



ATLAS and the Large Hadron Collider

The New High-Energy Frontier

Andreas Hoecker, CERN

Colloquium, Regensburg University, June 9, 2008



Colloquium Themes

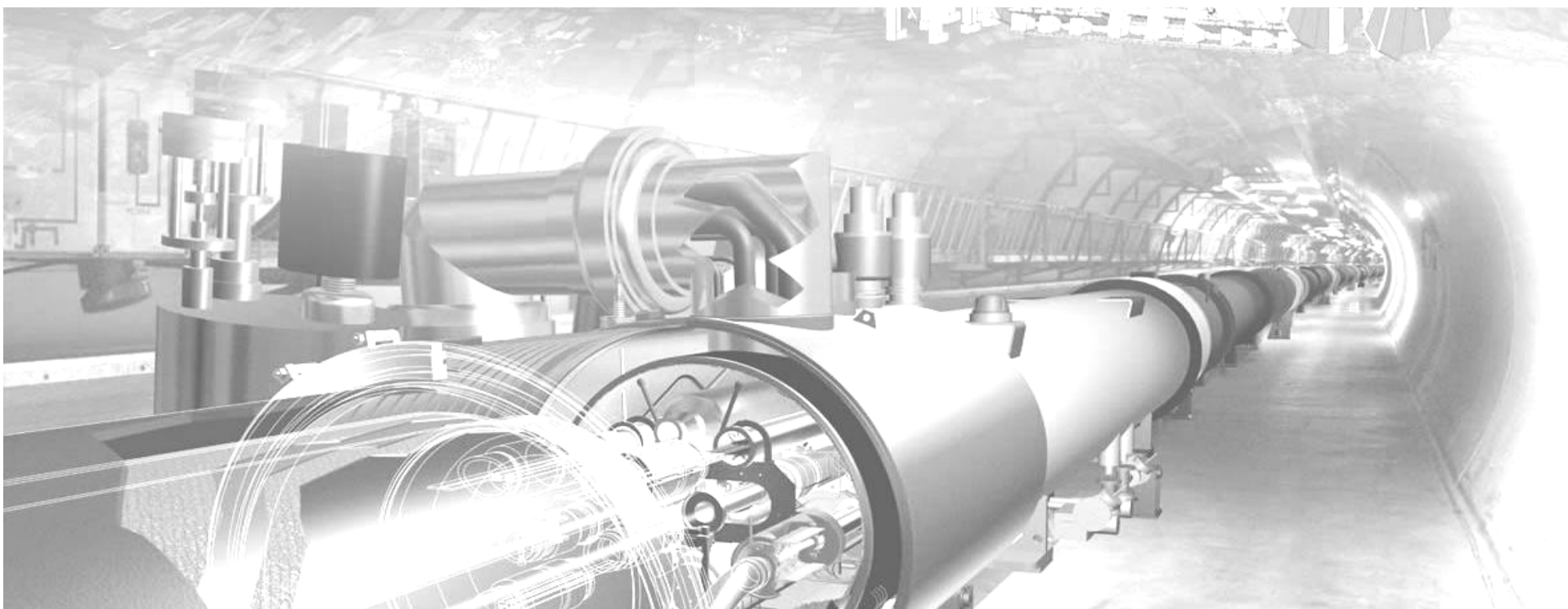
- I. ~~ATLAS Movie (Episode 2 – The particles strike back)~~
- II. Setting the Stage ... Motivation for a Huge Machine
 -  Is the Standard Model the end ?
 -  New Physics ?
- III. CERN and the Large Hadron Collider (LHC)
- IV. The ATLAS Experiment
 -  Detector challenges and concept
 -  Specific systems
- V. Outlook



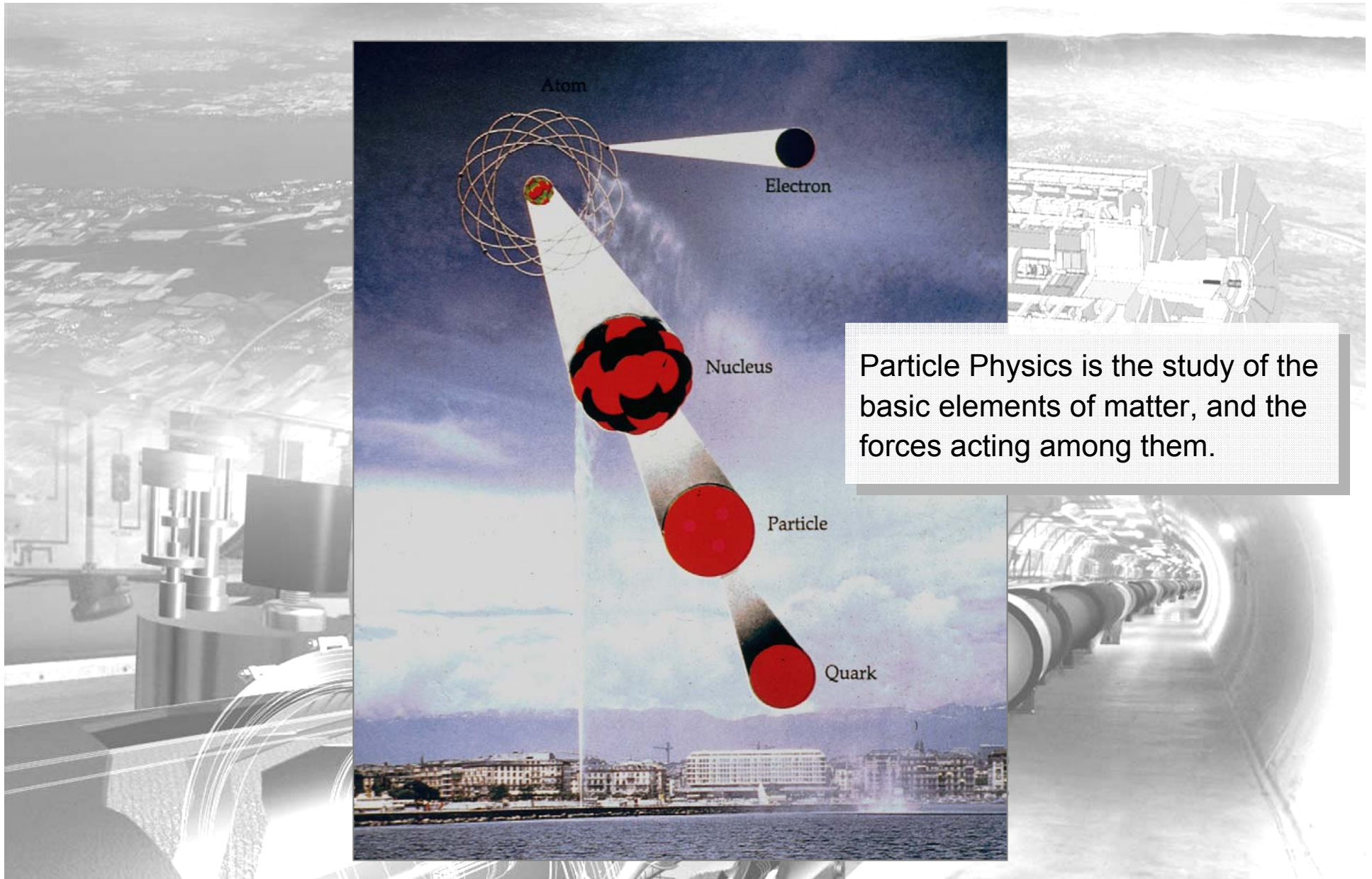
Yin–Yang talk: some parts
are easy, some are less...
Check the traffic light!



Setting the Stage



A Postcard from Geneva



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

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

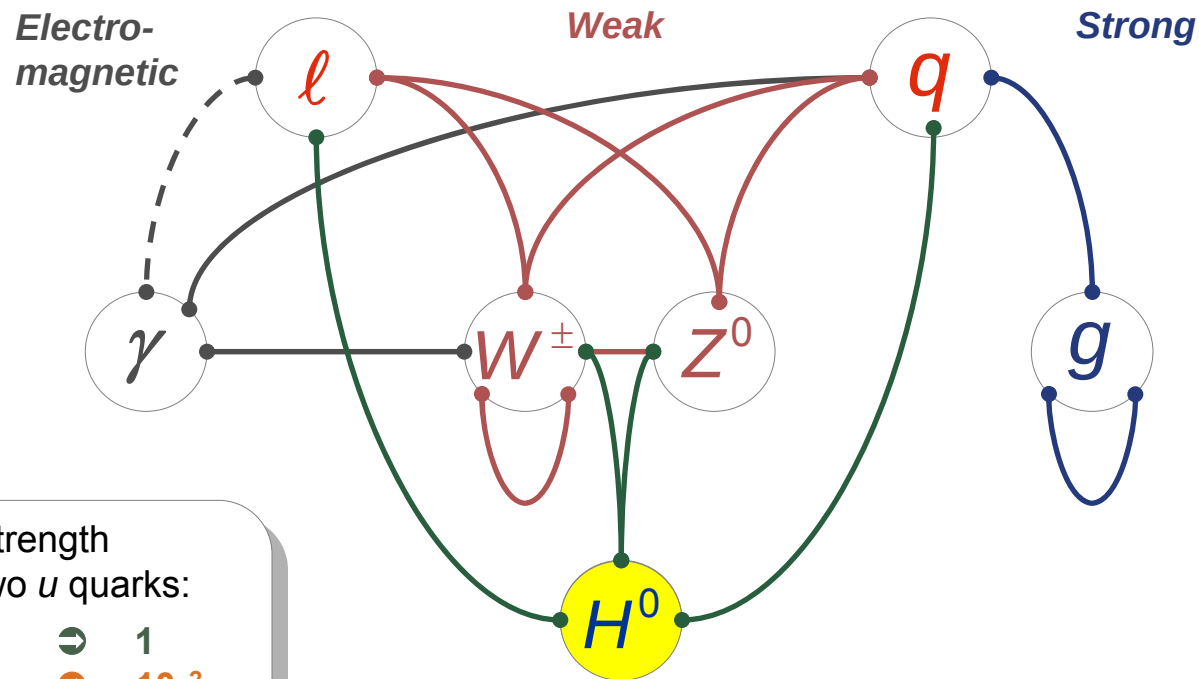


*Breaks electro-weak unification
Generates particle masses*

The Standard Model (SM)

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

Interactions



Coupling strength
between two u quarks:

Strong	$\Rightarrow$	1
EM	$\Rightarrow$	10^{-2}
Weak	$\Rightarrow$	10^{-6}
Gravitation	$\Rightarrow$	10^{-43}

The Standard Model (SM)

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

Interactions

Electro-
magnetic

l

Weak

q

Strong

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

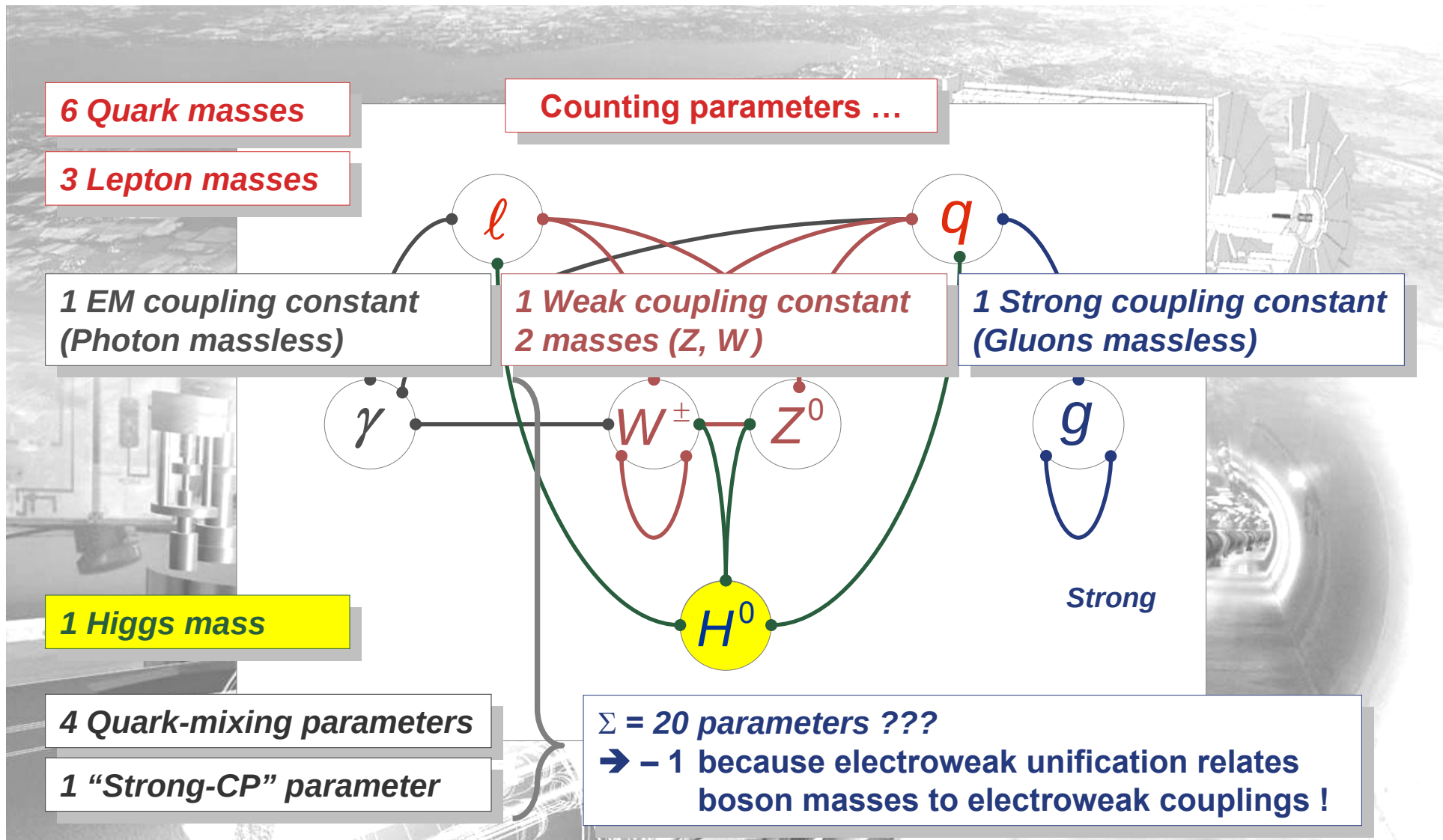
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H^0

The Standard Model (SM)

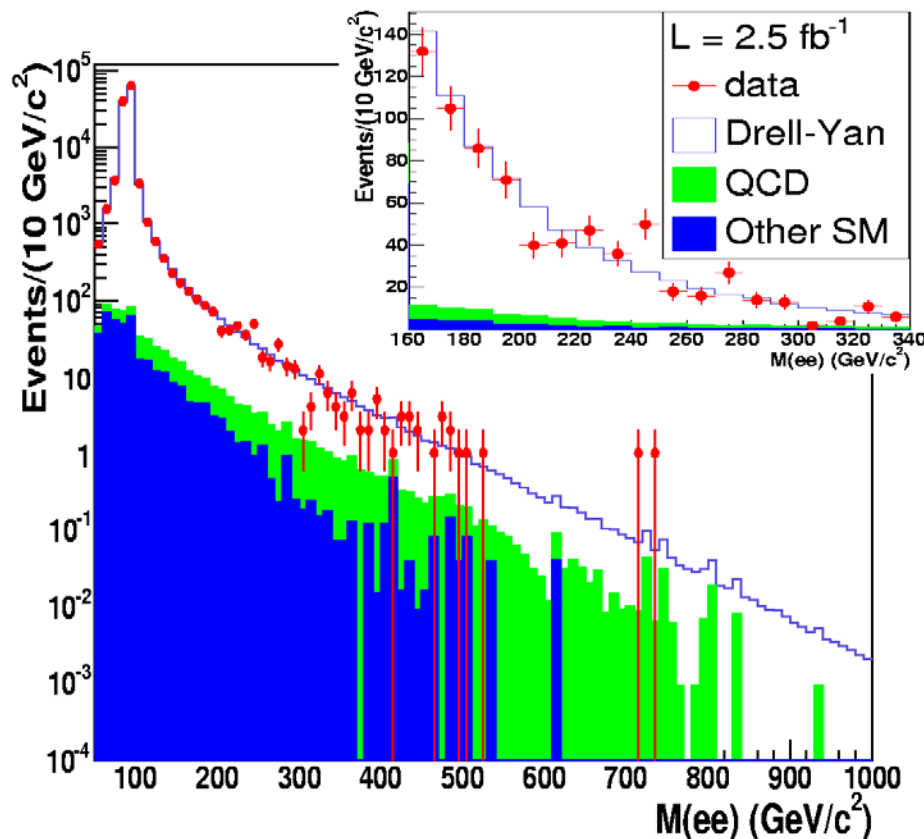
It has only 19 parameters ! (neglecting neutrino masses, which are of course of crucial importance)



The Standard Model (SM)

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

CDF Run II Preliminary

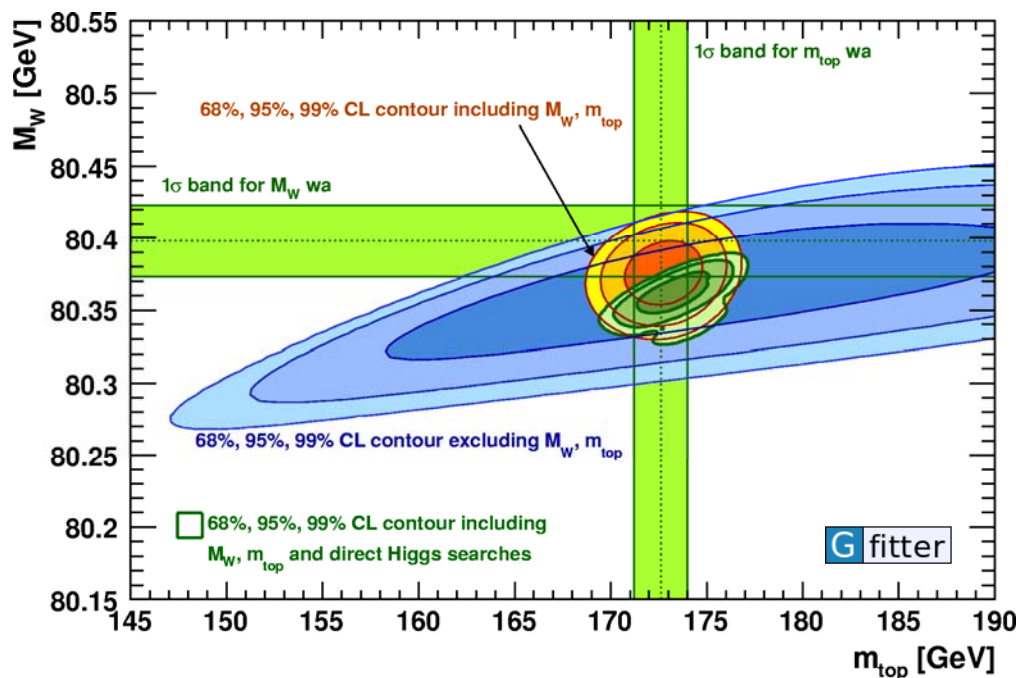


Cross sections of hadron and lepton-pair production have been verified up to $O(1 \text{ TeV})$

The Standard Model (SM)

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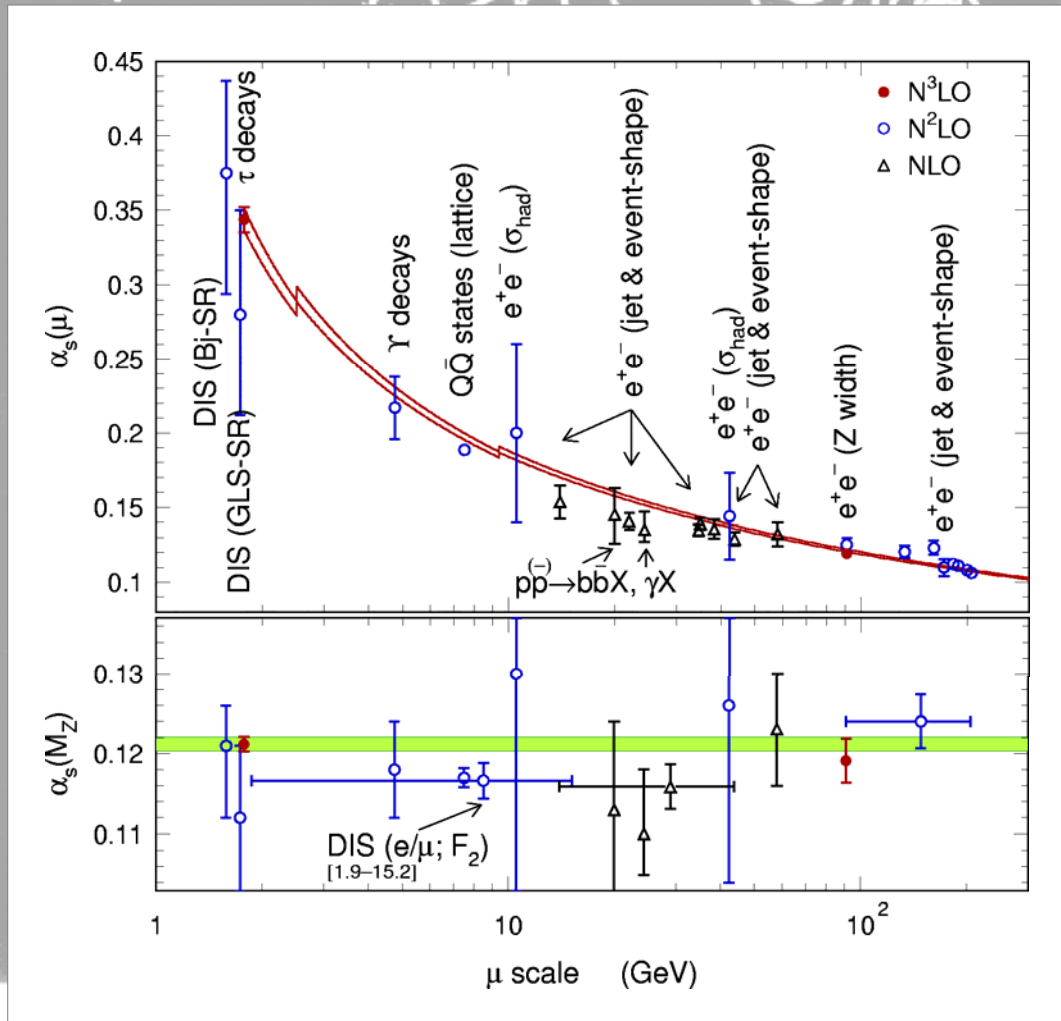
SM predicts top mass through virtual “loop” effects



Electromagnetic and weak unification at the electroweak scale has been well tested

The Standard Model (SM)

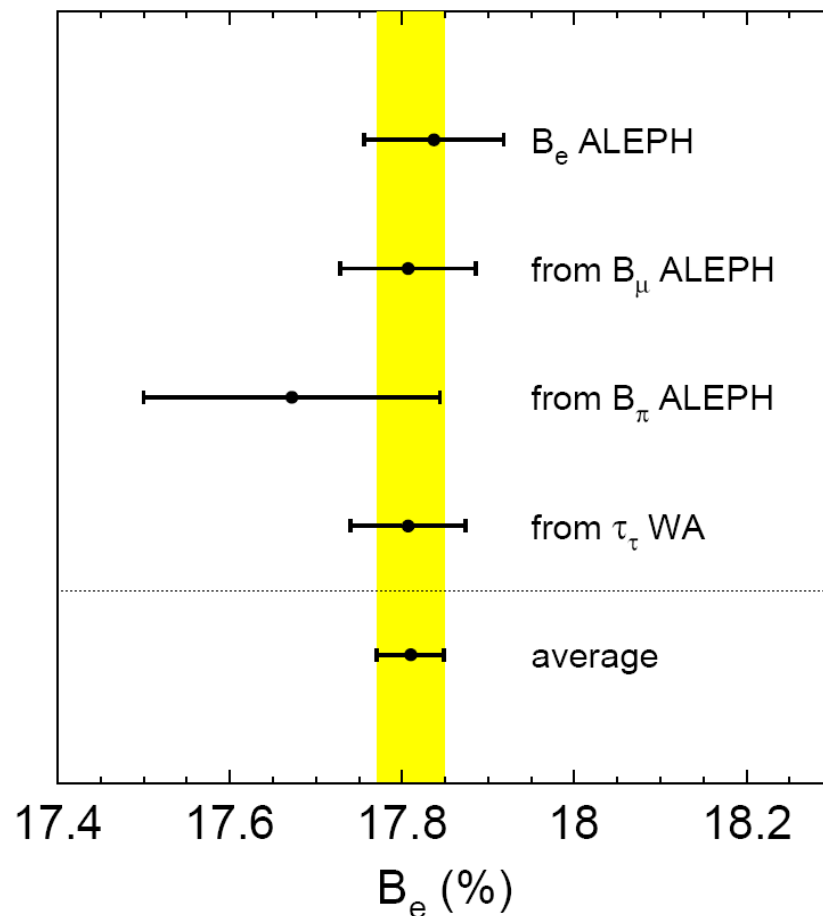
During the last 35 years, the SM has been experimentally verified to extreme precisions



The “asymptotic freedom” property of QCD has been tested to the percent level

The Standard Model (SM)

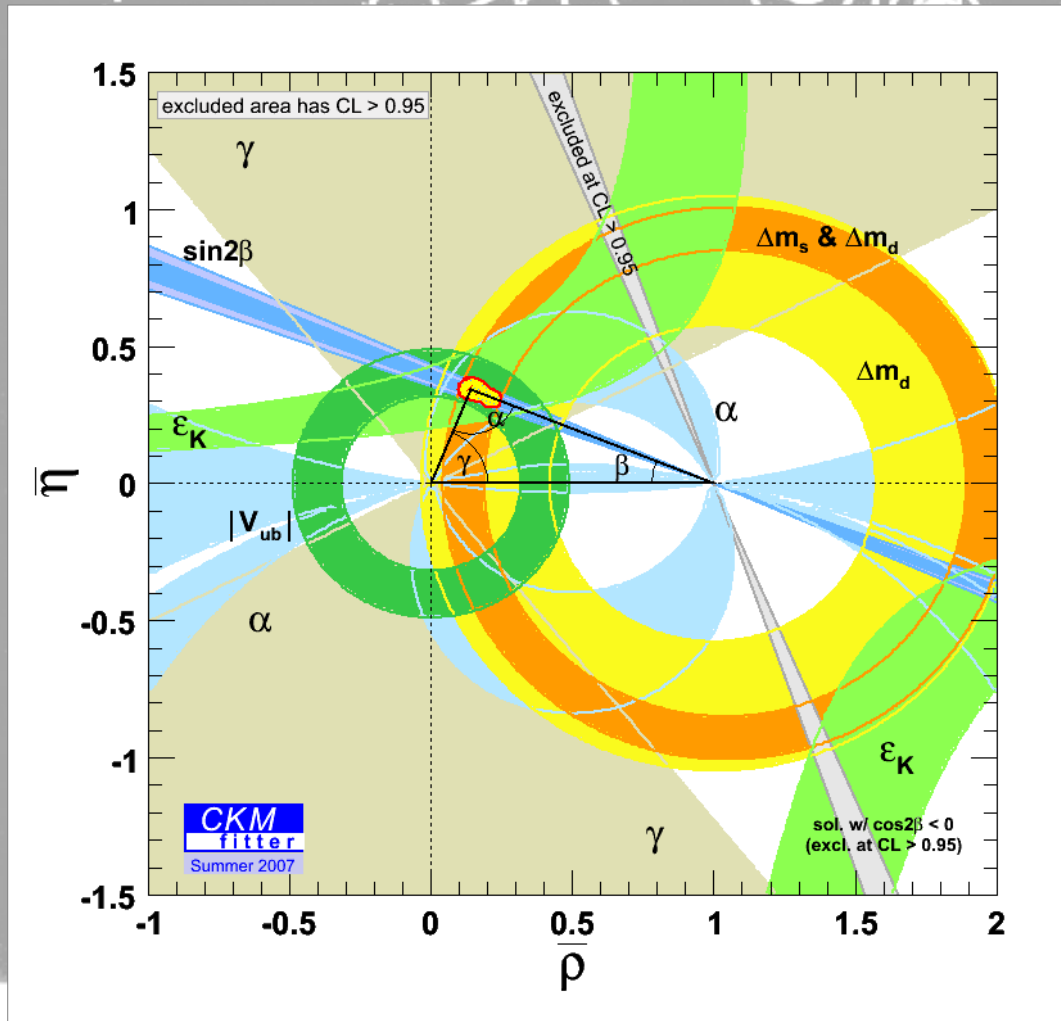
During the last 35 years, the SM has been experimentally verified to extreme precisions



The “universality” of the weak interaction has been verified to the 0.3% level

The Standard Model (SM)

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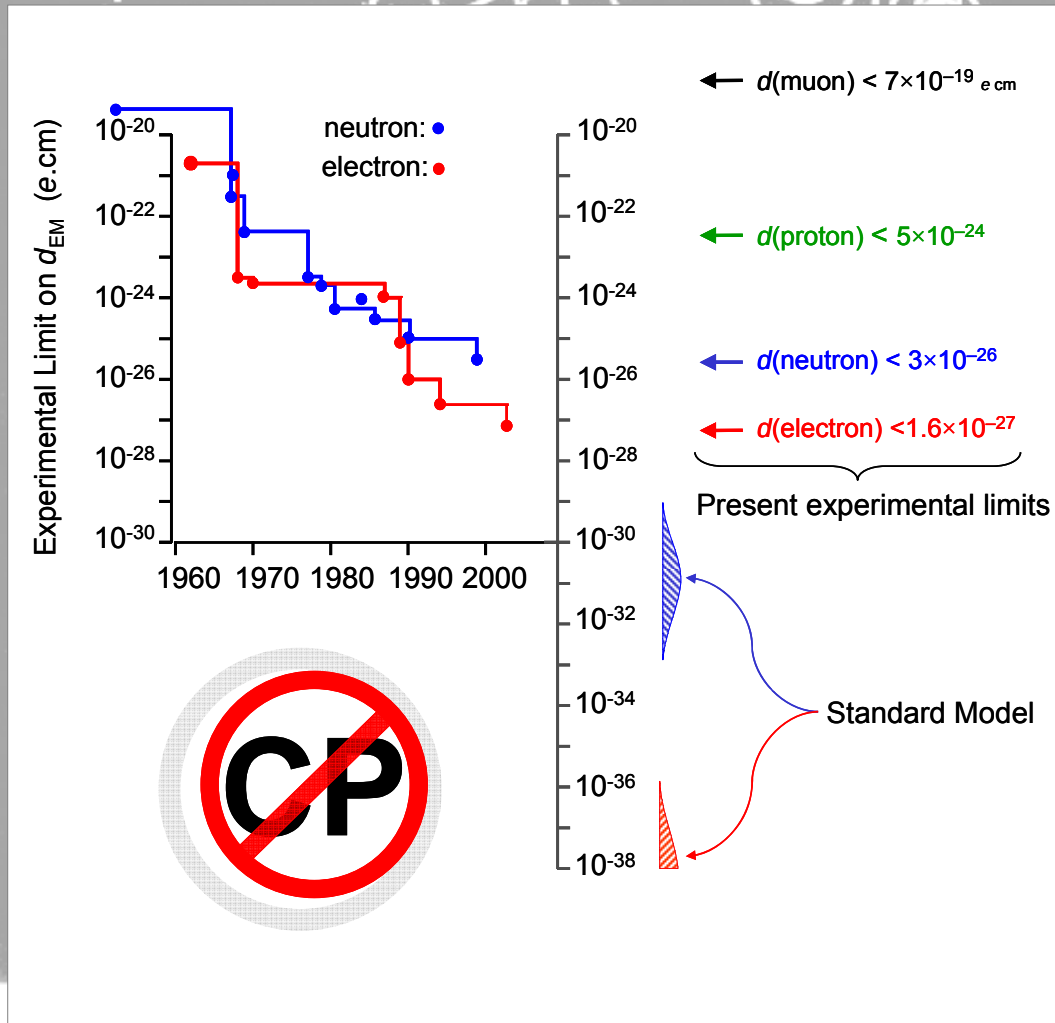


All observed processes violating matter-antimatter symmetry are predicted by the SM



The Standard Model (SM)

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

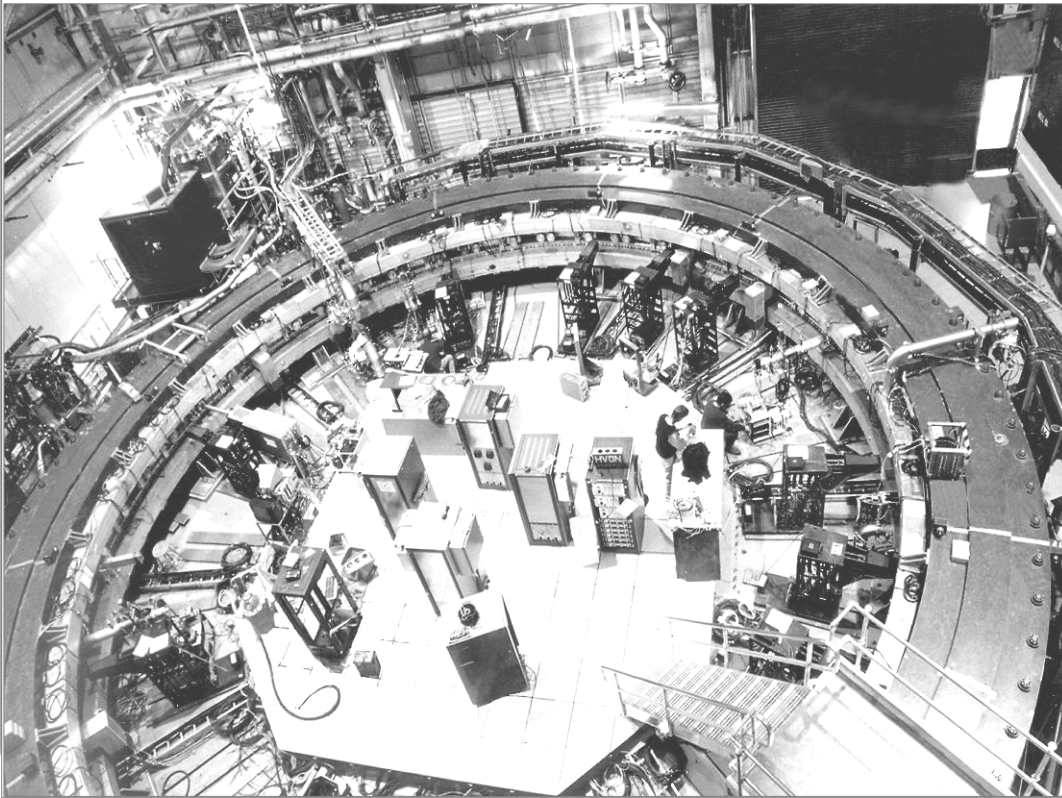


The predicted tininess of an elementary electric dipole moment has been verified to the 10^{-27} ecm level

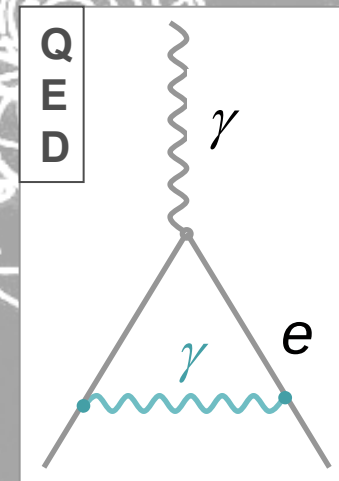
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Muon spin precession frequency in magnetic field measured at Brookhaven



