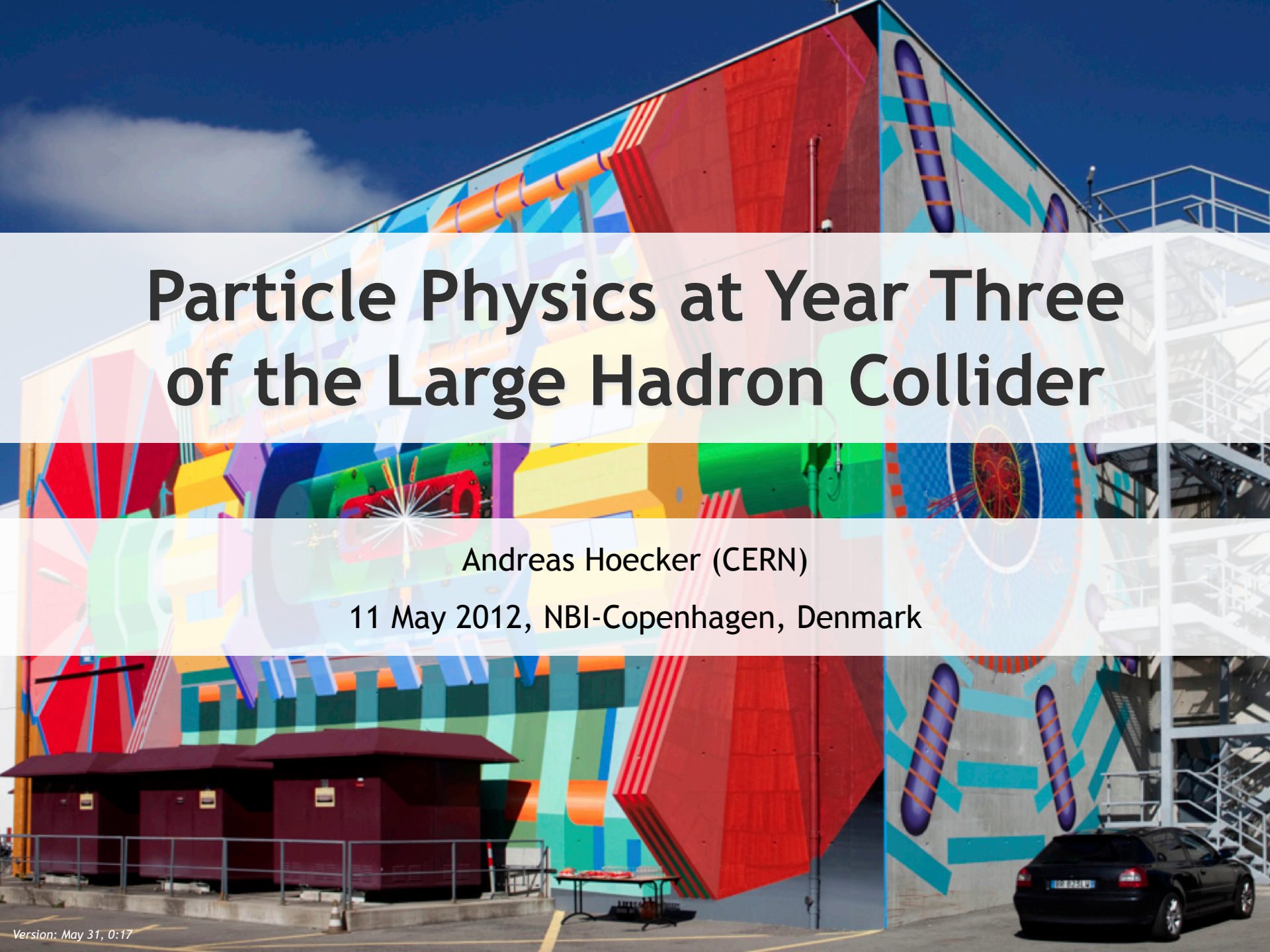
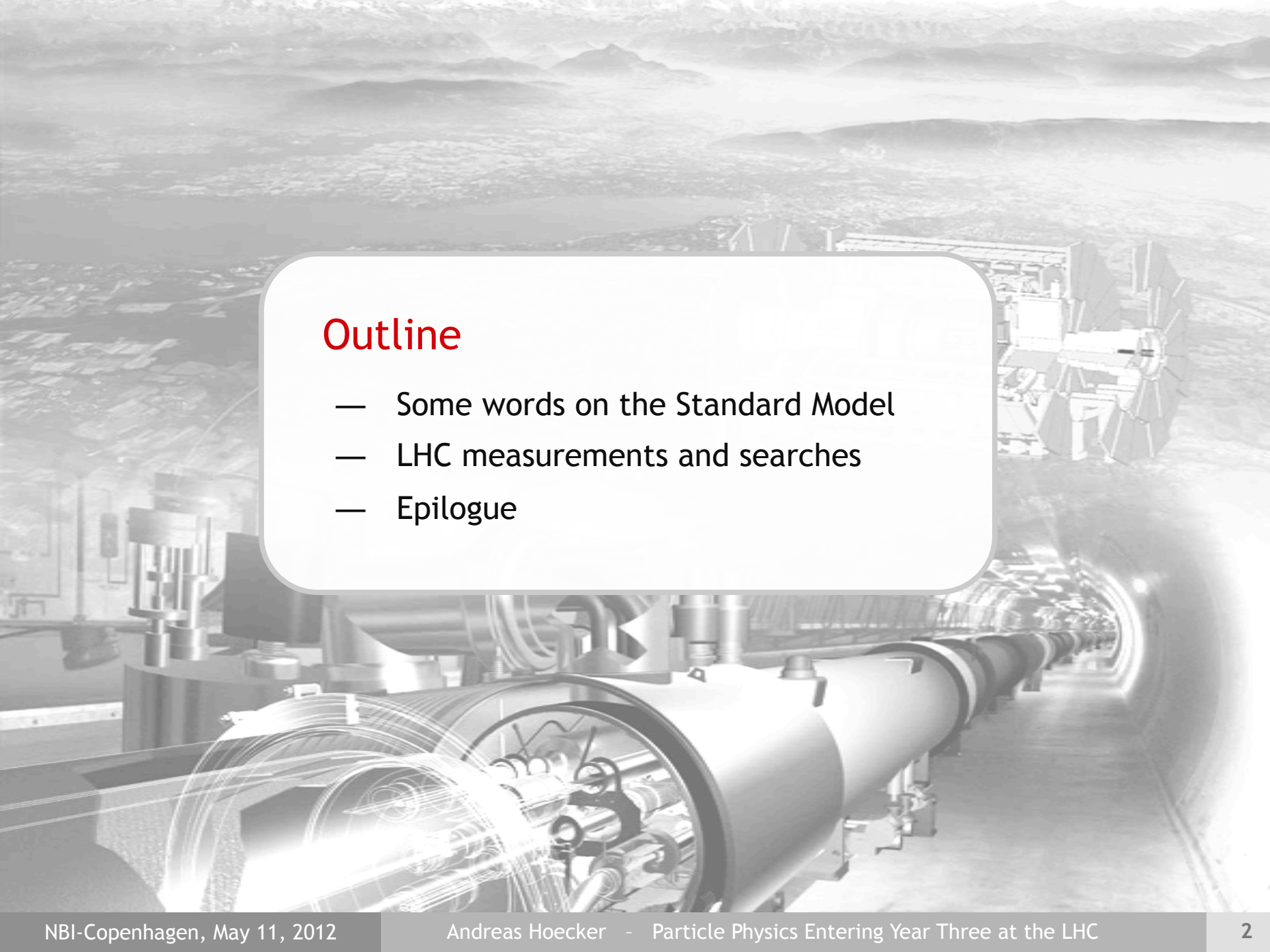




Particle Physics at Year Three of the Large Hadron Collider

Andreas Hoecker (CERN)

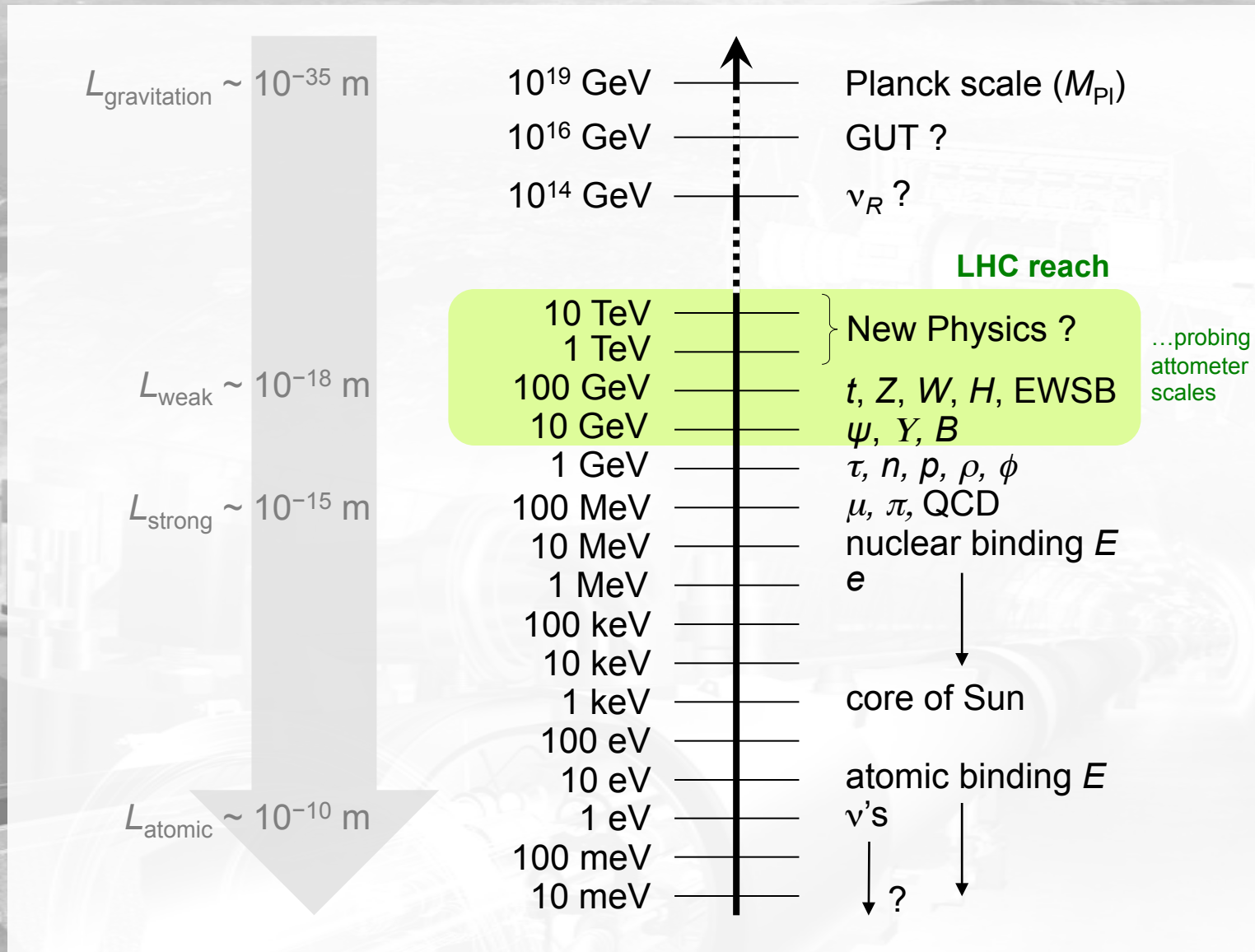
11 May 2012, NBI-Copenhagen, Denmark



Outline

- Some words on the Standard Model
- LHC measurements and searches
- Epilogue

Particle Physics Scales





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

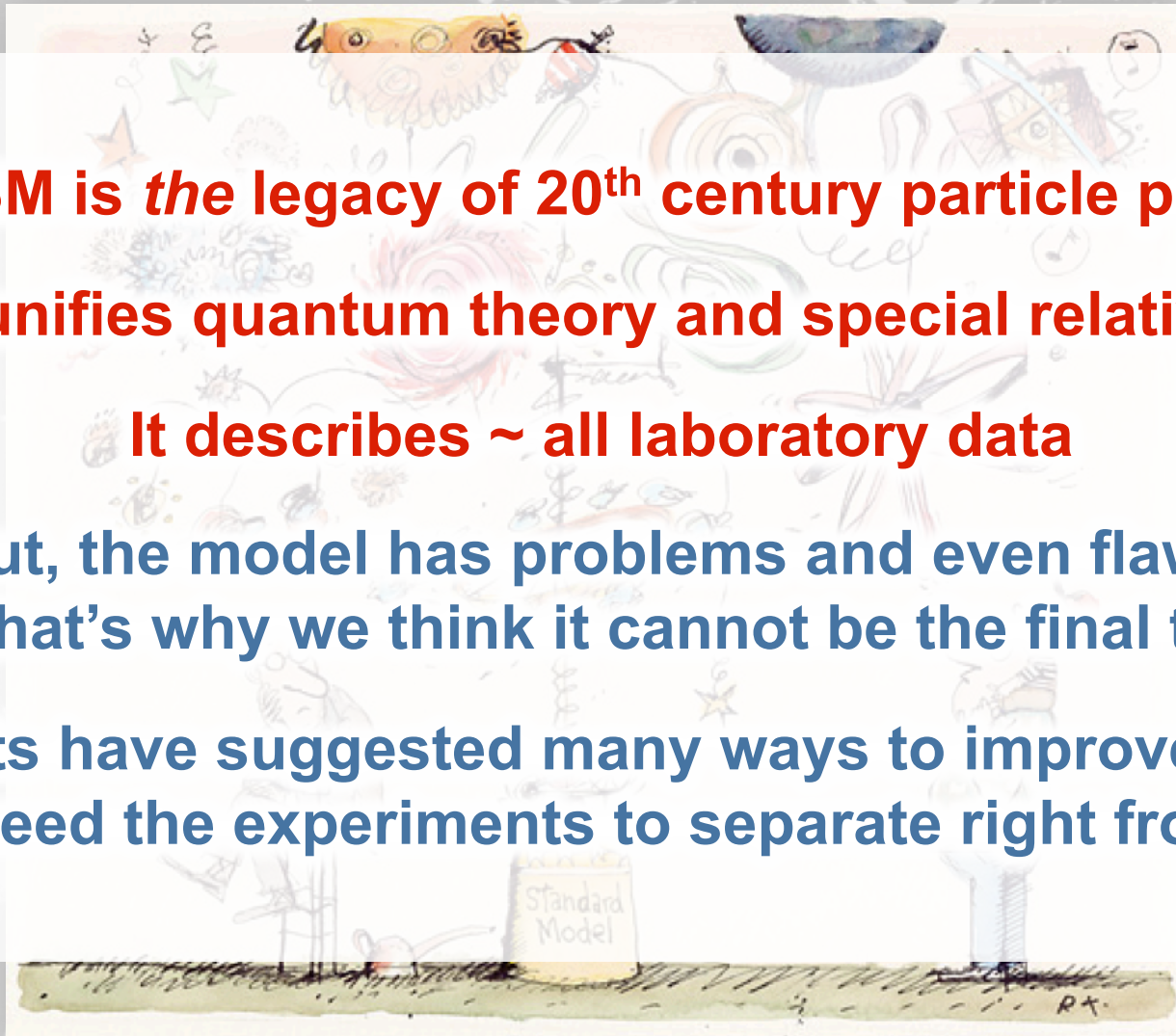
The SM is *the* legacy of 20th century particle physics

It unifies quantum theory and special relativity

It describes ~ all laboratory data

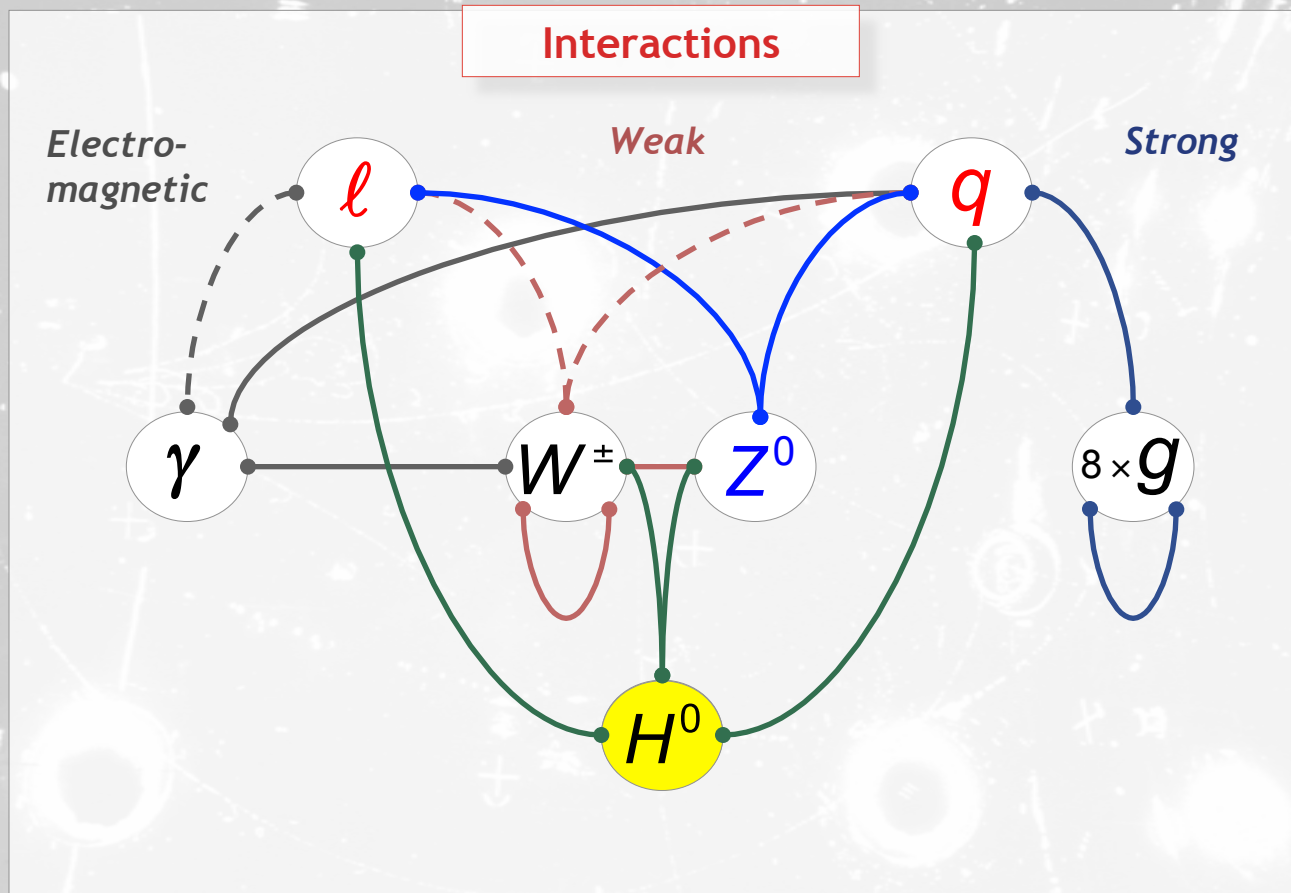
**But, the model has problems and even flaws,
and that's why we think it cannot be the final theory**

**Theorists have suggested many ways to improve the SM,
but we need the experiments to separate right from wrong**



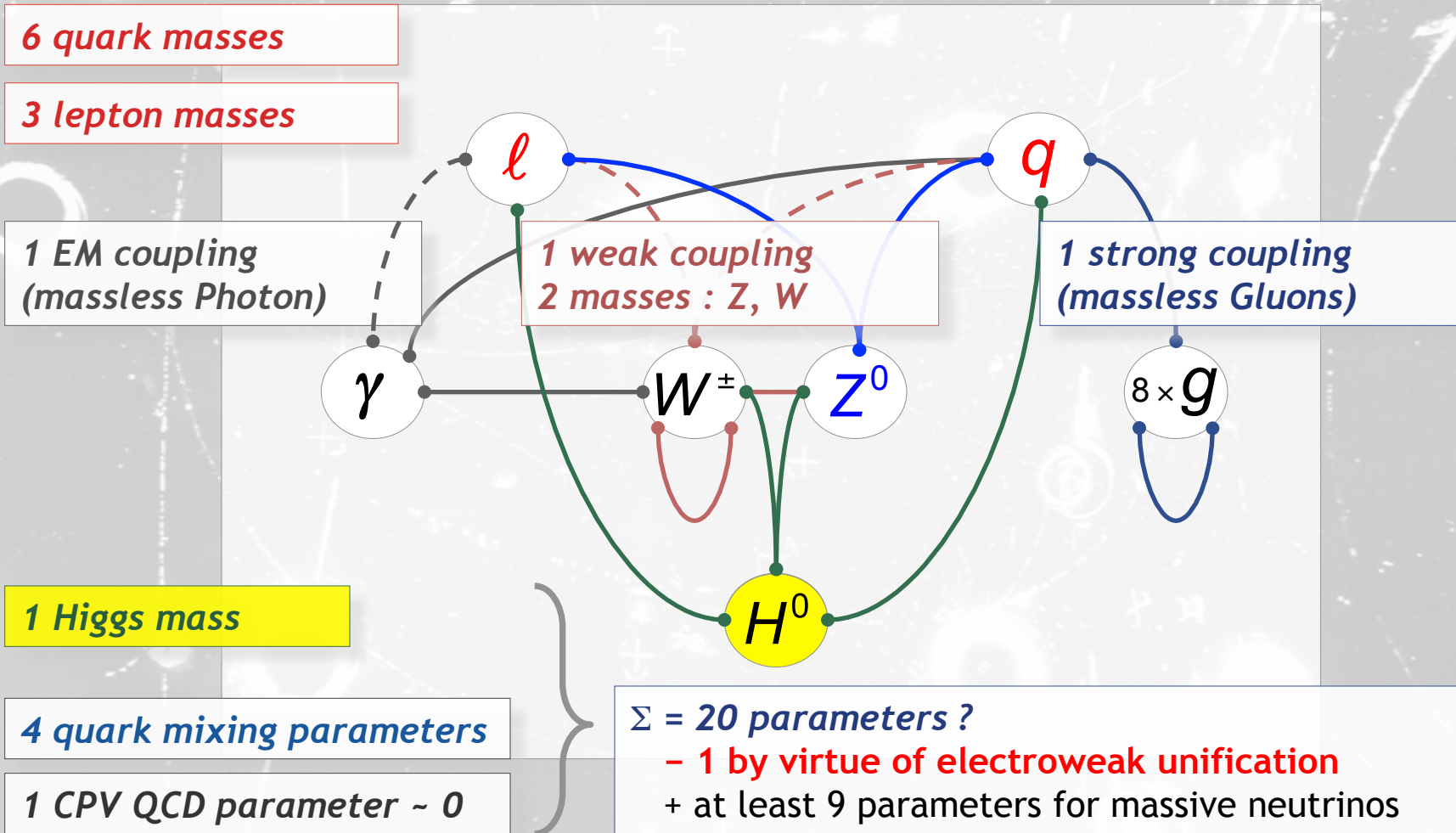
The Standard Model

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



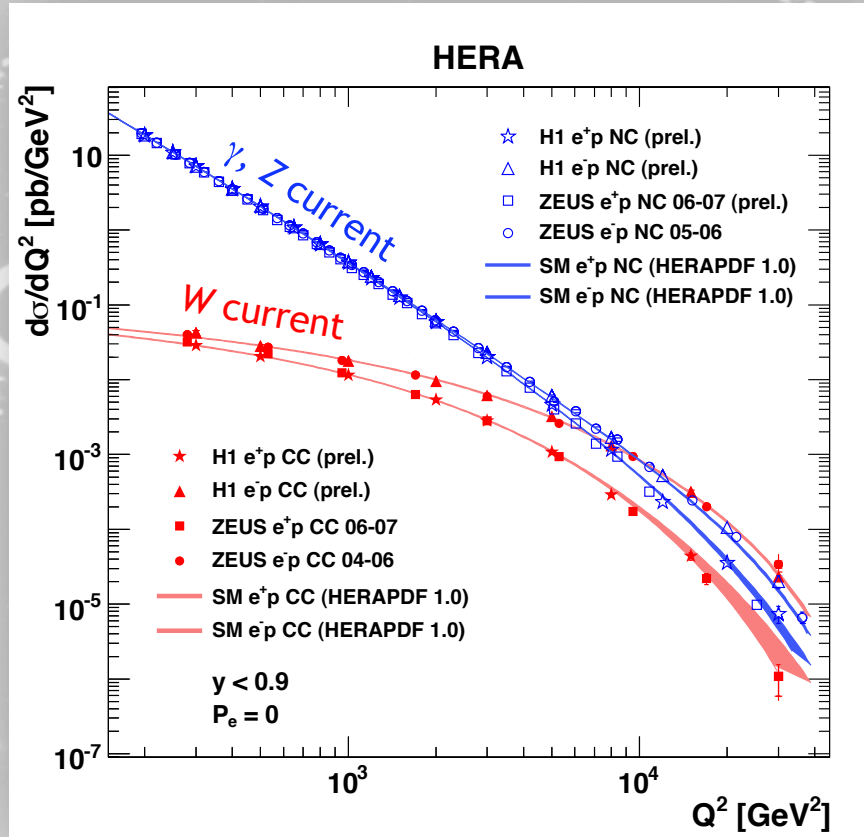
The Standard Model

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



The Standard Model

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



- Above ~ 100 GeV, electromagnetic and weak interactions are unified
- Below 100 GeV, **weak interaction** is weaker than **electromagnetism**
- ***Electroweak interaction***

HERA data from electron–quark scattering into $e+q$ (NC = γ, Z) or $\nu+q$ (CC = $W^\pm$)

$\Sigma = 20$ parameters ?

– 1 by virtue of electroweak unification

+ at least 9 parameters for massive neutrinos

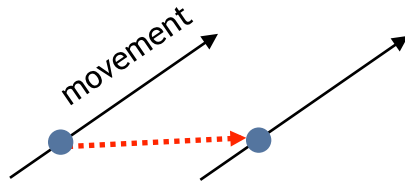
The Standard Model

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

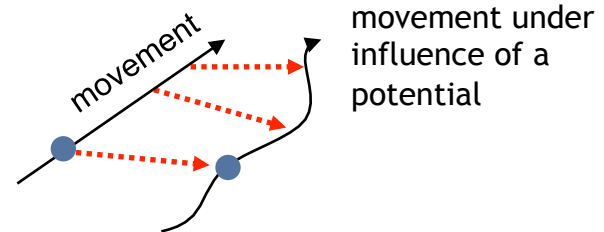
Example: translation group – uniform movement of particle

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**

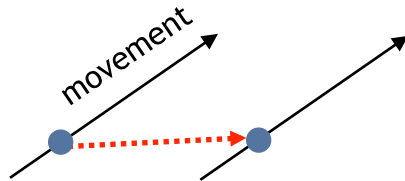
The Standard Model

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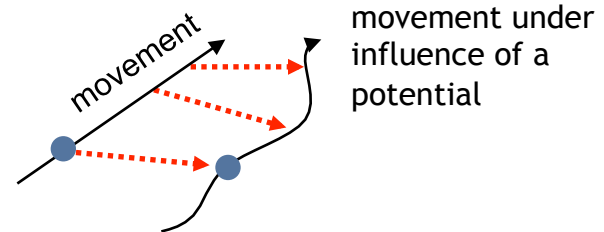
Example: translation group – uniform movement of particle

Global
symmetry:



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

Local
symmetry:



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

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

Geometric origin !

The Standard Model

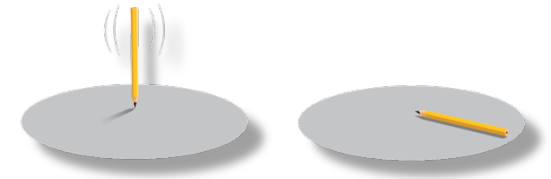
Brout-Englert-Higgs mechanism

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)

The particles interact with the Higgs field thus reducing their velocity, which is equivalent to acquiring a mass

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

Higgs quantum liquid in broken phase

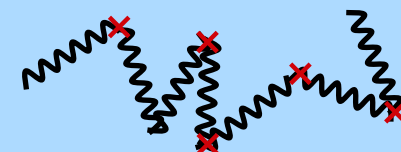
Gravity



Photon



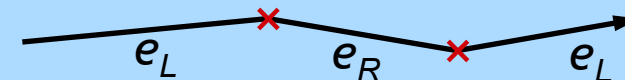
Weak boson



Neutrinos



Electrons



Top quark



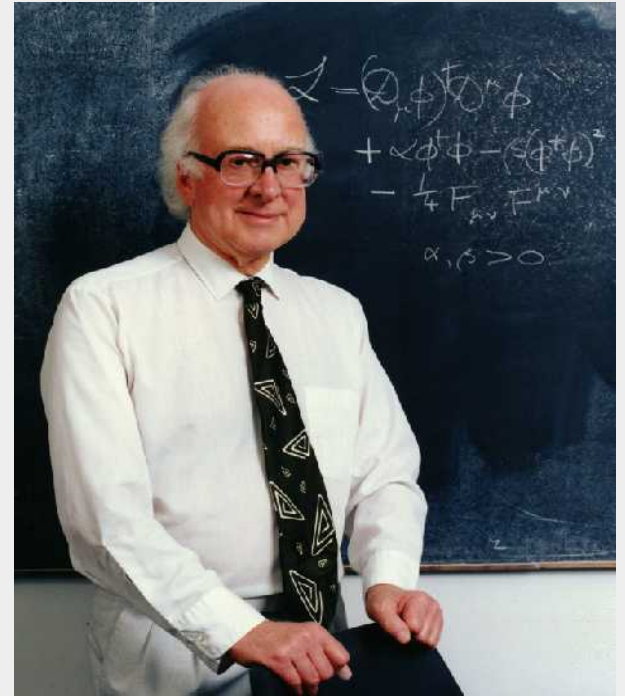
H. Murayama

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

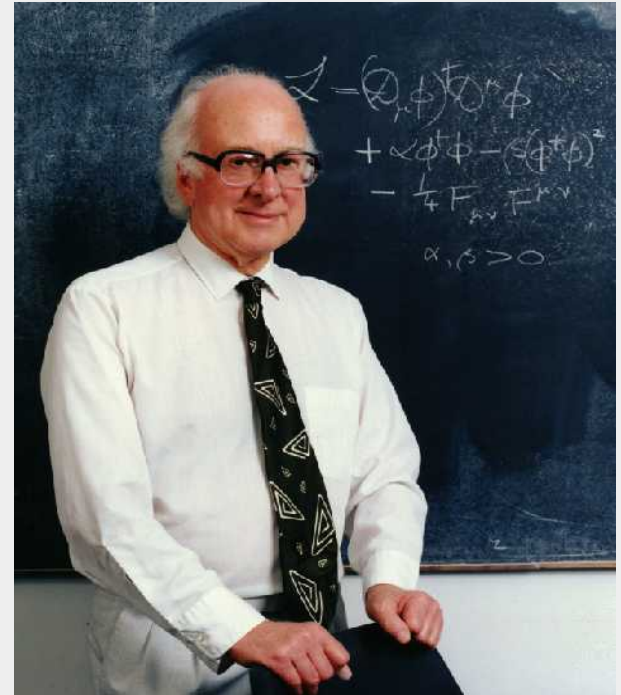
The Higgs boson is the last elusive elementary particle of the SM

Daniel Froidevaux (CERN):

The Higgs has been with us for >4 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

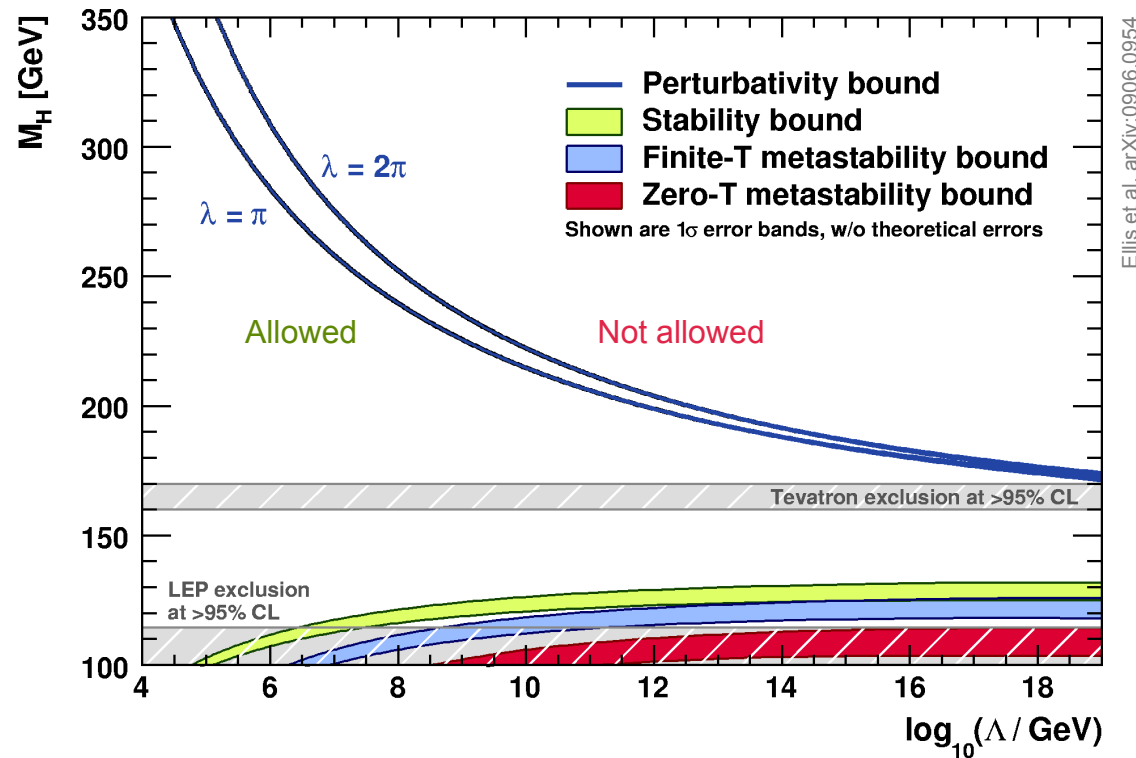


© CMS

© ATLAS

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

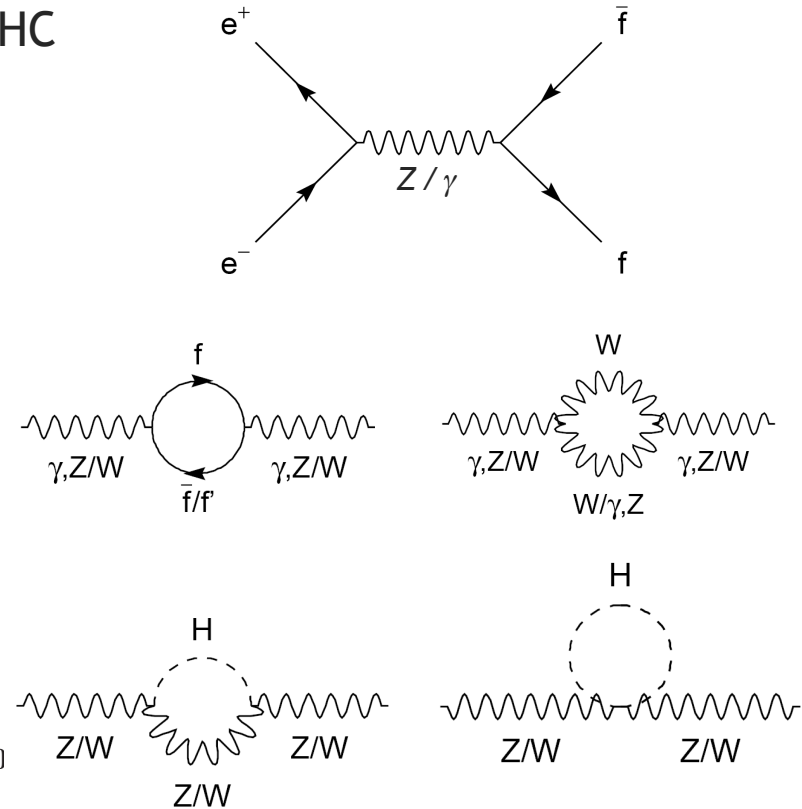
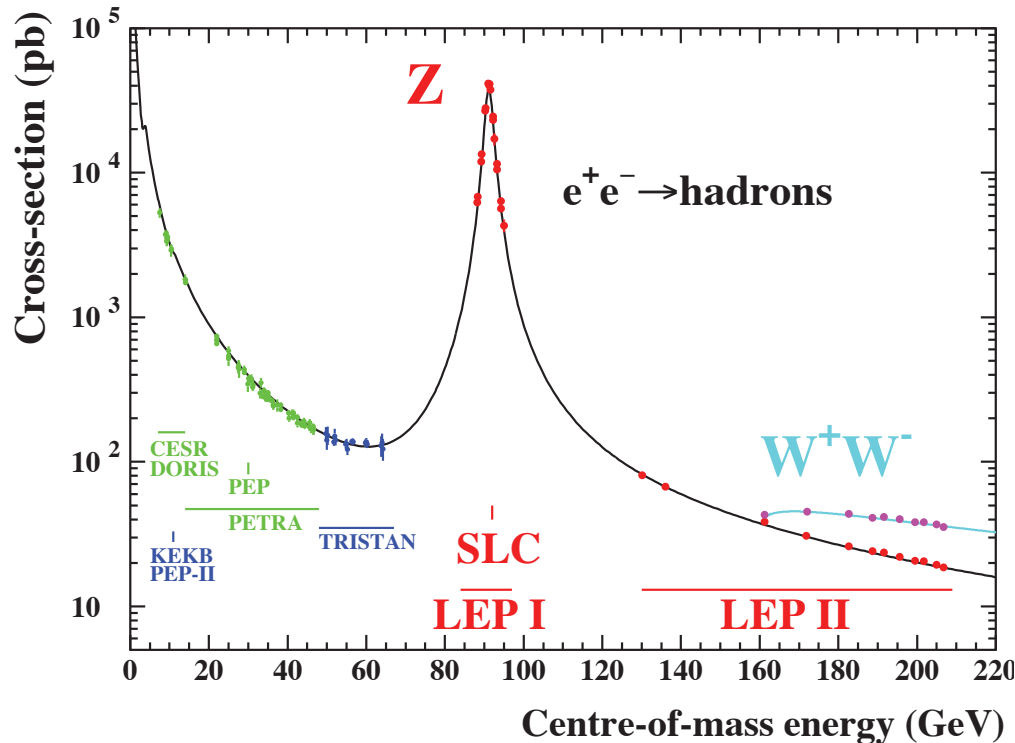
Perturbativity and (meta)stability bounds versus the SM cut-off scale Λ



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

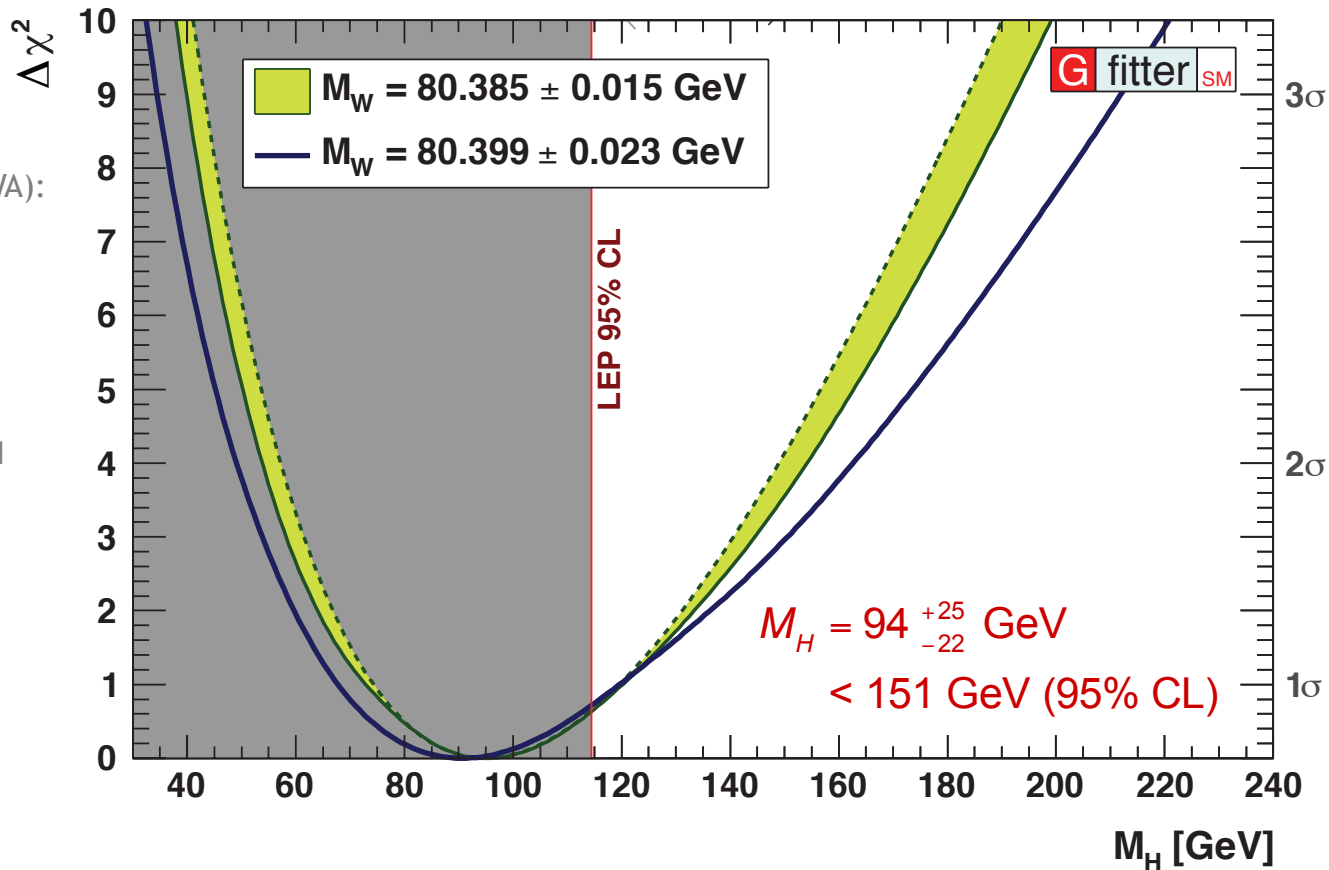
Precision results from LEP, Tevatron and soon LHC



Precisely measured couplings around the Z peak (M_W also at Tevatron) via Z decay widths and asymmetry observables sensitive to parity violation $\rightarrow$ fit constrains $\log(M_H)$ and m_t^2

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)]

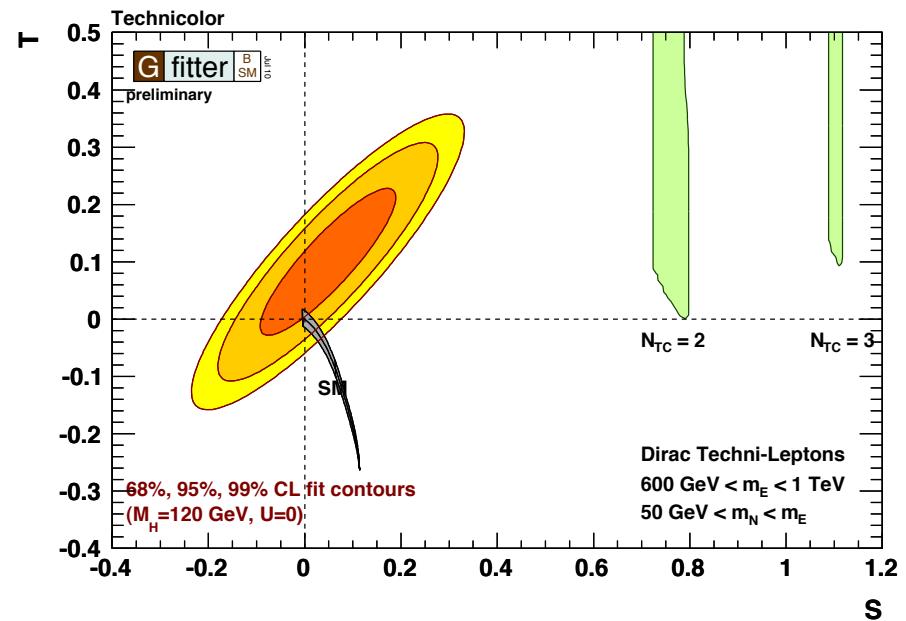
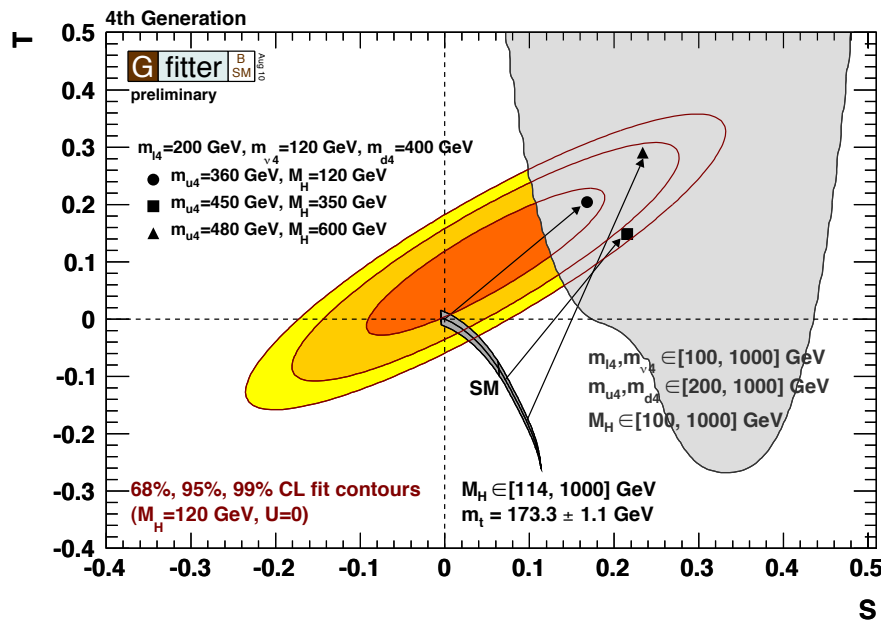
<http://gfitter.desy.de>

Constraints from global electroweak fit

We can also use the precision data to look beyond the SM !

For example: Can we add a 4th generation?

Or: can the vacuum be broken by a new strong interaction?



Gfitter: arXiv:1107.0975, <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 ?



