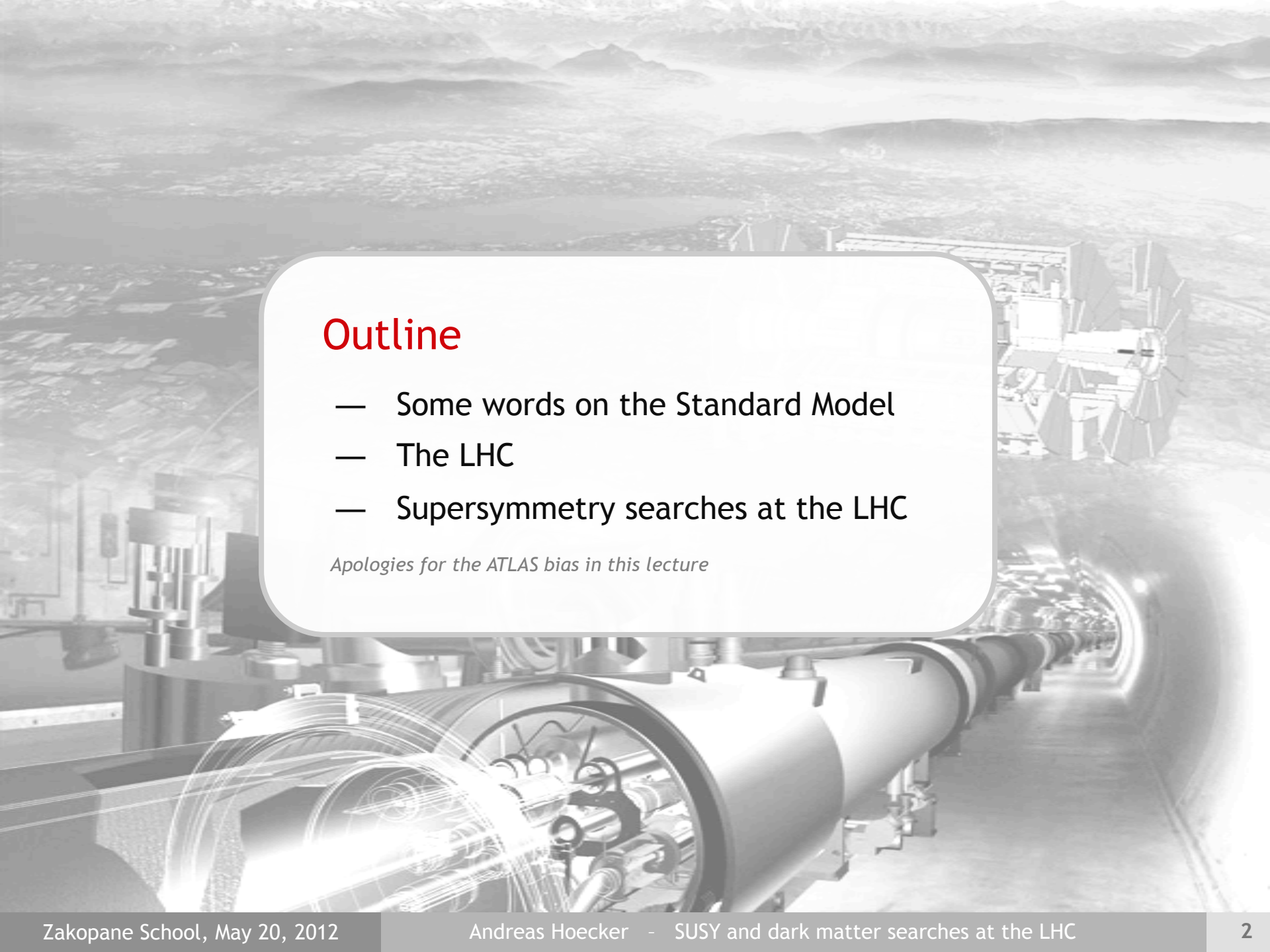




Searches for Supersymmetry and Dark Matter at the LHC

Andreas Hoecker (CERN)

20 May 2012, Zakopane, Poland

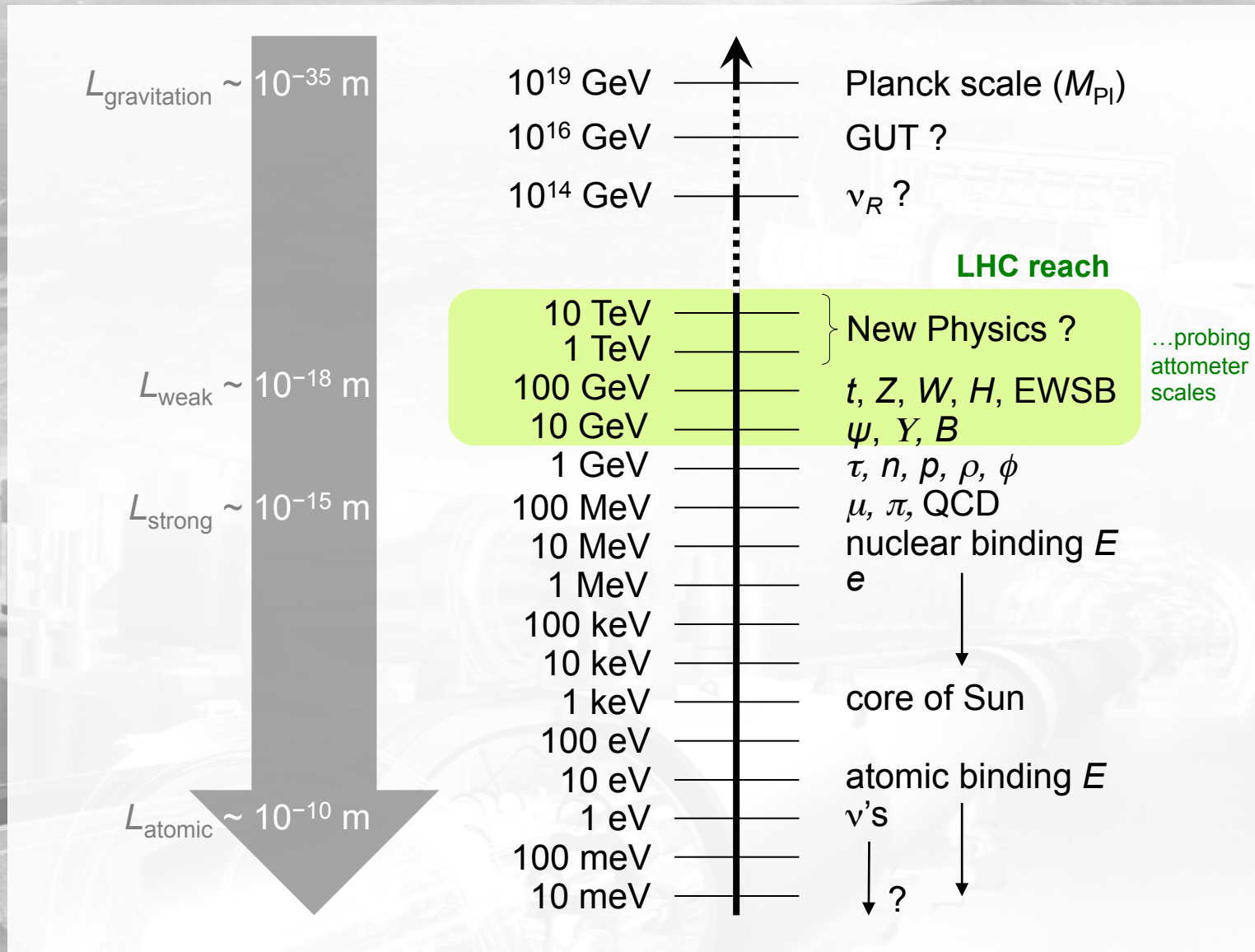
The background of the slide is a grayscale image showing the interior of the Large Hadron Collider (LHC) tunnel. In the foreground, there is a large, complex piece of scientific equipment, likely a detector or a part of the accelerator, with various pipes, cables, and structural elements. The tunnel extends into the distance, with a bright light at the far end, creating a sense of depth. The overall image has a technical and scientific feel.

Outline

- Some words on the Standard Model
- The LHC
- Supersymmetry searches at the LHC

Apologies for the ATLAS bias in this lecture

Particle Physics Scales



Everyday life (and particle physics) are described by the Standard Model



Everyday life (and particle physics) are described by the Standard Model

Standard Model (36+1 particles - 3 forces)

Courtesy: Pascal Pralavorio

Selected Nobel Prizes since 1957

$\text{Gauge group} = \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$
 $\text{SU}(3)_C \times \text{U}(1)_{EM}$

EWSB

The SM is *the* legacy of 20th century particle physics

The Standard Model

The Standard Model consists of **24 elementary matter particles** and **3 forces**

Fermions

Matter particles

Organised in 3 families

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

6 Leptons

$$\ell$$

6 Quarks

$$q$$

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

Bosons

Force quanta

Distinguishing 3 forces

Photon

$$\gamma$$

3 weak bosons

$$W^\pm$$

$$Z^0$$

8 Gluons

$$8 \times g$$

Electro-magnetic force

Weak force

Strong force

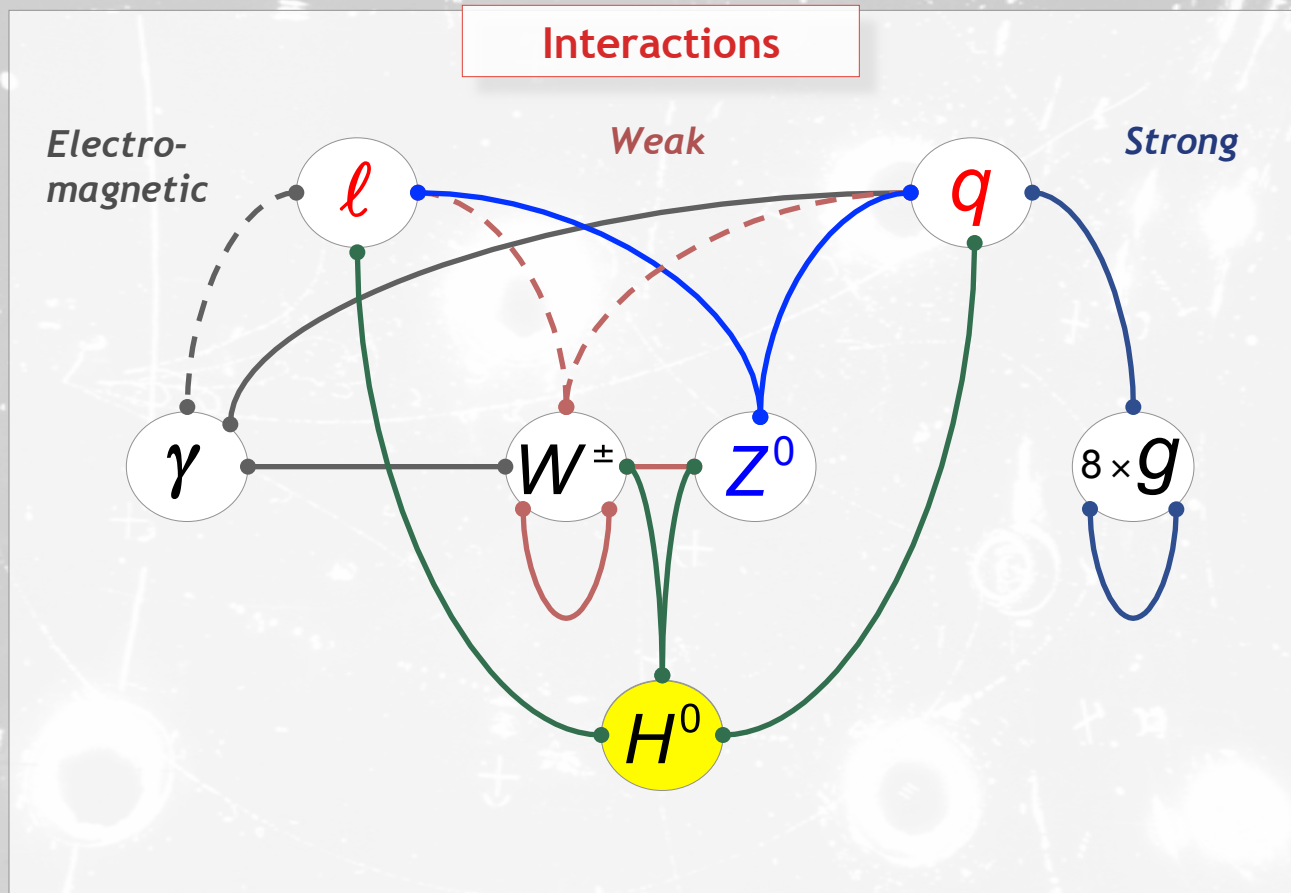
Higgs boson

$$H^0$$

*Breaks electroweak symmetry
Generates fermion and boson masses
Makes weak interaction short ranged*

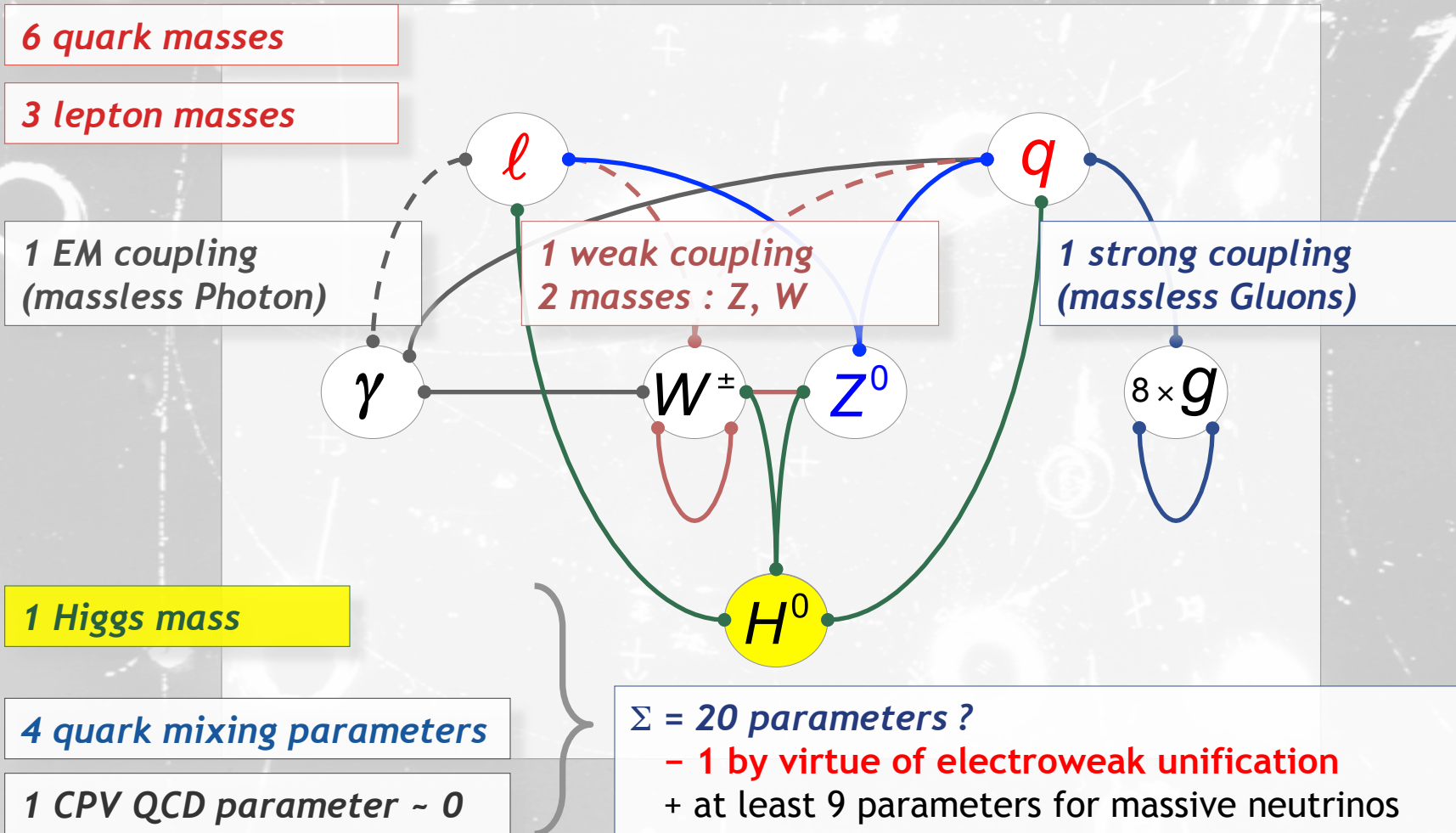
The Standard Model

The Standard Model consists of **24 elementary matter particles** and **3 forces**



The Standard Model

The SM describes all observed phenomena in particle physics by **19 parameters** (?)



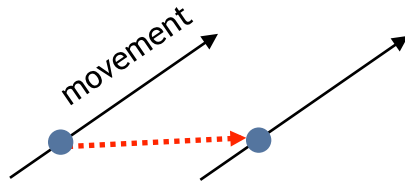
The Standard Model

Elementary particle physics is successfully described by **local gauge theories**

Gauge symmetry is the invariance of equations of motion with respect to a local transformation belonging to a symmetry group

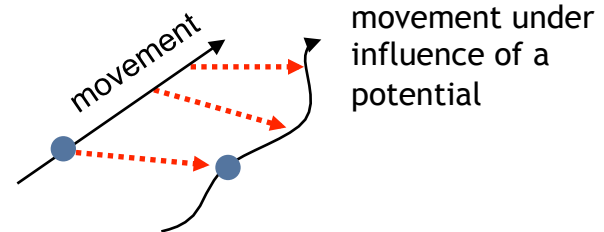
Example: translation group – uniform movement of particle

Global
symmetry:



$$\vec{x} \mapsto \vec{x} + \vec{a}$$

Local
symmetry:



$$\vec{x} \mapsto \vec{x} + \vec{a}(\vec{x}, t)$$

A new trajectory is possible, if **forces** act on the particle: a potential that restores the symmetry of the dynamic under this particular gauge transformation

The dynamic found is not just any dynamic, but one of the 4 forces of nature: **gravitation**

Requiring the same local gauge invariance for a wave function gives us: **QED**

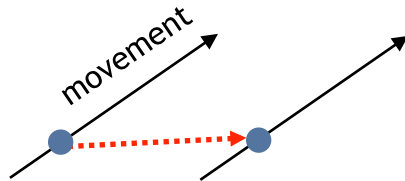
The Standard Model

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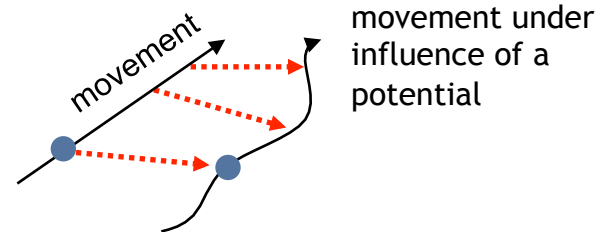
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Global
symmetry:



$$\vec{x} \mapsto \vec{x} + \vec{a}$$

Local
symmetry:



$$\vec{x} \mapsto \vec{x} + \vec{a}(\vec{x}, t)$$

We can do so for **all fundamental forces** of the Standard Model, which have thus a

Geometric origin !

The Standard Model

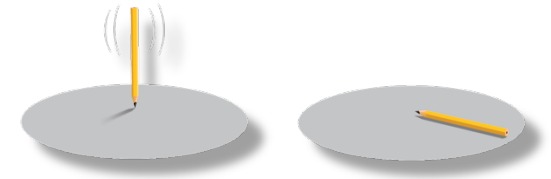
Brout-Englert-Higgs mechanism

A problem: local gauge symmetry requires **massless spin-1 “gauge” (=force) boson**

This has been well verified for QED, with a massless photon (= infinite range)

However, the **W, Z bosons are massive** (= finite range $\sim 10^{-15}$ cm)

Only way to break gauge symmetry consistently is to **spontaneously break the symmetry of the vacuum:**



$$M_{Z,W} \neq 0 \quad \Leftrightarrow \quad \langle 0 | \phi | 0 \rangle = v \neq 0 \quad [\text{non-zero vacuum expectation value}]$$

ϕ is a complex doublet field: 3 d.o.fs become Z, $W^\pm$ masses, remaining d.o.f is **massive scalar Higgs boson**

This is called the **Brout-Englert-Higgs Mechanism**

The Standard Model

Brout-Englert-Higgs mechanism

Let's imagine all particles have zero mass $\rightarrow$ gauge symmetry is respected

A **Higgs field** displaces ground state breaking gauge symmetry

It fills all space time (but w/o orientation as spin=0)

Particles interact with the Higgs field and reduce their velocity.
They acquire a mass proportional to interaction strength

$\rightarrow$ Action of the Higgs field creates a ***vacuum viscosity***

Higgs mechanism is a phase transition

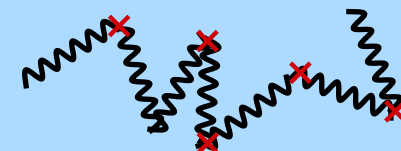
Gravity



Photon



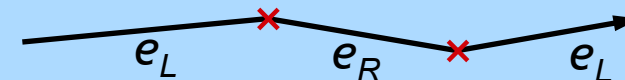
Weak boson



Neutrinos



Electrons



Top quark



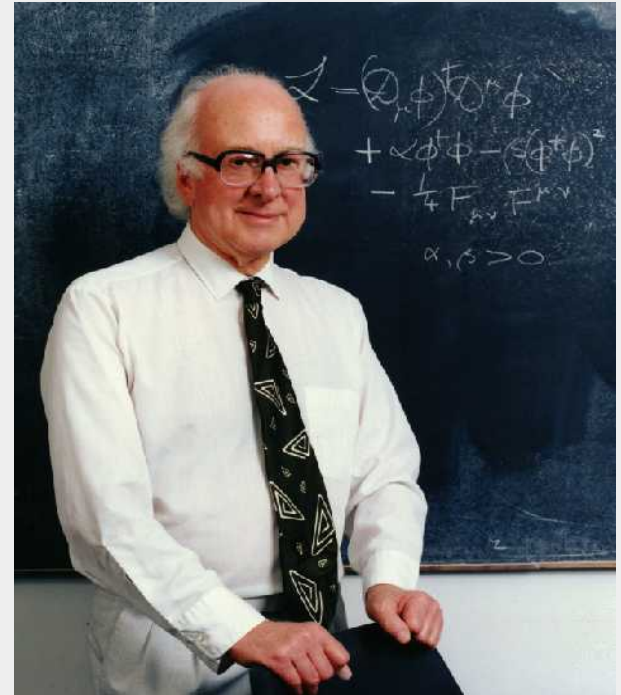
H. Murayama

The Higgs boson is the last elusive elementary particle of the SM

The Higgs boson - last of the particles ?

What is known about the Higgs Boson ?

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

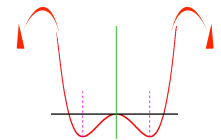
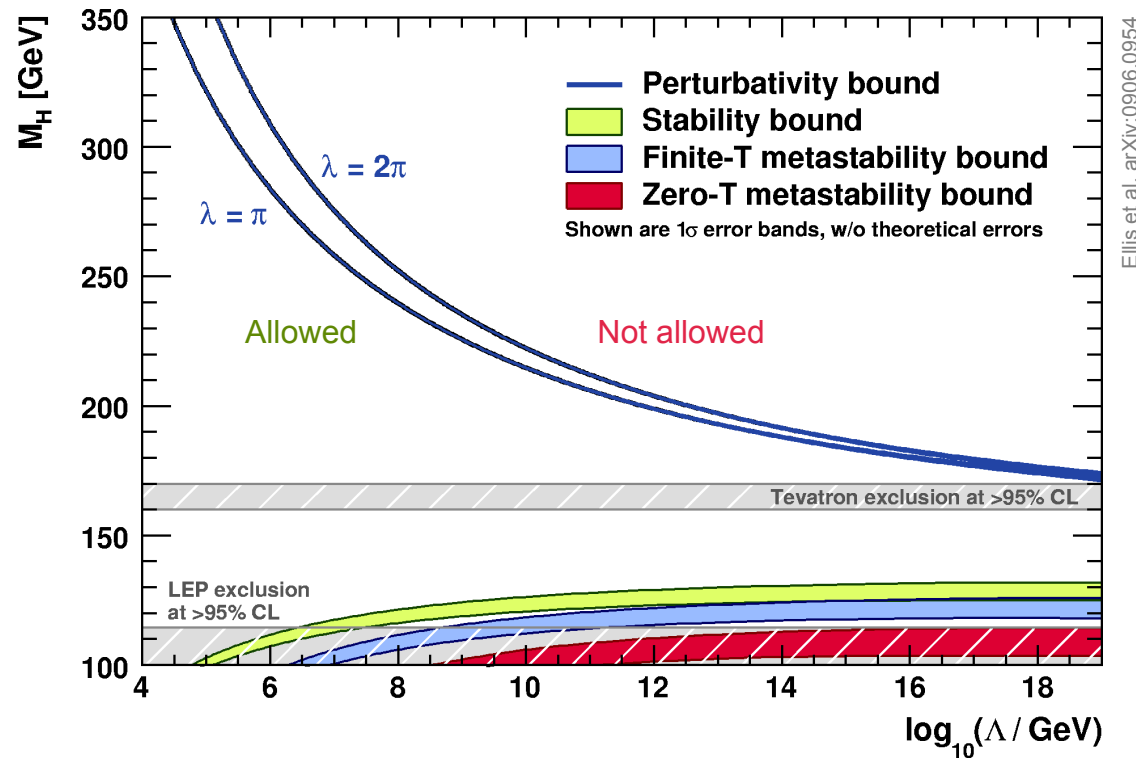


© CMS

© ATLAS

The Higgs boson should not be too light, and not too heavy...

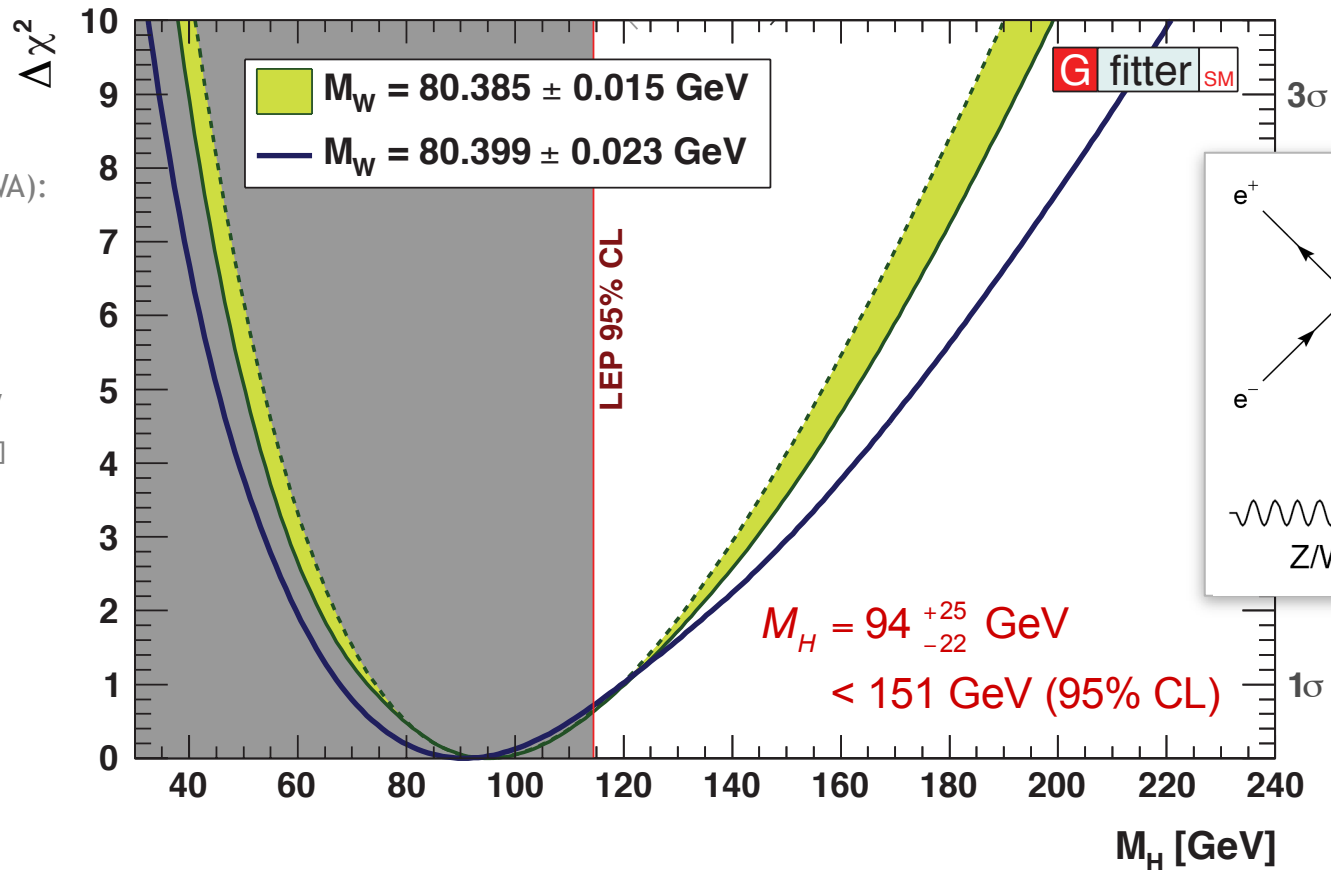
Perturbativity and (meta)stability bounds versus the SM cut-off scale Λ



The SM Higgs must steer a narrow course between two disastrous situations if the SM is to survive up to the Planck scale $M_p \sim 2 \times 10^{18}$ GeV

Constraints from global electroweak fit

Global fit of all EW precision measurements to SM prediction constrains M_H



New M_W average (WA):
arXiv:1204.0042

WA dominated by
recent CDF
measurement:
 80.387 ± 0.019 GeV
[PRL 108, 151803 (2012)]

<http://gfitter.desy.de>

Constraints from global electroweak fit

In the Standard Model the Higgs must be light.

BUT: Beyond the Standard Model the Higgs can be heavy !

→ MUST NOT stop searching for heavy Higgs boson !



Once the Higgs boson is discovered
The Standard Model is complete



But ... does it hold tight ?