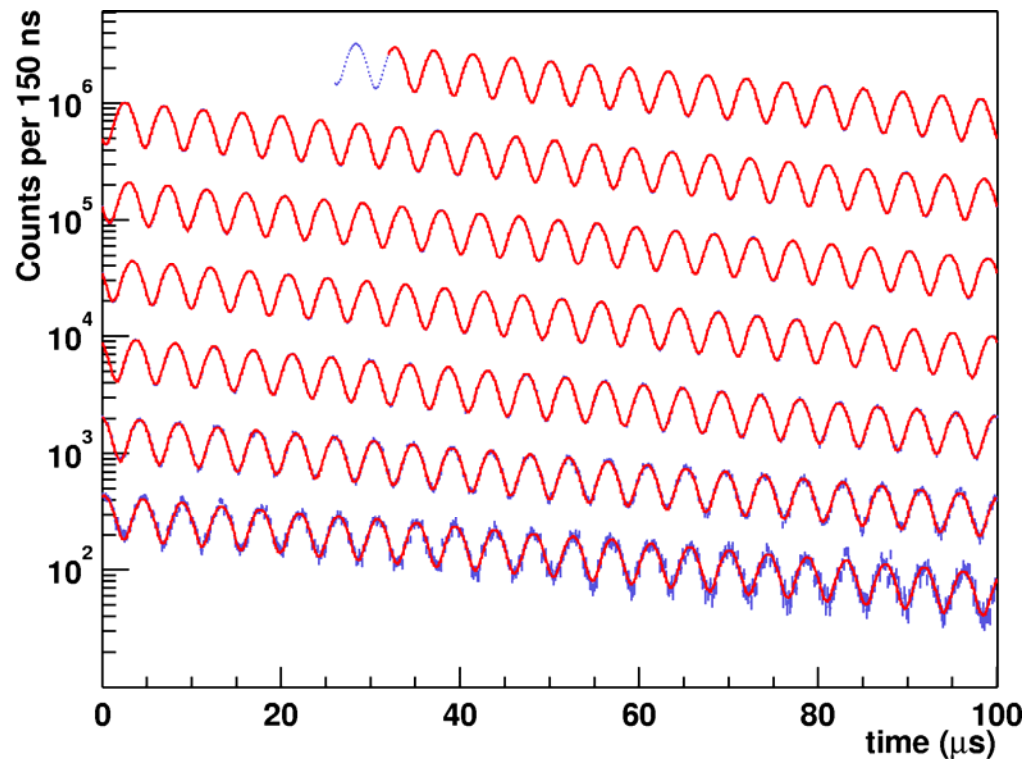
The predicted electron and muon magnetic moments have been verified to the parts per million level



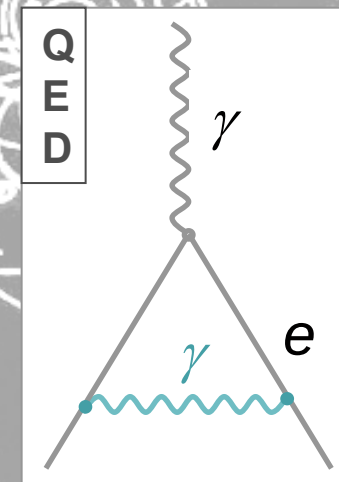
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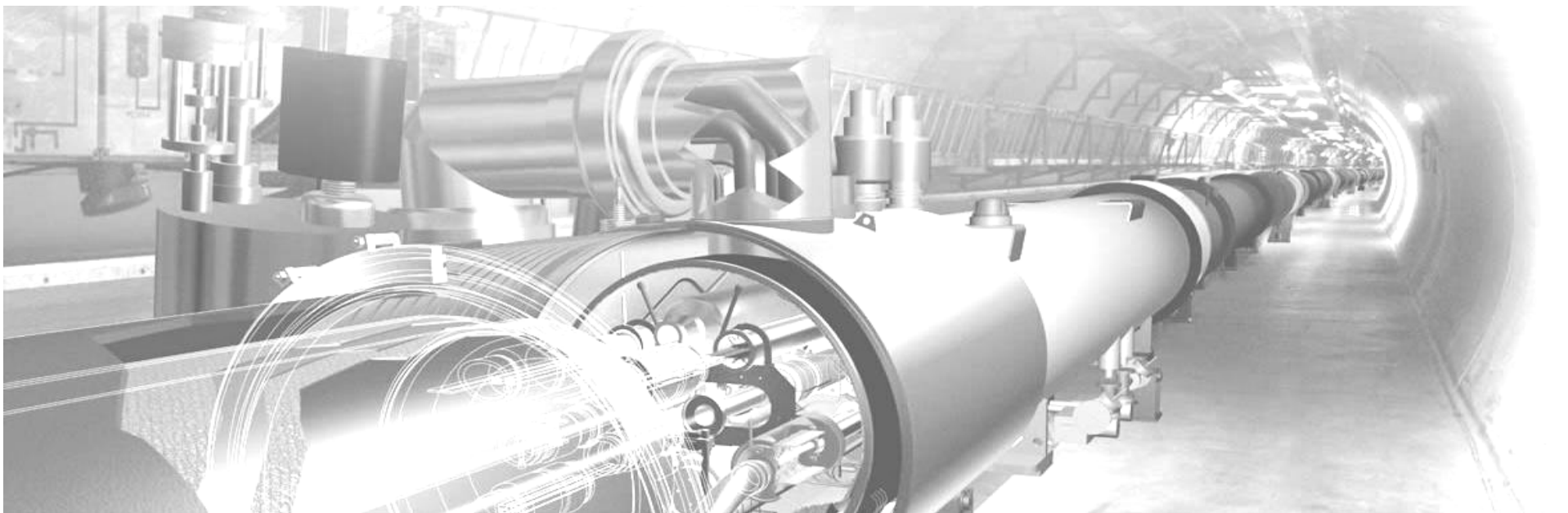


The Standard Model (SM)

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 ?**

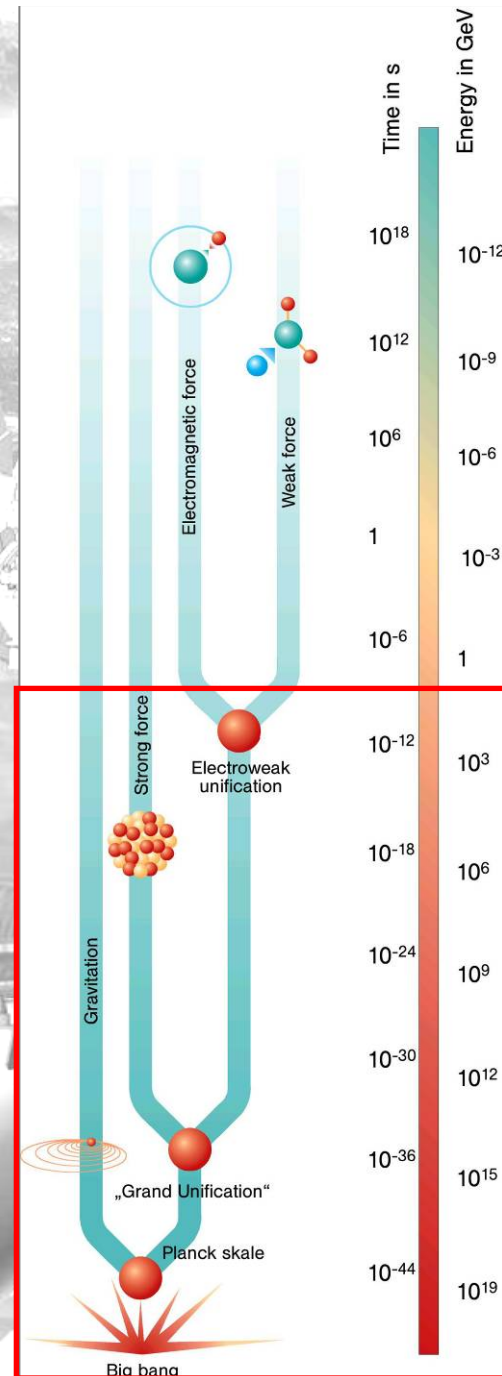
... and :

- **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]**

Neutrino masses and inclusion of **gravity** in the SM require new physics at the scales $\sim 10^{14}$ GeV and $\sim 10^{19}$ GeV, respectively !

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 observations**
 - galaxy rotation curves
 - anisotropy of cosmic microwave background radiation

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

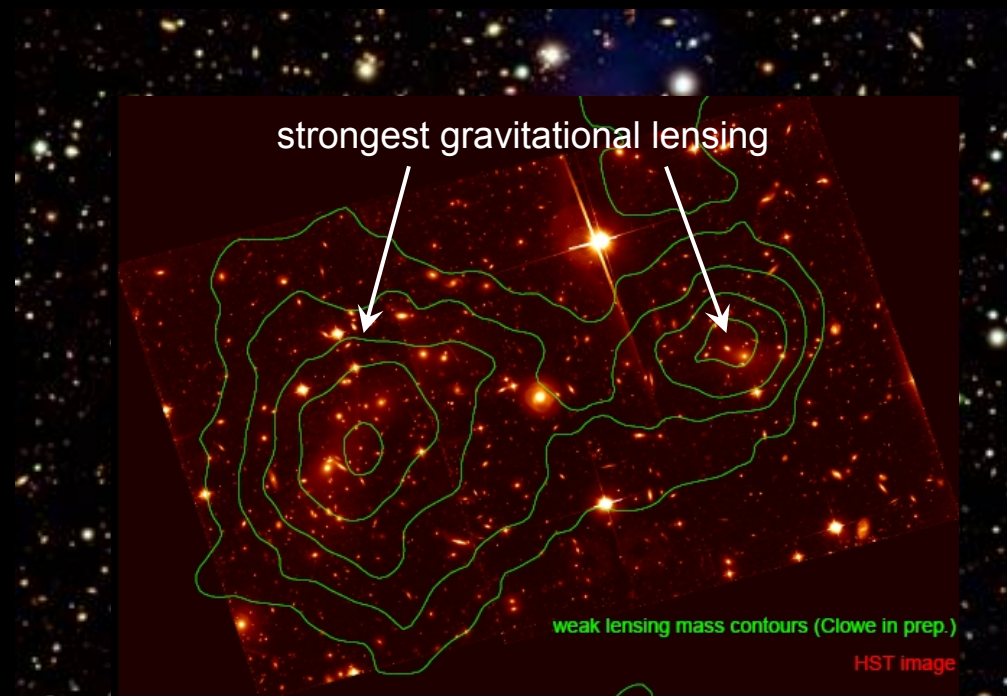


Mass density contours superimposed over photograph taken with Hubble Space Telescope

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Digression: 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)

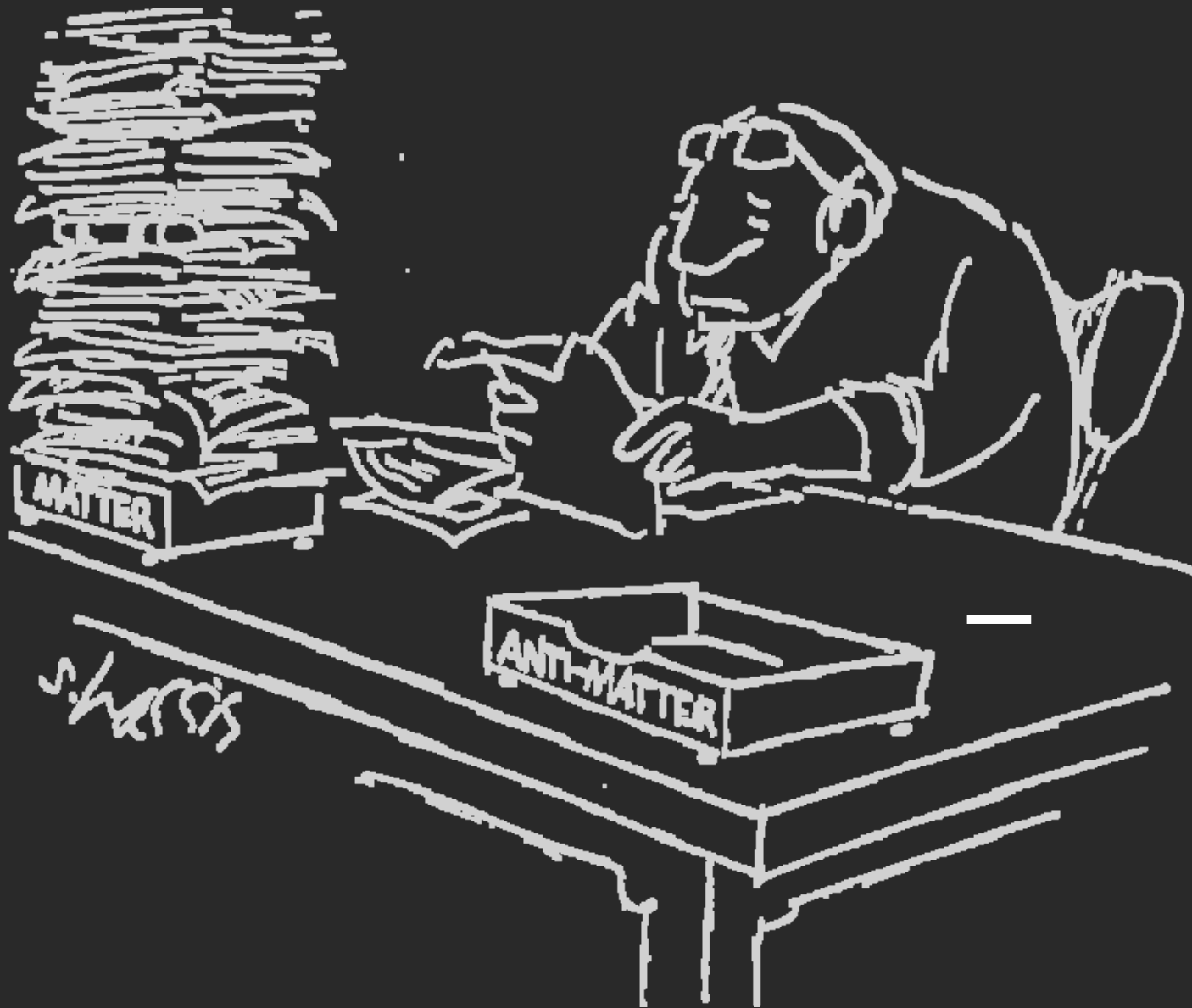
$$\chi\chi \rightarrow f\bar{f}$$

- 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

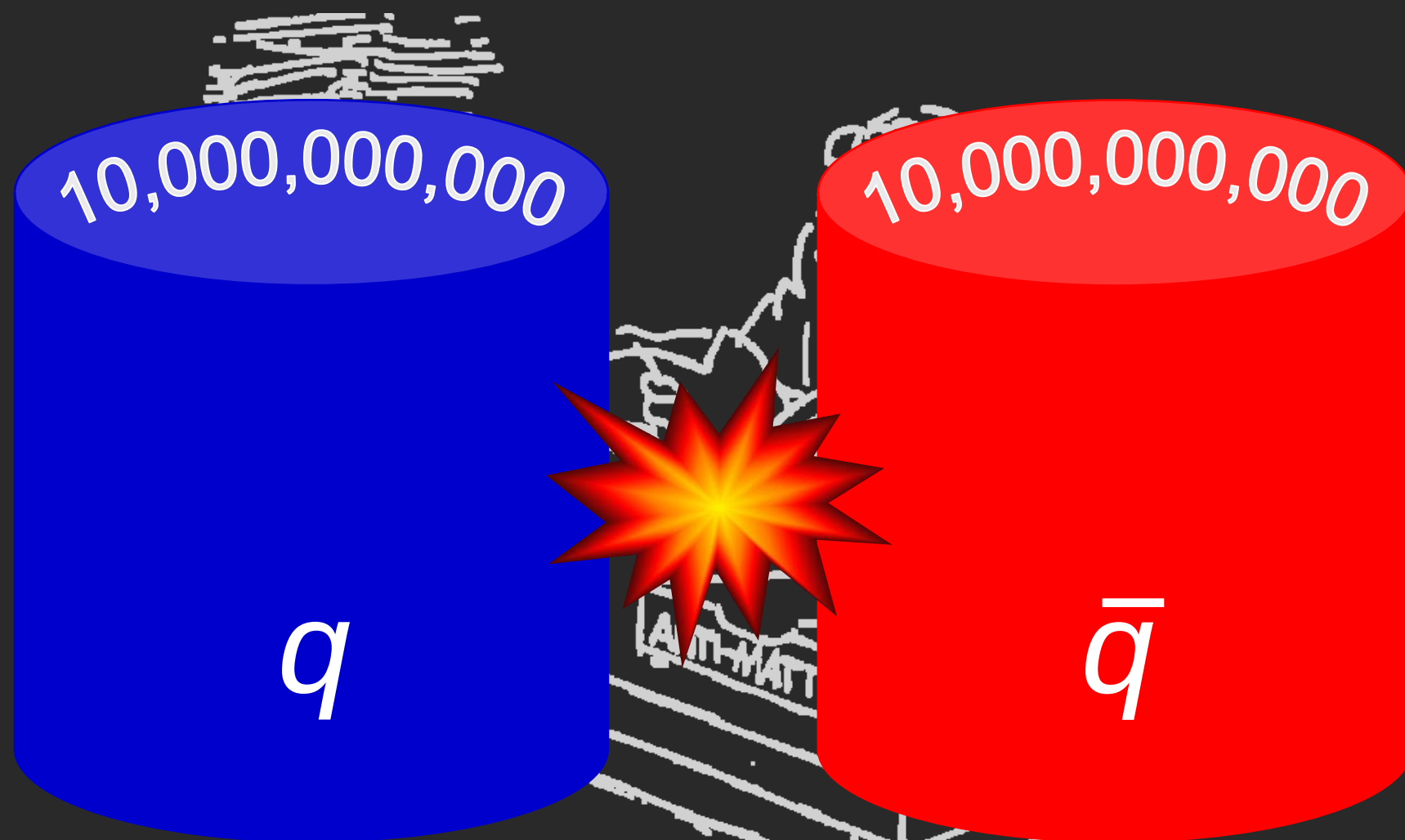
$$\Omega_{\text{DM}} \propto \frac{1}{\langle v\sigma_A \rangle} \propto m_\chi^2 \quad \Rightarrow \quad \Omega_{\text{DM}} \approx 0.1 \quad \rightarrow \quad m_\chi \sim 0.1 - 1 \text{ TeV}$$

COINCIDENCE ?

Matter-Antimatter Asymmetry

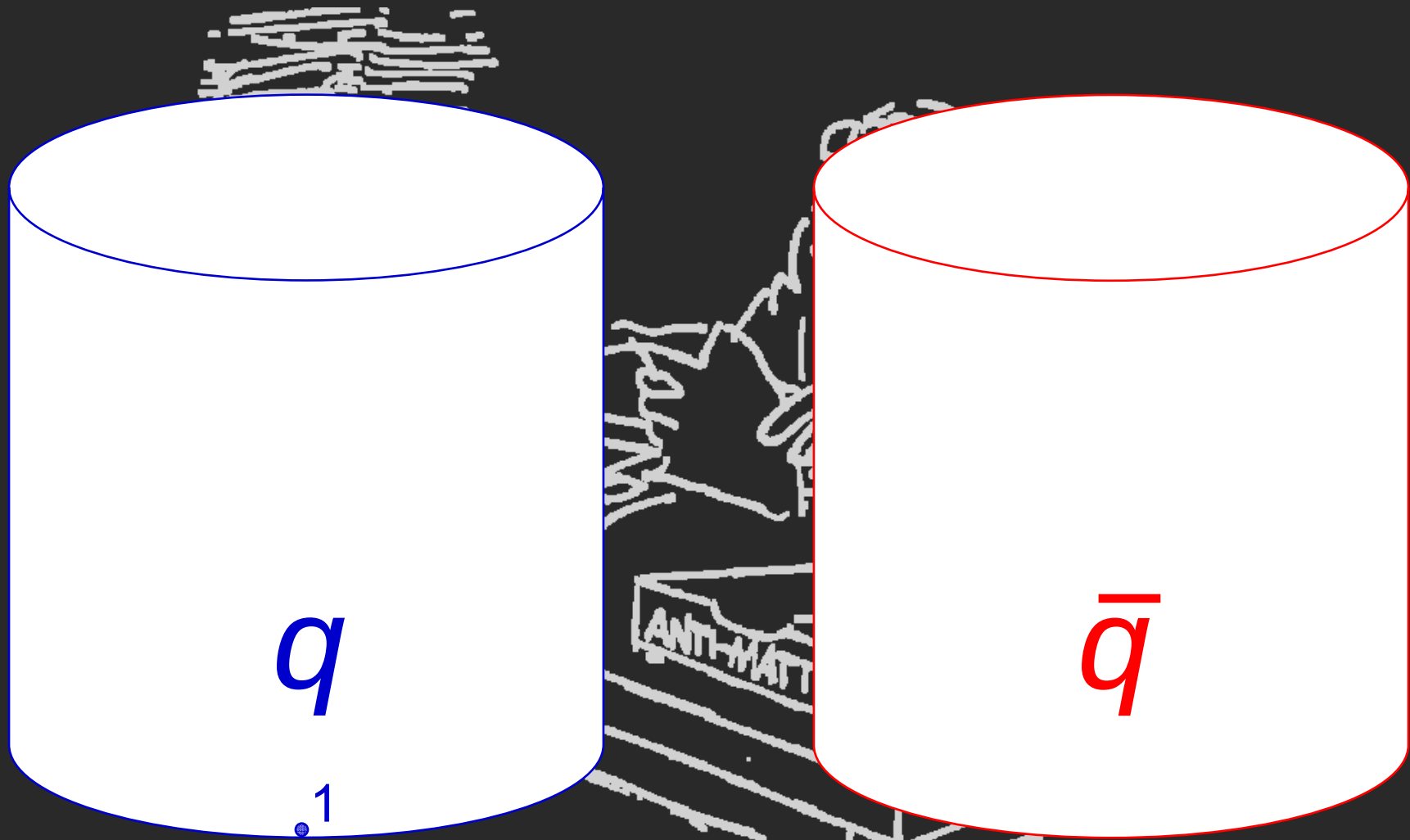


Matter-Antimatter Asymmetry



Early universe ?

Matter-Antimatter Asymmetry

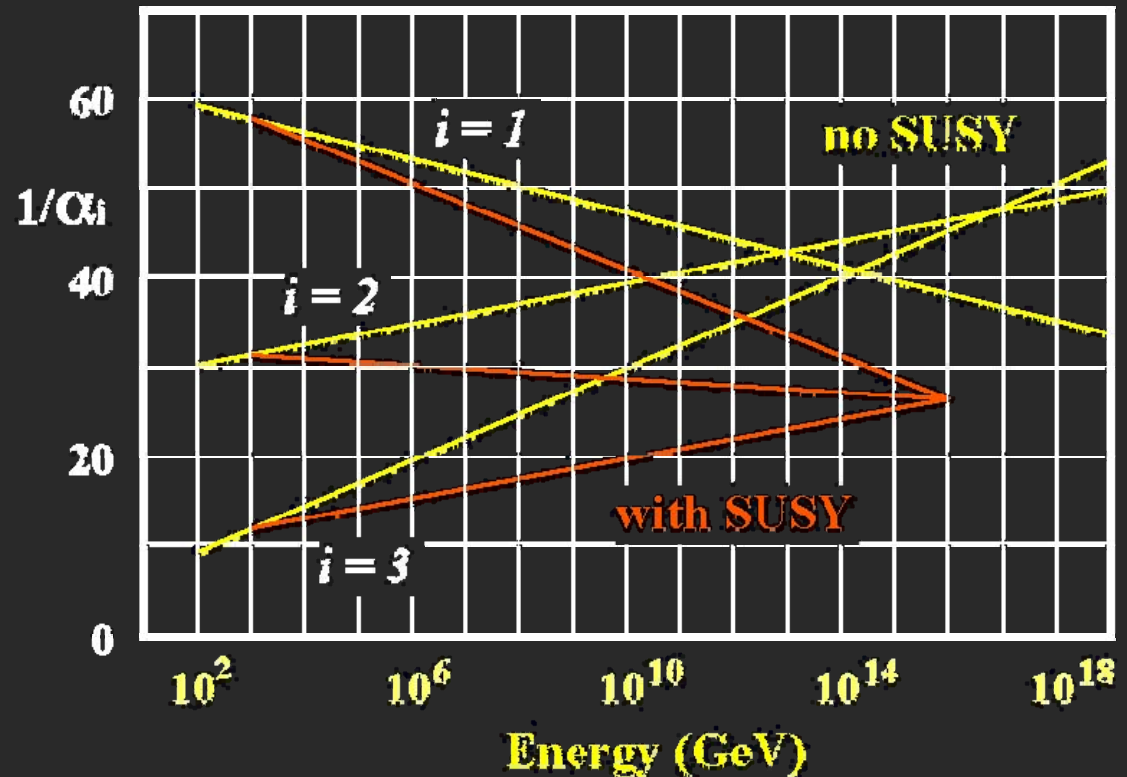


Current universe

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

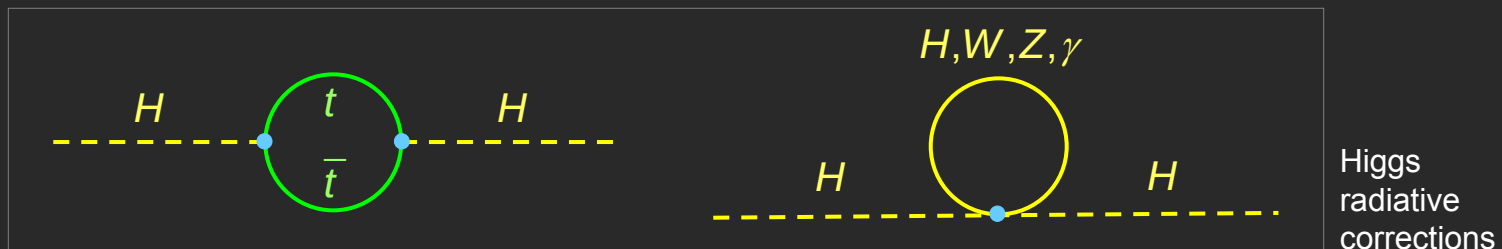


➡ **Exact unification does not need to occur, but wouldn't it be very appealing if it did ?**

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

The gauge Hierarchy Problem

- 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:



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

- 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

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

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

The gauge Hierarchy Problem

- If a Higgs boson with mass < 1 TeV is discovered
- However, when computing radiative corrections

**BUT ... again (!) ...
the Higgs is not yet
discovered !**

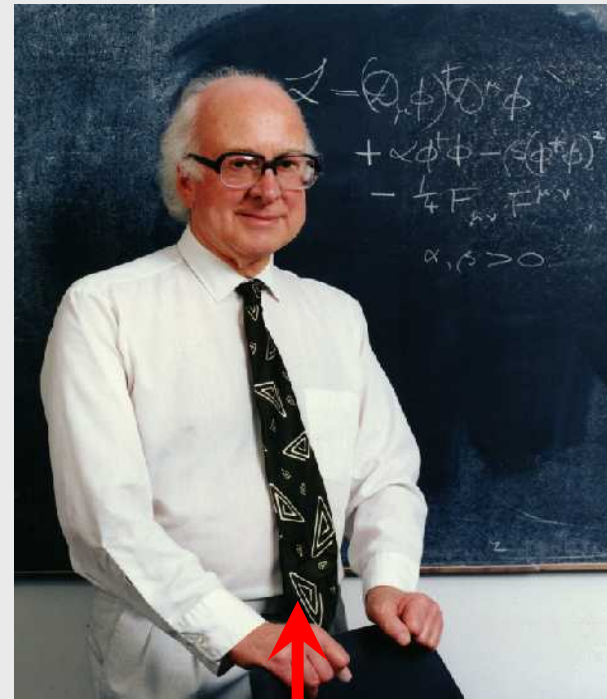
Integral quadra

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$$m_H^2 \stackrel{?}{=} (120 \text{ GeV})^2 =$$

experimentally favoured value...

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



**Only unambiguous example
of observed Higgs**

[Joke plagiarized from D. Froidevaux, CERN]

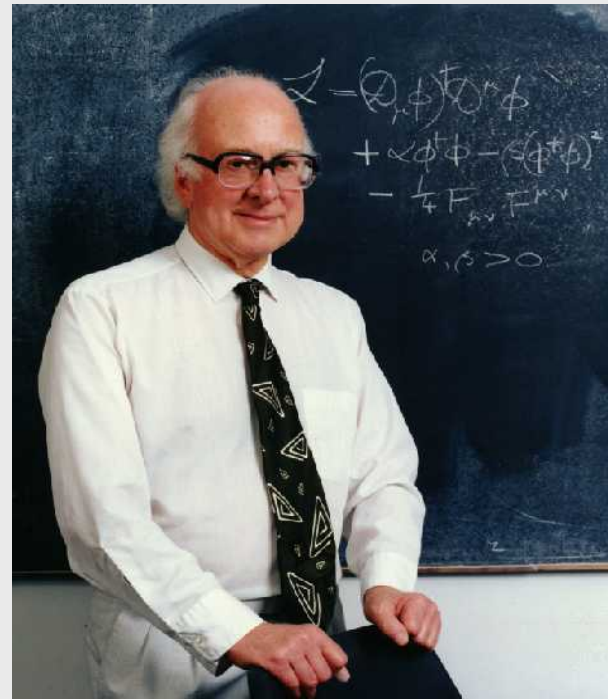
The Higgs

Let's follow Daniel Froidevaux some more:

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

- A theoretical concept
- 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

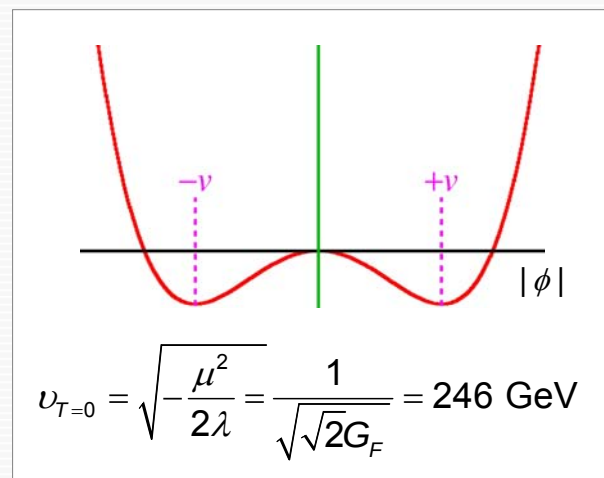
© ATLAS

Digression: 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”:

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

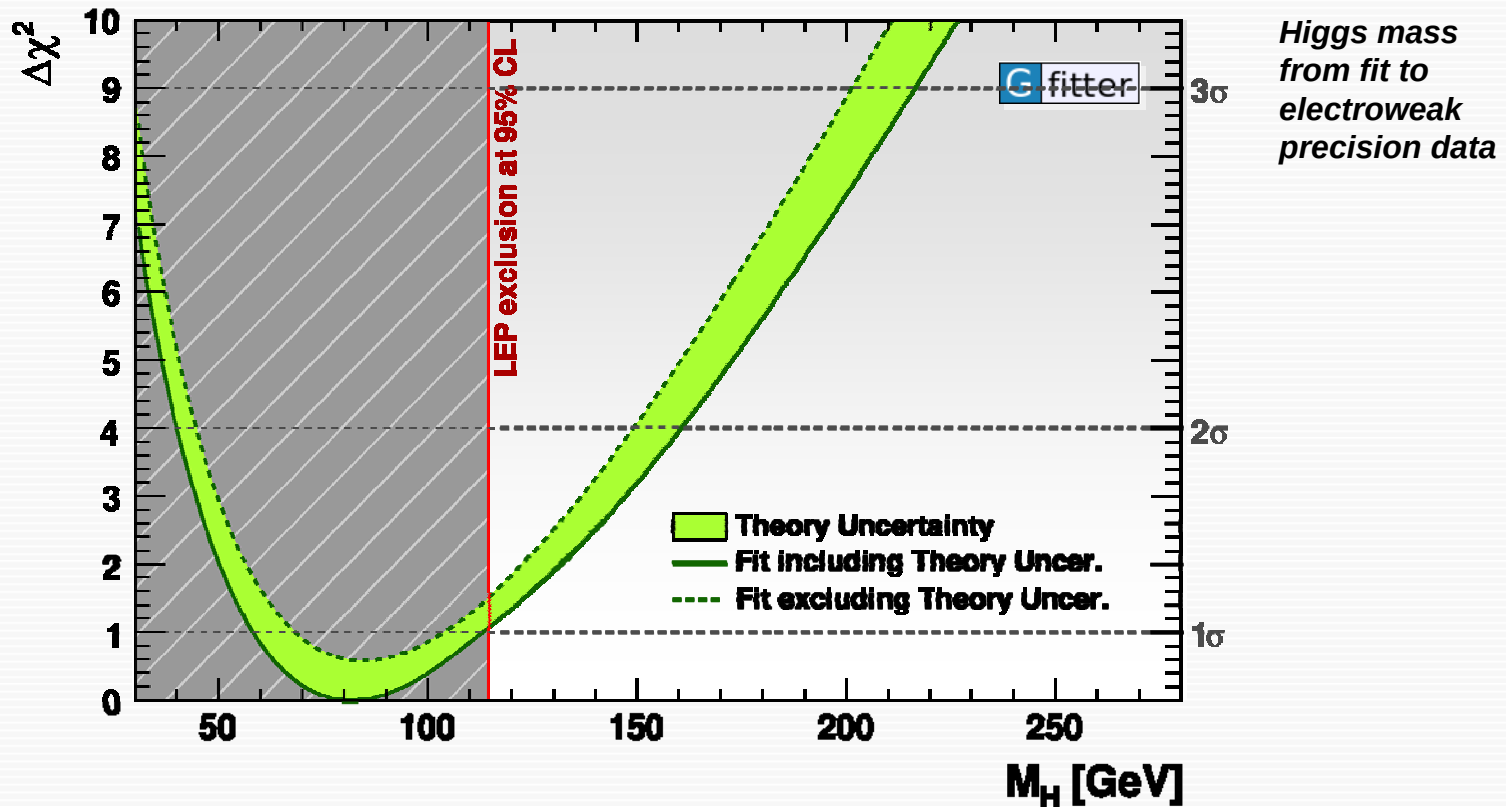
- Geometric series yields massive propagator creating effective mass for fermion:

