



Du modèle standard par le boson de Higgs vers la nouvelle physique

L'aventure du grand collisionneur LHC

Jiro Taniguchi, Furari, © Casterman (2012)

Andreas Hoecker (CERN)

Académie des sciences, 26/11/2013

*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

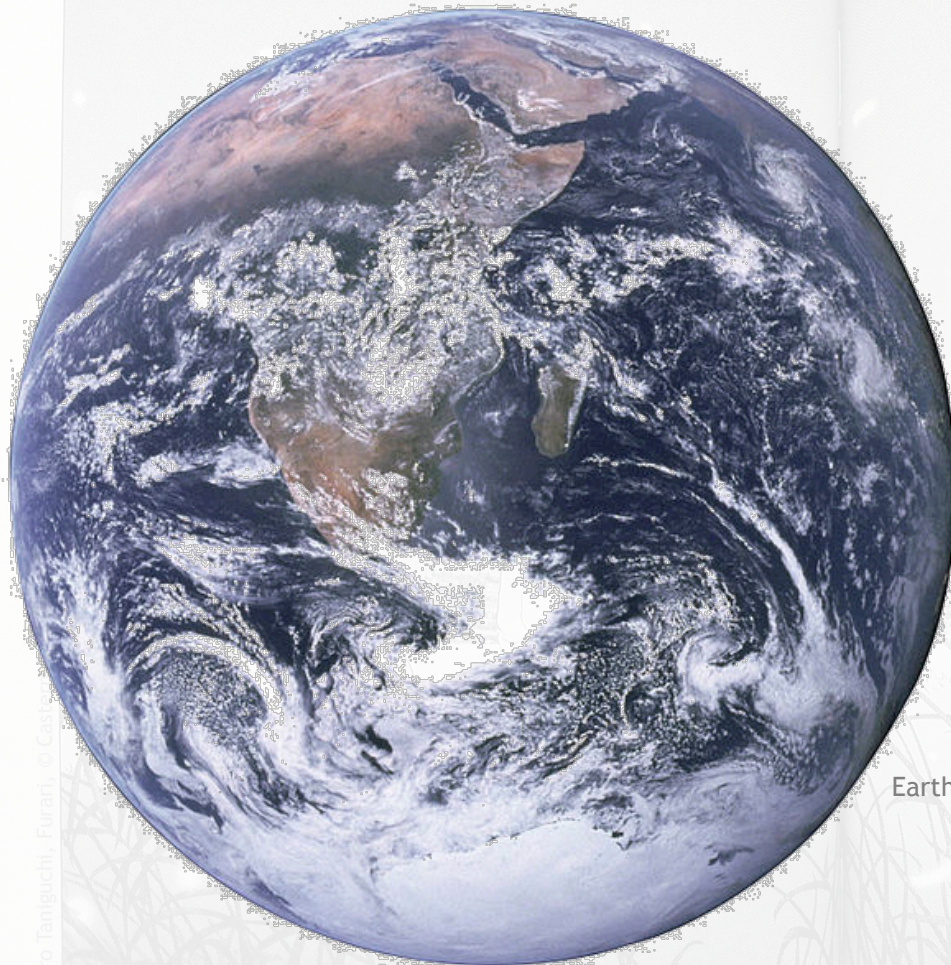
$\downarrow ?$

γ, g

...probing
attometer
scales

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

Nanoscience



Earth

Particle physics today (TeV scale)



Siphonaptera (flea)

The Standard Model (SM)

The SM has **24 elementary matter particles** and **3 forces** → 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



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

Photon

Electro-
magnetic force



3 weak bosons

Weak force



8 Gluons

Strong force



Higgs boson



Breaks electroweak symmetry
Generates boson and fermion masses

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

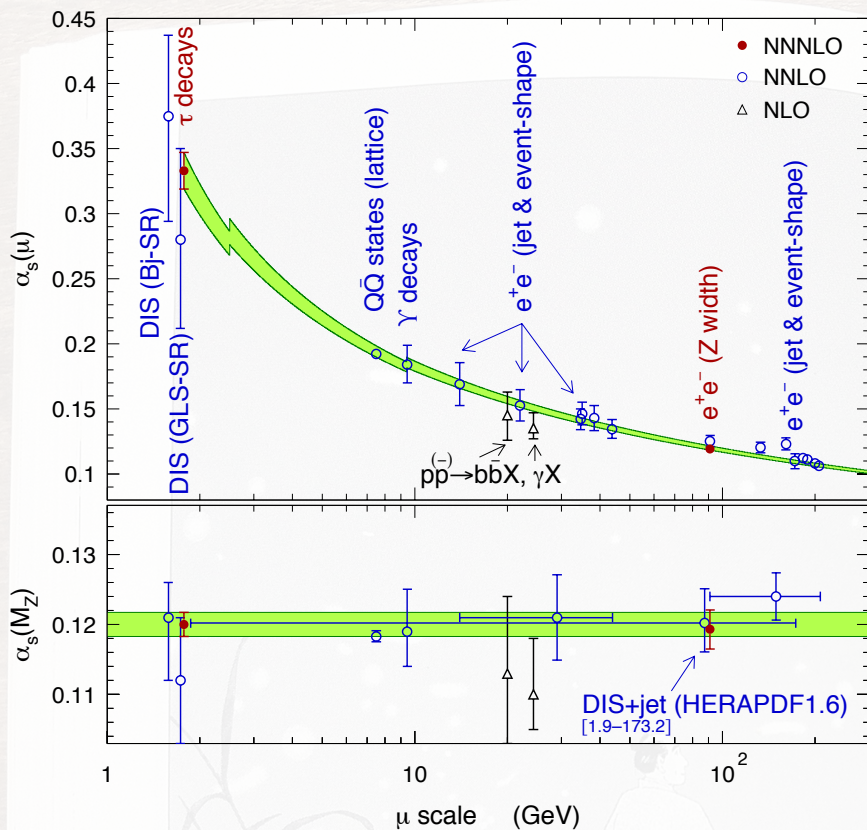
Jiro Taniguchi, Furari, © Casterman (2012)



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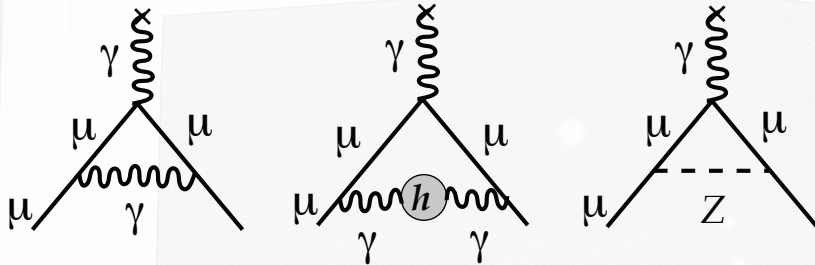
The strong force is asymptotically free

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

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

Example: lepton magnetic moment



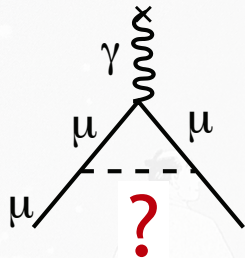
Experiment: $a_\mu = 11\,659\,209.1 \pm 6.3 \times 10^{-10}$

SM: $a_\mu = 11\,659\,180.3 \pm 4.9 \times 10^{-10}$

$\Delta(\text{Exp} - \text{SM})$

$= 28.8 \pm 8.0 \times 10^{-10}$

(3.6σ)



*Quantum corrections
to physical observables
can be very precisely
predicted*

**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 ...**

The Standard Model (SM)

The SM has **24 elementary matter particles and 3 forces** $\rightarrow$ 26 parameters

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

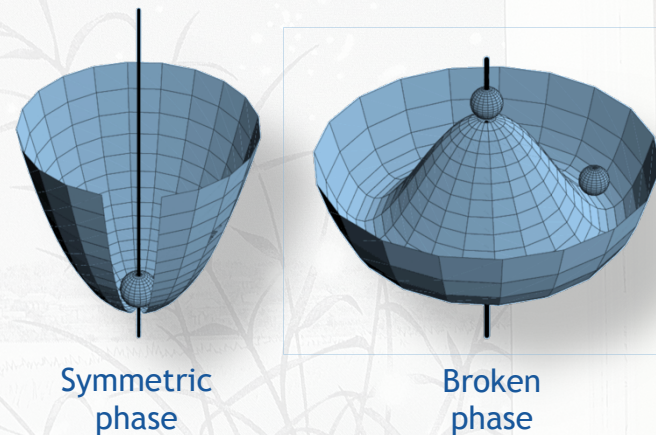
However, the **W, Z bosons are massive !**

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

$$M_{Z,W} \neq 0 \quad \Leftrightarrow \quad \langle 0 | \phi | 0 \rangle = v \neq 0$$

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**

Higgs potential $V(\phi)$



This is known as the **“Brout-Englert-Higgs 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

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

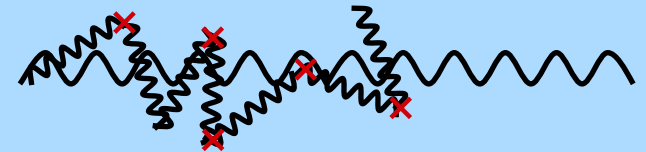
Gravity



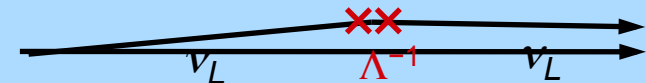
Photon



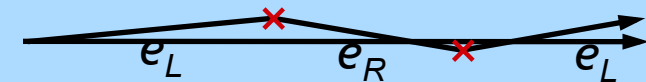
Weak boson



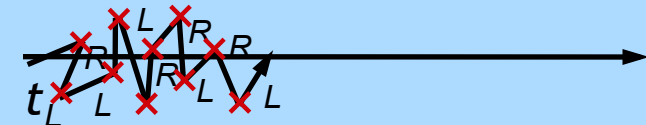
Neutrinos



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 ?

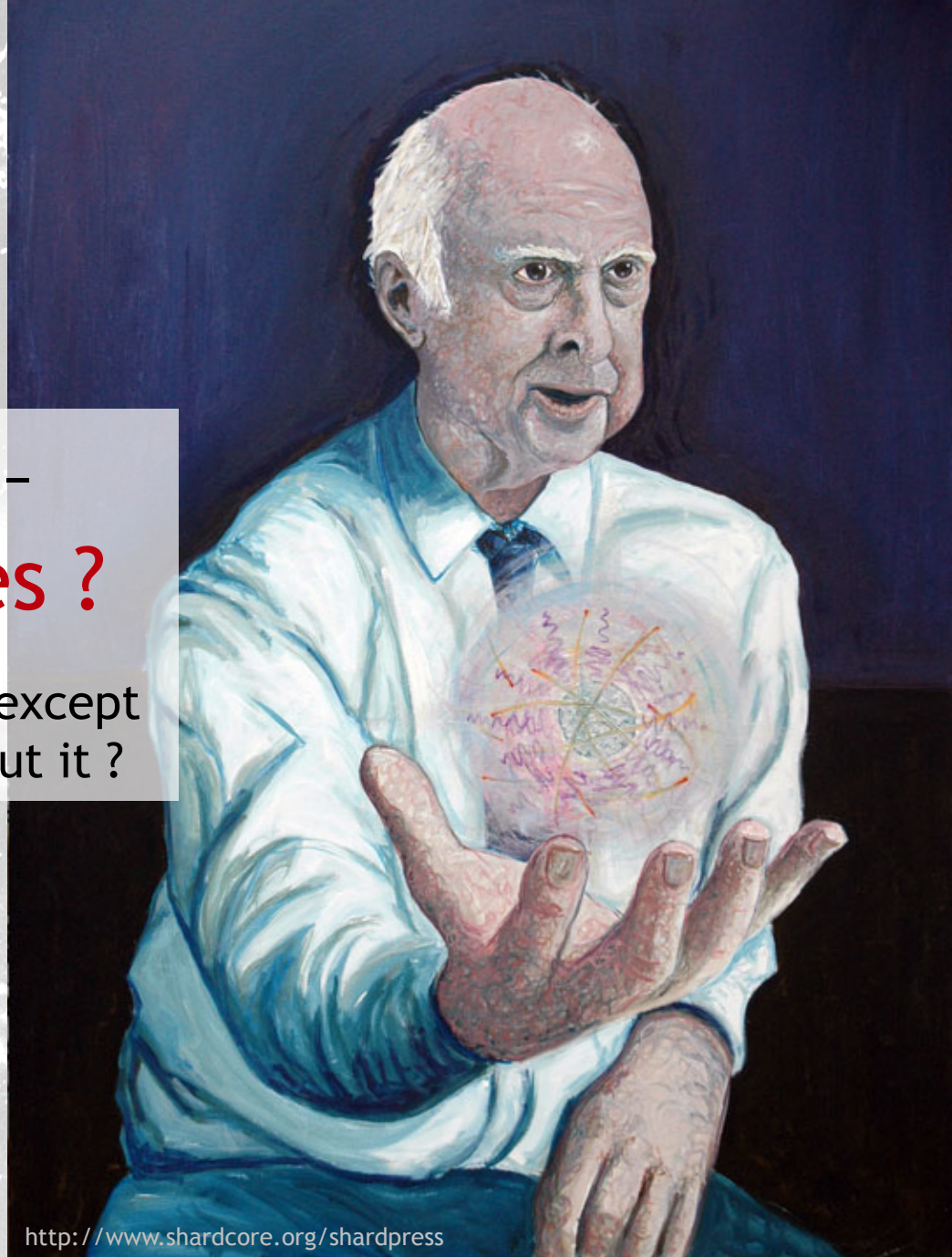
The SM predicts all its properties, except
for its mass. What was known about it ?

