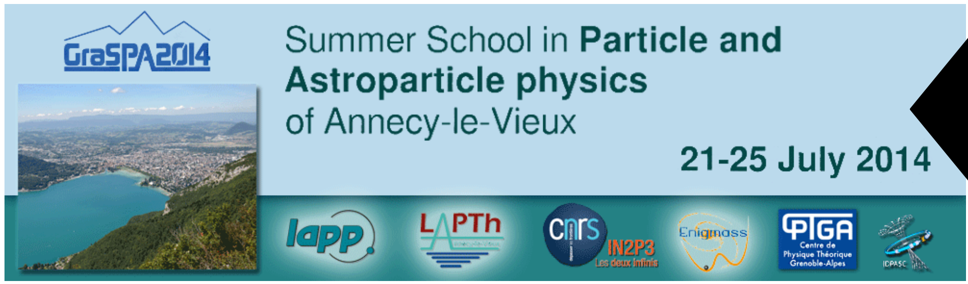
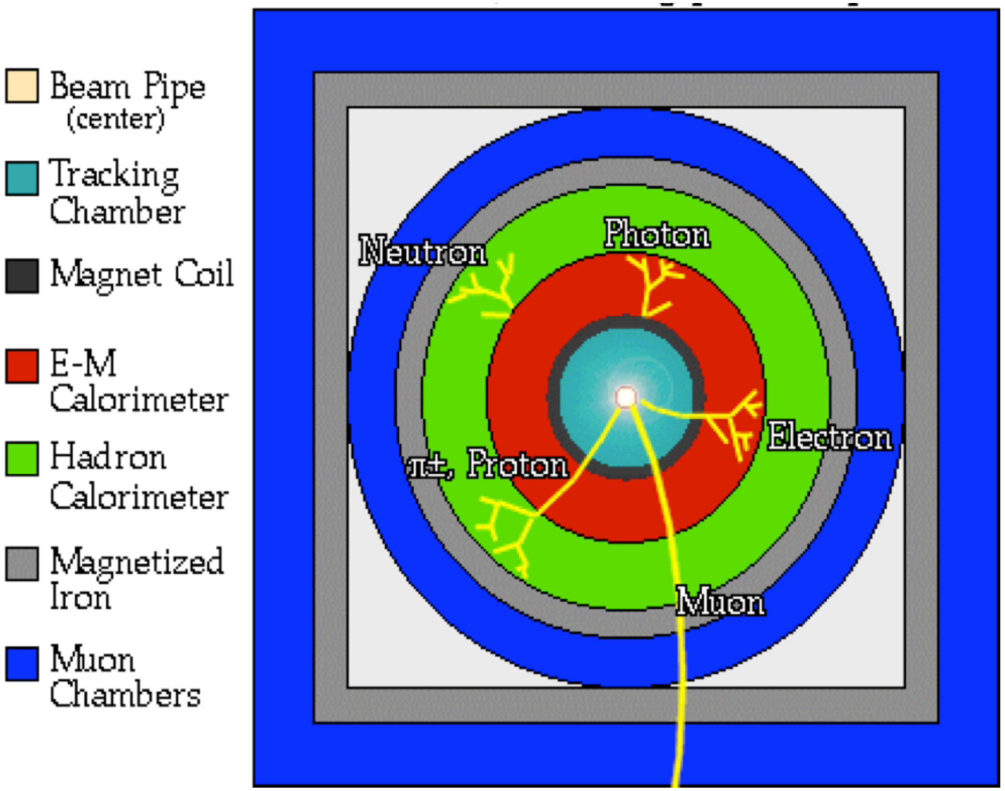
(experimental) LHC physics



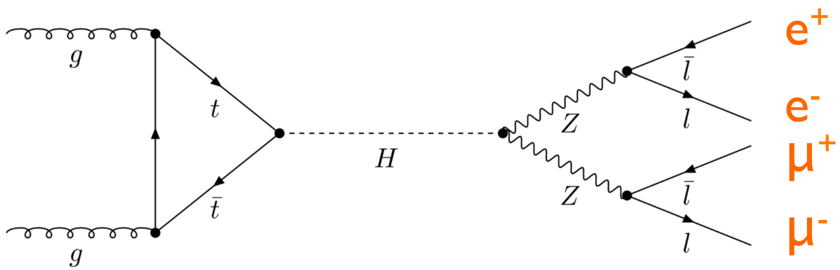
2. A brief overview of the (ATLAS+CMS) LHC physics program

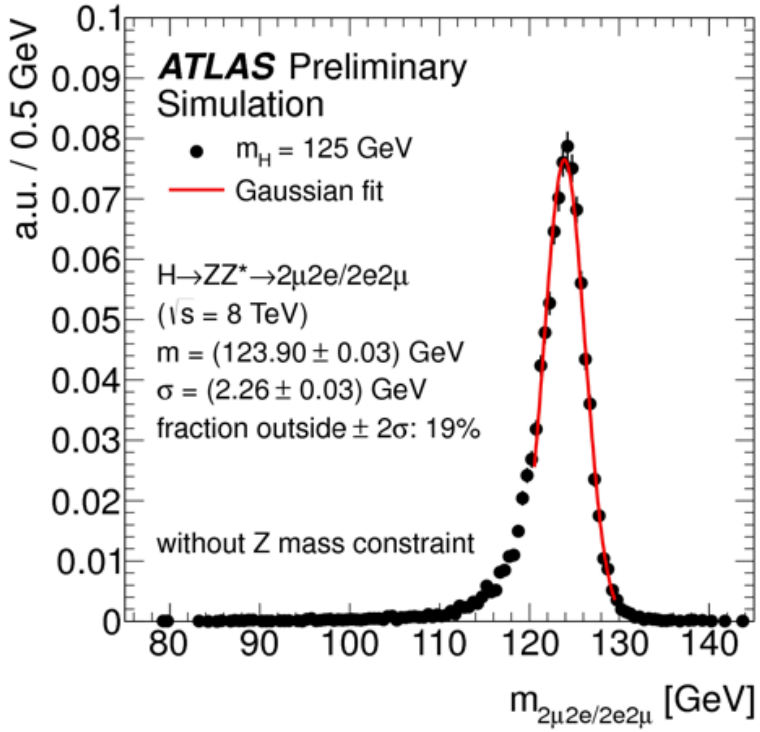
Recap from Lesson 1: how to find a new particle?

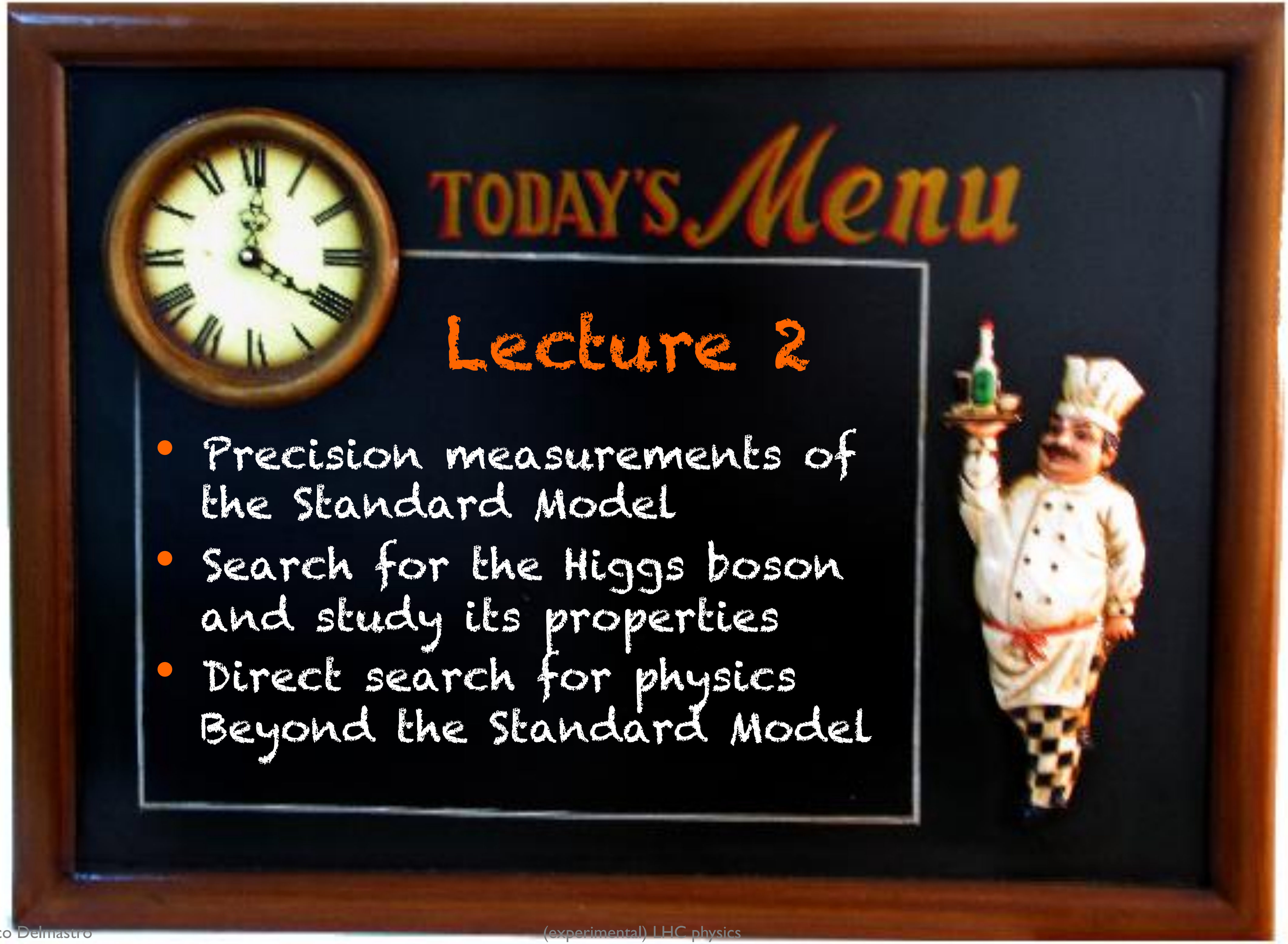
- Step 1: find events with the right ingredients
  - ✓ Cut on particle properties to reduce reducible background
  - ✓ Cut on event properties to distinguish signal from background



- Step 2: reconstruct properties of initial particle







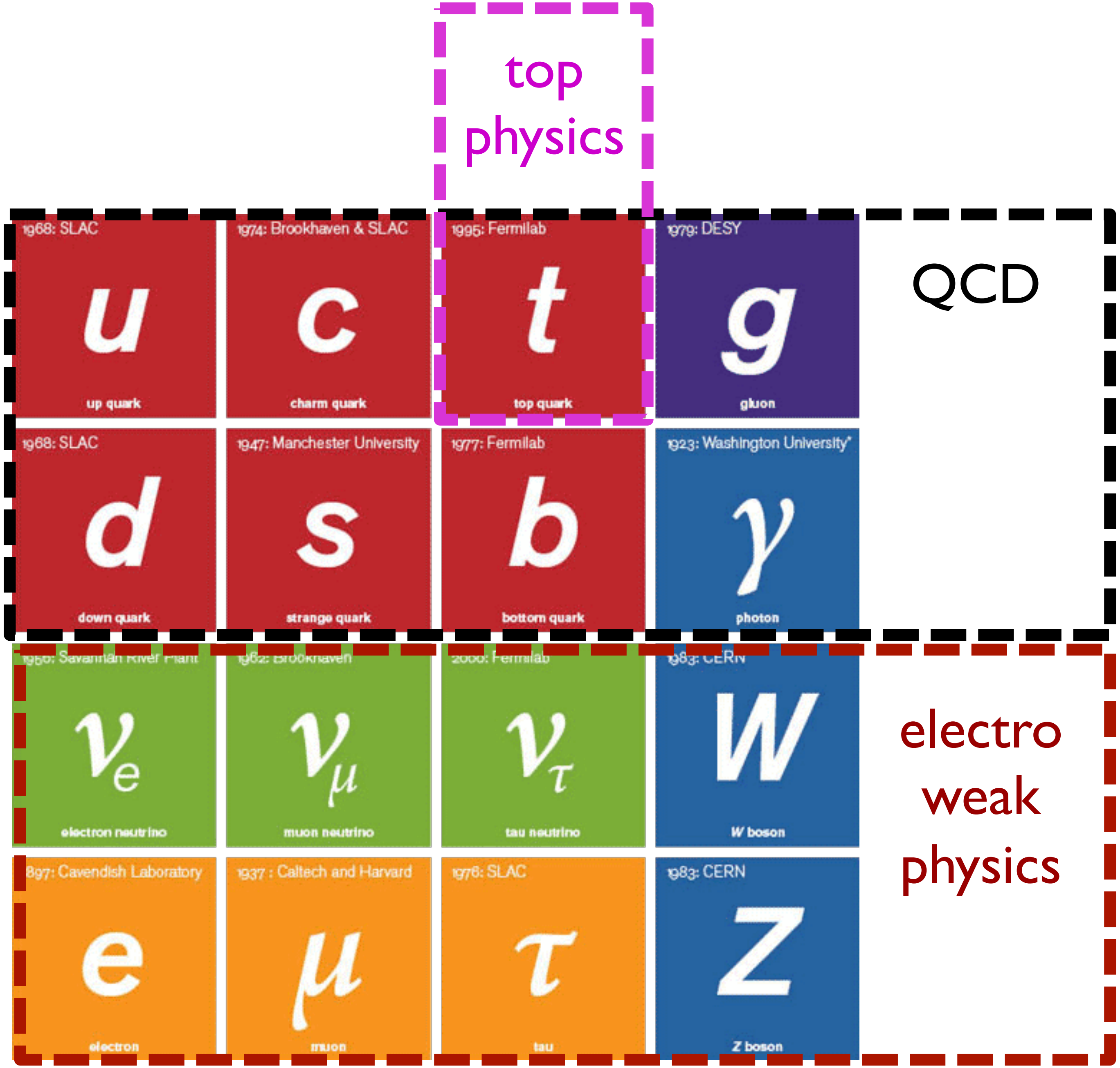
Lecture 2

- Precision measurements of the Standard Model
- Search for the Higgs boson and study its properties
- Direct search for physics Beyond the Standard Model