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

similar
for gauge
bosons

A Light Standard Model Higgs Boson

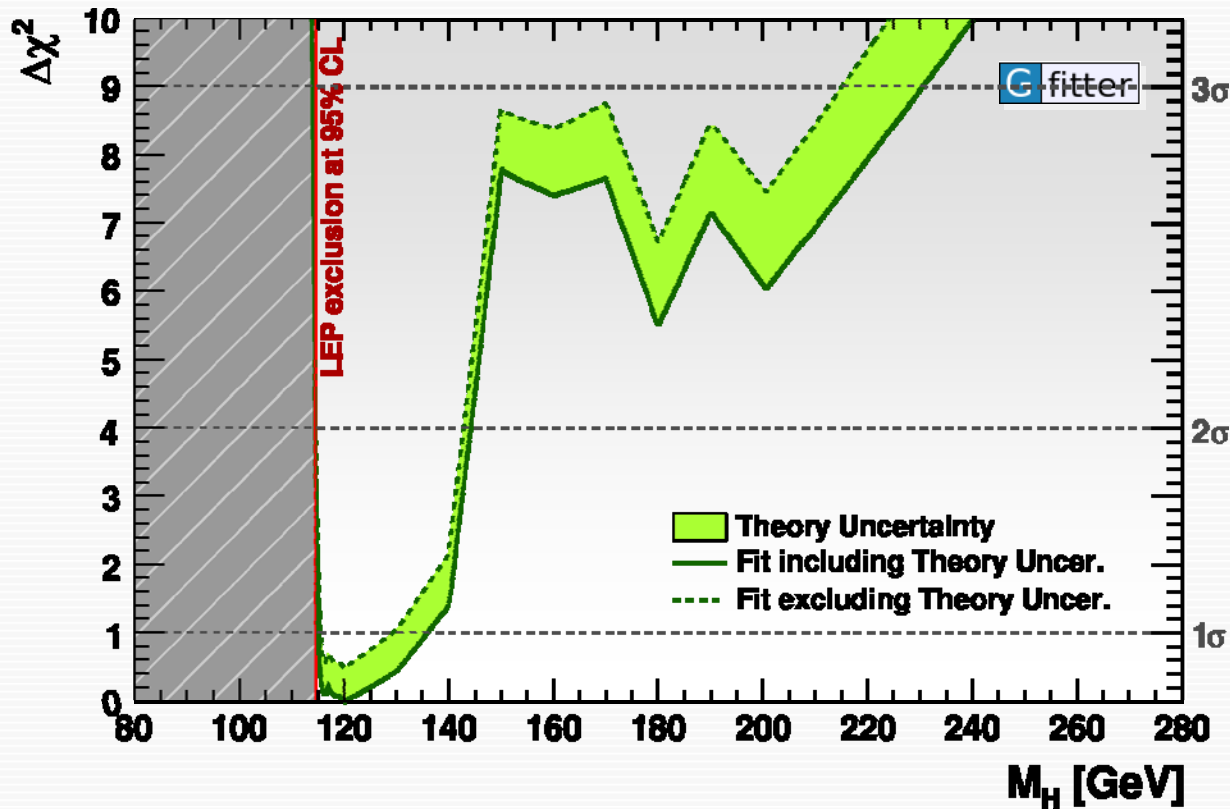
- If indeed the mass of the Higgs is light it will be produced at the LHC



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

A Light Standard Model Higgs Boson

- If indeed the mass of the Higgs is light it will be produced at the LHC



*Higgs mass
from fit to
electroweak
precision data*

*Fit including
constraint from
direct searches at
LEP and Tevatron*

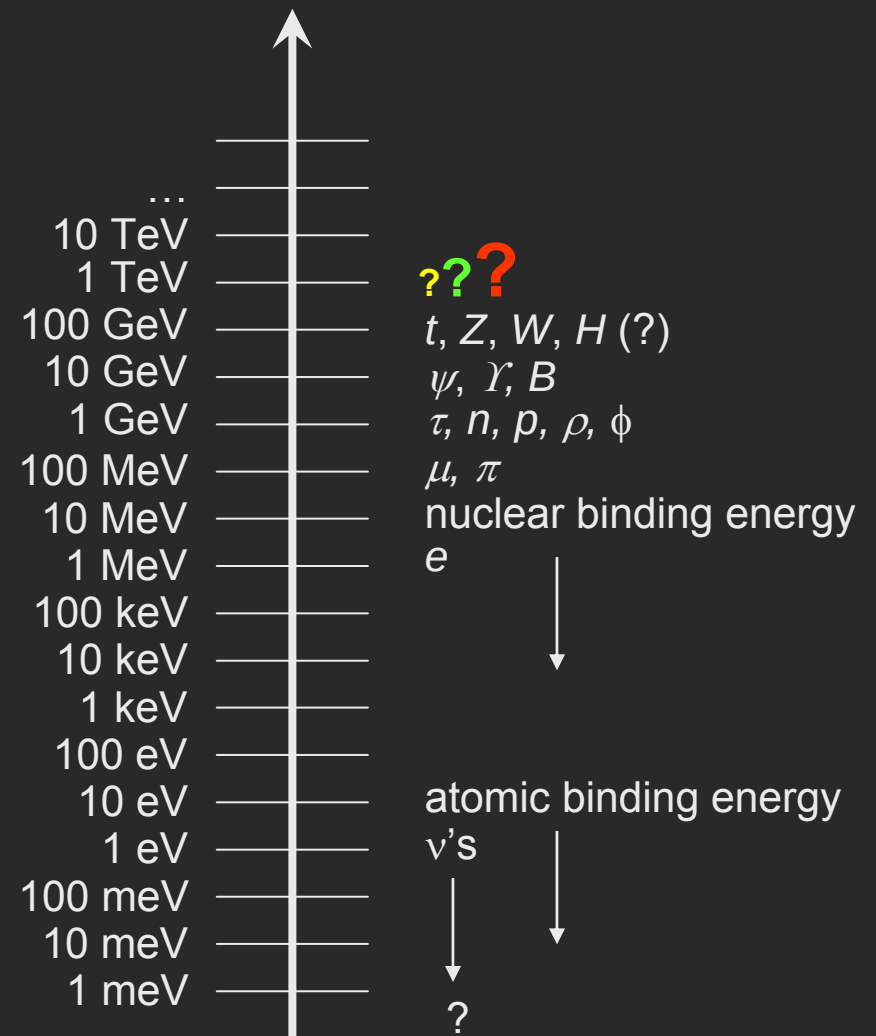


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New Physics: Why Not ?

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

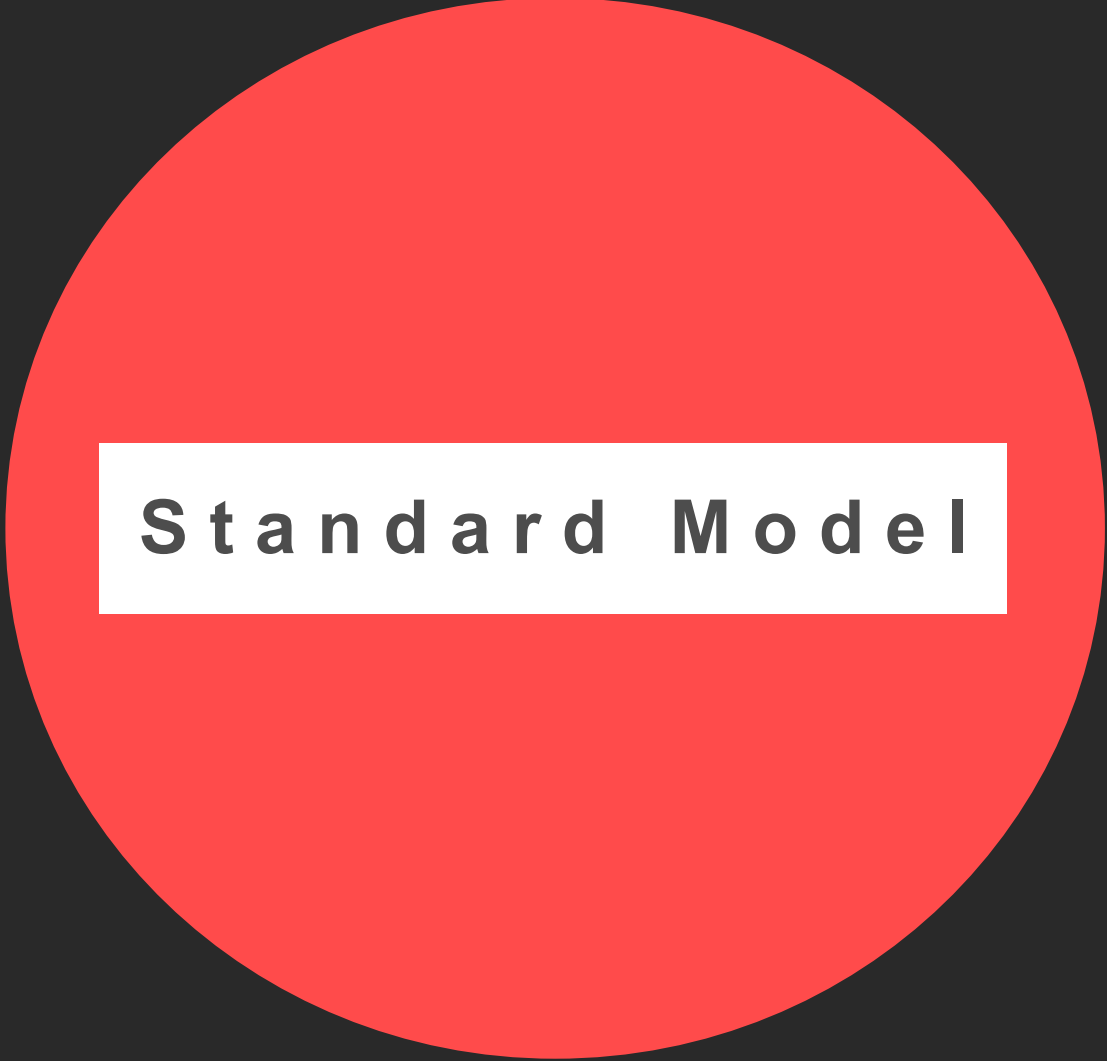
Why should there be a
desert in the logarithmic
energy scale ?



New Physics: Why ?

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



Standard Model

Extending the Standard Model

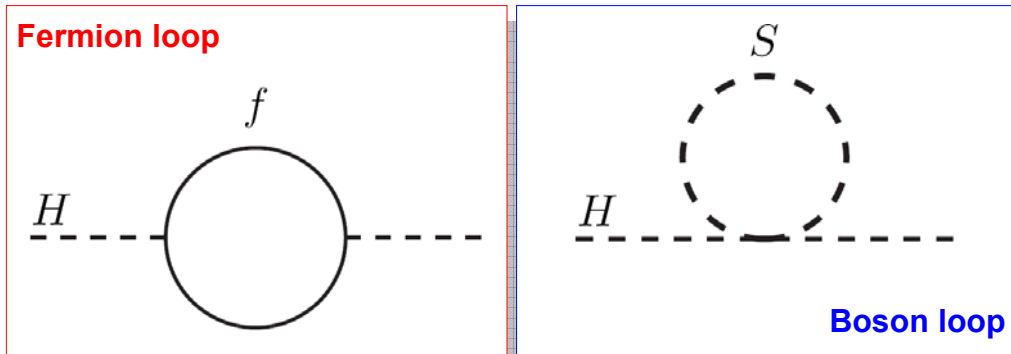
Models for new physics focus on curing the hierarchy problem and providing dark matter candidates

- ➡ **Supersymmetry**
- ➡ **Extra Dimensions**
- ➡ **Little Higgs**

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 (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

To avoid proton decay, a **new symmetry** is introduced: **R-parity**

- ➡ SUSY particles must be produced in pairs, and decay into other SUSY particles
- ➡ The **lightest SUSY particle is stable** $\rightarrow$ **dark matter candidate** !

SUSY also naturally achieves Grand Unification of the forces at $\sim 10^{16}$ GeV

(SM $\rightarrow$ SUSY)

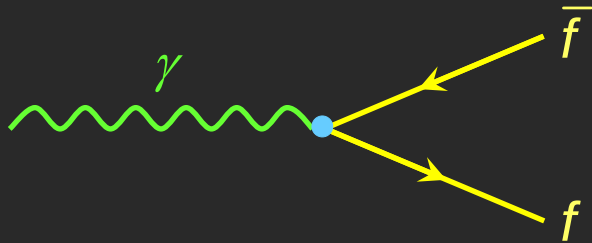
$e_L \rightarrow \tilde{e}_L$

$\gamma \rightarrow \tilde{\gamma}$

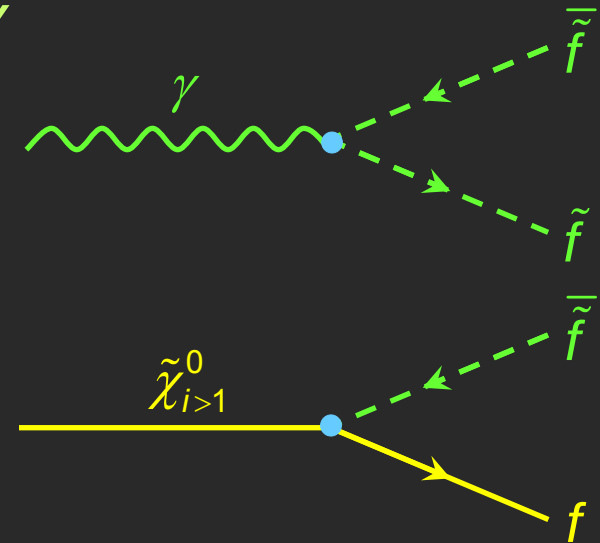
$\dots \rightarrow \dots$

Interactions of SUSY Particles

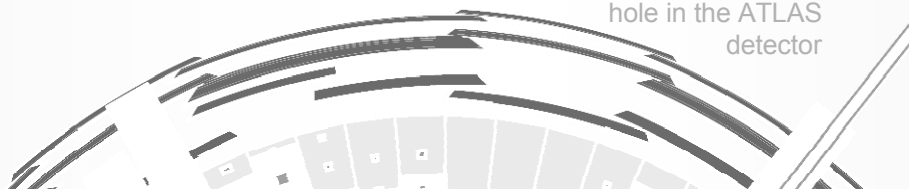
SM



SUSY

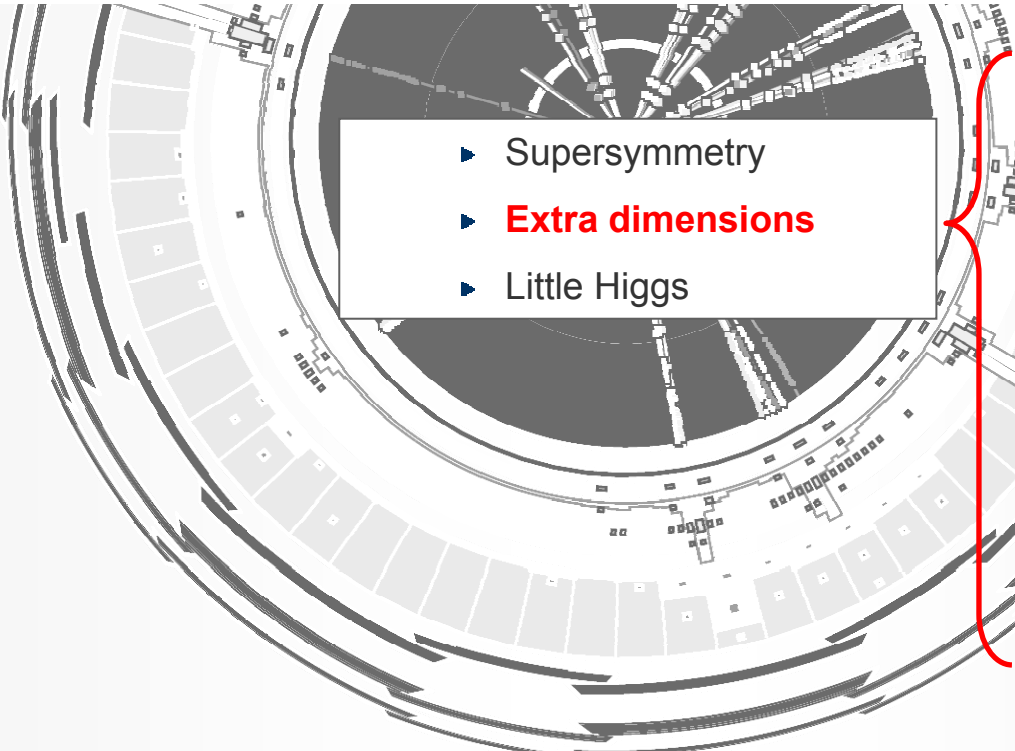


MSSM: take any SM diagram and switch the spin of two lines



Simulation of a black
hole in the ATLAS
detector

Extending the Standard Model

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

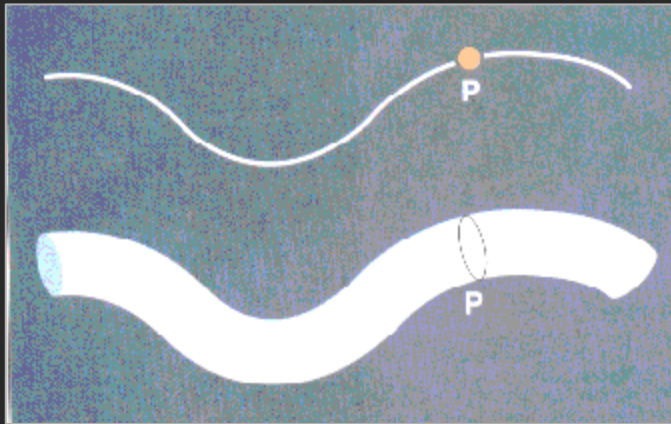
Perhaps the problem
with the hierarchy is that
we use the wrong M_{Pl} ?

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

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

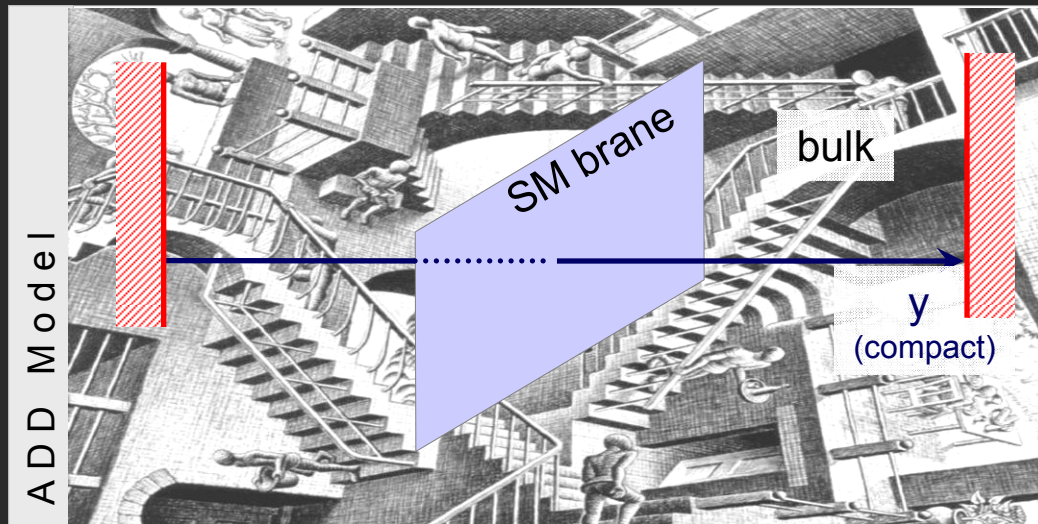
Extra Dimensions are Compactified ...



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

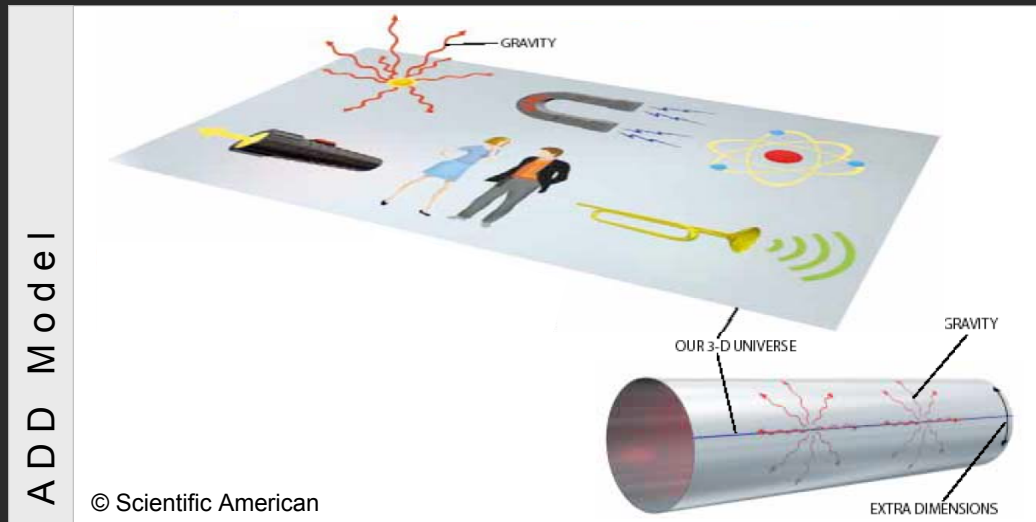
Extra Dimensions are Compactified ...



Compactification generates so-called “Kaluza-Klein (KK) towers” that can be associated with particles (resonances) propagating in the EDs

→ These particles can be observed if the EDs can be resolved with high energy accelerators

Extra Dimensions are Compactified ...



Arkani-Hamed, Dimopoulos,
Dvali, hep-ph/9803315
3442 citations to date !

Randal-Sundrum,
hep-ph/9905221
3757 citations to date !

Compactification generates so-called “Kaluza-Klein (KK) towers” that can be associated with particles (resonances) propagating in the EDs

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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



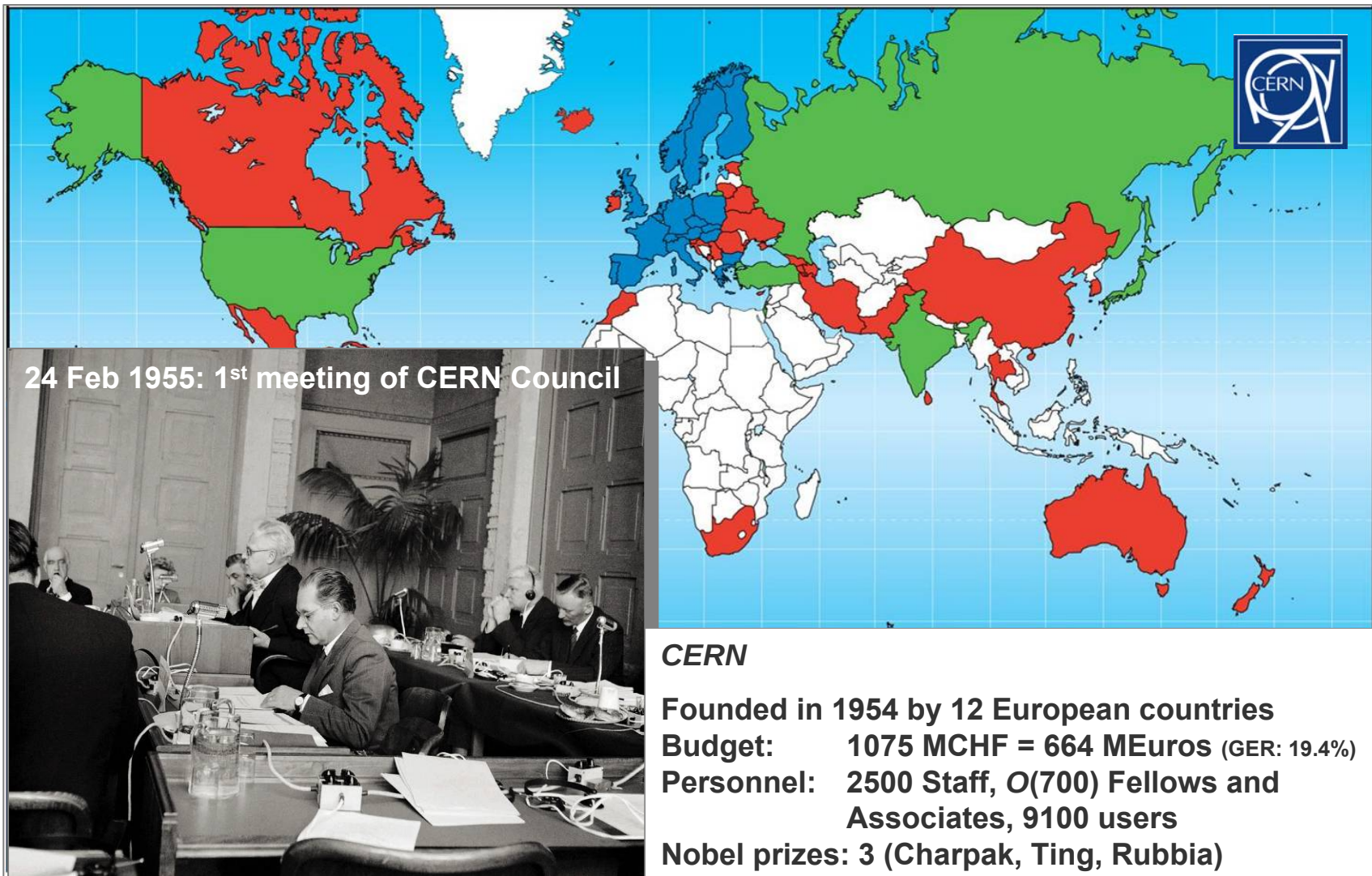
CERN, the LHC and ATLAS

Experimental Challenges



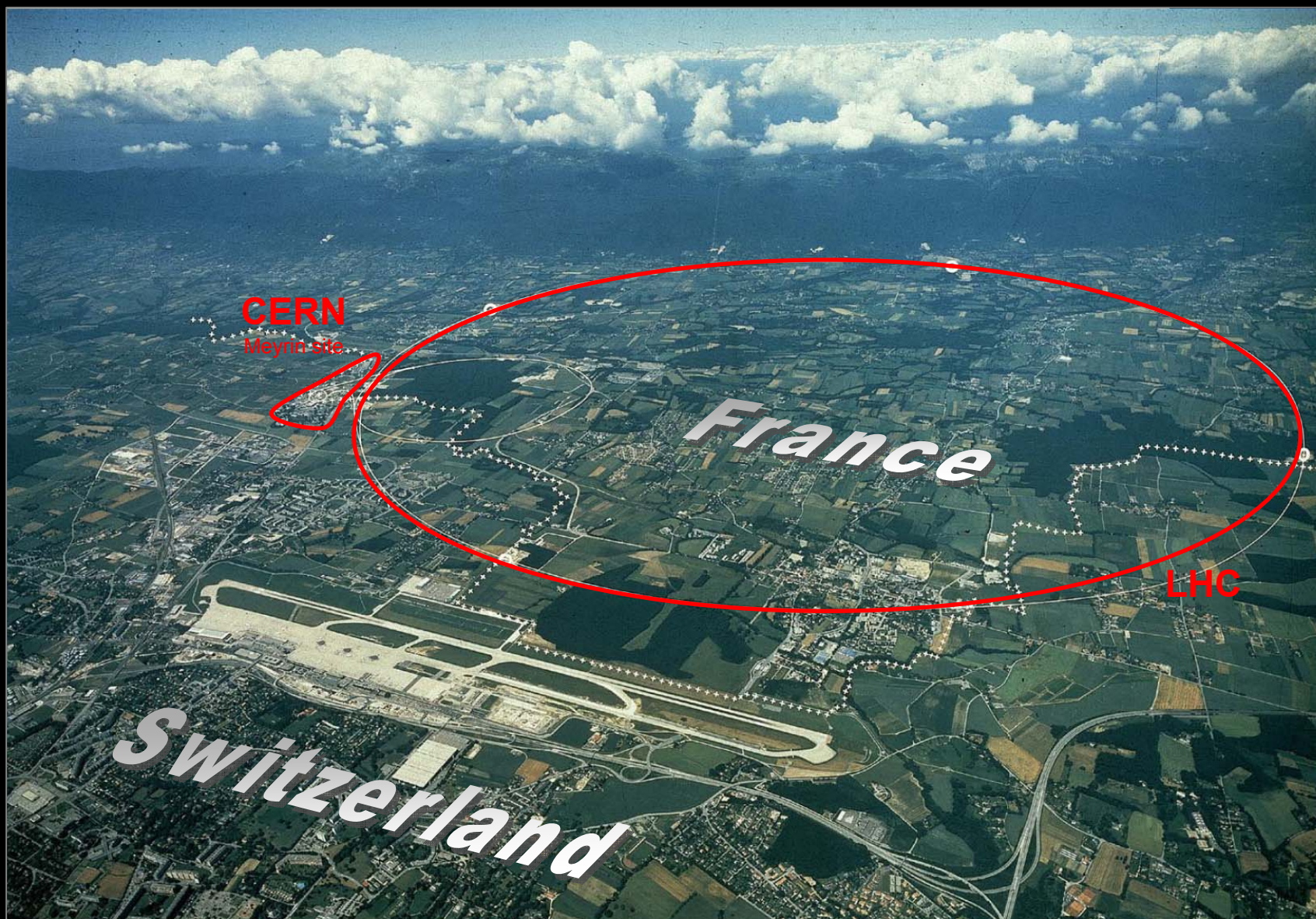
CERN AC/DI/MM 3324-07 07-1998

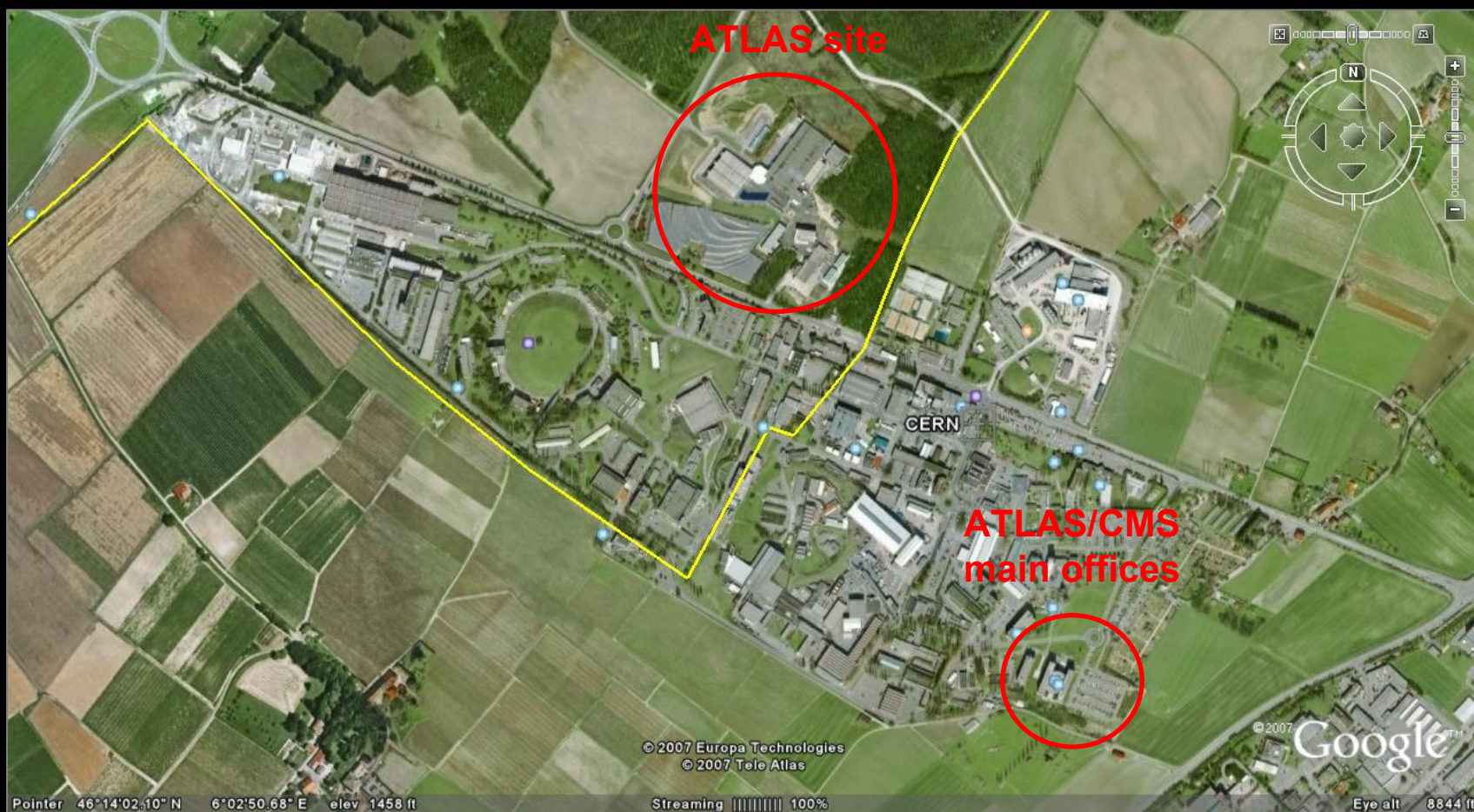
Distribution of all CERN Users by Nation of Institutes on 5 Feb 2008