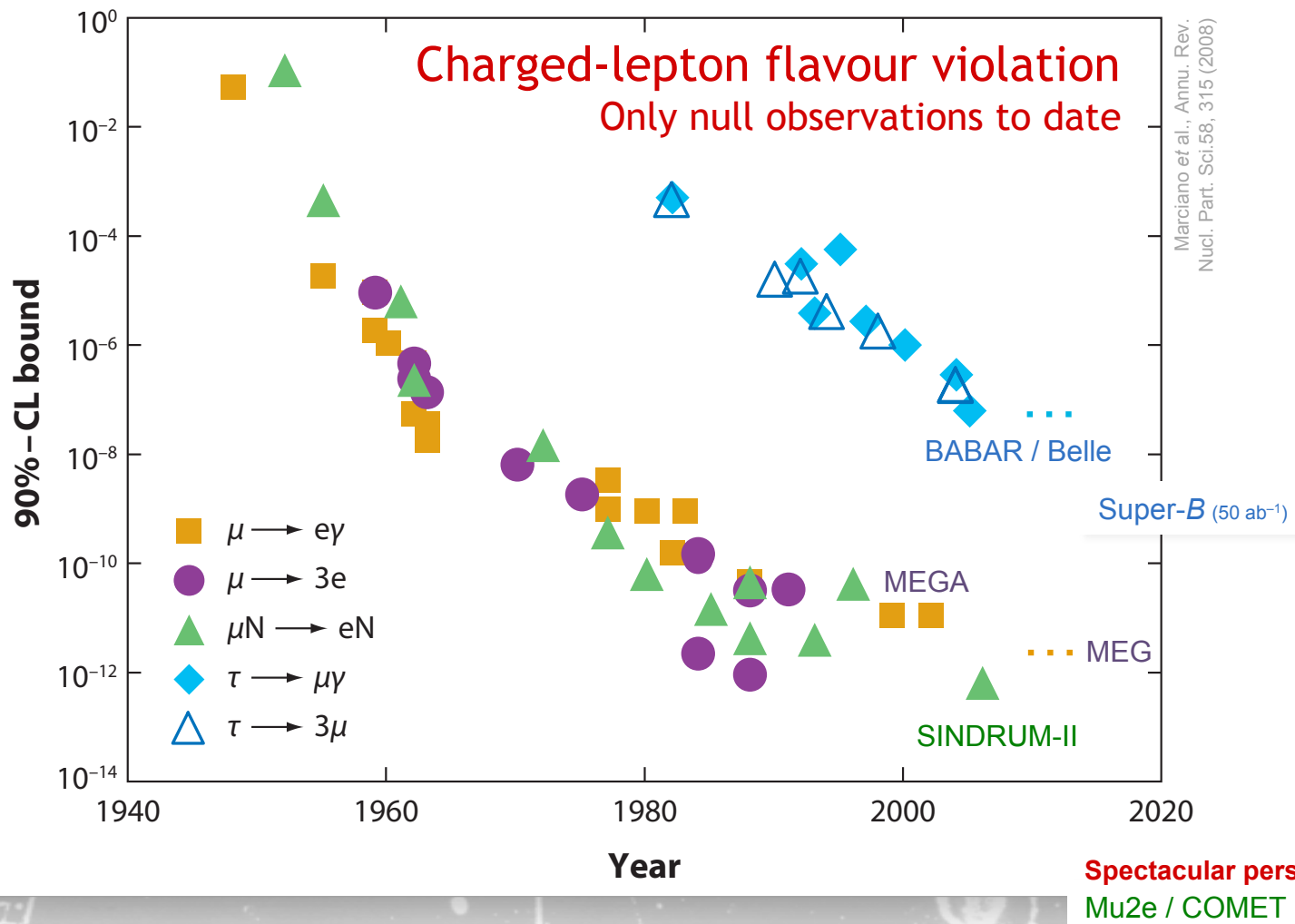
The Standard Model

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 ...*

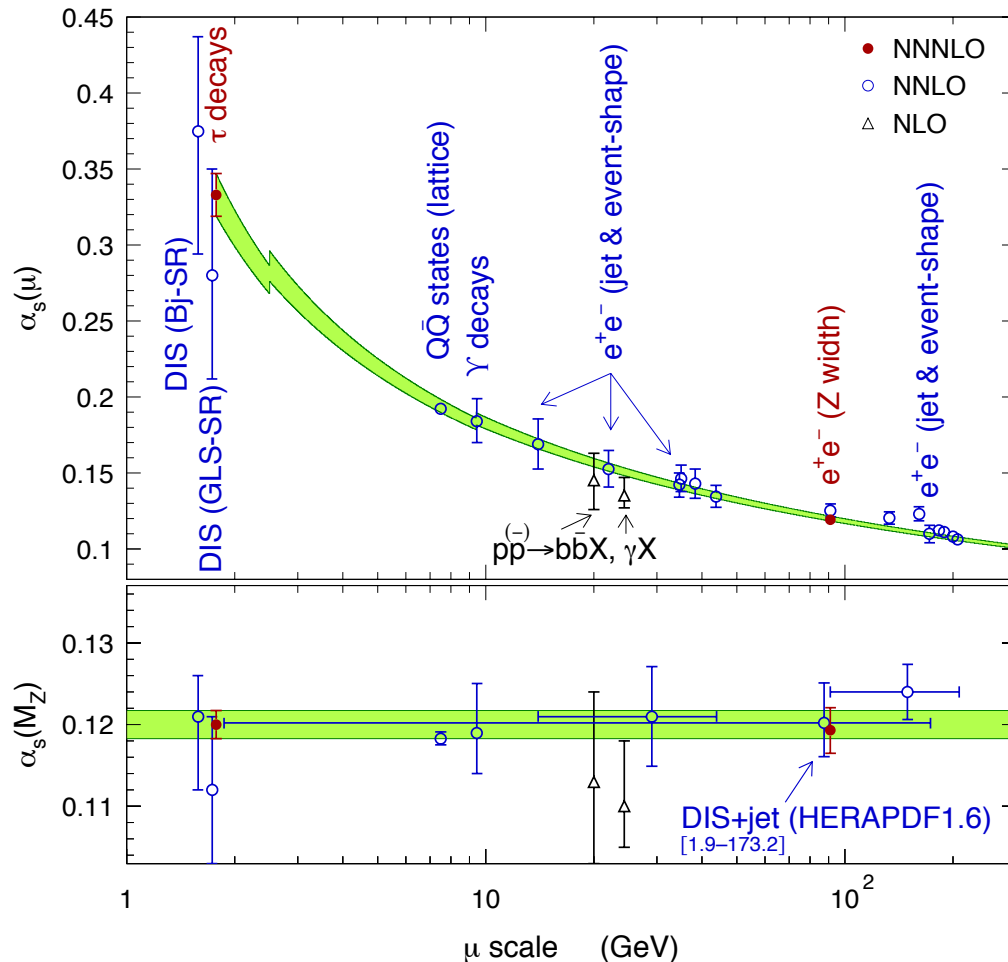
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The Standard Model

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NNNLO from tau data:

$$\alpha_s(M_Z) = 0.1200 \pm 0.0005_{\text{exp}} \pm 0.0008_{\text{theo}} \pm 0.0013_{\text{CIPT/FOPT}} \pm 0.0005_{\text{evol}} \quad (0.0017_{\text{tot}})$$

[Hoecker, arXiv:1201.5093]

Excellent agreement with NNNLO result from EW fit

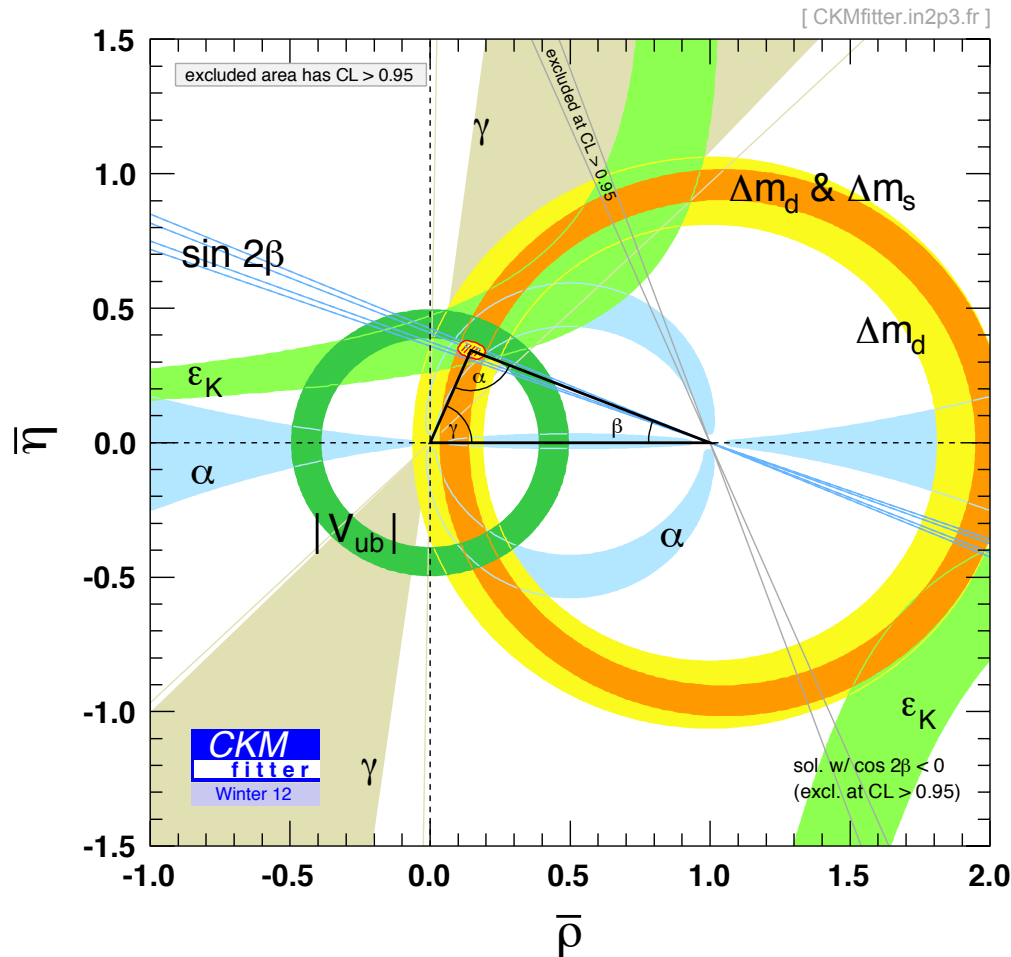
$$\alpha_s(M_Z) = 0.1193 \pm 0.0028$$

[Gfitter, arXiv:1107.0975]

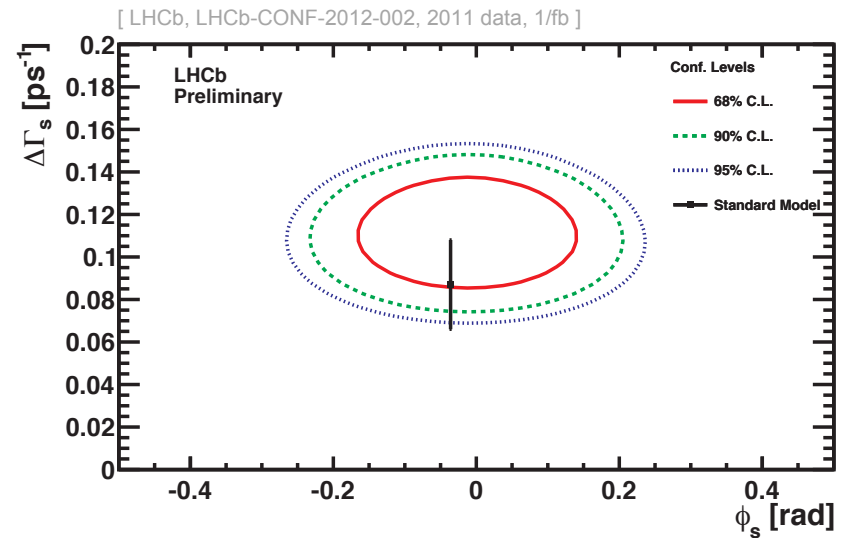
Precise test of asymptotic freedom property of QCD

The Standard Model

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

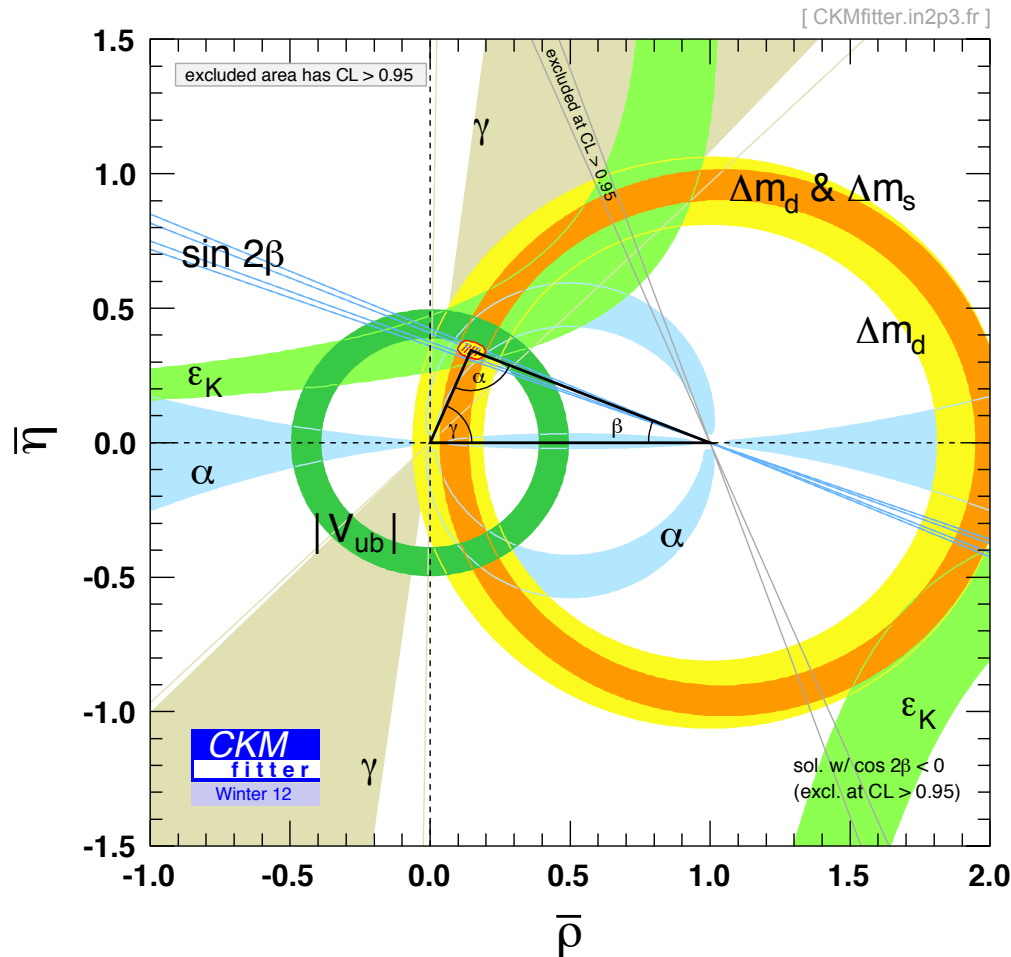


SM describes *CP* violation
— also in the B_s system

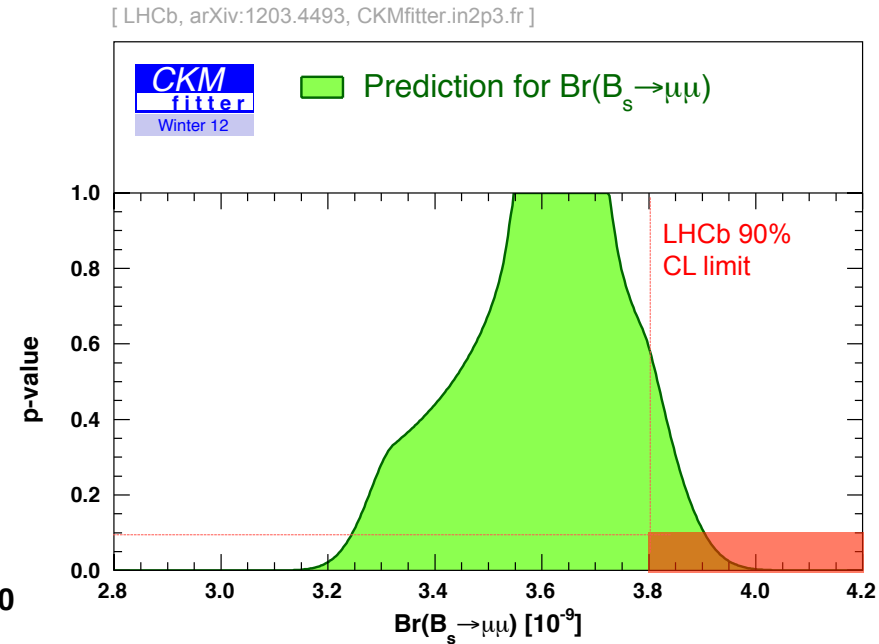


The Standard Model

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



Also, no enhancement in $B_s \rightarrow \mu\mu$ branching fraction seen



The Standard Model

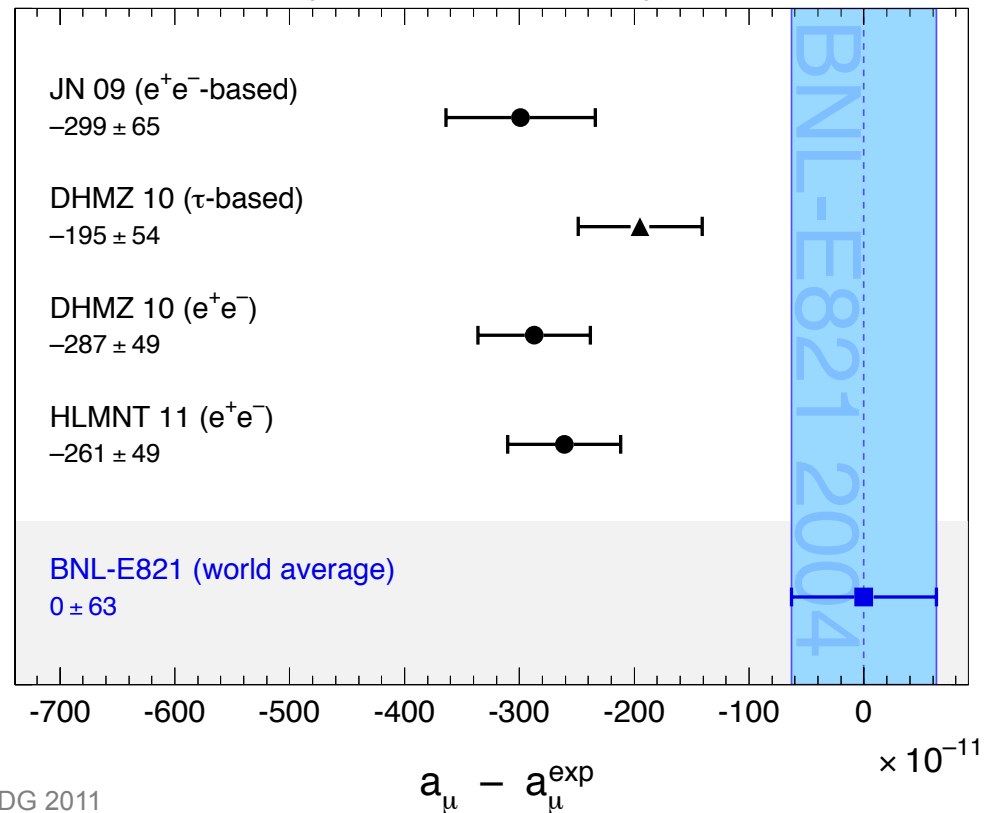
During the last 35 years the Standard Model has been tested to great precision

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 (see later)
- Why no matter-antimatter symmetry violation in strong interaction?
- Neutrino masses
- Gravitation

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 !

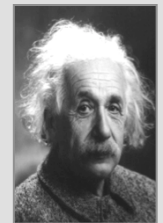
Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine

Particles accelerators:
accelerate particles to the highest energies to

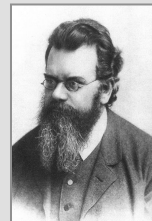
- Look deeper into matter (size $\sim 1/E$)
("powerful microscopes")
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie

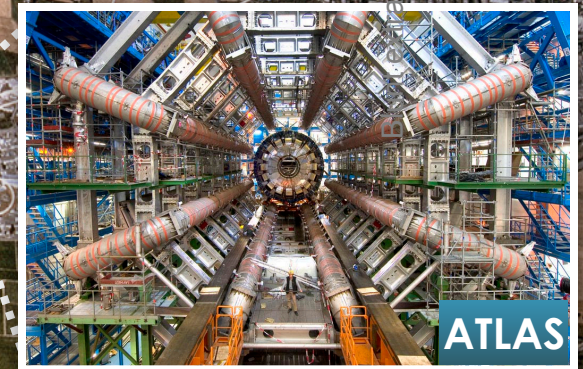
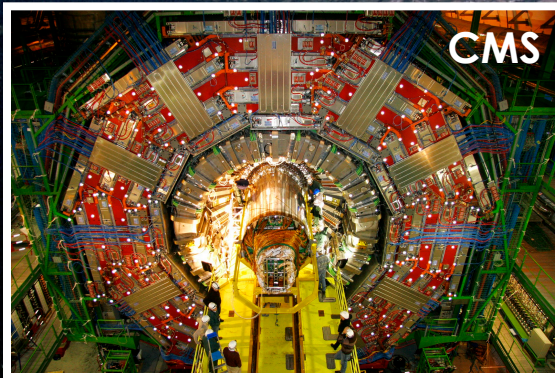


Einstein



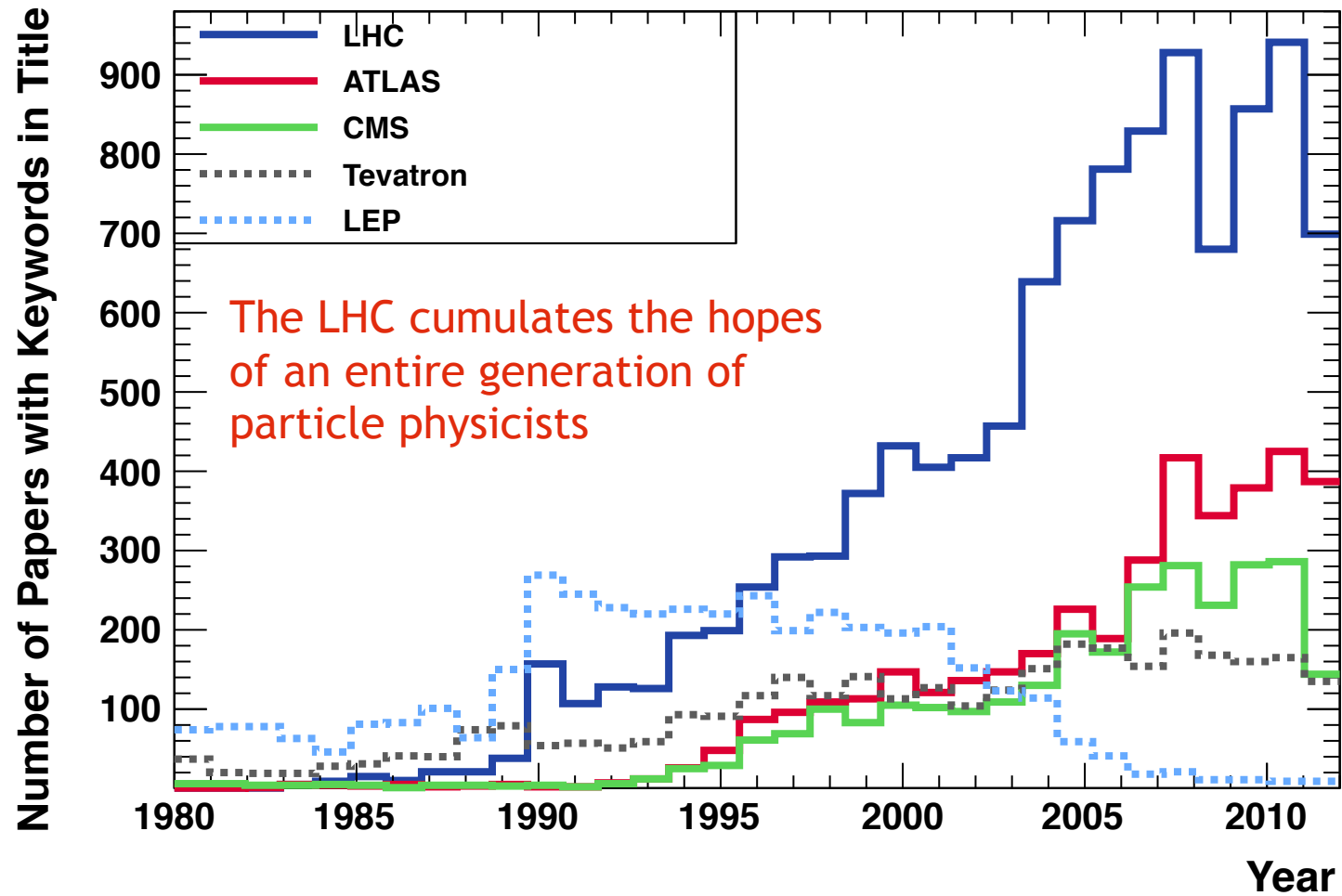
Boltzmann

LHC ring:
27 km circumference

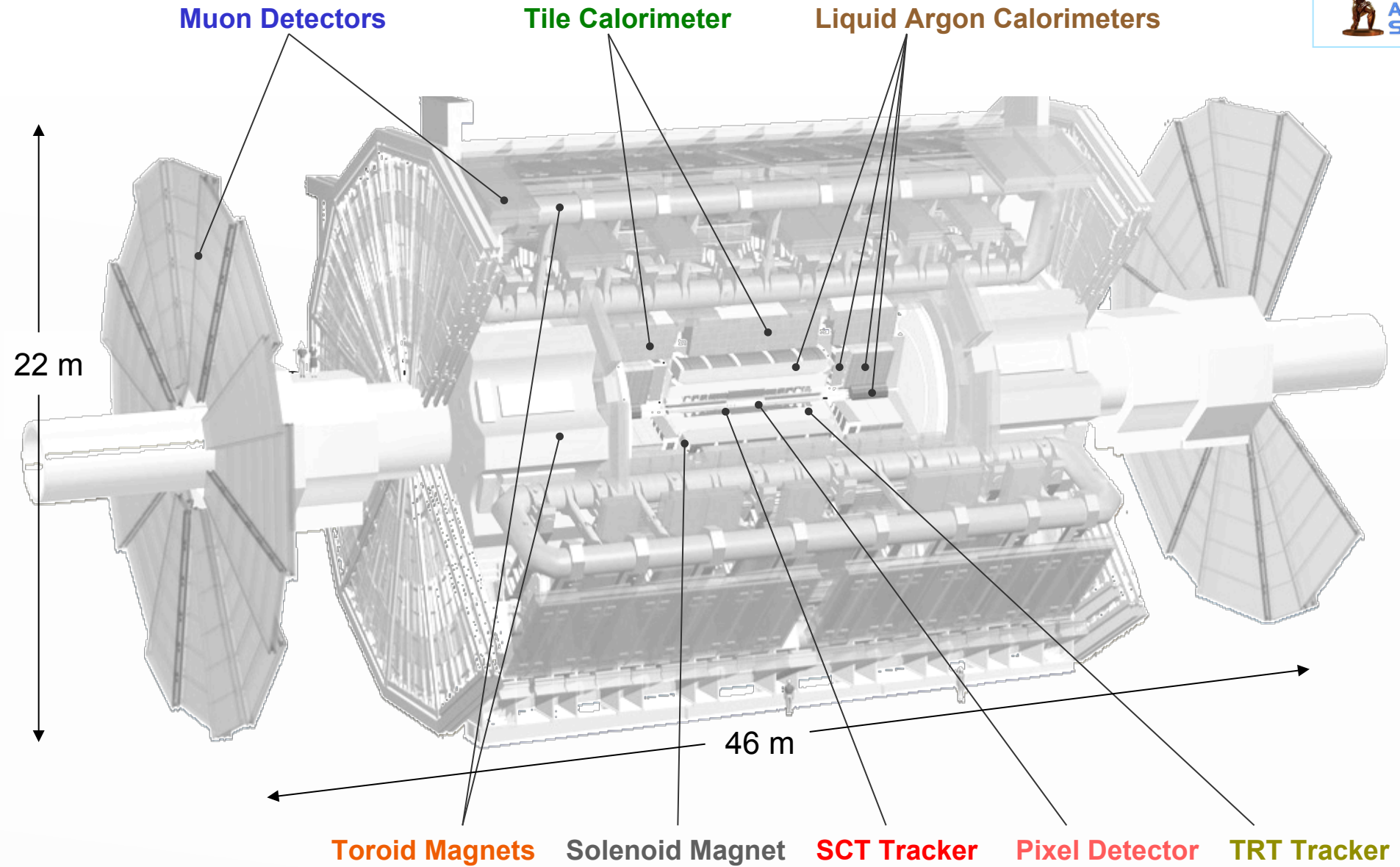


So far:
7/8 TeV proton—proton collisions
2.76 TeV Pb—Pb collisions

Paper Statistics in SPIRES



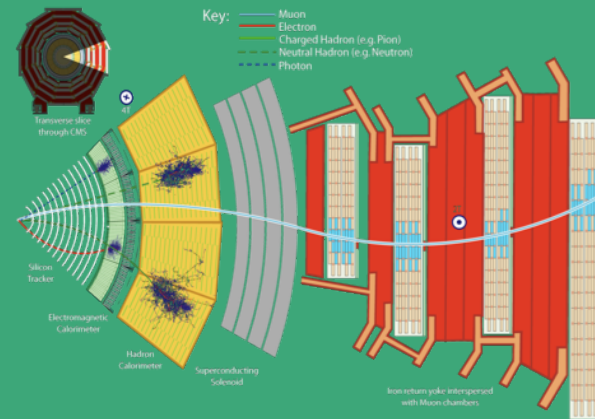
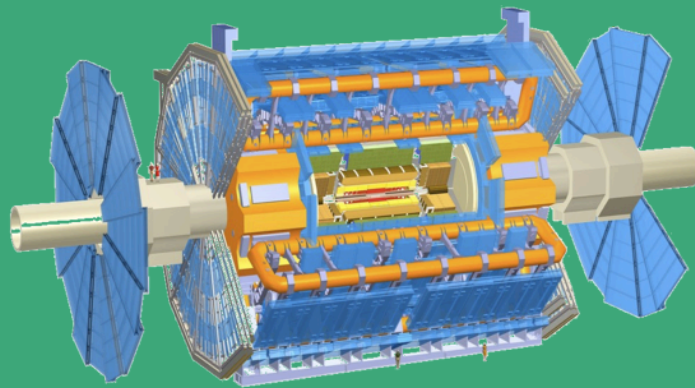
Caution: serious science ;-)



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

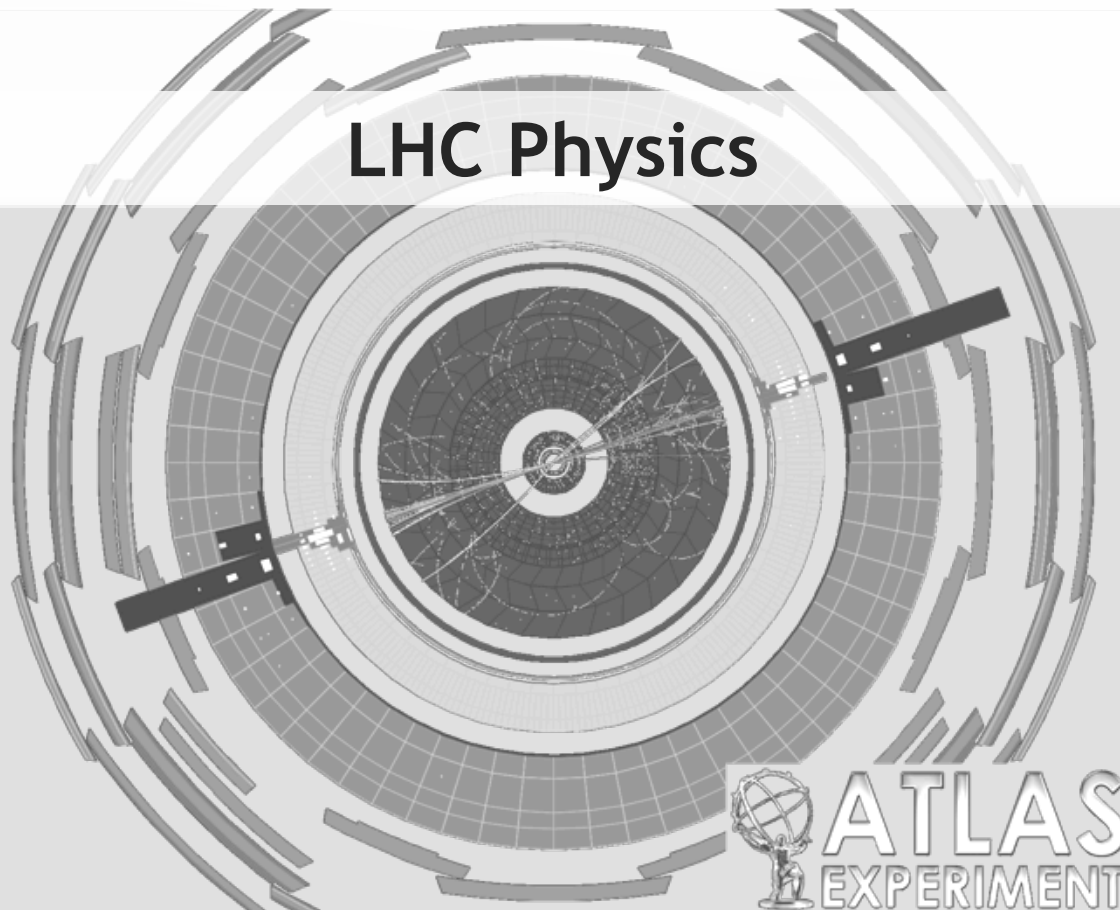
Solenoid Magnet

SCT Tracker

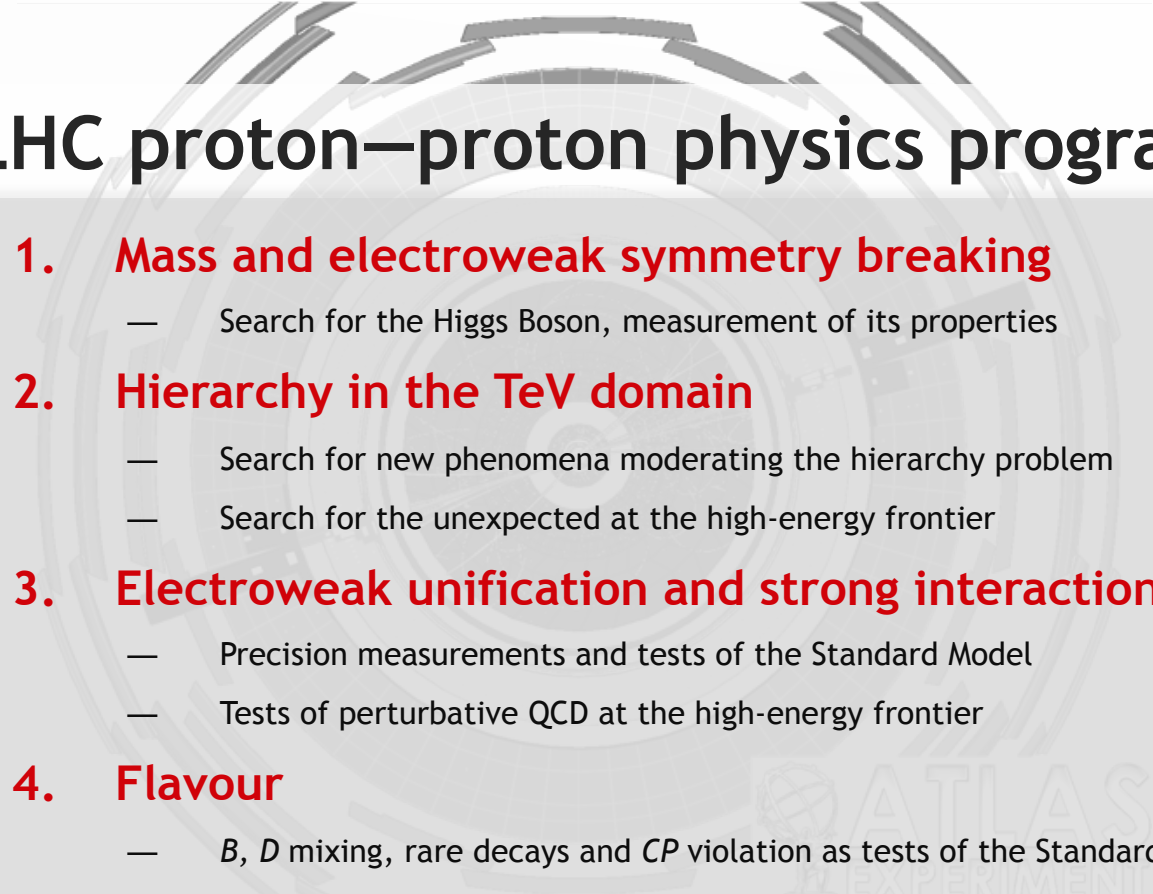
Pixel Detector

TRT Tracker

LHC Physics



ATLAS
EXPERIMENT



The LHC proton–proton physics programme

1. **Mass and electroweak symmetry breaking**
 - Search for the Higgs Boson, measurement of its properties
2. **Hierarchy in the TeV domain**
 - Search for new phenomena moderating the hierarchy problem
 - Search for the unexpected at the high-energy frontier
3. **Electroweak unification and strong interactions**
 - Precision measurements and tests of the Standard Model
 - Tests of perturbative QCD at the high-energy frontier
4. **Flavour**
 - B , D mixing, rare decays and CP violation as tests of the Standard Model

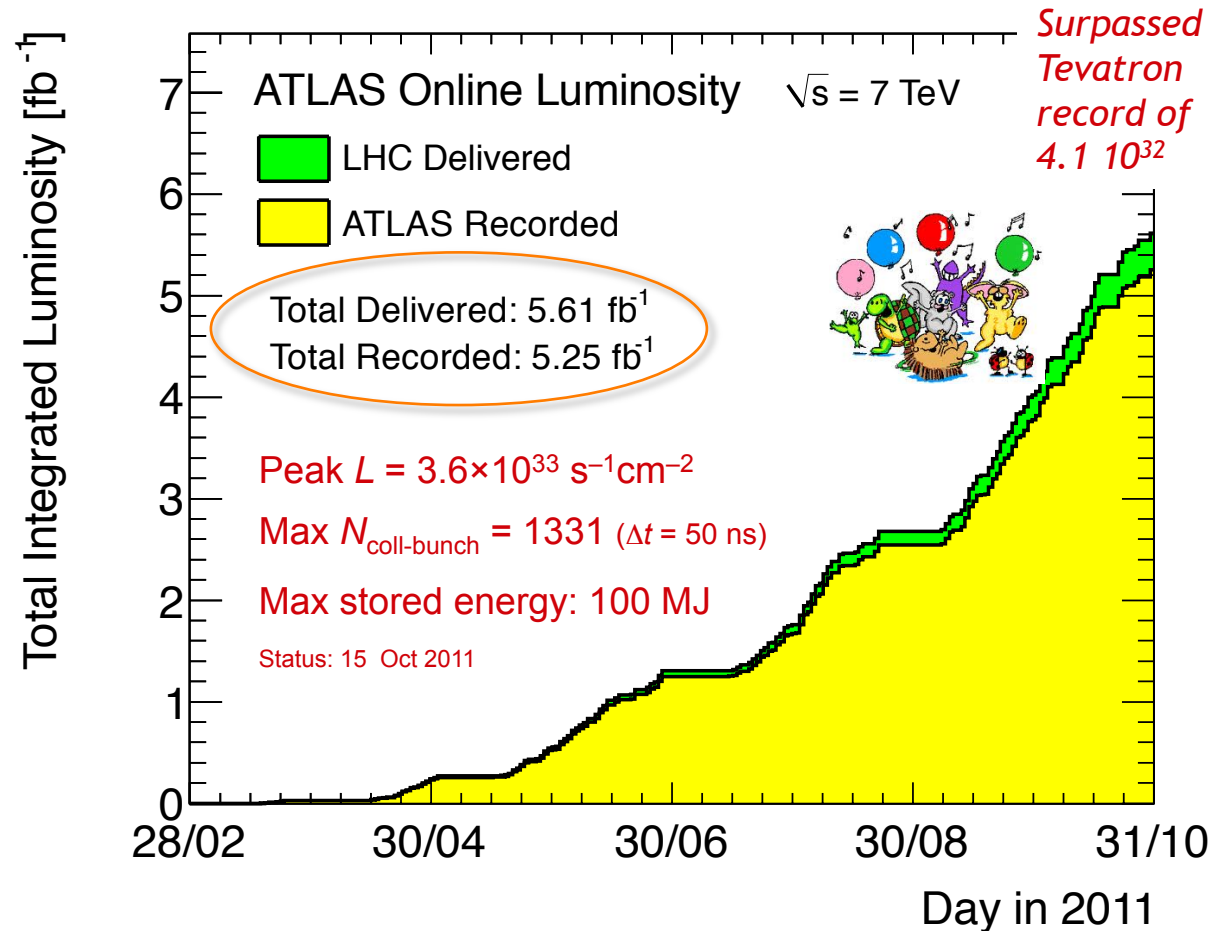
The LHC experiments have a prolific scientific production of which I can only discuss small parts here

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)

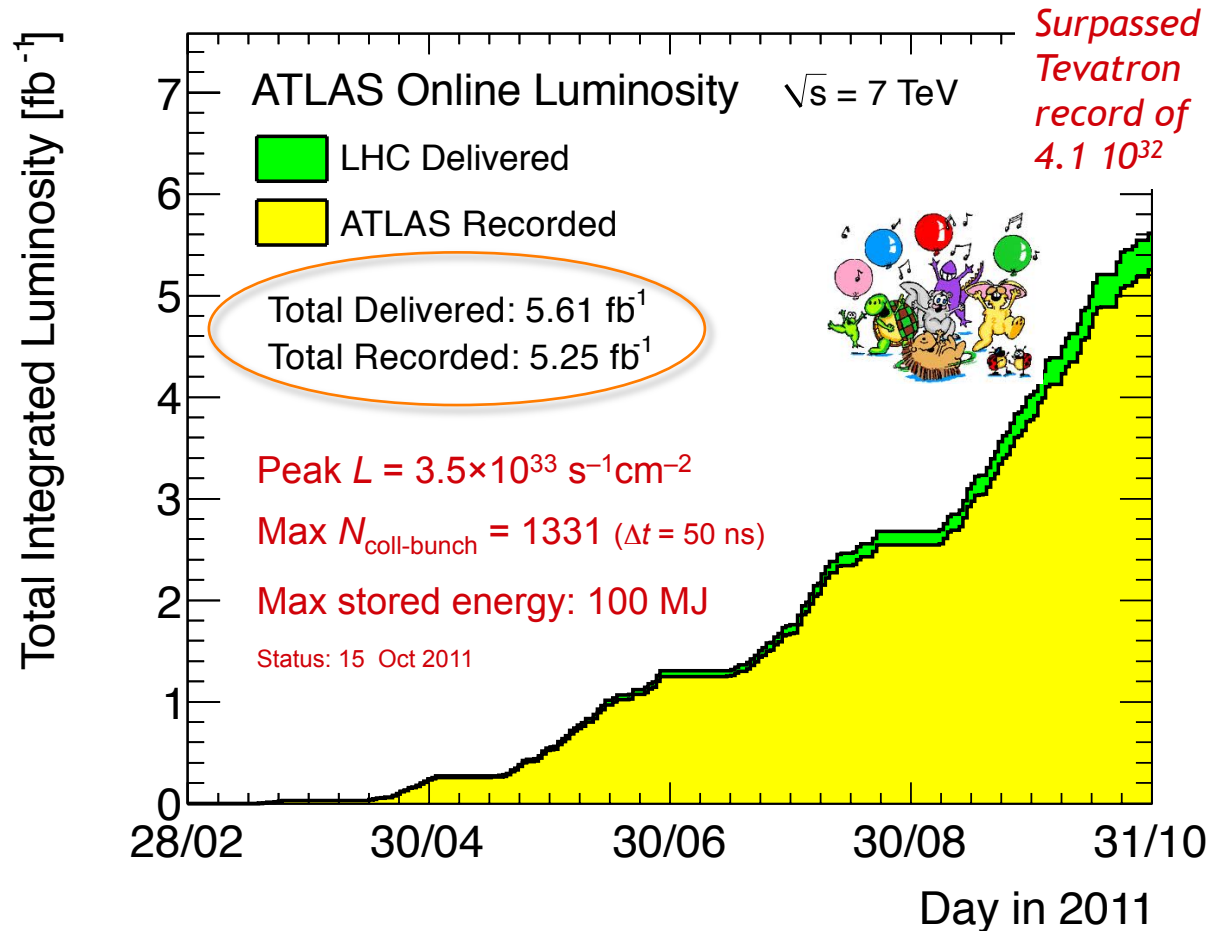


Recorded Luminosity in 2011

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) 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

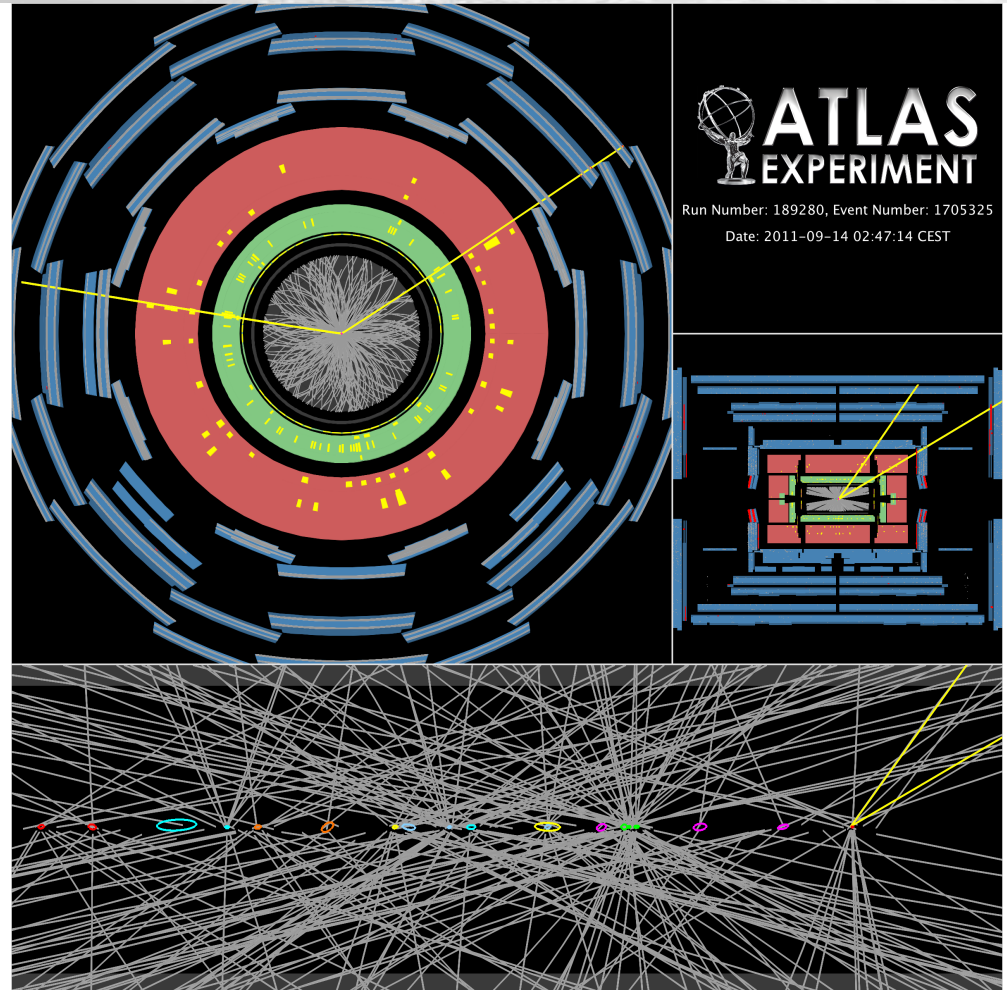
Measured with forward detectors, calibrated with beam separation scans