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.

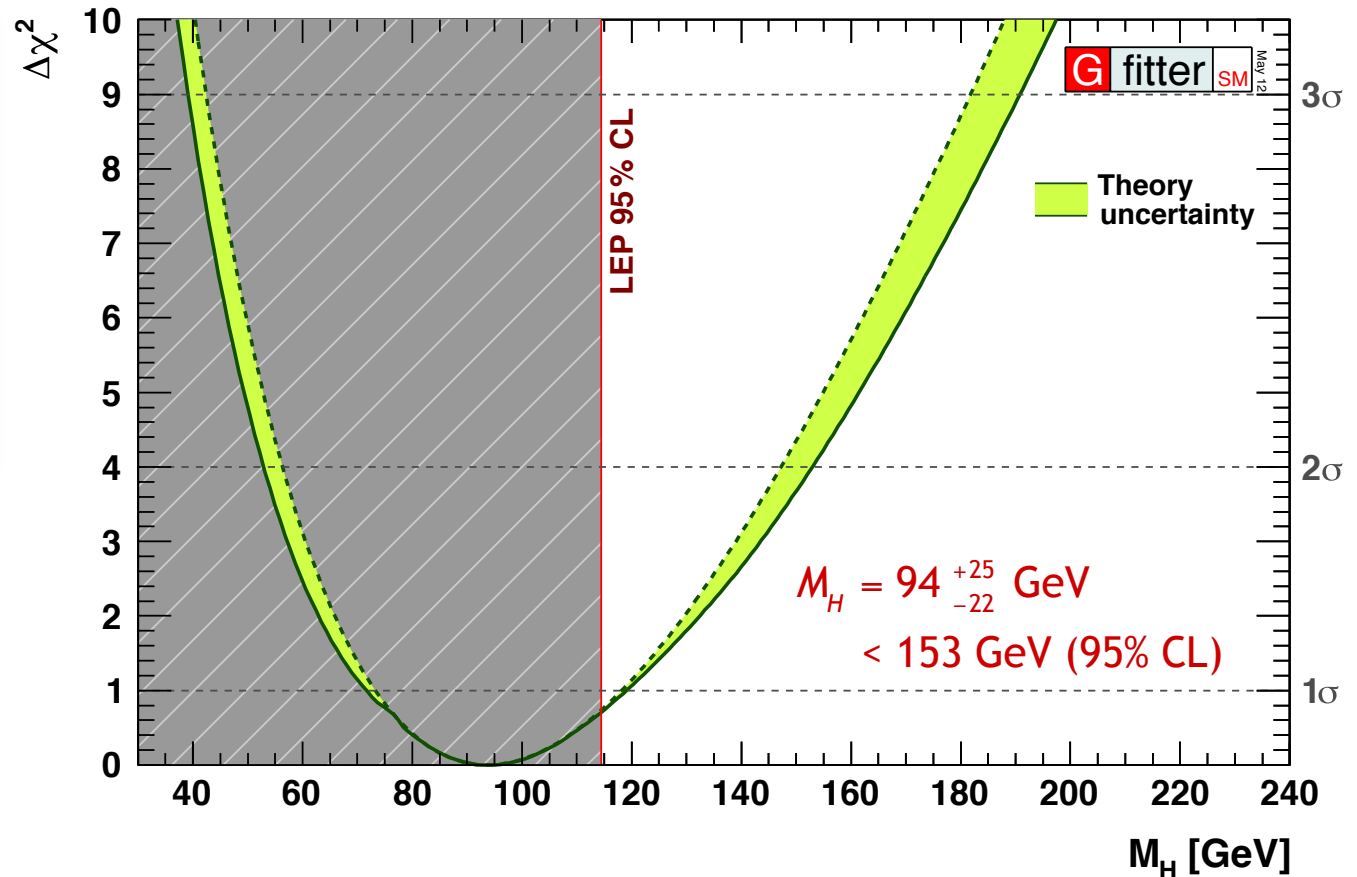
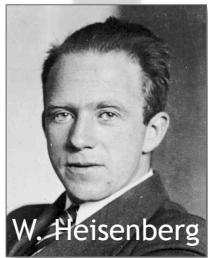
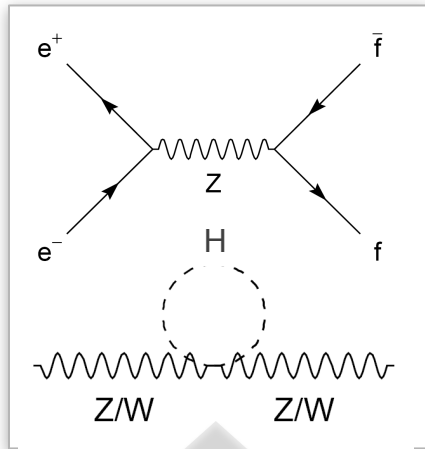
It is also of note that Landau and Ginzburg had proposed a field giving the photon a mass in a superconductor, the mathematics of which is identical to the “Higgs mechanism” and predates it by several years.

<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>

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



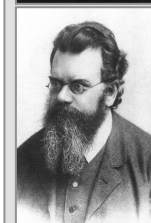
Lawrence

Particles accelerators:

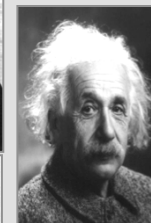
- Look deeper into matter (size $\sim 1/E$)
("powerful microscopes")
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie



Einstein

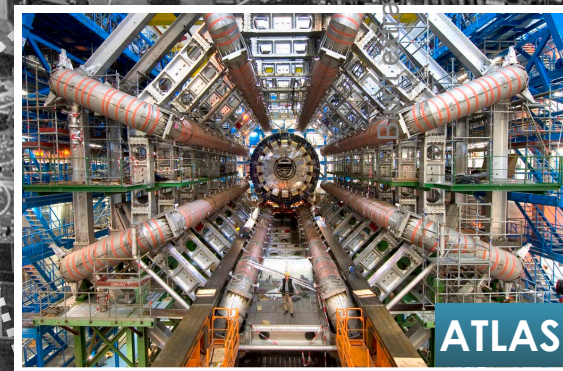
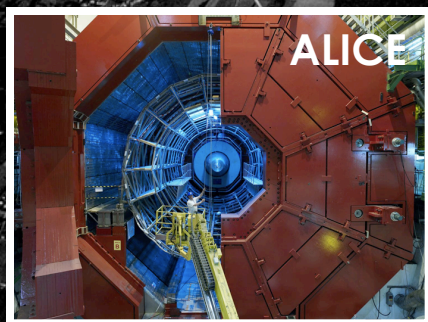
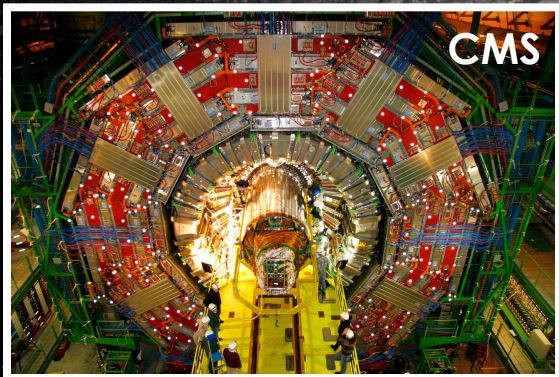


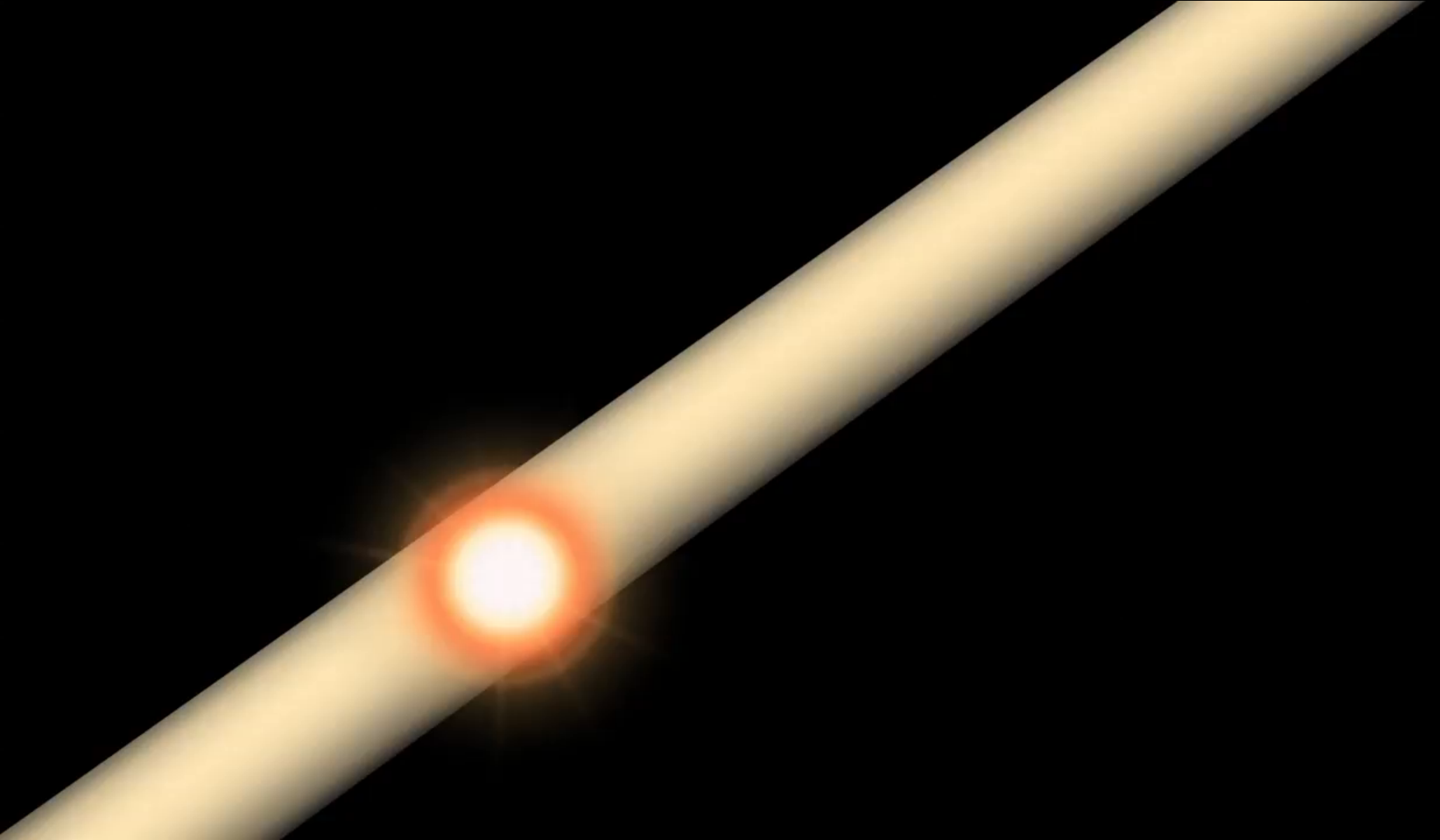
Boltzmann

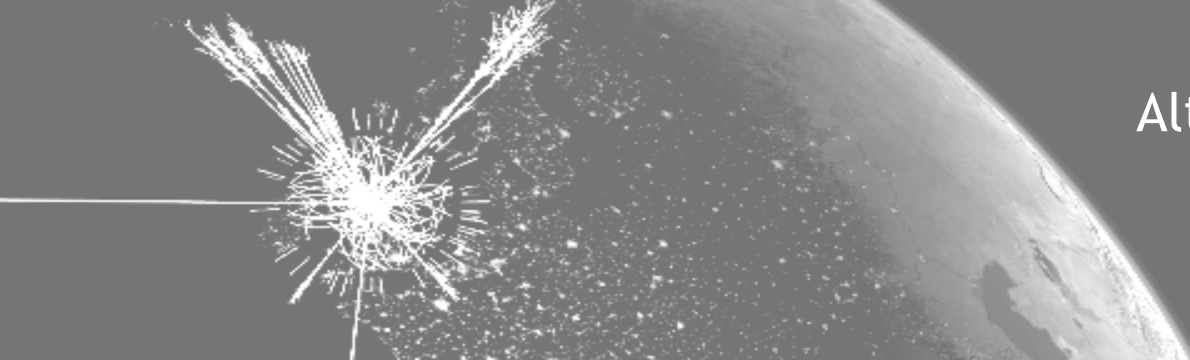
An aerial photograph of the CERN facility in Switzerland, showing the extensive LHC ring. The ring is a large, circular structure that spans across a vast, patchwork landscape of fields and forests. The text "LHC ring at CERN: 27 km circumference" is overlaid on the image. The landscape is a mix of green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