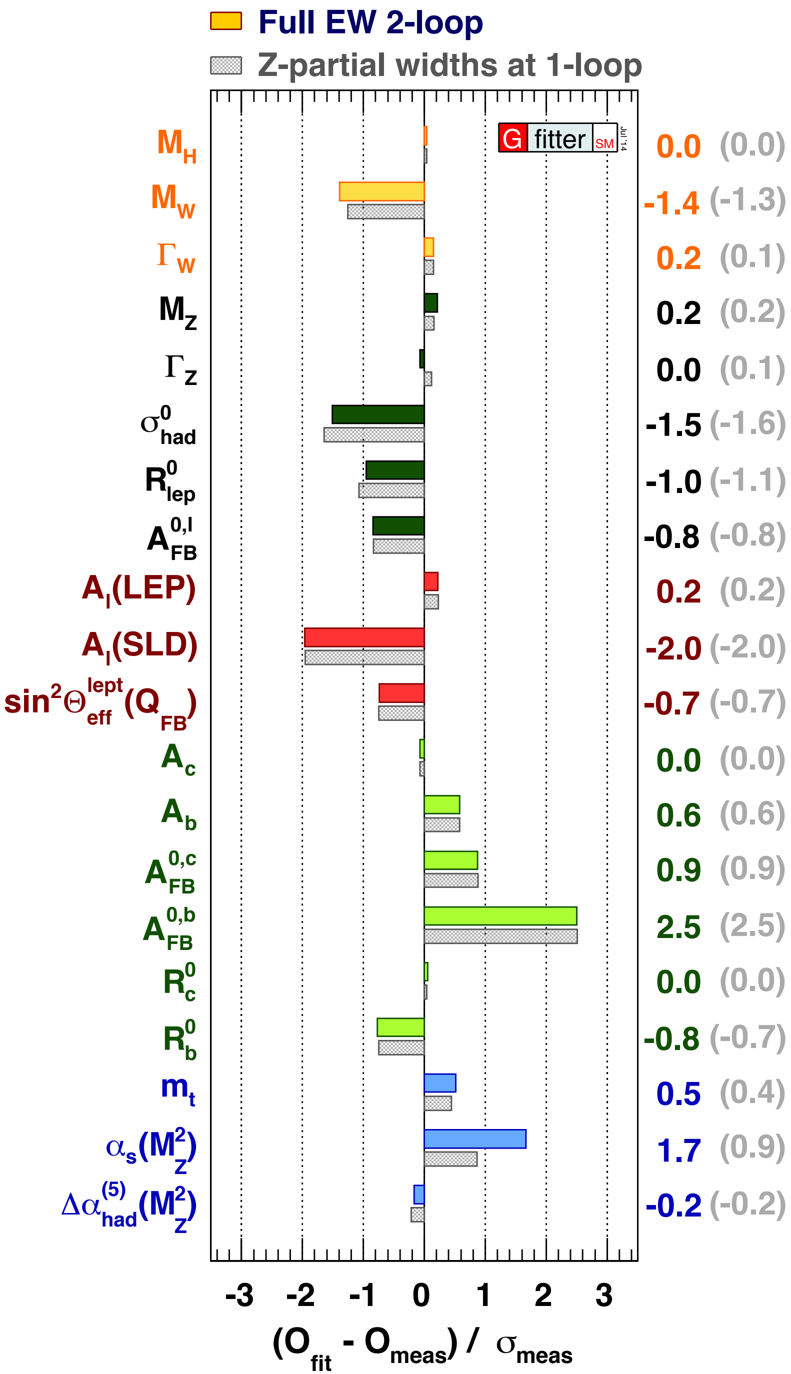
Standard Model

precision measurements

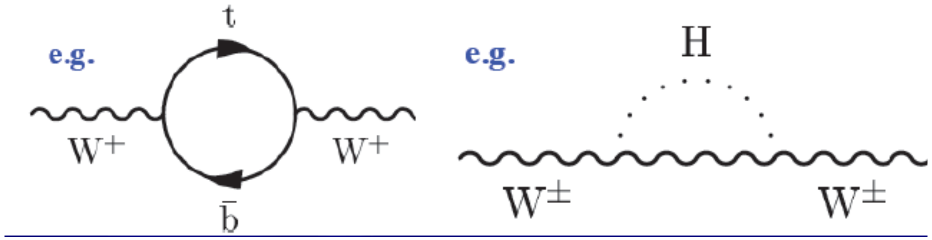
Standard Model measurements

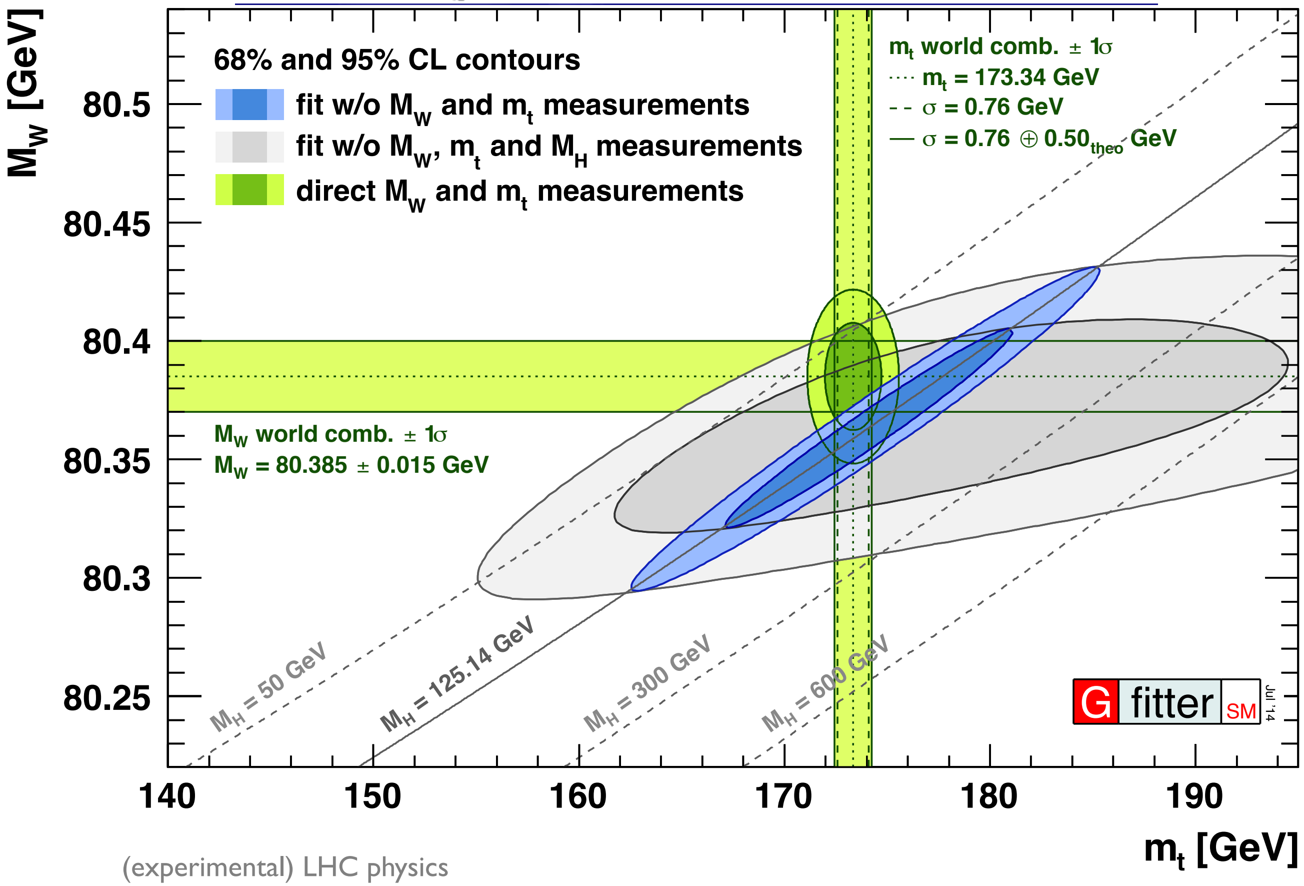


Standard Model measurements

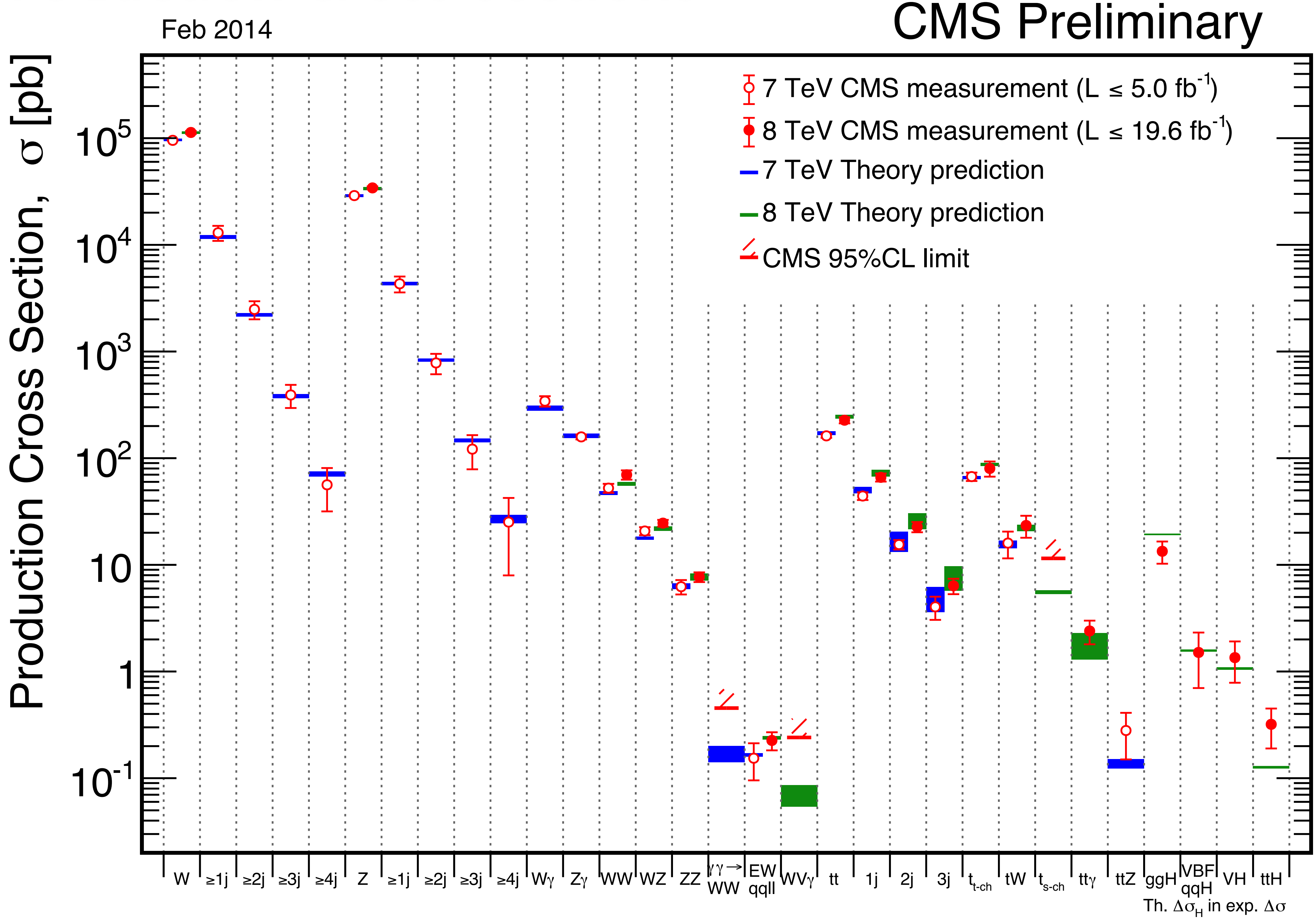


- Excellent agreement between measurements and SM prediction!
  - ✓ Very few tensions…
- More precise measurements of W and t mass needed: indirect constrain are now better!