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

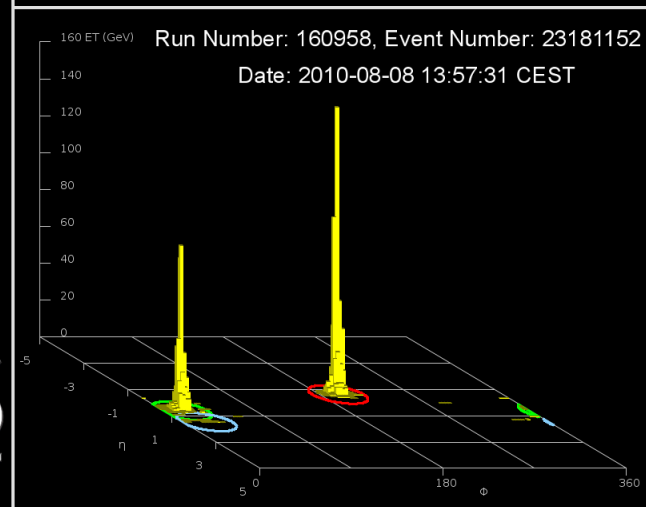
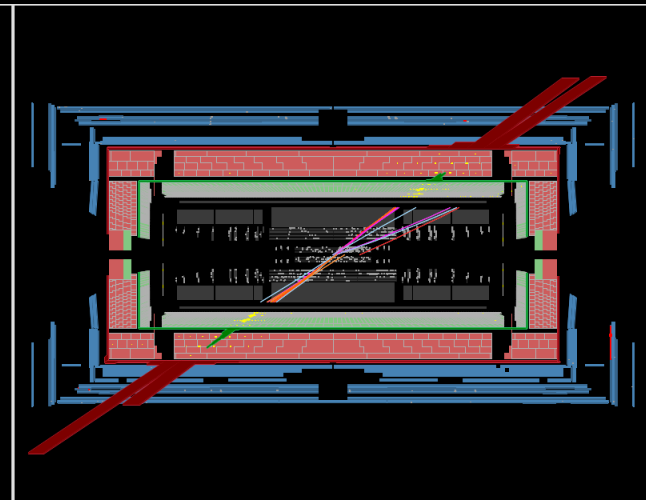
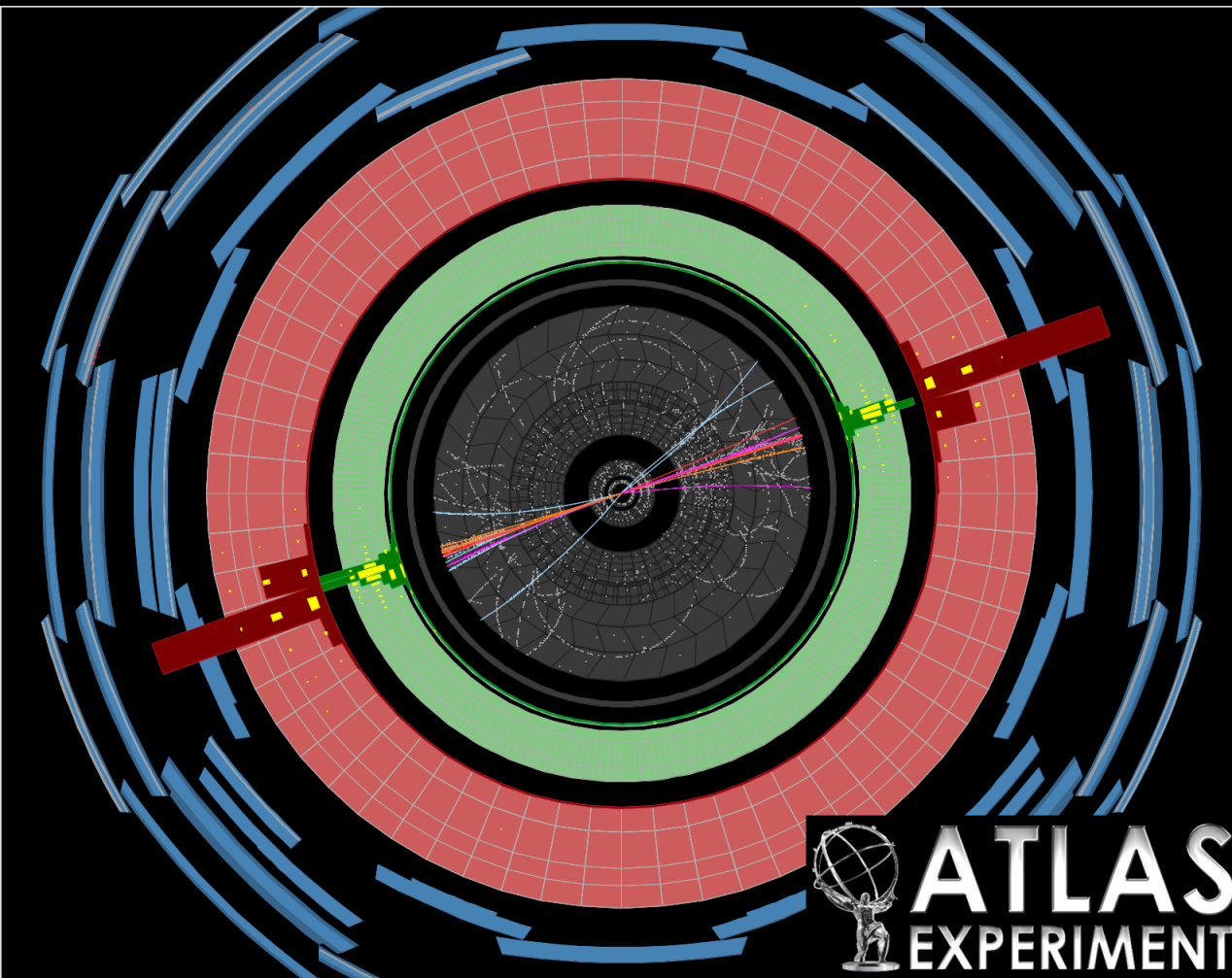
Peak of up to 22 collisions per crossing reached (almost doubled in 2012)

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

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

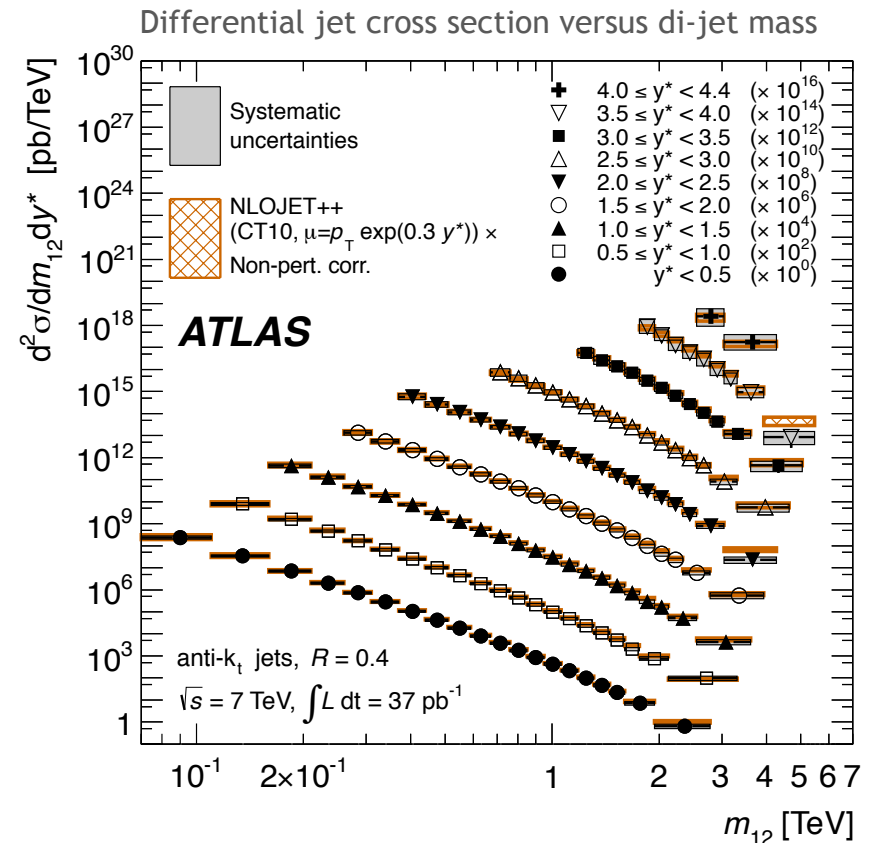
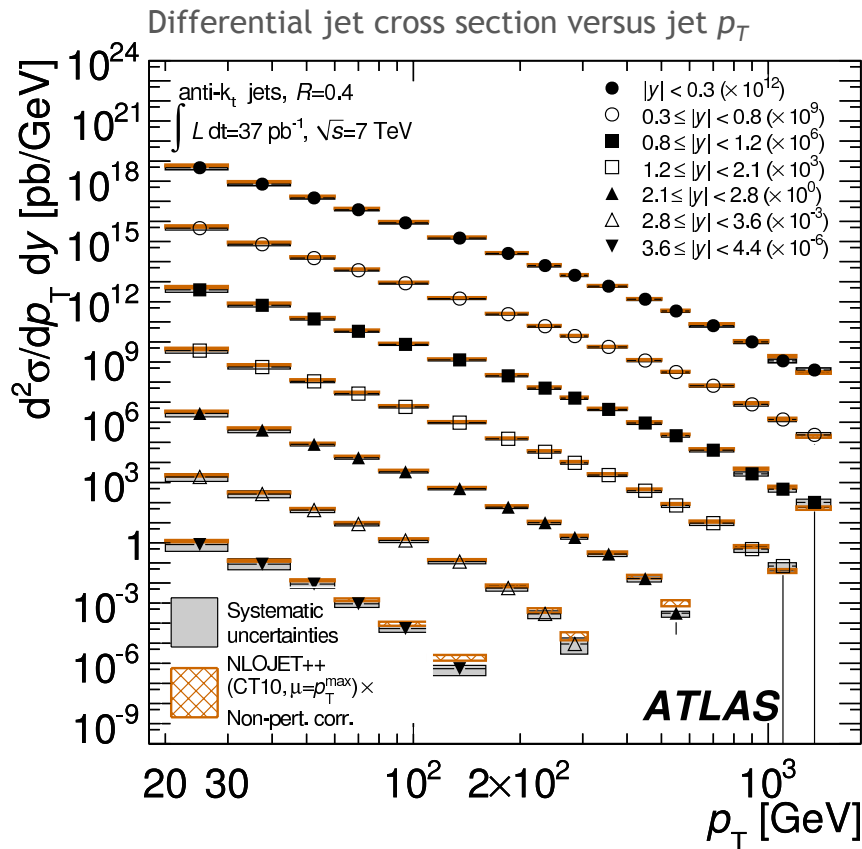


A beautiful dijet event from ATLAS: $m(\text{jet-jet}) = 1.9 \text{ TeV}$, $p_T : 0.9 \text{ TeV}, 0.8 \text{ TeV}$



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

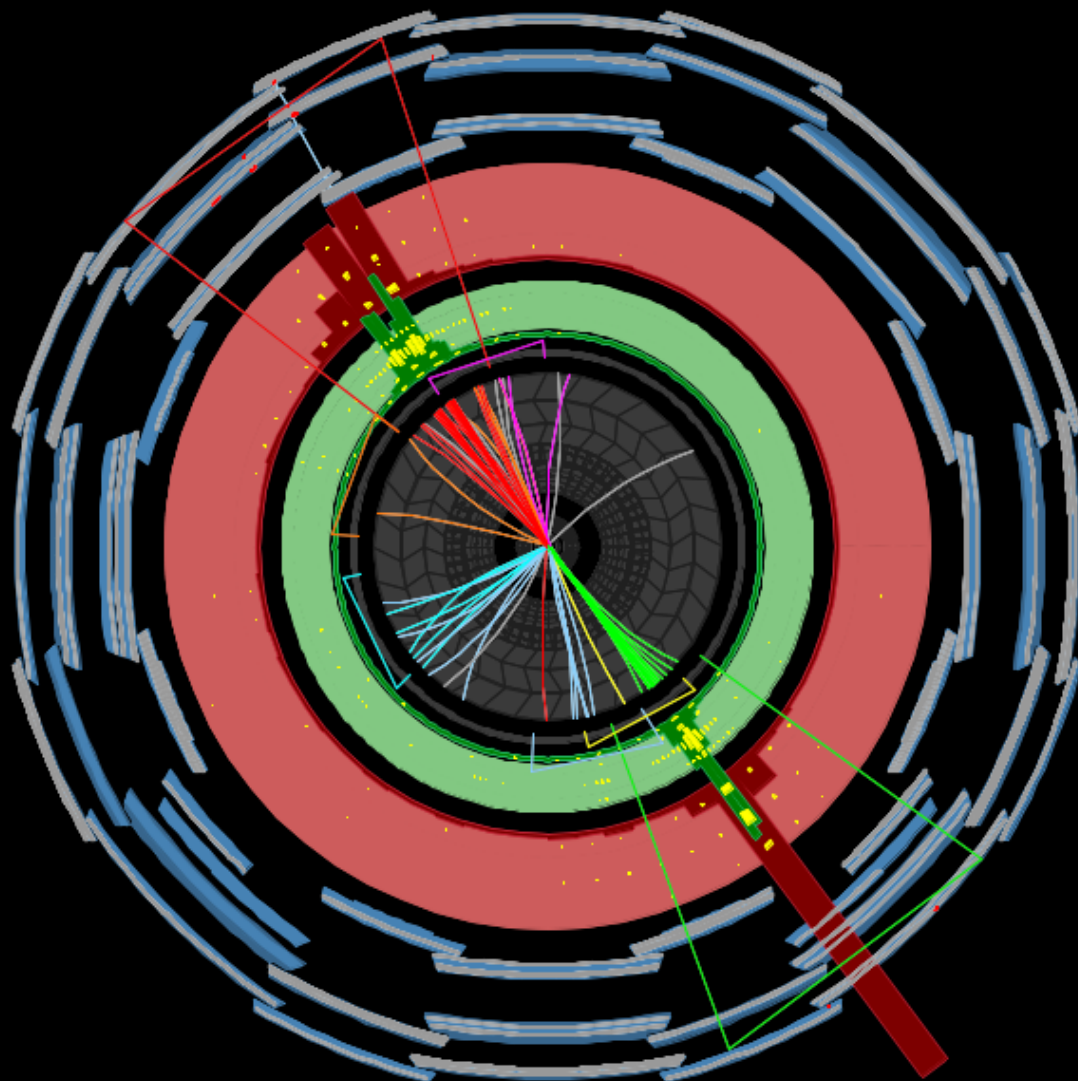
Tends to scatter at smaller angles than if there were new particles produced

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



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

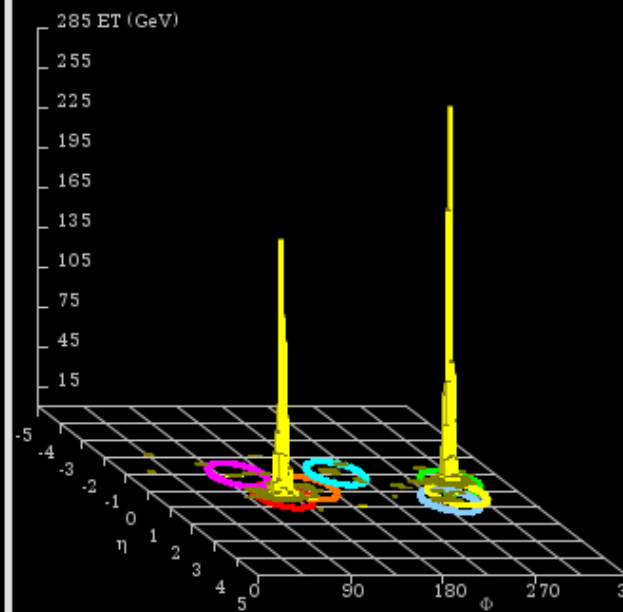
Event with 4.04 TeV dijet invariant mass



ATLAS EXPERIMENT

Run Number: 179938, Event Number: 12054480

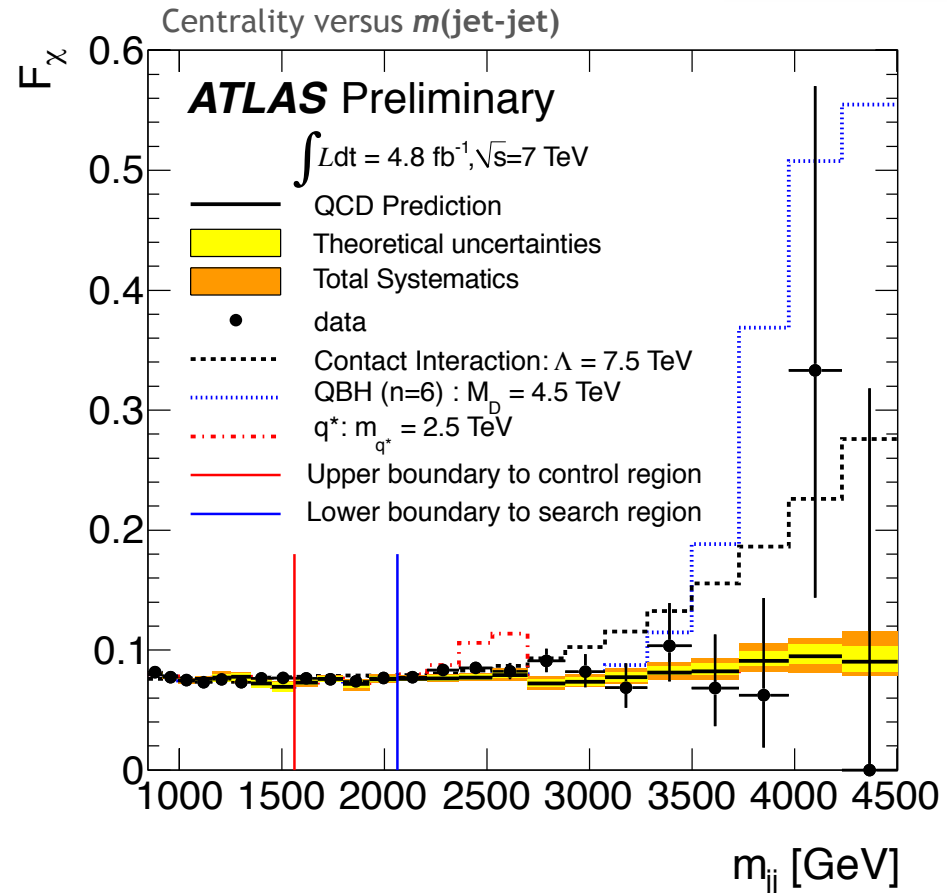
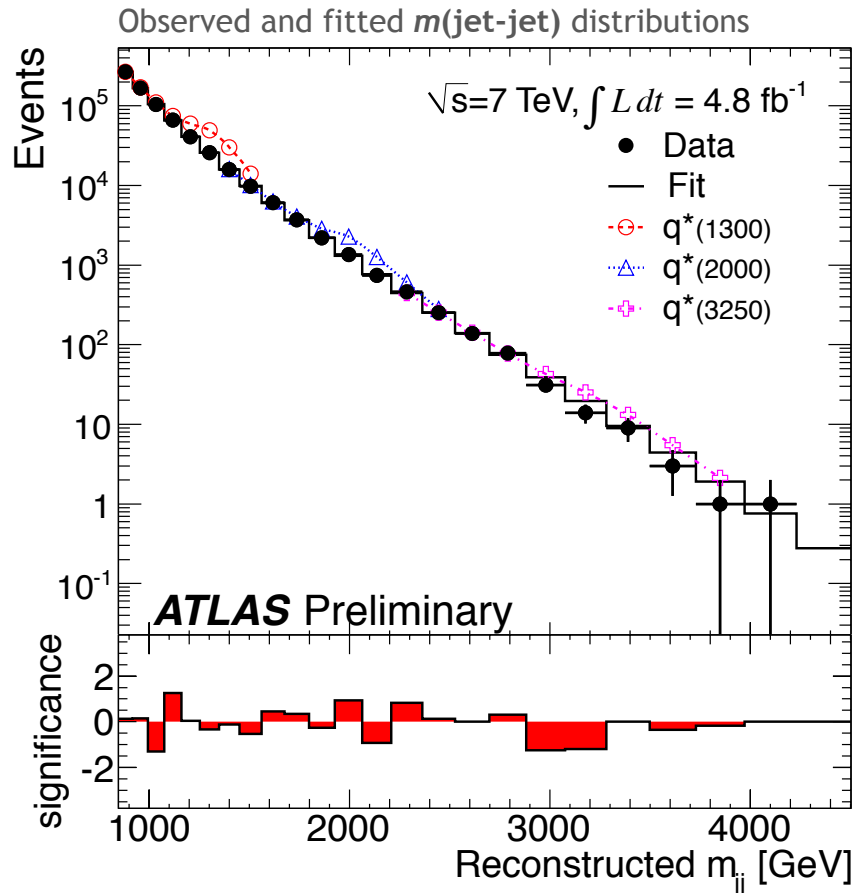
Date: 2011-04-18 17:57:29 EDT



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

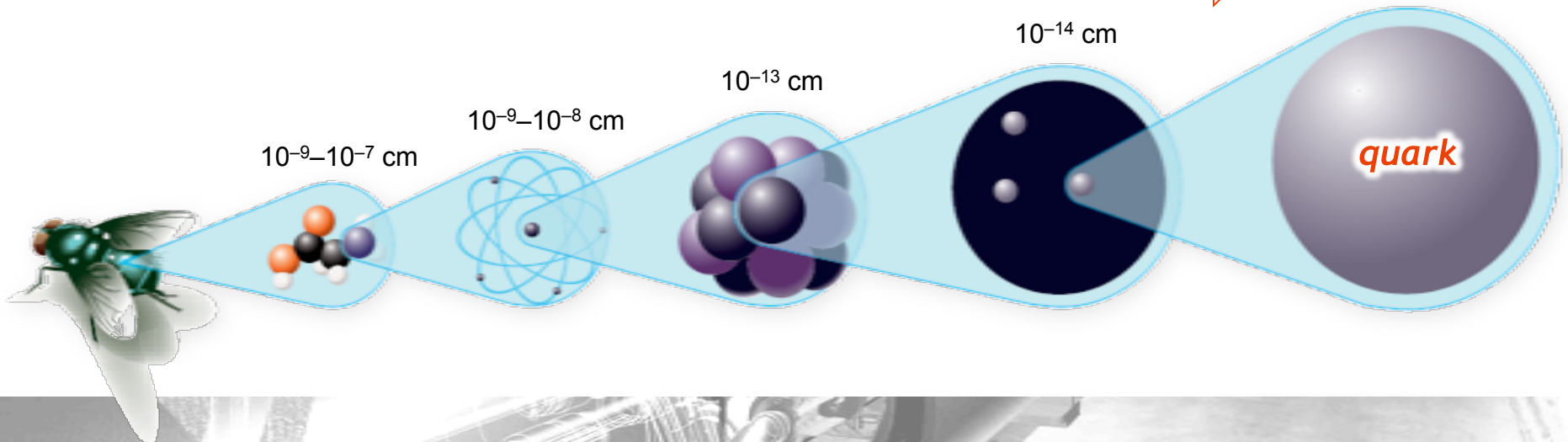
Measure di-jet invariant mass and angular distributions

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	$\Lambda > 7.8 \text{ TeV}$

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



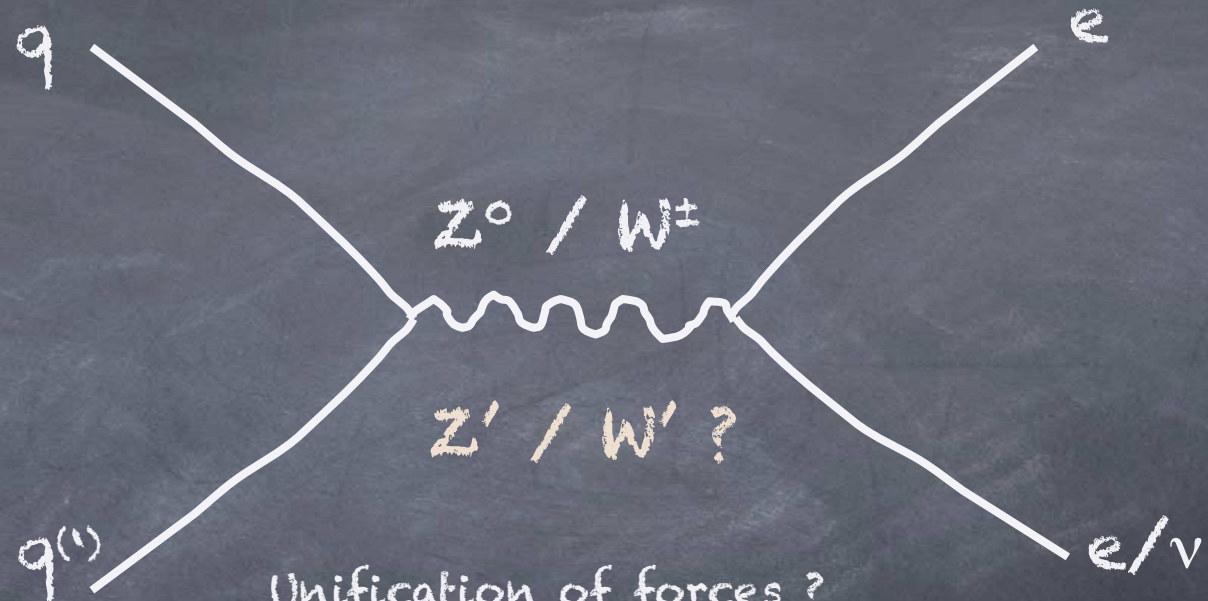
Leptons are pure SM and new physics probes with much reduced strong-interactions background

Z and W bosons have mass of $O(100)$ GeV

Created from quark initial states and decay to charged leptons and (undetected) neutrinos

Z and W are heaviest known resonances producing lepton pairs.

Many theories predict new heavy Z / W bosons with similar properties



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

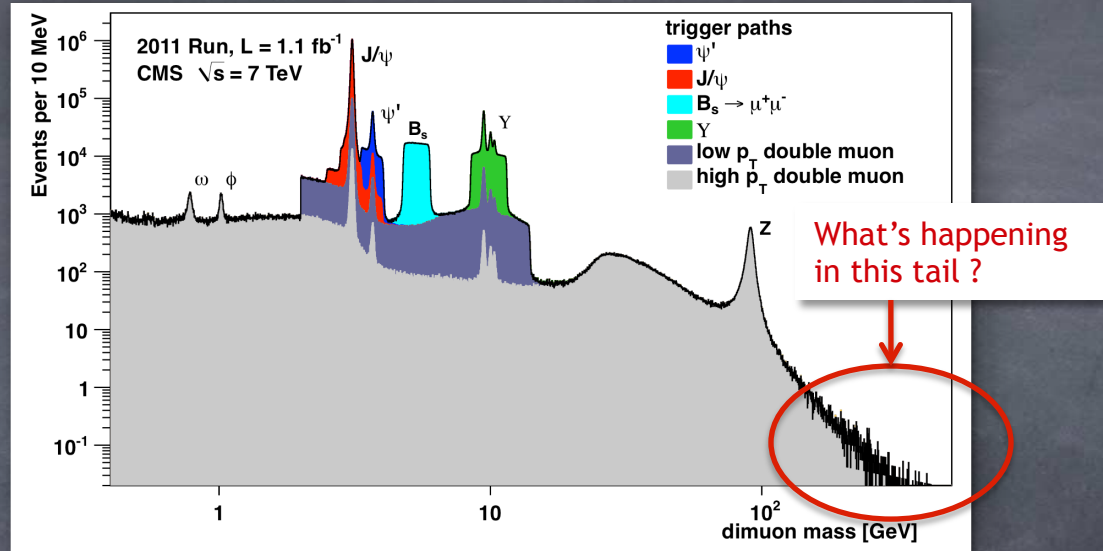
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Z and W are heaviest known resonances producing lepton pairs.

Many theories predict new heavy Z / W bosons with similar properties



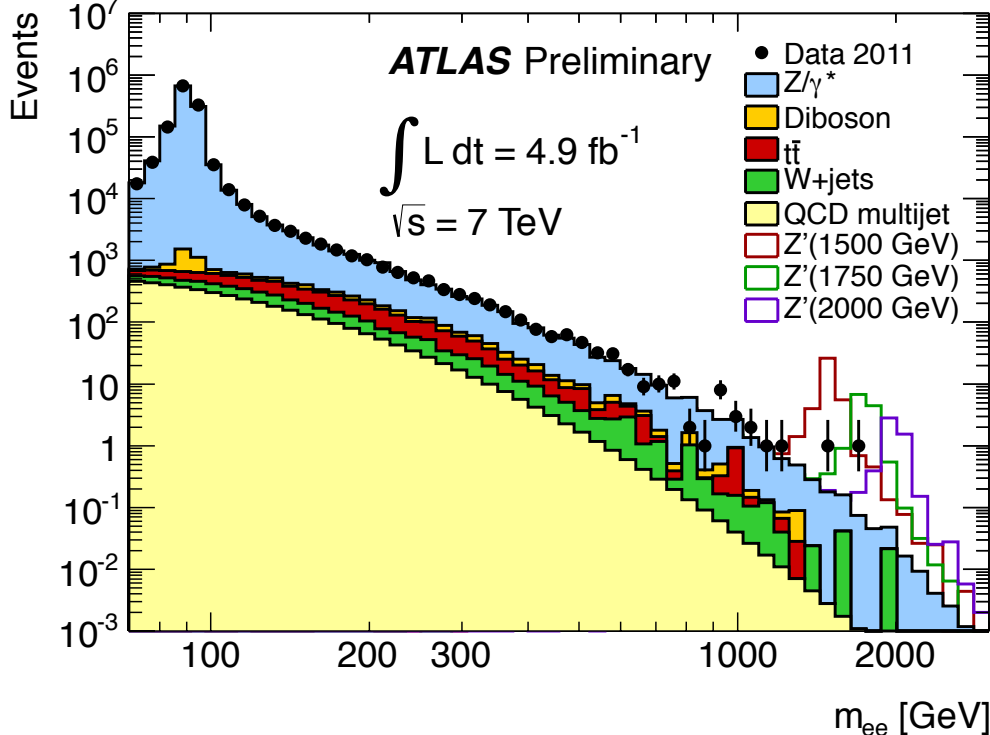
Unification of forces ?
Left-right symmetric models ?
Compact extra dimensions ?
Technicolour ?
Higgs extensions ?

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

Use dilepton / transverse mass to search for excess over SM

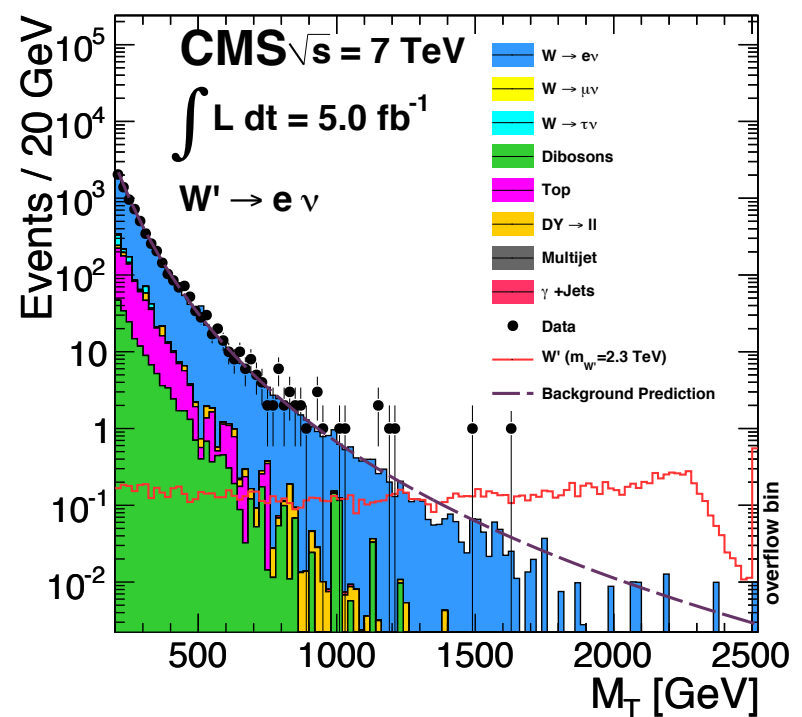
ATLAS-CONF-2012-007, CMS arXiv:1204.4764

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



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

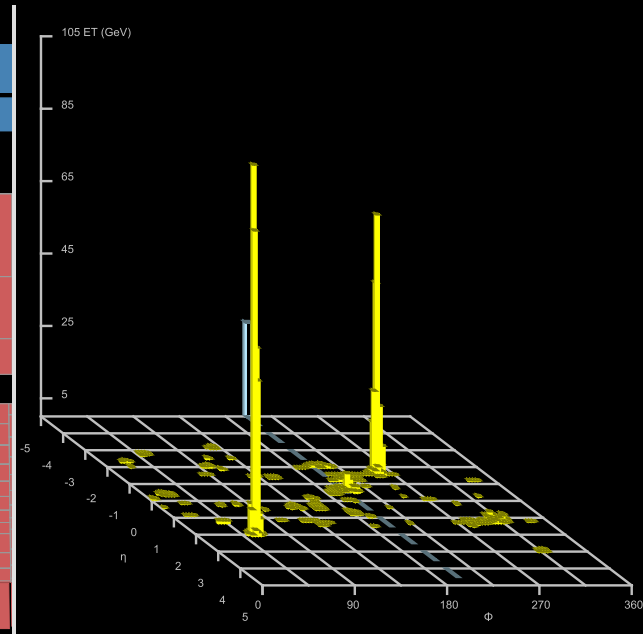
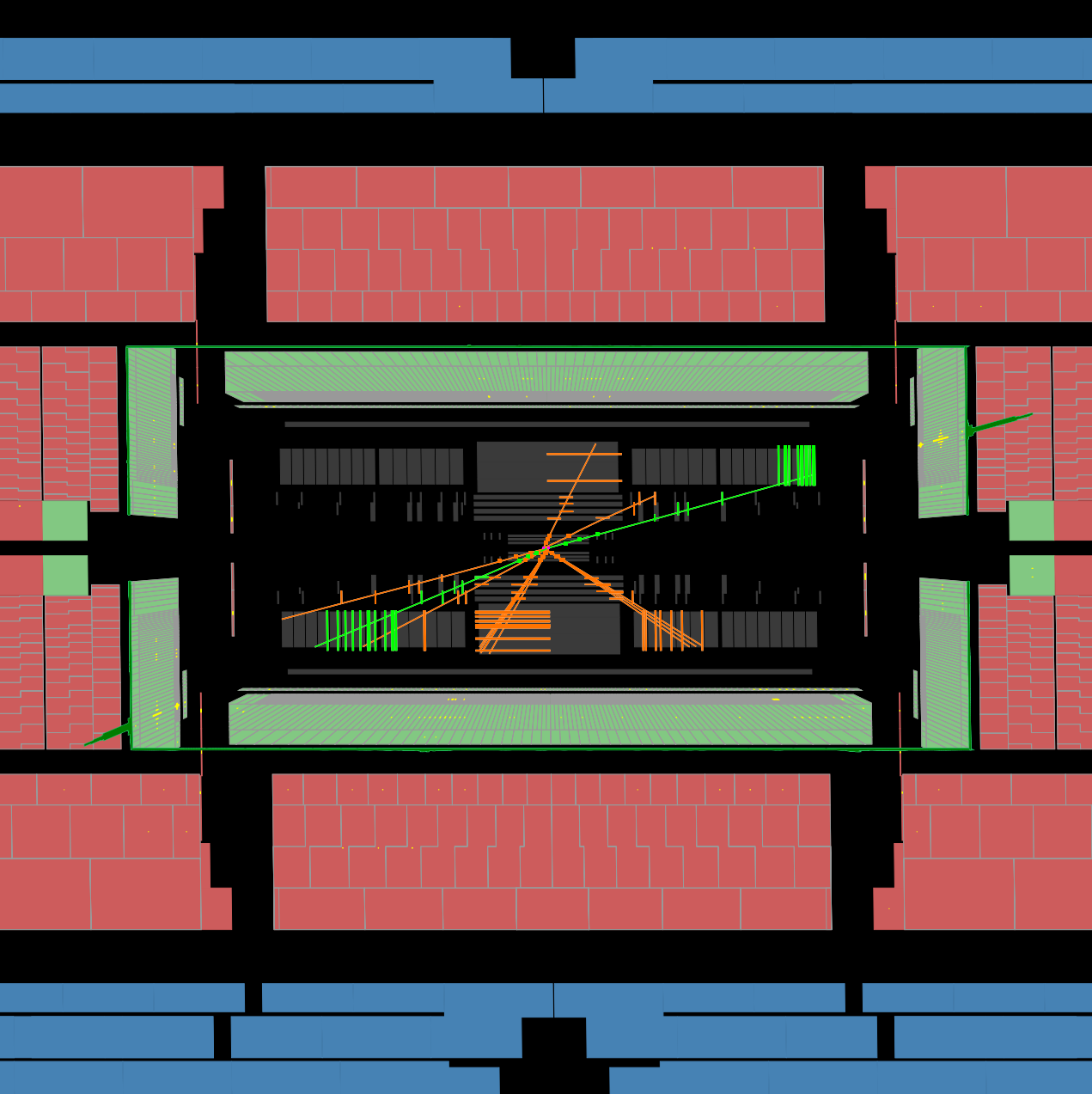
Observed and predicted e - n transverse mass



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

^(*)Constructive interference model

Highest mass dielectron event observed: $m(ee) = 1.66$ TeV (both electrons are in calorimeter endcaps)

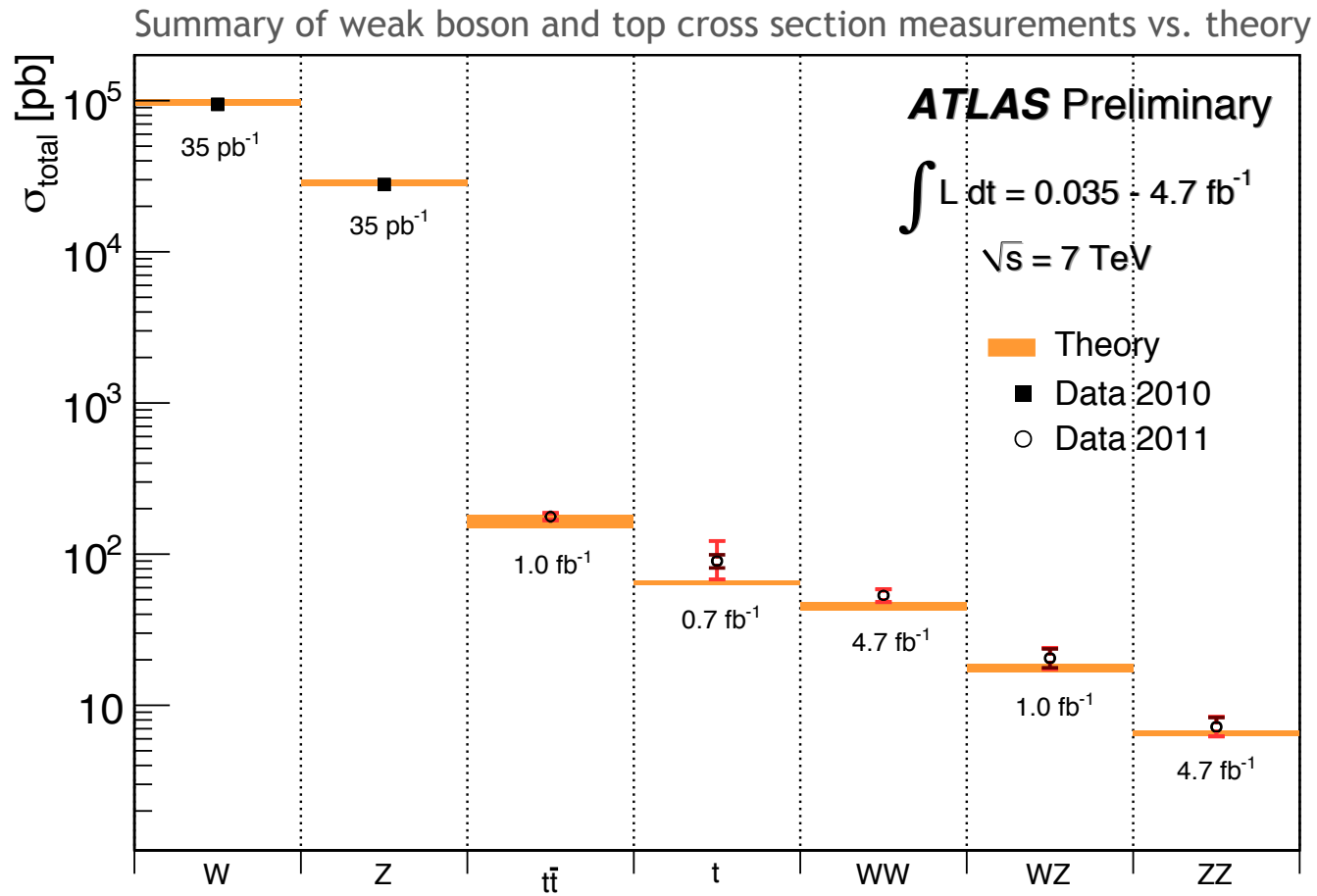


Run Number: 190300, Event Number: 75300042

Date: 2011-10-04 05:39:53 UTC

Electroweak and QCD measurements

Lots of truly novel results at unexplored centre-of-mass energies



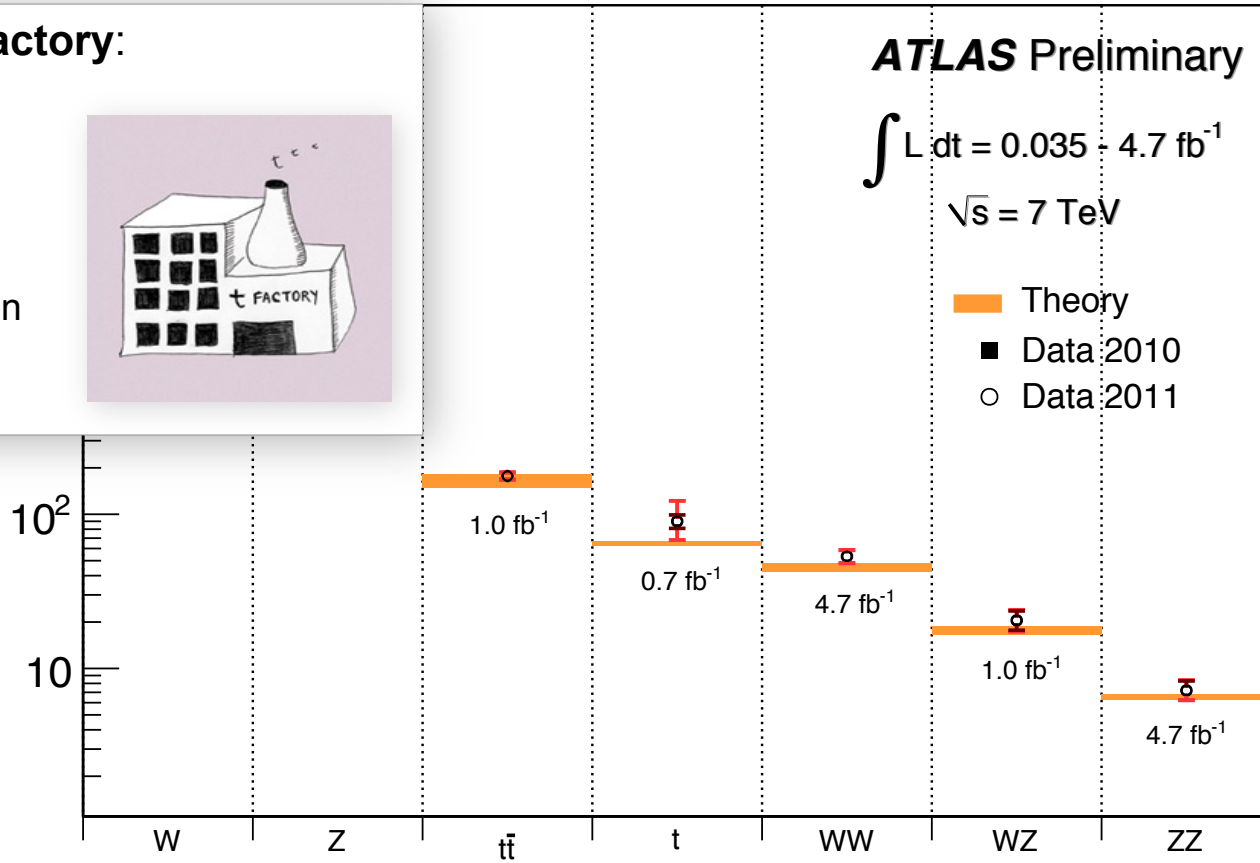
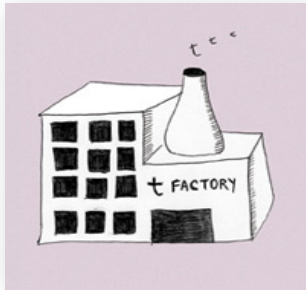
Electroweak and QCD measurements

Lots of truly novel results at unexplored centre-of-mass energies

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

LHC is **top** factory:

