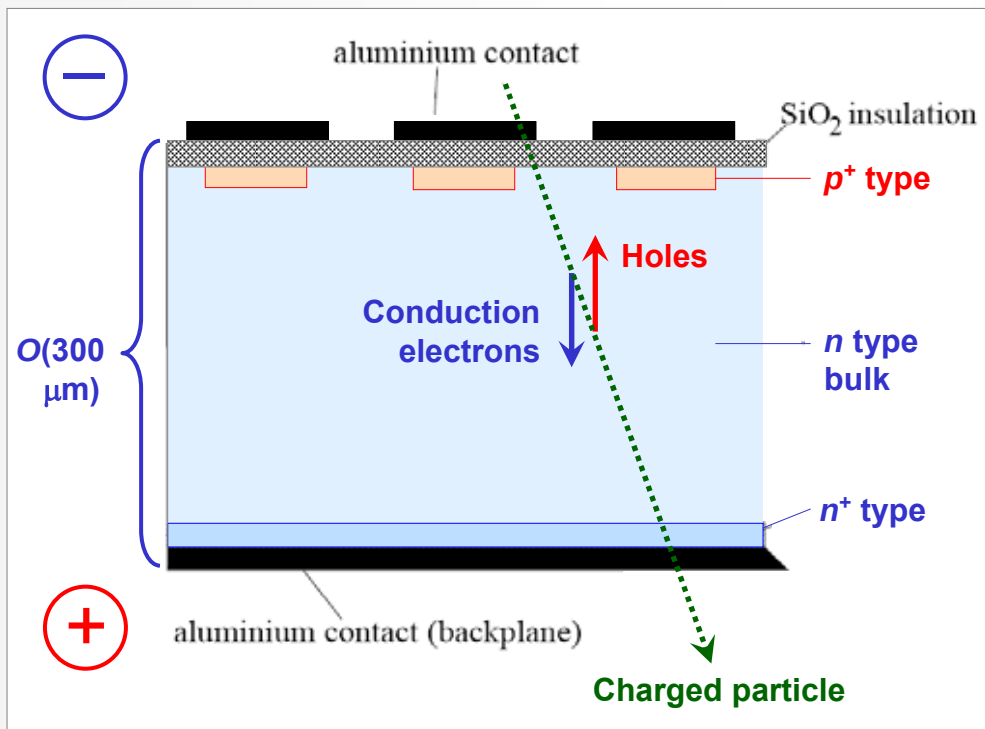
Reverse bias p – n junction



- The reversed bias voltage increases the potential barrier in the depletion zone, enhancing its resistance
- Minimal current across the junction

The p – n Junction as a Tracking Detector

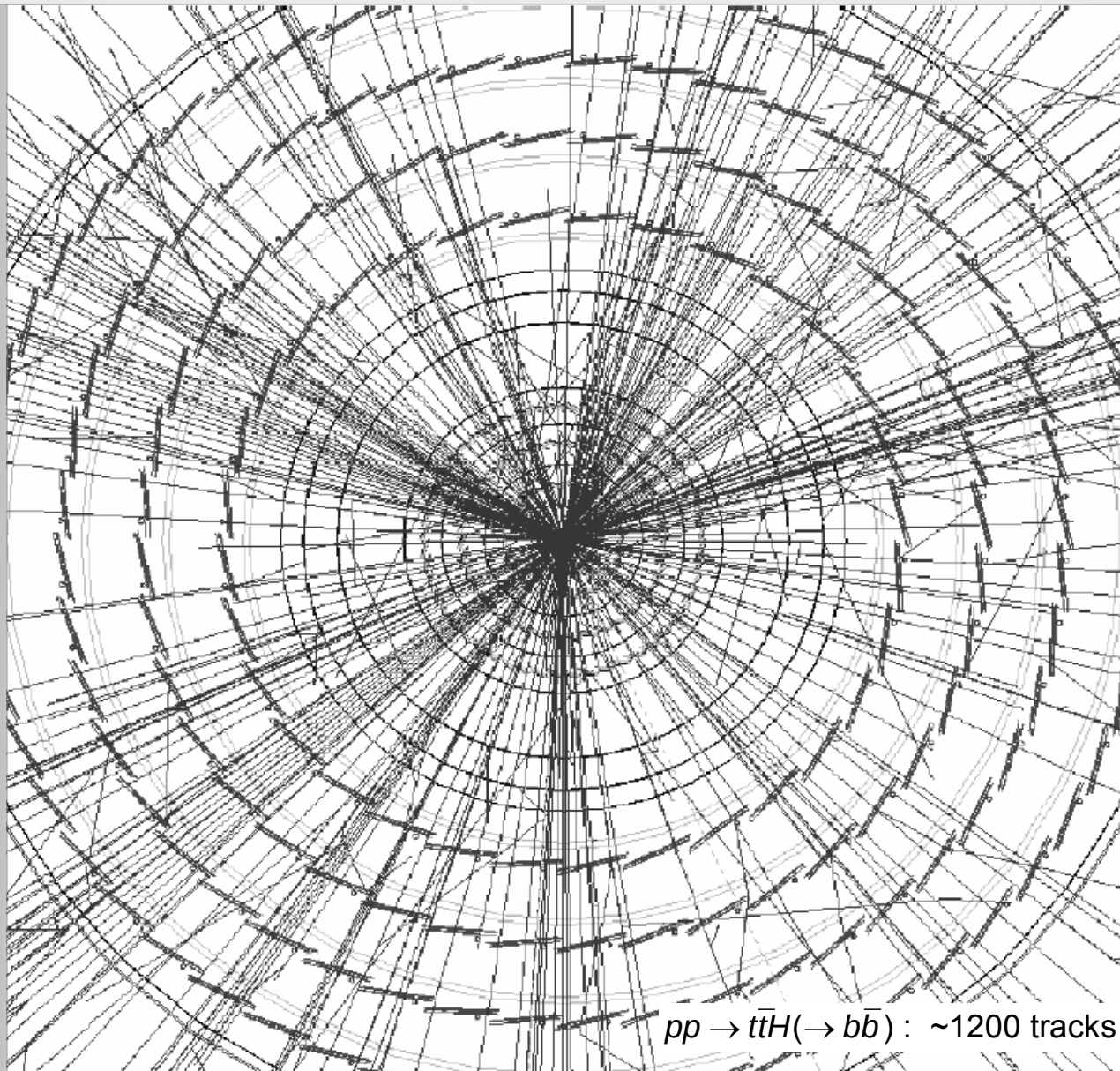
- Thin ($\sim\mu\text{m}$), highly doped p^+ ($\sim 10^{19}\text{ cm}^{-3}$) layer on lightly doped n ($\sim 10^{12}\text{ cm}^{-3}$) substrate
 - ➡ High mobility of charge carriers in Si allows fast charge collection ($\sim 5\text{ ns}$ for electron)
 - ➡ High Si density & low electron–hole creation potential (3.6 eV compared to $\sim 36\text{ eV}$ for gaseous ionisation) allows use of very thin detectors with reasonable signal



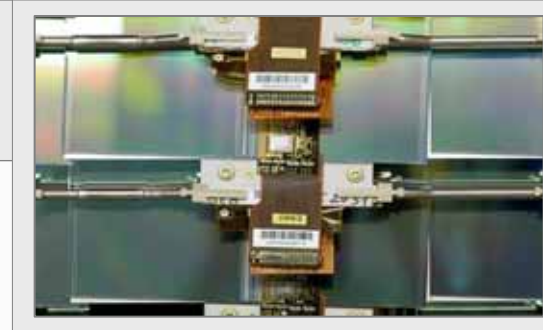
Schema of silicon microstrip sensor

- Reverse bias: backplane put to at positive voltage ($< 500\text{ V}$)
- A traversing charge particle ionises silicon, creating conduction electrons and holes that induce a measurable current by drifting to electrodes
- Metal-semiconductor transition forms charge (Schottky) barrier similar to p – n junction. Highly doped n^+ layer reduces width of potential barrier and hence resistance

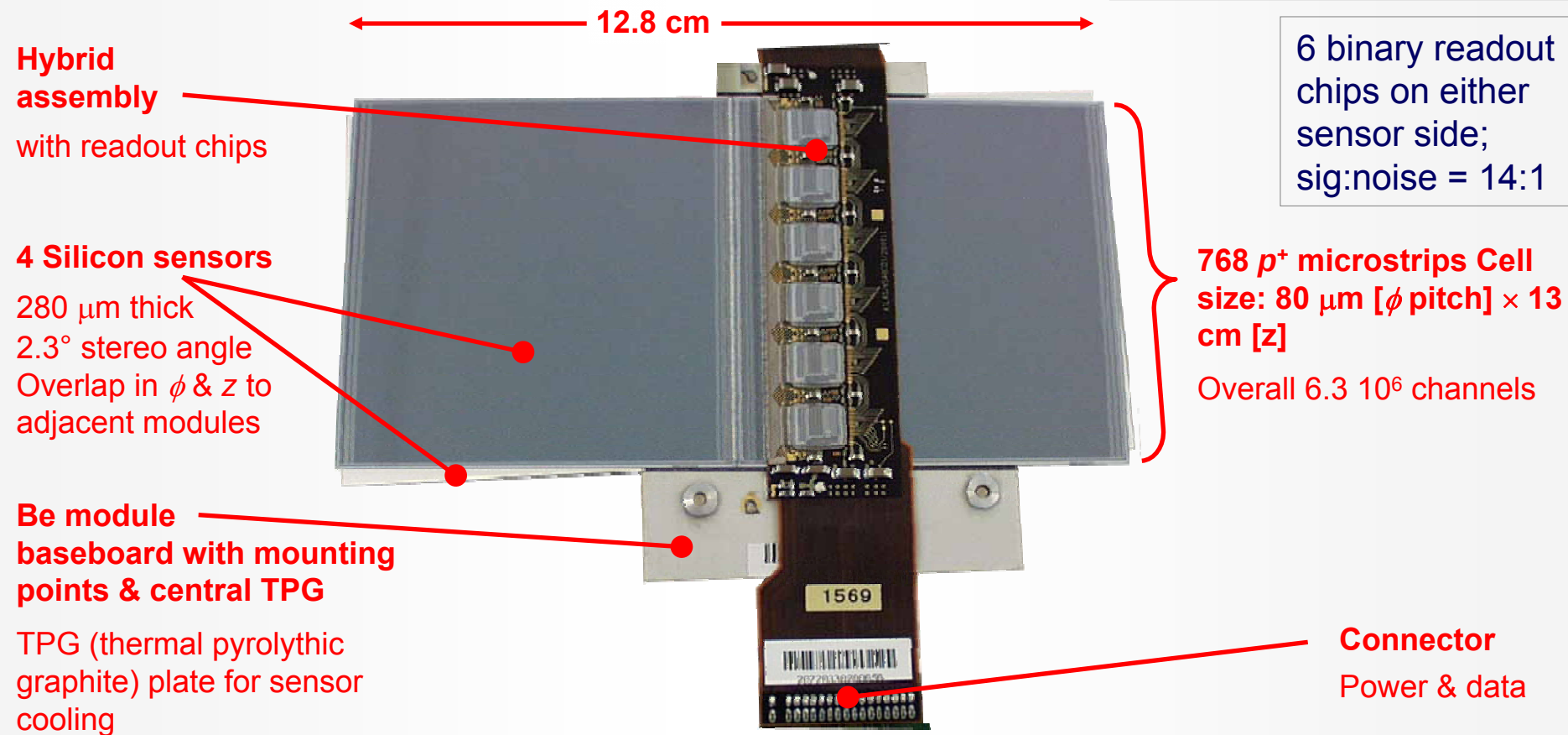
The ATLAS Semiconductor Tracker (SCT)



SCT Module

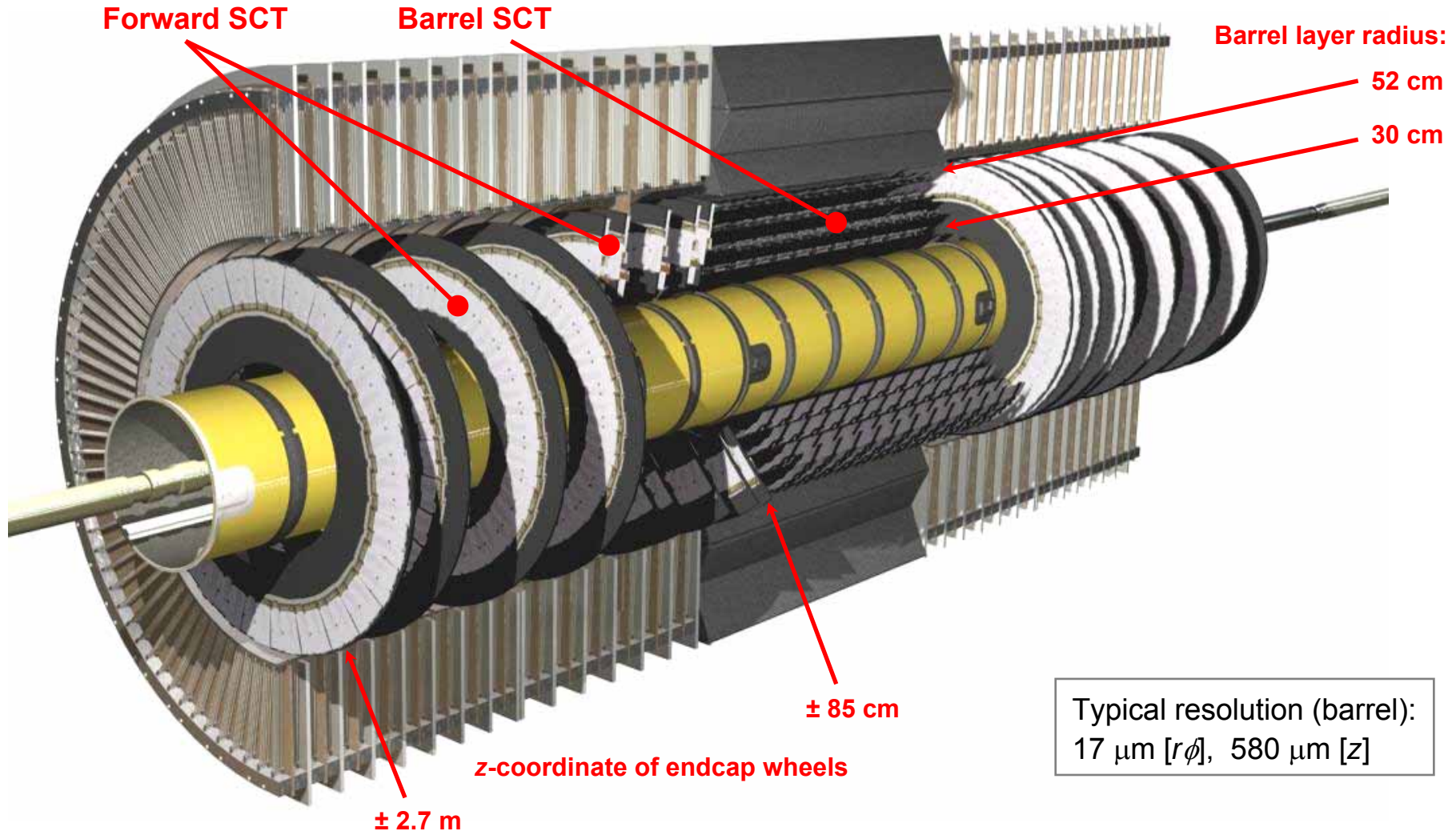


■ Barrel SCT module:

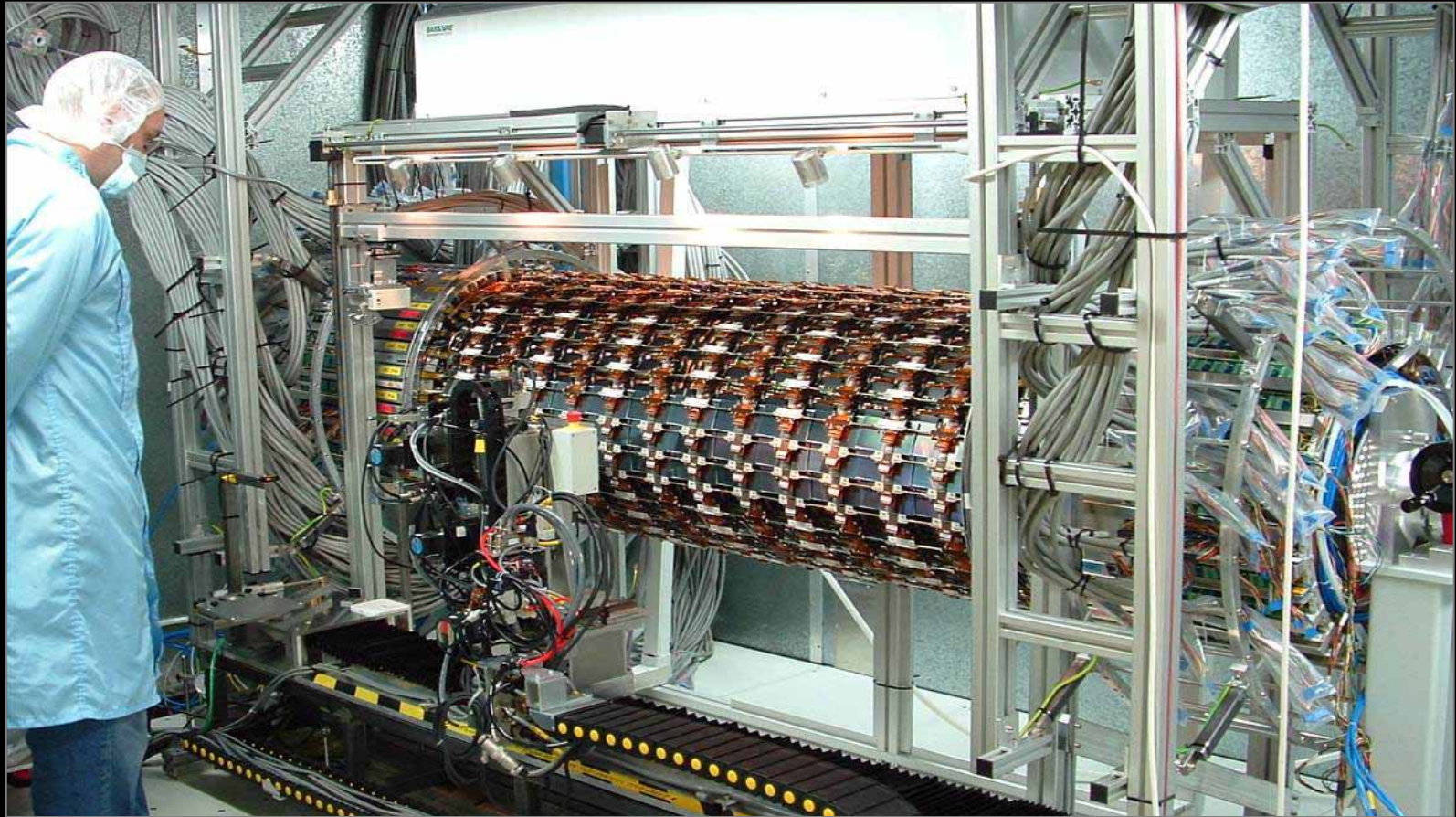


Fully equipped double sided electrical module with baseboard and readout hybrids

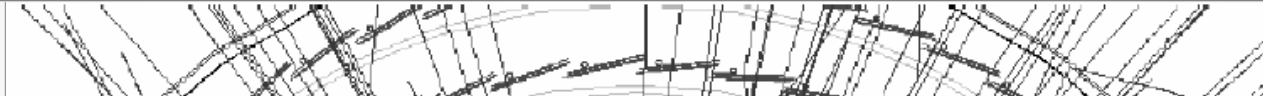
Geometry of ATLAS SCT



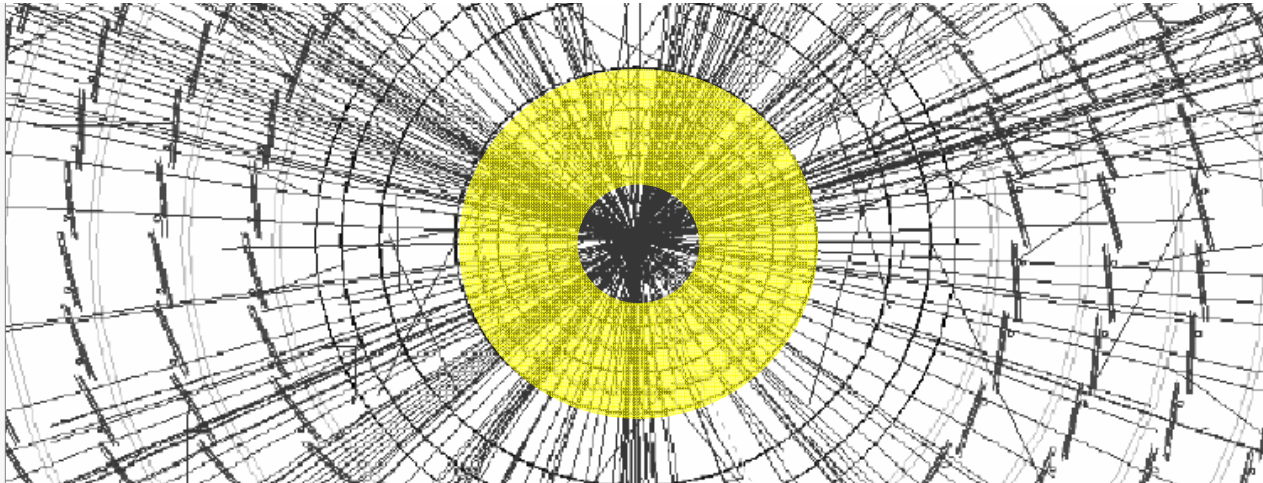
The ATLAS Semiconductor Tracker (SCT)



The ATLAS Pixel Detector



- Close to the beam pipe, high track rate invalidates the use of silicon strips
 - Silicon microstrips z pattern recognition too slow → **true 3D device required** → **Pixel**
 - Also: leakage currents due to radiation dose require small Si volumes per channel



- The ATLAS and CMS pixel detectors among 1. generation of high-rate pixel devices
- Its basic unit is a **module**

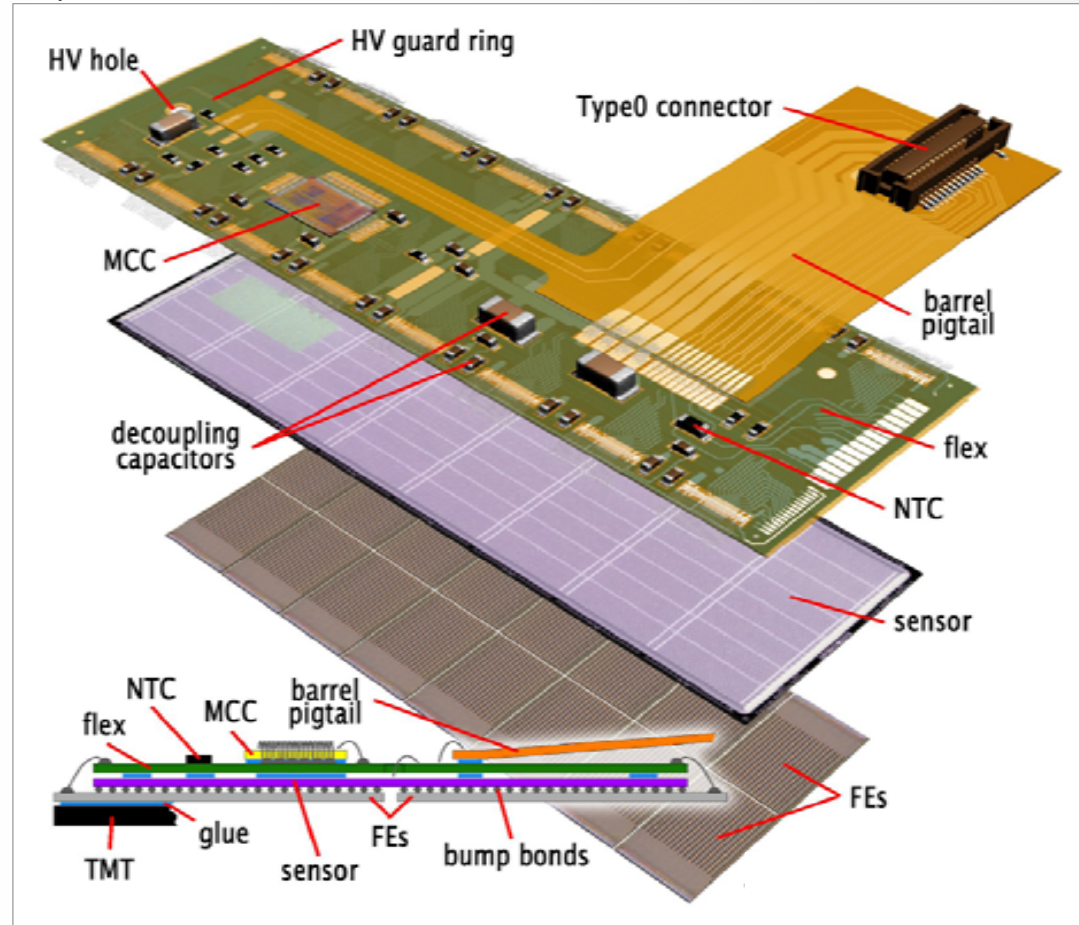


The Pixel Module

To cope with high rates, each pixel is read as individual electronics channel

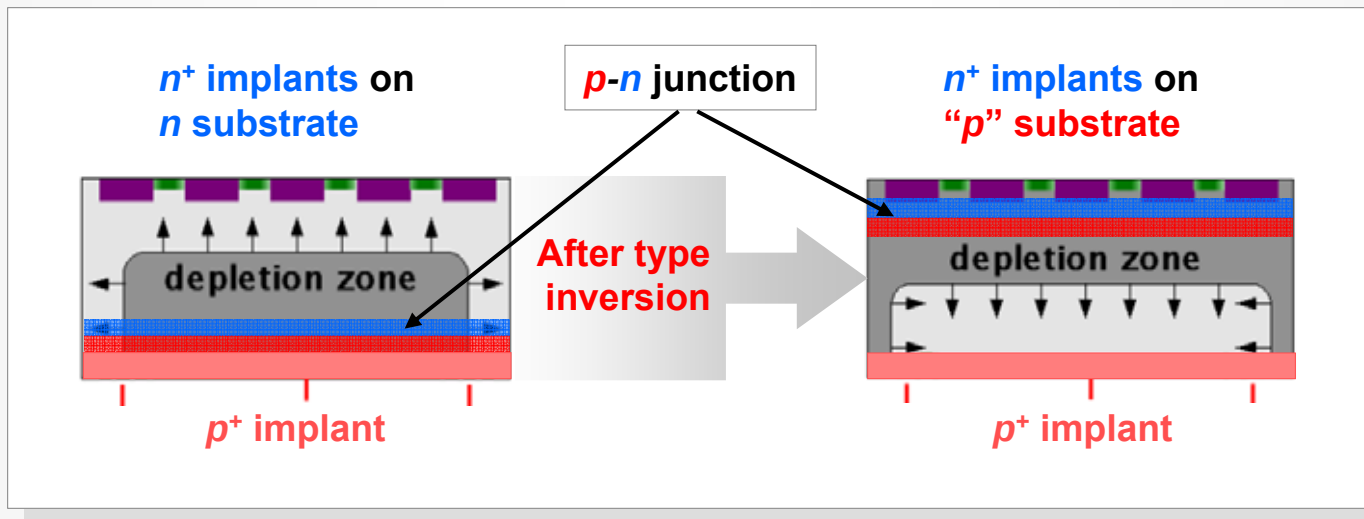
Module size: 6×2 cm, 46k pixels: $50[\phi] \times 400[z]$
 μm^2 (250 μm Si bulk), max. bias voltage: 600V, $T \approx -$
(5–10) $^\circ$

- 16 front-end chips, each containing 2880 pixel channels with programmable thresholds
- Number of channels: 67×10^6 (barrel) and 13×10^6 (endcap), signal-to-noise > 30
- Zero-suppressed detector read-out: 160 GB/sec
- Area covered by electronics exceeds sensor size
- 6 kW consumption in active volume requires powerful cooling (evaporative C_3F_8)



Pixel Sensors in Radiation Environment

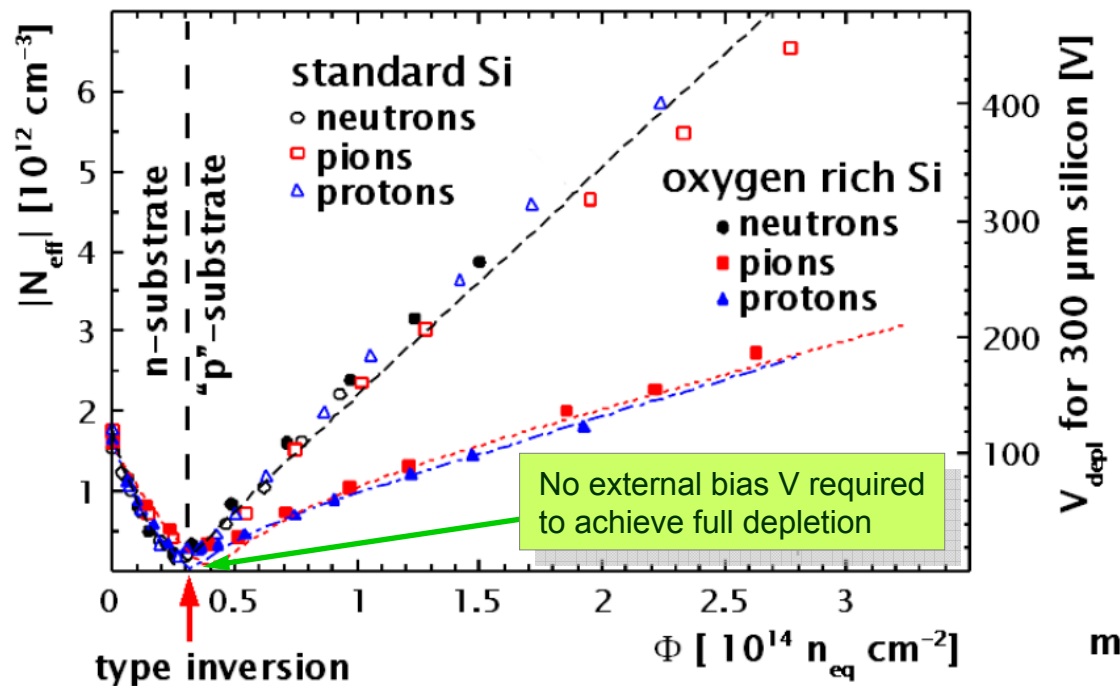
- Non-ionising energy loss (NIEL) from irradiation causes irreversible Si lattice damage
 - Increase of leakage current (linear), effective p doping, trapping of signal charge
 - ➡ “Type inversion” of the bulk



Pixel Sensors in Radiation Environment

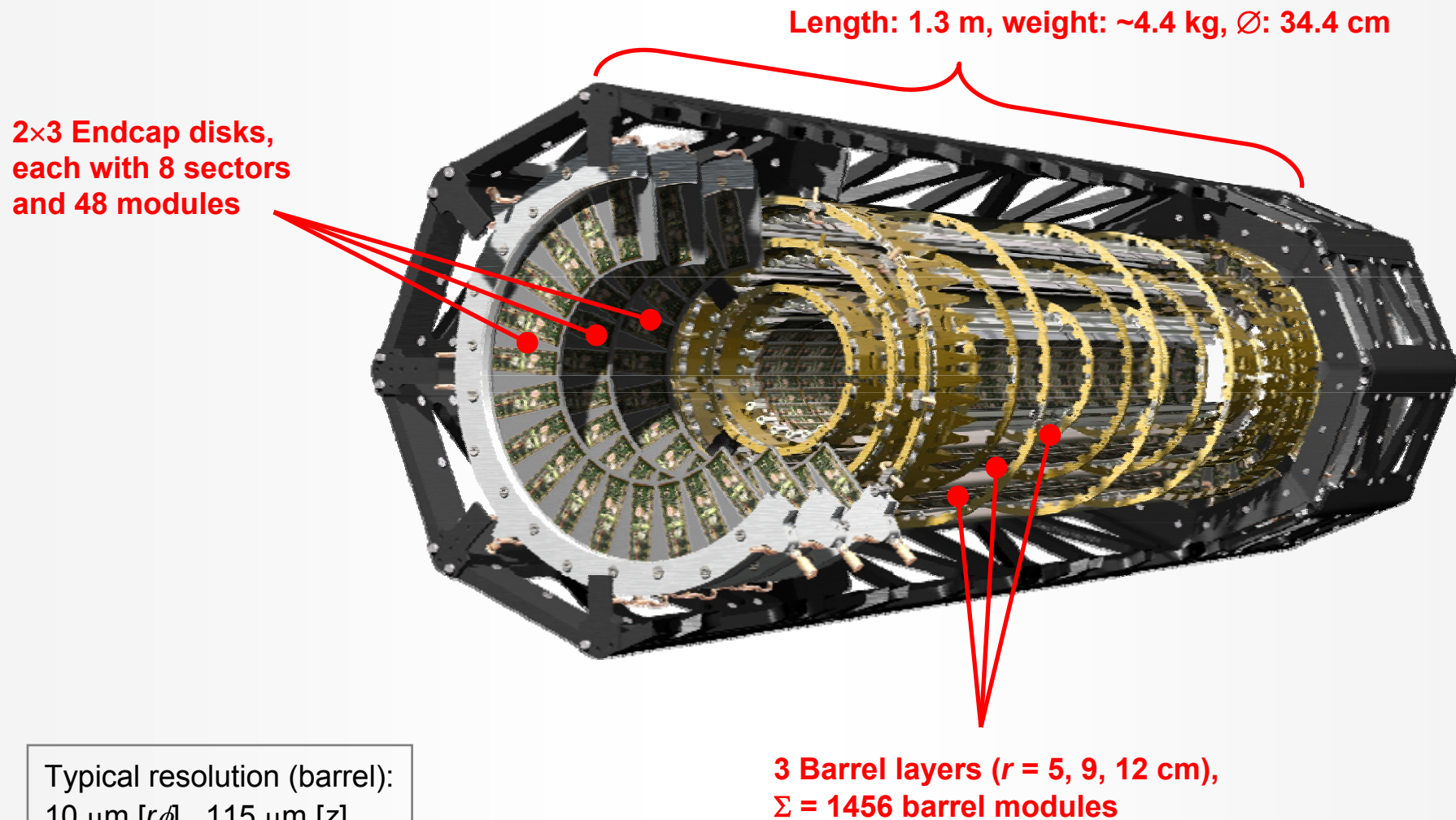
- Non-ionising energy loss (NIEL) from irradiation causes irreversible Si lattice damage
 - Increase of leakage current (linear), effective p doping, trapping of signal charge
 - ➡ “Type inversion” of the bulk

Change of depletion voltage with particle fluence

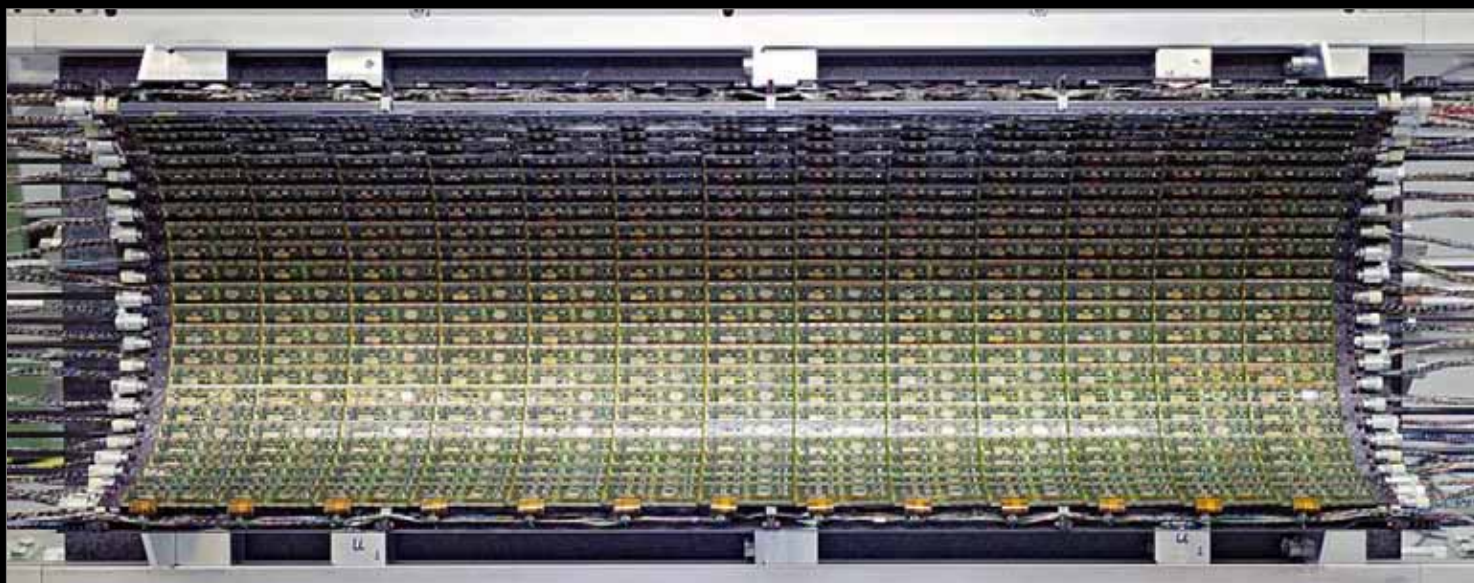


Si Oxygenation: keeps required bias voltage for full depletion within operational 600 V for ~10 yrs

The ATLAS Pixel Detector



Pixel Pix'



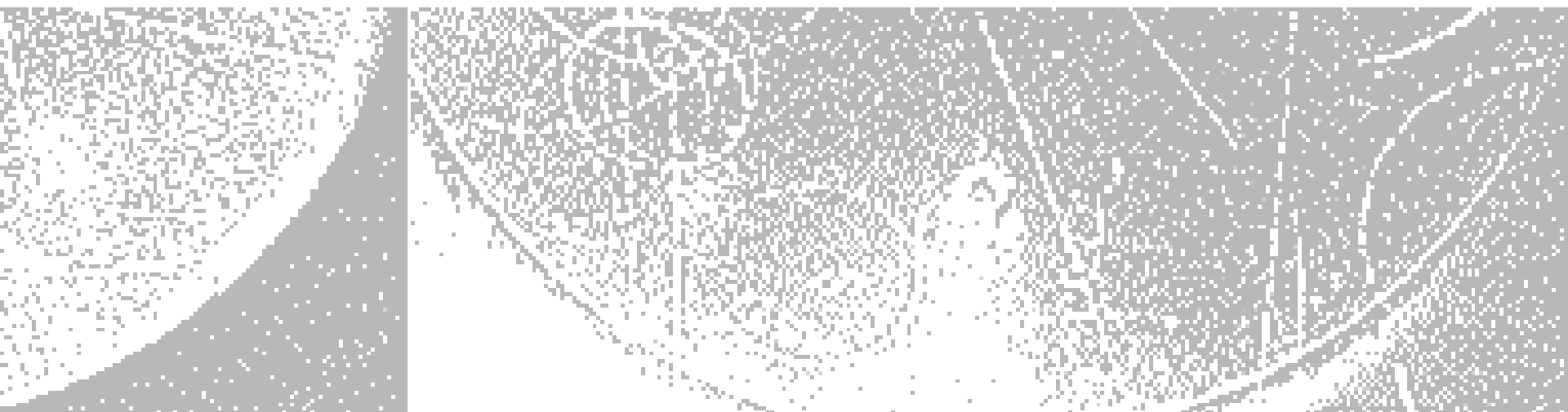
Pixel Pix'





Interlude

Charged Particle Interaction with Matter

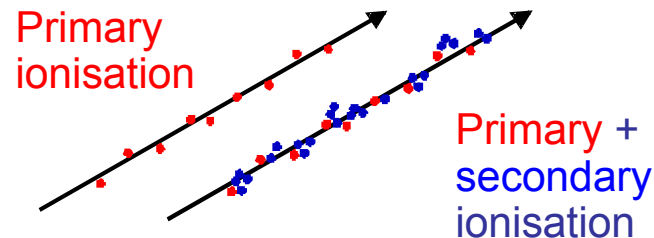


Charged Particle Interaction with Matter

- Particles are detected through their interaction with the active detector materials

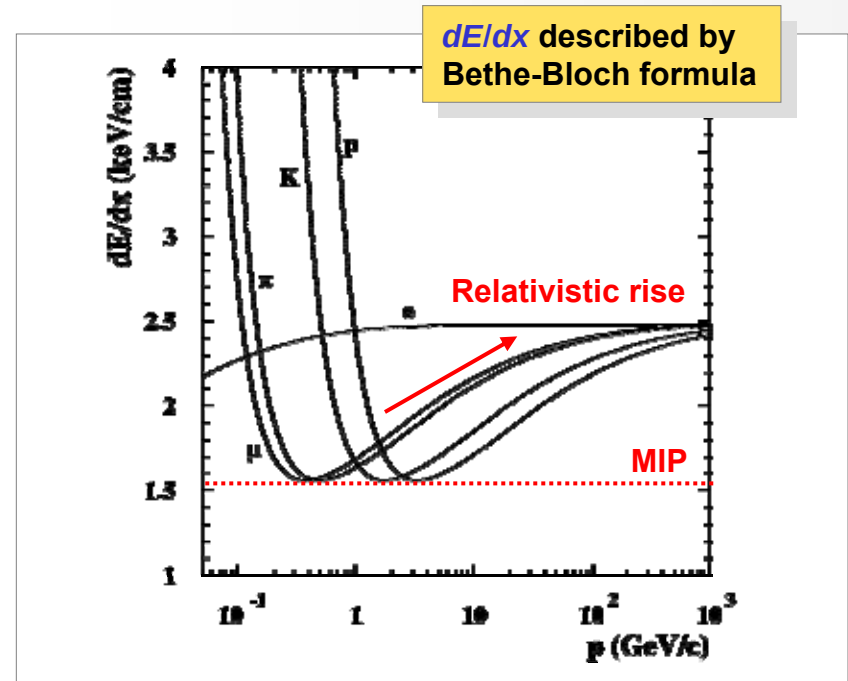
- **Energy loss by ionisation**

Primary ionisation can generate secondary ionisation



Typically:

Total ionisation = 3 x primary ionisation
→ ~ 90 electrons/cm in gas at 1 bar



➡ Not directly used for PID by ATLAS/CMS

Charged Particle Interaction with Matter

- Particles are detected through their interaction with the active detector materials
 - Energy loss by ionisation
 - **Bremsstrahlung**

Due to interaction with coulomb field of nucleus

Dominant energy loss mechanism for electrons down to low momenta (~ 10 MeV)

Initiates EM cascades (showers)

Charged Particle Interaction with Matter

- Particles are detected through their interaction with the active detector materials
 - Energy loss by ionisation
 - Bremsstrahlung
 - **Multiple scattering**

Charged particles traversing a medium are deflected by many successive small-angle scatters

Angular distribution $\sim$ Gaussian, $\sigma_{MS} \sim (L/X_0)^{1/2}/p$, but also large angles from Rutherford scattering $\sim \sin^{-4}(\theta/2)$

→ Complicates track fitting, limits momentum measurement

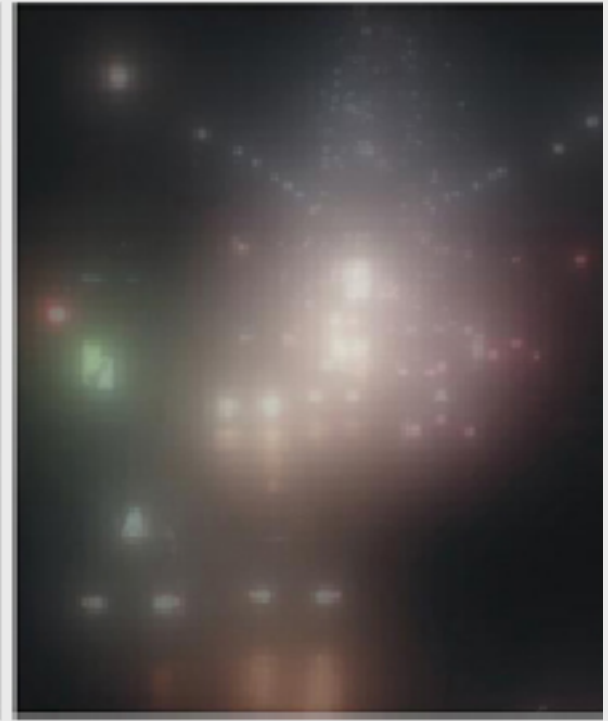
Charged Particle Interaction with Matter

■ Particles are detected through their interaction with the active detector materials

■ Energy loss by ionisation

■ Bremsstrahlung

■ **Multiple scattering**



Charged Particle Interaction with Matter

■ Particles are detected through their interaction with the active detector materials

■ Energy loss by ionisation ■ Bremsstrahlung ■ Multiple scattering

■ **Radiation length**

Material thickness in detector is measured in terms of dominant energy loss reactions at high energies:

- Bremsstrahlung for electrons
- Pair production for photons

Definition:

X_0 = Length over which an electron loses all but $1/e$ of its energy by bremsstrahlung

= 7/9 of mean free path length of photon before pair production

➡ Describe material thickness in units of X_0

Material	X_0 [cm]
Be	35.3
Si	9.4
Fe	1.8
PbWO ₄	0.9
Pb	0.6

↑
ATLAS LAr
absorber

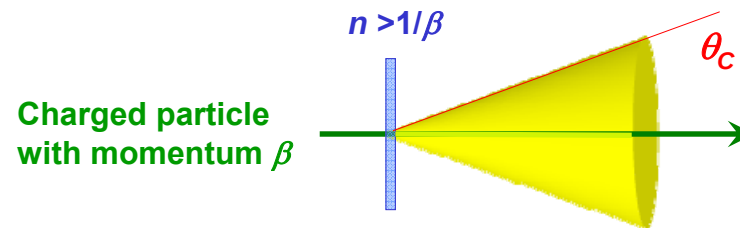
↑
CMS ECAL
crystals

Charged Particle Interaction with Matter

■ Particles are detected through their interaction with the active detector materials