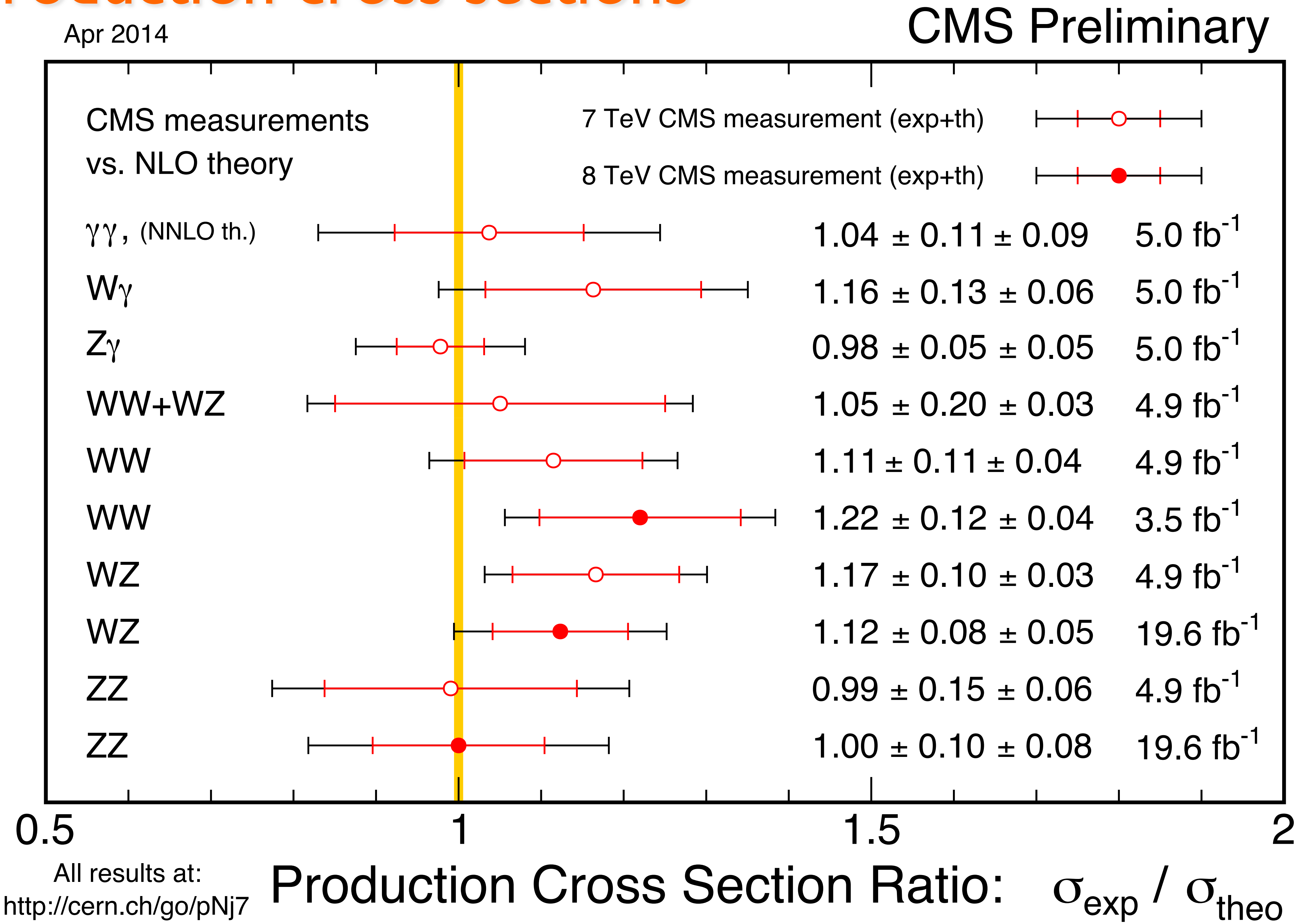




Production cross sections

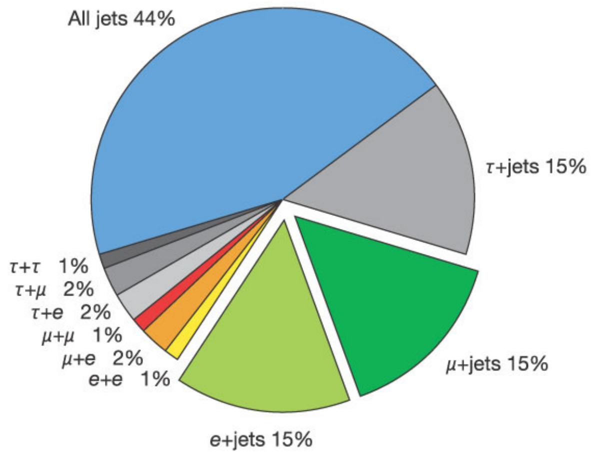


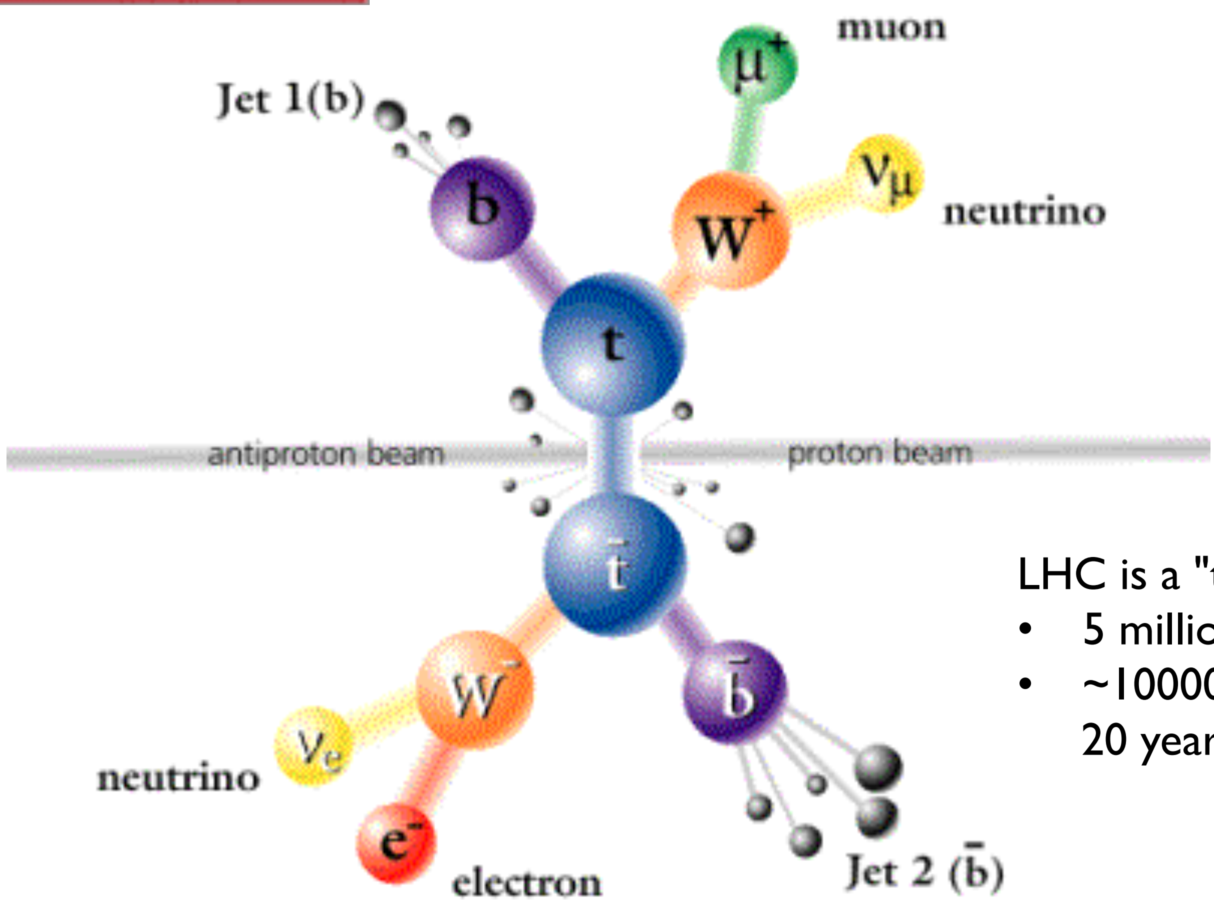
Production cross sections

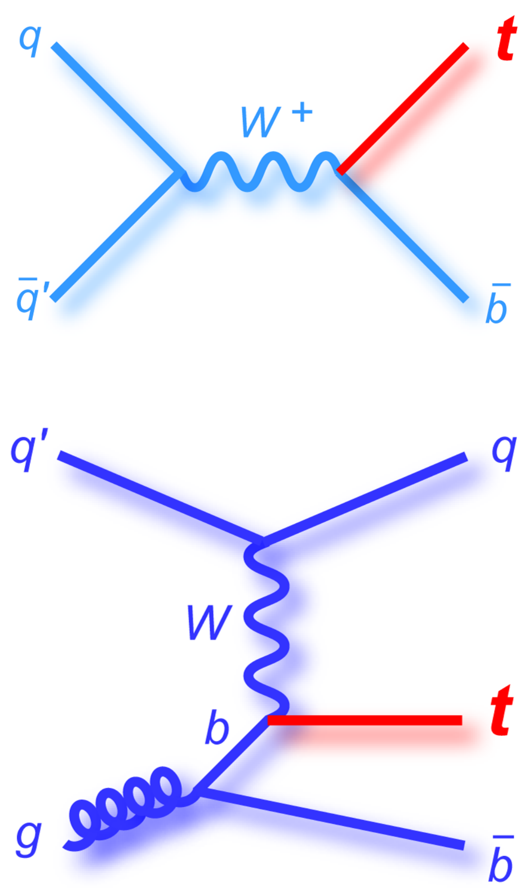


top quark

- Top quark has a mean lifetime of 5×10^{-25} s, shorter than time scale at which QCD acts: no time to hadronize!
  - ✓ It decays as $t \rightarrow Wb$
- Events with top quarks are very rich in (b) jets…





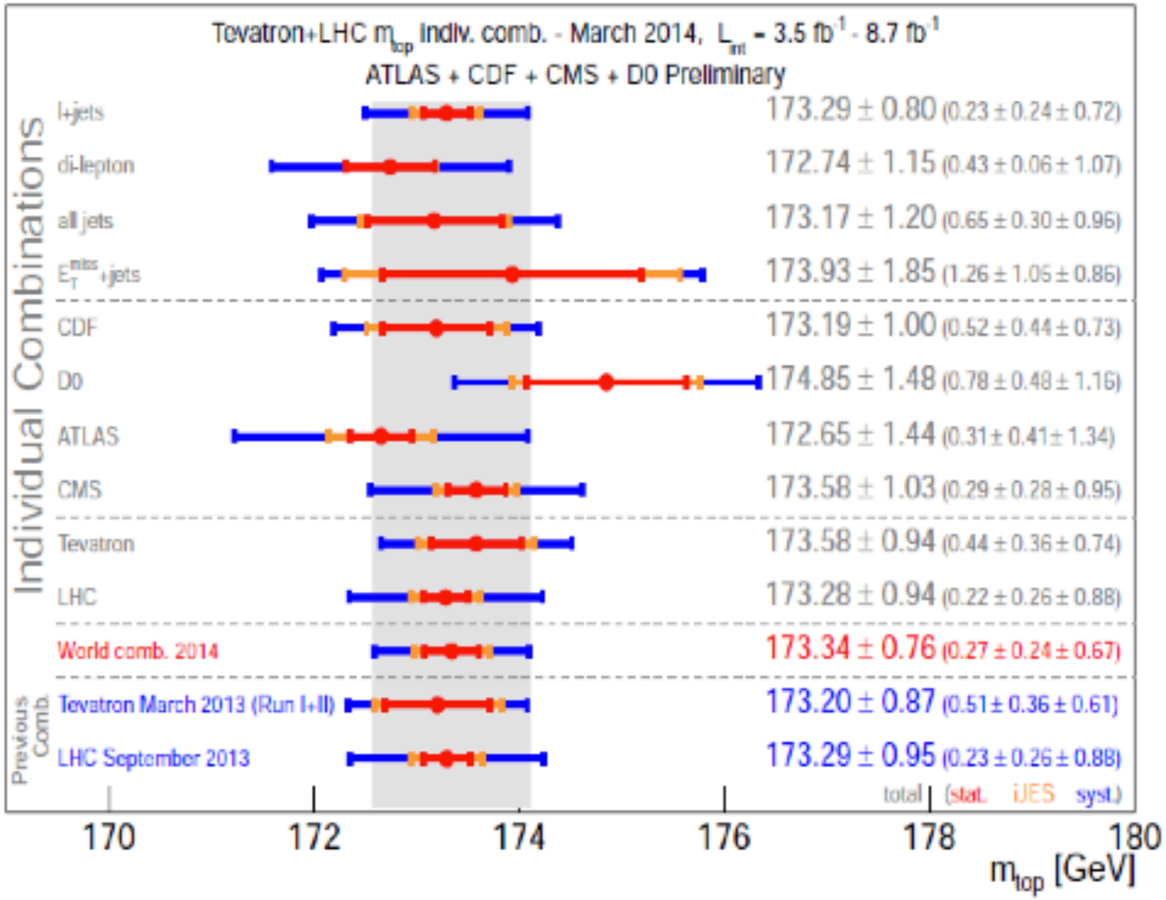


LHC is a "top factory"!

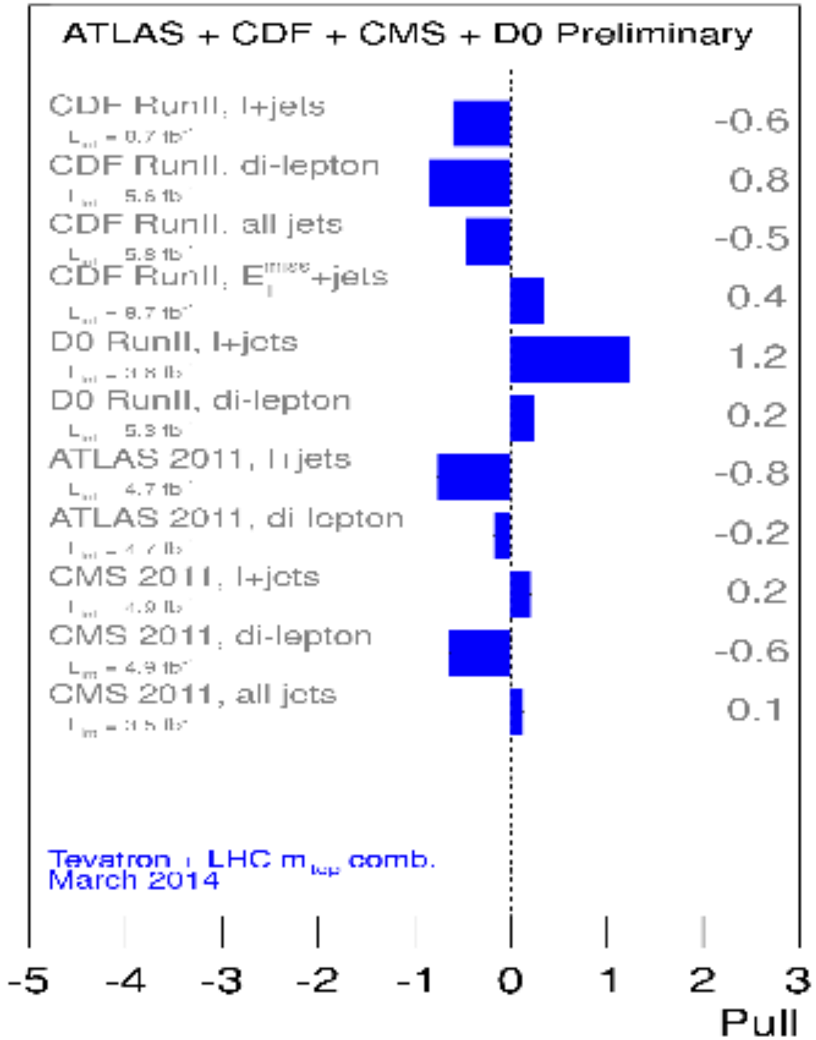
- 5 millions of $t\bar{t}$ pairs
- ~100000 in Tevatron in 20 years

Mass of the top quark

Tevatron combination November 2012 May 2013
LHC combination July 2012 September 2013
World combination March 2014 arXiv:1403.4427



Combination using BLUE



$$m_{top} = 173.34 \pm 0.27\,(\text{stat}) \pm 0.24\,(\text{iJES}) \pm 0.67\,(\text{syst})\ \text{GeV}$$

Consistency χ^2=4/10

precision on M_{top} 0.44%

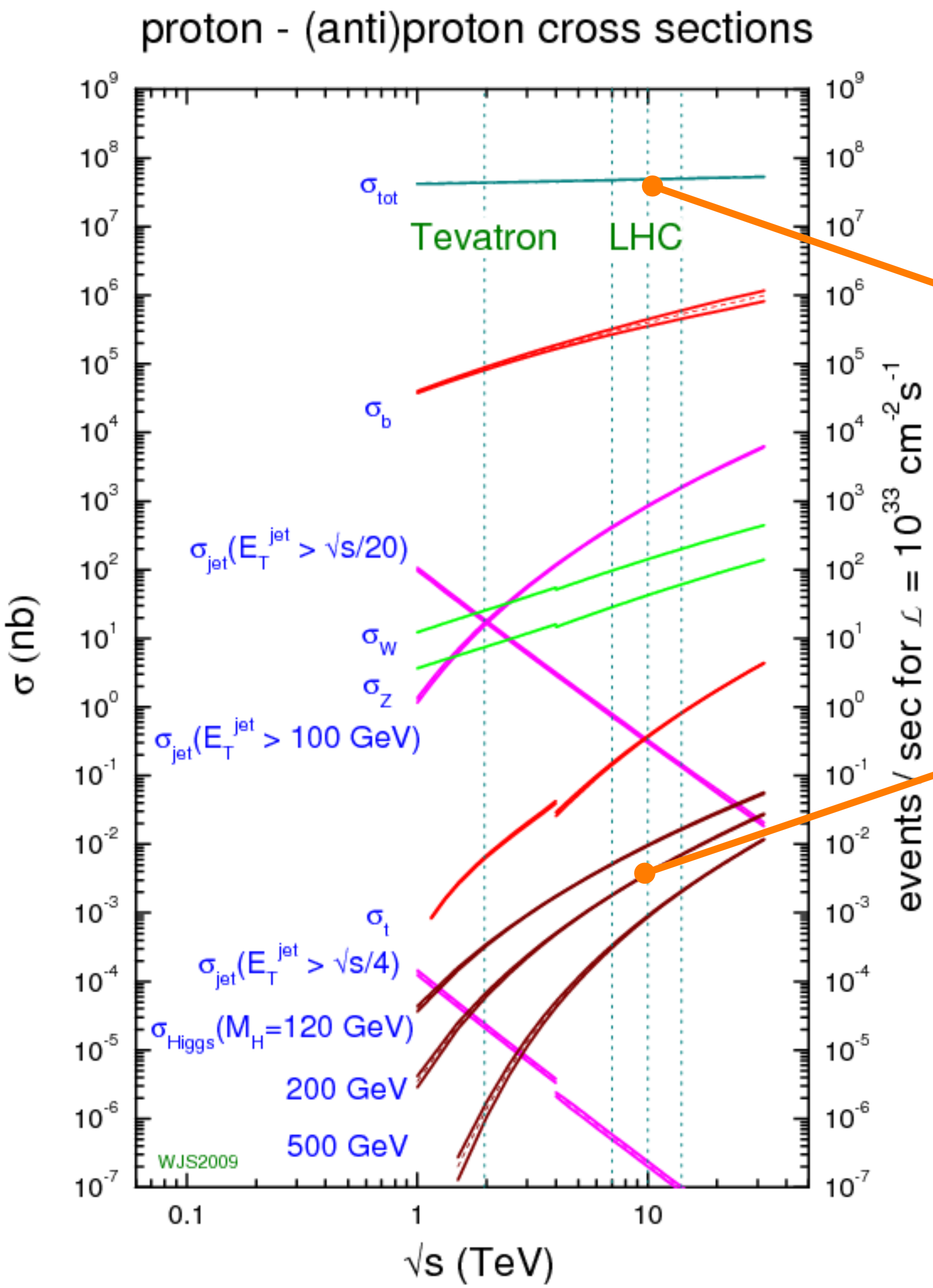
Highest precision in l+jet channel
Dilepton channel good precision
Fully hadronic channel respectable

11

interlude

How to find a new particle?