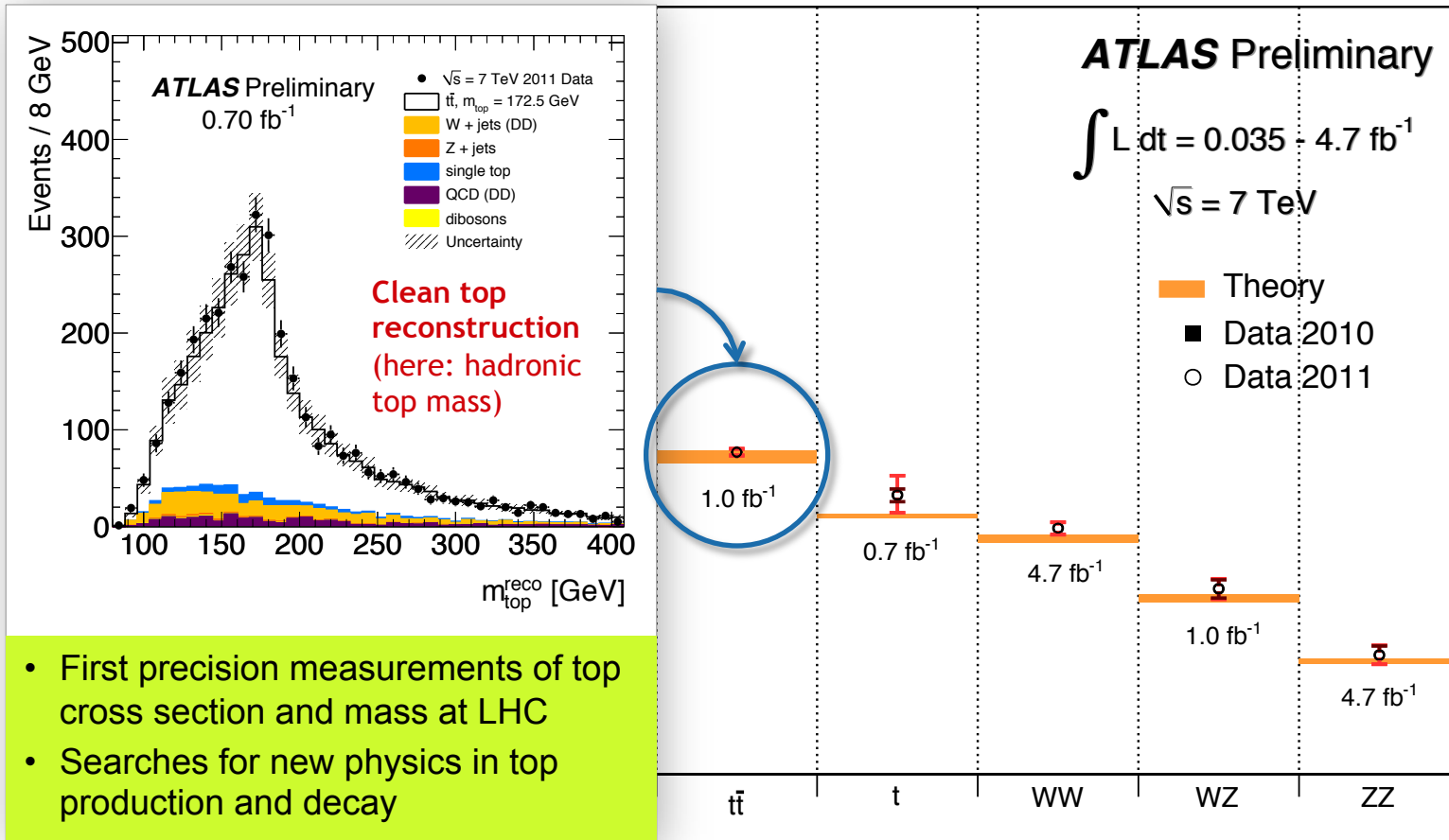
at 7 TeV CM
energy: ~25
times larger
cross section
than at Tevatron



Electroweak and QCD measurements

Lots of truly novel results at unexplored centre-of-mass energies

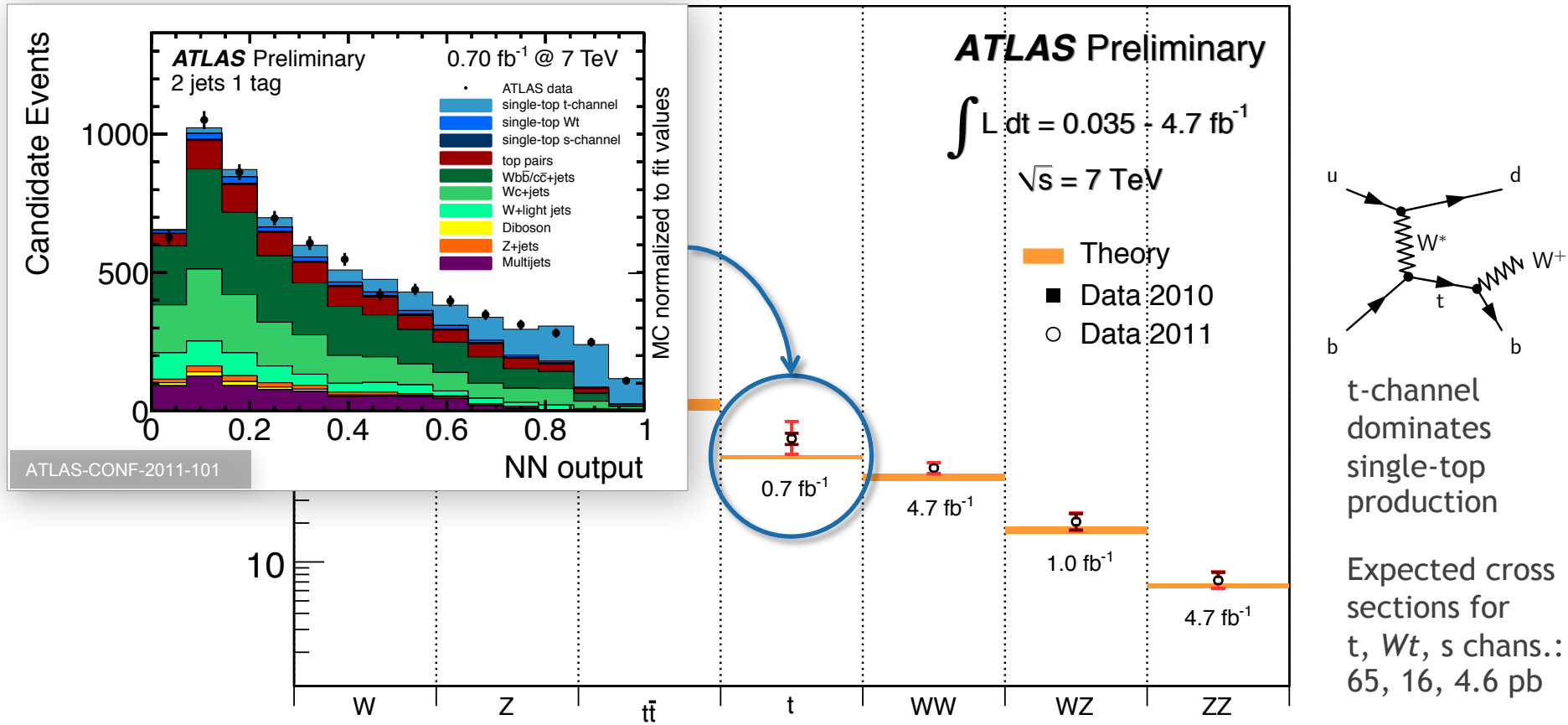
Summary of weak boson and top cross section measurements vs. theory



Electroweak and QCD measurements

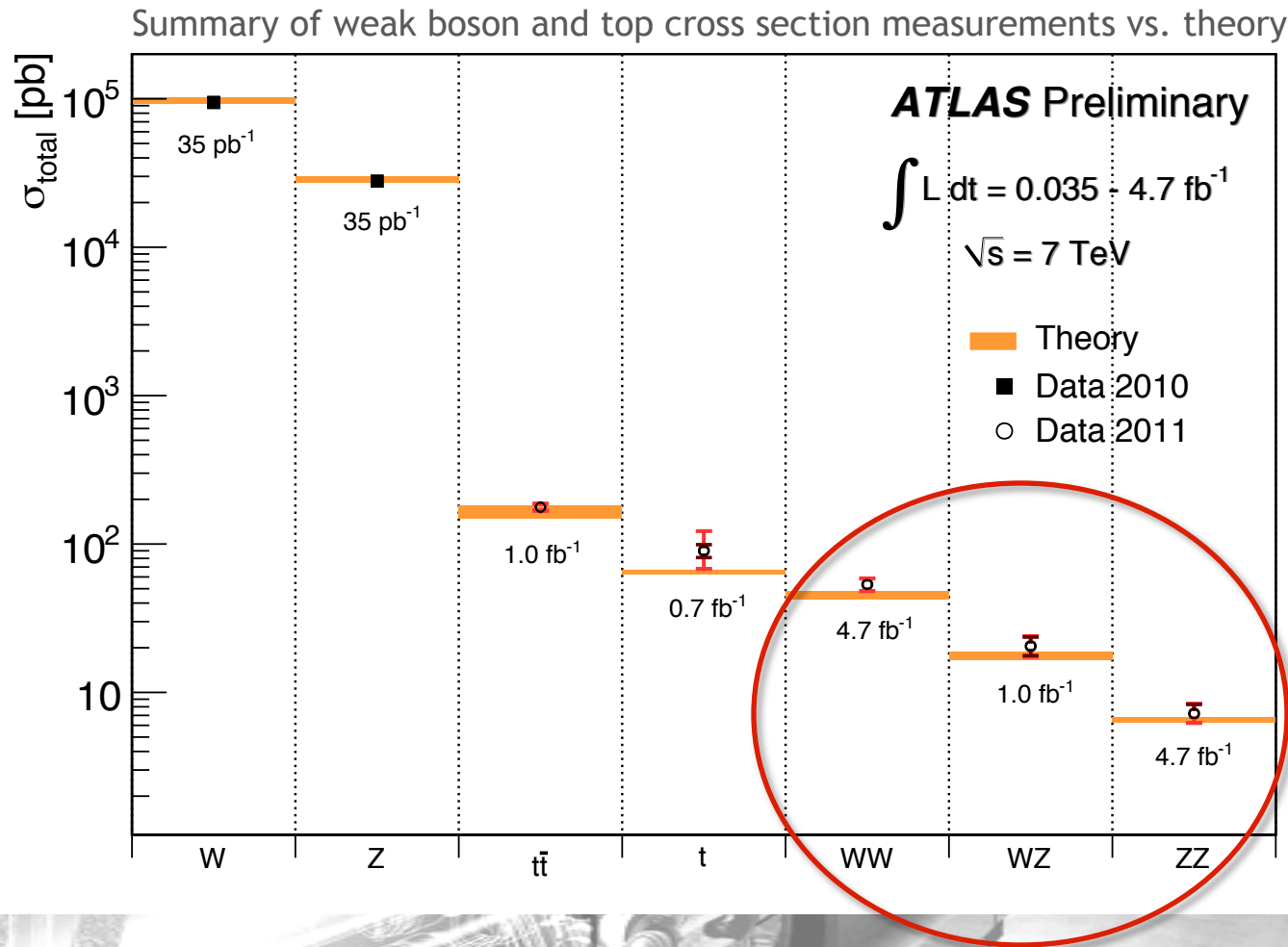
Lots of truly novel results at unexplored centre-of-mass energies

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



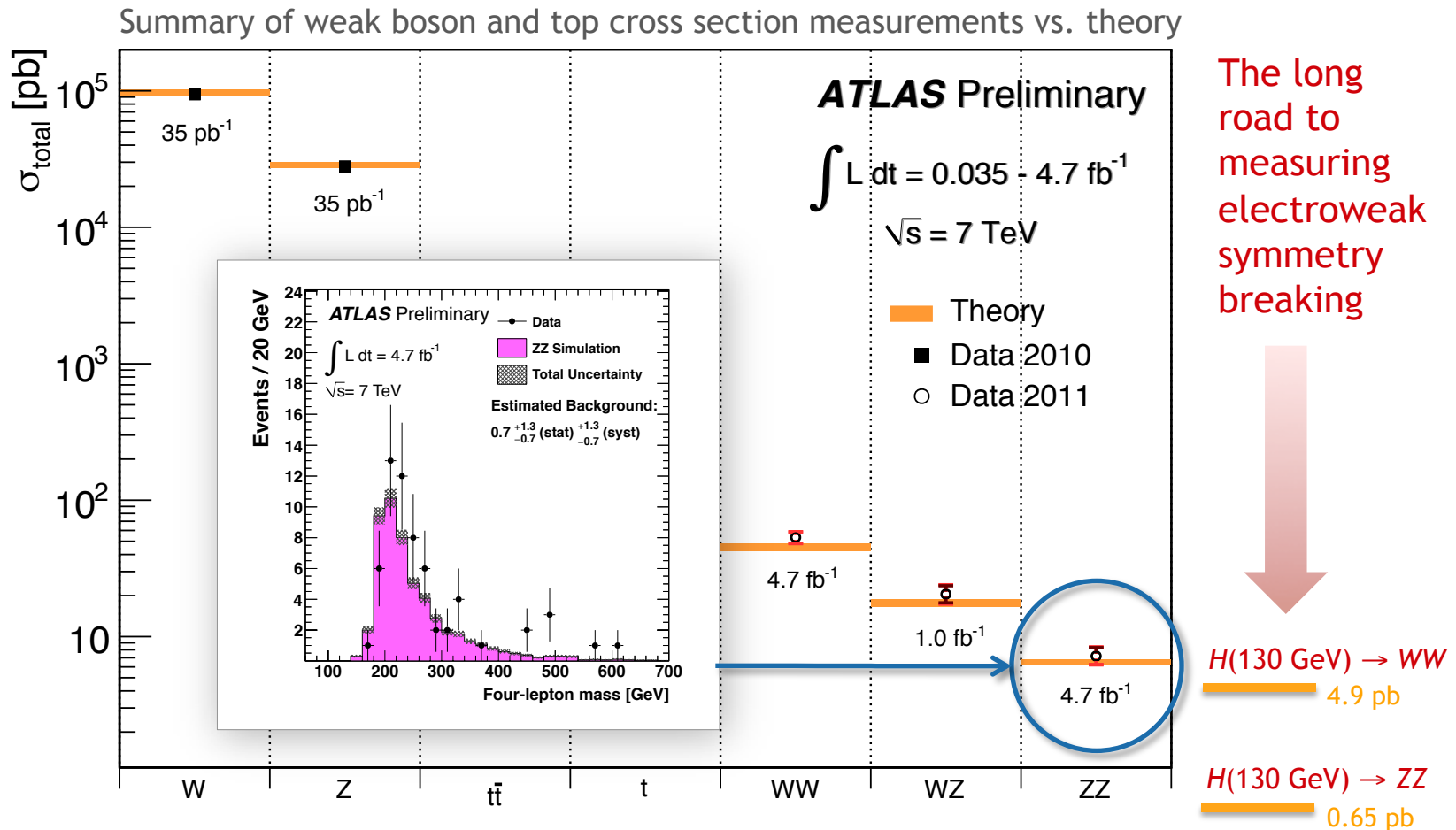
Electroweak and QCD measurements

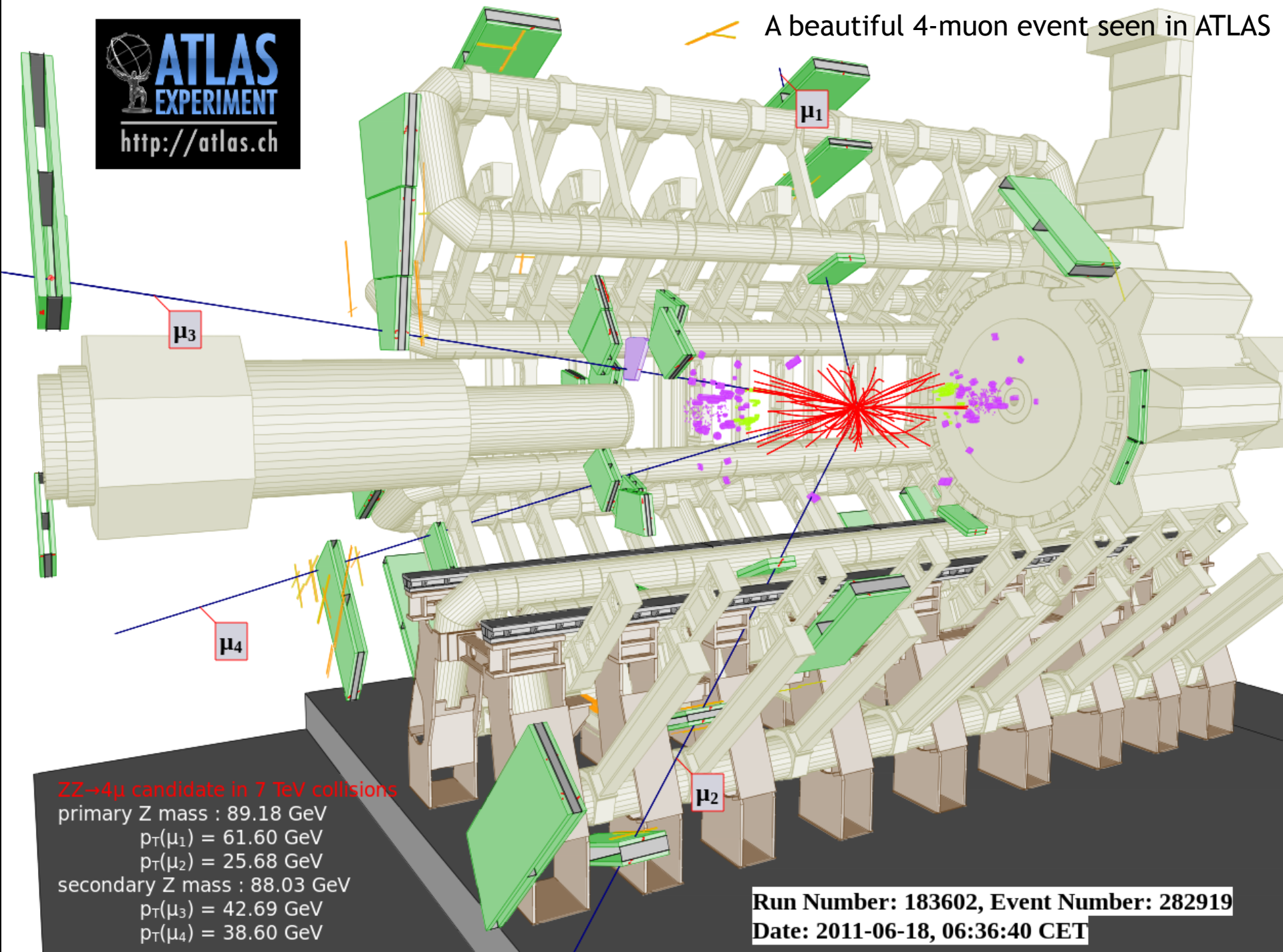
Lots of truly novel results at unexplored centre-of-mass energies



Electroweak and QCD measurements

Lots of truly novel results at unexplored centre-of-mass energies





$ZZ \rightarrow 4\mu$ 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

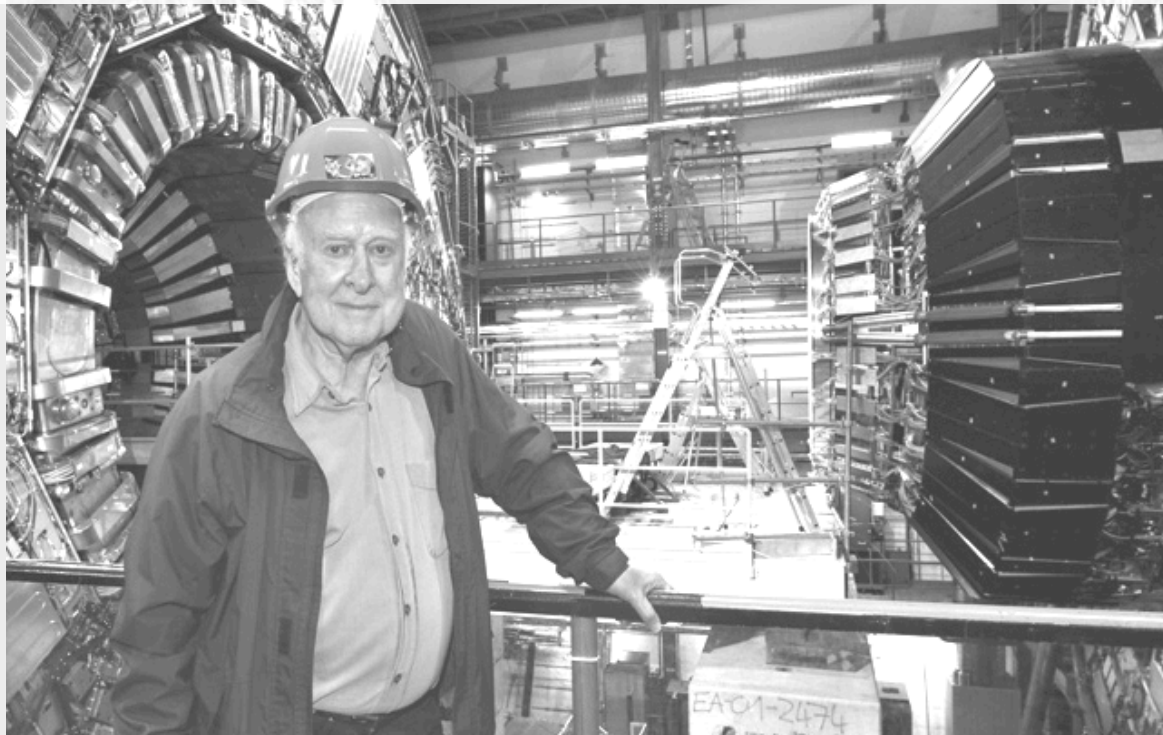
$p_T(\mu_3) = 42.69$ GeV

$p_T(\mu_4) = 38.60$ GeV

Run Number: 183602, Event Number: 282919

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

Hunting for the Higgs Boson



P. Higgs at CMS

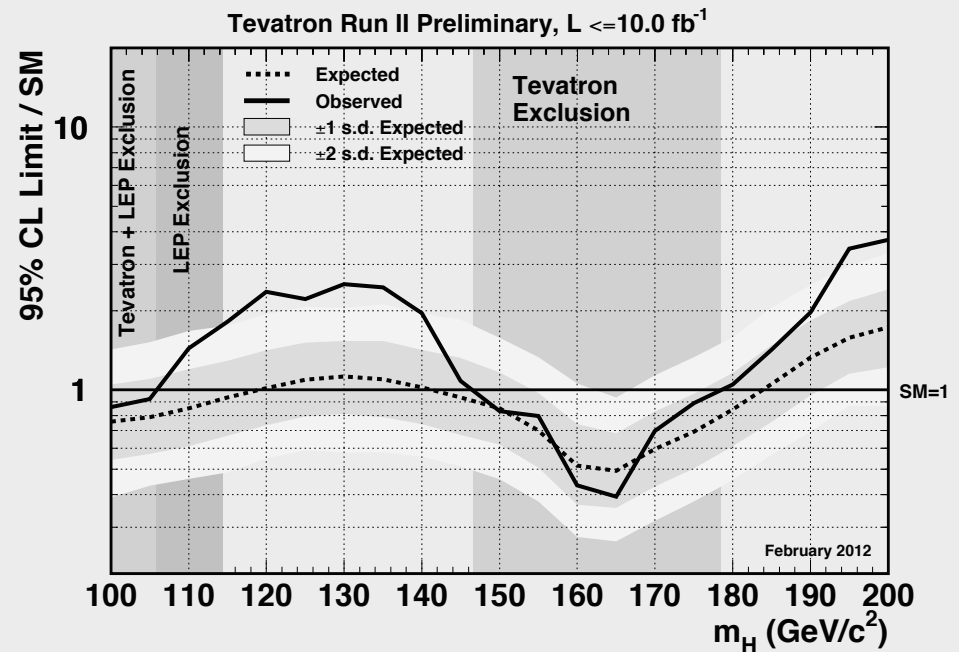
Hunting for the Higgs Boson

The Higgs boson has been vainly searched for at many accelerators

Best non-LHC 95% CL limits from LEP (CERN, 1989–2000) and Tevatron (Fermilab, 1990–2011):

$$m_H > 114 \text{ GeV}$$

$$147 \text{ GeV} < m_H < 179 \text{ GeV}$$



Higgs boson

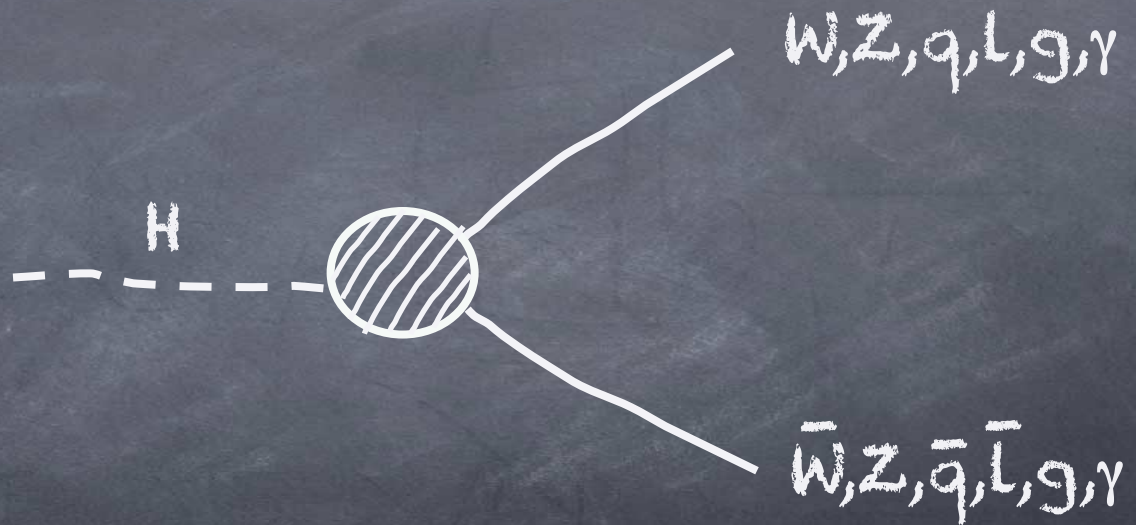
Higgs production and decay probabilities predicted vs. Higgs mass by SM

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:

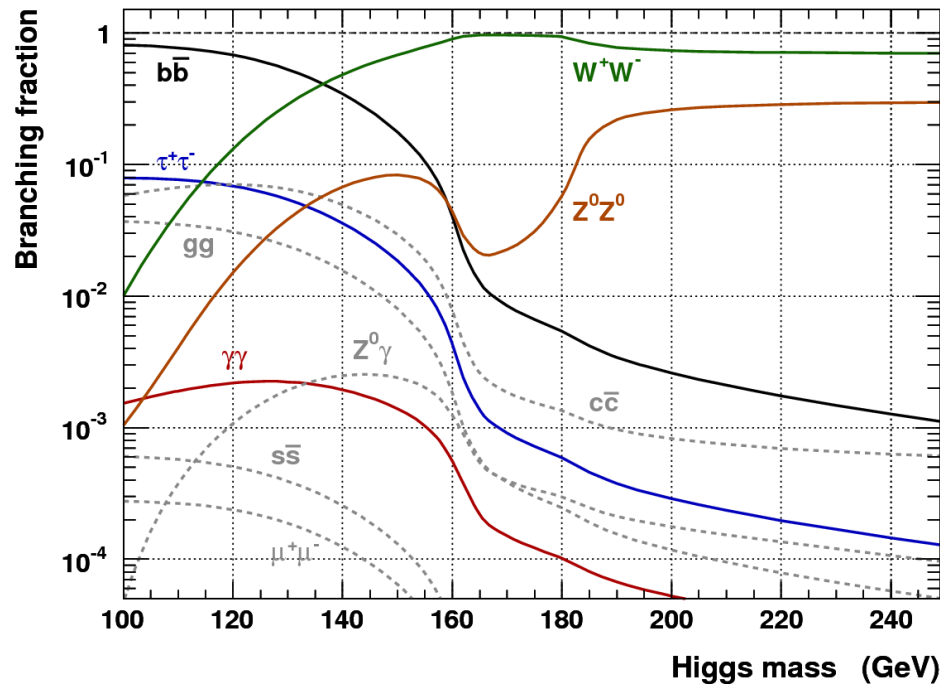
... the Higgs will decay with preference to the heaviest particles allowed

... 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 $WW^{(*)}$, $ZZ^{(*)}$

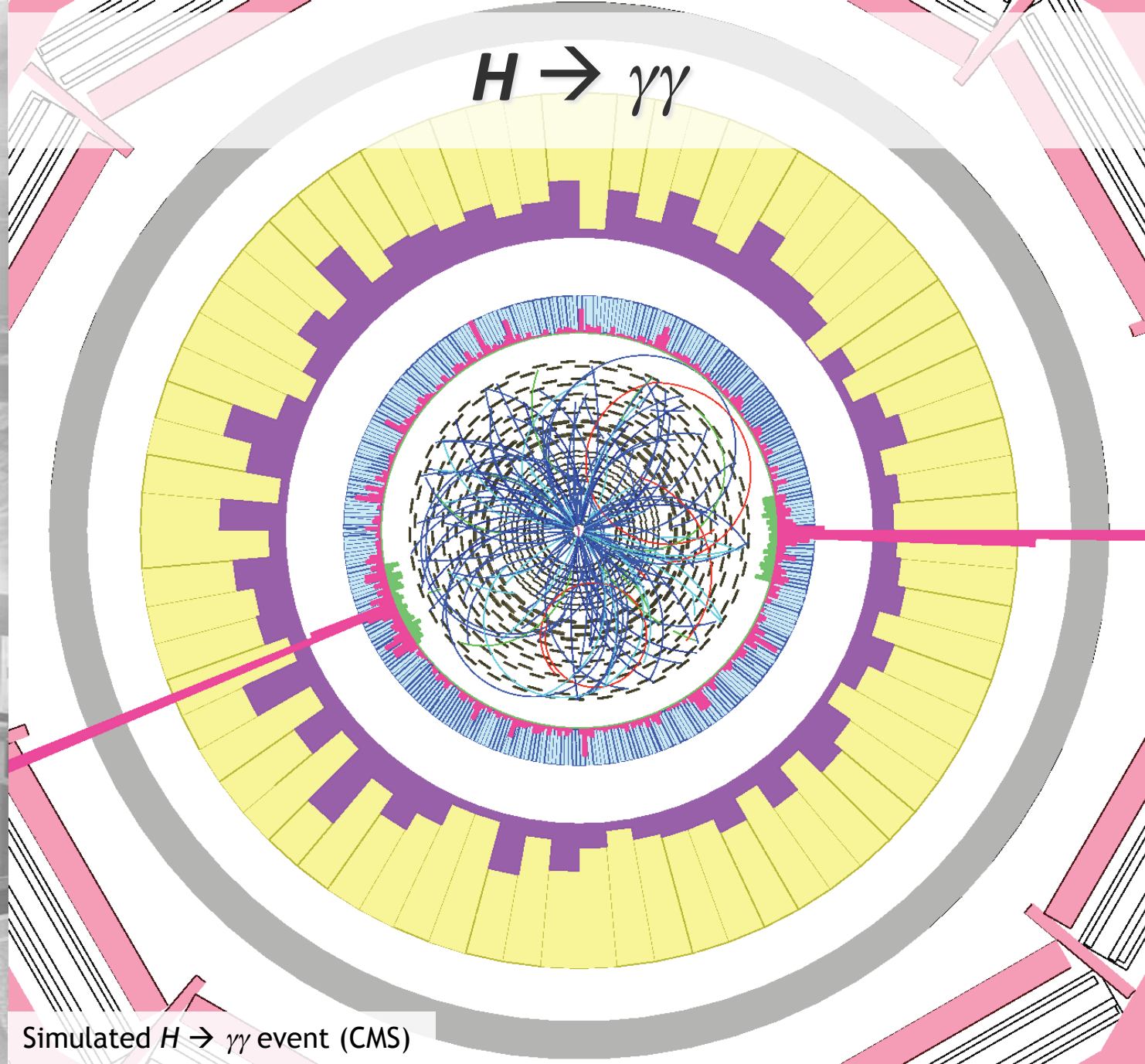
For **light Higgs**:

- 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, $s(bb) \sim \mathcal{O}(100 \mu\text{b})$

$$H \rightarrow \gamma\gamma$$



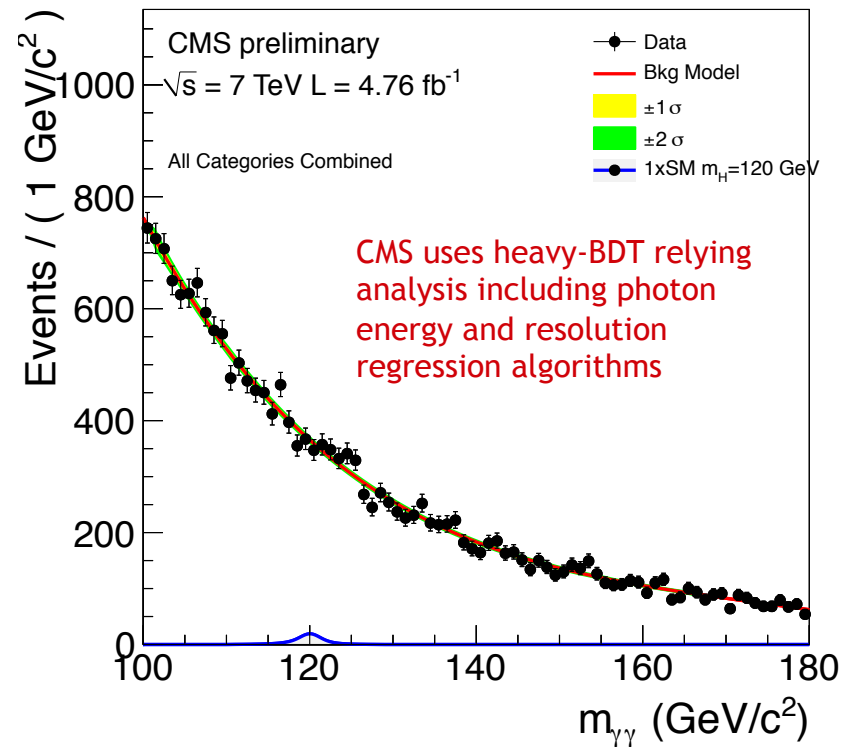
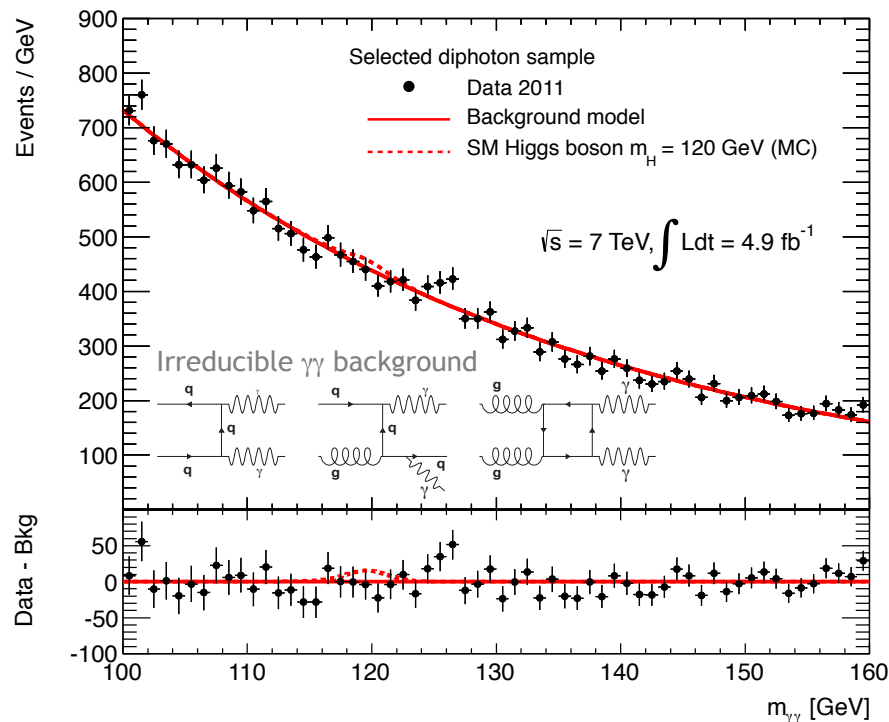
Simulated $H \rightarrow \gamma\gamma$ event (CMS)

$H \rightarrow \gamma\gamma$: clean discovery channel for light Higgs

$\sigma \times \text{BR}$ (115 / 140 GeV | $\sqrt{s}=7$ TeV) $\approx$ 48 / 28 fb

ATLAS arXiv:1202.1414, CMS-PAS-HIG-12-001

Signal selection: need excellent photon energy resolution, and efficient & pure photon identification



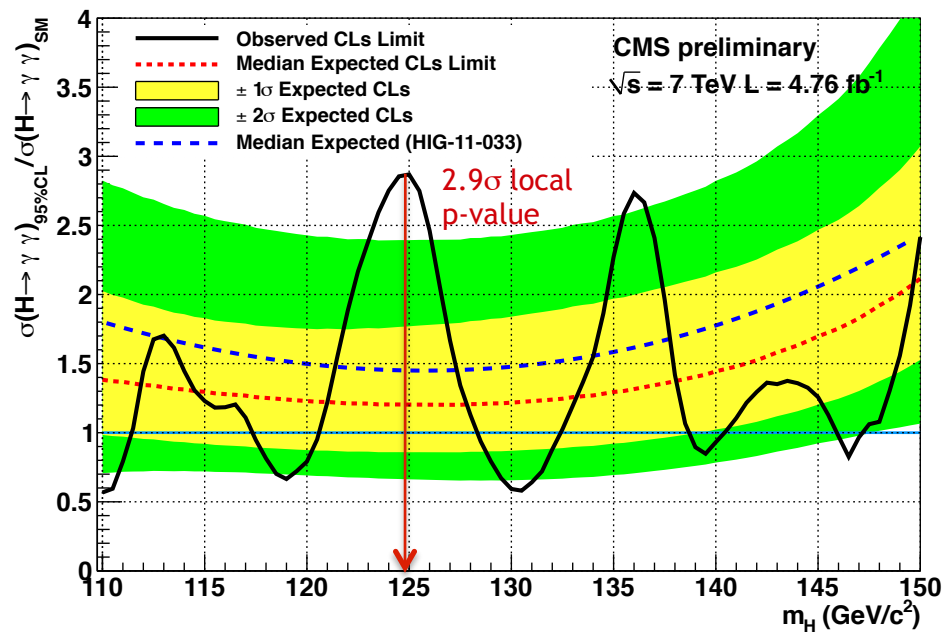
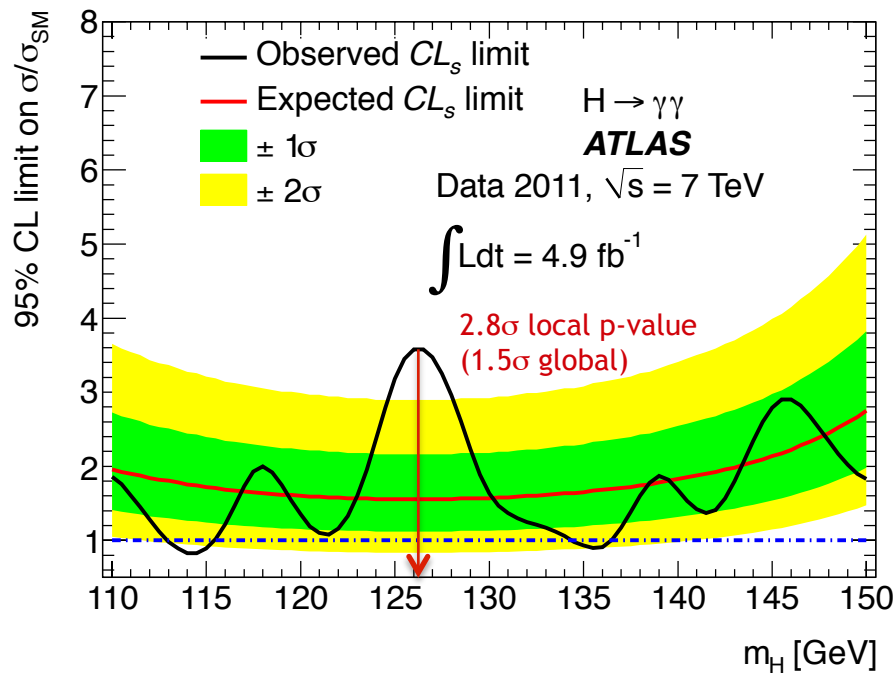
Both expts. classify events according to resolution and topology in ML fit

$H \rightarrow \gamma\gamma$: clean discovery channel for light Higgs

$\sigma \times \text{BR}$ (115 / 140 GeV | $\sqrt{s}=7$ TeV) $\approx$ 48 / 28 fb

ATLAS arXiv:1202.1414, CMS-PAS-HIG-12-001

Signal selection: need excellent photon energy resolution, and efficient & pure photon identification



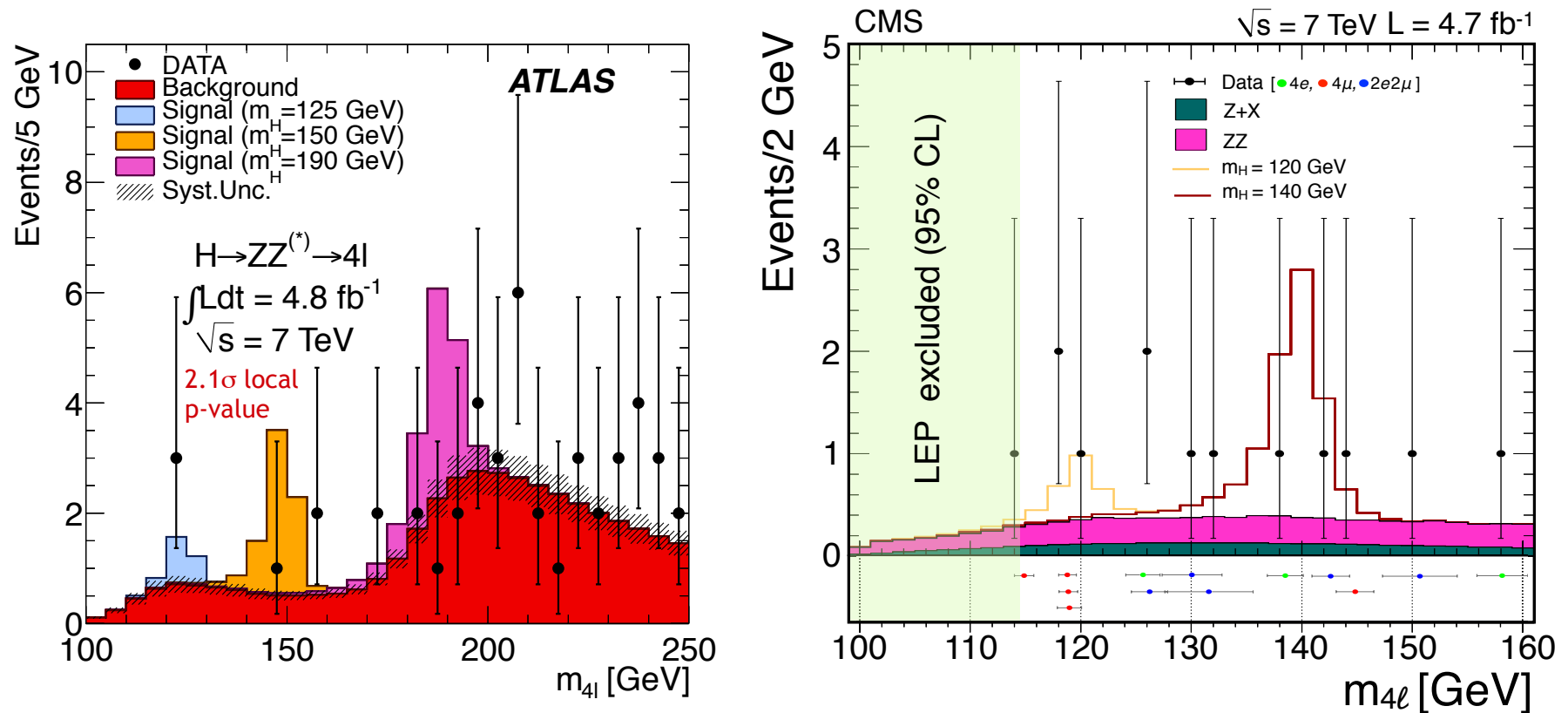
Data excesses around 125 GeV seen in both experiments; large look elsewhere effect because of good diphoton mass resolution

$H \rightarrow ZZ^{(*)} \rightarrow 2(e, \mu) + 2(e, \mu) : \text{“golden channel”}$

$\sigma \times \text{BR} (120 / 140 / 200 \text{ GeV} \mid \sqrt{s}=7 \text{ TeV}) \approx 1.3 / 4.2 / 6.8 \text{ fb}$

ATLAS arXiv:1202.1415, CMS arXiv:1202.1997

Signal selection: precisely reconstruct mass of Higgs from 4 leptons, exploit on-shell Z mass constraint

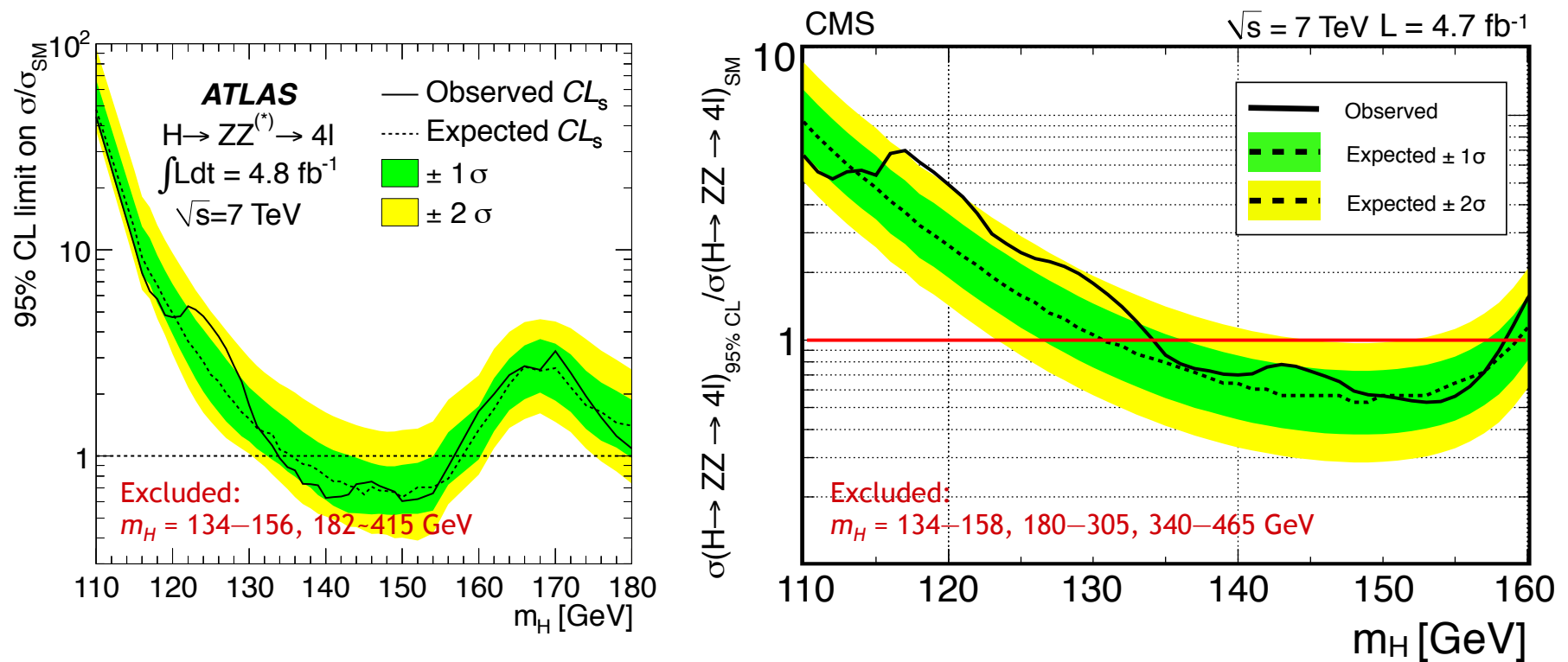


$H \rightarrow ZZ^{(*)} \rightarrow 2(e, \mu) + 2(e, \mu) : \text{“golden channel”}$

$\sigma \times \text{BR} (120 / 140 / 200 \text{ GeV} \mid \sqrt{s}=7 \text{ TeV}) \approx 1.3 / 4.2 / 6.8 \text{ fb}$

ATLAS arXiv:1109.5945, CMS-PAS-HIG-11-015

Signal selection: precisely reconstruct mass of Higgs from 4 leptons, exploit on-shell Z mass constraint



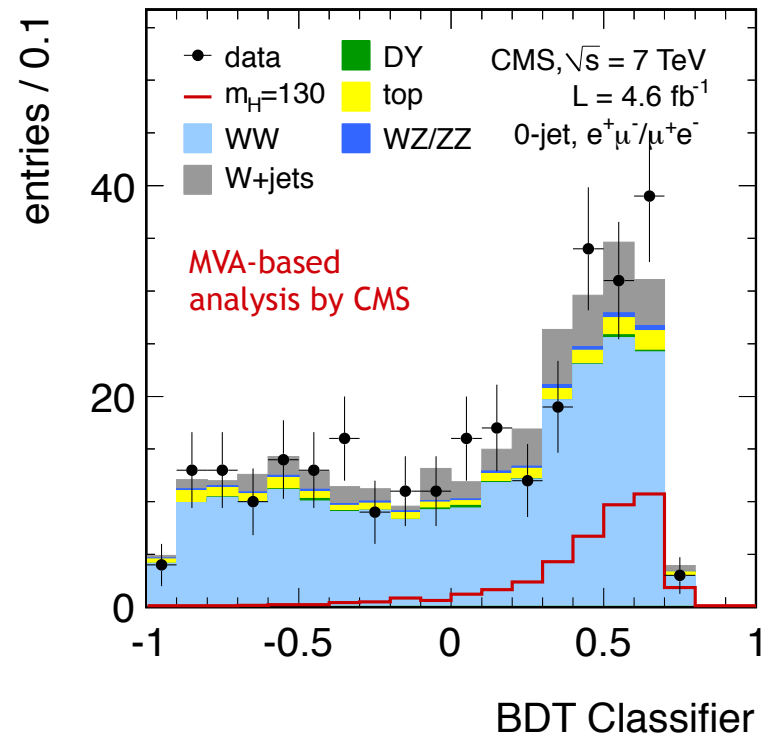
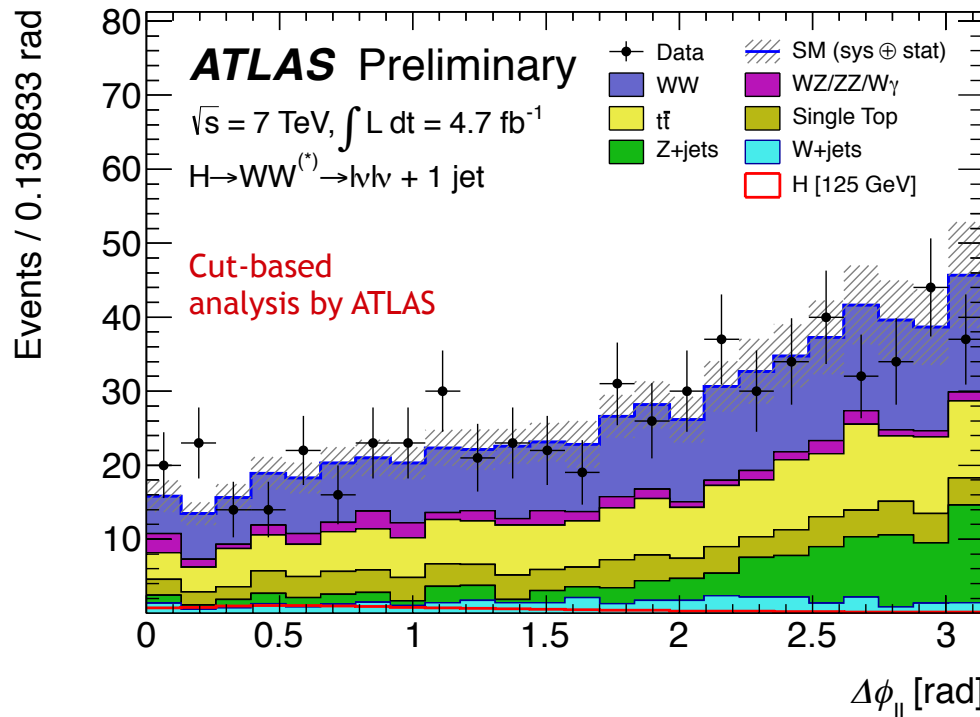
Non-concluding low-mass excesses; accidental coincidence in ALTAS ?