- Energy loss by ionisation
- Bremsstrahlung
- Multiple scattering
- Radiation length
- **Cherenkov radiation**

A relativistic charge particle traversing a dielectric medium with refraction index $n > 1/\beta$, emits Cherenkov radiation in cone with angle θ_C around track: $\cos \theta_C = 1/(n\beta)$



Light cone emission when passing thin medium

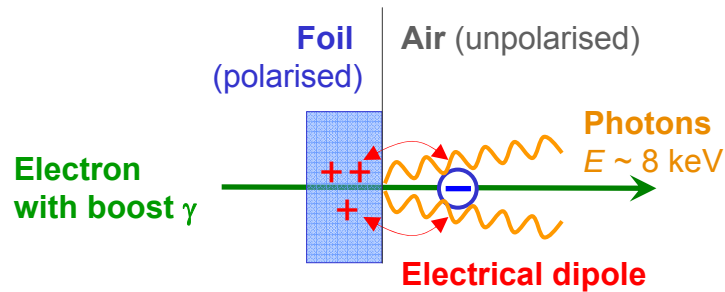
Detector types RICH (LHCb), DIRC, Aerogel counters (not employed by ATLAS/CMS))

Charged Particle Interaction with Matter

■ Particles are detected through their interaction with the active detector materials

- Energy loss by ionisation
- Bremsstrahlung
- Multiple scattering
- Radiation length
- Cherenkov radiation
- **Transition radiation**

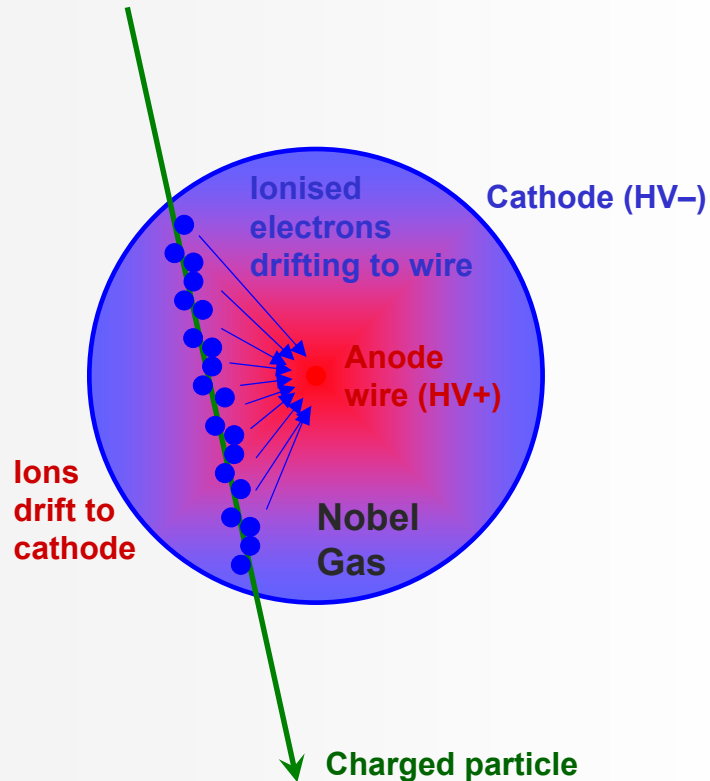
Photon radiation when charged ultra-relativistic particles traverse the boundary of two different dielectric media (foil & air)



- ➡ Significant radiation for $\gamma > 1000$
and > 100 boundaries

Drift Tubes (DT)

- Classical detection technique for charged particles based on gas ionisation and drift time measurement

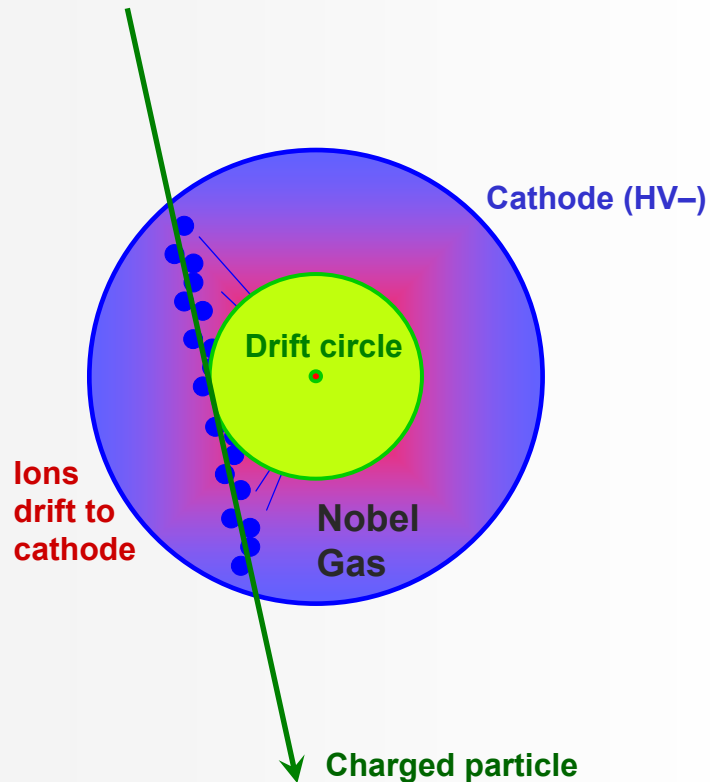


- Macroscopic drift time: $v_D/c \sim 10^{-4} \rightarrow \sim 30 \text{ ns/mm}$
- Determine v_D from difference between DT signal peaking time and expected particle passage

TRT: Kapton tubes, $\varnothing = 4 \text{ mm}$
MDT: Aluminium tubes, $\varnothing = 30 \text{ mm}$

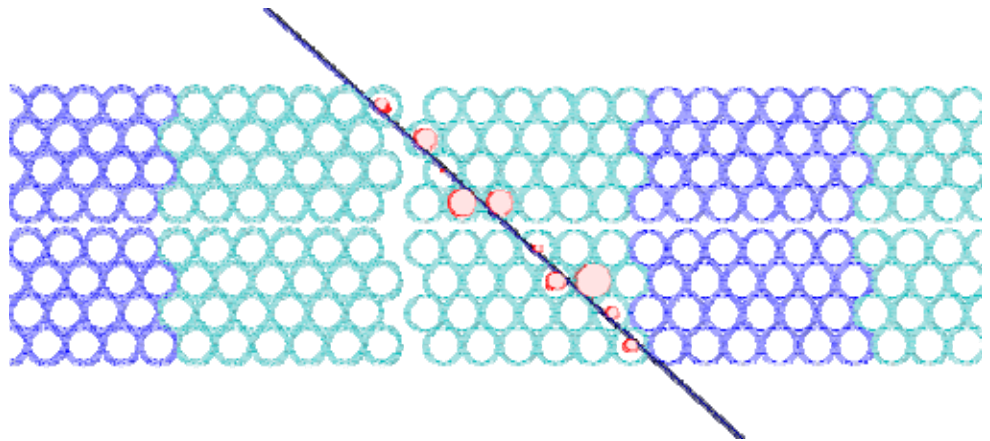
Drift Tubes (DT)

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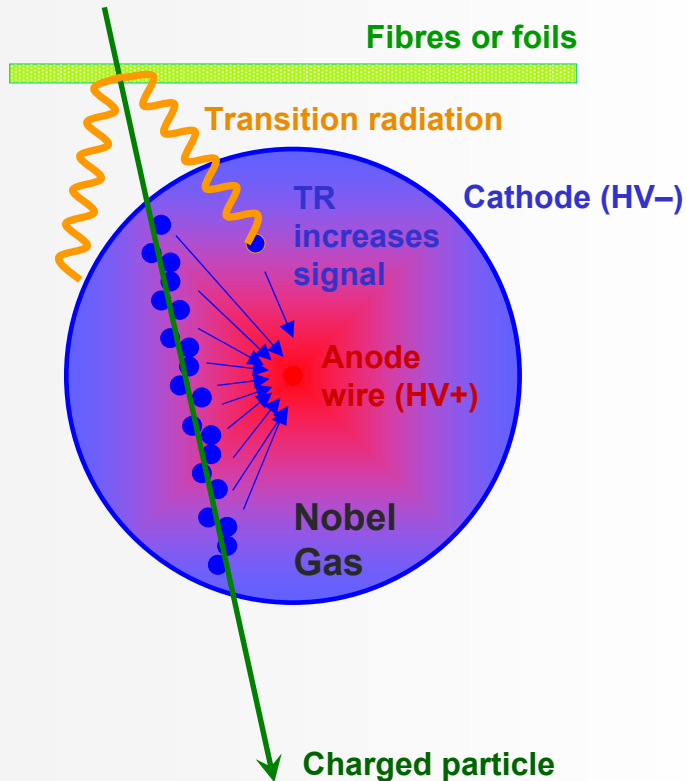
TRT: Kapton tubes, $\varnothing = 4$ mm
MDT: Aluminium tubes, $\varnothing = 30$ mm

Example: muon in MDTs

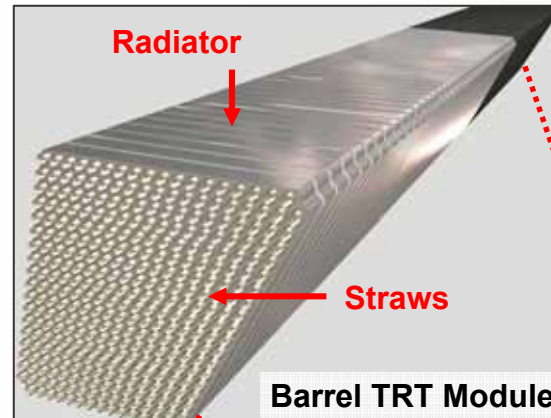


Combining Tracking with PID: the ATLAS TRT

- e/π separation via transition radiation: polymer (PP) fibres/foils interleaved with DTs



Electrons radiate more $\rightarrow$ higher signal;
PID info by counting high threshold hits

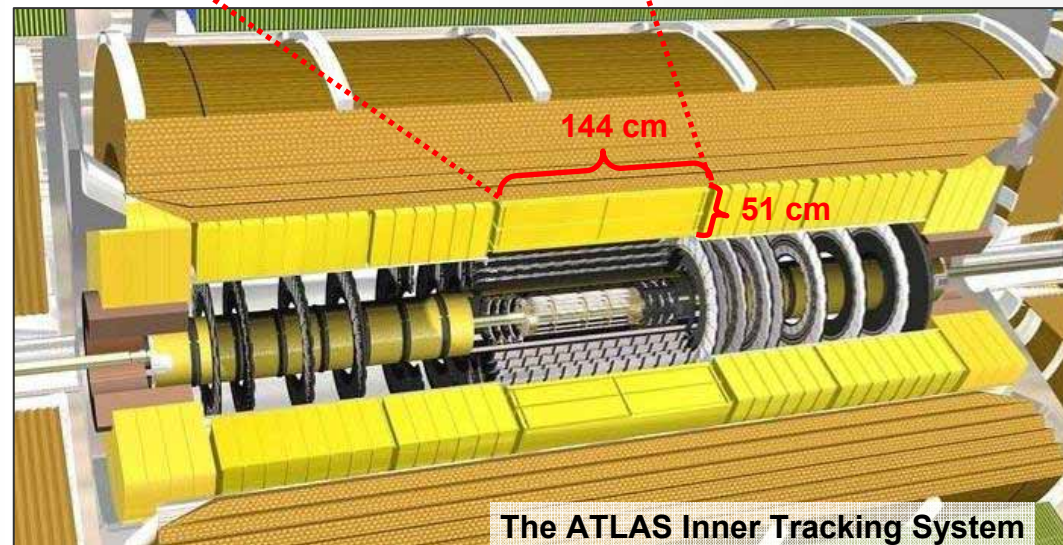


Total: 370k straws

Barrel ($|\eta| < 0.7$): 36 r - ϕ measurements / track

Resolution $\sim 130 \mu\text{m}$ / straw

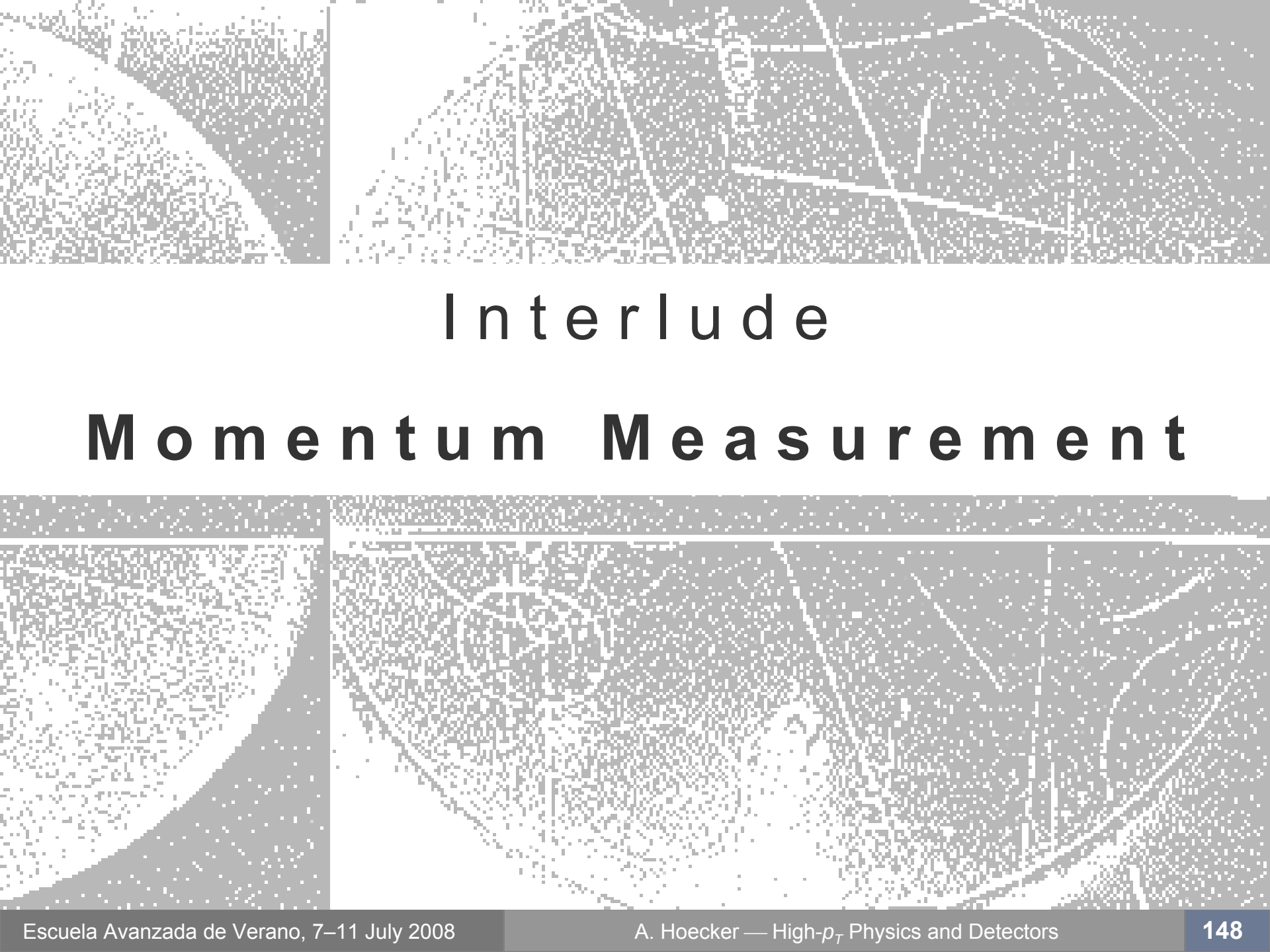
18 Endcap wheels ($|\eta| < 2.5$): 35 or less z - ϕ points



The ATLAS Inner Tracking System

Insertion of SCT into TRT Barrel



The background of the slide is composed of four panels, each showing a different event display from a particle detector. The top-left panel shows a curved, segmented structure, likely a calorimeter or tracker. The top-right panel shows a complex network of lines and points, representing particle tracks and vertices. The bottom-left panel shows a similar curved structure to the top-left. The bottom-right panel shows a dense network of lines and points, similar to the top-right panel.

Interlude

Momentum Measurement

Momentum Measurement in Tracking Device

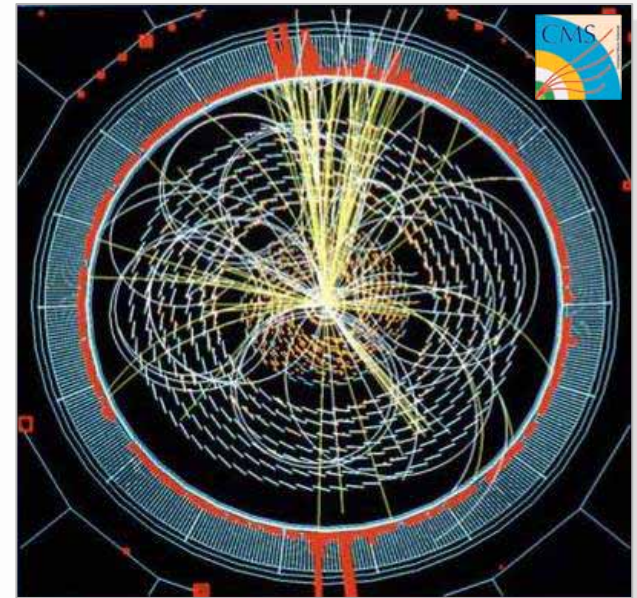
■ Charged particles deflection in magnetic field:

- Lorentz force $\perp$ to B -field and to particle direction

- Particle trajectory projected onto plane $\perp$ to B -field is *circle* with radius: $r[\text{m}] = \frac{p_T[\text{GeV}]}{0.3 \cdot B[\text{T}]}$

- ➡ For $p_T = 10 \dots 1000 \text{ GeV}$ and $B = 2 \text{ T} \rightarrow r = 17 \dots 1700 \text{ m}$ (cf, $r_{\text{ID}} \sim 1 \text{ m}$)

- ➡ ... and if $p_T < 0.7$ the particle is trapped in solenoid $\rightarrow$ “loopers”



Special thanks to L. Chevalier

Momentum Measurement in Tracking Device

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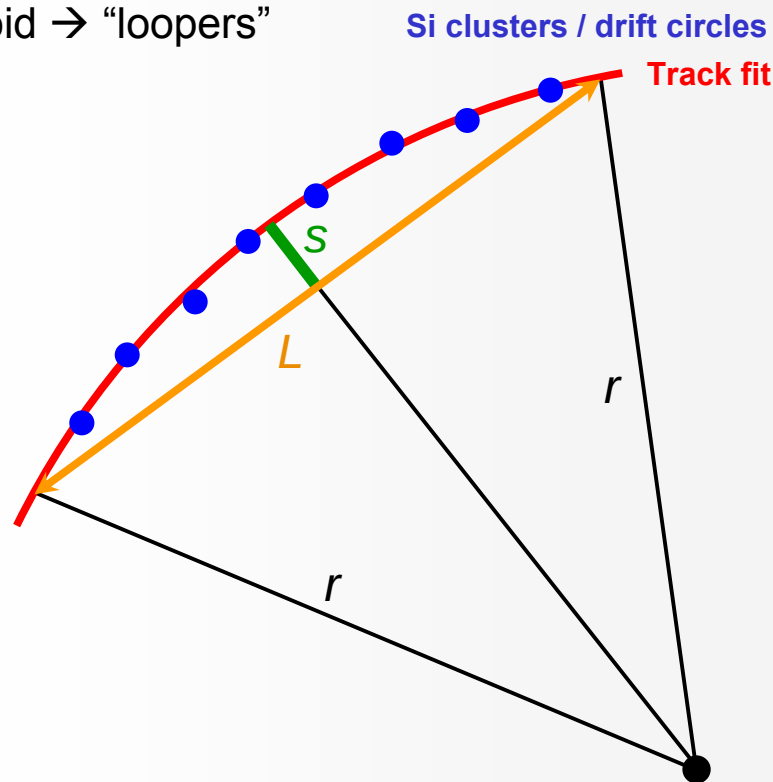


■ Obtain r and p_T from measurement of sagitta:

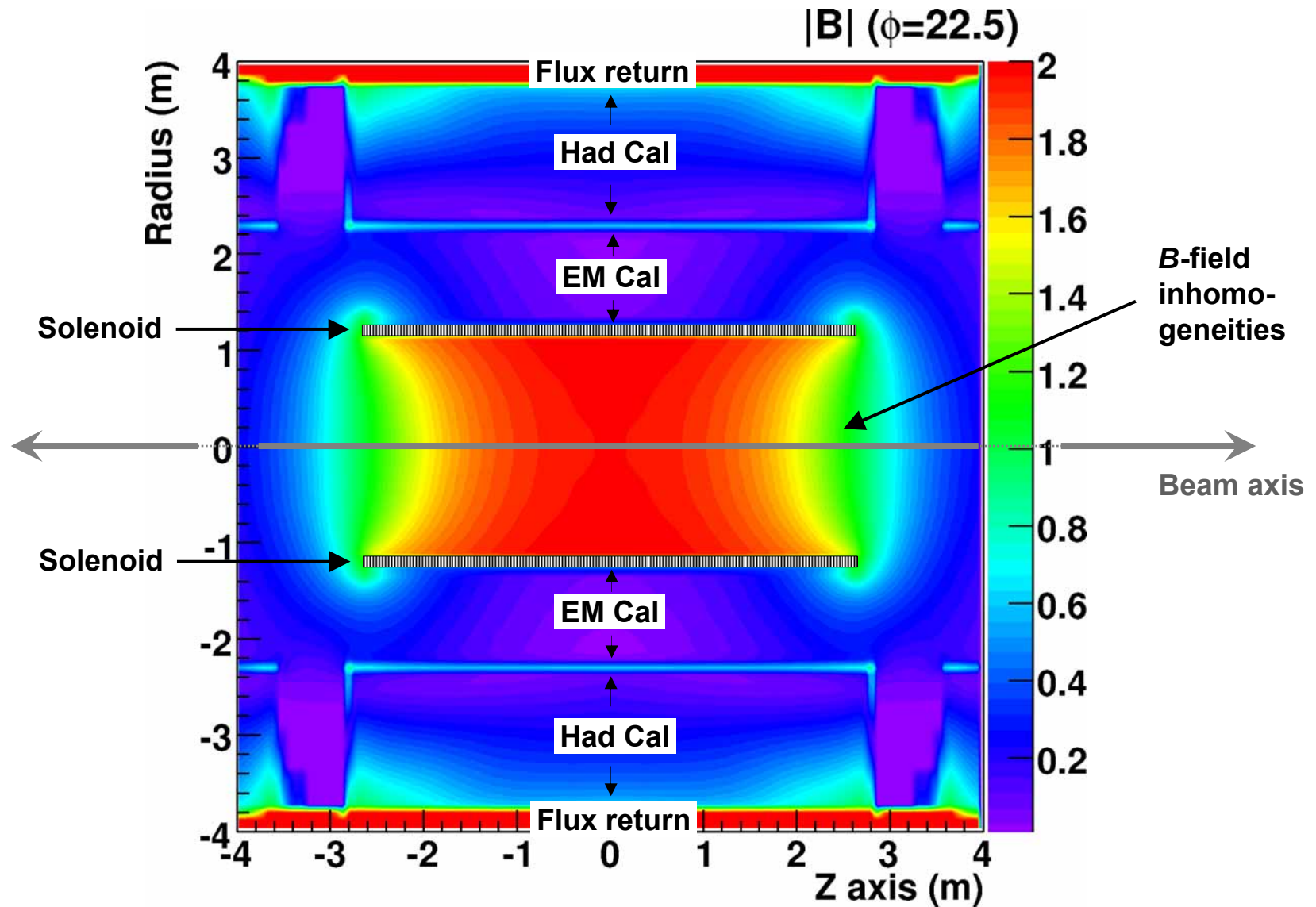
$$r \approx \frac{L}{8s} \quad (\text{if } s \ll L) \Rightarrow p_T \propto \frac{1}{s} \quad \text{and} \quad \frac{\sigma(p_T)}{p_T} \propto p_T$$

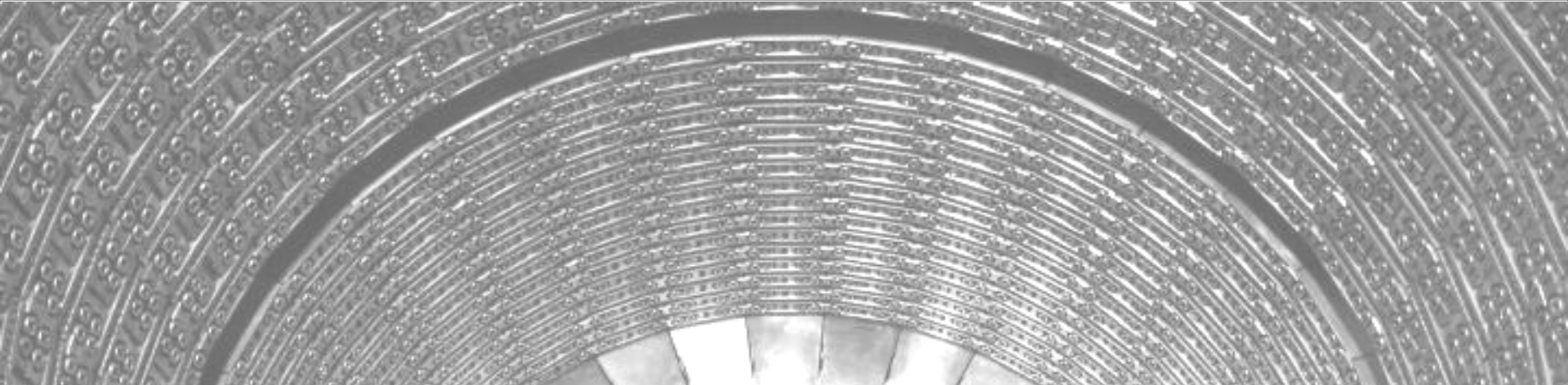
■ Track fitting in LHC environment challenging

- Must handle ambiguities, hit overlaps, multiple scattering, bremsstrahlung, multiple vertices, ...
- Track fitters take Gaussian noise (Kalman) and non-Gaussian noise (GSM) into account
- Fitter must be fast, used in high-level trigger

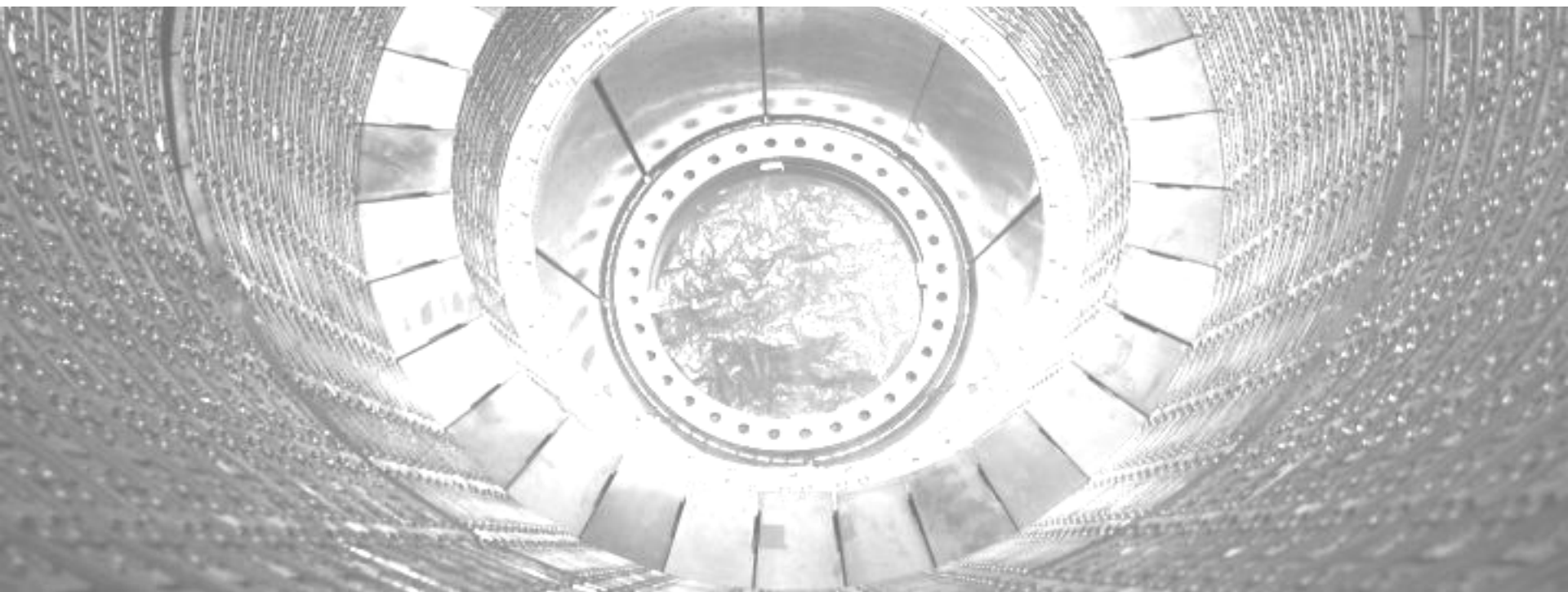


Solenoid Field





Calorimeters

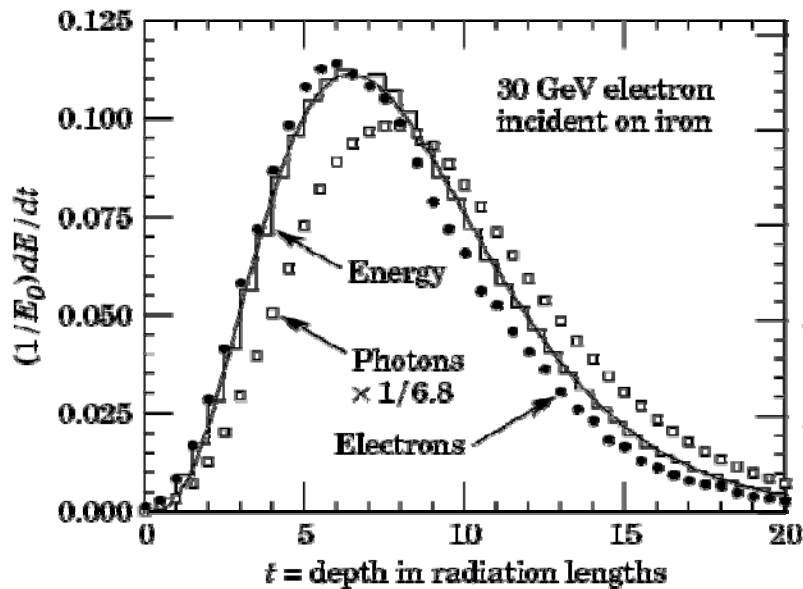


Electromagnetic Cascades

- A high-energy electron or photon incident on absorber initiates EM cascade
 - ➡ Bremsstrahlung and pair production generate lower energy electrons and photons
 - ➡ Shower profile strongly depends on the absorber's X_0

Longitudinal shower profile

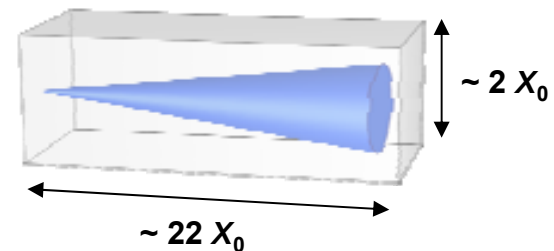
Governed by high-energy part of cascade
[for $E < E_c$ cascade exhausts by ionisation, Compton, ...]



Transverse shower profile

Width given by *Molière radius* :

$$R_M = \frac{21 \text{ MeV}}{E_c} X_0, \quad E_c \approx \frac{600}{Z + 1.2} \approx 7_{\text{Pb}}$$

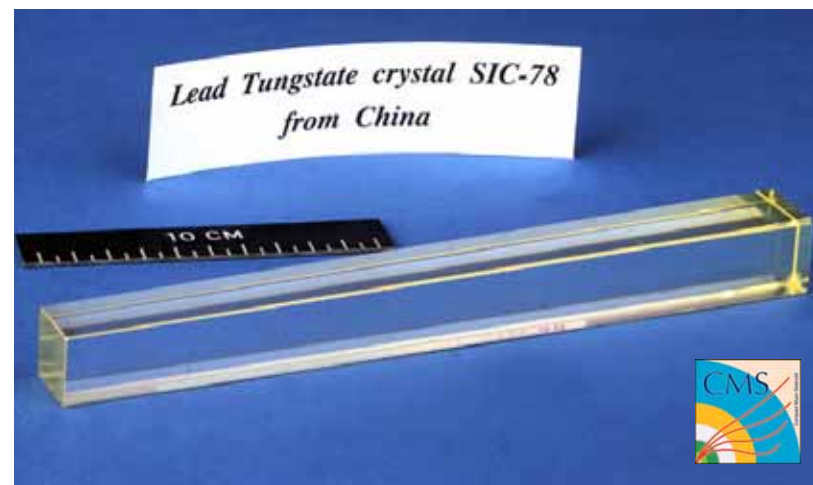


- ▶ Calorimeters aim at large X/X_0 (20 – 30)
- ▶ And wish transparent material in front
- ▶ Presampler corrects E for early showers

ATLAS and CMS EM Calorimeters

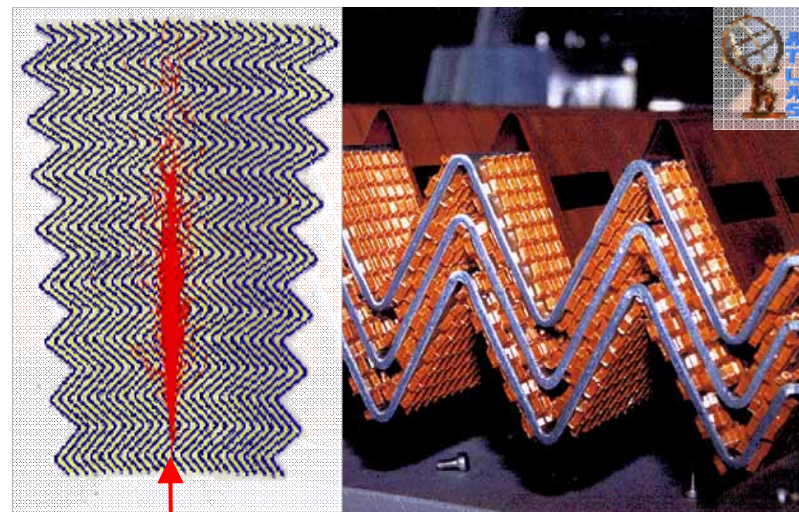
■ CMS: PbWO_4 Scint. Crystal Calorimeter

- Entire shower in active detector material
 - ▶ High density crystals ($28 X_0$)
 - ▶ Transparent, high light yield
 - ▶ No particles lost in passive absorber
 - ▶ High resolution: $\sim 3\%/\sqrt{E}$ (stochastic)
- Granularity
 - ▶ Barrel: $\Delta\eta \times \Delta\phi = 0.017^2$ rad
 - ▶ Longitudinal shower shape unmeasured

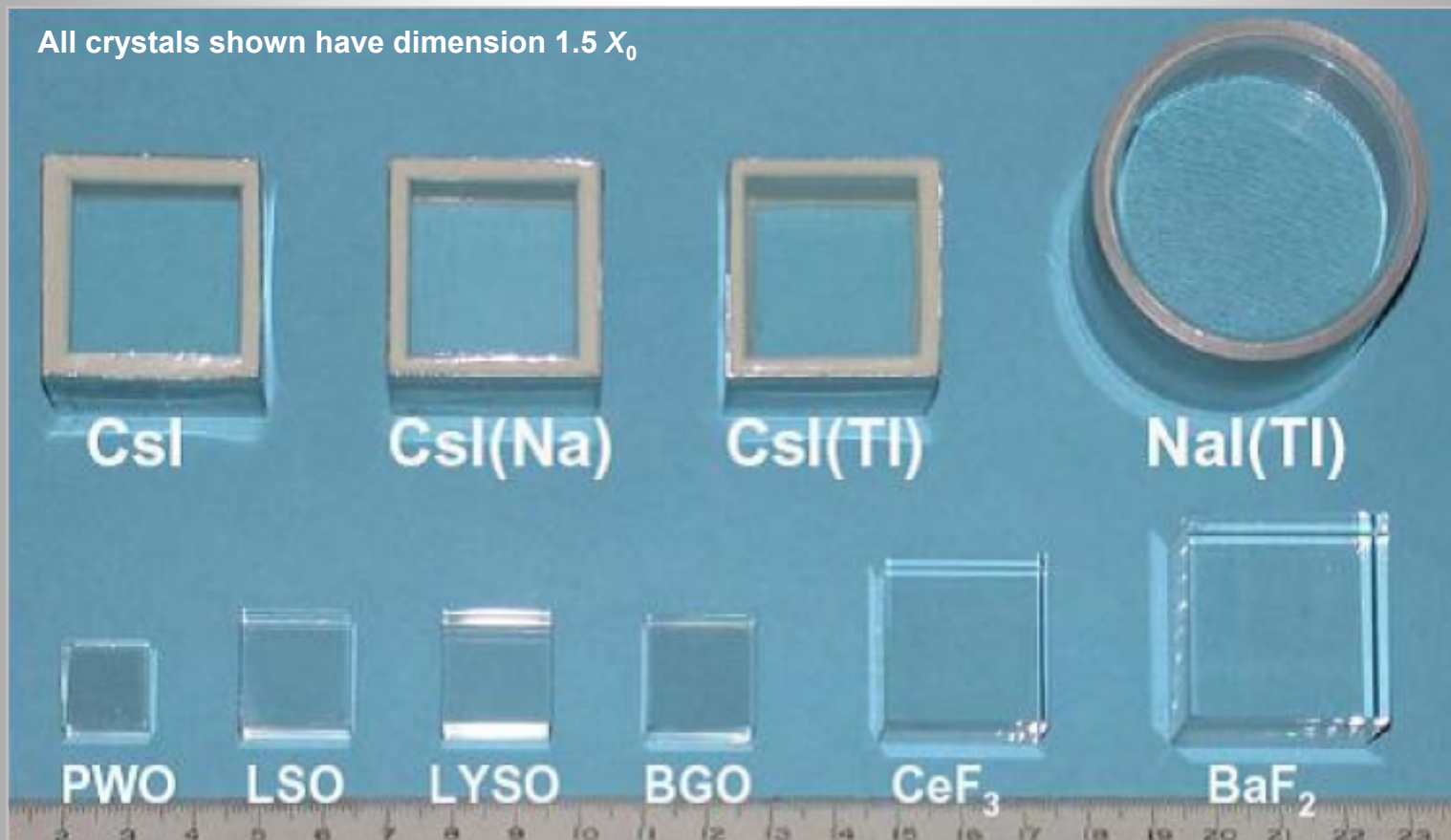


■ ATLAS: LAr Sampling Calorimeter

- Passive, heavy absorber (Pb, 1.1–1.5 mm thick [barrel]) inter-leaved with active detector material (liquid argon)
 - ▶ Overall $22 X_0$
 - ▶ Accordion structure for full ϕ coverage
 - ▶ Resolution: $\sim 10\%/\sqrt{E}$ (stochastic)
- Granularity
 - ▶ Barrel: $\Delta\eta \times \Delta\phi = 0.025^2$ rad (main layer)
 - ▶ Longitudinal segmentation (3 layers)

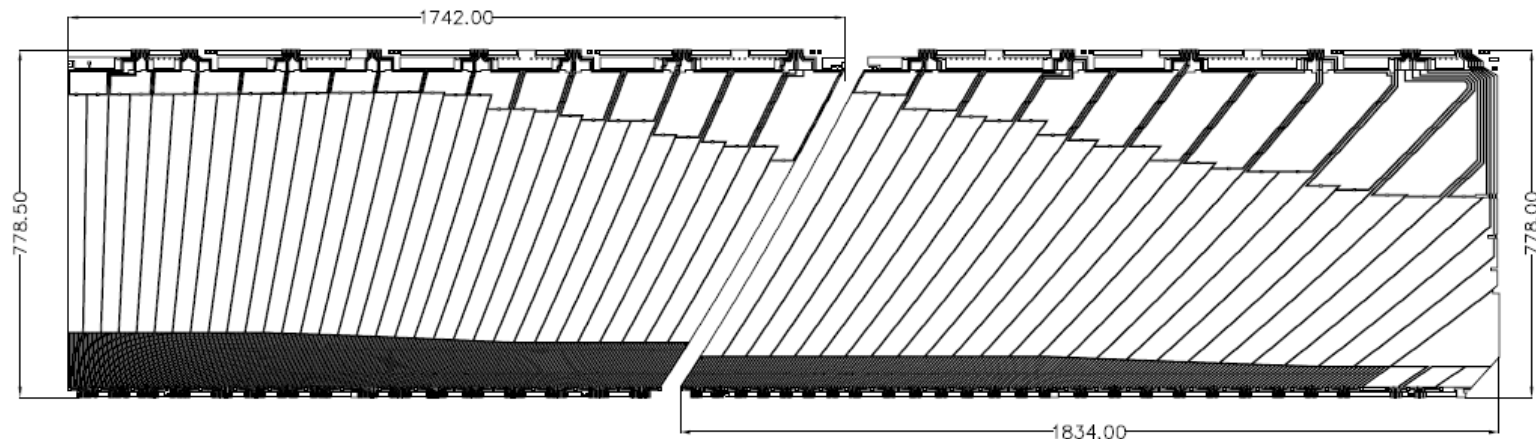


Crystal Comparisons



ATLAS Liquid Argon EM Calorimeter

Pointing 3-layer electrode structure for half-barrel of LAr calorimeter



Energy Resolution

■ Number of particles in shower $\propto$ energy of initial particle: $N_{\text{part}} \sim E/E_c$

■ Error in energy measurement due to statistical fluctuation in N_{part} : $\sigma(E) \sim \sqrt{N_{\text{part}}}$

$$\Rightarrow \frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{E}}$$

■ Phenomenological resolution formula:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E \text{ (GeV)}}} \oplus b \oplus \frac{c}{E \text{ (GeV)}}$$

“Stochastic term”
Shower fluctuations and containment

“Constant term”
Non-uniformities in calo response due to inhomogeneities, non-linearities

“Noise term”
Electronics noise (pile-up also contributes)

■ Sampling calorimeter: absorber material does not contribute to energy measurement

■ Sampling fractions in ATLAS LAr:

$$f_{\text{sampl}} = 0.17 \text{ } (|\eta| < 0.8), 0.20 \text{ } (|\eta| > 0.8)$$

$$E_{\text{true}} \approx \frac{1}{f_{\text{sampl}}} E_{\text{measured}} \Rightarrow \frac{\sigma(E)}{E} \propto \sqrt{\frac{d_{\text{sampl}}}{f_{\text{sampl}}}} \frac{1}{\sqrt{E}} \approx \frac{3}{\sqrt{E}}$$

Note: finer sampling (small d_{sampl}) $\rightarrow$ better resolution !