Interesting processes are rare!



10^8 events/s

$\sim 10^{10}$

10^{-2} events/s ~

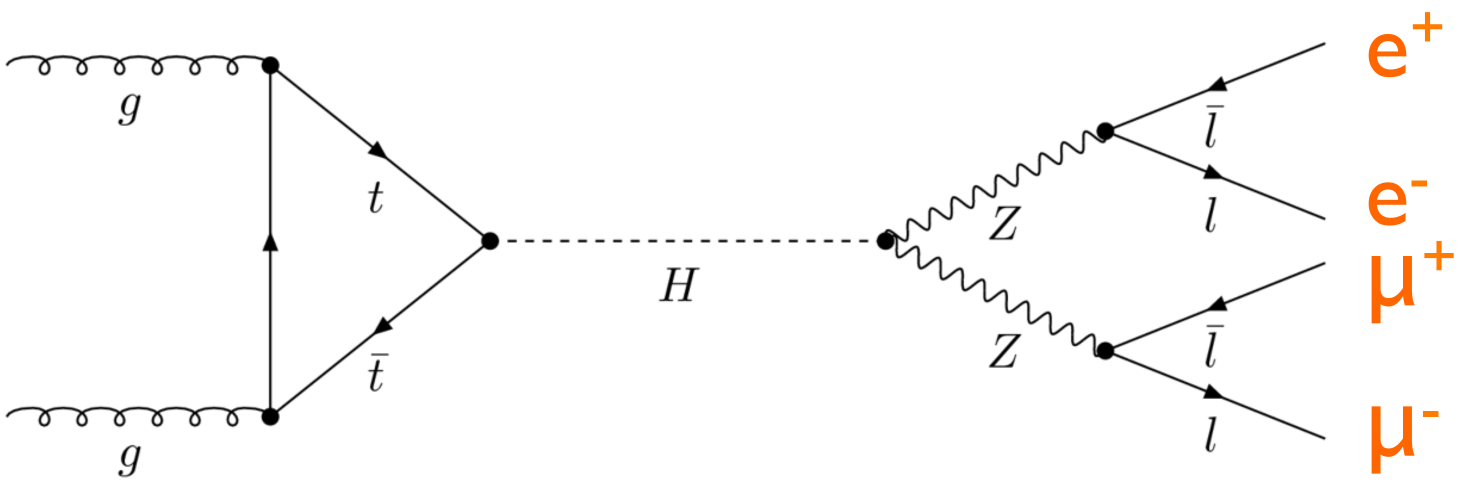
10 events/min

[m_H ~ 120 GeV]

0.2% H → γγ

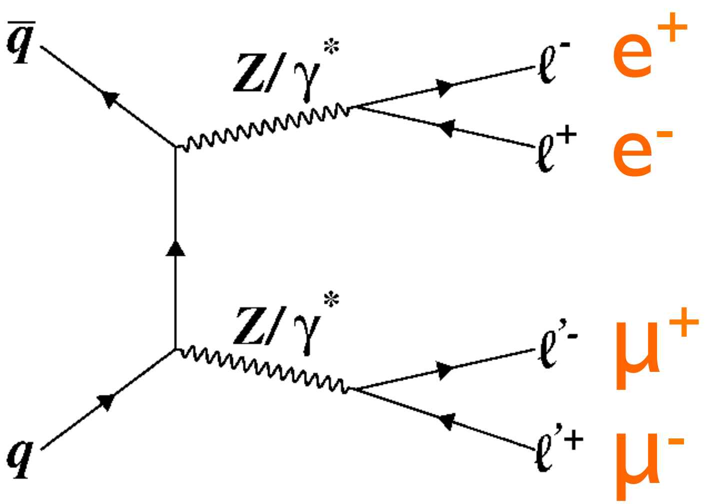
1.5% H → ZZ

Signal and background



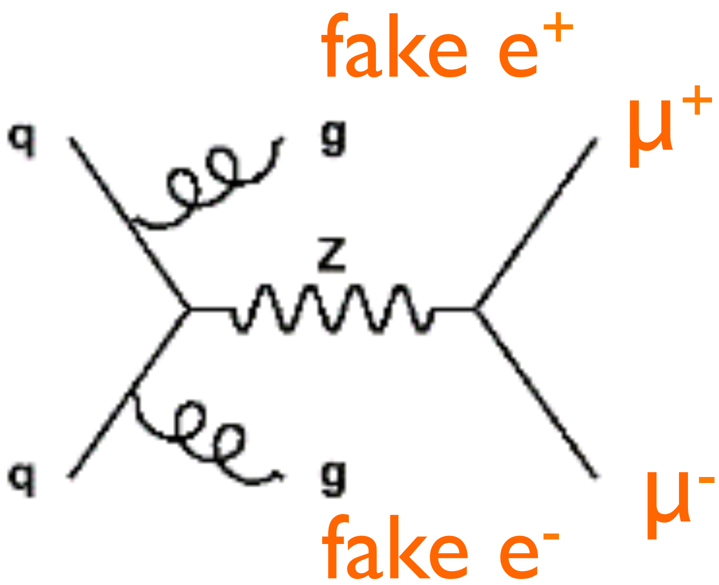
Irreducible background

The final state is exactly the same, but it does not come from the particle you are looking for



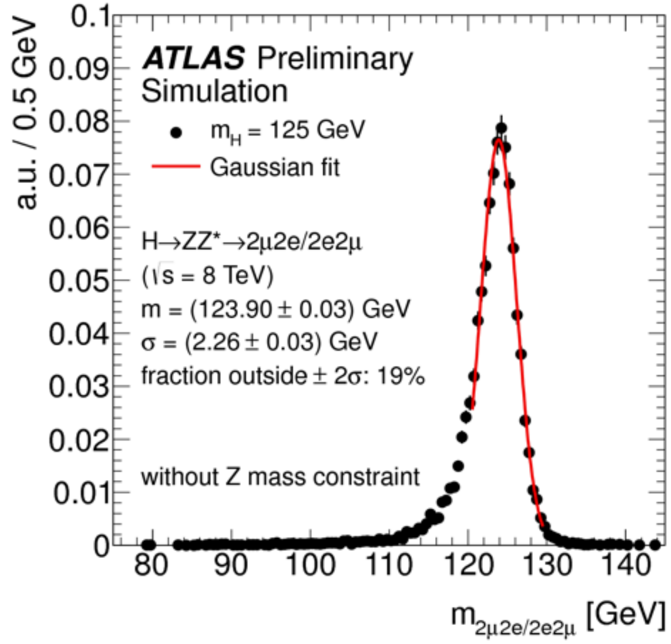
Reducible background

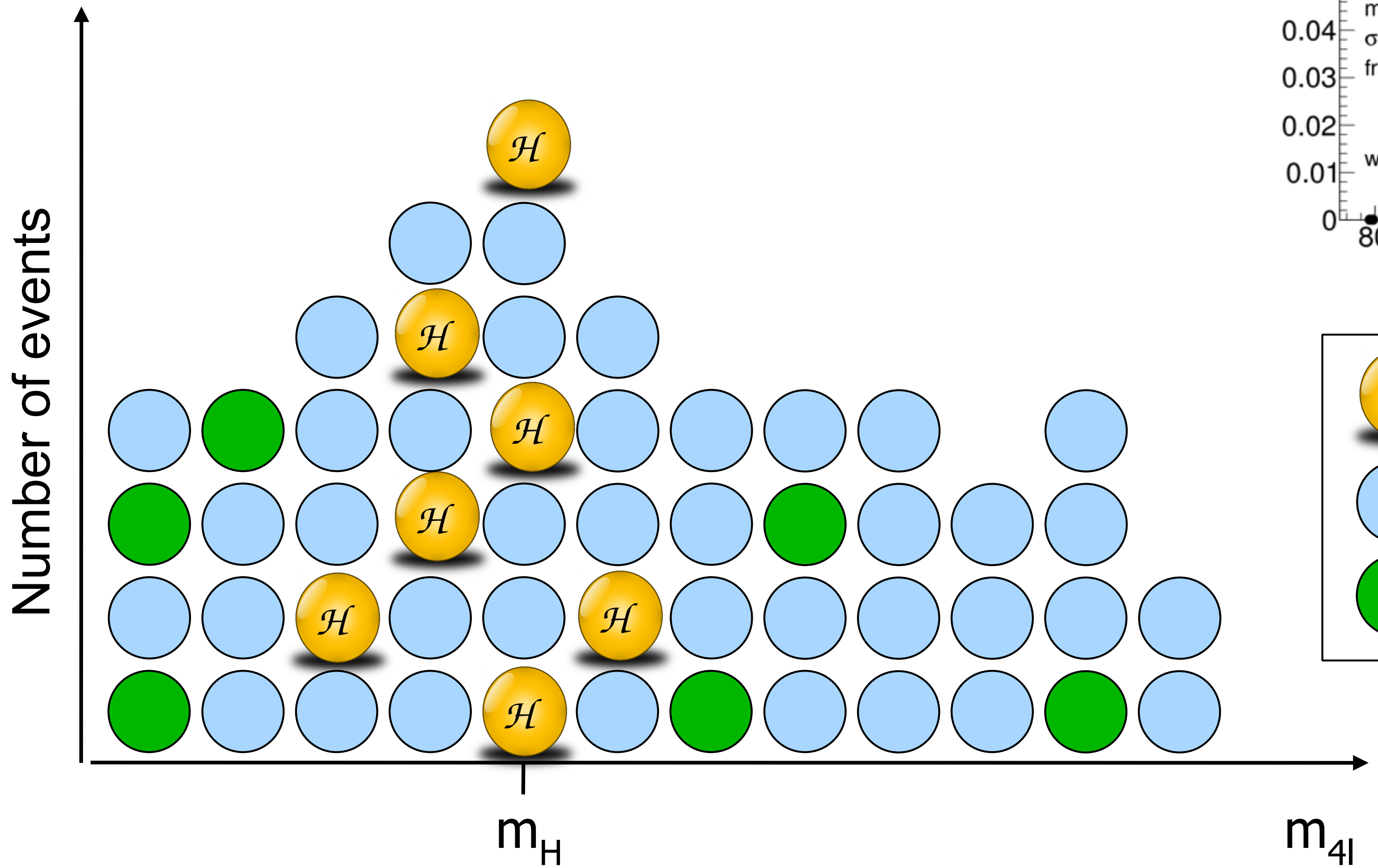
The final state looks like the same, but some f the particle fakes what you are looking for

