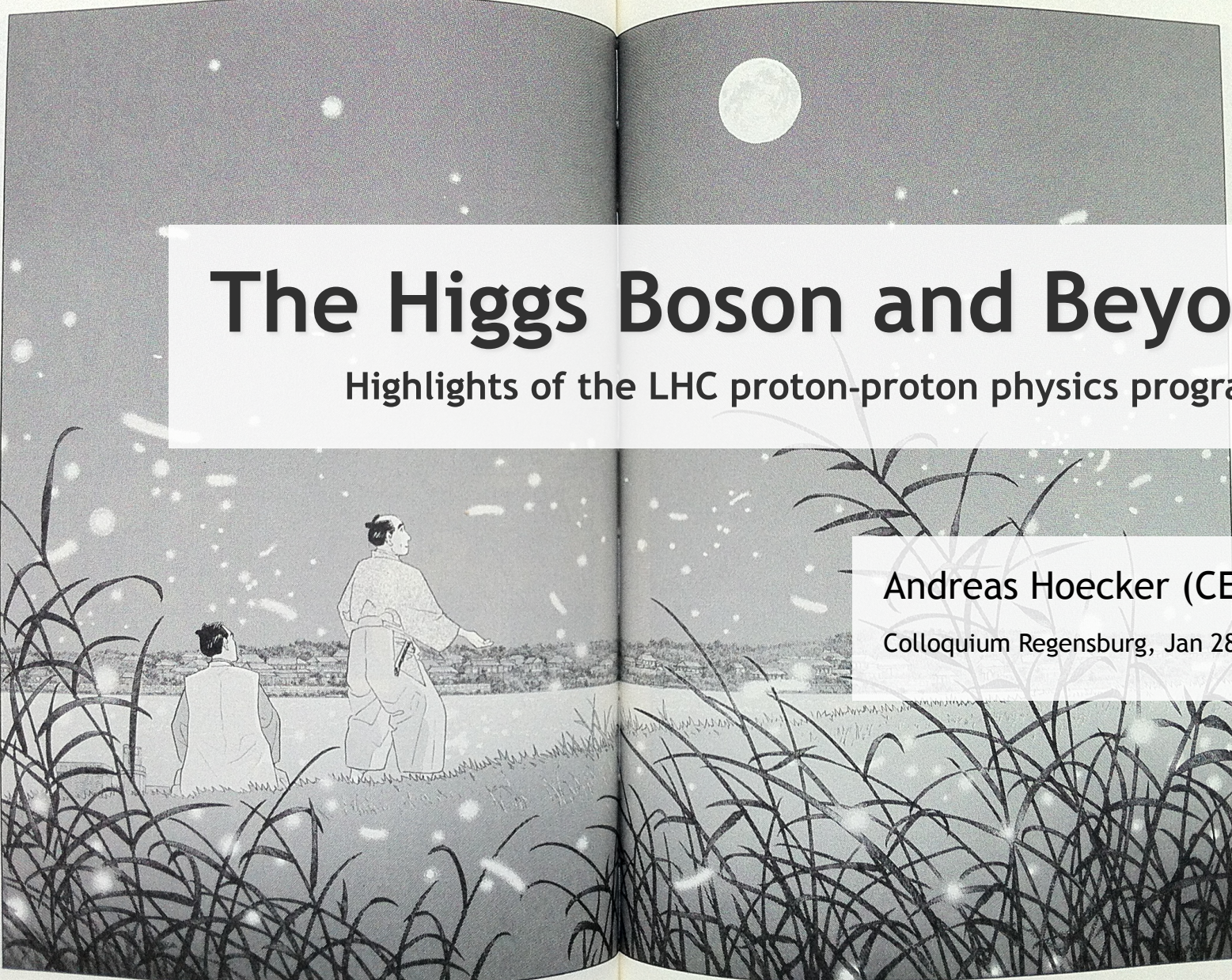




The Higgs Boson and Beyond

Highlights of the LHC proton-proton physics programme

Andreas Hoecker (CERN)

Colloquium Regensburg, Jan 28, 2013

What is particle physics ?

Jiro Taniguchi, Furari, © Casterman (2012)



*"It's all made of a handful
of particles and forces"*

*"Through its relation with
cosmology the study of
particles and forces is also
a journey back in time"*

Jiro Taniguchi, Furari, © Casterman (2012)



*"Can we truly grasp the magnitude of
everything that has unfolded in the
natural universe between those first
momentary particles and the present
day?"*

Brian Watson in *The Salem News* (Aug 16, 2012)

**Mankind's search for the smallest unit of
matter, its different forms, and the
forces acting is much, much older than
*particle physics***

***Particle physics* is a term naming the
search for the ultimate laws of Nature**

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

Jiro Taniguchi, Furari, © Casterman (2012)



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

- *It unifies quantum mechanics, special relativity and field theory*
- *It describes ~ all laboratory data*

**Is the SM the theory of everything?
Or rather of *almost* everything? Or ...**

Year
when
energy
reached
in labs

~2010

~1970

~1900

$L_{\text{gravitation}} \sim 10^{-35} \text{ m}$

$L_{\text{weak}} \sim 10^{-18} \text{ m}$

$L_{\text{strong}} \sim 10^{-15} \text{ m}$

$L_{\text{atomic}} \sim 10^{-10} \text{ m}$

10^{19} GeV

10^{16} GeV

10^{14} GeV

10 TeV

1 TeV

100 GeV

10 GeV

1 GeV

100 MeV

10 MeV

1 MeV

100 keV

10 keV

1 keV

100 eV

10 eV

1 eV

100 meV

10 meV

0

Planck scale (M_{Pl})

GUT ?

ν_R ?

LHC reach

New Physics ?

t, Z, W, H, EWSB

ψ, b, Y, B

$\tau, c, n, p, \rho, \phi$

μ, s, π, QCD

$u, d, \text{nuclear binding } E$

e

core of Sun

atomic binding E

ν 's

$\downarrow ?$

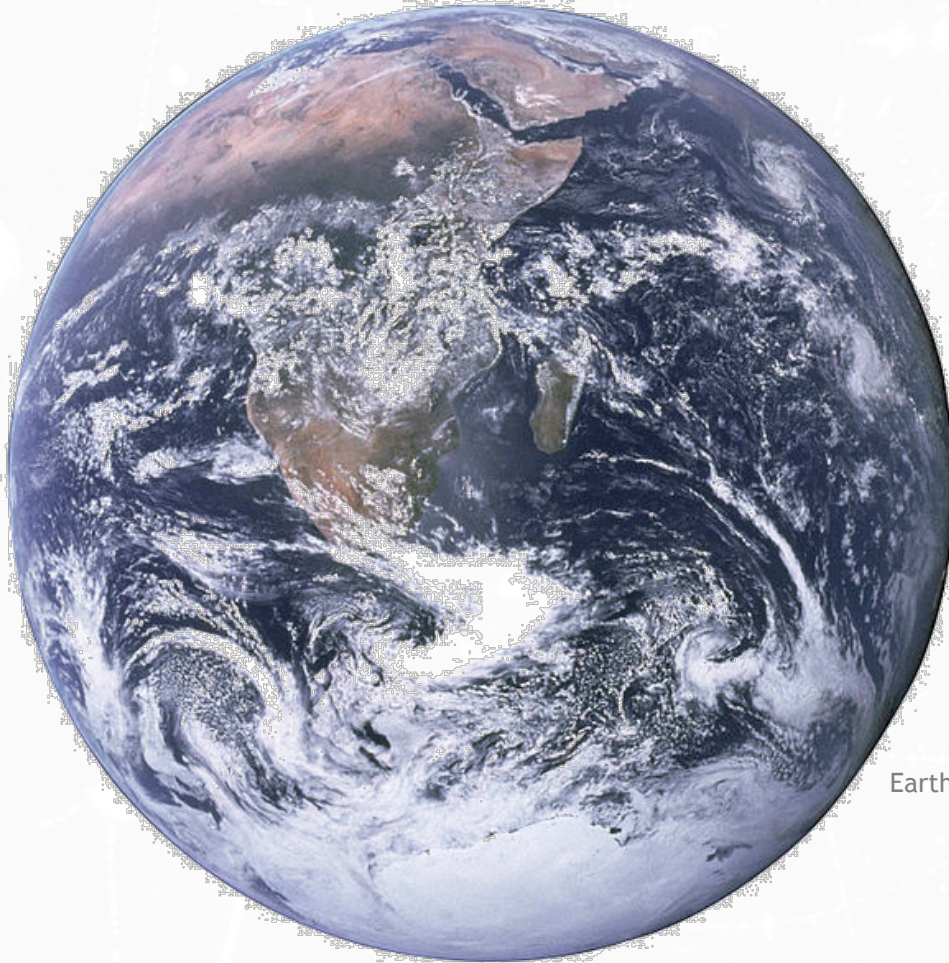
γ, g

...probing
attometer
scales

A 1 TeV-frequency microscope looks at really, really tiny objects...

Nanoscience

Particle physics today
(TeV scale)



Earth



Siphonaptera (flea)

The Standard Model

The SM consists of **24 elementary matter particles** and **3 forces** with total of 26 parameters

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 boson and fermion masses*

The Standard Model

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

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 with non-zero vacuum expectation value.

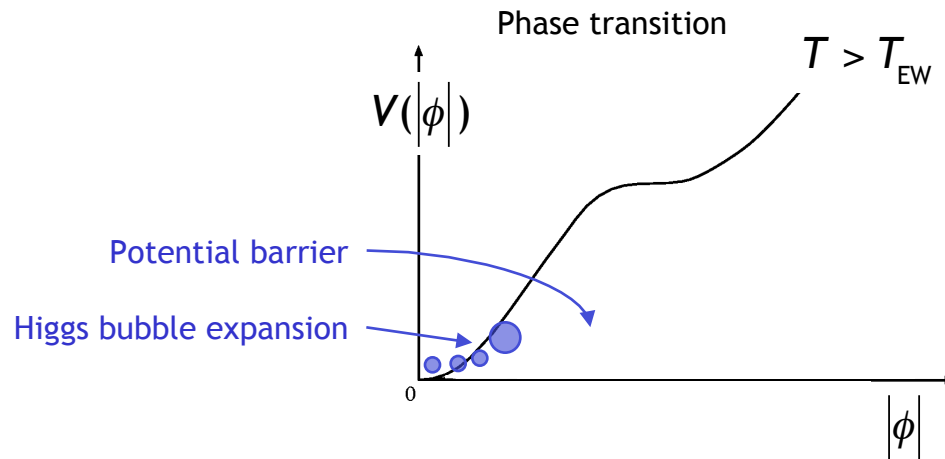
3 d.o.fs become Z, $W^\pm$ masses, remaining d.o.f is **massive scalar Higgs boson**

This is known as the **“Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism”**

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

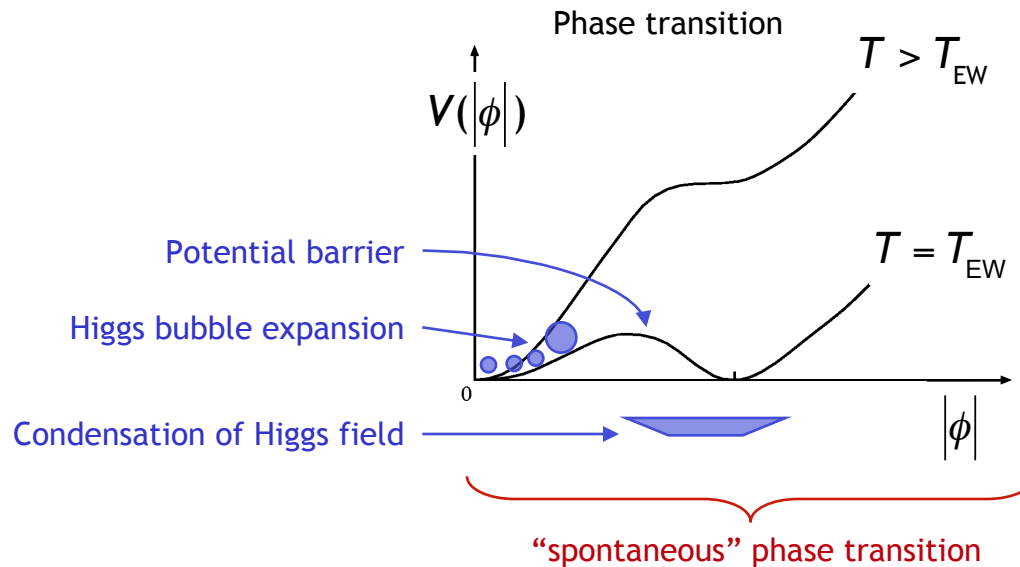
The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ (10^{-10} s after big bang) led to $|\phi_{min}| > 0$



The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ (10^{-10} s after big bang) led to $|\phi_{min}| > 0$



Higgs potential:
$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems.

Carries the seeds for new physics ...

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

Symmetric phase - early universe

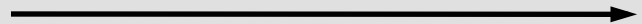
Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

Top quark 

H. Murayama

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ 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

→ Action of the Higgs field
creates a ***vacuum viscosity***

Higgs quantum liquid in broken phase

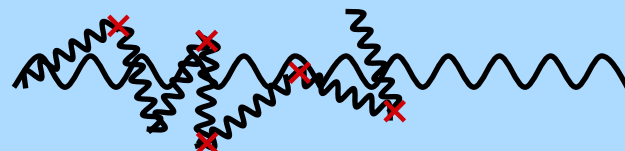
Gravity



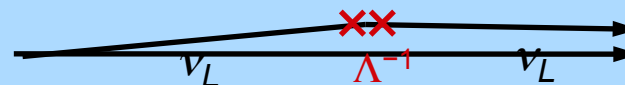
Photon



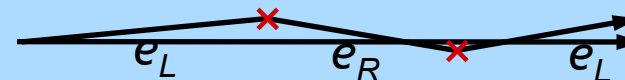
Weak boson



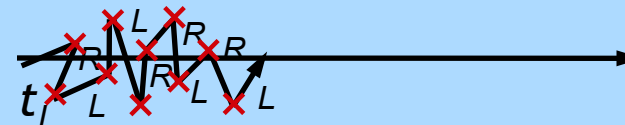
Neutrinos



Electrons



Top quark



H. Murayama

Massive particles
interacting with the
condensed Higgs field

*... like fireflies in the
night sky of Ochiai*



The Higgs boson – last of the particles ?

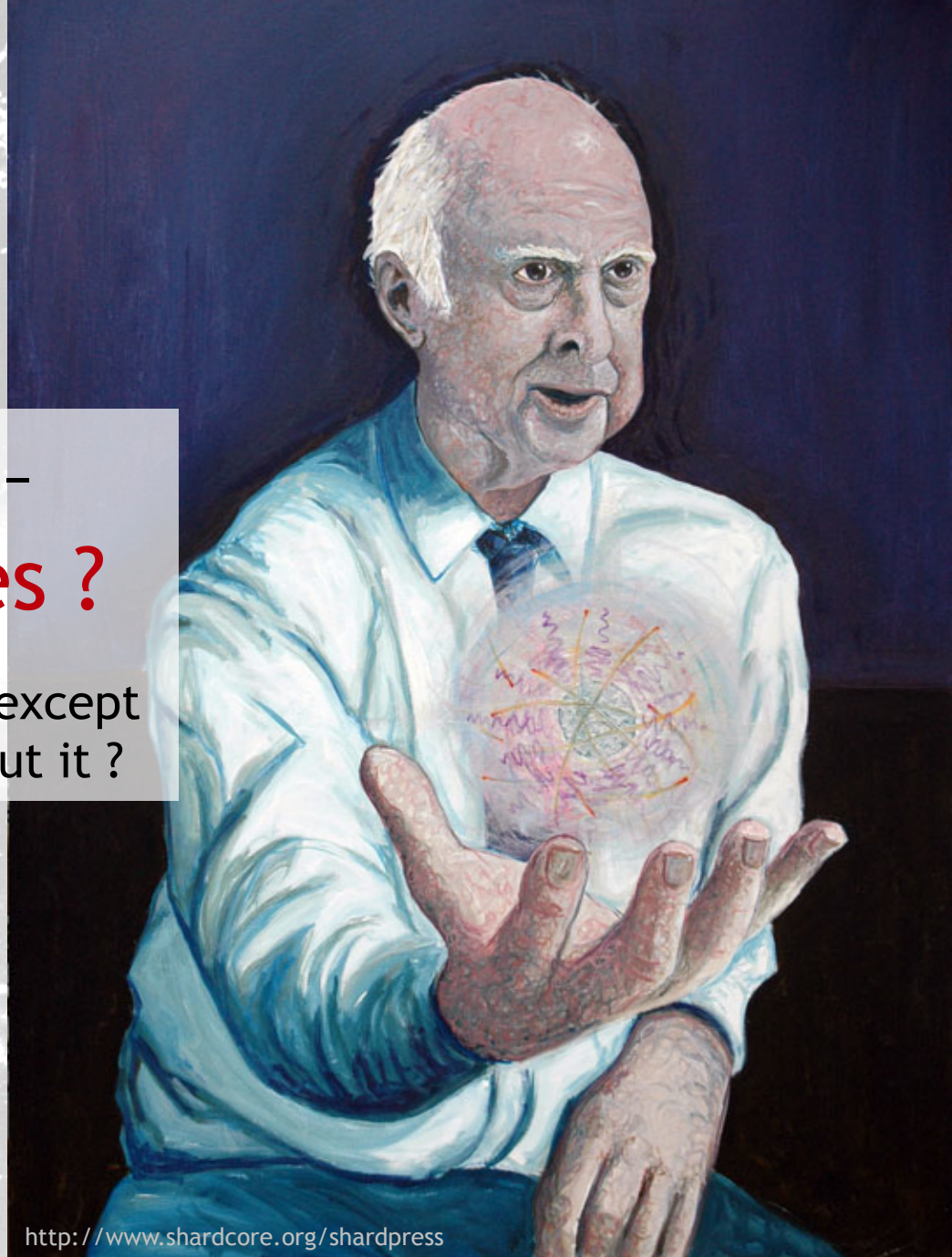
The SM predicts all its properties, except
for its mass. What was known about it ?

Full references for mechanism:

F. Englert and R. Brout, PRL 13 (1964) 321.
P.W. Higgs, PRL 13 (1964) 508.
G. Guralnik, C. Hagen, and T.W.B. Kibble, PRL 13 (1964) 585.

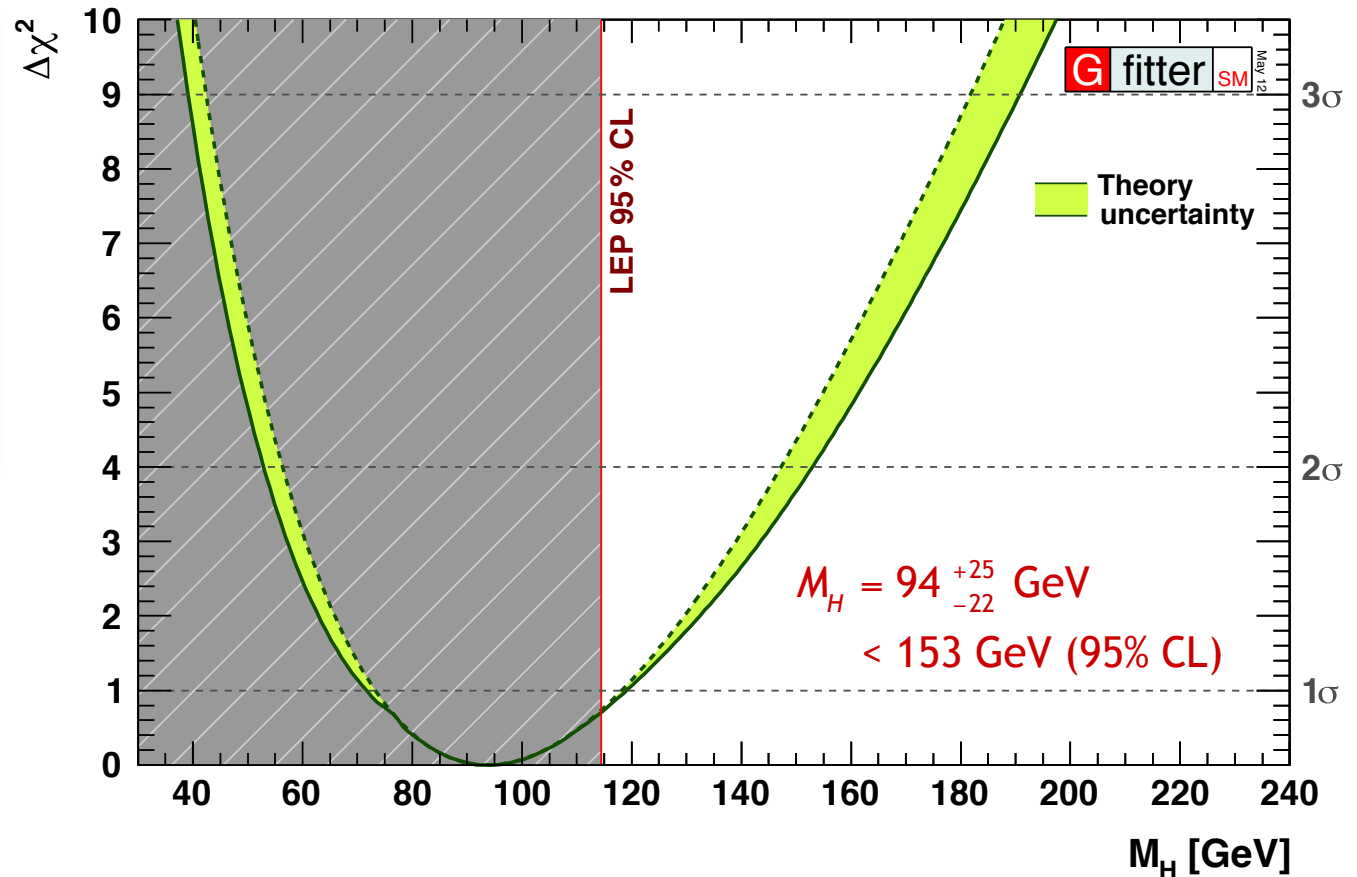
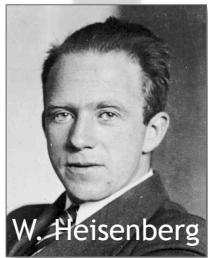
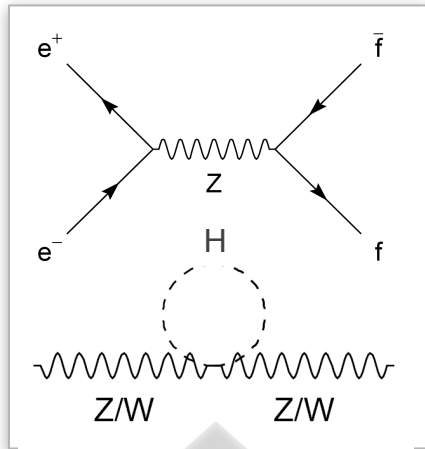
It is also of note that Landau and Ginzburg had proposed a field giving the photon a mass in a superconductor, the mathematics of which is identical to the “Higgs mechanism” and predates it by several years.

<http://www.shardcore.org/shardpress>



Constraints from global electroweak fit

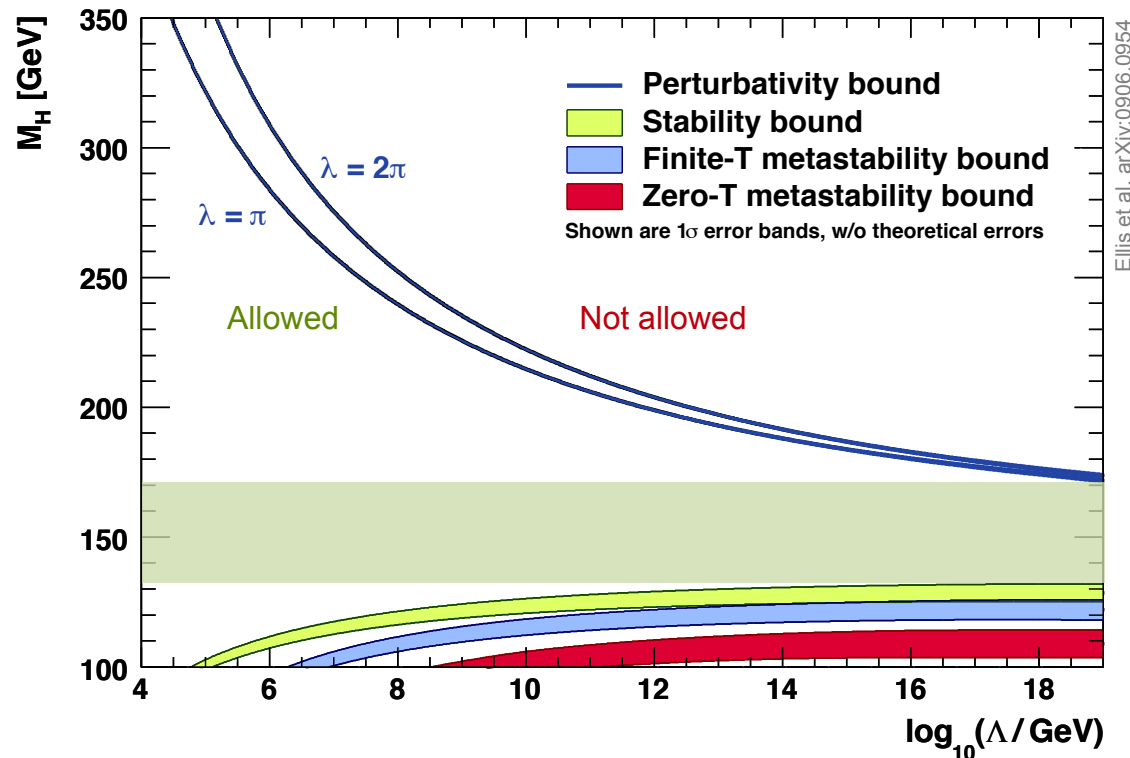
Global fit of all EW precision measurements to SM prediction constrains M_H



<http://gfitter.desy.de>

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



Global Effort → Global Success

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one...?)

Historic Milestone but only the beginning

Global Implications for the future



ps

LEP/LIBRARY



LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

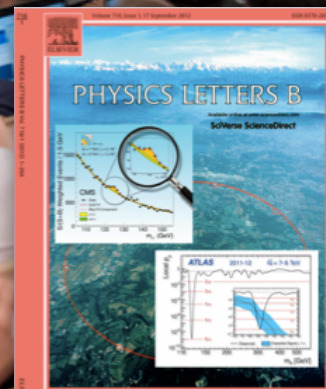
S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

Duration of projects /planning stability:
First LHC workshop 1984 !



Global Effort → Global Success

Results today only possible due to
extraordinary performance of
accelerators – experiments – Grid computing

Observation of a new particle consistent with
a Higgs Boson (but which one...?)

Historic Milestone but only the beginning



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



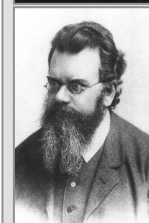
Particles accelerators:

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

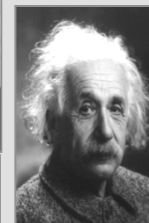
Lawrence



de Broglie



Einstein

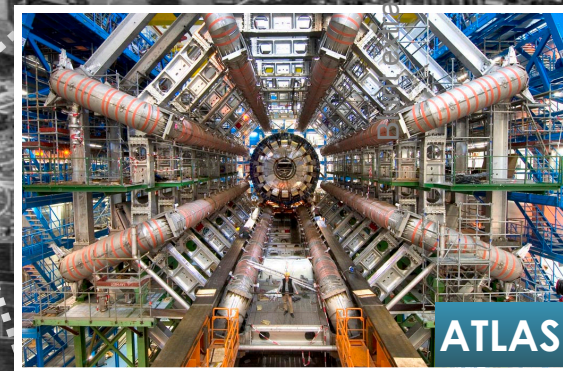
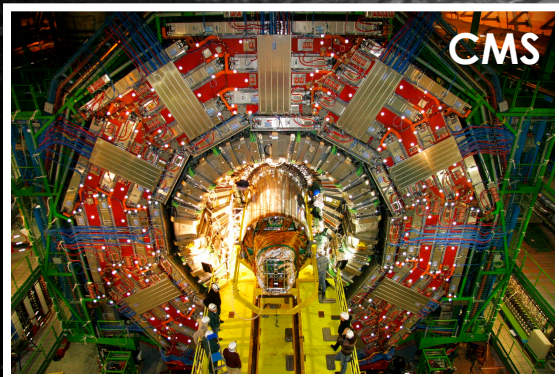


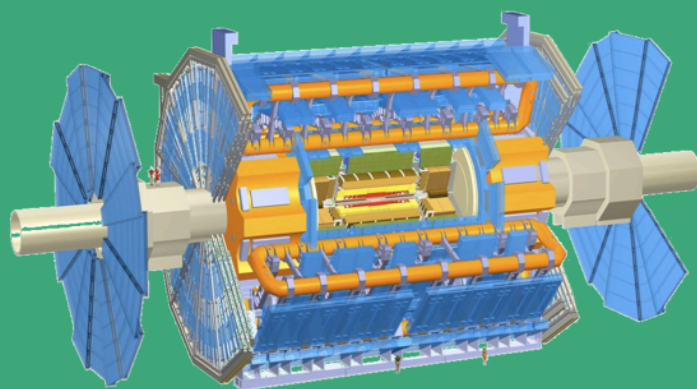
Boltzmann

An aerial photograph of the CERN facility in Switzerland, showing the extensive LHC ring. The ring is a large, circular structure that spans across a vast, patchwork landscape of fields and forests. The text "LHC ring at CERN: 27 km circumference" is overlaid on the image. The ring itself is a thin, light-colored line that forms a large circle, with several smaller circles and lines branching off from it, representing the various experimental areas and service roads. The landscape is a mix of green fields, brown patches, and dark forested areas. In the background, a large body of water is visible. The overall scene is a high-angle, wide-area view of the CERN complex.