Energy Resolution

- Phenomenological resolution formula:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E \text{ (GeV)}}} \oplus b \oplus \frac{c}{E \text{ (GeV)}}$$

“Stochastic term”
Shower fluctuations and containment

“Constant term”
Non-uniformities in calo response due to inhomogeneities, non-linearities

“Noise term”
Electronics noise (pile-up also contributes)

Constant	ATLAS	CMS
<i>a</i>	10–12 %	3–5.5 %
<i>b</i>	0.2–0.35 %	0.5 %
<i>c</i>	250 MeV	200–600 MeV

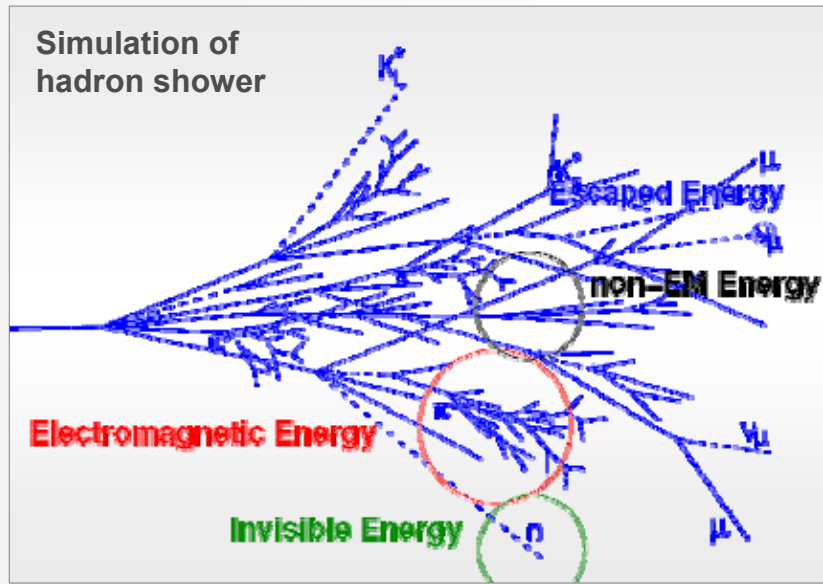
Hadron Showers

- Nuclear interaction length λ : *mean free path of hadrons between strong collisions*

Material	λ [cm]
Si	45.5
Fe	16.8
Pb	17.1

Interactions with nuclei leads to **hadronic (HAD) showers**

- Since $\lambda > X[X_0]$ one can separate EM (close) from HAD (far) showers



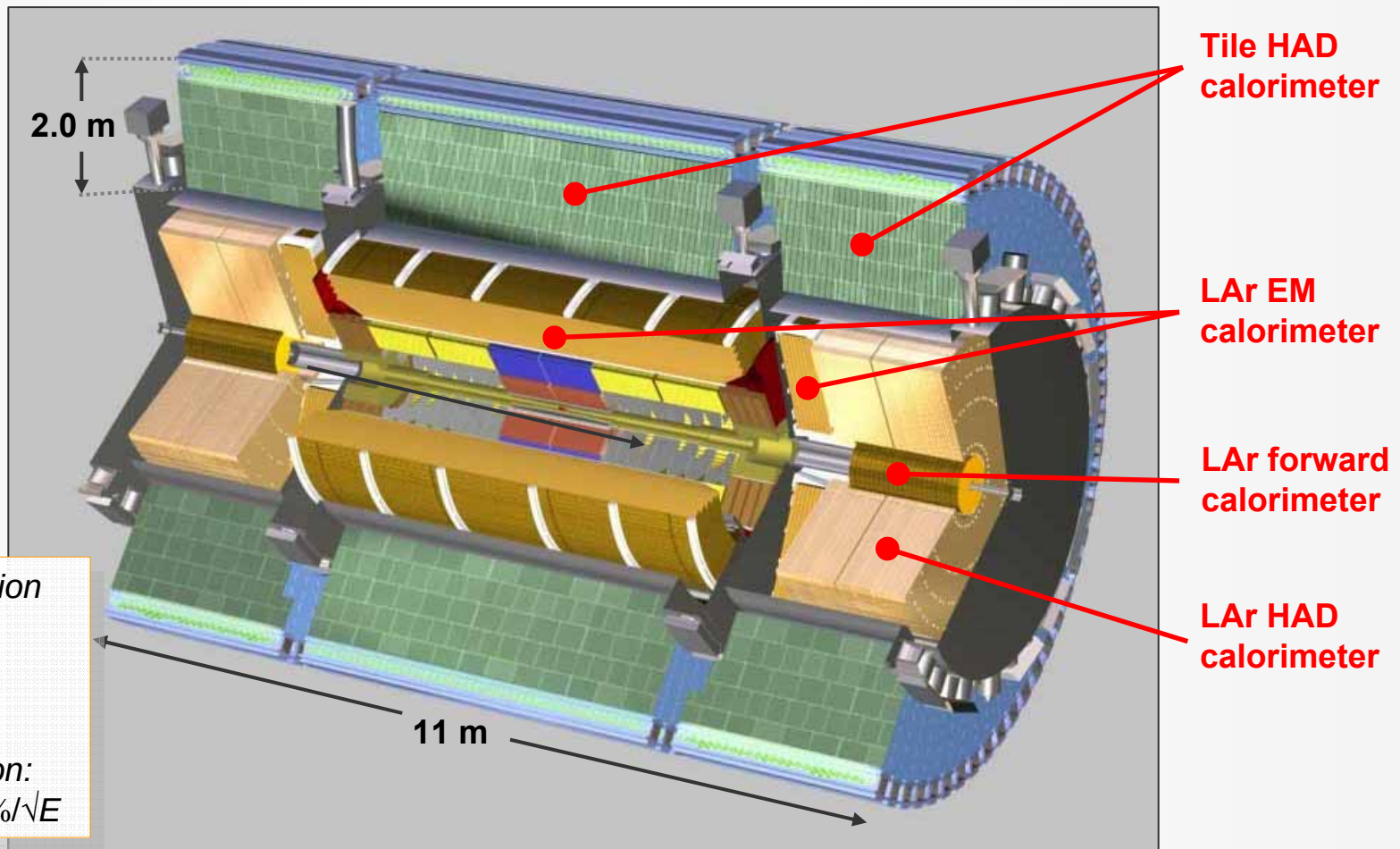
A hadronic shower consists of:

- ▶ EM energy (e.g., $\pi^0 \rightarrow \gamma\gamma$) $O(50\%)$
- ▶ Non-EM energy (e.g., dE/dx from $\pi^\pm, \mu^\pm, K^\pm$) $O(25\%)$
- ▶ Invisible energy (nuclear fission/excitation, neutrons) $O(25\%)$
- ▶ Escaped energy (e.g. neutrinos) $O(2\%)$

Invisible energy causes worse energy resolution for HAD showers

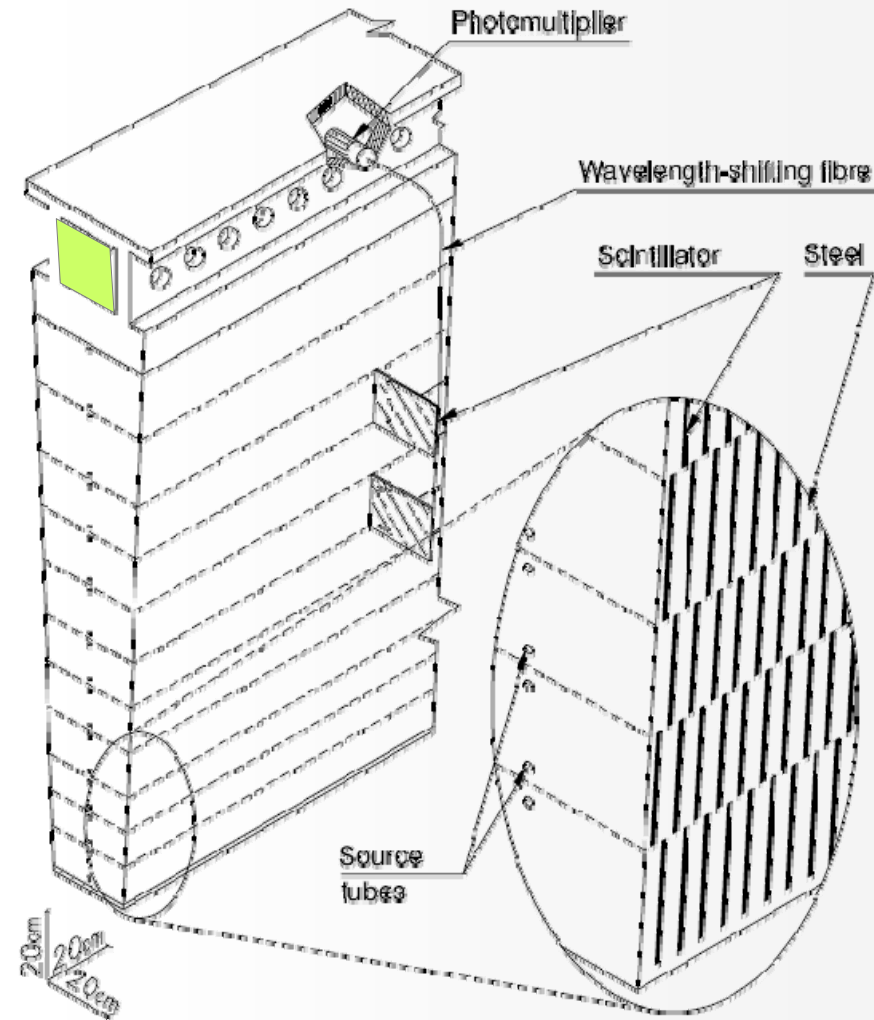
Hadronic Calorimeters

- EM calorimeter absorbs EM showers but only parts of showers initiated by hadrons
 - Following calorimeter layers (usually sampling calorimeters) fully absorb HAD showers



The ATLAS Tile Hadronic Calorimeter

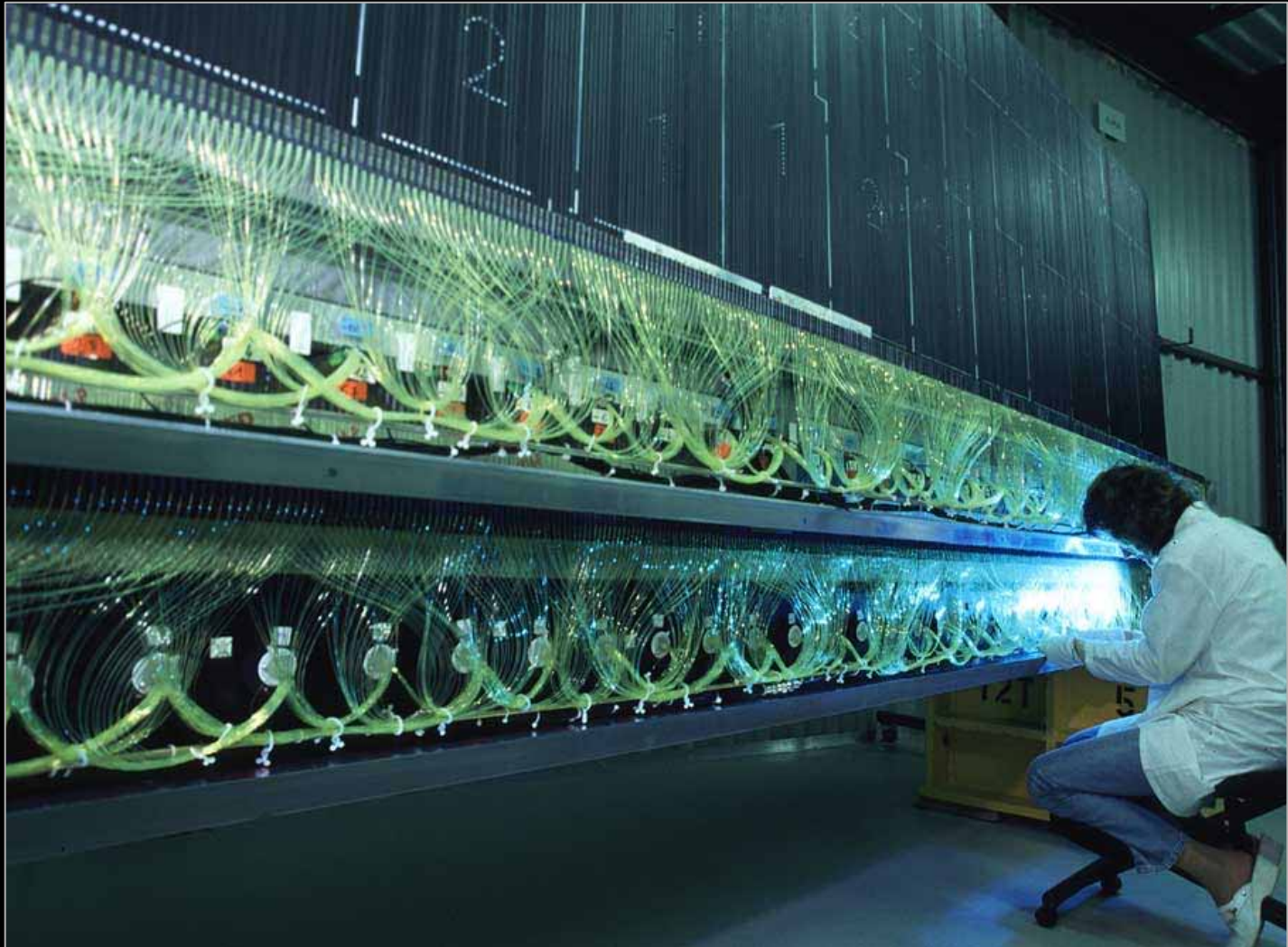
- Three Tile layers (9.7λ , CMS 7.2λ at $|\eta| = 0$) cover extended barrel region ($|\eta| < 1.7$)
 - Alternating samplings of iron absorber plates (14 mm) and scintillating tiles (3 mm)
 - Tile edges read out by optical fibers transporting light to 2 photomultipliers
 - Projective PMT grouping with $\sim 10k$ channels, granularity $\Delta\eta \times \Delta\phi = 0.1^2$ rad
- Resolution (EM & HAD calorimeters)
At high E_T , ~ 60 % of jet energy released in EM calo
 - Hadrons (test beam): stochastic: ~ 52 %, constant: ~ 3 %, noise: ~ 0.5 GeV
 - Jets (central, MC): stochastic: ~ 60 %, constant: ~ 3 %, noise: ~ 0.5 GeV
 - Missing transverse energy:
 $\sigma(E_{T,\text{miss}}) / \Sigma E_T \approx 55$ %



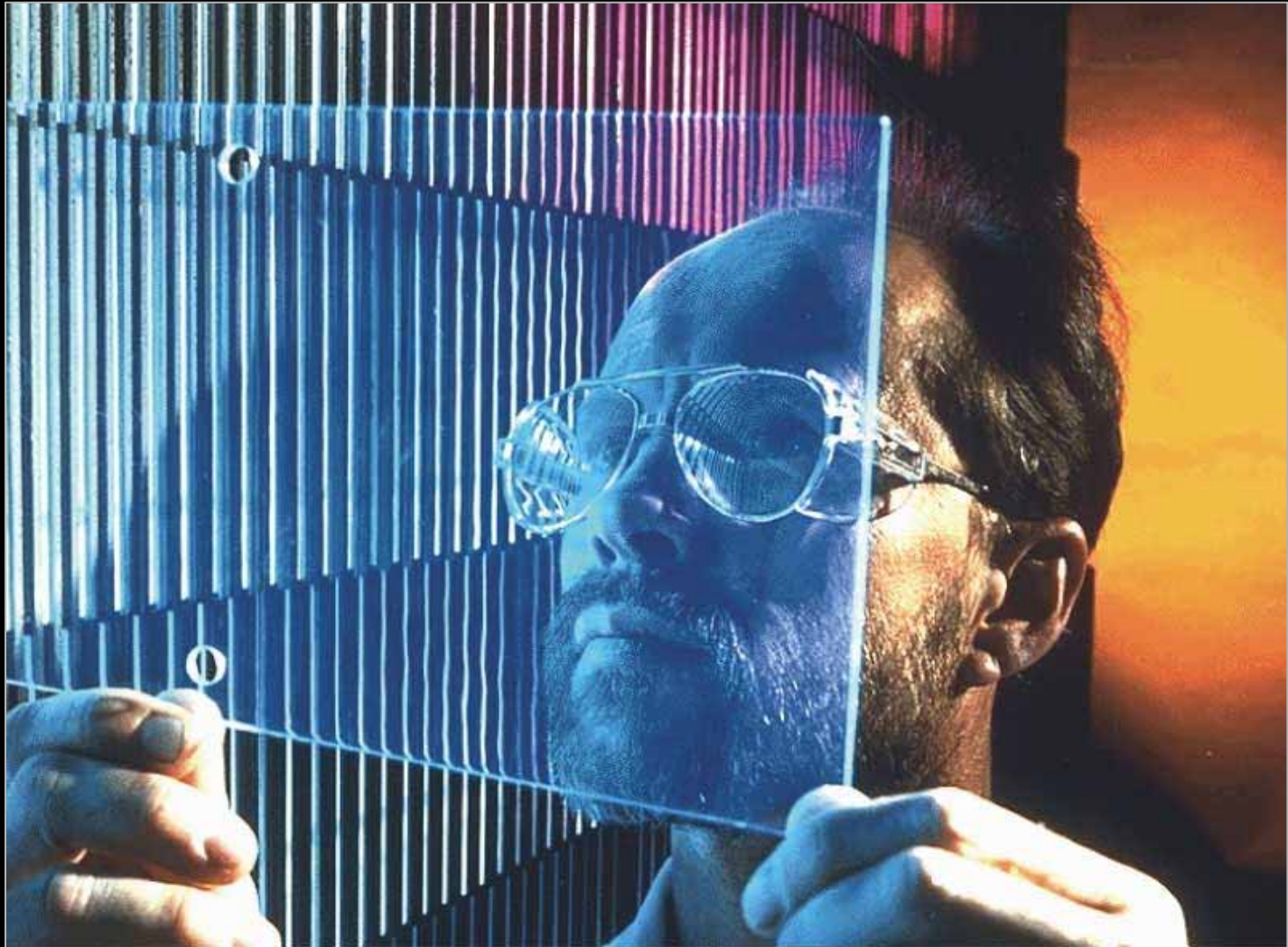
The ATLAS Tile Hadronic Calorimeter



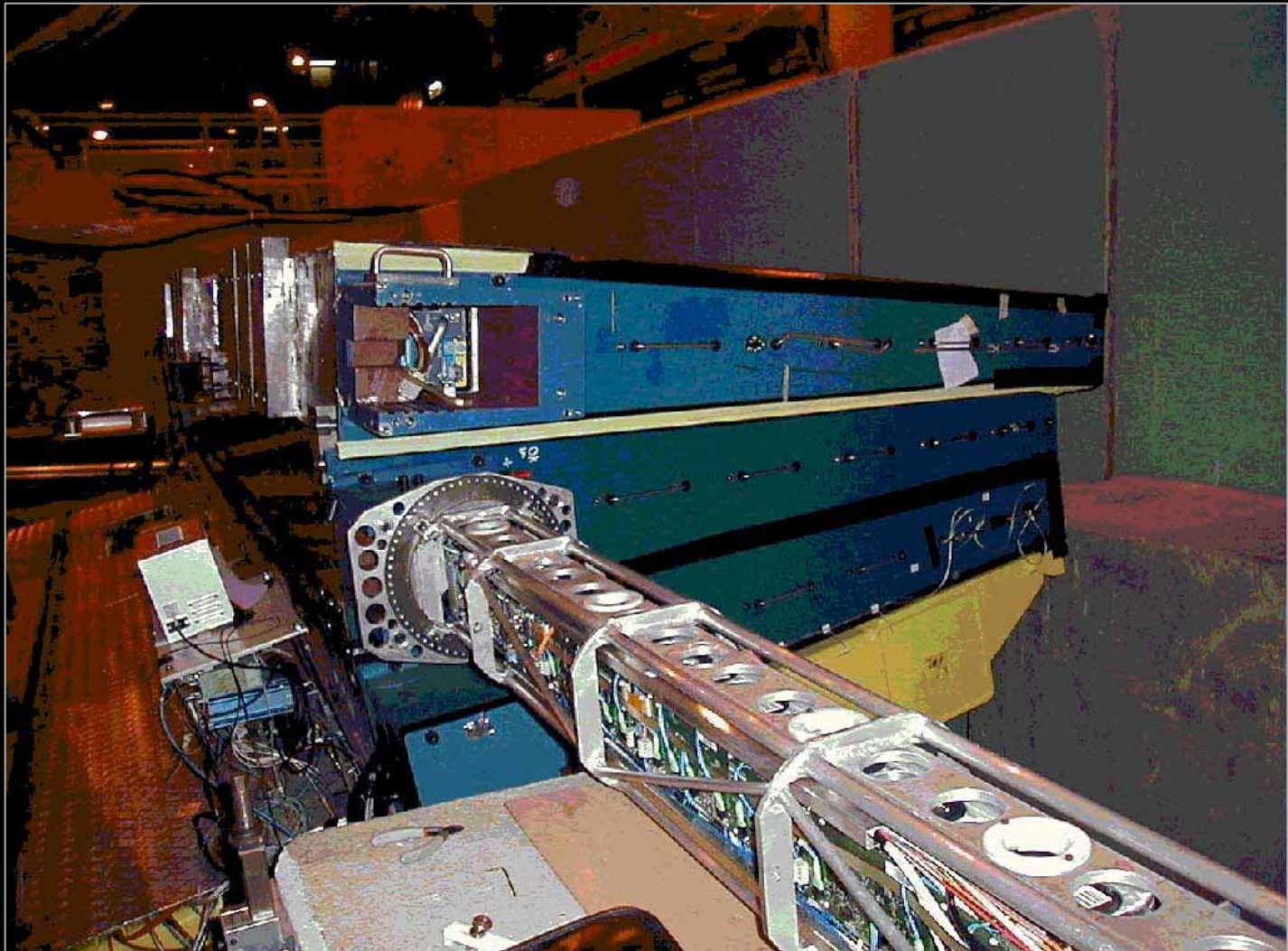
The ATLAS Tile Hadronic Calorimeter



The ATLAS Tile Hadronic Calorimeter

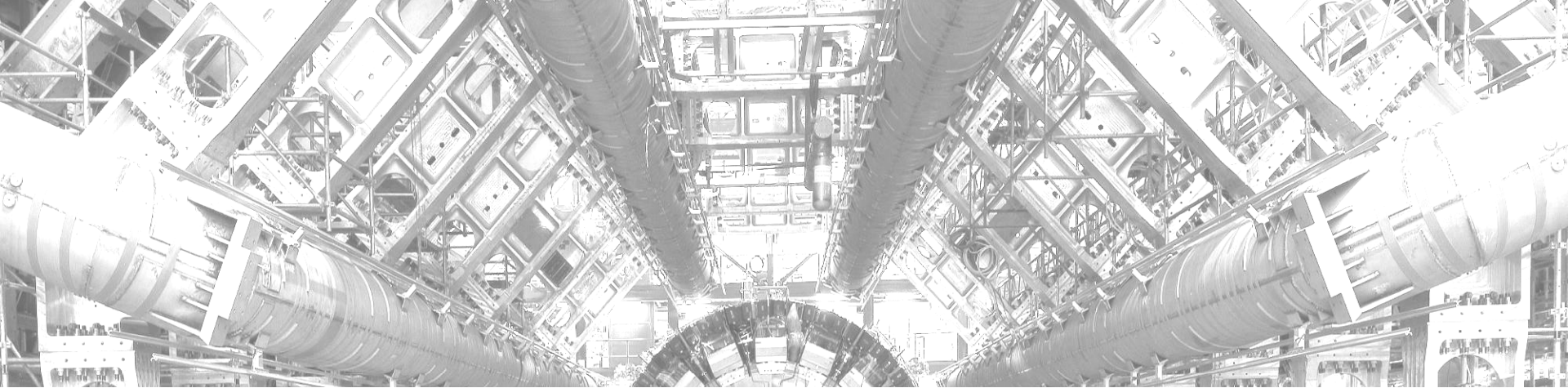


The ATLAS Tile Hadronic Calorimeter

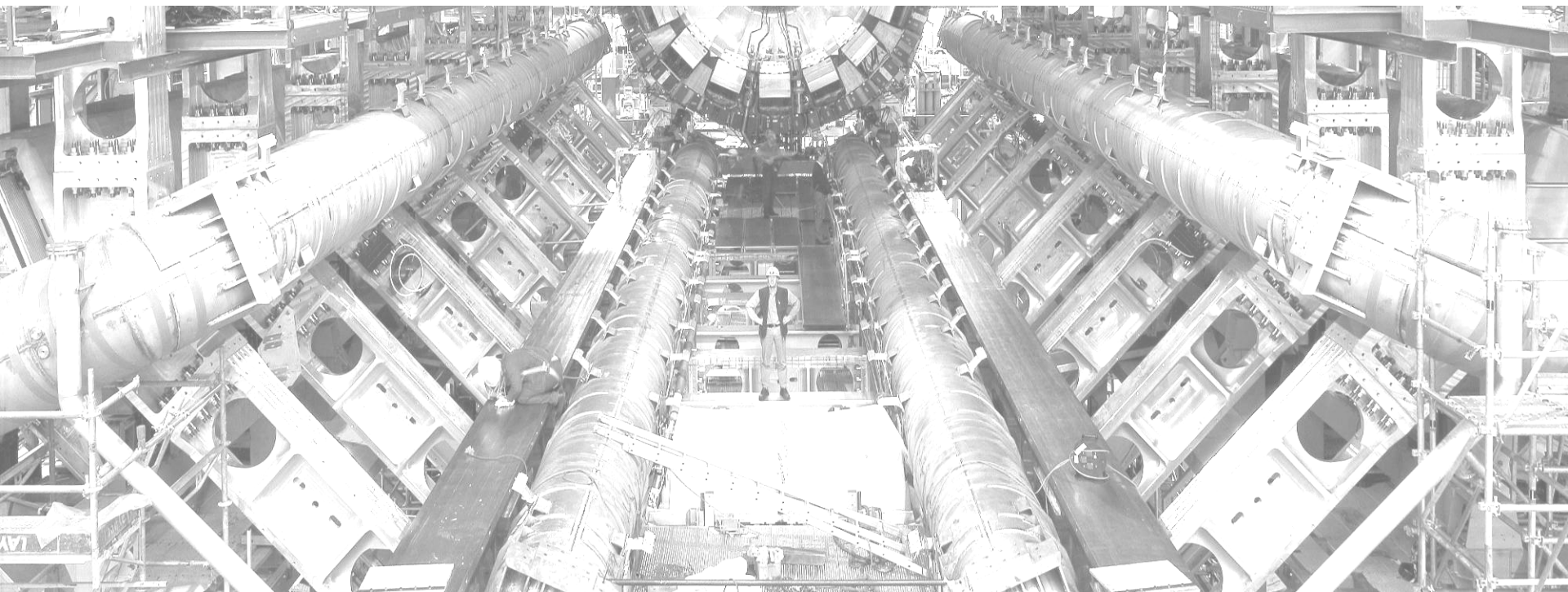


The ATLAS Tile Hadronic Calorimeter

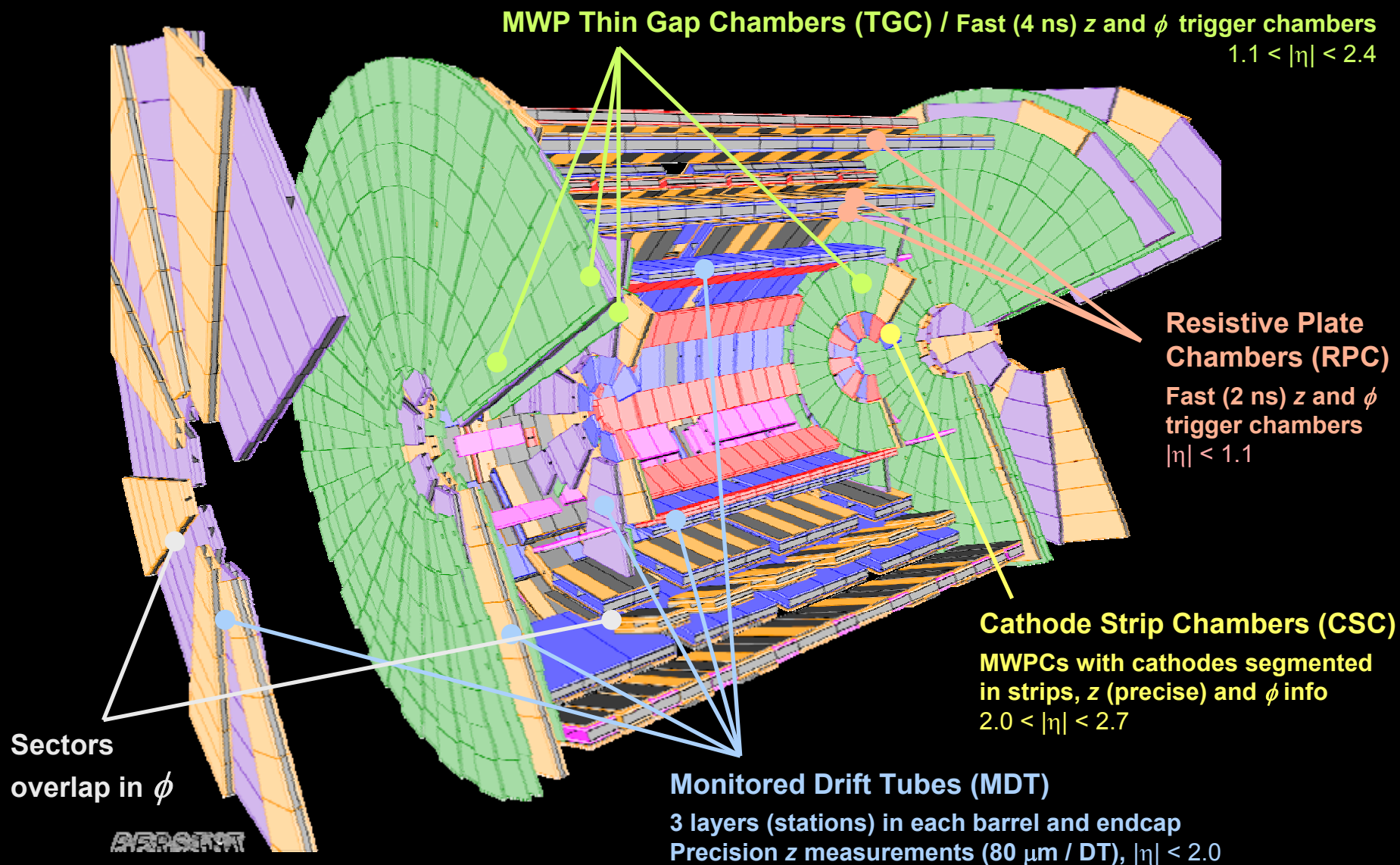




The Muon Spectrometer



The ATLAS Muon Spectrometer (Active Material)

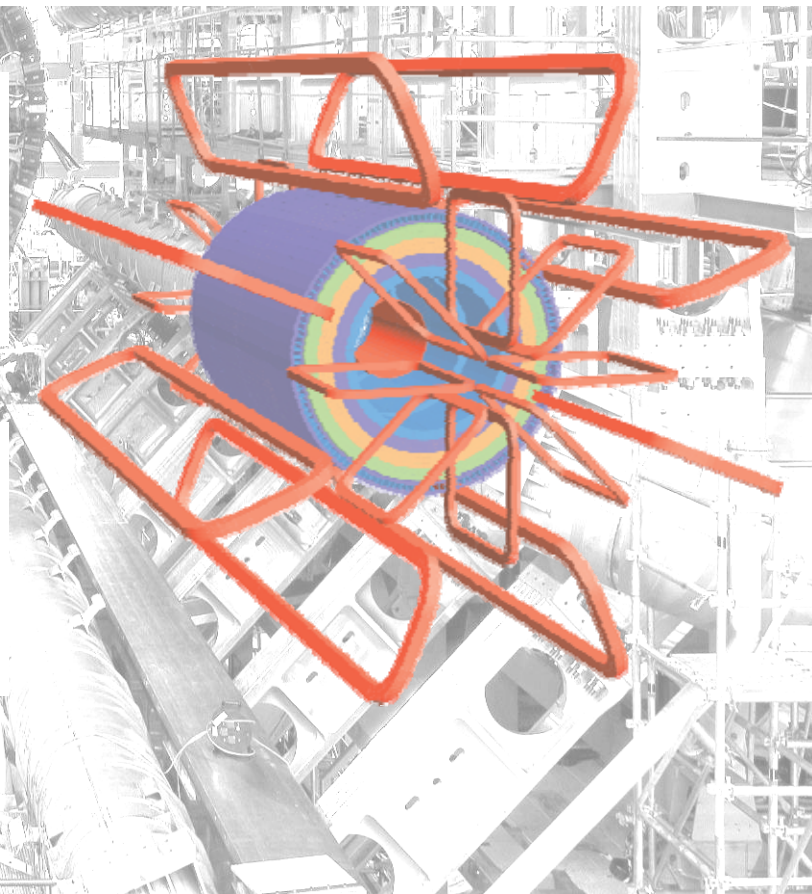


The ATLAS Muon Spectrometer

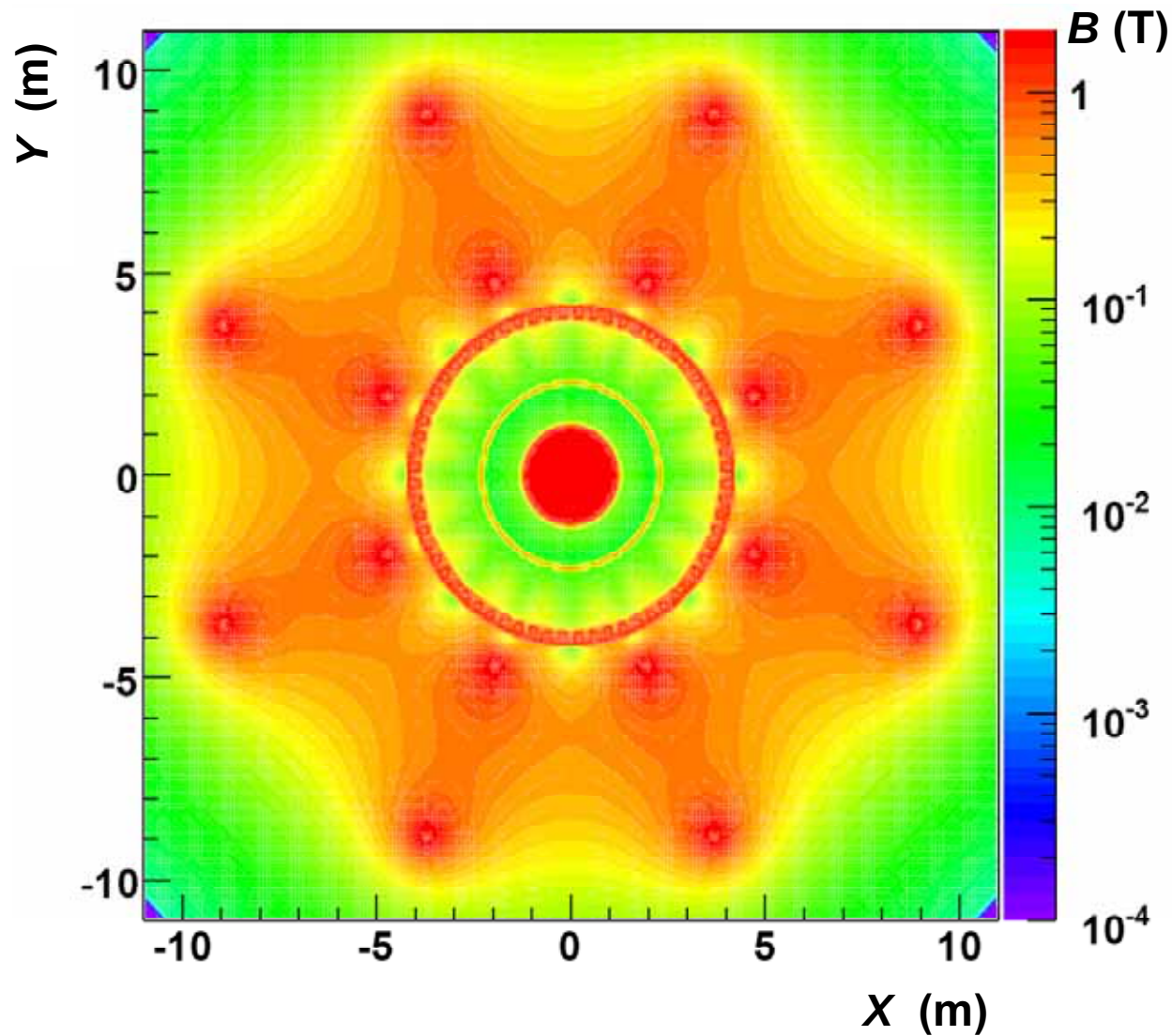
- Outer layer of LHC detectors, only reached by $Wl(M)Ps$ (ν , χ) or EM MIPs (μ)
 - Good containment of jets requires $\sim 11 \lambda$ before muon systems
 - ATLAS opted for good standalone tracking (for HLT) if too high-backgrounds in ID

- Huge magnetic volume
 - ATLAS has 8 (barrel) $3 T_{\max}$ and 2×8 (endcap) $6 T_{\max}$ superconducting toroid magnets

- Huge mechanical structure
 - Challenging tolerances for mechanical stability, positioning and alignment (optical sensors)

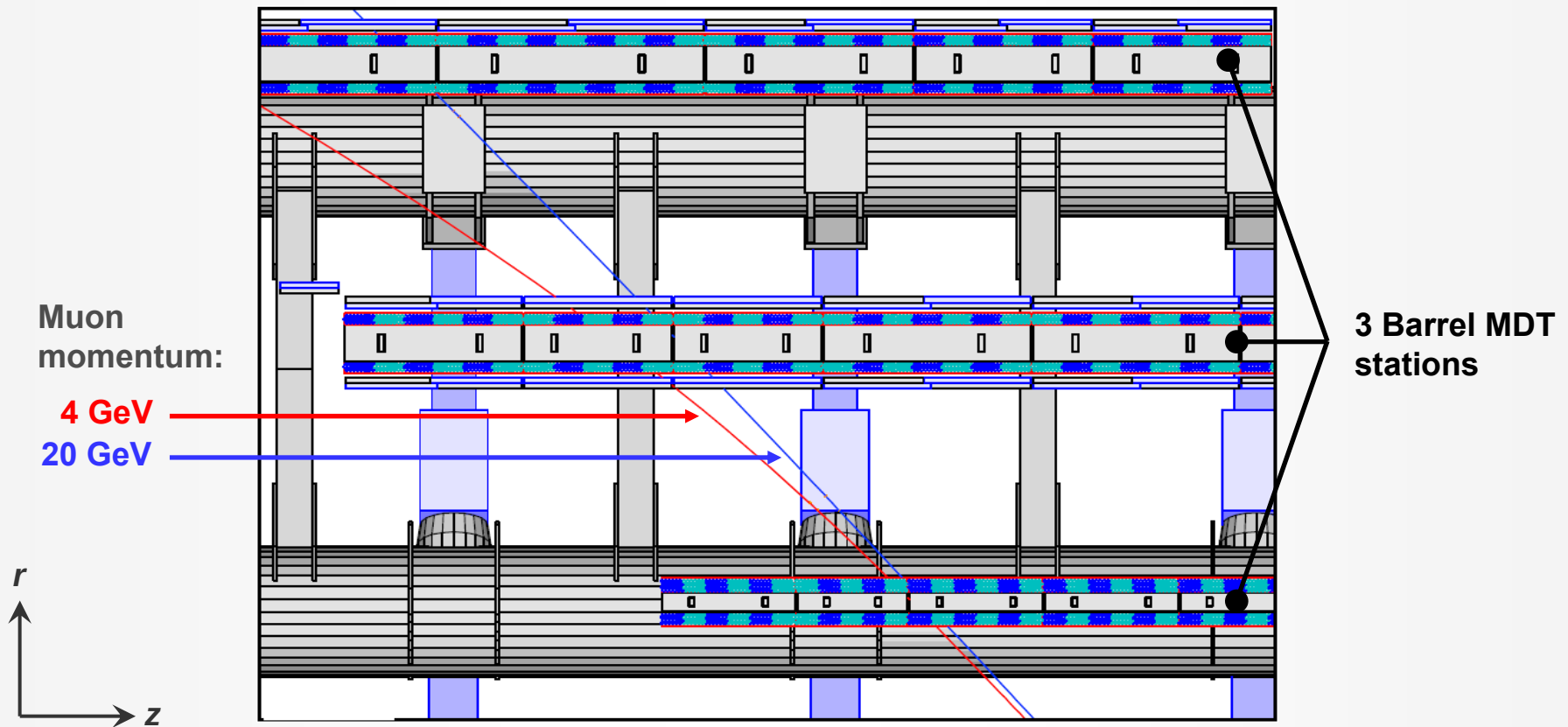


ATLAS Toroid Fields



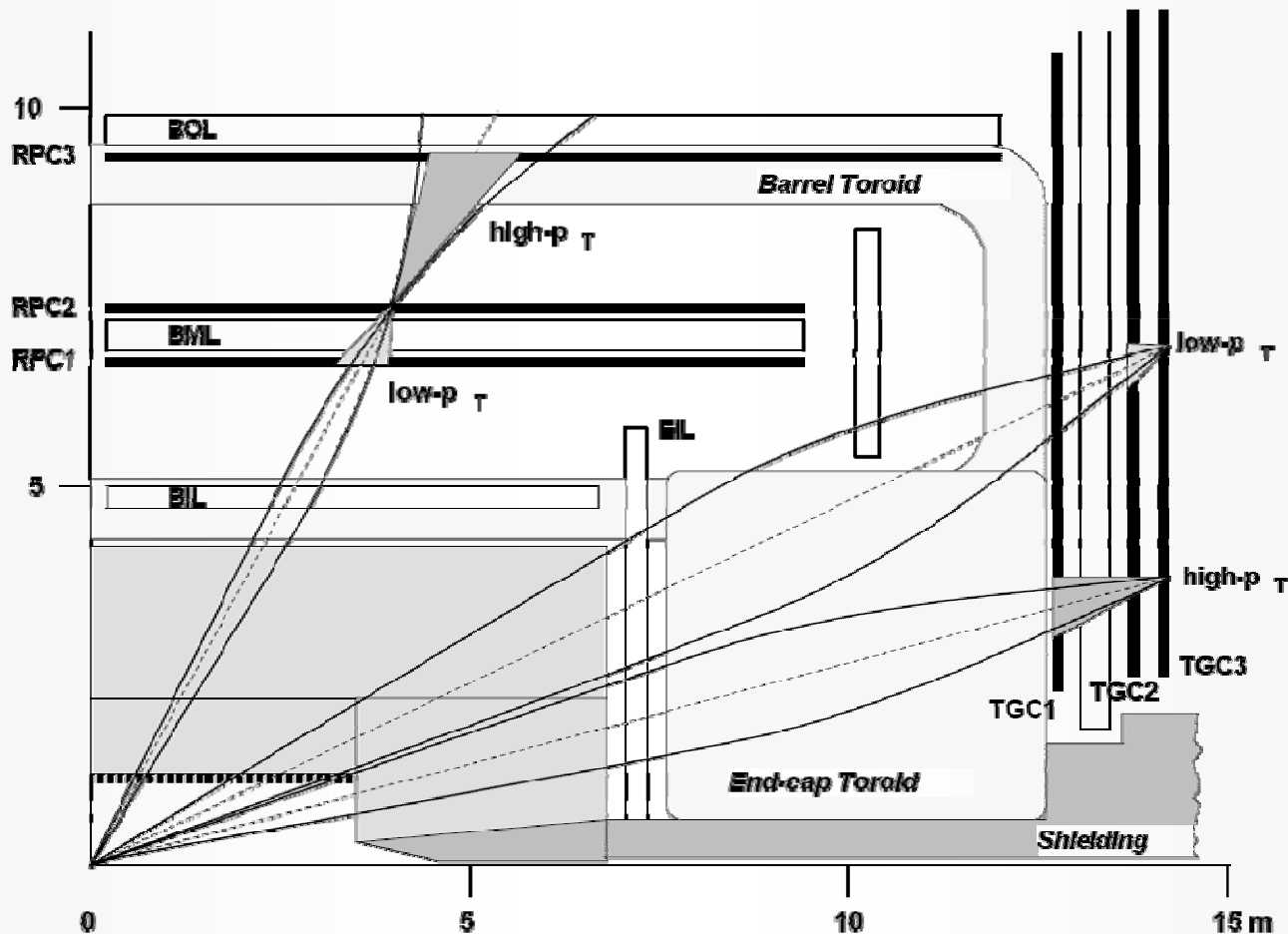
Momentum Measurement

- Toroid fields bend tracks in **z direction**, instead of $r-\phi$ as in the inner detector

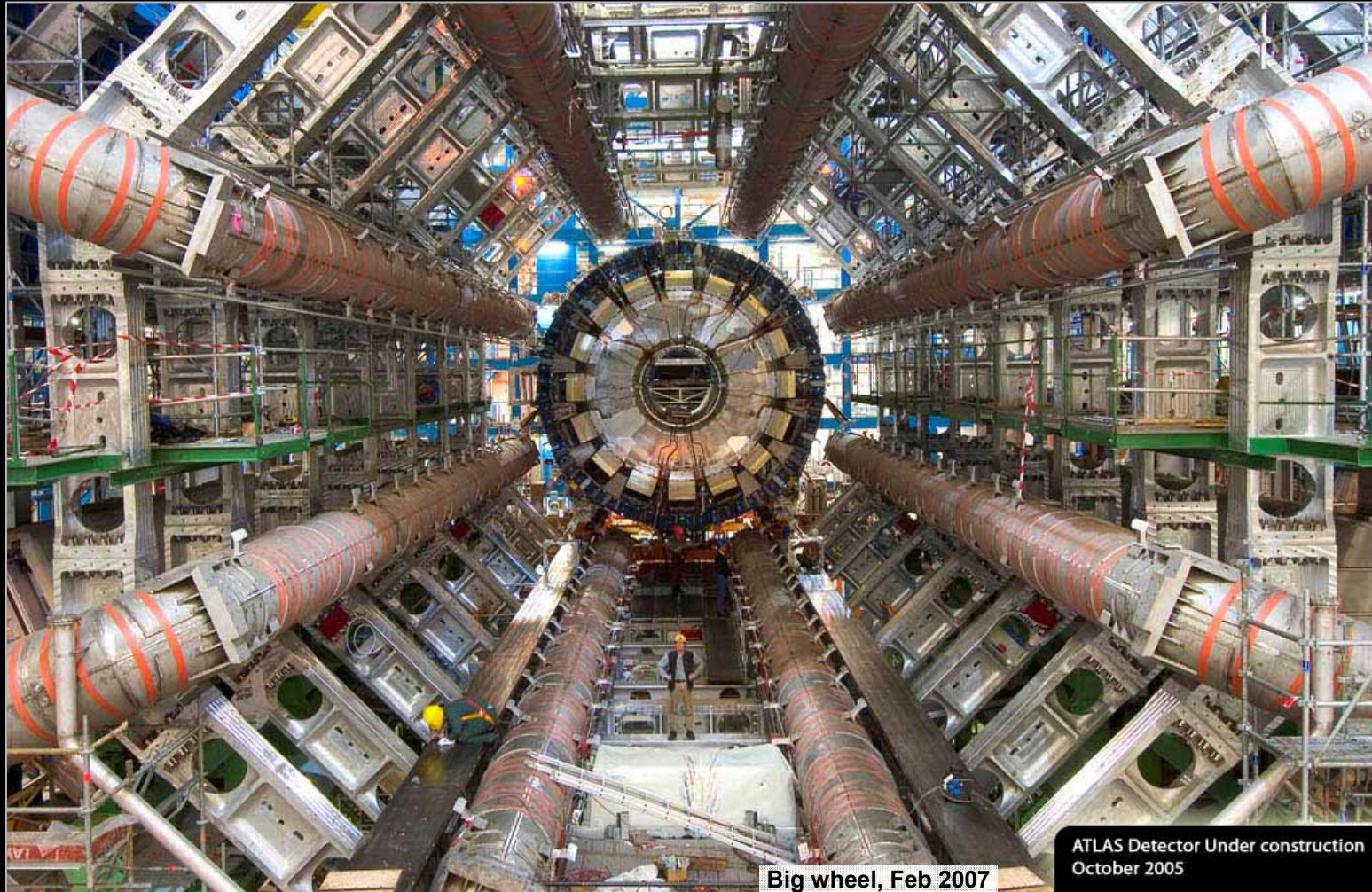


Triggering with Muons

- Ultra-fast Level-1 trigger requires coincident hits in 3 RPC (barrel) or 3 TGC (endcaps) layers within “roads” corresponding to predefined momenta (thresholds)