The Standard Model

During the last 35 years the Standard Model has been tested to great precision

- Excited fundamental bosons or fermions have been excluded up to the TeV scale
- Electroweak unification has been verified at, below and above the Z-boson scale
- Universality of weak interaction has been verified at the per-mil level
- The tininess of electric dipole moments has been verified at 10^{-27} ecm
- Conservation of the charged lepton number verified at 10^{-12} level
- Asymptotic freedom of strong interaction has been verified at the percent level
- All observations of matter-antimatter symmetry violations are described by single complex parameter in the quark mixing matrix
- The electron and muon magnetic moments have been verified at ppm level...
- *Examples only, there are many more successful tests ...*

The Standard Model

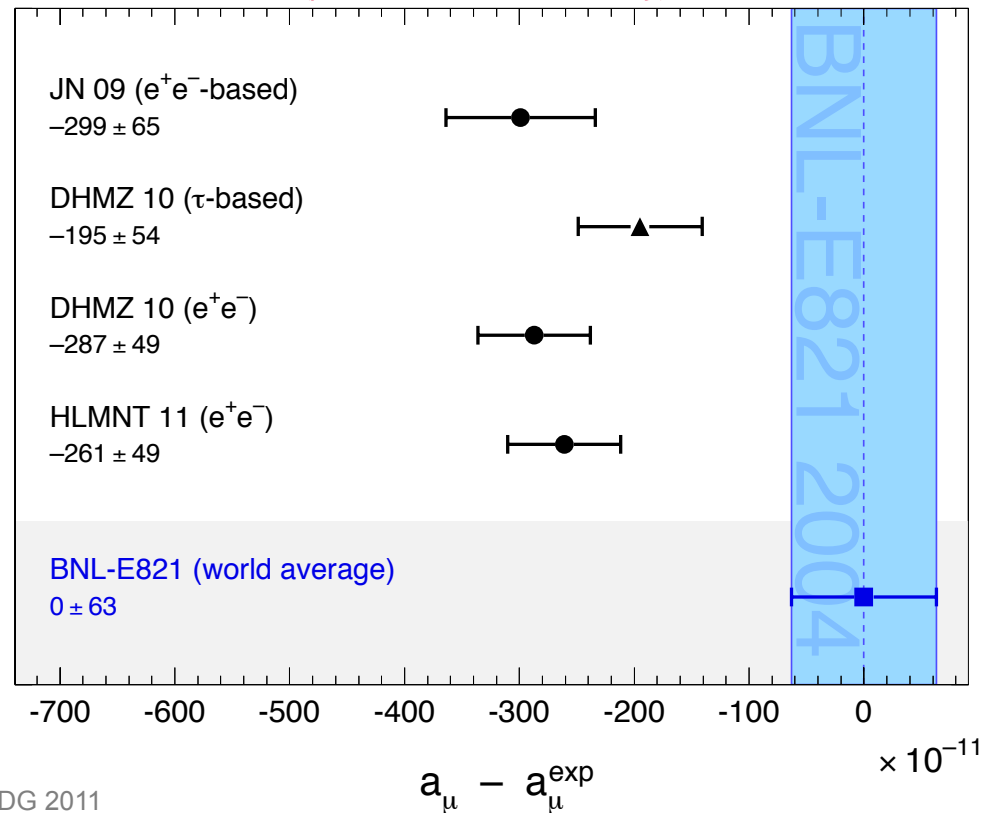
During the last 35 years the Standard Model has been tested to great precision

But not **everything** perfectly agrees with expectation:

- Top pairs produced in hadron collisions (at Tevatron) may have large angular asymmetry
- Di-muon events (at Tevatron) may exhibit unexpected charge asymmetry
- The muon anomalous magnetic moment may be stronger than expected

Muon magnetic moment: comparison between measurement (blue band) and predictions (dots)

Status: summer 2011 (*published results shown only*)



Problems and Unexplained Observations

The success of the SM should not make us forget that it is an incomplete theory

- The Higgs is not yet discovered !
- The Higgs is the only fundamental scalar
- Huge mass hierarchy between matter particles
- Dark matter (particle) and accelerated expansion of universe
- Causally connected observable universe
- Matter-antimatter asymmetry in universe
- Grand unification of the forces (related to baryon decay)
- Gauge hierarchy / stability of the scalar SM sector (see later)
- Why no matter-antimatter symmetry violation in strong interaction?
- Neutrino masses
- Gravitation

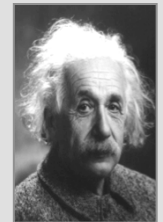
Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine

Particles accelerators:
accelerate particles to the highest energies to

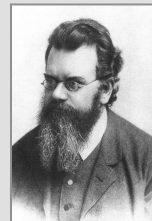
- Look deeper into matter (size $\sim 1/E$)
("powerful microscopes")
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie

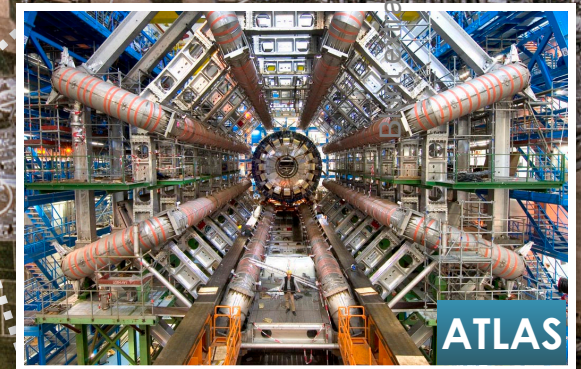
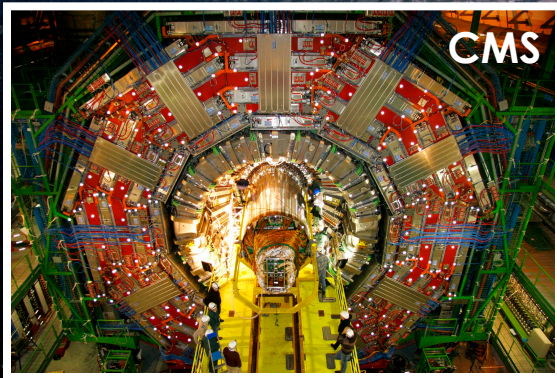


Einstein



Boltzmann

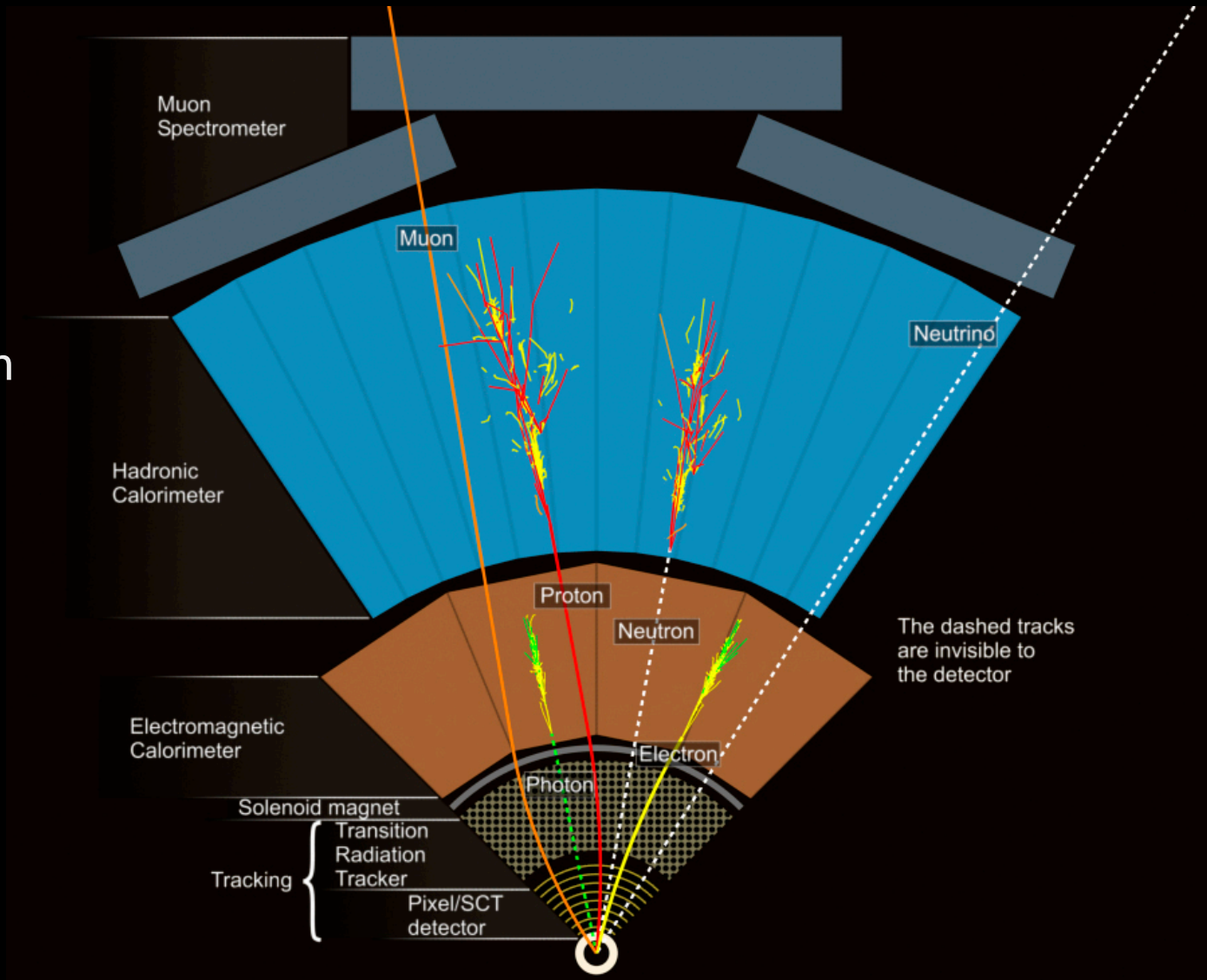
LHC ring at CERN:
27 km circumference

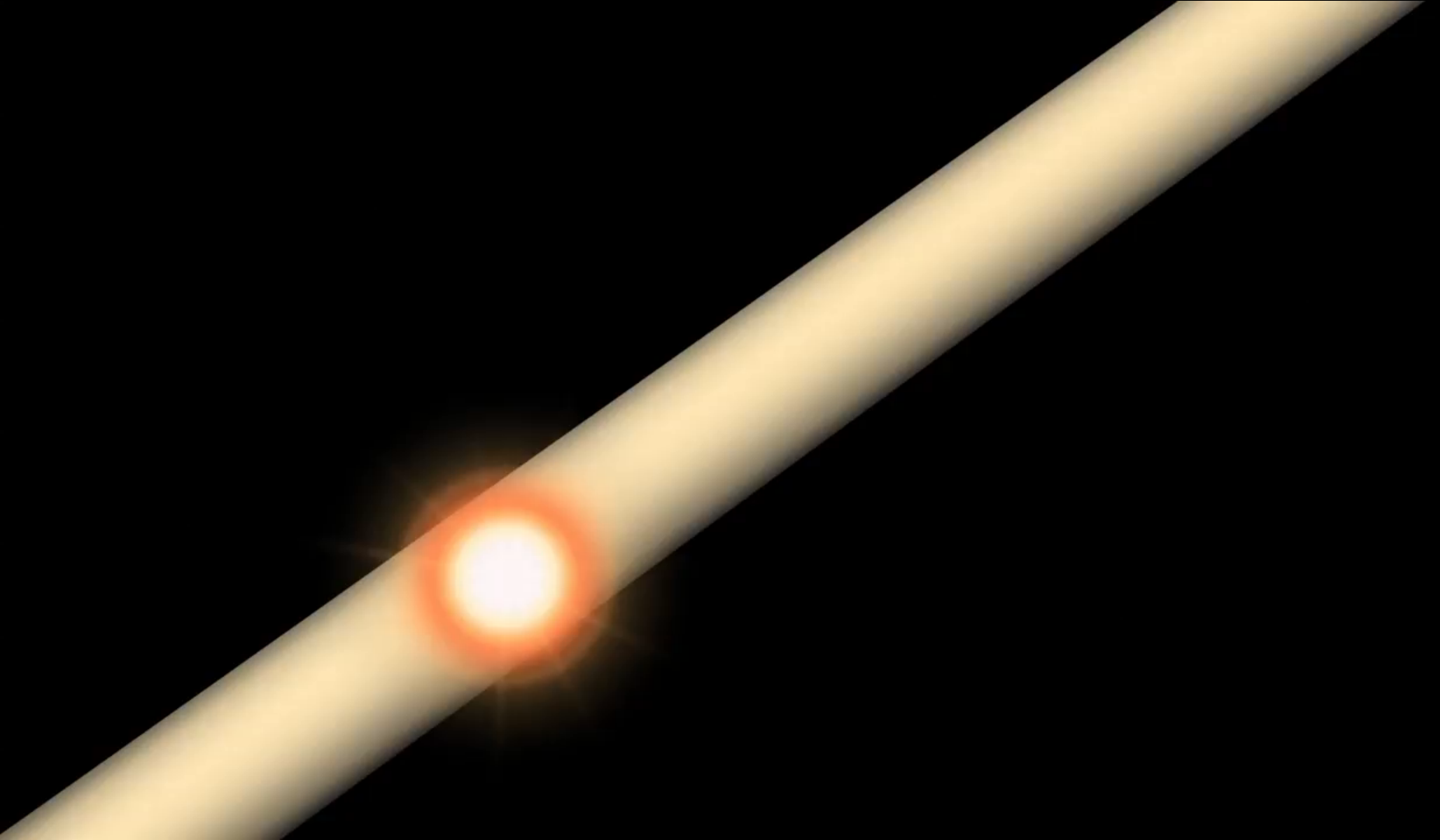


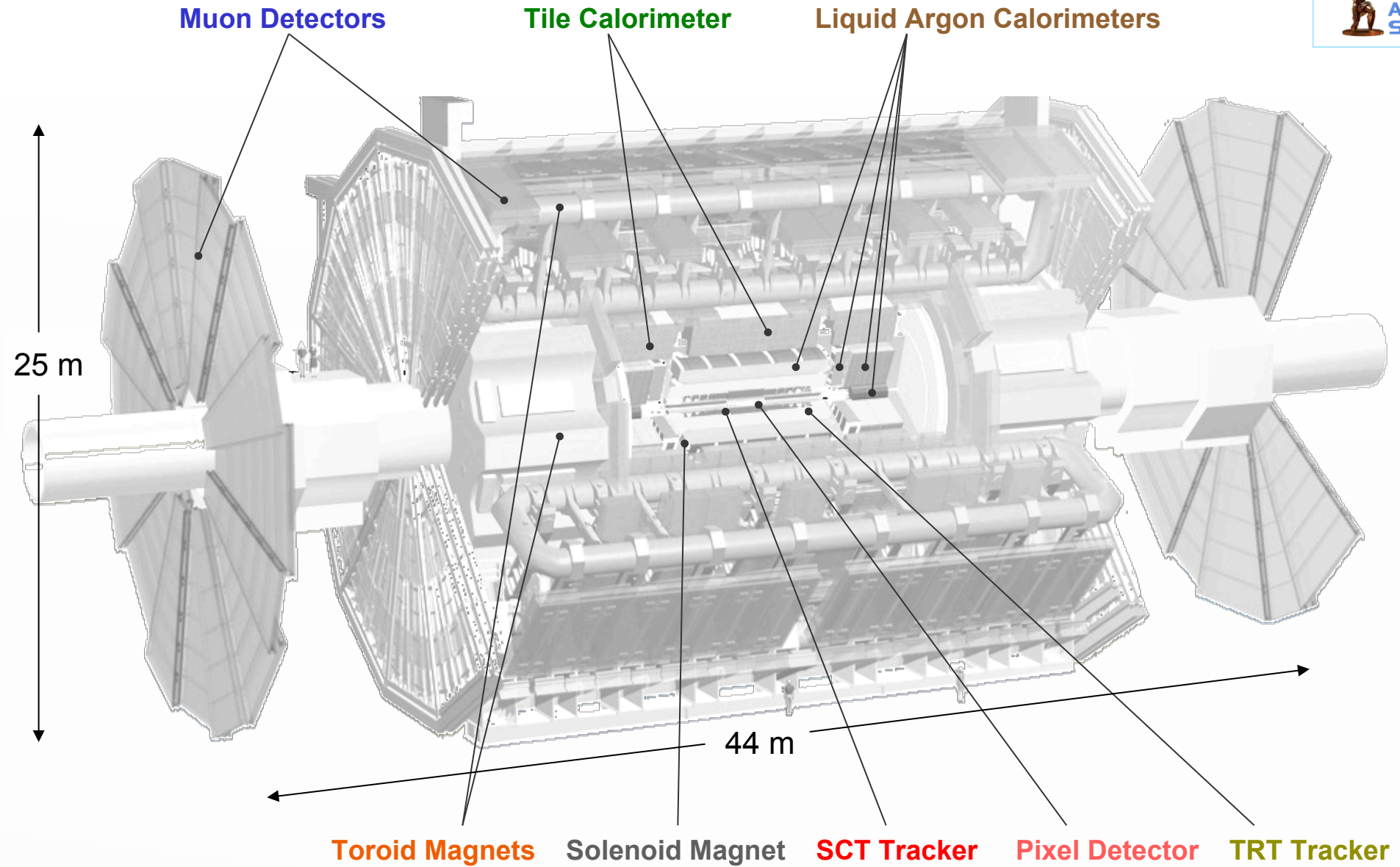
So far:
7/8 TeV proton—proton collisions
2.76 TeV Pb—Pb collisions

Detector Layers

Particles are detected through their interaction with the active detector materials



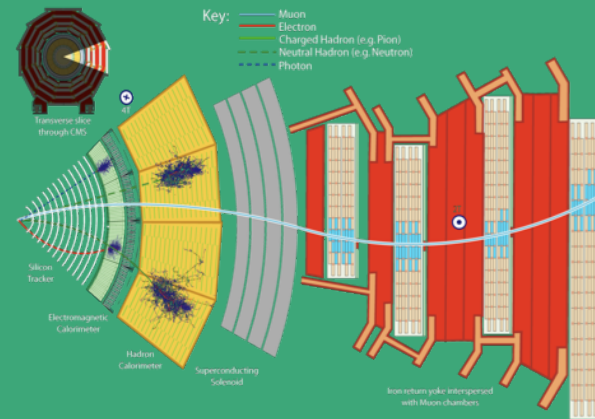
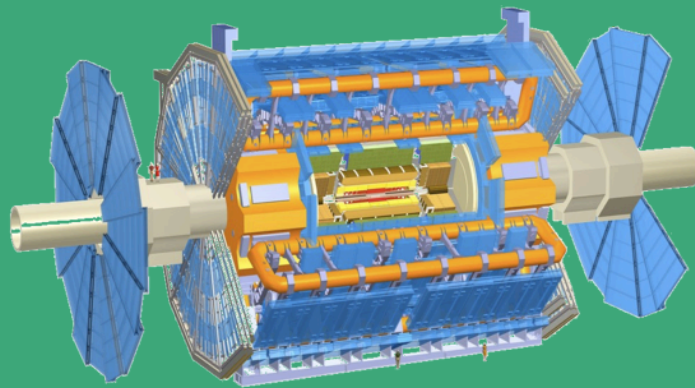




Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeters



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

CMS: emphasis on excellent electron/photon and tracking (muon) resolution

Both: excellent hermeticity - very few “cracks”

Toroid Magnets

Solenoid Magnet

SCT Tracker

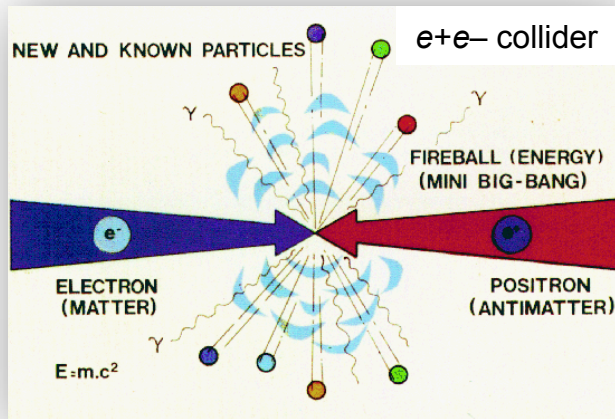
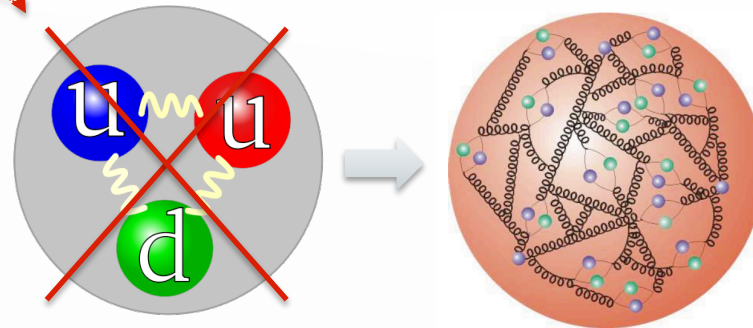
Pixel Detector

TRT Tracker

Proton–Proton Collisions

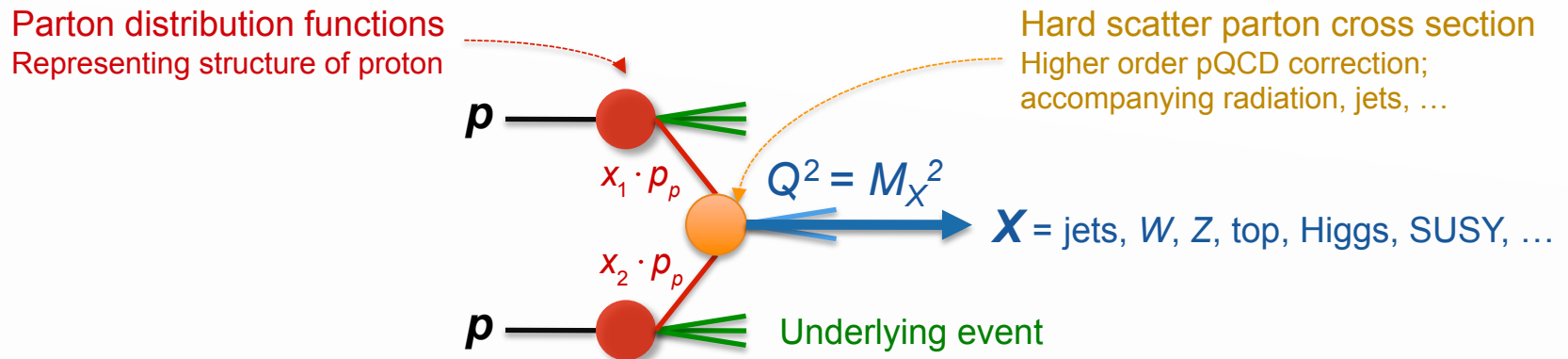
- For proton–proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element

Parton distribution functions
Representing structure of proton



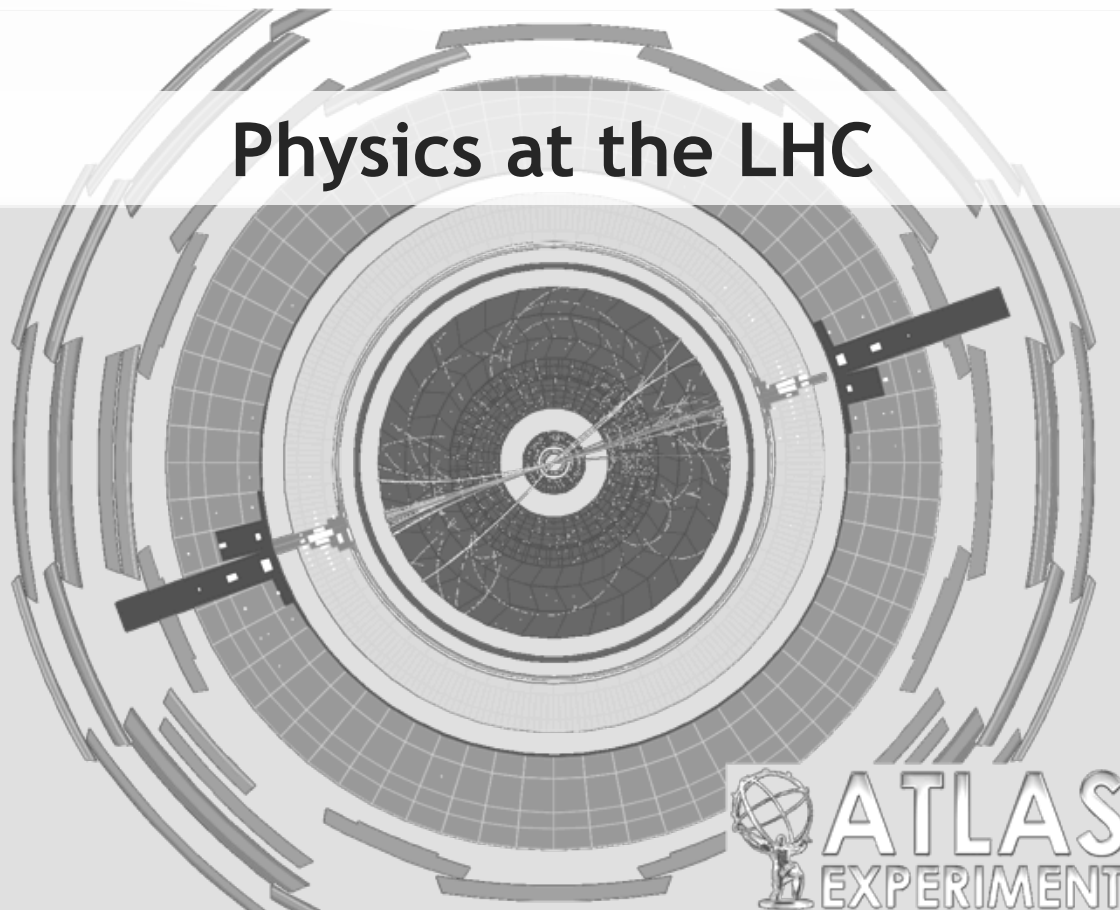
Proton–Proton Collisions

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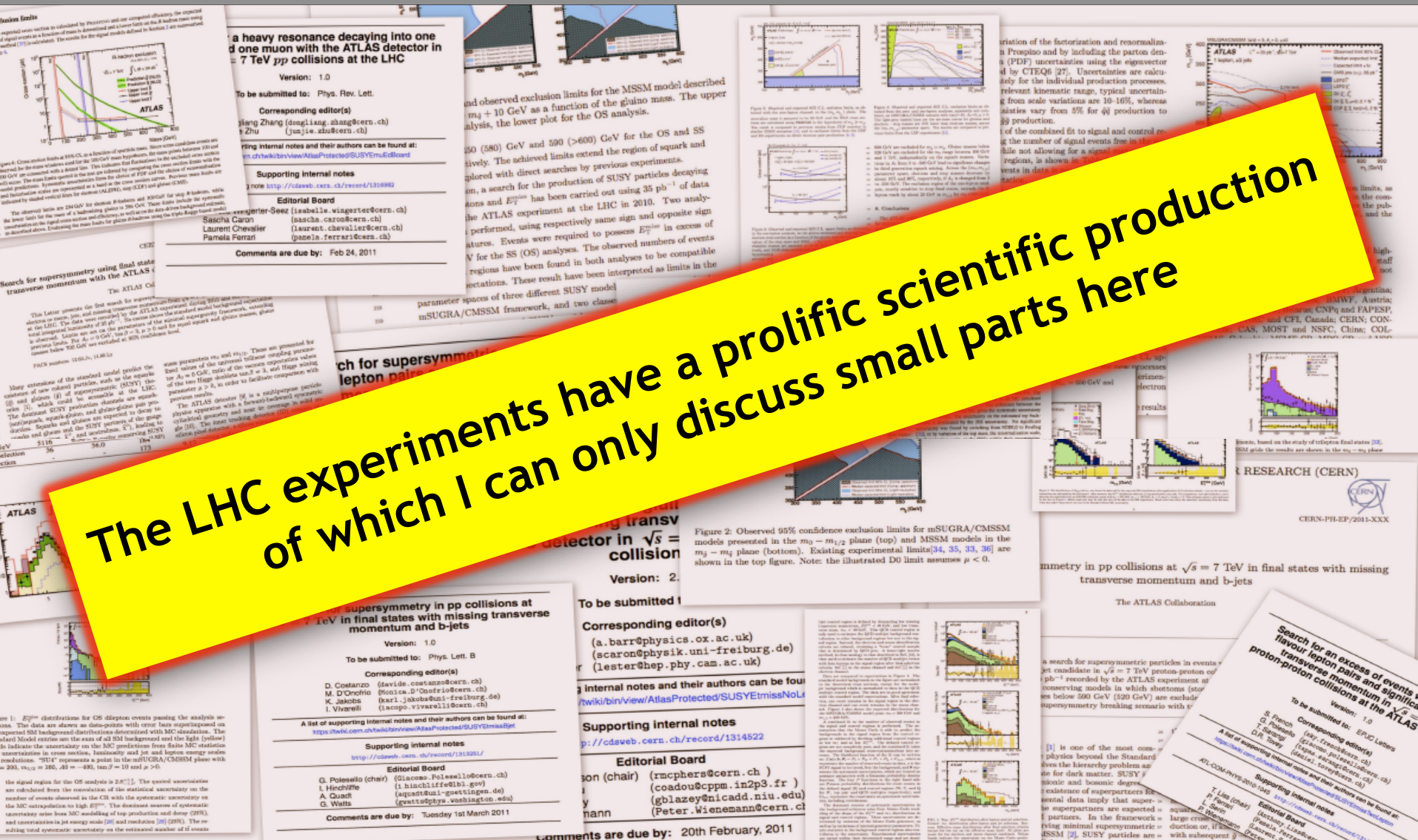
- CM energy of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- The parton density functions rise dramatically towards low x :
 - Higher cross section at higher proton–proton collision energy
 - More luminosity also achieves higher effective energy
 - Low- x (eg, Higgs) dominated by gluon–gluon collisions: “gluon collider”

Physics at the LHC



ATLAS
EXPERIMENT

The LHC experiments have a prolific scientific production of which I can only discuss small parts here

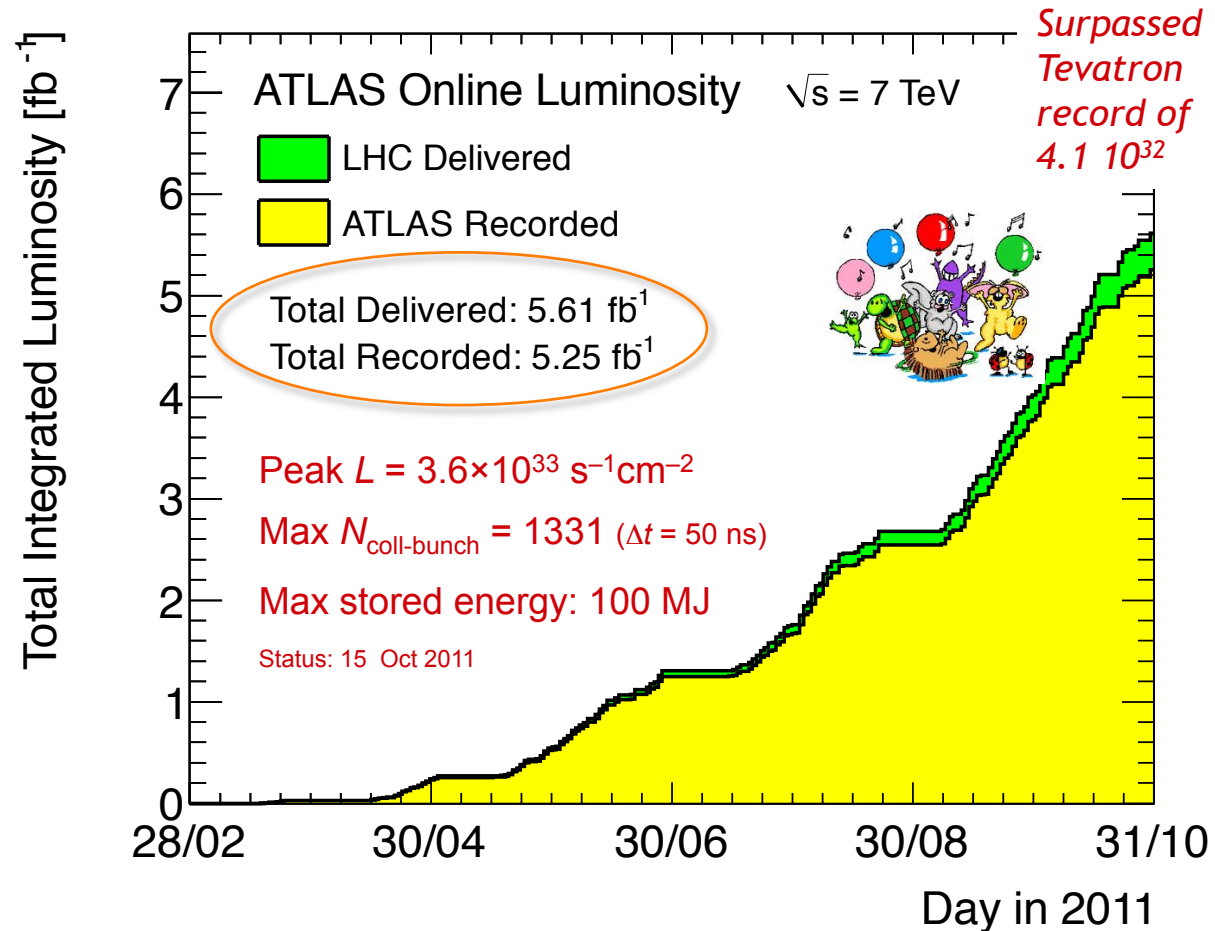


Recorded Luminosity in 2011

Luminosity is key quantity: $\text{rate} = \text{cross section} \times \text{efficiency} \times \text{luminosity}$

ATLAS integrated
luminosity in 2011

(in 2010: 0.04 fb^{-1} collected)