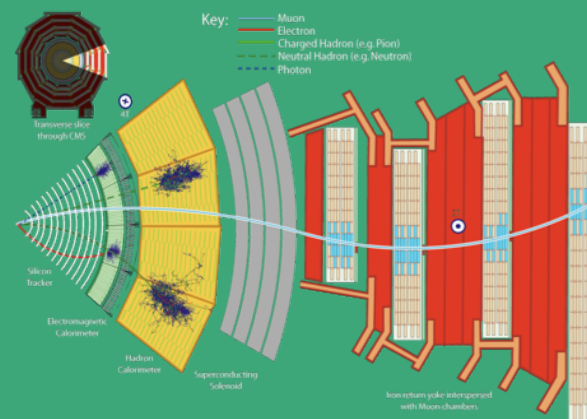
**LHC ring at CERN:
27 km circumference**

**So far:
7/8 TeV proton–proton collisions
2.76 TeV Pb–Pb collisions**



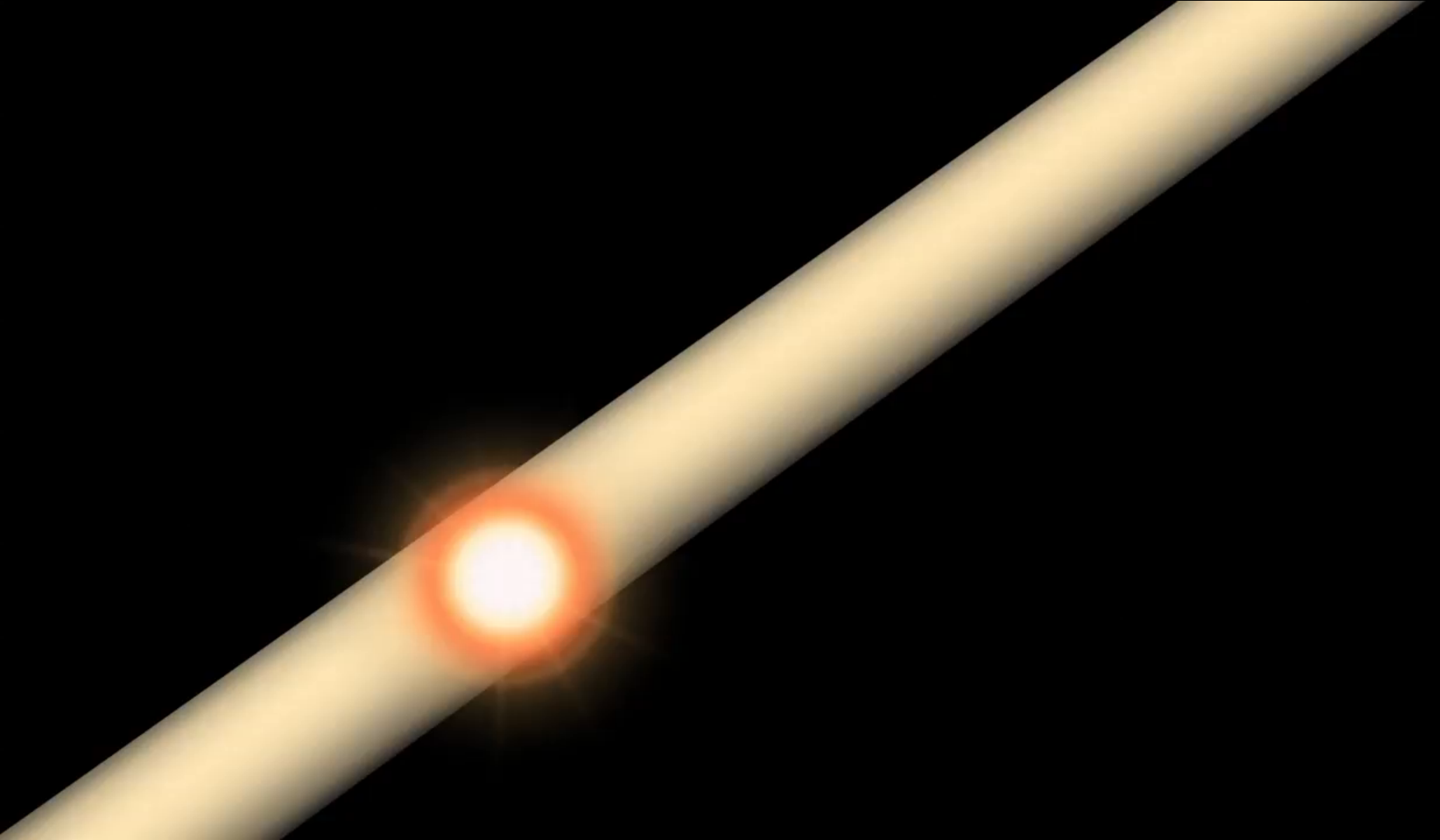


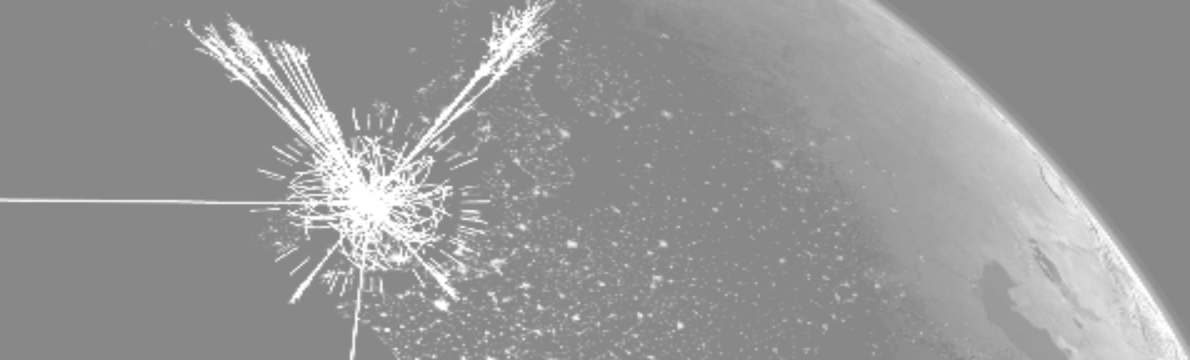
ATLAS: emphasis on excellent jet and missing- E_T resolution, particle identification, and standalone muon measurement



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

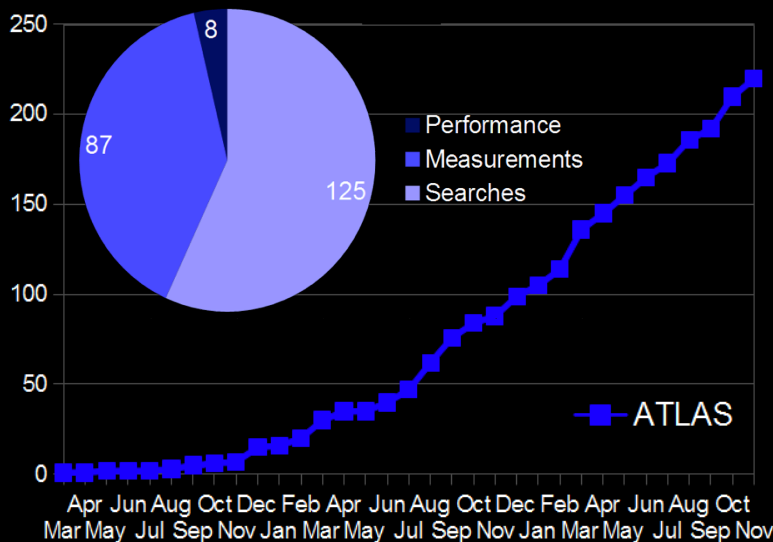
Both: excellent hermeticity - very few “cracks”





Small extract of huge amount
of results available

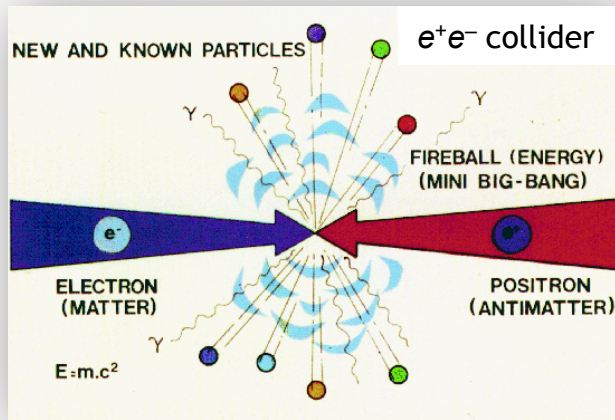
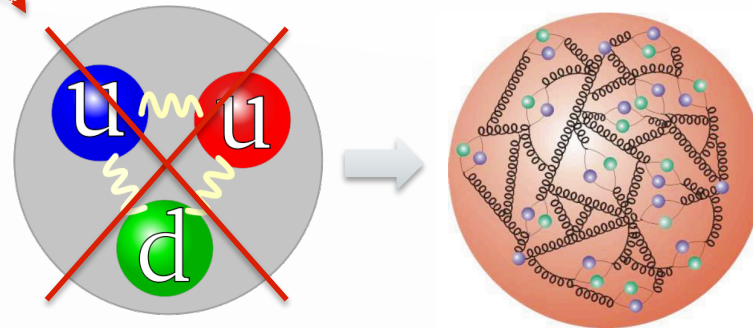
LHC High- p_T Physics



Proton–Proton Collisions

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

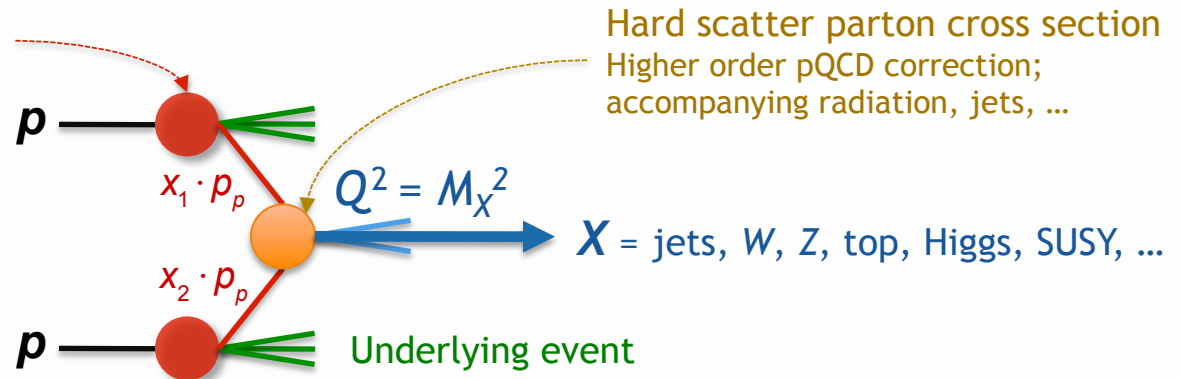
Parton distribution functions
Representing structure of proton



Proton–Proton Collisions

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

Parton distribution functions
Representing structure of proton



- 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”

Recorded Luminosity in 2012

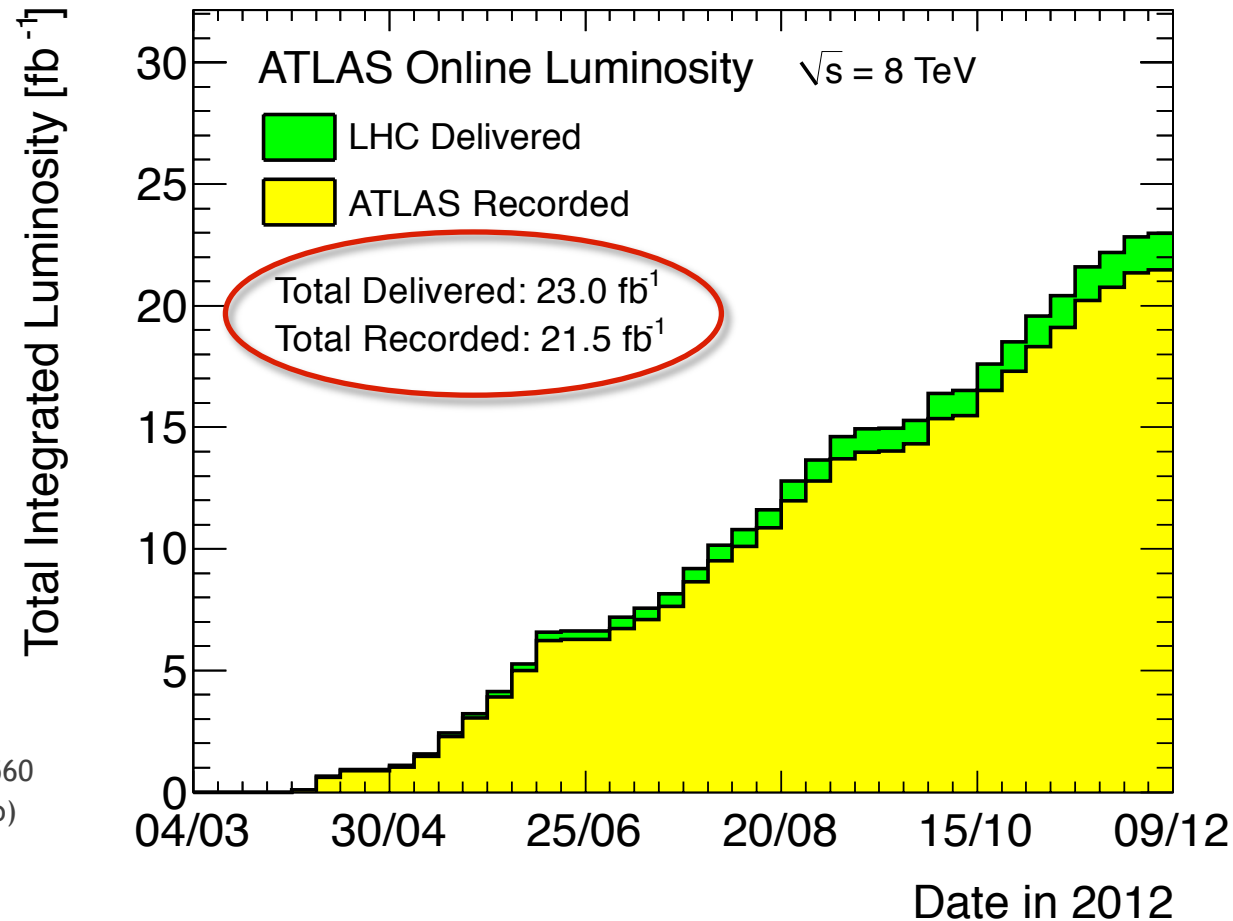
Luminosity is key quantity: $\text{rate} = \text{cross section} \times \text{efficiency} \times \text{luminosity}$

ATLAS integrated luminosity in 2012

- Peak $L = 7.7 \times 10^{33} \text{ s}^{-1} \text{ cm}^{-2}$ (Aug)
- Max L/fill : 237 pb^{-1} (June)
- Weekly record: 1350 pb^{-1} (June)
- Longest stable beams: 22.8 h (July)
- Fastest turn-around between stable beams: 2.1 h (April)
- Best weekly data-taking efficiency: 92 h (55%) (July)

At $L = 7 \times 10^{33} \text{ s}^{-1} \text{ cm}^{-2}$ and 8 TeV pp collisions, 560 Higgs bosons of mass 125 GeV ($\sigma_{pp \rightarrow H} = 22.3 \text{ pb}$) are produced in ATLAS and CMS per hour

Or: every 45 min. 1 $H \rightarrow \gamma\gamma$, need ~ 2 typical 160 pb^{-1} fills to produced one $H \rightarrow 4l$ ($l=e/\mu$)



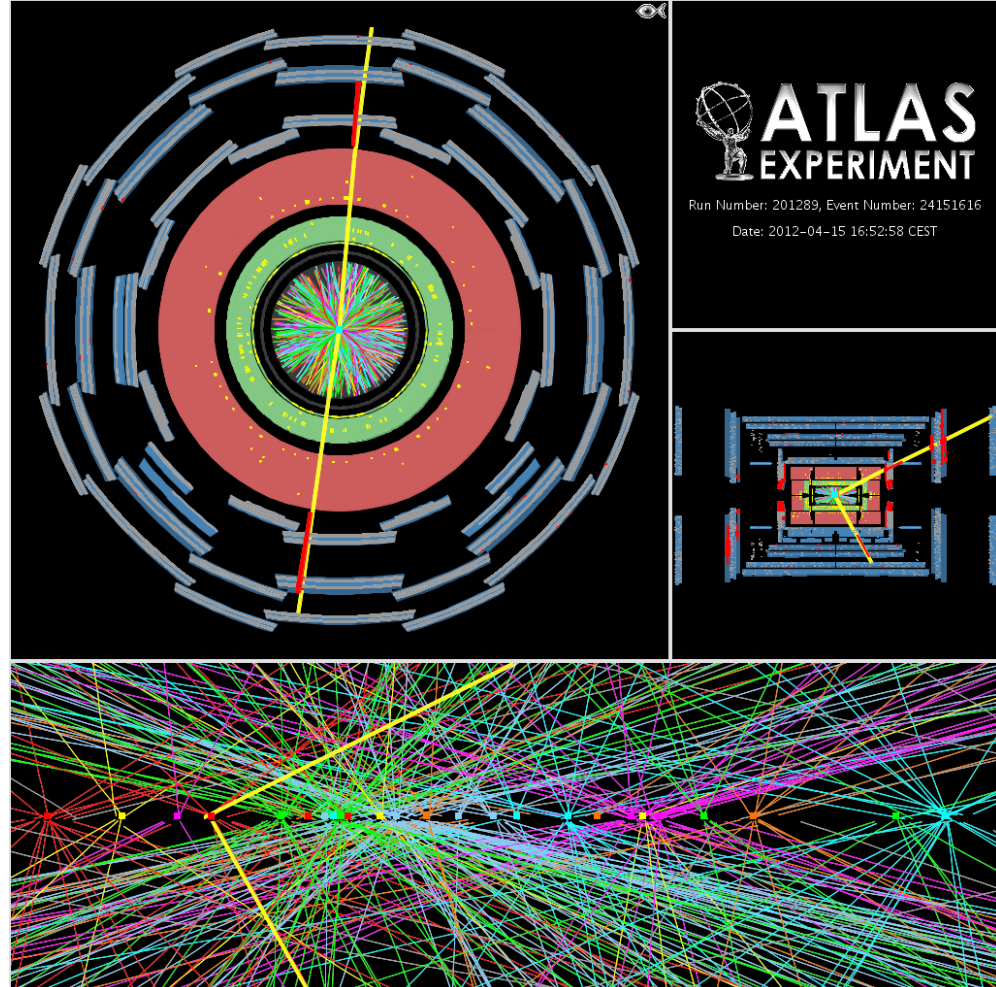
Many interactions per bunch crossing: “Pileup”

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

Average of 21 (peak: 40) collisions per crossing in 2012

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

$Z \rightarrow \mu\mu$ event in ATLAS with 25 reconstructed vertices



Many interactions per bunch crossing: “Pileup”

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

Average of 21 (peak)

collisions per bunch crossing

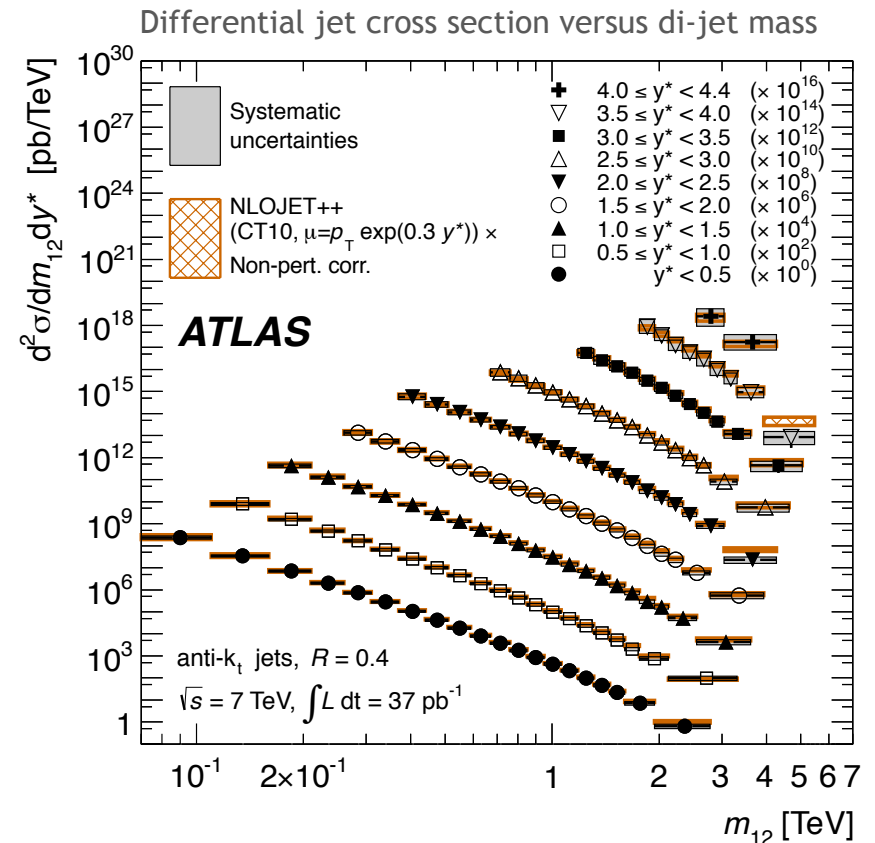
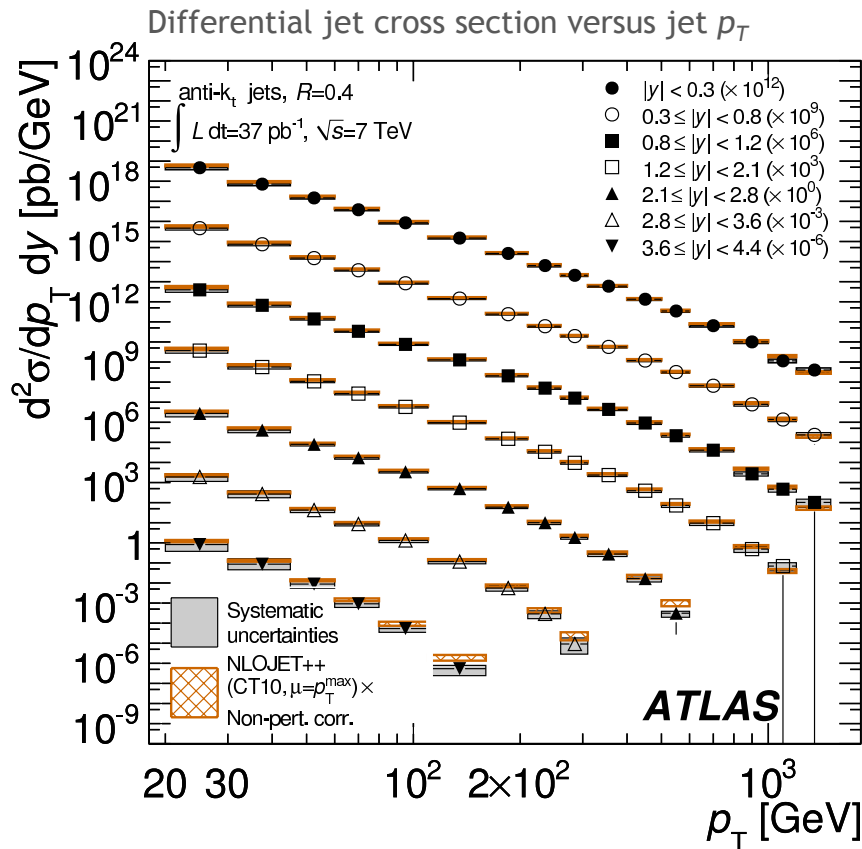
To search for “new” physics, we must make sure the “old” physics is well under control in our experiments

$Z \rightarrow \mu\mu$ event in ATLAS with 25 reconstructed vertices



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

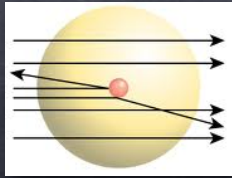
High-energy jets probe new particles and interactions

Measure di-jet invariant mass and angular distributions

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

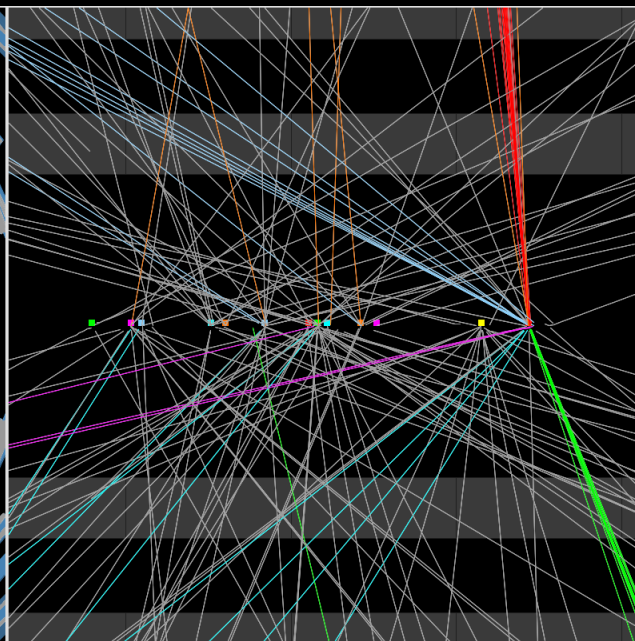
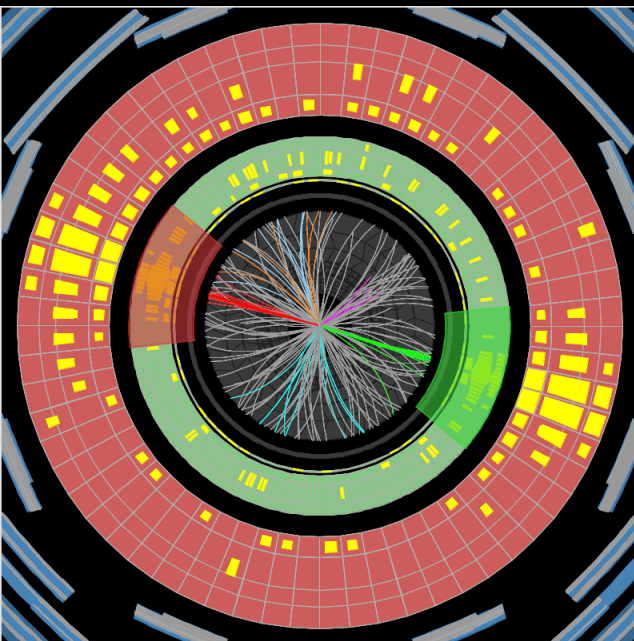
Tends to scatter at smaller angles than if there were new particles produced

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



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

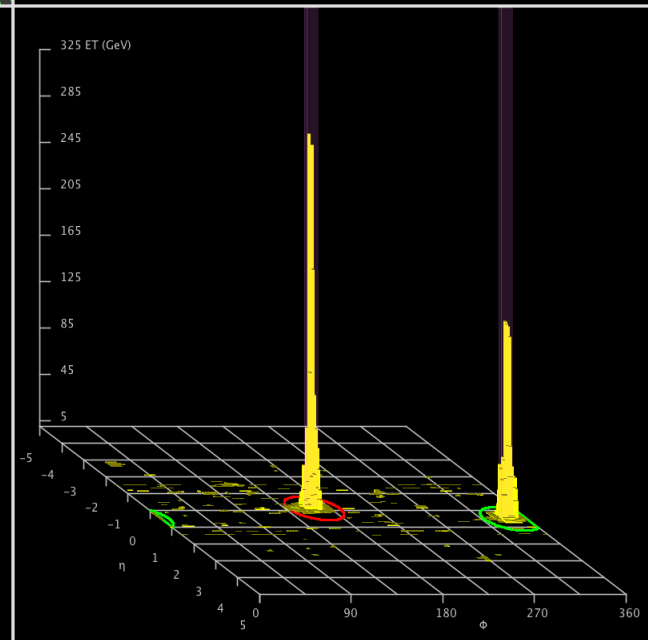
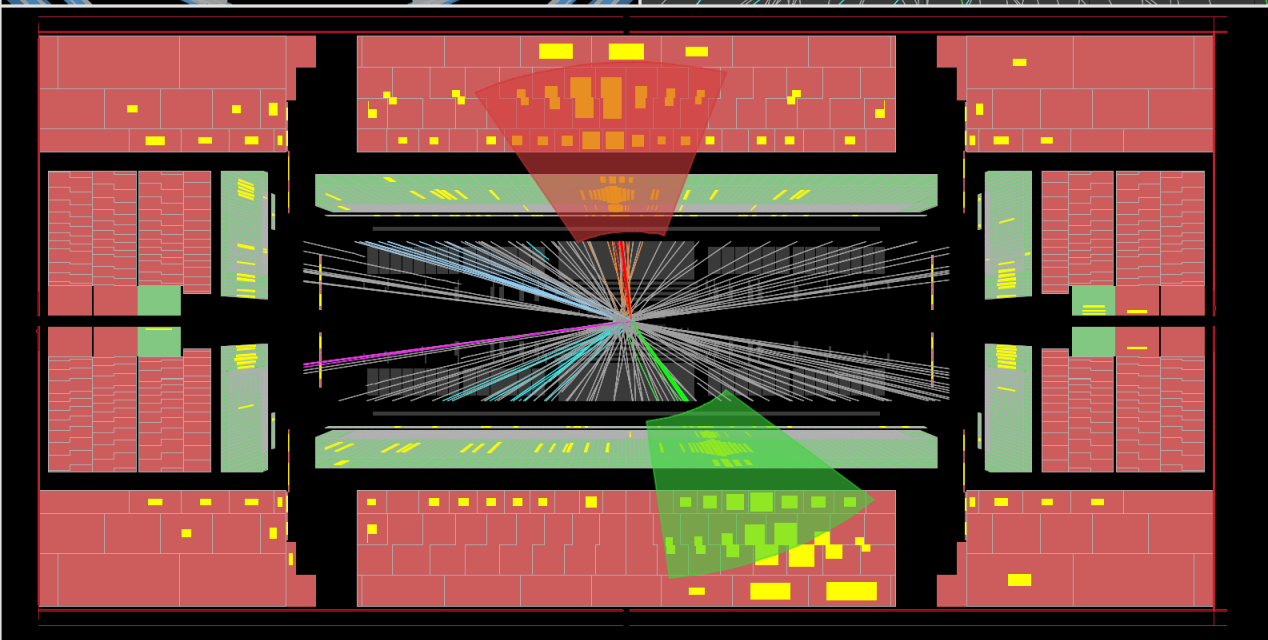
The highest-mass central dijet event collected. The two central high- p_T jets have an invariant mass of 4.69 TeV



 **ATLAS**
EXPERIMENT

Run Number: 209580, Event Number: 179229707

Date: 2012-08-31 20:24:29 CEST

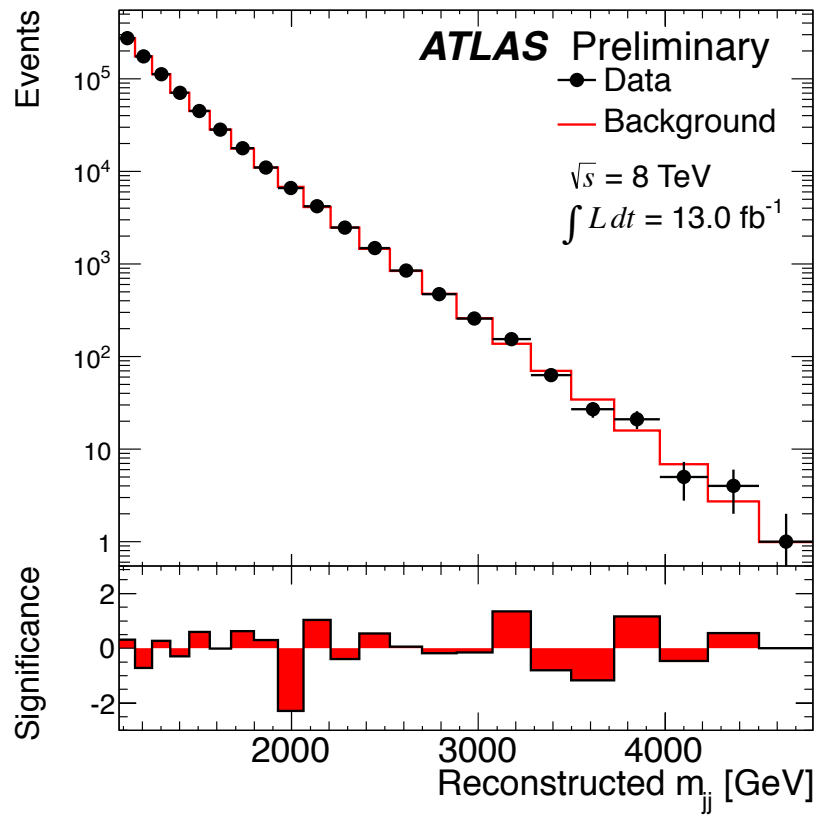


High-energy jets probe new particles and interactions

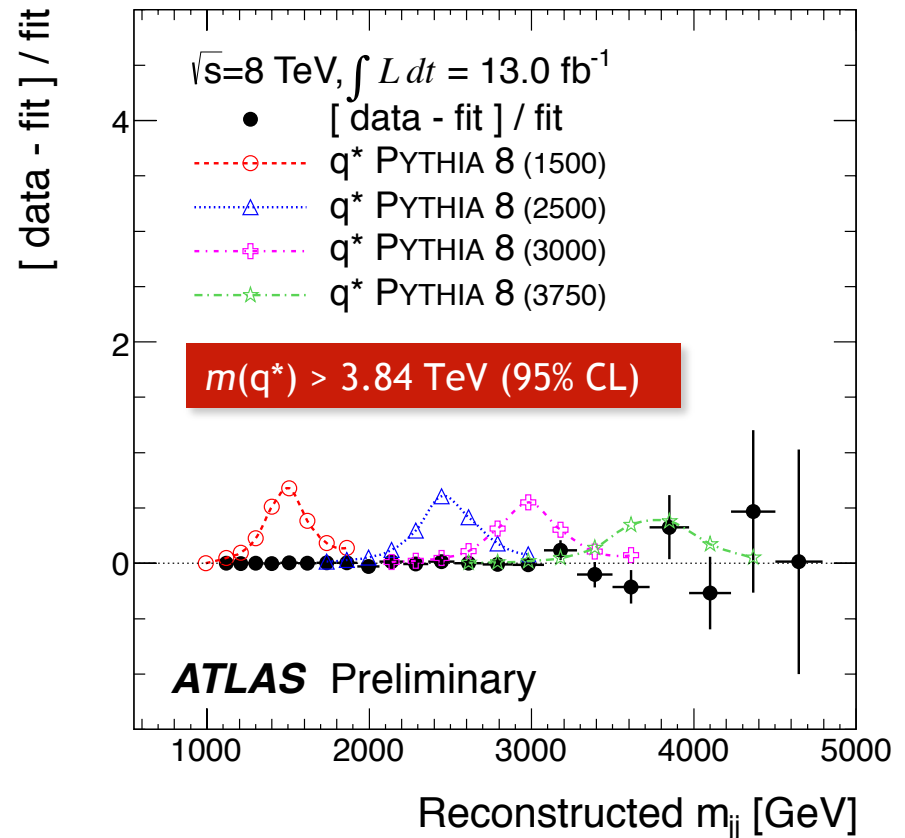
Measure di-jet invariant mass and angular distributions

ATLAS-CONF-2012-148, CMS PAS EXO-12-016

Observed and fitted dijet mass



Data / fit ratio, compared to four q^* models



High-energy jets probe new particles and interactions

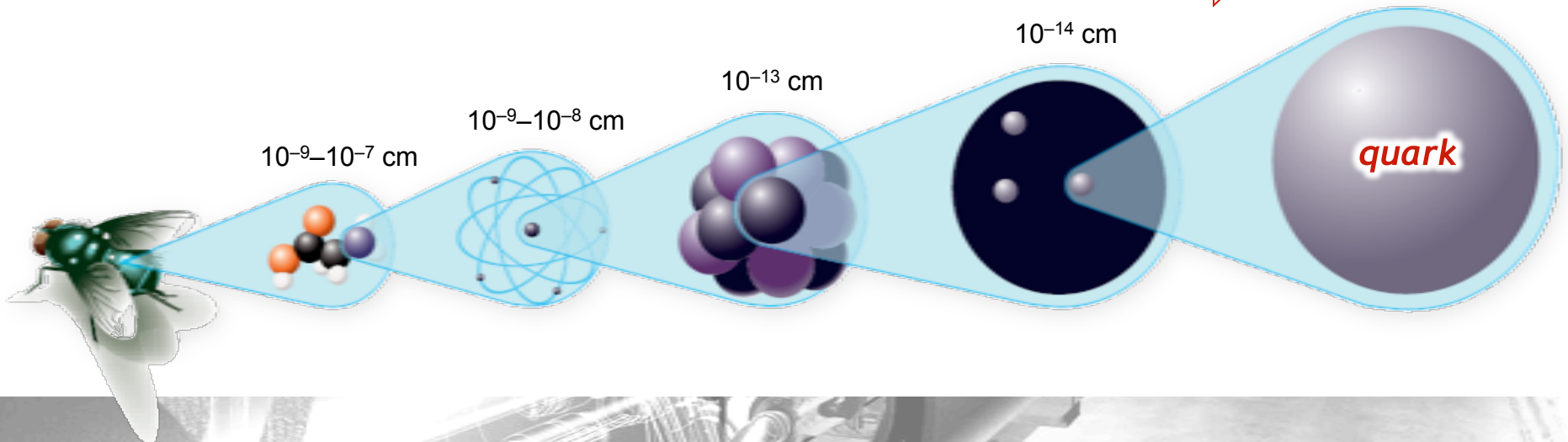
Measure di-jet invariant mass and angular distributions