The ATLAS Muon Spectrometer



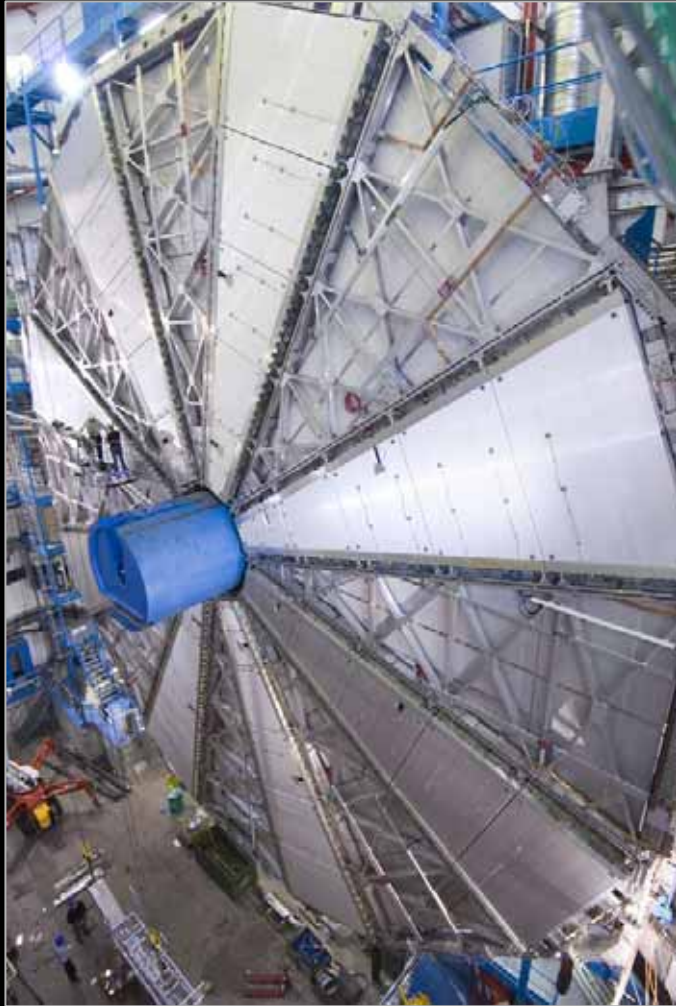
Big wheel, Feb 2007

ATLAS Detector Under construction
October 2005

The ATLAS Muon Spectrometer



The ATLAS Muon Spectrometer



Big wheel, Feb 2007

The ATLAS Muon Spectrometer



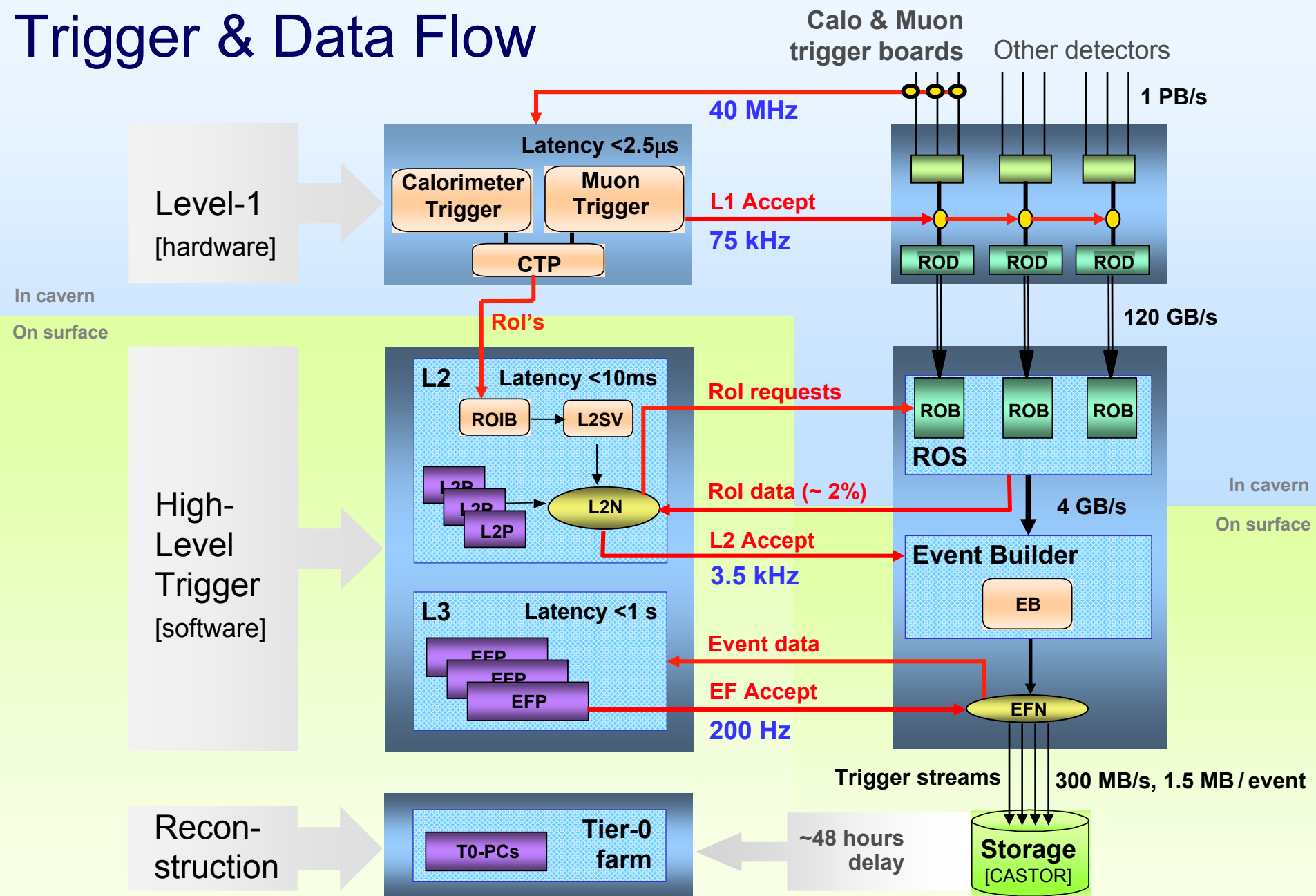


Trigger, Data Acquisition and Computing

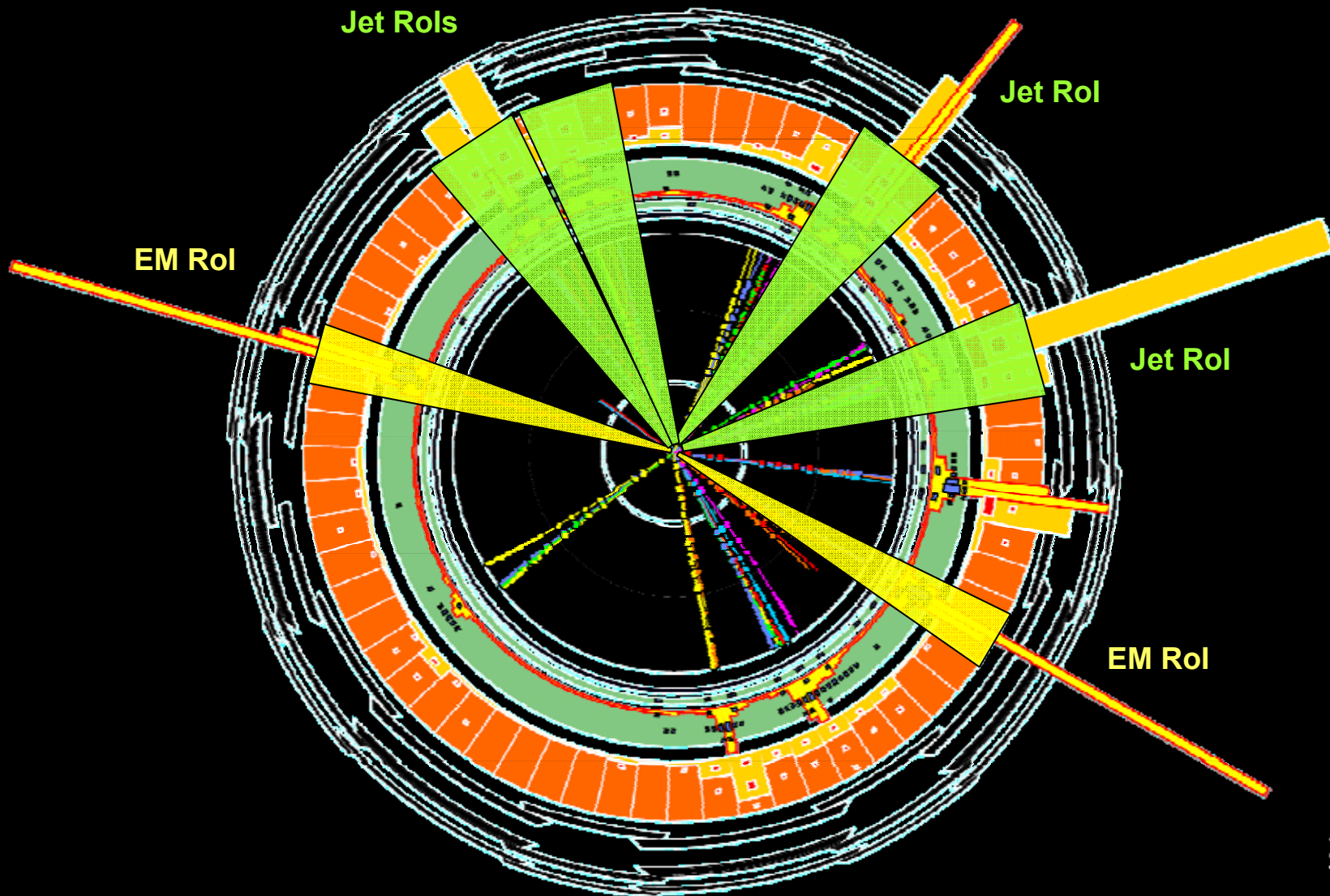


Three Trigger Levels

Trigger & Data Flow



Regions of Interest (RoI)

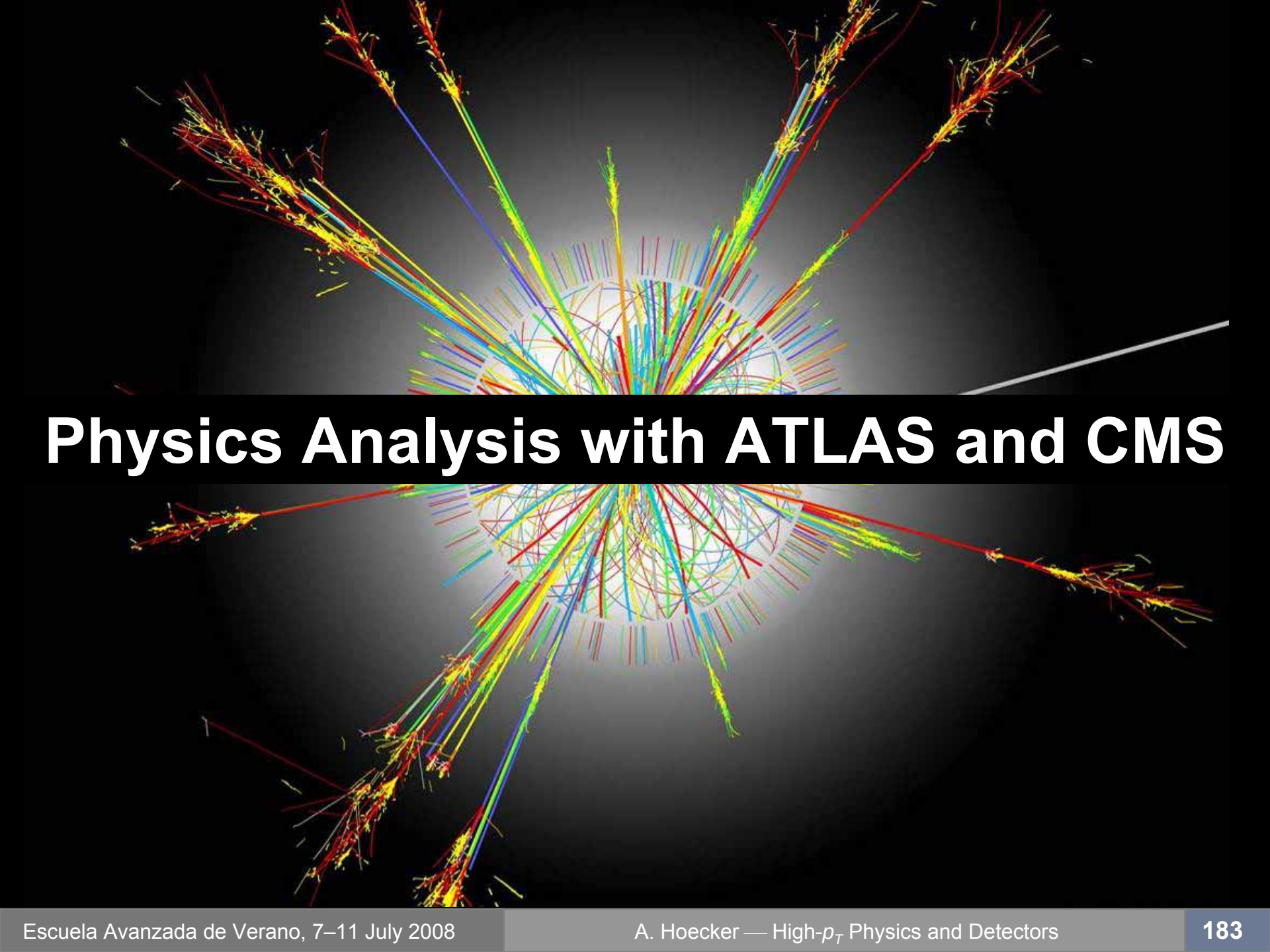




- Each LHC experiment will produce 10 000 TB of data each year
- Data analysis requires 100 000 of the fastest PC processors
- ATLAS collaboration spread all over the world → need distributed computing
- Transfer of data from CERN at **10 Gbits/s** rate to 11 world-wide computing centres
- These centres send and receive data to 200 smaller centres within “clouds”
- User analysis philosophy: “Avoid copying data: run the program where the data is”



and **tomorrow** ...

A visualization of a particle detector event, showing a central point from which numerous colored lines (representing particle tracks) radiate outwards. The tracks are color-coded, likely by energy or particle type. The background is dark, and the tracks are concentrated in the center, with some tracks extending towards the edges of the frame.

Physics Analysis with ATLAS and CMS

The LHC Physics Programme

1. Mass

- Search for the Higgs Boson

2. Electroweak unification

- Precision measurements (M_W , m_{top}) & tests of the Standard Model

3. Hierarchy in the TeV domain

- Search for Supersymmetry, Extra dimensions, Higgs composites, ...

4. Flavour

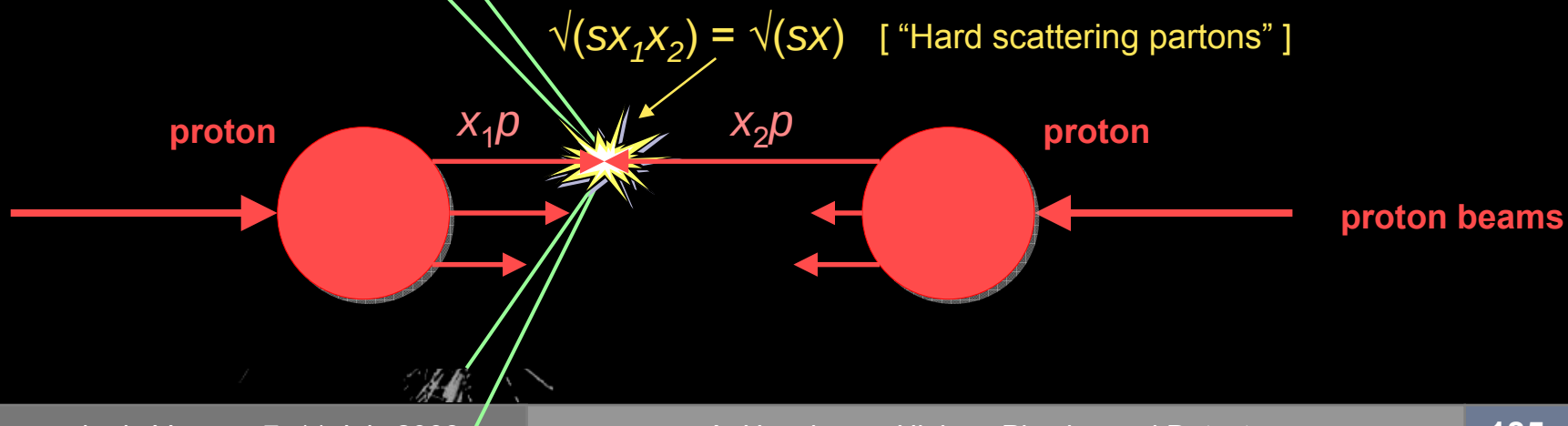
- B mixing, rare decays and CP violation as tests of the Standard Model

Proton-Proton Collisions are Complex

- Most events are due to interactions at large distance between protons
 - Large longitudinal, but small transverse momentum: $\langle p_T \rangle = 0.5 \text{ GeV}$



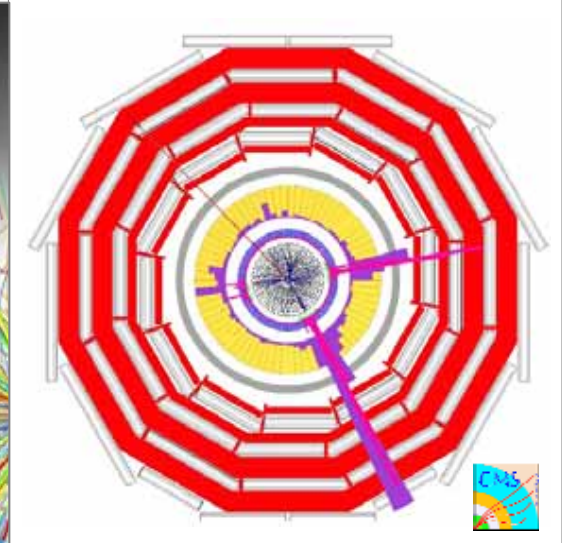
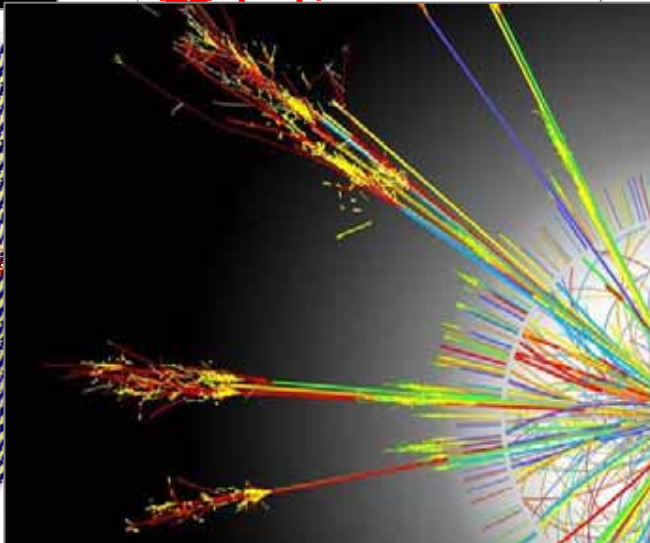
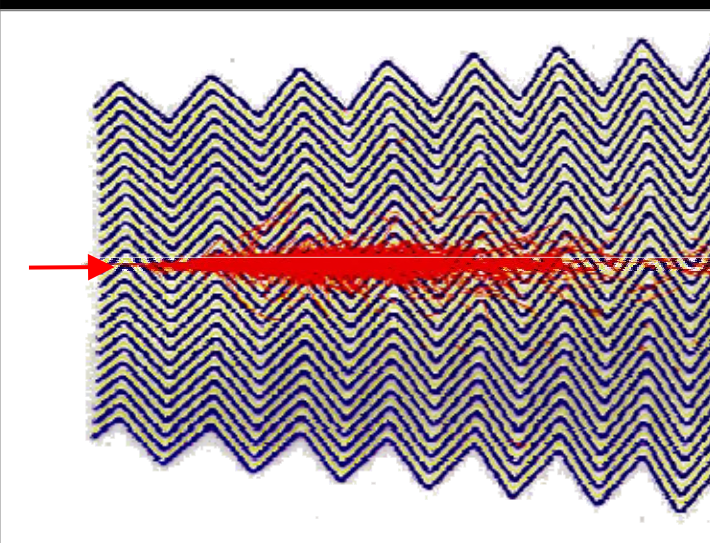
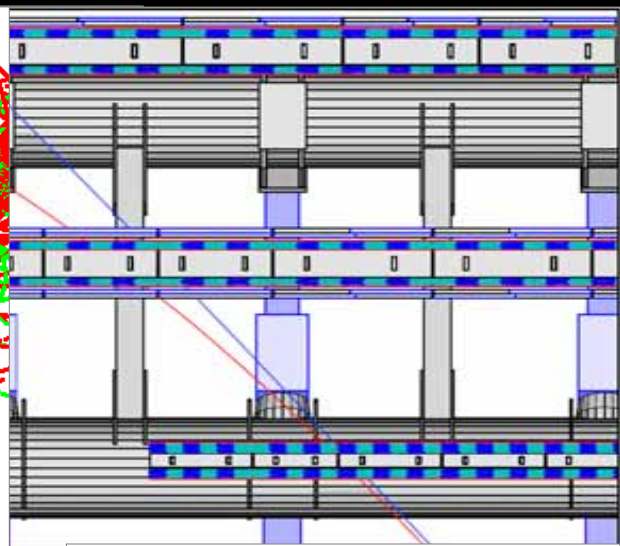
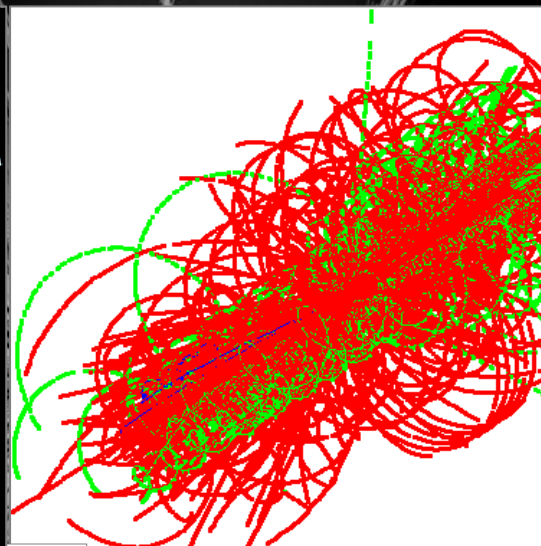
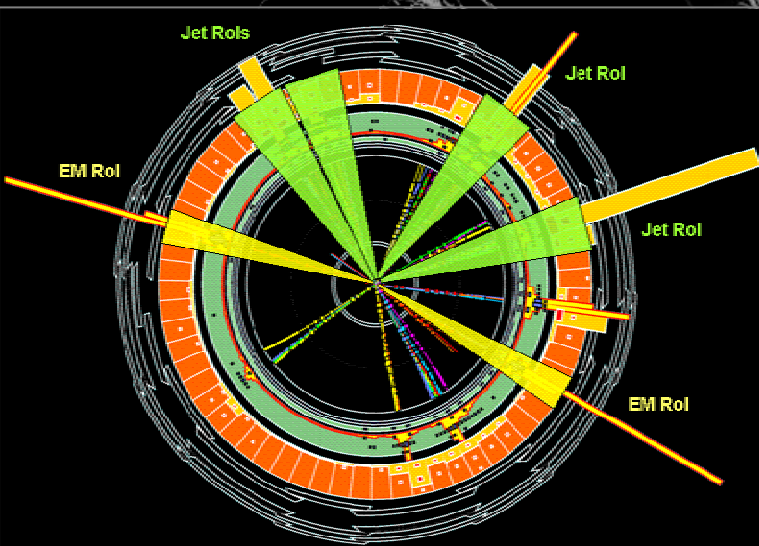
- The constituents of the protons carry only a fraction of the proton's momentum



Event Reconstruction – Basic

- Trigger an event
- Reconstruct tracks in inner detector
- Reconstruct tracks muon system
- Reconstruct electromagnetic clusters
- Reconstruct hadronic clusters and jets
- Reconstruct missing transverse energy
- Identify particles and objects: muon, electron, photon, tau, jet

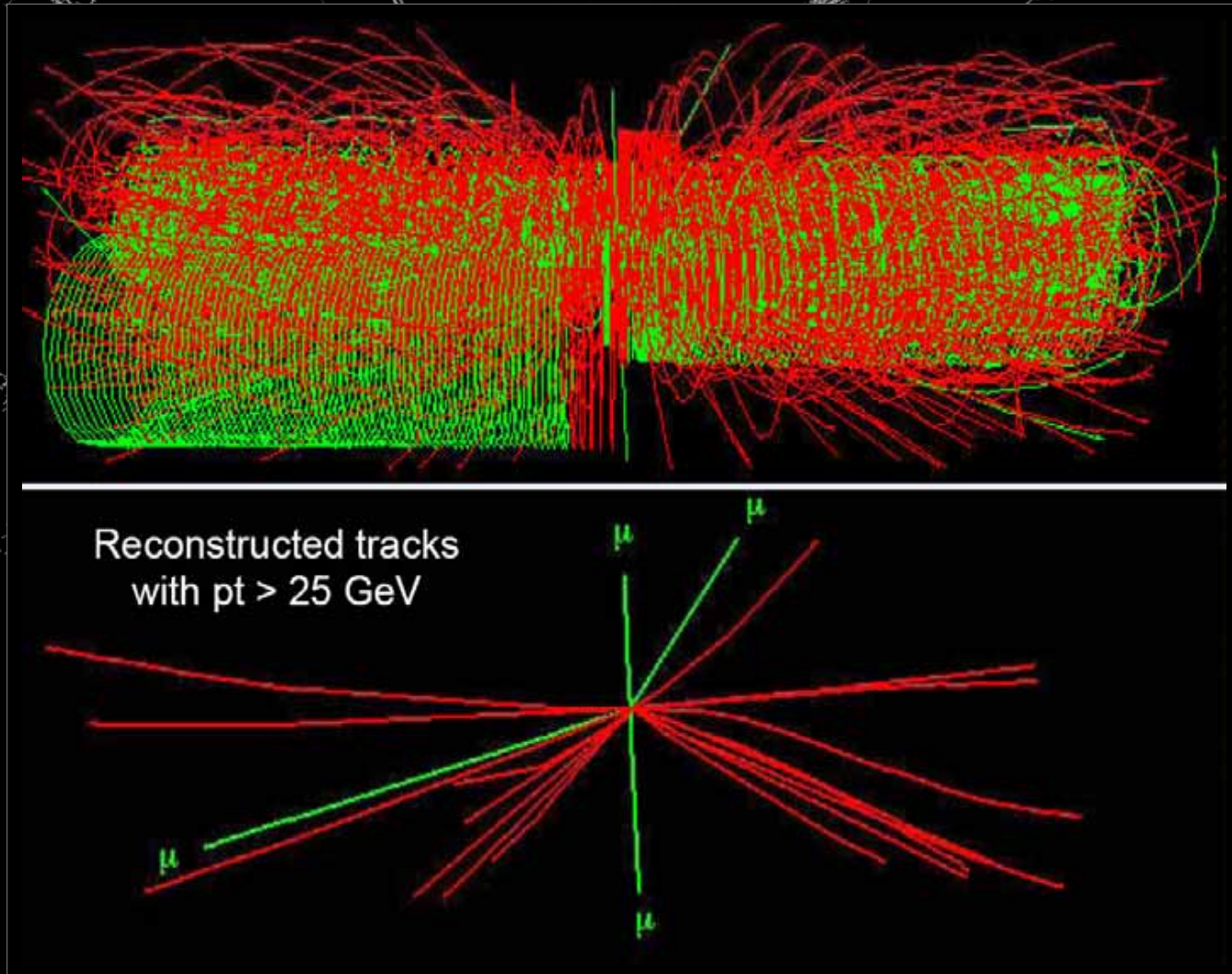
Event Reconstruction – Basic



Event Reconstruction – Cleaning

- Background suppression exploits **detector response** and **event properties**, both depending on the physics channel to be analysed
 - *Particle identification:*
 - Absorption in detector layers distinguishes e/γ from hadrons/jets from μ
 - Track isolation and shower shapes further distinguish e/γ from jets
 - Shower shapes distinguish hadron/jet types
 - *Event properties:*
 - Select objects with large transverse energy
 - QCD events rarely produce leptons $\rightarrow$ require leptons (if possible)
 - Random backgrounds usually don't peak in mass $\rightarrow$ compute masses
 - Momenta or angles between objects may have specific features in signal
 - The topological “shape” of the event may be specific in signal or background

Event Reconstruction – Cleaning



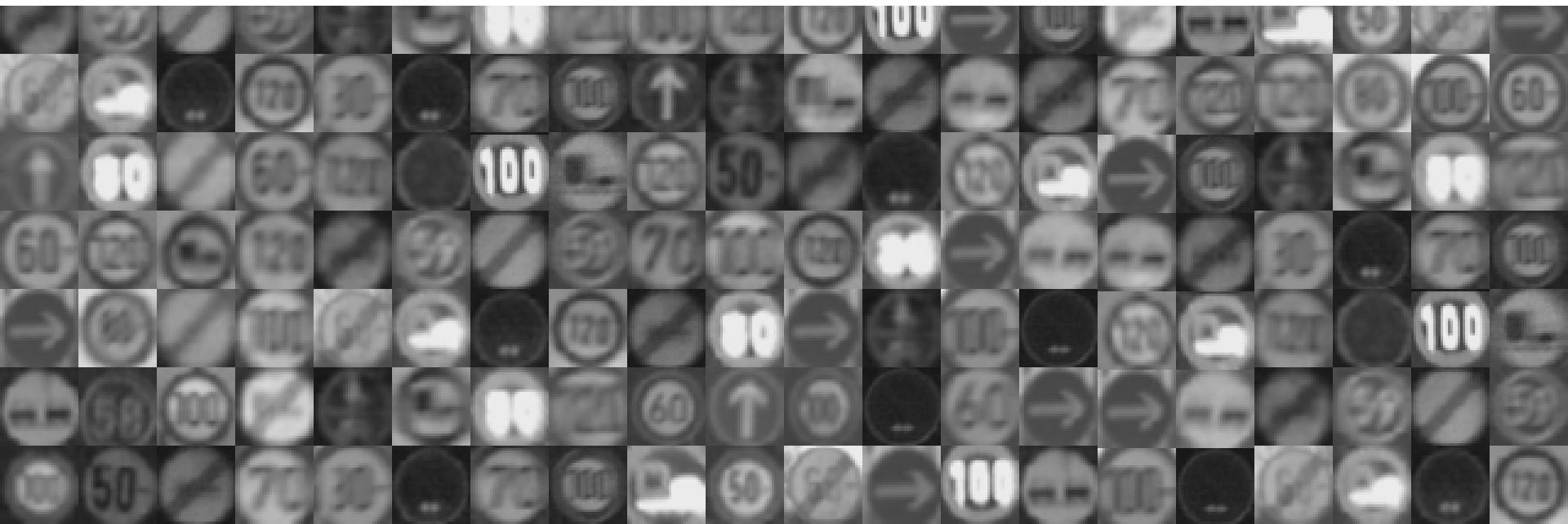
Event Reconstruction – Topological

- The physics analysis drives the topological reconstruction of an event:
 - *Inclusive analyses count events with leptons, γ , jets or missing E_T – examples*
 - QCD : select events with high-energetic (or many) jets
 - QCD / EW : select events with leptons or photons in final state
 - SUSY : select events with large missing E_T (with or without leptons)
 - *Exclusive analyses kinematically combine reconstructed objects – examples*
 - $W \rightarrow \mu\nu$: identify muon and approximate W mass with $m_T(\mu, \text{missing } E_T)$
 - $tt \rightarrow (be\nu)(bqq)$: identify electron and 2 b -jets, and compute top mass as $m(b,qq)$
 - $H \rightarrow \gamma\gamma$: identify 2 photons and compute mass: $m^2 = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos\theta_{\gamma\gamma})$
 - $H \rightarrow e^+e^-\mu^+\mu^-$: identify 2e and 2 μ and compute mass
 - $G_{\text{RS}} \rightarrow e^+e^-$: identify 2 electrons and compute mass
- Combine all available information via “multivariate statistical techniques”



Interlude

Multivariate Classification

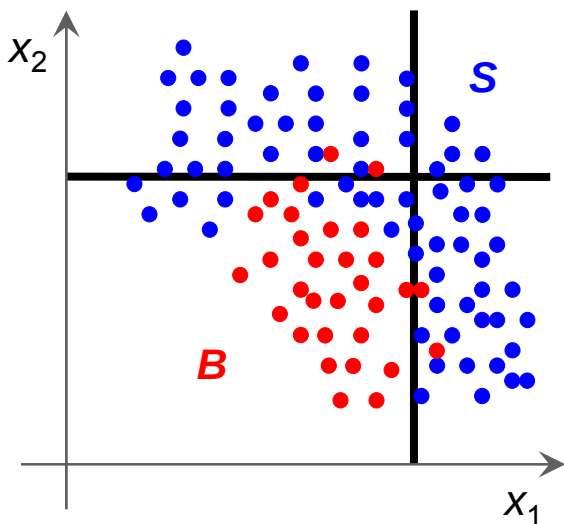


Multivariate Event Classification

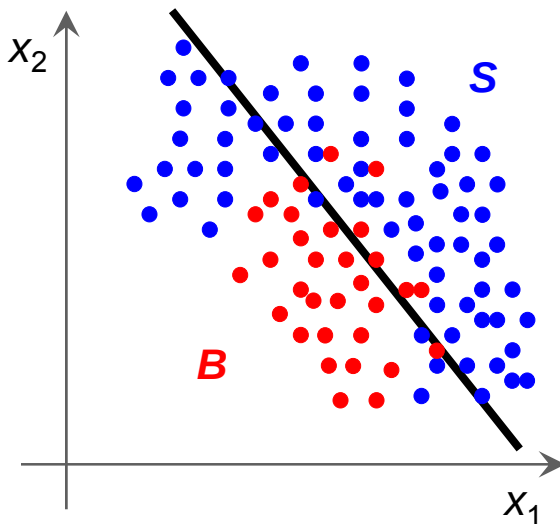
■ Suppose data sample with two types of events: *Signal*, *Background*

- We have found discriminating input variables $x_1, x_2, \dots$
- What decision boundary should we use to select events of type *Signal* ?

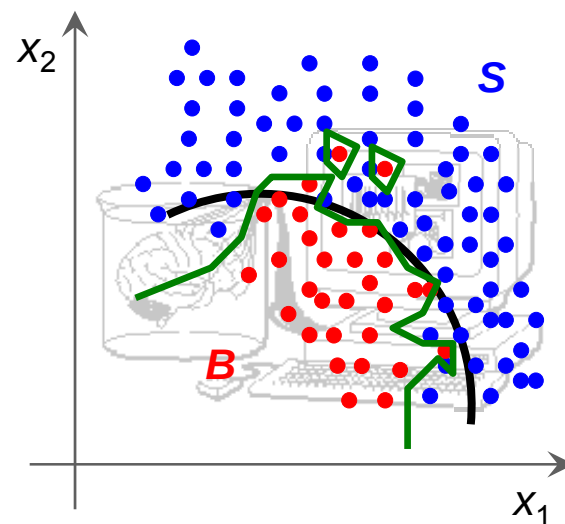
Rectangular cuts?



A linear boundary?



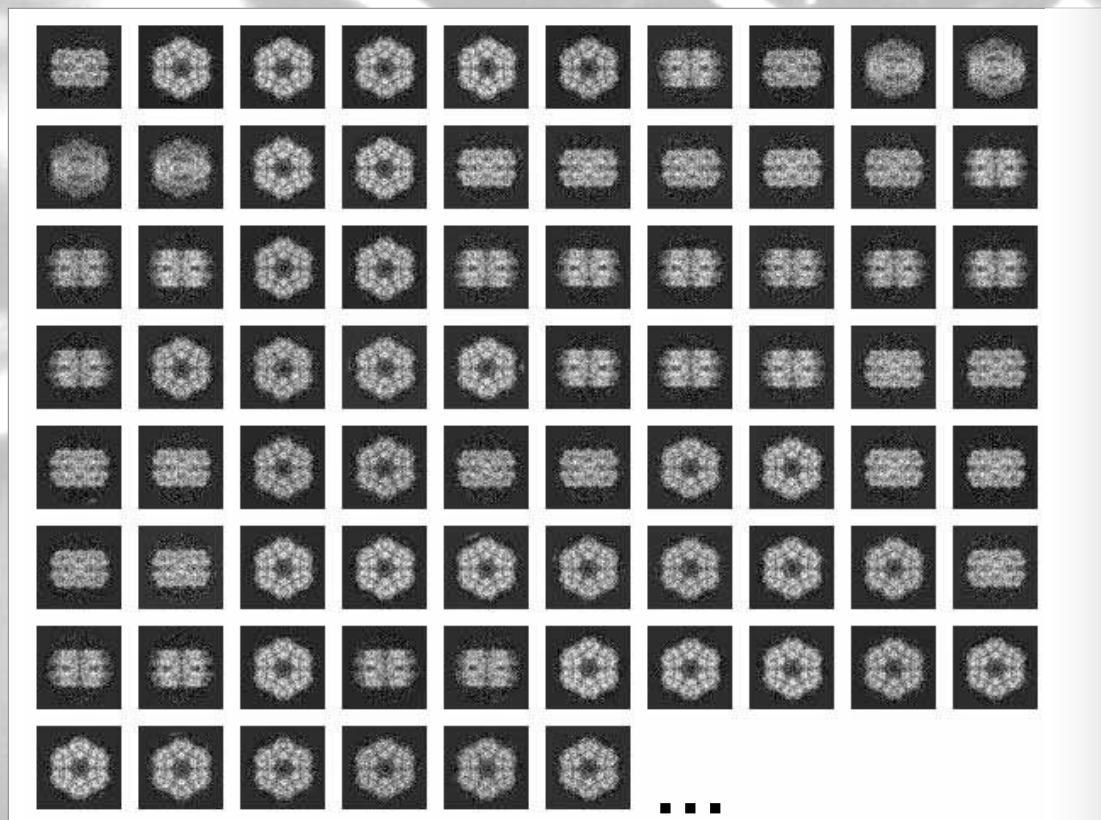
A nonlinear one?



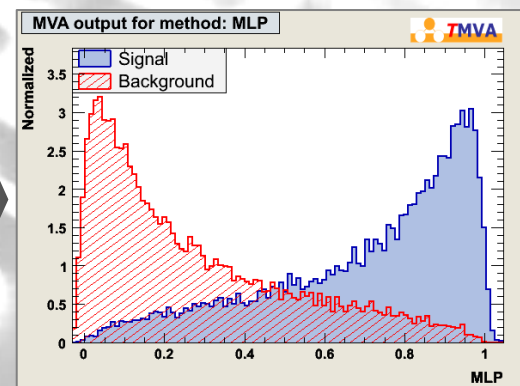
■ How can we decide this in an optimal way ? → Let the machine learn it !