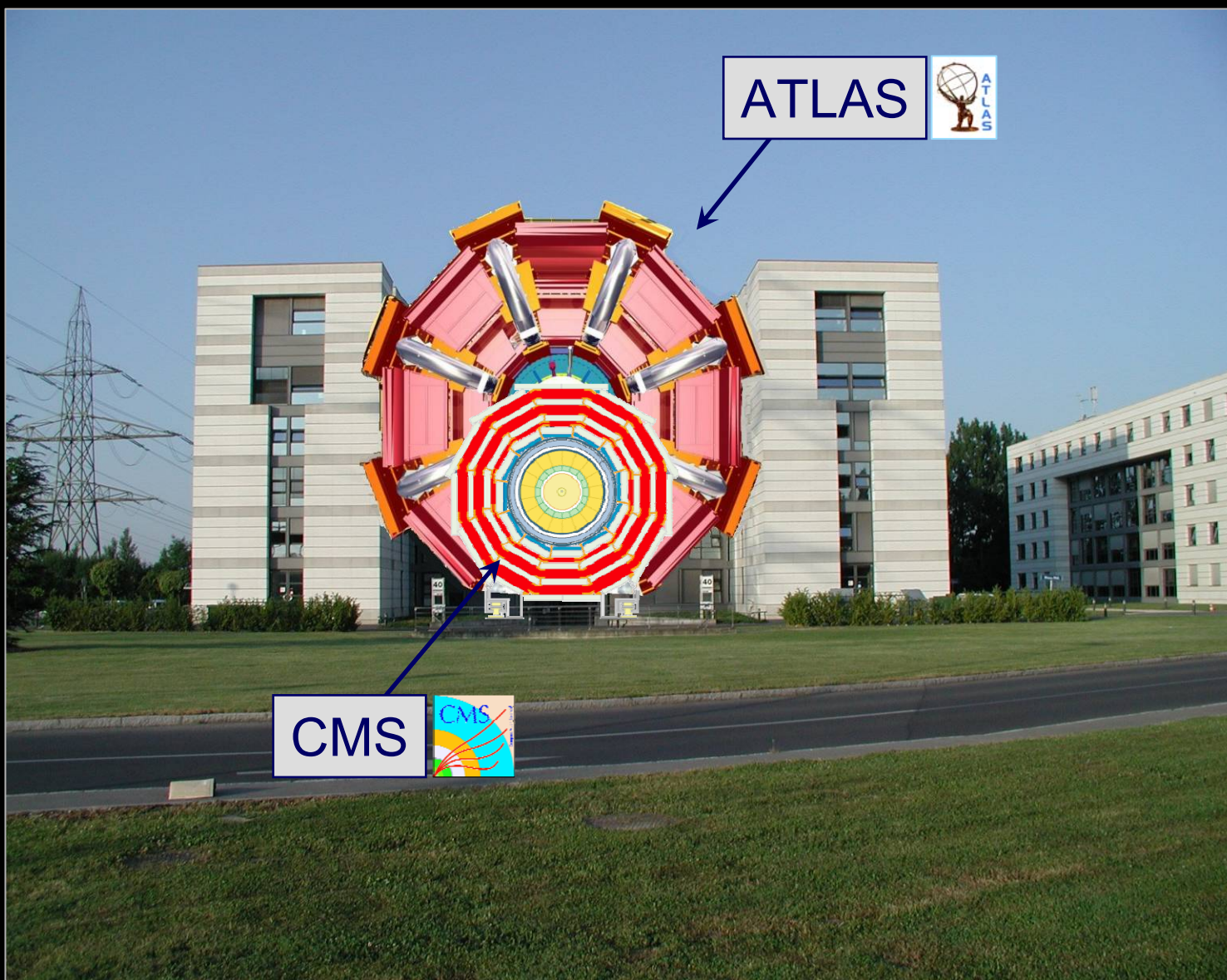
CERN & THE LHC





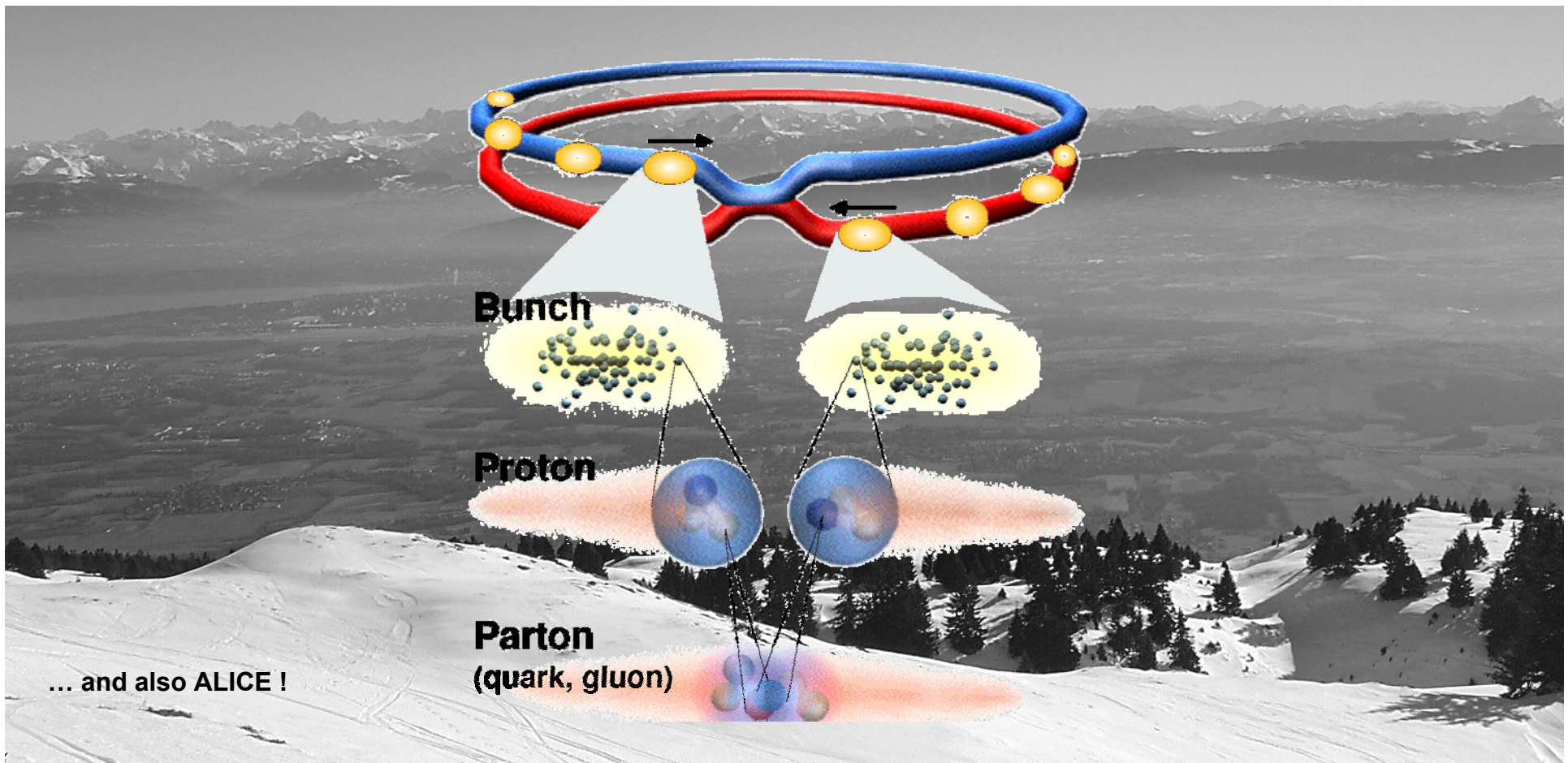






LHC: The Accelerator Challenge

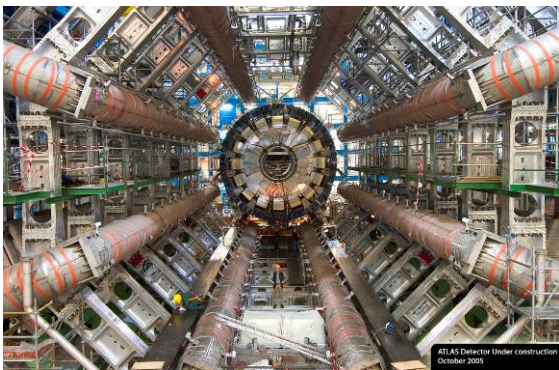
- The search for new phenomena exploits **ever smaller distances** → **ever larger energies**
- The LHC collides protons at $E_{\text{CM}} = 14 \text{ TeV}$ → probing a distance of $1.4 \cdot 10^{-18} \text{ cm}$?
... not quite, since protons are composites: the energy is distributed among its partons



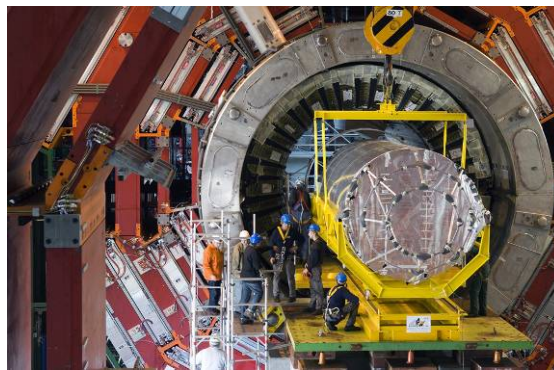
LHC: The Accelerator Challenge

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- The LHC collides protons at $E_{\text{CM}} = 14 \text{ TeV}$ → probing a distance of $1.4 \cdot 10^{-18} \text{ cm}$?
... 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

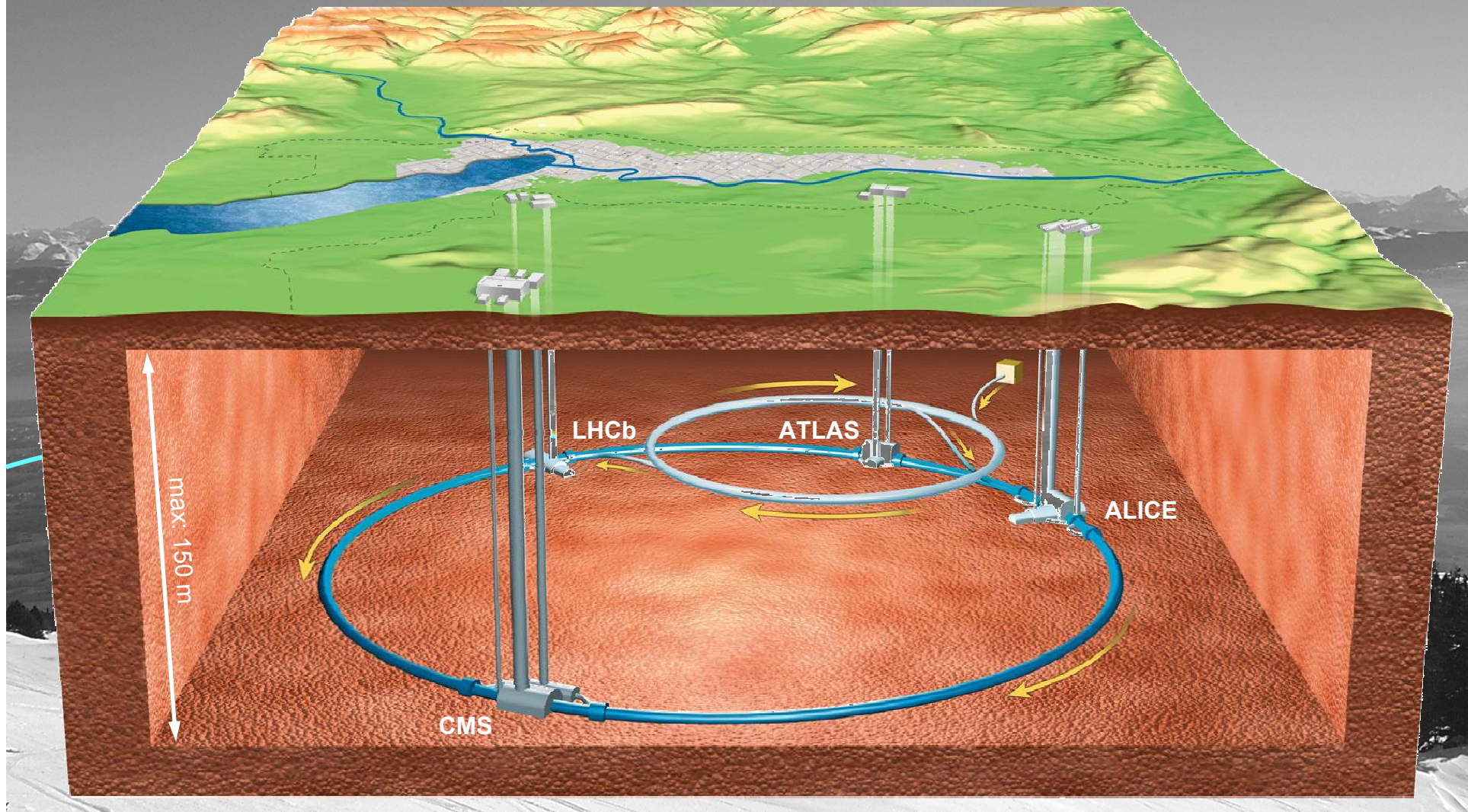


... and also ALICE !

Accelerators for the LHC



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



Accelerators for the LHC

7 TeV



LHC

450 GeV



SPS

26 GeV



PS

1.4 GeV



BOO-
STER

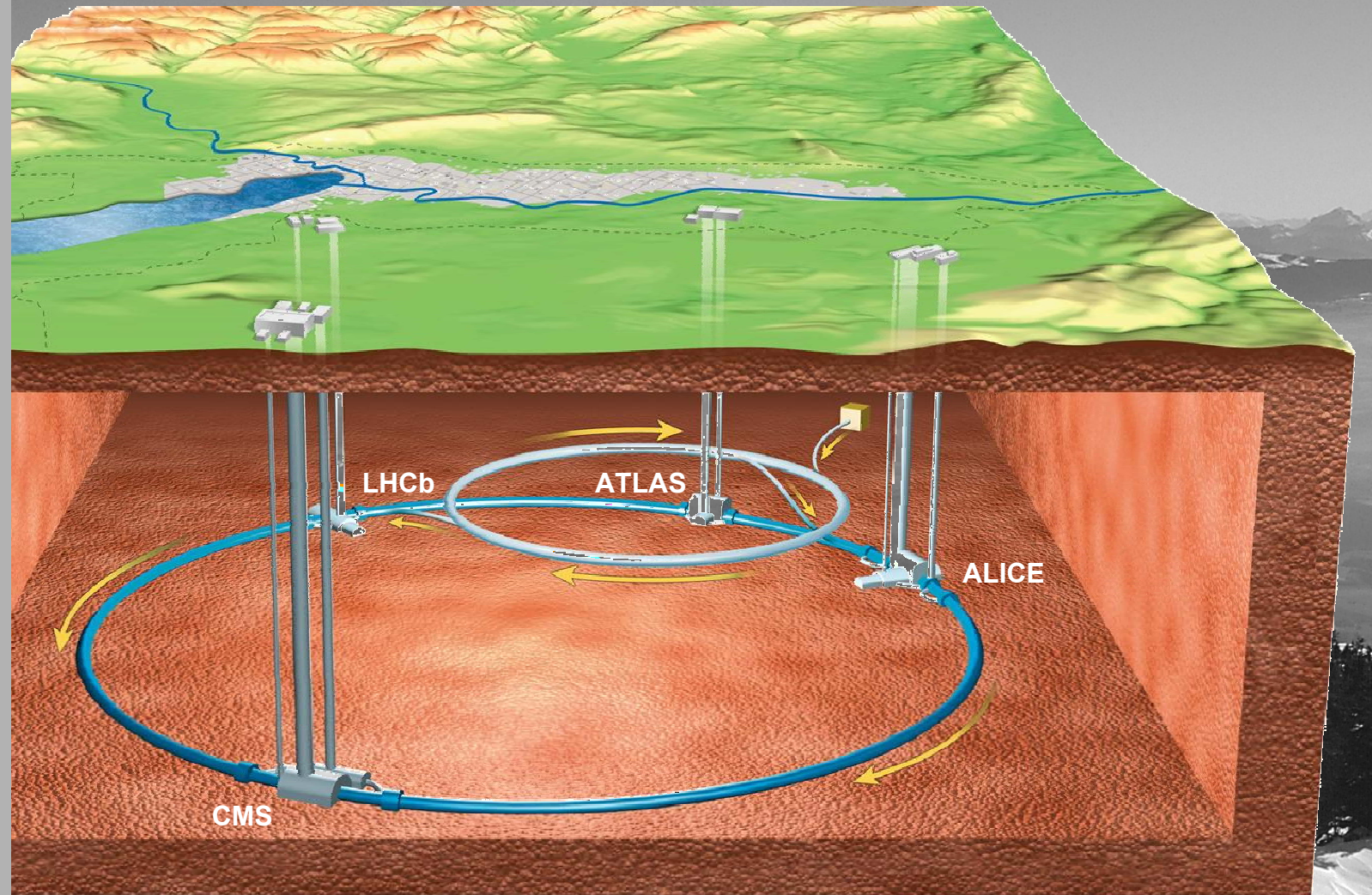
50 MeV



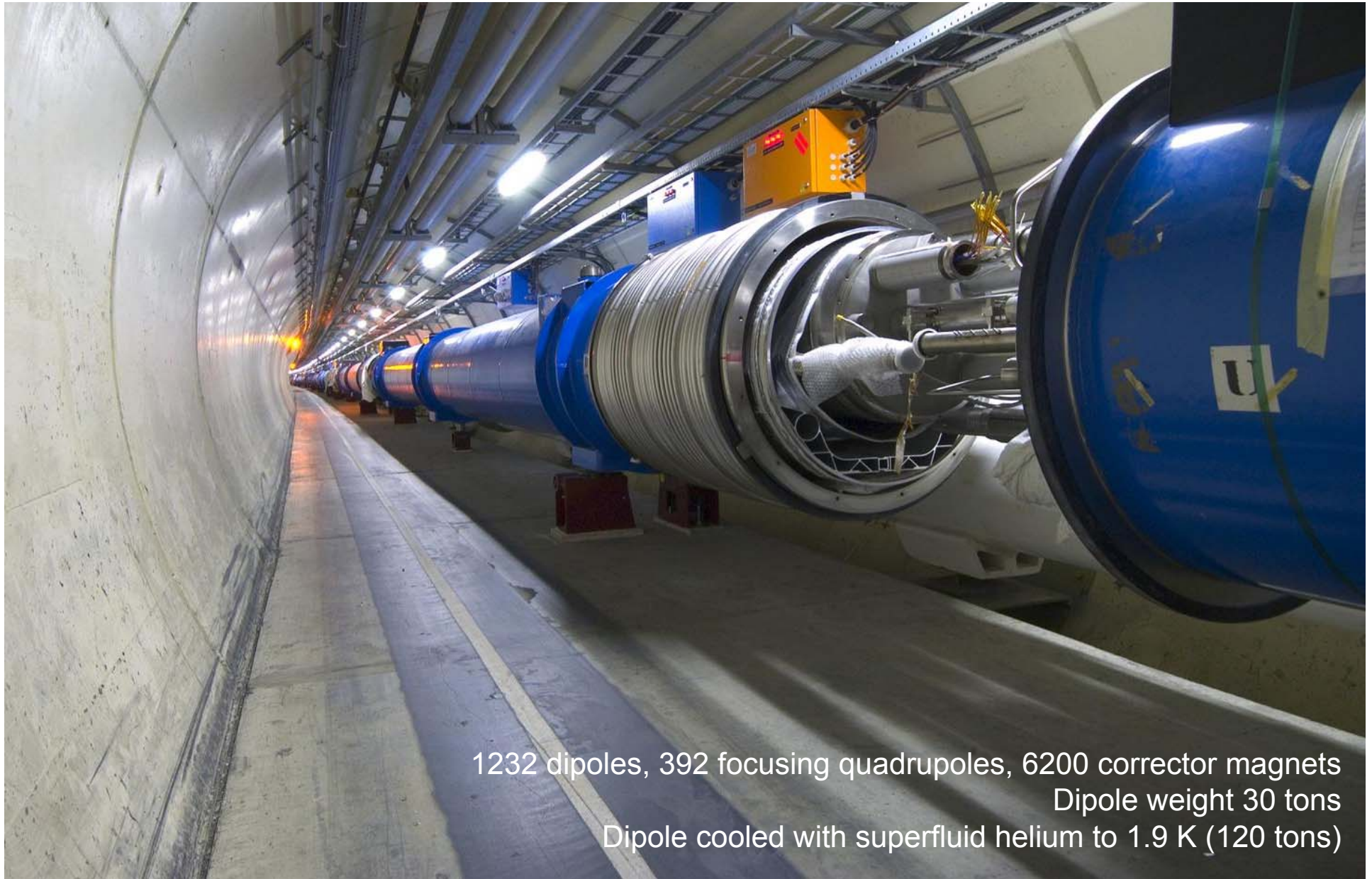
LIN-
AC2



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

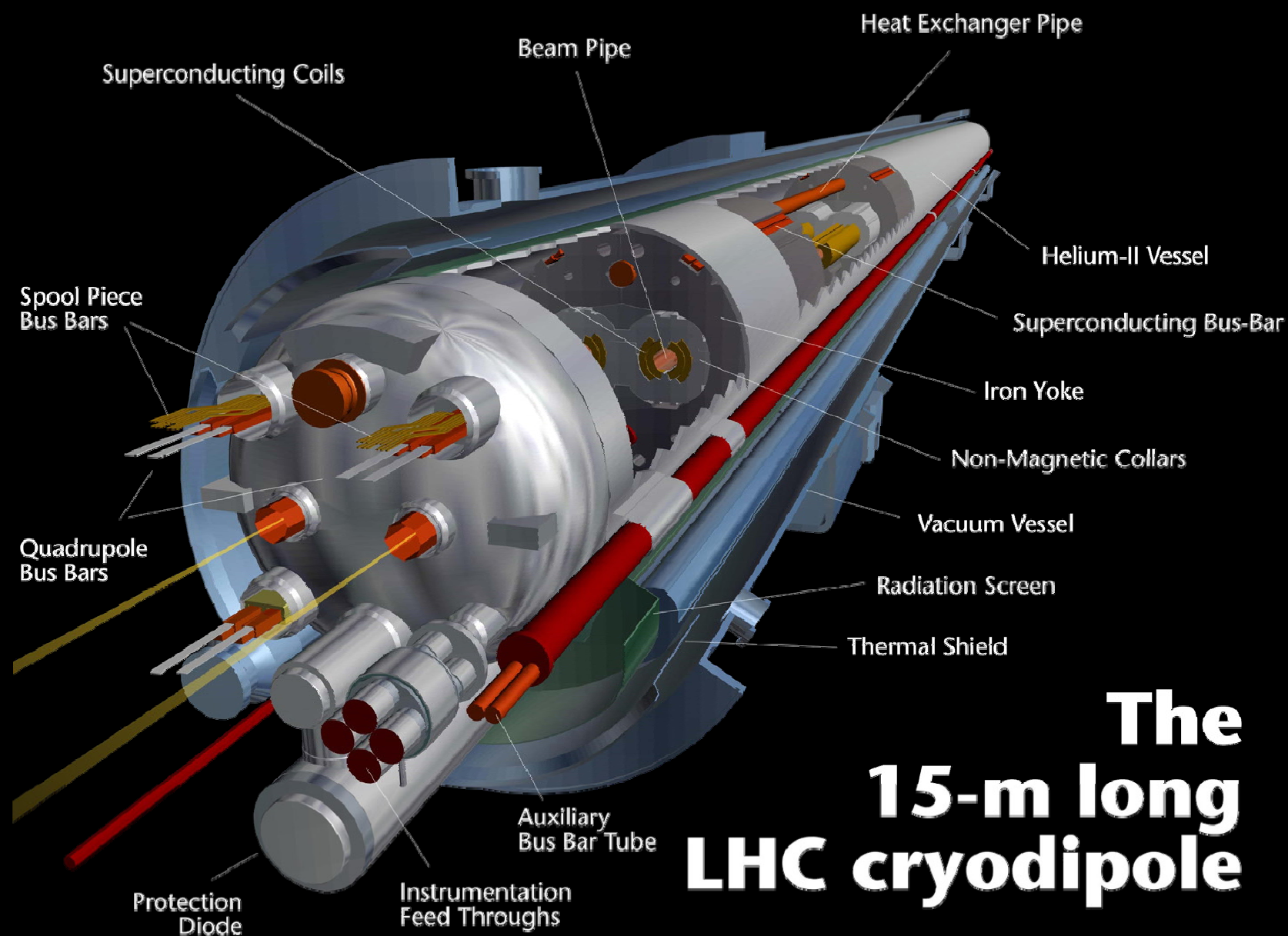


The LHC — Dipole Section



1232 dipoles, 392 focusing quadrupoles, 6200 corrector magnets
Dipole weight 30 tons
Dipole cooled with superfluid helium to 1.9 K (120 tons)

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): $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - ➡ Tevatron/SppbarS: $2.5 \times 10^{32} / 6 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$

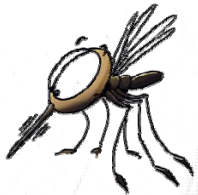
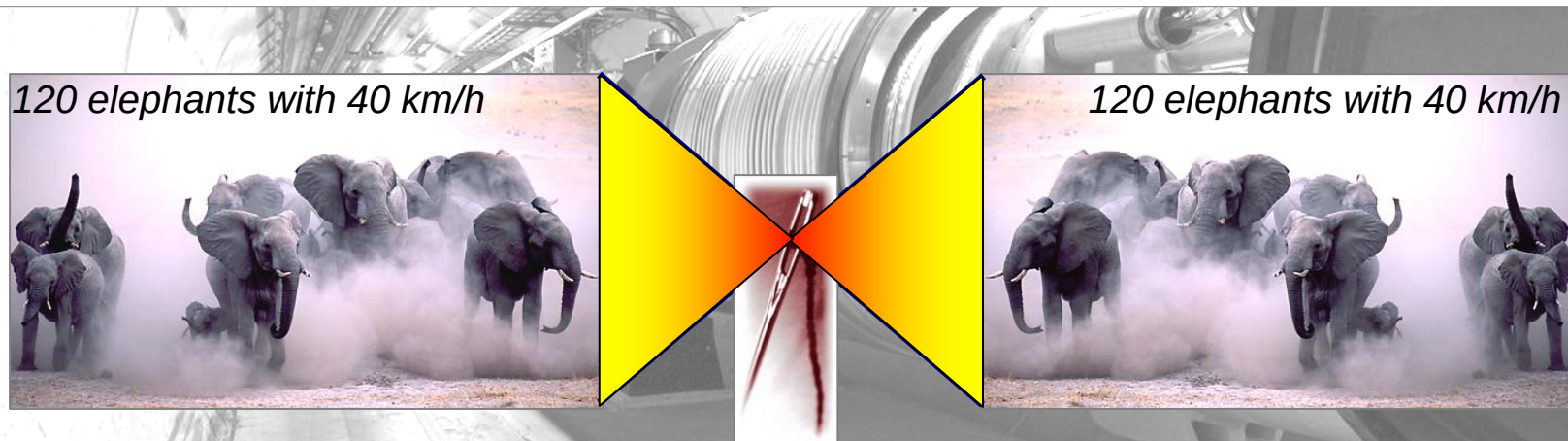
The combination of very high field magnets and very high beam intensities required to reach luminosity targets makes LHC operation a great challenge

The LHC — Stored Energy

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

➡ 350 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 10x smaller: **0.03 mm diameter**

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

The LHC — Pictures



Dipole storage on car-parks all over CERN

The LHC — Pictures



Lowering through an elliptical shaft

The LHC — Pictures

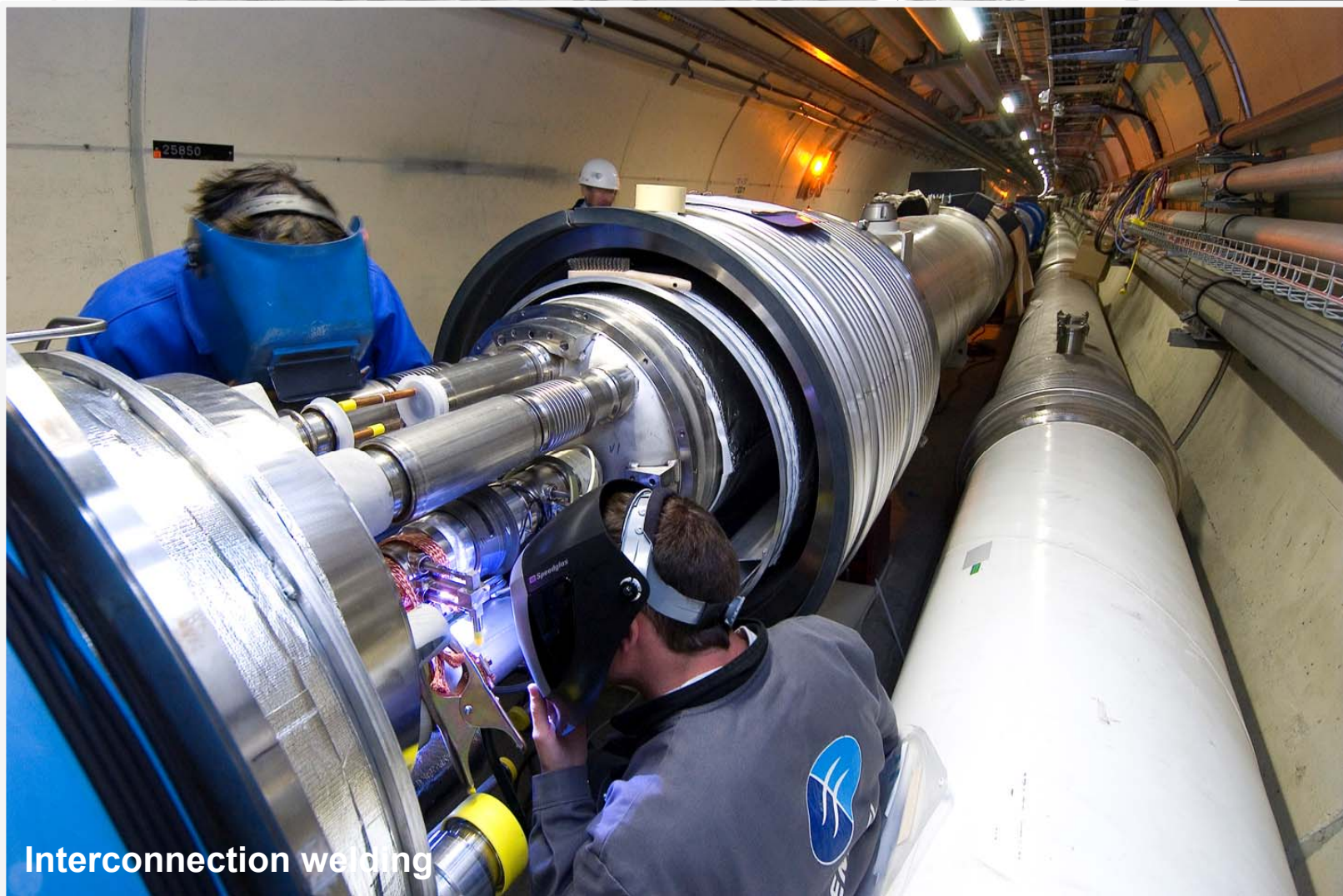


The LHC — Pictures



Quality Control

The LHC — Pictures



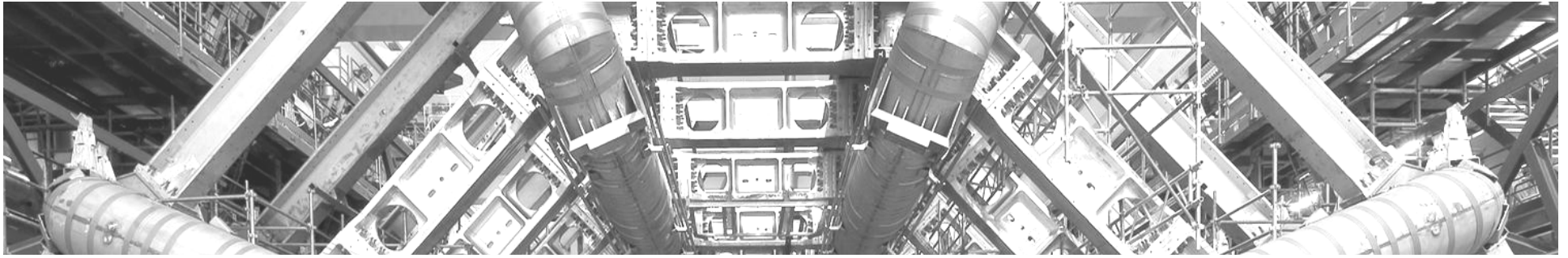
Interconnection welding

The LHC — Pictures



The LHC — Pictures



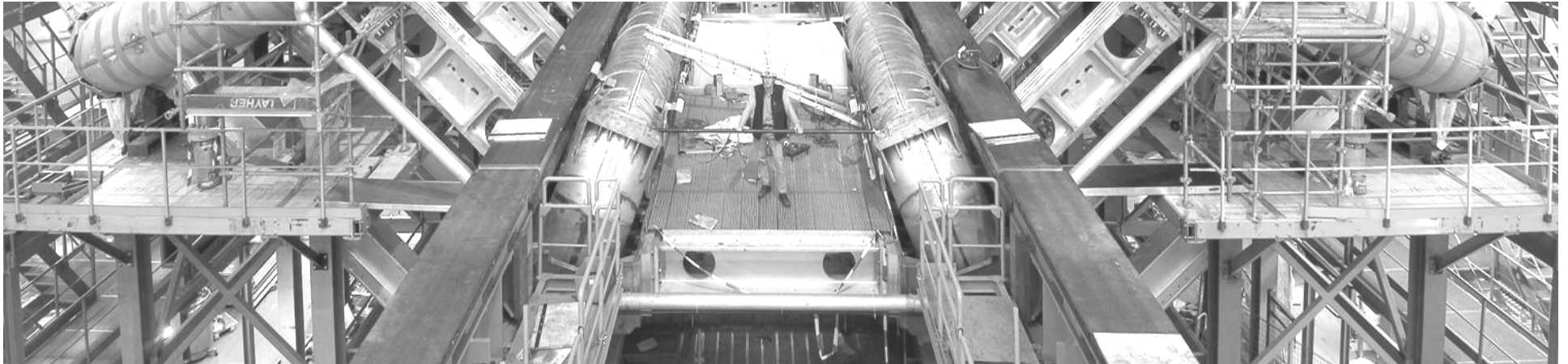


The High- p_T LHC Detectors

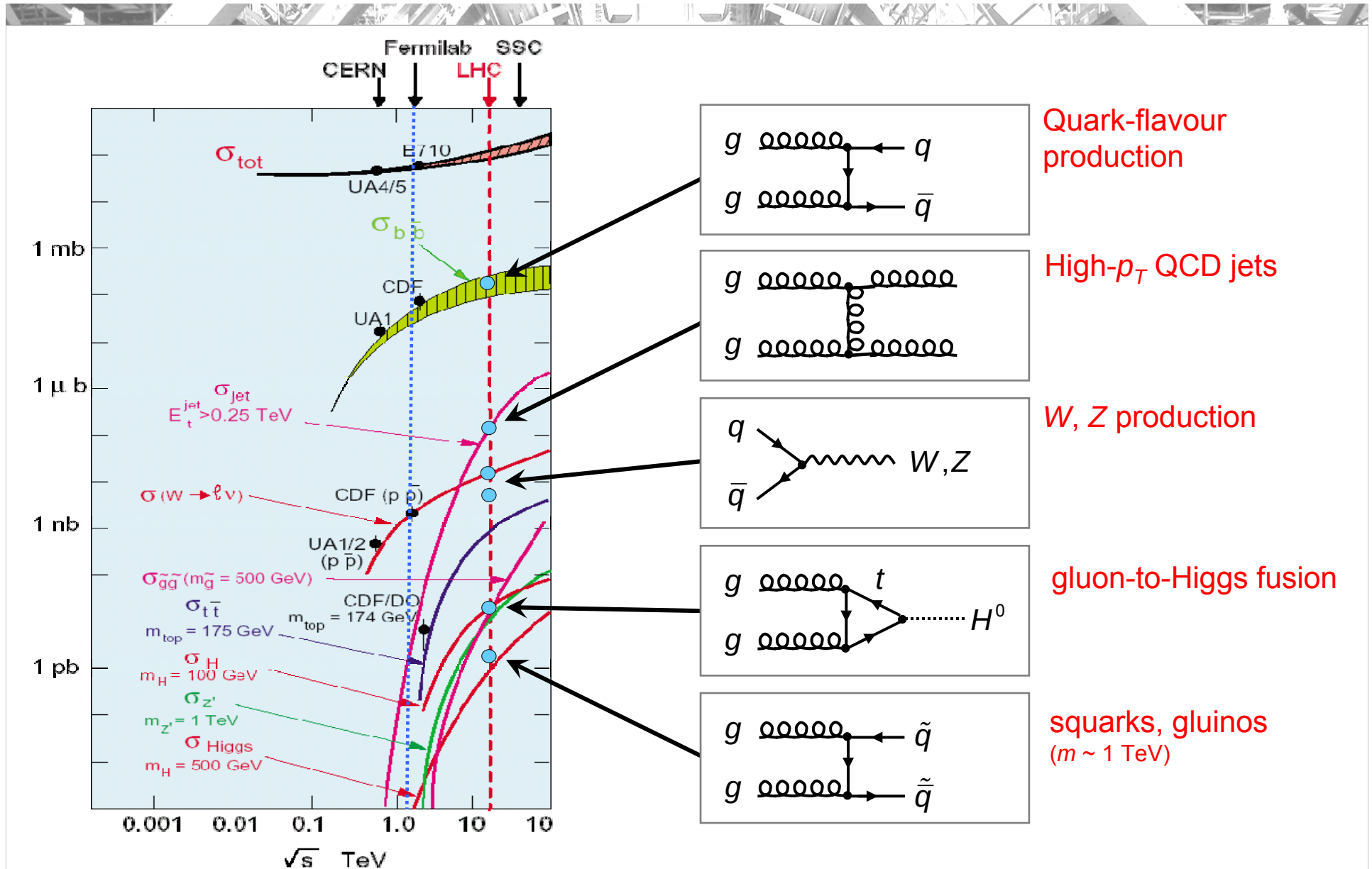


ATLAS and CMS are “general purpose detectors”, capable of adequately covering the entire physics programme reachable with high-luminosity 14 TeV pp collisions