ATLAS-CONF-2012-148, CMS PAS EXO-12-016

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

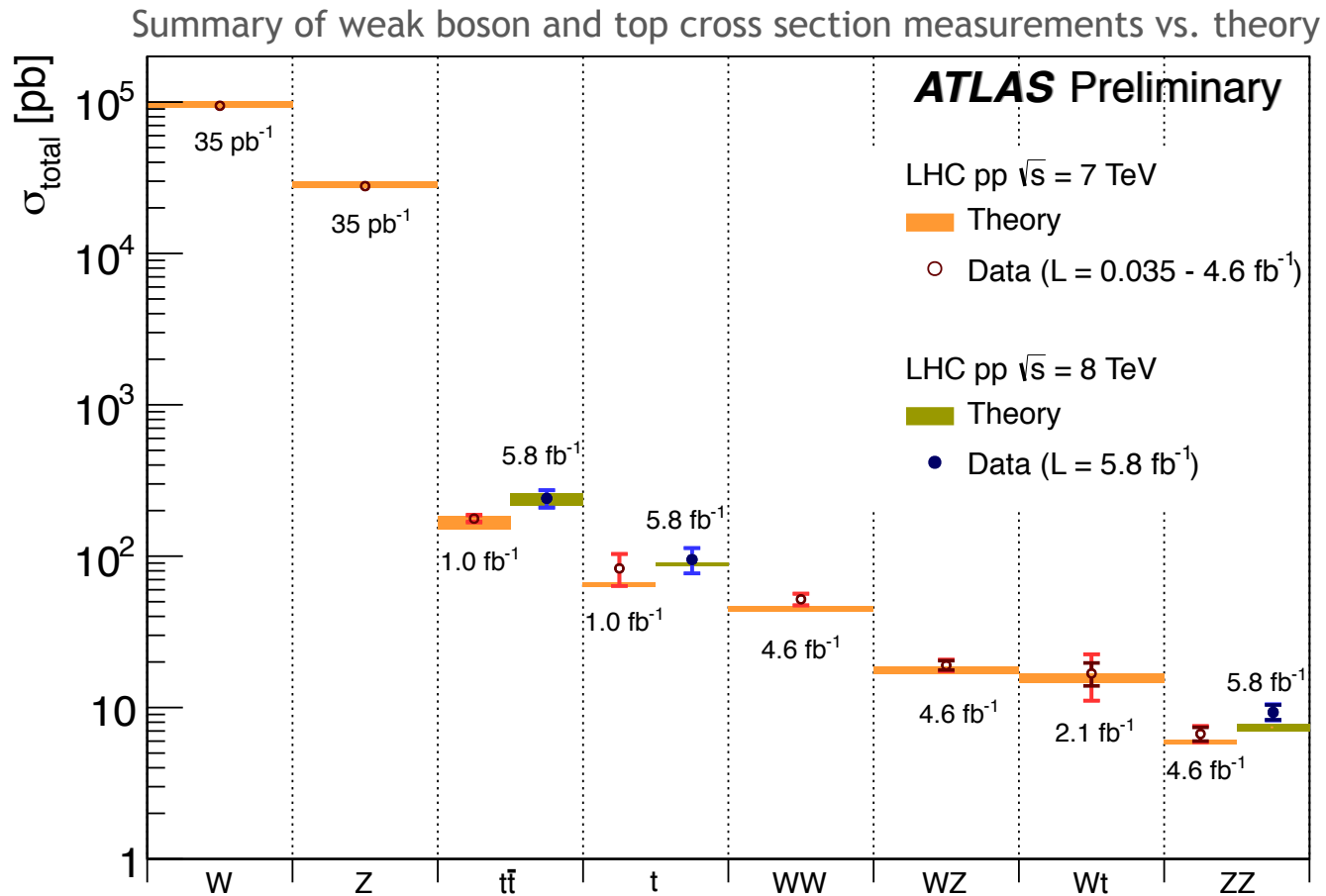
	Benchmark model	Observed limit at 95% CL
Resonant	Excited quarks	$m(q^*) > 3.8 \text{ TeV}$
Non-resonant	4-quark contact interactions	$\Lambda > 7.8 \text{ TeV}$

$< \sim 2 \times 10^{-18} \text{ cm}$



QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections



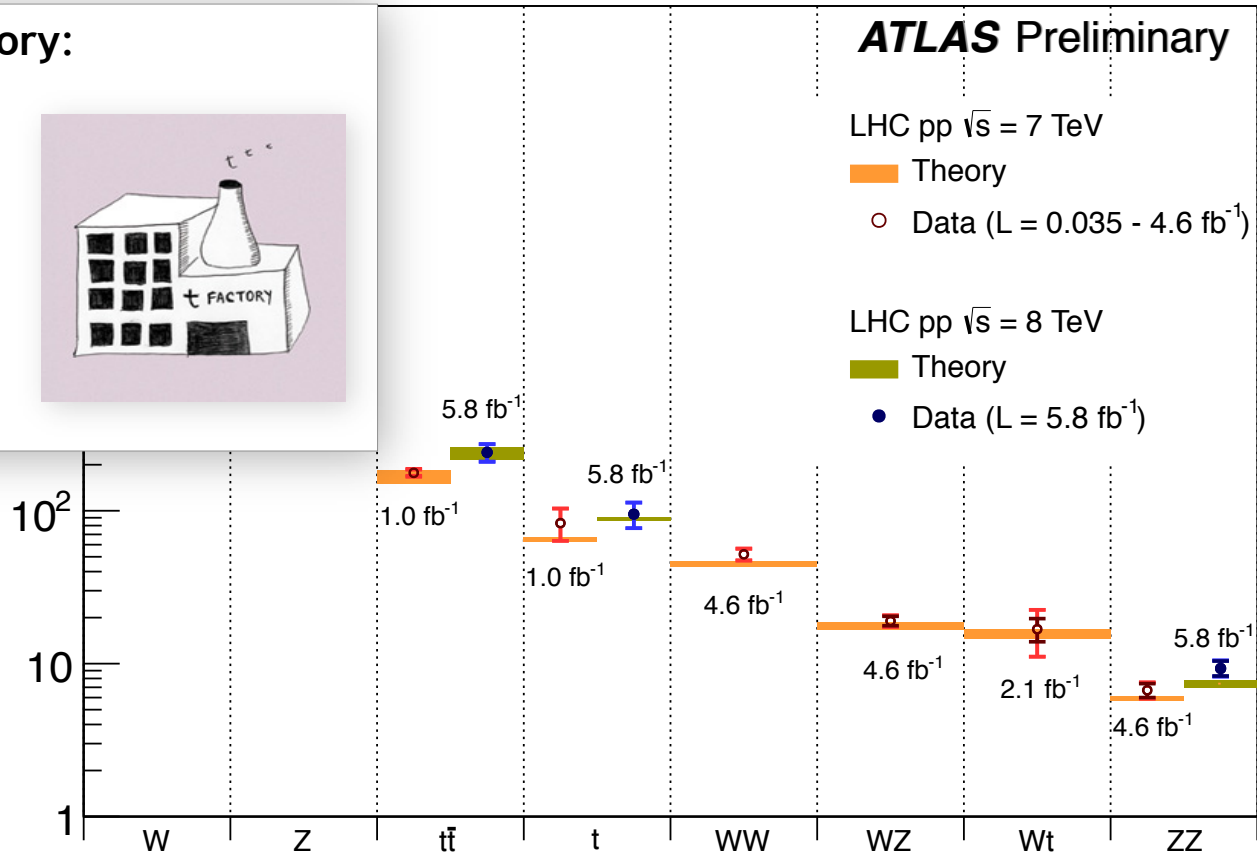
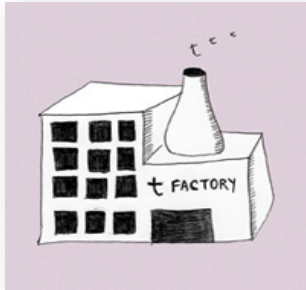
QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections

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

LHC is top factory:

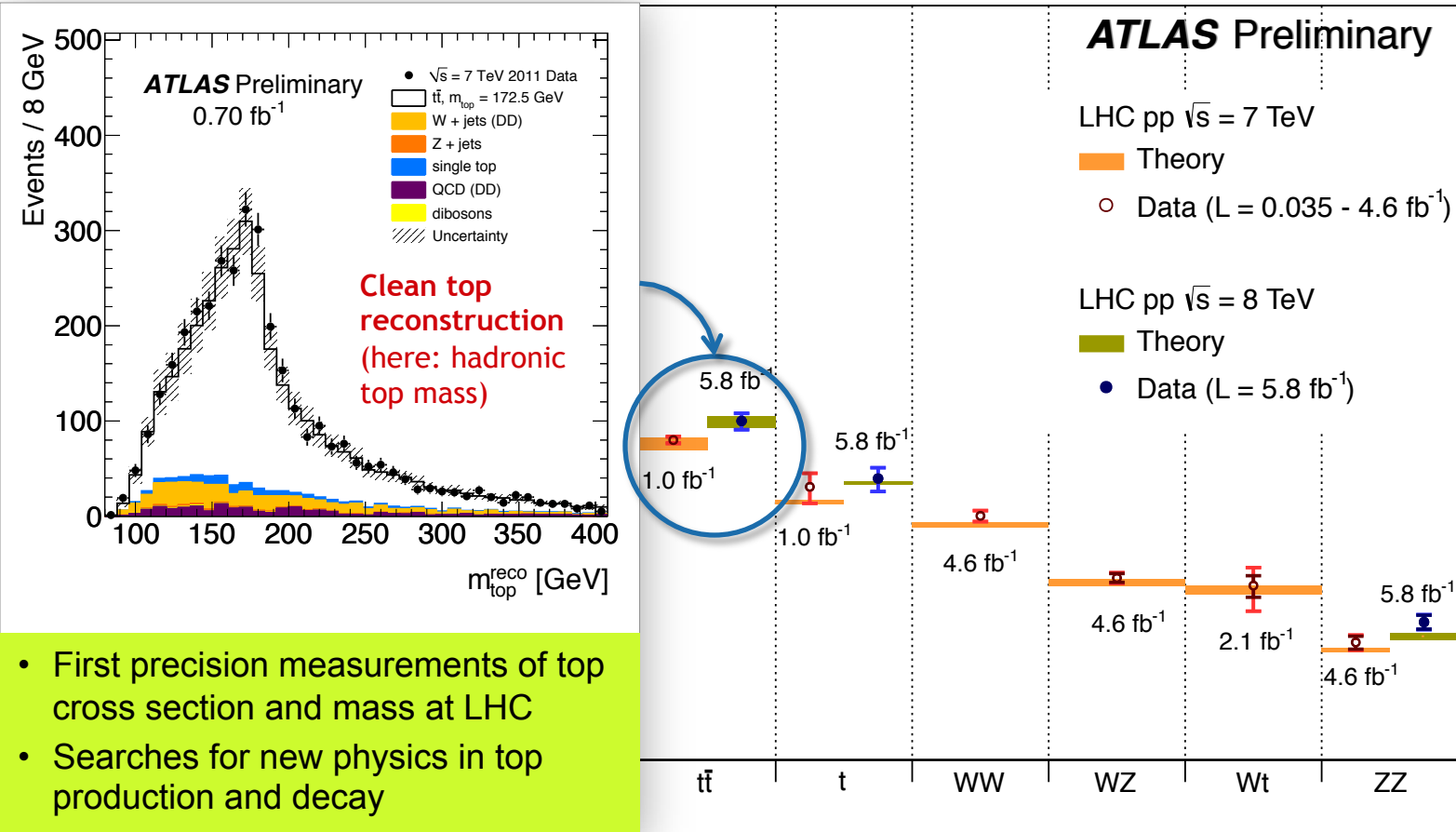
At 8 TeV CM
energy: $\sim 36 \times$
larger cross
section than at
Tevatron



QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections

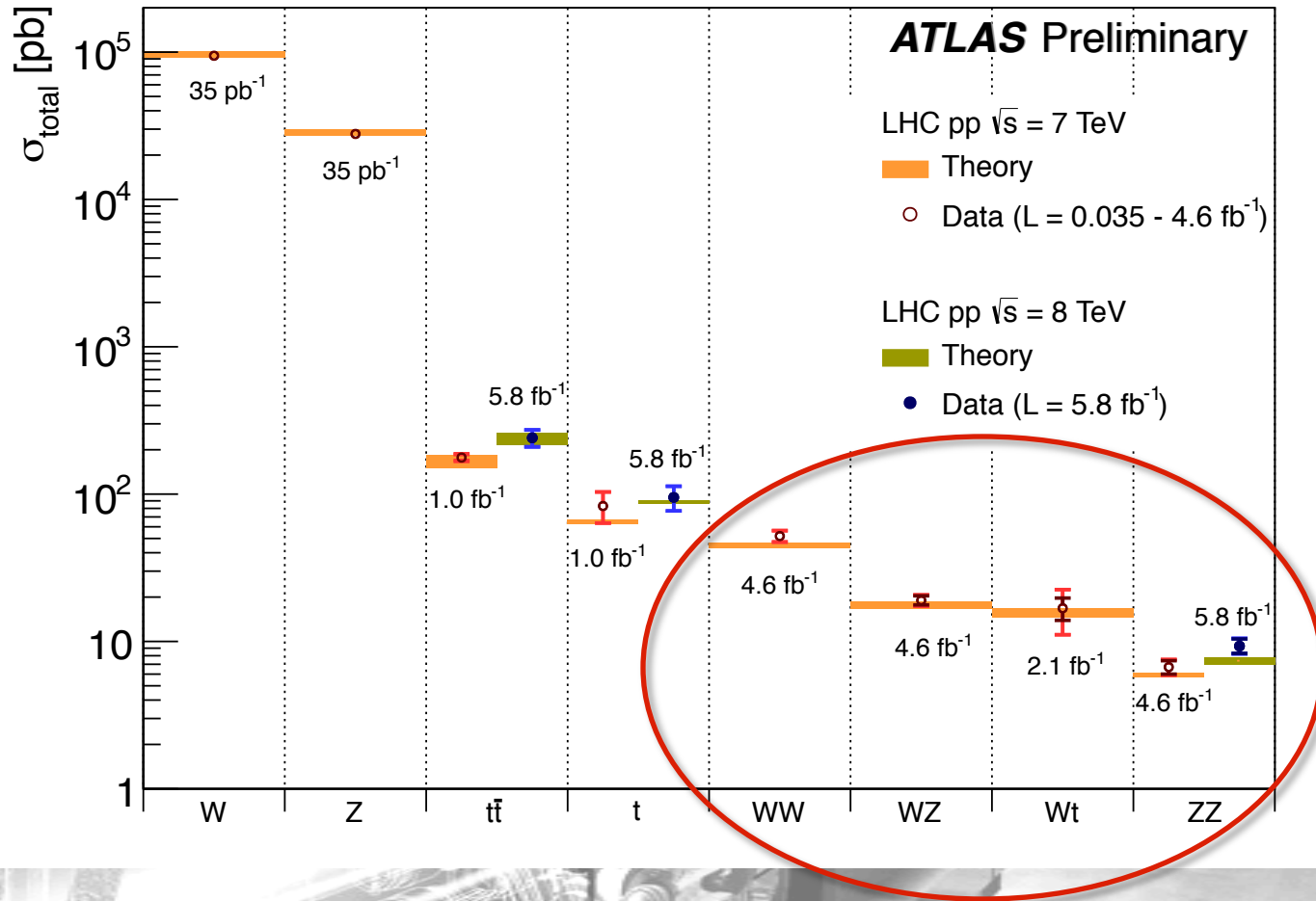
Summary of weak boson and top cross section measurements vs. theory



QCD and electroweak measurements

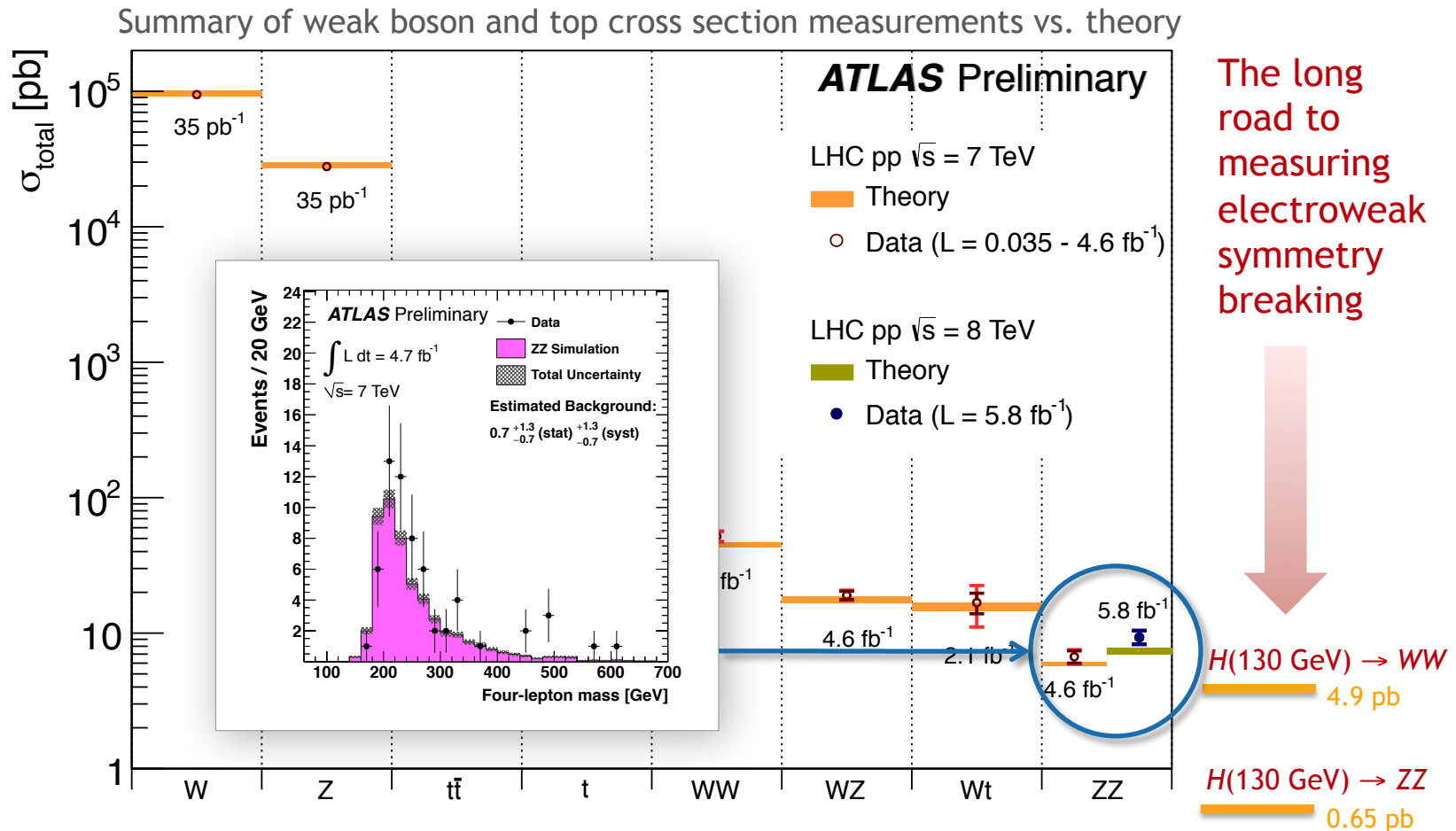
With more luminosity we are sensitive to ever smaller cross sections

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

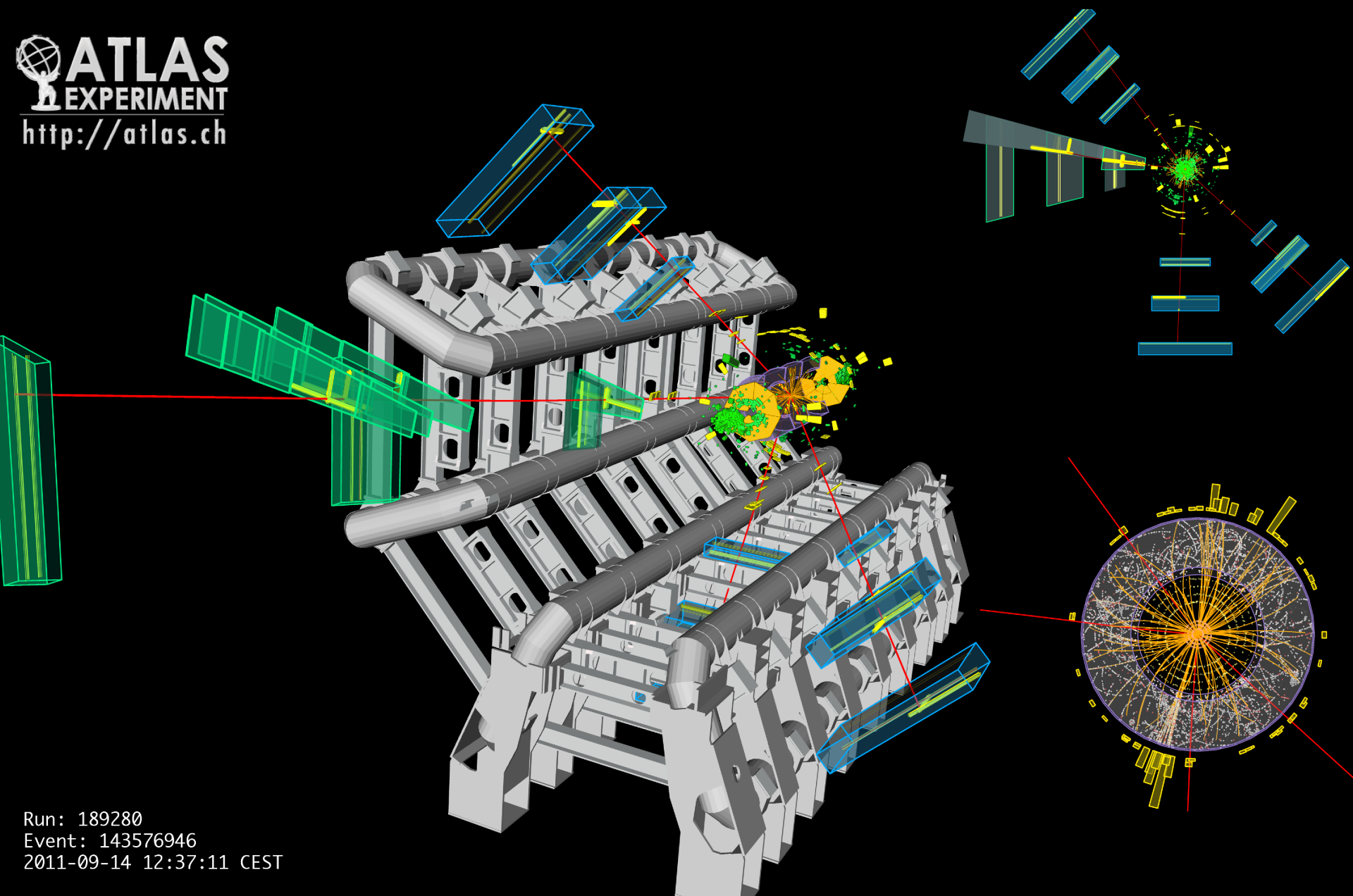


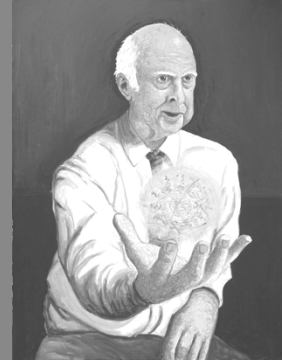
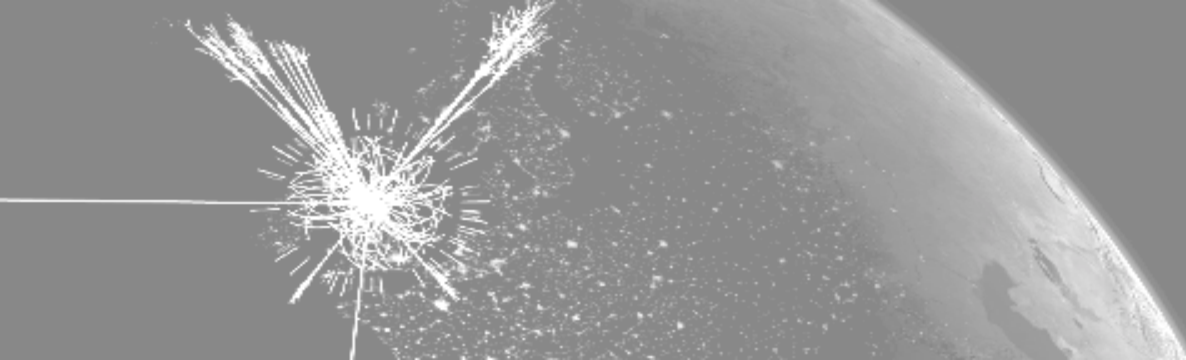
QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections



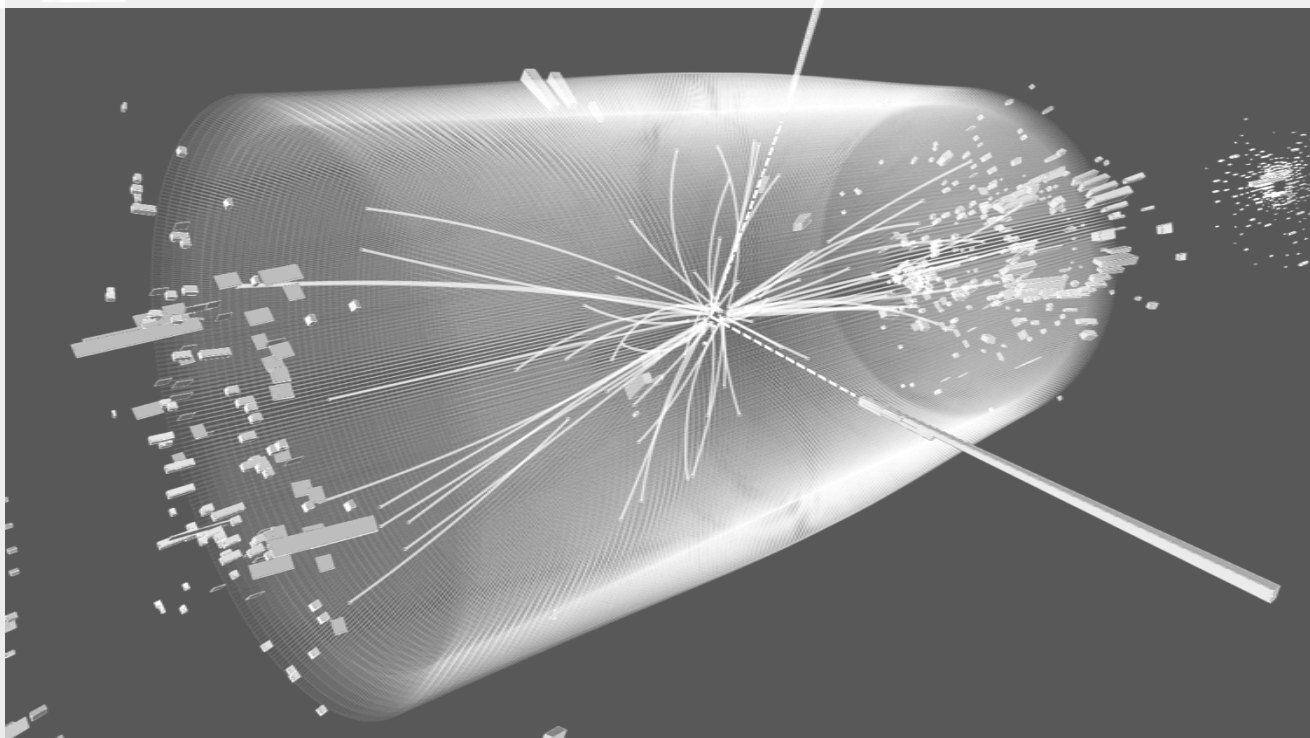
A 4μ event seen in ATLAS

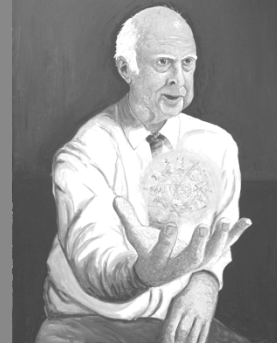
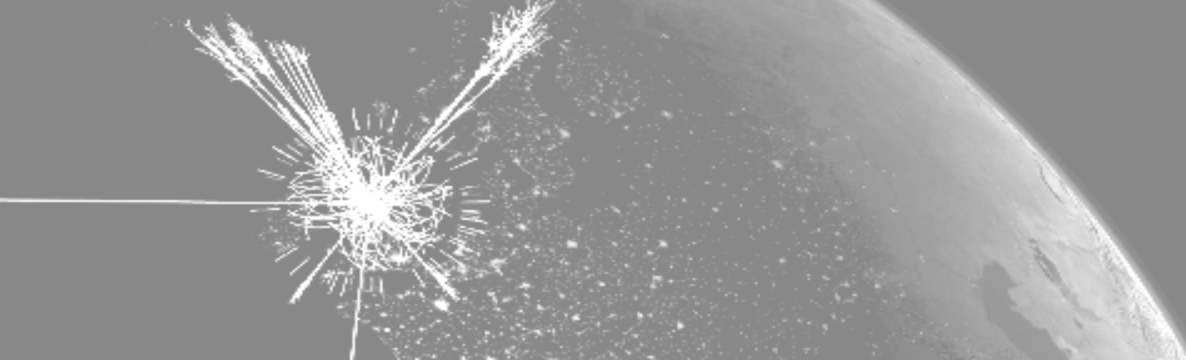




CMS Experiment at the LHC
Data
Run

Hunting for the Higgs Boson





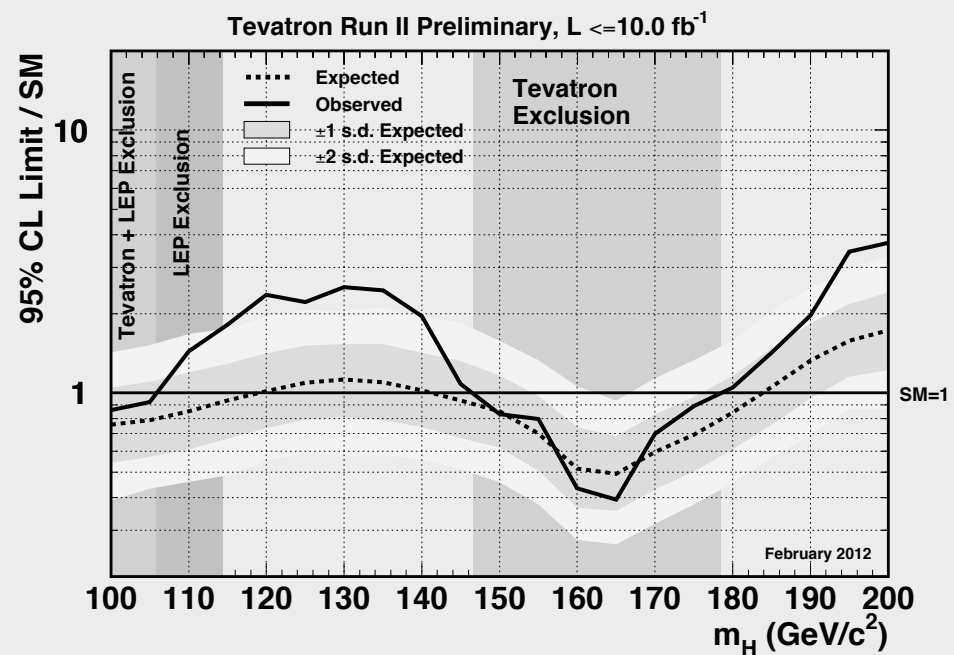
Hunting for the Higgs Boson

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):

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

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



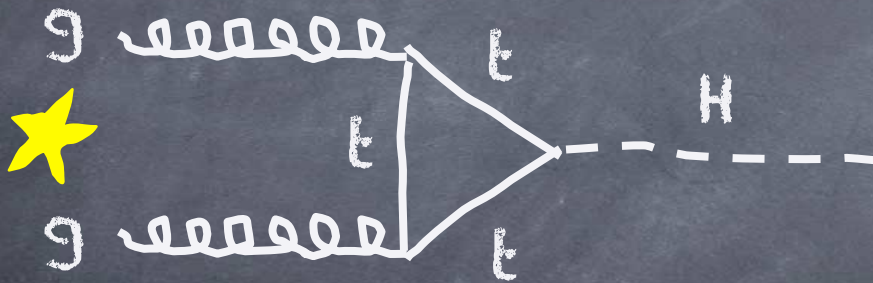
Higgs boson searches at the LHC

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

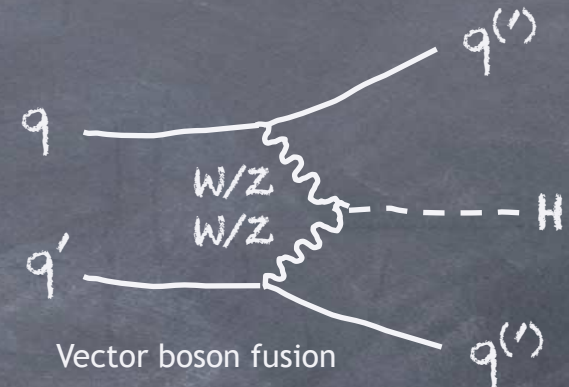
At the LHC, the Higgs boson is produced dominantly via **gluon fusion**

$\sigma_{H,\text{total}} \sim 22 \text{ pb}$ at 8 TeV for $m_H = 125 \text{ GeV}$ ($\sim 20 \times$ Tevatron; $>200 \times$ rate given luminosity)

Cross section steeply falling with Higgs mass



Total production of ~ 470 thousand SM Higgs bosons of 125 GeV in 2012 in each ATLAS and CMS