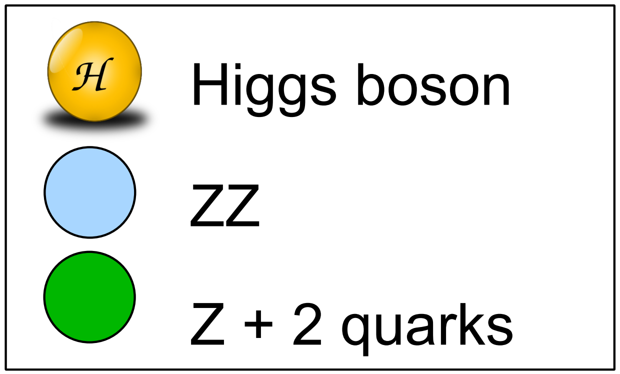


Extract signal from background

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$







Extract signal from background

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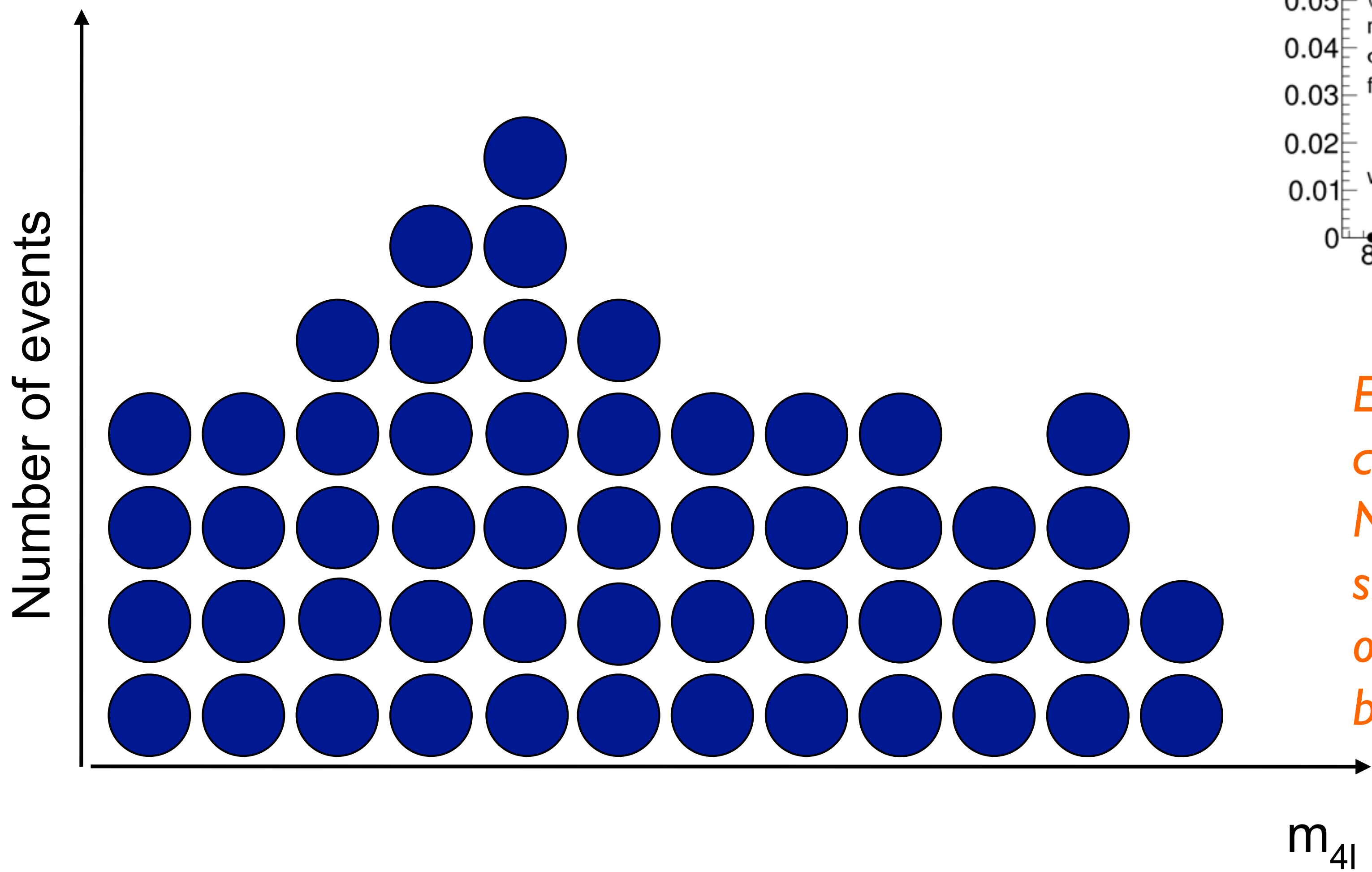
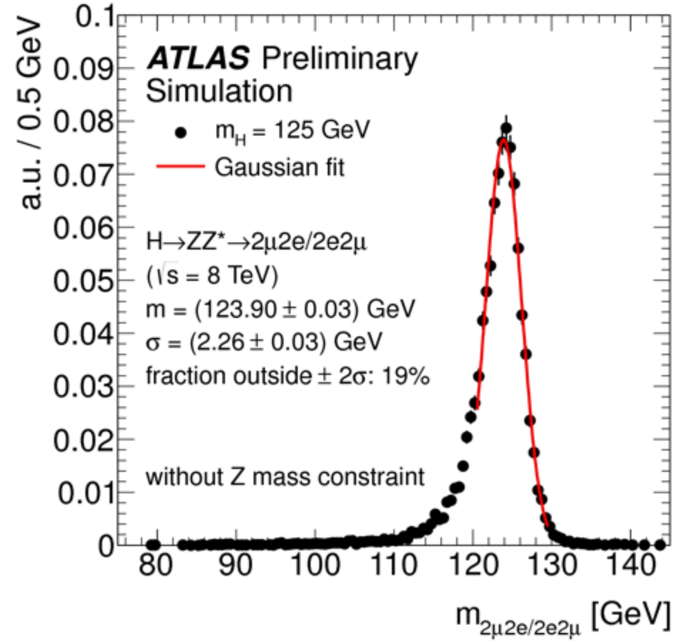
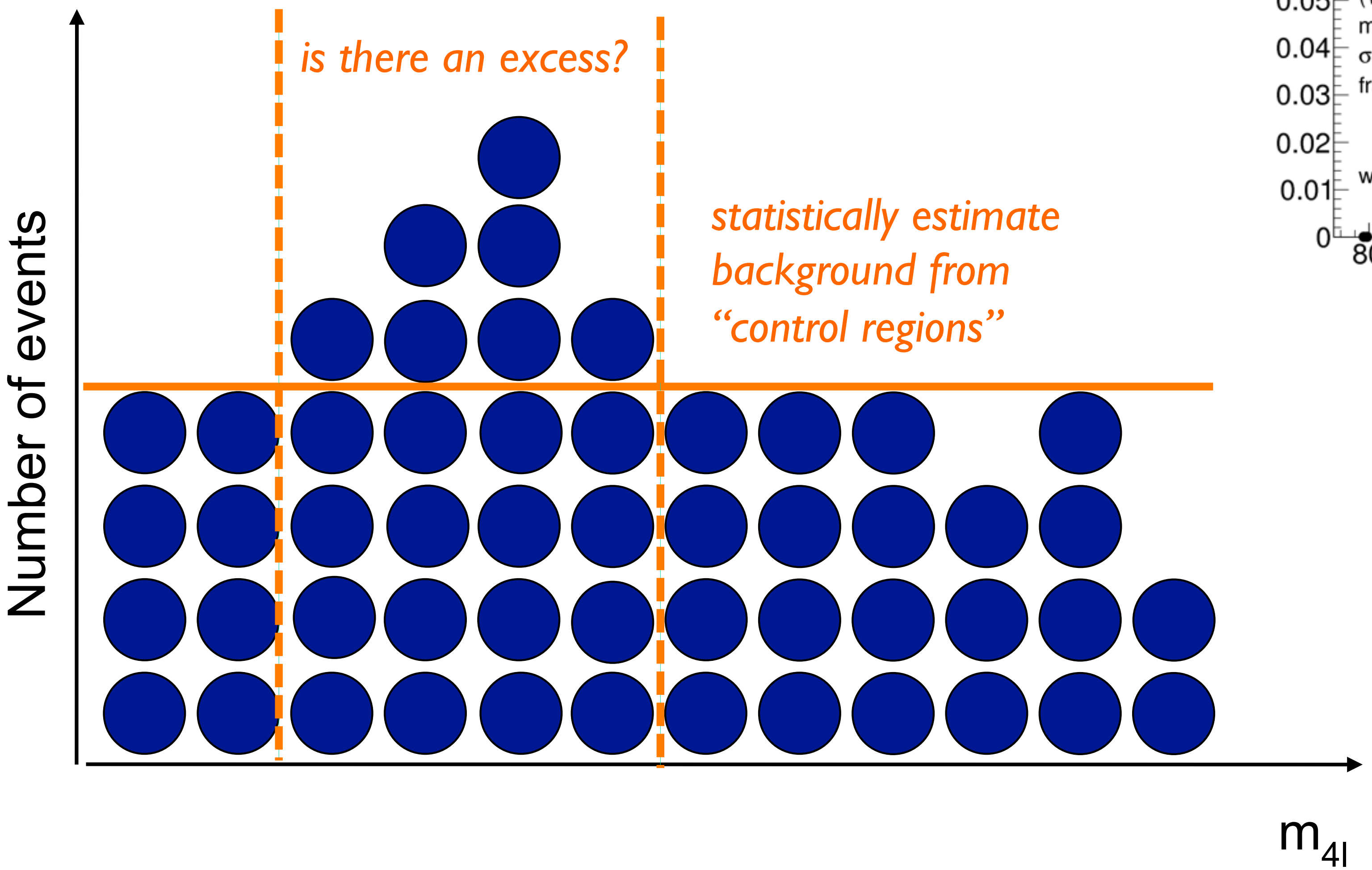


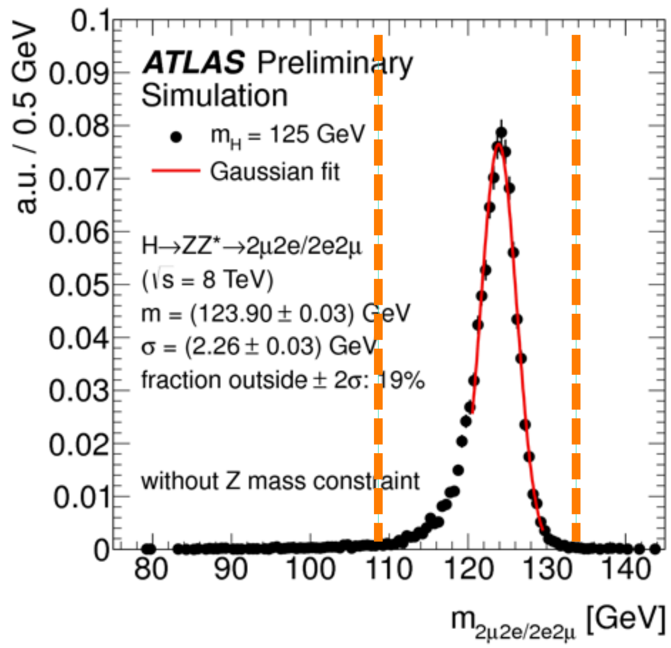


Events in real life do not come with a label! No way to distinguish signal from background on an event-by-event base…

Extract signal from background

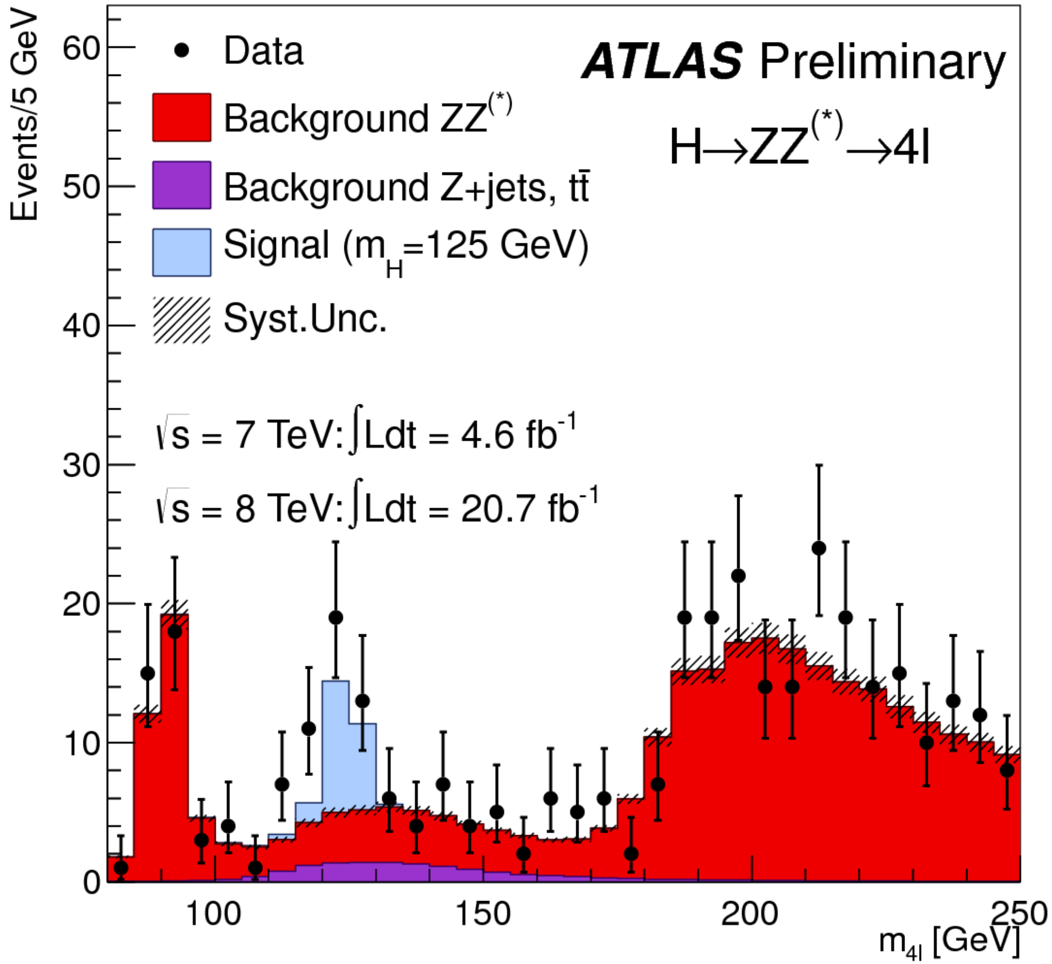
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$





Extract signal from background

- Background gets estimated…
  - ✓ … from simulation (normalized to data)
  - ✓ … directly from data ("control regions", enriched in background events)

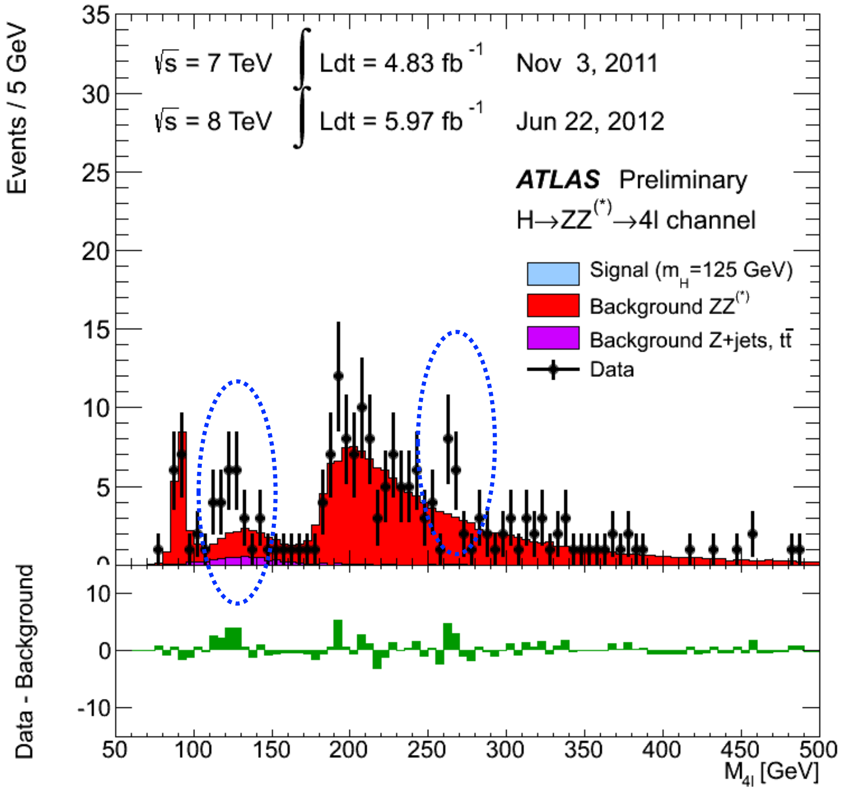


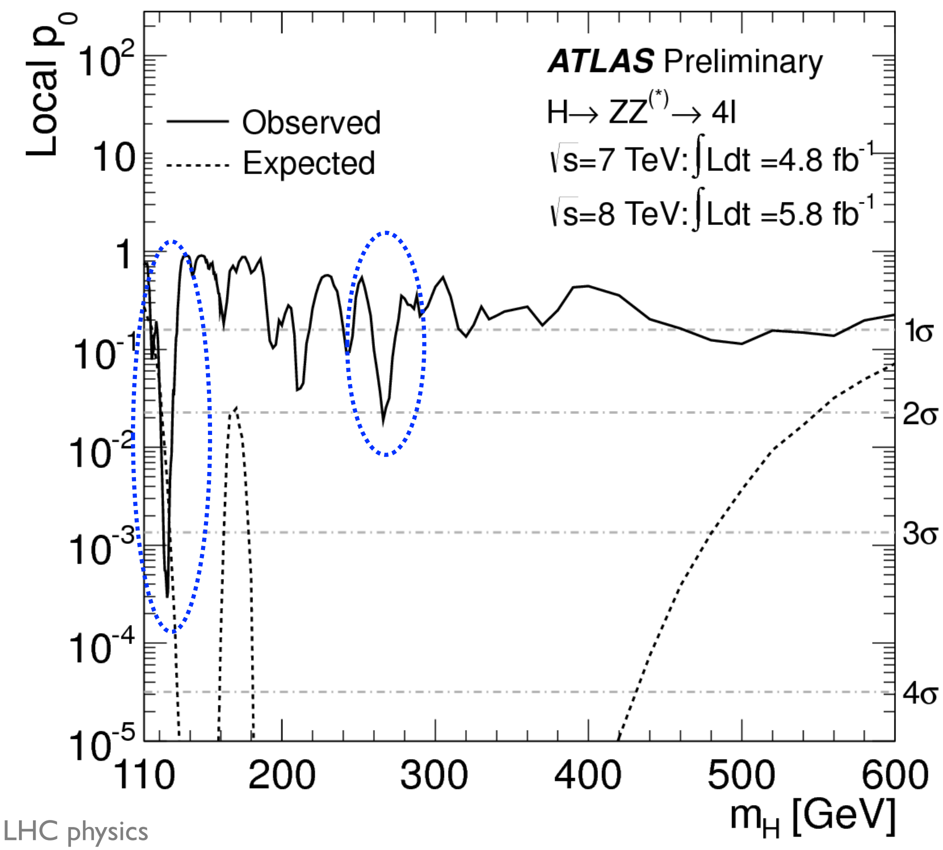
How significant is an excess?