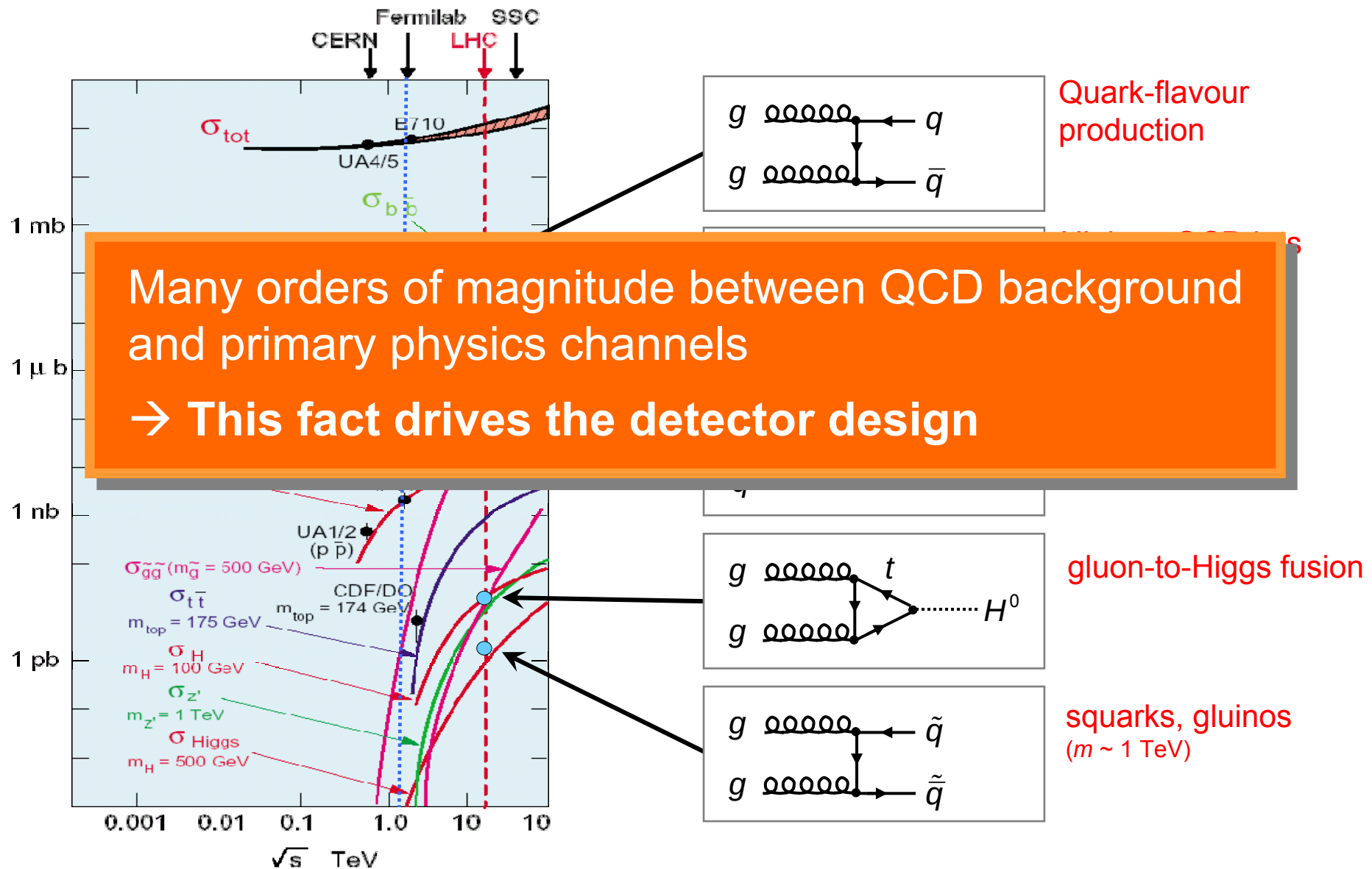
- ➡ From charm and beauty physics at lowest transverse momenta (~ 3 GeV) ...
- ➡ ... to New Physics searches up to the highest reachable scales (~ 4 TeV)



Cross Sections



Cross Sections



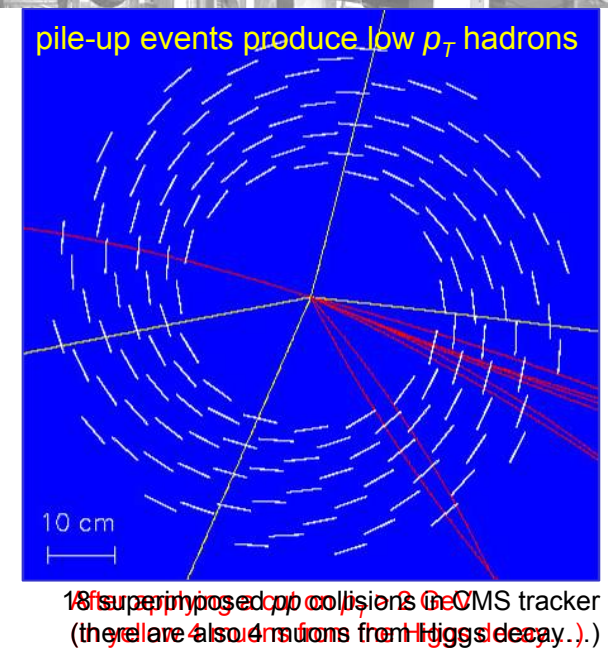
Principles of Particle Detection

Basic detector concepts:

- Symmetric beams → symmetric detector, geometry pointing w.r.t. to collision point
- Collision products move from the collision point outwards
- Tracking detectors measure trajectories of charged particles bending in magnetic field
- Calorimeters measure electron, photon, hadron energy deposits
- Tracks of remaining (unabsorbed) muons are measured

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



Requirements from LHC Conditions

■ LHC and data conditions:

- ➡ **40 MHz bunch crossing rate**
(25ns = 7.5m bunch spacing)
- ➡ **~1 GHz interaction rate at $L = 10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$** (~25 ias. per bunch crossing)
- ➡ **~300 Mbytes/seconds data rate**
(200 Hz $\times$ $O(1.5 \text{ MB/event})$)
- ➡ **Irradiation rate / 10 LHC years:**
 $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (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 $< 2.5\mu\text{s}$**
- Efficient pattern recognition to reduce:**
GHz $\rightarrow$ L1 $\rightarrow$ 75 kHz $\rightarrow$ HLT $\rightarrow$ 200 Hz $\rightarrow$ 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**

Requirements from Physics Programme

■ Some benchmark analyses:

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

■ Design challenges:

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

Requirements from Physics Programme

■ Some benchmark analyses:

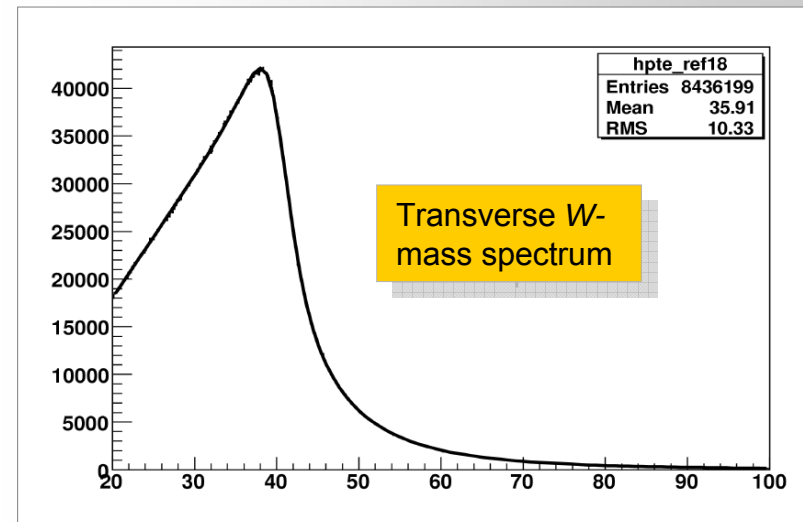
➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

➡ 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**, **resolution and low noise**



Requirements from Physics Programme

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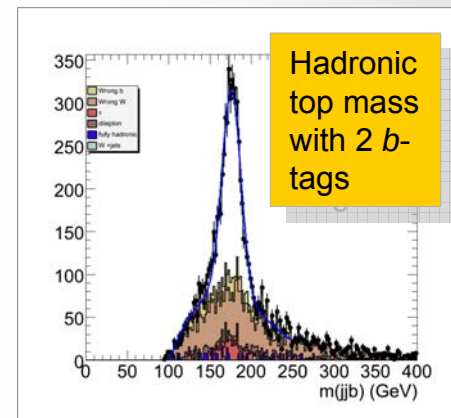
➡ top mass

■ Design challenges:

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

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

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



Requirements from Physics Programme

■ Some benchmark analyses:

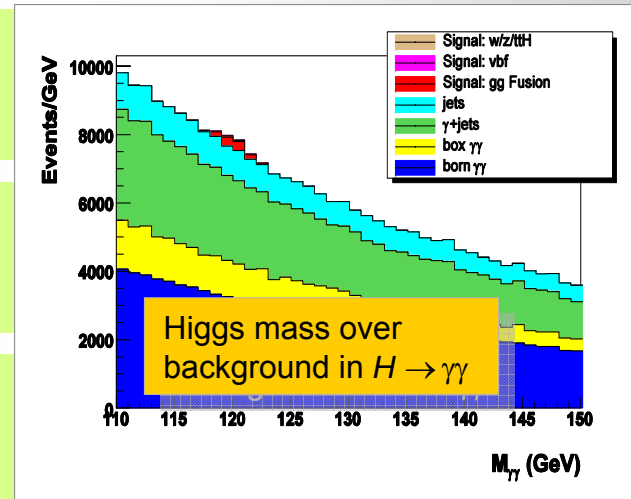
➡ $B_{s(d)} \rightarrow \mu\mu$ and $B_s \rightarrow J/\psi \phi$

➡ W mass

➡ top mass

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

■ Design challenges:



purity
(B mass)

perimeter
noise

energy
at b -tagging

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

Requirements from Physics Programme

■ Some benchmark analyses:

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

➡ W mass

➡ top mass

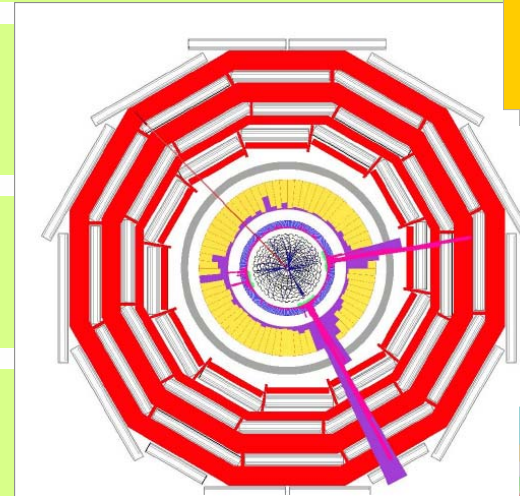
➡ $H \rightarrow \gamma\gamma, 4e, 4\mu, \tau\tau$ (VBF)

➡ 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



eter

noise

e energy
nt b -tagging

ormity,
ward jets

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

Requirements from Physics Programme

■ Some benchmark analyses:

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

➡ W mass

➡ top mass

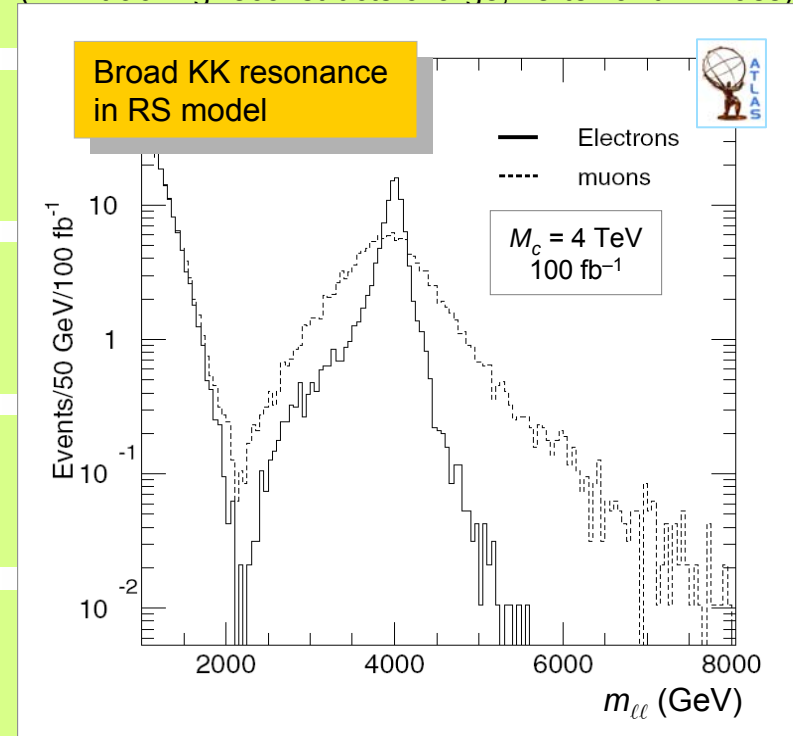
➡ $H \rightarrow \gamma\gamma, 4e, 4\mu, \tau\tau$ (VBF)

➡ SUSY with R -parity, SUSY Higgs

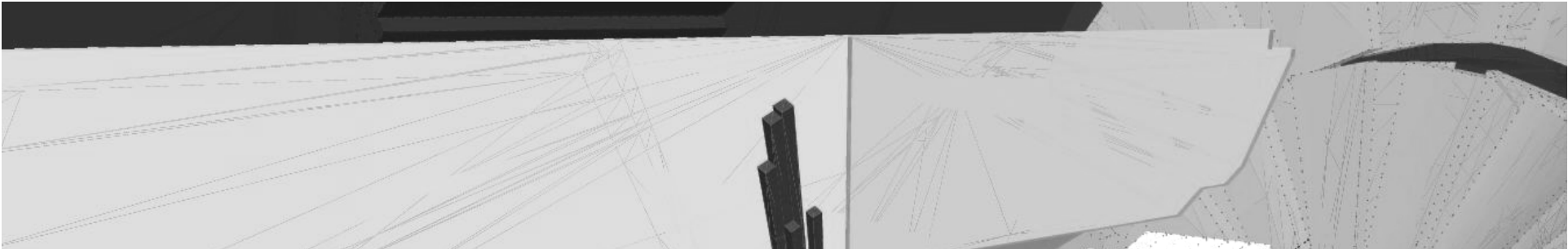
➡ RS KK modes

■ Design challenges:

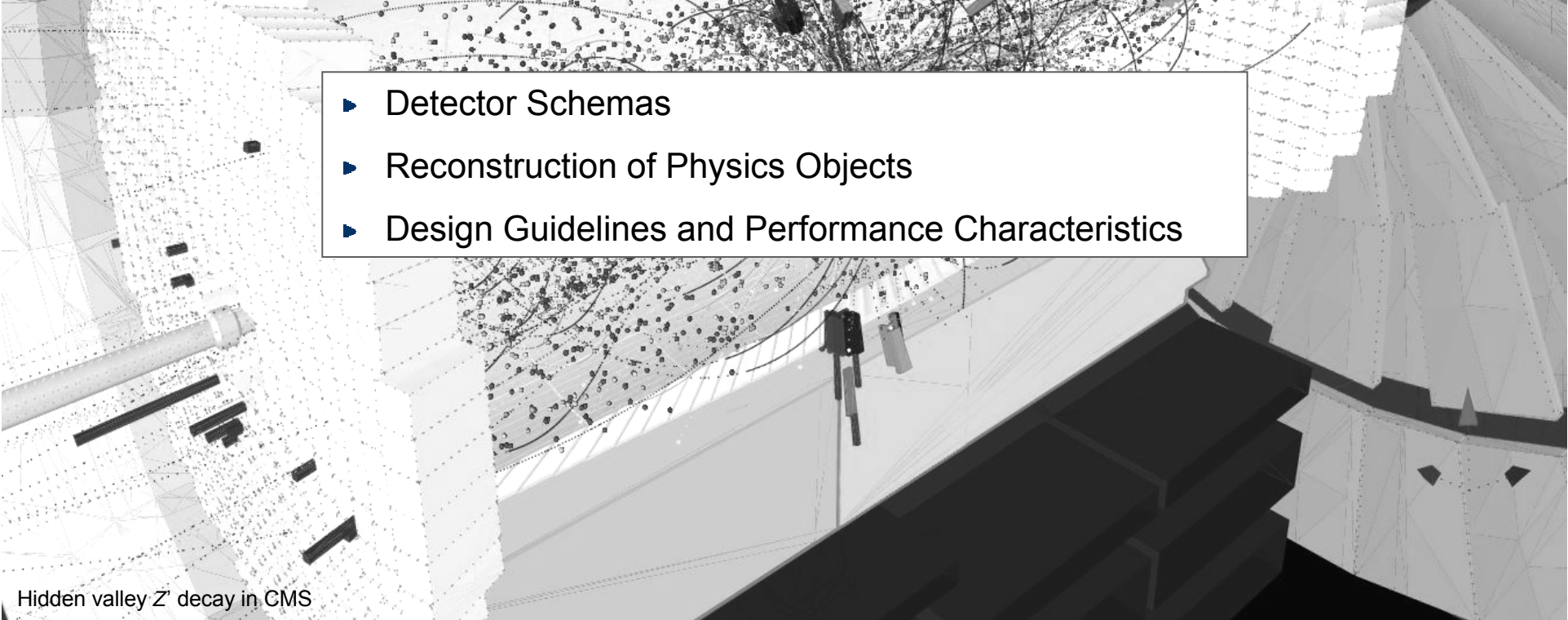
Trigger efficiency ($p_T(\mu) > 3$ GeV) and purity
(HLT tracking reconstructs charge, vertex and B mass)



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



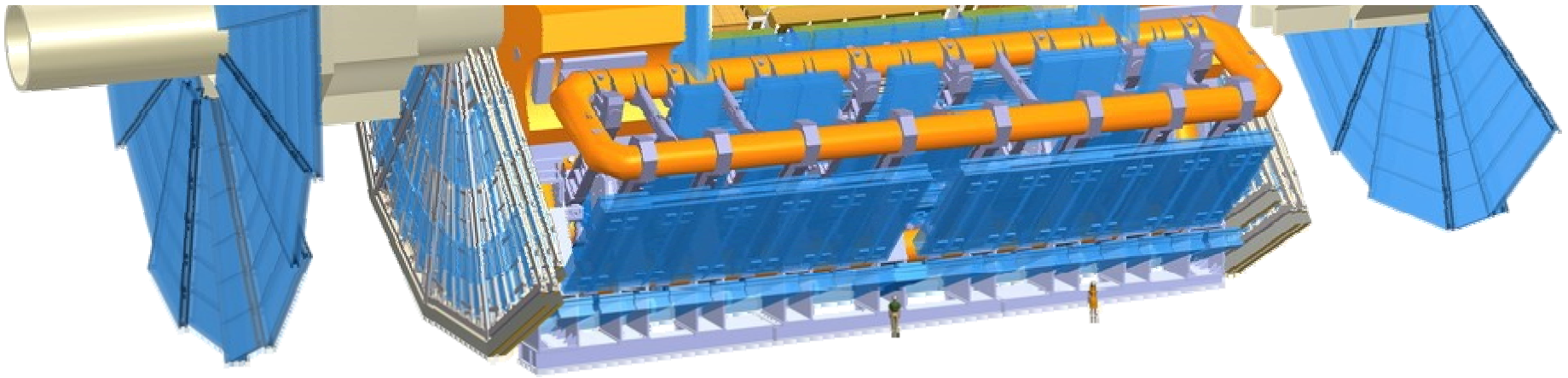
Trading the Requirements ATLAS & CMS

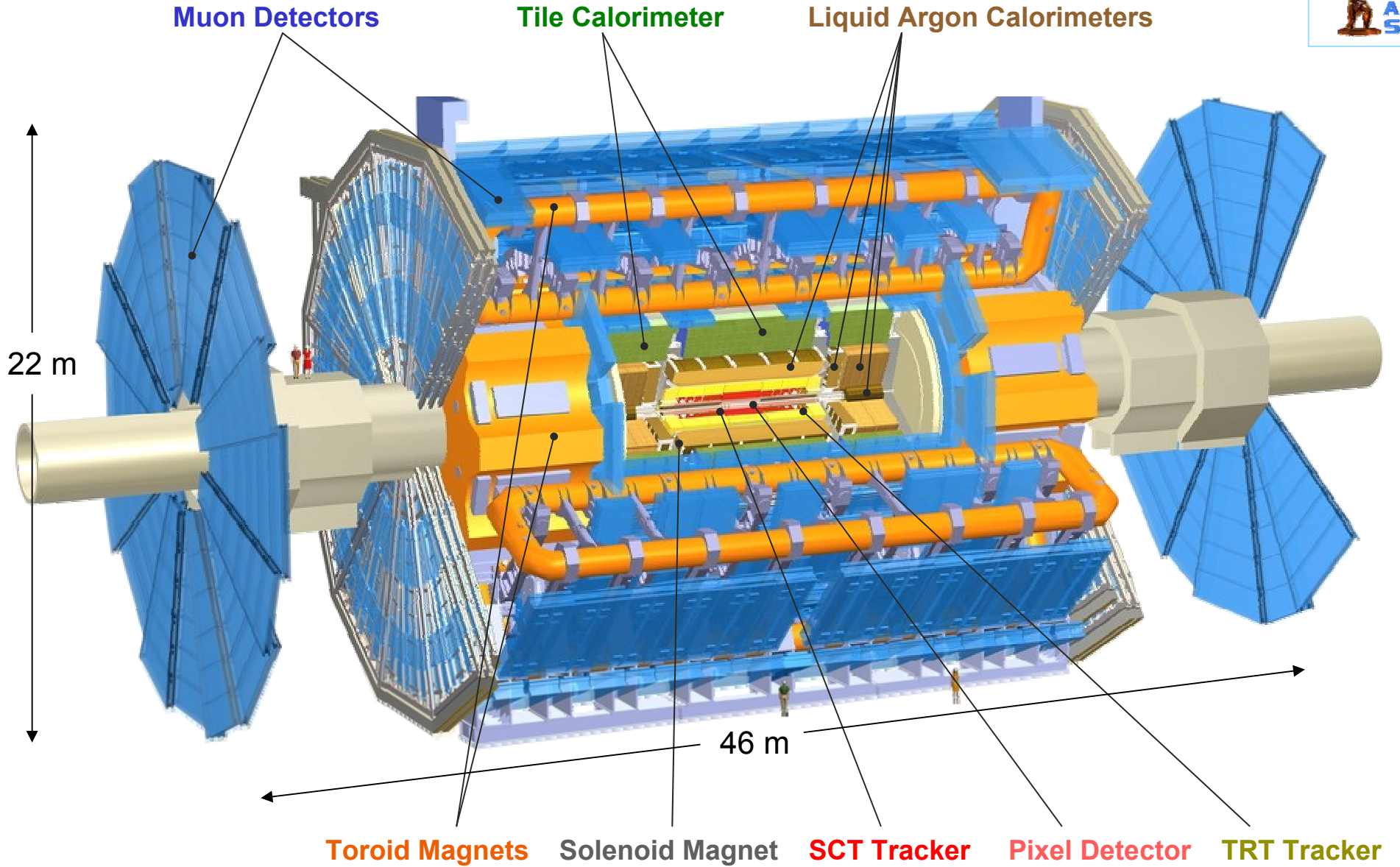
- 
- ▶ Detector Schemas
 - ▶ Reconstruction of Physics Objects
 - ▶ Design Guidelines and Performance Characteristics

Hidden valley Z' decay in CMS



The ATLAS Experiment





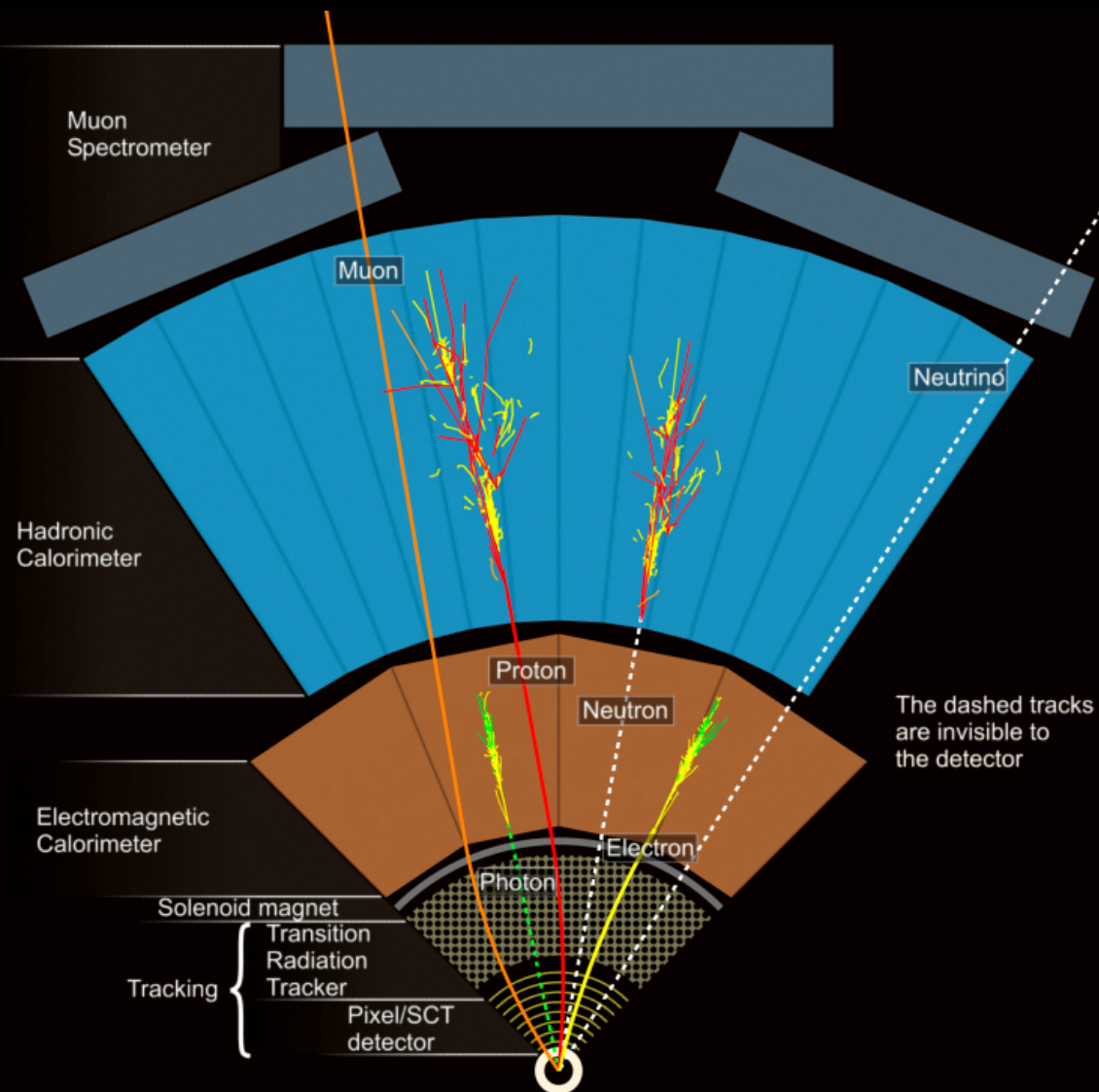
ATLAS Detector Layers

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

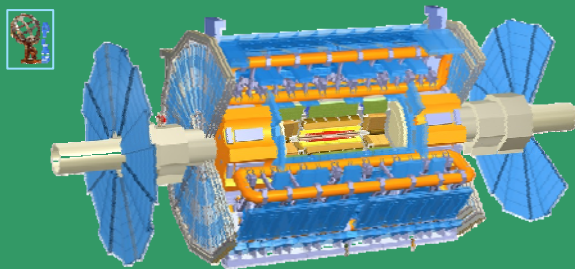


ATLAS & CMS: Design & Performance Overview

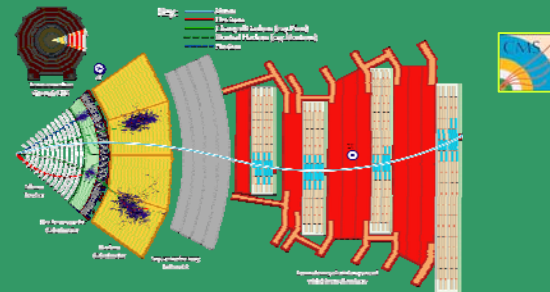
	ATLAS (7 ktons) 	CMS (12.5 ktons) 
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • $B = 2\text{T}$ • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • $B = 4\text{T}$ • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
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)

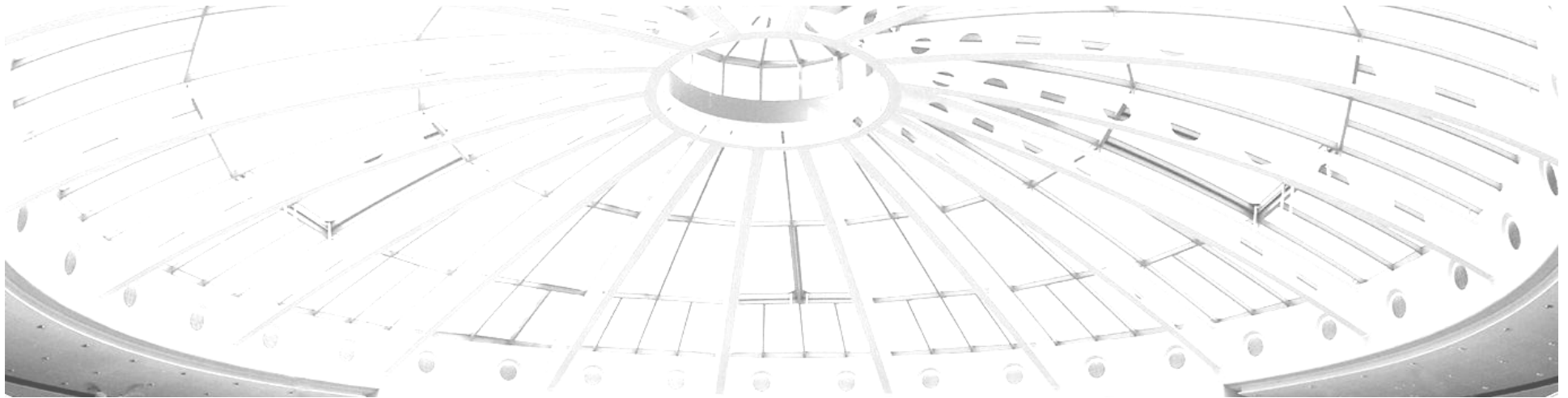
ATLAS & CMS: Design & Performance Overview



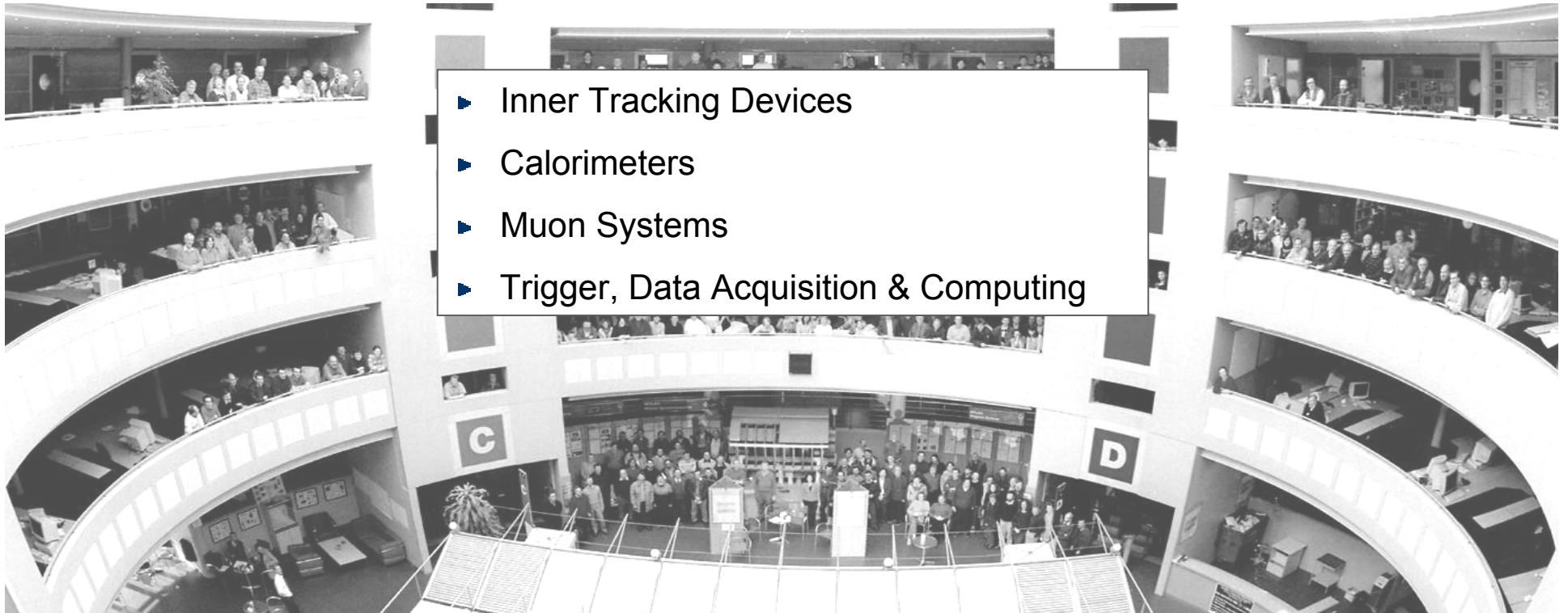
ATLAS: emphasis on excellent jet and missing- E_T resolution, and on particle identification