Higgs boson searches at the LHC

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

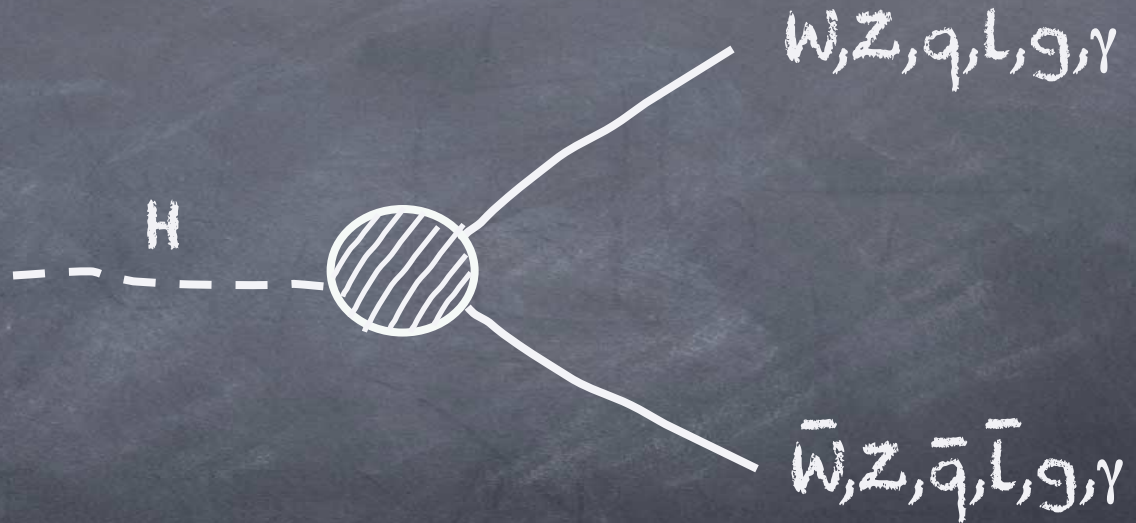
At the LHC, the Higgs boson is produced dominantly via **gluon fusion**

$\sigma_{H,\text{total}} \sim 22 \text{ pb}$ at 8 TeV for $m_H = 125 \text{ GeV}$ ($\sim 20 \times$ Tevatron; $> 200 \times$ rate given luminosity)

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

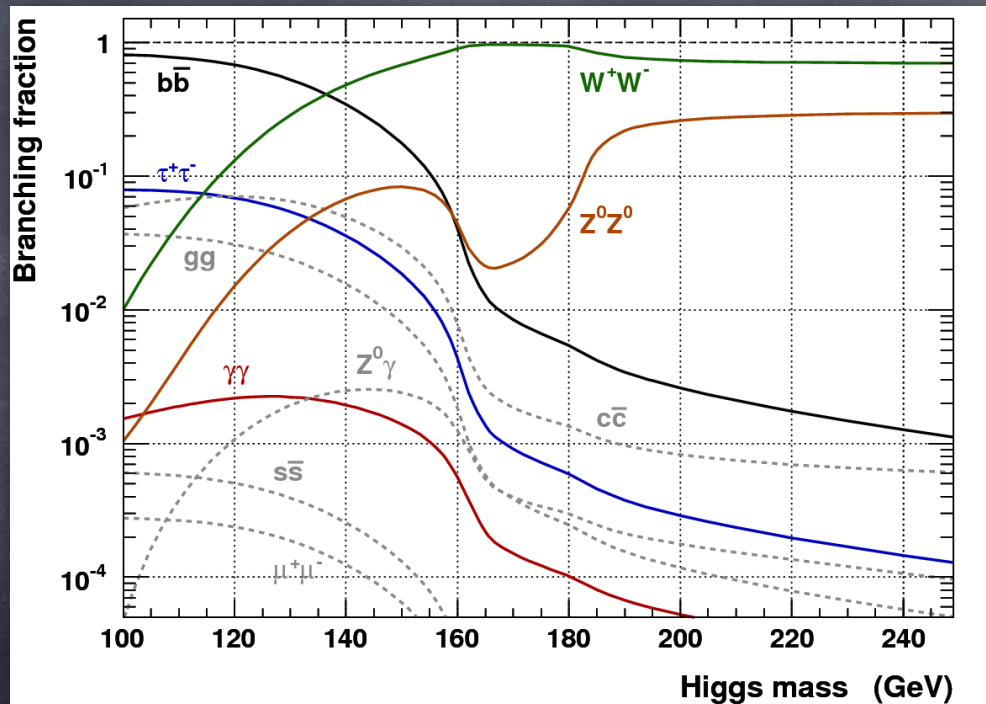
... the Higgs will decay with preference to the heaviest particles allowed

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



Higgs boson 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:

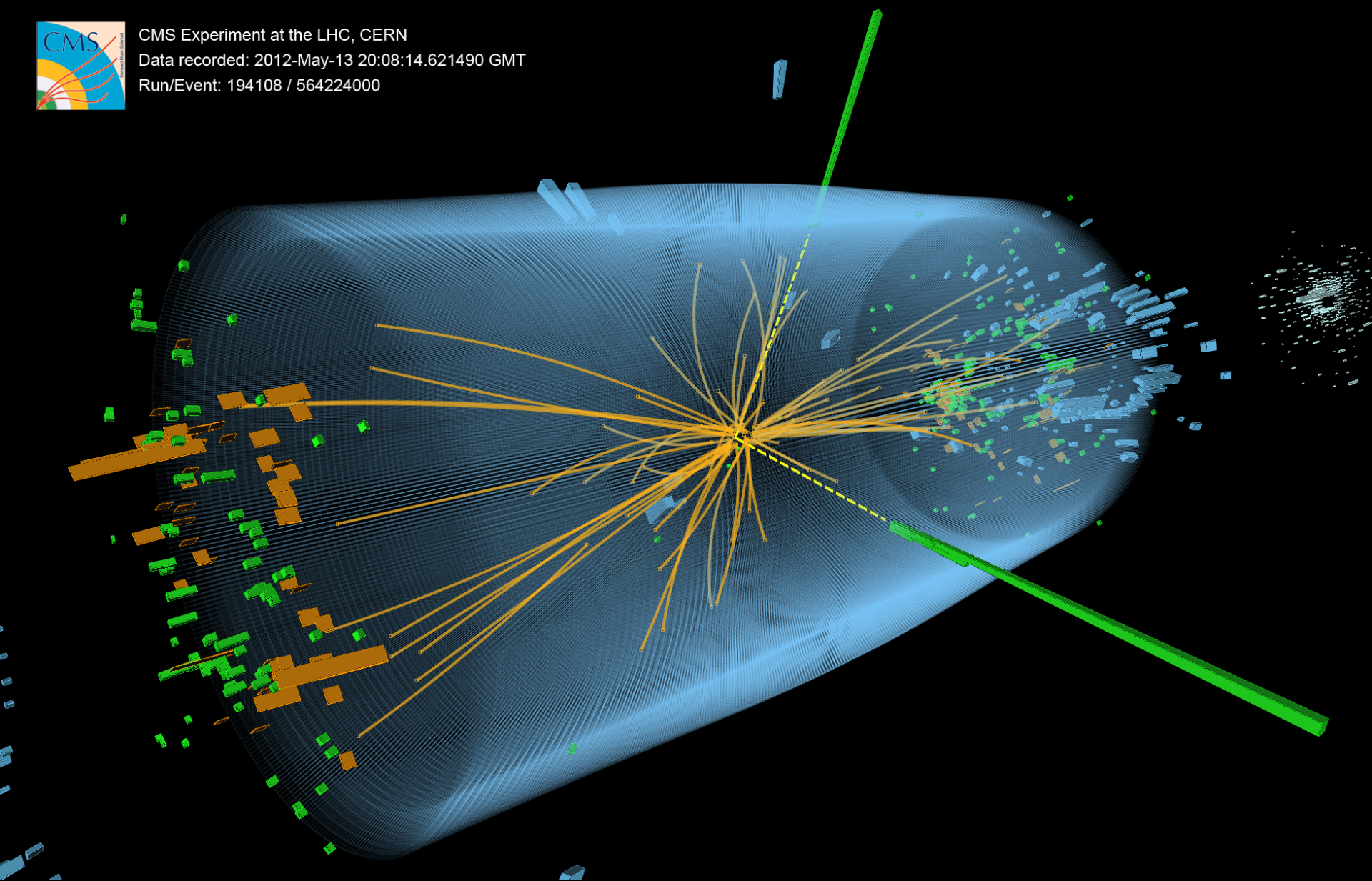
- Lepton final states via WW^* , ZZ^*
- Di-photon final state
- Di-tau final state

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



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



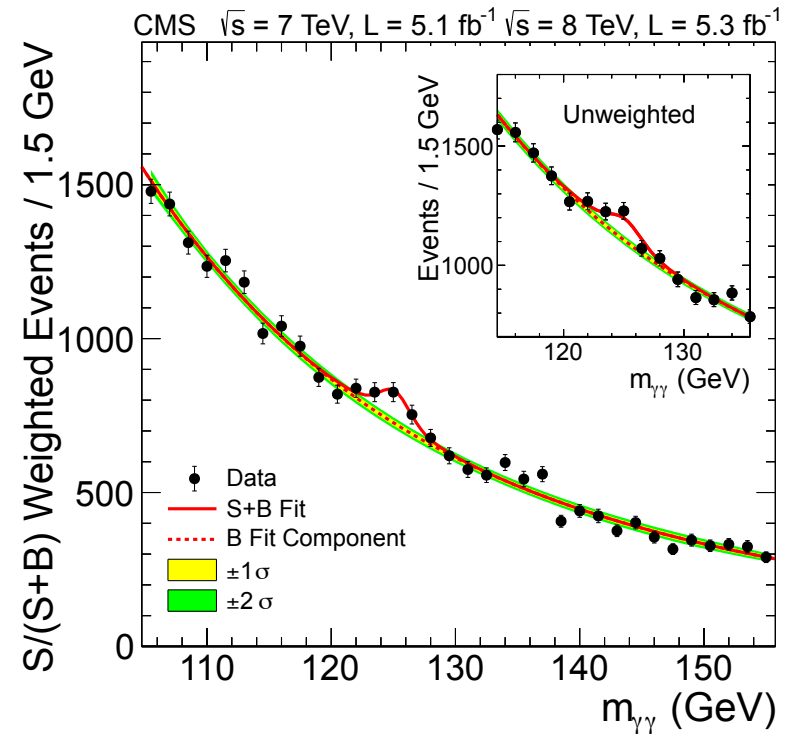
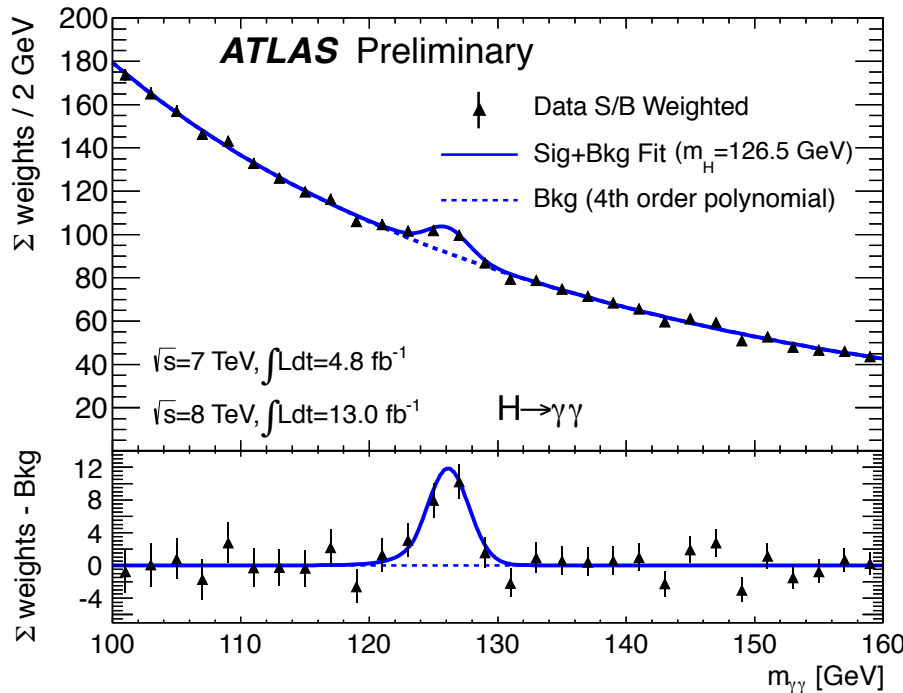
$H \rightarrow \gamma\gamma$ candidate event (CMS) — note: background dominated sample

$$H \rightarrow \gamma\gamma$$

Clean discovery channels for Higgs, allowing precise mass determination

ATLAS-CONF-2012-168, CMS arXiv:1207.7235

Benefit from excellent energy resolution and photon identification capabilities of ATLAS/CMS



Both experiments classify events according to resolution and topology in ML fit

Maximum excess of 6.1σ (4.1σ) seen by ATLAS (CMS) at $126.6 \pm 0.3 \pm 0.7$ GeV (125 GeV)

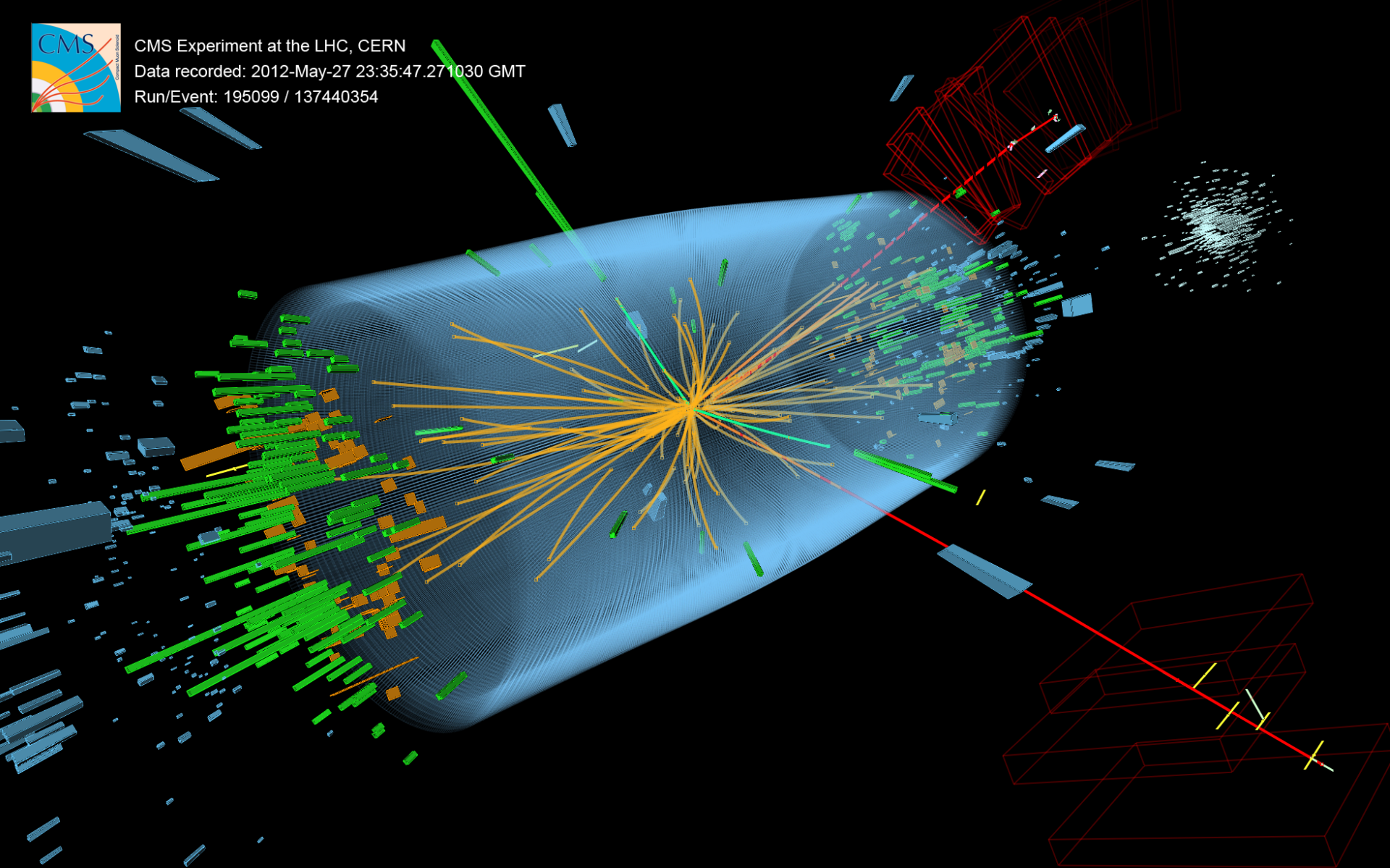
ATLAS signal strength: $\sigma(pp \rightarrow H \rightarrow \gamma\gamma)[\text{exp}] / [\text{SM}] = 1.80 \pm 0.30(\text{stat})^{+0.21}_{-0.15}(\text{syst})^{+0.20}_{-0.14}(\text{theory})$



CMS Experiment at the LHC, CERN

Data recorded: 2012-May-27 23:35:47.271030 GMT

Run/Event: 195099 / 137440354



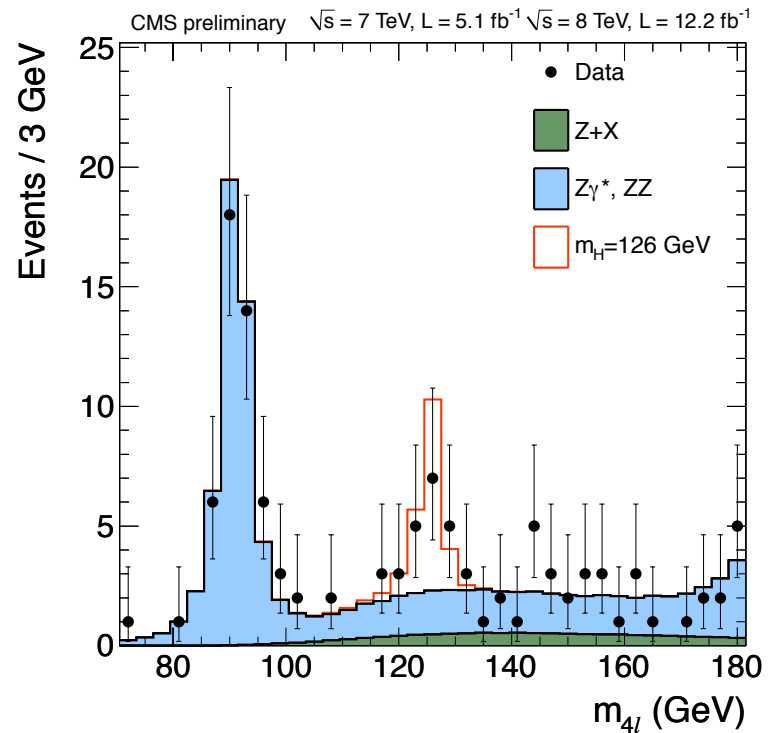
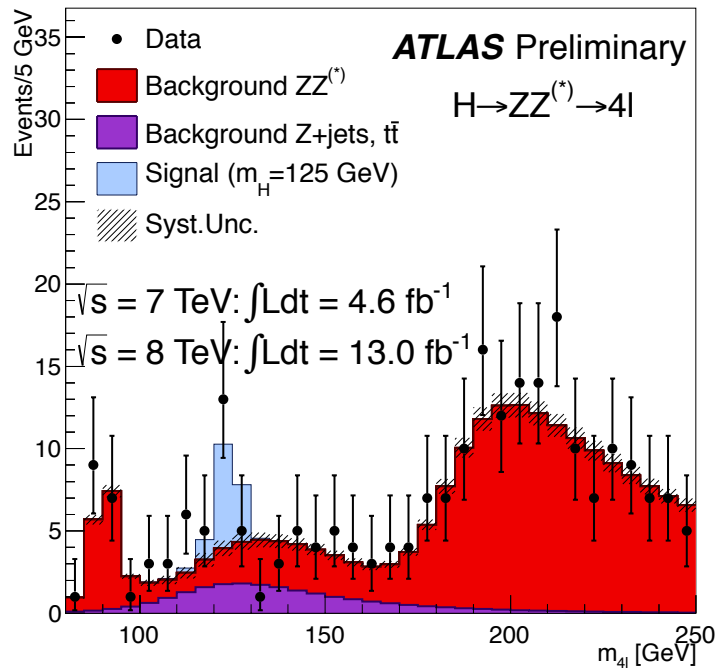
$H \rightarrow 2e2\mu$ candidate event (CMS)

$$H \rightarrow ZZ^{(*)} \rightarrow 2(e, \mu) + 2(e, \mu)$$

Clean discovery channels for Higgs, allowing precise mass determination

ATLAS-CONF-2012-169, CMS-PAS-HIG-12-041

Benefit from excellent energy/momentum resolution and identification capabilities at ATLAS/CMS



Maximum excess of 4.1σ (4.5σ) seen by ATLAS (CMS) at $123.5 \pm 0.9 \pm 0.3$ GeV (126.2 GeV)

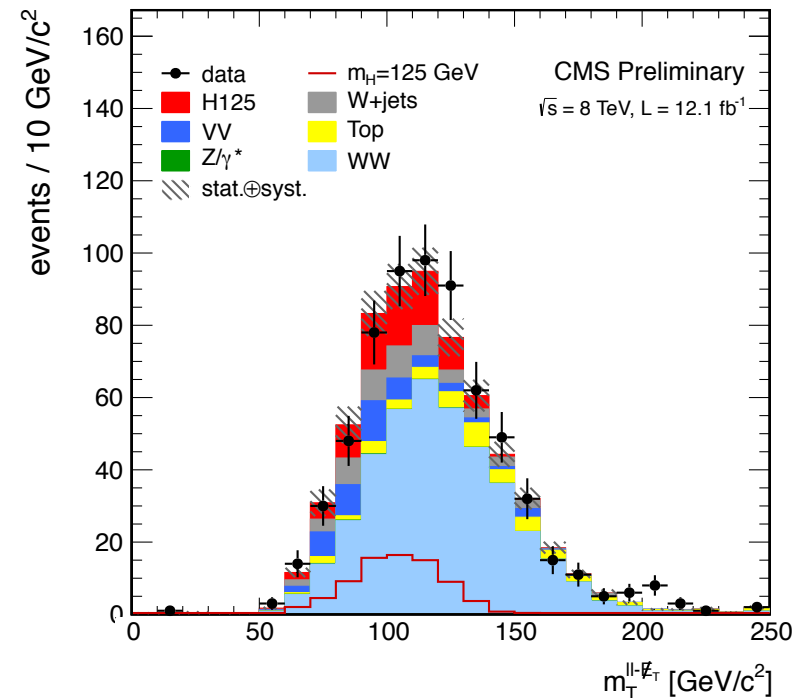
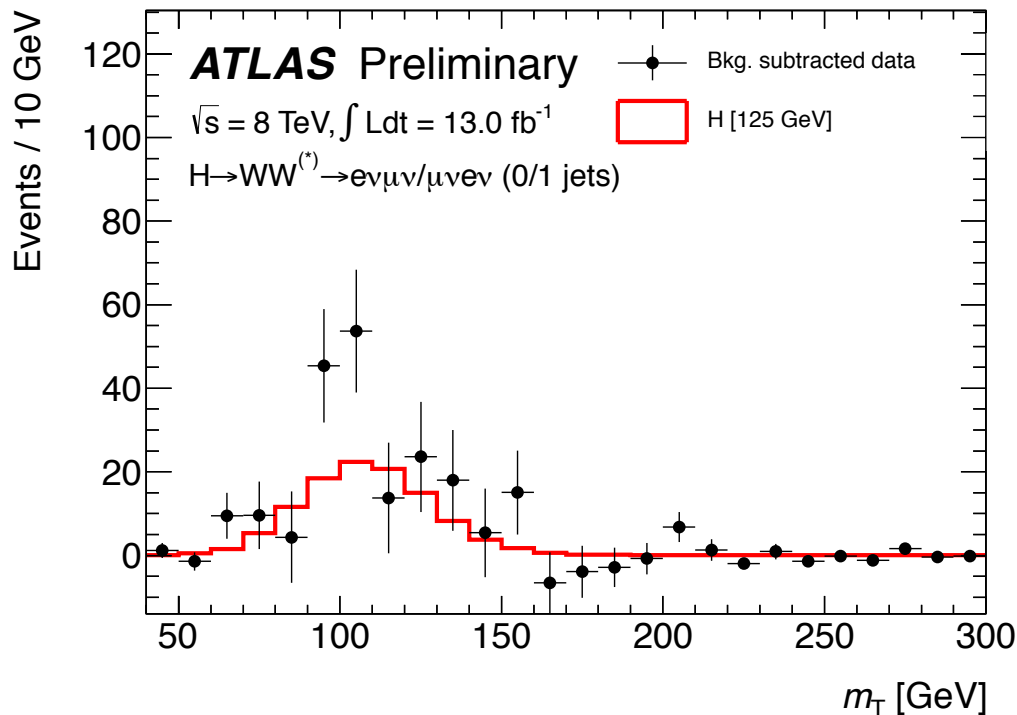
ATLAS (CMS) signal strength: $\sigma(pp \rightarrow H \rightarrow 4l)[\text{exp}] / [\text{SM}] = 1.3^{+0.5}_{-0.4}$ (0.8)

$$H \rightarrow WW^{(*)} \rightarrow 2(e, \mu) + 2\nu$$

Not clean, but abundant (competitive at 125 GeV) – little mass sensitivity

ATLAS-CONF-2012-158, CMS-PAS-HIG-12-042

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



Some excess seen by both experiments: 2.8σ (3.1σ) for ATLAS (CMS) at $\sim 125 \text{ GeV}$

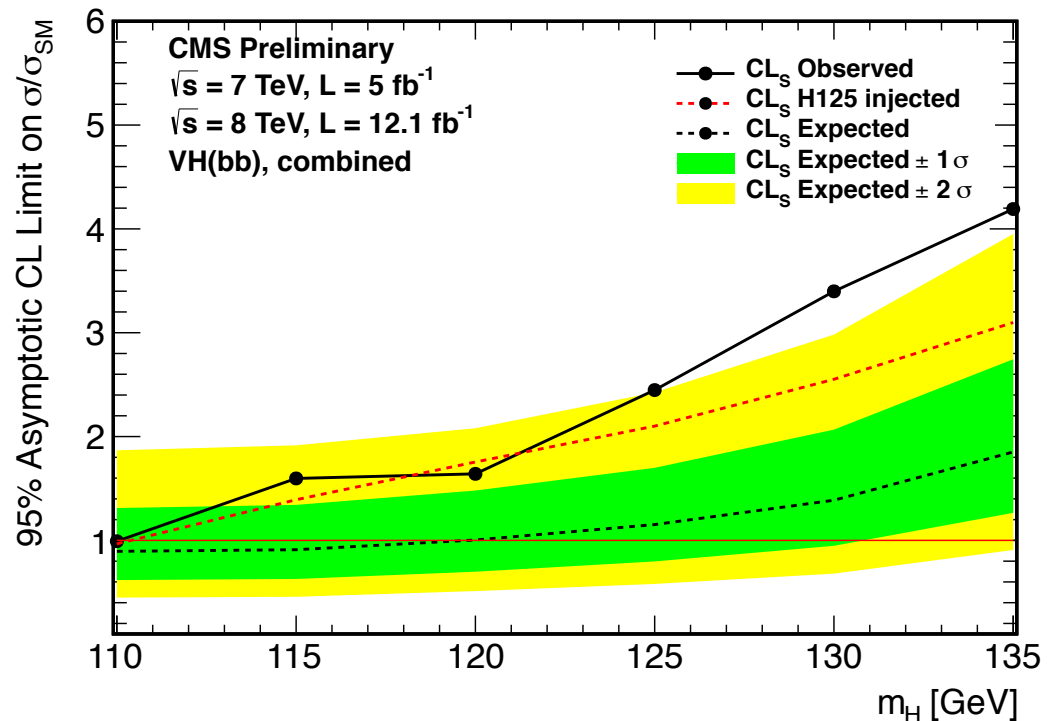
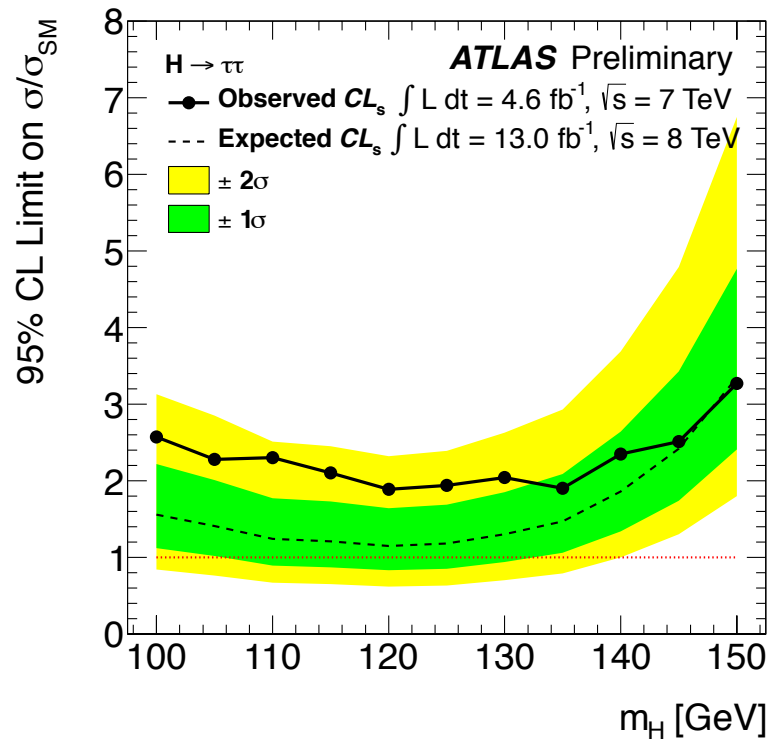
ATLAS (CMS) signal strength: $\sigma(pp \rightarrow H \rightarrow 2\ell 2\nu)[\text{exp}] / [\text{SM}] = 1.5 \pm 0.6$ (≈ 0.8)

$H \rightarrow \tau\tau$ and $(W/Z)+H \rightarrow (l\nu/ll, \nu\nu)+bb$

Challenging, non-clean channels – not yet significant

ATLAS-CONF-2012-160, ATLAS-CONF-2012-161, CMS-PAS-HIG-12-043, CMS-PAS-HIG-12-044

Signal selection: reconstruct (broad) Higgs mass peak, close to Z, background understanding crucial



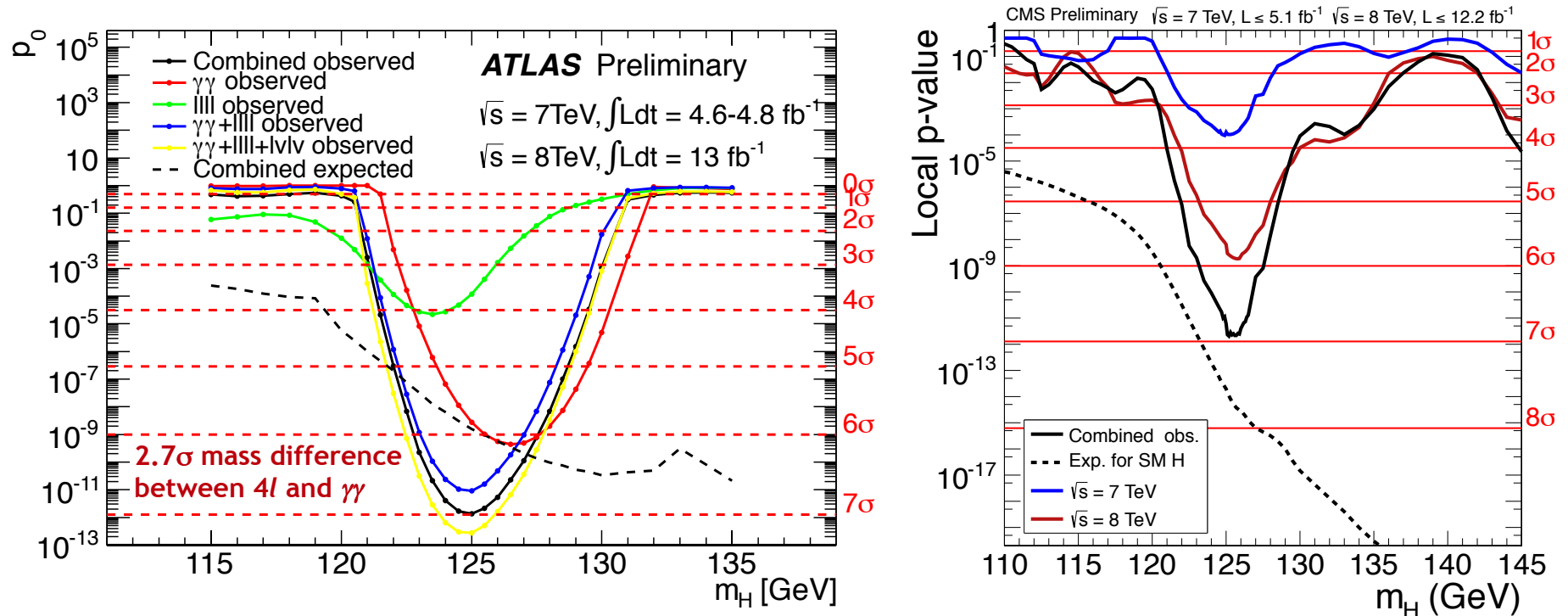
Slight excess seen by both experiments for $\tau\tau$, ATLAS does not yet see excess in bb

Combining all the channels – discovery significance

One new boson with Higgs-like properties ... nothing else around

ATLAS-CONF-2012-170, CMS-PAS-HIG-12-045

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



Maximum excess of 7.0 σ (6.9 σ) seen by ATLAS (CMS) at $125.2 \pm 0.3 \pm 0.6$ ($125.8 \pm 0.4 \pm 0.4$) GeV

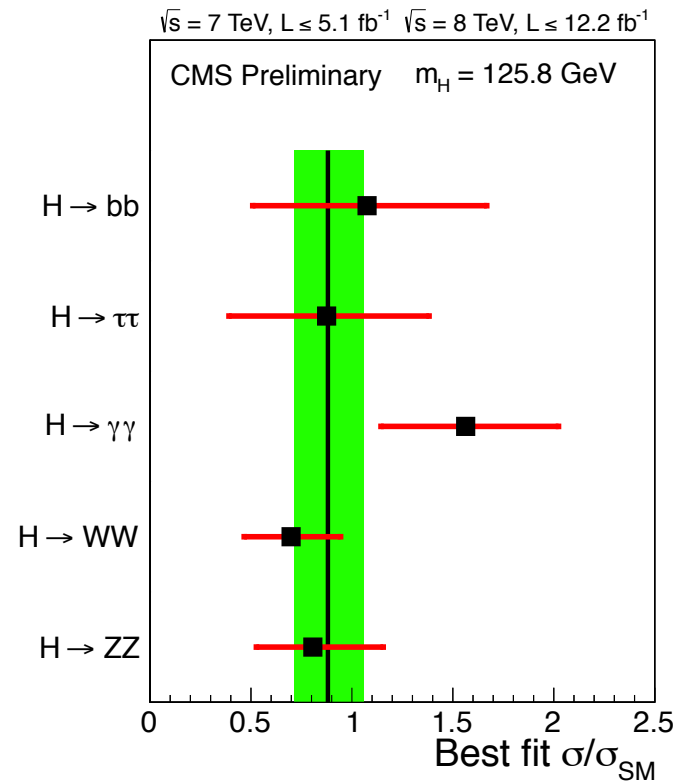
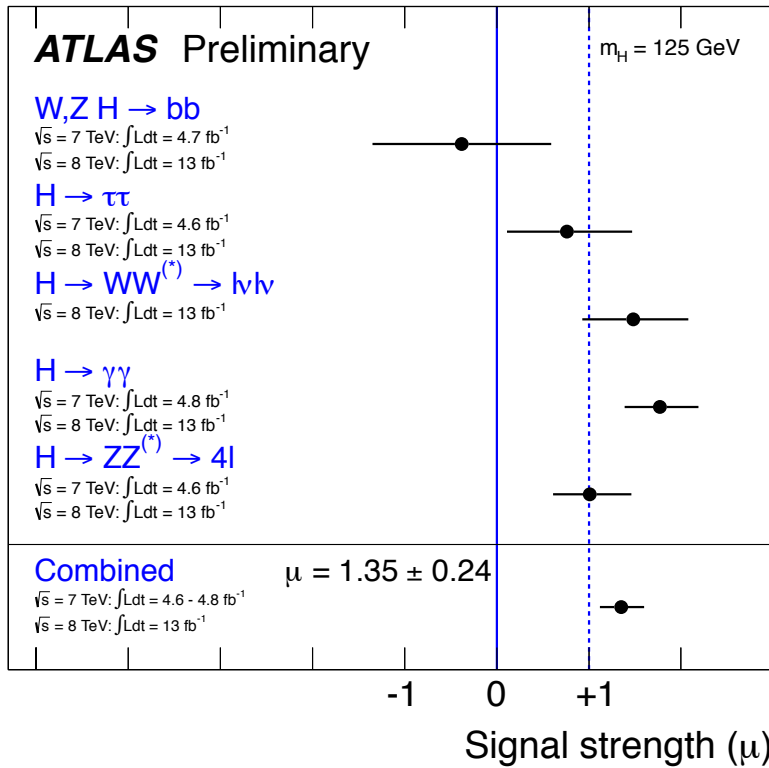
ATLAS (CMS) signal strength: $\sigma(pp \rightarrow H)[\text{exp}] / [\text{SM}] = 1.35 \pm 0.24$ (0.88 ± 0.21)

Combining all the channels — cross section

Are channel-by-channel cross sections $\times$ branching fractions SM-like ?