- p0: probability that the excess is due to a fluctuation of background
- Significance:

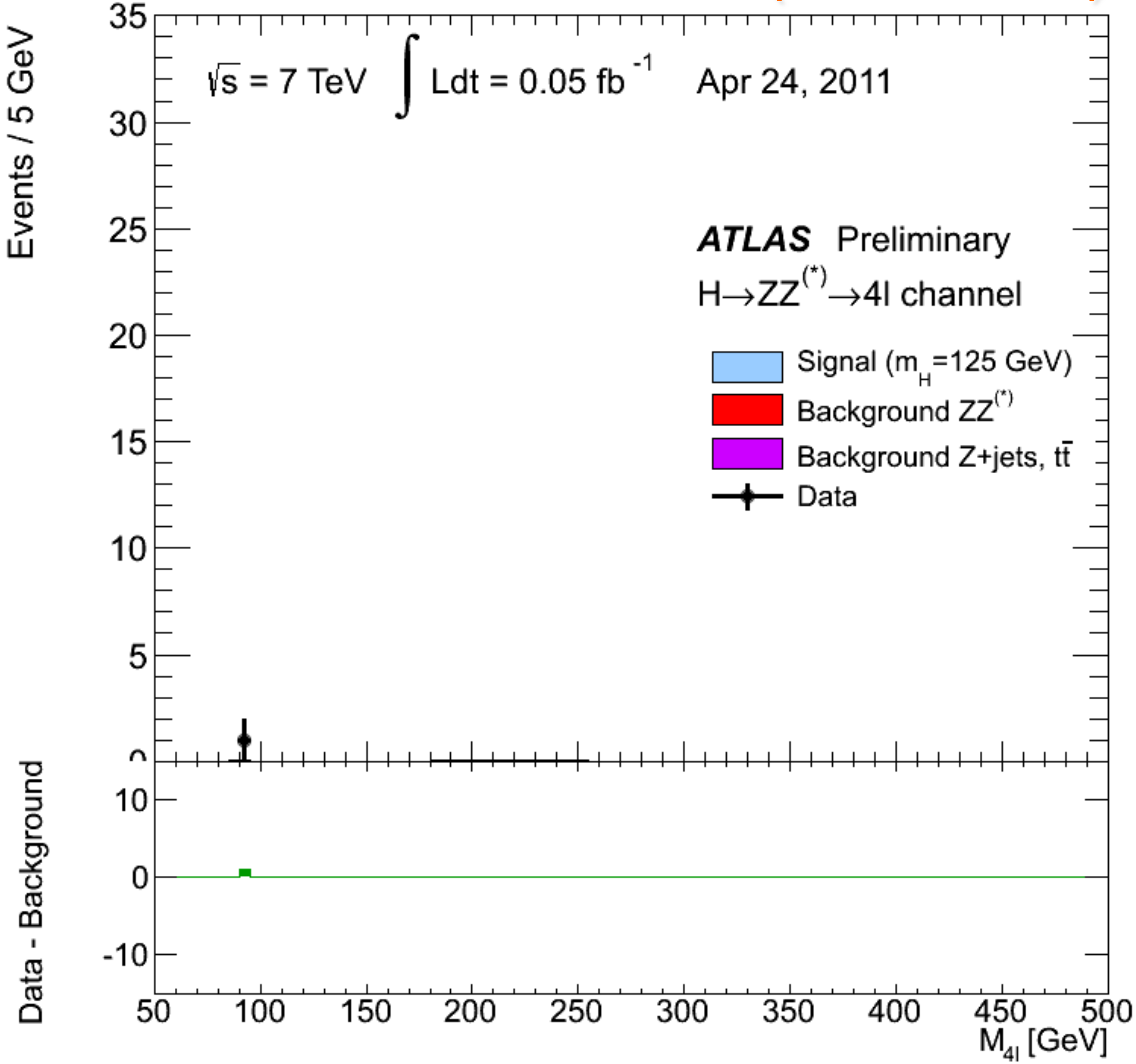
$$Z \sim \frac{S}{\sqrt{B}} \qquad p_0 = 1 - \mathrm{Erf}\left(\frac{Z}{\sqrt{2}}\right)$$

- Convention:
  - 3 σ is an evidence (p_0 = 0.27%)
  - 5 σ is a discovery (p_0 = 5.7.10^{-7})





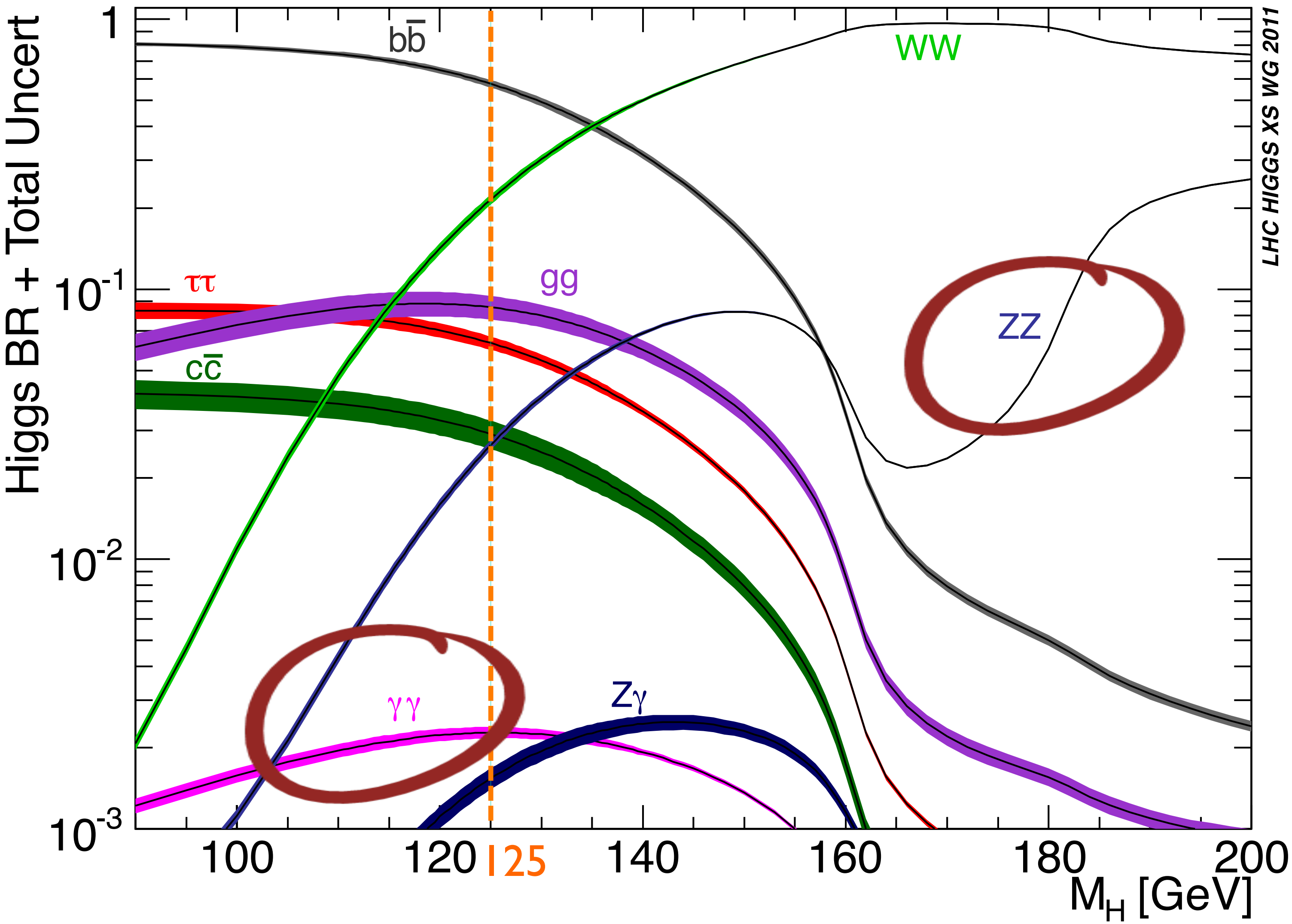
Significance increase with data (and time!)



Higgs boson

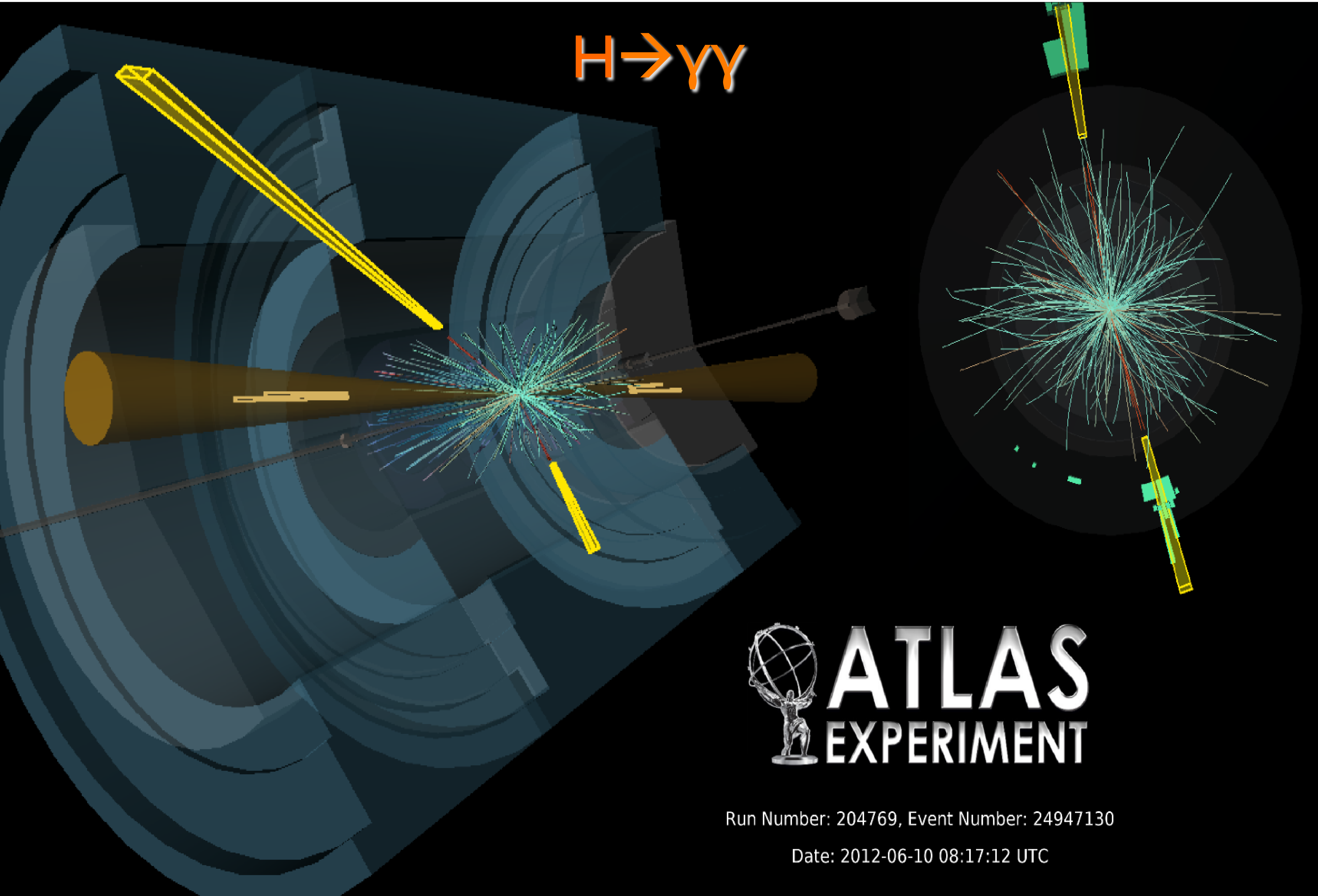
discovery & properties

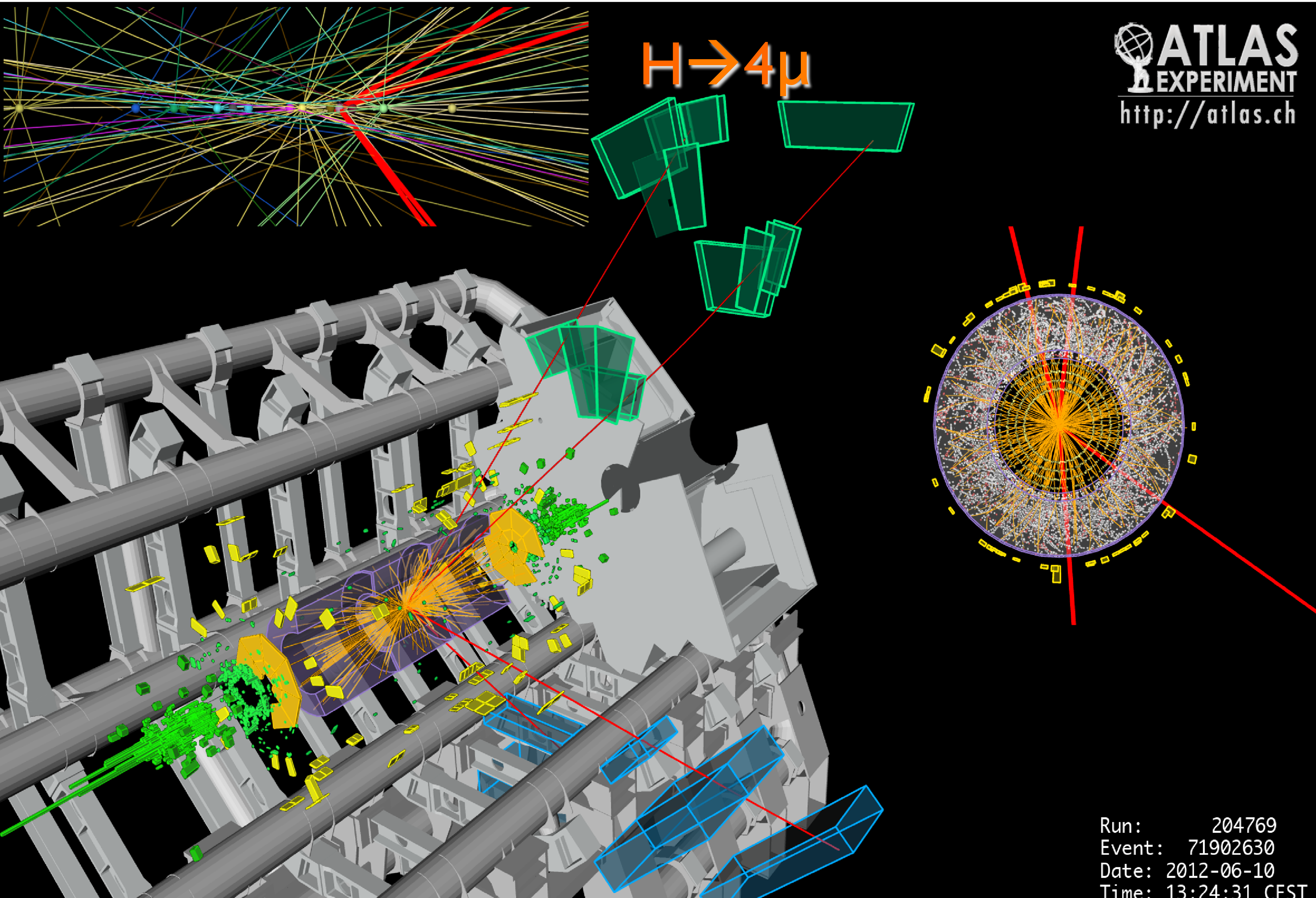
Standard Model Higgs decays



- 1 Higgs every 10 s
- 1 $H \rightarrow \gamma\gamma$ every 1.5 h
- 1 $H \rightarrow ZZ \rightarrow 4\ell$ (ℓ = e or μ) every 2 days