CMS: emphasis on excellent electron/photon and muon resolution



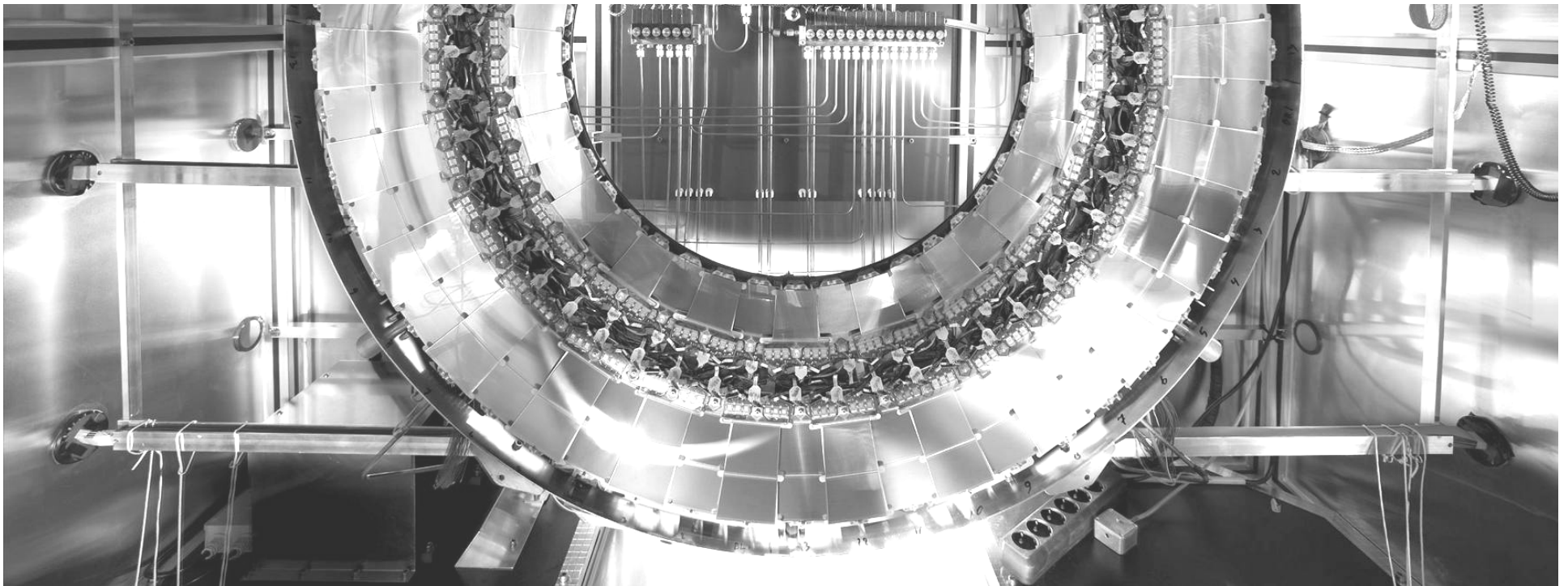
ATLAS – Specific Systems



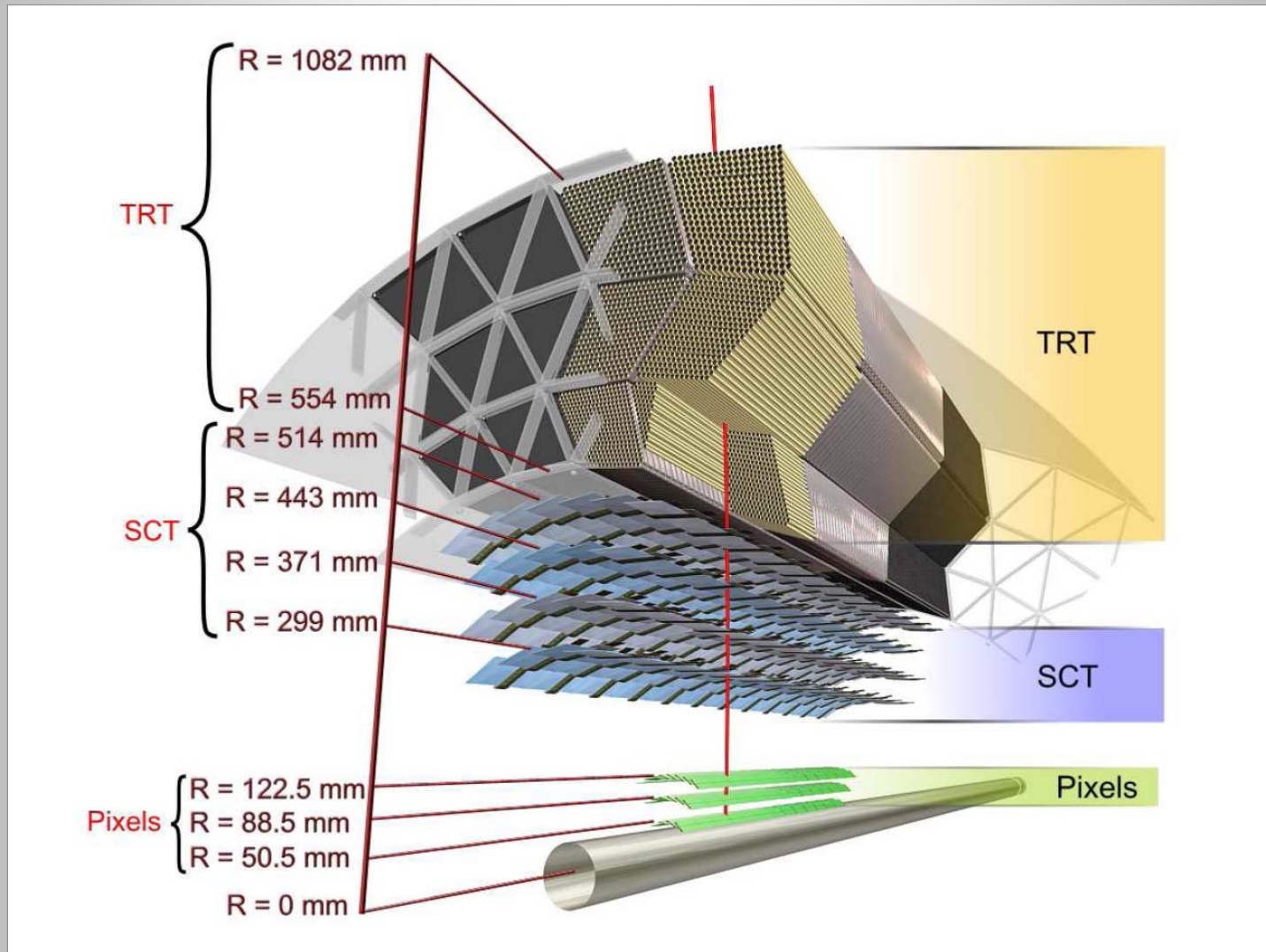
- ▶ Inner Tracking Devices
- ▶ Calorimeters
- ▶ Muon Systems
- ▶ Trigger, Data Acquisition & Computing



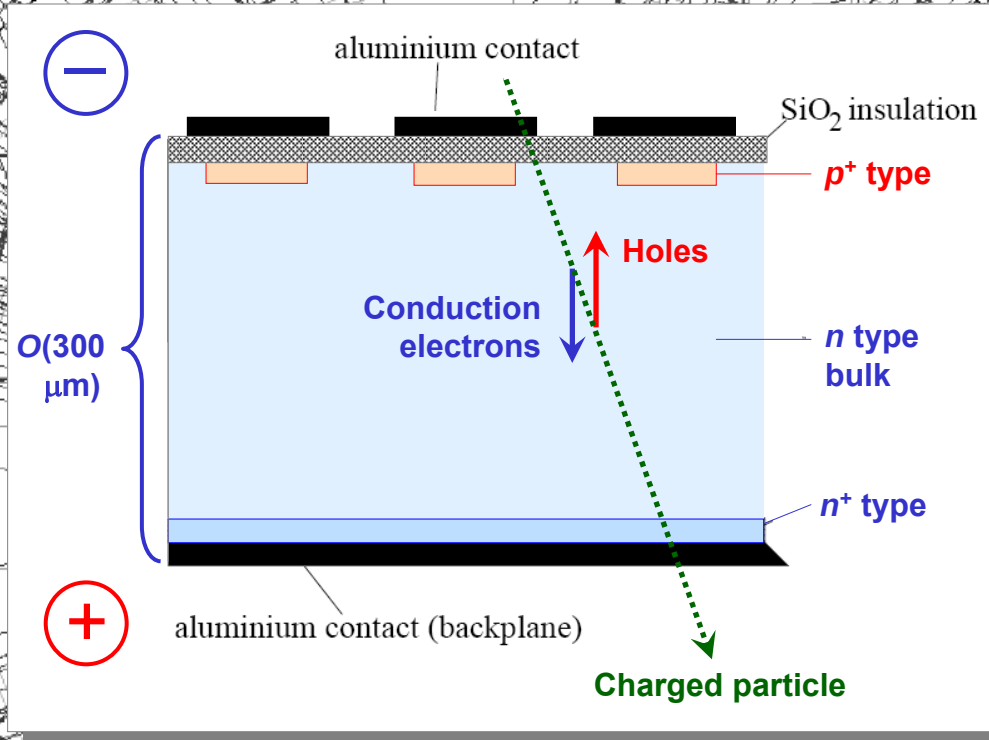
Inner Tracking Devices



The ATLAS Inner Tracker (Barrel)



Silicon Detectors

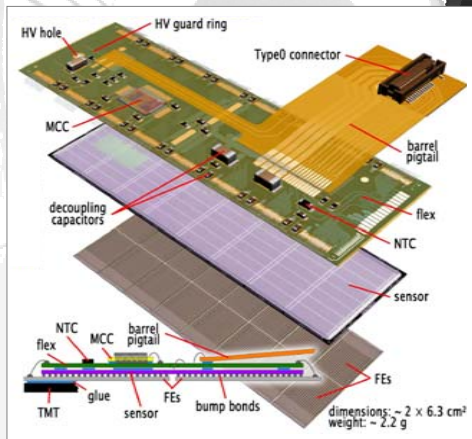


- ATLAS & CMS pixel detectors are among 1st generation of high-rate pixel devices
- Its basic unit is a module with 46 000 channels (pixels) each

The ATLAS Pixel Detector

Length: 1.3 m, weight: ~4.4 kg, $\varnothing$: 34.4 cm

2x3 Endcap disks,
each with 8 sectors
and 48 modules

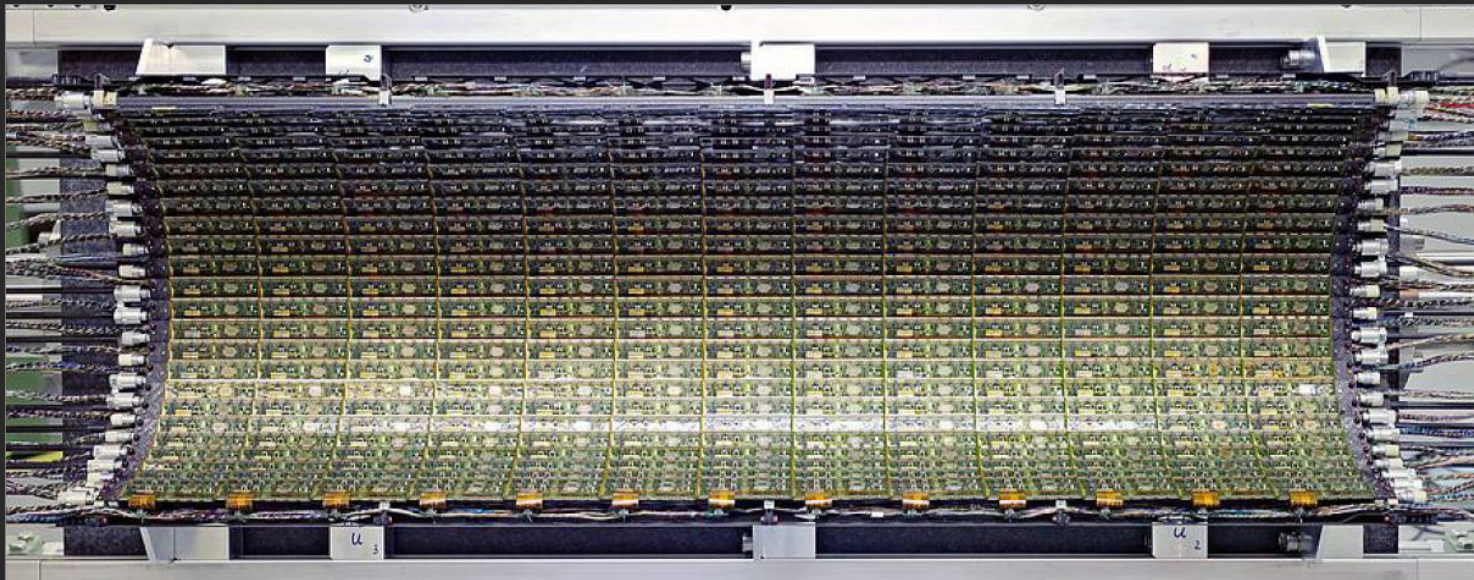


80 million channels

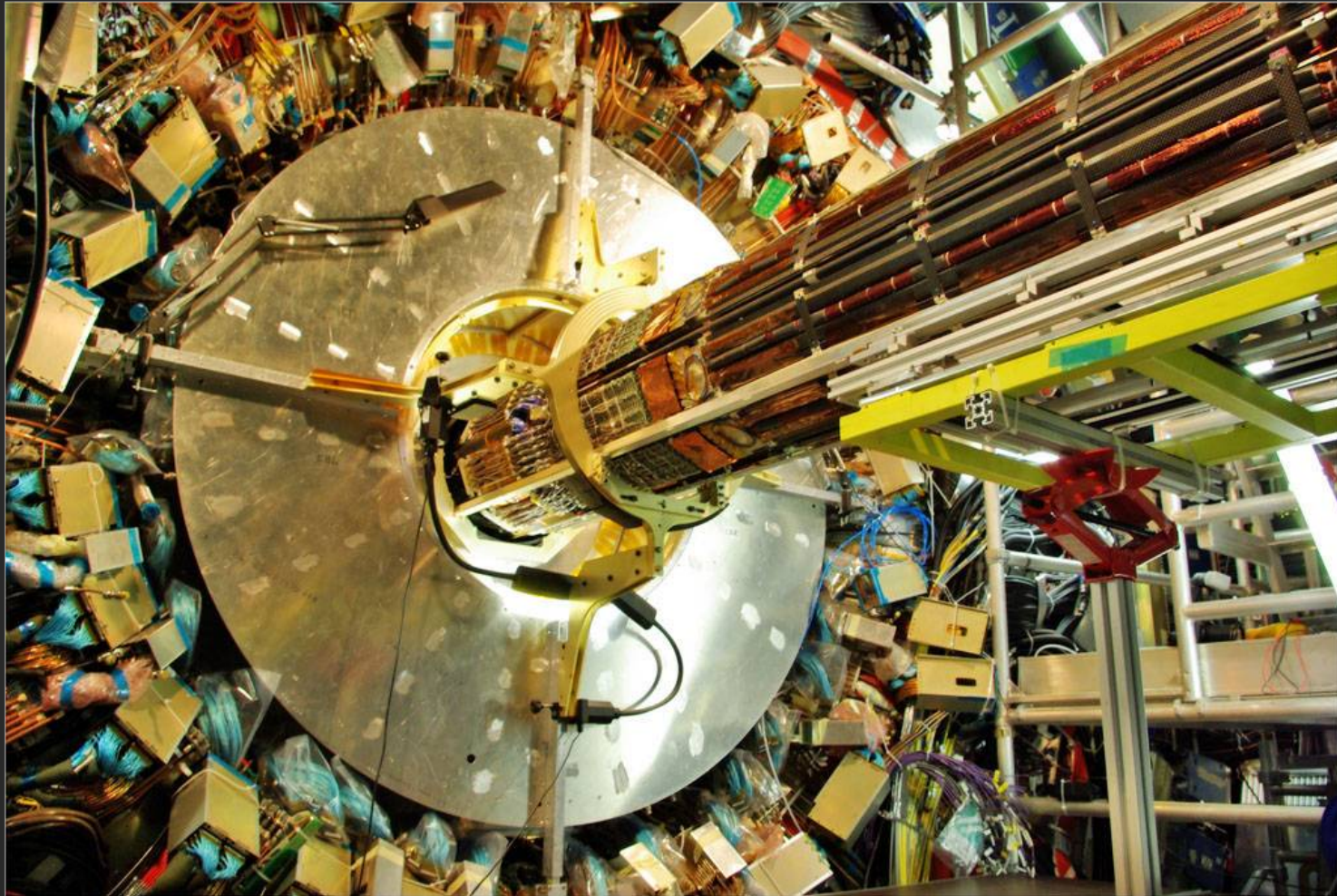
Typical resolution (barrel):
 $10 \mu\text{m}$ [$r\phi$], $115 \mu\text{m}$ [z]

3 Barrel layers ($r = 5, 9, 12 \text{ cm}$),
 $\Sigma = 1456$ barrel modules

Pixel Pictures

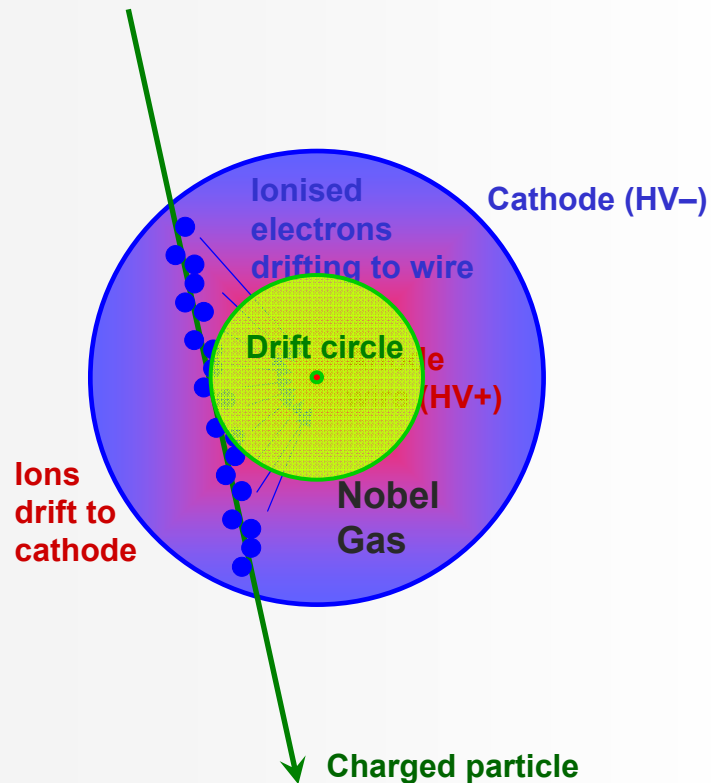


Pixel Pictures



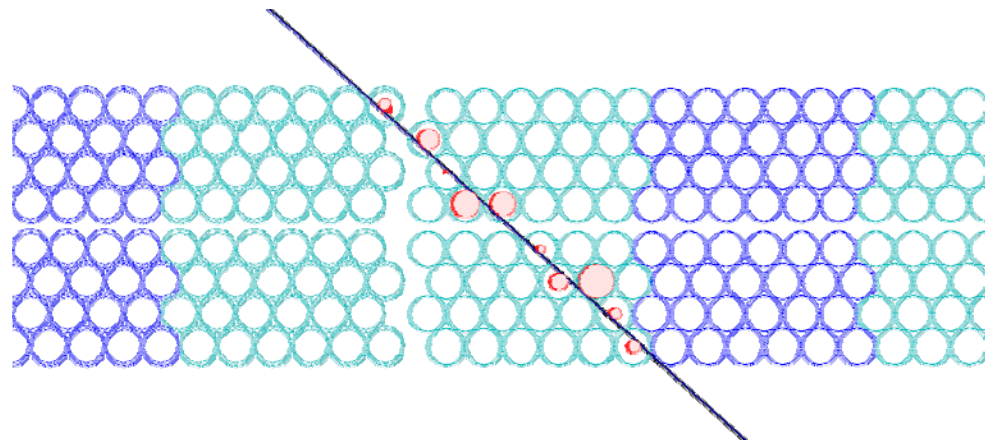
Drift Tubes (DT)

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



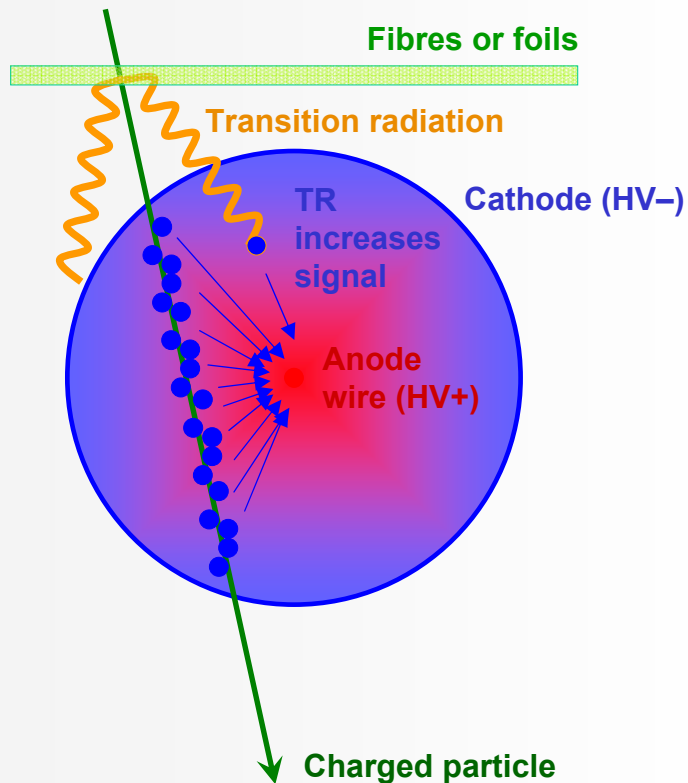
TRT: Kapton tubes, $\varnothing = 4 \text{ mm}$
MDT: Aluminium tubes, $\varnothing = 30 \text{ mm}$

Example: muon in ATLAS Muons chambers

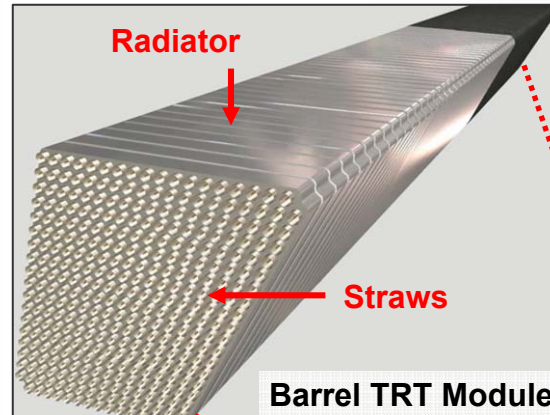


Combining Tracking with PID: the ATLAS TRT

- 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

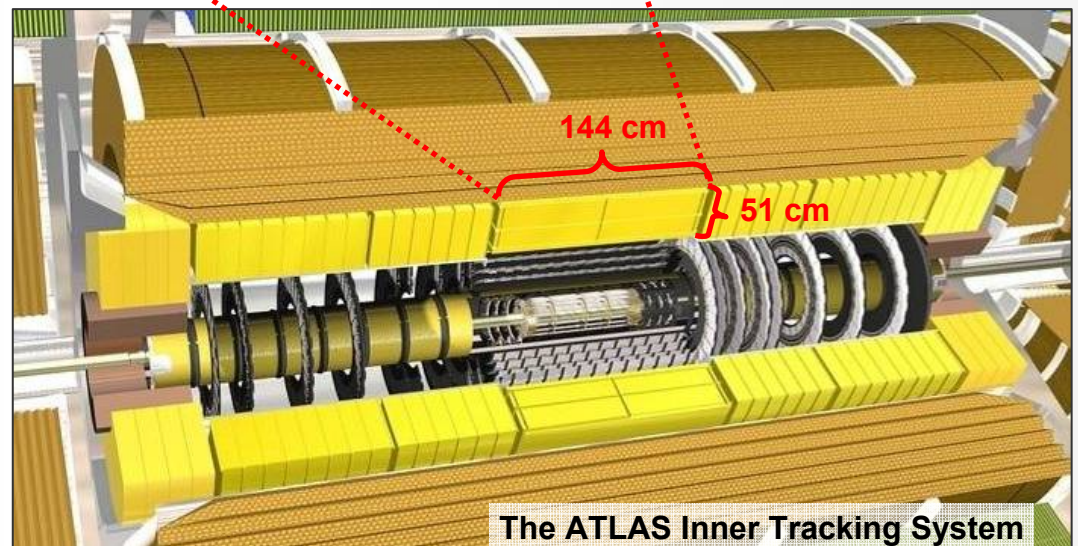


Total: 370k straws

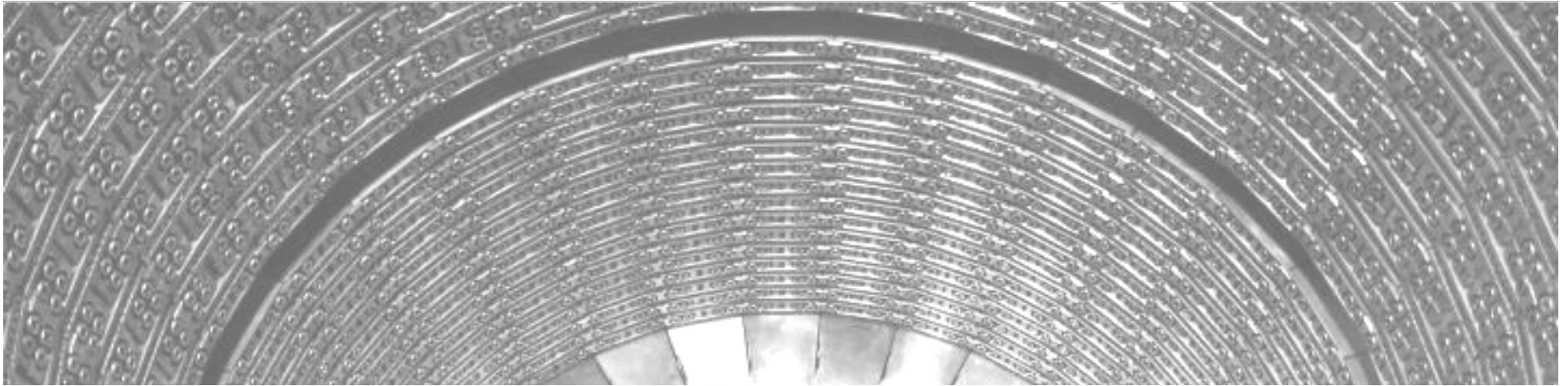
Barrel ($|\eta| < 0.7$): 36 r - ϕ
measurements / track

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

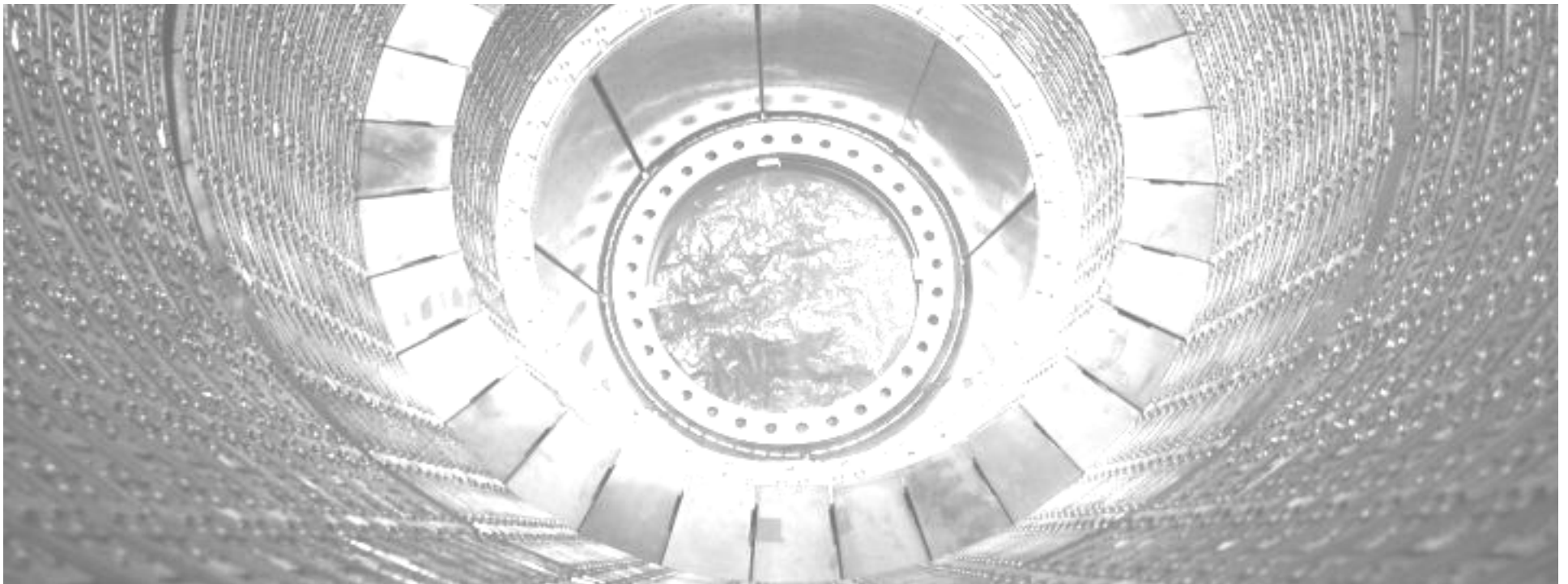
18 Endcap wheels ($|\eta| < 2.5$): 35 or less z - ϕ points



The ATLAS Inner Tracking System



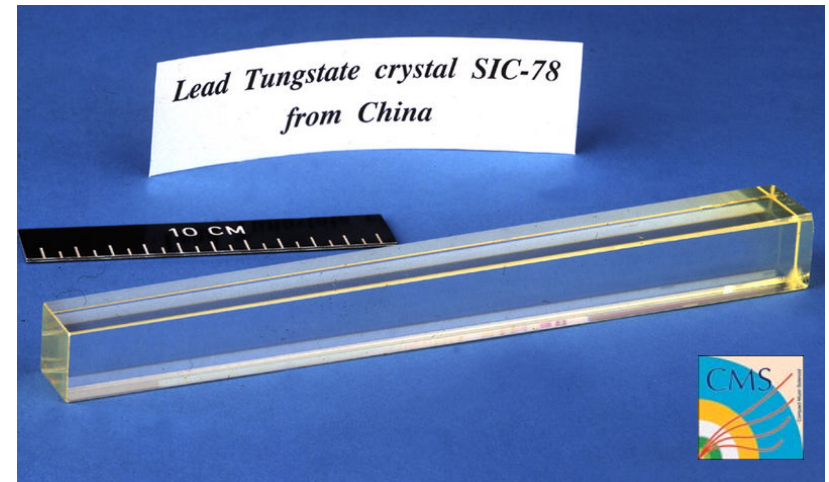
Calorimeters



ATLAS and CMS EM Calorimeters

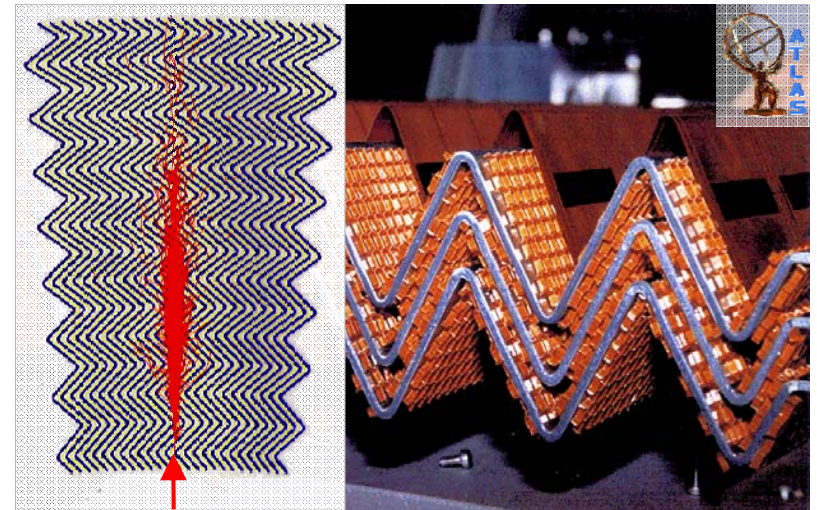
■ CMS: PbWO_4 Scint. Crystal Calorimeter

- Excellent energy resolution: entire shower in active detector material
- Excellent granularity (barrel: $\Delta\eta \times \Delta\phi = 0.017^2$ rad)
- No longitudinal segmentation

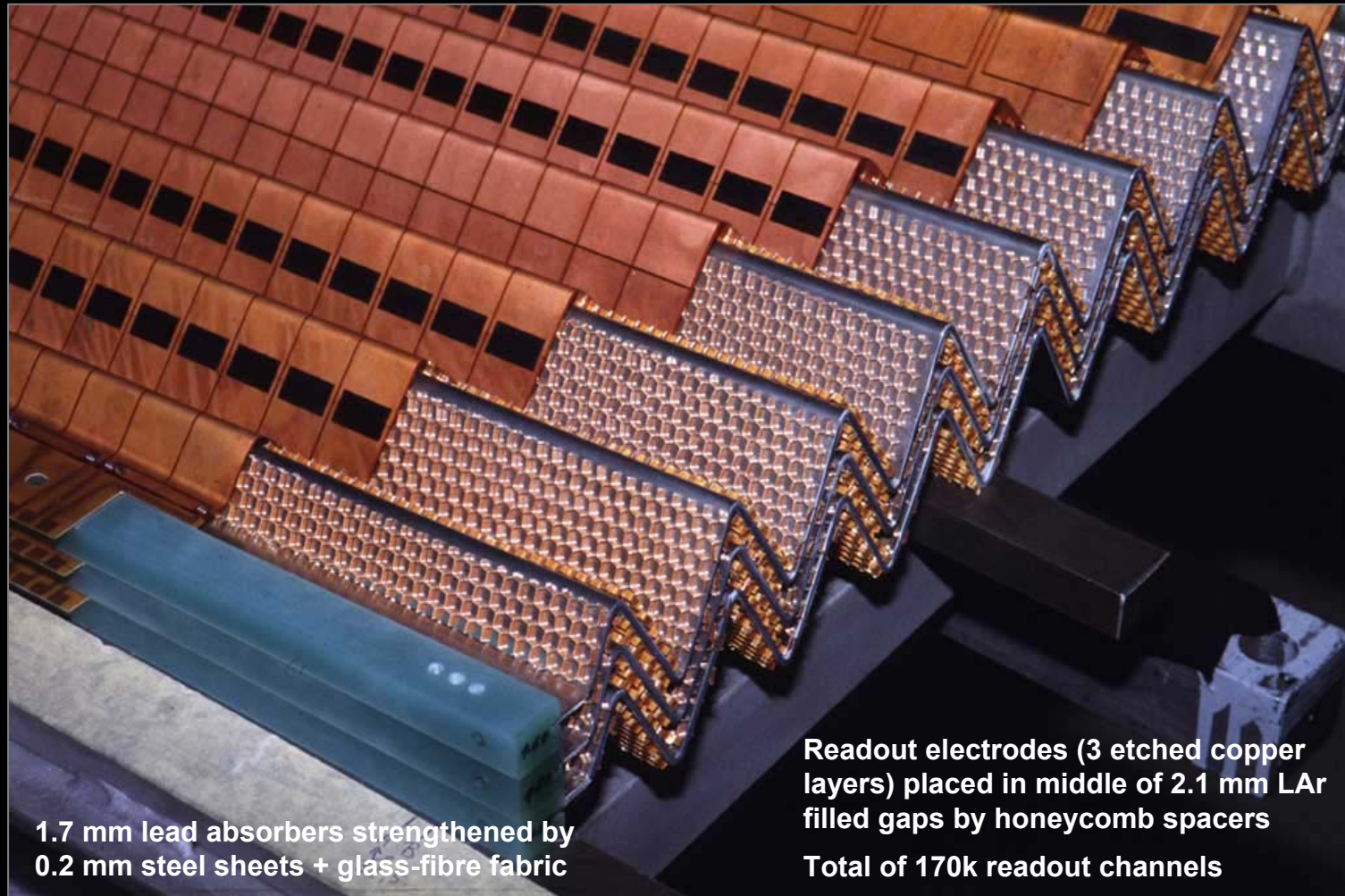


■ ATLAS: LAr Sampling Calorimeter

- Passive, heavy absorber (Pb, 1.1–1.5 mm thick [barrel]) inter-leaved with active detector material (liquid argon)
- Granularity (Barrel: $\Delta\eta \times \Delta\phi = 0.0252$ rad)
- Longitudinally segmented (3 layers + preshower)