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

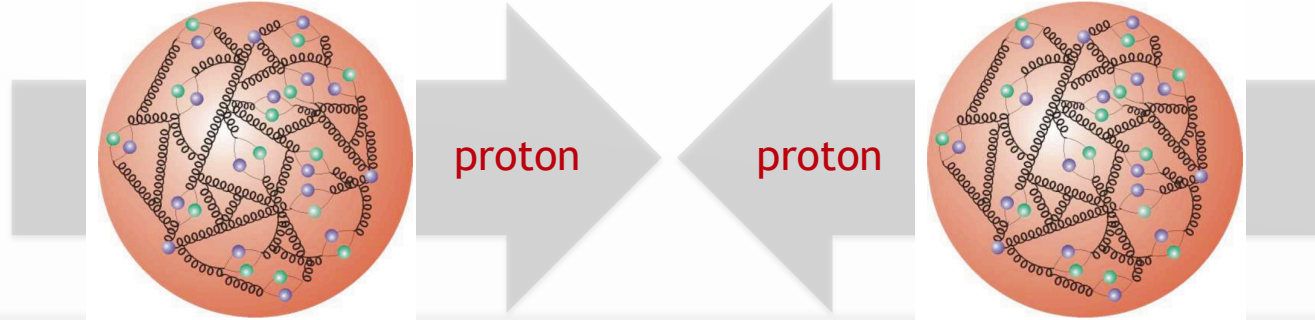
**So far:
7/8 TeV proton–proton collisions
2.76 TeV Pb–Pb collisions**







Although proton collisions are complex, we have gained excellent understanding

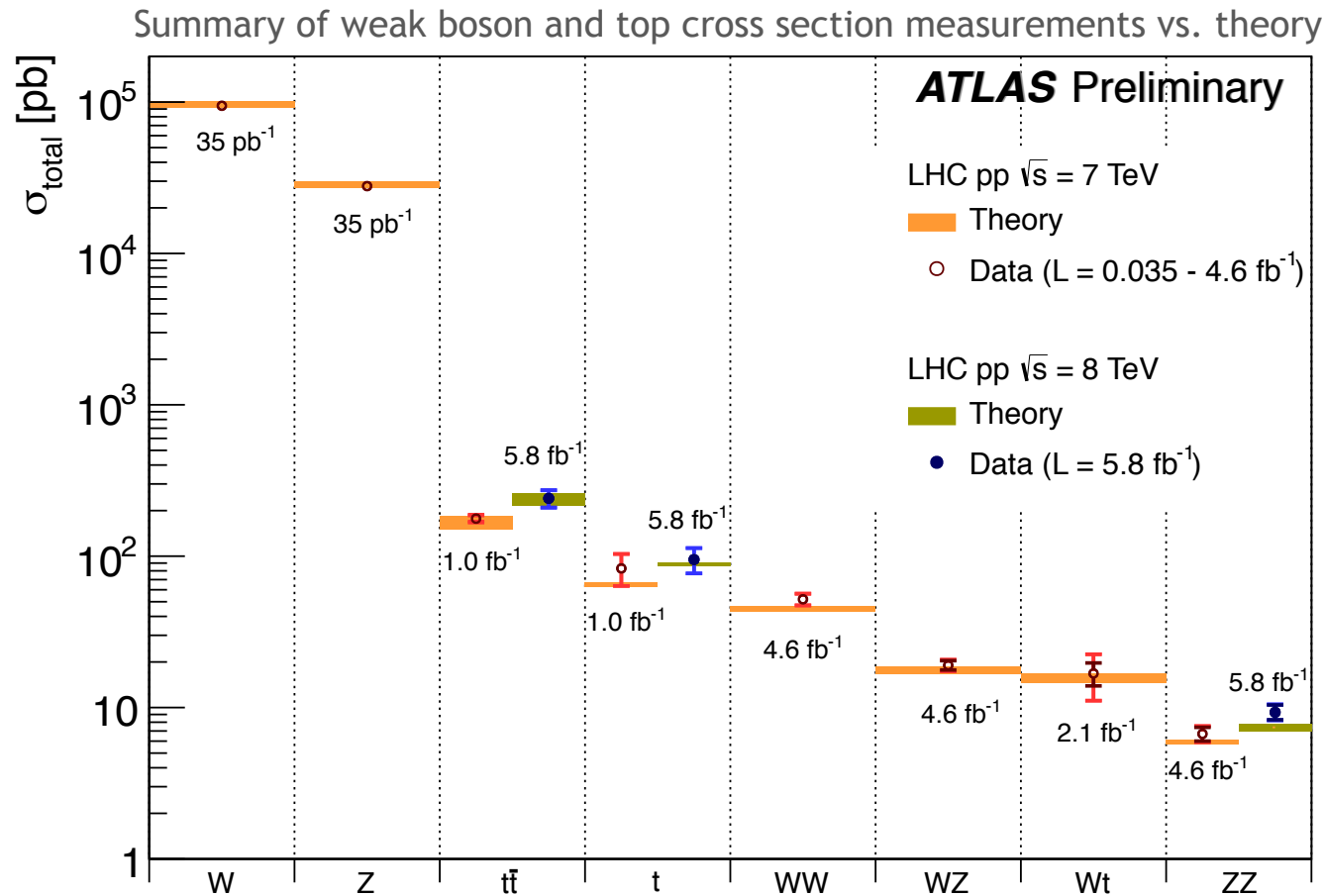


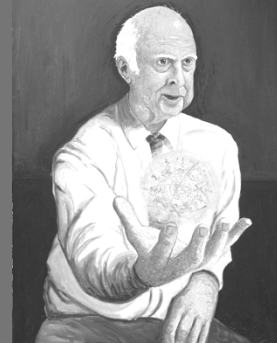
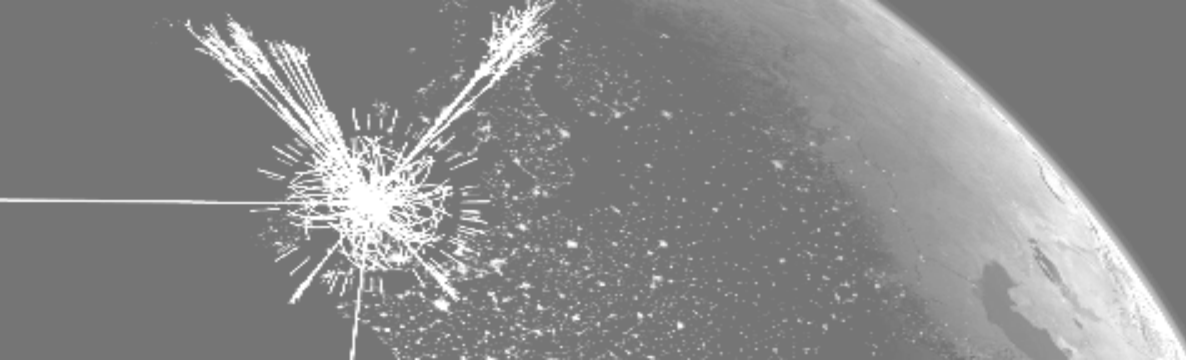
We can precisely predict the rates and properties of all produced SM particles, including those of the yet unseen Higgs boson

Particle production and their interaction with the detector layers are described with sophisticated numerical (“Monte Carlo”) simulations

Measurements of QCD and electroweak processes

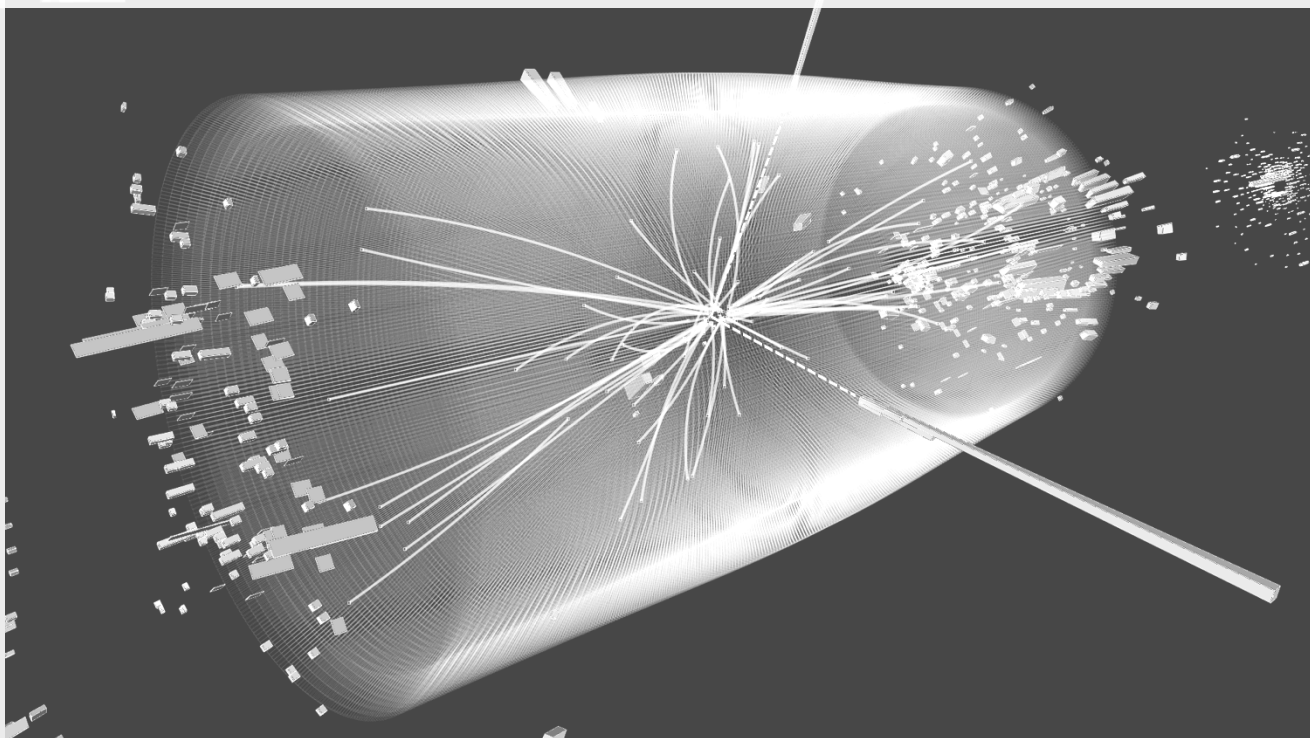
Production rates spanning many orders of magnitude are understood