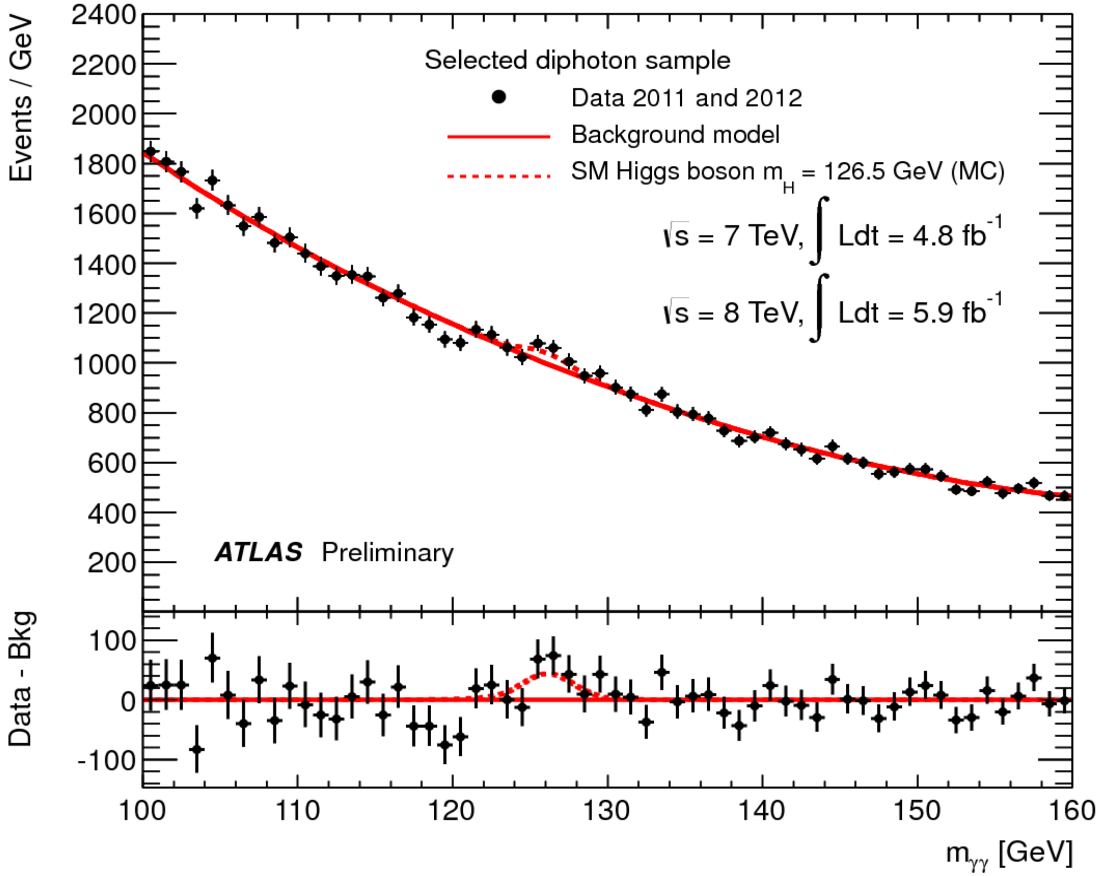
H→γγ


ATLAS
EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC

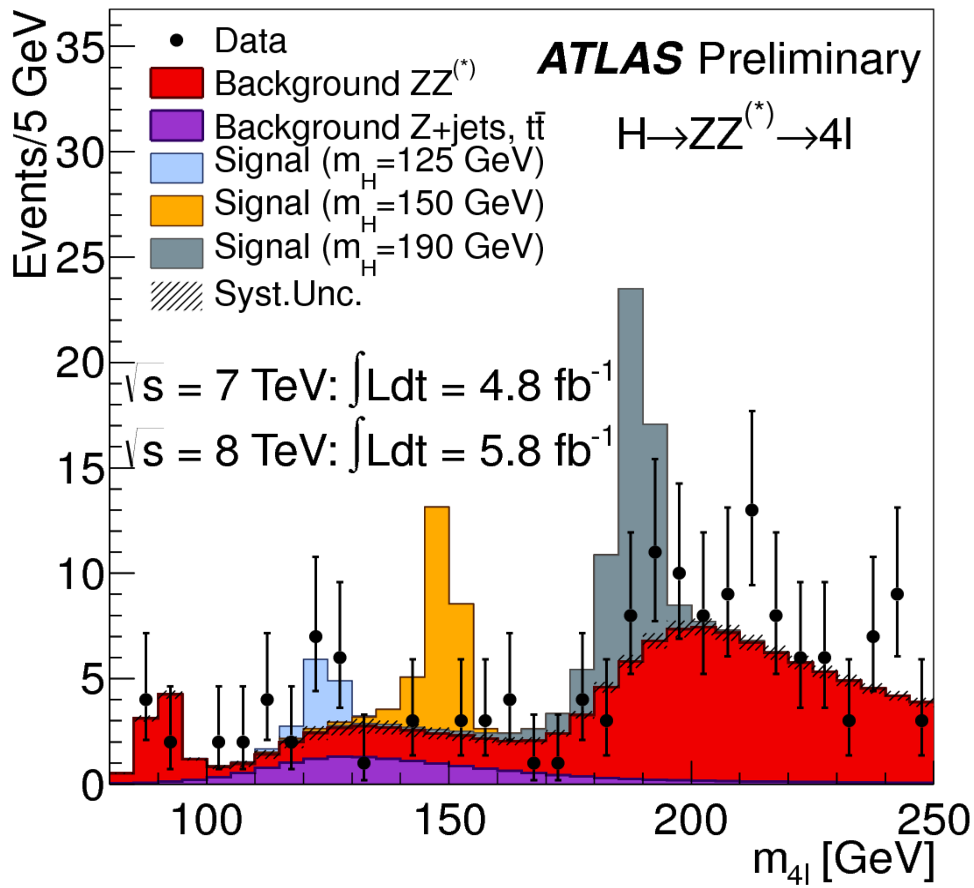

H→4μ
ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

“Higgs-like” signals on July 4th 2012 (in ATLAS)

H→γγ

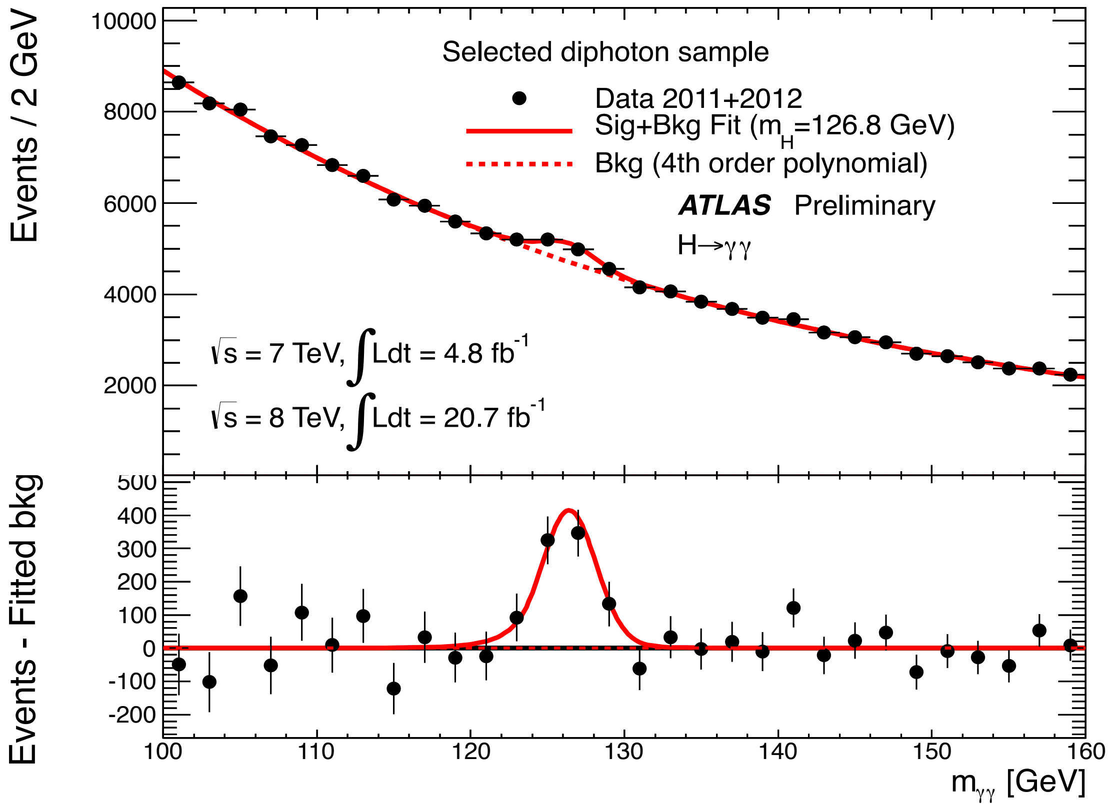


H→4l



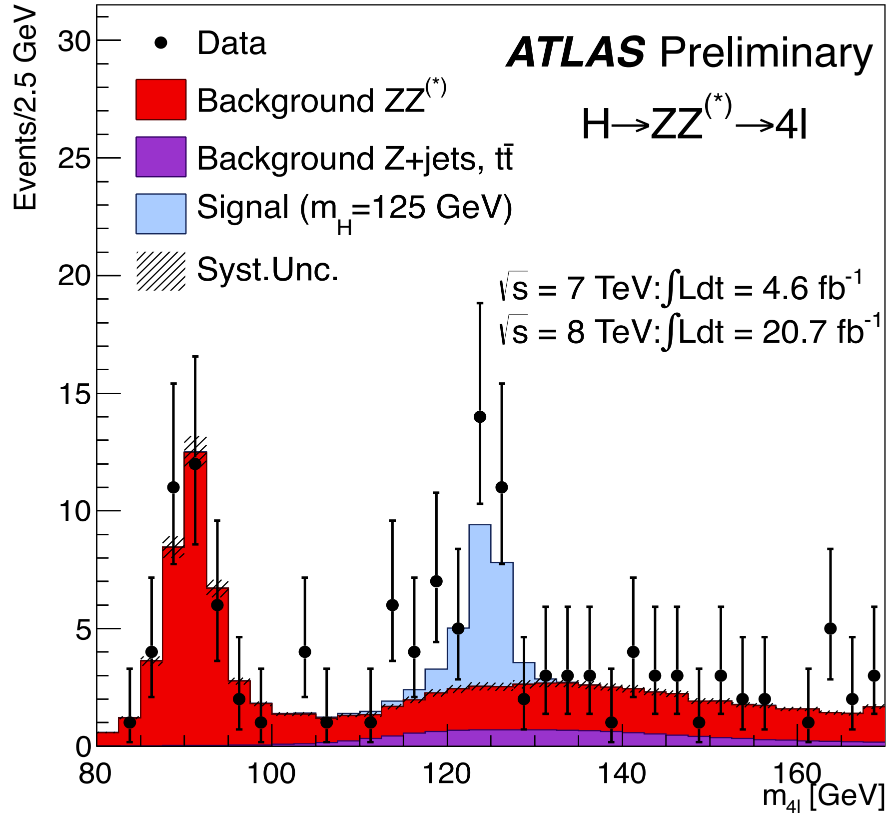
"Higgs-like" signals with all 7 and 8 TeV data…

H→γγ



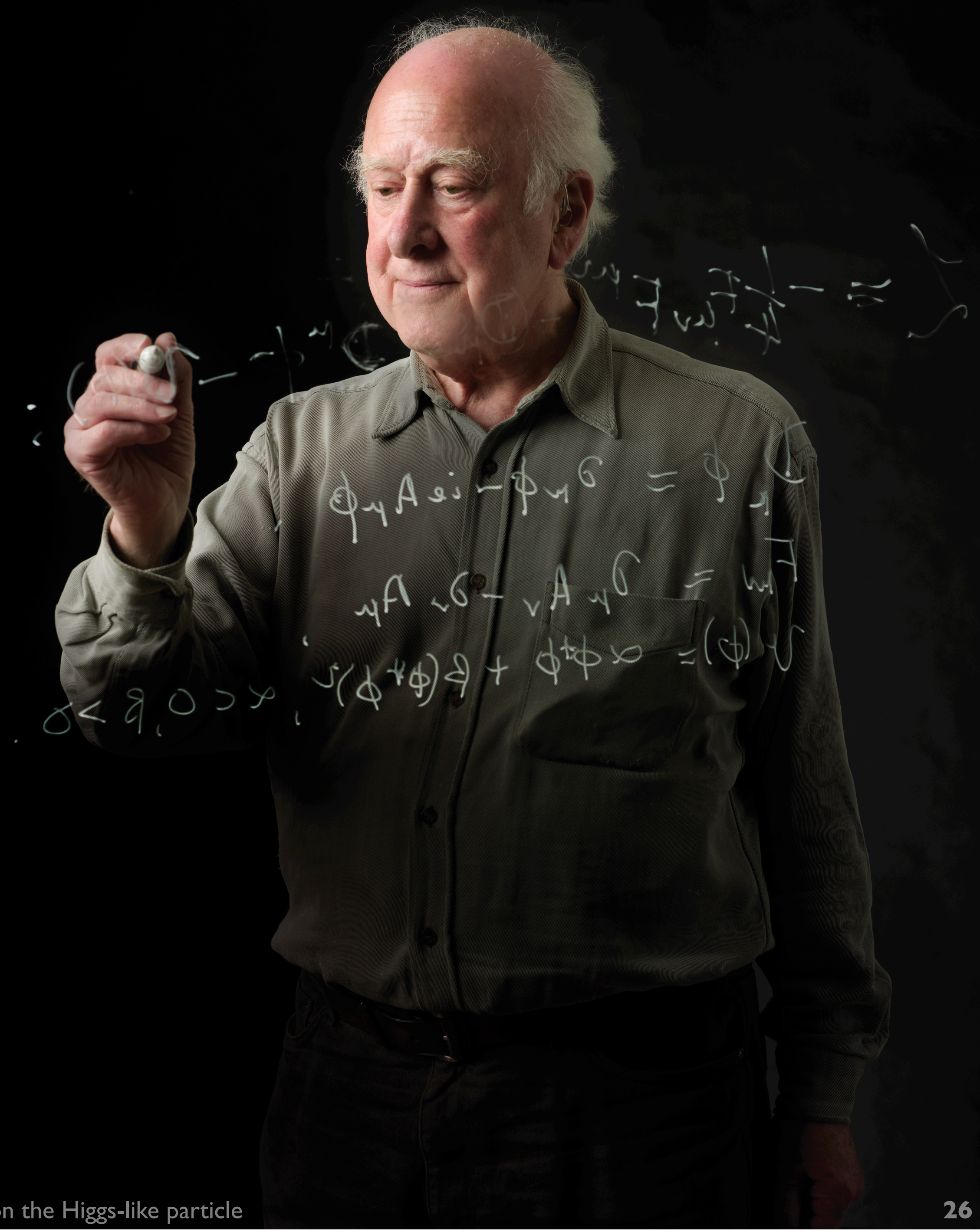
- Signal significance = 7.4 σ
- m_H = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
- μ = 1.65 ± 0.34 (deviation w.r.t. SM at 2.3σ)