ATLAS Liquid Argon EM Calorimeter

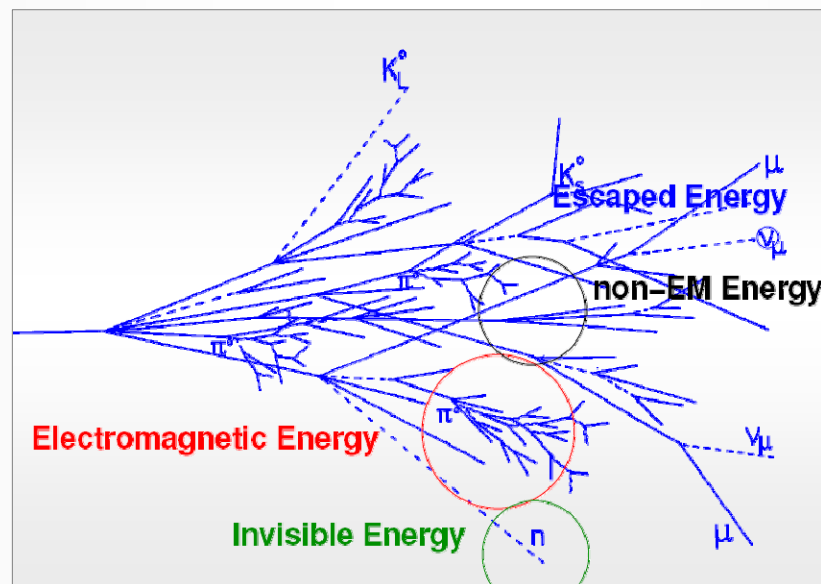


1.7 mm lead absorbers strengthened by
0.2 mm steel sheets + glass-fibre fabric

Readout electrodes (3 etched copper
layers) placed in middle of 2.1 mm LAr
filled gaps by honeycomb spacers
Total of 170k readout channels

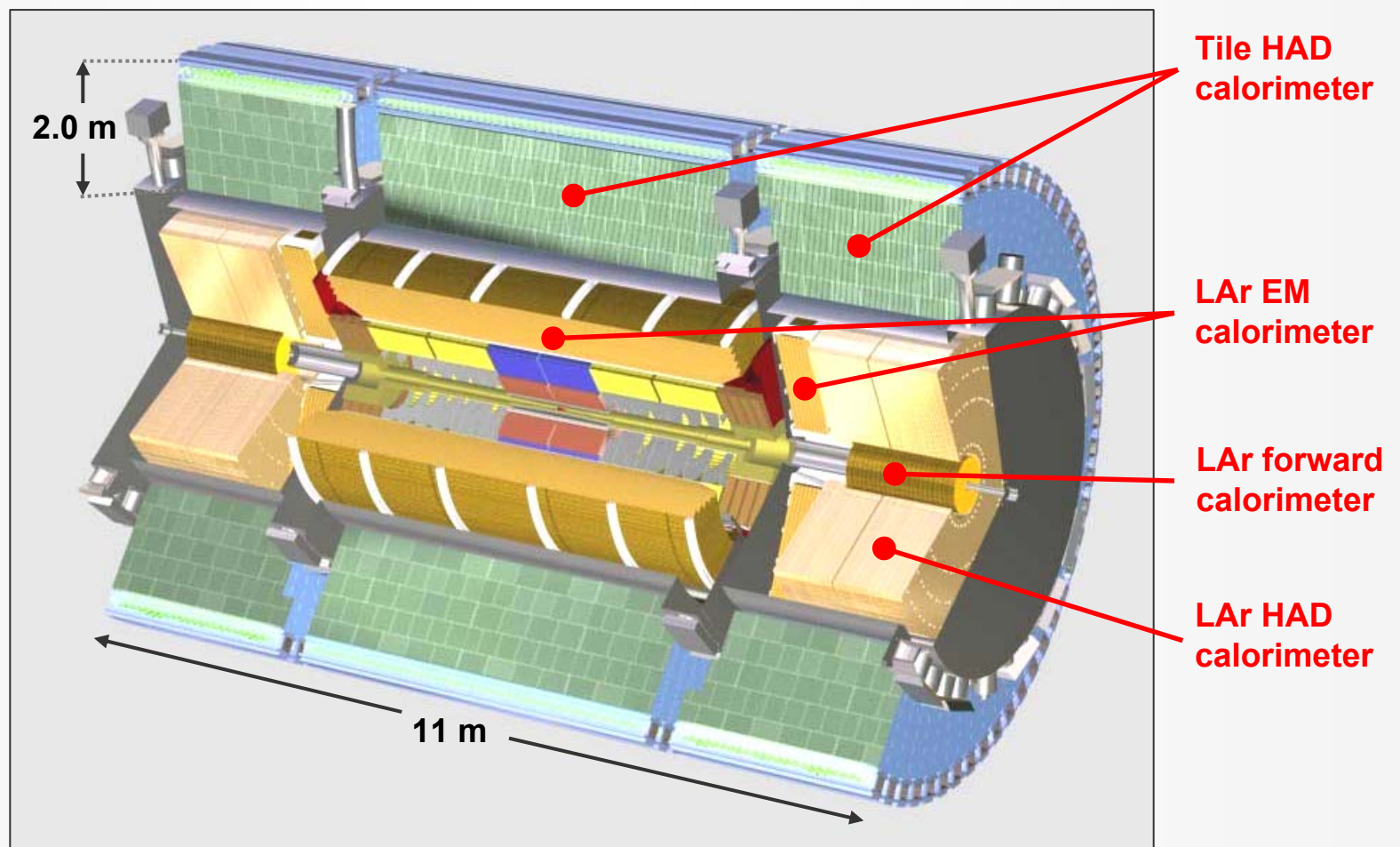
Hadronic Calorimeters

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



Hadronic Calorimeters

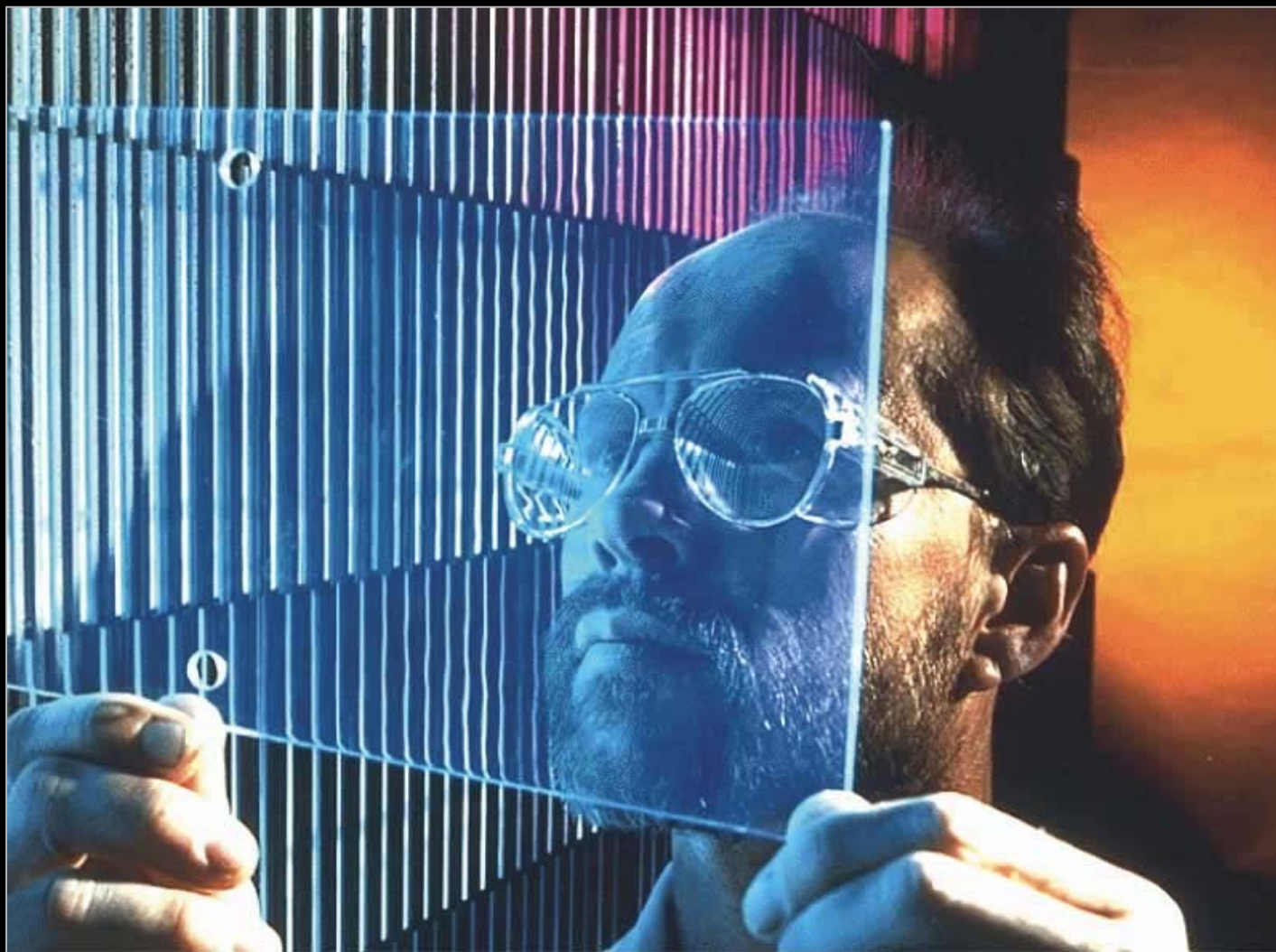
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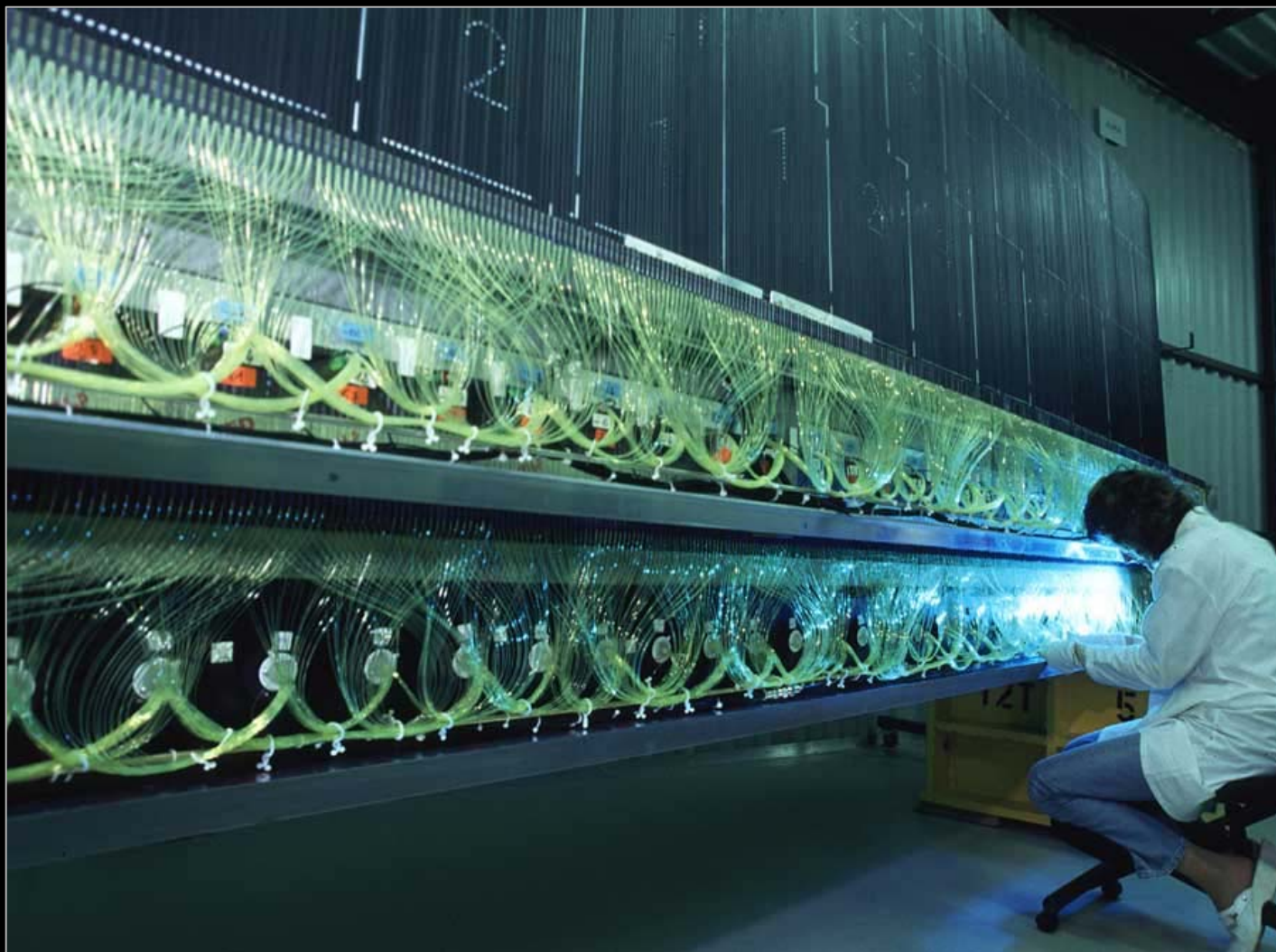
The ATLAS Tile Hadronic Calorimeter



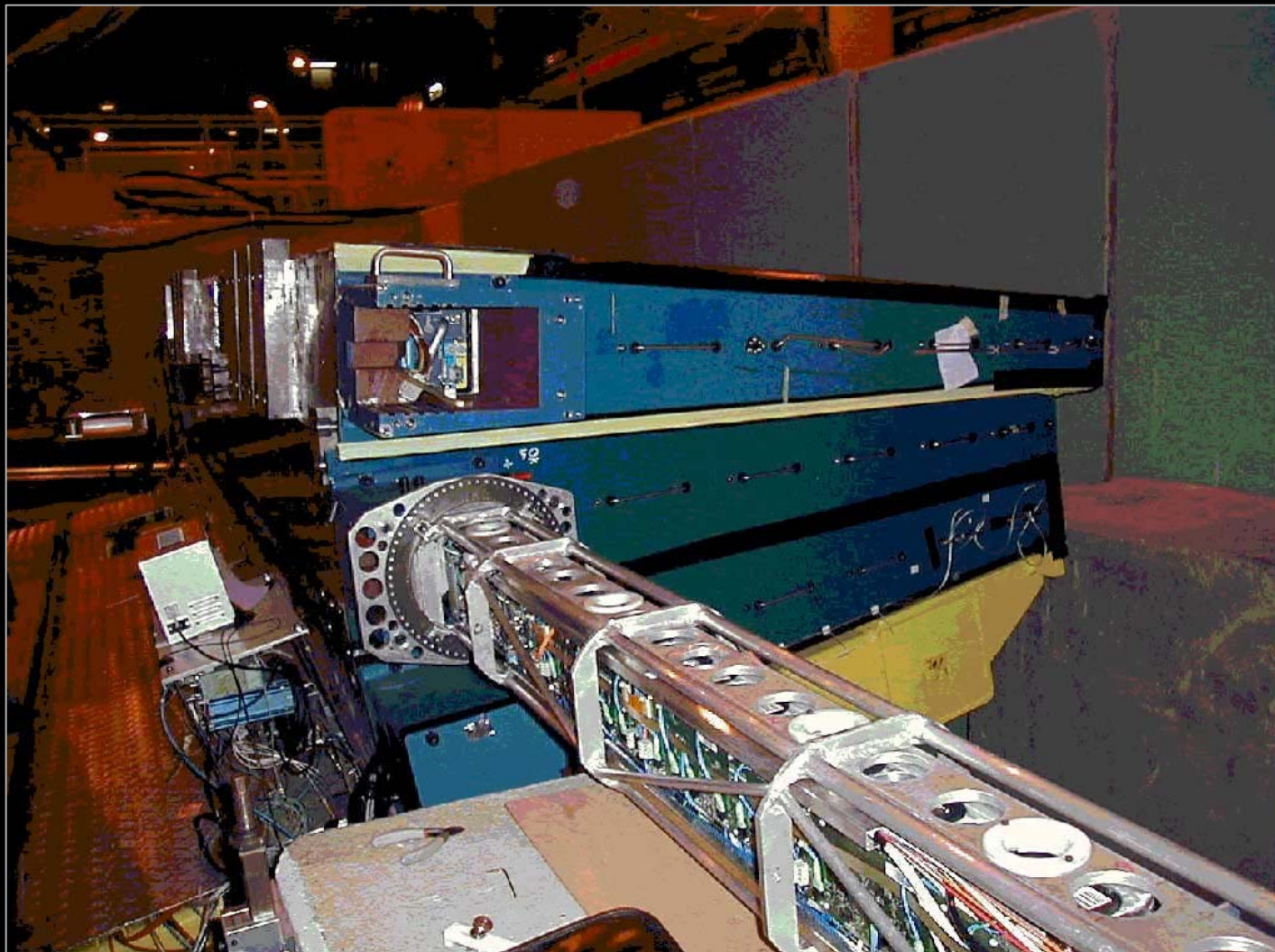
The ATLAS Tile Hadronic Calorimeter

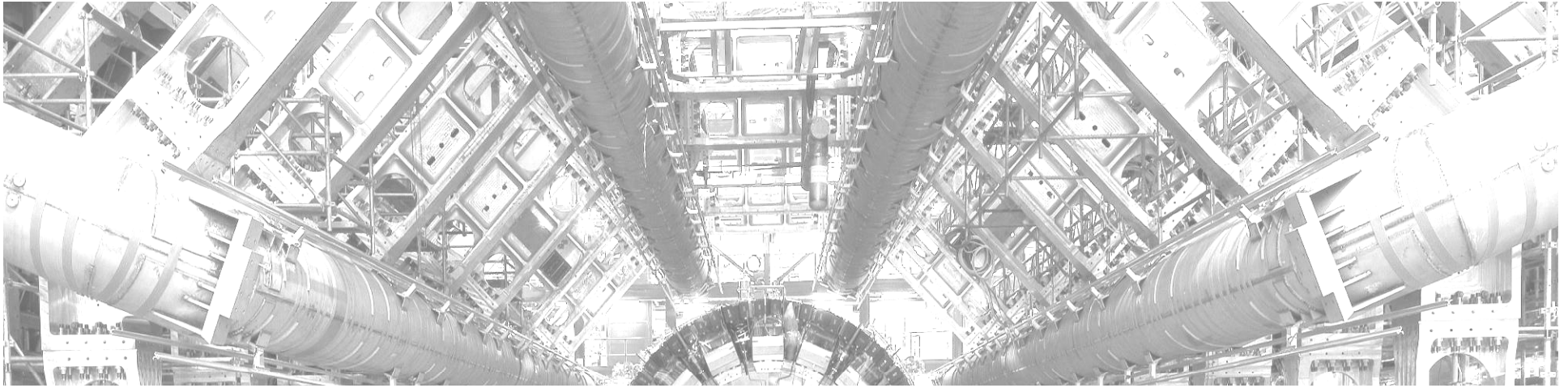


The ATLAS Tile Hadronic Calorimeter

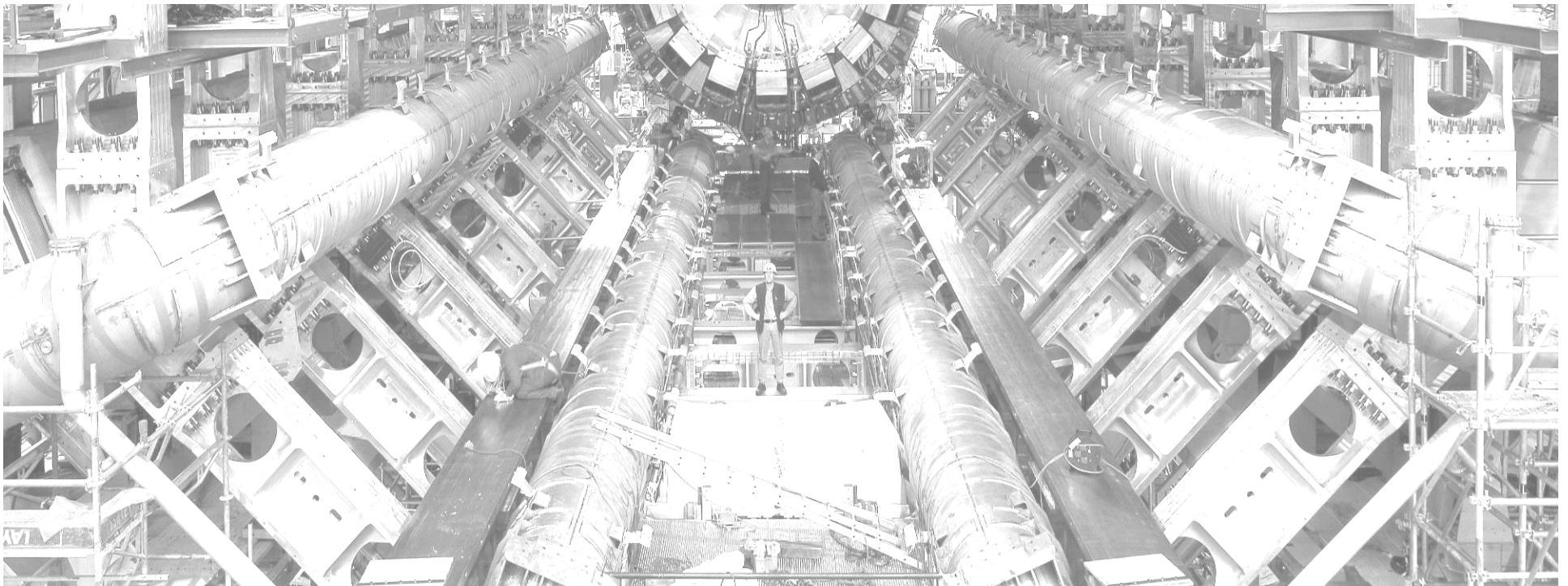


The ATLAS Tile Hadronic Calorimeter

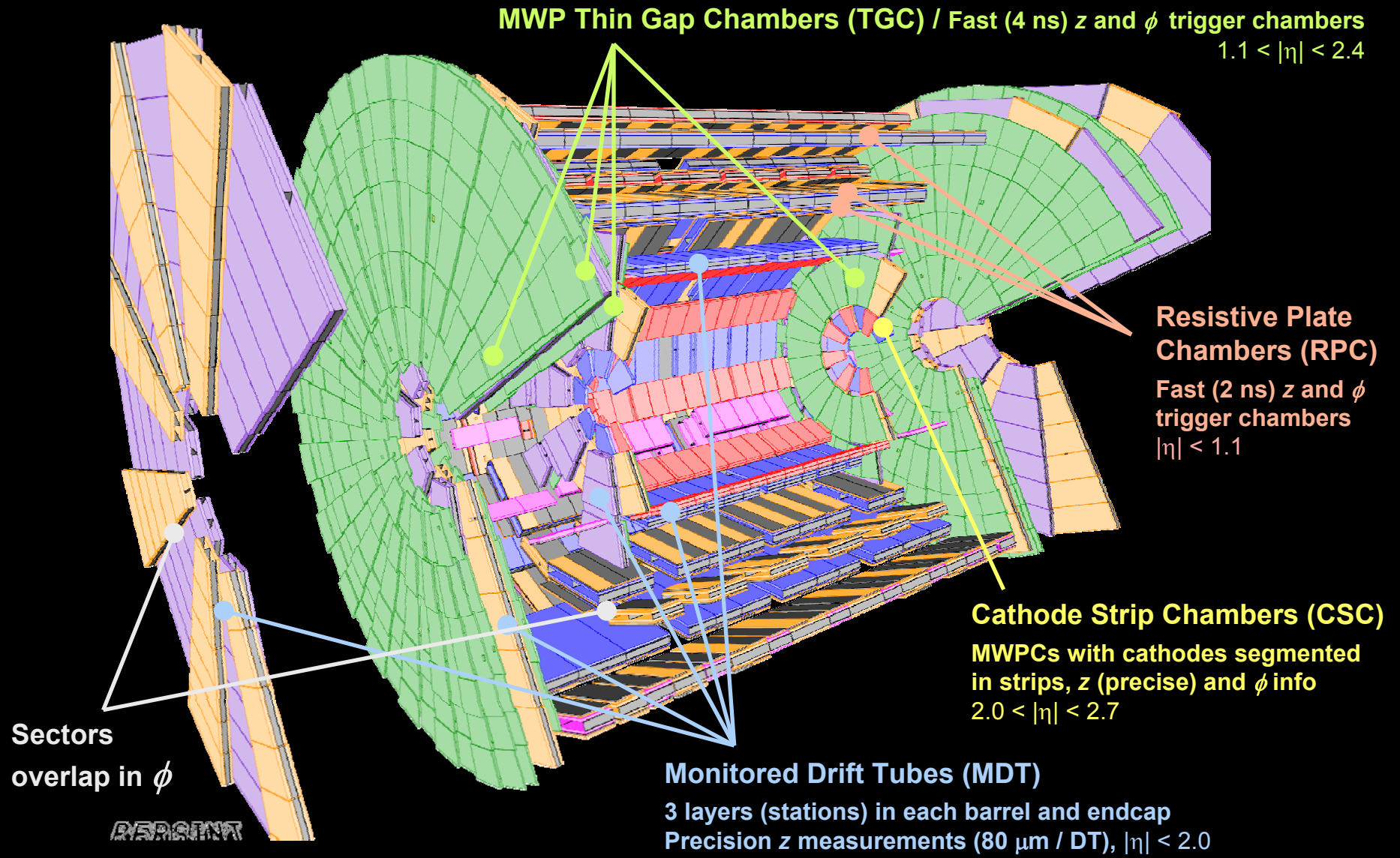




The Muon Spectrometer



The ATLAS Muon Spectrometer (Active Material)



The ATLAS Muon Spectrometer

- Huge magnetic volume

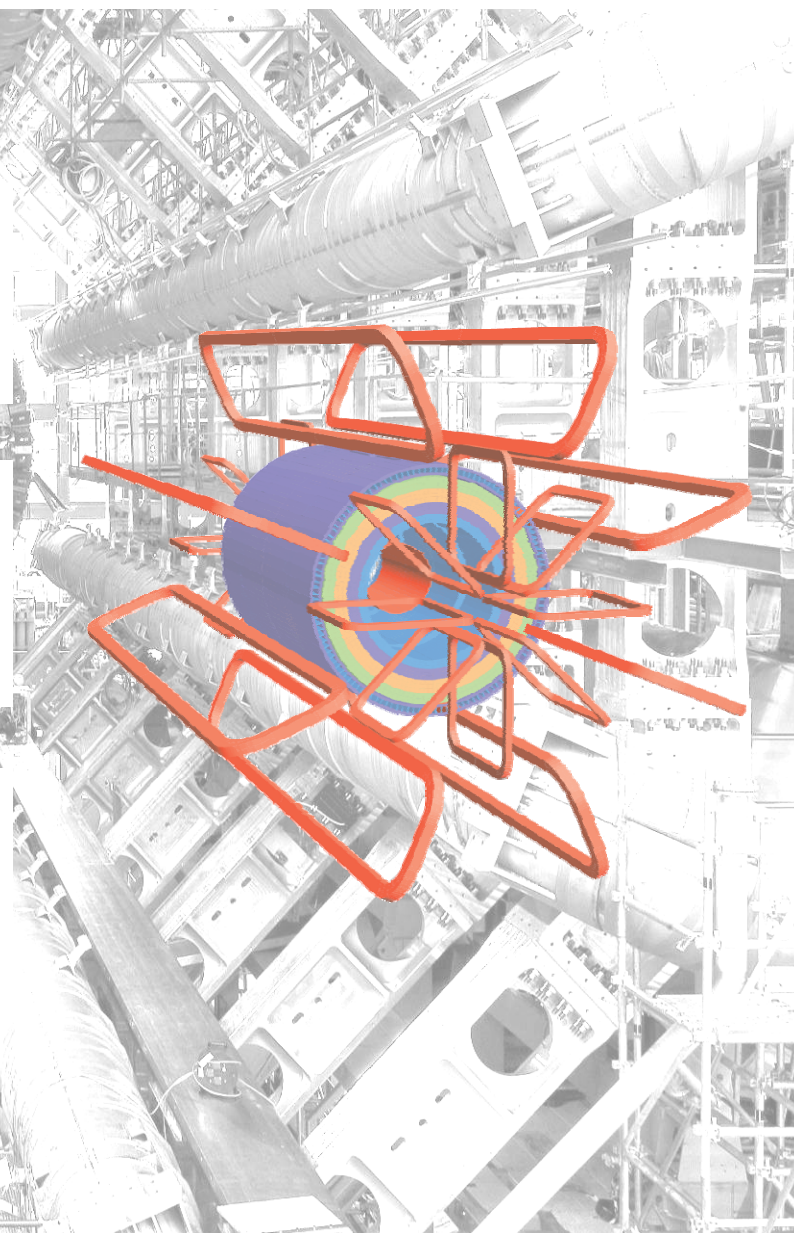
- ATLAS has 8 (barrel) $3 T_{\max}$ and 2×8 (endcap) $6 T_{\max}$ superconducting toroid magnets

- Huge active detectors area

- Open structure minimises multiple scattering
- Dedicated trigger chambers

- Huge mechanical structure

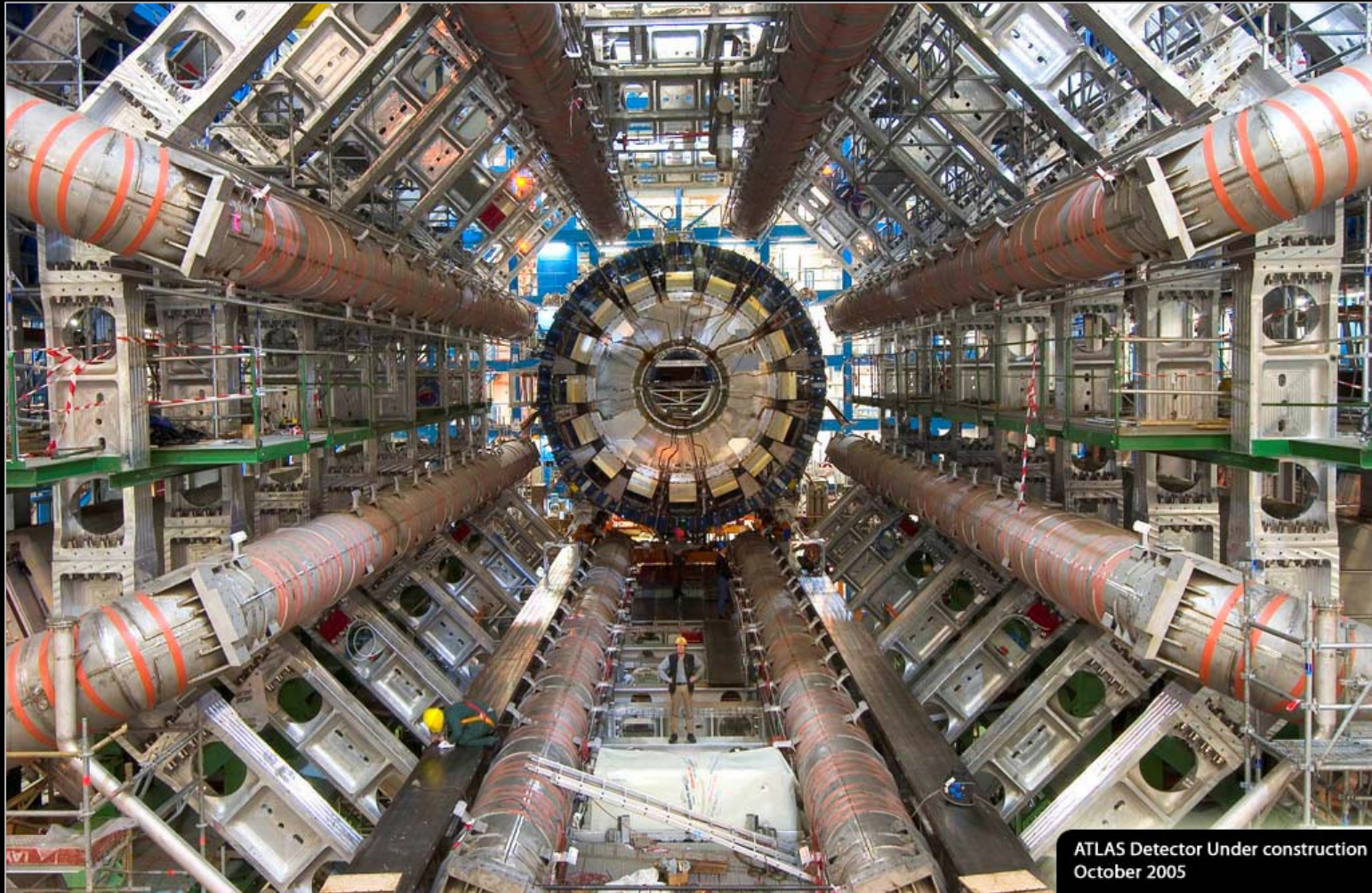
- Challenging tolerances for mechanical stability, positioning and alignment (optical sensors)