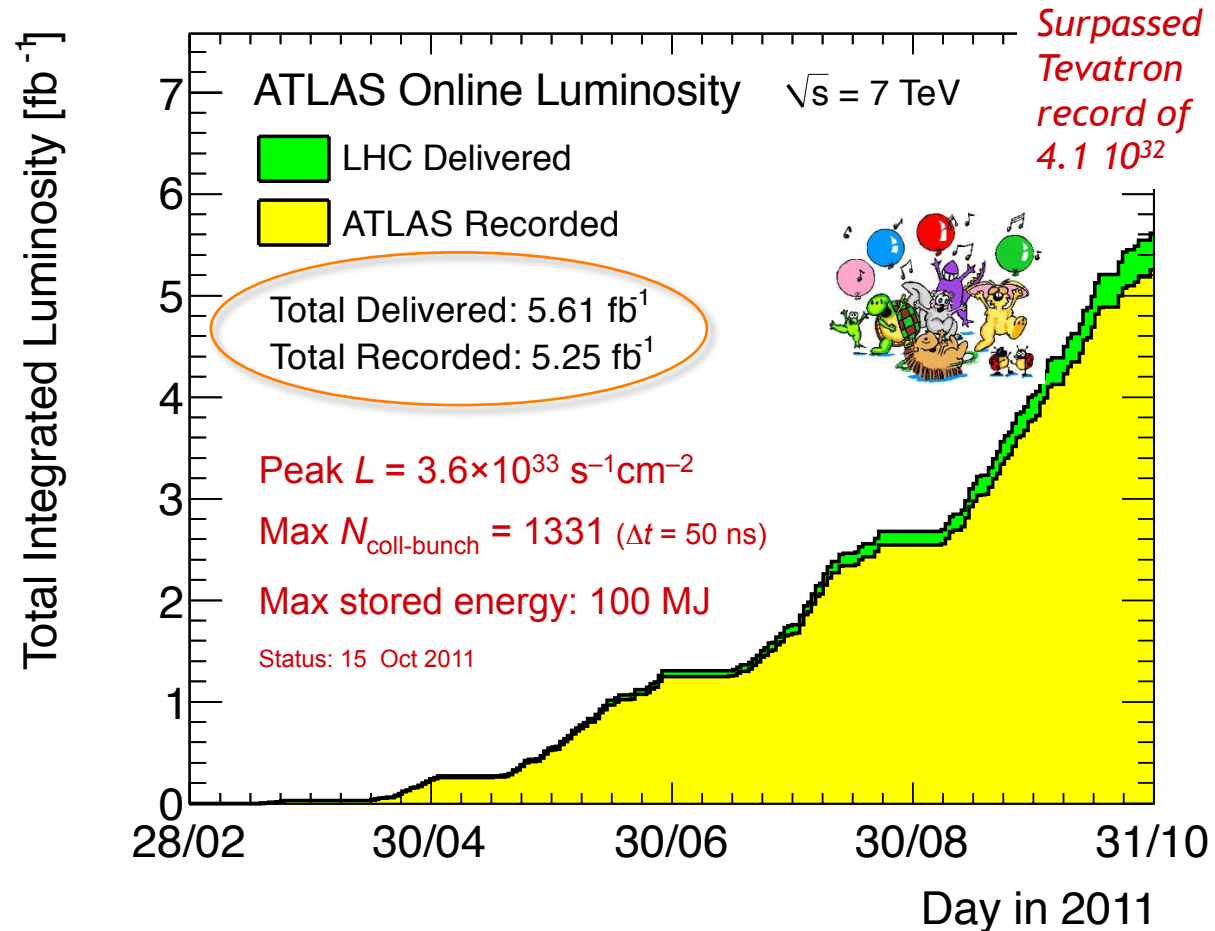


Recorded Luminosity in 2011

Luminosity is key quantity: $\text{rate} = \text{cross section} \times \text{efficiency} \times \text{luminosity}$

At $L = 3 \times 10^{33} \text{ s}^{-1} \text{ cm}^{-2}$,
produce 225 (129) SM
Higgs bosons of 115
(150) GeV mass in
ATLAS and CMS per hour

Tevatron @ 115 GeV: 2/h at max luminosity



Recorded Luminosity in 2011

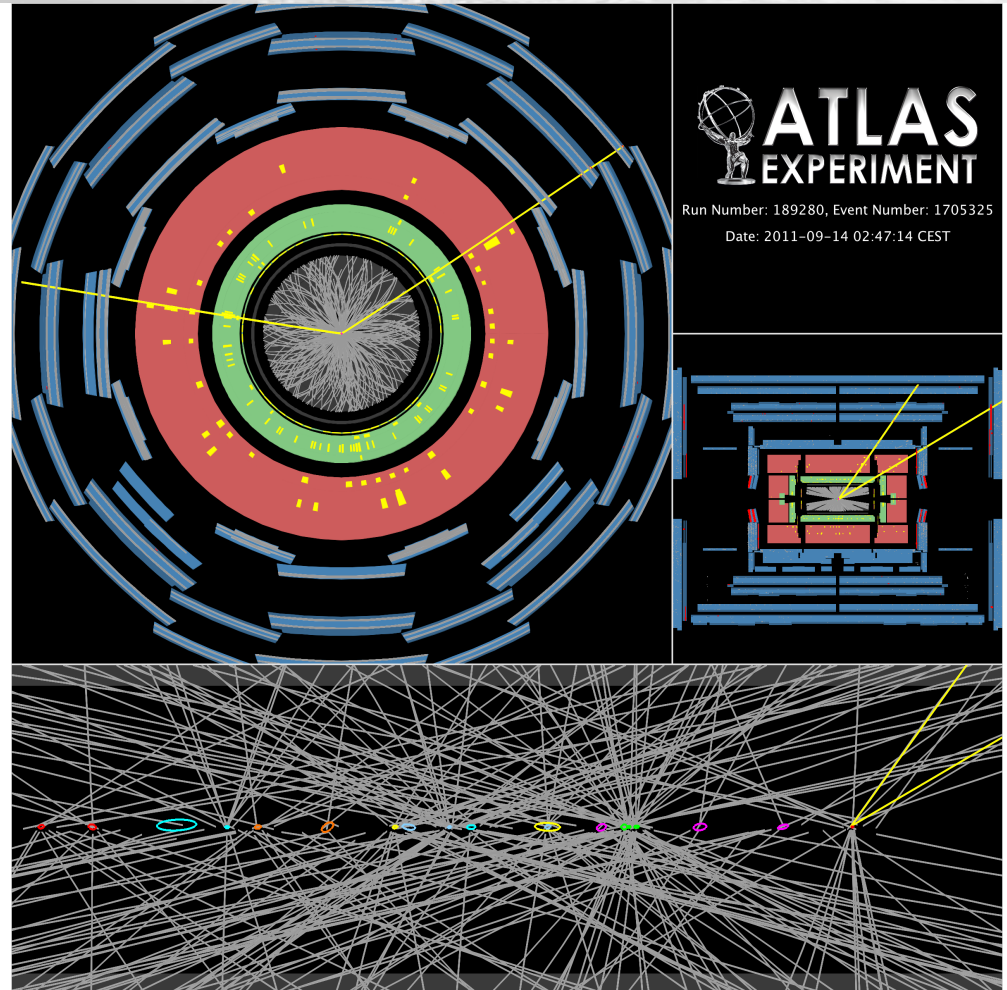
Measured with forward detectors, calibrated with beam separation scans

High luminosity comes at a price: probability of parasitic collisions in one bunch crossing (= *pileup*) increases

Peak of up to 22 collisions per crossing reached (almost doubled in 2012)

Another price to pay: higher trigger thresholds $\rightarrow$ low- p_T physics suffers

$Z \rightarrow \mu\mu$ event in ATLAS with 20 reconstructed vertices



Recorded Luminosity in 2011

Measured with forward detectors, calibrated with beam separation scans

High luminosity comes at a price: probability of parasitic collisions in one bunch crossing (= *pileup*) increases

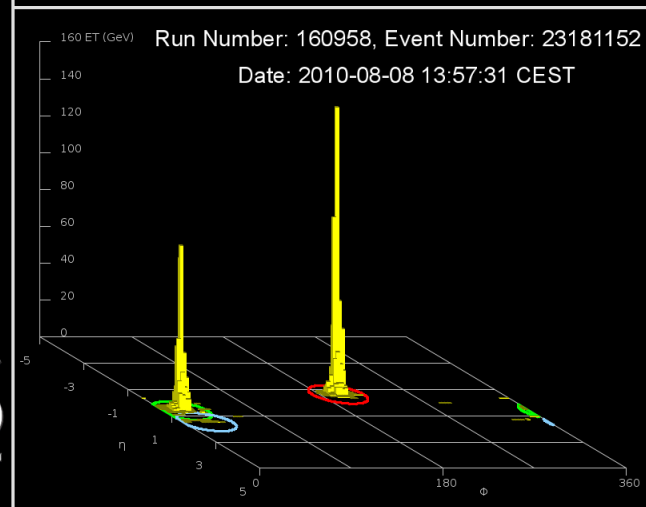
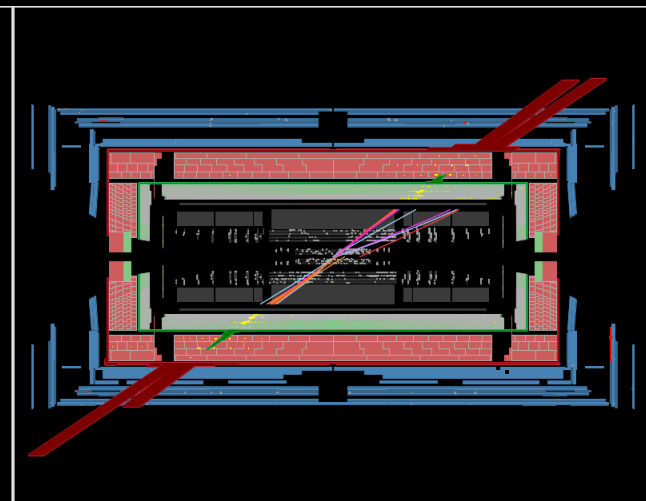
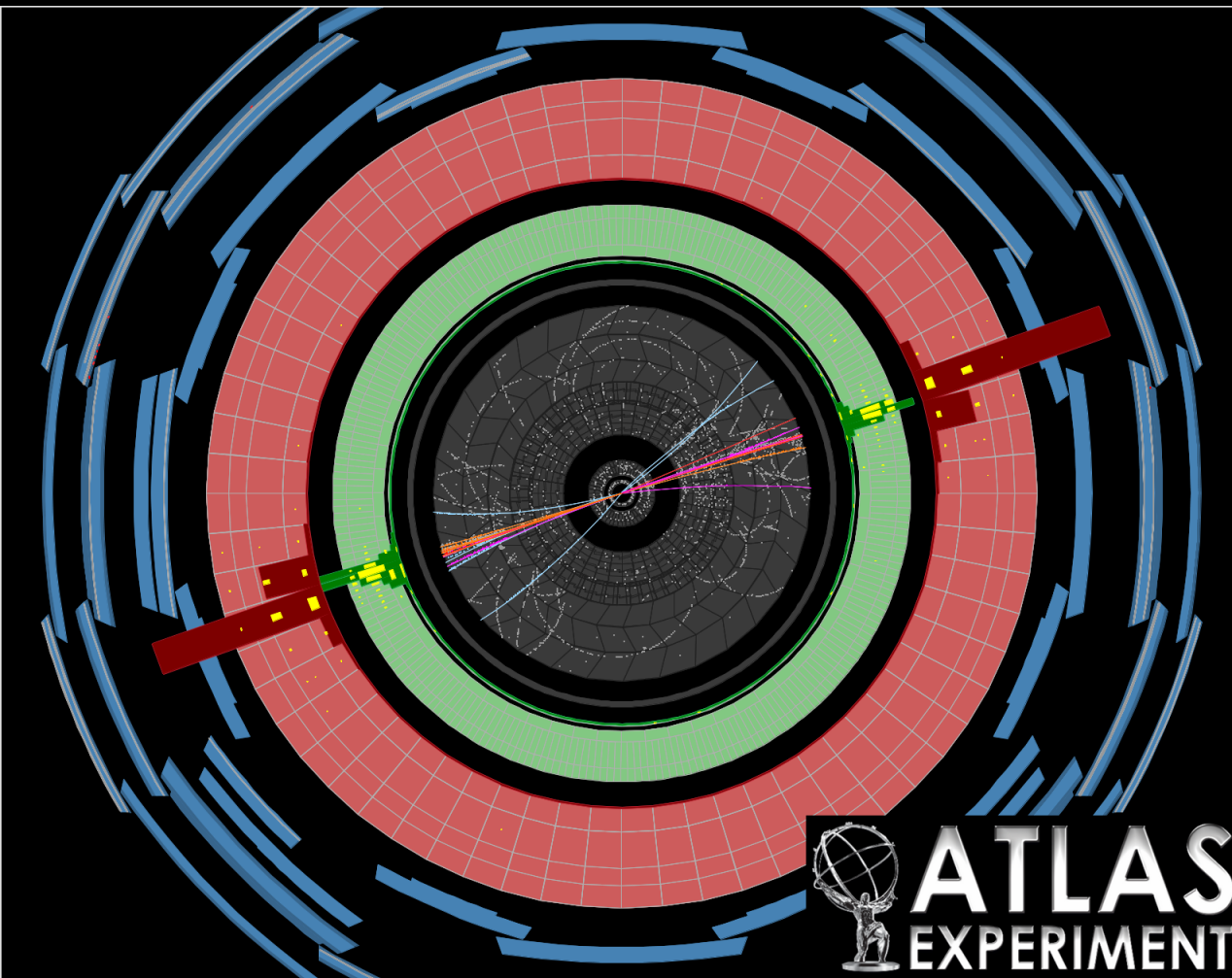
Peak of up to 22 collisions per crossing

At high luminosity, the signal is buried in the background of low- p_T physics processes

$Z \rightarrow \mu\mu$ event in ATLAS with 20 reconstructed vertices

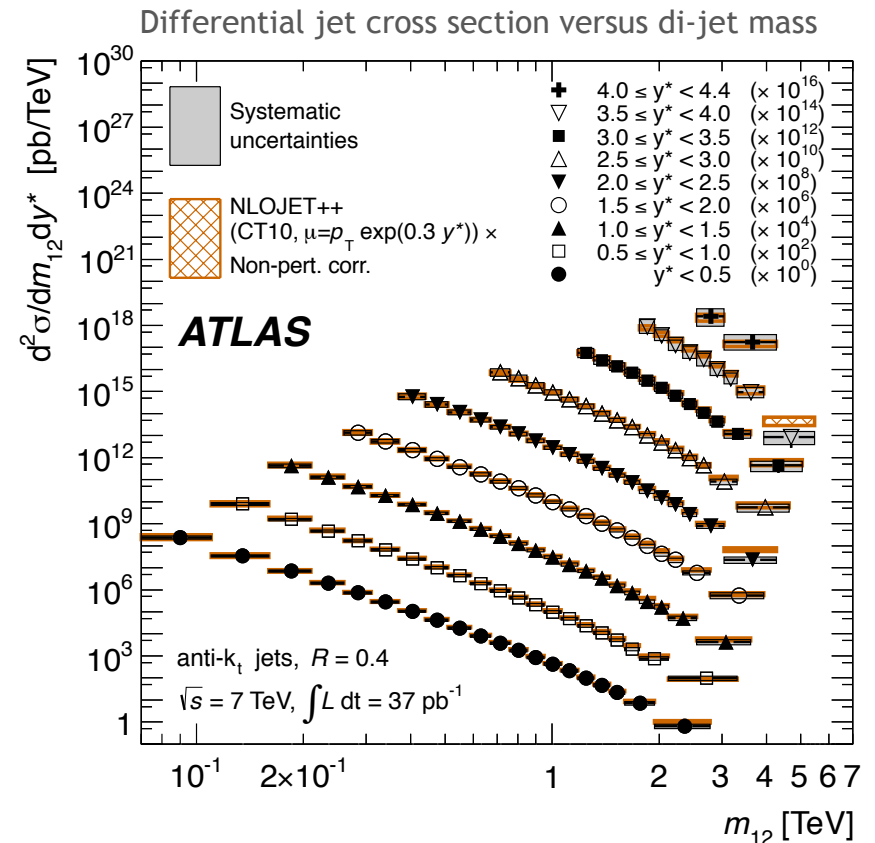
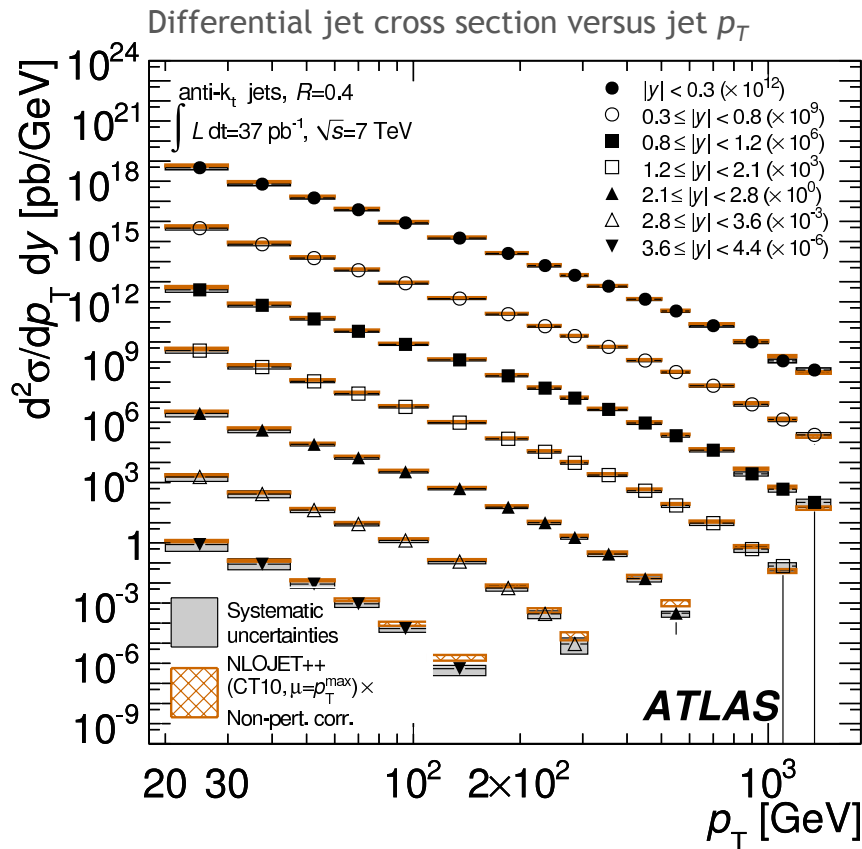


A beautiful dijet event from ATLAS: $m(\text{jet-jet}) = 1.9 \text{ TeV}$, $p_T : 0.9 \text{ TeV}, 0.8 \text{ TeV}$



ATLAS and CMS have Measured Inclusive and Exclusive Jet Cross Sections at never Explored Energies

ATLAS arXiv:1112.6297



Agreement over many orders of magnitude gives confidence for new physics searches

High-energy jets probe new particles and interactions

Measure di-jet invariant mass and angular distributions

$2 \rightarrow 2$ parton scattering to two jets described by QCD

Tends to scatter at smaller angles than if there were new particles produced

Recall atomic substructure discovery in Rutherford scattering: **deflection at large angles !**

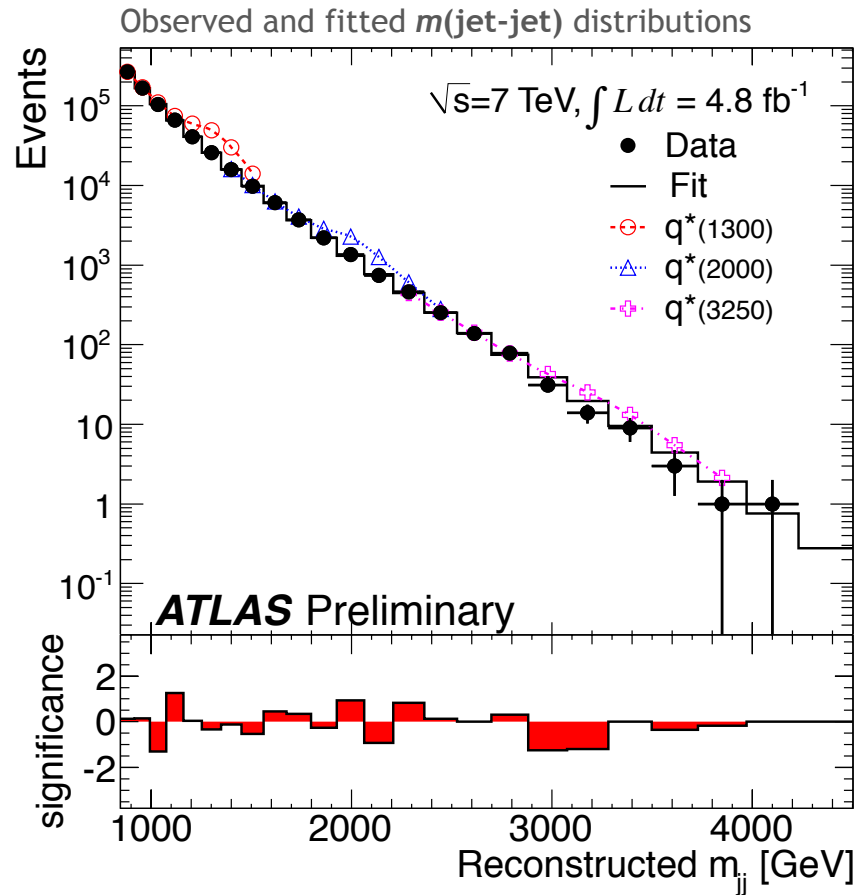


New, high-scale interaction ?
New bound state (particle) ?
Are quarks composites ?

High-energy jets probe new particles and interactions

Measure di-jet invariant mass and angular distributions

ATLAS-CONF-2012-038



High-energy jets probe new particles and interactions

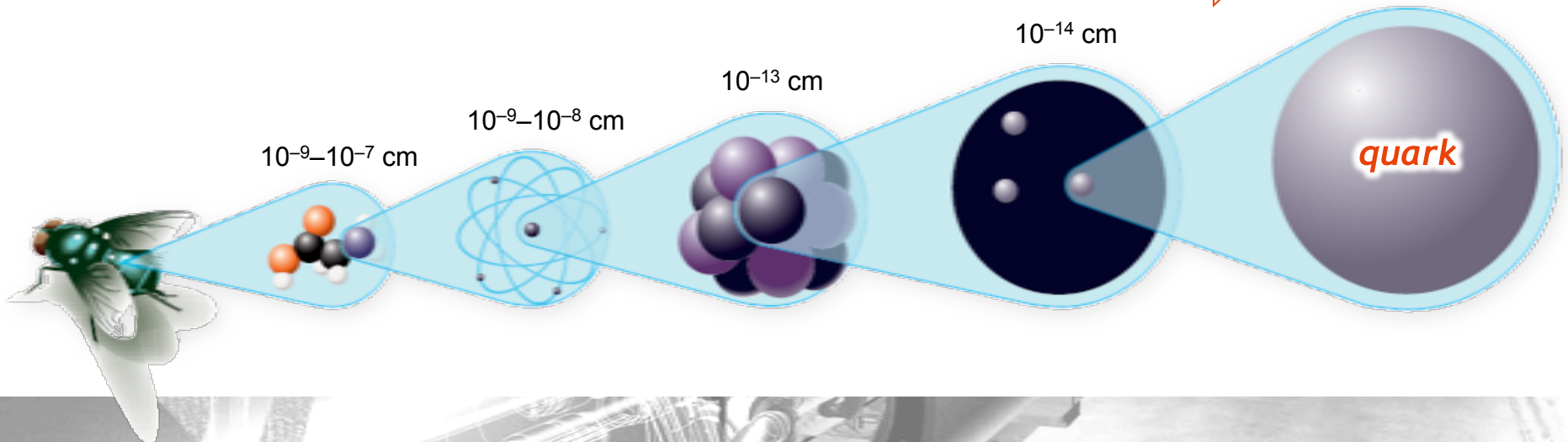
Measure di-jet invariant mass and angular distributions

ATLAS-CONF-2012-038

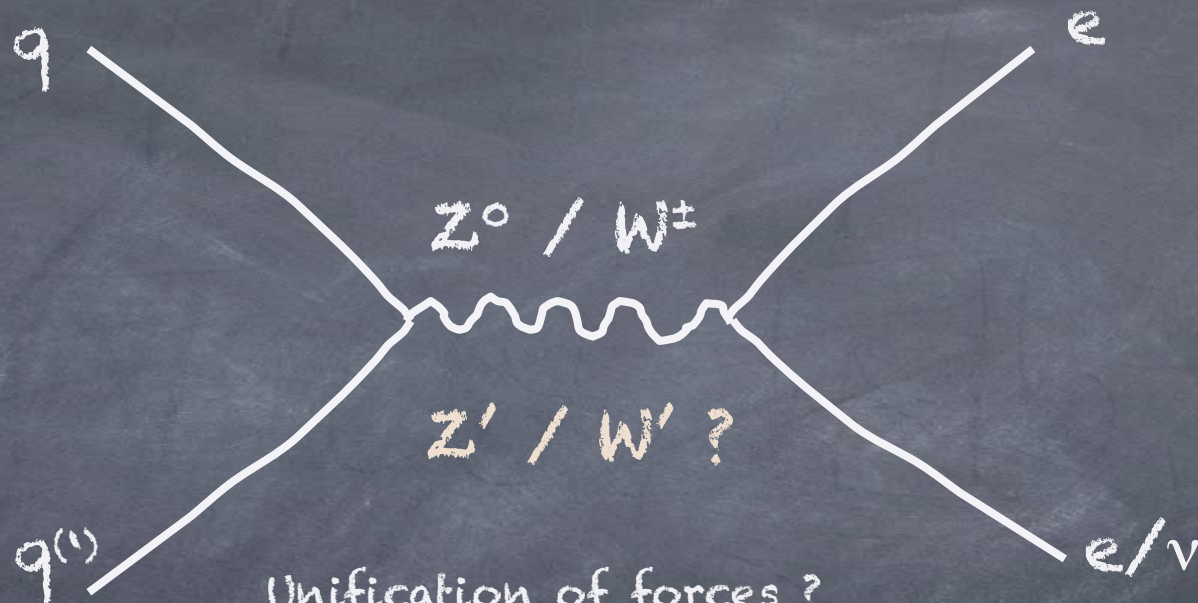
No deviations from SM seen $\rightarrow$ set limits on new phenomena:

	Benchmark model	Observed limit at 95% CL
Resonant	Excited quarks	$m(q^*) > 3.4 \text{ TeV}$
Non-resonant	4-quark contact interactions	$\Lambda > 7.8 \text{ TeV}$

$< 1.8 \times 10^{-18} \text{ cm}$



Leptons are pure SM and new physics probes with much reduced strong-interactions background



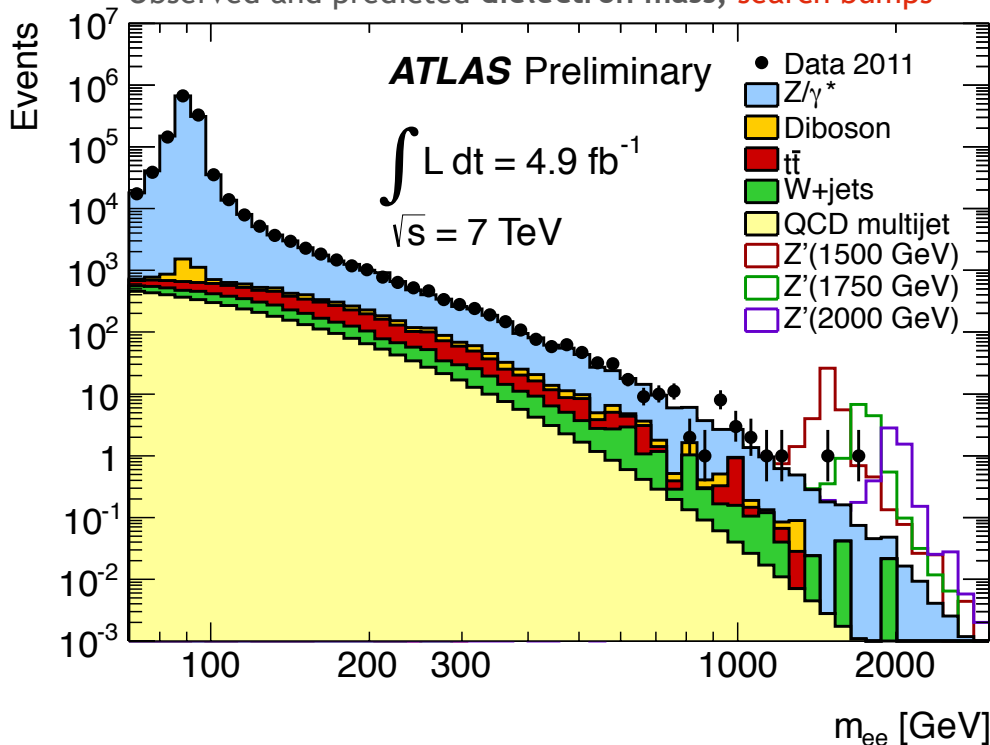
Unification of forces ?
Left-right symmetric models ?
Compact extra dimensions ?
Technicolour ?
Higgs extensions ?