ATLAS-CONF-2012-170, CMS-PAS-HIG-12-045

Individual $\sigma[\text{exp}] / \sigma[\text{SM}]$ ratio for the channels: $\gamma\gamma$, ZZ , WW , $\tau\tau$, bb . Left: ATLAS, right: CMS



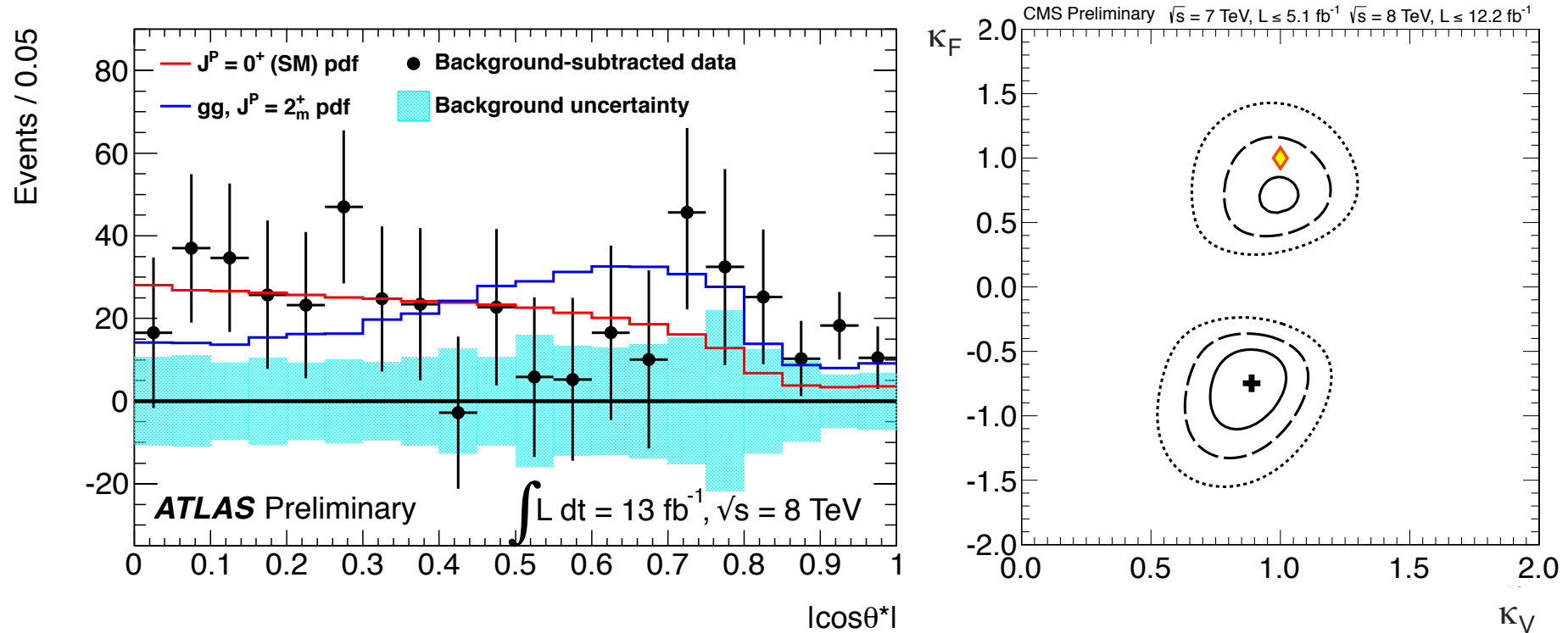
Compatibility with SM ($\mu=1$): 13% for ATLAS, $> 50\%$ for CMS

Combining all the channels – couplings

Is it the Higgs boson with $J^{PC} = 0^{++}$ and SM couplings ?

ATLAS-CONF-2012-168, CMS-PAS-HIG-12-045

$$\text{Observed } \sigma: \left[\sigma \cdot \text{BR} \right] \left(ii \rightarrow H \rightarrow ff \right) \Big|_{\text{obs}} = \sigma_{\text{SM}} \left(ii \rightarrow H \right) \cdot \text{BR}_{\text{SM}} \left(H \rightarrow ff \right) \cdot \kappa_i^2 \kappa_f^2 / \kappa_H^2 \quad \left[\text{where: } \kappa_a^2 = \Gamma_{aa} / \Gamma_{aa}^{\text{SM}} \right]$$



Spin-0 hypothesis slightly favoured; Higgs to vector and fermion couplings agree with SM

Combining all the channels — couplings

Is it the Higgs boson with $J^{PC} = 0^{++}$ and SM couplings ?

Michael Peskin, in theoretical summary talk at HiggsHunting (July 2012) [arXiv:1208.5152]:

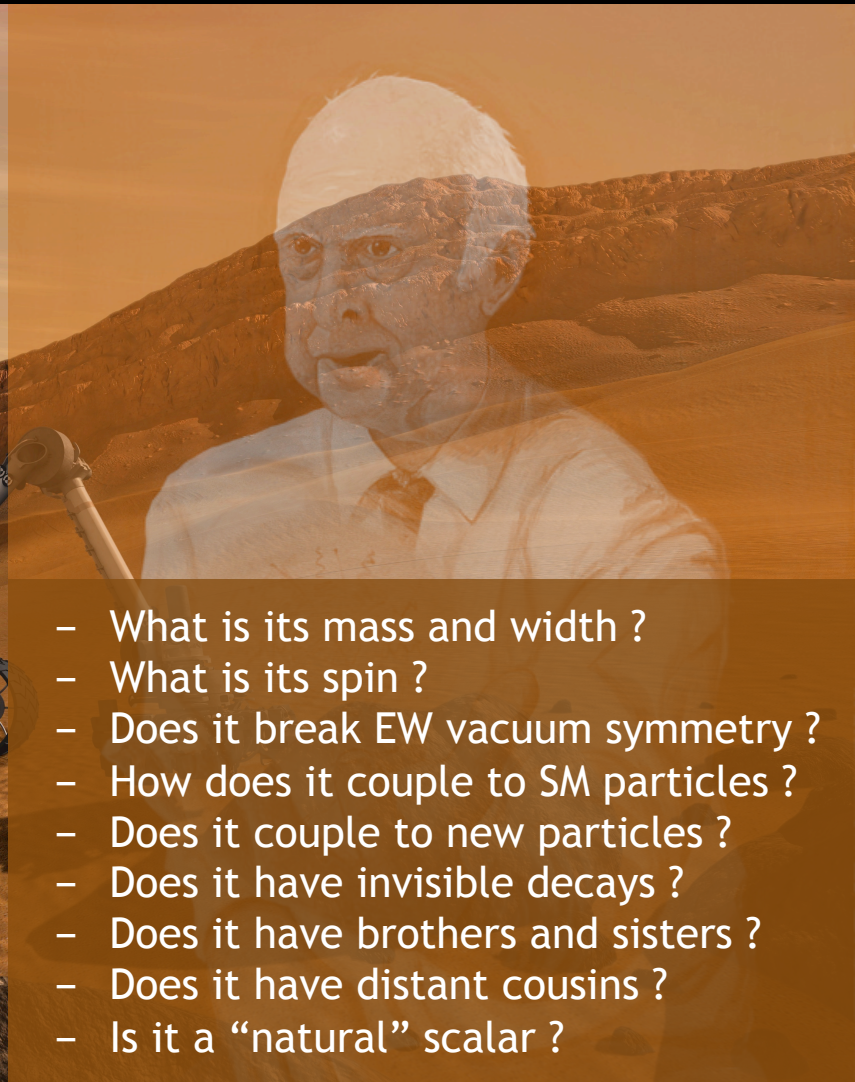
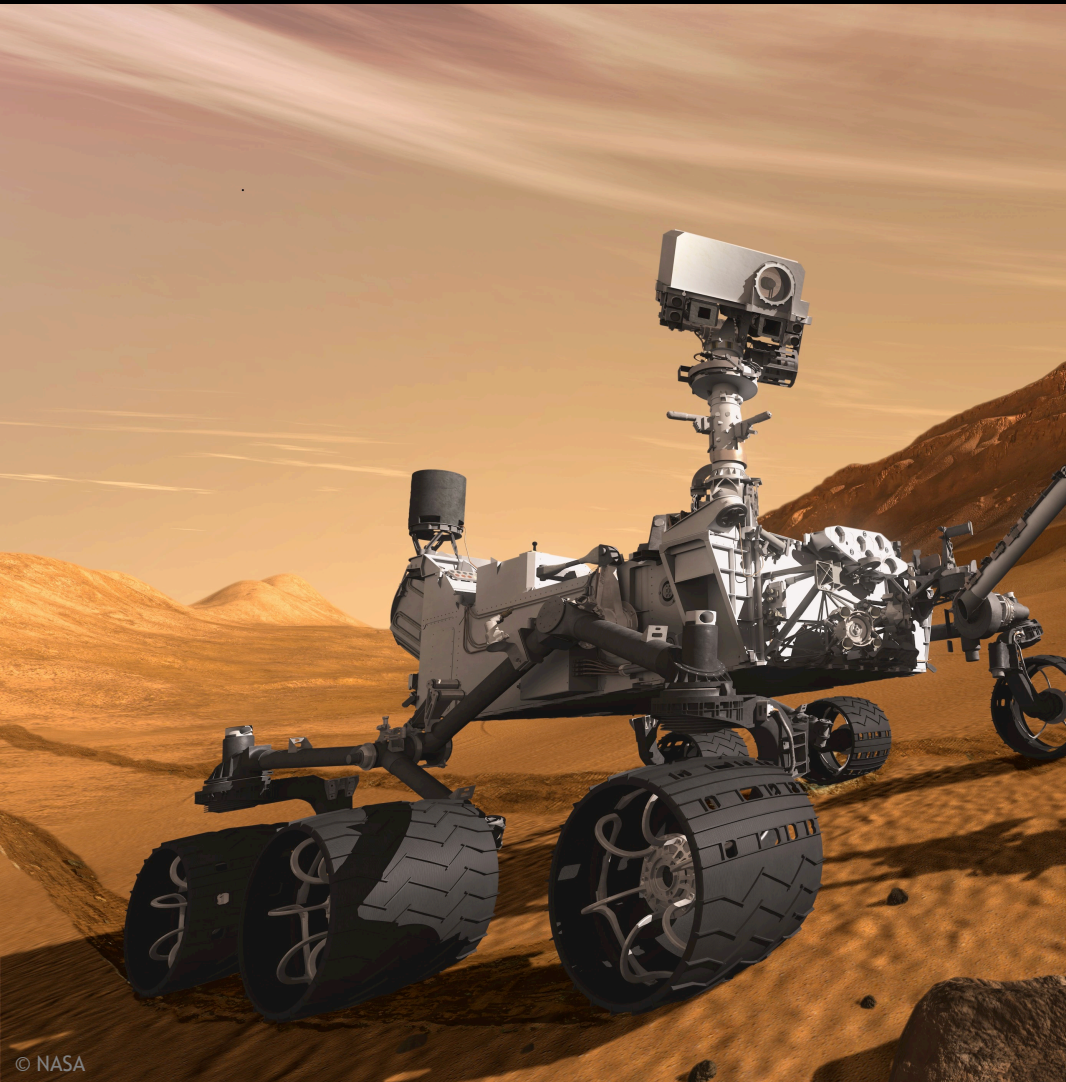
SM strength (i.e., ‘large’) coupling to WW , ZZ is
“ *prima facie evidence that the new particle is CP even spin zero field with a vacuum expectation value that breaks $SU(2) \times U(1)$. This is what we call a ‘Higgs boson’.* ”



PRESS COVERAGE after July 4th seminars at CERN

— Intense curiosity —

A new era in particle physics has begun: the exploration of planet Higgs

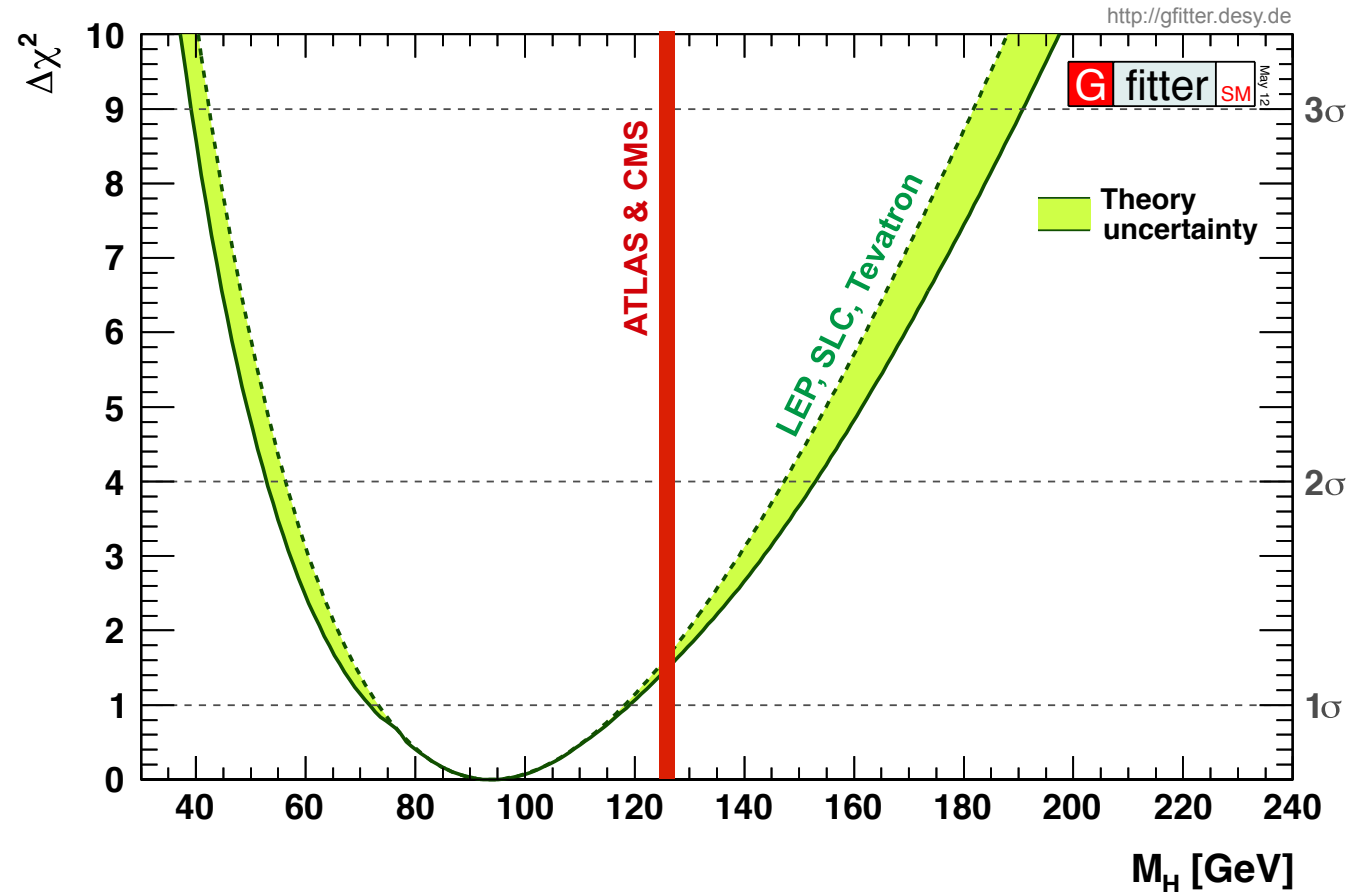
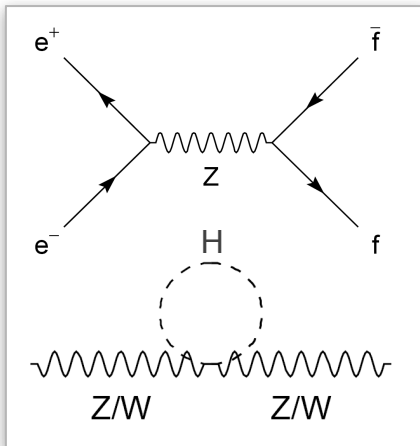


- What is its mass and width ?
- What is its spin ?
- Does it break EW vacuum symmetry ?
- How does it couple to SM particles ?
- Does it couple to new particles ?
- Does it have invisible decays ?
- Does it have brothers and sisters ?
- Does it have distant cousins ?
- Is it a “natural” scalar ?

What can we conclude from this discovery

Recall: light Higgs was predicted from SM fit to precision measurements

Discovery of light Higgs boson — if confirmed — is a *huge success* of the Standard Model

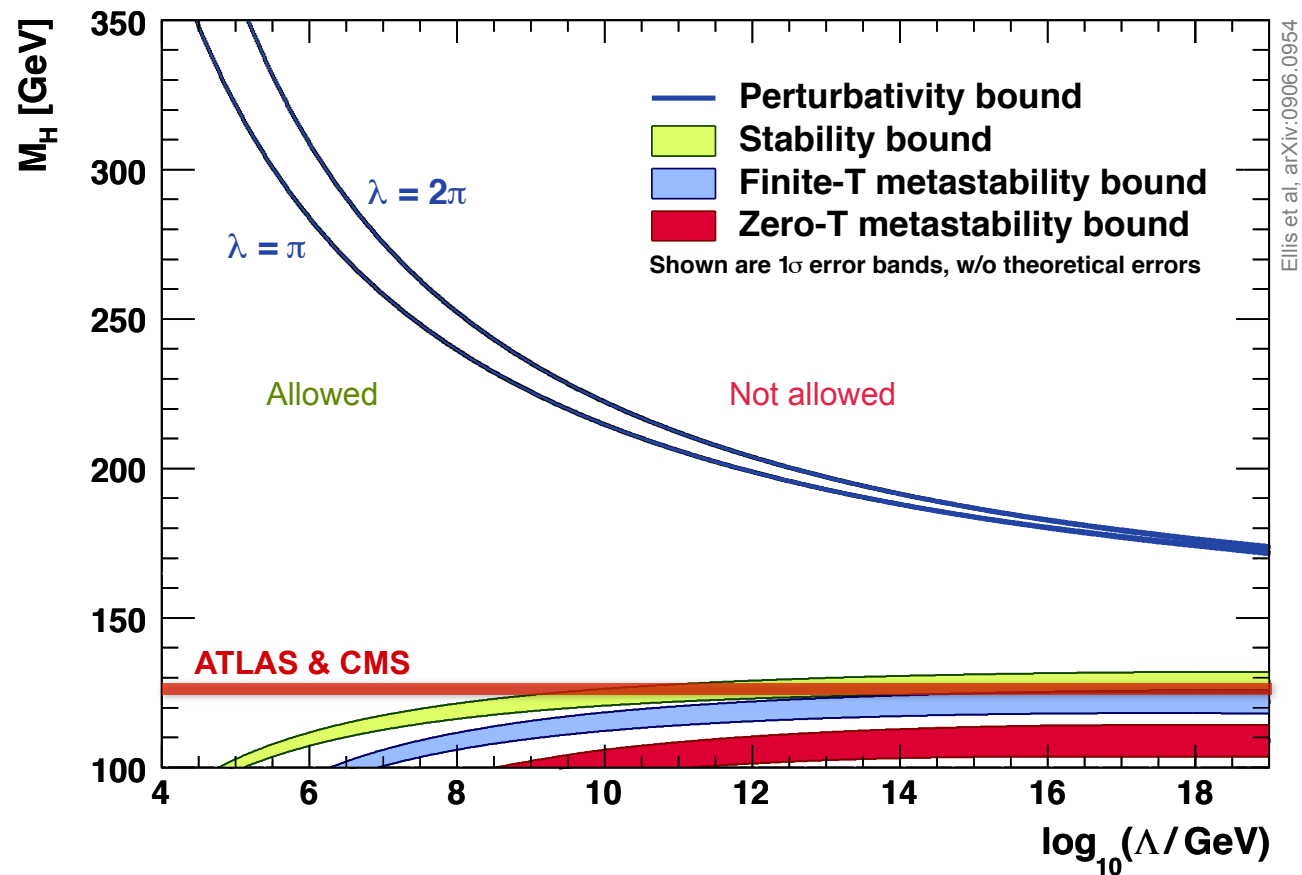


What can we conclude from this discovery

Is the electroweak vacuum stable or metastable (if SM holds) ?

Barely stable ?

But: prediction of the stability bound suffers from theoretical uncertainties ...



What can we conclude from this discovery

Is the electroweak vacuum stable or metastable (if SM holds up to M_{Pl}) ?

Barely stable ?

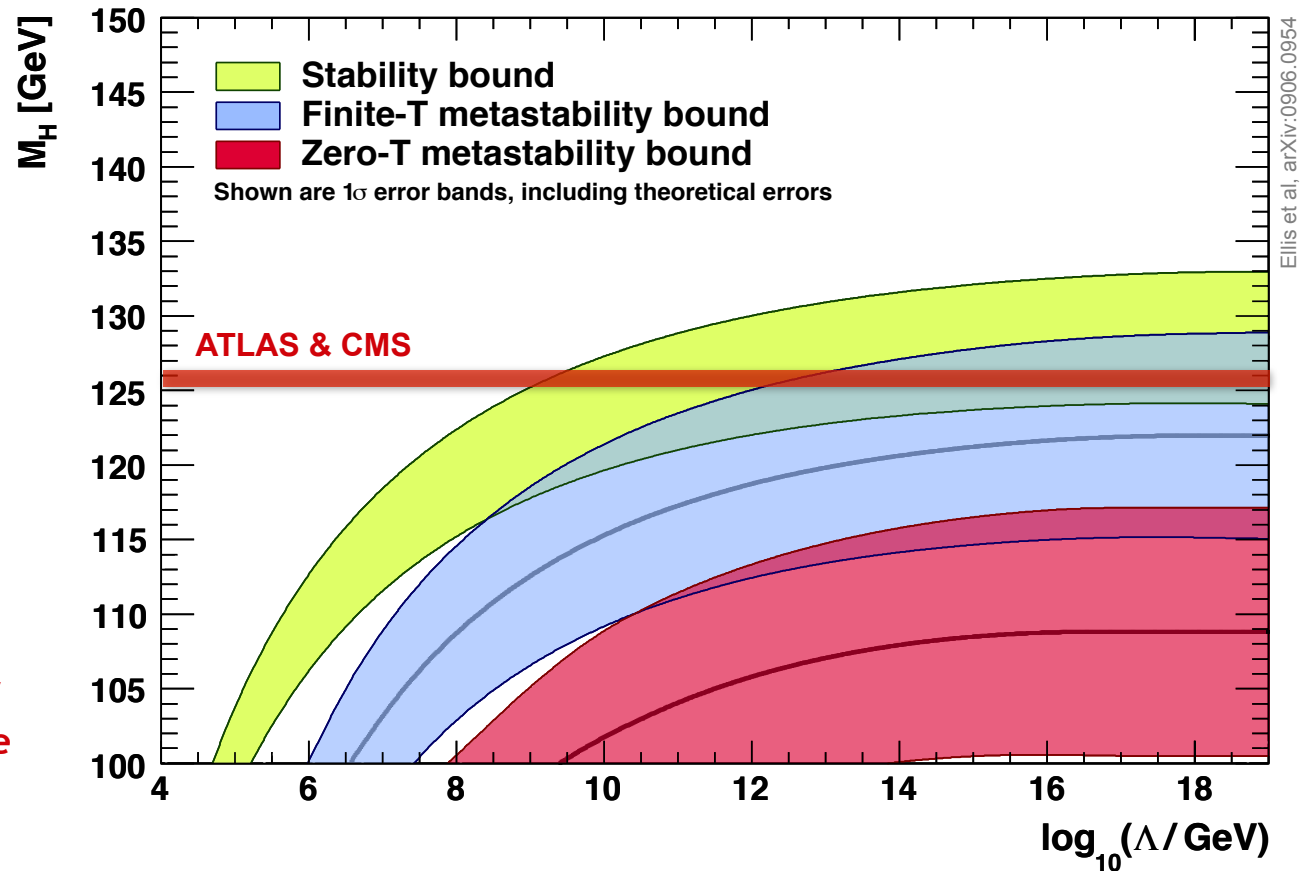
But: prediction of the stability bound suffers from theoretical uncertainties ...

Let's zoom into the interesting region

Newest full NNLO result moves up stability bound at Planck mass by +0.8 GeV and reduces uncertainty

→ **barely stable or metastable, but certainly the Higgs self coupling would become very weak at M_{Pl}**

Degrassi et al, arXiv:1205.6497



100 years after the discovery of cosmic rays...

The discovery of the
Higgs boson — if
confirmed — completes
the Standard Model

Jiro Taniguchi, Furari, © Casterman (2012)



It is a triumph for the
imagination and rigour
of the human mind

It is a triumph for the
greatest experimental
undertaking ever:

Frontier of accelerator
& detector technologies

Global data sharing,
analysis & collaboration

100 years after the discovery of cosmic rays...

The discovery of the
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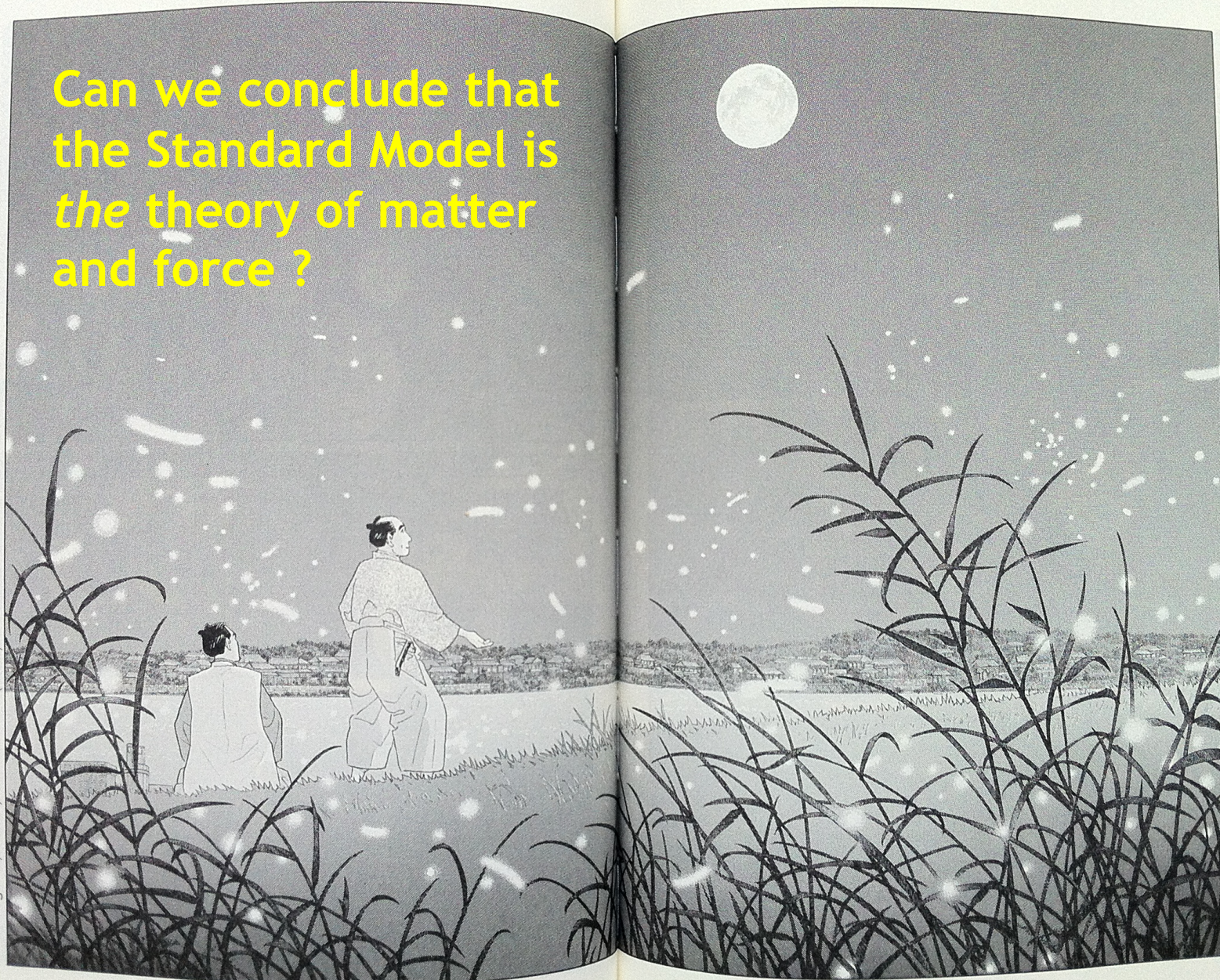
But ...

Jiro Taniguchi, Furari, © Casterman (2012)



Can we conclude that
the Standard Model is
the theory of matter
and force ?

Jiro Taniguchi, Furari, © Casterman (2012)



The SM cannot be the final theory, because ...

Higgs is only fundamental scalar

neither matter, nor force,
- all known scalars are composite states

Huge mass hierarchy between matter particles

Gauge hierarchy / scalar SM sector is unstable

Dark matter and dark energy

Grand unification of the forces

Causally connected observable universe

Matter-antimatter asymmetry in universe

Strong CP problem

Massive neutrinos

Gravitation

The SM cannot be the final theory, because ...

The Higgs potential ($\mu < 0$, $\lambda \geq 0$: *physics or just mathematics?*) exemplifies our success with description but lack of understanding

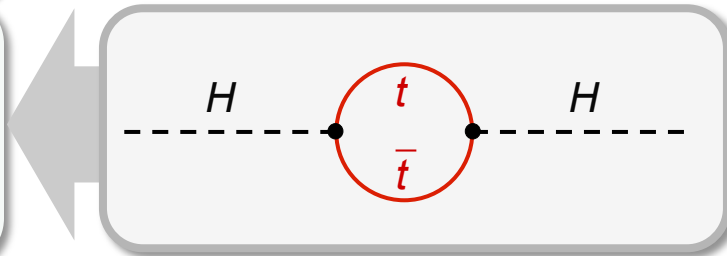
$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Higgs boson mass term

$$\delta m_H^2 \sim |\delta \mu_H^2| \propto \Lambda_{\text{cut-off}}^2$$

“Hierarchy problem”

→ new physics at ~TeV



The SM cannot be the final theory, because ...