Multivariate Event Classification

- Multivariate classification condenses multi-variable input information in a single scalar output variable
- It is a $R^n \rightarrow R$ regression problem; classification is in fact a *discretised regression*



$$y(\textcolor{red}{B}) \rightarrow 0, y(\textcolor{blue}{S}) \rightarrow 1$$



Event Reconstruction – Challenges

■ Some benchmark analyses:

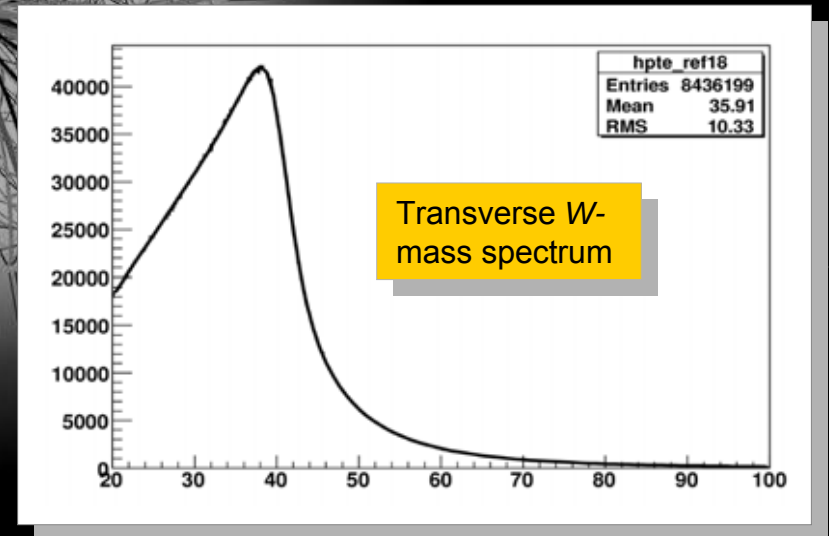
➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

➡ W mass

■ Design challenges:

Trigger efficiency ($p_T(\mu) > 3$ GeV) and purity
(HLT tracking reconstructs charge, vertex and B mass)

Excellent **tracking alignment**, **calorimeter uniformity** & **missing transv. E resolution**



Event Reconstruction – Challenges

■ Some benchmark analyses:

➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

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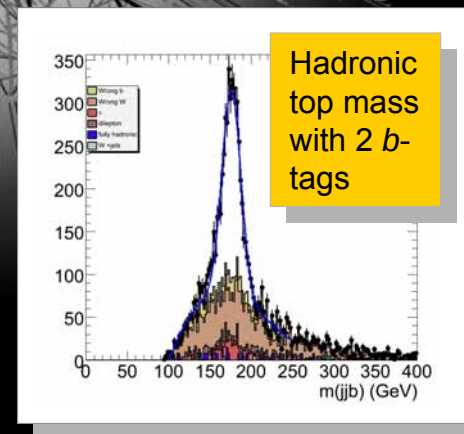
➡ top mass

■ Design challenges:

Trigger efficiency ($p_T(\mu) > 3$ GeV) and purity
(HLT tracking reconstructs charge, vertex and B mass)

Excellent **tracking alignment**, calorimeter
uniformity & missing transv. E resolution

Excellent **jet energy calibration**, resolution
and **uniformity**, excellent **b -tagging**



Event Reconstruction – Challenges

■ Some benchmark analyses:

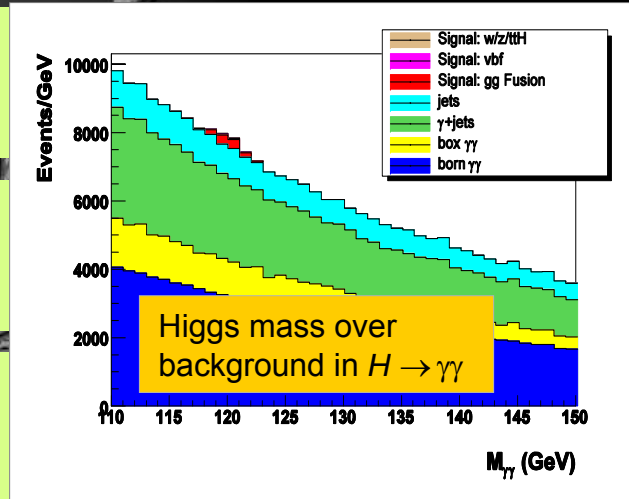
➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

➡ W mass

➡ top mass

➡ $H \rightarrow \gamma\gamma, 4e, 4\mu, \tau\tau$ (VBF)

■ Design challenges:



Excellent **PID**, **resolution & uniformity**,
efficient high-lumi tracking, forward jets

Event Reconstruction – Challenges

■ Some benchmark analyses:

➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

➡ W mass

➡ top mass

➡ $H \rightarrow \gamma\gamma, 4e, 4\mu, \tau\tau$ (VBF)

➡ SUSY with R -parity, SUSY Higgs

■ Design challenges:

Trigger efficiency ($p_T(\mu) > 3$ GeV) and purity
(HLT tracking reconstructs charge, ... mass)



SUSY event
with missing
 E_T in CMS
detector

jet
resolution

resolution
ing

ormity,
ward jets

Excellent **jet & $E_{T,miss}$ resolution**, low noise,
 τ identification, maximum acceptance

Event Reconstruction – Challenges

■ Some benchmark analyses:

➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

➡ W mass

➡ top mass

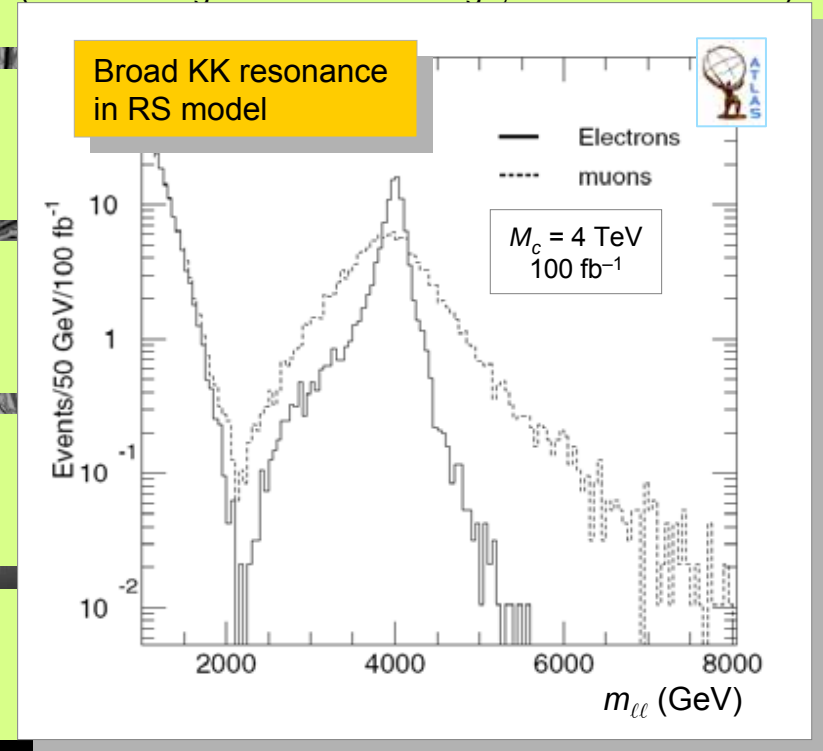
➡ $H \rightarrow \gamma\gamma, 4e, 4\mu, \tau\tau$ (VBF)

➡ SUSY with R -parity, SUSY Higgs

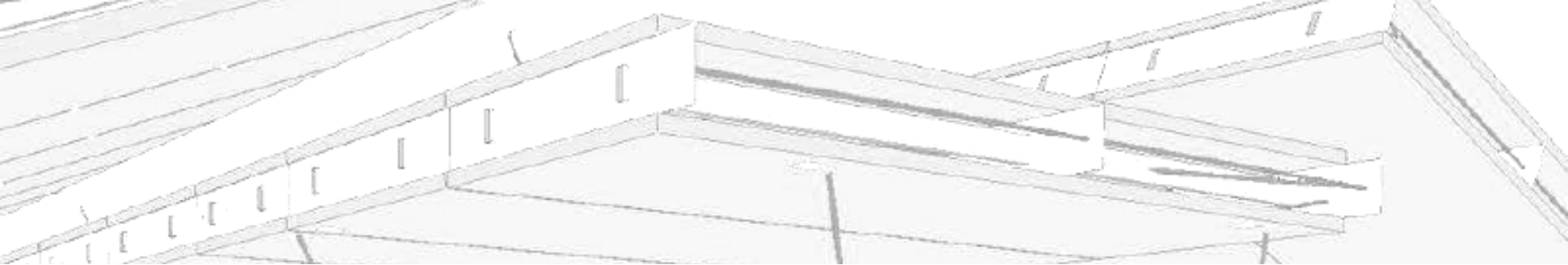
➡ RS KK modes

■ Design challenges:

Trigger efficiency ($p_T(\mu) > 3$ GeV) and purity
(HLT tracking reconstructs charge, vertex and B mass)



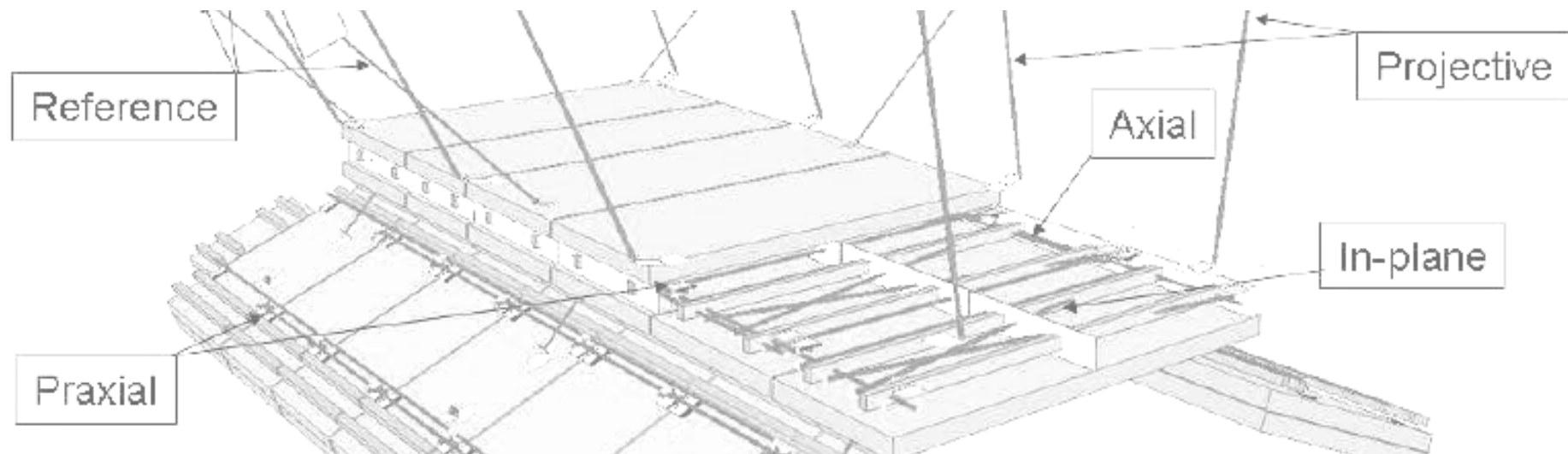
Good **tracking** (incl.charge ID) and **calorimeter resolution** at $O(\text{TeV})$, little calo saturation



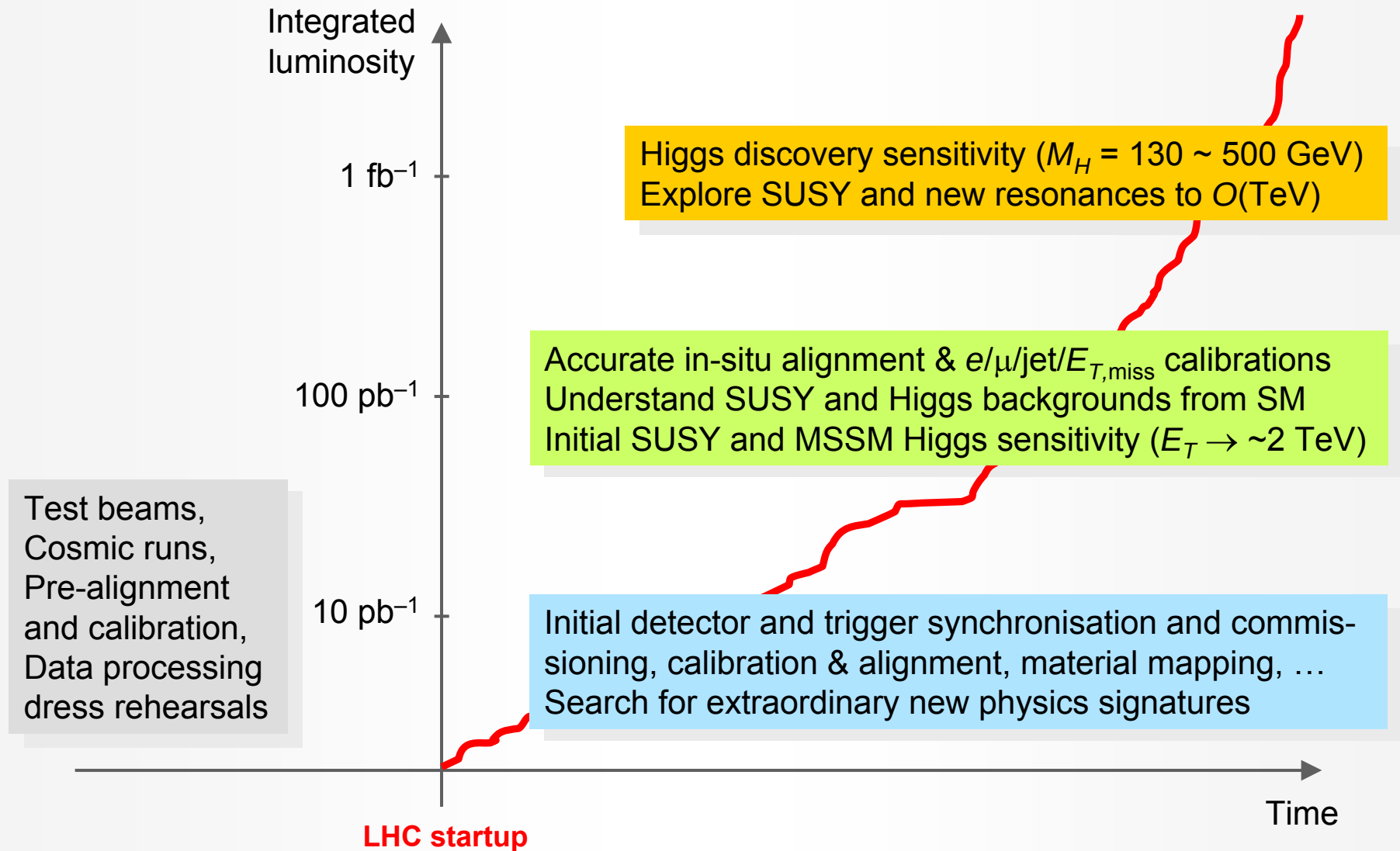
Detector Commissioning

including

Calibration & Alignment

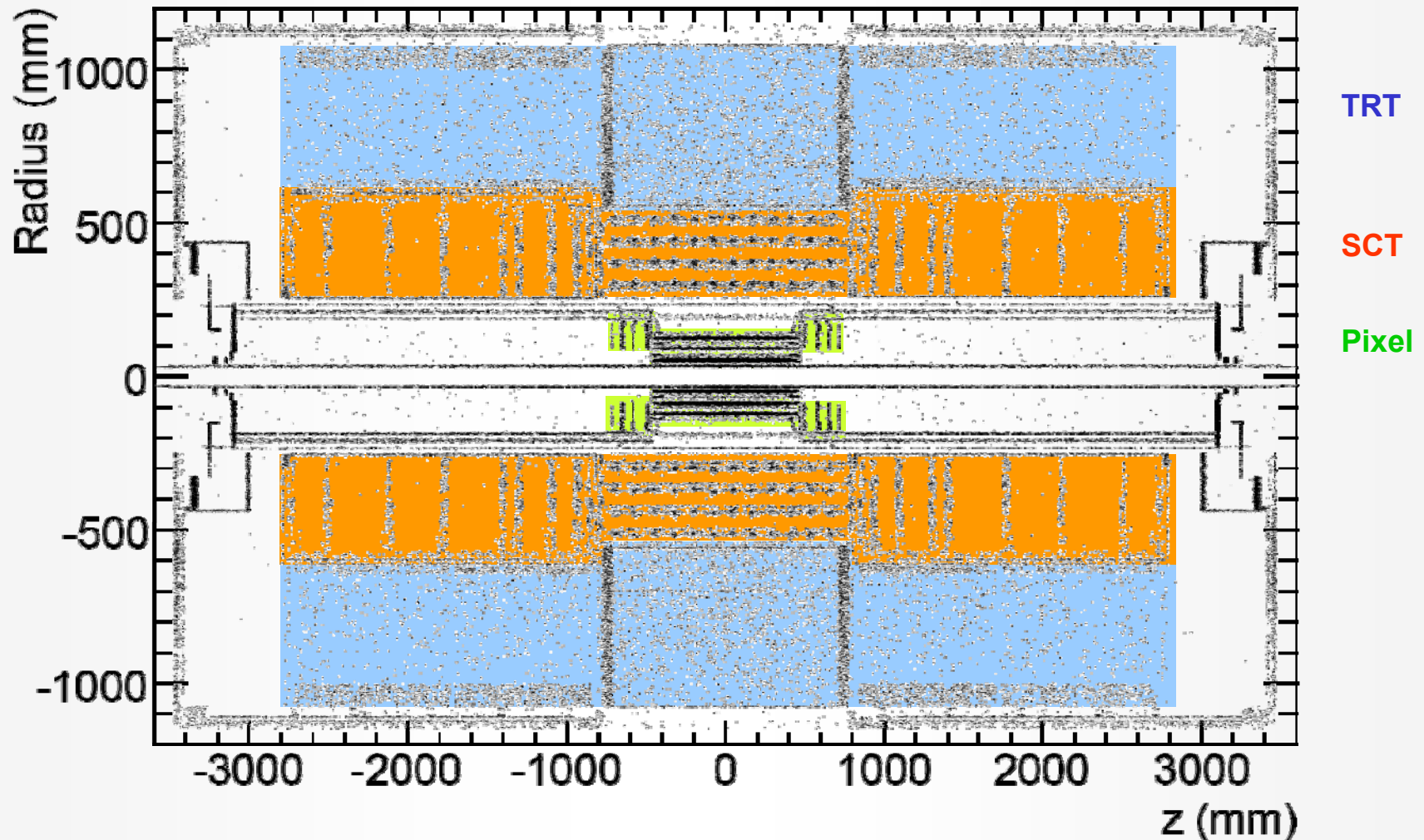


Start-up Programme in a Nutshell



Start-up Programme in a Nutshell

ID Material Mapping With $\gamma \rightarrow e^+e^-$ Conversions



Made with 500k simulated minimum bias events (~40 mins data taking at 200 Hz) yielding ~90k conversions

Start-up Detector Commissioning: top Signal

Can we observe an early top signal with limited detector performance (no b -tag) ?

Can we use it to understand detector **and** physics ?

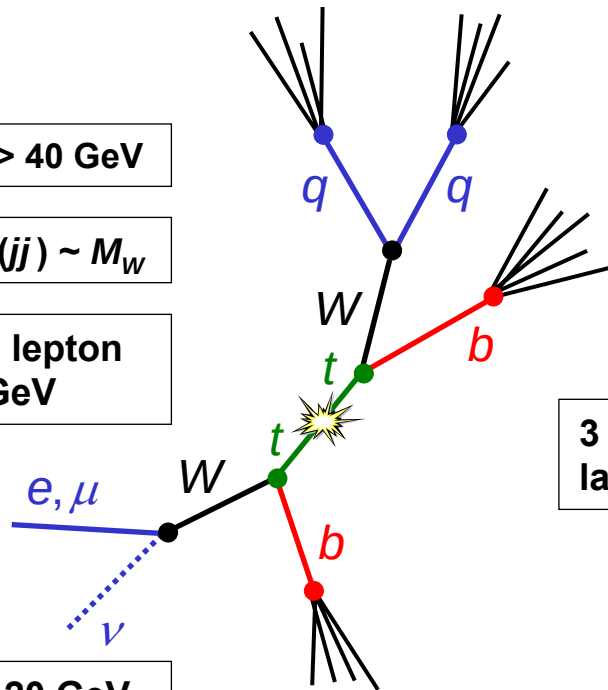
$$\sigma_{tt} \approx 250 \text{ pb for } tt \rightarrow bW bW \rightarrow b\ell\nu bjj$$

4 jets $p_T > 40 \text{ GeV}$

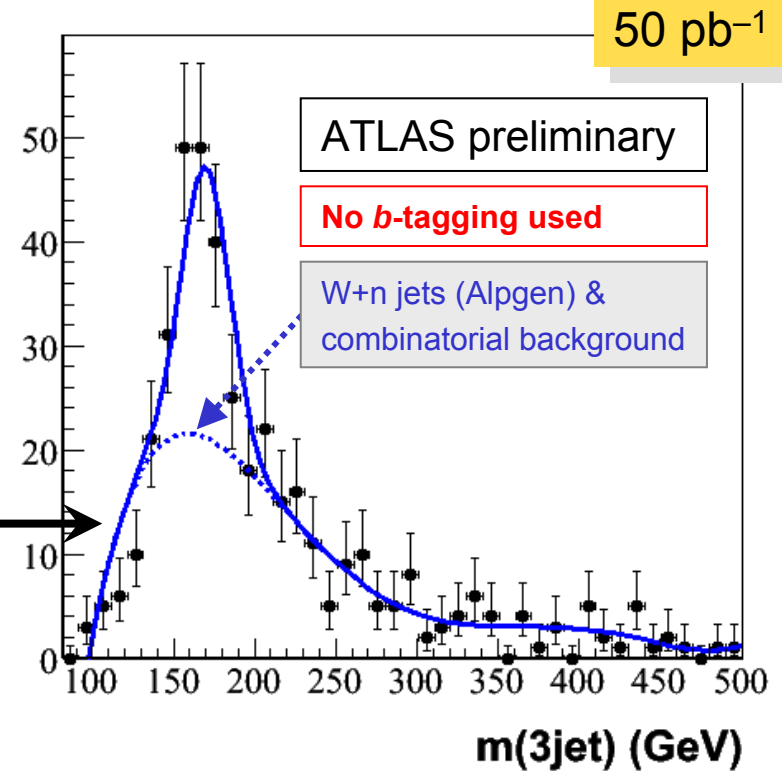
2 jets $M(jj) \sim M_W$

Isolated lepton
 $p_T > 20 \text{ GeV}$

$E_{T,\text{miss}} > 20 \text{ GeV}$



3 jets with
largest $\sum p_T$



Be Ready for Surprises

Example: SUSY with **very light stop** ($m_{\text{stop}} \sim 137 \text{ GeV} < m_{\text{top}}$)

(Conflict with m_h lower limit ☹)

Final state similar to t -pair production, but more $E_{T,\text{miss}}$ and softer lepton, jets

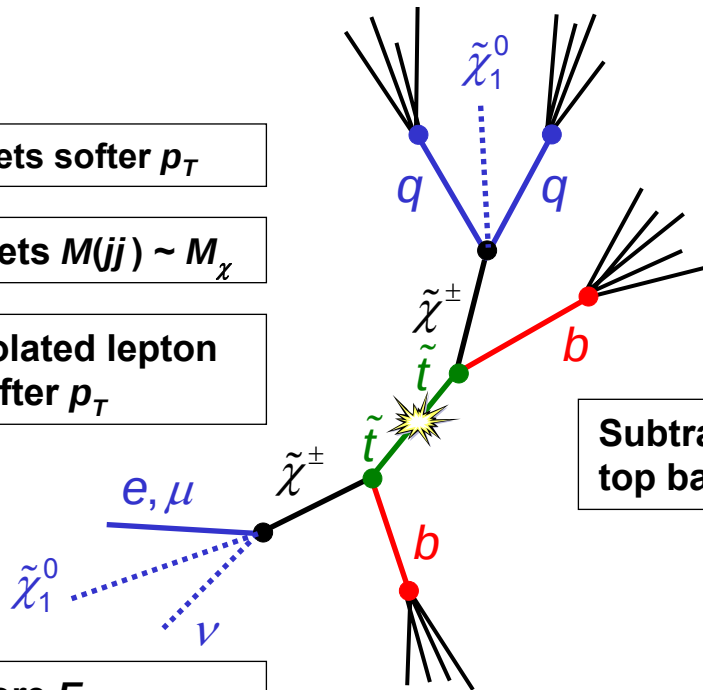
$$\sigma_{st\,st} \approx 412 \text{ pb for } st\,st \rightarrow b\chi\,b\chi \rightarrow b\chi^0\ell\nu\,b\chi^0jj$$

4 jets softer p_T

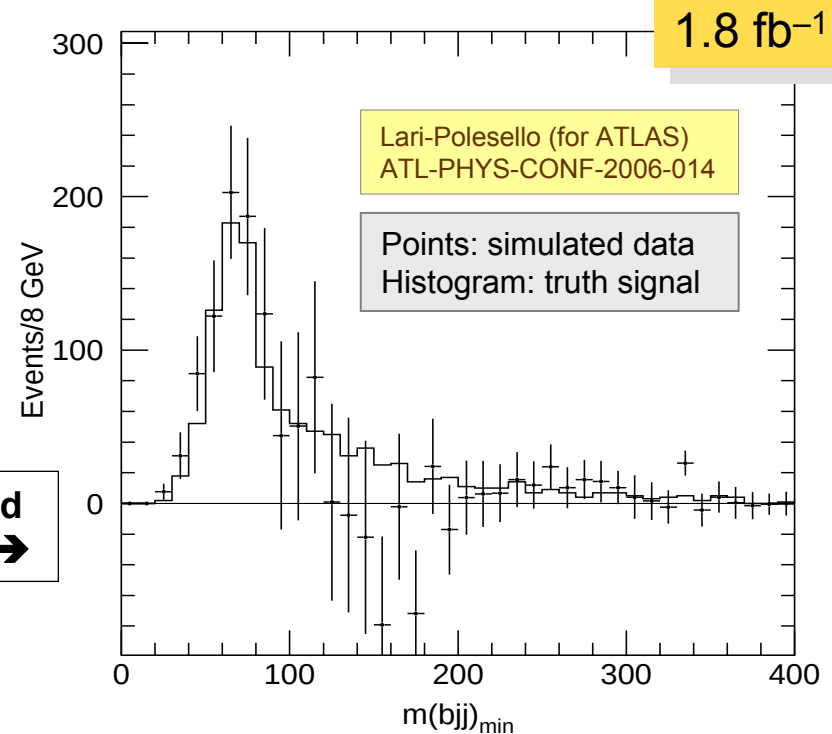
2 jets $M(jj) \sim M_\chi$

Isolated lepton
softer p_T

more $E_{T,\text{miss}}$



Subtract expected
top background →





Higgs and New Phenomena Searches at the LHC



Recall: $1 \text{ pb}^{-1} = 10^{36} \text{ cm}^{-2}$
1 second at $L = 10^{31} \text{ cm}^{-2}\text{s}^{-1} \rightarrow \int L dt = 10^{-5} \text{ pb}^{-1}$
1 10h running day at $L = 10^{31} \text{ cm}^{-2}\text{s}^{-1} \rightarrow \int L dt = 0.36 \text{ pb}^{-1}$

Searches at the LHC

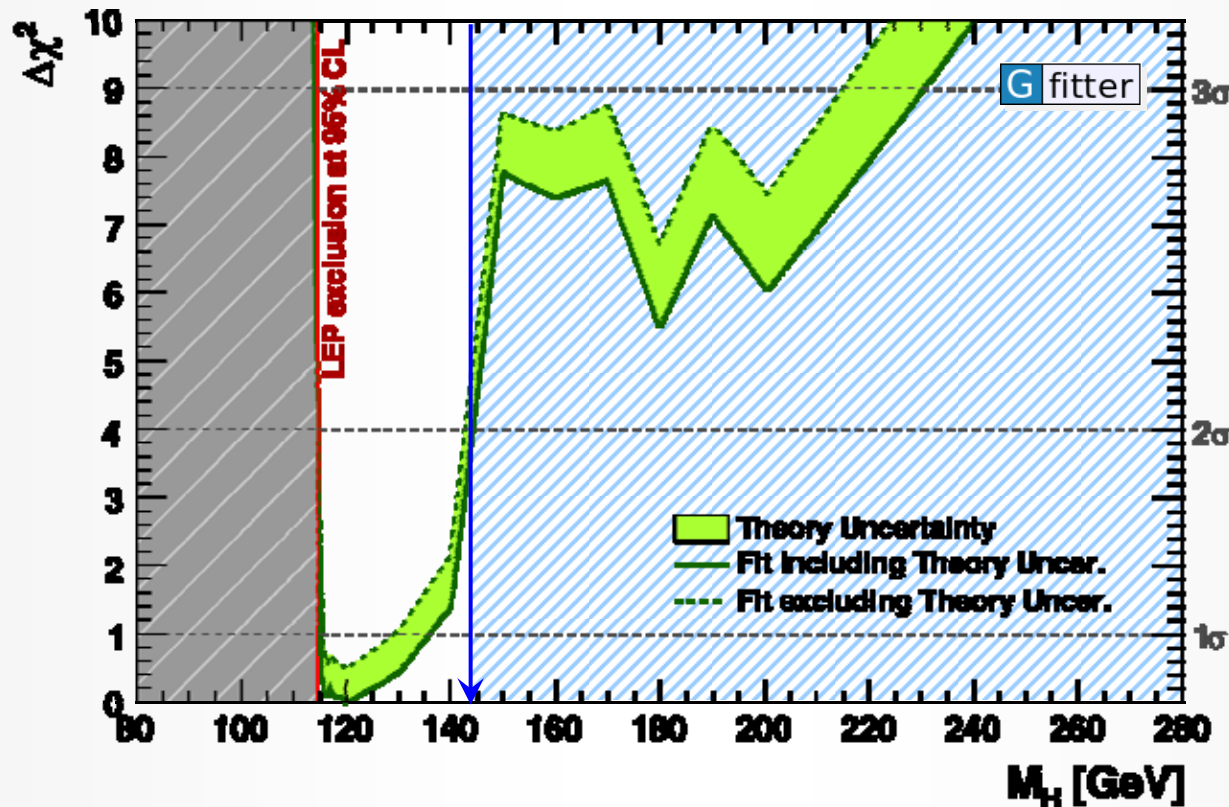
— The Higgs Boson —

Search strategy:

1. Inclusive searches. Discovery and determination of SUSY mass scale.
2. If signal, exclusive searches and reconstruction of decay cascades.

A Light Standard Model Higgs Boson

- The global fit of all the electroweak precision data from experiments at LEP, SLC, Tevatron accelerators constraints the Higgs to be light !



Higgs mass from fit to electroweak precision data

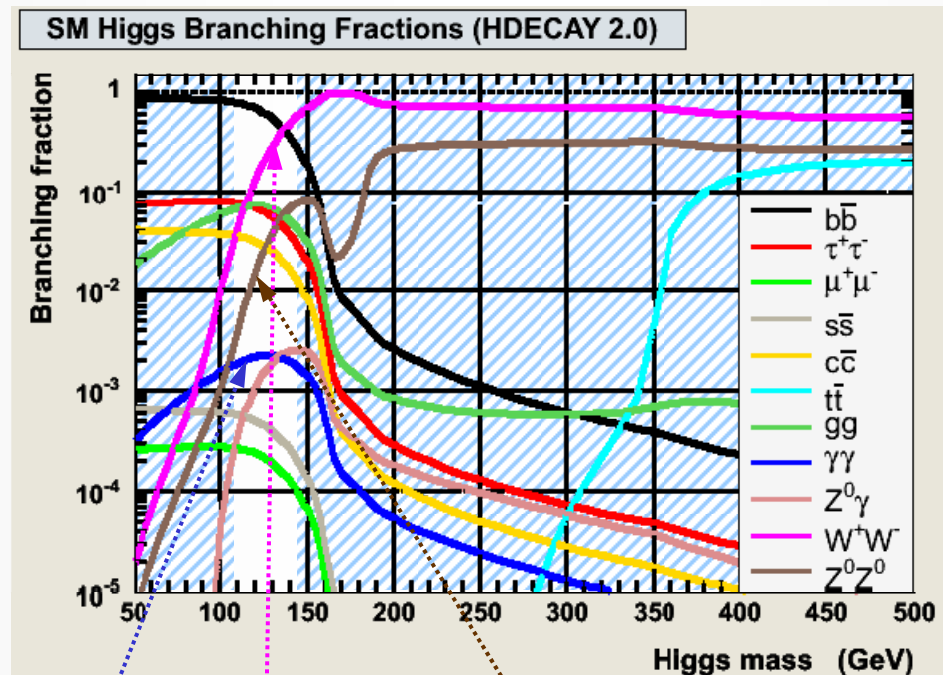
Fit including constraint from direct searches at LEP and Tevatron



$$\Delta\rho_{(\text{Higgs})} = \frac{11G_F m_Z^2 \cos^2 \theta_W}{24\sqrt{2}\pi^2} \log \left(\frac{m_H^2}{m_W^2} \right)$$

Standard Model Higgs @ LHC

- Inclusive SM Higgs production cross section (left) and branching fractions (right)



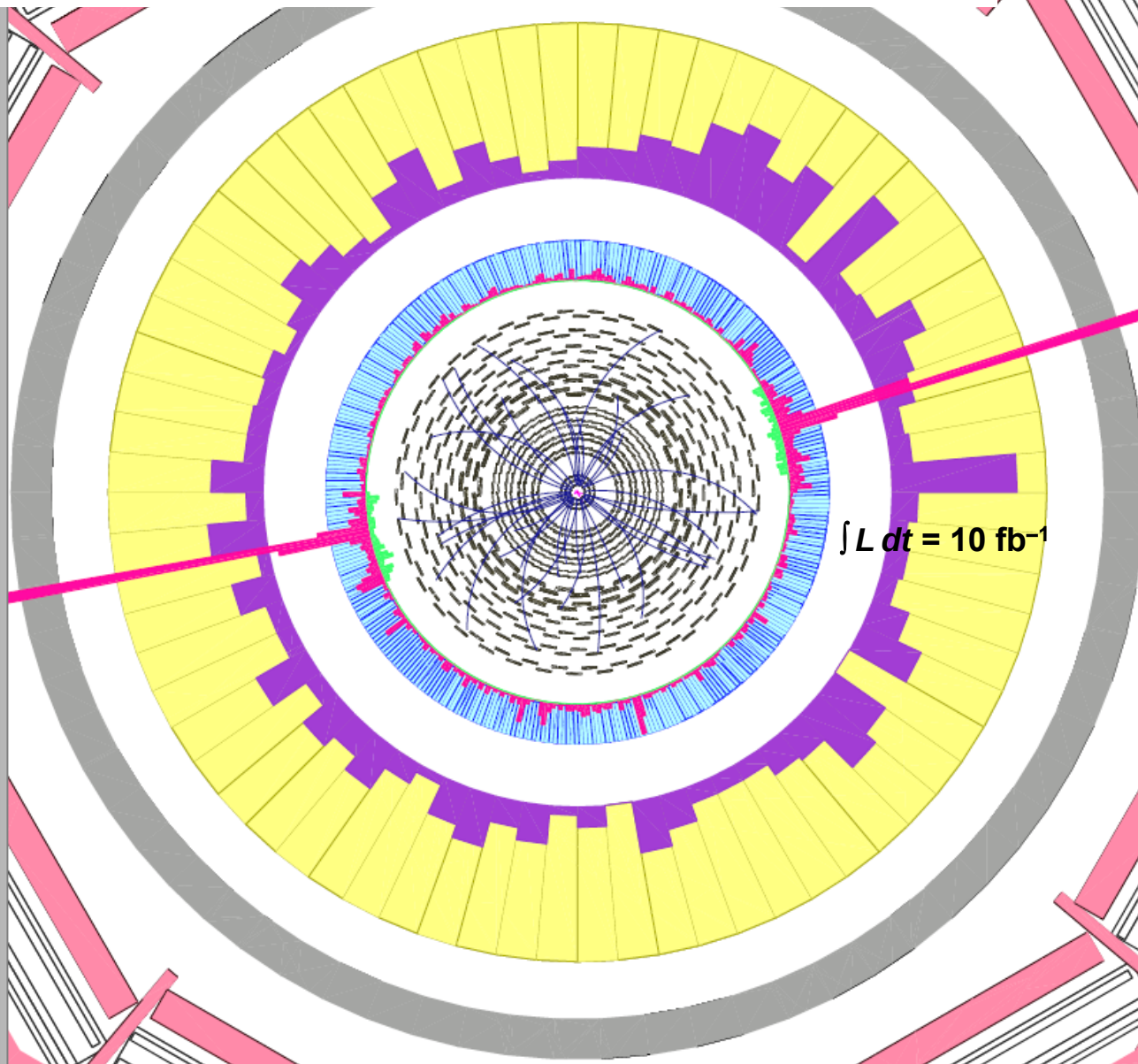
$H \rightarrow \gamma\gamma$:
rare, but
clean

$H \rightarrow WW^*$:
abundant,
but not clean

$H \rightarrow ZZ^*$:
sizable branching
fraction, and clean

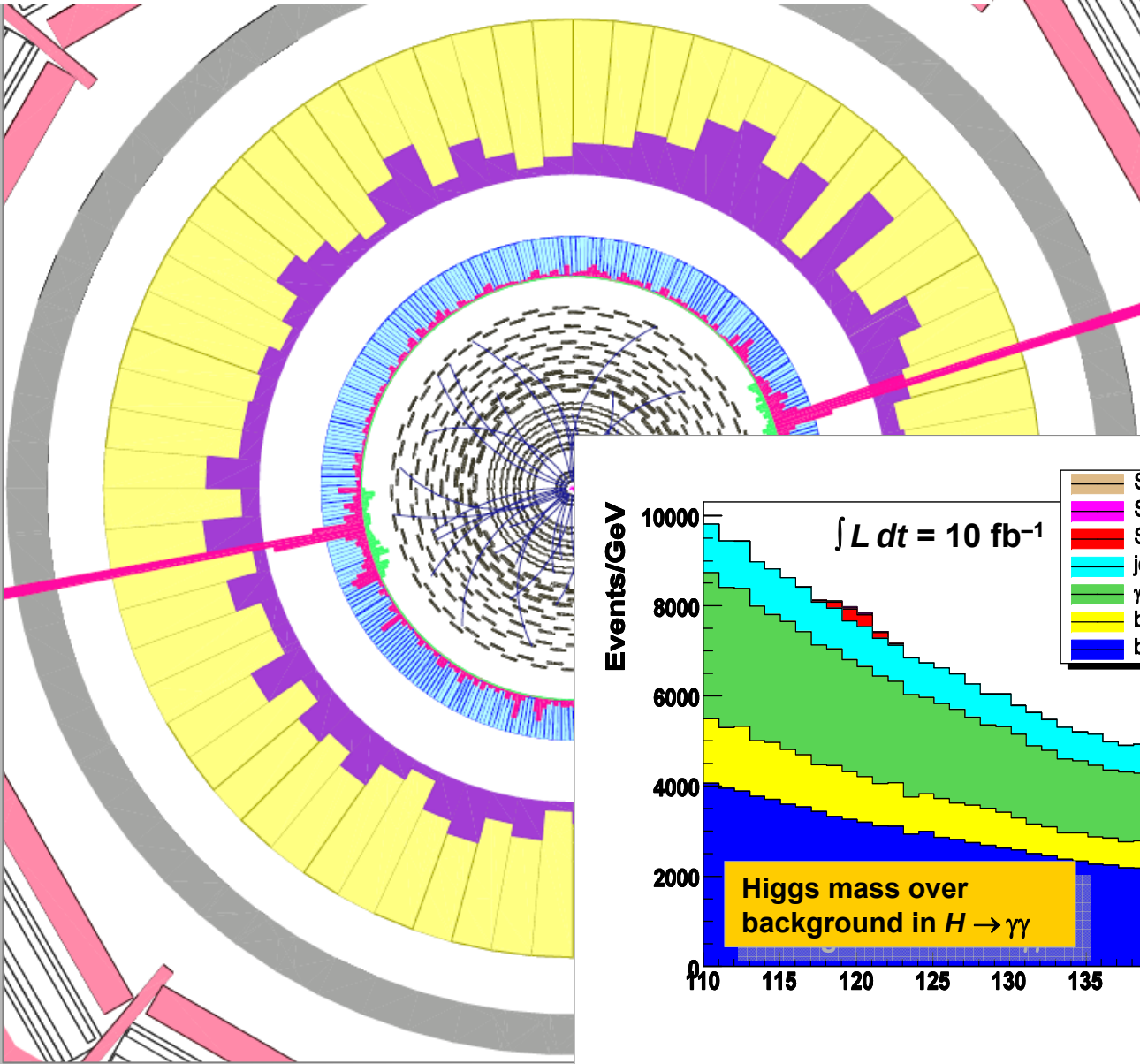
Golden
search
modes

Simulation of a Higgs to 2 photons event in CMS

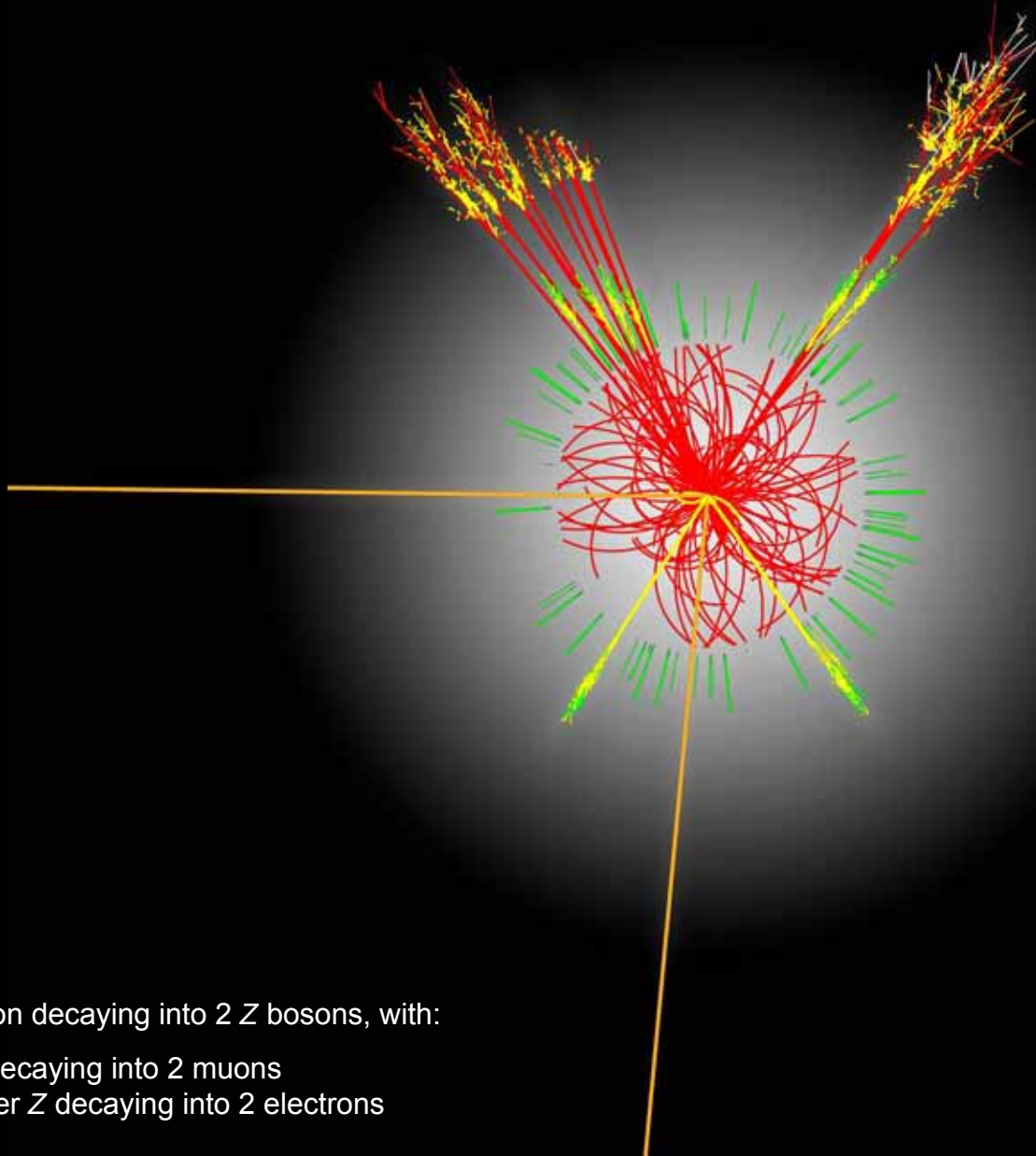


$H \rightarrow \gamma\gamma$

Simulation of a Higgs to 2 photons event in CMS



Simulation of a Higgs to 4 leptons event in ATLAS

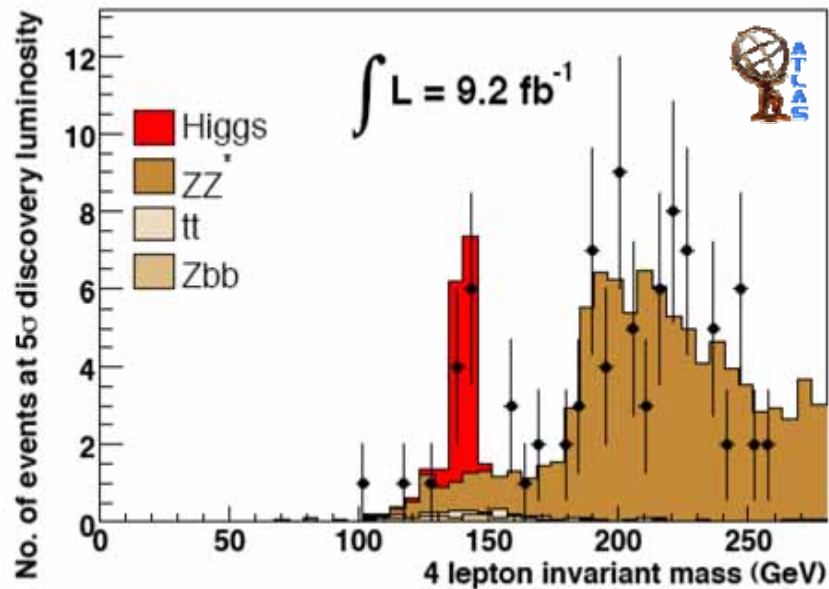


Higgs boson decaying into 2 Z bosons, with:

- One Z decaying into 2 muons
- The other Z decaying into 2 electrons

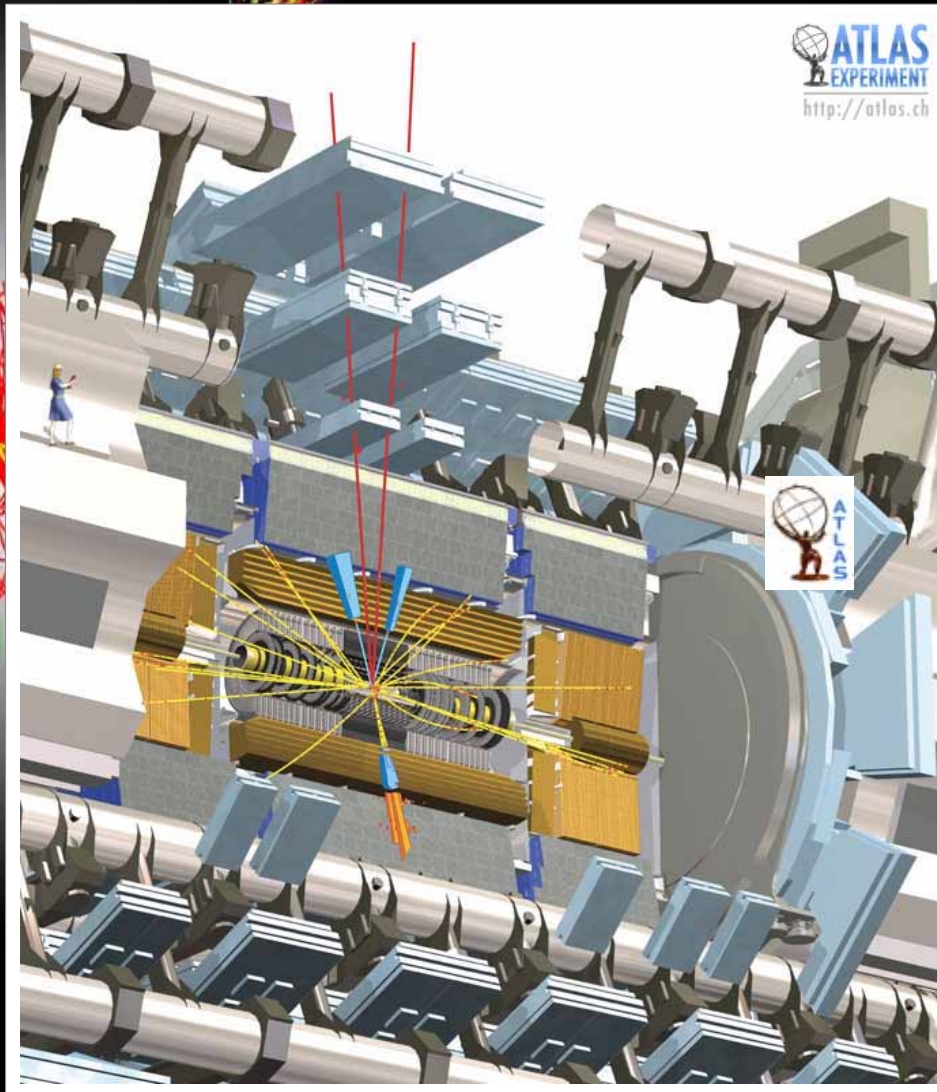


Simulation of a Higgs to 4 leptons event in ATLAS



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Searches at the LHC

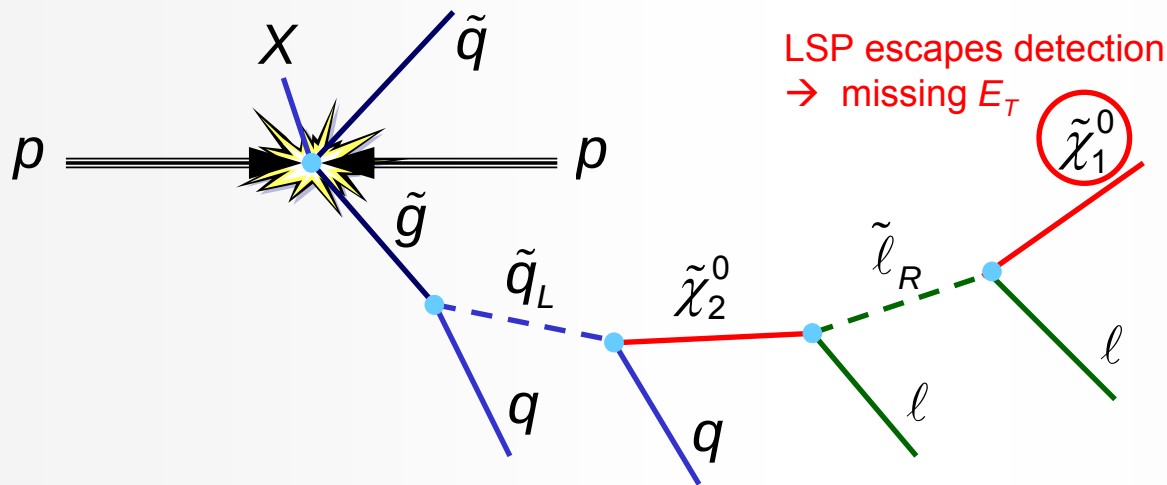
— Supersymmetry —

Search strategy:

1. Inclusive searches. Discovery and determination of SUSY mass scale.
2. If signal, exclusive searches and reconstruction of decay cascades.