CMS Experiment at the LHC
Data
Run Level

Hunting for the Higgs Boson



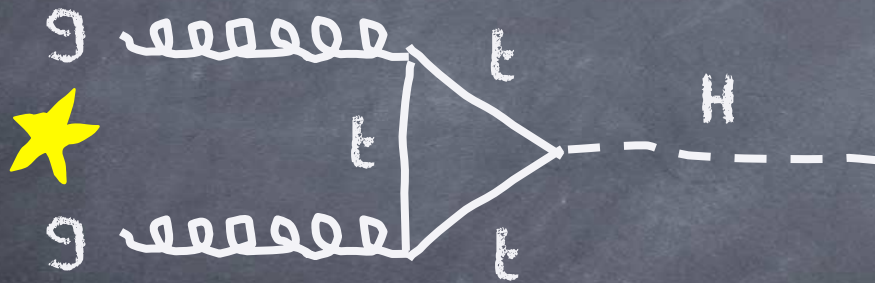
Higgs boson searches at the LHC

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

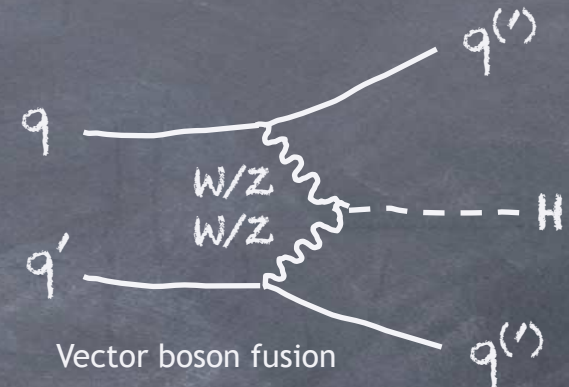
At the LHC, the Higgs boson is produced dominantly via **gluon fusion**

$\sigma_{H,\text{total}} \sim 22 \text{ pb}$ 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**

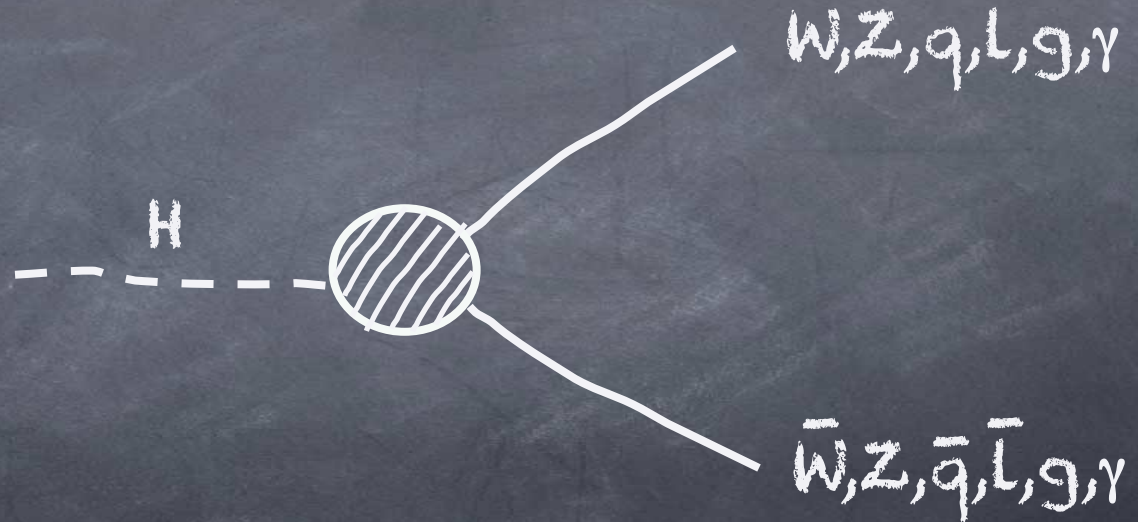
$\sigma_{H,\text{total}} \sim 22 \text{ pb}$ at 8 TeV for $m_H = 125 \text{ GeV}$ ($\sim 20 \times$ Tevatron; $>200 \times$ rate given luminosity)

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

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

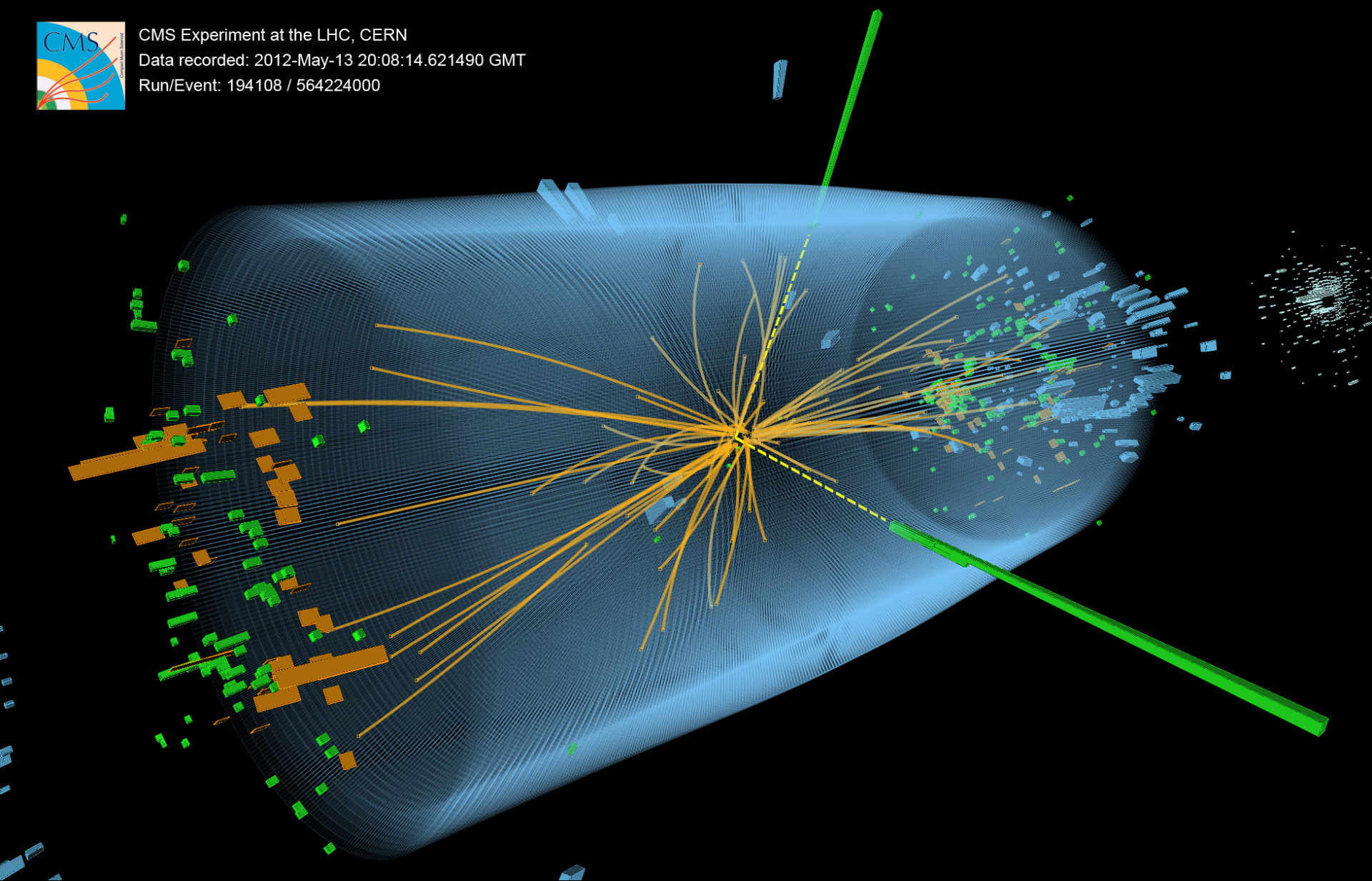
For light Higgs, discovery channels are

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$
- $H \rightarrow WW^{(*)} \rightarrow 2l2\nu$





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



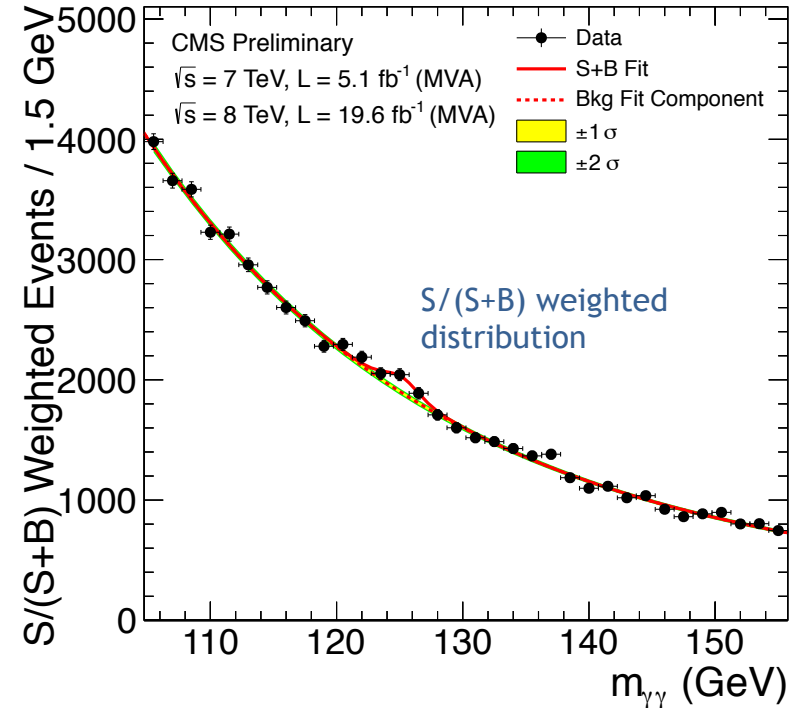
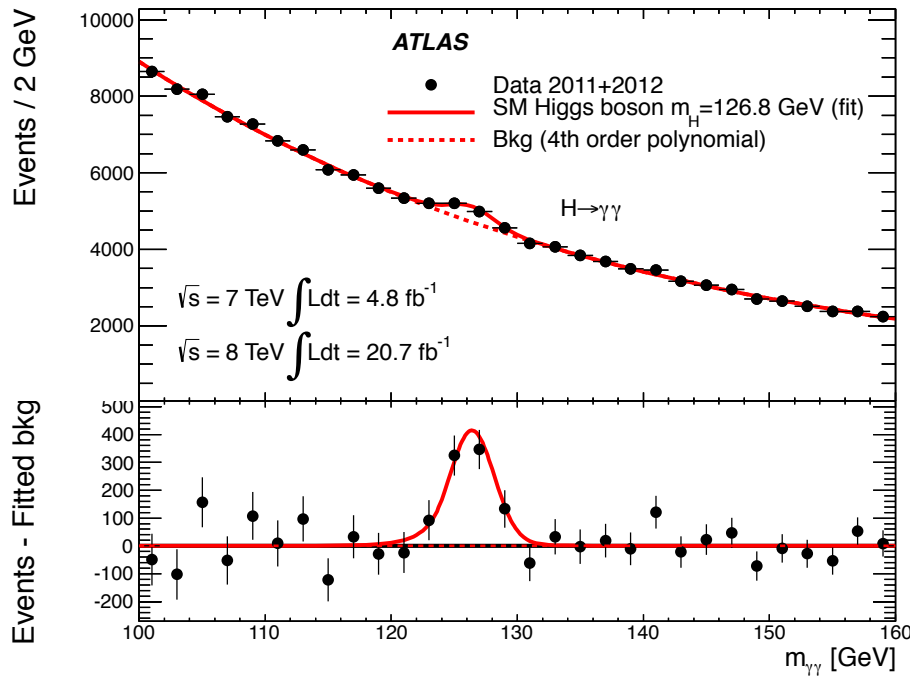
$H \rightarrow \gamma\gamma$ candidate event (CMS) — note: background dominated sample

$$H \rightarrow \gamma\gamma$$

Clean discovery channels for Higgs, allowing precise mass determination

ATLAS 1307.1427, CMS-PAS-HIG-13-001

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



Maximum excess of 7.4σ (3.9σ) seen by ATLAS (CMS) at $126.8 \pm 0.2 \pm 0.7$ GeV (125.4 GeV)