The Higgs potential ($\mu < 0$, $\lambda \geq 0$: *physics or just mathematics*?) exemplifies our success with description but lack of understanding

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Is this the right potential?

If the Higgs field fills all space-time, is it related to inflation and dark energy?

Higgs boson mass term

$$\delta m_H^2 \sim |\delta \mu_H^2| \propto \Lambda_{\text{cut-off}}^2$$

“Hierarchy problem”

→ new physics at ~TeV

Higgs self coupling

$$\lambda_{\text{SM}} = G_F m_H^2 / \sqrt{2} \sim 0.13$$

EW vacuum may be meta-stable

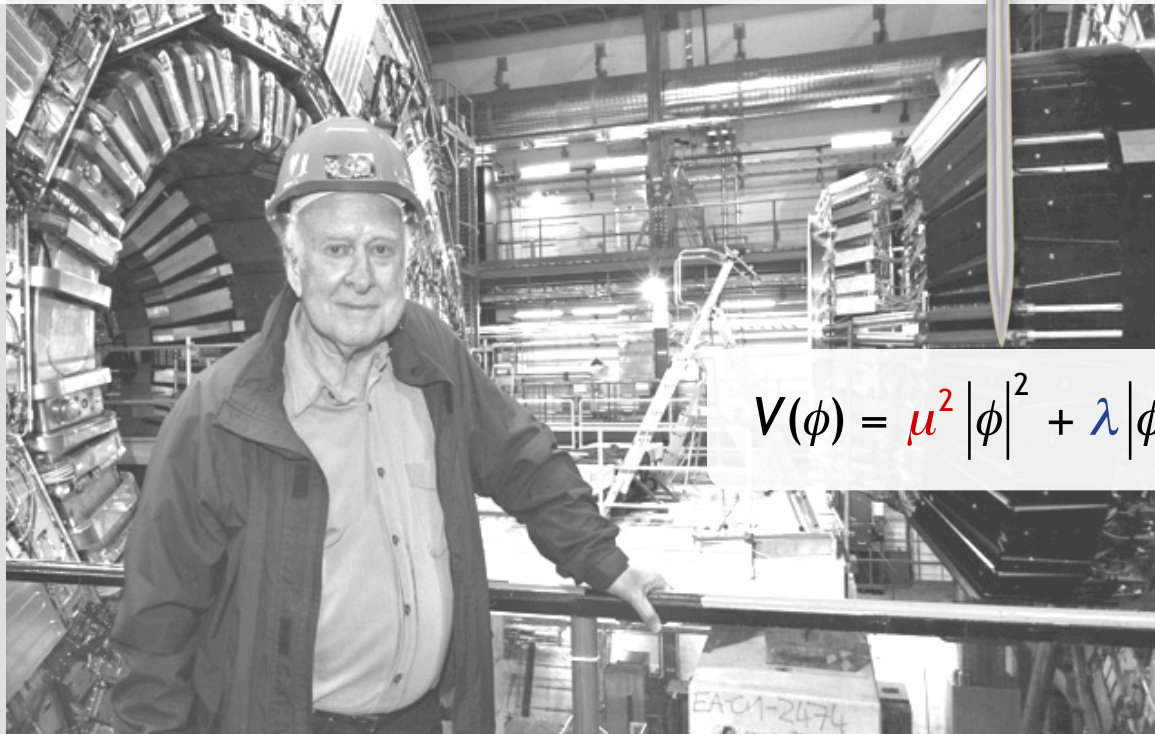
Higgs–fermion couplings

“SM flavour problem”:
large mass hierarchy
between fermion families

G. Isidori at HiggsHunting 2012

Through the missing protection of the scalar potential to high-scale physics (no symmetry for $m_H = 0$!), the Higgs boson is considered a “*portal to new physics*”

Higgs discovery puts these questions into spotlight



$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

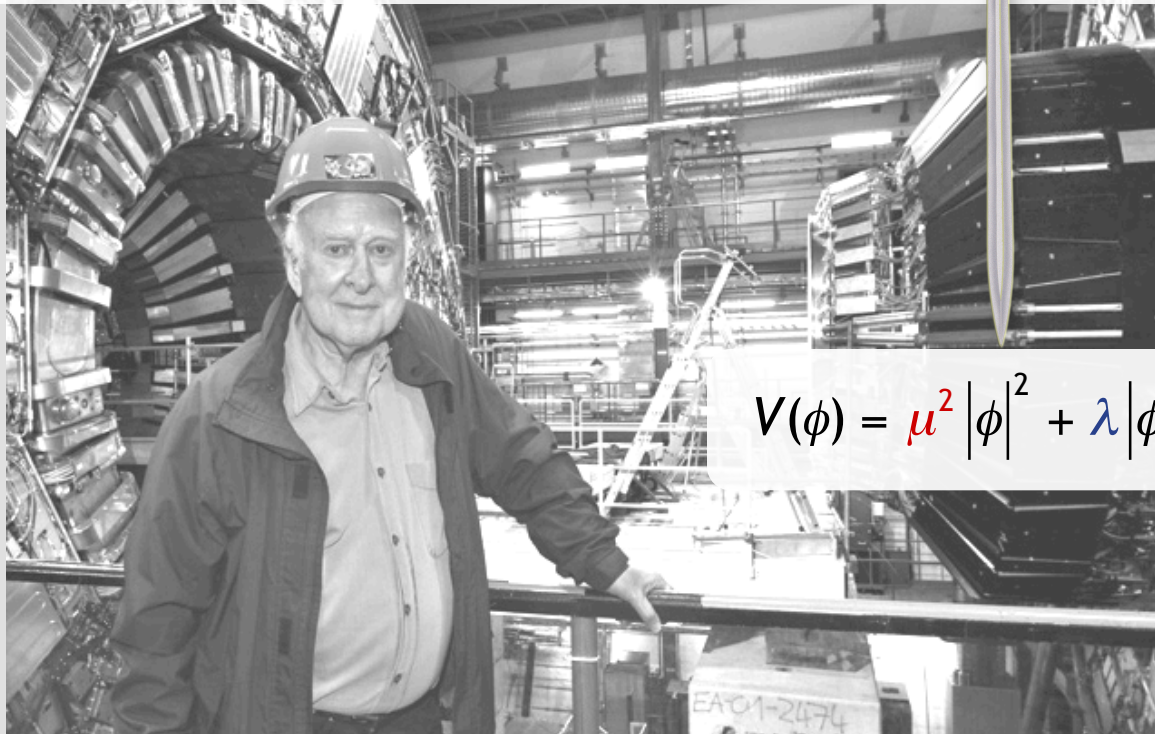
P. Higgs at CMS

Proposed solutions to hierarchy problem

- **Weakly coupled:** Supersymmetry, ...
- **Strongly coupled:** Little Higgs, Composite Higgs, ...

Different manifestations of similar scenarios. Many models also provide dark matter candidates

Higgs discovery puts these questions into spotlight



$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

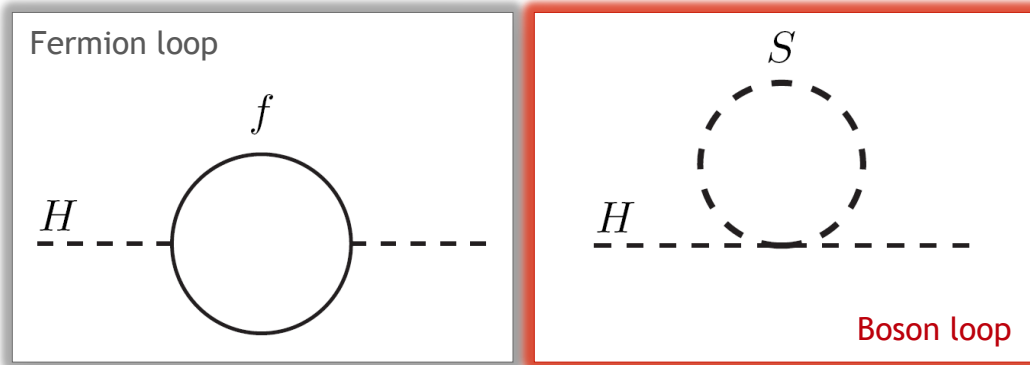
P. Higgs at CMS

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

Supersymmetry (SUSY)



P. Higgs at CMS



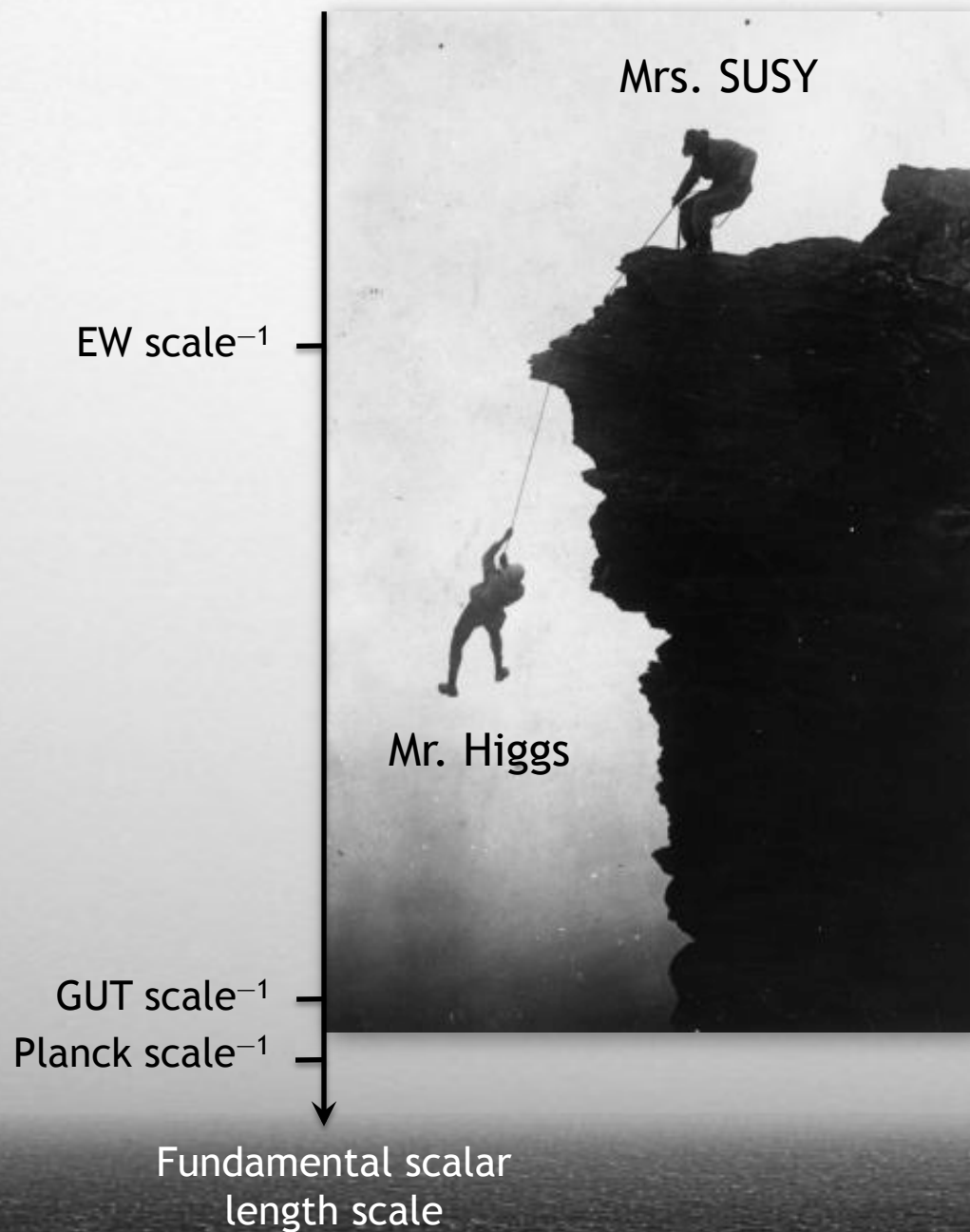
Supersymmetry (SUSY)

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

Supersymmetry realises this by transforming bosons $\leftrightarrow$ fermions

This solves the hierarchy and naturalness problems of the SM (and other problems)
 Each SM particle has thus a supersymmetric partner (which is of $\sim \text{TeV}$ scale – “broken SUSY”)

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		

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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- Need to introduce an additional Higgs doublet to the non-SUSY side → 5 Higgs bosons
- SUSY breaking introduces lots (> 100) of new parameters (masses, mixing angles, phases)

Supersymmetry (SUSY)

	SM		SUSY	
	Spin 0	Spin 1/2	Spin 1	
Eigenstates of mass	$\tilde{\ell}_1, \tilde{\ell}_2$	ℓ		Squark/slepton mixing proportional to SM partner masses → largest for 3 rd gen. → can become lightest squarks / sleptons
	$\tilde{q}_1, \tilde{q}_2$	q		
	h^0, H^0, A^0	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	γ, Z^0	
	$H^\pm$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$W^\pm$	
		$\tilde{g}_a$	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

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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- Superpartners have opposite spin statistics but otherwise equal quantum numbers
- Need to introduce an additional Higgs doublet to the non-SUSY side $\rightarrow 5$ Higgs bosons
- SUSY breaking introduces lots (> 100) of new parameters (masses, mixing angles, etc.)

Problem: since ~30 years SUSY is supposed to be “around the corner”, but has not been observed yet ...

Eigenstates	Spin 1		
	ℓ	q	
h^0, H^0, A^0	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	γ, Z^0	
$H^\pm$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$W^\pm$	
	$\tilde{g}_a$	g_a	

Squark/slepton mixing proportional to SM partner masses

$\rightarrow$ largest for 3rd gen.

$\rightarrow$ can become lightest squarks / sleptons

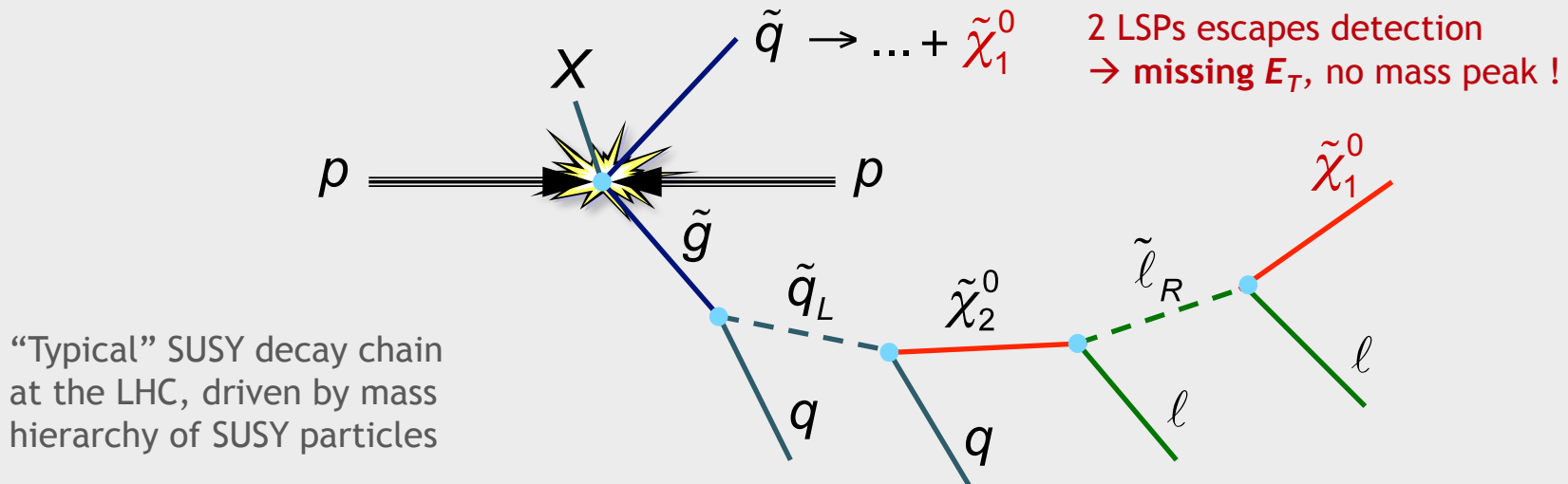
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Characteristic SUSY Decay Cascades

- 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

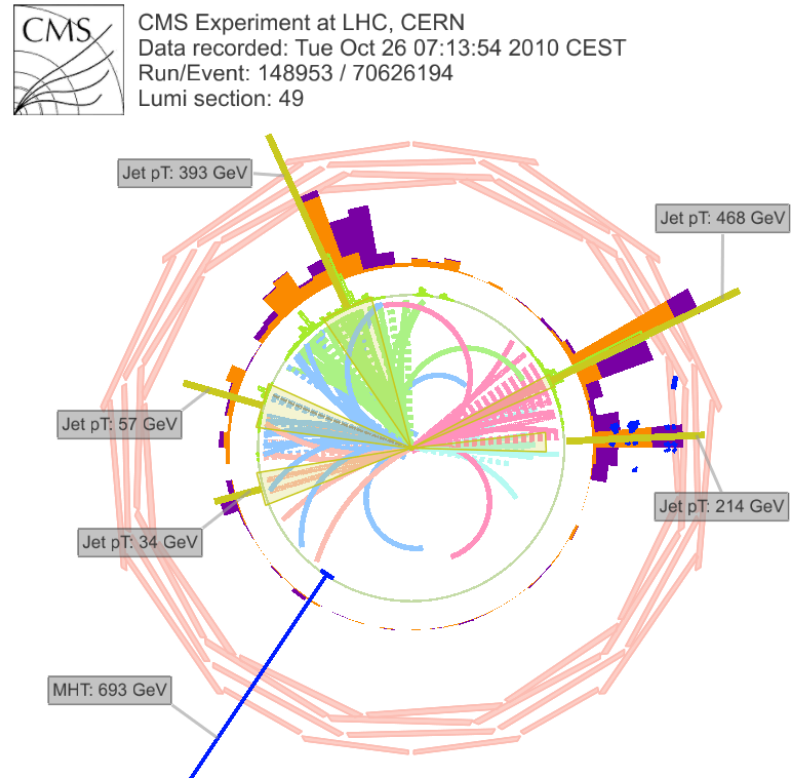
Signatures of the SUSY “cascades” are driven by masses of the SUSY particles

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

Many different search channels along expected SUSY event topologies

ATLAS-CONF-2012-109, ATLAS-CONF-2012-103

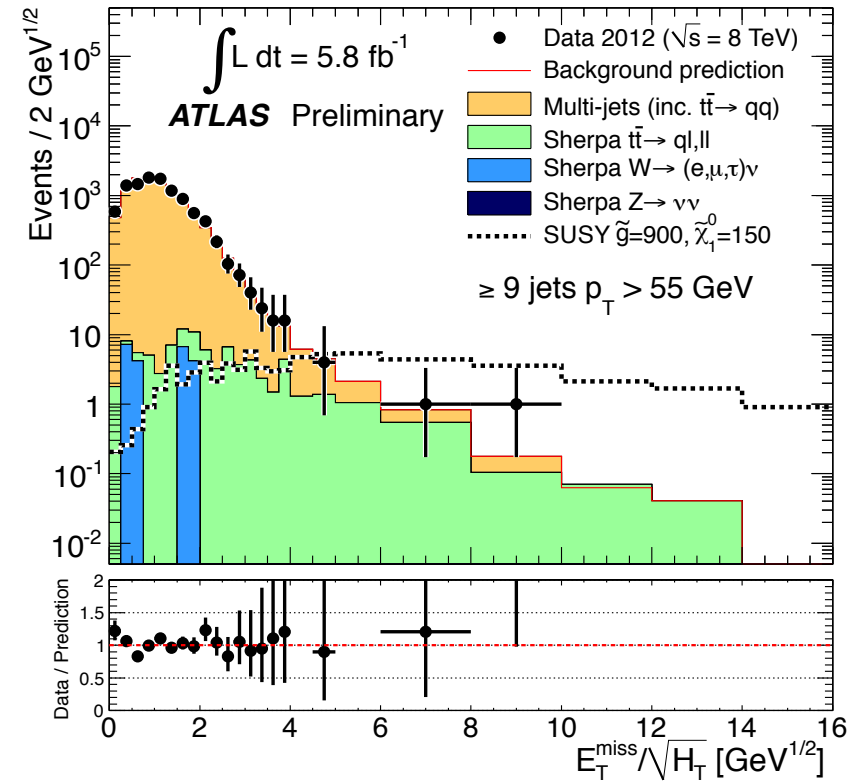
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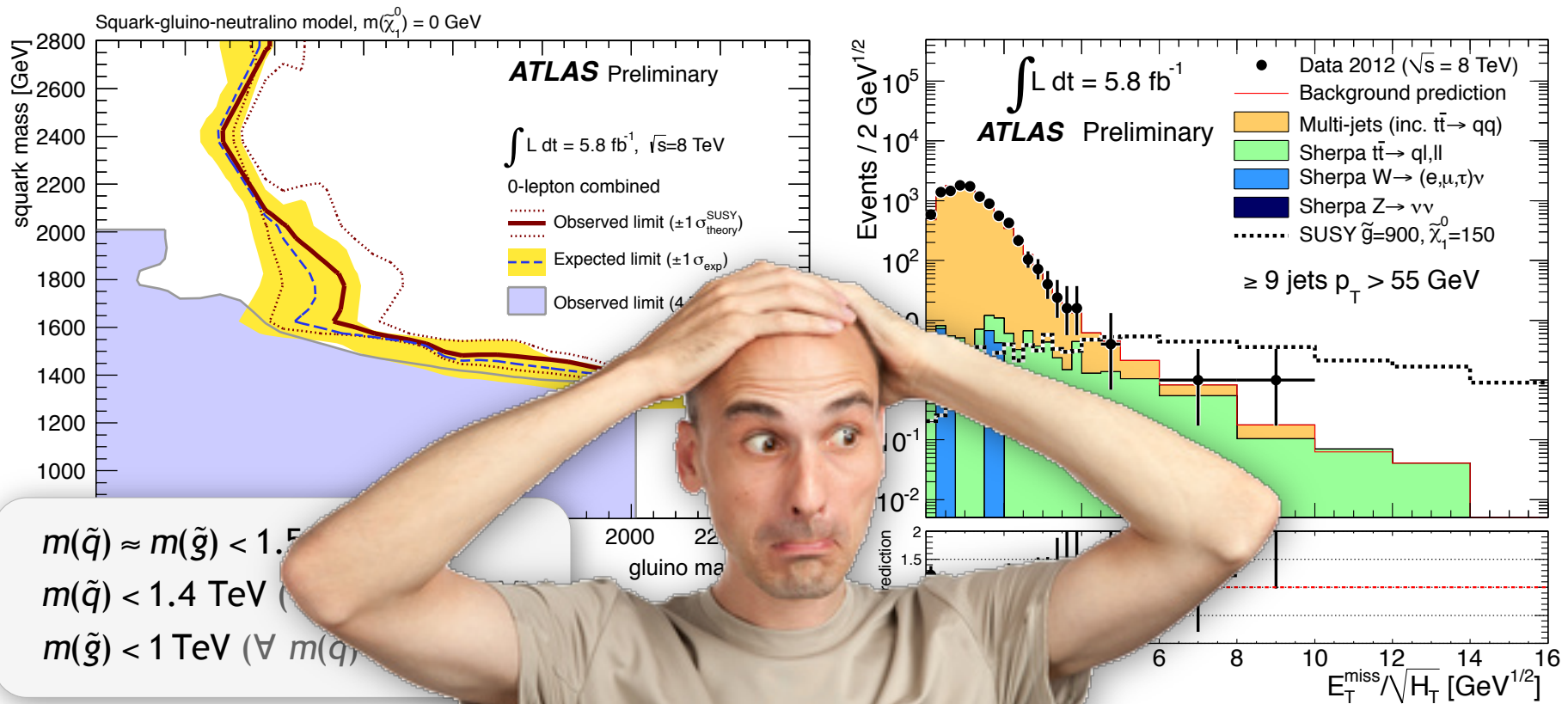


SUSY searches at the LHC

Many different search channels along expected SUSY event topologies

ATLAS-CONF-2012-109, ATLAS-CONF-2012-103

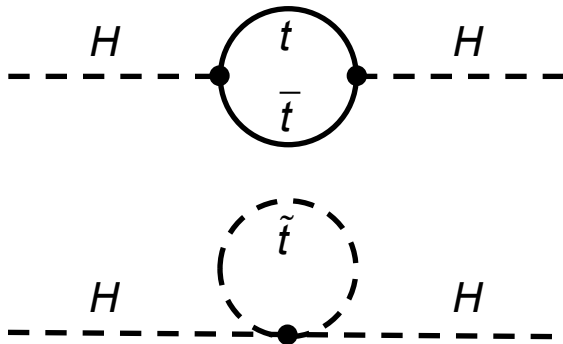
Signatures of the SUSY “cascades” are driven by masses of the SUSY particles



Does SUSY hide from our analyses?

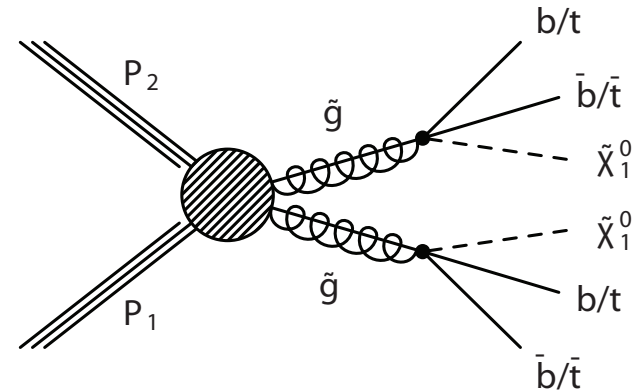
What is required to keep SUSY “natural” ?

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

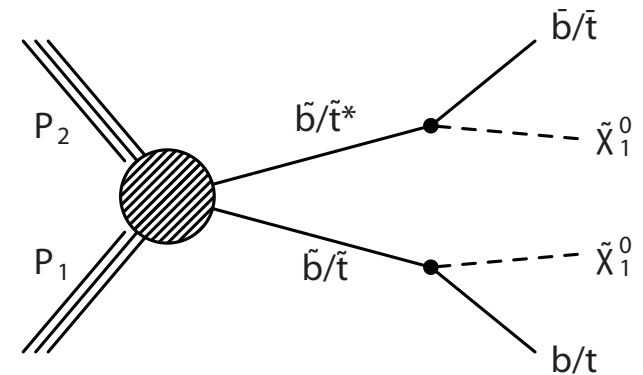


Contrary to the SM, 3rd generation squarks can be lighter than 1st and 2nd generations

Watch out for tops and b 's in final state (“natural SUSY”)



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

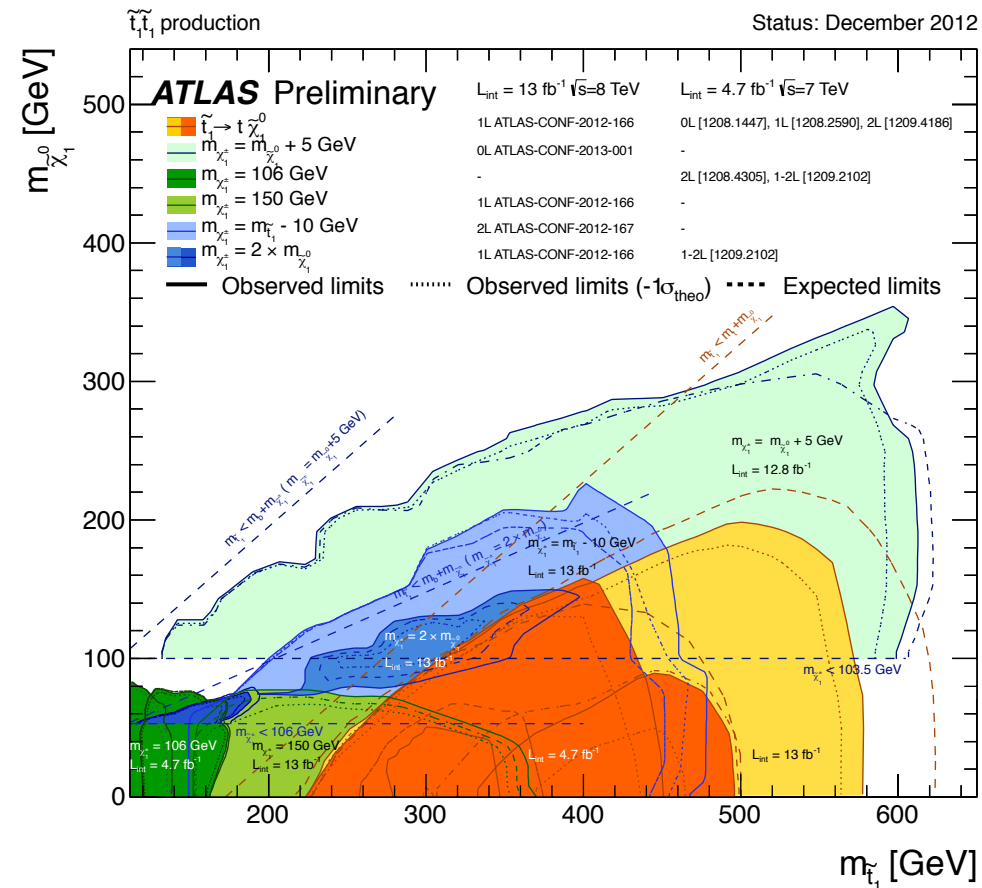
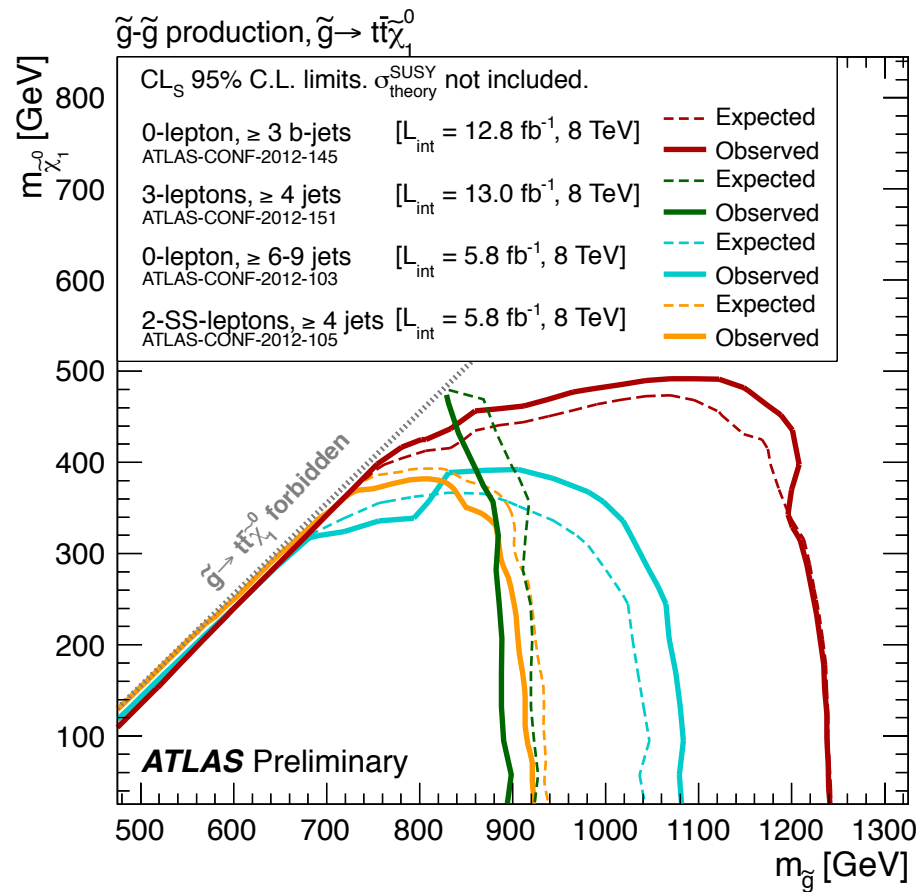


Direct $\tilde{b}/\tilde{t}$ pair production

Does SUSY hide from our analyses?

Dedicated searches for gluino-mediated (left) and direct stop production (right)

See: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>



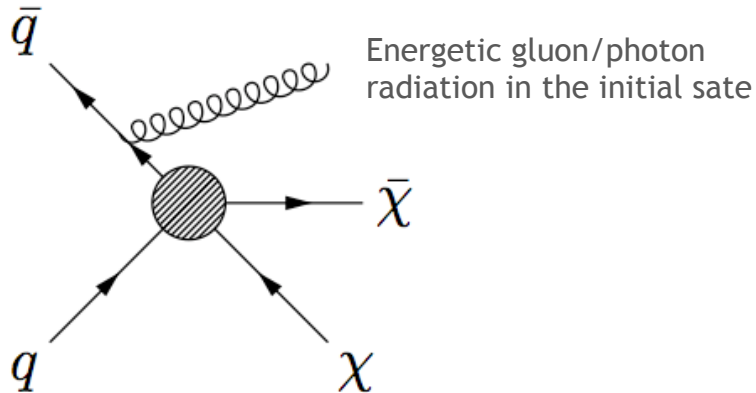
Should we forget about SUSY ?