Characteristic SUSY “Cascades” at the LHC

- Conserved ***R*-parity** requires existence of a **lightest stable SUSY particle (LSP) → WIMP** (LSP signature just as heavy neutrino)
- The LSP is typically found to be a spin- $\frac{1}{2}$ **neutralino**, a linear combination of gauginos (in much of the SUSY parameter space the neutralino is a mixture of photino and zino)
- With *R*-parity: **SUSY** production in **pairs** only → **requires energy $2 \times$ SUSY mass !**



“Typical” SUSY decay chain at the LHC

But why the “ T ” in missing E_T ?



The hard-scattering processes
are not longitudinally balanced

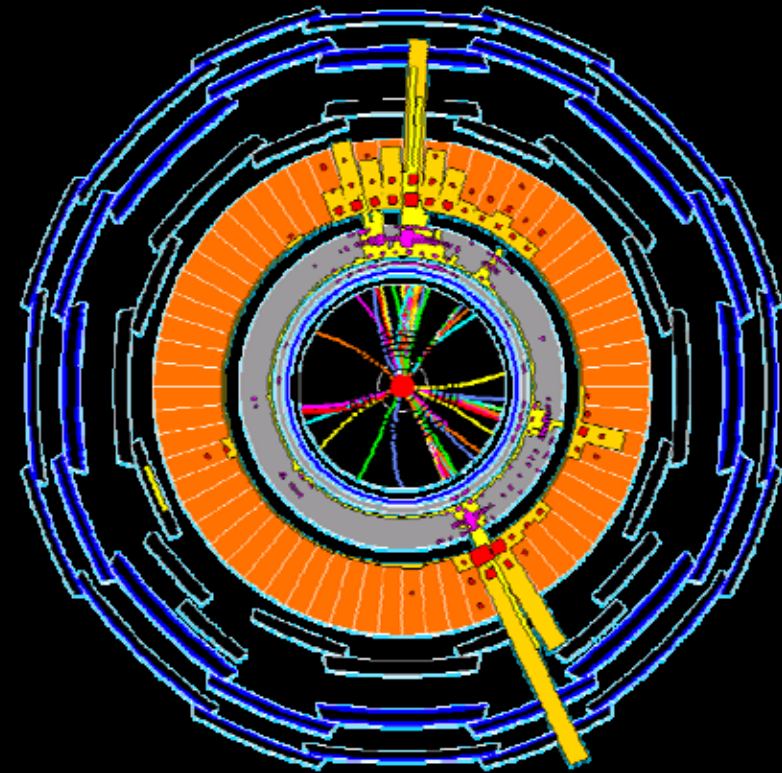
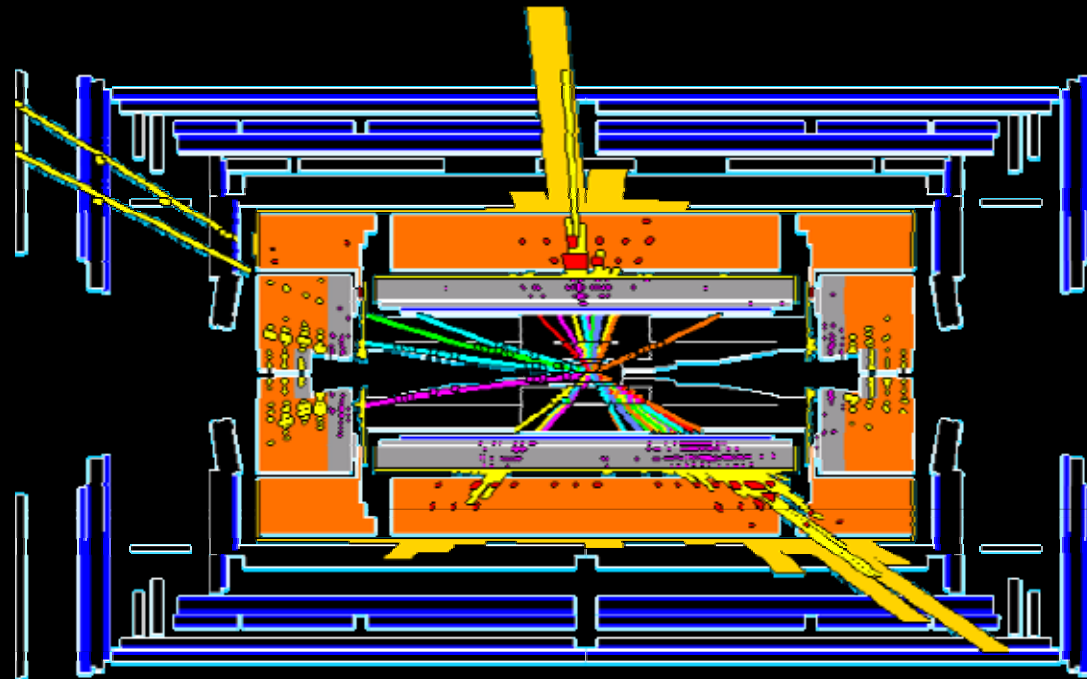


Hence, we do not know what longitudinal energy to expect



Fortunately, the events are transversely balanced !

Simulation of a Supersymmetry event in ATLAS



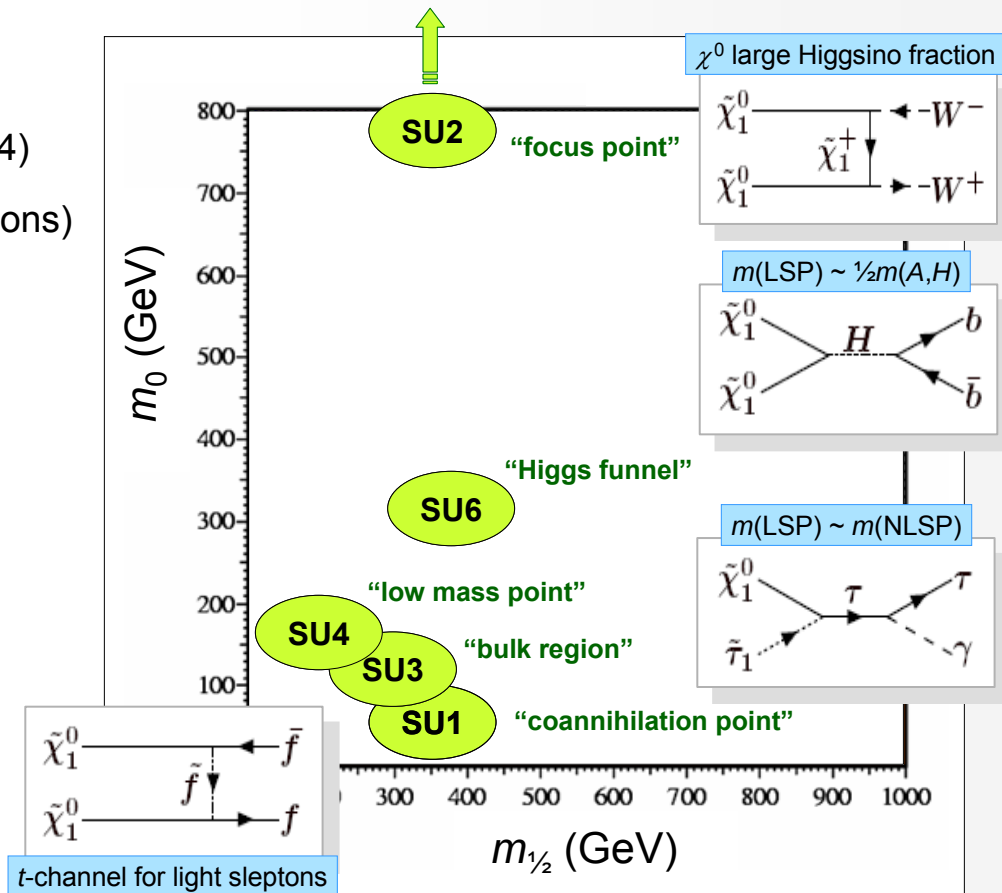
Pair of SUSY particles decaying via:

- Six particle jets
- Two muons with opposite charges (visible in the side view going to the left, but not in the end view because they exited the detector in the forward direction)
- Large missing transverse energy



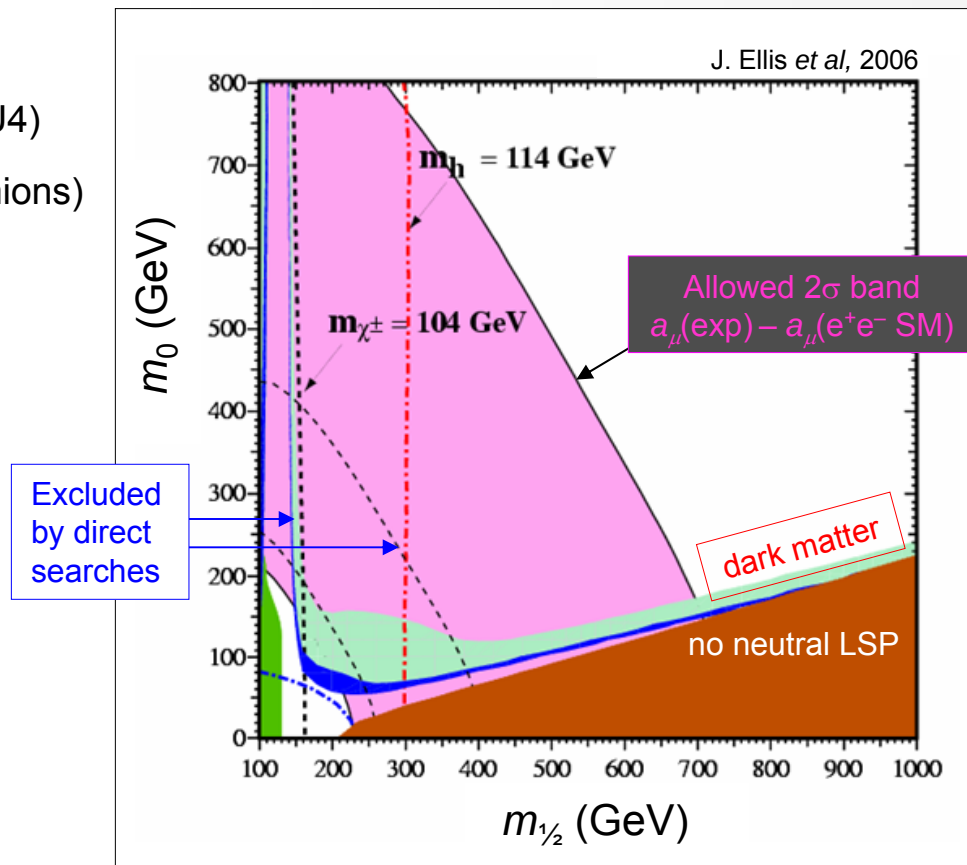
Inclusive SUSY Searches

- Prepare SUSY searches with Monte Carlo: since SUSY parameters unknown, choose “representative” scenarios (e.g., mSUGRA) → points need to respect $\Omega_{\text{DM}} \sim 0.1$
- Choose a few “characteristic” points
 - At the limit of experimental exclusion (SU4)
 - “Typical” point (SU3, light LSP and sfermions)
 - Special-feature points (SU1, SU2, SU6)



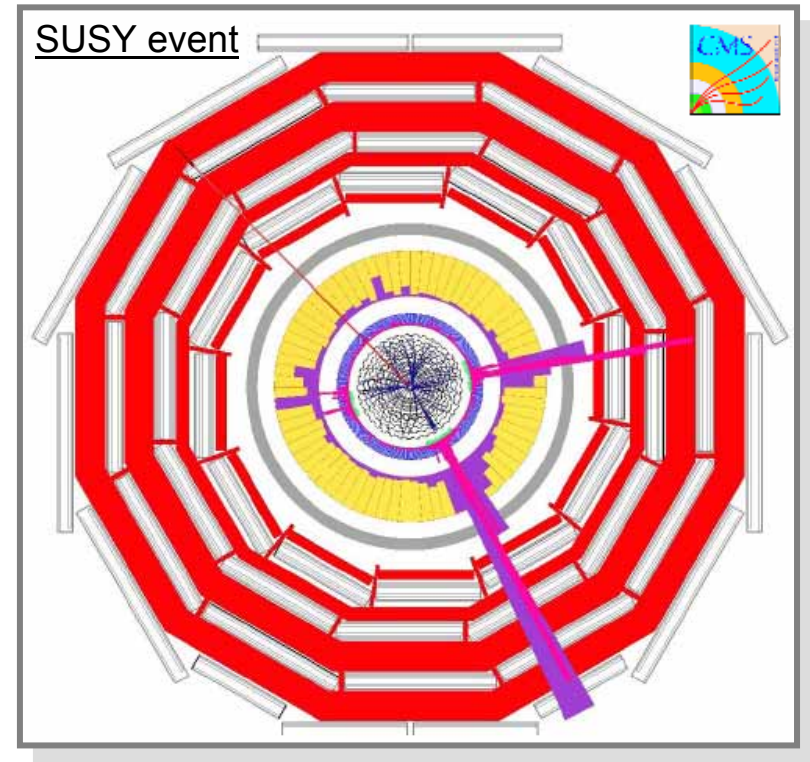
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- Choose a few “characteristic” points
 - At the limit of experimental exclusion (SU4)
 - “Typical” point (SU3, light LSP and sfermions)
 - Special-feature points (SU1, SU2, SU6)
- Since mSUGRA has only 5 parameters, it is highly constraining ...and can be already well constrained from data !
 - From direct accelerator searches
 - From indirect accelerator searches
 - From cosmology



Inclusive SUSY Searches

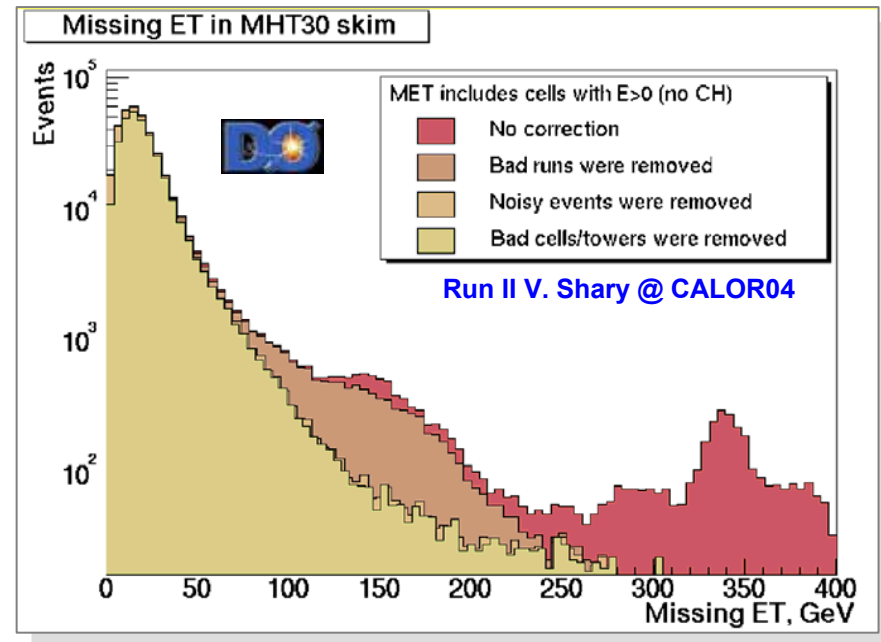
- The precise signatures of the SUSY “cascades” are driven by the masses of the SUSY particles
- To good generality we can expect:
 - High- p_T jets from squark & gluino decays
 - Leptons from gaugino & slepton decays
 - Missing energy from LSPs
- ➡ This lays out an **inclusive** search strategy
- Detector requirements:
 - Excellent EM & jet-energy measurement
 - Excellent lepton identification
 - Hermeticity (good acceptance)



Inclusive SUSY Searches

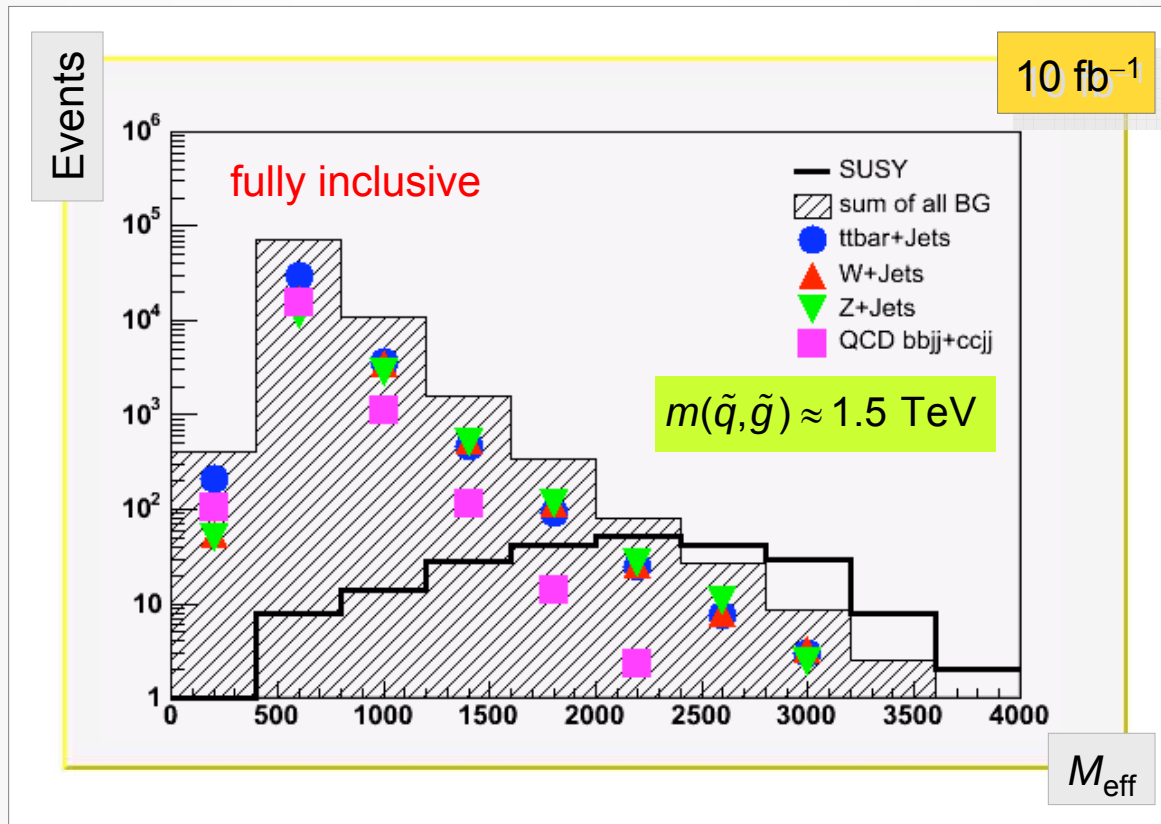
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Measuring missing energy is a tough task !



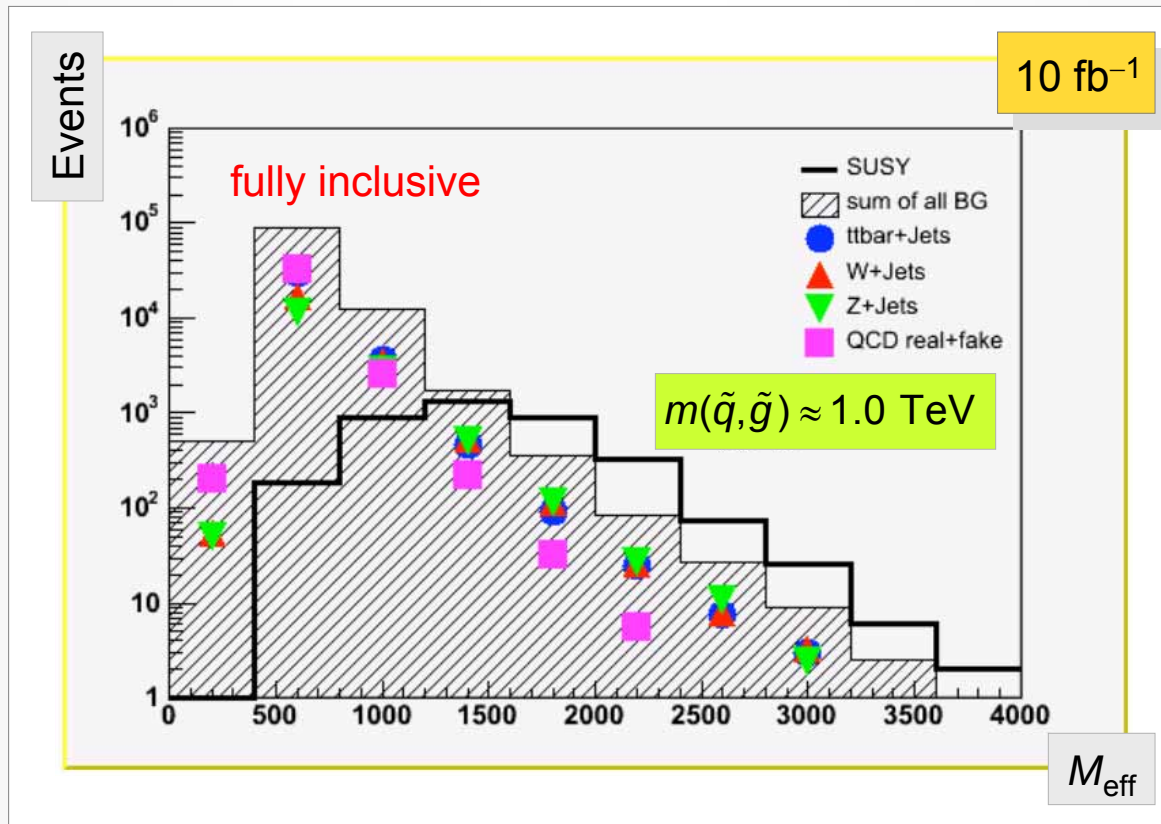
Inclusive SUSY Searches ... continued

- A sensitive variable to detect SUSY decays is the “**effective mass**”: $M_{\text{eff}} = E_{T,\text{miss}} + \sum_{\text{jets, leptons}} p_T$



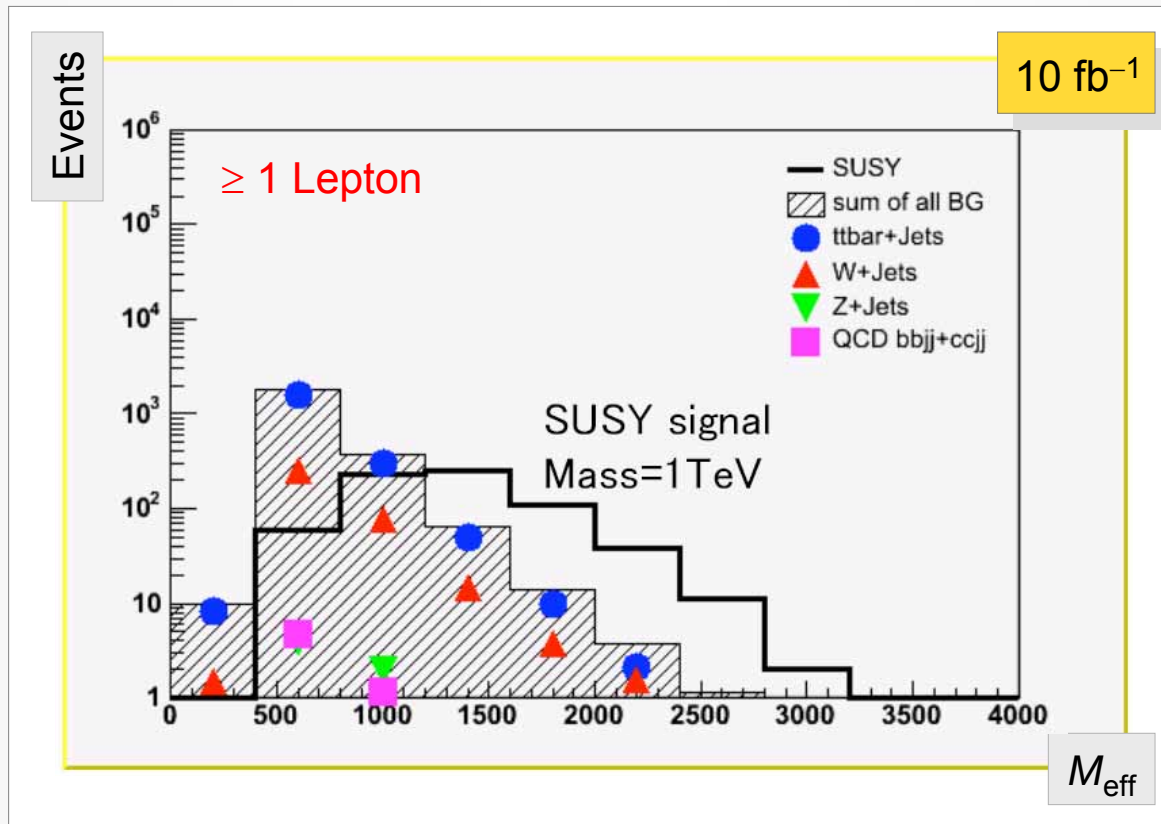
Inclusive SUSY Searches ... continued

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Inclusive SUSY Searches ... continued

- A sensitive variable to detect SUSY decays is the “**effective mass**”: $M_{\text{eff}} = E_{T,\text{miss}} + \sum_{\text{jets, leptons}} p_T$



- Requiring ≥ 1 lepton reduces QCD background by factor of 20–30, with signal loss of only factor of ~ 3 (production through weak interaction) $\rightarrow$ better S/B than fully inclusive analysis

Squarks and Gluinos: Reach of the LHC

- Experiments evaluate their SUSY discovery potential using some “standard” mSUGRA setup

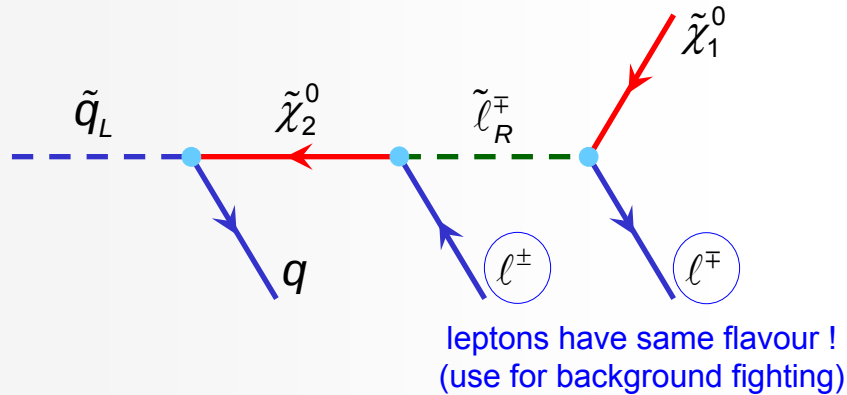
5 σ discovery reach for SUSY:		
Time period	Luminosity [cm ⁻² s ⁻¹]	squark/gluino masses
1 month	10 ³³	~1.3 TeV
1 year	10 ³³	~1.8 TeV
1 year	10 ³⁴	~2.5 TeV
Ultimate	$\int = 300 \text{ fb}^{-1}$	~2.5–3 TeV
D0 & CDF	$\int = 0.3 \text{ fb}^{-1}$	> _(2σ) 0.35 TeV

Once SUSY has been Discovered ... Measure it !

- **Inclusive SUSY discovery** will provide indications about underlying scenario:
 - SUSY mass scale and cross section
 - R -parity ($E_{T,\text{miss}}$ spectrum), Gauge-mediated SB (hard γ 's, NLSP's, long-lived gluinos), large $\tan\beta$ (τ 's)
- However, fundamental SUSY parameters (**masses, couplings, spins, ...**) can only be inferred from direct measurements of **sparticle properties**
- **Exclusive reconstruction** of SUSY final states is possible:
 - Select final state signatures that identify exclusive decay chains (e.g., 2 or 3 final state leptons)
 - Apply kinematic constraints to eliminate escaped particles (e.g., LSP)
 - Fit, e.g., masses of particles in decay chain
- Remarks:
 - R -parity conservation: at least two LSP's in event $\rightarrow$ no direct mass peaks, but kinematic “endpoints”
 - These endpoints depend on the masses of the involved particles
 - When cascade of at least 3 consecutive two-body decays occurred $\rightarrow$ full kinematics accessible

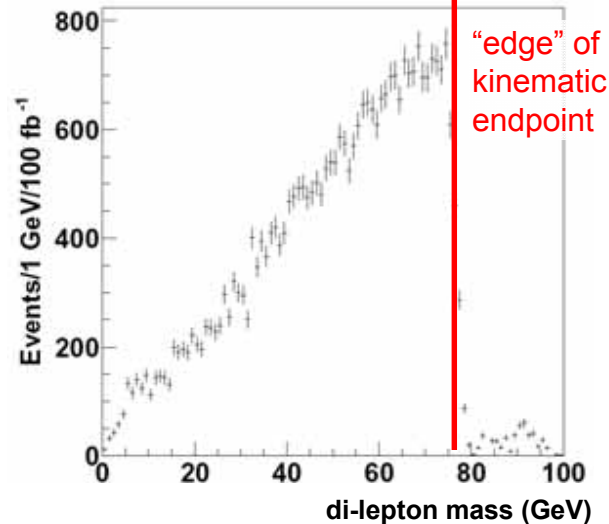
Exclusive Reconstruction: An Example

- Let's look again at the process: $pp \rightarrow X + \tilde{g} + \tilde{g} \left(\rightarrow q + \tilde{q}_L \left(\rightarrow q + \tilde{\chi}_2^0 \left(\rightarrow \ell^\pm + \tilde{\ell}_R^\mp \left(\rightarrow \ell^\mp + \tilde{\chi}_1^0 \right)_{LSP} \right) \right) \right) \right)$
- 3 two-body decays ! ($m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0}$)



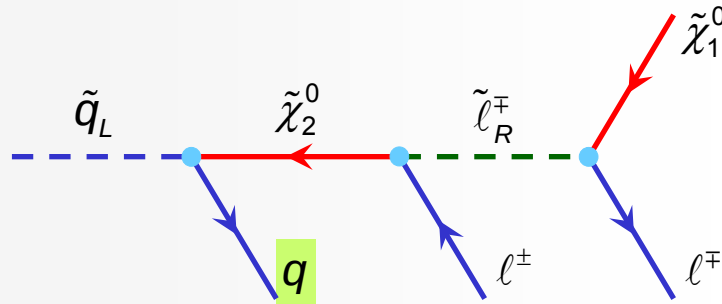
Di-lepton kinematic endpoint:

$$m_{\ell\ell}^{\max} = \frac{1}{m_{\tilde{\ell}_R}} \sqrt{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}_R}^2)(m_{\tilde{\ell}_R}^2 - m_{\tilde{\chi}_1^0}^2)}$$



... Also Reconstructing the Jet

- We can also use jets from: $pp \rightarrow X + \tilde{g} + \tilde{g} \left(\rightarrow q + \tilde{q}_L \left(\rightarrow q + \tilde{\chi}_2^0 \left(\rightarrow \ell^\pm + \tilde{\ell}_R^\mp \left(\rightarrow \ell^\mp + \tilde{\chi}_1^0 \Big|_{LSP} \right) \right) \right) \right) \right)$



3 two-body decays ! ($m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0}$)

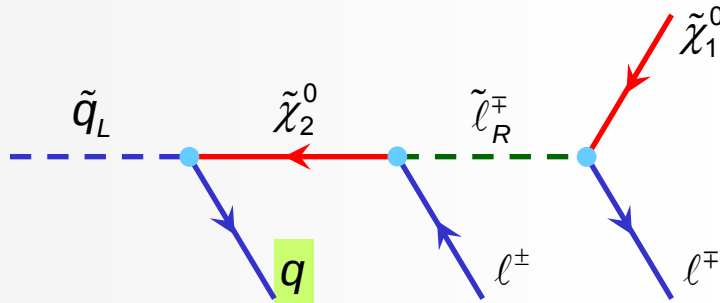
Theoretical kinematic endpoint of the $q\ell^+\ell^-$ system:

$$m_{q\ell\ell}^{\max} = \frac{1}{m_{\tilde{\chi}_2^0}} \sqrt{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}$$

- One can also look into the corresponding **$q\ell$ endpoints and thresholds**
- In total **6 distributions can be fit** to determine the corresponding sparticle masses
 - An ATLAS study for 100 fb^{-1} finds mass precisions of 12% (χ_1), 6% (χ_2), 9% (ℓ_R), 3% (q_R)
- Thorough experimental and theoretical work will be necessary to **control the backgrounds** from other jet-lepton(-lepton) combinations in the event and initial state radiation of jets

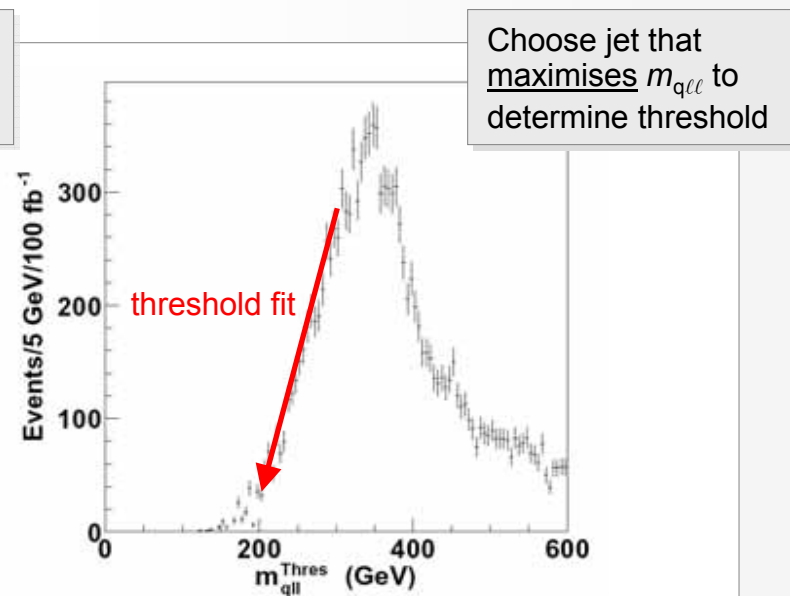
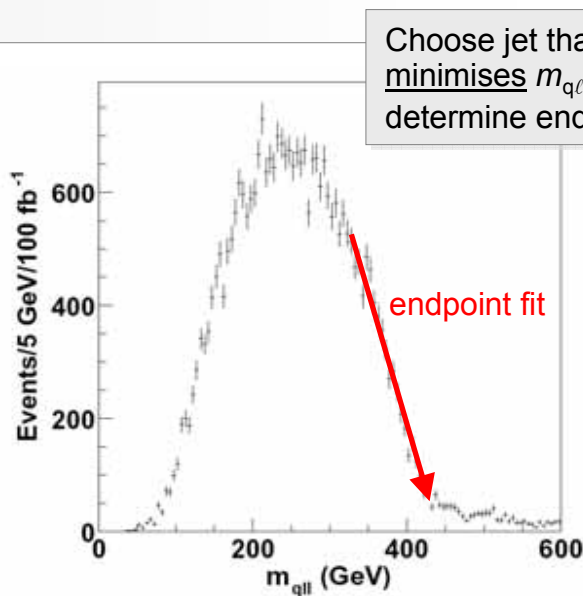
... Also Reconstructing the Jet

- We can also use jets from: $pp \rightarrow X + \tilde{g} + \tilde{g} \left(\rightarrow q + \tilde{q}_L \left(\rightarrow q + \tilde{\chi}_2^0 \left(\rightarrow \ell^\pm + \tilde{\ell}_R^\mp \left(\rightarrow \ell^\mp + \tilde{\chi}_1^0 \Big|_{LSP} \right) \right) \right) \right) \right)$
- 3 two-body decays ! ($m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0}$)



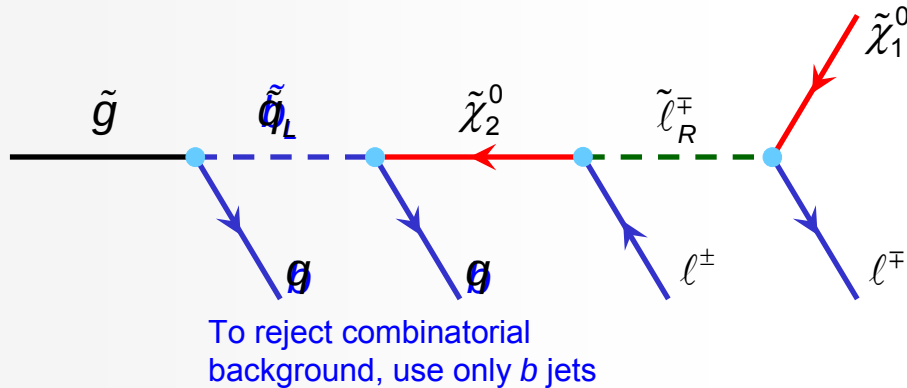
Theoretical kinematic endpoint of the $q\ell^+\ell^-$ system:

$$m_{q\ell\ell}^{\max} = \frac{1}{m_{\tilde{\chi}_2^0}} \sqrt{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}$$



... Reconstructing sbottom and gluino Masses

- Let's look again at the full decay chain:



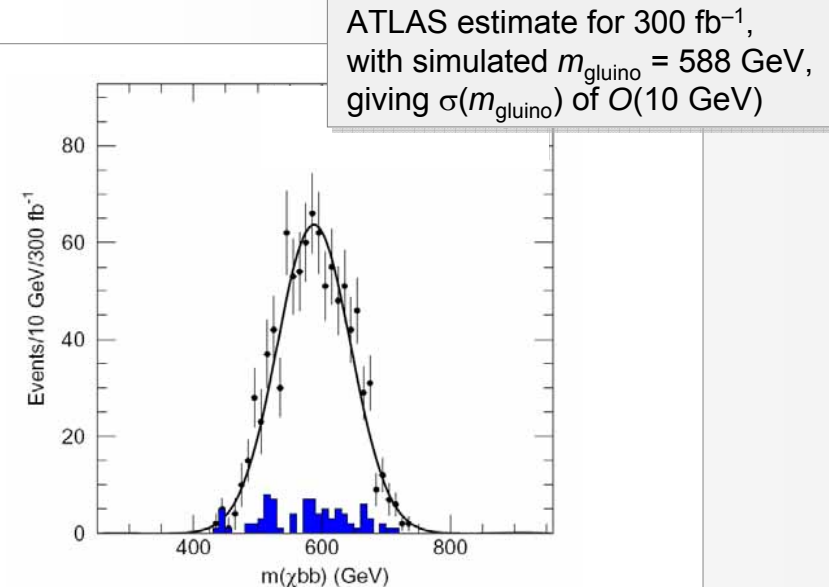
Close to the $\ell^+\ell^-$ endpoint, the χ_2 (~in rest) has residual momentum:

$$\vec{p}(\tilde{\chi}_2^0) \approx \left(1 + \frac{m_{\tilde{\chi}_1^0}}{m_{\ell\ell}}\right) \cdot \vec{p}(\ell^+\ell^-)$$

The neutralino masses are known from the preceding analysis

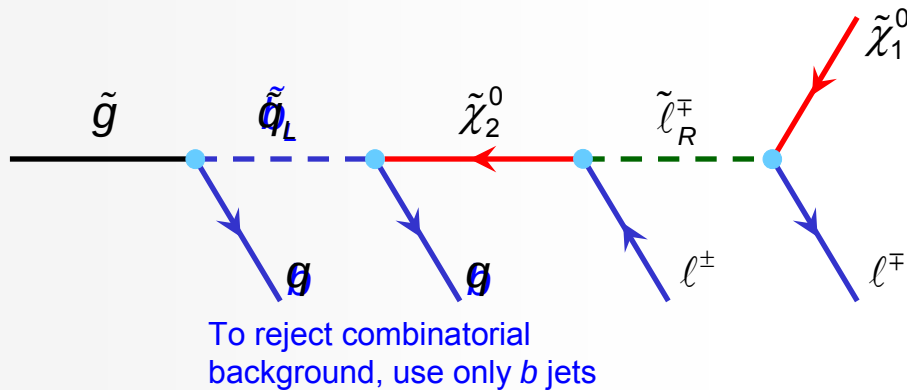
→ χ_2 4-vector is known

- ➡ The gluino and sbottom masses are then obtained from the $bb\chi_2$ and $b\chi_2$ invariant masses, respectively



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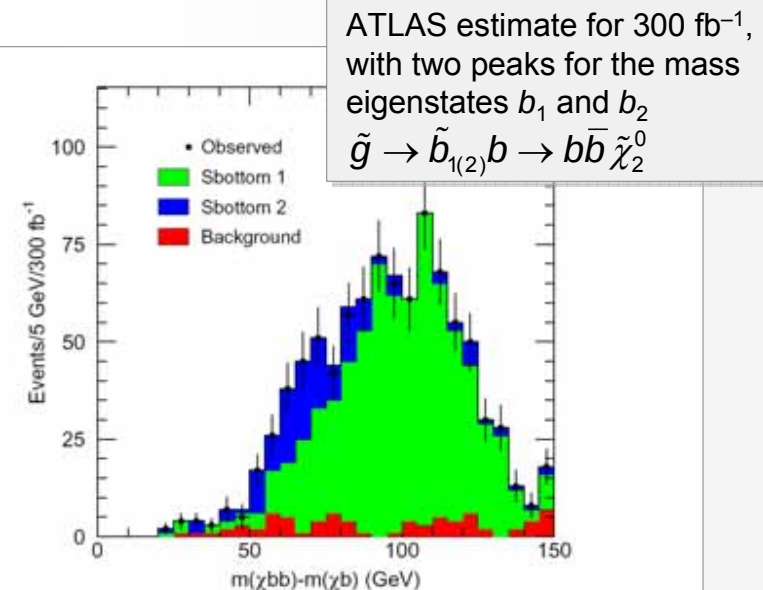


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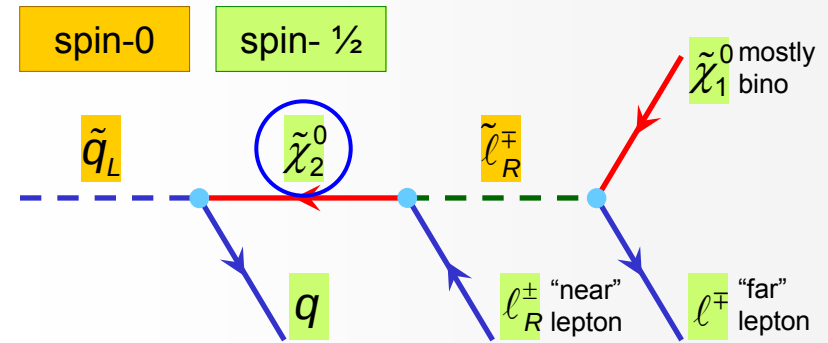
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- The gluino and sbottom masses are then obtained from the $bb\chi_2$ and $b\chi_2$ invariant masses, respectively
- The sbottom mass is then best obtained from mass difference (reduces errors)



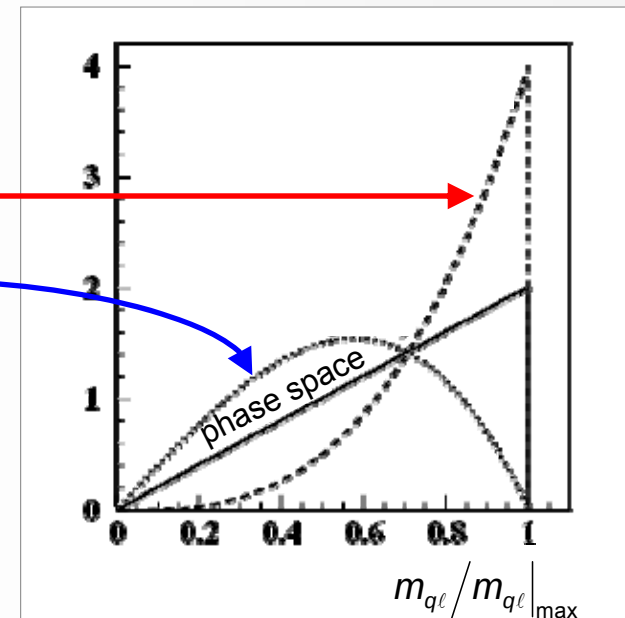
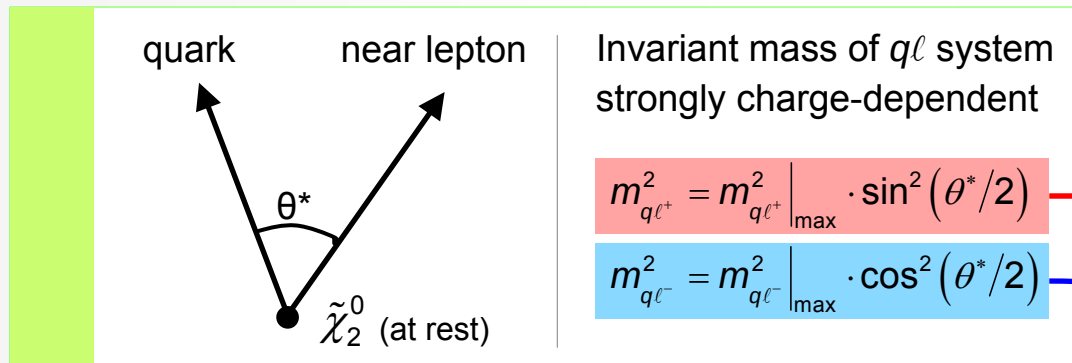
If we Discovered Something... is it SUSY ? (*)

- If observed, the signatures discussed so far provide **strong hints for SUSY**
- To verify that the new fields are indeed the SM Superpartners → **measure their spins**
- Not easy at LHC, but (hopefully) possible



Decay chain sensitive to fermionic character of χ_2

- Invariant mass of quark-lepton system depends on the polarization of neutralino



- Problem: this effect is inverted for anti-squark decay !