Searches for Z' and W' resonances in decays to e/μ

Use dilepton / transverse mass to search for excess over SM

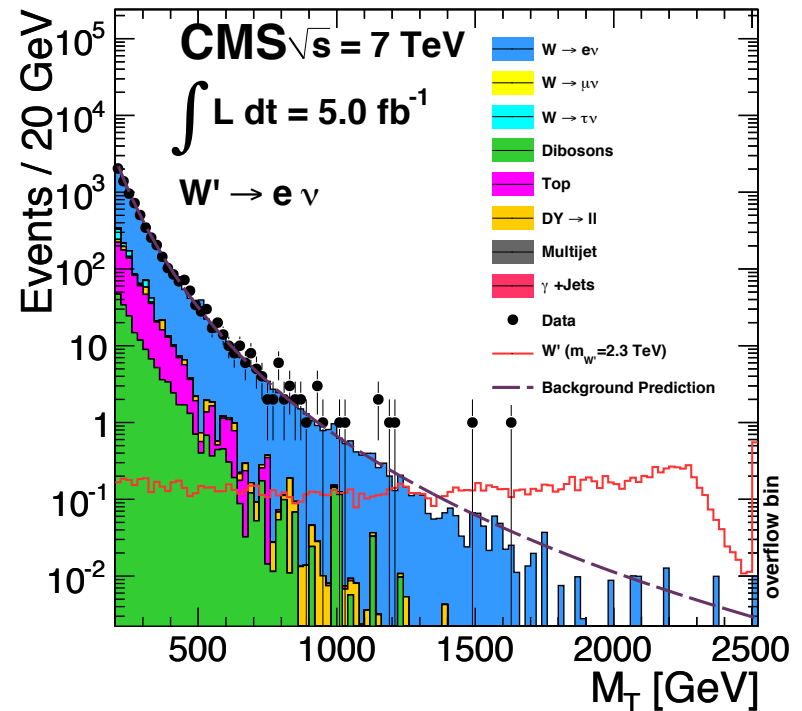
ATLAS-CONF-2012-007, CMS arXiv:1204.4764

Observed and predicted dielectron mass, **search bumps**



95% CL lower limit: $m(Z'_{SSM}) > 2.2 \text{ TeV}$

Observed and predicted e - n transverse mass

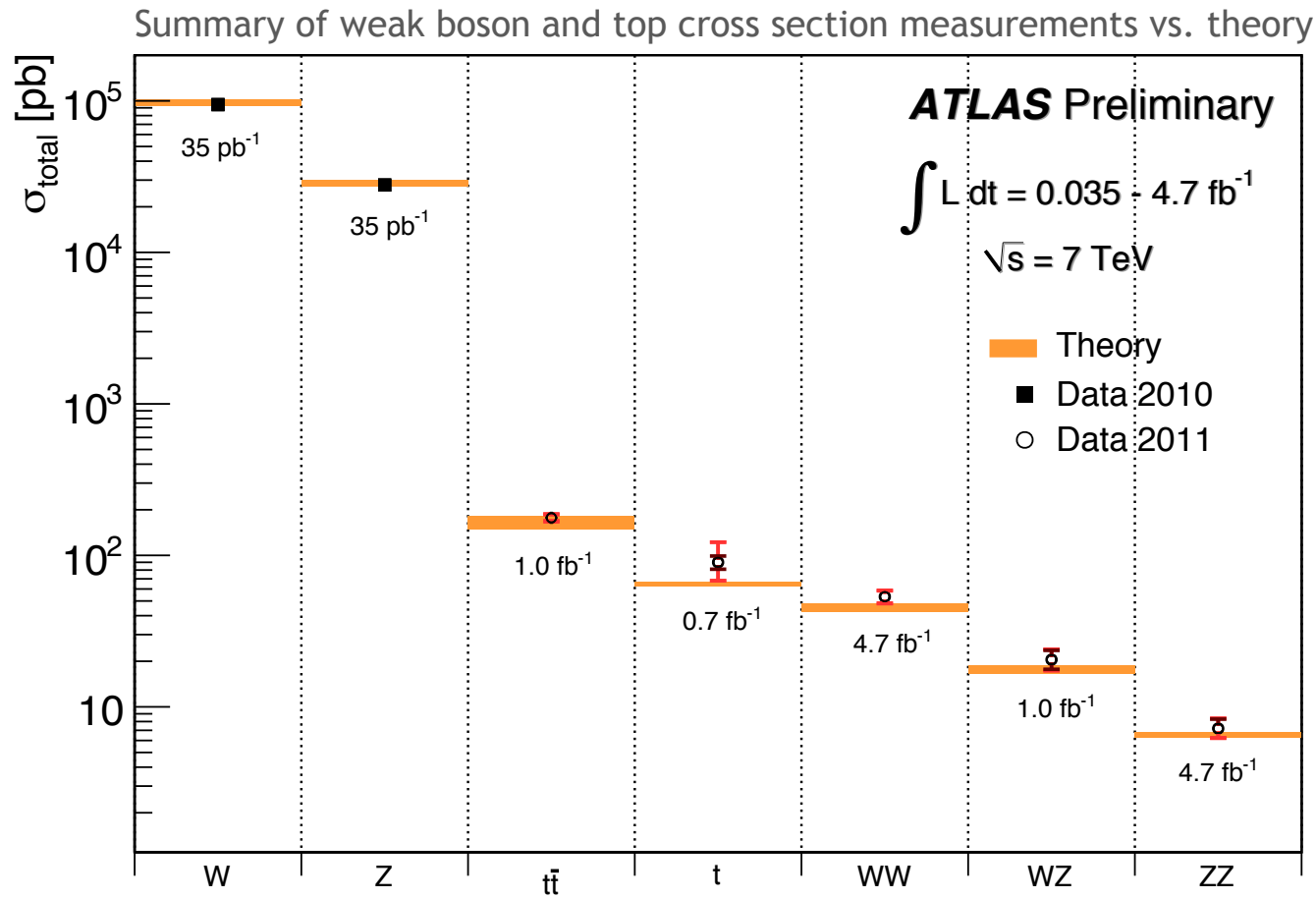


95% CL lower limit: $m(W'_{SSM}) > 2.6 \text{ TeV}^{(*)}$

^(*)Constructive interference model

QCD and electroweak measurements

With more luminosity we are sensitive to every smaller cross sections



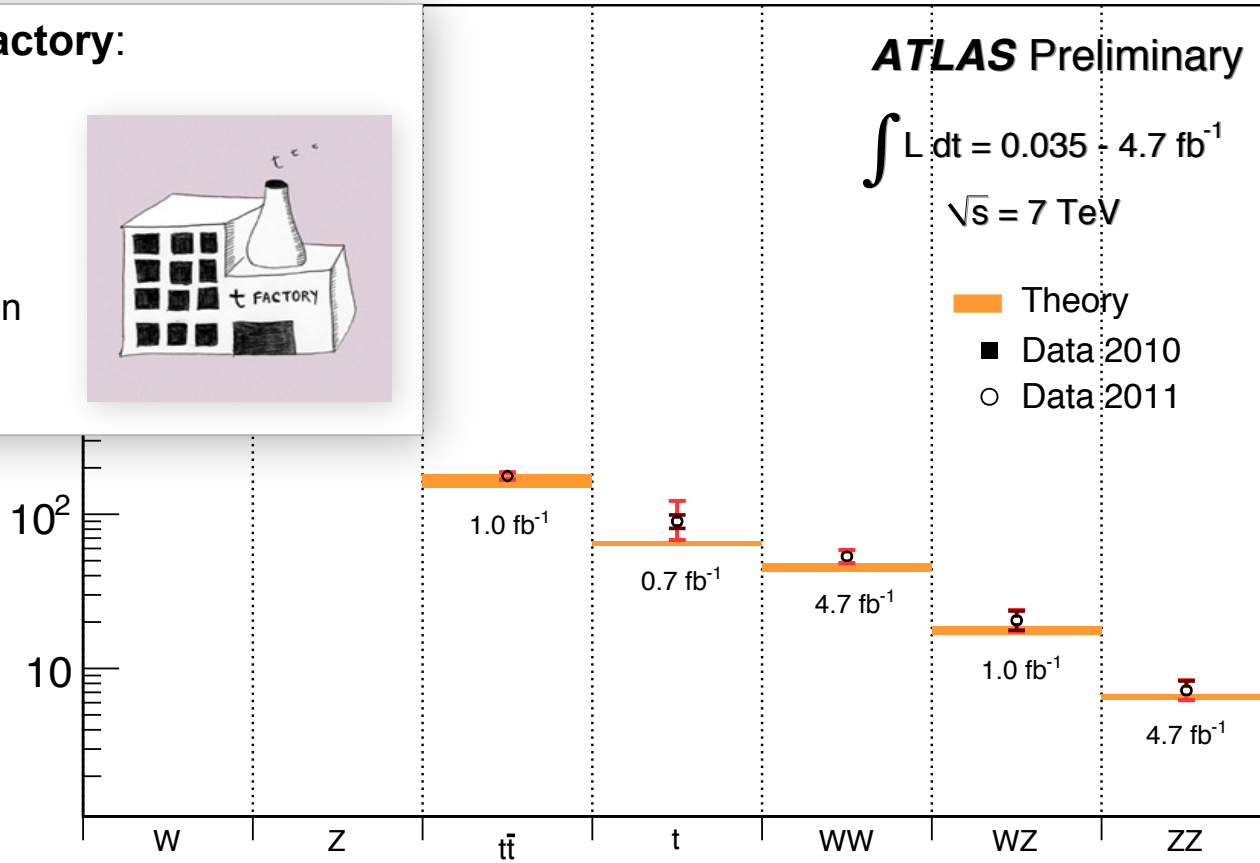
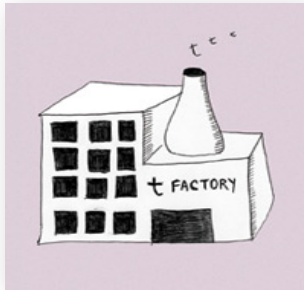
QCD and electroweak measurements

With more luminosity we are sensitive to every smaller cross sections

Summary of weak boson and top cross section measurements vs. theory

LHC is **top** factory:

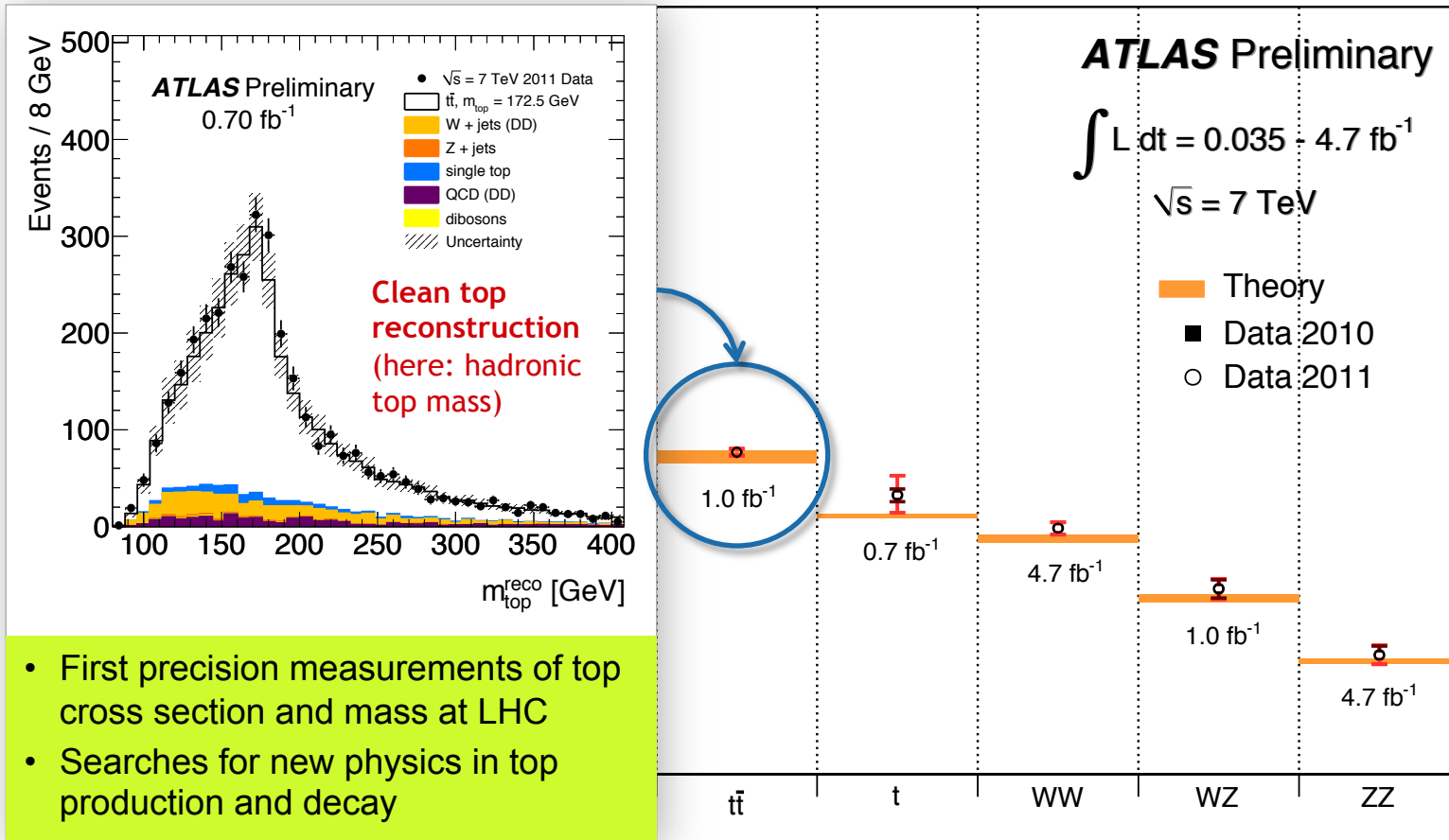
at 7 TeV CM
energy: ~25
times larger
cross section
than at Tevatron



QCD and electroweak measurements

With more luminosity we are sensitive to every smaller cross sections

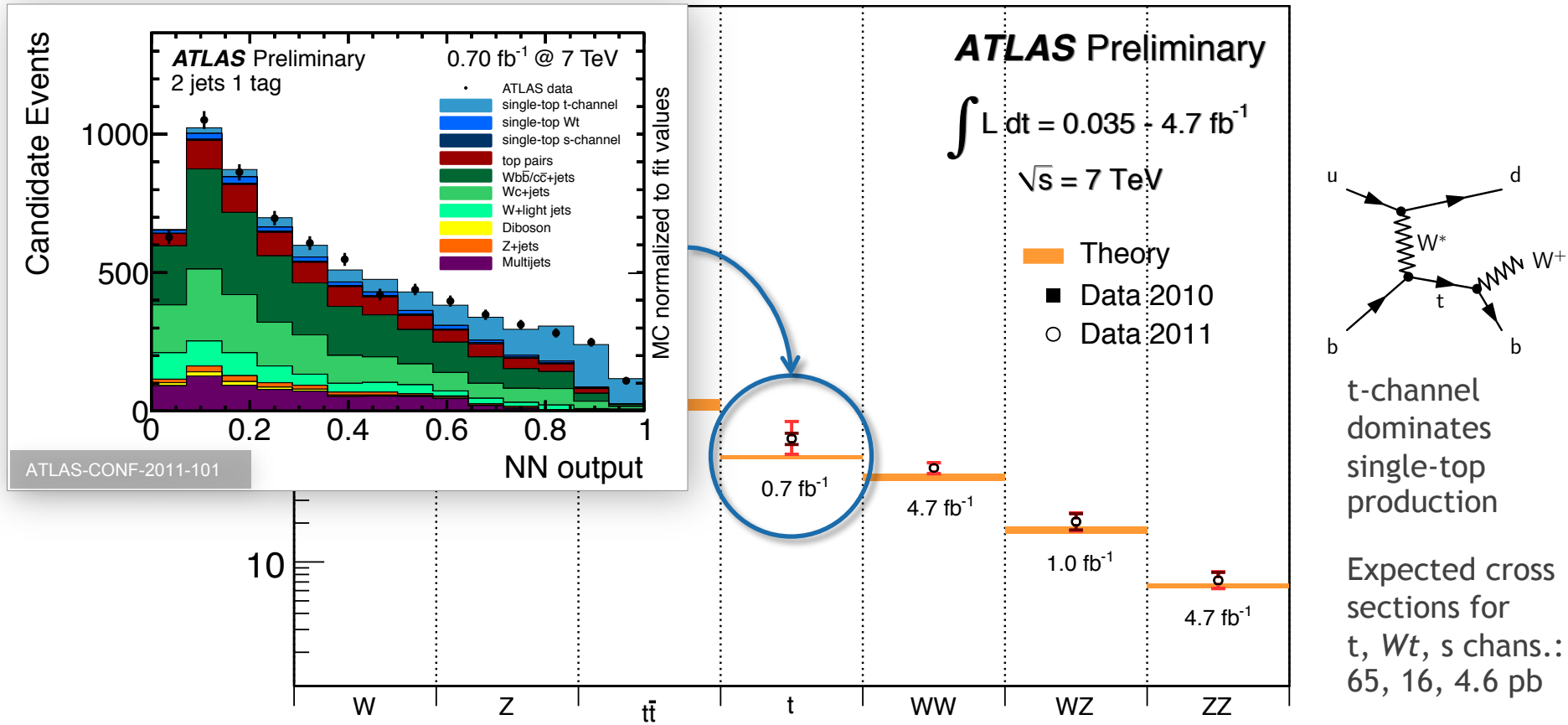
Summary of weak boson and top cross section measurements vs. theory



QCD and electroweak measurements

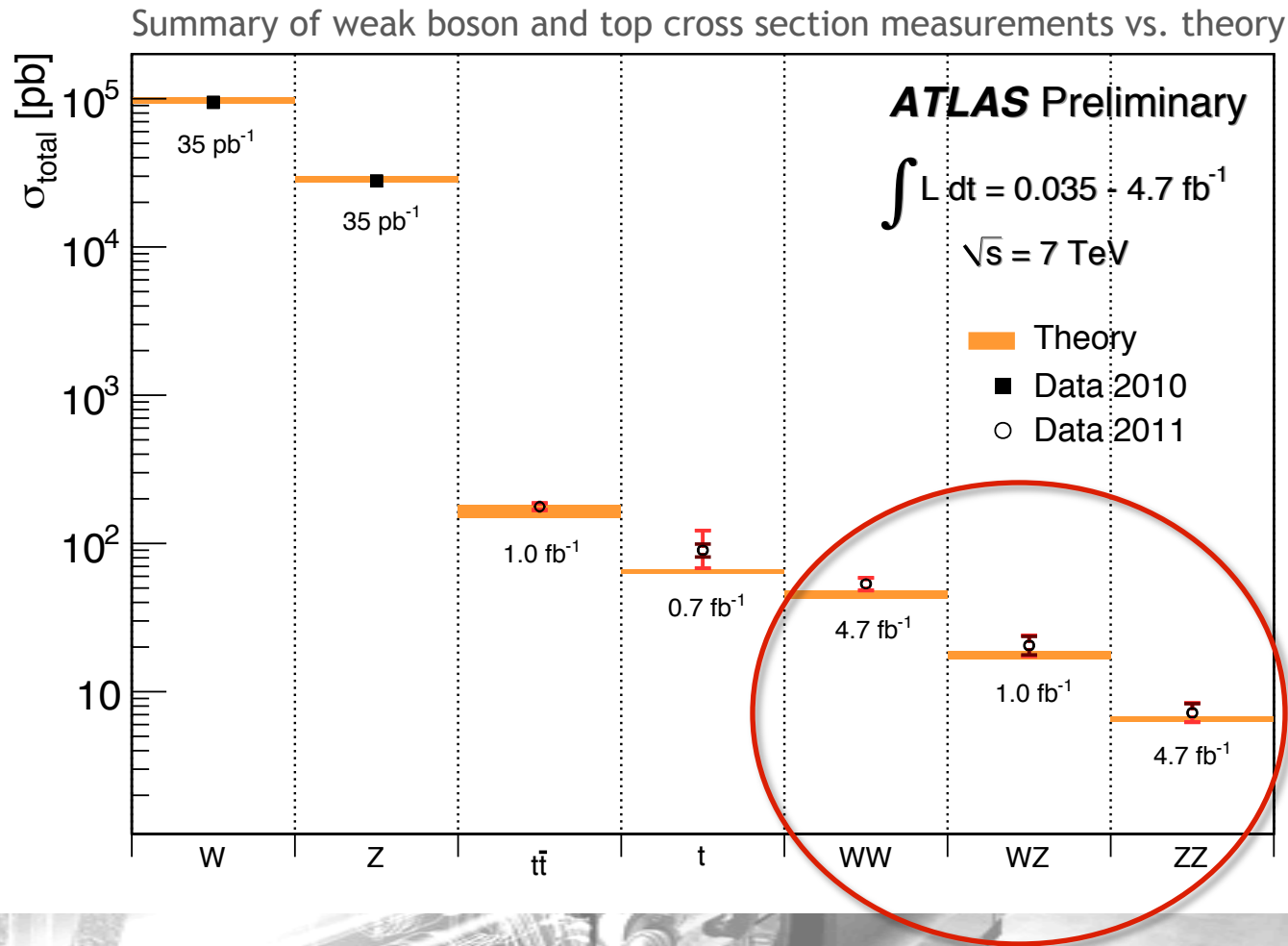
With more luminosity we are sensitive to every smaller cross sections

Summary of weak boson and top cross section measurements vs. theory



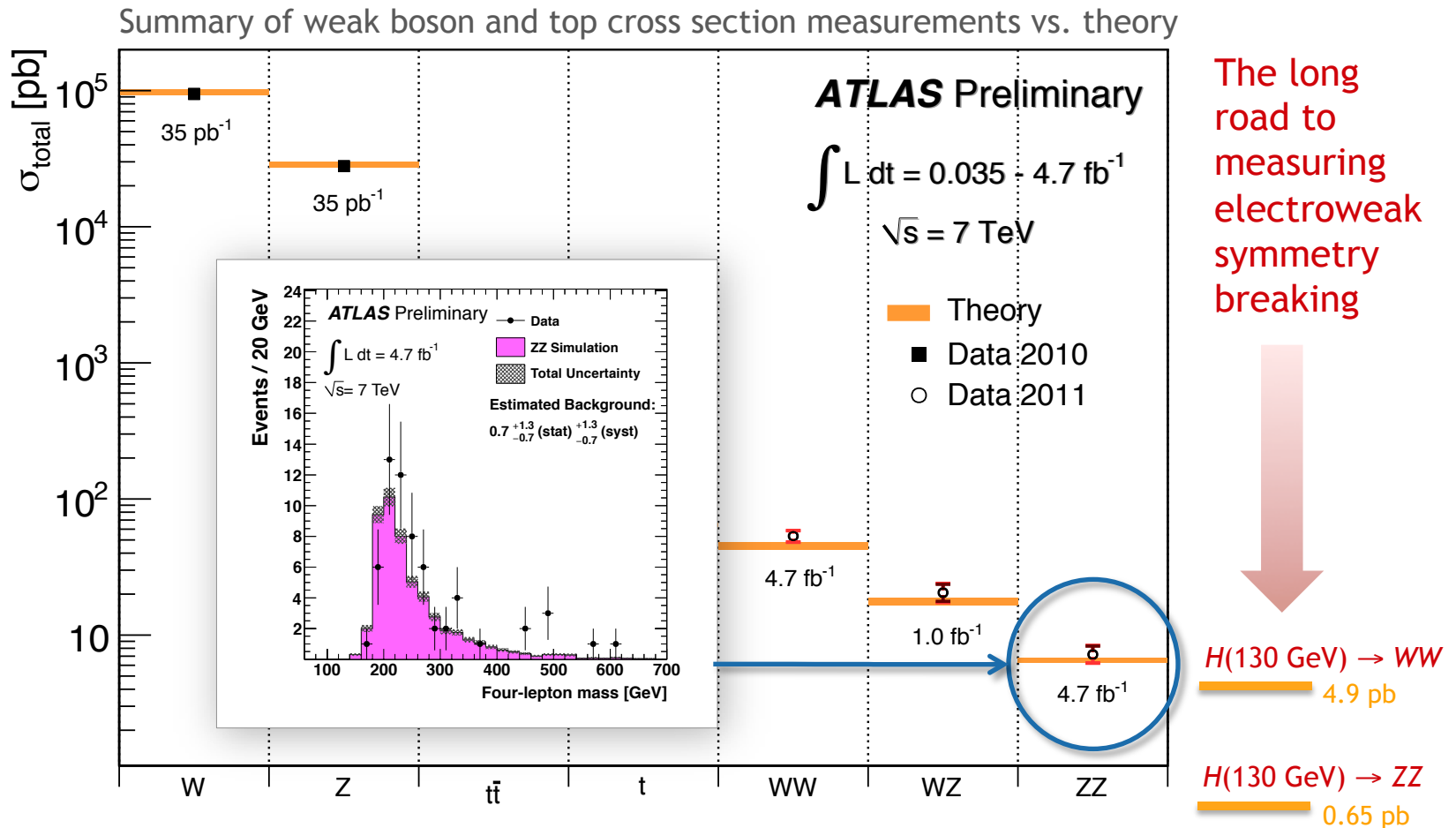
QCD and electroweak measurements

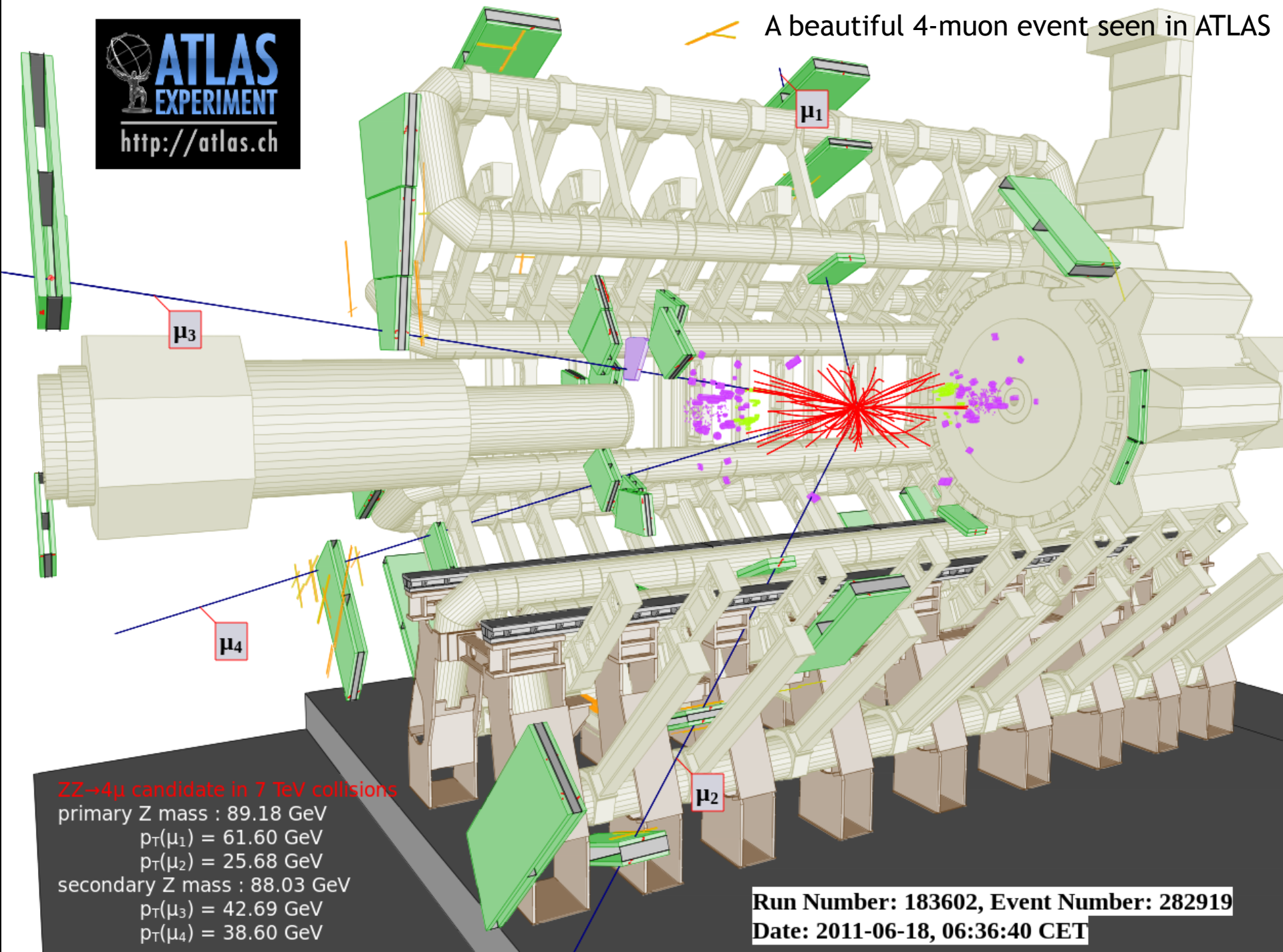
With more luminosity we are sensitive to every smaller cross sections



QCD and electroweak measurements

With more luminosity we are sensitive to every smaller cross sections





ZZ→4μ candidate in 7 TeV collisions

primary Z mass : 89.18 GeV

$p_T(\mu_1) = 61.60$ GeV

$p_T(\mu_2) = 25.68$ GeV

secondary Z mass : 88.03 GeV

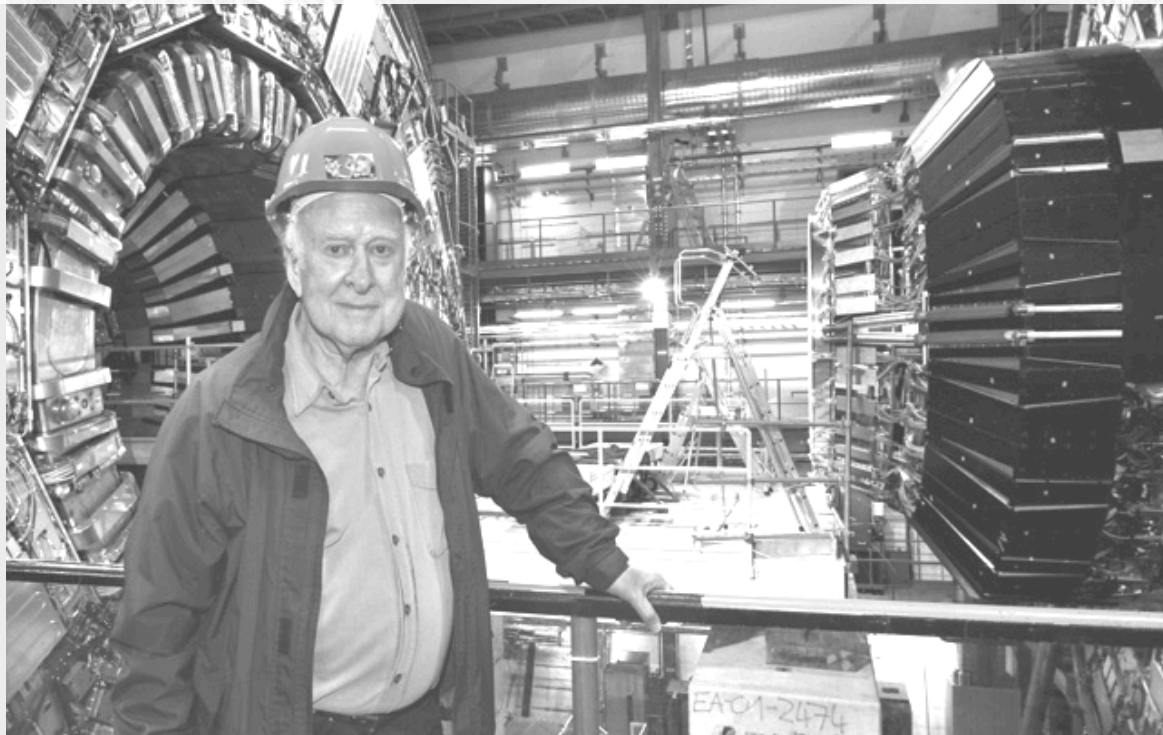
$p_T(\mu_3) = 42.69$ GeV

$p_T(\mu_4) = 38.60$ GeV

Run Number: 183602, Event Number: 282919

Date: 2011-06-18, 06:36:40 CET

Hunting for the Higgs Boson



P. Higgs at CMS

Higgs boson

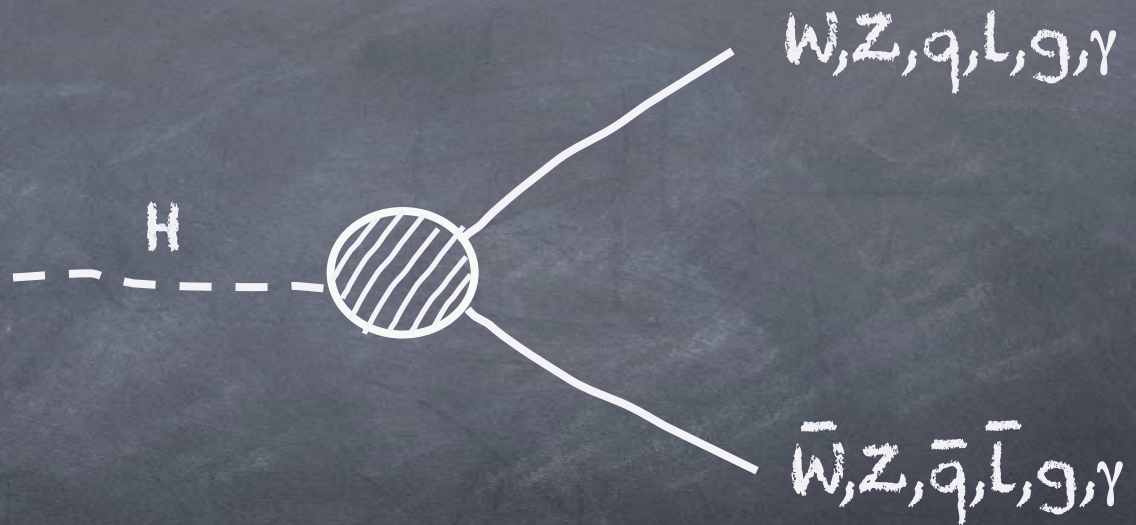
Higgs production and decay probabilities predicted vs. Higgs mass by SM

At the LHC, the Higgs boson is produced dominantly via gluon fusion
 $\sigma_{H,\text{total}} \sim 15 \text{ pb}$ at 125 GeV (40–50 times larger rate than at Tevatron)

Because of the coupling to the mass of the decay particles:

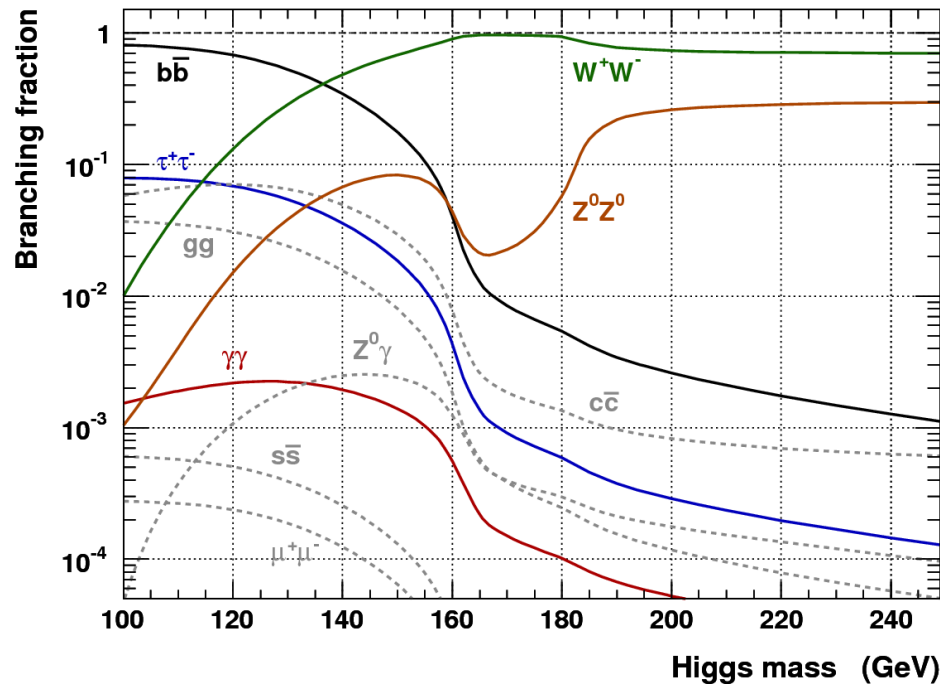
... the Higgs will decay with preference to the heaviest particles allowed