$H \rightarrow WW^{(*)} \rightarrow 2(e, \mu) + 2\nu$: not clean, but abundant

$\sigma \times \text{BR}$ (120 / 165 / 200 GeV | $\sqrt{s}=7$ TeV) $\approx$ 120 / 400 / 200 fb

ATLAS-CONF-2012-012, CMS arXiv:1202.1489

Signal selection: reconstruct transverse Higgs mass, exploit W polarisation (leptons emitted in same dir.)



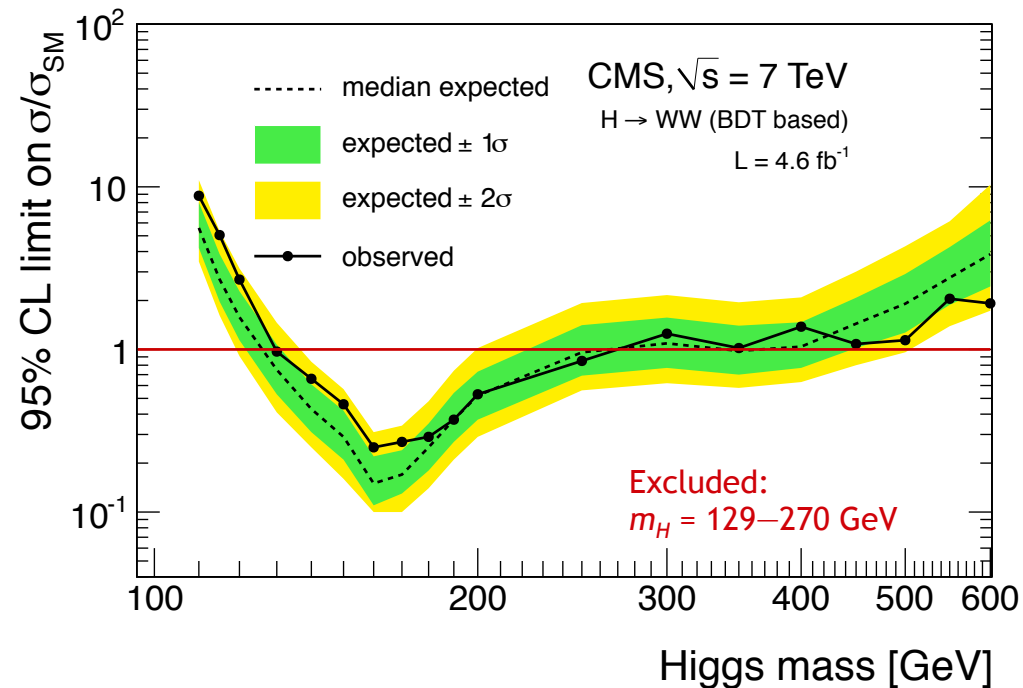
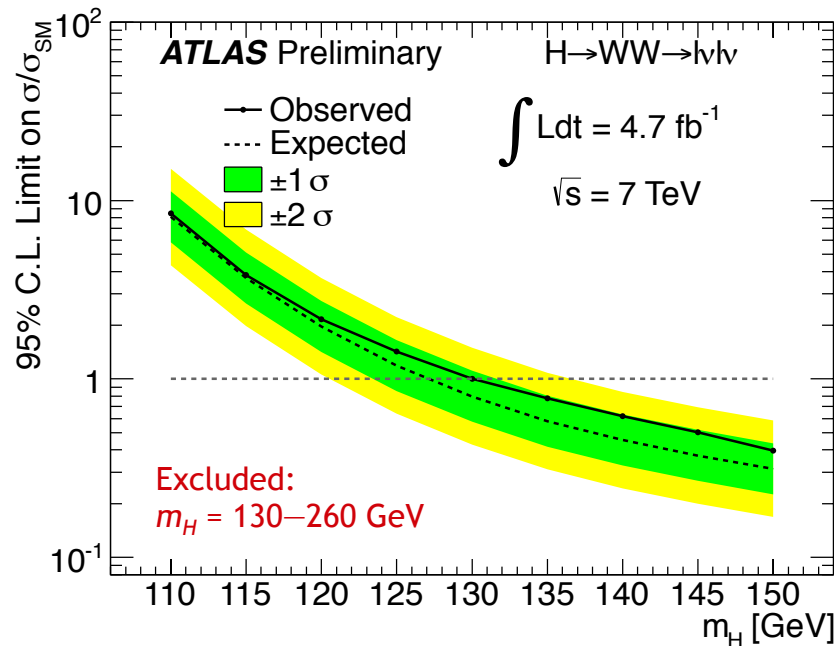
Insufficient sensitivity at low mass, no overall sign of excess

$H \rightarrow WW^{(*)} \rightarrow 2(e, \mu) + 2\nu$: not clean, but abundant

$\sigma \times \text{BR}$ (120 / 165 / 200 GeV | $\sqrt{s}=7$ TeV) $\approx$ 120 / 400 / 200 fb

ATLAS-CONF-2012-012, CMS arXiv:1202.1489

Signal selection: reconstruct transverse Higgs mass, exploit W polarisation (leptons emitted in same dir.)



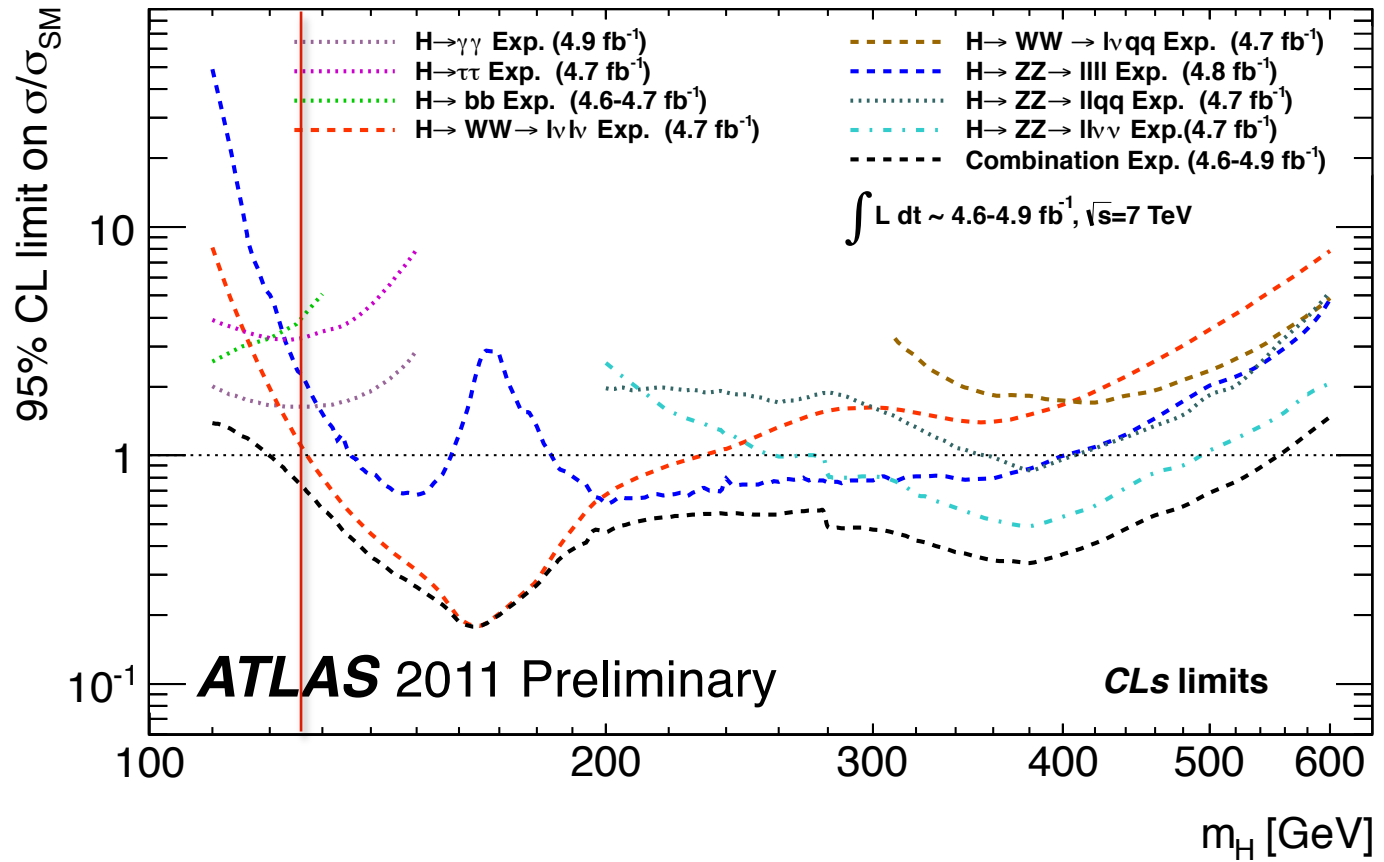
Insufficient sensitivity at low mass, no overall sign of excess

Combining all channels (status: Lepton-Photon 2011)

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

ATLAS-CONF-2012-019

Individual
channels
sensitivities
in one plot

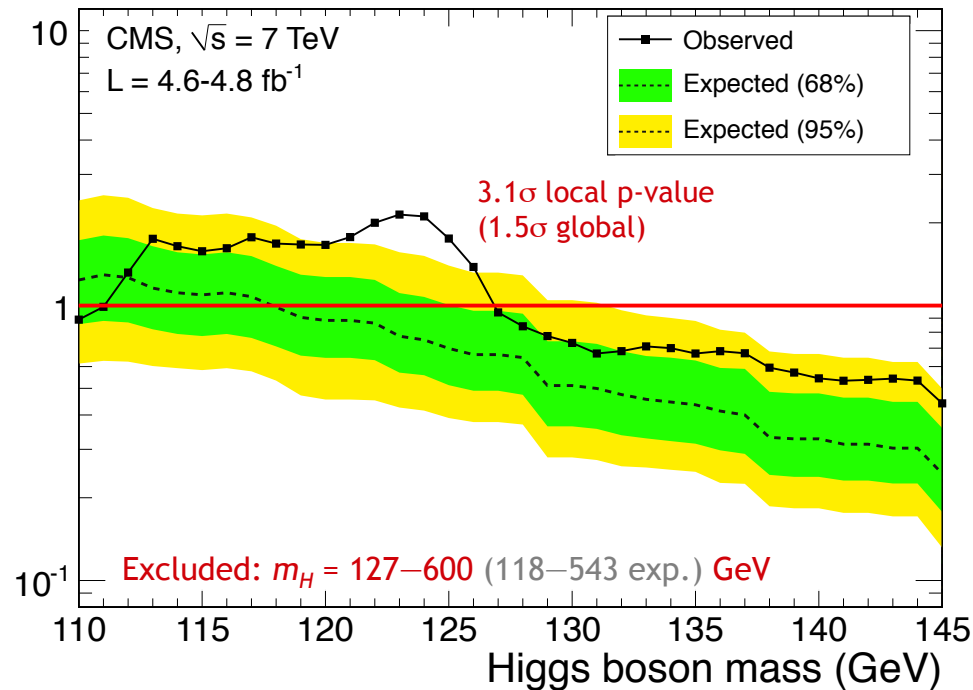
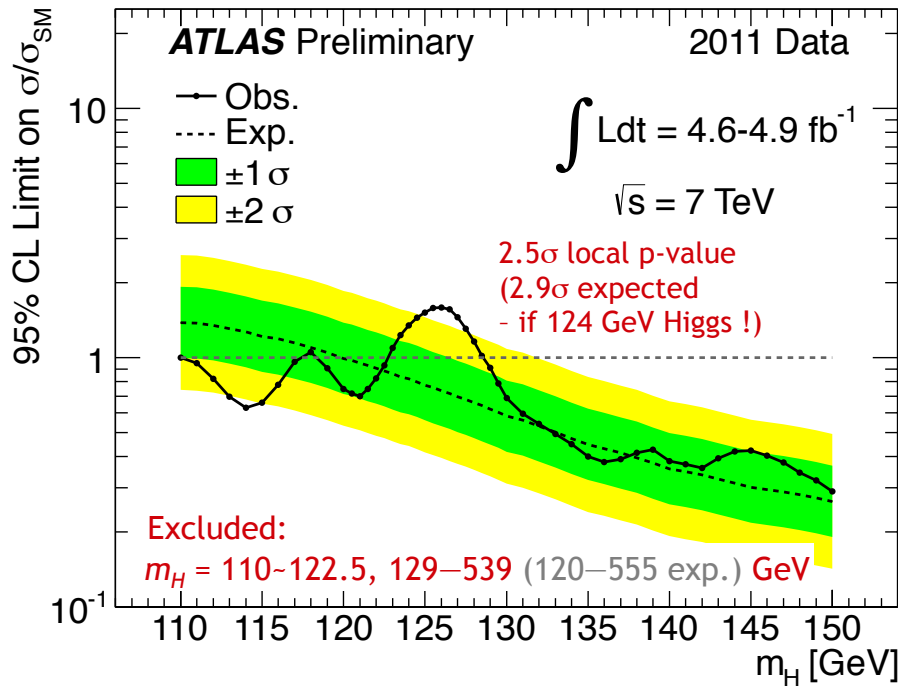


Combining all channels (status: Lepton-Photon 2011)

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



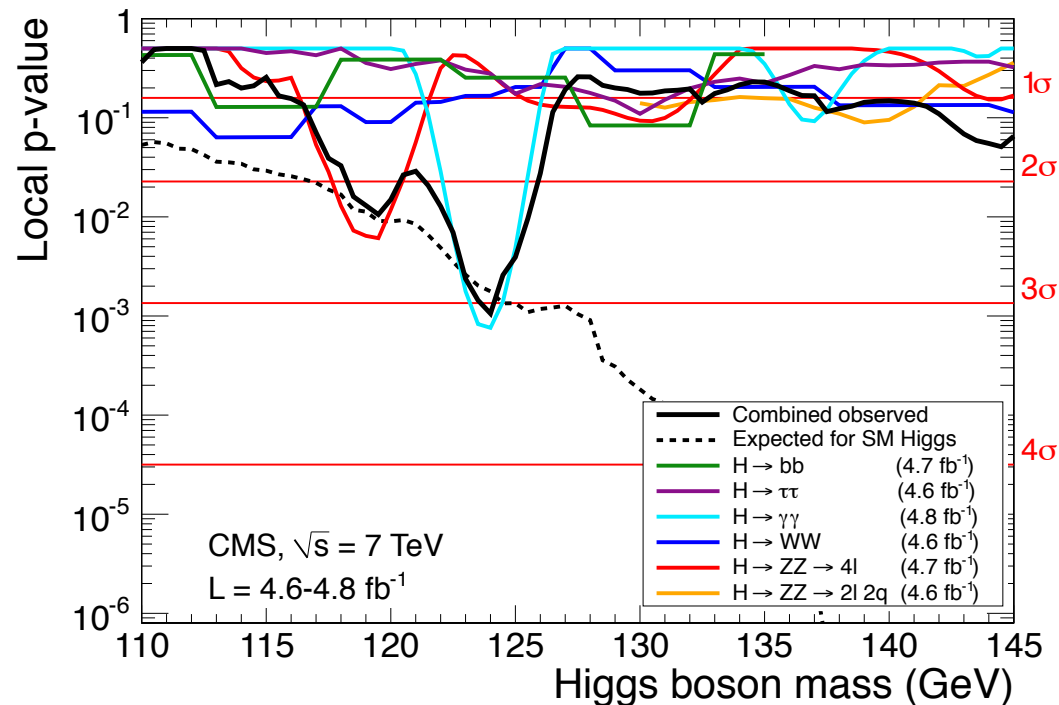
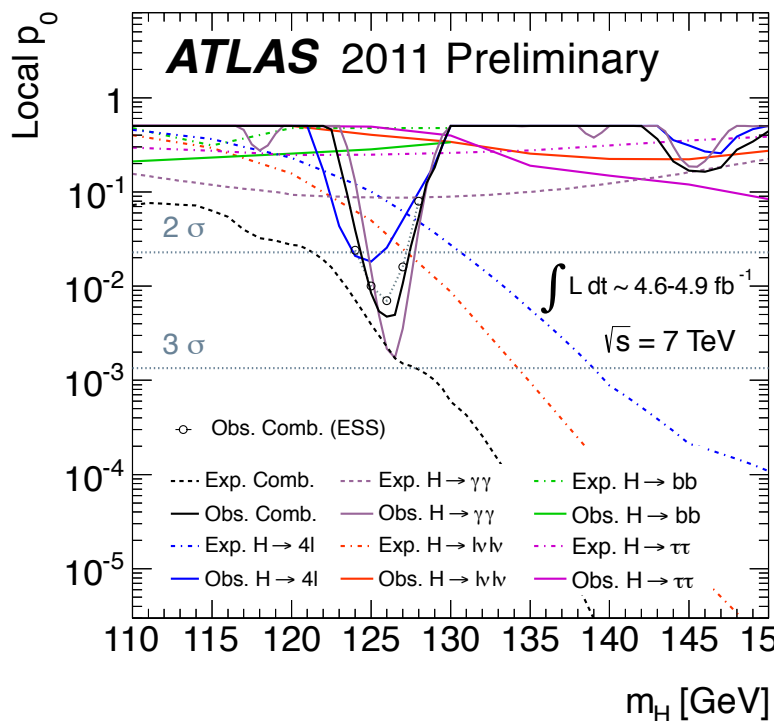
Both experiments see a $>2\sigma$ combined excess at 123~127 GeV ...

Combining all channels (status: Lepton-Photon 2011)

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

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

Comparing local p-values for no-Higgs hypothesis versus Higgs mass



Size of excess would be expected in presence of Higgs; single-channel excess only in CMS data

Combining all channels (status: Lepton-Photon 2011)

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

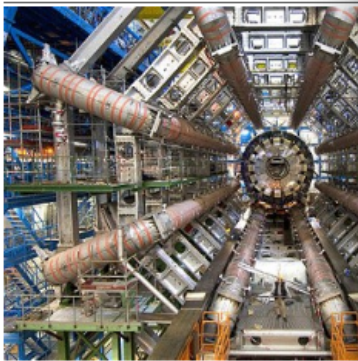
The Telegraph

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Science News Space Roger Highfield

Large Hadron Collider

Large Hadron Collider rumour Particle

Scientists at the Large Hadron Collider have found the Higgs boson, so-called "God Particle".



Scientists working on the Atlas experiment at the Large Hadron Collider have found the Higgs boson. Photo: REX FEATURES



By Richard Gray, Science Correspondent
8:10AM BST 24 Apr 2011

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A leaked internal memo contains unconfirmed reports that the Large Hadron Collider at CERN, Switzerland, has found an unexpected abundance of pairs of W bosons, which carry the weak nuclear force, with energies between about 120 to 140 gigaelectronvolts (GeV).



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'God particle' rumour

CBC News Posted: Apr 25, 2011 1:24 PM ET

Rumoured evidence of the so-called "God particle" has been heavily downplayed by a spokeswoman for the Large Hadron Collider.

"Only ... results that have undergone all the necessary scientific checks by the [ATLAS] Collaboration should be taken seriously," Fabiola Gianotti, spokeswoman for the collaboration, told the journal Nature Monday in response to the discovery of the Higgs boson, popularly known as the "God particle".

The rumour originated from an internal memo from four researchers at ATLAS, one of several international collaborations of researchers at the LHC, the world's



The rumour on the powerful particle

NewScientist

Home News In-Depth Analysis

SPACE TECH ENVIRONMENT

Short Story

Cutting-edge science, culture

Surprise LHC

22:49 22 July 2011

Physics & Math

David Shiga, reporter

Particle watchers could be glimpsed at the Large Hadron Collider, a hypothetical particle though

The news raises hopes that on somewhat firmer ground, a false alarm. However, the blip is not enough to rule out a statistical fluctuation.

In the wreckage of colliding

Switzerland, has found an unexpected abundance of pairs of W bosons, which carry the weak nuclear force, with energies between about 120 to 140 gigaelectronvolts (GeV).

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Published online 22 August 2011 | Nature | doi:10.1038/news

News

Higgs signal sinks from view

Early hints of the boson grow weaker with fresh data.

Geoff Brumfiel

The Higgs boson, the most sought-after particle in all of physics, is proving tougher to find than physicists had hoped.

Last month, a flurry of 'excess events' hinted that the Higgs could be popping up inside the Large Hadron Collider (LHC), the world's most powerful particle accelerator located at CERN, Europe's high-energy physics lab near Geneva, Switzerland. But new data presented today at the Lepton conference in Mumbai, India, show the signal fading. It means "this excess is probably just a statistical fluctuation", says Falkowski, a theorist at the University of Paris-South in Orsay, France.



Still no sign of the Higgs in h
M. Brice; M. Hoch; J. Goble

Combining all channels (status: Lepton-Photon 2011)

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

theguardian

News Sport Comment Culture

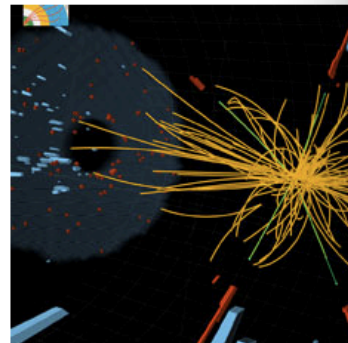
News Science Higgs boson

NOTES&THE
DISPATCHES FROM THE SCIENCE

Higgs boson seminar found the 'God particle'

Physicists announce the latest results from experiments at the Large Hadron Collider, providing tentative evidence for the existence of the Higgs boson.

Alok Jha, science correspondent
guardian.co.uk, Tuesday 13 December 2011
Article history



EXTREME

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CERN to at LHC

By Sebastian Anthony



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December 13, 2011 8:54 AM

Higgs boson hunt



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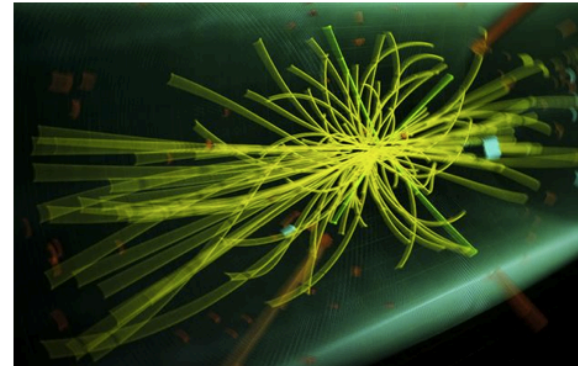
U.S. physicists confirm Higgs finding is near

AGENCE FRANCE-PRESSE MARCH 8, 2012

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STORY PHOTOS (1)



A graphic shows traces of collision of particles during a Compact Muon Solenoid experiment. Scientists at the CERN believe they have identified the location of the Higgs boson, an elusive particle.

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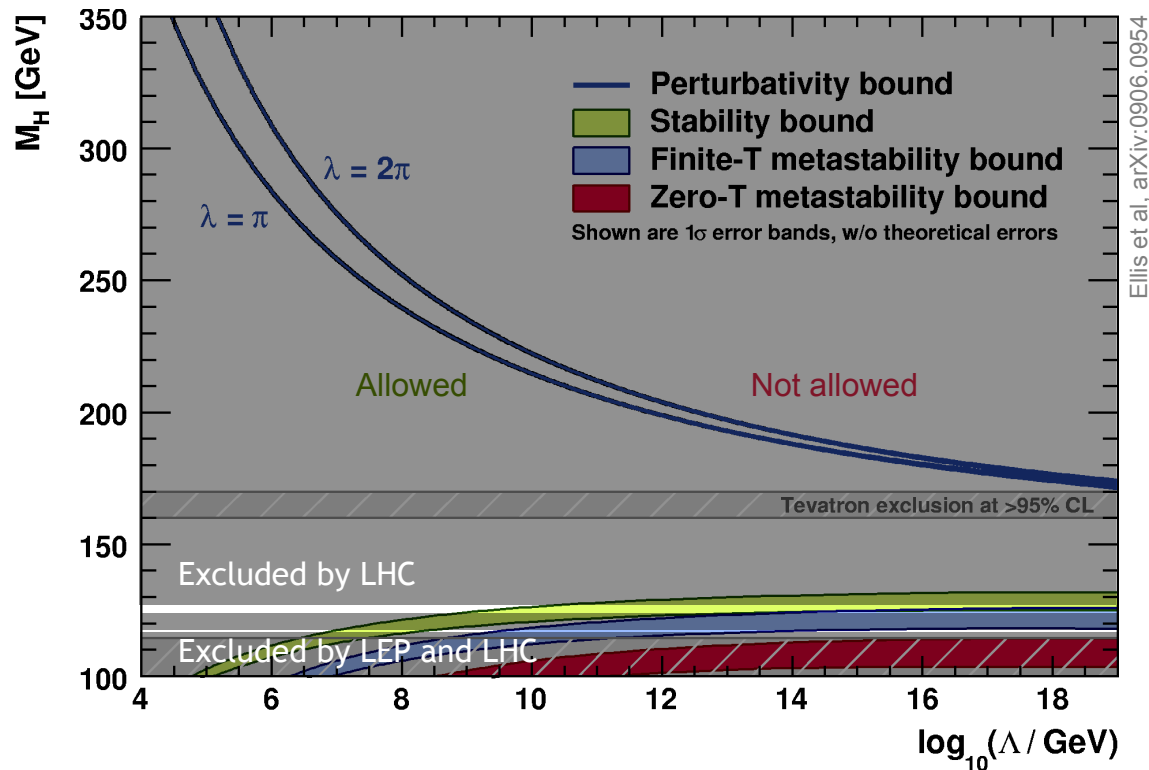
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Combining all channels (status: Lepton-Photon 2011)

Compare with constraints from perturbativity and (meta)stability

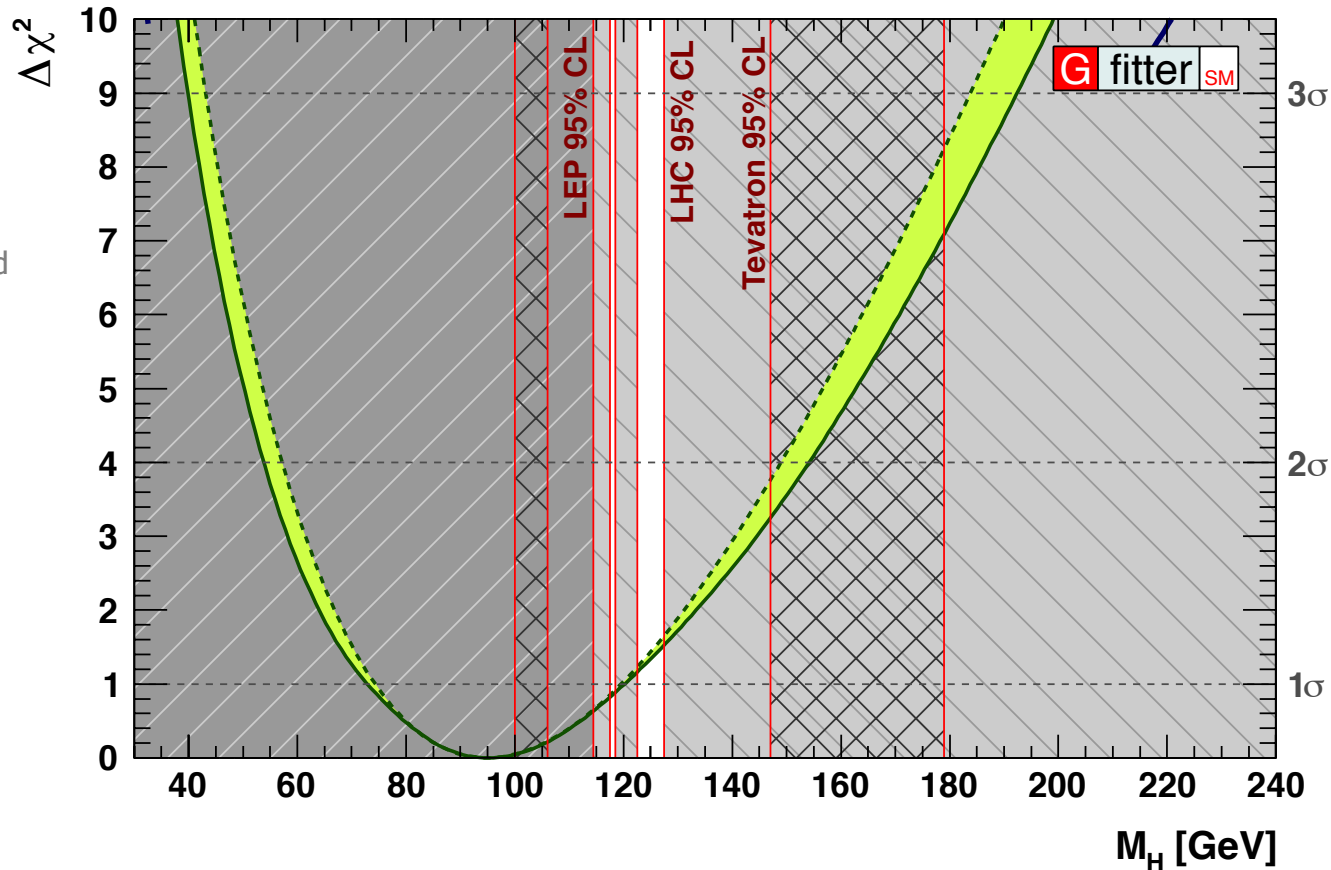


Still – barely – a
stable solution up
to M_p possible ...

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

Constraints from global electroweak fit

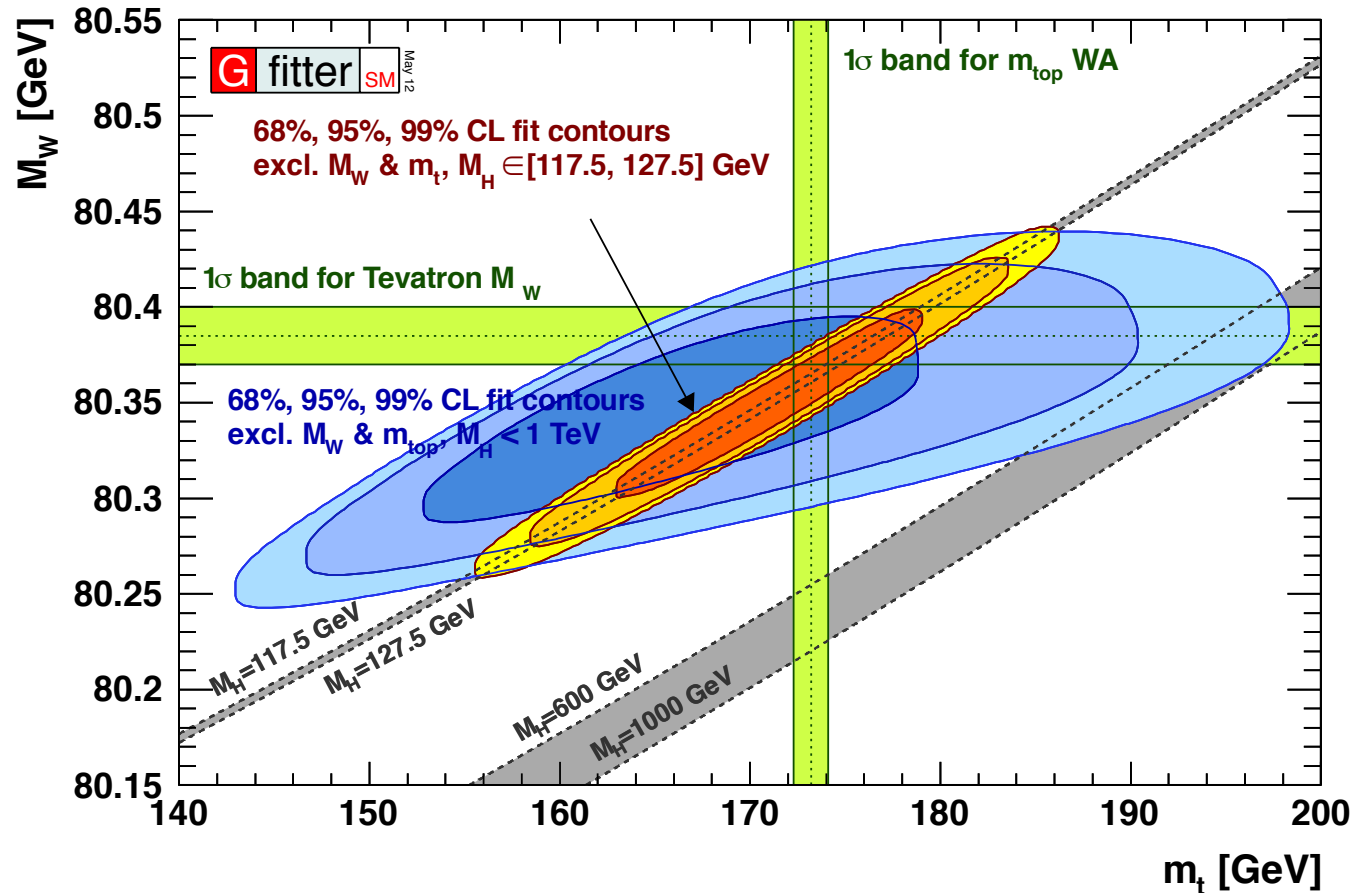
Global fit of all EW precision measurements to SM prediction constrains M_H



<http://gfitter.desy.de>

Constraints from global electroweak fit

Vice versa, the strong direct Higgs mass constraints allow to predict M_W and m_{top}



<http://gfitter.desy.de>



Unfortunately, there is a problem with the Higgs!



P. Higgs at CMS

The Mass of the Scalar is Unprotected

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



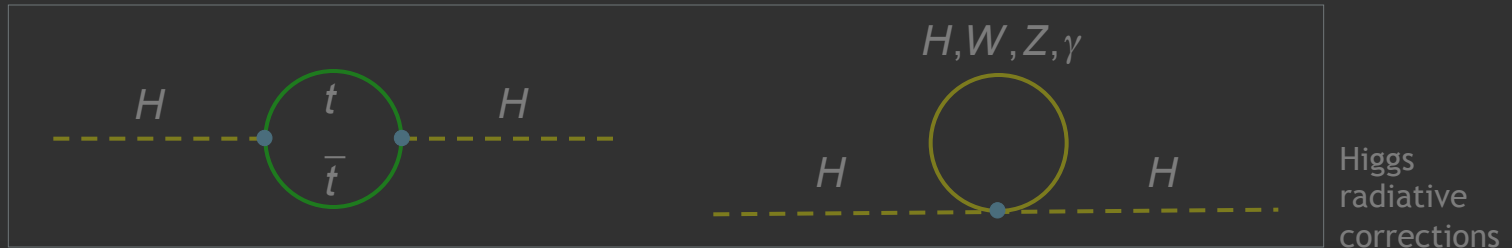
$$\Rightarrow m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \underbrace{\int_0^\infty d^4k \frac{k^2 + m_f^2}{(k^2 + m_f^2)^2}}_{\text{Integral quadratically divergent}} + \dots$$

- 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

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

The Mass of the Scalar is Unprotected

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



$$\propto \int_0^\infty \frac{k^2 dk^2}{k^2 + m^2}$$

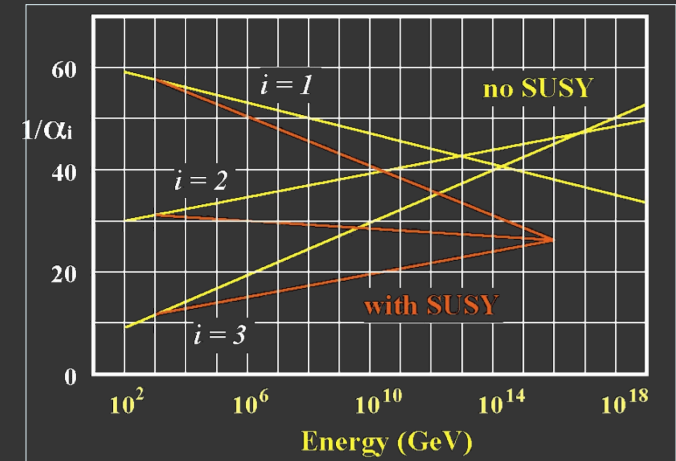
Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**.
Setting $m_H = 0$ in SM Lagrangian, **does not restore any symmetry in the model**.