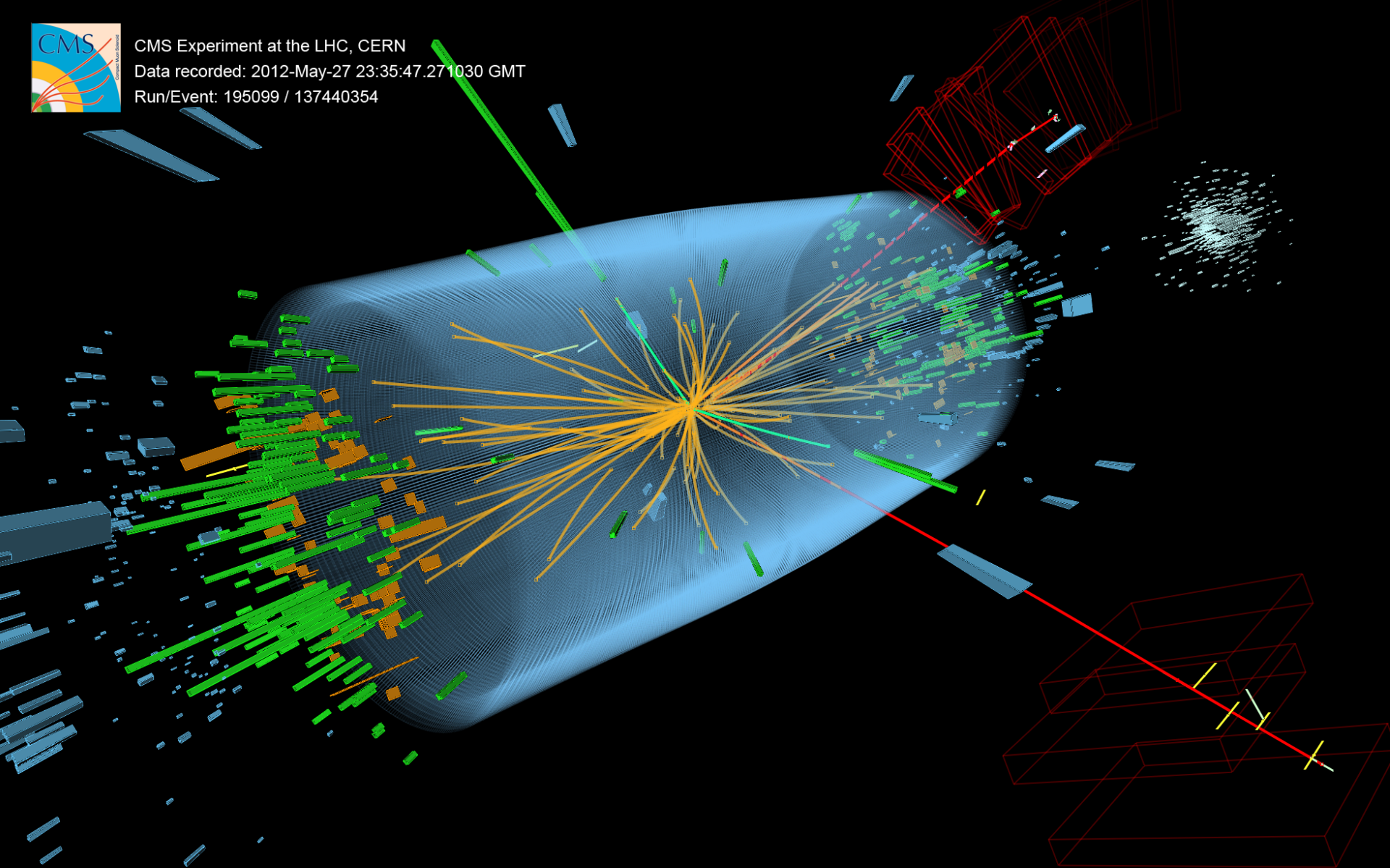
ATLAS (CMS) signal strength relative to SM expectation: 1.6 ± 0.3 (1.1 ± 0.3)



CMS Experiment at the LHC, CERN

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

Run/Event: 195099 / 137440354



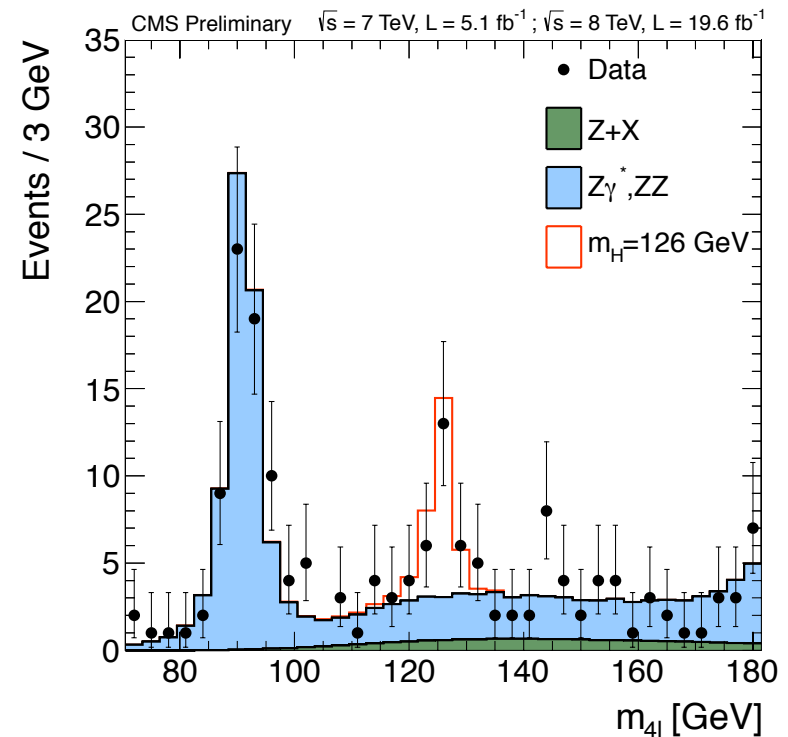
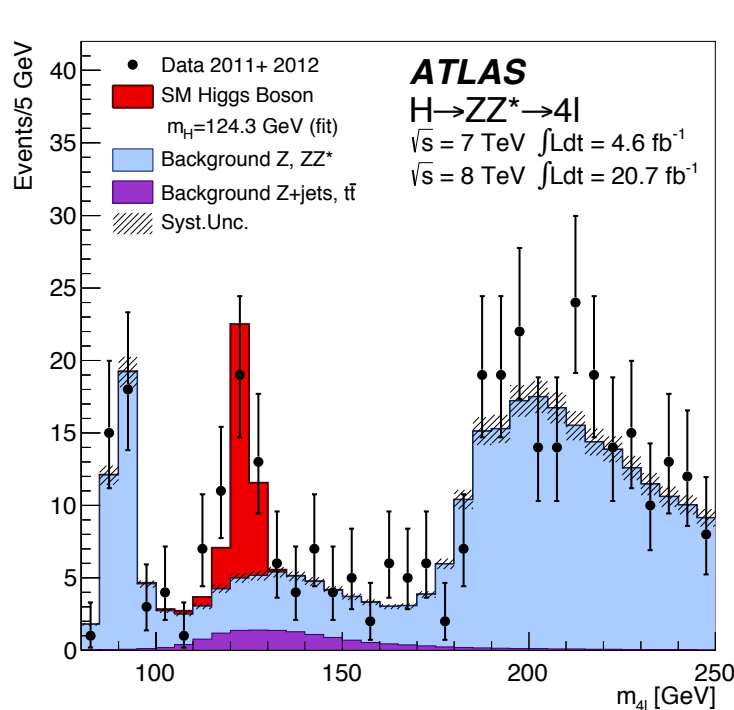
$H \rightarrow 2e2\mu$ candidate event (CMS)

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

Clean discovery channels for Higgs, allowing precise mass determination

ATLAS 1307.1427, CMS-PAS-HIG-13-002

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



Maximum excess of 6.6σ (6.7σ) seen by ATLAS (CMS) at $124.3 \pm 0.6 \pm 0.4 \text{ GeV}$ (125.8 GeV)

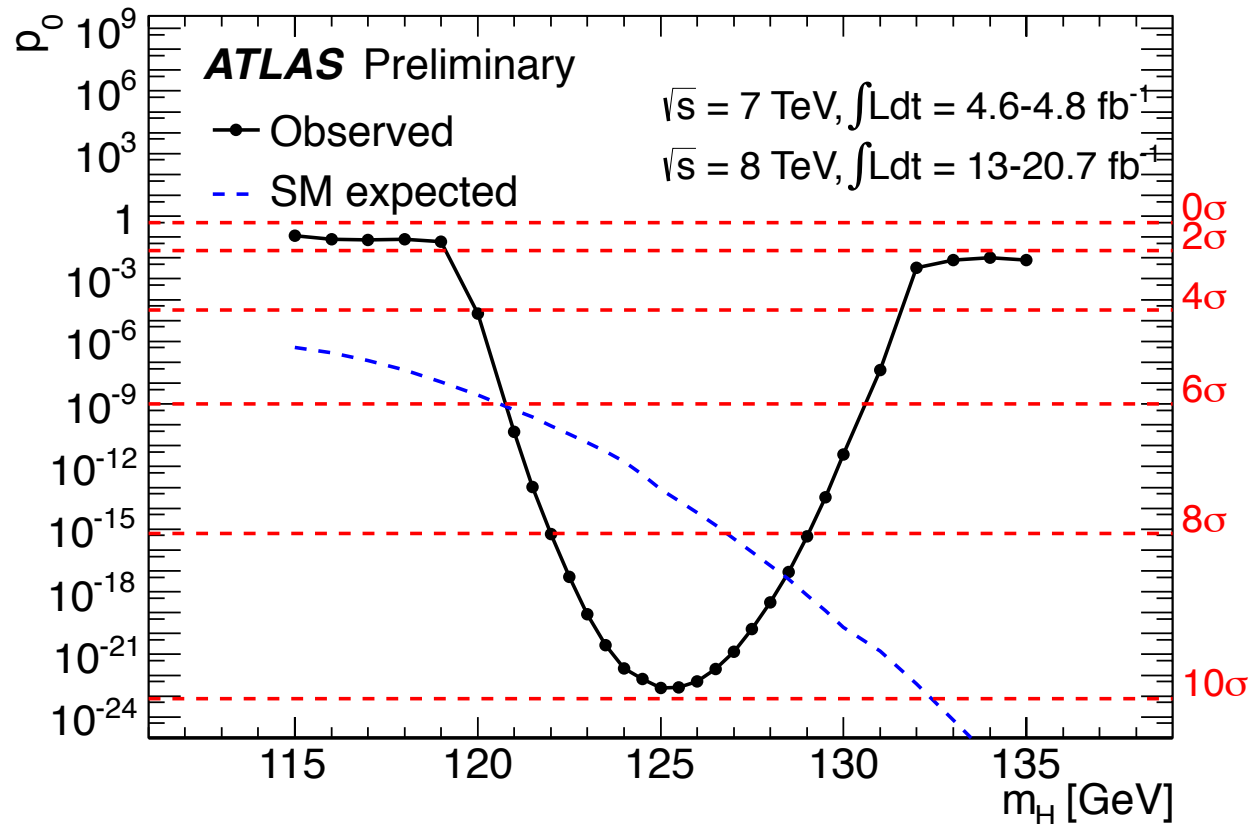
ATLAS (CMS) signal strength relative to SM expectation: 1.5 ± 0.4 (0.9 ± 0.3)

Combining all the channels – discovery significance

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

ATLAS-CONF-2013-034, CMS-PAS-HIG-13-005

All results [$\gamma\gamma$, ZZ , WW , $\tau\tau$, bb] combined. Here: ATLAS – no doubts left !