... the Higgs does not couple directly to photons and gluons, but only via “loops” involving heavy particles (e.g., top, W)



Higgs searches at the LHC

Dependence of the branching fractions on M_H drives search strategy



For **medium to heavy Higgs**:

- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$

For **light Higgs**:

- Lepton final states via WW^* , ZZ^*
- Di-photon final state
- Di-tau final state

The dominant $H \rightarrow bb$ mode is only exploitable in association with W/Z or tt , also with strong Higgs boost

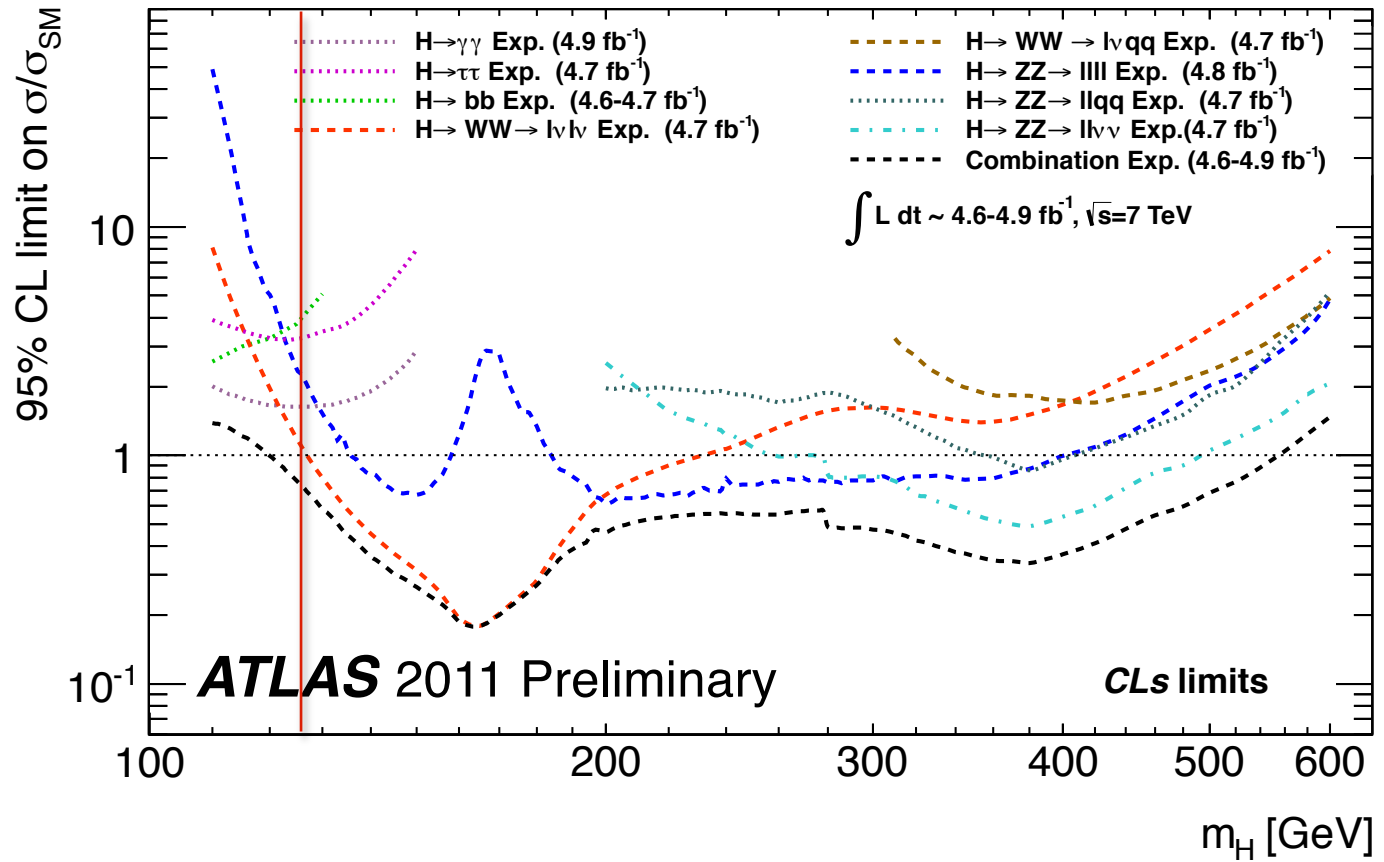
Associated leptons provide trigger signal as they help to reduce huge QCD background, $s(bb) \sim \mathcal{O}(100 \text{ } \mu\text{b})$

Combining all channels

At high mass also $WW \rightarrow llqq$ and $ZZ \rightarrow ll\nu\nu$ channels contribute

ATLAS-CONF-2012-019

Individual
channel
expected
sensitivities
in one plot

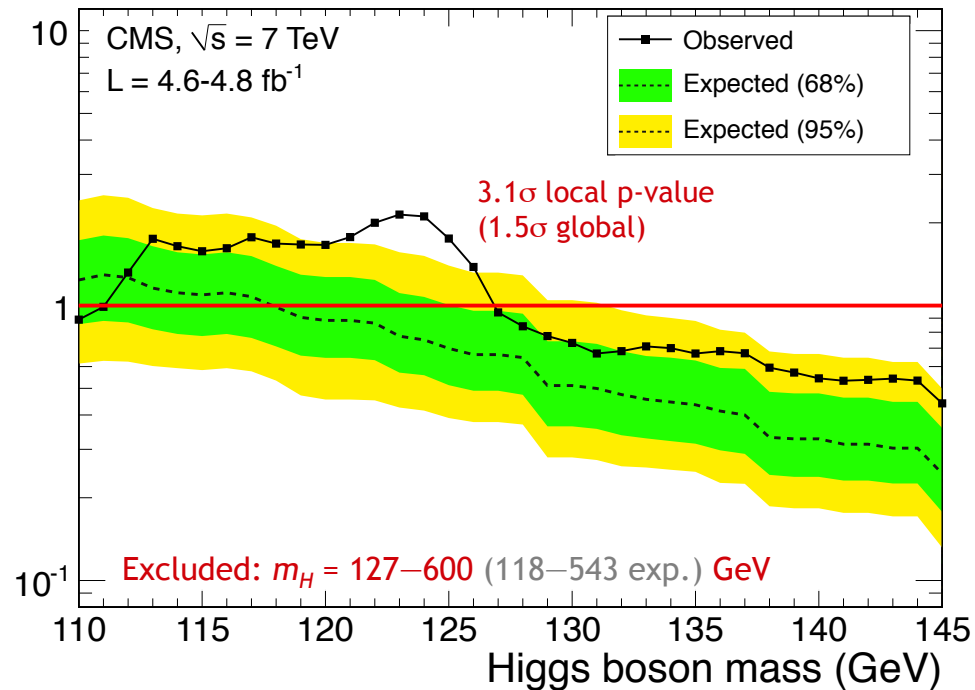
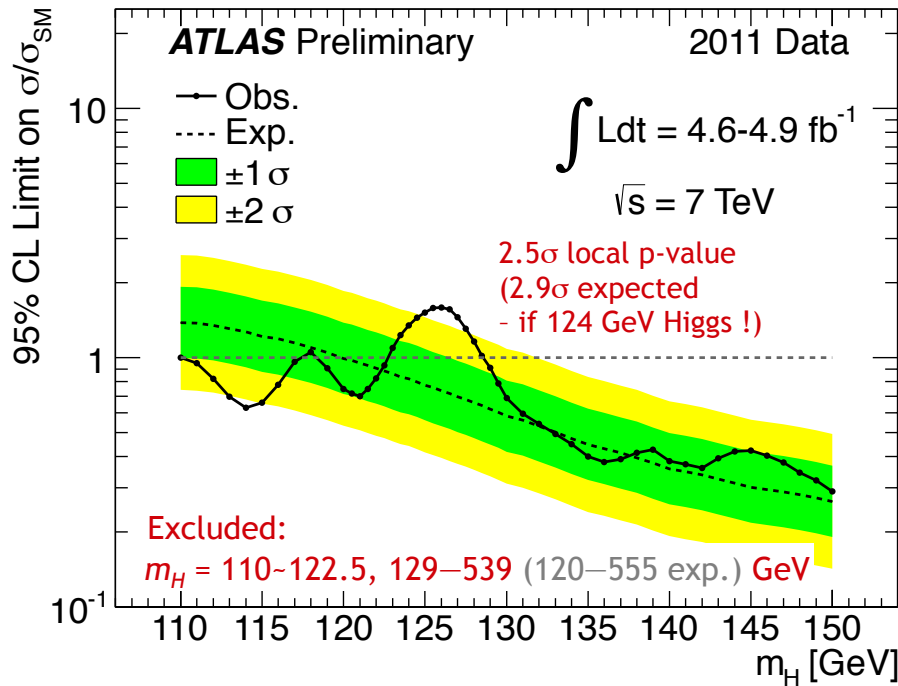


Combining all channels

At high mass also $WW \rightarrow llqq$ and $ZZ \rightarrow ll\nu\nu$ channels contribute

ATLAS-CONF-2011-135, CMS-PAS-HIG-11-022

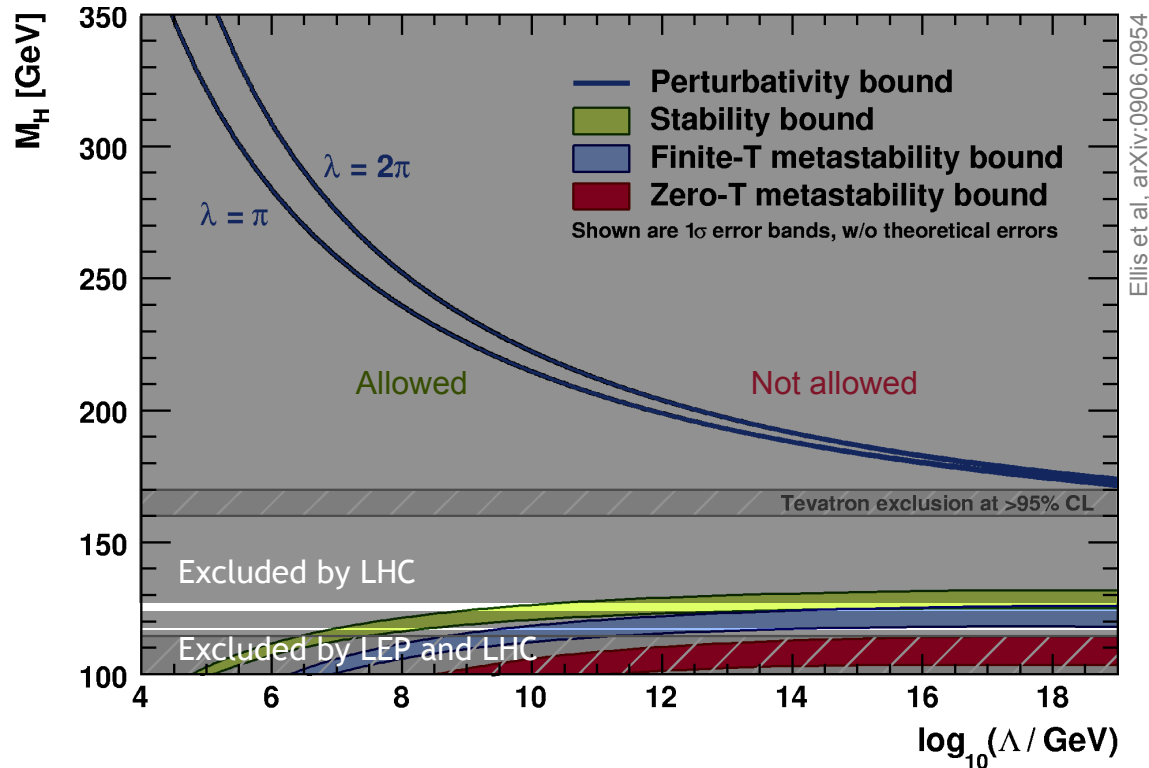
All results [$\gamma\gamma$, ZZ , WW , $\tau\tau$, bb] combined. Left: ATLAS – low mass region, right: CMS – all masses



Both experiments see a $>2\sigma$ combined excess at 123~127 GeV ...

Combining all channels (status: Lepton-Photon 2011)

Compare with constraints from perturbativity and (meta)stability



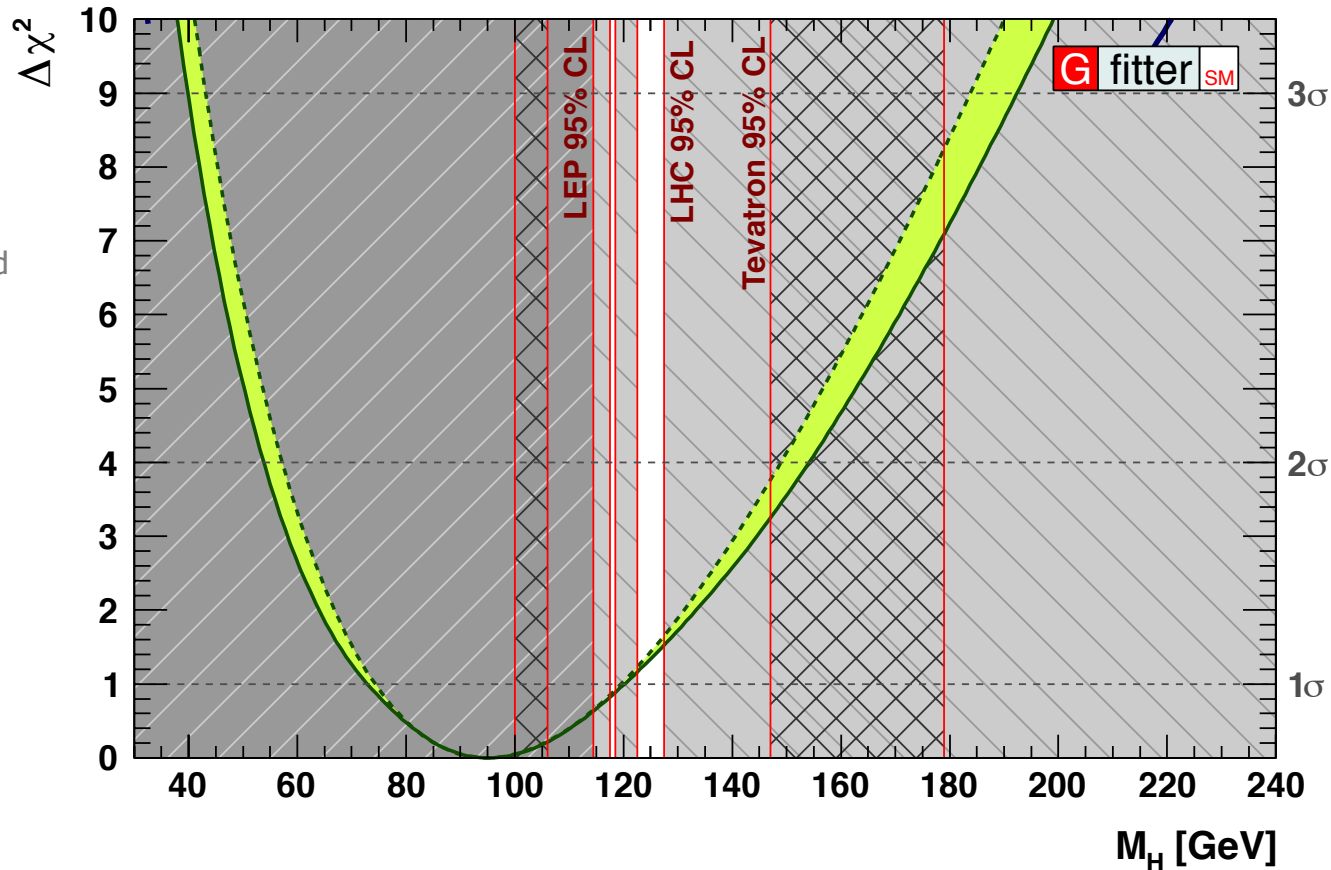
Still – barely – a stable solution up to M_p possible ...

$$M_H > 128.6 \text{ GeV} + 2.6 \text{ GeV} \cdot \left(\frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 2.2 \text{ GeV} \cdot \left(\frac{\alpha_s(M_Z) - 0.1193}{0.0028} \right) \pm 1 \text{ GeV}$$

Ellis et al, arXiv:0906.0954

Constraints from global electroweak fit

Global fit of all EW precision measurements to SM prediction constrains M_H



<http://gfitter.desy.de>



Unfortunately, there is a problem with the Higgs!



P. Higgs at CMS

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:



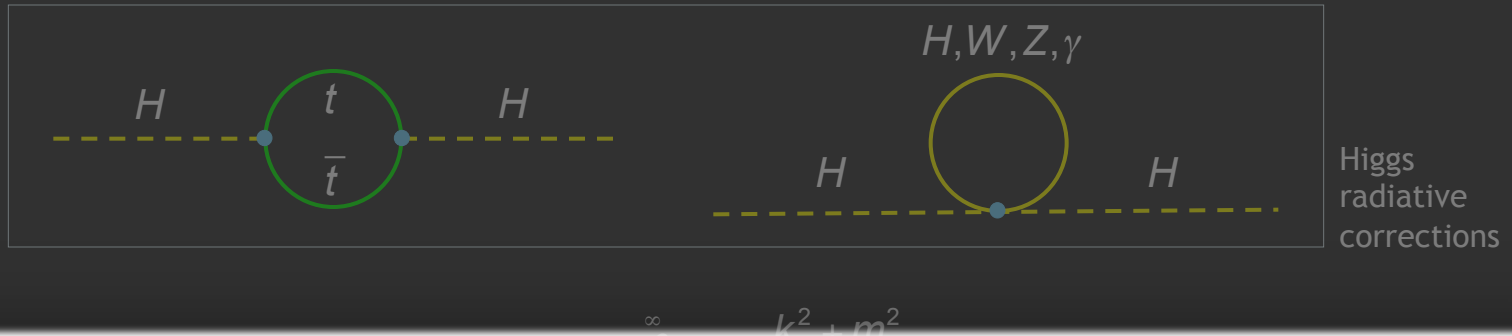
$\Rightarrow m_H^2 = m_0^2 + \delta m_H^2$ where: $\delta m_H^2 \propto \underbrace{\int_0^\infty d^4k \frac{k^2 + m_f^2}{(k^2 + m_f^2)^2}}_{\text{Integral quadratically divergent}} + \dots$

- 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

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

The “Gauge Hierarchy Problem”

- If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !
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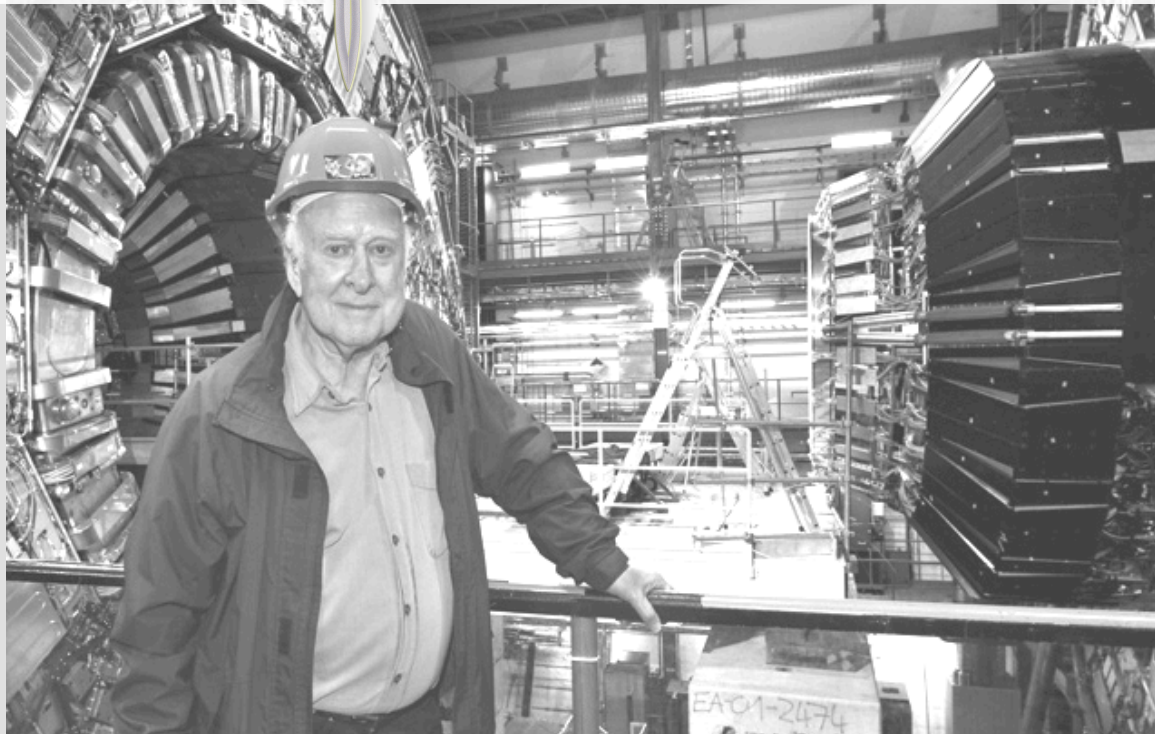
Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**.
Setting $m_H = 0$ in SM Lagrangian, **does not restore any symmetry in the model**.

New physics models should address this. M_H should become a deviation from some exact symmetry, and is thus **intrinsically small** !

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

- The crisis of the Standard Model calls for new physics at the TeV scale
- Many models addressing the hierarchy and the dark matter problem have similar experimental signatures
- Searching for them is another central pillar of the LHC physics programme

Unfortunately, there is a problem with the Higgs!



P. Higgs at CMS

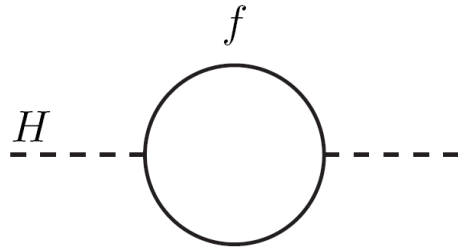
Could a symmetry between fermions and bosons
regularise the Higgs radiative corrections ?

(TeV-scale) Supersymmetry (SUSY)



P. Higgs at CMS

Fermion loop



S

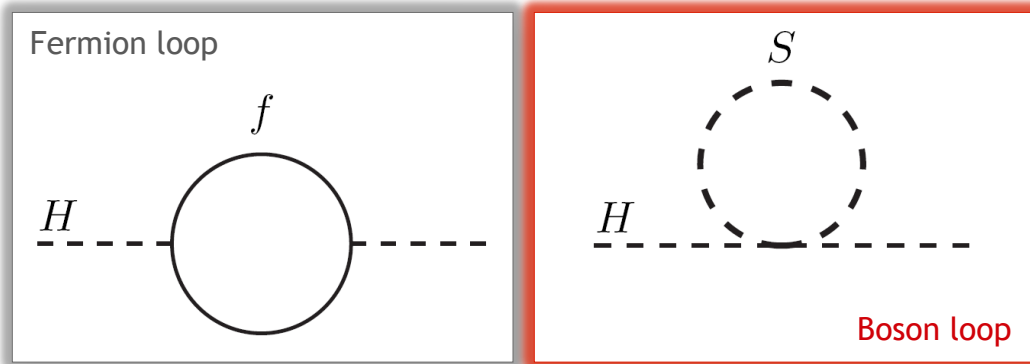


Boson loop

(TeV-scale) Supersymmetry (SUSY)



P. Higgs at CMS



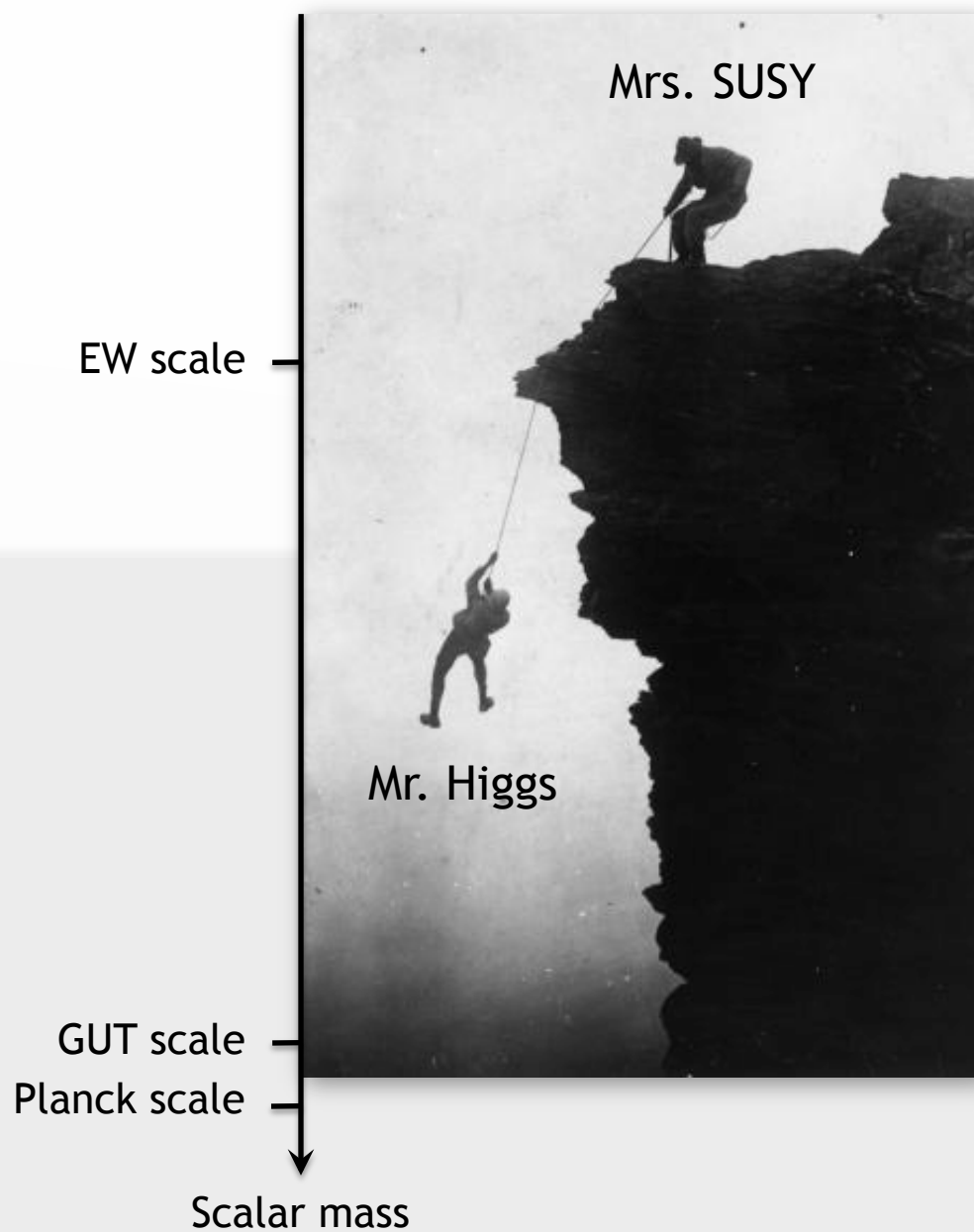
(TeV-scale) Supersymmetry (SUSY)

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 Higgs

Supersymmetry realises this by transforming bosons $\leftrightarrow$ fermions

- SUSY transforms, e.g., 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, which naturally introduces the spin-2 graviton, assumed to mediate the gravitational force

The scalar precipice



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

Supersymmetry (SUSY)

Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sLeptons	Leptons		Gravitino	Graviton
sQuarks	Quarks			
Higgs	Higgsino			
	Photino	Photon		
	Zino	Z		
	Wino	W		
	Gluino	Gluon		

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- Need to introduce an additional Higgs doublet to the non-SUSY side → 5 Higgs bosons

Supersymmetry (SUSY)

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

Squark/slepton mixing proportional to SM partner masses

→ largest for 3rd gen.

→ can become lightest squarks / sleptons

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

SUSY has: $N_{\text{dof}}(\text{bosons}) = N_{\text{dof}}(\text{fermions})$ [cf. SM: $N_{\text{dof}}(\text{bosons}) \ll N_{\text{dof}}(\text{fermions})$]

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- SUSY breaking introduces lots (> 100) of new parameters (masses, mixing angles, phases)

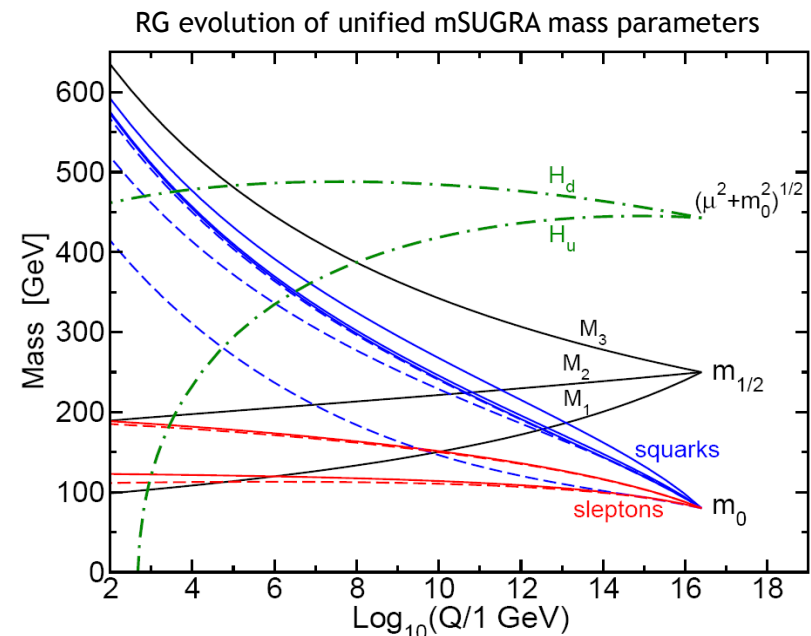
Supersymmetry (SUSY)

SUSY breaking (SSB): assume some hidden sector transmitting through flavour-blind interactions SSB to the observables



Very predictive gravity / gauge / anomaly mediated SSB mechanisms invented

Can be tested (& falsified) experimentally!