New physics models should address this. M_H should become the 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 “Gauge Hierarchy Problem”

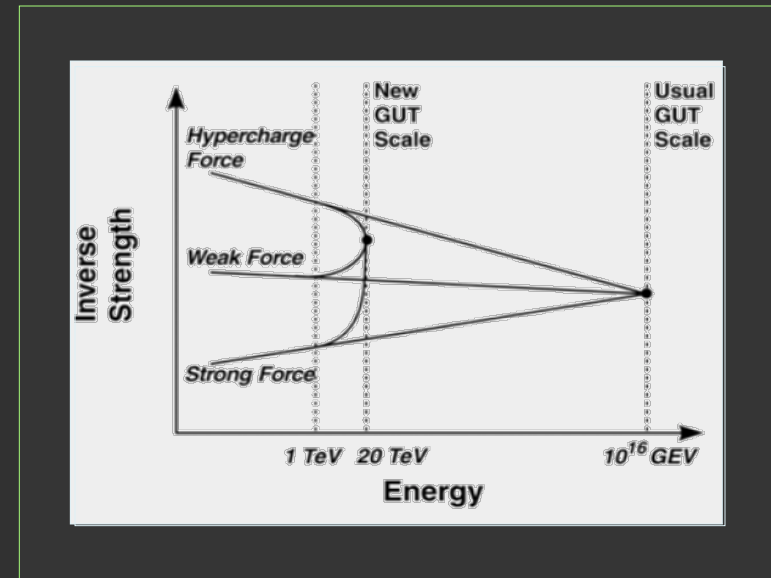
This strong dependence of the Higgs to the ultraviolet physics makes it a powerful probe to new physics



Possible solutions to the hierarchy problem:

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

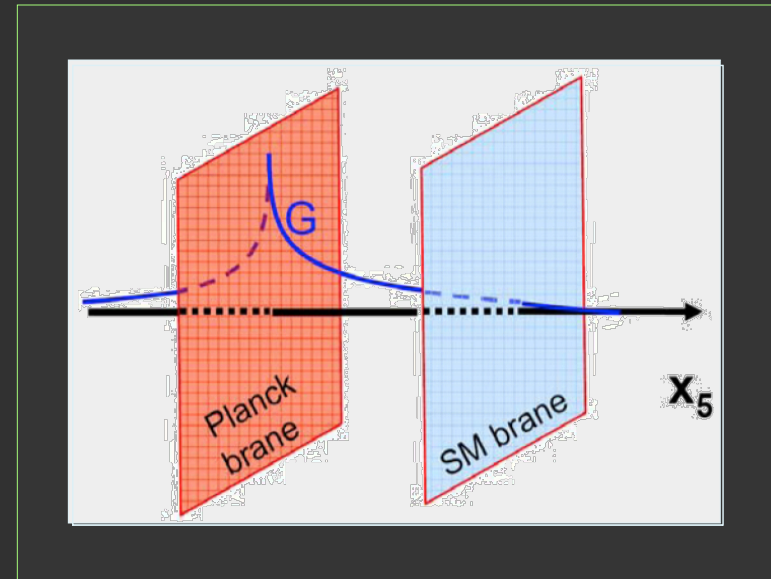
The “Gauge Hierarchy Problem”



Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences
- New physics modifies the running of the couplings, approaching GUT to the EW scale

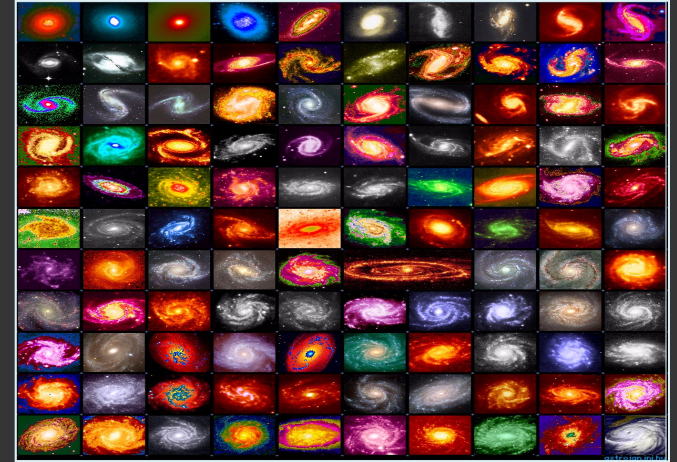
The “Gauge Hierarchy Problem”



Possible solutions to the hierarchy problem:

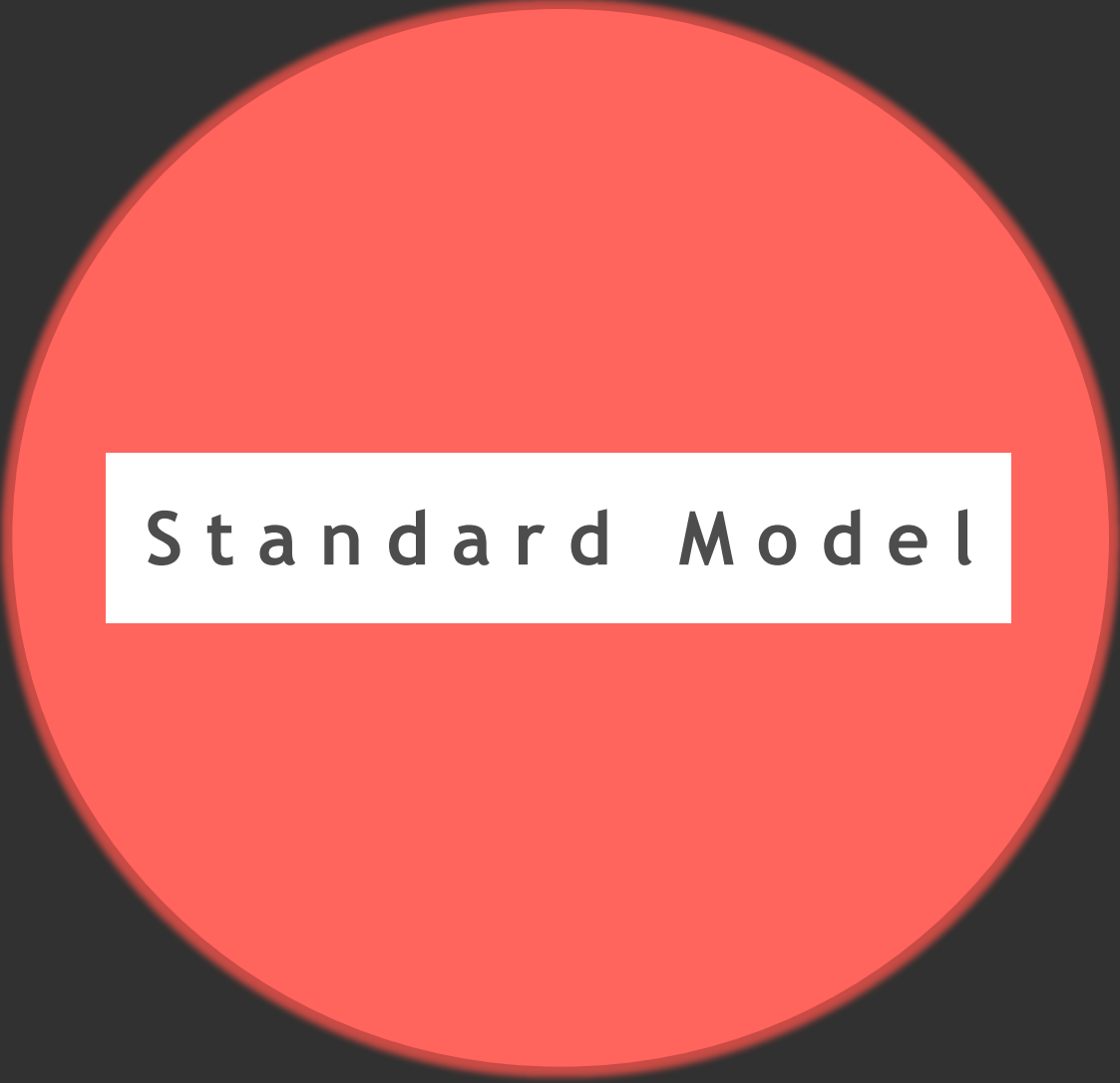
- New physics appears not much above the EW scale and regularises the quadratic divergences
- New physics modifies the running of the couplings, approaching GUT to the EW scale
- Gravity is not as weak as we think, it's only diluted in our 4D world but it is as strong as EW interactions at the TeV scale in, e.g., 5 or more dimensions, $(M_{\text{Pl}})^{5\text{D}} \sim O(\text{TeV})$

The “Gauge Hierarchy Problem”

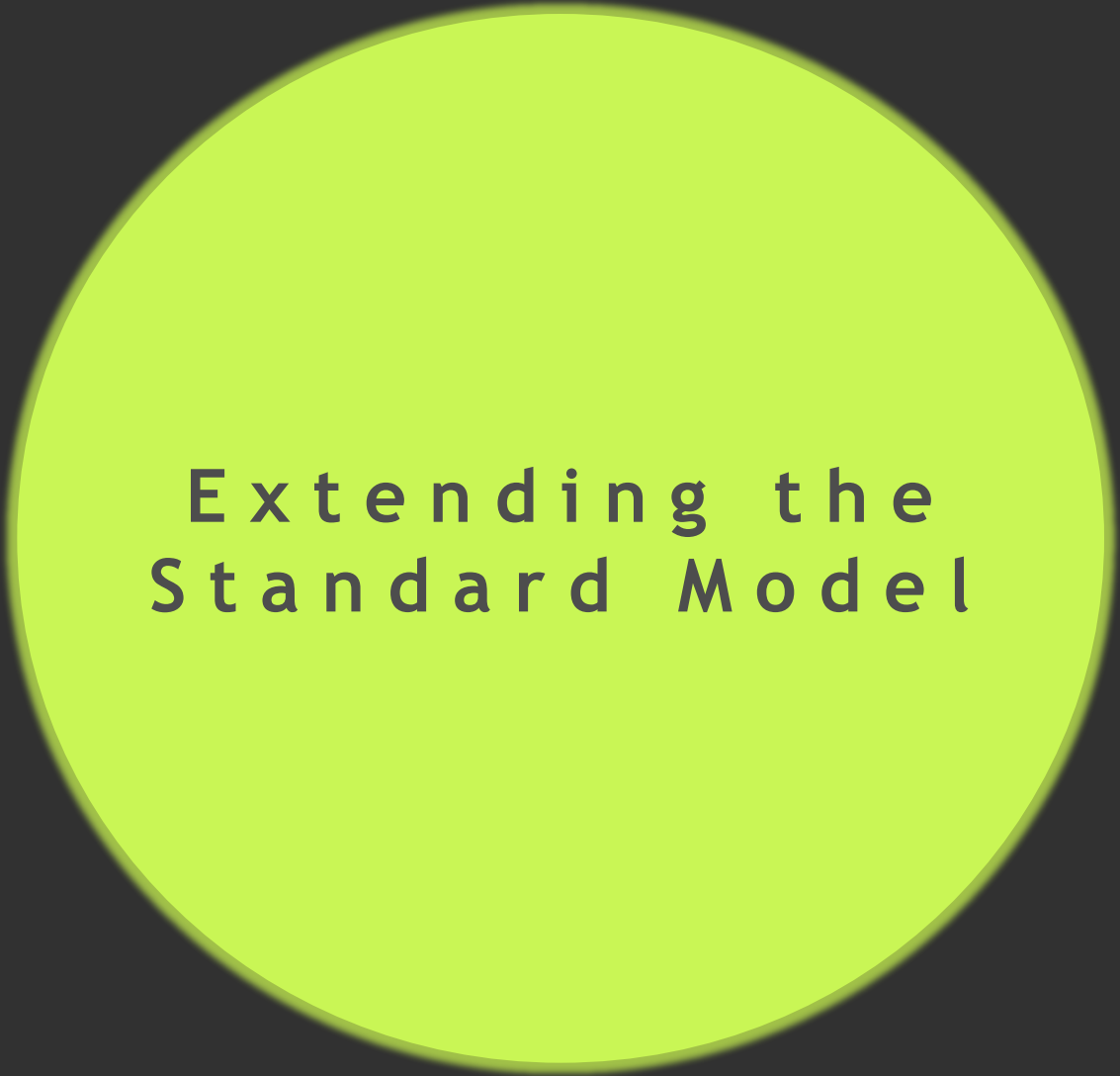


Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences
- New physics modifies the running of the couplings, approaching GUT to the EW scale
- Gravity is not as weak as we think, it's only diluted in our 4D world but it is as strong as EW interactions at the TeV scale in, e.g., 5 or more dimensions, $(M_{\text{Pl}})^{5\text{D}} \sim O(\text{TeV})$
- The theory is finetuned: explanation for parameter values is statistical rather than dynamic (anthropic multiverse solution)



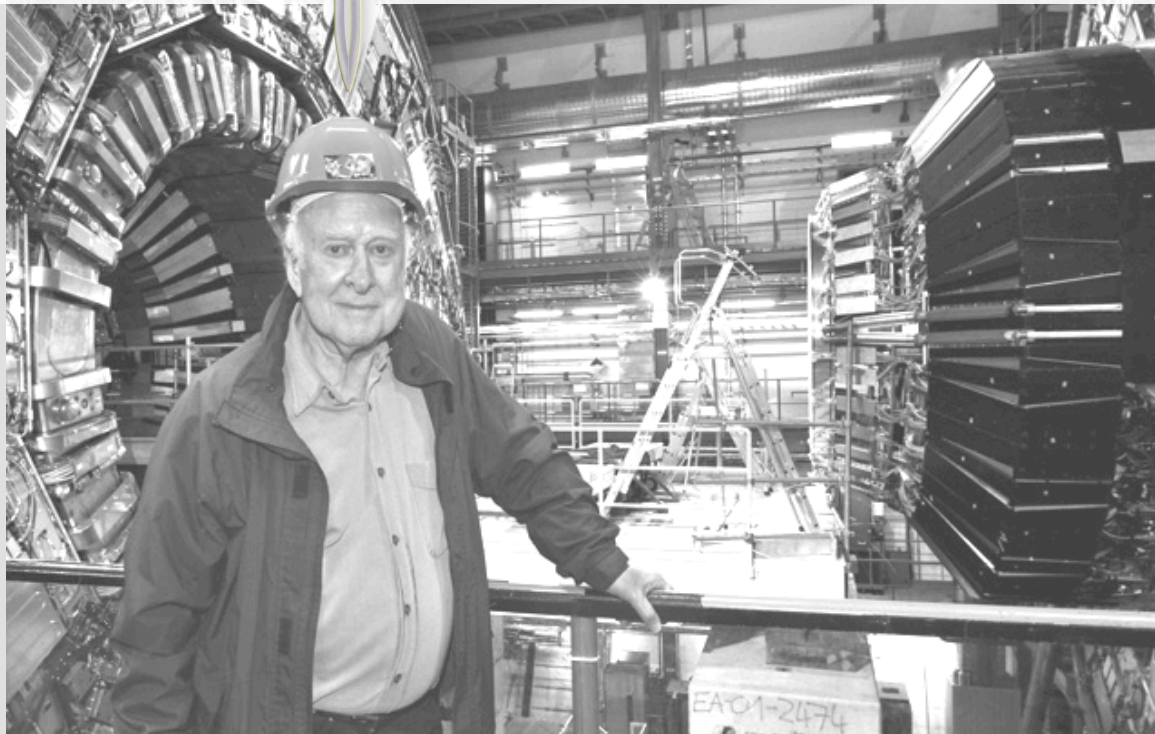
Standard Model



Extending the Standard Model

- 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

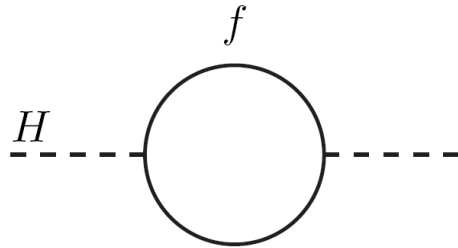
Could a symmetry between fermions and bosons
regularise the Higgs radiative corrections ?

Supersymmetry (SUSY)



P. Higgs at CMS

Fermion loop



S

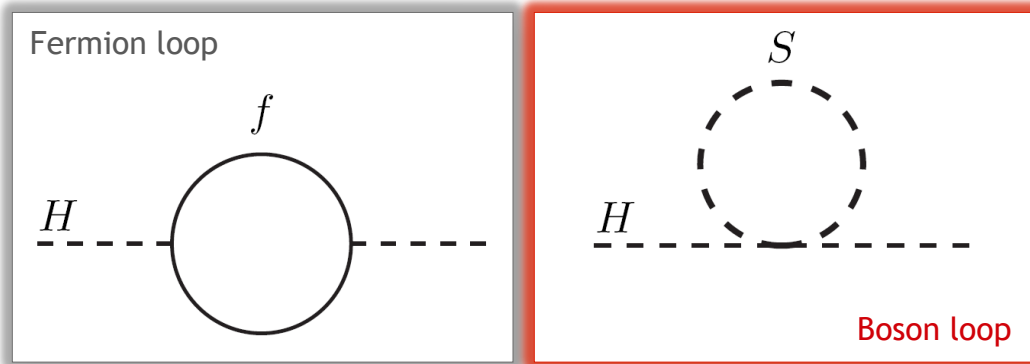


Boson loop

Supersymmetry (SUSY)



P. Higgs at CMS



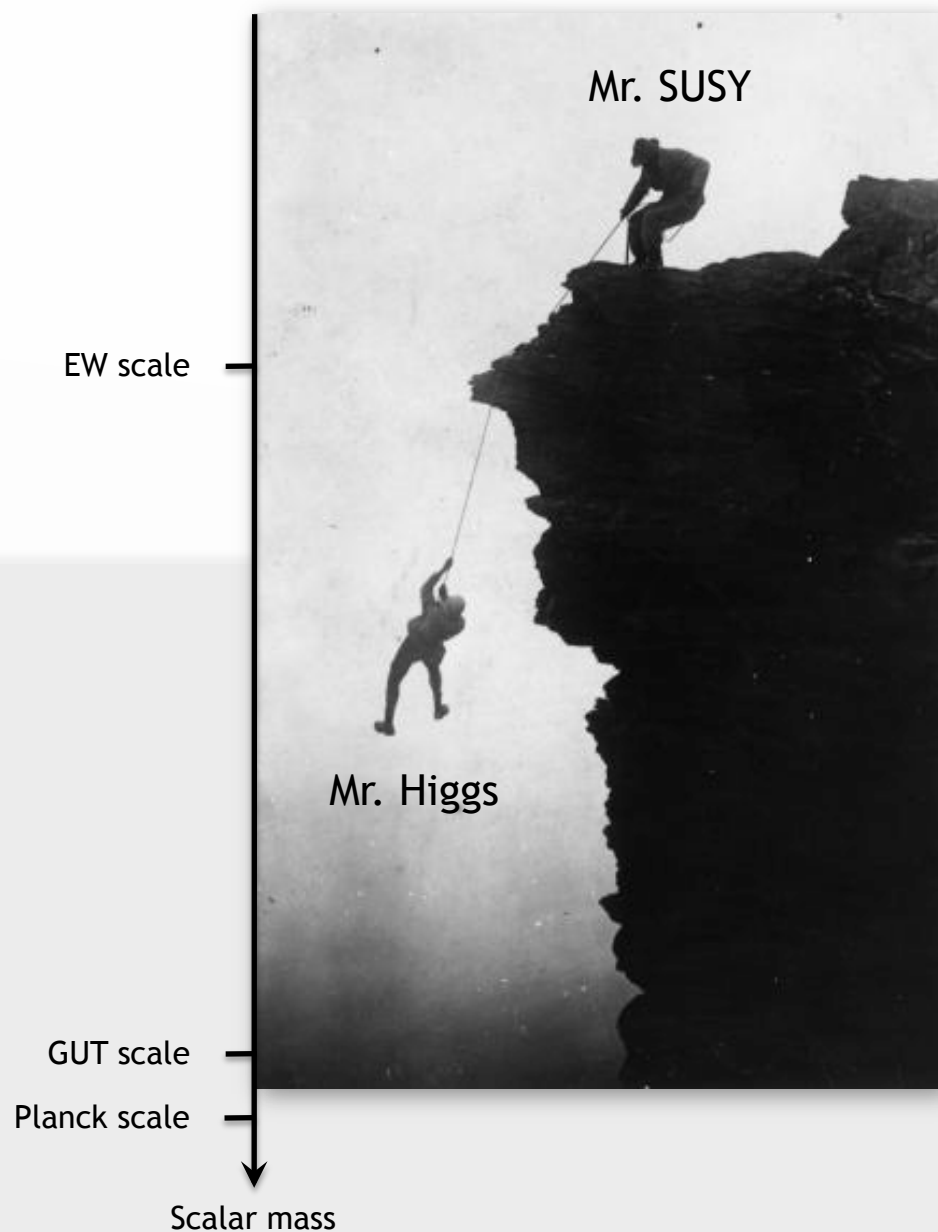
Supersymmetry (SUSY)

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

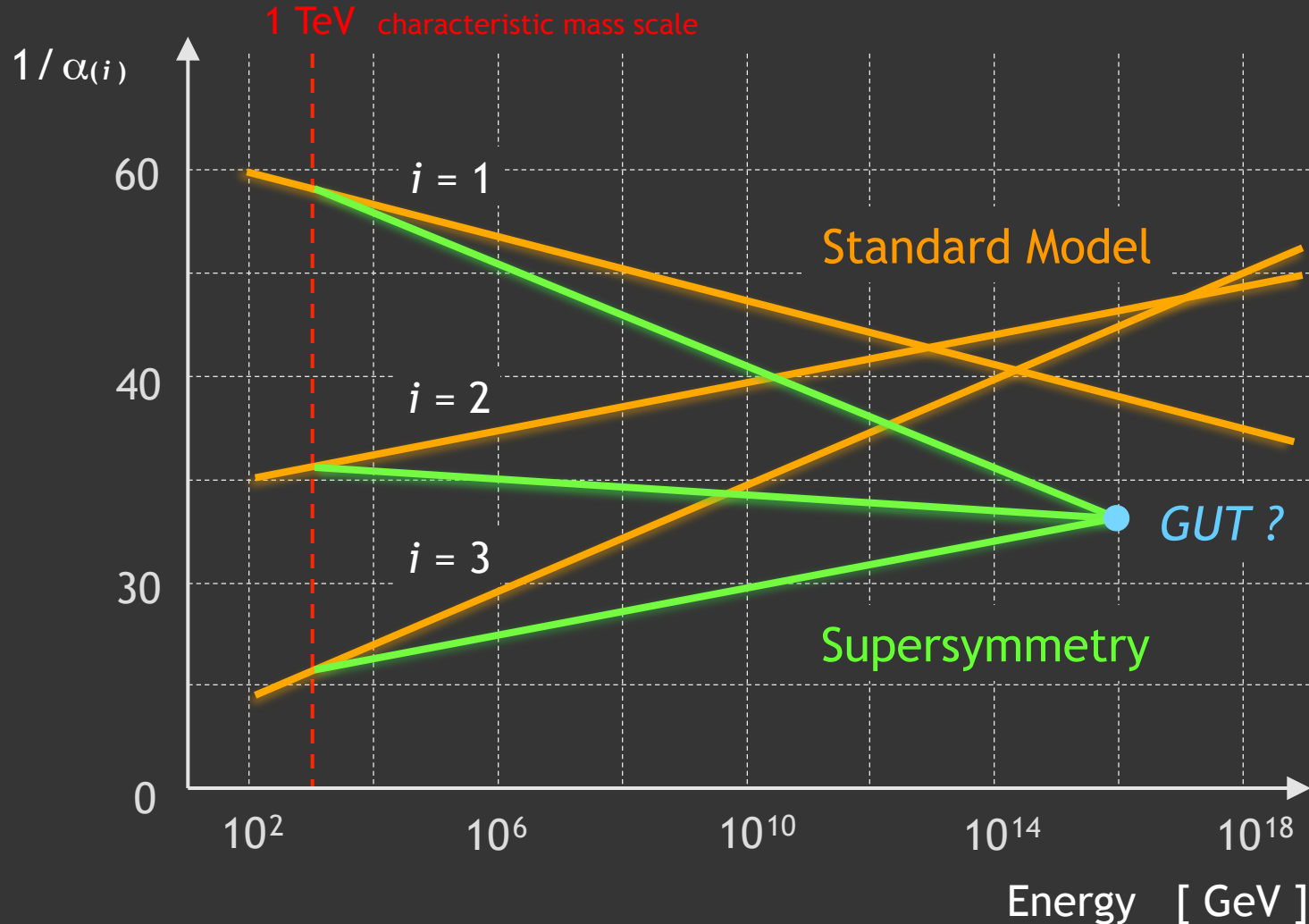
- SUSY transforms, e.g., a scalar boson into a spin- $\frac{1}{2}$ fermion, whose mass is protected
- Hence, the scalar mass is also protected (precisely through SUSY)
- This solves the naturalness and the hierarchy problems of the SM (at least technically)
- Local gauge invariance of SUSY requires existence of spin- $\frac{3}{2}$ and spin-2 particles, which naturally introduces the spin-2 graviton, assumed to mediate the gravitational force

The Higgs precipice



Grand Unification of the Gauge Couplings (GUT)

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



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

- To create *supermultiplets*, we need to add one *superpartner* to each SM particle
- Superpartners have opposite spin statistics but otherwise equal quantum numbers
- Need to introduce an additional Higgs doublet to the non-SUSY side
- SUSY breaking introduces lots (> 100) of new parameters (masses and mixing angles)

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		

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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Supersymmetry (SUSY)

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

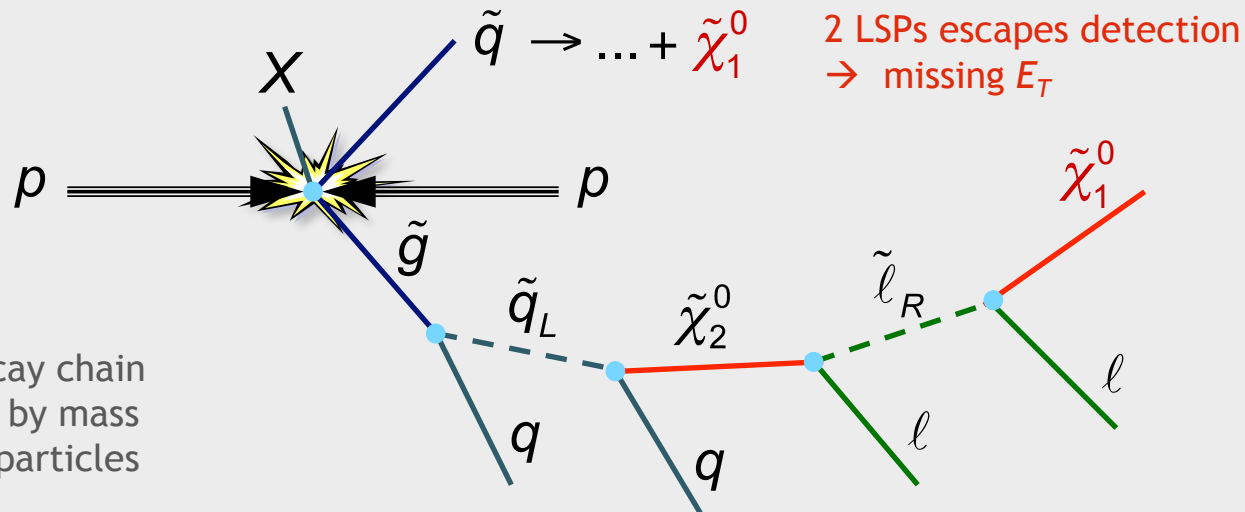
The gauge-mixed physical states that propagate in space and time and that can be observed.

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

Charginos : mass eigenstates of winos and charged higgsinos

Characteristic SUSY Decay Cascades

- To avoid proton decay, a new conserved quantum number is introduced, which forces a SUSY particle to decay in at least in 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 !



“Typical” SUSY decay chain
at the LHC, driven by mass
hierarchy of SUSY particles

SUSY searches at the LHC

Many different search channels along expected SUSY event topologies

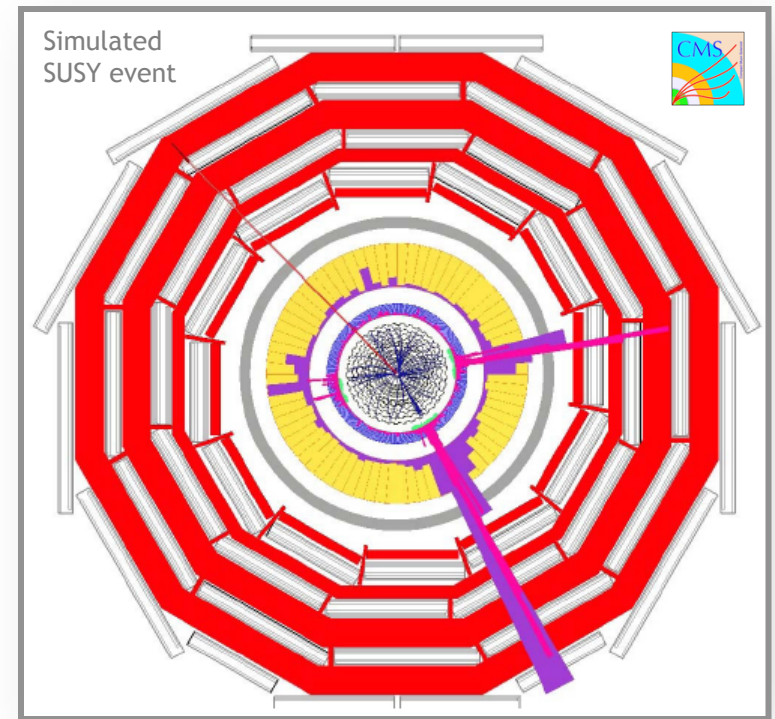
Signatures of the SUSY “cascades” are driven by masses of the SUSY particles

To good generality we can expect:

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

This lays out an **inclusive search strategy**

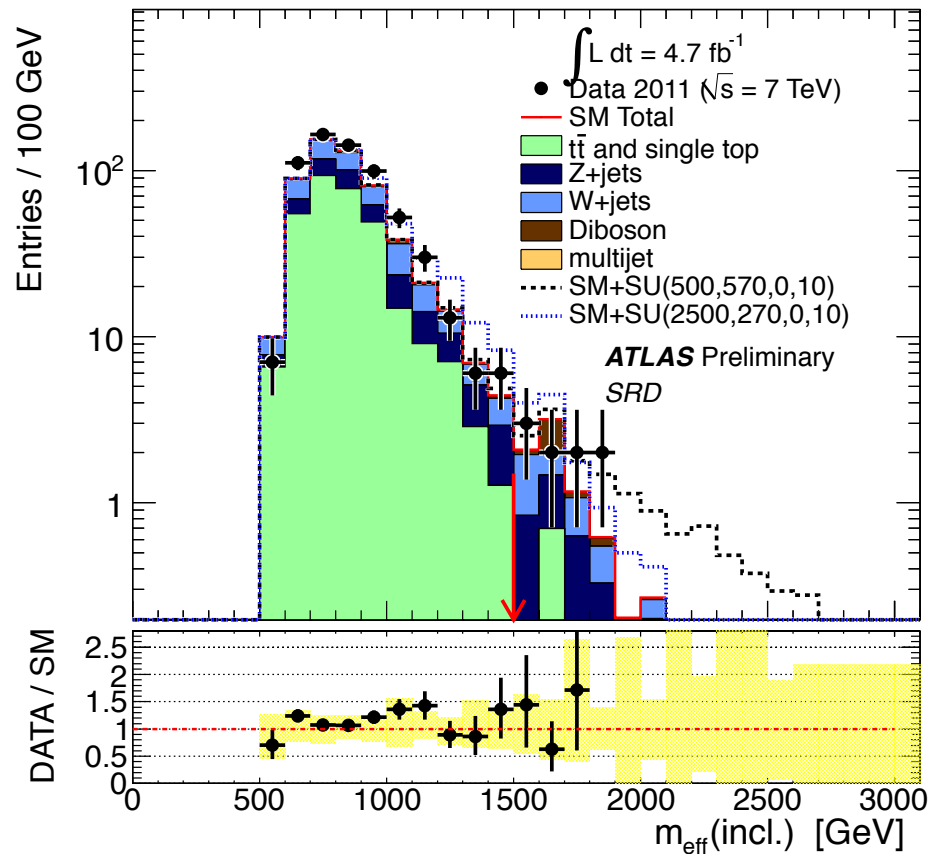
- ➡ Most of the hard analysis work consists of understanding and modeling backgrounds from SM processes !



Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

ATLAS-CONF-2012-033



Plot shows measured sum of jet and missing transverse momenta

Heavy squarks and gluinos would lead to excess over expected SM events at high tail of distribution

No such excess seen in current data, neither in ATLAS, nor in CMS

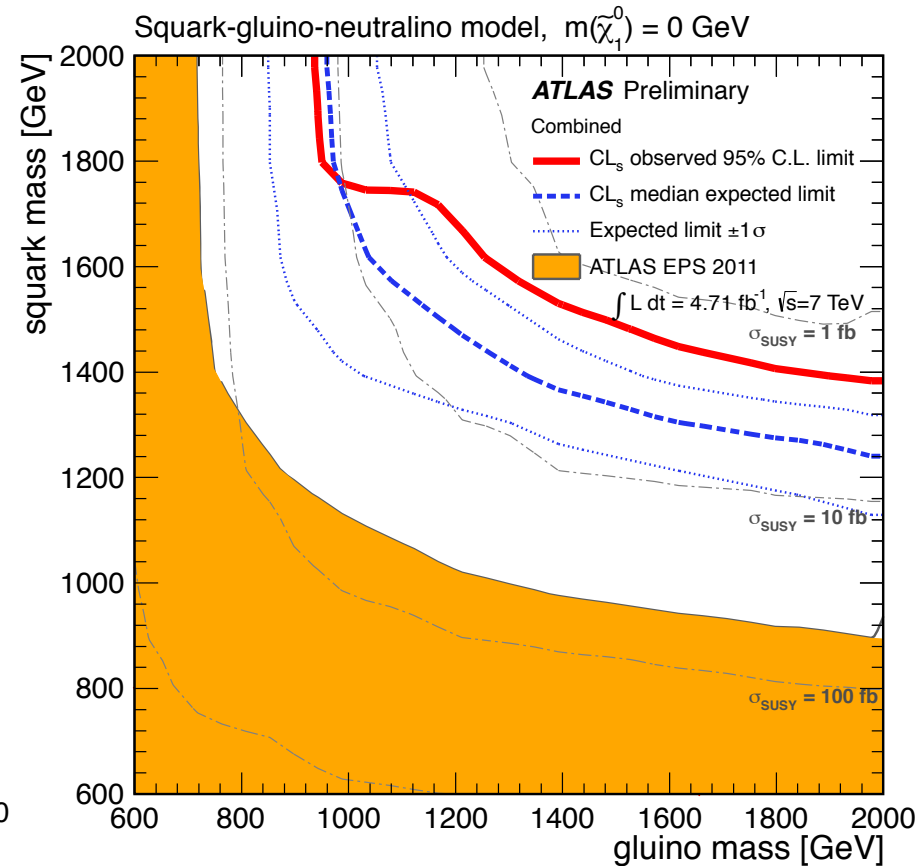
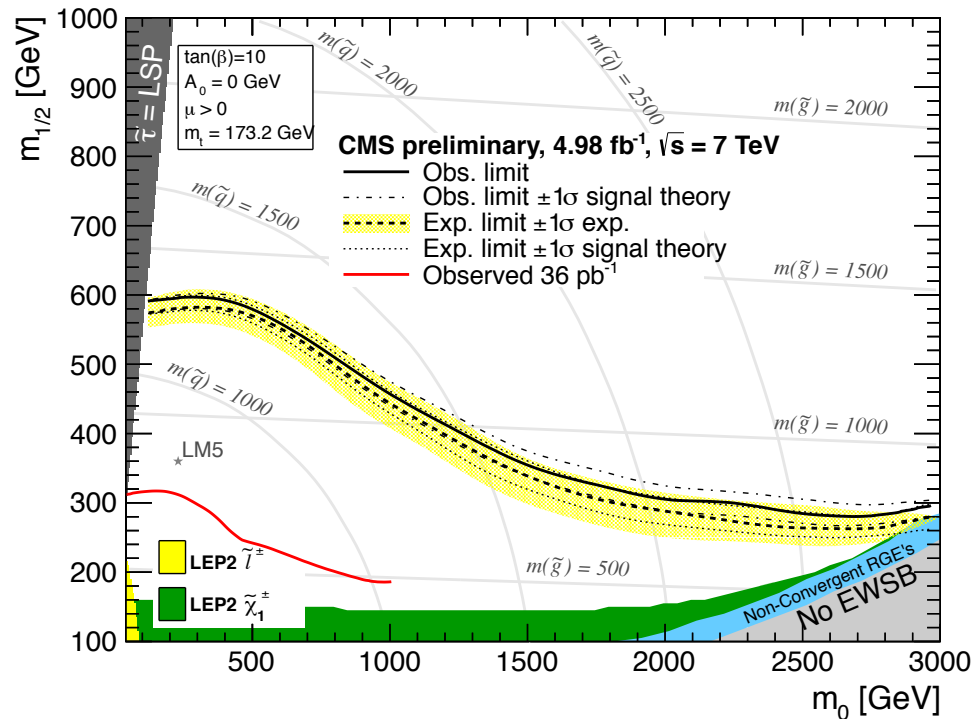
Can translate into limit on SUSY mass scale

Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

ATLAS-CONF-2012-033, CMS-SUS-12011

Interpretation in terms of *SUSY breaking*,
phenomenological or *simplified* models



Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

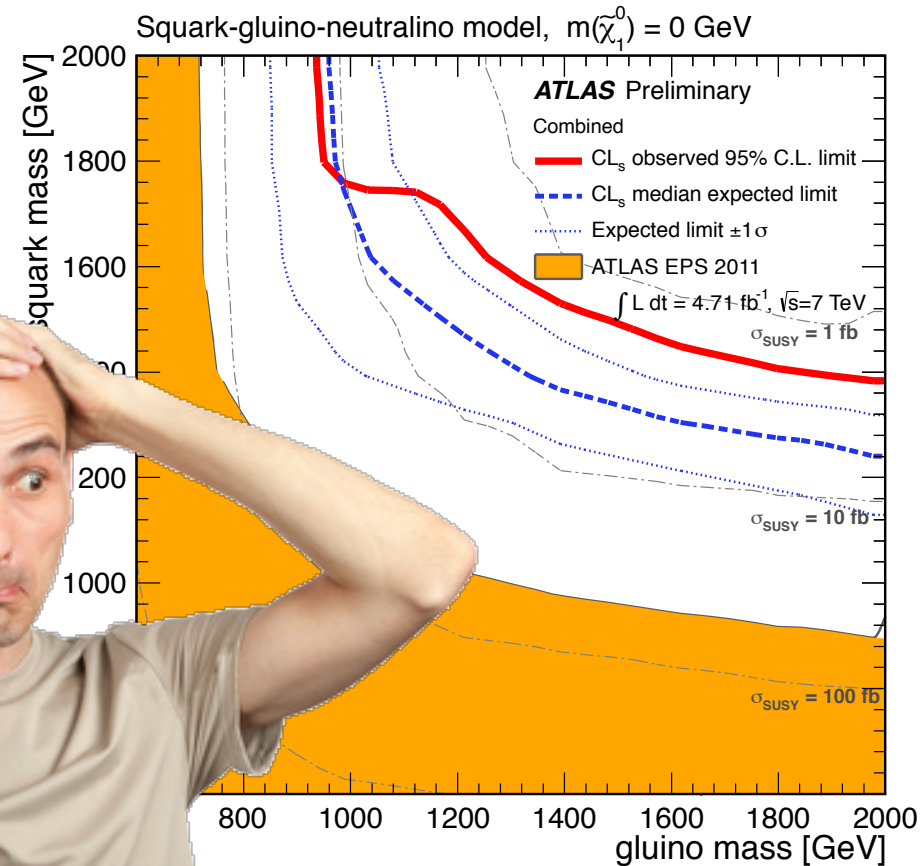
ATLAS ArXiv:1109.6572, CMS-PAS-SUS-11-004

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

$$m(\tilde{q}) \approx m(\tilde{g}) < 1.5 \text{ TeV}$$

$$m(\tilde{q}) < 1.4 \text{ TeV } (\forall m(\tilde{g}) < 2 \text{ TeV})$$

$$m(\tilde{g}) < 1 \text{ TeV } (\forall m(\tilde{q}) < 2 \text{ TeV})$$



Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

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Published online 28 February 2011 | *Nature* **471**, 1
doi:10.1038/471013a

News

Beautiful theory collides with particle data

Latest results from the LHC are casting doubt on supersymmetry.

[Geoff Brumfiel](#)

"Wonderful, beautiful and unique" is how Gordon Kane describes supersymmetry theory. Kane, a theoretical physicist at the University of Michigan in Ann Arbor, has spent about 30 years working on supersymmetry, a theory that he and many others believe solves a host of problems with our understanding of the subatomic world.

Yet there is growing anxiety that the theory, however elegant it might be, is wrong. Data from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

Theorists working in the field have told BBC News that they may have to come up with a completely new idea.

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27 August 2011 Last updated at 06:41 GMT

LHC results put supersymmetry theory 'on the spot'

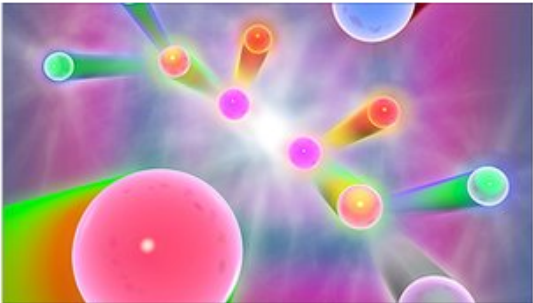
By Pallab Ghosh
Science correspondent, BBC News



Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

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Supersymmetry predicts the existence of mysterious super particles.

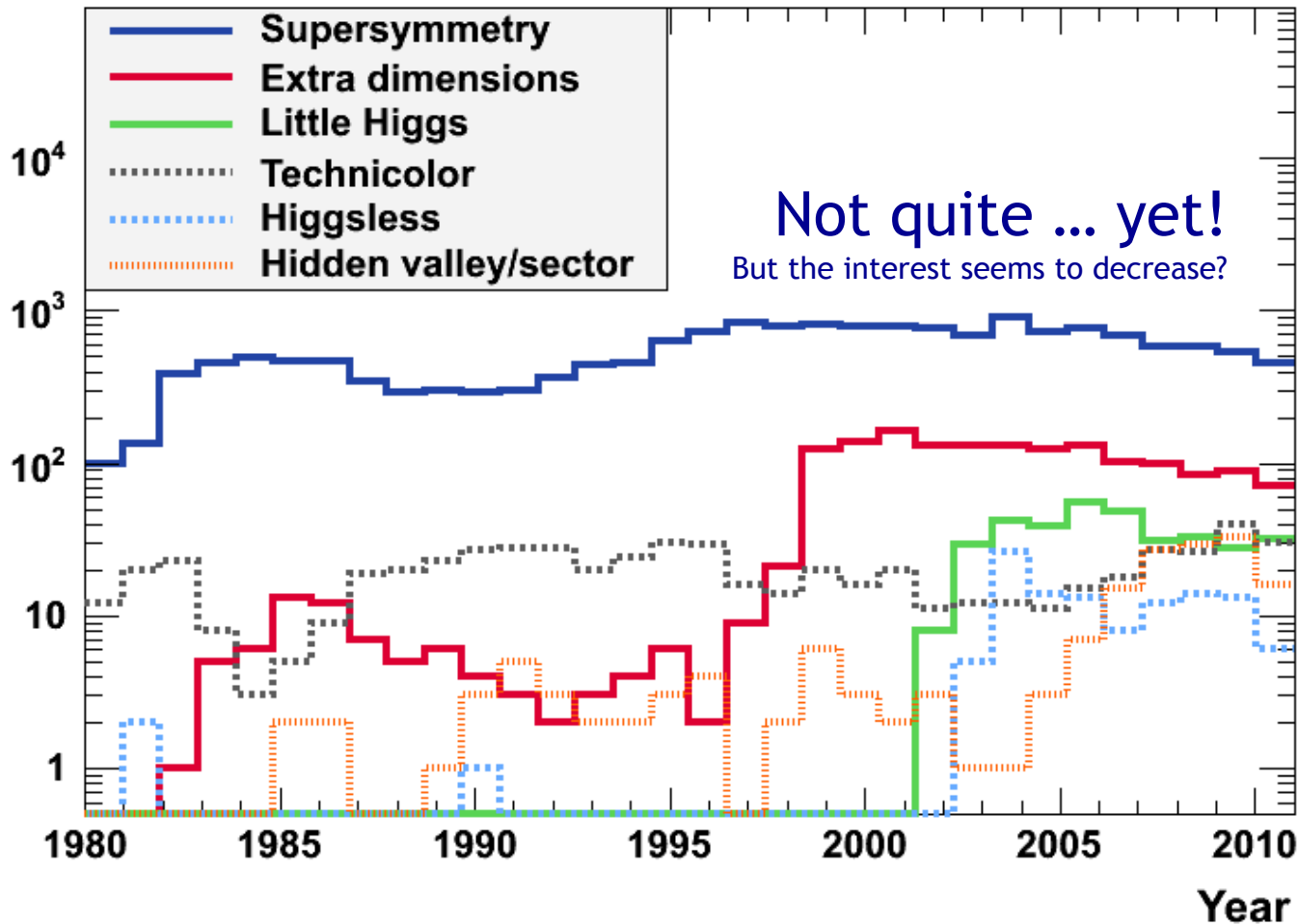
Searches for strongly produced squarks and gluinos

... do

Paper Statistics in SPIRES

Is SUSY *out* already?

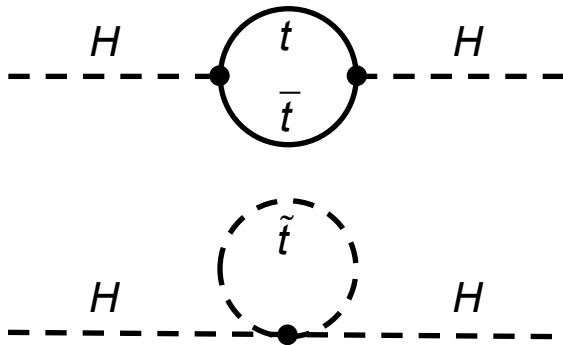
Number of Papers with Keywords in Title



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



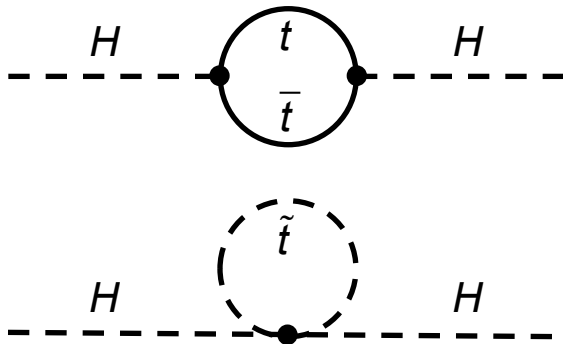
Contrary to the SM, 3rd generation squarks can be lighter than 1st and 2nd generations

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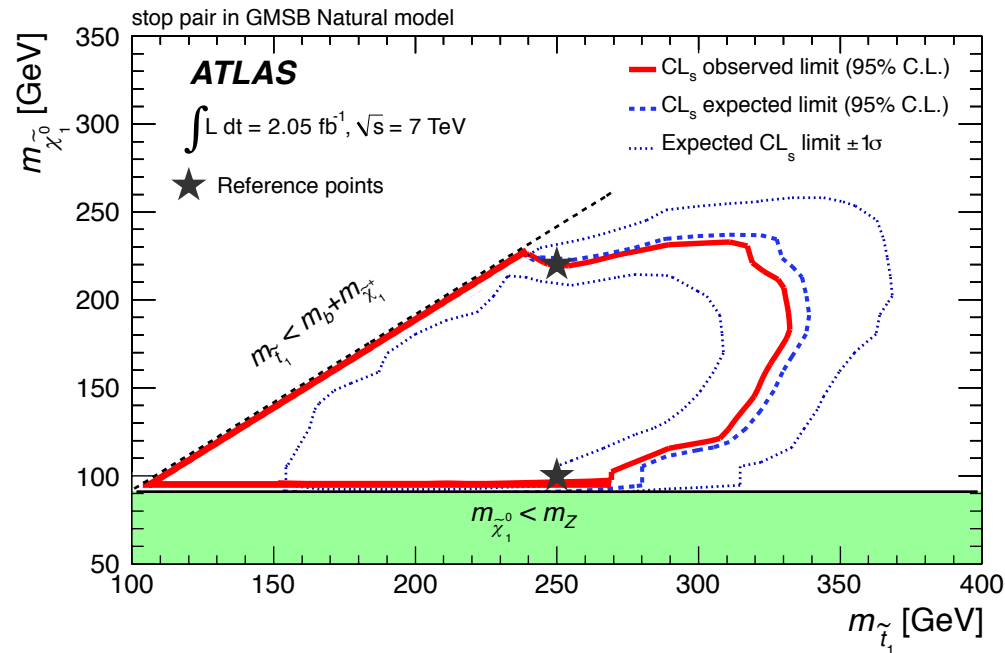
ATLAS arXiv:1204.6736

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

→ Maybe all squarks except stop and sbottom are heavy?



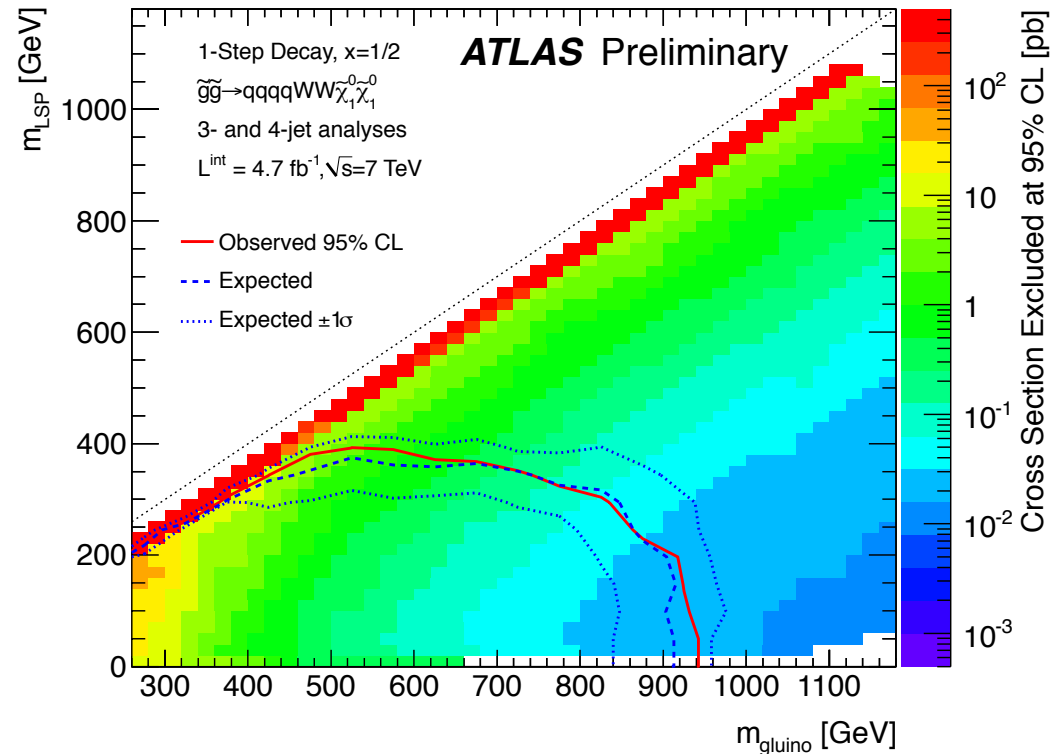
Glueballs and 1/2nd generation squarks are too heavy to be directly produced. Lightest top squark cascade-decays to b -jets + Z + MET

Does SUSY hide from our analyses?