The ATLAS Muon Spectrometer



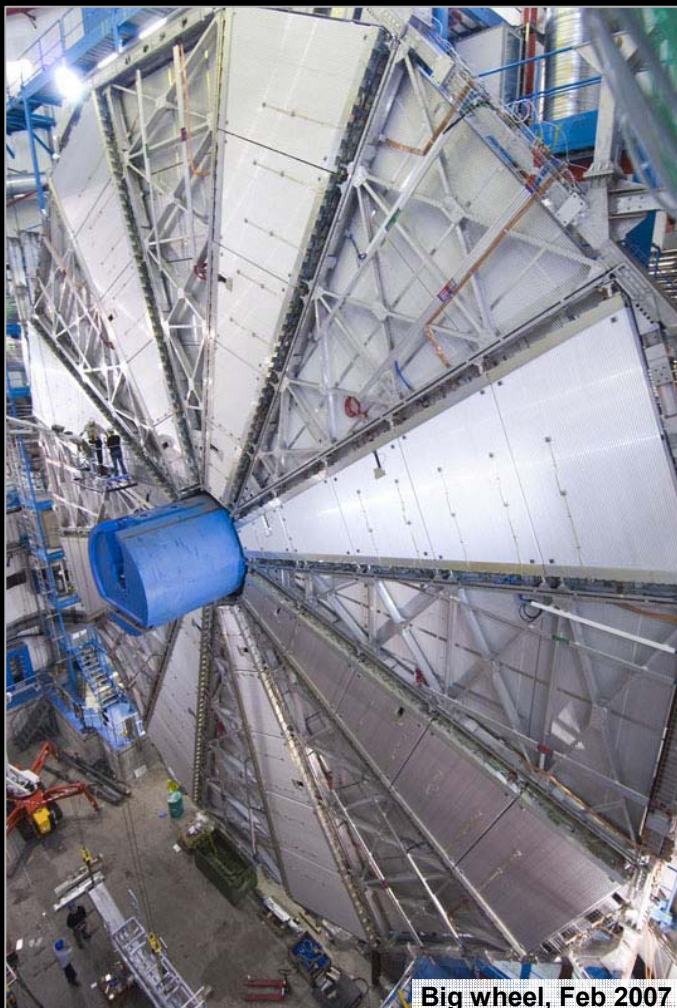
The ATLAS Muon Spectrometer



The ATLAS Muon Spectrometer



The ATLAS Muon Spectrometer

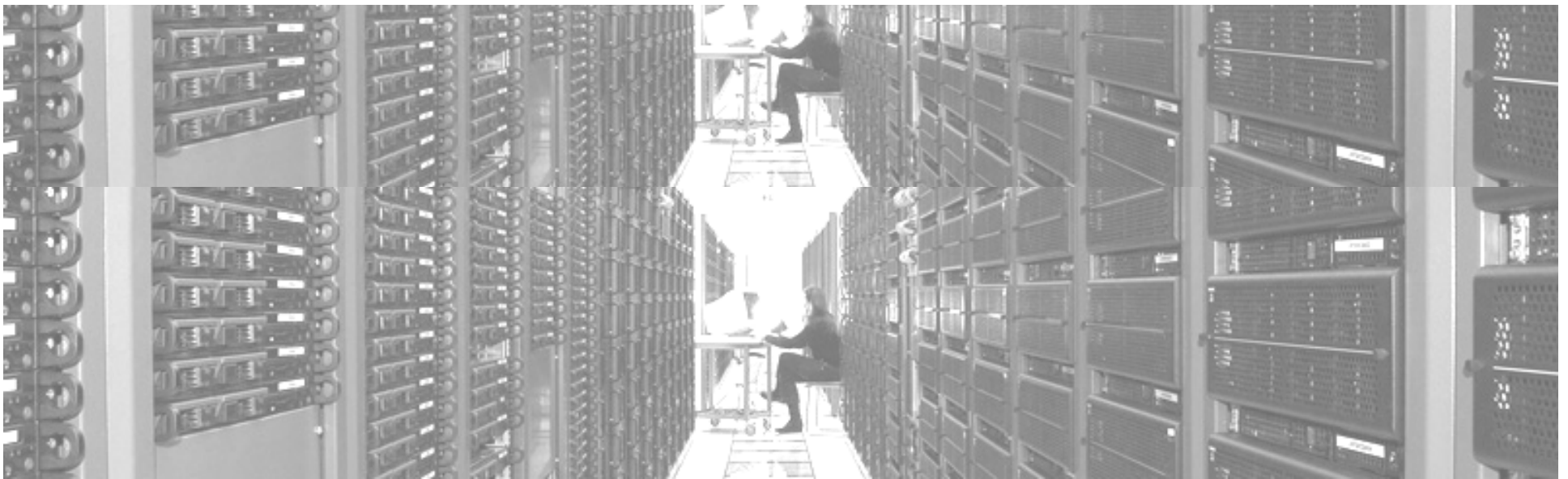


The ATLAS Muon Spectrometer

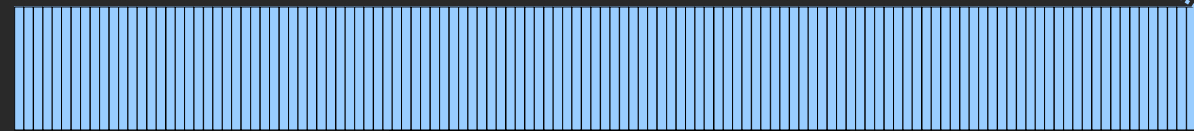




Trigger, Data Acquisition and Computing



Bunch crossing rate (40 MHz)



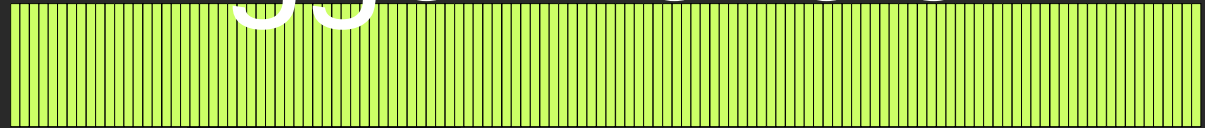
Each package provides 200 Hz rate

$\times 1681$

Level-1 trigger-accept rate (75 kHz)



Three Trigger Levels



Level-2 trigger-accept rate (3.5 kHz)

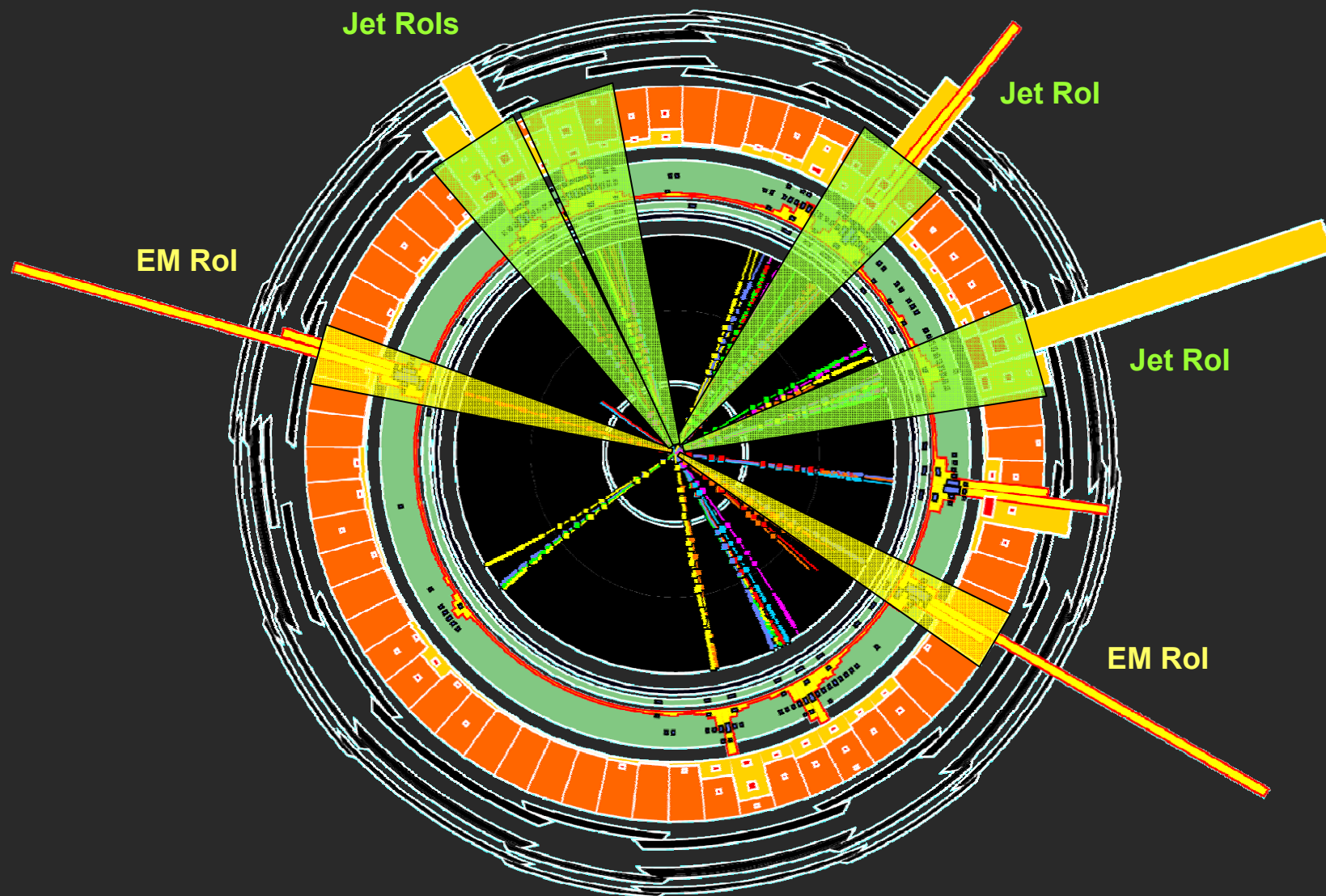


Level-3 trigger-accept rate (200 Hz)



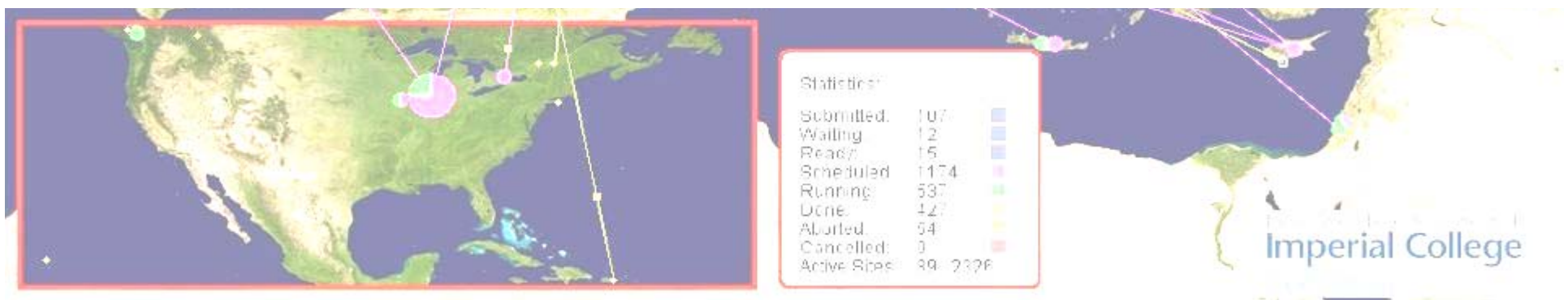
**Write to tape and
reconstruct**

Regions of Interest (RoI)



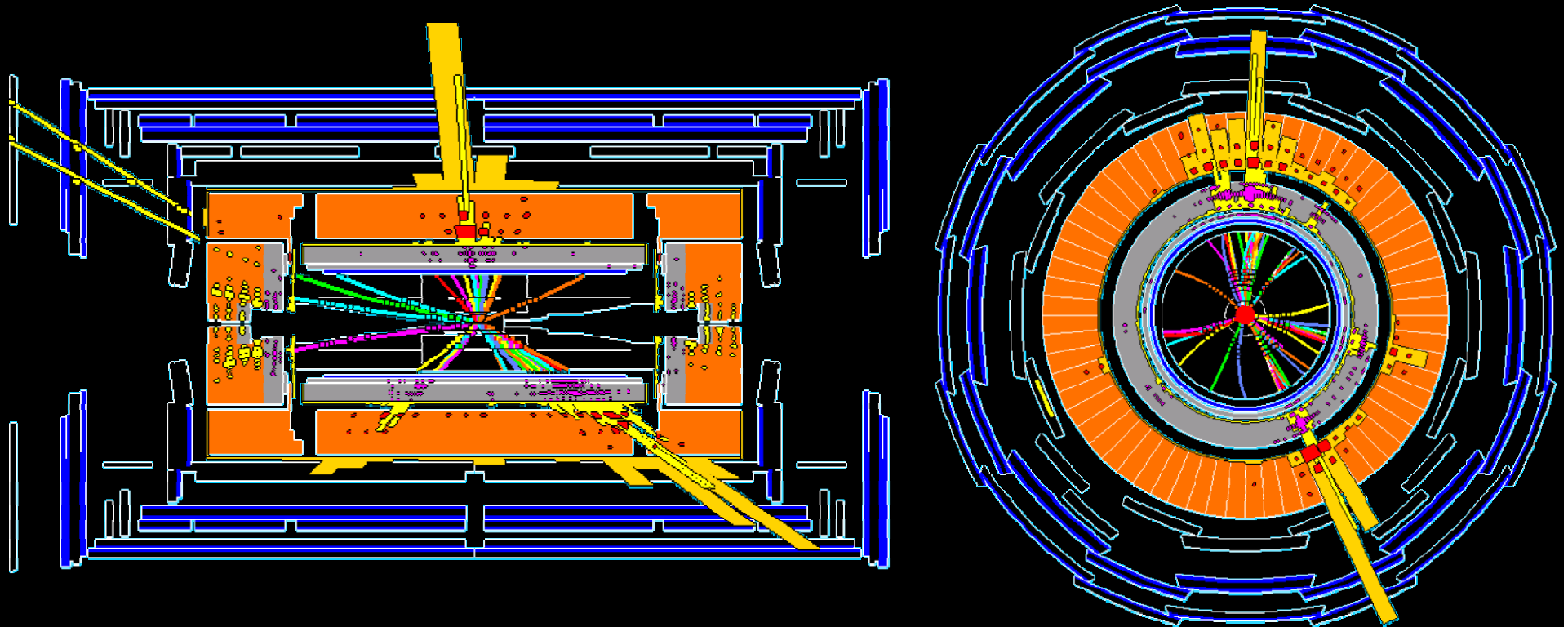


- Each LHC experiment will produce 10 000 TB of data each year
- Data analysis requires 100 000 of the fastest PC processors
- ATLAS collaboration spread all over the world → need distributed computing
- Transfer of data from CERN at **10 Gbits/s** rate to 11 world-wide computing centres
- These centres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



Conclusions ...

Simulation of a Supersymmetry event in ATLAS

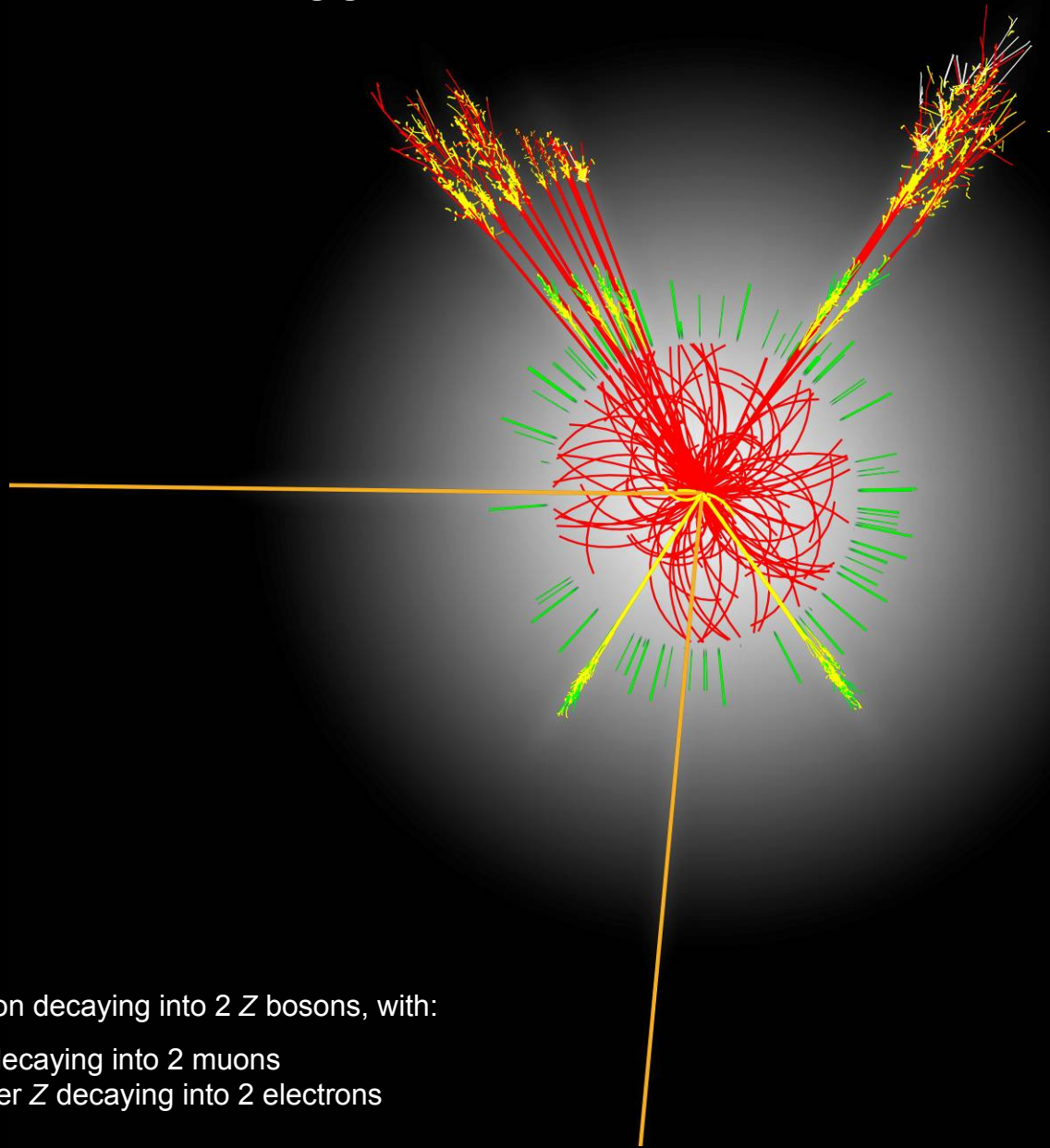


Pair of SUSY particles decaying via:

- 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



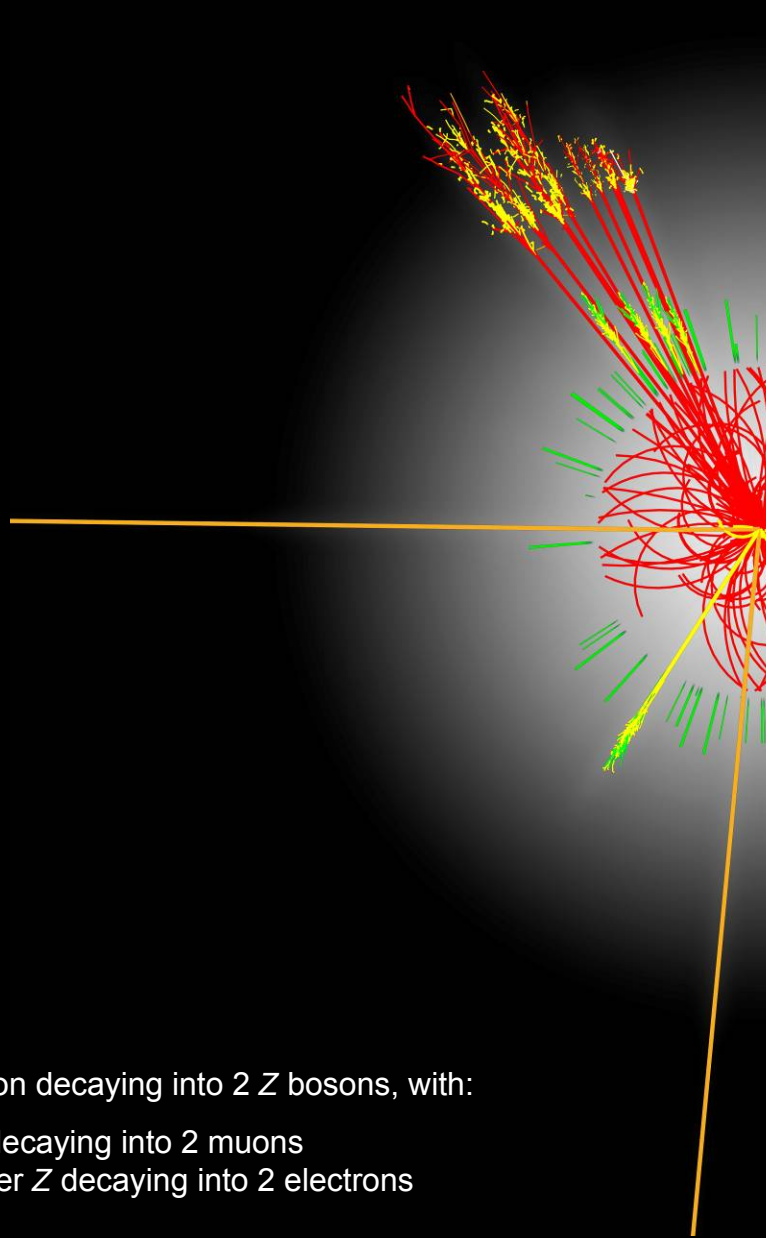
Simulation of a Higgs event in ATLAS



Higgs boson decaying into 2 Z bosons, with:

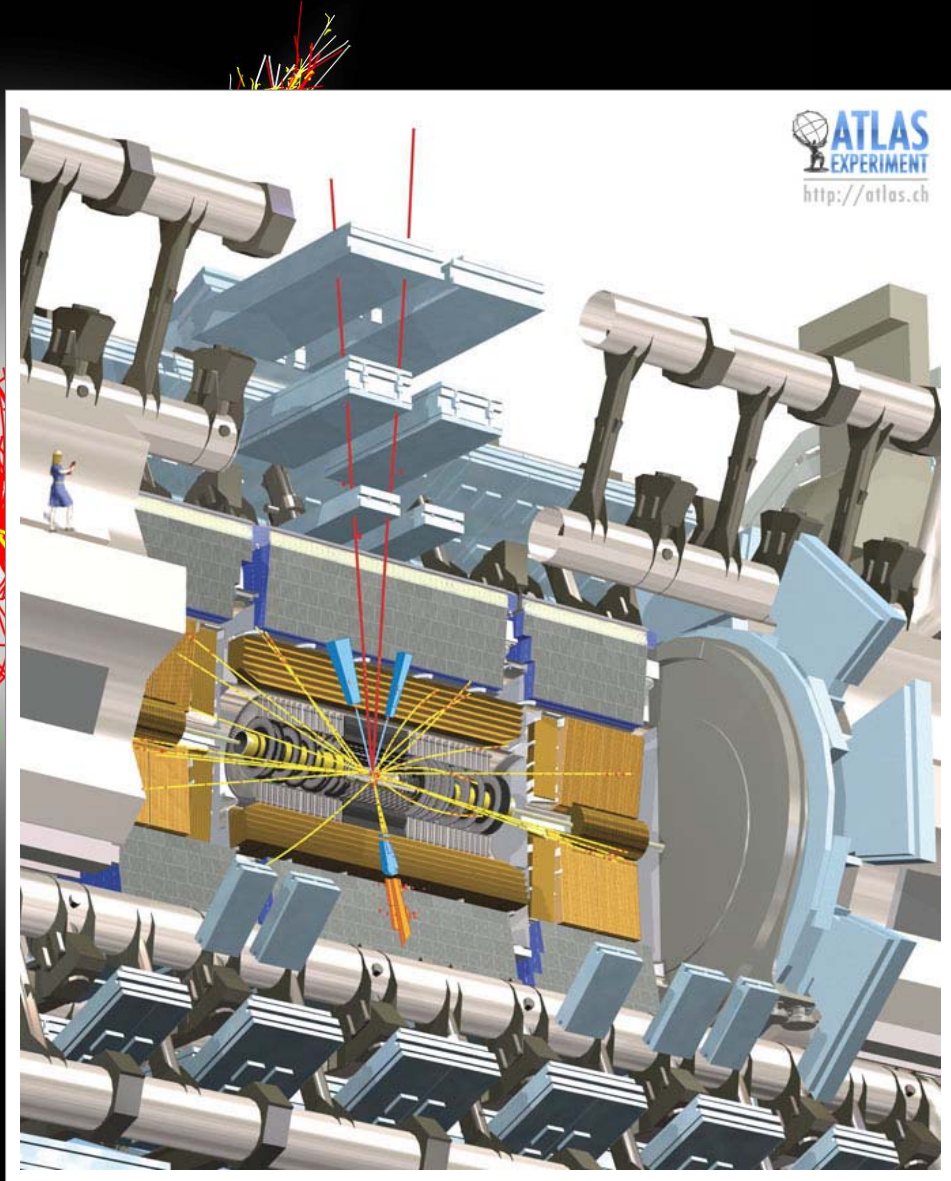
- One Z decaying into 2 muons
- The other Z decaying into 2 electrons

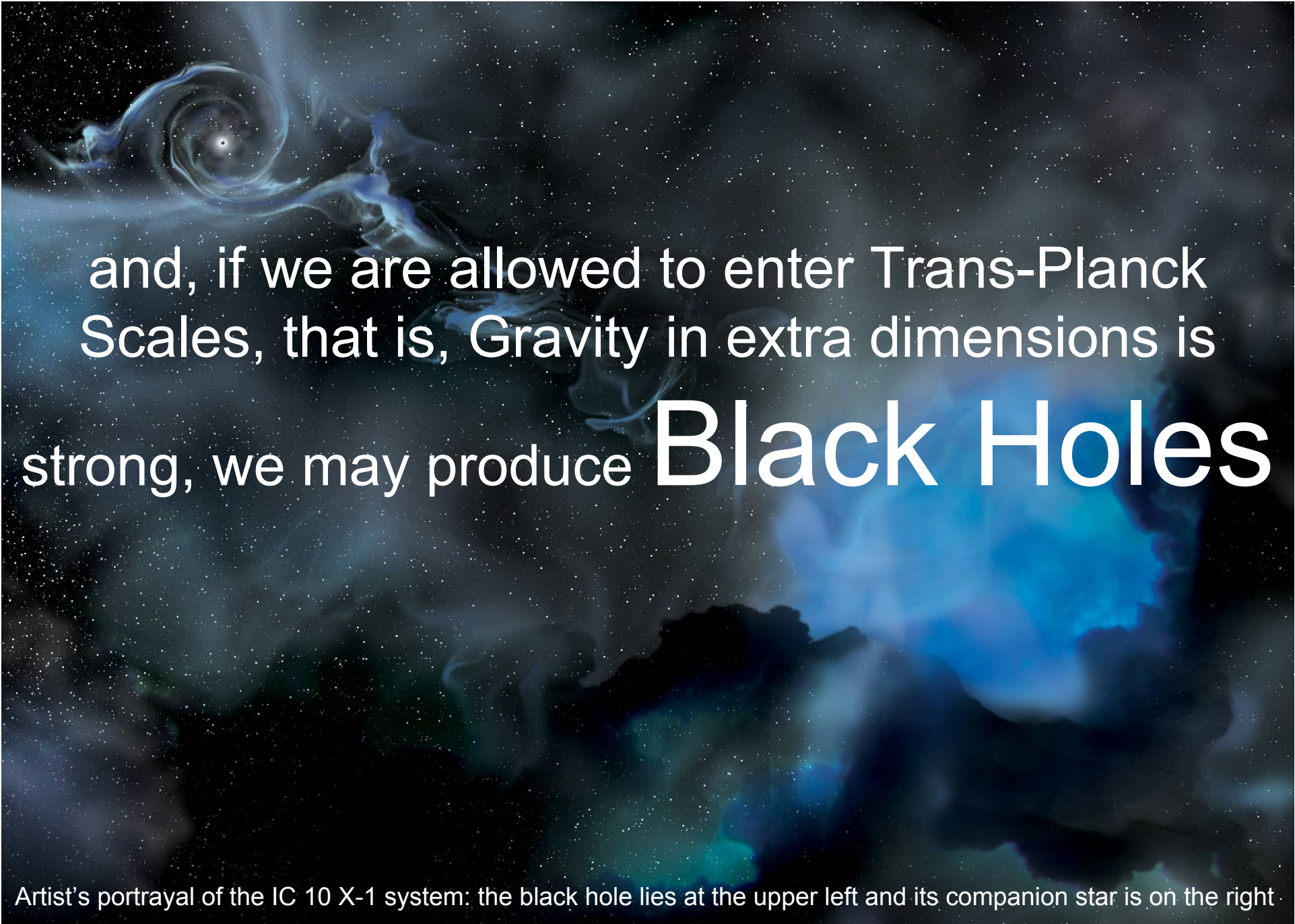
Simulation of a Higgs event in ATLAS



Higgs boson decaying into 2 Z bosons, with:

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

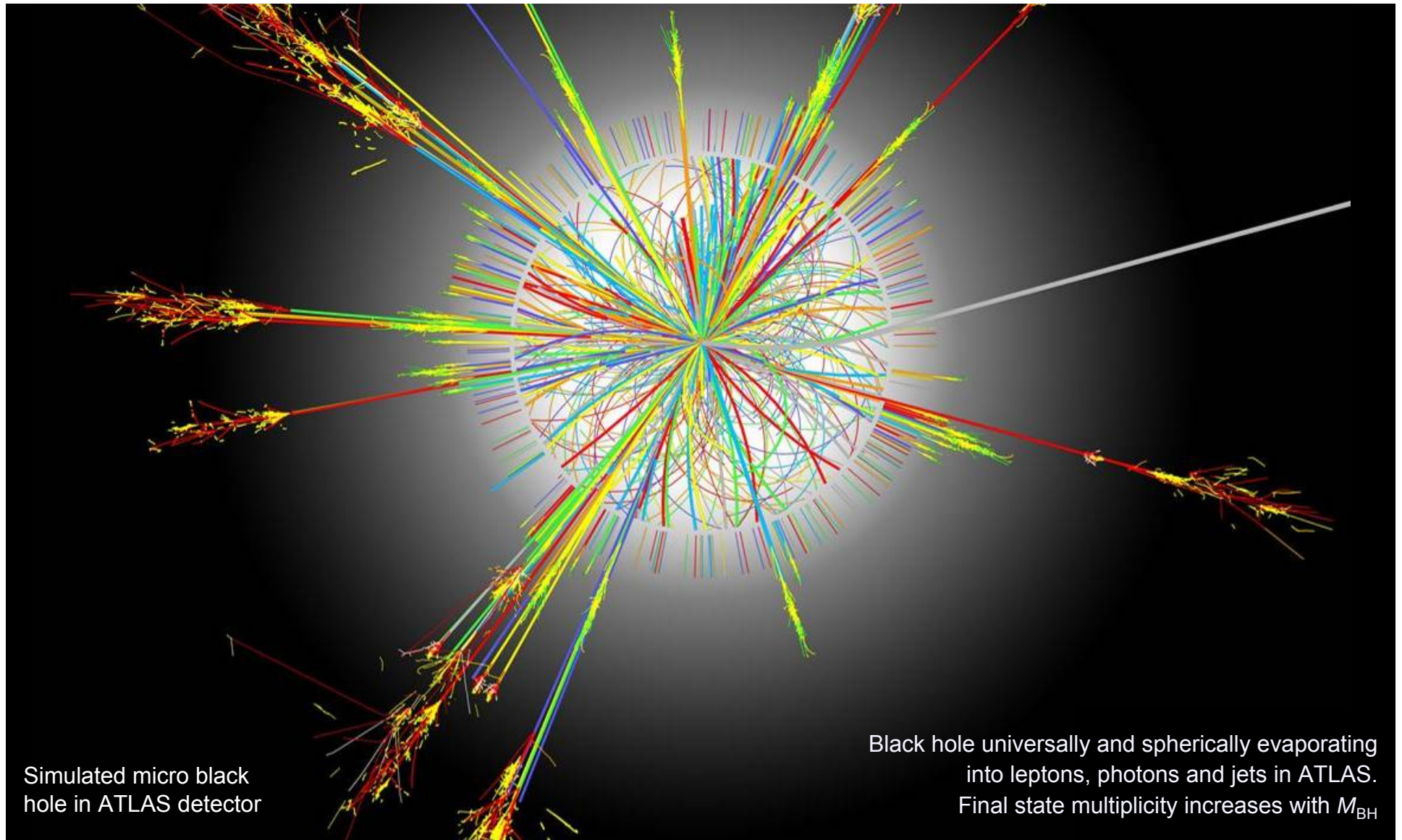


An artistic rendering of the IC 10 X-1 system. In the upper left, a black hole is depicted as a bright, swirling accretion disk. To its right, a companion star is shown as a bright, blue, nebula-like structure. The background is a dark, star-filled space.

and, 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.

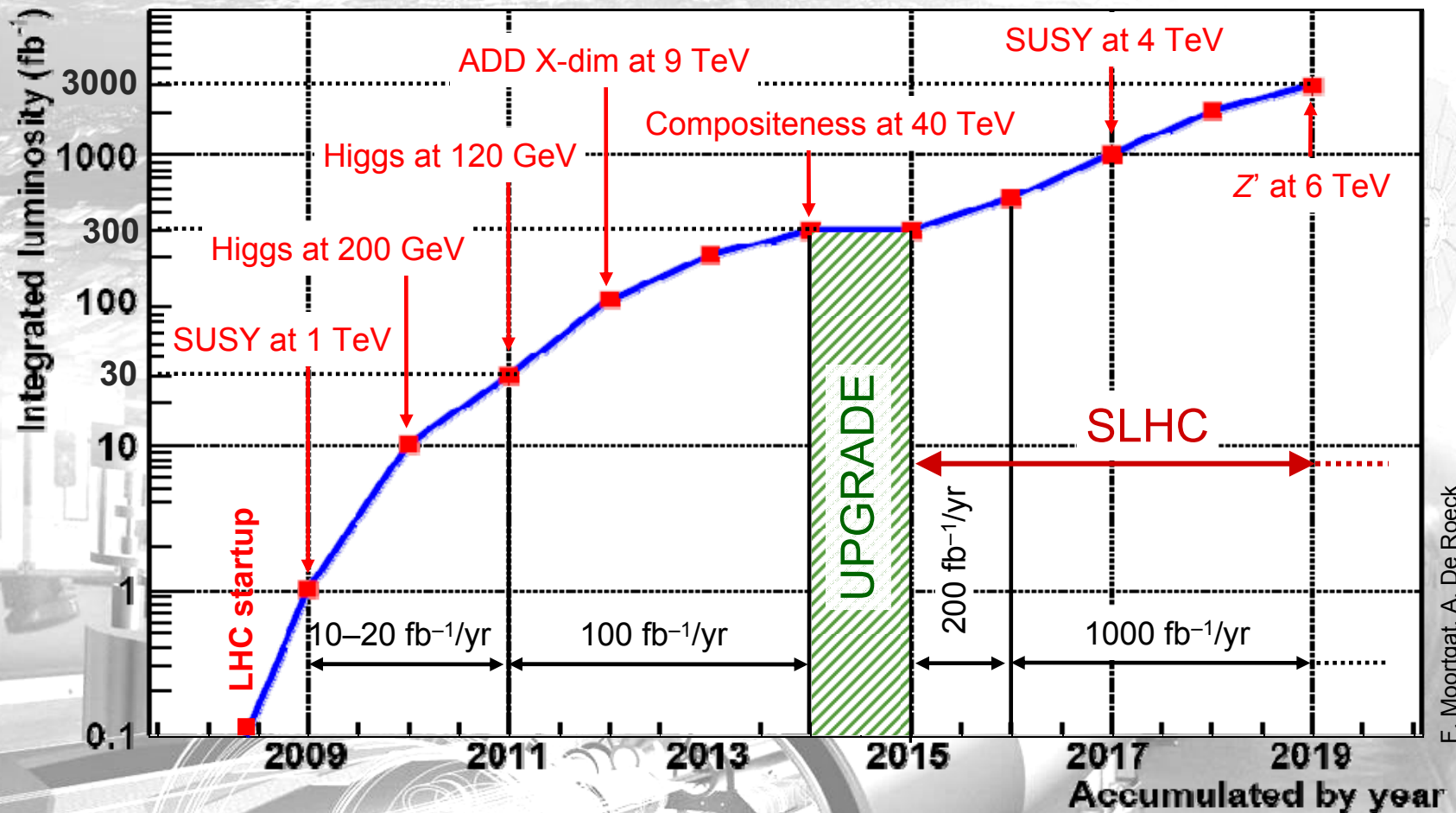
Strong gravity in extra dimensions could allow black hole production at the LHC
Fast ($\tau \sim 10^{-27}$ s) thermal decay via Hawking radiation
Speed of growth: 10 microgram mass in 1 billion years !





Outlook to the Future

Last Slide: The LHC Programme in a Nutshell



Recent V.I.P. Visits at ATLAS

Peter Higgs



Stephen Hawking



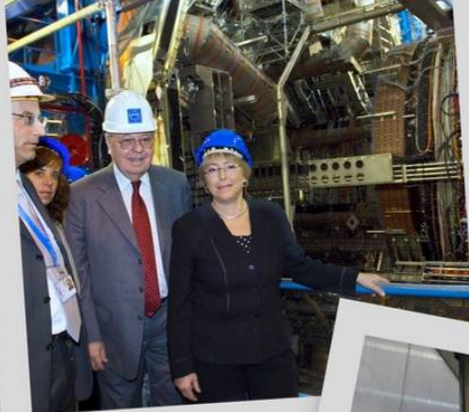
Gerard t'Hooft



Angela Merkel



Michelle Bachelet



George Smoot



Simon van der Meer



Tsung Dao Lee



Angela Merkel



Lisa Randall