ATLAS (CMS) combined results

Higgs mass:

$$m_H = 125.5 \pm 0.2 \pm 0.5 \text{ GeV} \\ (125.7 \pm 0.3 \pm 0.3 \text{ GeV})$$

Cross section relative to SM:

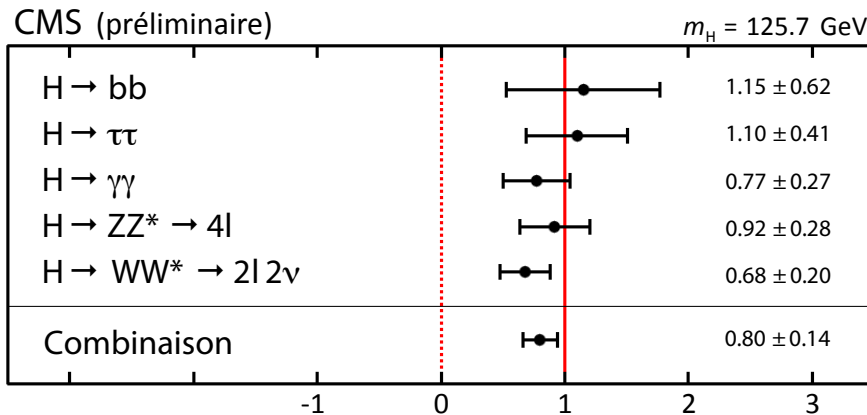
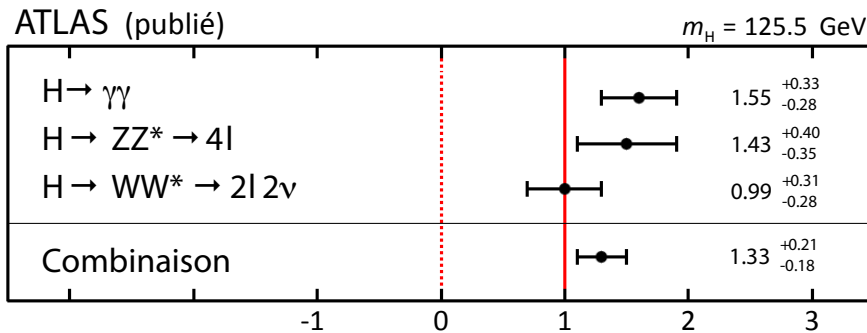
$$\mu = 1.30 \pm 0.13 \pm 0.14 \\ (0.80 \pm 0.14)$$

Combining all the channels – cross section / couplings

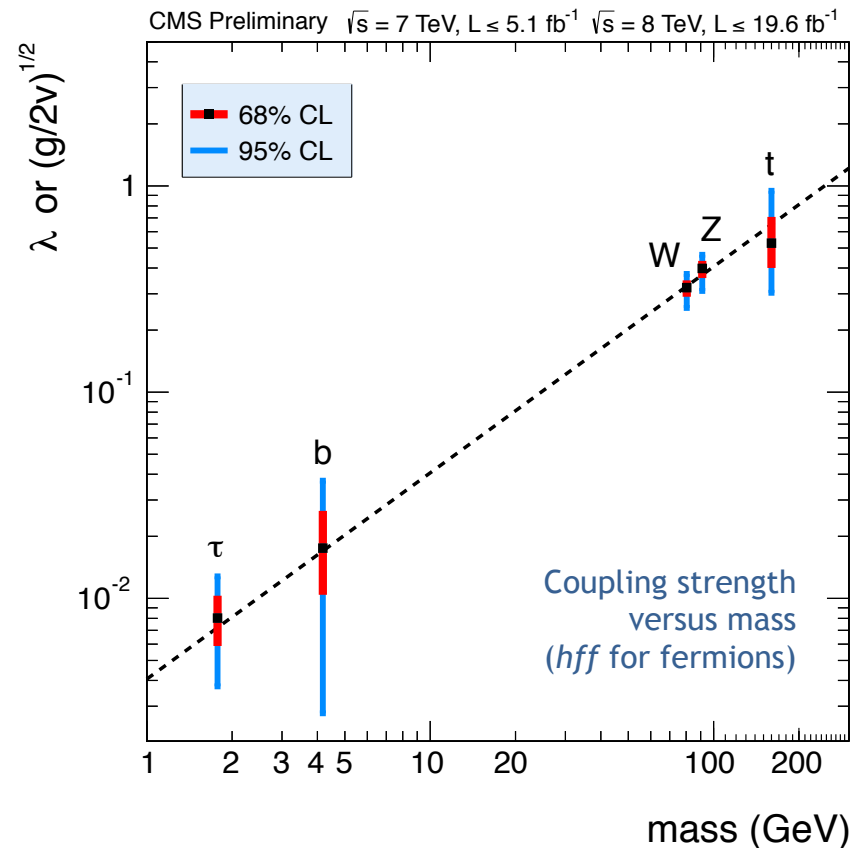
Are channel-by-channel cross sections $\times$ branching fractions SM-like ?

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



Mesure / Prédiction du modèle standard

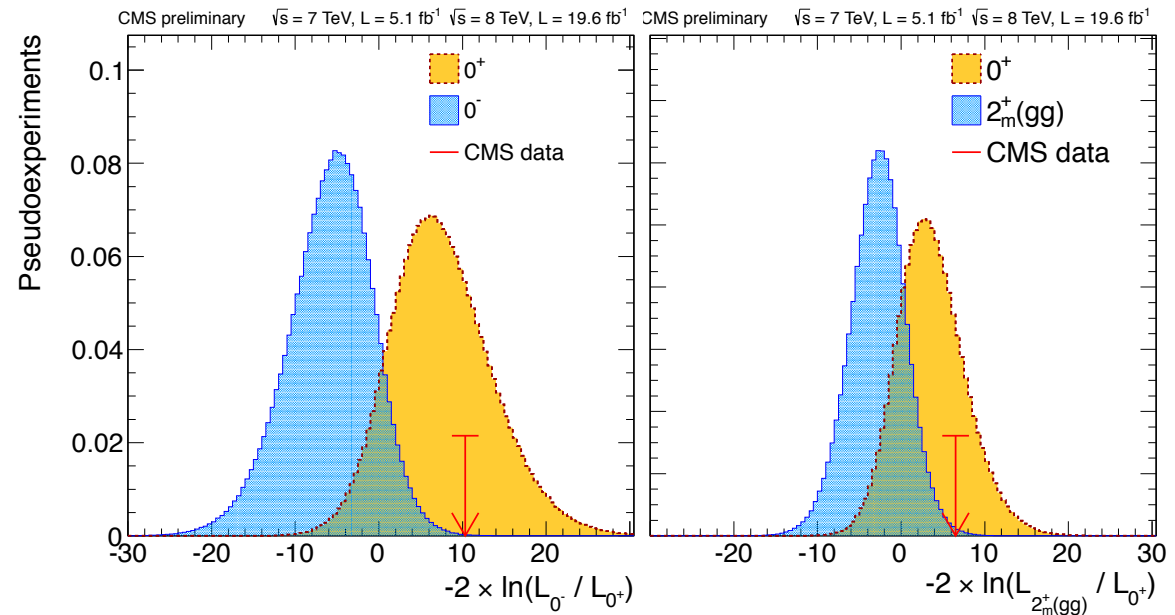
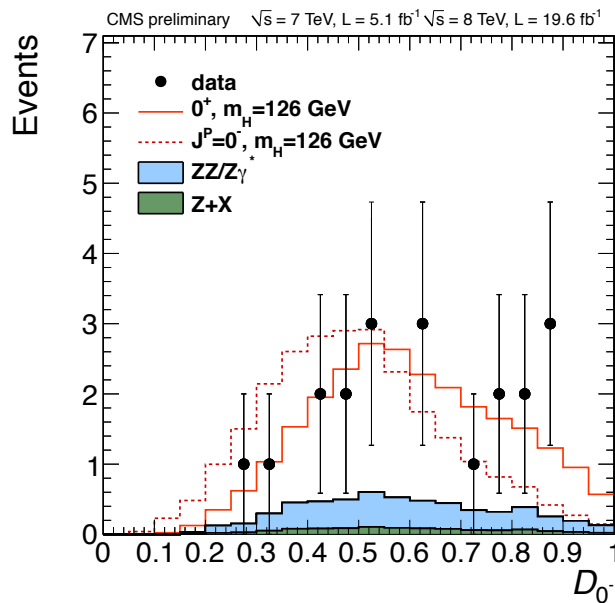


Combining all the channels

Does it have Higgs-like quantum numbers (spin 0 and positive parity) ?

ATLAS-CONF-2013-040, CMS-PAS-HIG-13-002/005

Use angular correlations in $H \rightarrow 4l$ (see below) and $H \rightarrow \gamma\gamma$ to measure spin-parity



Spin-0 hypothesis strongly favoured (0^- hypothesis rejected with 3.3σ , 2^+ similarly)



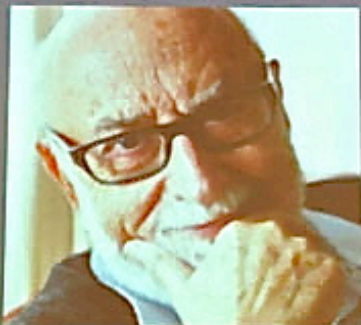
PRESS COVERAGE after July 4th seminars at CERN



Nobelpriset 2013

The Nobel Prize 2013

The Nobel Prize in Physics 2013



François Englert
Université Libre de Bruxelles, Belgium



Peter W. Higgs
University of Edinburgh, UK

"För den teoretiska upptäckten av en mekanism som bidrar till förståelsen av massans ursprung hos subatomära partiklar, och som nyligen, genom upptäckten av den förutsagda fundamentala partikeln, bekräftats av ATLAS- och CMS-experimenten vid CERN:s accelerator LHC."

"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

© Kungl. Vetenskapsakademien

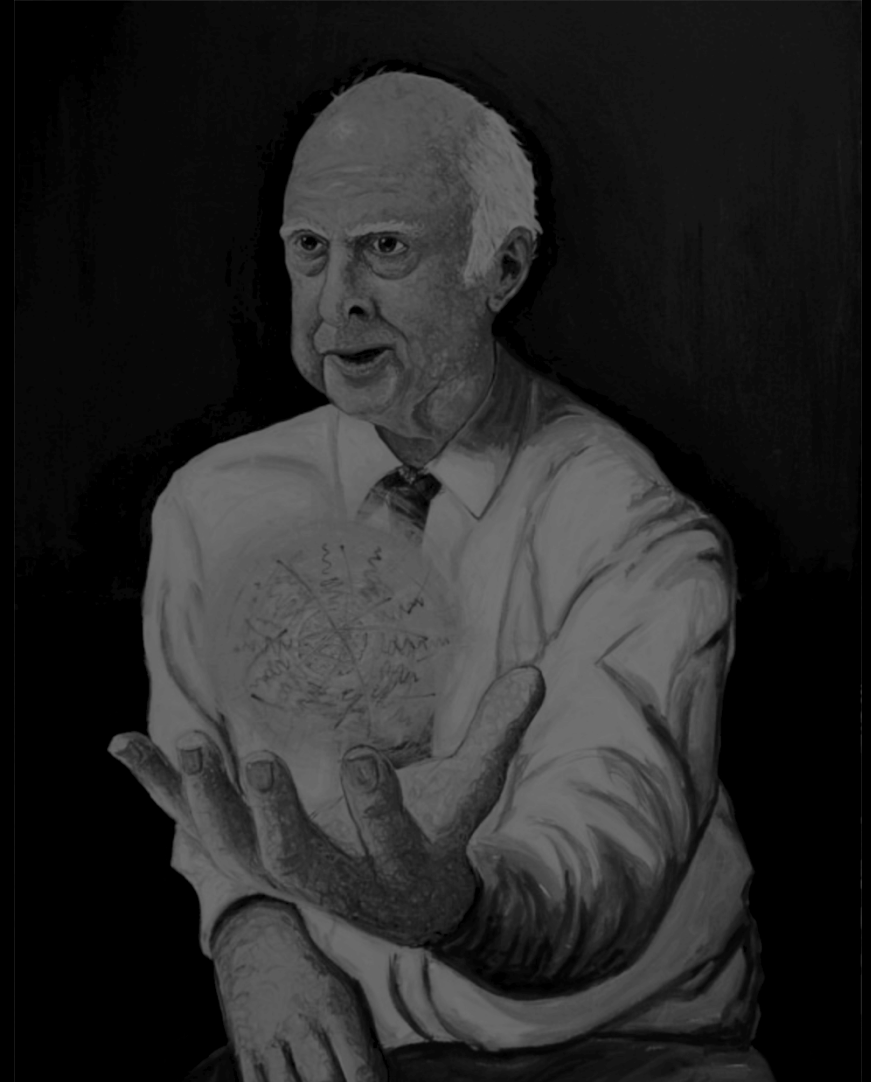
« Pour la découverte théorique d'un mécanisme qui contribue à notre compréhension de l'origine de la masse des particules subatomiques, et qui a récemment été confirmé par la découverte de la particule fondamentale prédite, par les expériences ATLAS et CMS auprès du grand collisionneur de hadrons du CERN »

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

A feast for experimentalists



- 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 ?