What mechanisms could camouflage strong SUSY production?

ATLAS-CONF-2012-041

Maybe the neutralinos are almost as heavy as the squarks and gluinos so that not enough missing E_T is produced in the decays to select SUSY events?



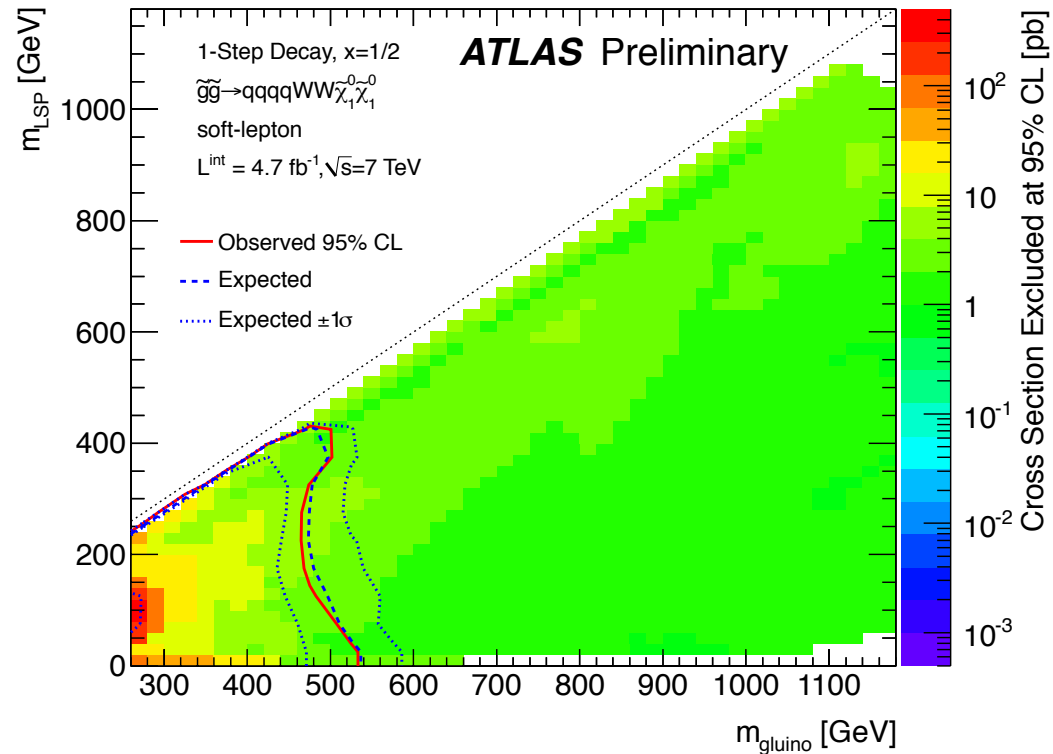
Mass degeneracy close to diagonal in plot
Little discovery reach there

Does SUSY hide from our analyses?

What mechanisms could camouflage strong SUSY production?

ATLAS-CONF-2012-041

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Use dedicated “soft” spectra analyses

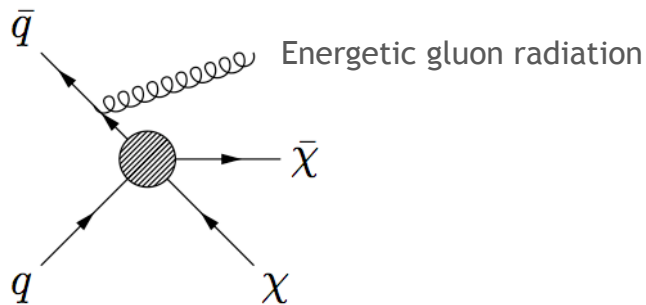
Does SUSY hide from our analyses?

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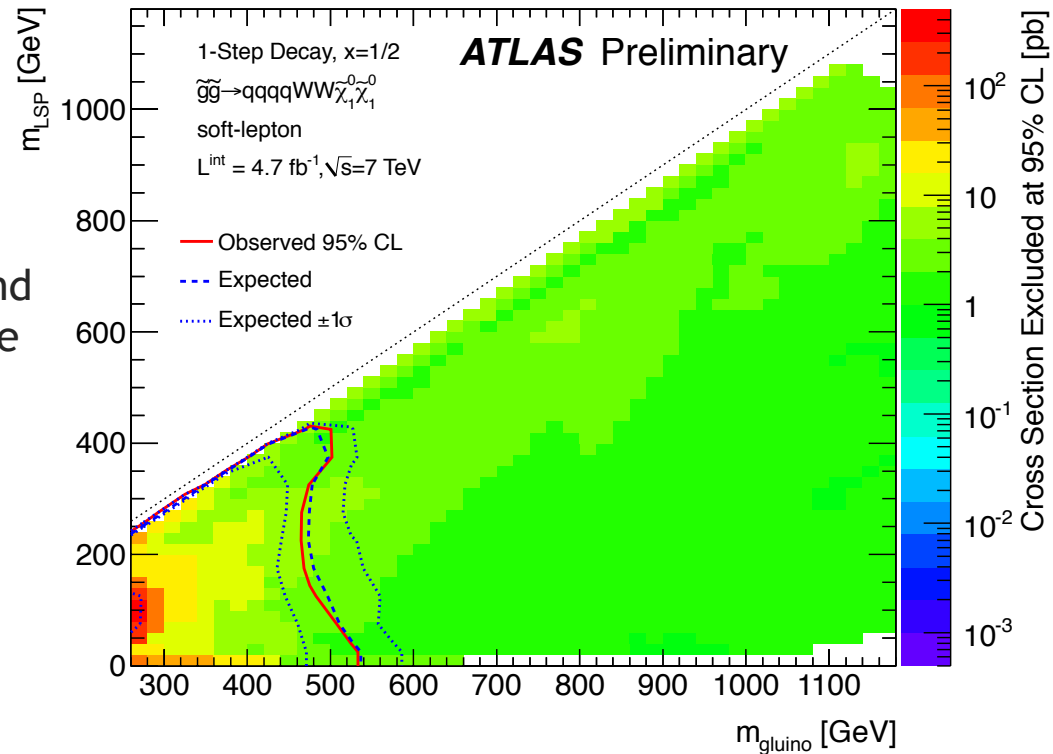
ATLAS-CONF-2012-041

Maybe the neutralinos are almost as heavy as the squarks and gluinos so that not enough missing E_T is produced in the decays to select SUSY events?

Maybe squarks & gluinos are too heavy and only neutralinos or dark matter WIMPs are produced? *How can we detect them?*



→ Search for mono-jets events!



Use dedicated “soft” spectra analyses

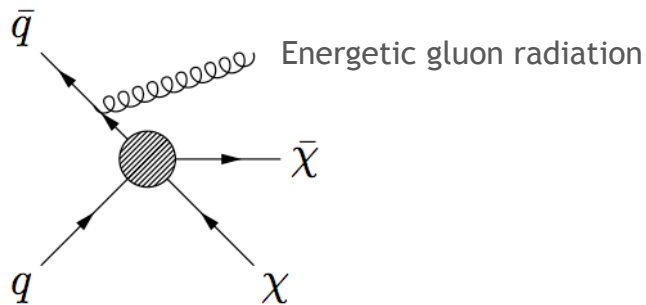
Does SUSY hide from our analyses?

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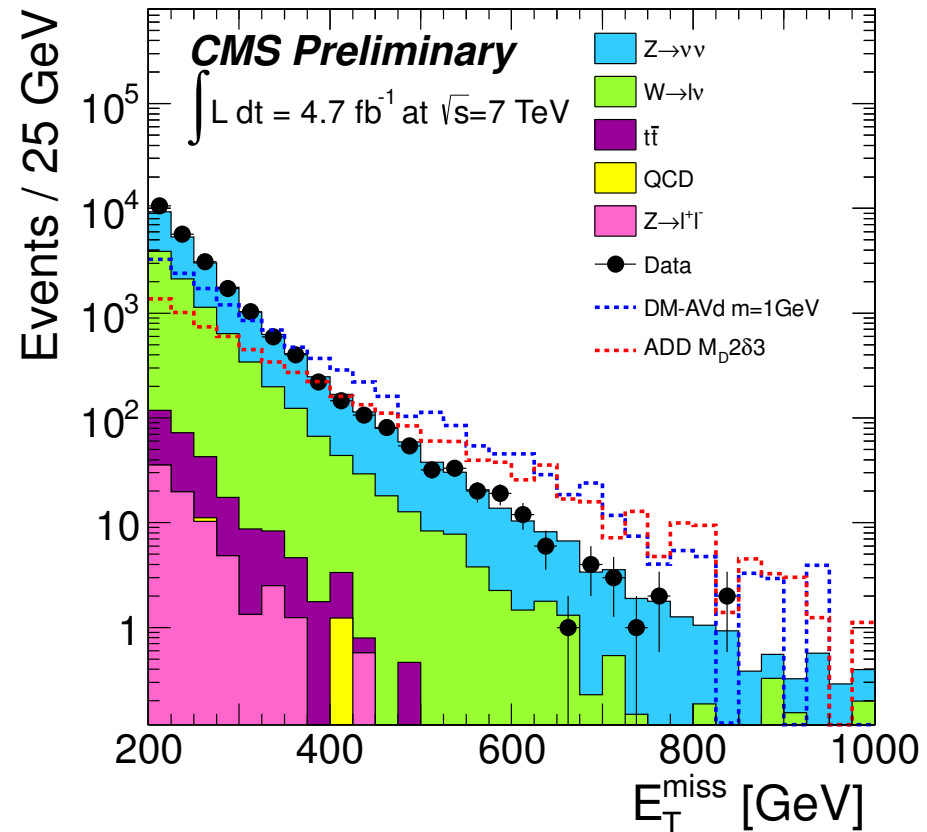
CMS-EXO-11059

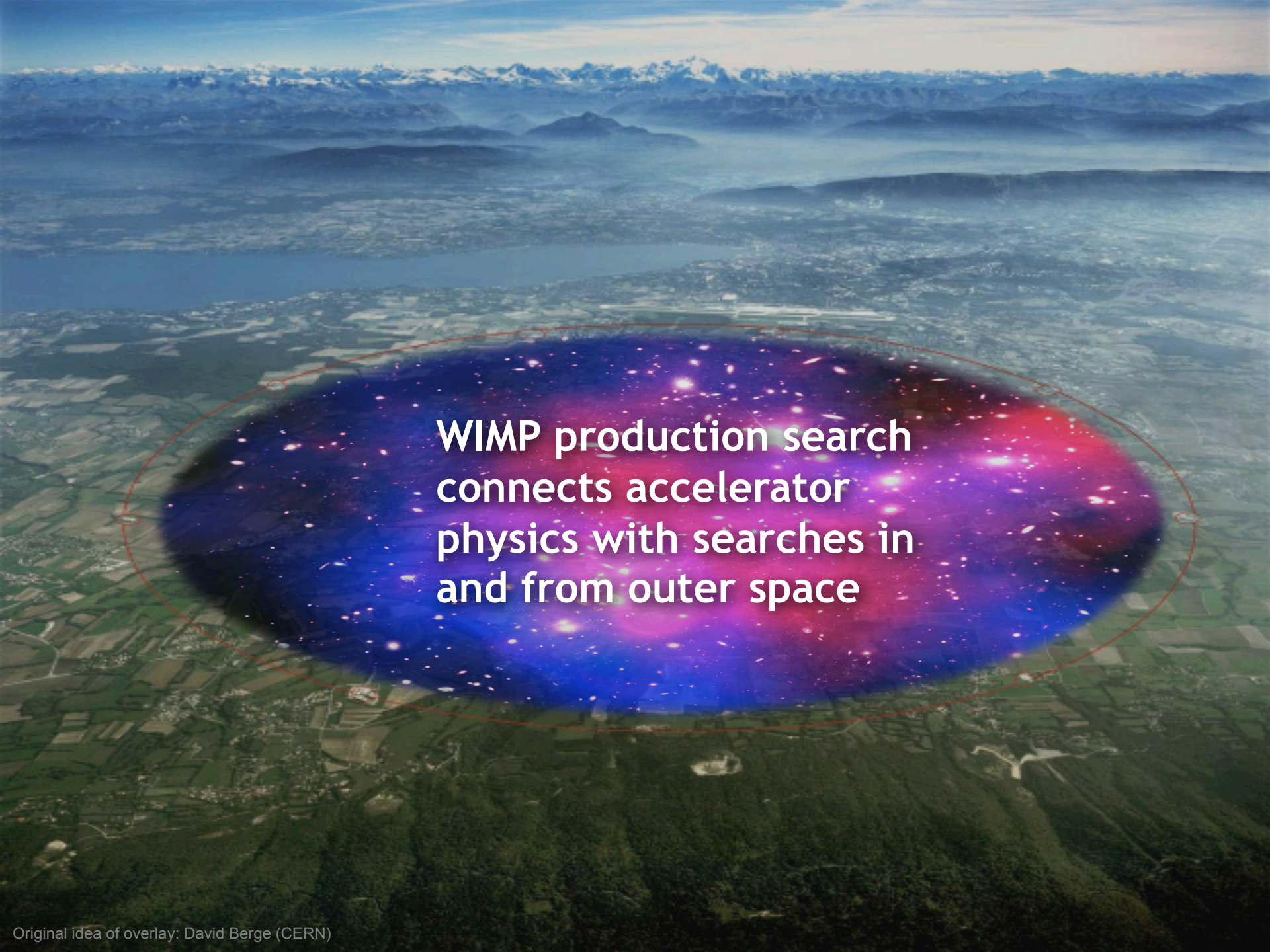
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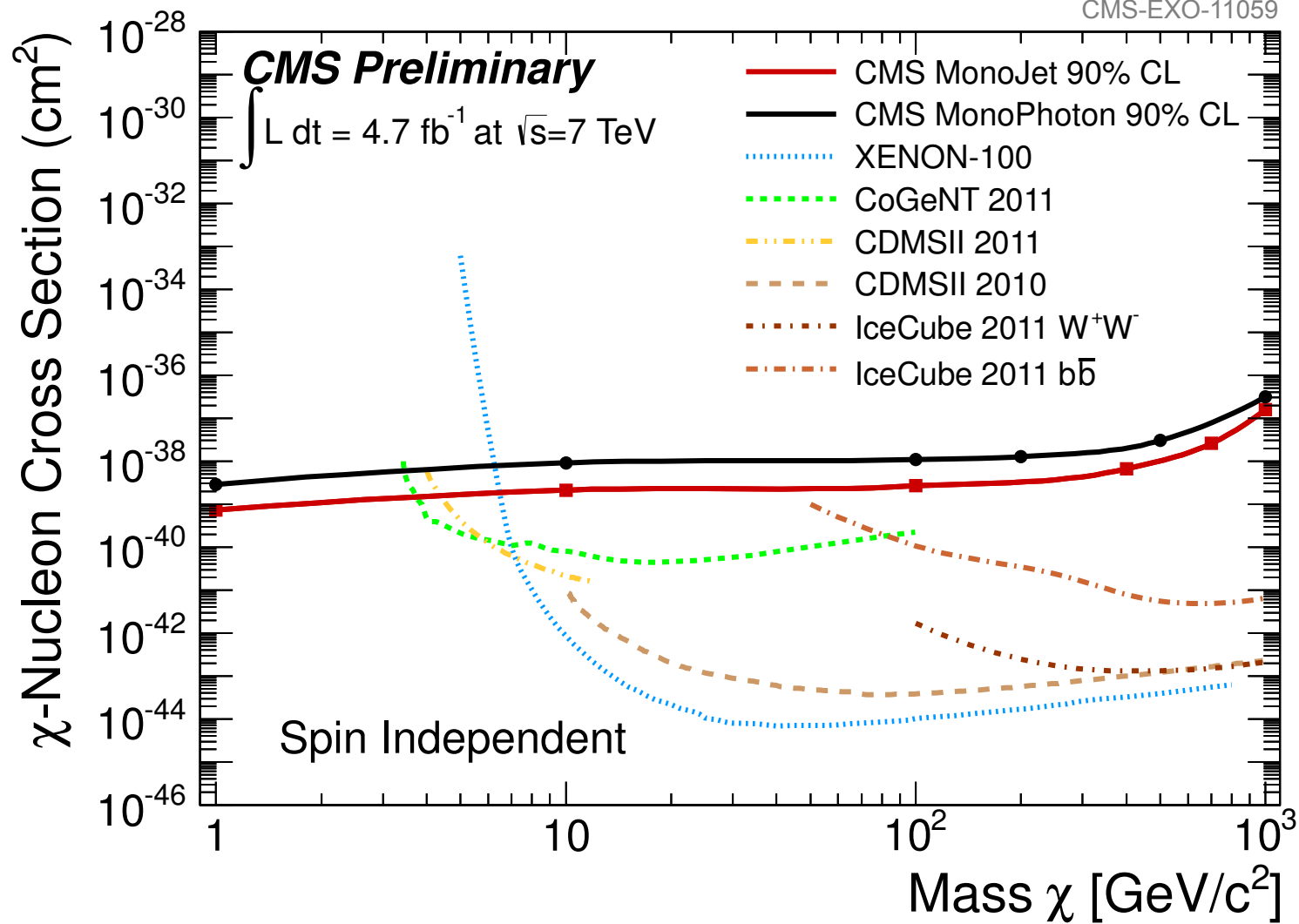


→ Search for mono-jets events!



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**



Several models other than Supersymmetry deal with the hierarchy problem ...

- some also provide dark matter candidates,
- some also grand unification,
- some of them provide new sources of matter-antimatter violation to create the remaining matter,
- some may explain the hierarchy in the observed particle masses,
- some are only valid up to several tenth of TeV, others up to GUT scales...

Many of these models have fascinating features.

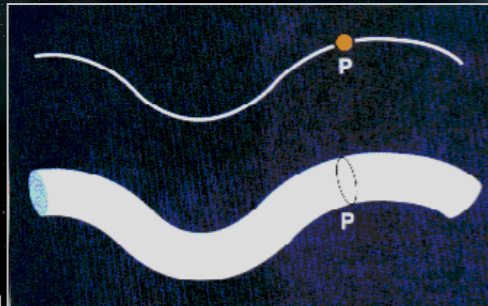
Compact extra dimensions, for example, are small, curled dimensions of micron size or much smaller.

If gravitons propagate in them gravity may become strong and we should observe coupling of SM particles to gravity.

We might then even reach into the trans-Planck regime at the LHC! If also the SM fields propagate in the extra dimensions, they may develop new high-mass states.

If the new phenomena are of TeV scale we should see them.

We hence must search for them at the LHC!



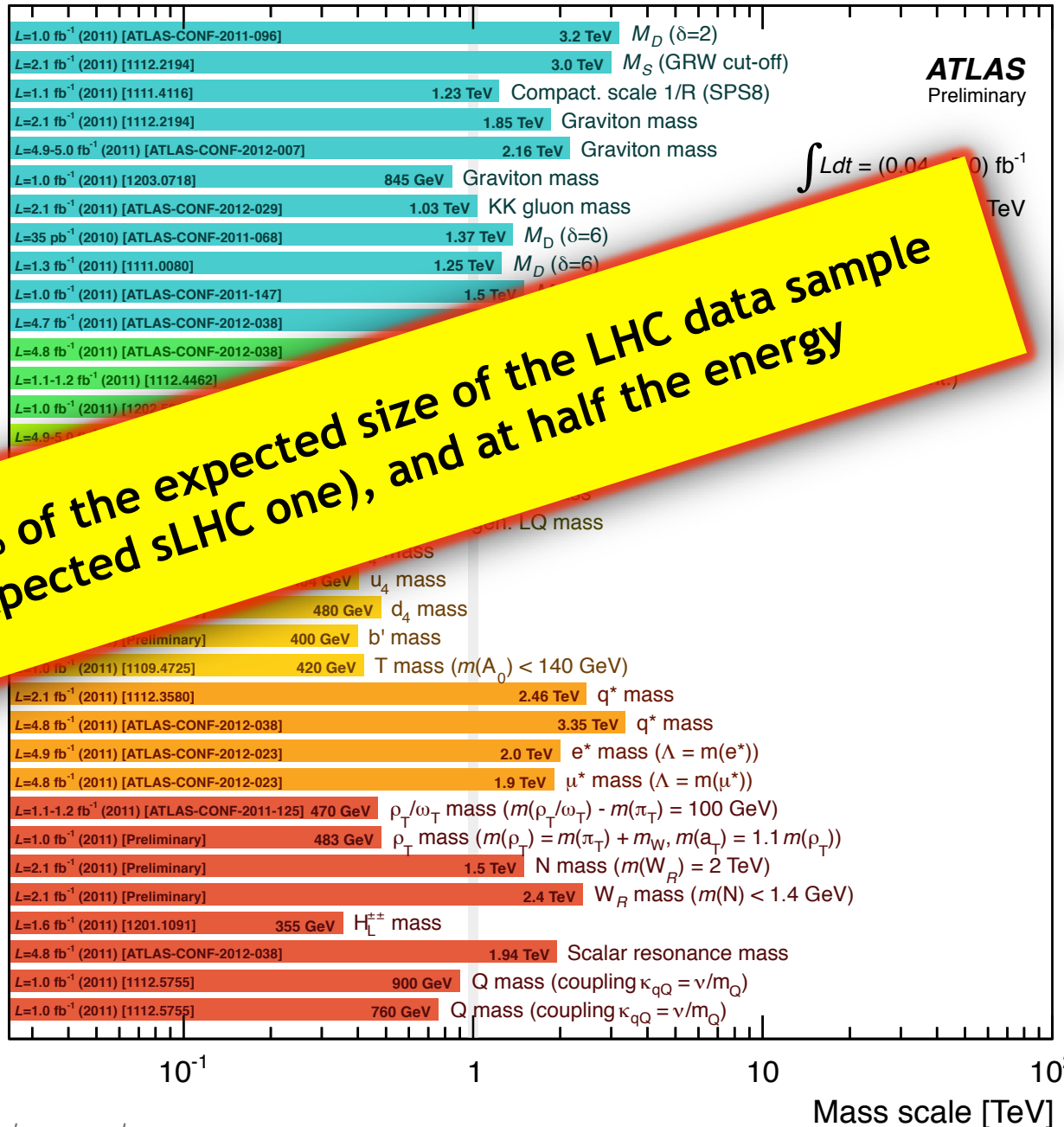
Artist's portrayal of the IC 10 X-1 system: the black hole lies at the upper left and its companion star is on the right

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: March 2012)

ATLAS
Preliminary

$\int L dt = (0.04 \dots 0.1) \text{ fb}^{-1}$
TeV

**We are still below 2% of the expected size of the LHC data sample
(0.2% of the expected sLHC one), and at half the energy**



*Only a selection of the available mass limits on new states or phenomena shown

The LHC is performing marvelously
What are the next steps?

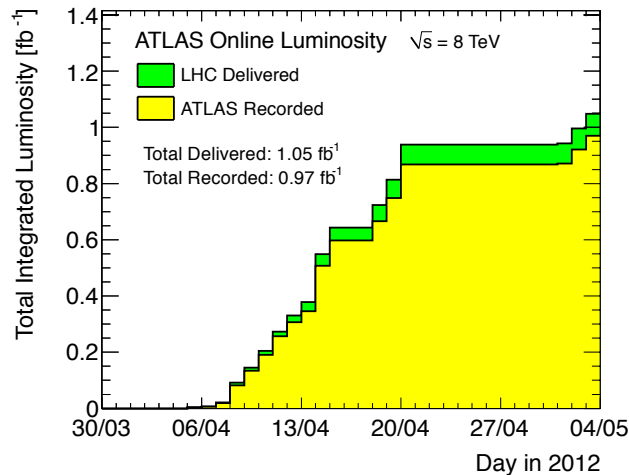
Where are we heading to



Next Steps at the LHC

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

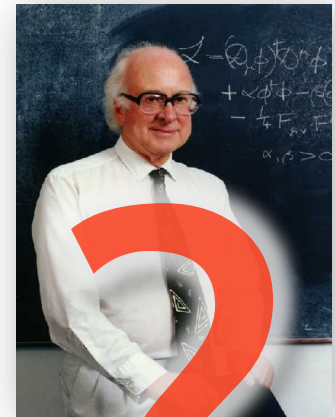
- 2012: LHC runs at 8 TeV until October 2012 $\rightarrow \sim 15 \text{ fb}^{-1}$



LHC on schedule. Current 2012 records:

- peak Lumi: $5.6 \times 10^{-33} \text{ cm}^{-2}\text{s}^{-1}$
- #bunches: 1331
- max. of 0.56 fb^{-1} / 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





Conclusions

The experiments are chasing the last and most important (and peculiar) particle of the Standard Model: the Higgs boson

- So far, we managed to exclude Higgs masses between ~ 118 and ~ 127 (< 600) GeV
- Precision data predict via virtual Higgs effects: $M_H = 94^{+25}_{-22}$ GeV
- Stability of the Standard Model up to the Planck mass requires $M_H > \sim 127$ GeV

The Higgs gives mass, but renders the Standard Model unstable

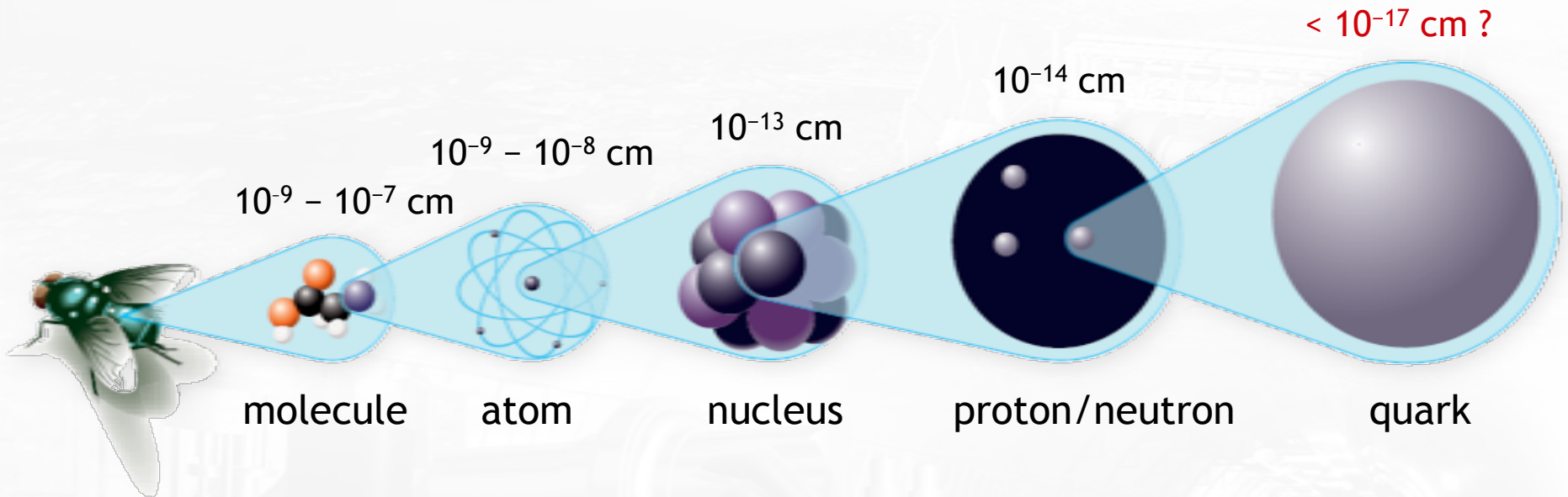
- New theories exist that can stabilise the Standard Model Higgs
- Some of these theories also explain dark matter, lead to grand unification, ...
- We are mining our data for their manifestations, but none have yet been observed
- These results are corroborated by precision measurements (also from the LHC)

We are participating in the largest experiments ever built by mankind

It is our responsibility to work hard, be patient and humble,
in order to observe and interpret Nature as it reveals itself to us

Spare slides...

Particle Physics Scales



Length scale (am) $\sim \frac{200 \text{ GeV am}}{\text{Energy (GeV)}}$

a = atto = 10^{-18}

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



6 Quarks



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

Bosons

Force quanta

Distinguishing 3 forces

Electro-magnetic force

Photon



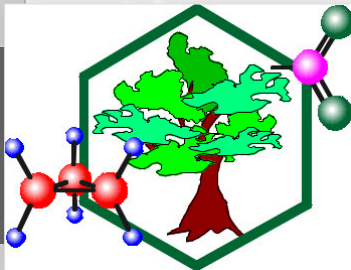
3 weak bosons

Weak force



8 Gluons

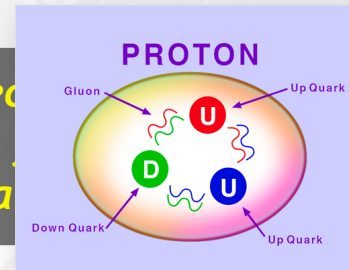
Strong force



liggs bo



*aks elec
erates
es wea*



*ry
n masses
t ranged*

The Standard Model

Brout-Englert-Higgs mechanism

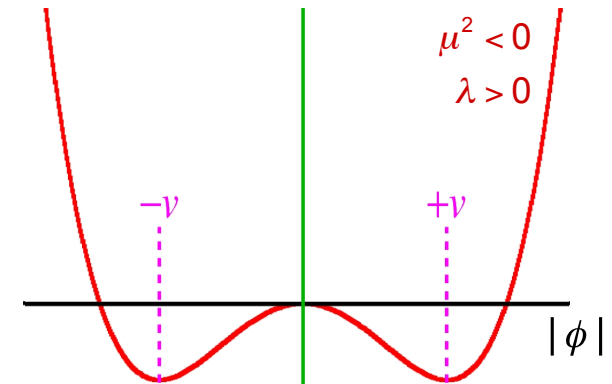
Potential $V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$, ϕ scalar doublet

For $\mu^2 < 0$, the minimum moves away from $\phi = 0$

The ground state ($T = 0$) acquires a non-zero vacuum expectation value (vev) v

Perturbation theory around ground state: $\phi \propto v + H$

H is the Higgs boson. The other 3 components of the doublet ϕ are absorbed to give mass to $W^\pm$ and Z



$$v_{T=0} = |\phi_{\min}| = \sqrt{-\frac{\mu^2}{2\lambda}} = 246 \text{ GeV}$$

v precisely known from muon decay

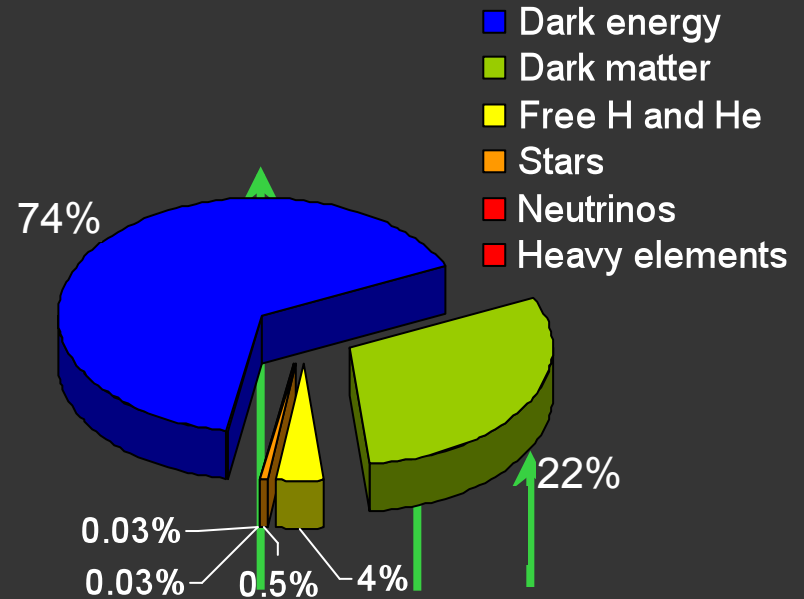
Dark Matter

- *Dark matter* does not emit or reflect sufficient electromagnetic radiation to be detected

- Evidence for dark matter stems from:

- Gravitational lensing obs.
- Rotation curves galaxies
- Anisotropy of cosmic microwave background radiation

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



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

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)

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

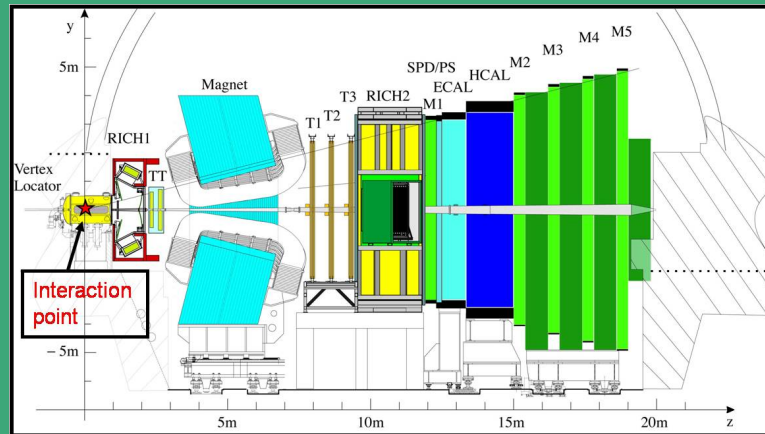
When $\sigma_A \ll H(T)$, some χ freeze out and create weakly interacting dark matter Ω_{DM}

The abundance of the dark matter inverse proportional to the annihilation cross section

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

COINCIDENCE ?

Dedicated B physics Experiment



LHCb: emphasis on low- p_T physics with large forward cross section. Excellent vertex and momentum resolution, π / K separation

Physics aims: search for new physics through measurement of CP violation and rare B decays

Why Colliding Hadrons instead of e^+e^- ?

Advantage of hadron collider

- Can reach higher energies in ring (less synchrotron radiation)

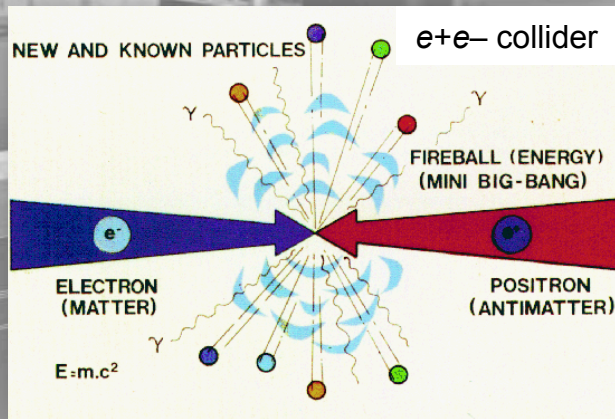
Energy loss per turn:

$$-\Delta E \approx \frac{4\pi\alpha}{3 \cdot R} \left(\frac{E}{m} \right)^4 \approx \begin{cases} 3.5 \text{ GeV for LEP-II at } E_{\text{beam}} = 104.5 \text{ GeV} \\ 6.2 \text{ keV for LHC at } E_{\text{beam}} = 7000 \text{ GeV} \end{cases}$$

High e^+e^- energy
requires linear
collider: *ILC, CLIC*

Disadvantages

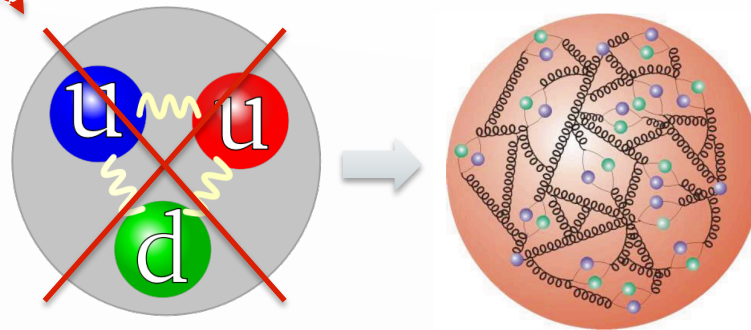
- Hadrons are composites $\rightarrow$ parasitic collisions beyond hard parton scattering
- Energy and type of colliding parton unknown $\rightarrow$ kinematics partially unconstrained



Proton-Proton Collisions

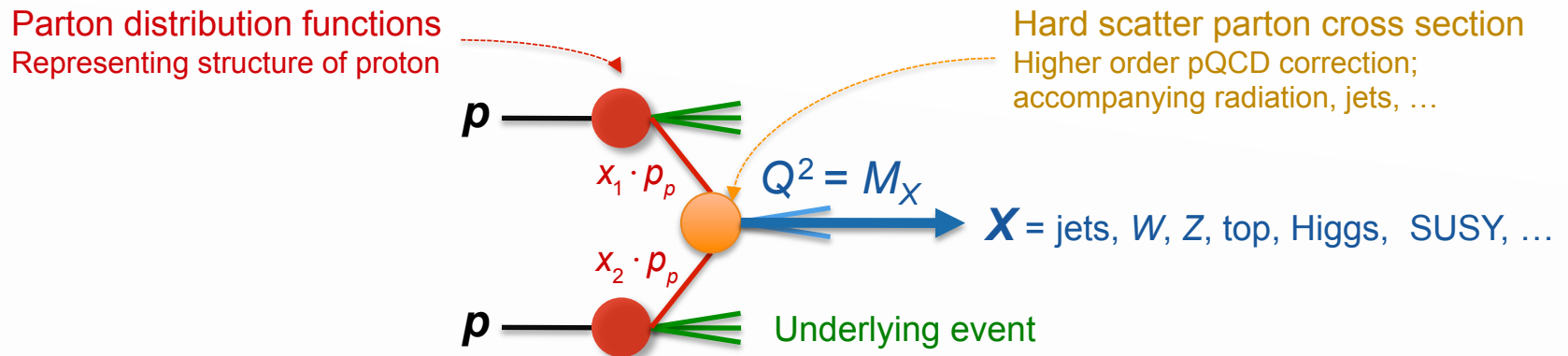
- For proton-proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element

Parton distribution functions
Representing structure of proton



Proton–Proton Collisions

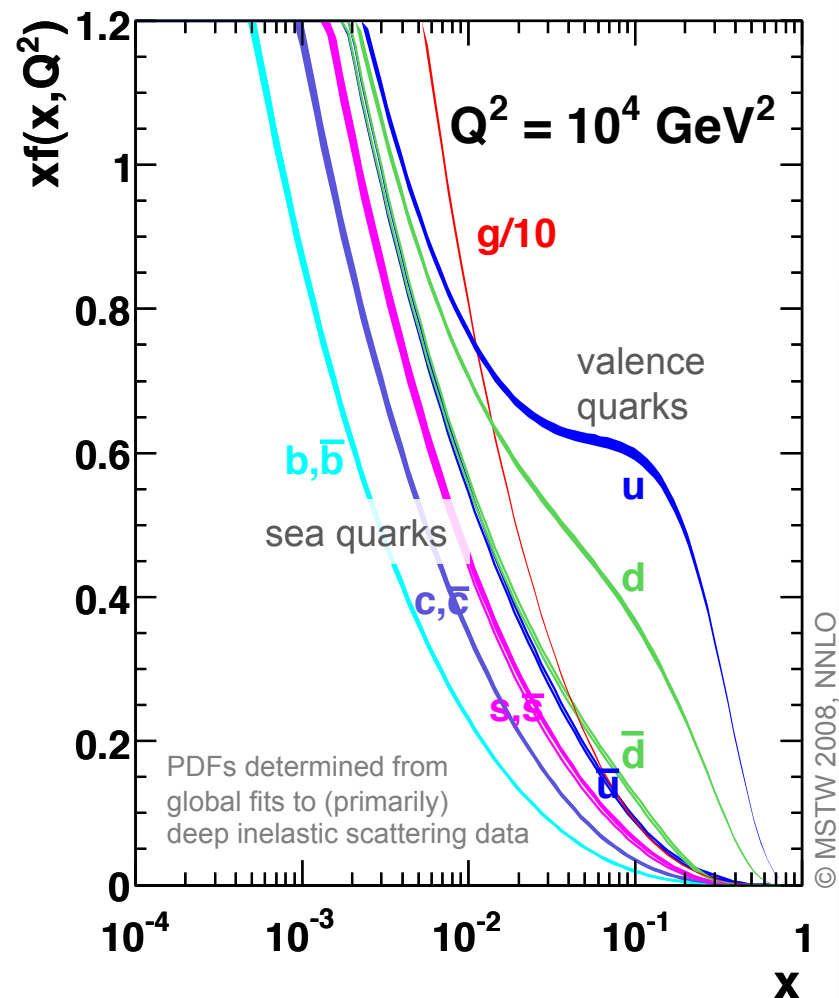
- For proton–proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element



- 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
 - Low- x (eg, Higgs) dominated by gluon–gluon collisions: “gluon collider”

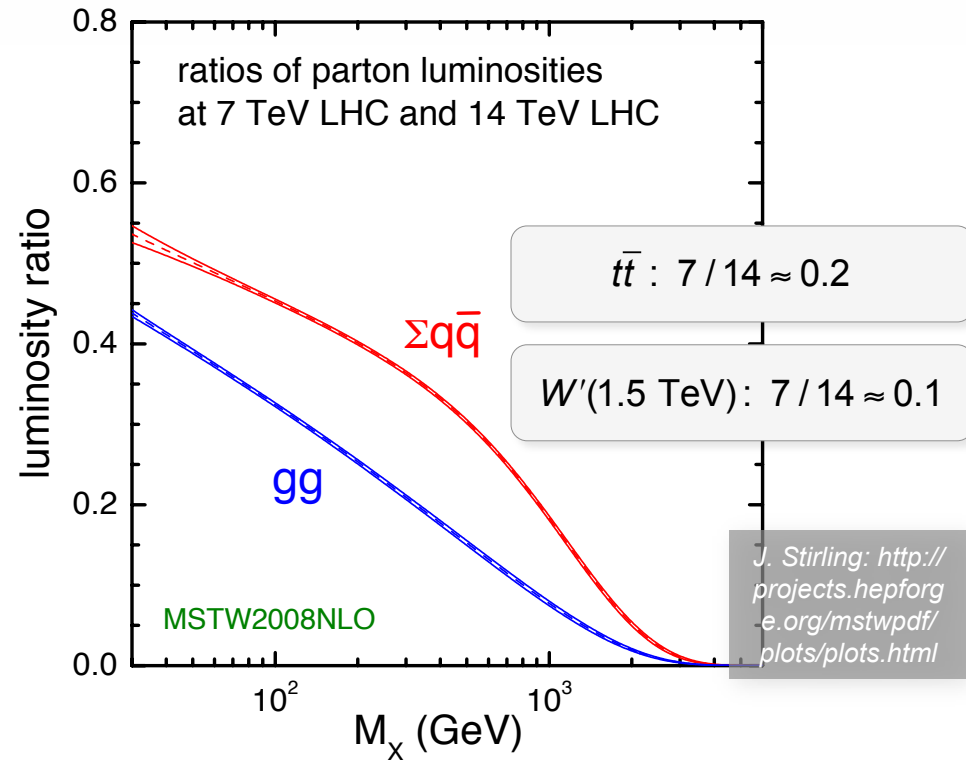
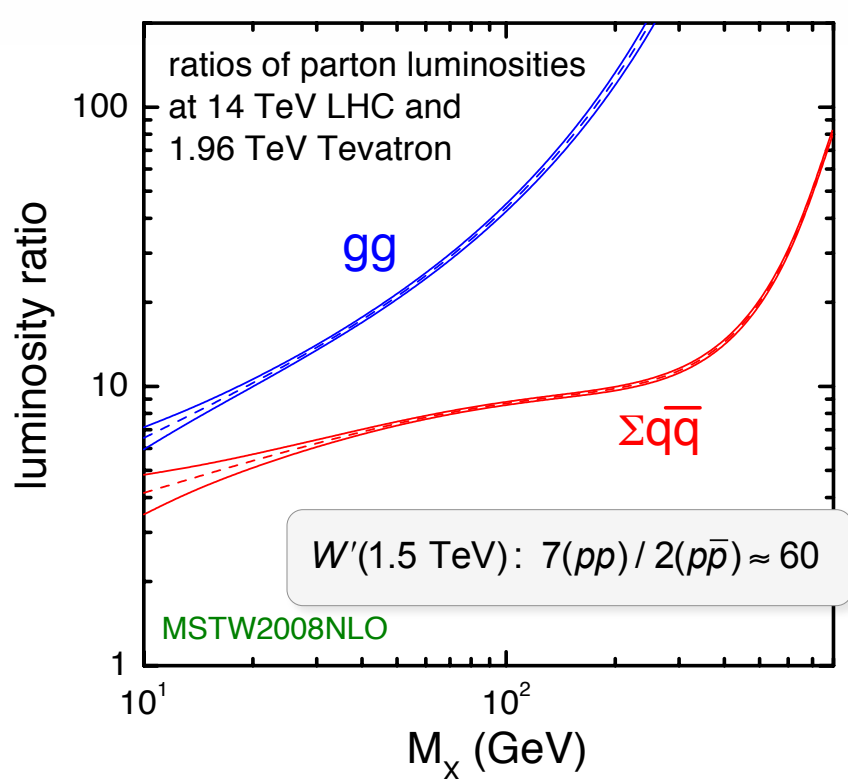
Proton–Proton Collisions

- Proton is complicated composite of valence quarks, gluons and sea quarks
- PDF depends on 2D mixture of
 - Q^2 (evolution in $\ln(Q^2)$ predicted by QCD)
 - Bjorken x momentum fraction
- CM energy of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- Typical ‘ x ’ values (assume: $x_1 = x_2$)
 - LHC ($\sqrt{s} = 14 \text{ TeV}$):**
 - $M_X = 100 \text{ GeV (1 TeV)} \rightarrow \langle x \rangle = 0.007 \text{ (0.07)}$
 - Tevatron ($\sqrt{s} = 2 \text{ TeV}$):**
 - $M_X = 100 \text{ GeV (1 TeV)} \rightarrow \langle x \rangle = 0.05 \text{ (0.5)}$
- PDFs rise dramatically towards low x
 - **larger cross sections at LHC**
 - “gluon collider”