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

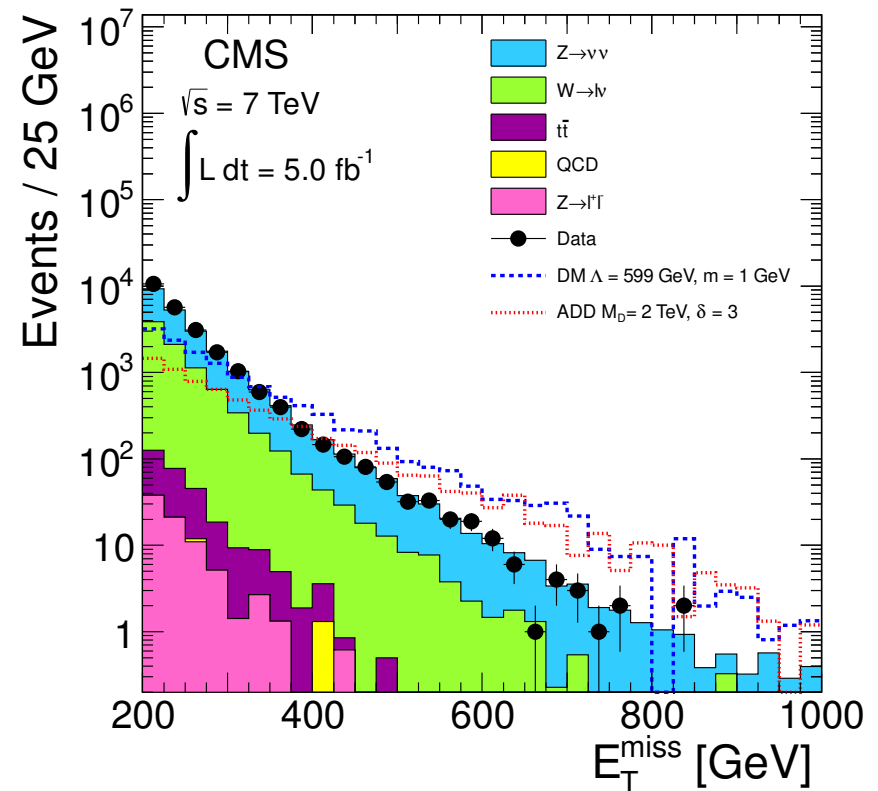
CMS arXiv:1206.5663

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 events!



Should we forget about SUSY ?

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

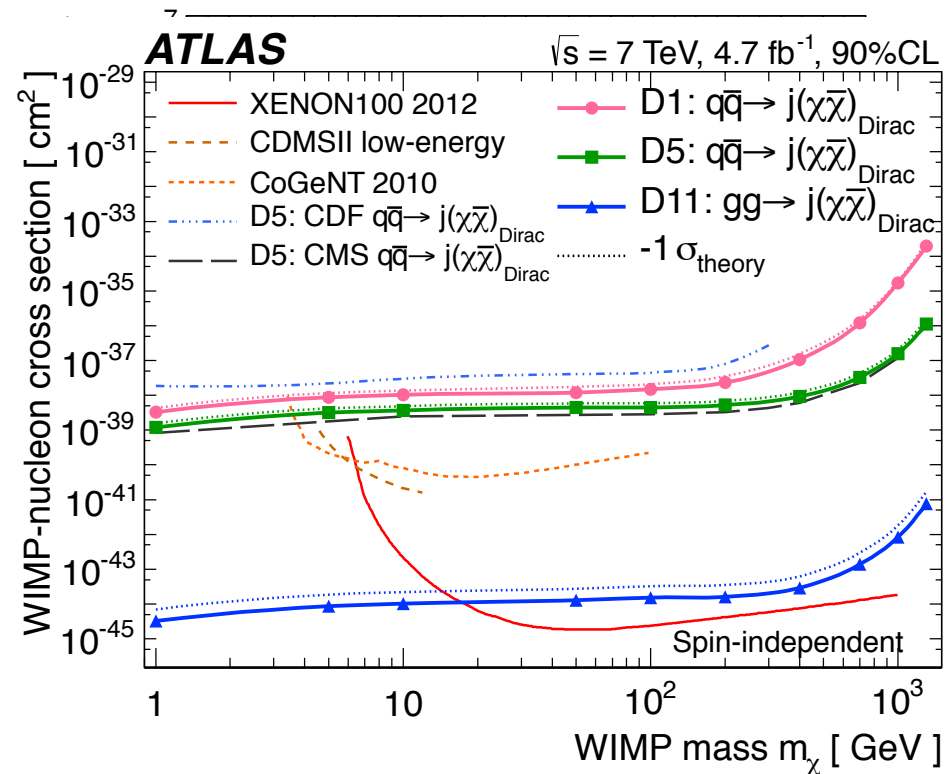
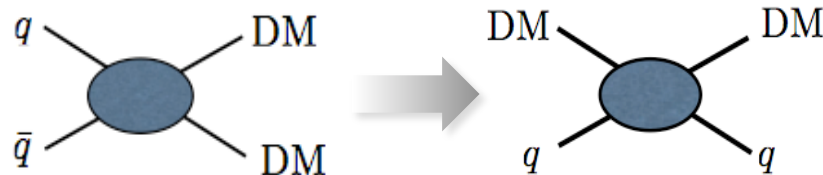
CMS arXiv:1206.5663, ATLAS 1210.4491

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

Vector (SI): $(\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q) \cdot \Lambda^{-2}$

Axial-v. (SD): $(\bar{\chi}\gamma_{\mu}\gamma^5\chi)(\bar{q}\gamma^{\mu}\gamma^5q) \cdot \Lambda^{-2}$

WIMP-nucleon scattering cross-section: $\sigma \propto \frac{1}{\Lambda^4}$

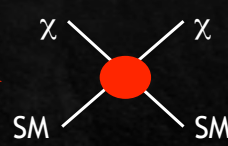


**WIMP production search
connects accelerator
physics with searches in
and from outer space**

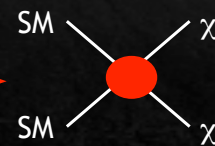
Particle Dark Matter Searches based on:



Indirect



Direct



Colliders

Many 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.

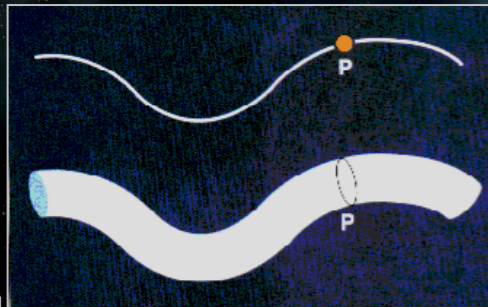
Compact extra dimensions, for example, are small, curled dimensions of micron size or much smaller.

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.

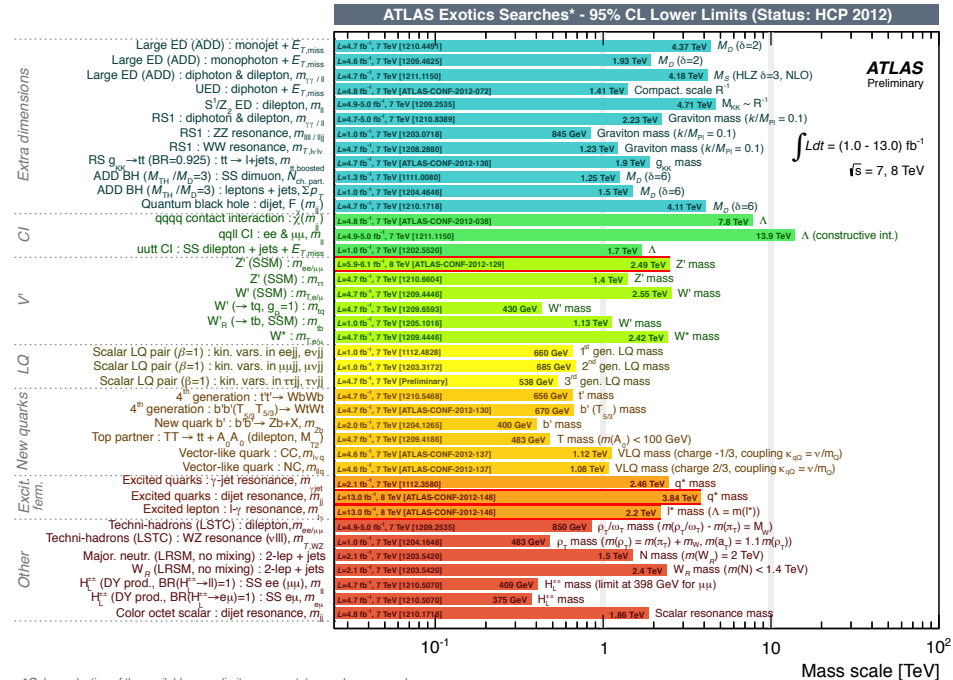
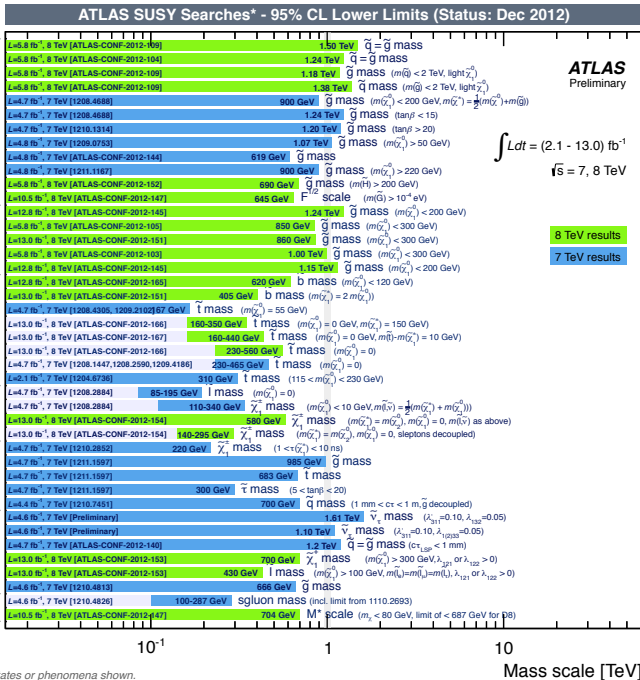
If the new phenomena are of TeV scale we should see them.

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

Record Black Hole with 24.33 Solar Masses in IC 10 dwarf galaxy



Mass reach of searches for SUSY (left) and other new phenomena (right) (here: ATLAS)

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

Broad search spectrum at ATLAS and CMS

The LHC is *pushing* the limits on new phenomena

We are still below 10% of the expected size of the LHC data sample
(below 1% of the expected HL-LHC one), and at half the energy



What's next ?

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV,
~25 fb⁻¹ int. lumi

2013/14 LS1: prepare LHC
for design E & lumi

Collect ~30 fb⁻¹ per
year at 13/14 TeV

To answer these question
we need more data and
higher collision energy

2018 Phase-1 upgrade
for ultimate lumi

Twice nominal lumi
at 14 TeV,
~100 fb⁻¹ per year

~2022 Phase-2 upgrade
to HL-LHC

~300 fb⁻¹ per year,
run up to > 3 ab⁻¹
collected

~2030



Is the new boson the SM Higgs ?

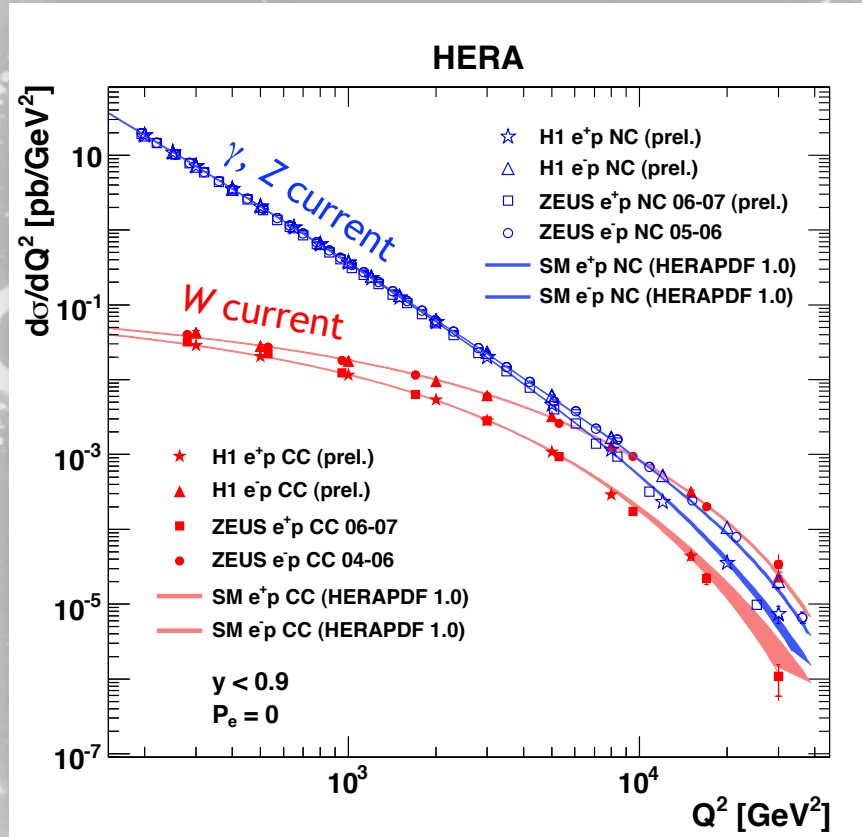
If so, what protects it ?



Thank you !

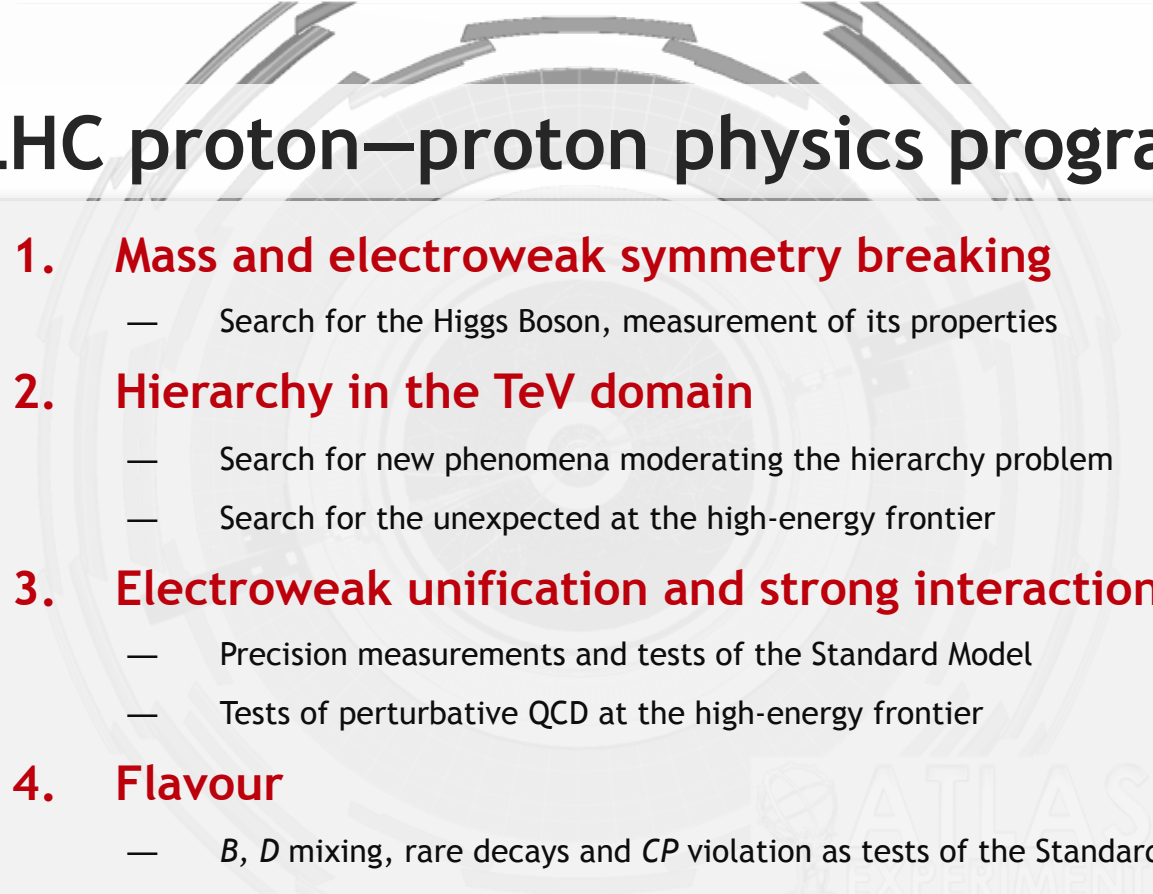
The Standard Model

The SM consists of **24 elementary matter particles** and **3 forces** with total of 26 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 = $W^\pm$)



The LHC proton–proton physics programme

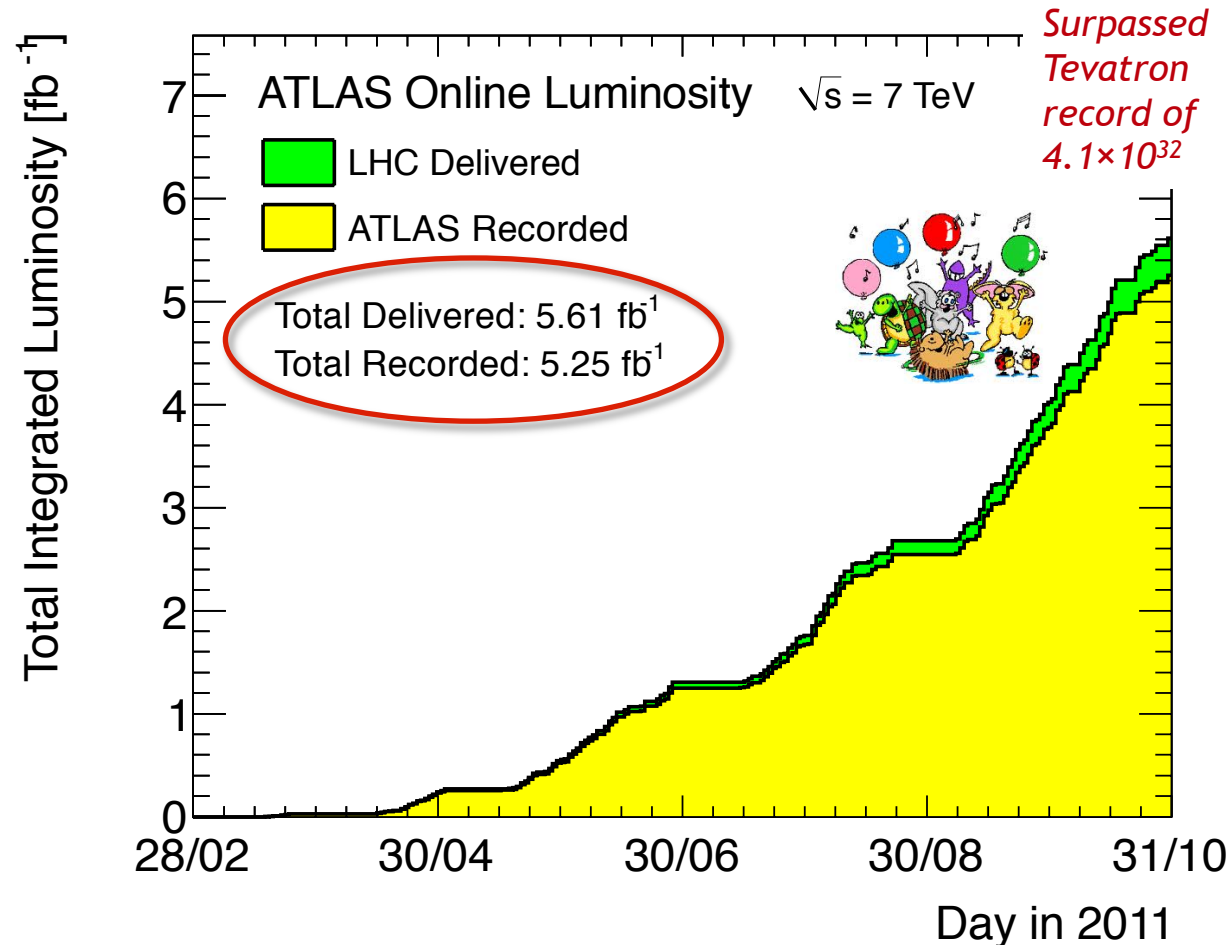
1. **Mass and electroweak symmetry breaking**
 - Search for the Higgs Boson, measurement of its properties
2. **Hierarchy in the TeV domain**
 - Search for new phenomena moderating the hierarchy problem
 - Search for the unexpected at the high-energy frontier
3. **Electroweak unification and strong interactions**
 - 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

Recorded Luminosity in 2011

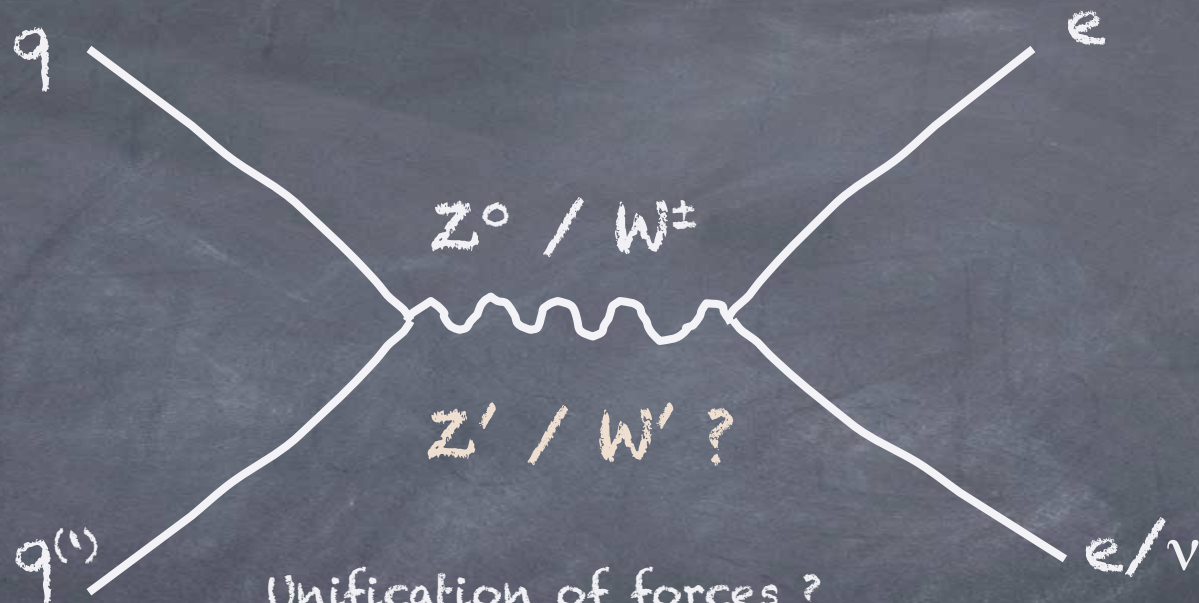
Luminosity is key quantity: $\text{rate} = \text{cross section} \times \text{efficiency} \times \text{luminosity}$

ATLAS integrated luminosity in 2011

- Peak $L = 3.6 \times 10^{33} \text{ s}^{-1} \text{ cm}^{-2}$ (Aug)
- Max coll-bunch: 1331 ($\Delta t = 50 \text{ ns}$)
- Weekly record: 580 pb^{-1} (June)

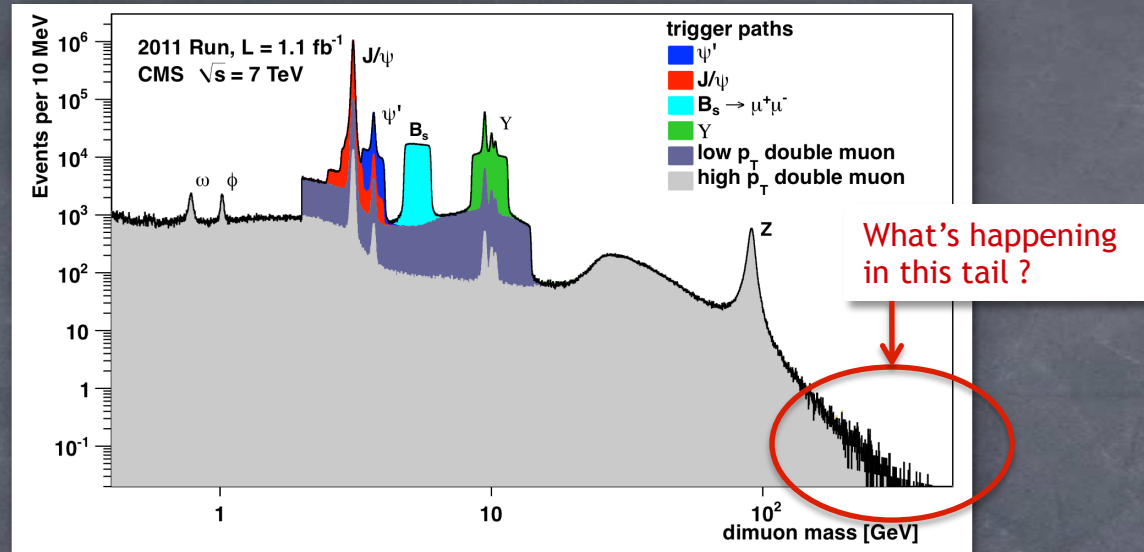


Leptons are pure SM and new physics probes with much reduced strong-interactions background



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

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



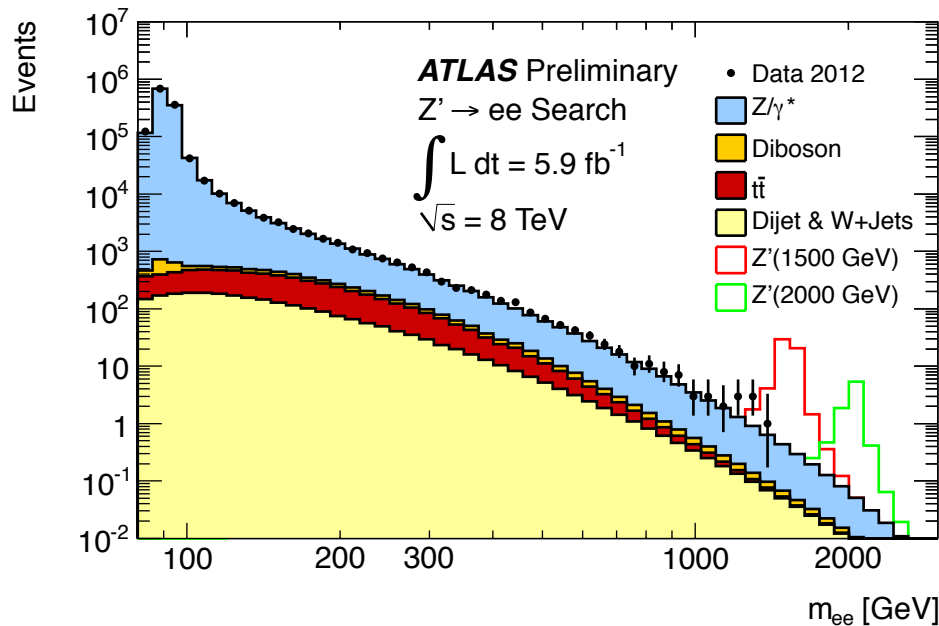
Unification of forces ?
Left-right symmetric models ?
Compact extra dimensions ?
Technicolour ?
Higgs extensions ?

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

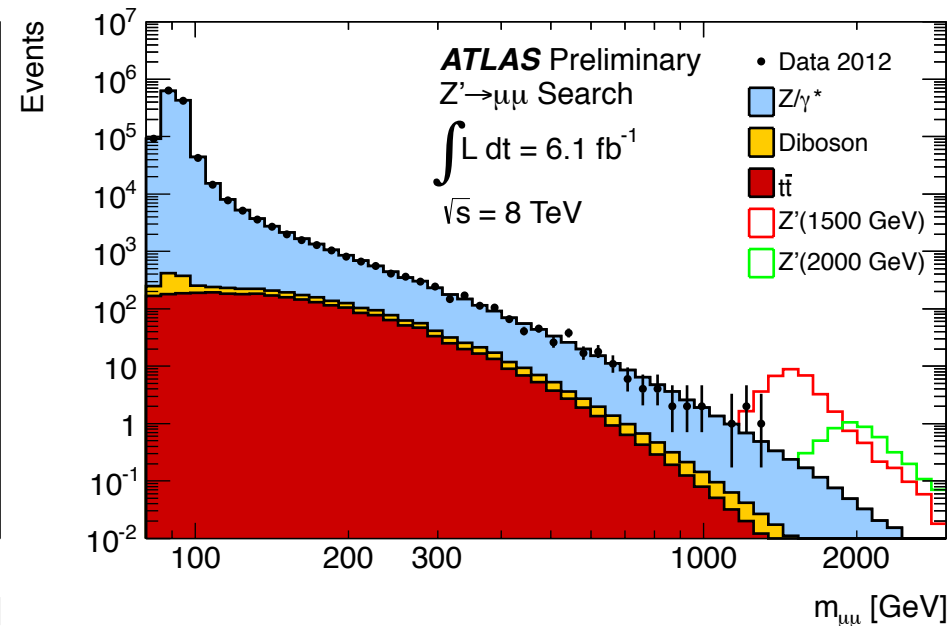
Use dilepton / transverse mass to search for excess over SM

ATLAS-CONF-2012-129

Observed and predicted dielectron mass spectrum
→ Search for bumps



Observed and predicted dimuon mass spectrum



95% CL lower limit: $m(Z'_{\text{SSM}}) > 2.5 \text{ TeV}$

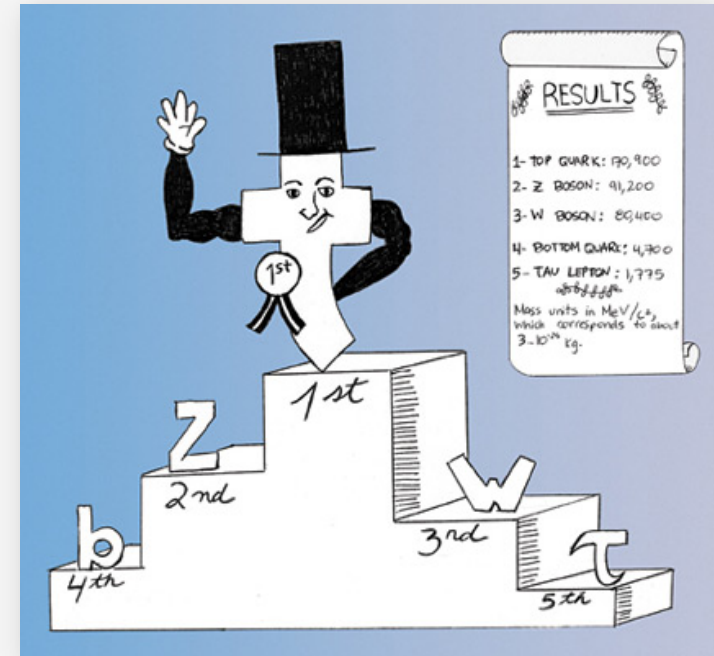
(*)Constructive interference model

QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections

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**

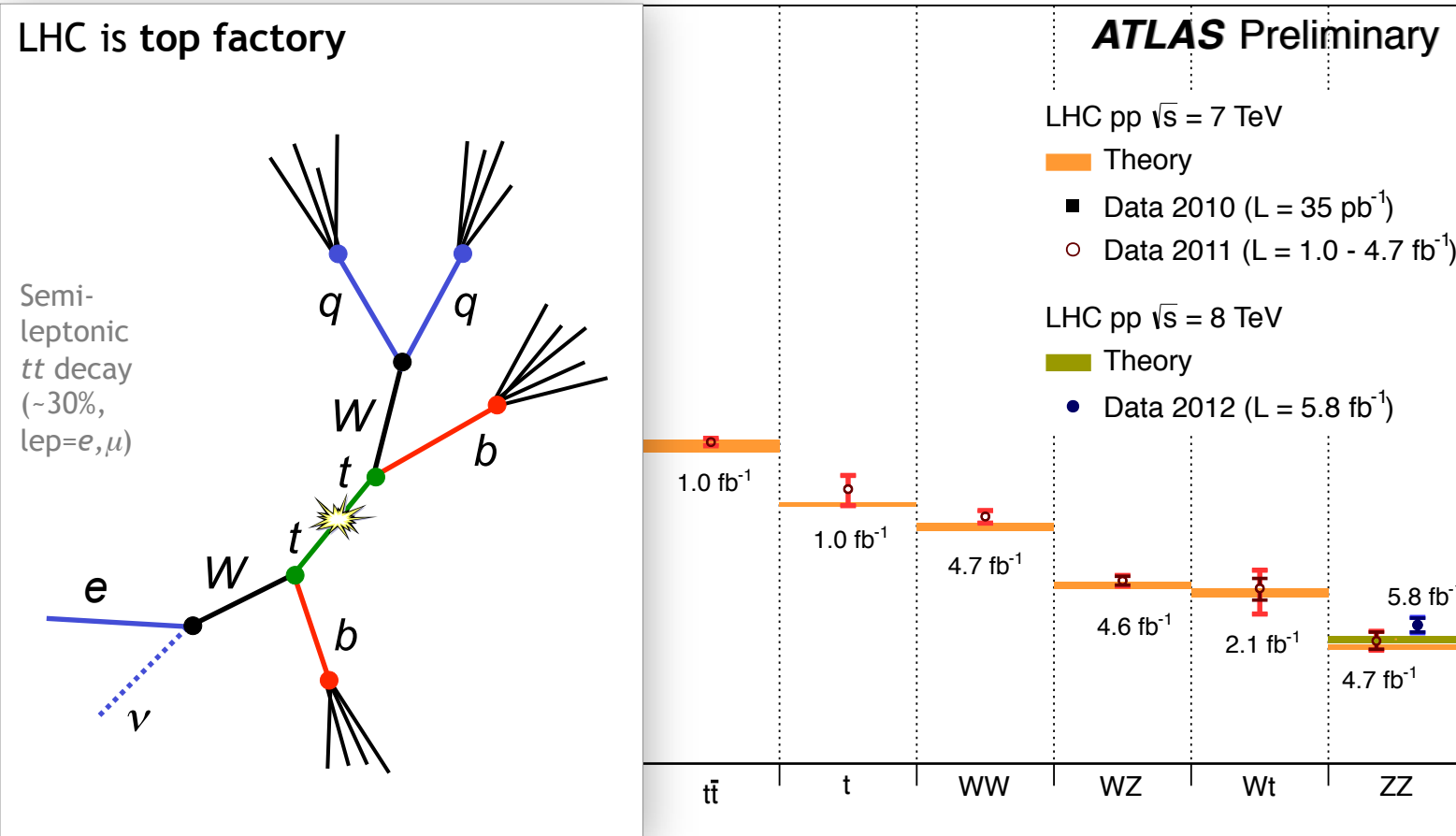


© Kurt Riesselmann, Symmetry 04-05-07

QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections

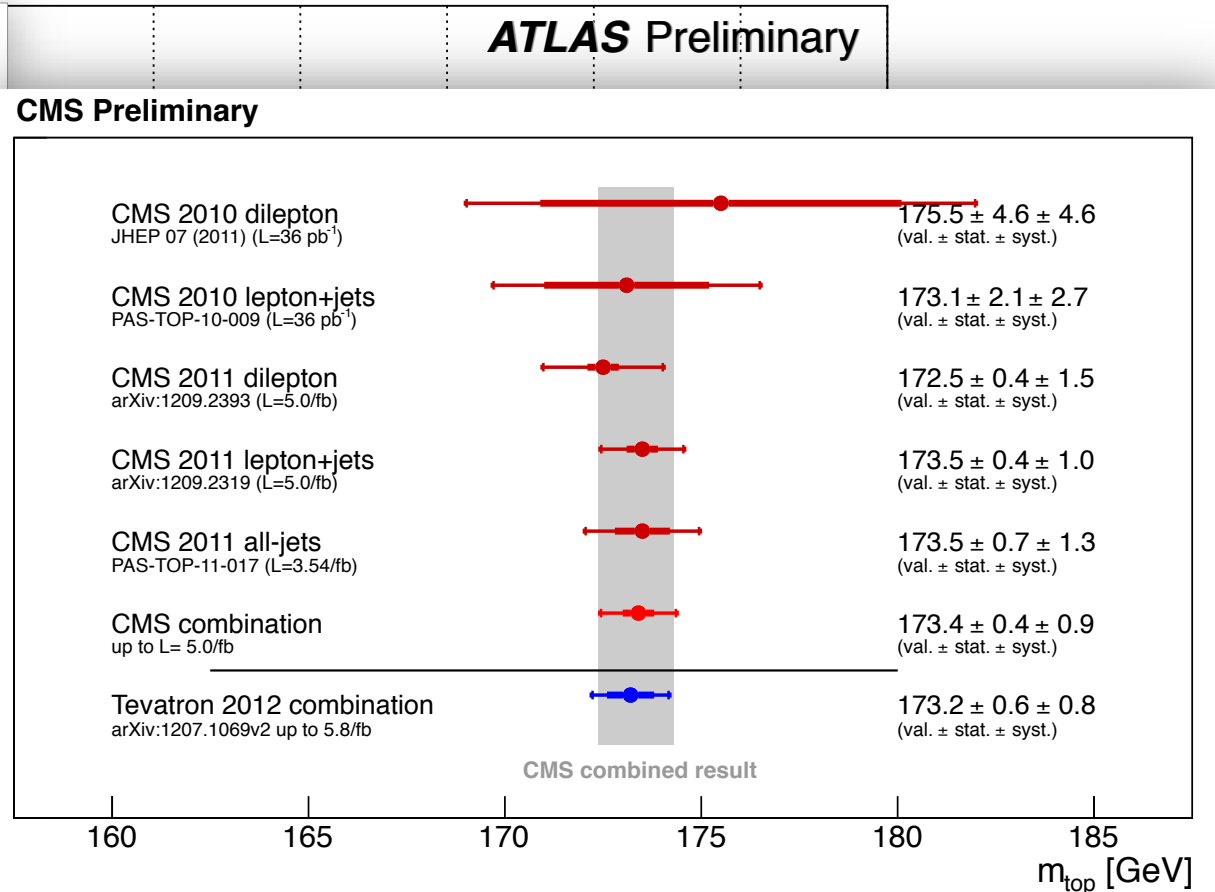
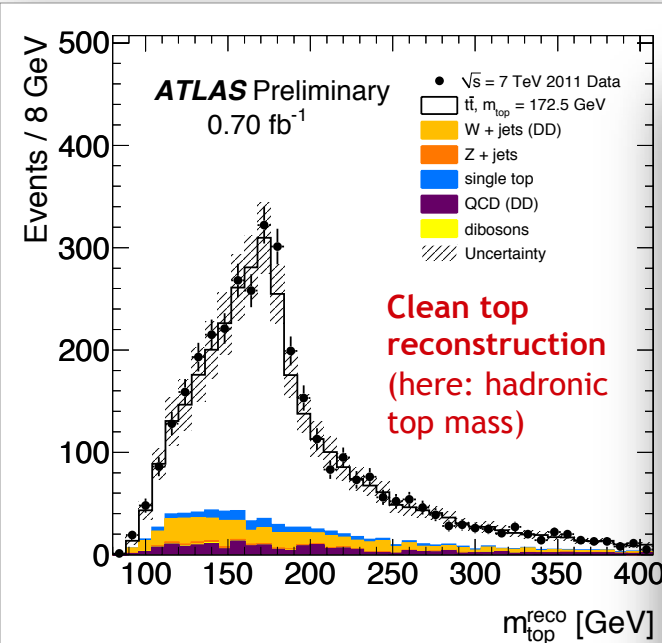
Summary of weak boson and top cross section measurements vs. theory



QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections

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

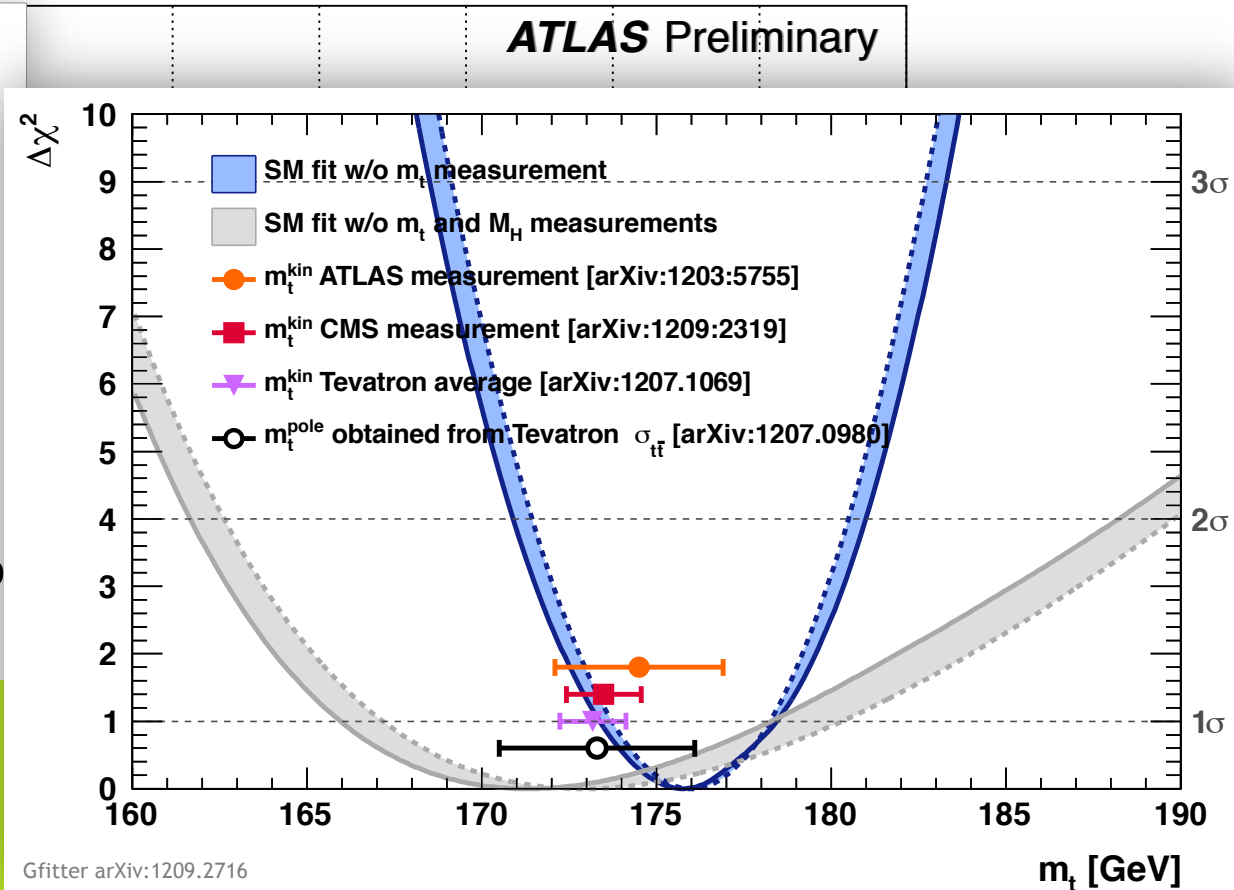
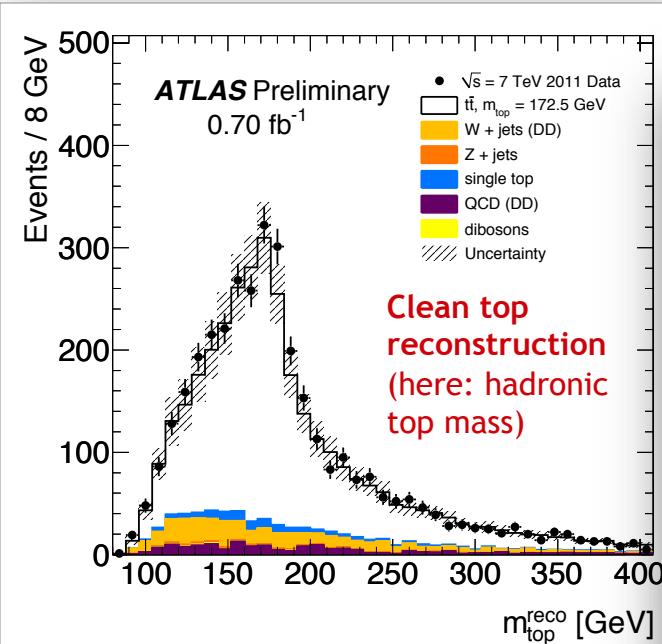


- First precision measurements of top cross section and mass at LHC
- Searches for new physics in top production and decay

QCD and electroweak measurements

With more luminosity we are sensitive to ever smaller cross sections

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

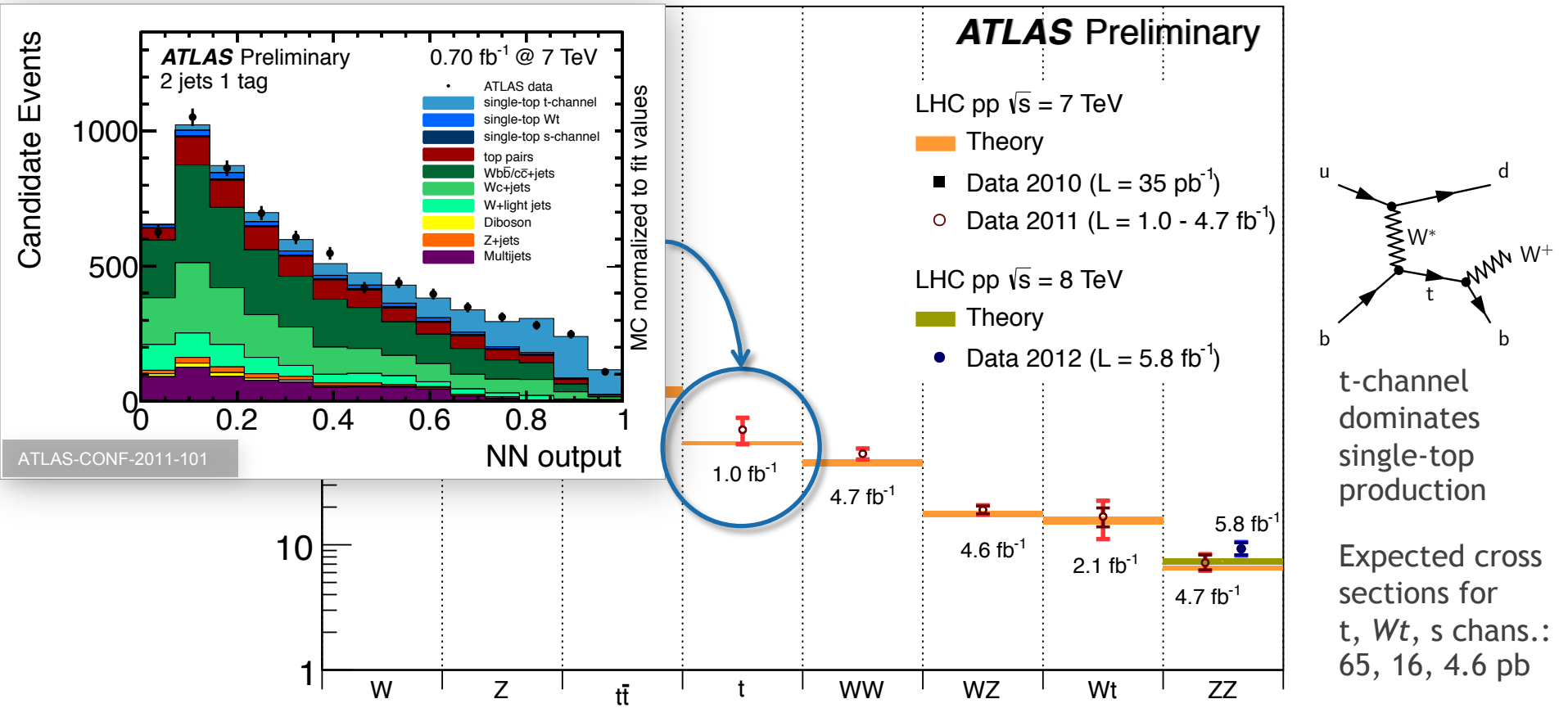


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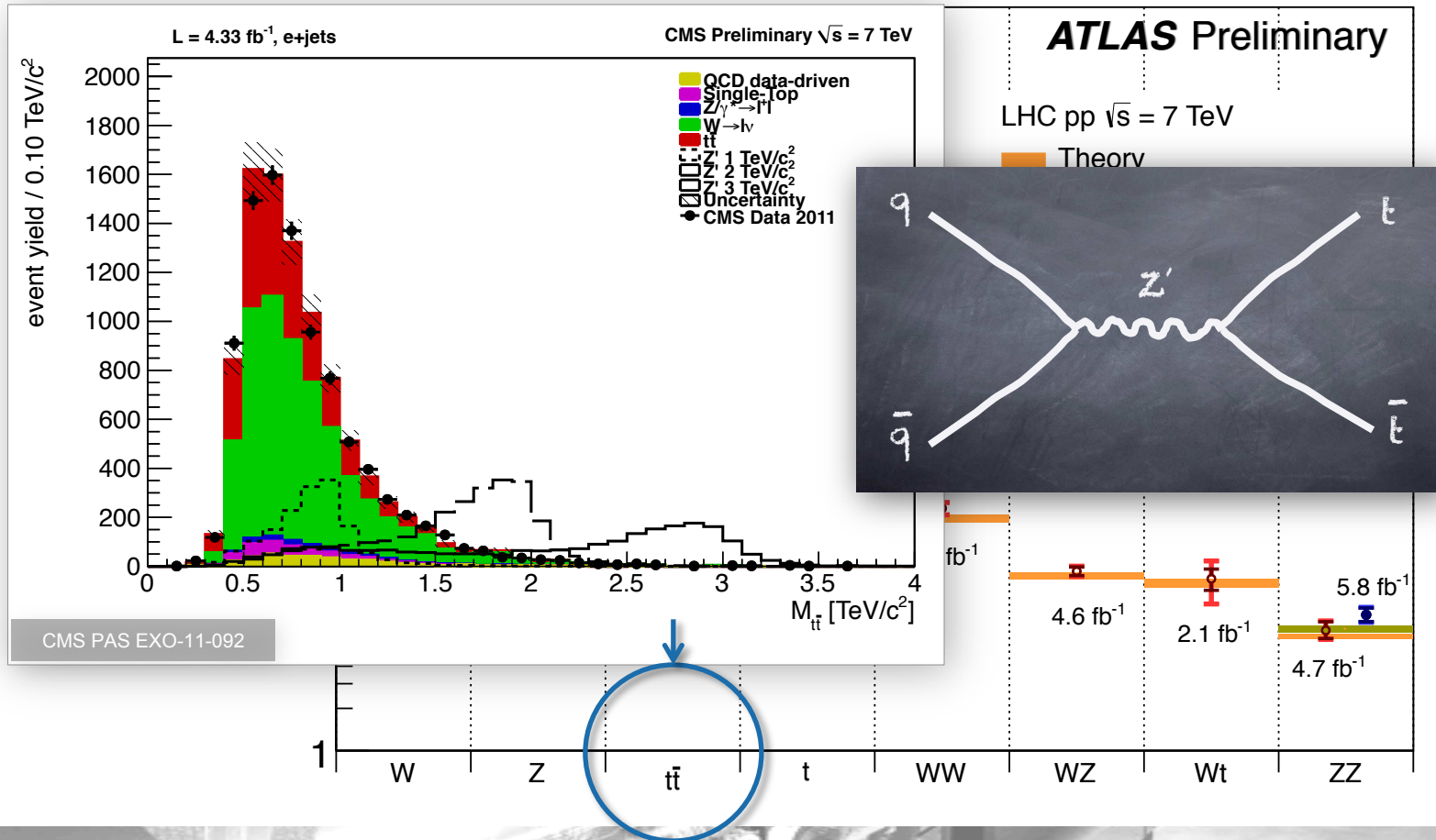
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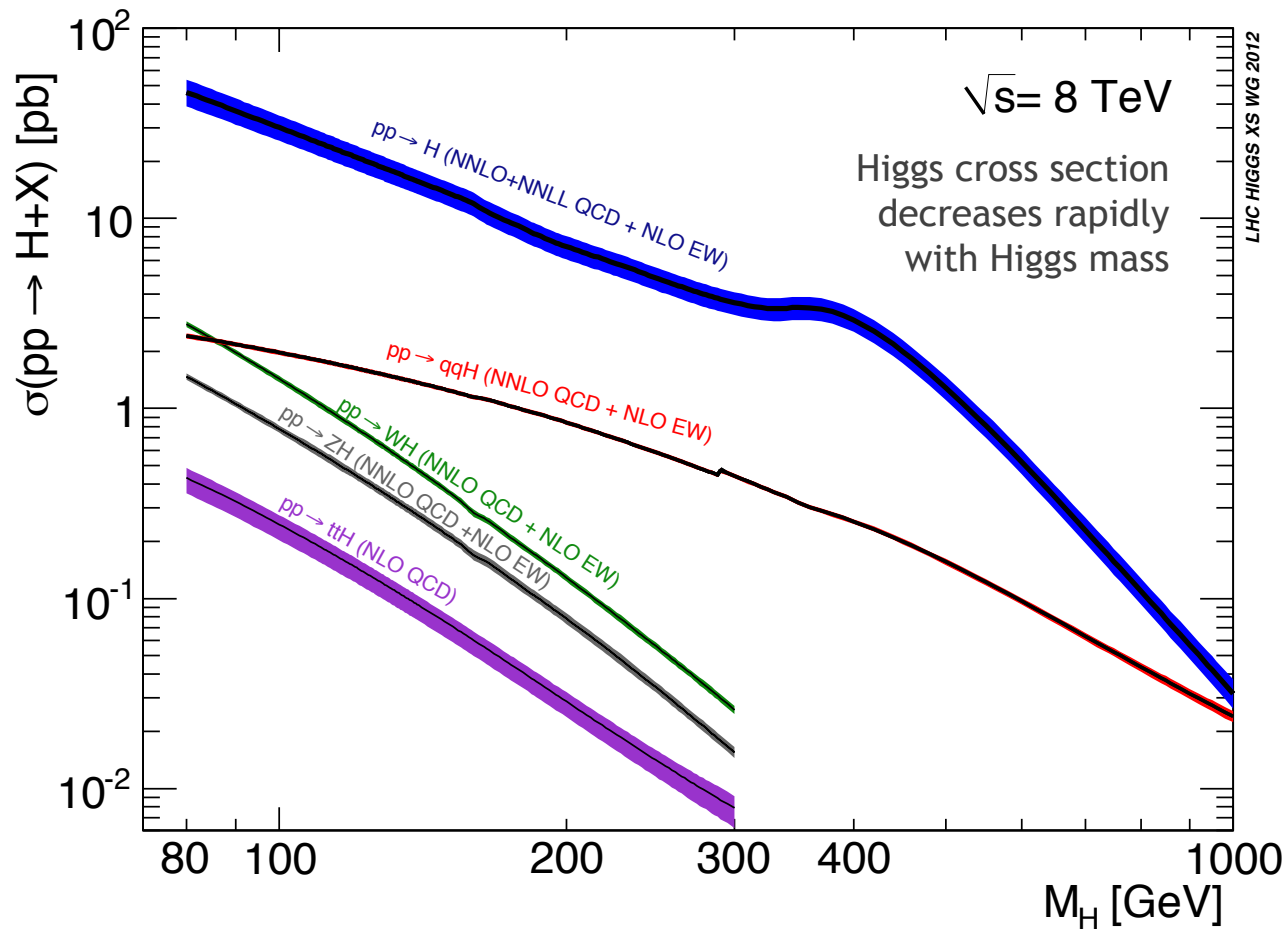
CMS PAS EXO-11-092

Higgs boson searches at the LHC

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

At the LHC, the total cross section $\sigma_{H,\text{total}} \sim 22 \text{ pb}$

Total production at 125 GeV in 2011



q

H

q'

H

W/Z

What can we conclude from this discovery

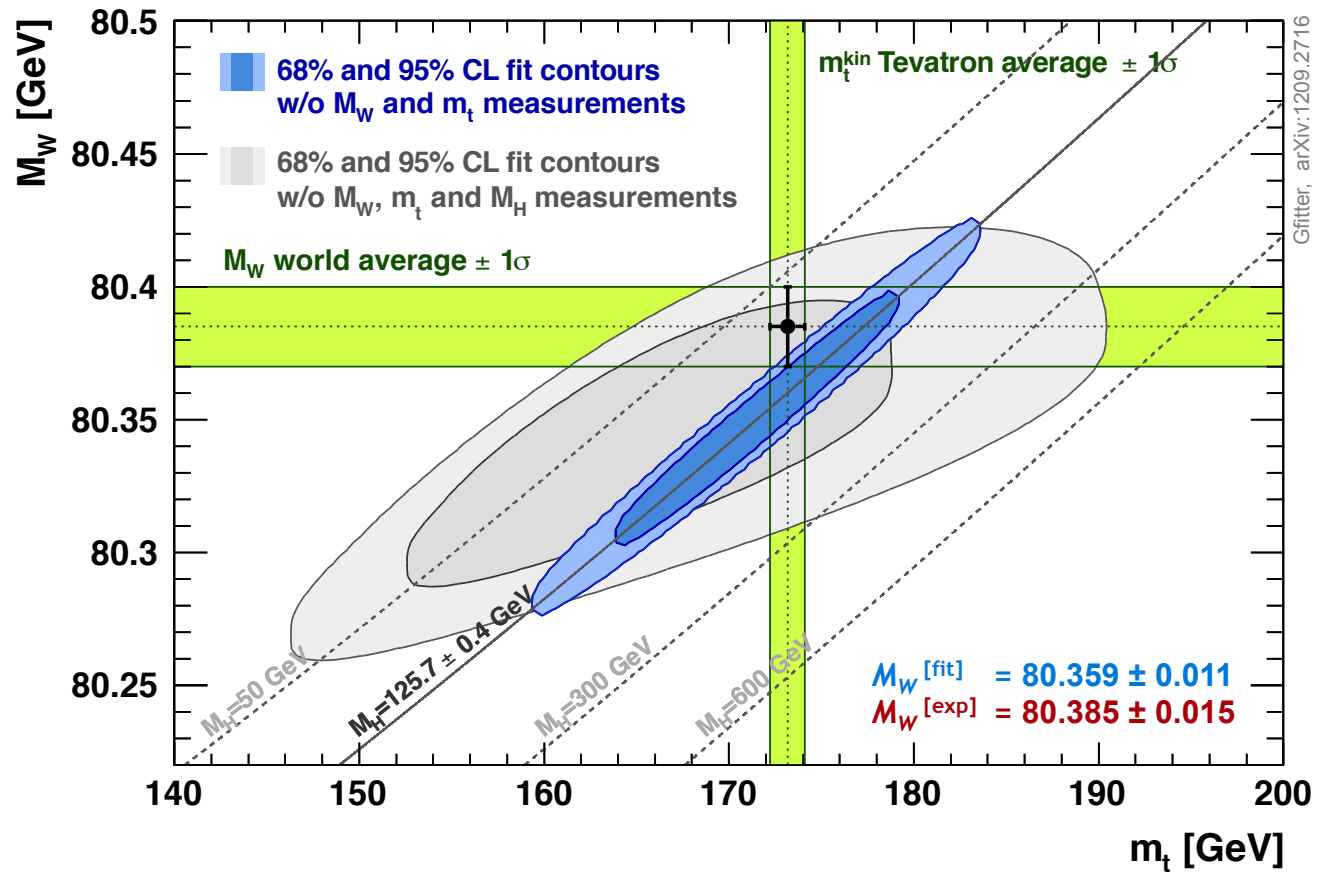
Under the SM hypothesis, the global EW fit is complete and over-constrained

Gauge sector of SM at tree level is given by 3 free parameters, e.g.: α , M_Z , G_F

→ M_W , $\sin^2(\theta_W)$ predicted

Radiative corrections introduce quark mass dependence

→ m_{top} predicted



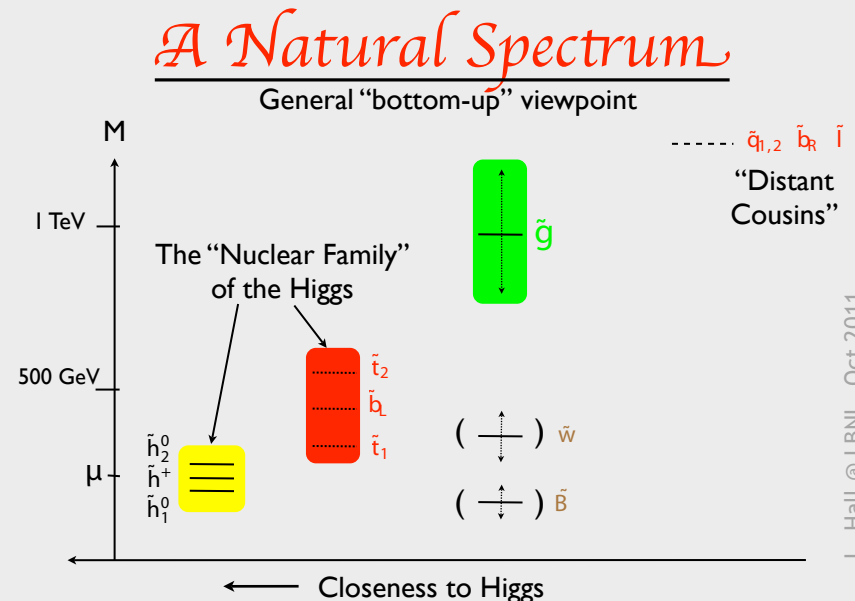
SUSY has: $N_{\text{dof}}(\text{bosons}) = N_{\text{dof}}(\text{fermions})$ [cf. SM: $N_{\text{dof}}(\text{bosons}) \ll N_{\text{dof}}(\text{fermions})$]

- 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 $\rightarrow$ 5 Higgs bosons
- SUSY breaking introduces lots (> 100) of new parameters (masses, mixing angles, phases)

Supersymmetry (SUSY)

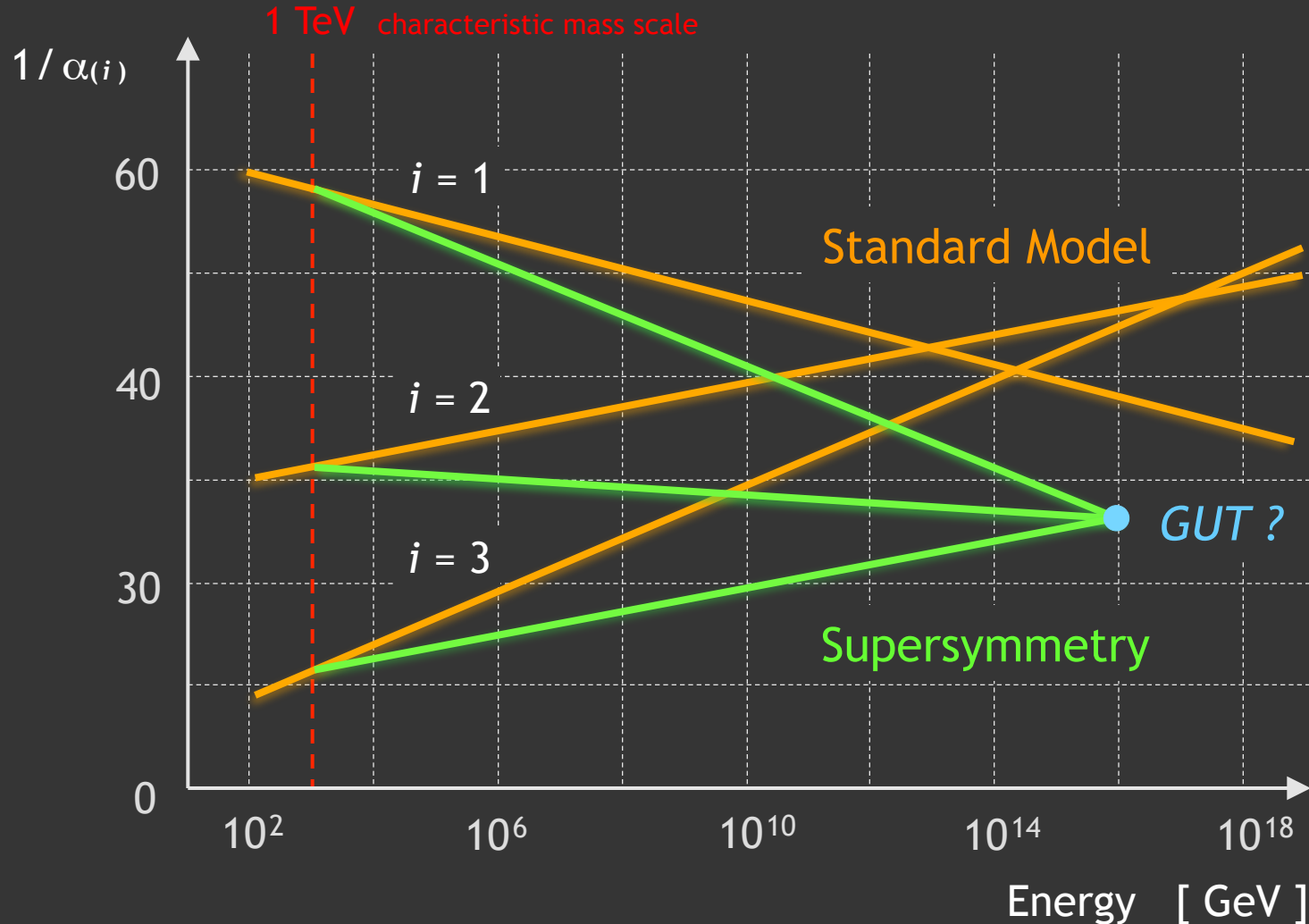
Broken SUSY spectrum (if exists) unknown, but some guidance principles:

- 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
- 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 $1/3$



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:

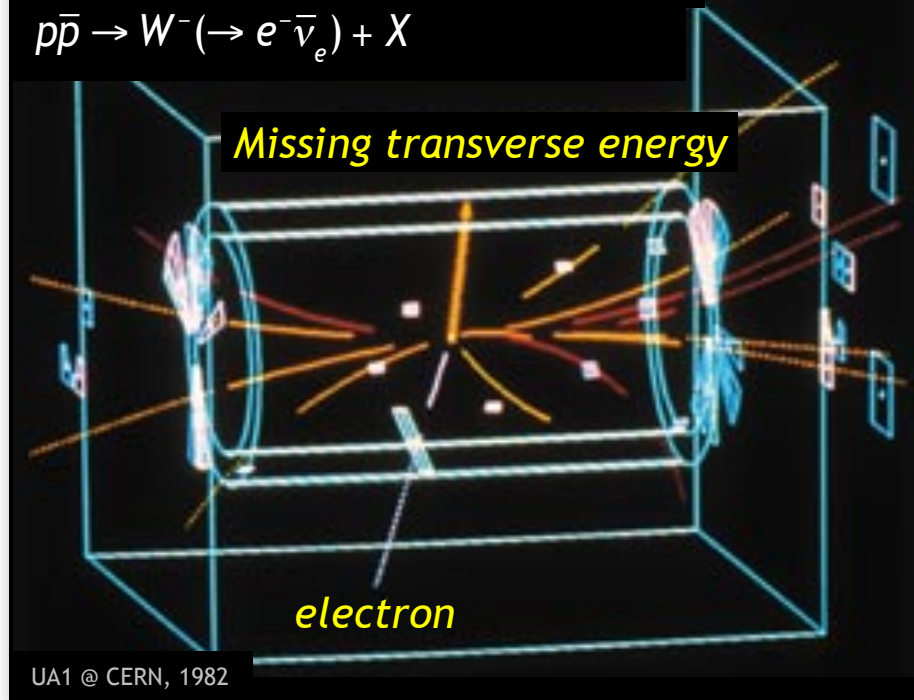
- High- p_T jets from squark & gluino decays
- Leptons from gaugino & slepton decays
- **Missing transverse energy from LSPs**

This lays out an **inclusive search strategy**

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

W boson discovery at UA1 (CERN)

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



Should we forget about SUSY ?

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

Consider a new stable weakly interacting particle χ

During an early universe, its annihilation reaction is in thermal equilibrium:

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

As the universe expands it cools down, so that: $\chi\chi \rightarrow f\bar{f}$

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

Its abundance is inverse proportional to its annihilation cross section:

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

COINCIDENCE ?



Broad search spectrum at ATLAS and CMS

The

Paper Statistics in SPIRES

Is SUSY *out* already?