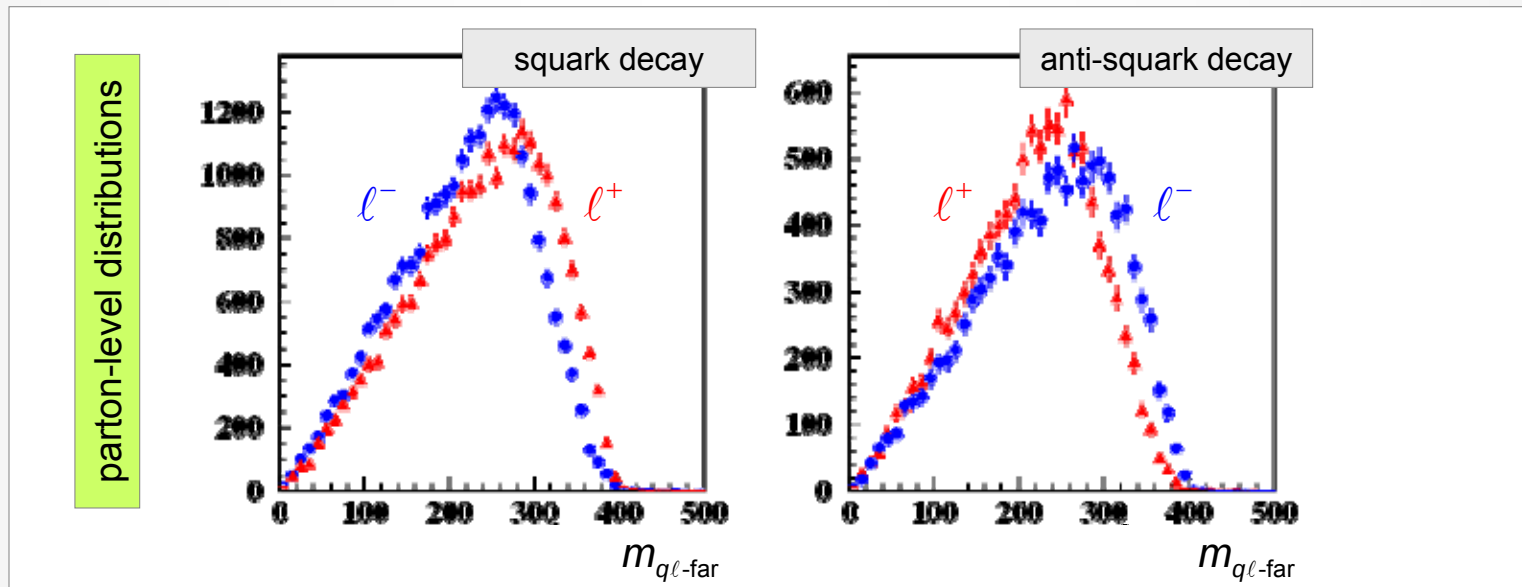
(*) For example, UED KK signals with WIMP LKPs could fool us !

Measuring the χ_2 Spin

■ Experimental Problems:

- 1) Cannot distinguish “near” from “far” lepton
 - 2) Cannot distinguish quark from anti-quark jet
- ➡ Plot $m_{q\ell}$ for both leptons
 - ➡ Fortunately: LHC produces $\sim 2\times$ more squarks than anti-squarks

- To 1) : Some residual asymmetry left from boost of slepton in the χ_2 rest frame
→ see quark-lepton(far) invariant mass (parton-level):

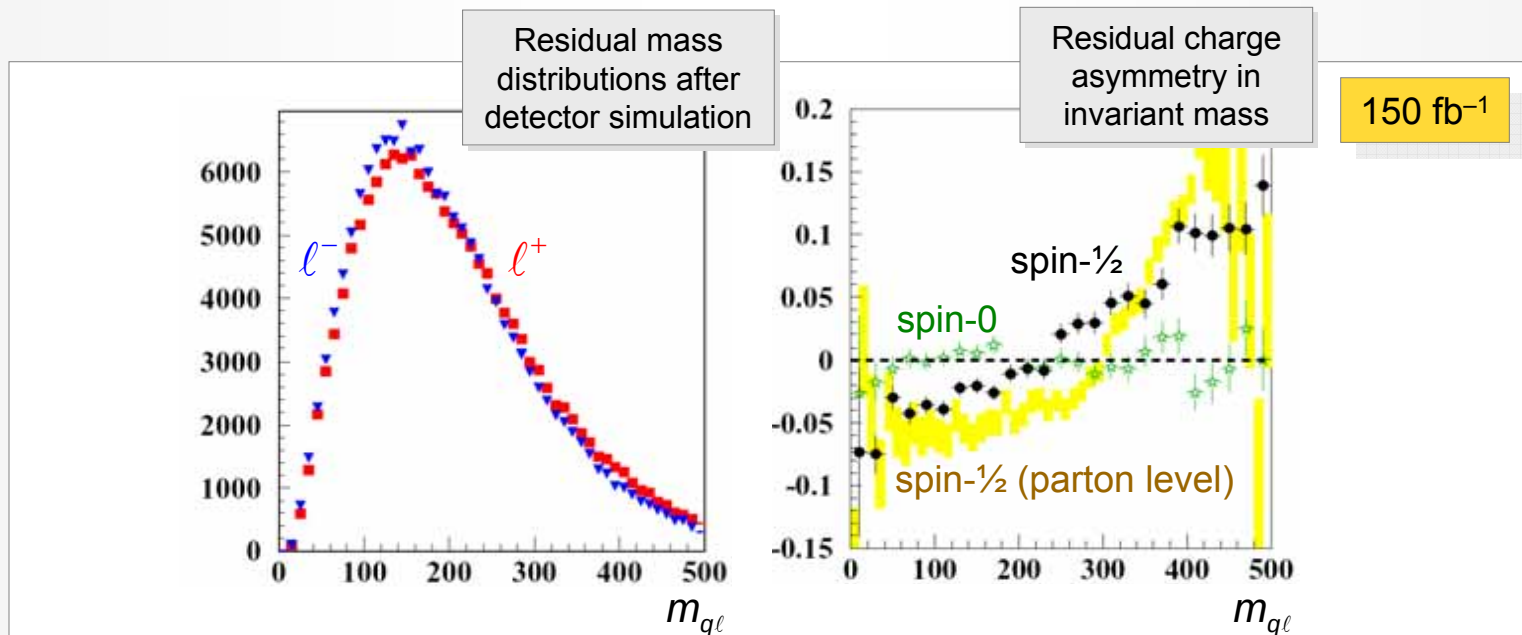


Measuring the χ_2 Spin

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■ Measure the asymmetry: $A^{+-}(\sin(\theta^*/2)) = \frac{dN/dm_{q\ell^+} - dN/dm_{q\ell^-}}{dN/dm_{q\ell^+} + dN/dm_{q\ell^-}} = \begin{cases} A^{\tilde{q}\tilde{q}} (2\sin(\theta^*/2) - 1), & \text{if } |s_{\tilde{\chi}_2^0}| = 1/2 \\ 0, & \text{if } |s_{\tilde{\chi}_2^0}| = 0 \end{cases}$



Gauge Mediated SUSY Breaking

- Messenger scale $M_m \ll M_{\text{Pl}}$, SUSY breaking scale $F_m \ll (10^{10} \text{ GeV})^2$
- Very light gravitino ($\ll 1 \text{ GeV}$) is LSP
- Signatures determined by NLSP: either neutralino or slepton ...
and by C_{grav} parameter determining lifetime of NLSP

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} \gamma \quad \text{or} \quad \tilde{\ell}_R \rightarrow \tilde{G} \ell$$

Distinguish 4 cases:

Cases	Phenomenology and signature	Observables	Results
$C_{\text{grav}} = 1$ (fast decay) NLSP = neutralino	2 high- E_T γ 's & jets & leptons & $E_{T,\text{miss}}$	Lepton- γ edges: $M_{\ell\ell,\text{max}}, M_{\ell\ell\gamma,\text{max}}, M_{\ell(1,2)\gamma,\text{max}}$	$M_{\tilde{\ell}_R}, M_{\tilde{\chi}_1^0}, M_{\tilde{\chi}_2^0}$ also: $M_{\tilde{g}}, M_{\tilde{q}}$
$C_{\text{grav}} \gg 1$ (slow decay) NLSP = neutralino	$c\tau(\chi^0) \sim 1 \text{ km}$, $\approx$ SUGRA, more $E_{T,\text{miss}}$ & non-pointing high- E_T γ 's	ATLAS can measure γ angle with long. EM calo layers	For 30 fb^{-1} , can exclude $C_{\text{grav}} \rightarrow 10^8$, i.e., $F_m/M_m > 10^4 \text{ GeV}$
$C_{\text{grav}} = 1$ (fast decay) NLSP = slepton	If $N_5 > 5$, NLSP RH sleptons, large X-section $\rightarrow 25 \text{ pb}$, leptons & $E_{T,\text{miss}}$	Several lepton edges, large measurement potential	Various SUSY masses (see above)
$C_{\text{grav}} \gg 1$ (slow decay) NLSP = slepton	stau NLSP, $c\tau \sim 1 \text{ km}$, new heavy quasi-stable lepton	Detect in muon system by time-of-flight (late arrival compared to μ 's)	stau and all neutralino masses

SUSY – Final Remarks...

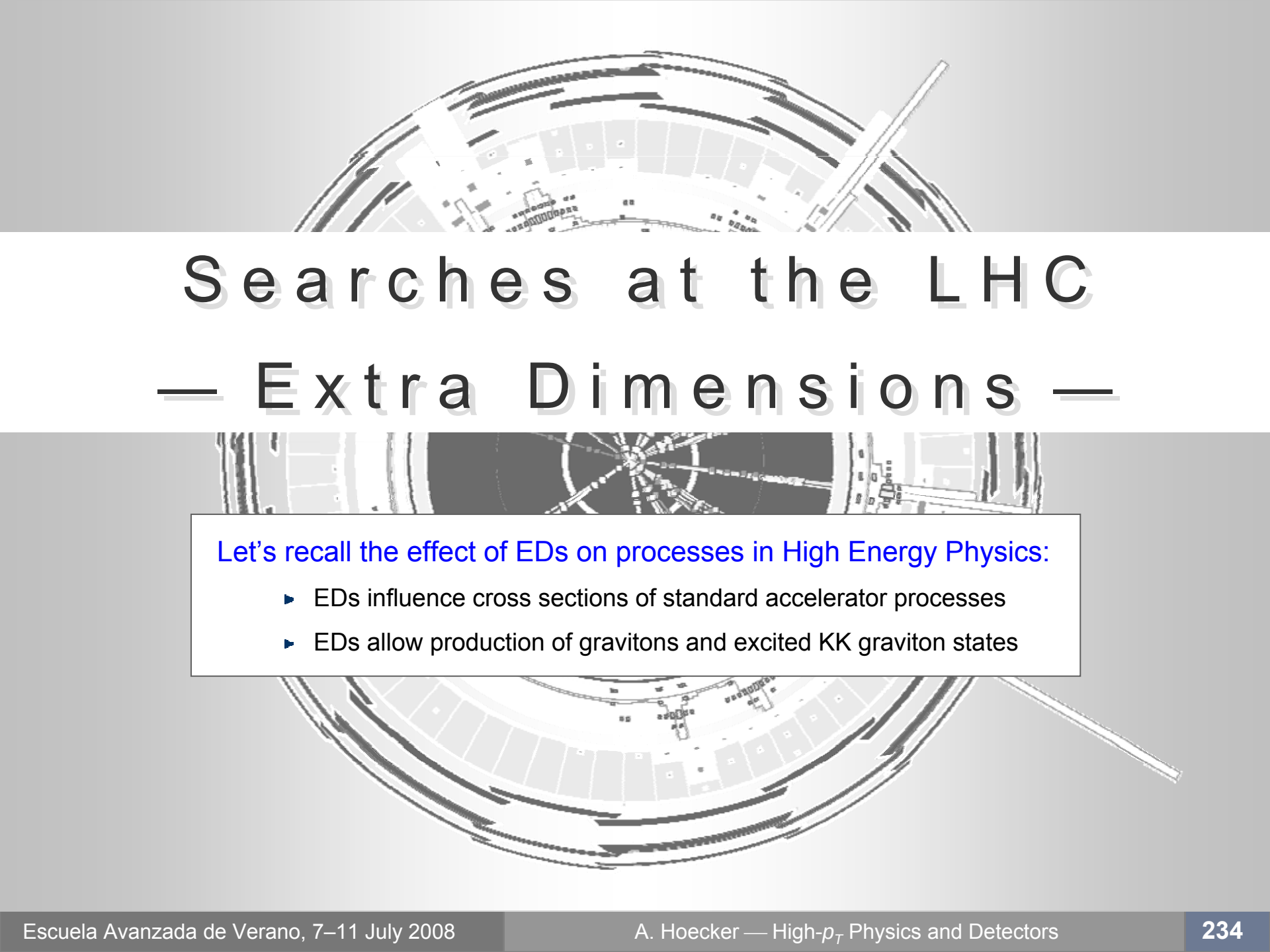
SUSY could also break R -parity

(The signature could be τ 's in final state from $\tilde{\chi}^0 \rightarrow \tilde{\tau}\tau$ decays)

Signals due to other phenomena could look like SUSY

Proceed SUSY search as model-independently as possible

Check for anomalies: γ 's, τ 's, strange t 's



Searches at the LHC — Extra Dimensions —

Let's recall the effect of EDs on processes in High Energy Physics:

- ▶ EDs influence cross sections of standard accelerator processes
- ▶ EDs allow production of gravitons and excited KK graviton states

Large Extra Dimensions (ADD)

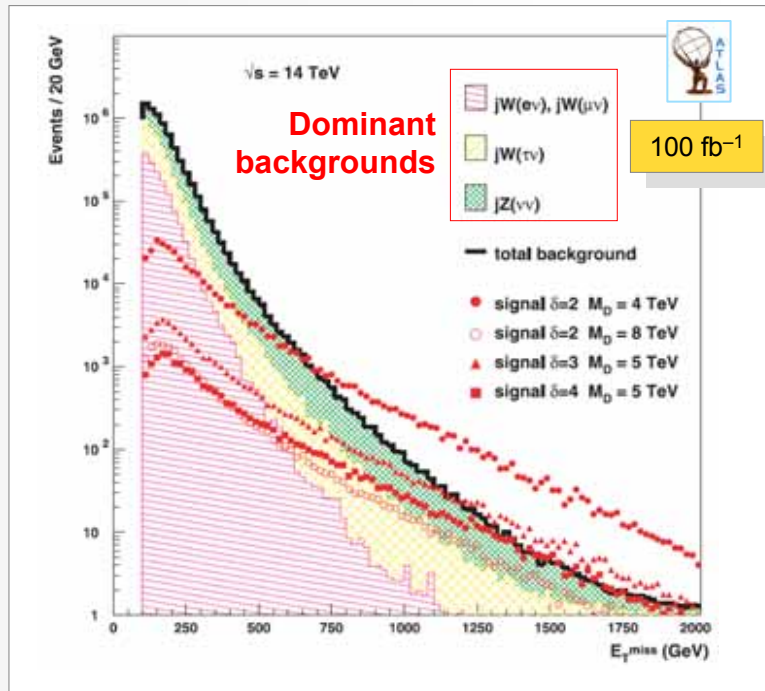
- The most direct manifestation of EDs would be the presence of **KK gravitons: G_{KK}**
- Tiny graviton coupling: $\sim 1/M_{Pl}$ compensated by large G_{KK} multiplicity: $\sim (R\sqrt{s})^d$ (in E interval $\sqrt{s}$)
- ➡ (partonic) **cross section: $\sigma \sim (\sqrt{s} / M_D^2)^d$ can be macroscopic**
- The produced **gravitons do not interact in detector**
- Signature: **mono-jet or high- $E_T \gamma + E_{T,miss}$, no lepton ($\rightarrow$ veto)**

Typical processes are:

$$q\bar{q} \rightarrow (g, \gamma) + G_{KK}$$

$$qg \rightarrow q + G_{KK}$$

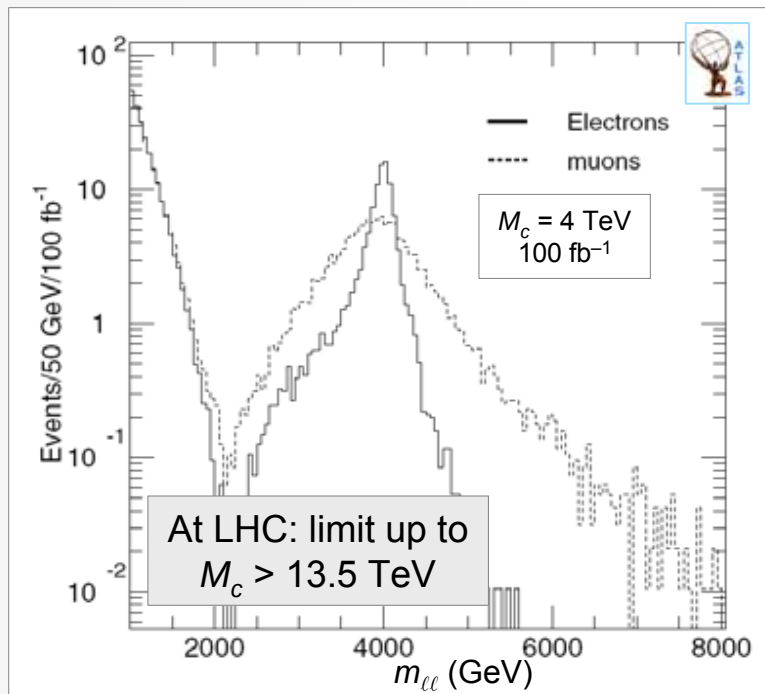
$$gg \rightarrow g + G_{KK}$$



- $E_{T,miss}$ distribution for signal for varying M_D and d , and for the dominant background
- ➡ For example: $M_D \sim 9$ (6) TeV and $d = 2$ (4) EDs yields compactification radius of $10^{-6}\mu m$;
- ➡ No sensitivity to larger scales or EDs at LHC
- ➡ In case of a discovery, it will be difficult to extract both M_D and d

Small Extra Dimensions

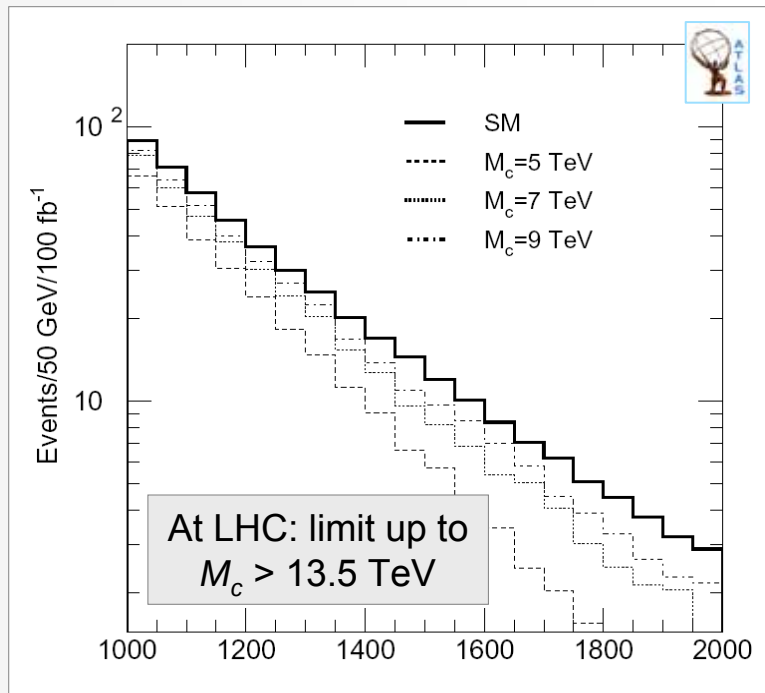
- In the previous example, the SM particles were confined within the SM brane; if gauge fields propagated into the bulk, KK excitations of γ or Z should be observed, if EDs not too small
- The characteristic size of the compact dimensions is then $R \sim 1/M_c \sim 1 \text{ TeV}^{-1}$
- The masses of the KK excitations of the gauge bosons are given by: $m_{Vn}^2 = m_V^2 + (n \cdot M_c)^2$



- The peak corresponds to the first KK excitation of Z : Z^1 (Z^1 and γ^1 are $\sim$ degenerated)
- For ATLAS: the excellent resolution of the calorimeter at high p_T , allows to measure the width of the excitation in the mode e^+e^-
- Not as good for the muons

Small Extra Dimensions

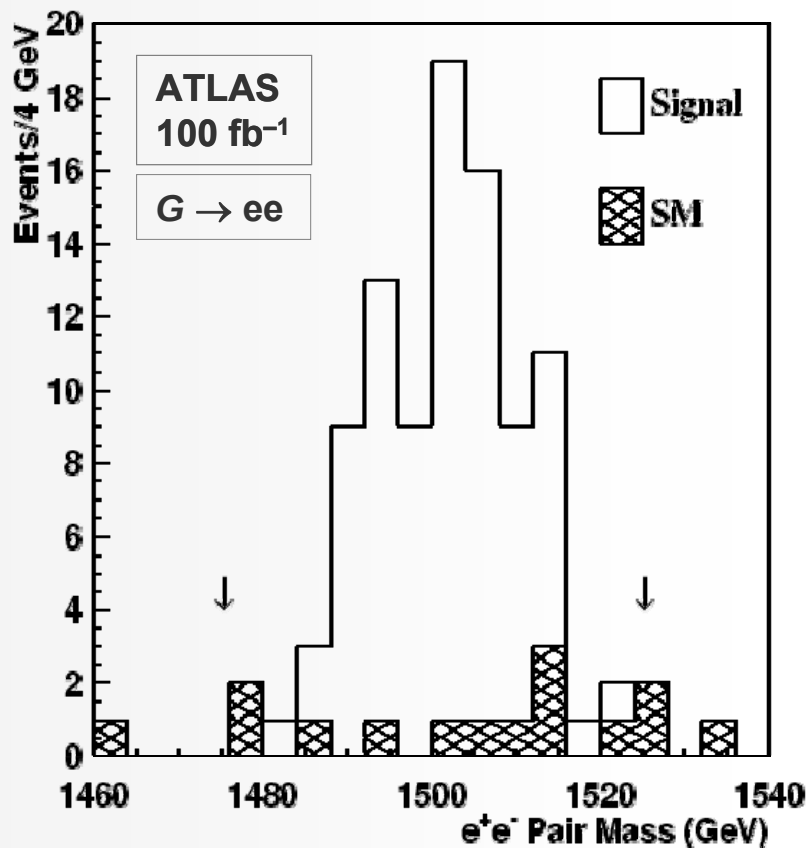
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 - Not as good for the muons
- ➔ Larger masses than 4 TeV are accessible through interference of the SM di-lepton amplitude with the KK excitations

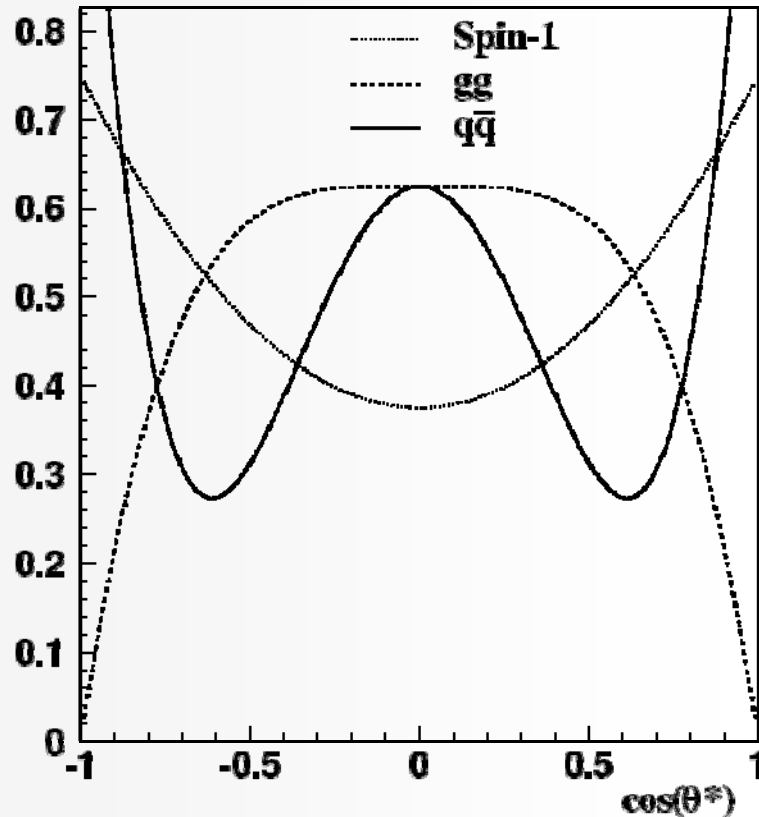
Randall-Sundrum Graviton decays to e^+e^-

- 1500 TeV G_{KK} resonance over small Drell-Yan SM background



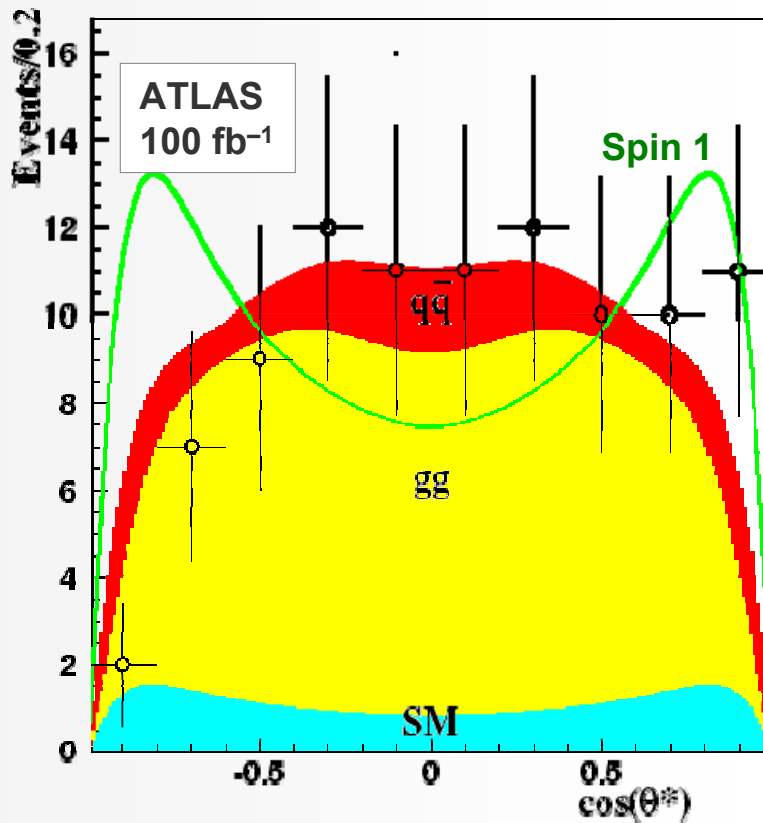
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- Angular distribution of e^+ in G_{KK} rest frame sensitive to G_{KK} spin and production



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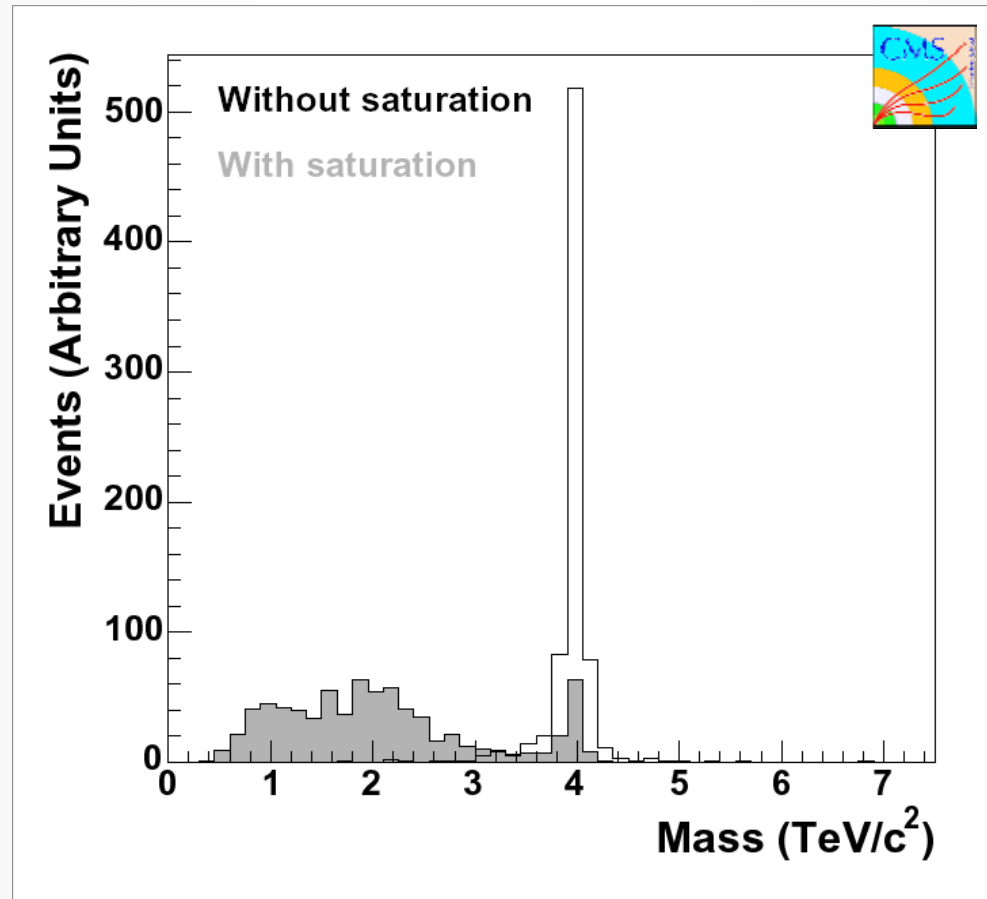


- G_{KK} production dominantly via gluon fusion
- Acceptance discards events at $|\cos\theta^*| \rightarrow 1$

Randall-Sundrum Graviton decays to e^+e^- (II)

- At very high p_T , di-electrons have better intrinsic mass resolution than di-muons
- However: the EM calorimeters suffers from saturation of dynamic range (CMS > ATLAS)

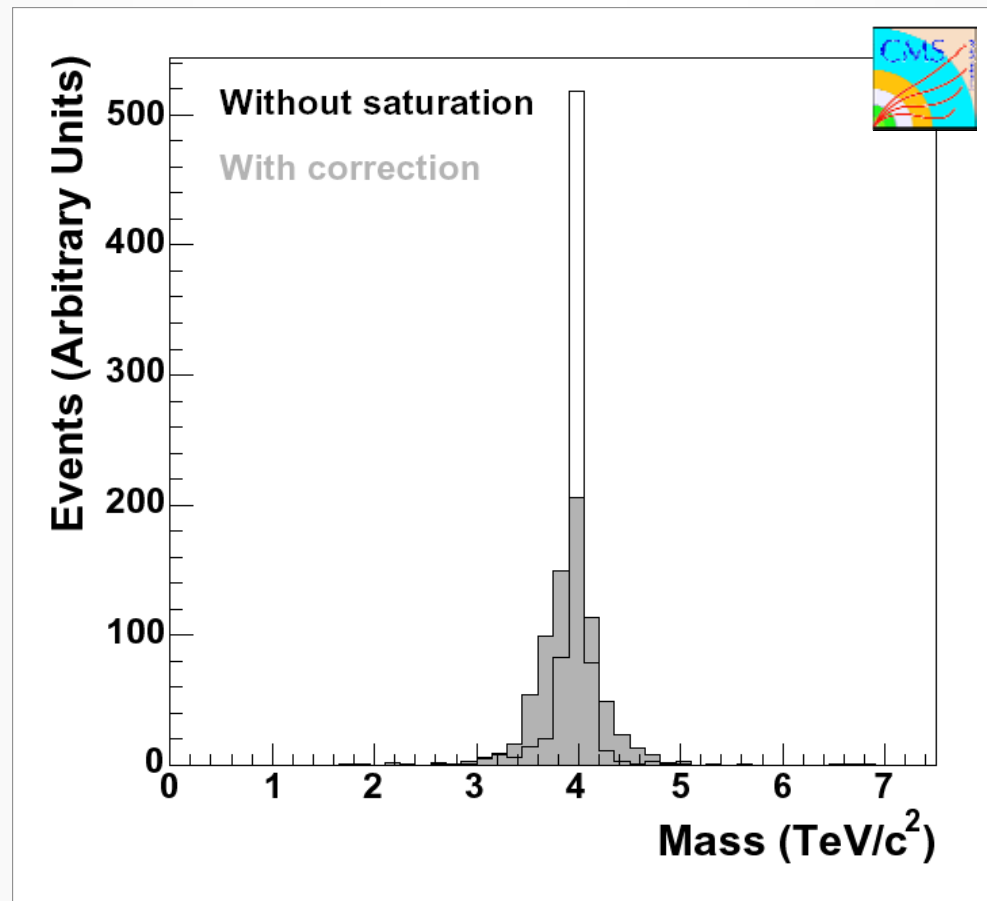
Note: width of KK gravitons smaller than experimental resolution



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Randall-Sundrum Graviton Exploration

- Once discovered, verify that the coupling of G_{KK} is universal
 - ➡ Measure branching fractions of $G_{KK} \rightarrow ee, \mu\mu, jj, bb, WW, ZZ$
 - ➡ Use angular distributions to separate gg from qq couplings
 - Estimate model parameters r_c and k from G_{KK} mass and $\sigma \times \text{BR}$
 - In our example of $m(G_{KK}) = 1.5 \text{ TeV}$, measure mass to $O(1 \text{ GeV})$ precision, and $\sigma \times \text{BR}$ to 14% from ee channel alone (stat. limited)
- ➡ With this measure:

Recall warp factor:

$$e^{-kr_c\pi}$$

$$\left. \begin{aligned} r_c &= (8.2 \pm 0.6) \cdot 10^{-32} \text{ m} \\ k &= (2.4 \pm 0.2) \cdot 10^{16} \text{ GeV} \end{aligned} \right\} kr_c = (9.8 \pm 1.1)$$

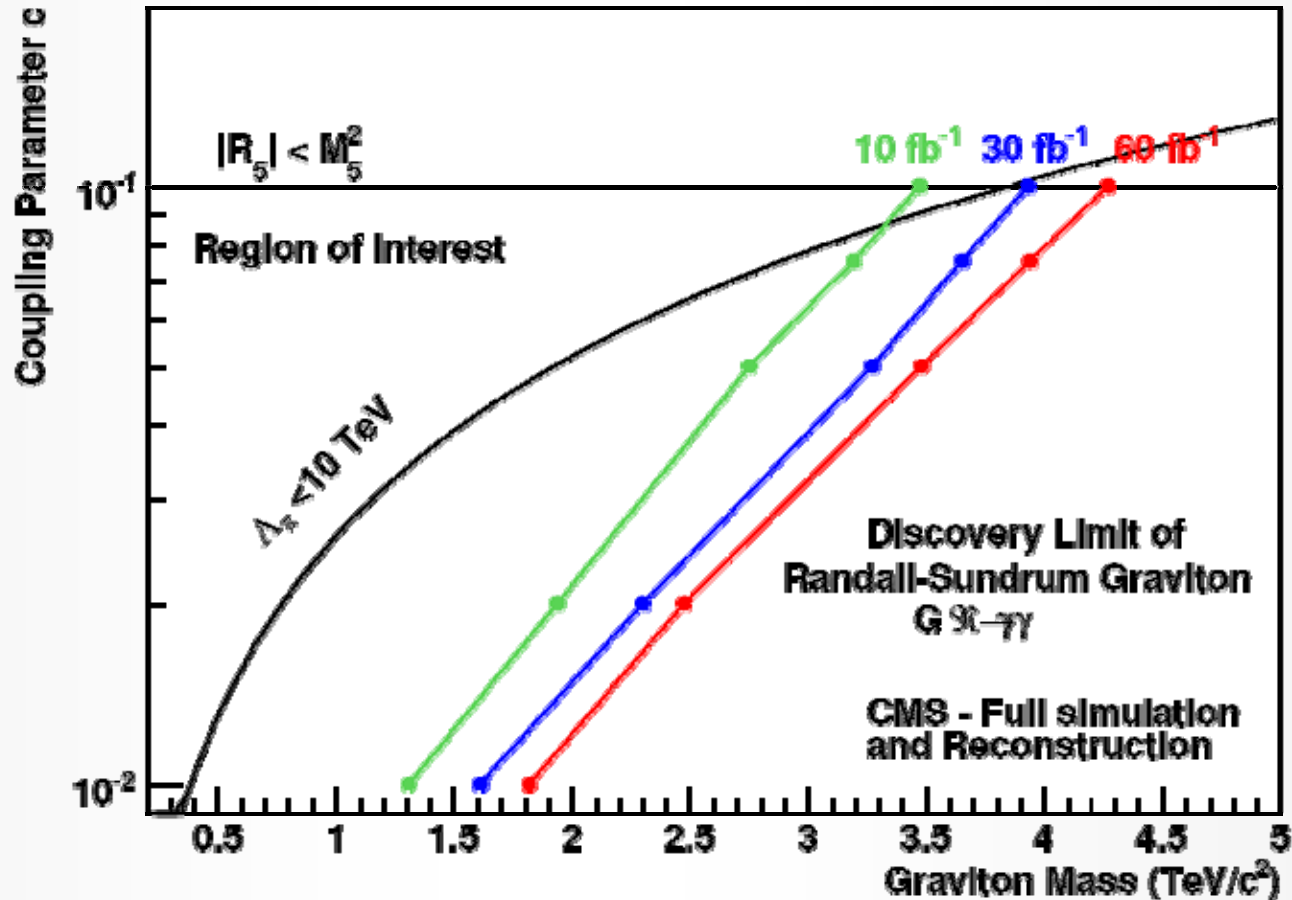
Randall-Sundrum Graviton Search Reach

Discovery Limit of Randall-Sundrum Graviton: $G \mathcal{R} \rightarrow \gamma\gamma$

$$c = k / M_{\text{Pl}}$$

Recall: k is curvature of AdS_5 space

Note: theory only valid for $c < 0.1$ and only useful to solve hierarchy problem for $\Lambda_\pi = M_{\text{Pl}} \exp(-k r_c \pi) = M_G / (3.8 \cdot c) \sim 10 \text{ TeV}$



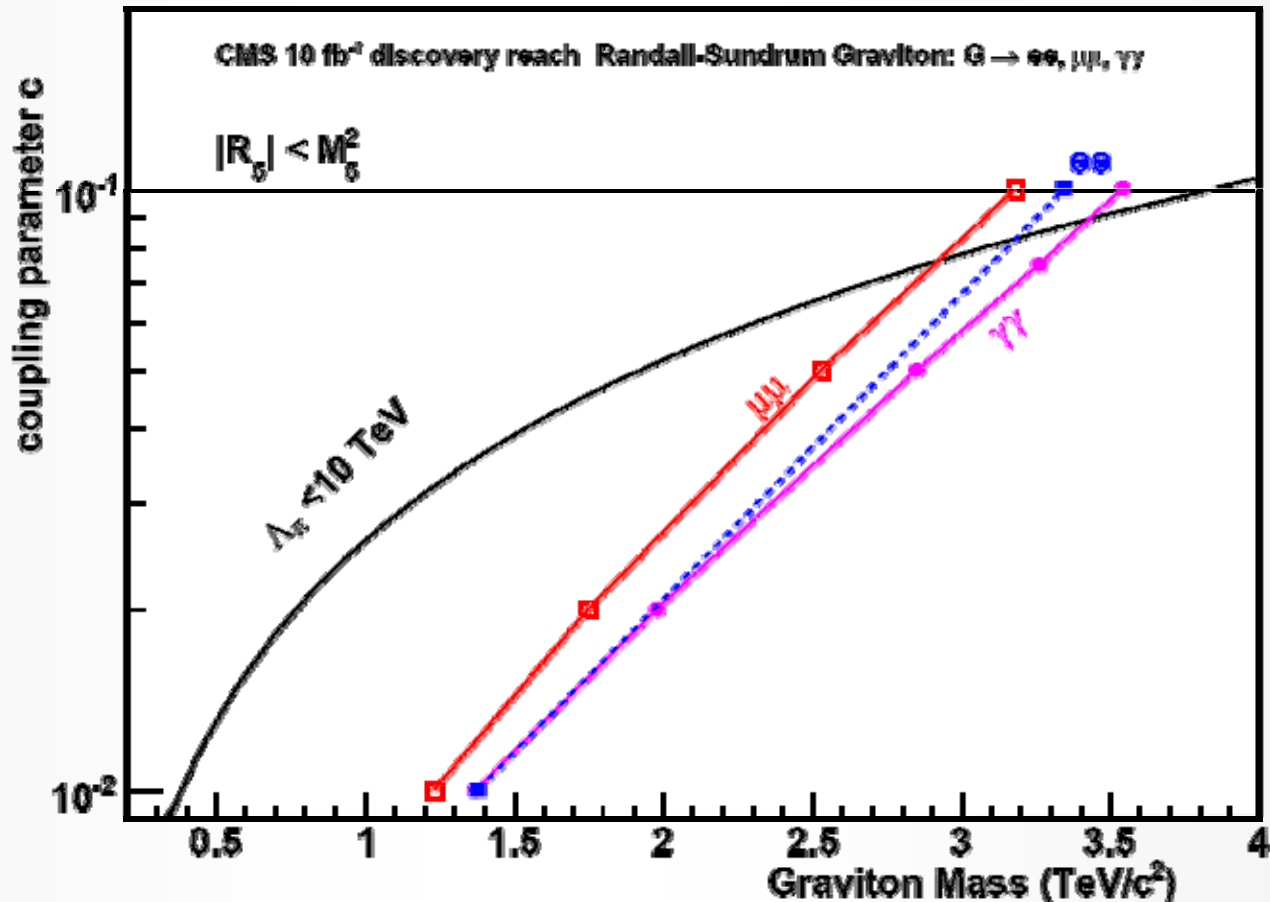
All of the interesting parameter space for 1 ED can be probed with 30 fb⁻¹

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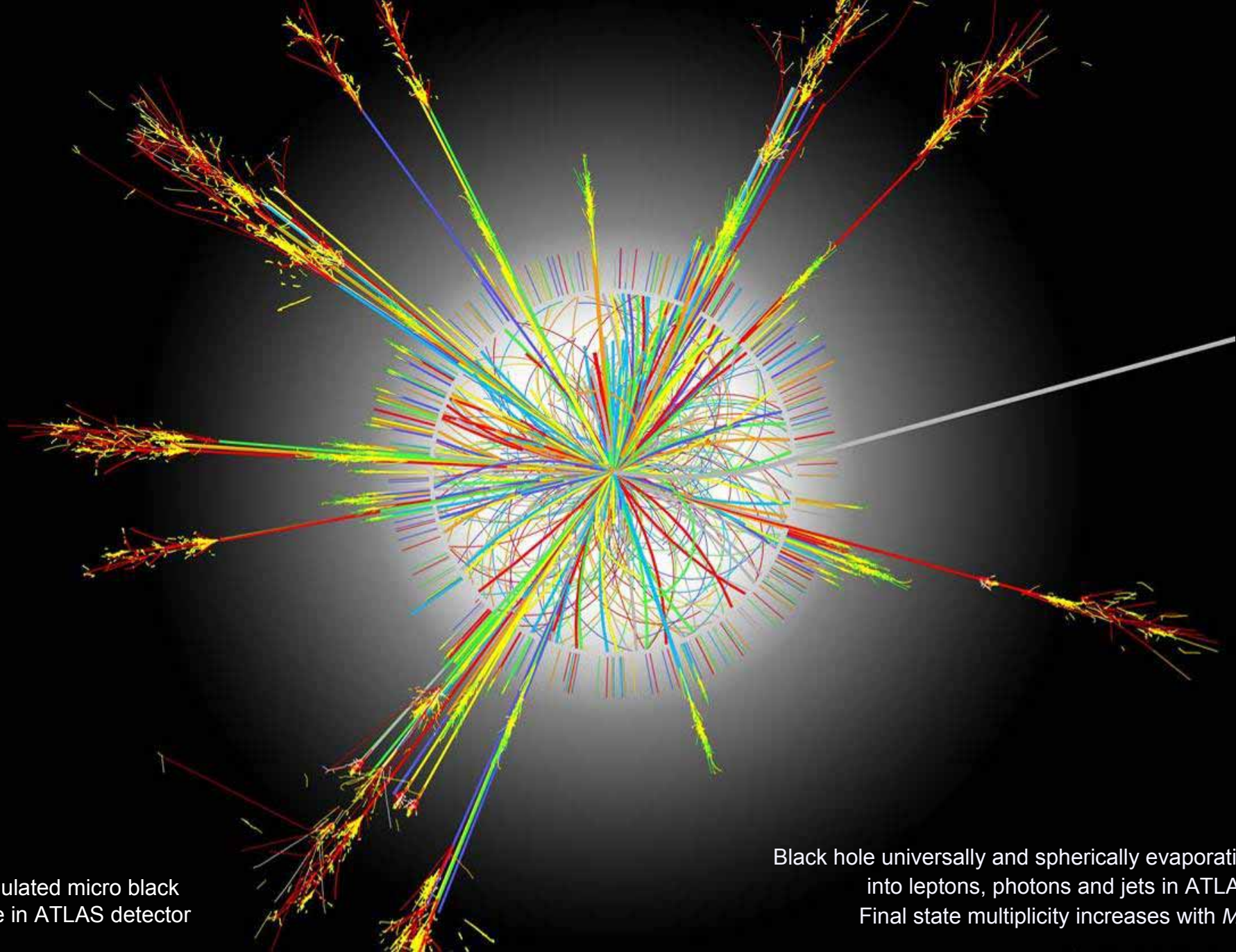
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All of the interesting parameter space for 1 ED can be probed with 30 fb⁻¹

But ... if we are allowed to enter Trans-Planck scales, that is, Gravity in extra dimensions is strong, we may produce **Black Holes**

Artist's portrayal of the IC 10 X-1 system: the black hole lies at the upper left and its companion star is on the right

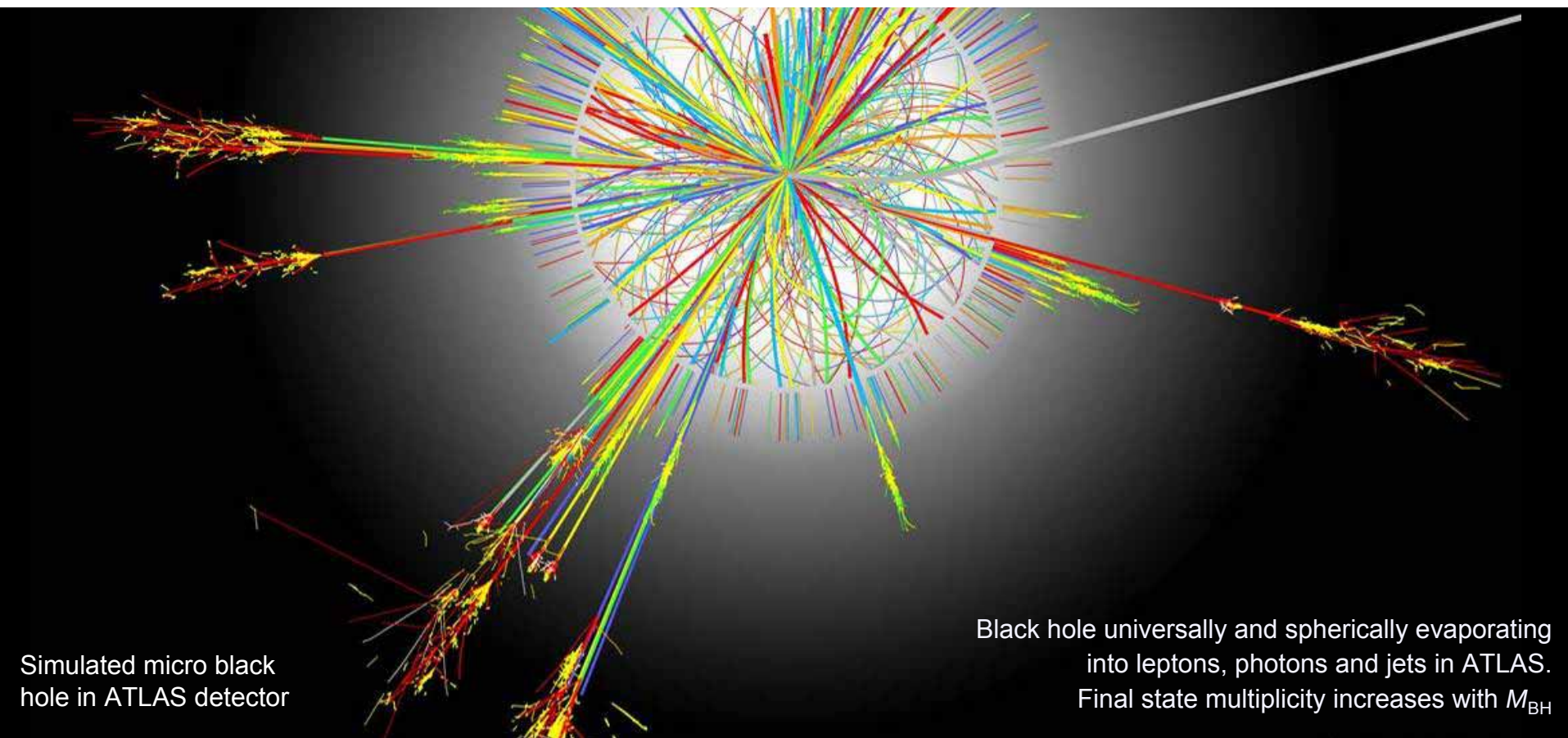


Simulated micro black
hole in ATLAS detector

Black hole universally and spherically evaporating
into leptons, photons and jets in ATLAS.
Final state multiplicity increases with M_{BH}

Strong gravity in extra dimensions could allow black hole production at the LHC

- An object becomes a black hole if it is smaller than Schwarzschild radius: $r = 2GM/c^2$
- In extra $4+d$ dimensions: $r = 2G^{(4+d)} M_D / c^2$
- Cross section: $\sigma_{\text{BH}} \sim \pi r^2$
- With $M_D \sim 2\text{--}3 \text{ TeV} \rightarrow \sigma_{\text{BH}} \sim \text{O}(\text{pb}) \rightarrow$ fast discovery for $M_{\text{BH}} < 4 \text{ TeV}$, $d = 2\text{--}6$
- Fast ($\tau \sim 10^{-27} \text{ s}$) thermal decay via Hawking radiation, $T_H \sim M_D \cdot (M_D/M_{\text{BH}})^{1/(d+1)}$
- Speed of growth: 10 microgram mass in 1 billion years !