Parton Luminosities at LHC and Tevatron

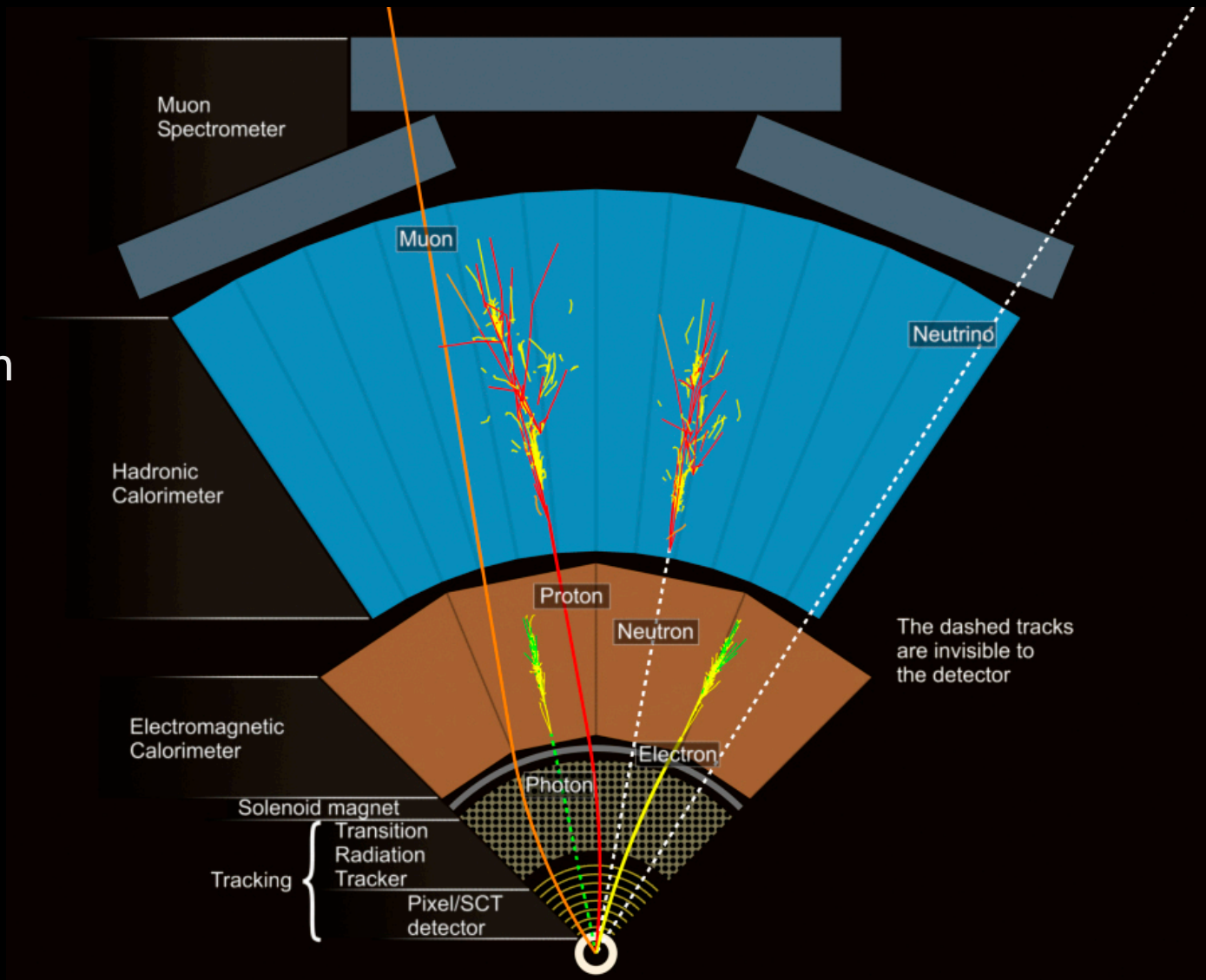
Ratio of “parton luminosities” of LHC-to-Tevatron and LHC 7 TeV-to-14 TeV

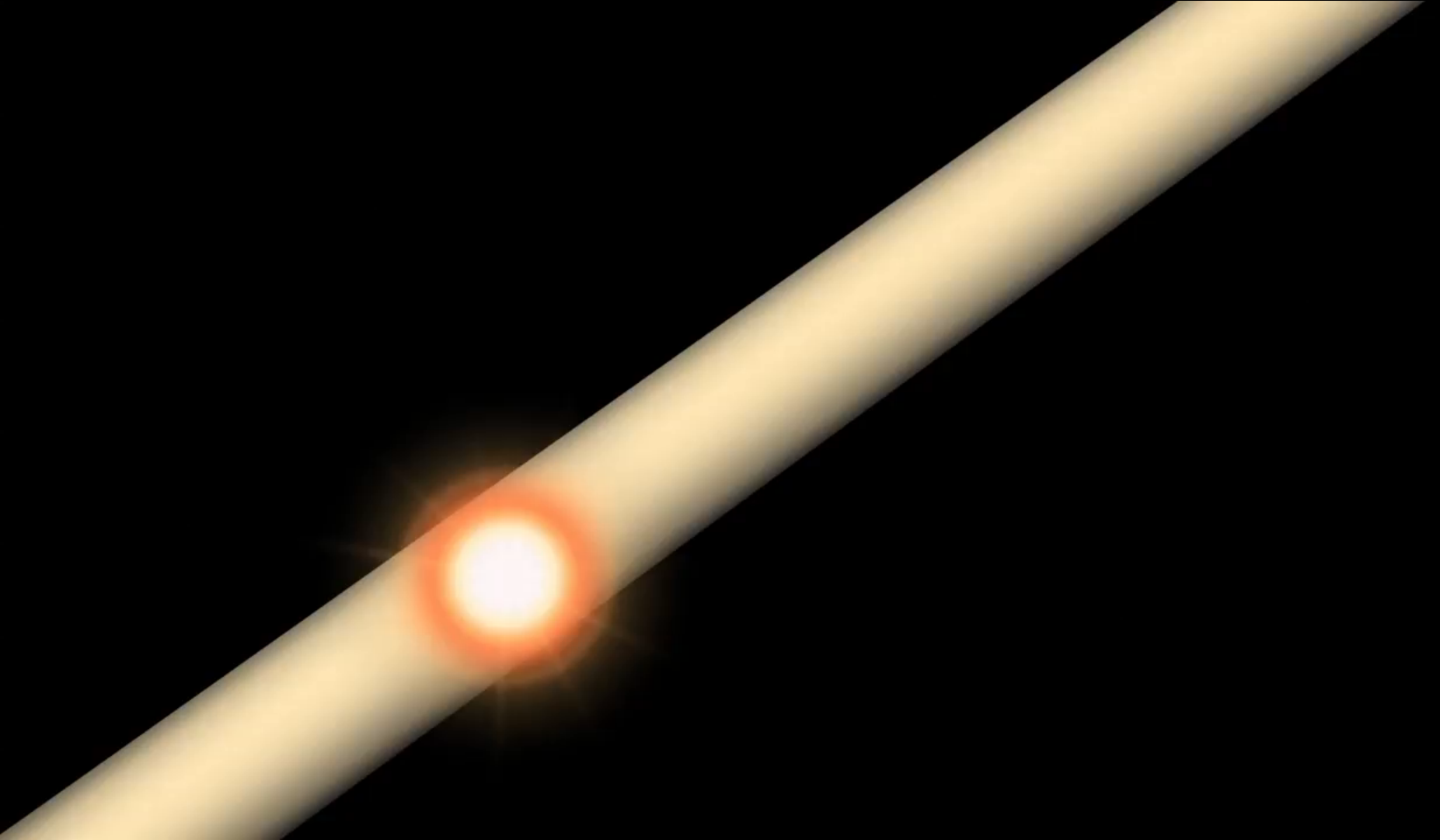


- High M_X production through gluon fusion requires large CM energy
- Less so for quark-antiquark scattering which has slow rise for $M_X < 300 \text{ GeV}$

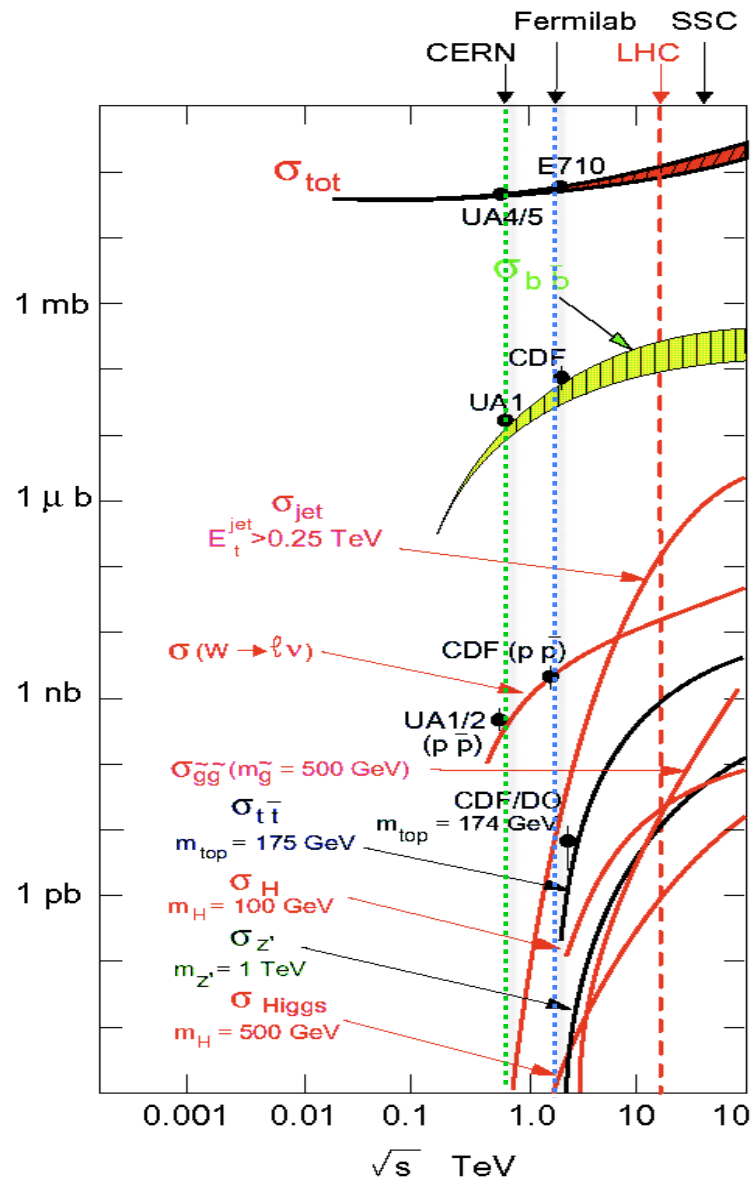
Detector Layers

Particles are detected through their interaction with the active detector materials





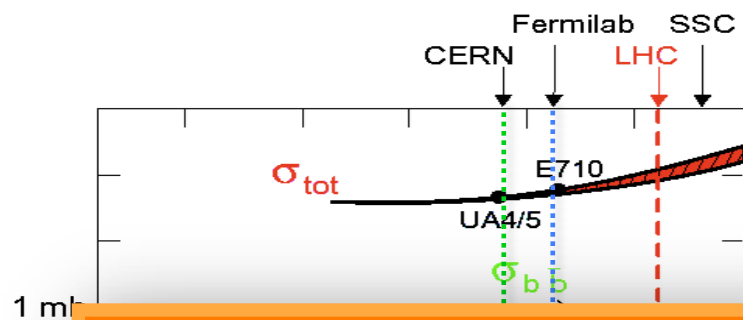
$pp(\text{bar})$ Cross Sections



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

Recall: $1 \text{ pb}^{-1} \triangleq 10^{36} \text{ cm}^{-2}$
 $\Rightarrow 15 \text{ nb} \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} =$
 $15 \text{ nb} \times 10^{-2} \text{ pb}^{-1}\text{s}^{-1} = 150 \text{ Hz}$

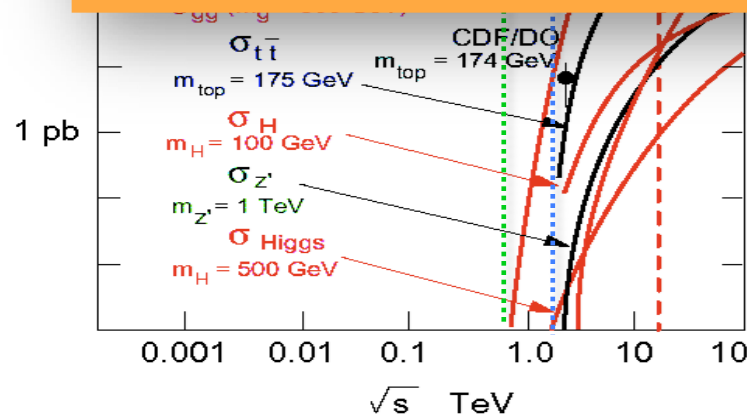
$pp(\text{bar})$ Cross Sections



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

Many orders of magnitude between QCD background and primary physics channels (only one in five billion events is Higgs - Tevatron: only every trillionth event!)

→ This fact drives the trigger and detector design



H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

Recall: $1 \text{ pb}^{-1} \triangleq 10^{36} \text{ cm}^{-2}$
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The LHC proton-proton Physics Programme

1. Mass and electroweak symmetry breaking

- Search for the Higgs Boson, measurement of its properties

2. Hierarchy in the TeV domain

- Search for new phenomena moderating the hierarchy problem
- Search for the unexpected at the high-energy frontier

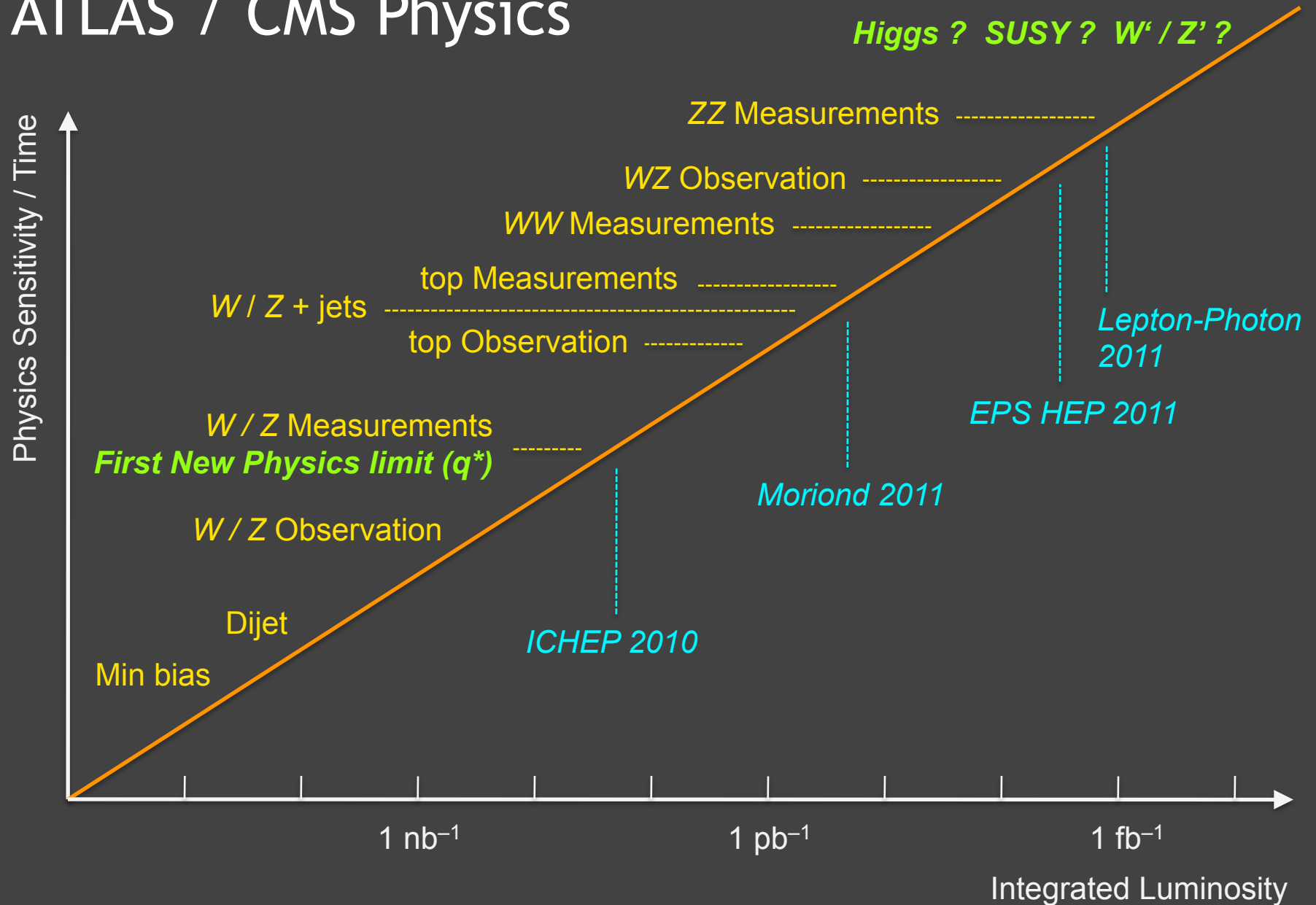
3. Electroweak unification and strong interactions

- Precision measurements and tests of the Standard Model
- Tests of perturbative QCD at the high-energy frontier

4. Flavour

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

ATLAS / CMS Physics

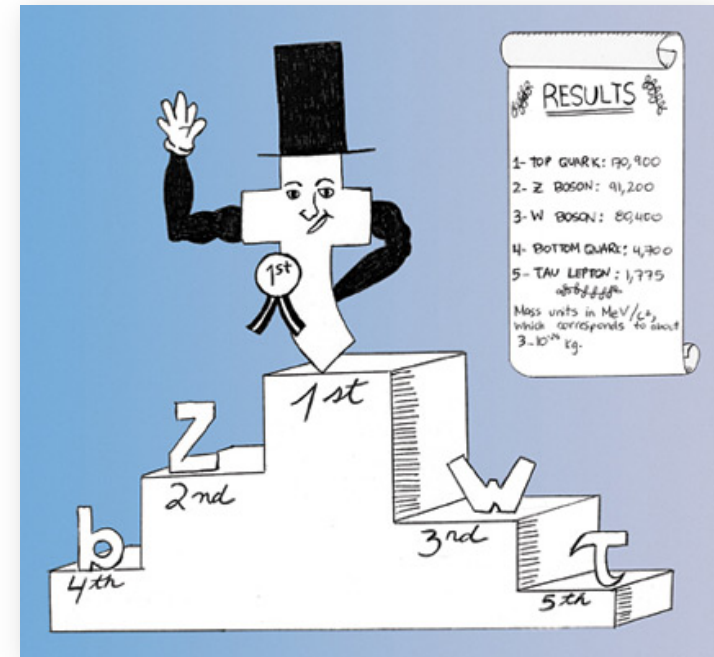


ATLAS and CMS have unambiguously seen top events

Both experiments measured cross sections and top properties

The top quark is the heaviest known elementary particle

- Almost as heavy as a gold atom...
- It is that heavy that it decays to bW^+ before it can form hadrons: its lifetime of 5×10^{-25} s (half a *yoctosecond*, $\Gamma t \approx 1.5$ GeV) is smaller than hadronization time: $1/\Lambda_{\text{QCD}} \sim 3 \times 10^{-24}$ s
- When a top pair is produced at LHC, it can only fly ~ 0.1 fm within its lifetime, but the typical hadron size is 1 fm. At 0.1 fm, QCD is weak due to asymptotic freedom
- There are thus no toponium bound states
- Top is believed to be preferably involved in reactions with **heavy new physics particles**



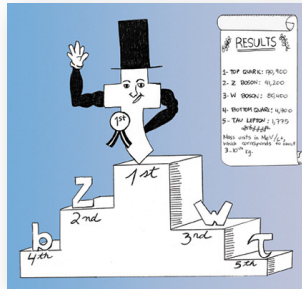
© Kurt Riesselmann, Symmetry 04-05-07

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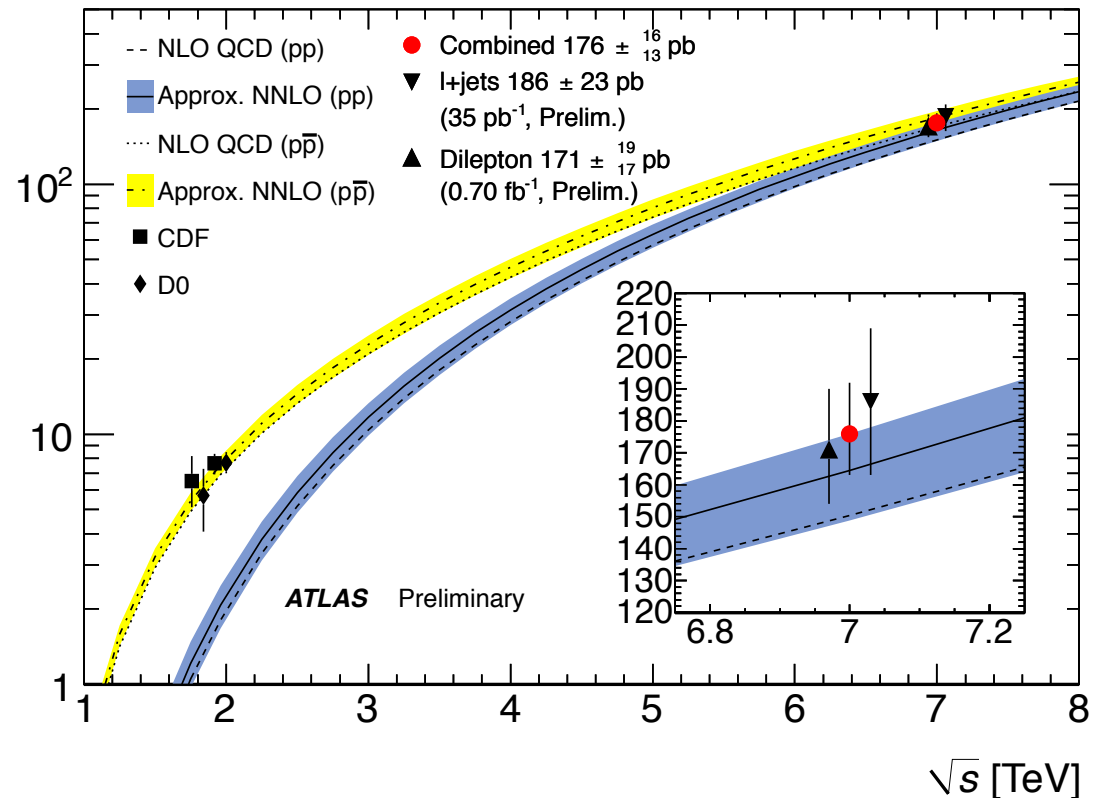
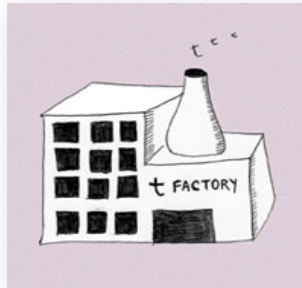
ATLAS-CONF-2011-108

Heaviest
known
particle



LHC is **top** factory:

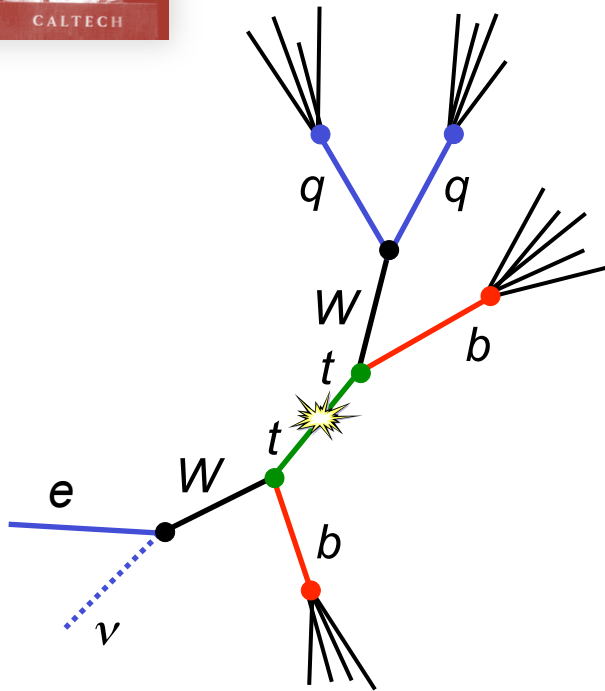
at 7 TeV CM
energy: ~25
times larger
cross section
than at Tevatron



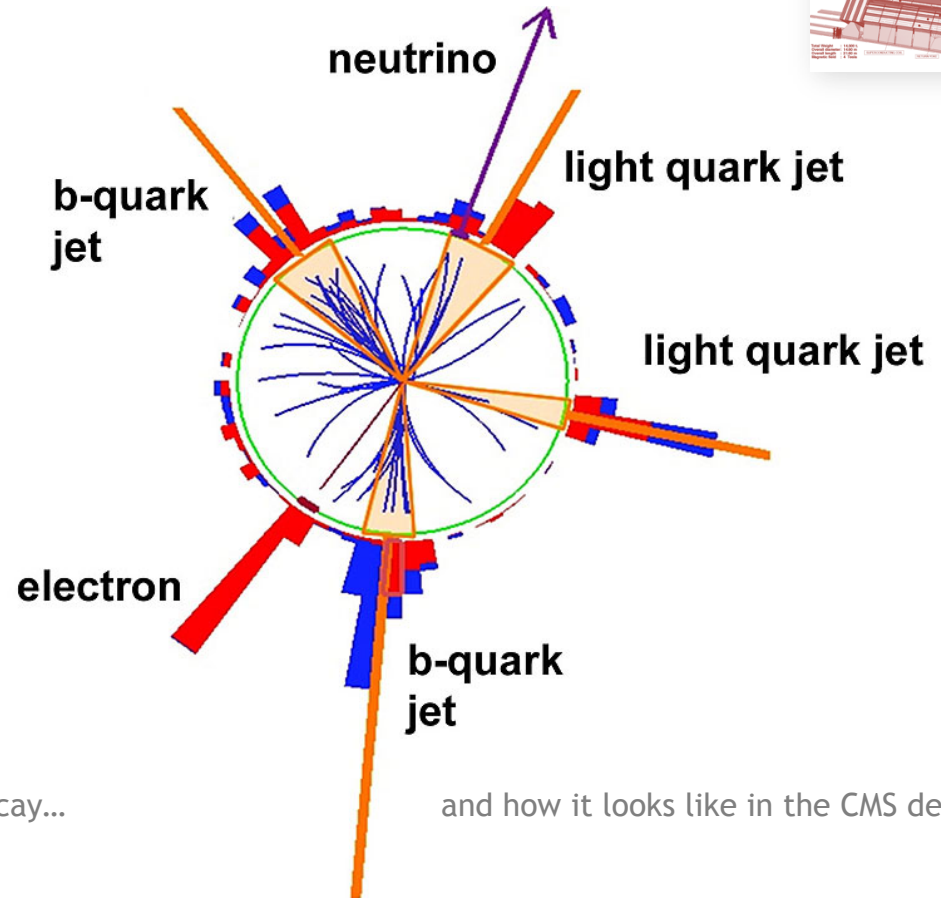
First precision measurements of top cross section and mass at LHC
Searches for new physics in top production and decay

ATLAS and CMS have unambiguously seen top events

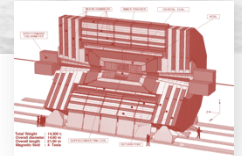
Both experiments measured cross sections and top properties



Sketch of top pair production and semileptonic decay...

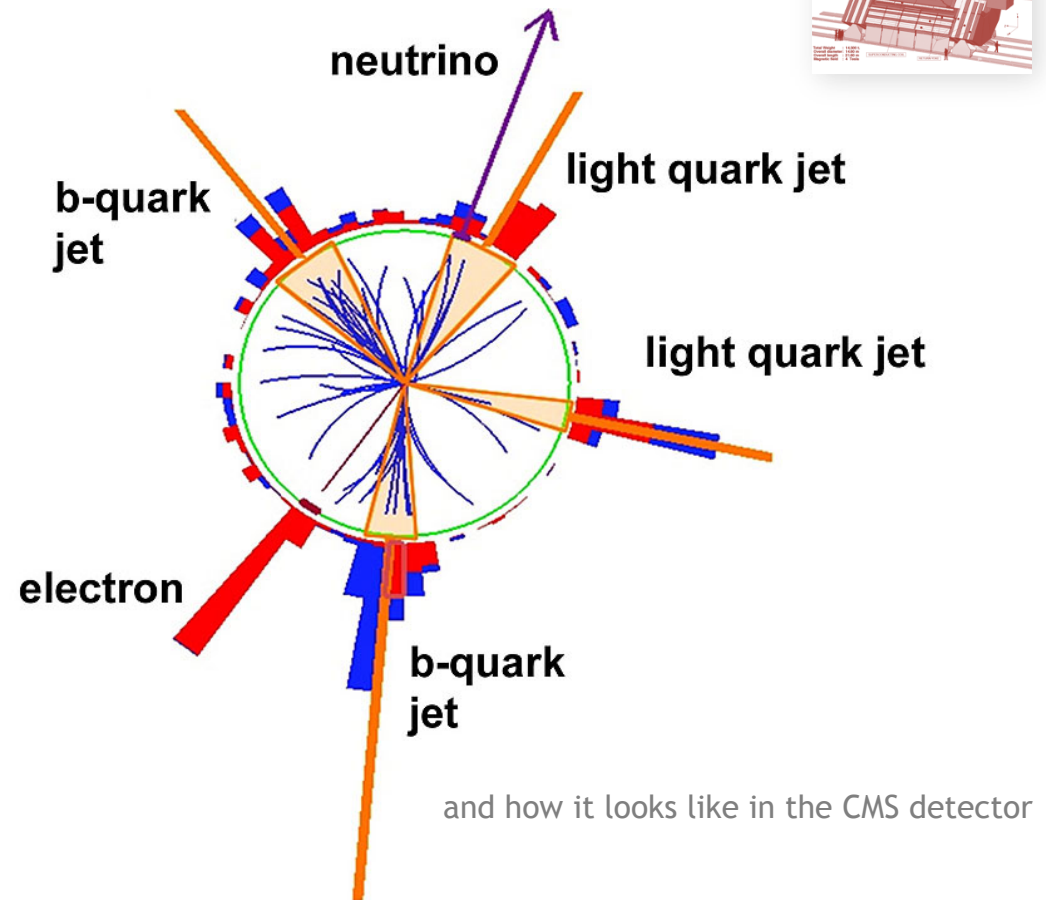
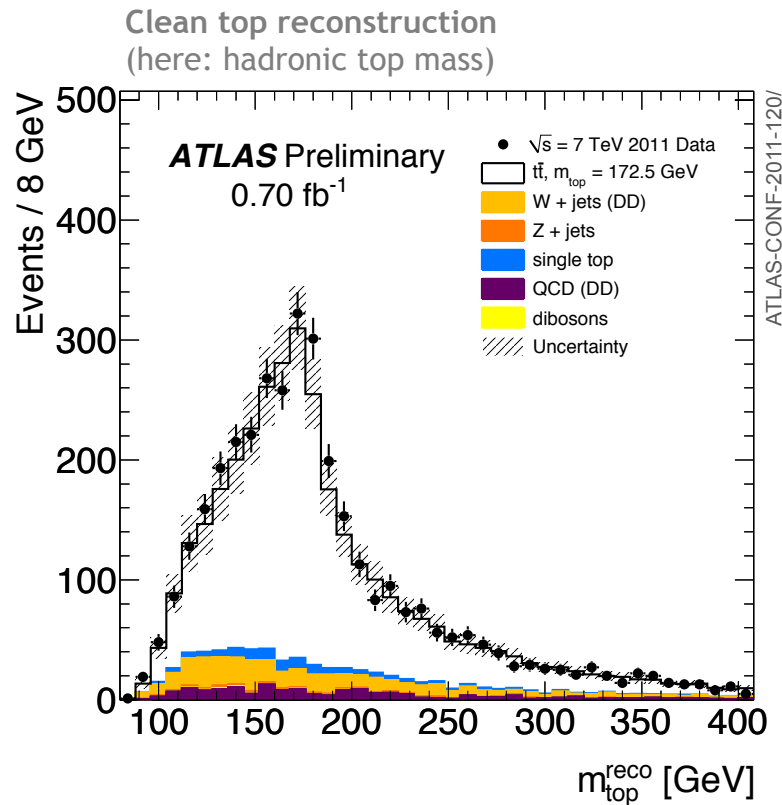


and how it looks like in the CMS detector



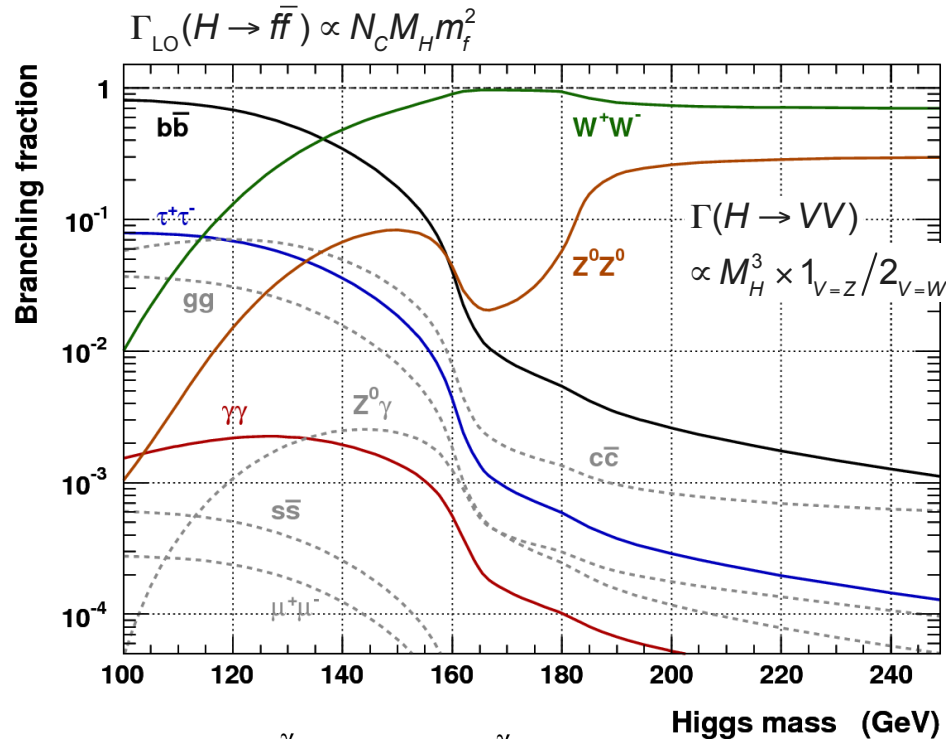
ATLAS and CMS have unambiguously seen top events

Both experiments measured cross sections and top properties



Higgs searches at the LHC

Dependence of the branching fractions on M_H drives search strategy



For **medium to heavy Higgs**:

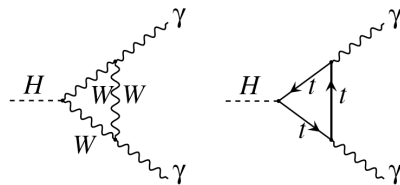
- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$

For **light Higgs**:

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

The dominant $H \rightarrow b\bar{b}$ mode is only exploitable in association with W/Z or $t\bar{t}$, also with strong Higgs boost

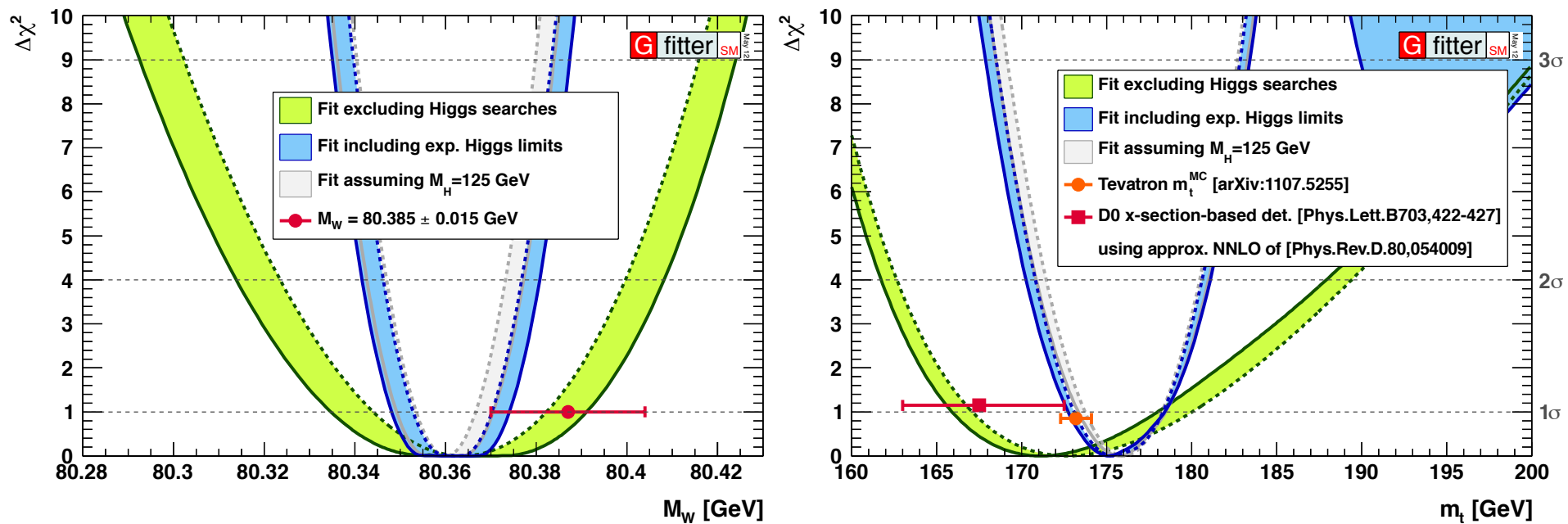
Associated leptons provide trigger signal as they help to reduce huge QCD background, $s(b\bar{b}) \sim \mathcal{O}(100 \mu\text{b})$



$$\Gamma(H \rightarrow \gamma\gamma) \propto \alpha^2 \cdot M_H^3 \cdot |N_c Q_t^2 A_t^H + A_W^H|^2$$

Constraints from global electroweak fit

Vice versa, the strong direct Higgs mass constraints allow to predict M_W and m_{top}

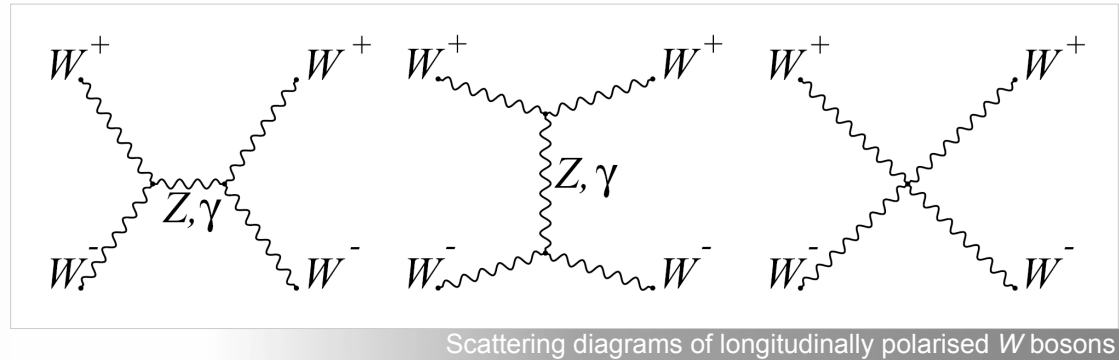


<http://gfitter.desy.de>

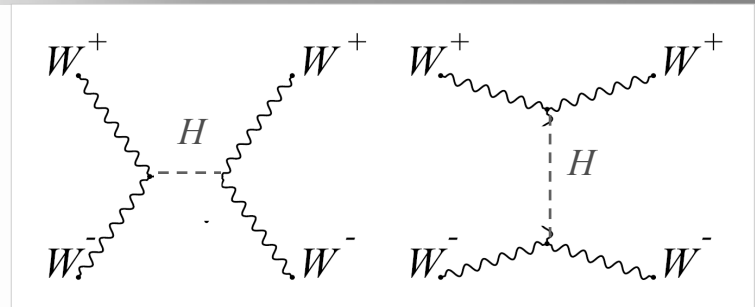
Unitarity – the Higgs Boson as UV Regulator

Unitarity problem: the amplitude of (longitudinal – since the W 's are massive) W^+W^- scattering diverges if only Z bosons and photons are exchanged:

$$\mathcal{M}_{Z,\gamma}(W_L^+W_L^- \rightarrow W_L^+W_L^-) \propto \sqrt{2}G_F \cdot (s+t)$$



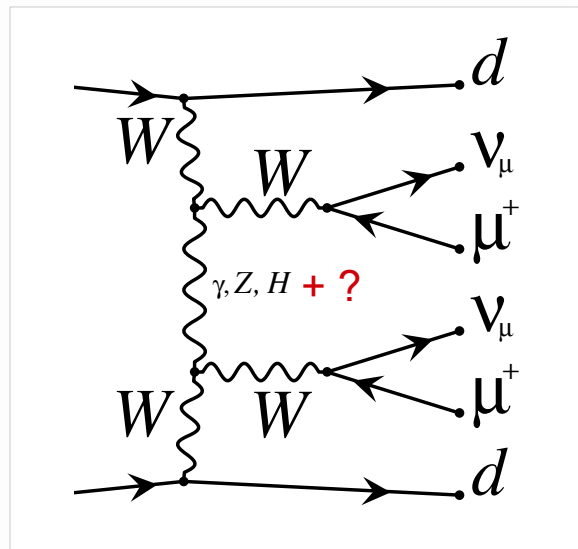
$$\mathcal{M}_{Z,\gamma,H}(W_L^+W_L^- \rightarrow W_L^+W_L^-) \propto -\sqrt{2}G_F \cdot M_H^2 \cdot \left(\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2} \right)$$



- Higgs exchange regularises matrix element (if $M_H \leq 1/\sqrt{G_F} \sim 300$ GeV, while when doing a proper partial wave analysis of the scattering amplitude, the limit weakens)
- Higgs is a “UV Moderator”

Strong WW Scattering ?

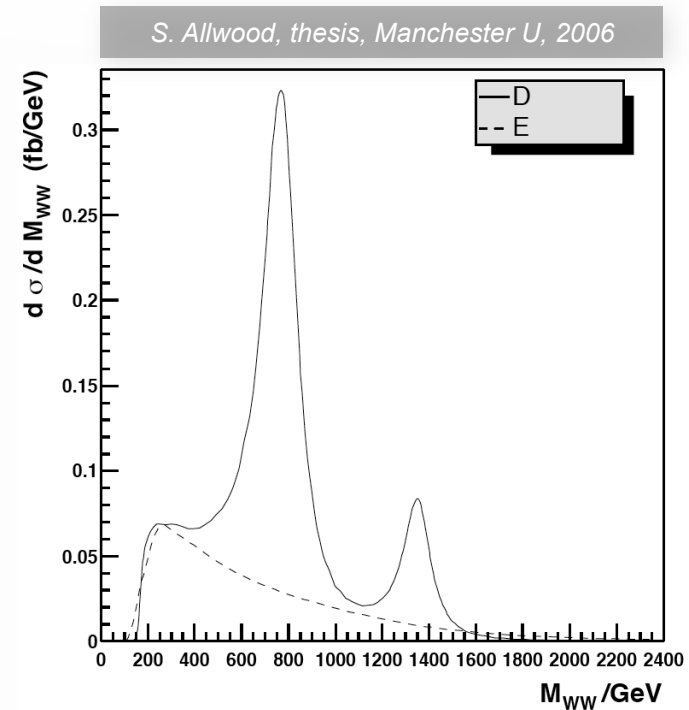
If the Higgs is very heavy, or if EW symmetry is broken by something else than a Higgs condensate (e.g., by strong interactions), W bosons would become **strongly interacting particles at TeV scale**.



Fusion of longitudinally polarised W at the LHC

Growth of scattering amplitude cancelled at $O(\text{TeV})$ by exchange of new fields

The experimental signature could be strong **WW** resonances



Strong WW Scattering ?

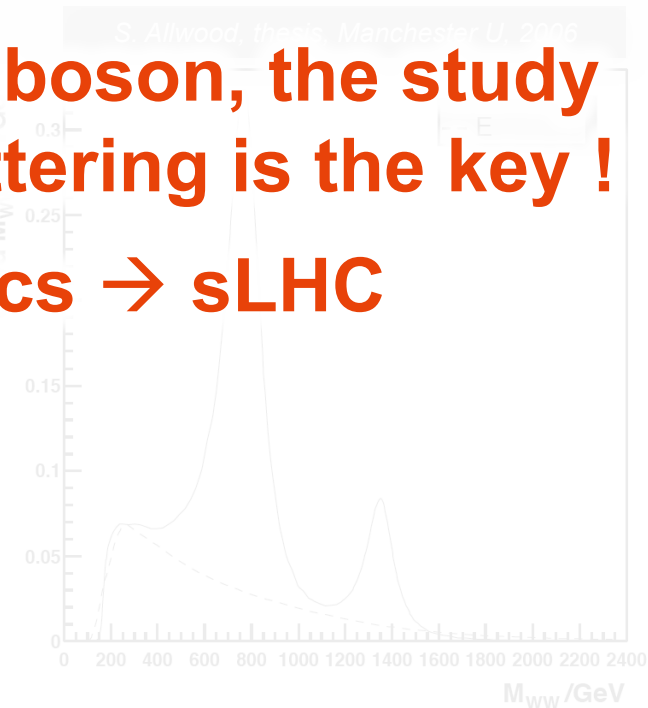
If the Higgs is very heavy, or if EW symmetry is broken by something else than a Higgs condensate (e.g., by strong interactions), W bosons would become **strongly interacting particles at TeV scale**.

If the LHC does not find a Higgs boson, the study of longitudinal gauge boson scattering is the key !

This requires large statistics $\rightarrow$ sLHC

The growth of the scattering amplitude is cancelled at scale M_{SB} of $O(\text{TeV})$ (unitarity limit) by exchange of new fields from L_{SB}

The experimental signature could be strong **WW resonances**



The Mass of the Scalar is Unprotected

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



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

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

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

The “Gauge Hierarchy Problem”

The Gauge Hierarchy Problem...

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

Ultimately, the missing protection of the scalar Higgs boson mass is related to the **absence of a symmetry principle**. Indeed, setting the Higgs mass to zero in the SM Lagrangian, **does not restore any symmetry in the model**.

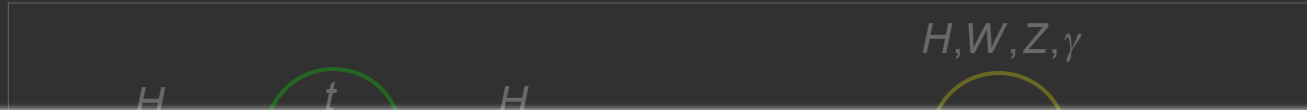
New physics models should address this. **Supersymmetry** for example offers the feature that fermionic and bosonic d.o.f. conspire to cancel the quadratic loop divergences, when the symmetry is exact

Other models, like the **Little Higgs**, interpret the Higgs as Goldstone boson of some approximate symmetry.

→ M_H becomes a deviation from some exact symmetry, and thus is **intrinsically small !**

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Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**.
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$$m_H^2 = (120 \text{ GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

Paper Statistics in SPIRES

Is SUSY out already?