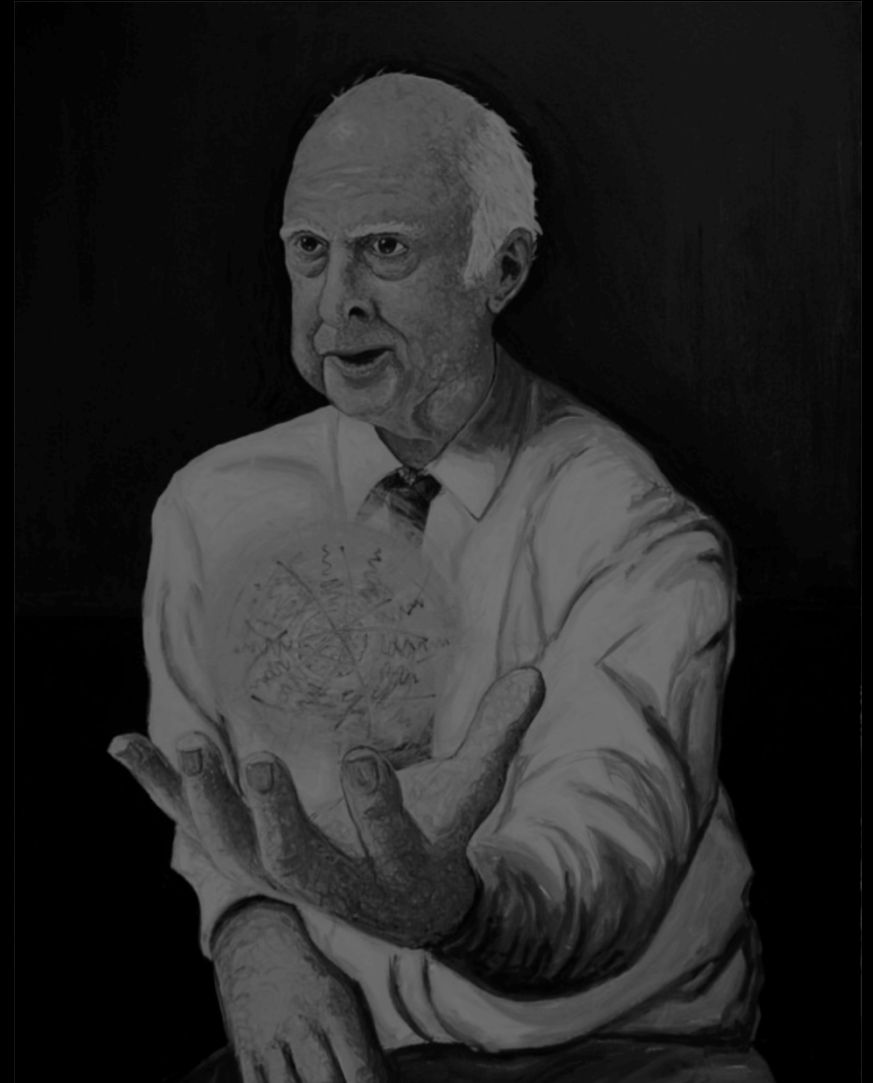


A new era in particle physics has begun: the exploration of the Higgs boson

Diet for theorists (?)



- Is it all just Standard Model ?



100 years after the discovery of cosmic rays...

The discovery of the Higgs boson completes the Standard Model

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
Higgs boson completes
the Standard Model

But ...

Jiro Taniguchi, Furari, © Casterman (2012)



100 years after the discovery of cosmic rays...

The discovery of the
Higgs boson completes
the Standard Model

But ...

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

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

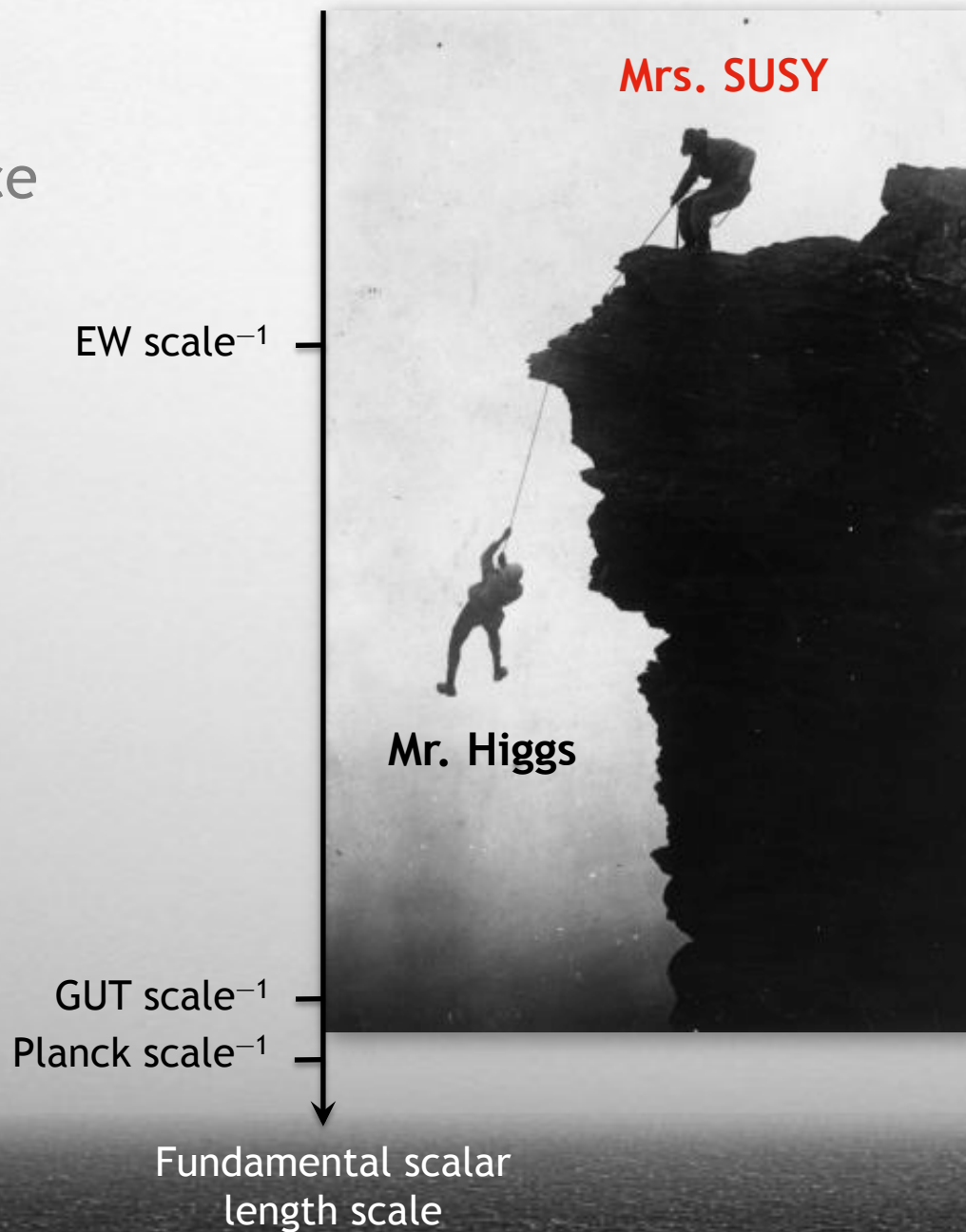
Matter-antimatter asymmetry in universe

Strong CP problem

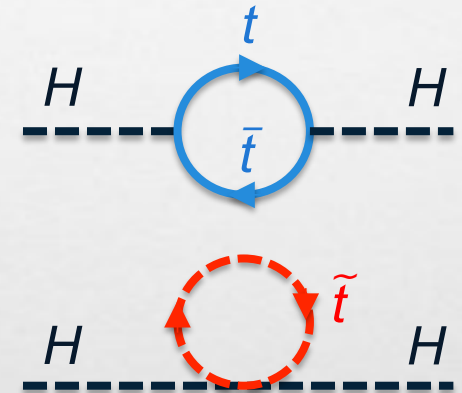
Massive neutrinos

Gravitation

The scalar precipice



Double the particle spectrum?



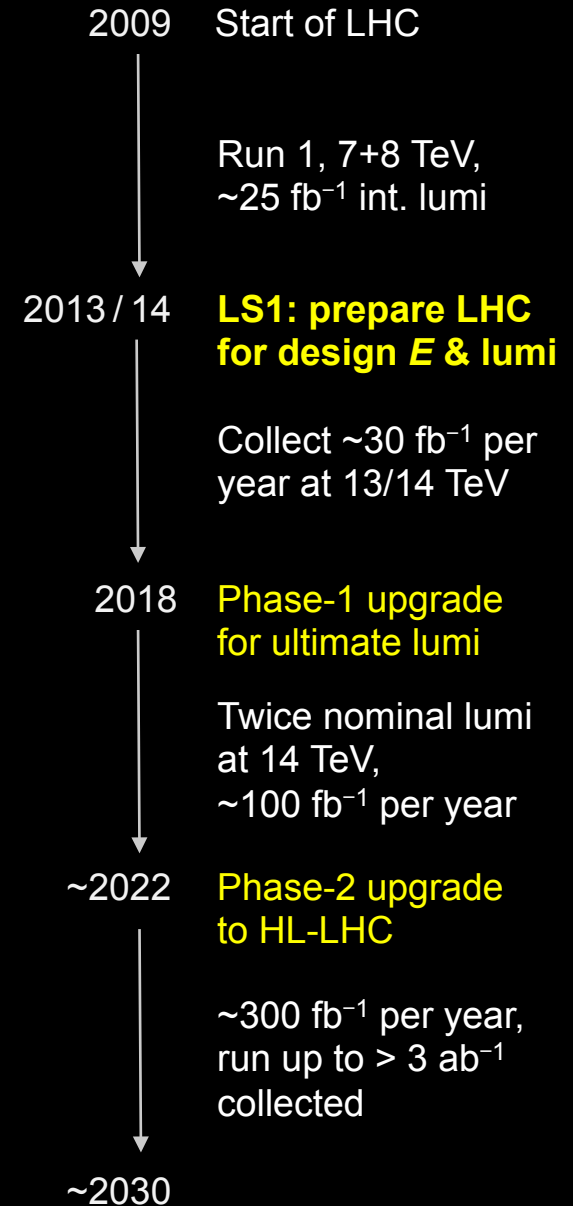
Étudier certaines de ces questions et mesurer
précisément les propriétés du boson de Higgs
seront les tâches à venir pour les expériences au LHC

Is the new boson the SM Higgs ?