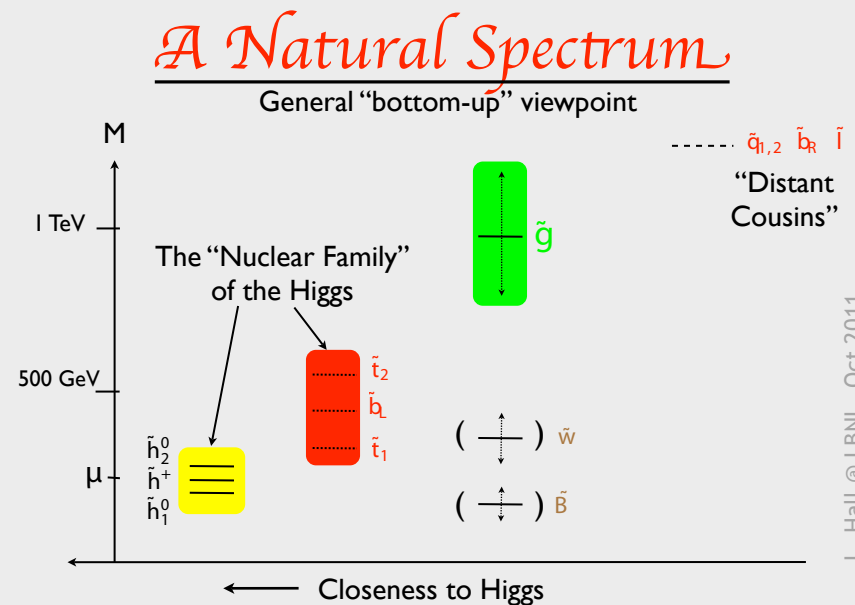
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Supersymmetry (SUSY)

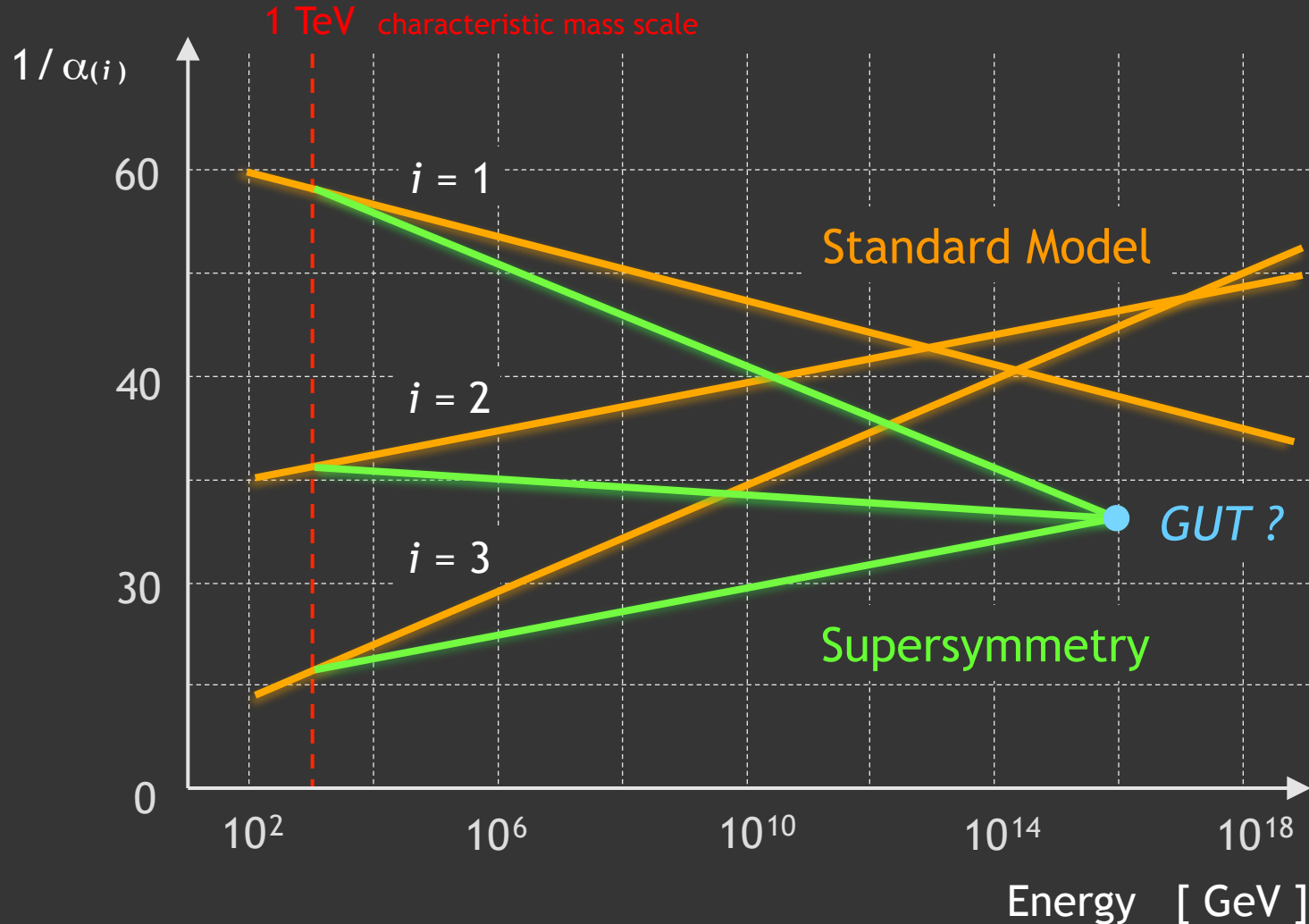
True SUSY spectrum (if exists) unknown, but some guidance principles:

- At least one light (< 135 GeV) neutral Higgs
- Naturalness requires: $m(\tilde{t}, \tilde{b}, \tilde{\chi}) < 1$ TeV to compensate top and W contributions to Higgs
- LSP is $\tilde{\chi}_1^0$ or $\tilde{G}$
- To avoid large FCNC: squarks, sleptons of 1st & 2nd generations heavy and degenerate



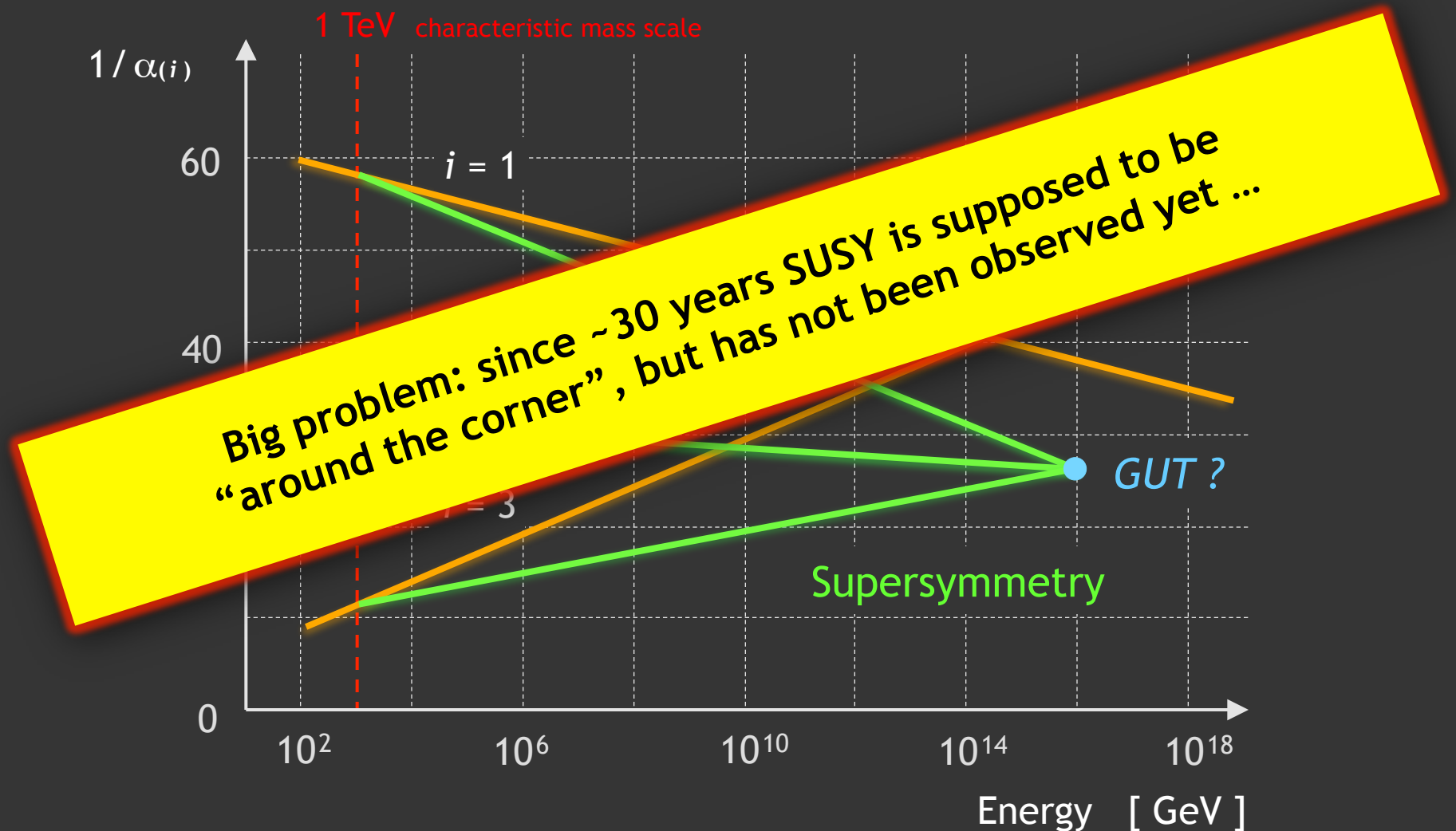
Grand Unification of the Gauge Couplings (GUT)

Recall: GUT motivated by quantisation of electric charge in multiples of $1/3$



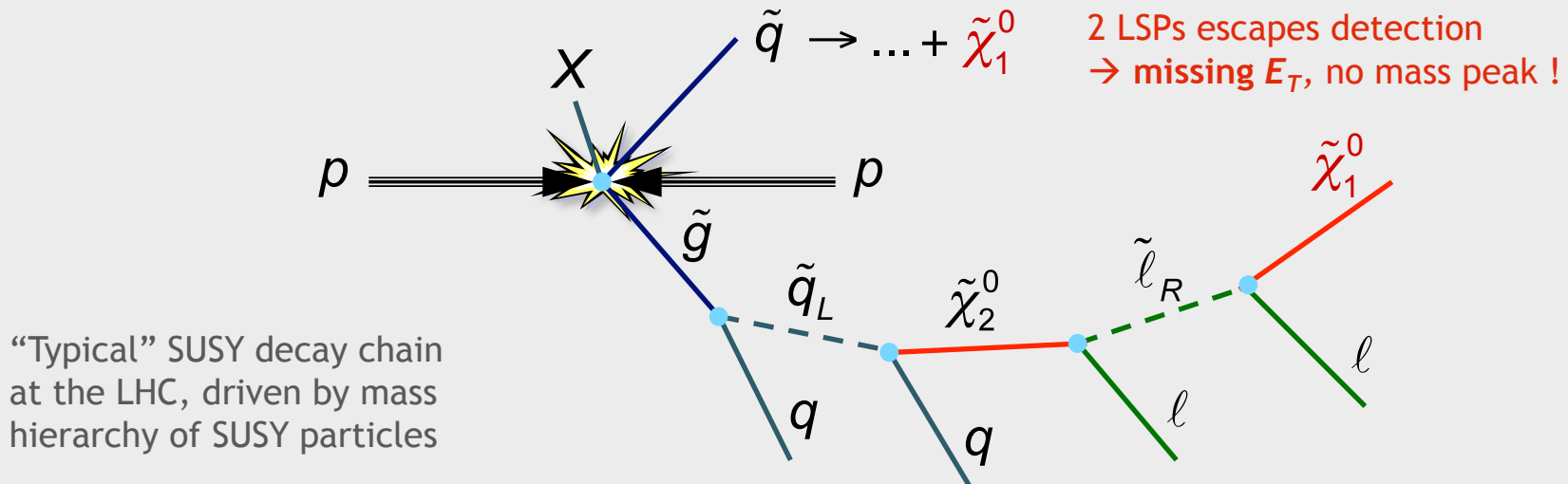
Grand Unification of the Gauge Couplings (GUT)

Recall: GUT motivated by quantisation of electric charge in multiples of $1/3$



Characteristic SUSY Decay Cascades

- To avoid proton decay, a new conserved quantum number (R) is introduced, which forces a SUSY particle to decay in at least one other SUSY particle
- The lightest SUSY particle is thus stable (LSP), and must be neutral and colourless $\rightarrow$ WIMP (dark matter candidate)
- Typical **LSP is spin- $\frac{1}{2}$ neutralino**. It could also be a gravitino
- With R parity: SUSY production in pairs only $\rightarrow$ requires energy $2 \times$ SUSY mass !



SUSY searches at the LHC

Many different search channels along expected SUSY event topologies

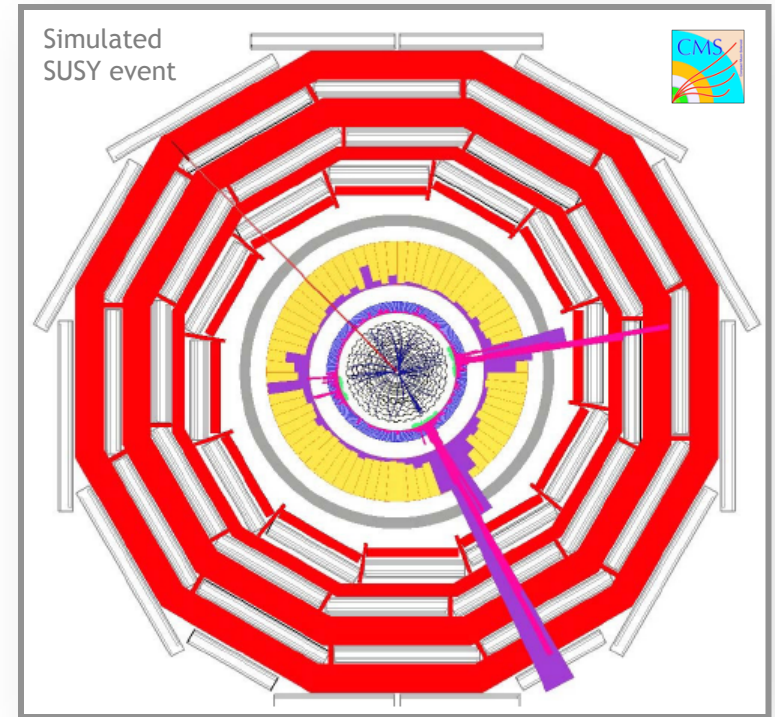
Signatures of the SUSY “cascades” are driven by masses of the SUSY particles

To good generality we can expect:

- High- p_T jets from squark & gluino decays
- Leptons from gaugino & slepton decays
- Missing transverse energy from LSPs

This lays out an **inclusive search strategy**

- ➡ Most of the hard analysis work consists of understanding and modelling backgrounds from SM processes !



SUSY searches at the LHC

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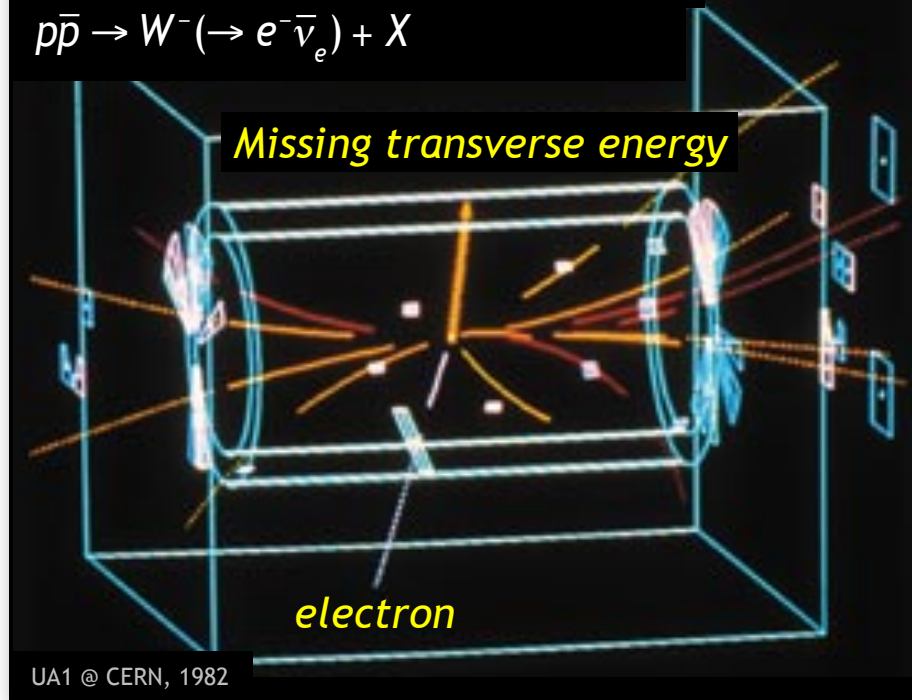
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W boson discovery at UA1 (CERN)

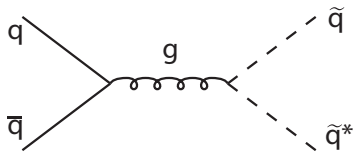
$$p\bar{p} \rightarrow W^- (\rightarrow e^- \bar{\nu}_e) + X$$



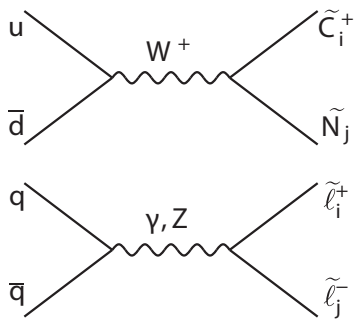
Once mass spectrum fixed, all cross sections predicted

Spin structure of SUSY spectrum: lower σ than other BSM models, harder to find !

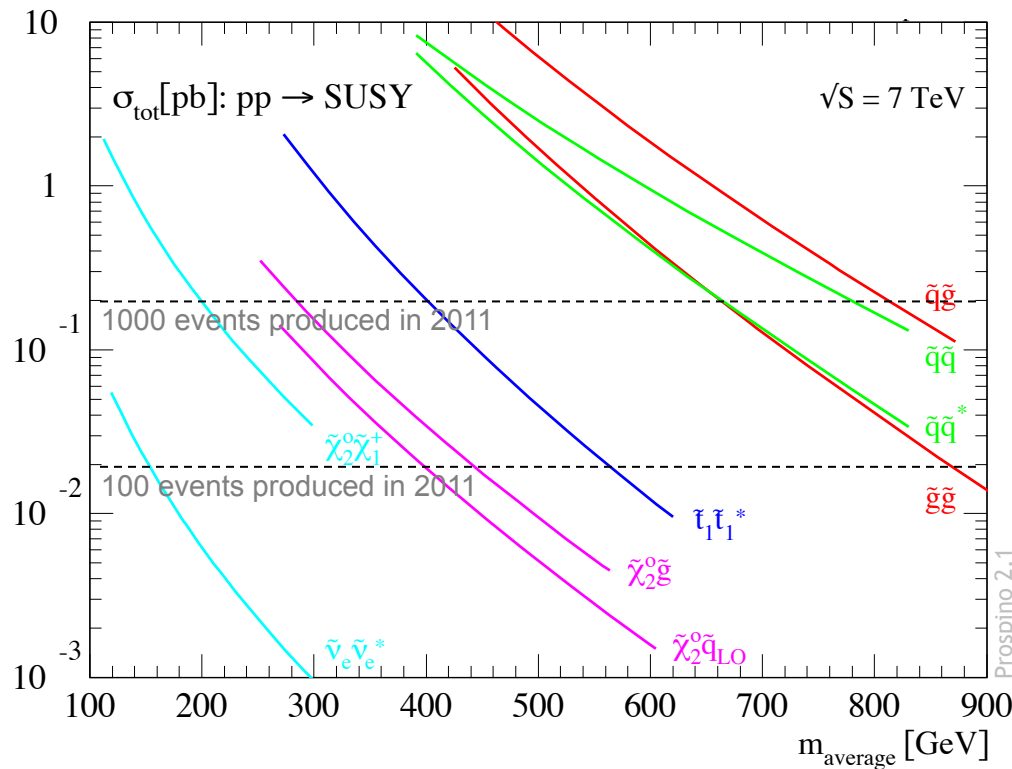
Direct squark pair production (example)



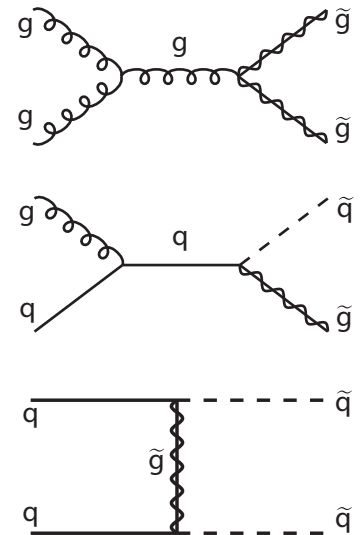
Direct gaugino/slepton pair production (example)



SUSY cross section versus sparticle mass



Gluino & squark production (examples)



SUSY searches at the LHC

Huge backgrounds from SM processes

1983/1984: SpS (CERN)
W, Z discovery

1995: Tevatron (FNAL)
Top discovery

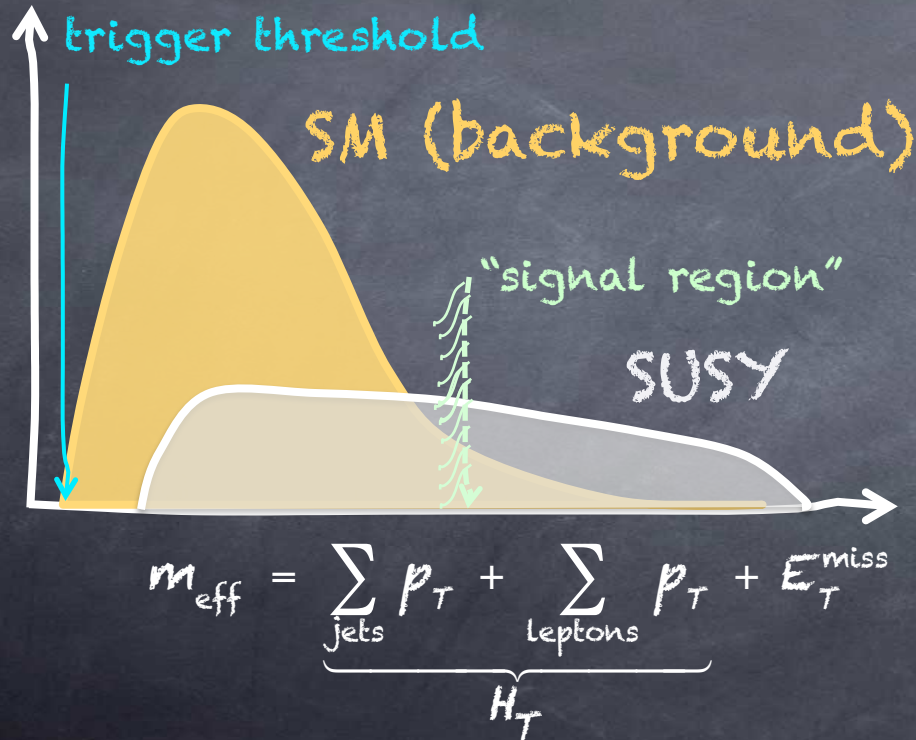
➡ Most of the hard analysis work consists of understanding and modelling backgrounds from SM processes !

Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34} \text{ cm}^{-2}\text{s}^{-2}$
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \rightarrow \ell \nu$	15	150
$Z \rightarrow \ell \ell$	2	20
$t\bar{t}$	1	10
Z' (1 TeV)	0.05	0.5
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

SUSY searches at the LHC

Analysis and background determination strategy

SUSY search analyses look for tails in distributions of observables sensitive to high produced event mass: m_{eff}



Can only exploit tails if detector response and **SM backgrounds in signal region** are understood

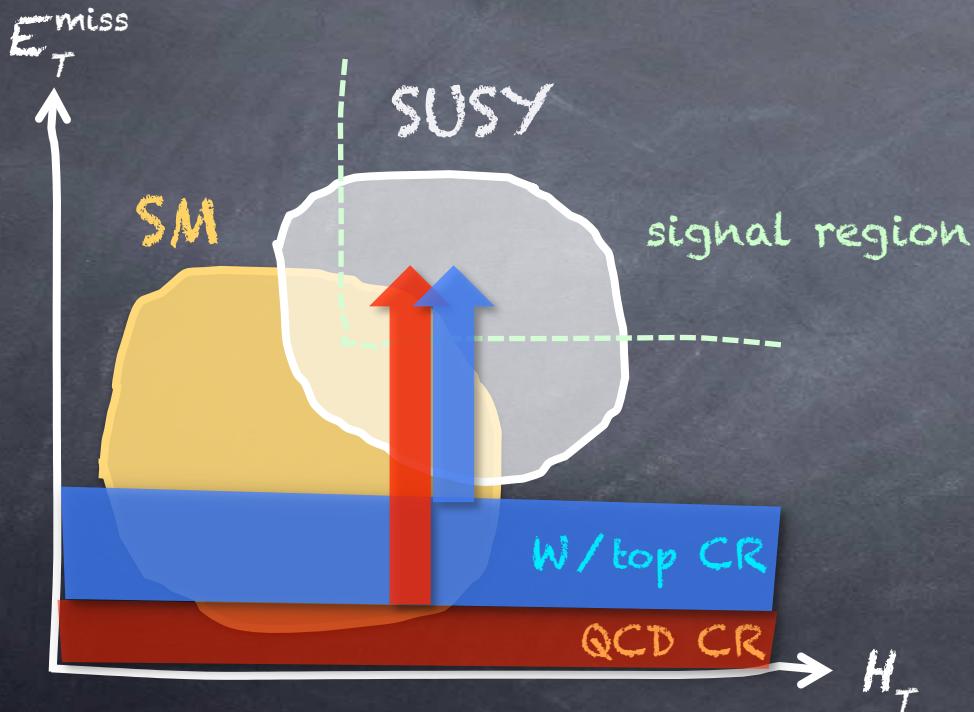
Main background sources:

- $tt \rightarrow W(\rightarrow l(\tau)\nu) b + W(\rightarrow qq) b$
- $W(\rightarrow l\nu) + \text{jets}$
- $Z(\rightarrow \nu\nu) + \text{jets}$
- QCD multijets ("fake" E_T^{miss})
- $WW, WZ, ZZ, tt+W/Z$ (+ jets)

SUSY searches at the LHC

Analysis and background determination strategy

Normalisation of dominant backgrounds obtained from “control regions” (CR) with small expected signal contamination



CR $\rightarrow$ SR transfer factors taken from MC simulation (many systematic effects cancel)

Also: exploit close-by SM processes, e.g., $Z(\nu\nu) + \text{jets}$ from $\gamma + \text{jets}$

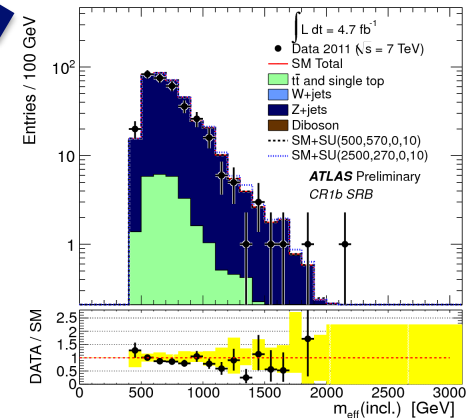
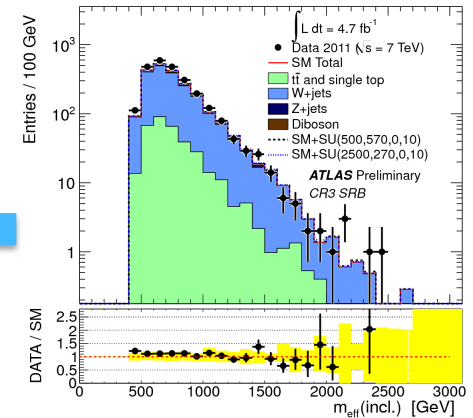
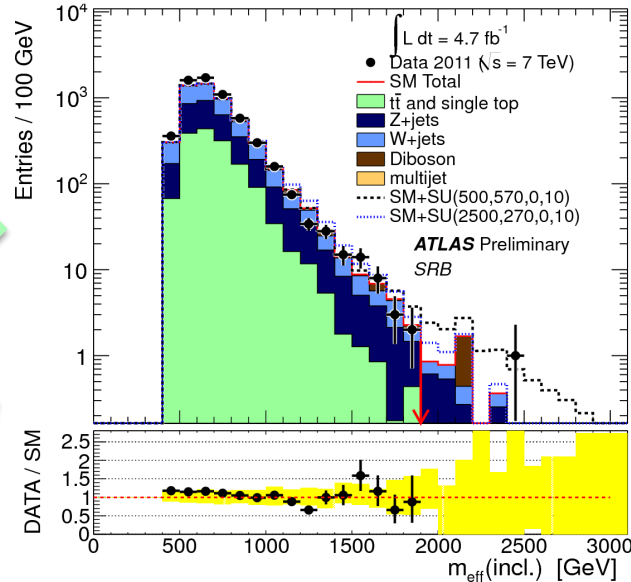
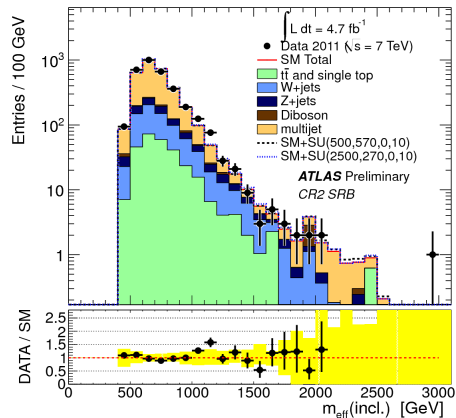
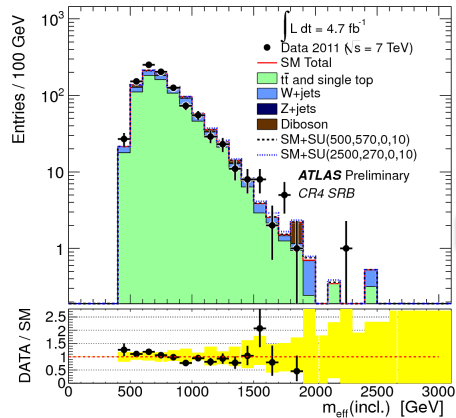
Fake backgrounds estimated from data using samples with known composition (Z, dijet) or from data-driven smearing techniques

Small backgrounds taken from MC

SUSY searches at the LHC

Example: ATLAS inclusive jets + E_T^{miss} SUSY search

ATLAS-CONF-2012-033

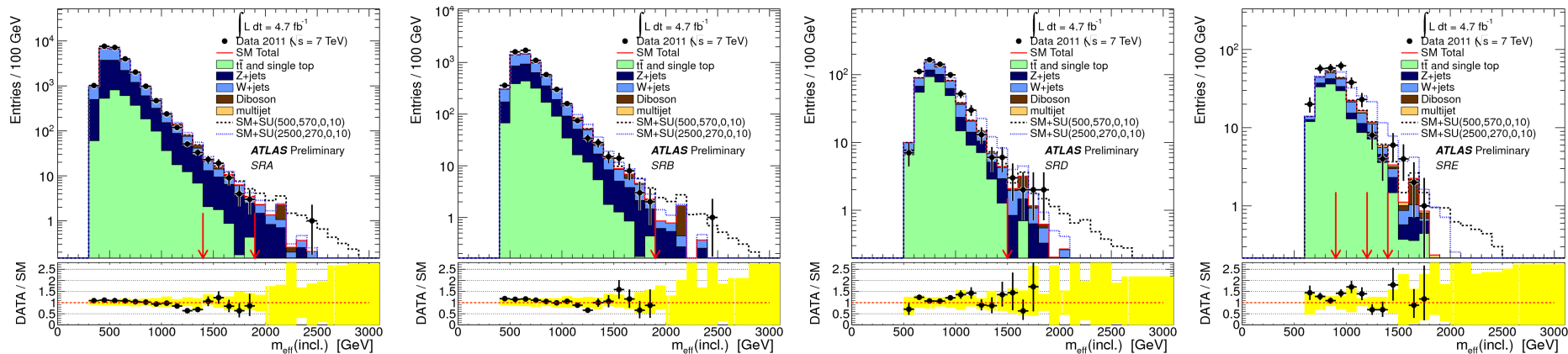


Normalisations obtained in all CR and signal regions simultaneously by combined maximum likelihood fit

SUSY searches at the LHC

Example: ATLAS inclusive jets + E_T^{miss} SUSY search

ATLAS-CONF-2012-033



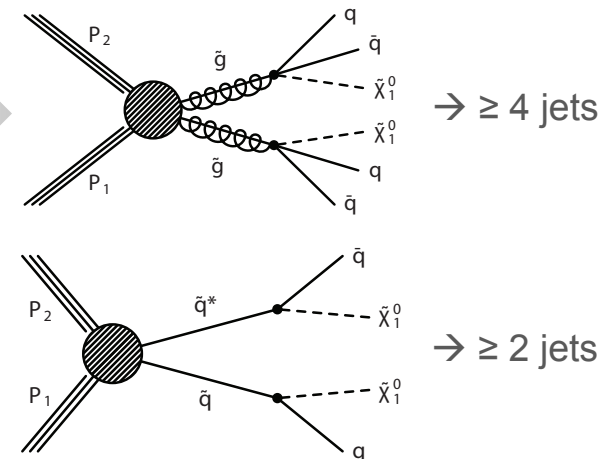
Define several signal regions, sensitive to different SUSY mass spectra and cascade patterns

Squarks and gluino production would lead to excess over expected SM events at high tail of m_{eff} distribution