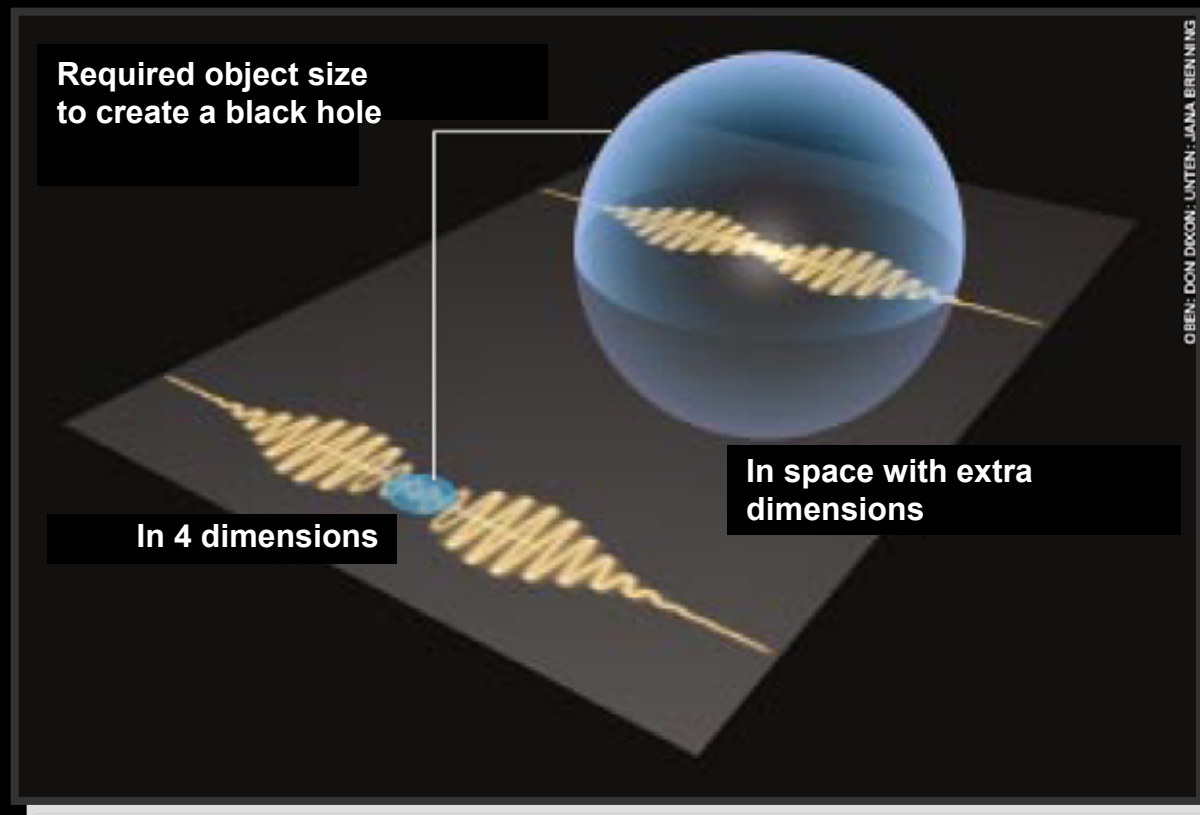


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Life Cycle of a 10 TeV Micro Black Hole

Source: Spektrum der Wissenschaft
Sep 2005

Creation



Mass: 10 TeV

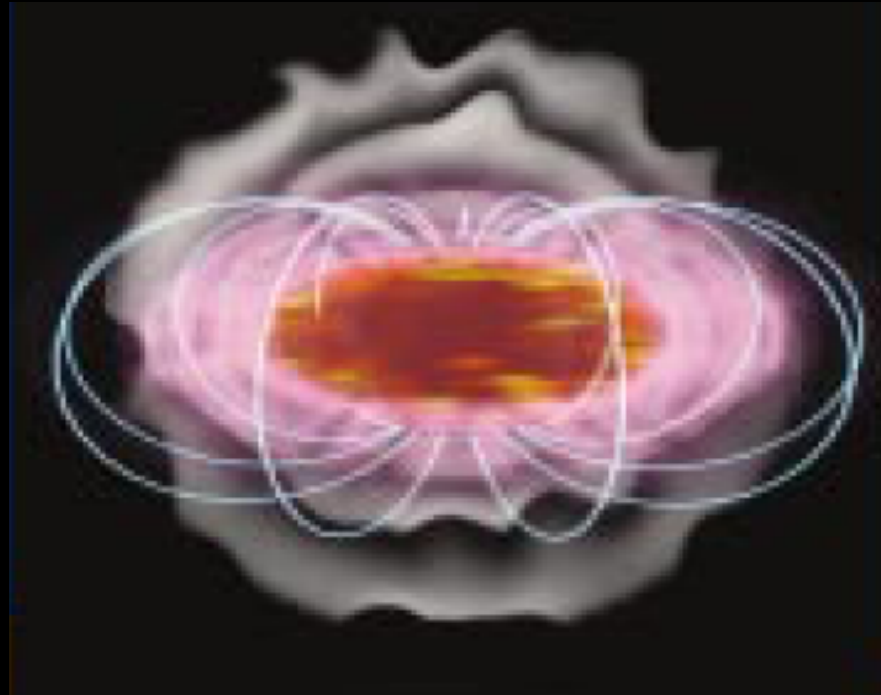
Time: 0 s

The micro black hole is created in a pp collision: it is asymmetric, may vibrate and rotate, and may be electrically charged

Life Cycle of a 10 TeV Micro Black Hole

Source: Spektrum der Wissenschaft
Sep 2005

“Baldness phase”



Mass: 10^{-8} TeV

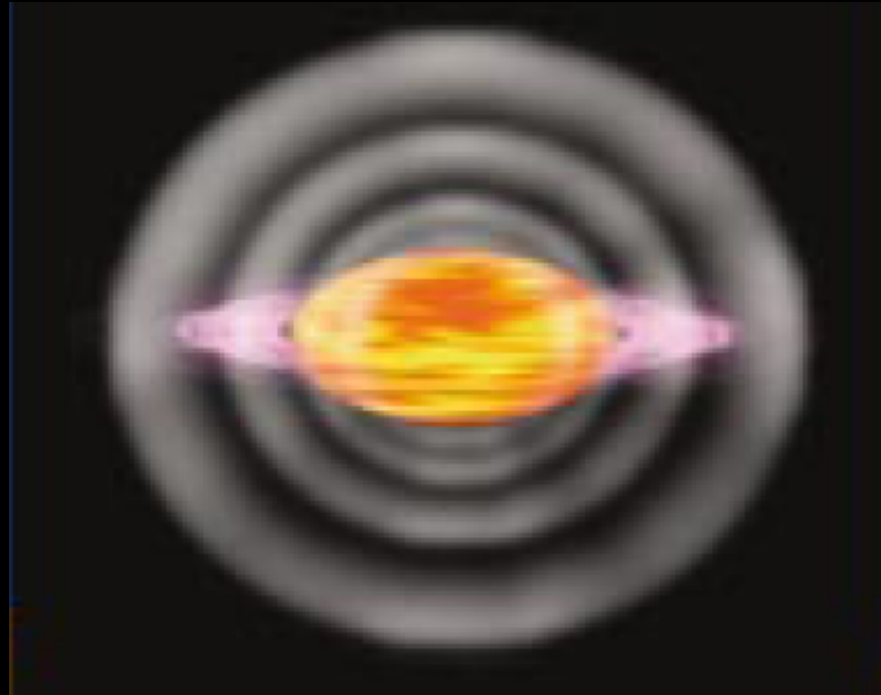
Time: $0 - 1 \times 10^{-27}$ s

Emission of gravitational and electromagnetic waves, and charged particles. The black hole is solely characterised by mass and angular momentum

Life Cycle of a 10 TeV Micro Black Hole

Source: Spektrum der Wissenschaft
Sep 2005

Slowing down



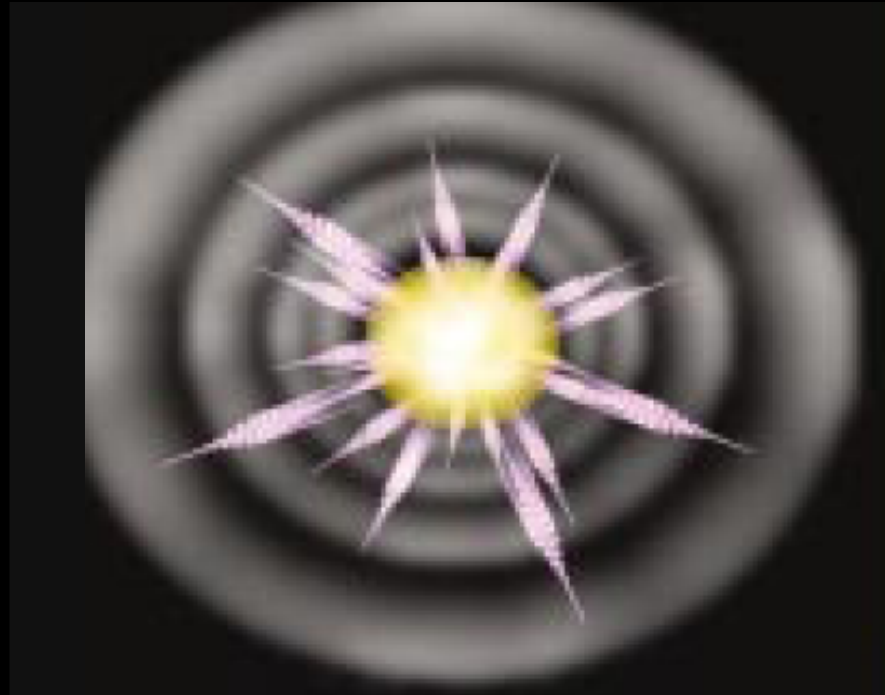
Mass: $8 - 6 \text{ TeV}$

Time: $1 - 3 \times 10^{-27} \text{ s}$

**The black hole is not black but radiates by reducing its angular momentum.
Its form becomes spherical.**

Life Cycle of a 10 TeV Micro Black Hole

Schwarzschild phase



Mass: 6 – 2 TeV

Time: 3 – 20×10^{-27} s

Source: Spektrum der Wissenschaft
Sep 2005

After loosing its angular momentum, the micro black hole evaporates its mass via Hawking radiation.

Life Cycle of a 10 TeV Micro Black Hole

Planck phase

Source: Spektrum der Wissenschaft
Sep 2005

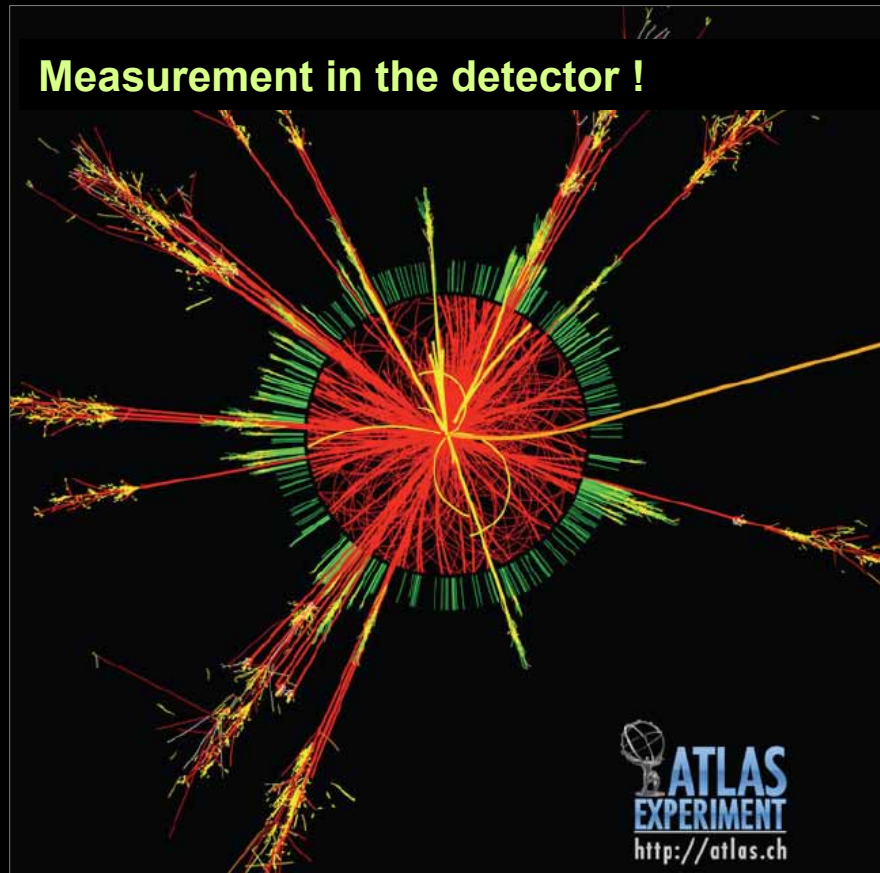


Mass: $2 - 0$ TeV

Time: $20 - 22 \times 10^{-27}$ s

The black hole shrinks down to the Planck mass (M_D) and fully decays into all particles with probabilities according to their degrees of freedom.

Life Cycle of a 10 TeV Micro Black Hole

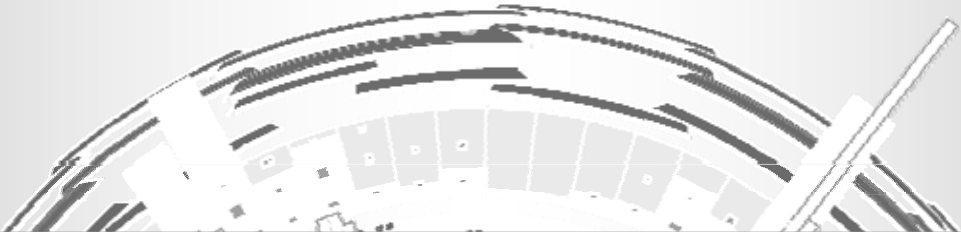


Source: Spektrum der Wissenschaft
Sep 2005

Life Cycle of a 10 TeV Micro Black Hole

It may be possible to determine from the observed final state energy spectrum and the BH cross section the characteristic Hawking temperature T_H of the BH. T_H can then be related to the mass of the BH and finally to the number of EDs.

Conclusions ...



A **large number of interesting SM extensions** has been proposed of which only a few have been mentioned in this short lecture. Among those left out are:

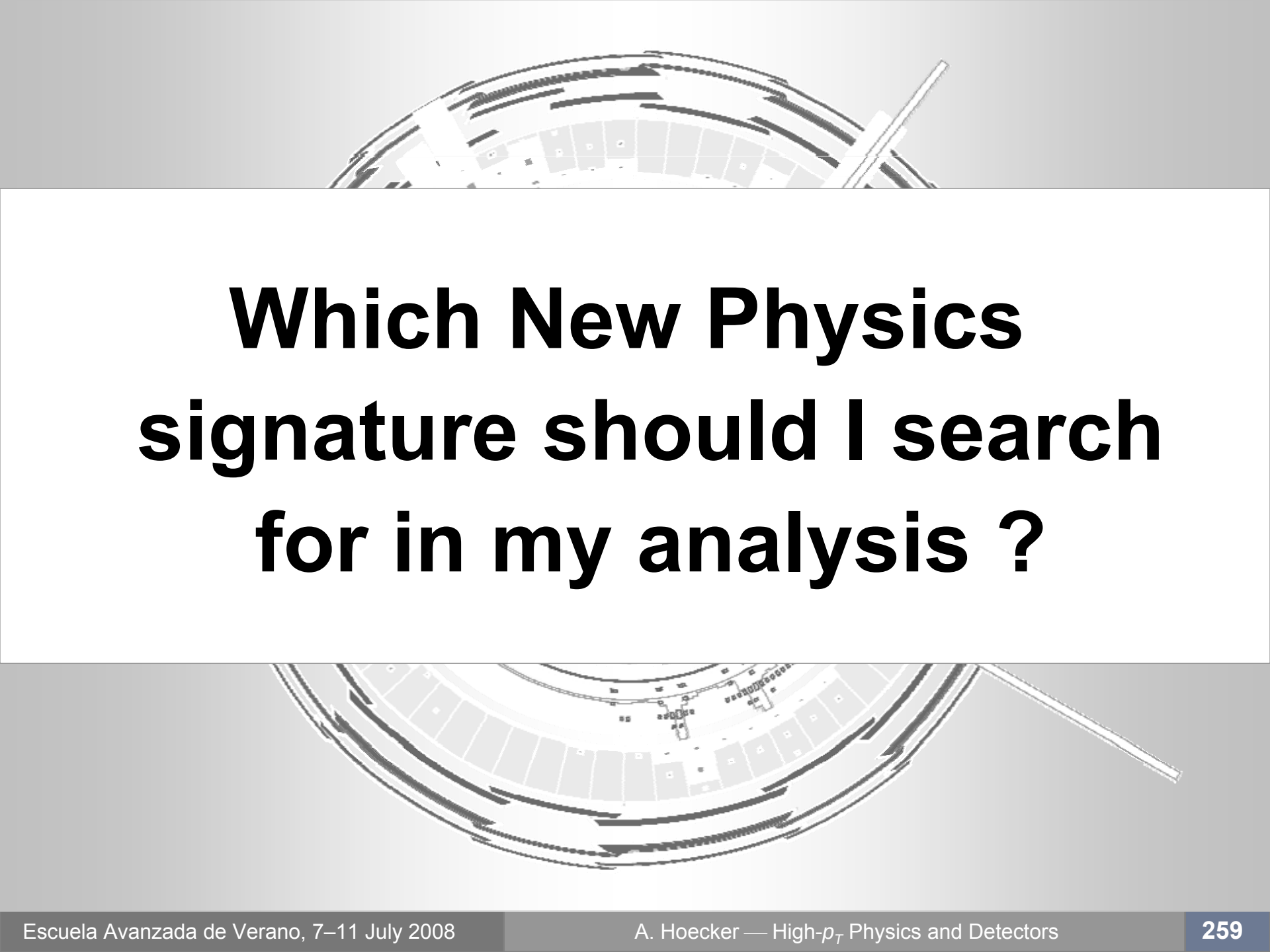
Next-to-MSSM extension:

- ▶ Additional singlet solving the m_h problem (however, may sacrifice unification of gauge couplings)
- ▶ Extends Higgs sector by CP -even and odd fields, drastically changing Higgs phenomenology

Generic Z' and other heavy resonances:

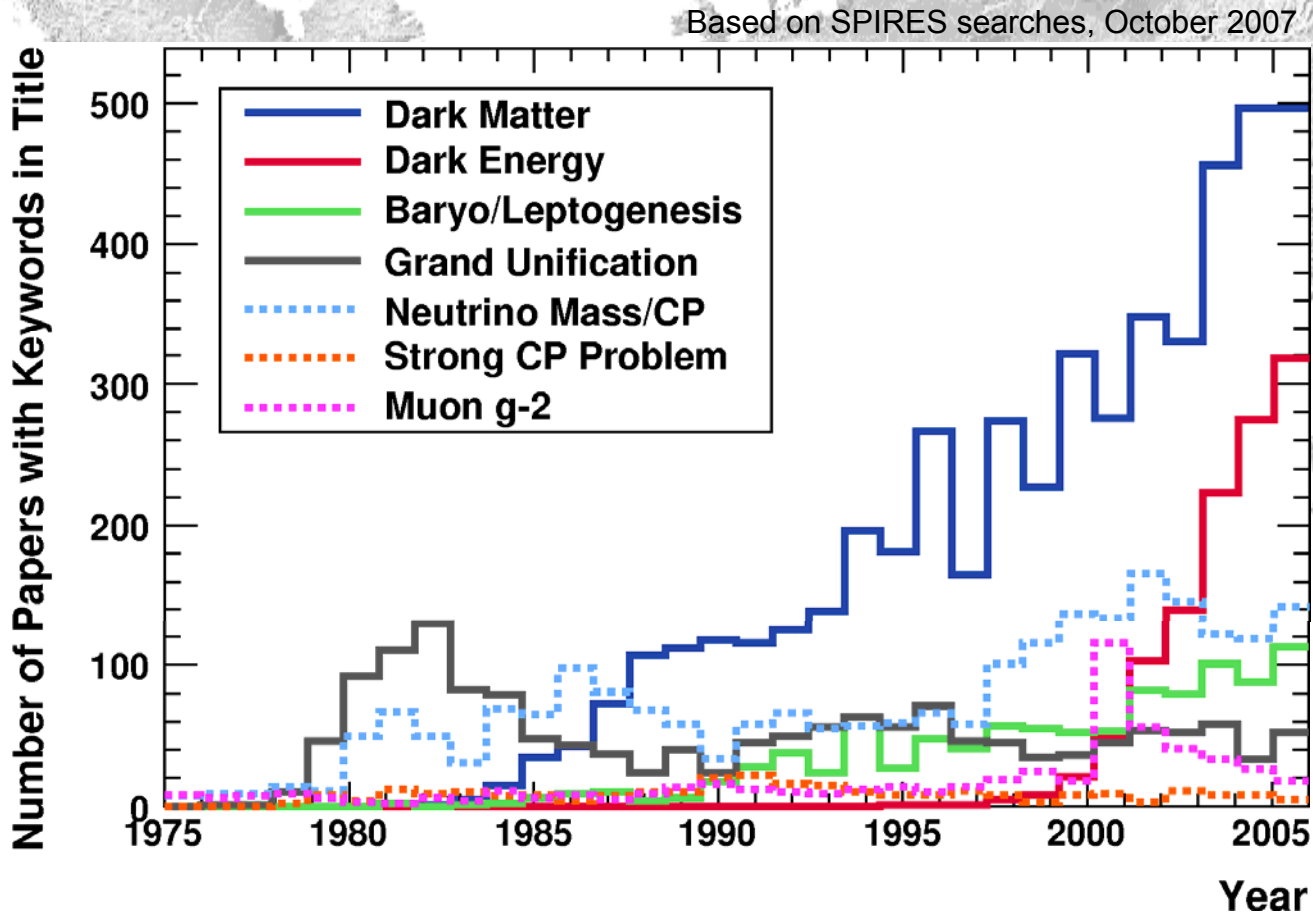
- ▶ Occur, e.g., in GUT models
- ▶ Signature is heavy di-lepton invariant mass peaks

Many more: Technicolor, (Higgs) Compositeness & Contact interactions, Leptoquarks, ...



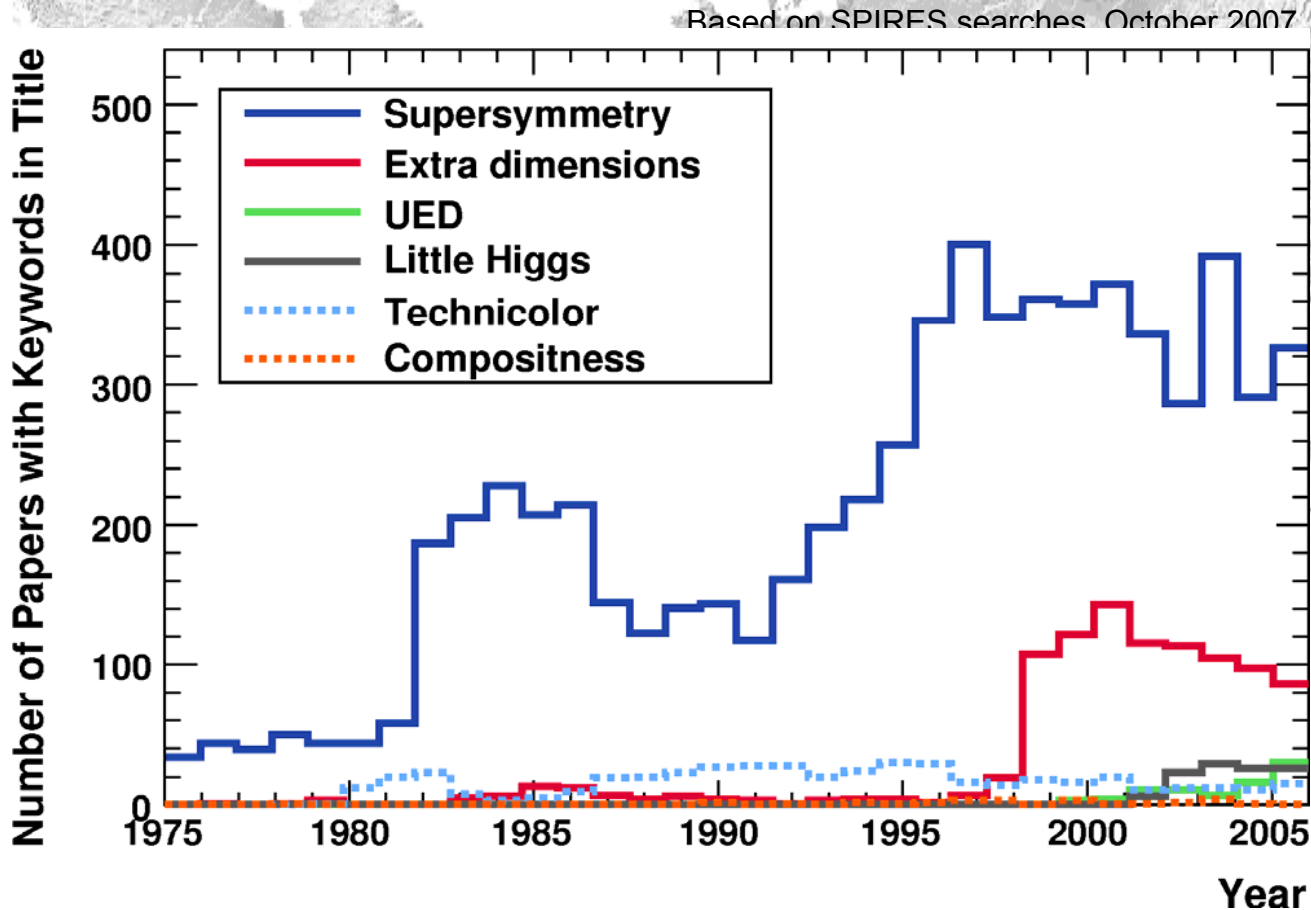
Which New Physics signature should I search for in my analysis ?

What SPIRES Finds Important



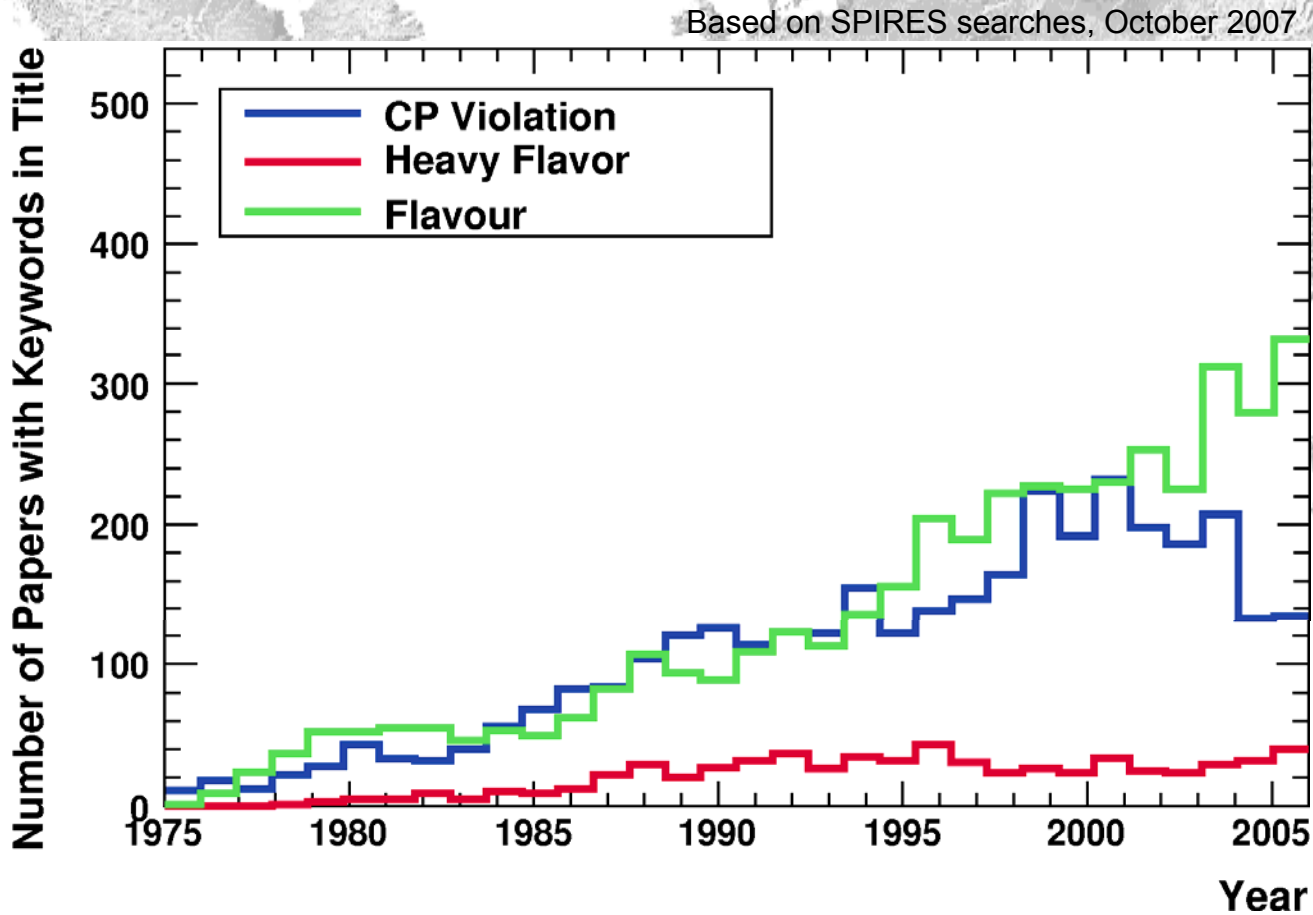
Disclaimer: keywords based on paper titles, not including abstract or text; also: keywds. not necessarily fully representative for a topic

What SPIRES Finds Important

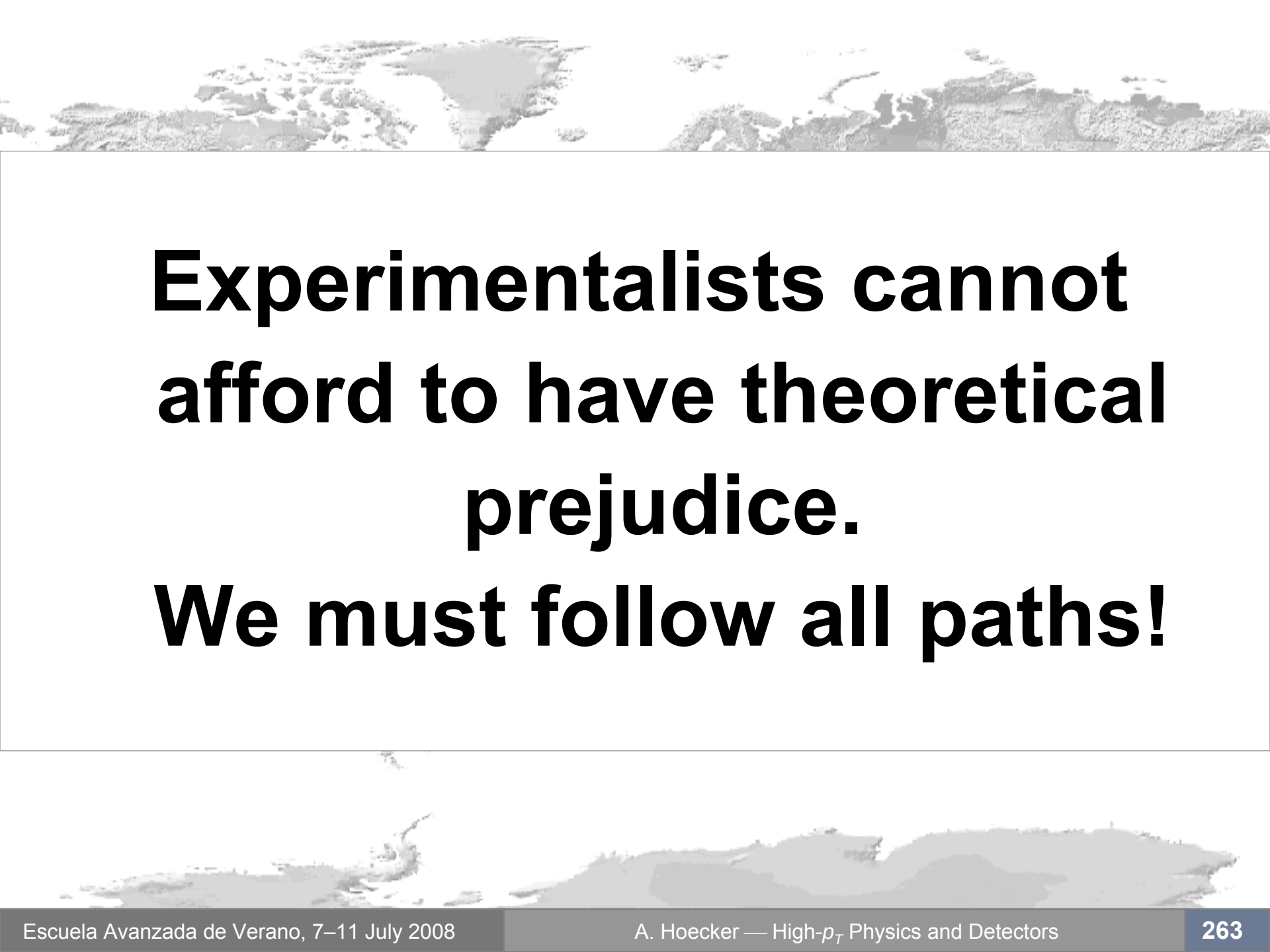


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**Experimentalists cannot
afford to have theoretical
prejudice.**

We must follow all paths!

**Most new-physics signatures
are ambiguous**

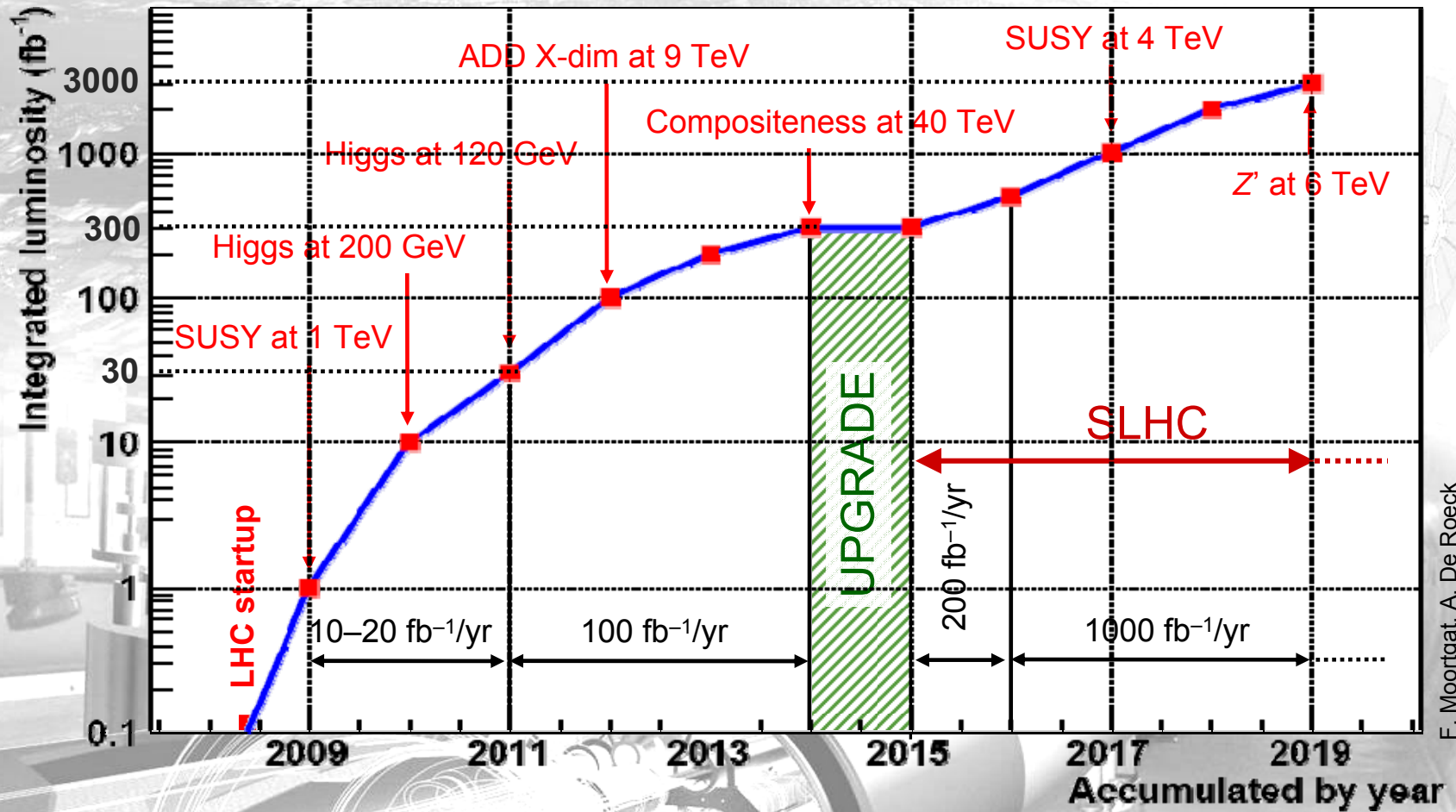
**Only the combination of
observations and precision
measurements can guide us
to the fundamental theory**





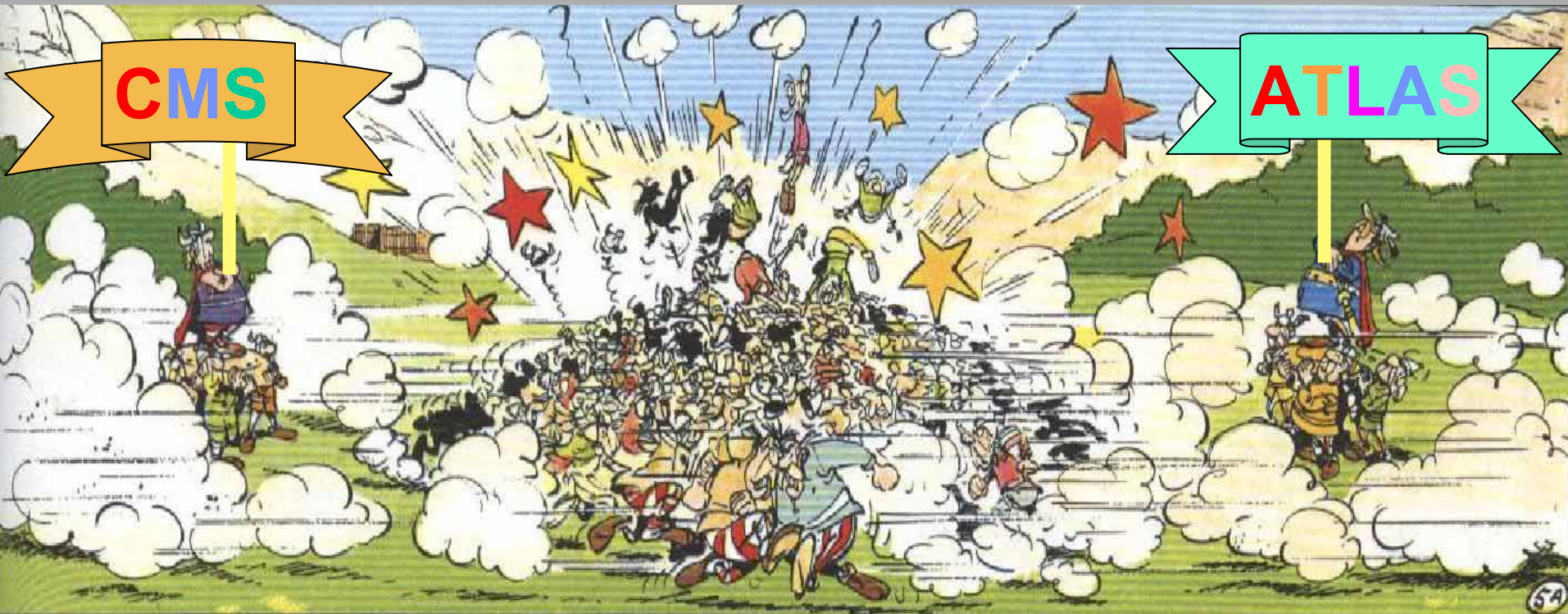
Outlook to the Future

The LHC Programme in a Nutshell



F. Moortgat, A. De Roeck

Let the data in !



Source: Fido Dittus, CERN

Recent V.I.P. Visits at ATLAS



Peter Higgs



Michelle Bachelet



Angela Merkel



Lisa Randall

Stephen Hawking



George Smoot

Gerard t'Hooft



Angela Merkel



Simon van der Meer



Tsung Dao Lee