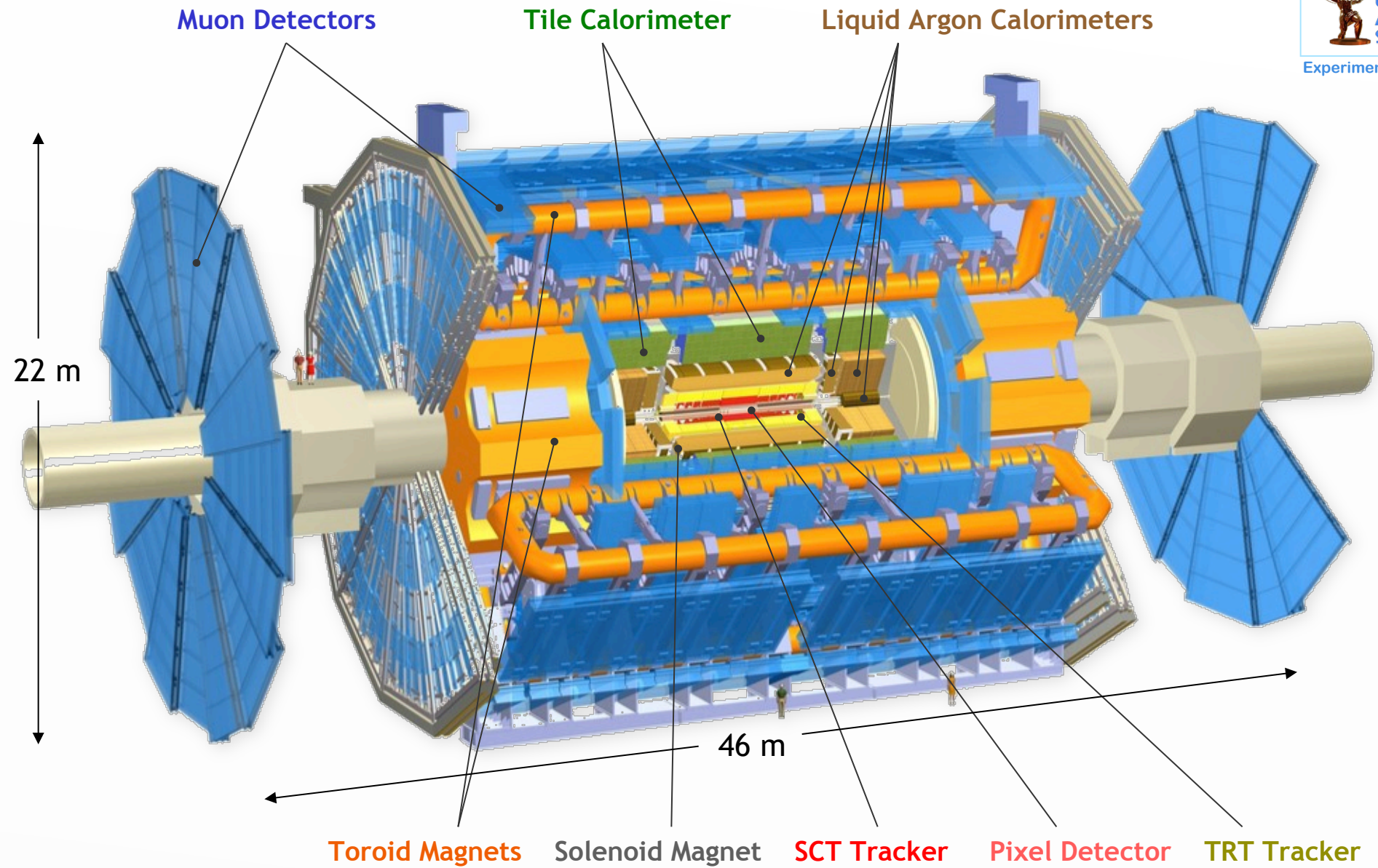
If so, what protects it ?



LHC timeline



Spares...



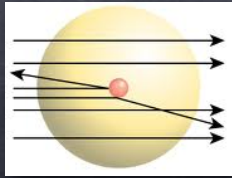
High-energy jets probe new particles and interactions

Measure di-jet invariant mass and angular distributions

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

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

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



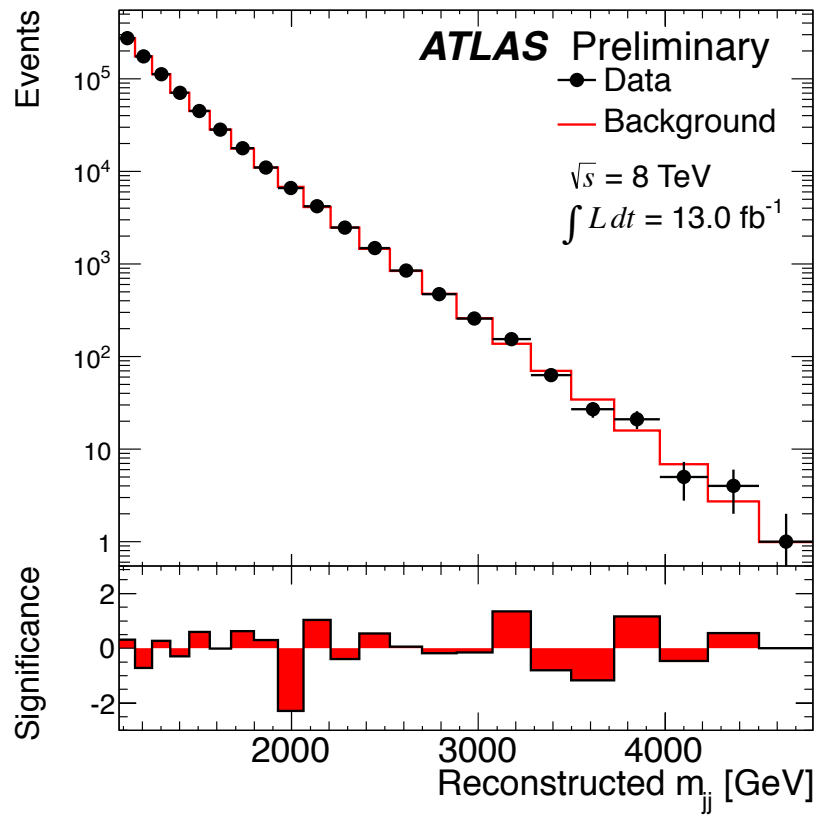
New, high-scale interaction ?
New bound state (particle) ?
Are quarks composites ?

High-energy jets probe new particles and interactions

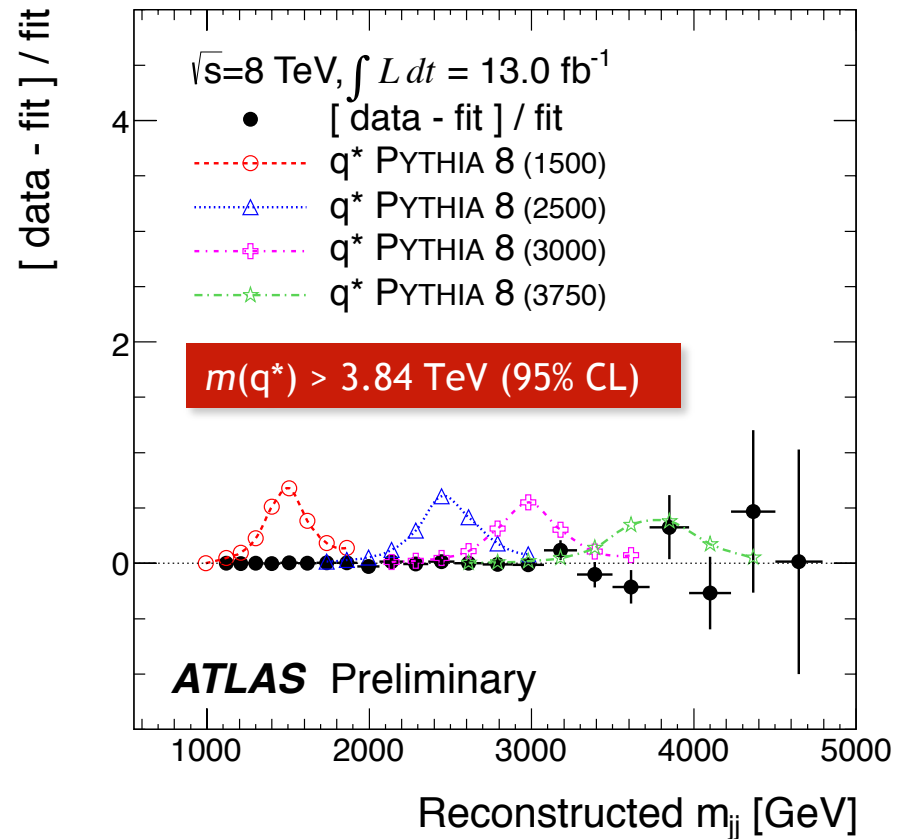
Measure di-jet invariant mass and angular distributions

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

Observed and fitted dijet mass



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



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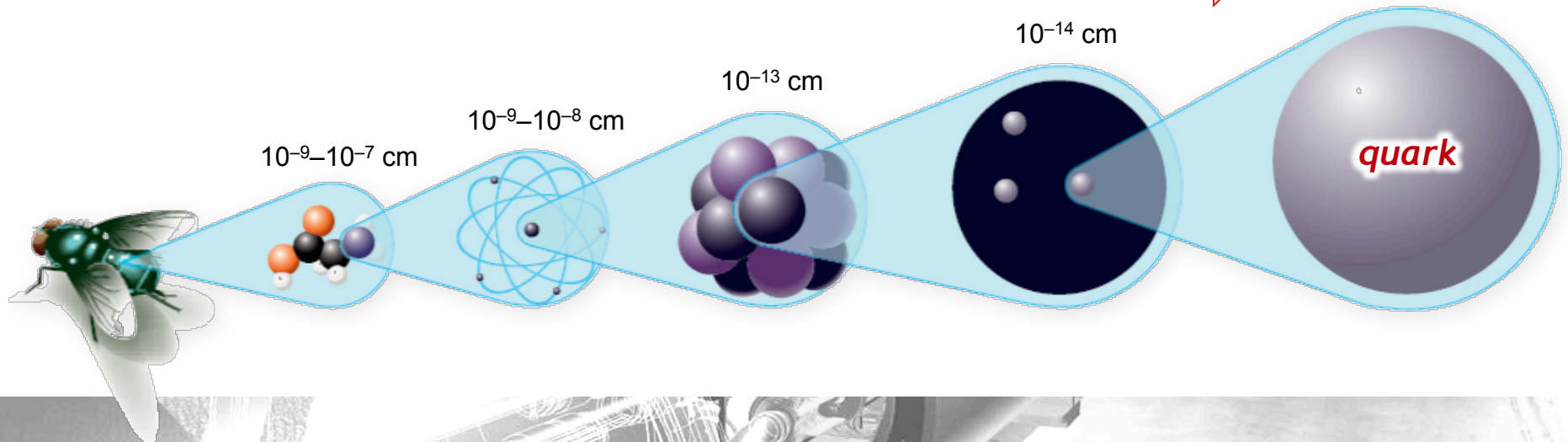
Measure di-jet invariant mass and angular distributions

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

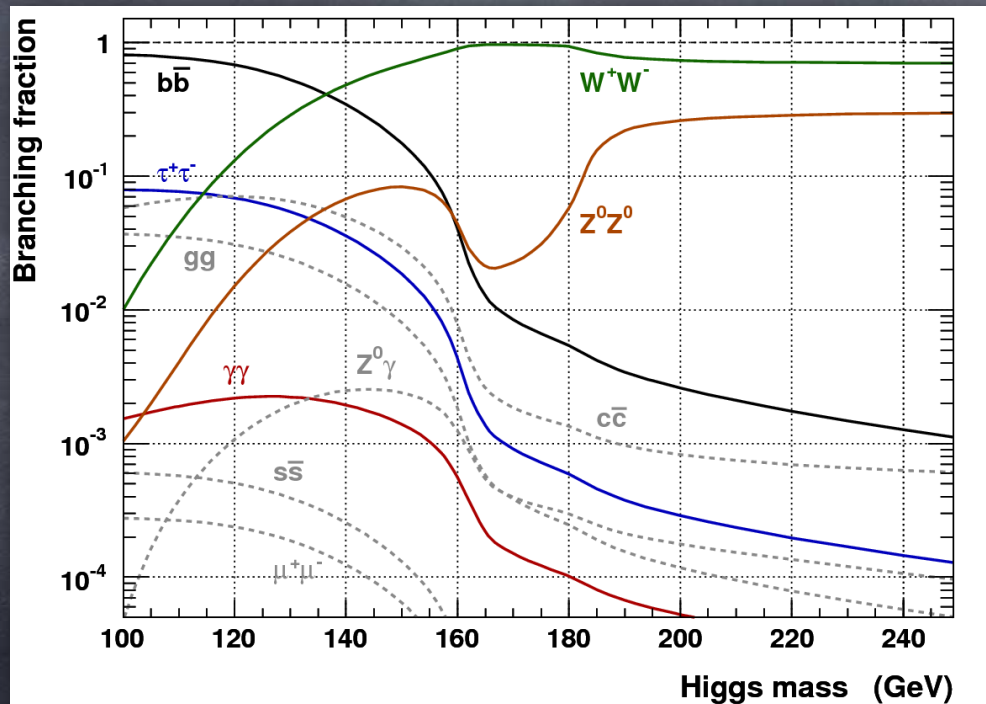
	Benchmark model	Observed limit at 95% CL
Resonant	Excited quarks	$m(q^*) > 3.8 \text{ TeV}$
Non-resonant	4-quark contact interactions	$\Lambda > 7.8 \text{ TeV}$

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



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