No such excess seen in current ATLAS or CMS data

Translate into limit on SUSY cross section

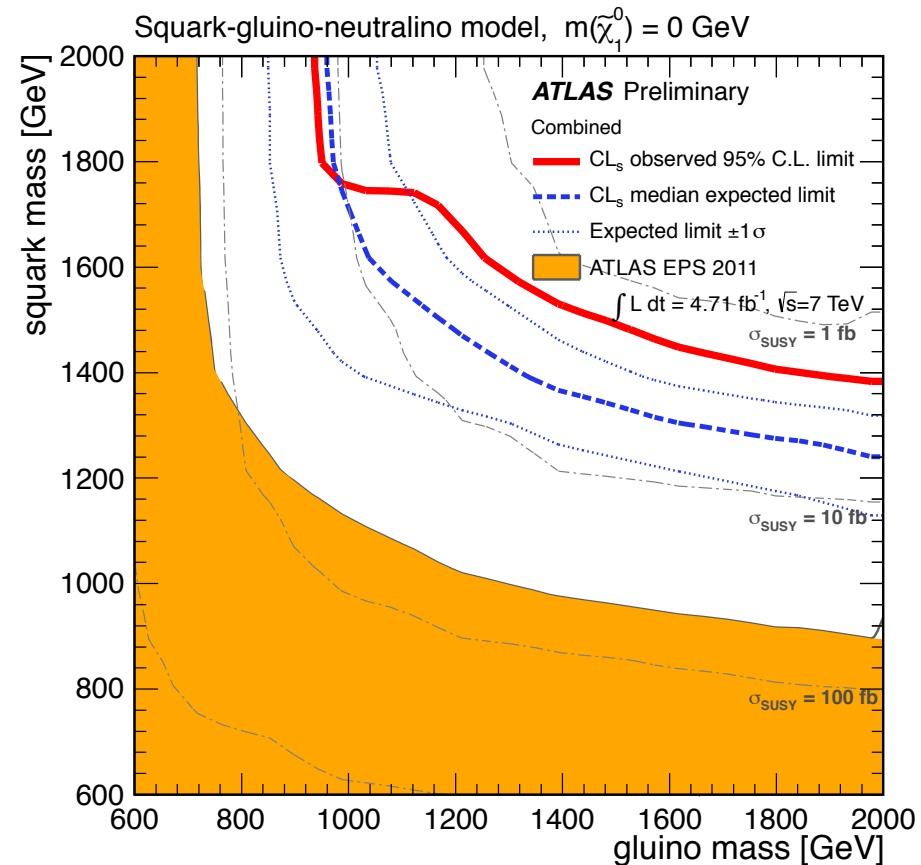
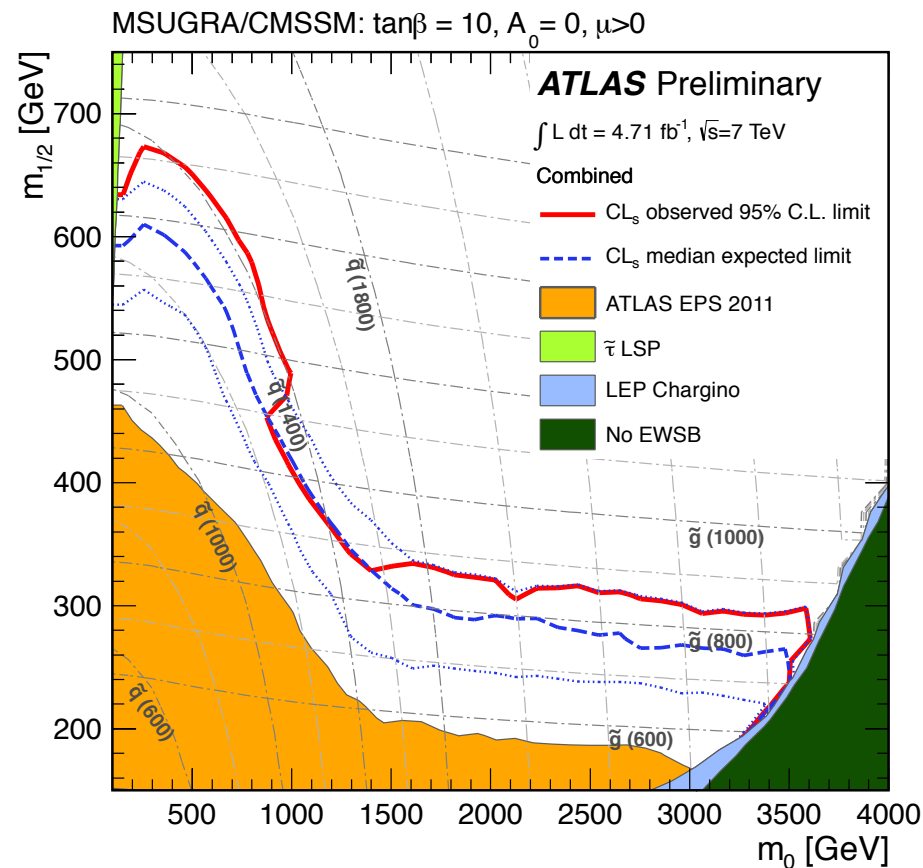
→ limit on SUSY particle masses



ATLAS inclusive jets + E_T^{miss} SUSY search

Limits expressed in MSUGRA (left) and phenomenological model (right)

ATLAS-CONF-2012-033



ATLAS inclusive jets + E_T^{miss} SUSY search

Limits expressed in MSUGRA (left) and phenomenological model (right)

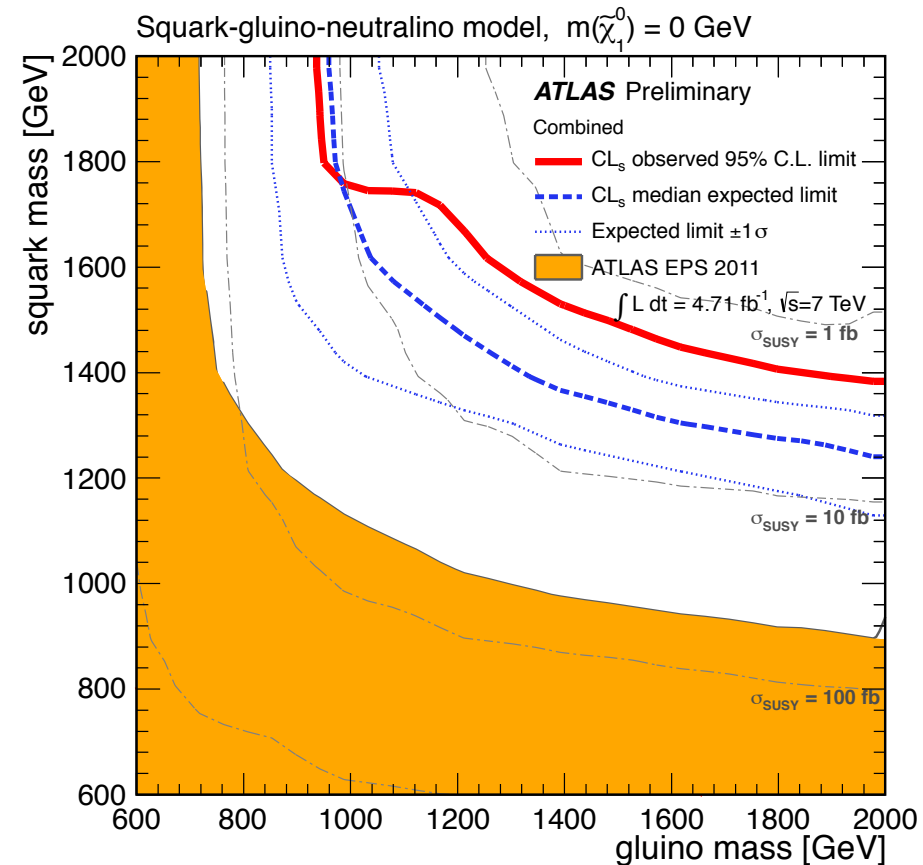
ATLAS-CONF-2012-033

Under moderate assumptions on the SUSY mass hierarchy, ATLAS (similarly CMS) excludes:

$$\begin{aligned} m(\tilde{q}) &\approx m(\tilde{g}) < 1.5 \text{ TeV} \\ m(\tilde{q}) &< 1.4 \text{ TeV} \quad (\forall m(\tilde{g}) < 2 \text{ TeV}) \\ m(\tilde{g}) &< 1 \text{ TeV} \quad (\forall m(\tilde{q}) < 2 \text{ TeV}) \end{aligned}$$

Perhaps such an inclusive analysis is not sensitive enough ?

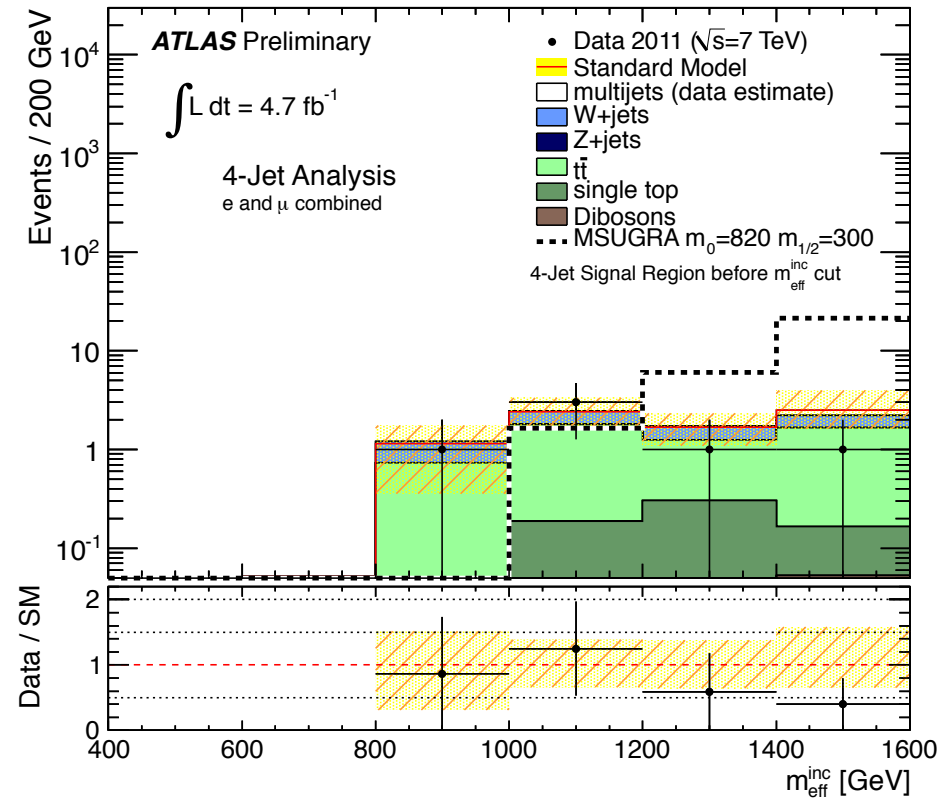
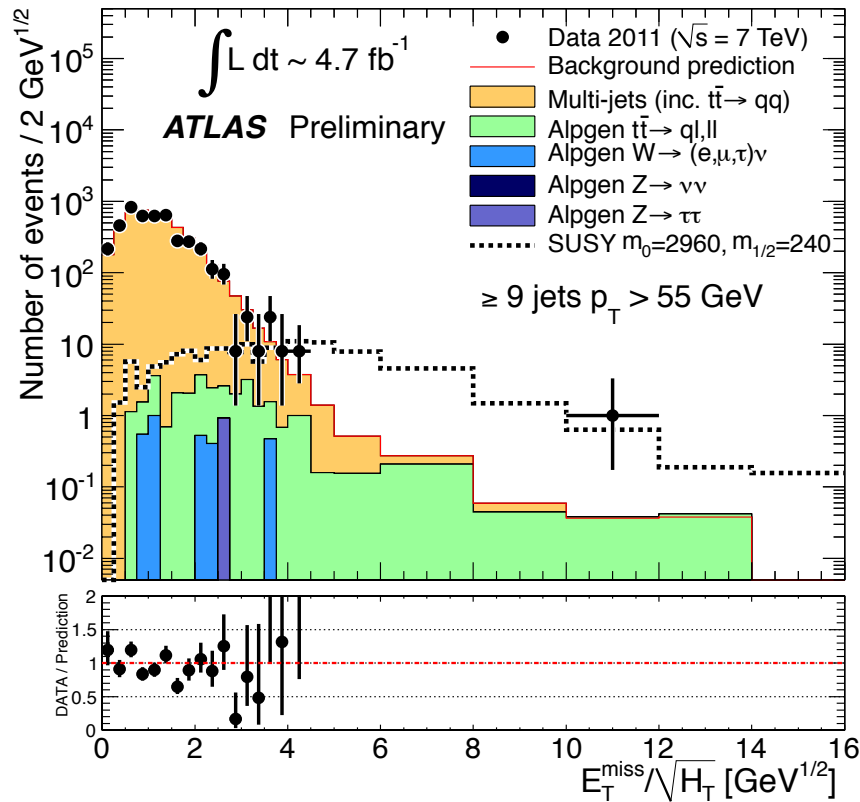
→ Looked also in events with many jets (up to 9!) and with at least 1 lepton



ATLAS multi-jets / 1-lepton + E_T^{miss} SUSY search

No excess seen either

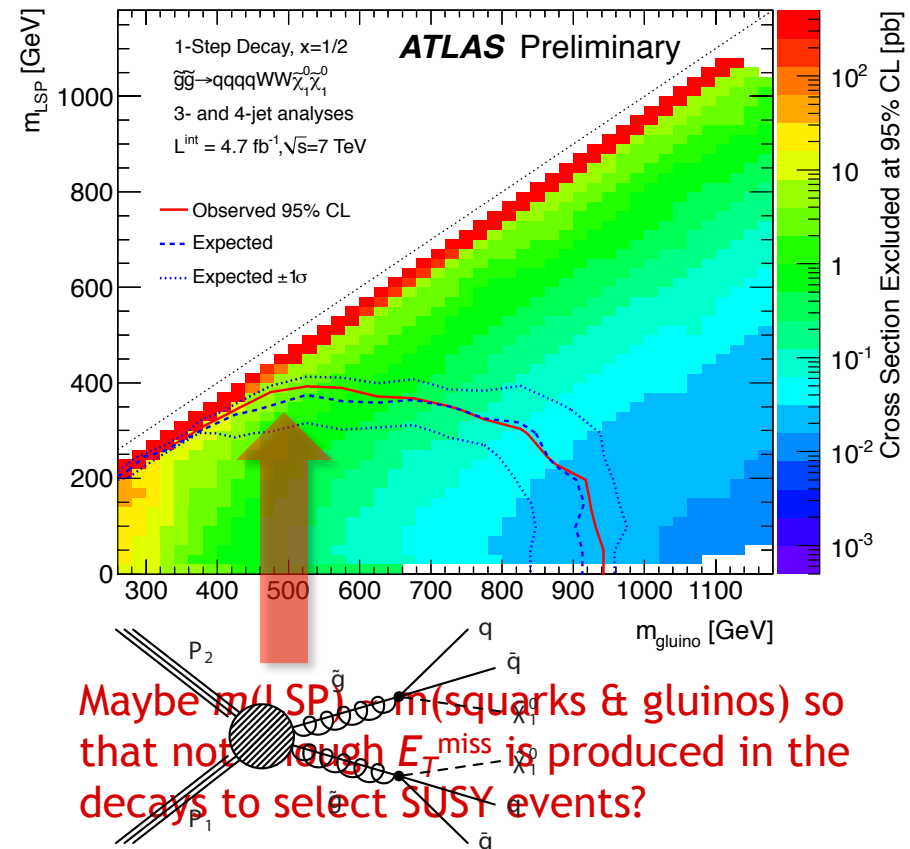
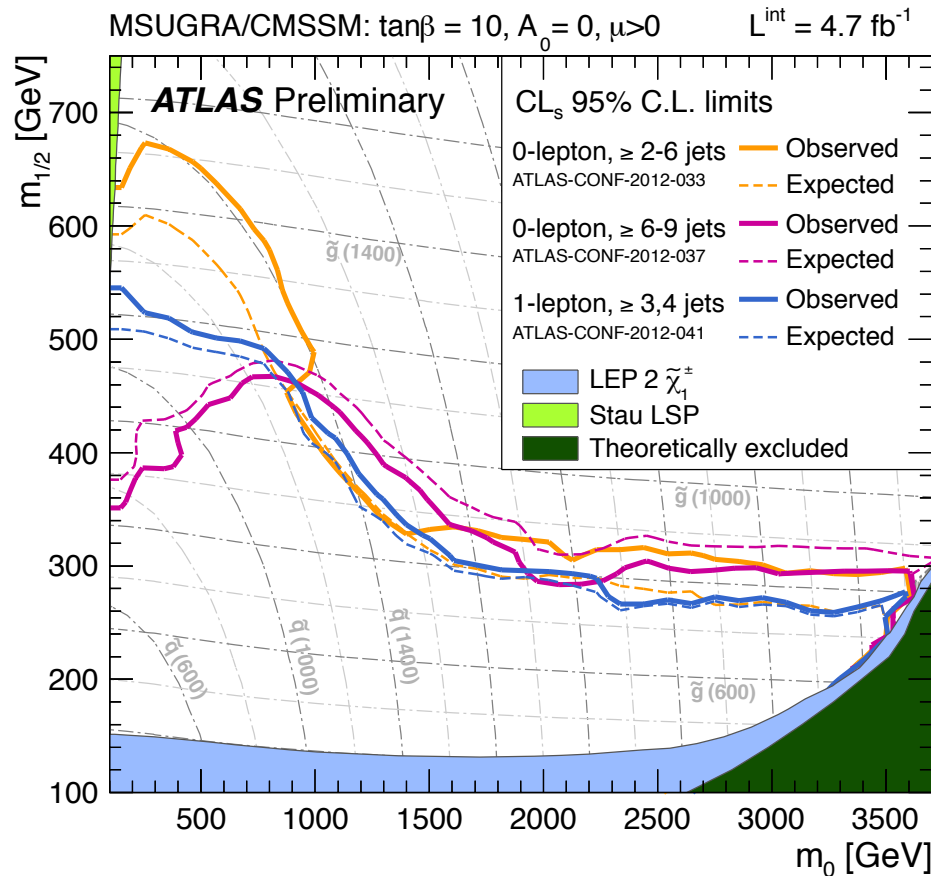
ATLAS-CONF-2012-037, ATLAS-CONF-2012-041



ATLAS multi-jets / 1-lepton + jets + E_T^{miss} SUSY search

Limits expressed in MSUGRA (left) and simplified model (right)

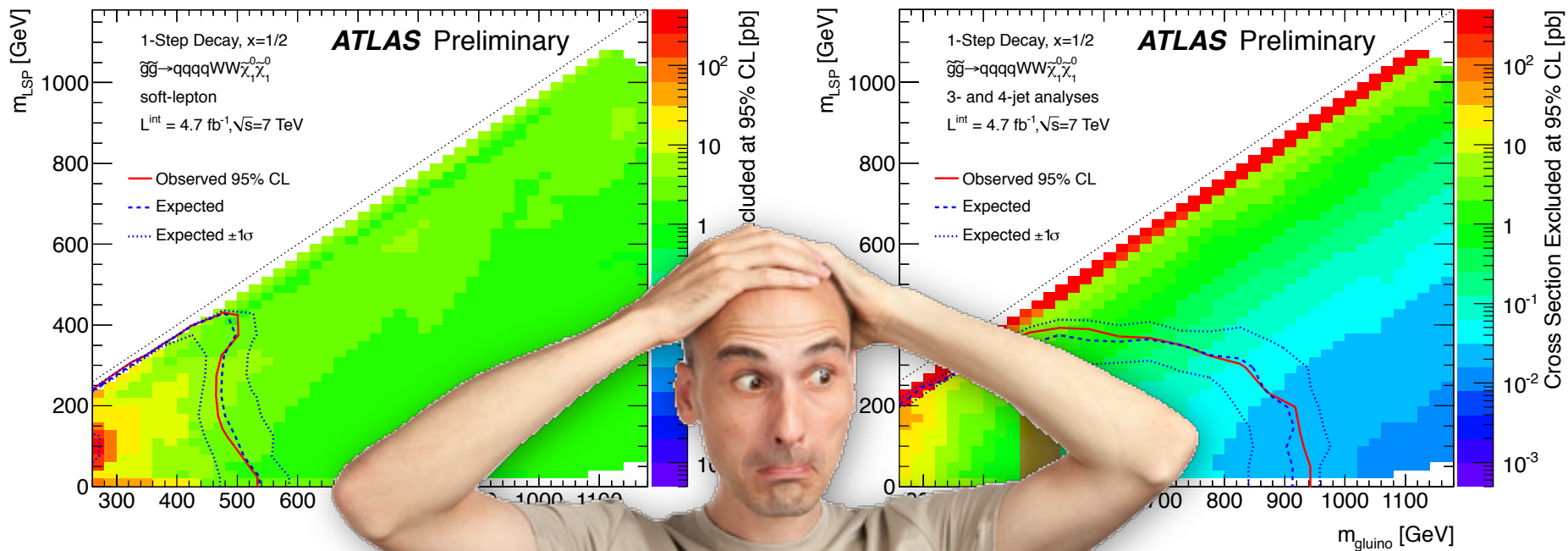
ATLAS-CONF-2012-037, ATLAS-CONF-2012-041



ATLAS 1-lepton + jets + E_T^{miss} SUSY search

Limits expressed in and simplified model (left and right)

ATLAS-CONF-2012-041

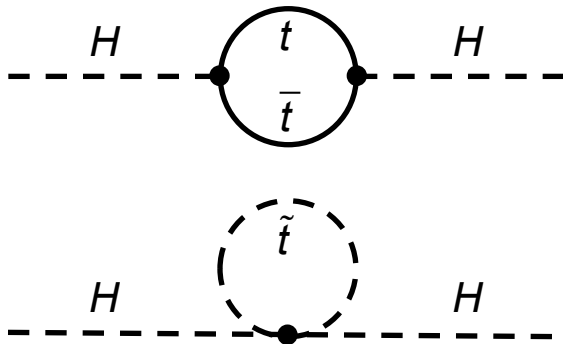


Use dedicated “soft” spectra ($m_{\text{LSP}} \sim m(\text{squarks \& gluinos})$) so
 → But again, no sign of SUSY : not enough E_T^{miss} is produced in the
 events to select SUSY events?

Does SUSY hide from our analyses?

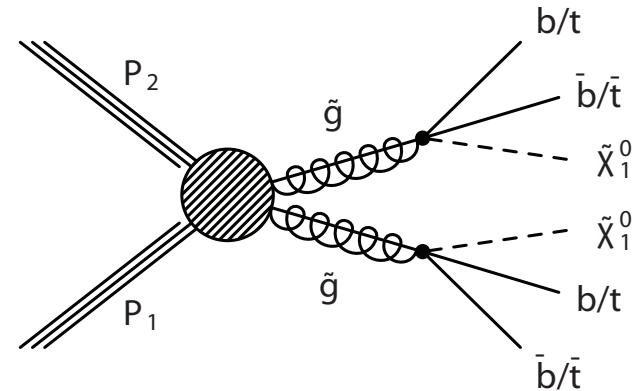
What mechanisms could camouflage strong SUSY production?

Recall: we need to cancel the Higgs virtual corrections. Most important is top loop

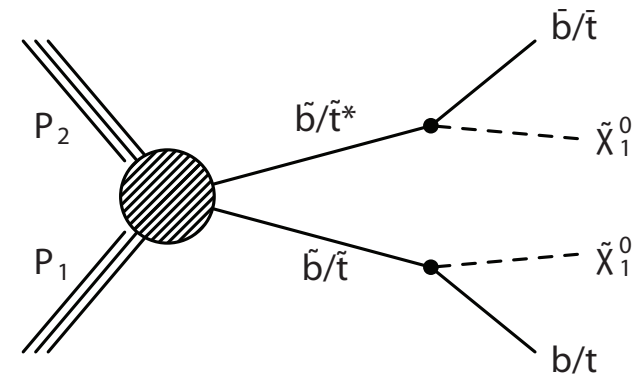


Contrary to the SM, 3rd generation squarks can be lighter than 1st and 2nd generations

Watch out for tops
and b 's in final state !



Gluino-mediated virtual $\tilde{b}/\tilde{t}$ production



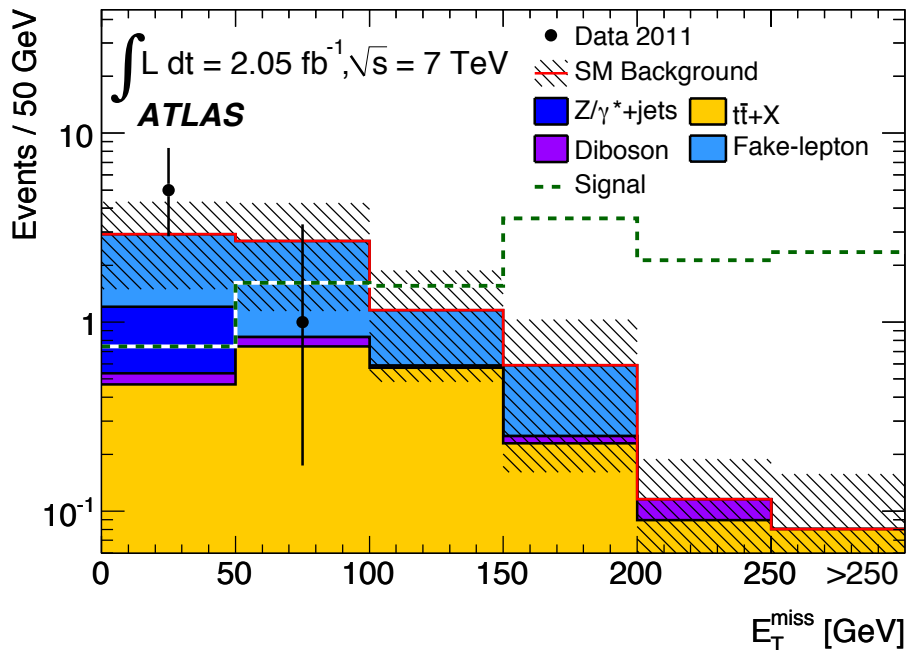
Direct $\tilde{b}/\tilde{t}$ pair production

Does SUSY hide from our analyses?

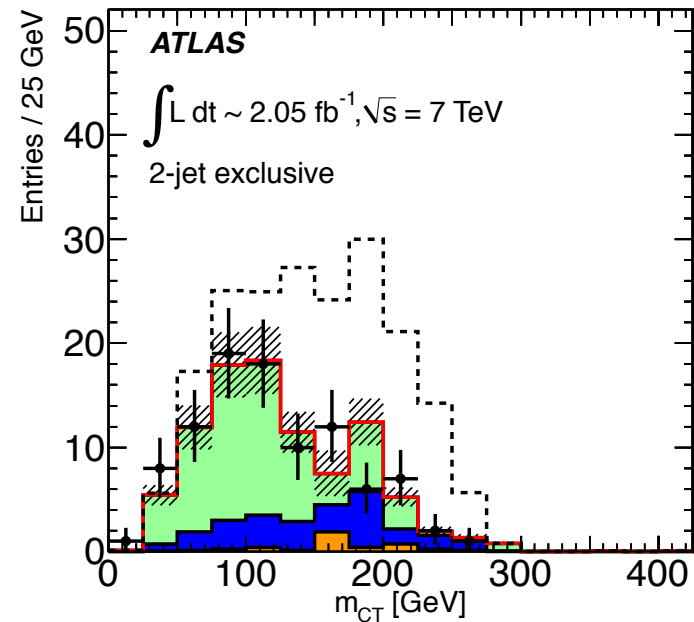
What mechanisms could camouflage strong SUSY production?

ATLAS arXiv:1203.5763, ATLAS arXiv:1112.3832, CMS-PAS-SUS-11-020

Gluino-mediated stop production (4 tops!) produces events with same-sign leptons, and also many jets
→ very low SM backgrounds



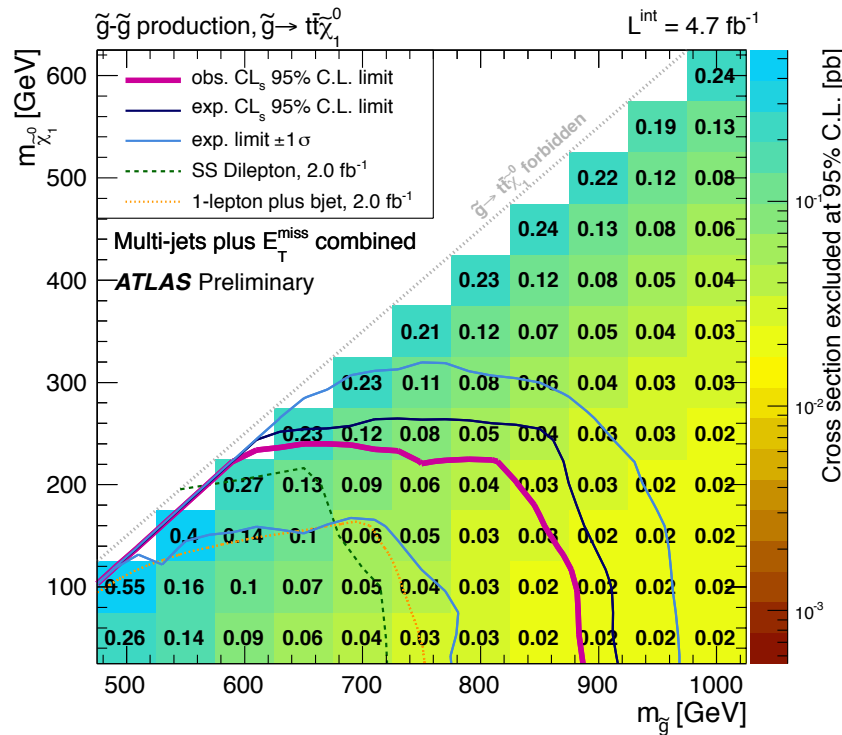
Direct stop production is very similar to top (but smaller cross section), direct sbottom production has 2 b-jets + E_T^{miss}
→ kinematic reconstruction



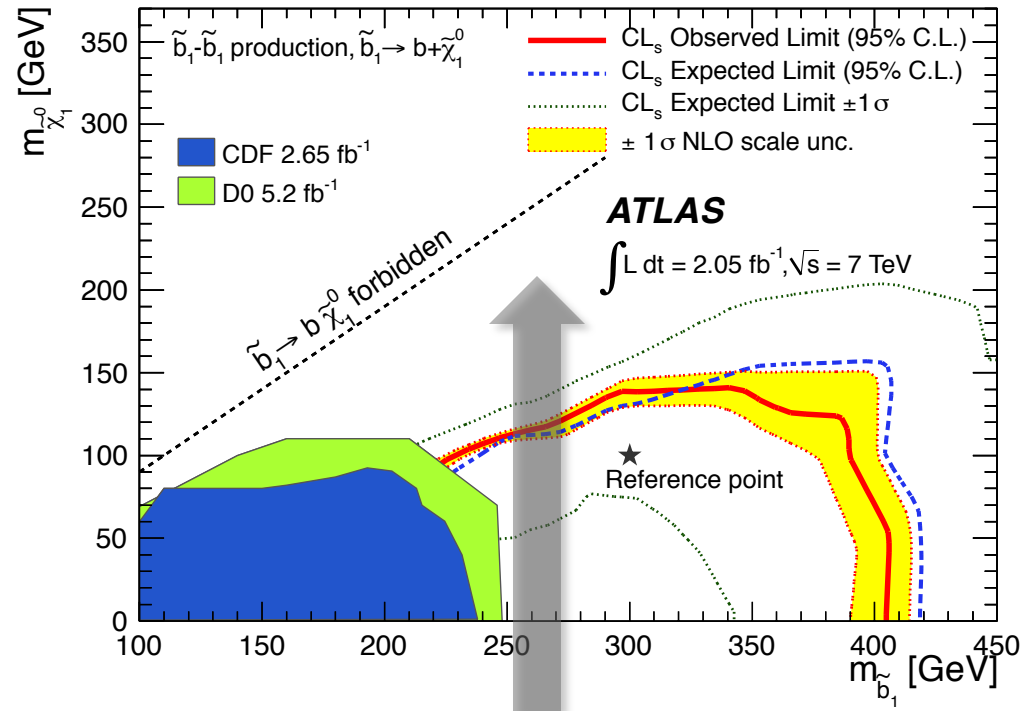
Does SUSY hide from our analyses?

Limits on gluino-mediated stop (left) and direct sbottom production (right)

ATLAS-CONF-2012-037, ATLAS arXiv:1112.3832



Strongest limit from ATLAS multijet analysis



Weak limits for heavy LSP; insensitivity due to high trigger thresholds

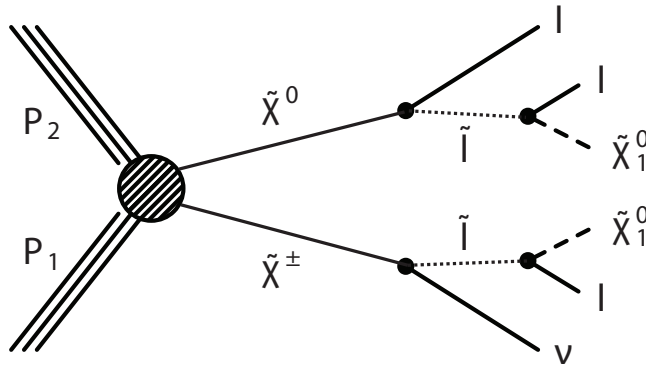
Does SUSY hide from our analyses?

What mechanisms could camouflage strong SUSY production?

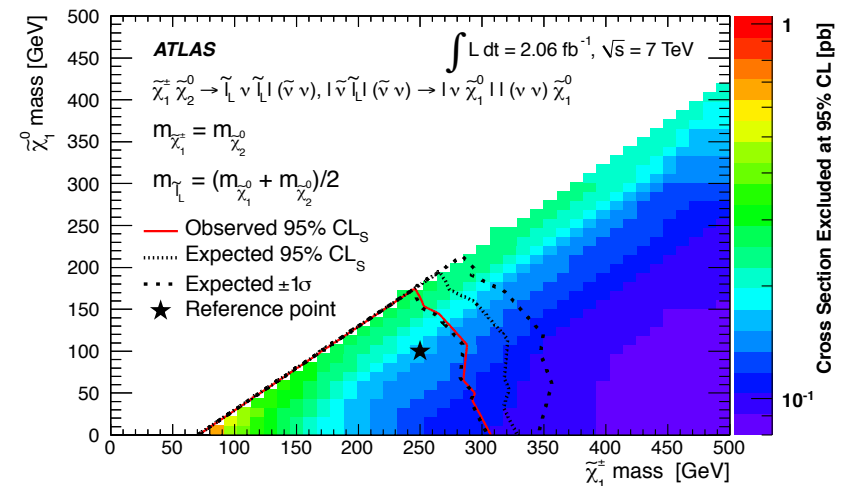
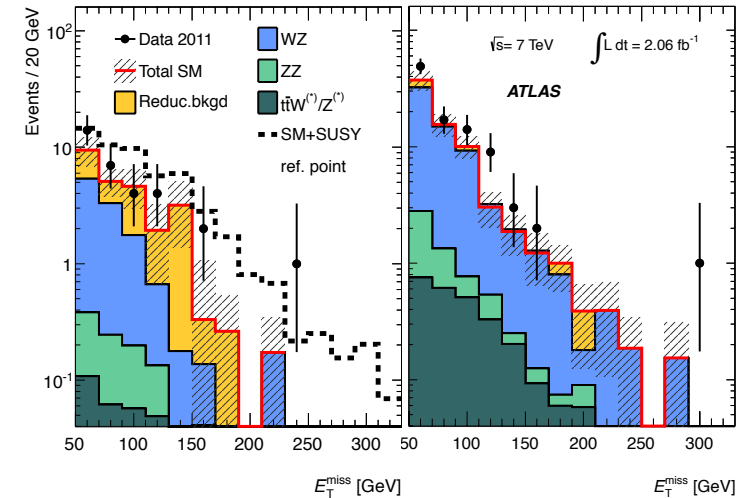
ATLAS arXiv:1204.5638

The limits on direct stop/sbottom production are still too weak to exclude them up to TeV (“naturalness”) scale

Perhaps, all strong production sparticles are yet too heavy to be produced with sufficient statistics and only gauginos are produced?



→ Select events with 2–3 leptons + E_T^{miss} & no jets!



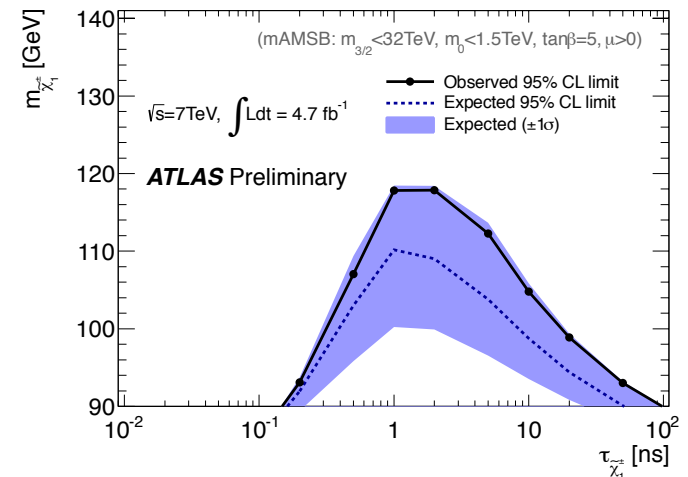
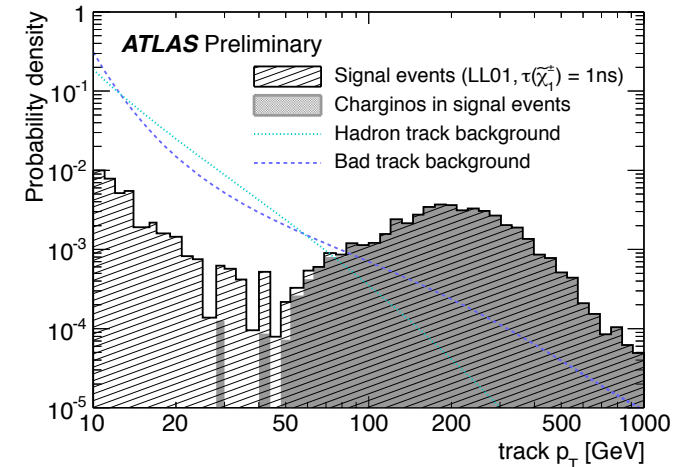
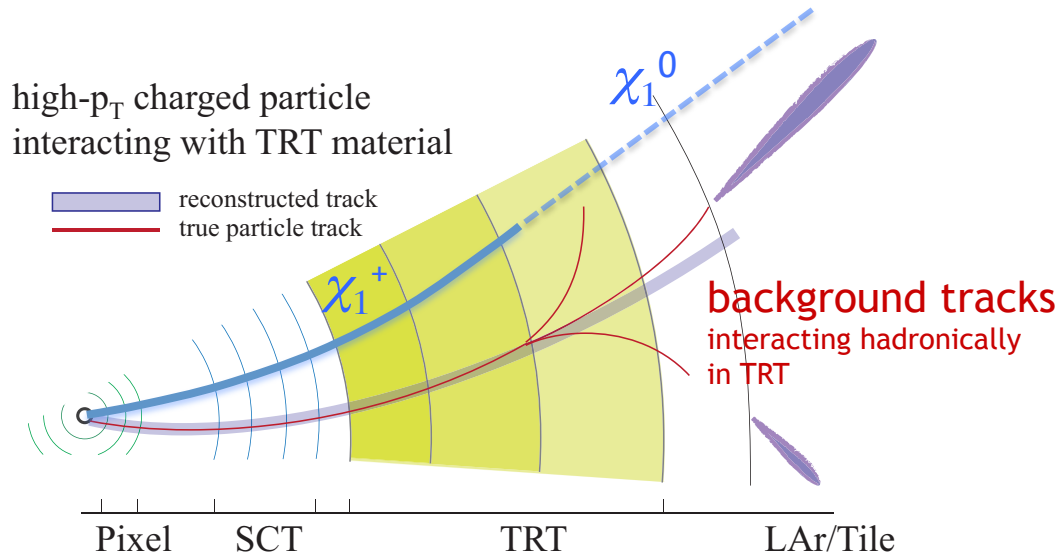
Does SUSY hide from our analyses?

What mechanisms could camouflage strong SUSY production?

ATLAS-CONF-2012-034

Some scenarios (AMSB) have a large degeneracy among gaugino masses, rendering the $\chi_1^\pm$ long-lived

→ Search for heavy particles decaying in inner detector, giving a “disappearing track” in ATLAS TRT

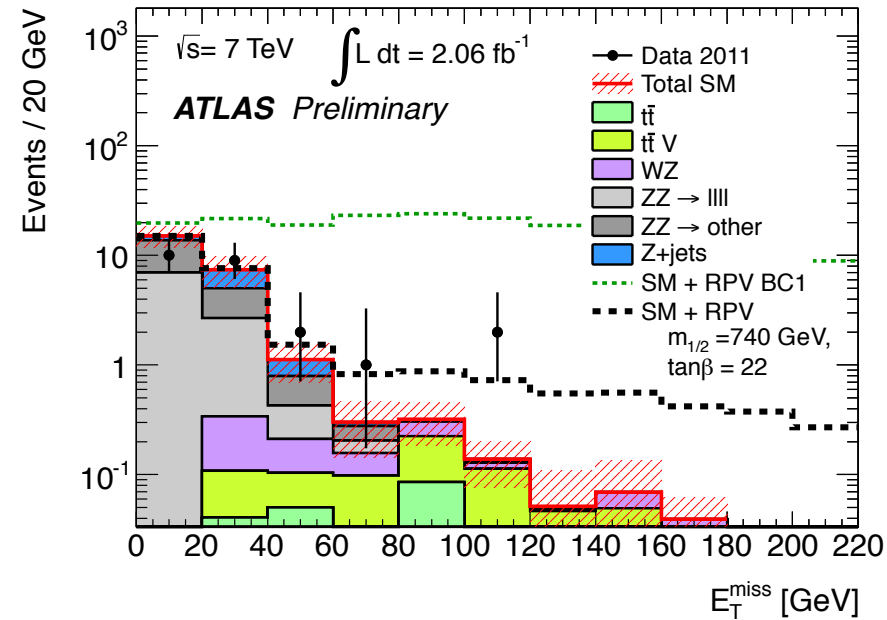
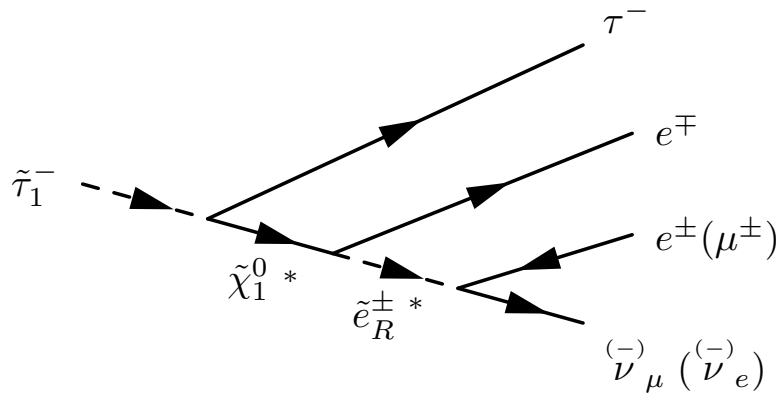


Does SUSY hide from our analyses?

What mechanisms could camouflage strong SUSY production?

ATLAS-CONF-2012-035

R-parity could also be broken (RPV). Proton decay requires lepton and baryon-number violating couplings. If either one of them vanishes, the proton is stable, but neutralinos may decay:



No significant excess found in any channel combination (neither does CMS)

- Search for events with many leptons with or w/o E_T^{miss}
- If RPV coupling is small, search also for displaced vertices

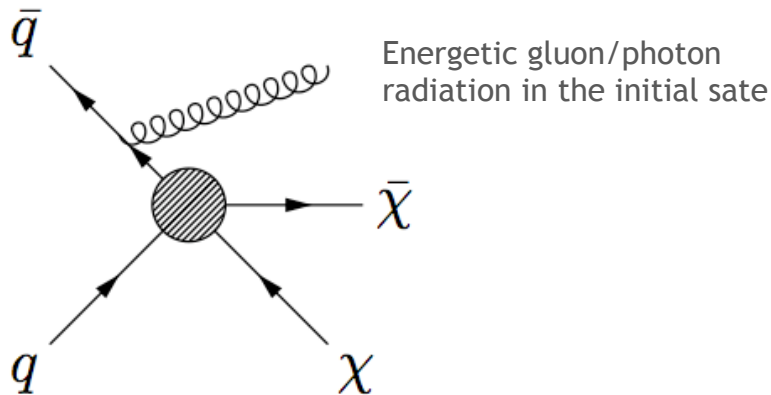
Should we forget about SUSY ?

Maybe the electroweak scale is finetuned. But what about dark matter ?

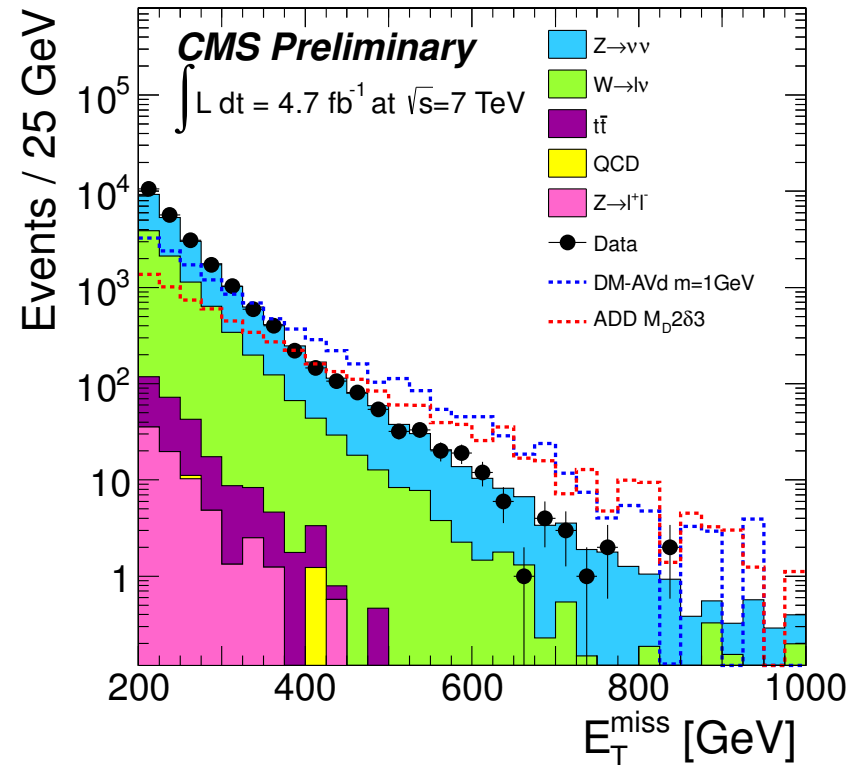
CMS-EXO-11059

Should we give up on natural SUSY and directly search for WIMP (dark matter) production in proton-proton collisions ?

How can we detect (and trigger) them ?



→ Search for mono-jets or mono-photon events!



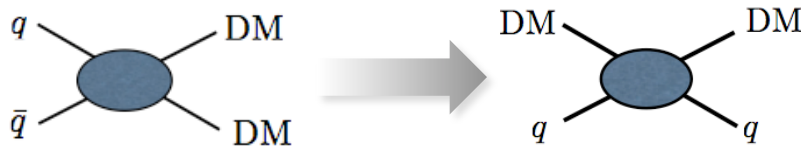
Should we forget about SUSY ?

Maybe the electroweak scale is finetuned. But what about dark matter ?

CMS-EXO-11059

Limit on WIMP pair production cross section can be transformed into limit on effective WIMP-hadronic contact interaction:

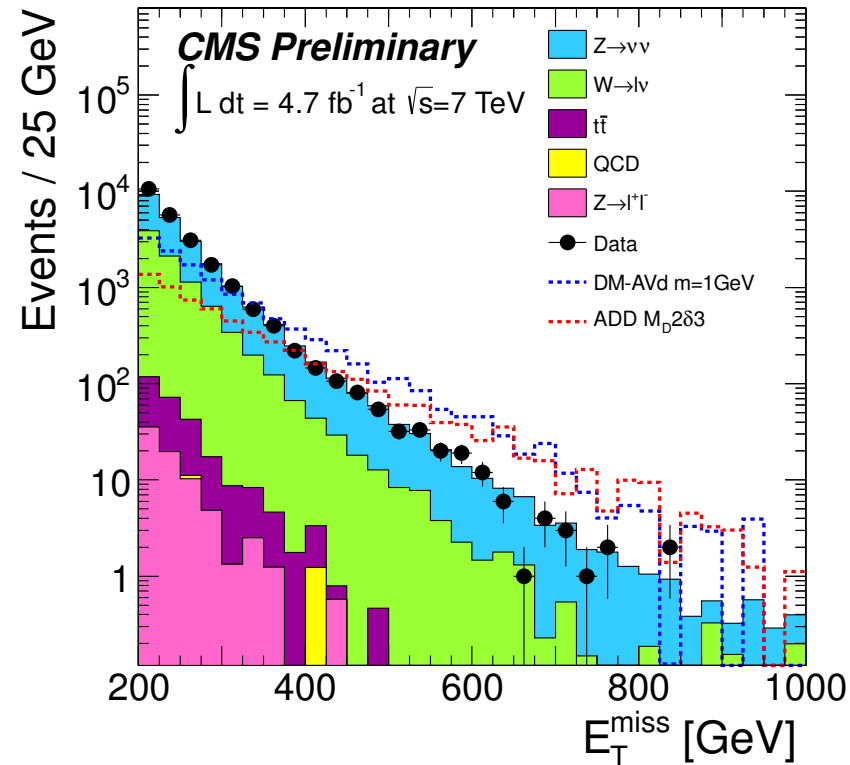
$$\left. \begin{array}{l} \text{Vector (SI): } (\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q) \cdot \Lambda^{-2} \\ \text{Axial-v. (SD): } (\bar{\chi}\gamma_{\mu}\gamma^5\chi)(\bar{q}\gamma^{\mu}\gamma^5q) \cdot \Lambda^{-2} \end{array} \right\} \sigma \propto \frac{1}{\Lambda^4}$$

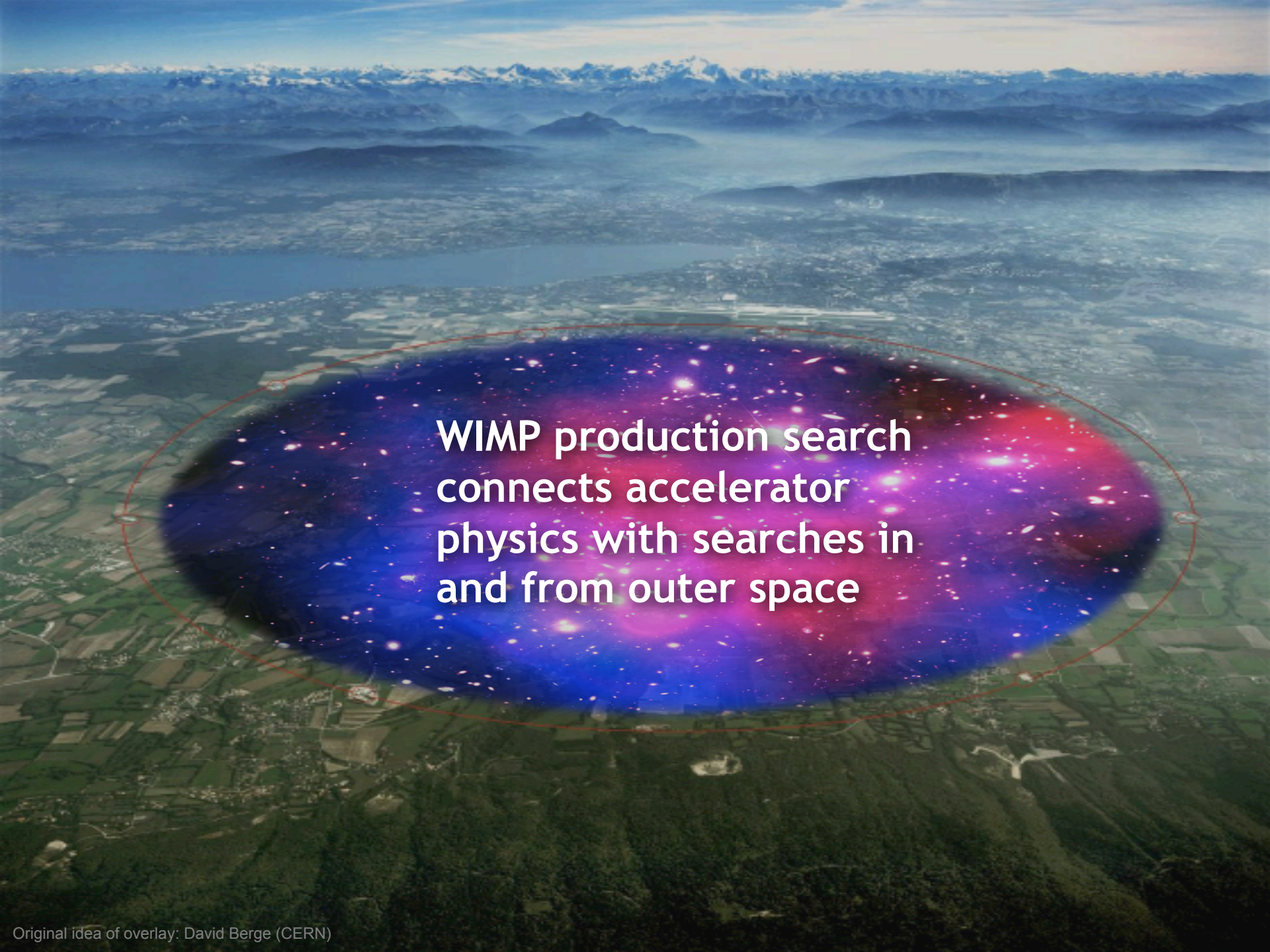


WIMP-nucleon scattering cross section:

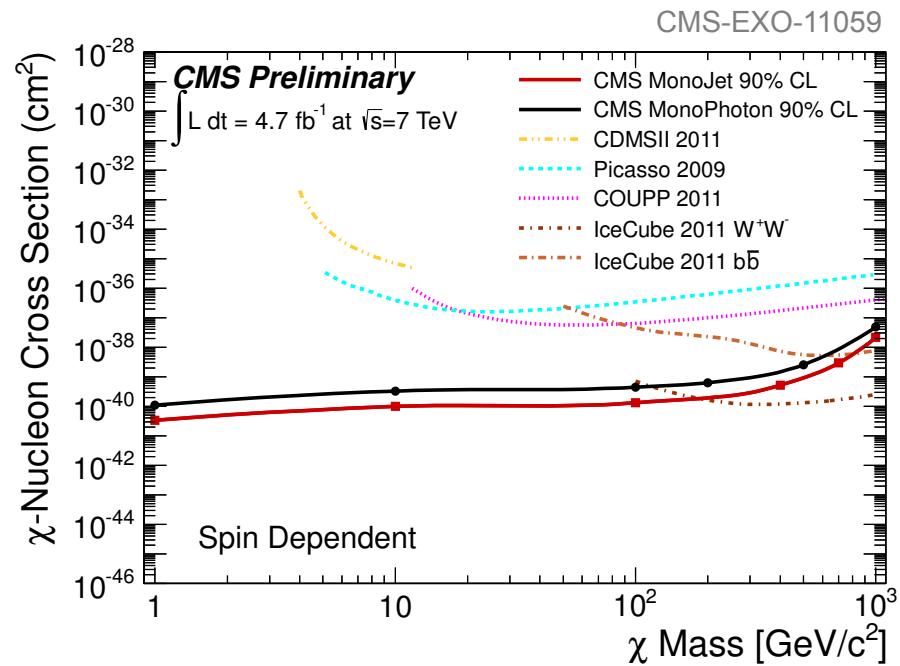
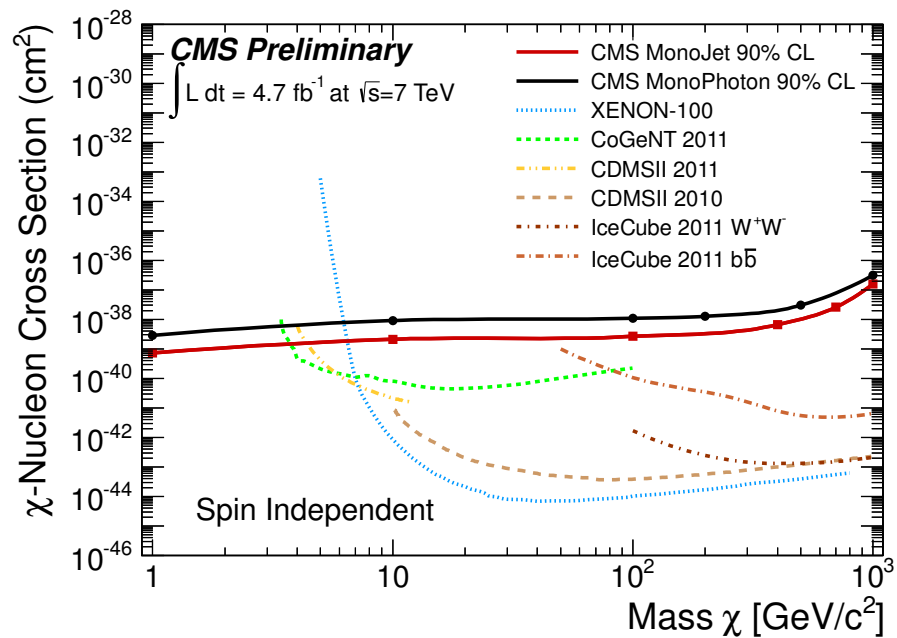
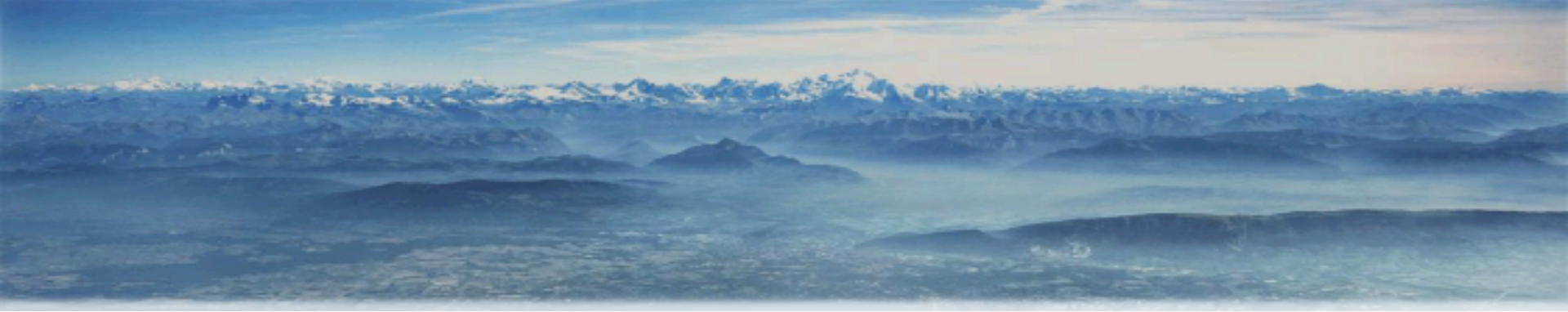
$$\sigma = \frac{\mu_{\chi}^2}{1 \text{ GeV}^2} \left(\frac{300 \text{ GeV}}{\Lambda} \right)^4 \begin{cases} 1.4 \cdot 10^{-37} \text{ cm}^2 & [\text{SI}] \\ 9.2 \cdot 10^{-40} \text{ cm}^2 & [\text{SD}] \end{cases}$$

μ_{χ} = reduced mass of WIMP-nucleon system



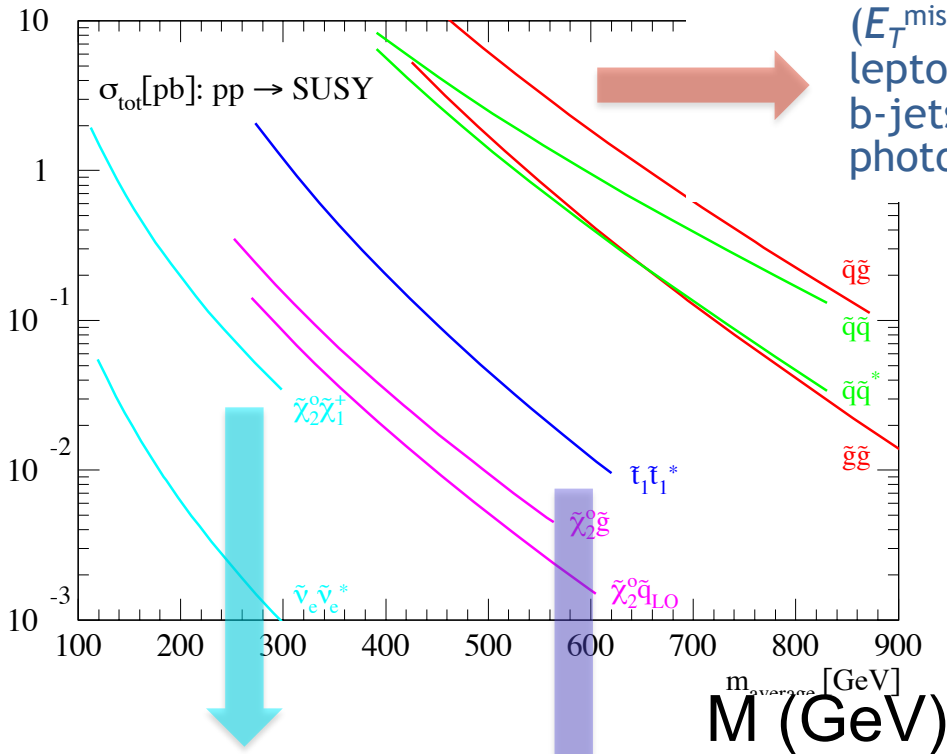
An aerial photograph of a vast landscape featuring a large lake, rolling green hills, and distant mountain ranges under a clear blue sky. Overlaid on the center of the image is a large, horizontal, elliptical graphic representing a galaxy or nebula. This graphic has a vibrant color gradient from deep blue on the left to bright magenta and pink on the right, with numerous white and yellow star-like specks scattered throughout. A thin, faint red line forms an oval border around the galaxy graphic.

**WIMP production search
connects accelerator
physics with searches in
and from outer space**



Overall search strategy

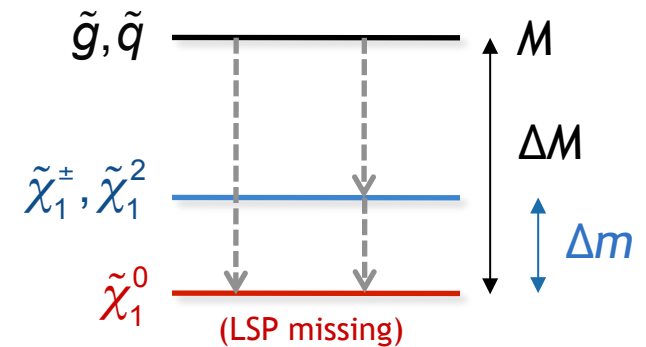
Production



3. Direct gauginos

2. Direct stop / sbottom

Decay



- 4. **High $\Delta M/M$ explored.** Focus also on low $\Delta M/M$ (*compressed spectra*)
- 5. **Almost degenerate case (low Δm):** LLP, displaced vertex, kinked track
- 6. **RPV signatures:** lower MET (no LSP), resonances, multijets, multileptons

The LHC is performing marvelously
What are the next steps?

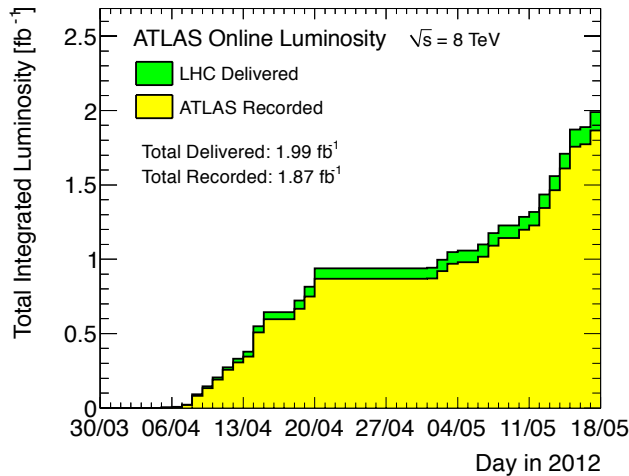
Where are we heading to



Next Steps at the LHC

One more year 8 TeV, then shutdown in 2013/2014 $\rightarrow$ ~ 14 TeV

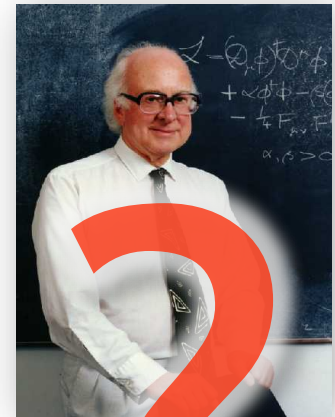
- 2012: LHC runs at 8 TeV until October 2012 $\rightarrow \sim 15 \text{ fb}^{-1}$



LHC on schedule. Current 2012 records:

- 2.0 fb^{-1} integrated lumi delivered
- peak Lumi: $6.0 \times 10^{-33} \text{ cm}^{-2}\text{s}^{-1}$
- #bunches: 1377
- max. of $0.83 \text{ fb}^{-1} / \text{week}$
- max peak interactions / crossing: 44
- max ave. interactions / crossing: 30

- First Higgs & SUSY results expected at ICHEP 12 (4th of July)
- 2013/2014: repair and upgrade LHC to 13~14 TeV
- Then long run until ~ 2018 , before further upgrade





Thank you !