H→4l



- Signal significance = 6.6 σ
- m_H = 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.6}_{-0.3}$ (syst) GeV
- μ = 1.7 ± 0.34

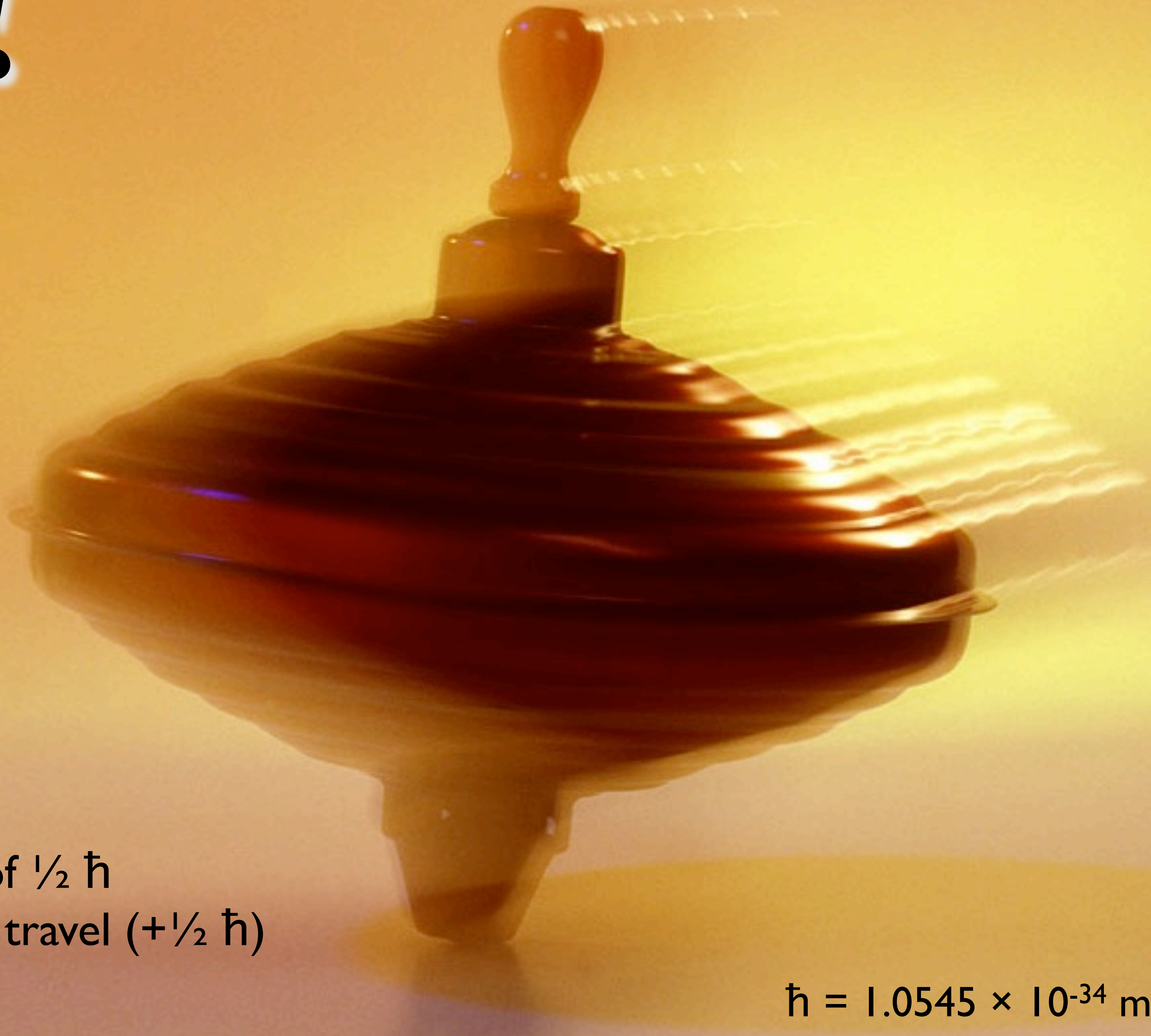
is it the Higgs boson?



Spin!

What's a particle spin?

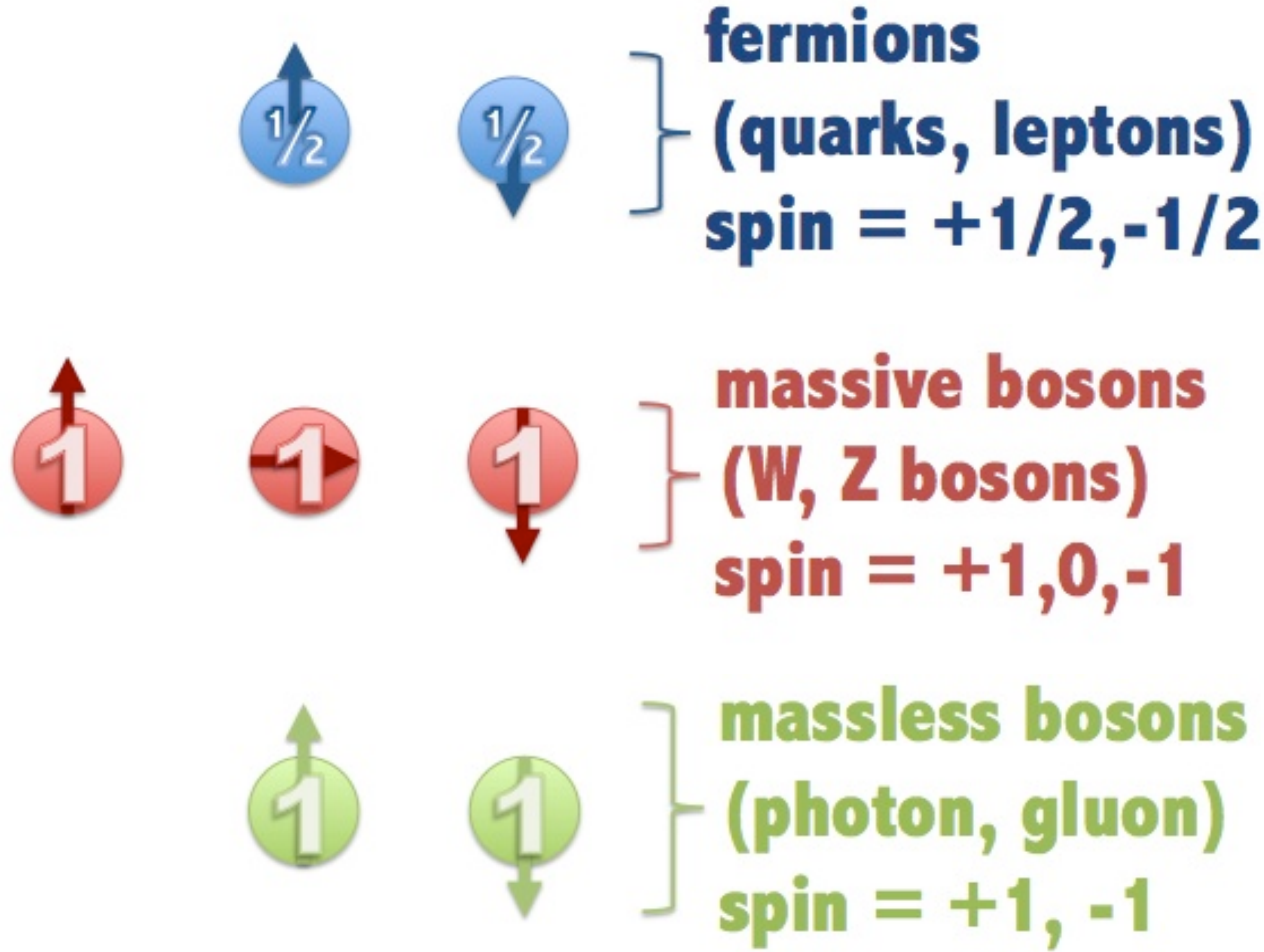
"An *amount of rotation* that is somehow quantized"



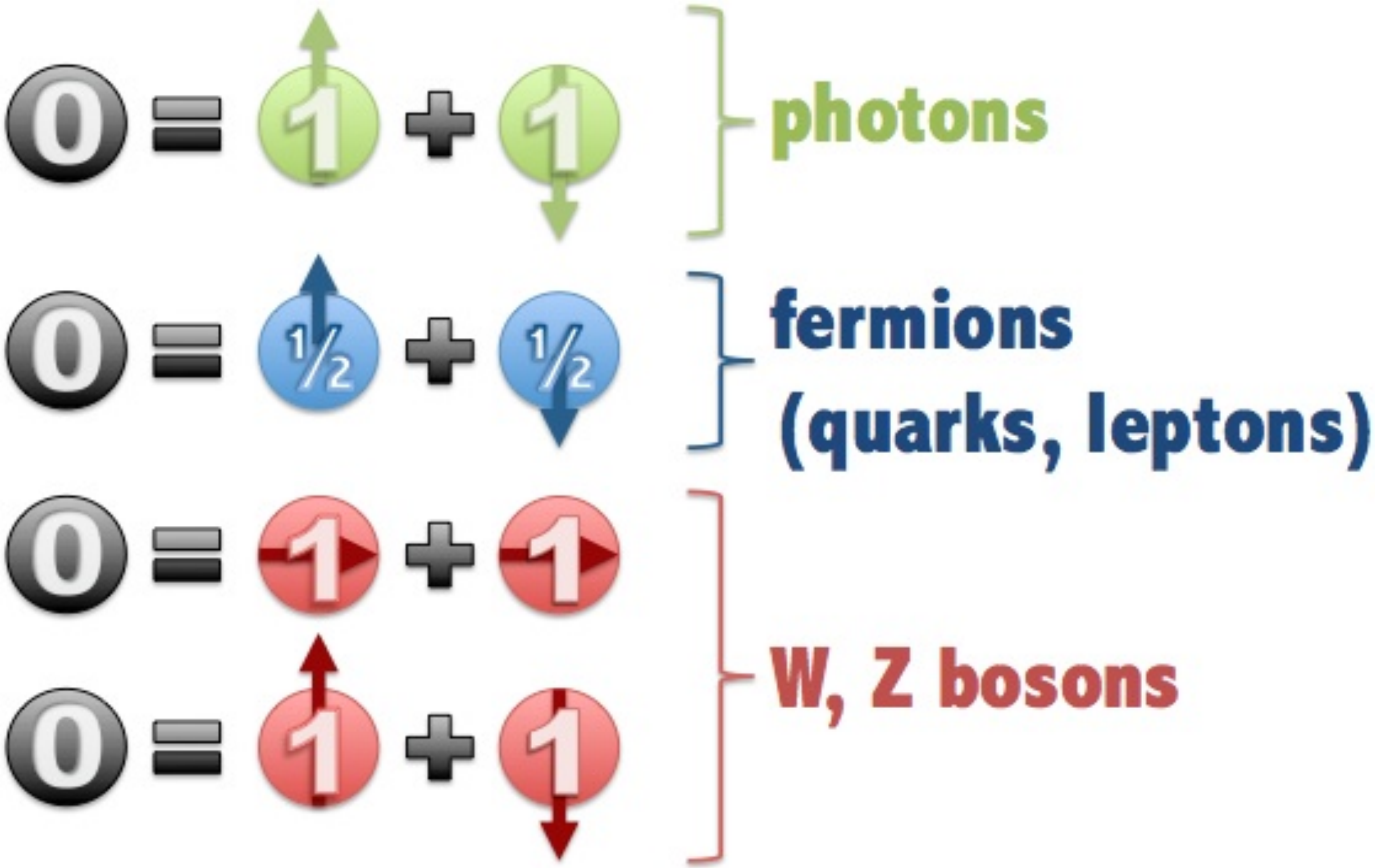
An electron has always
an angular momentum of ½ ħ
either in its direction of travel (+½ ħ)
or opposite to it (-½ ħ)

$\hbar = 1.0545 \times 10^{-34}\ m^2\ kg / s$

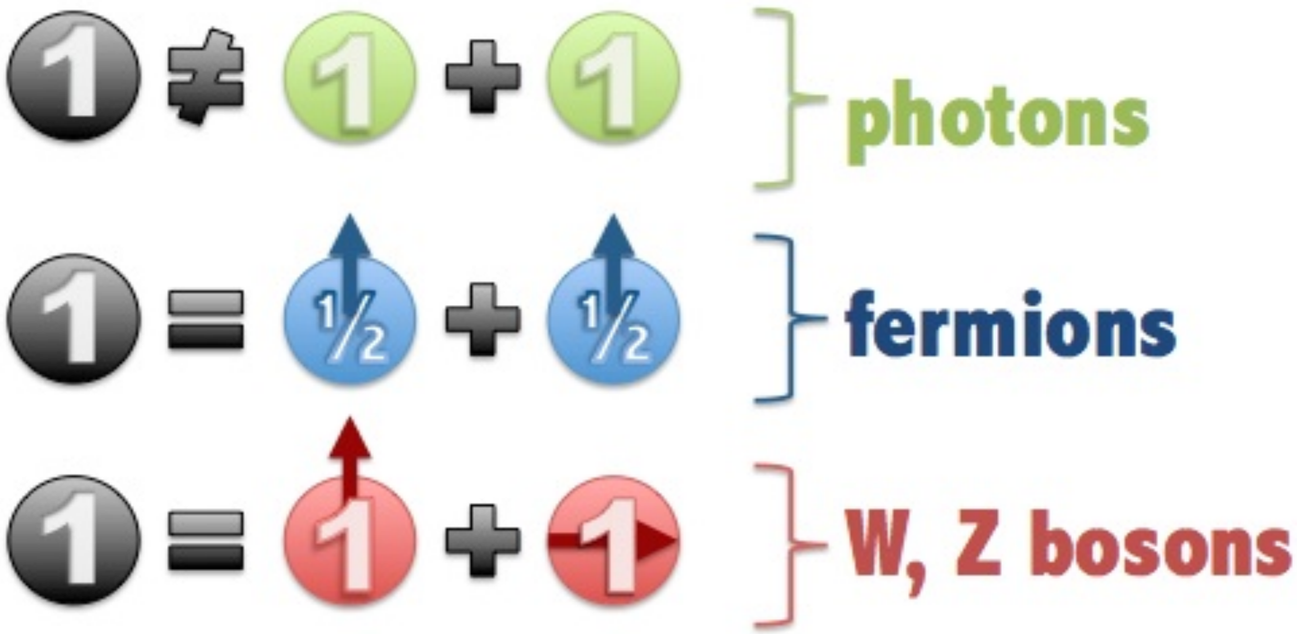
What spin do particles have?



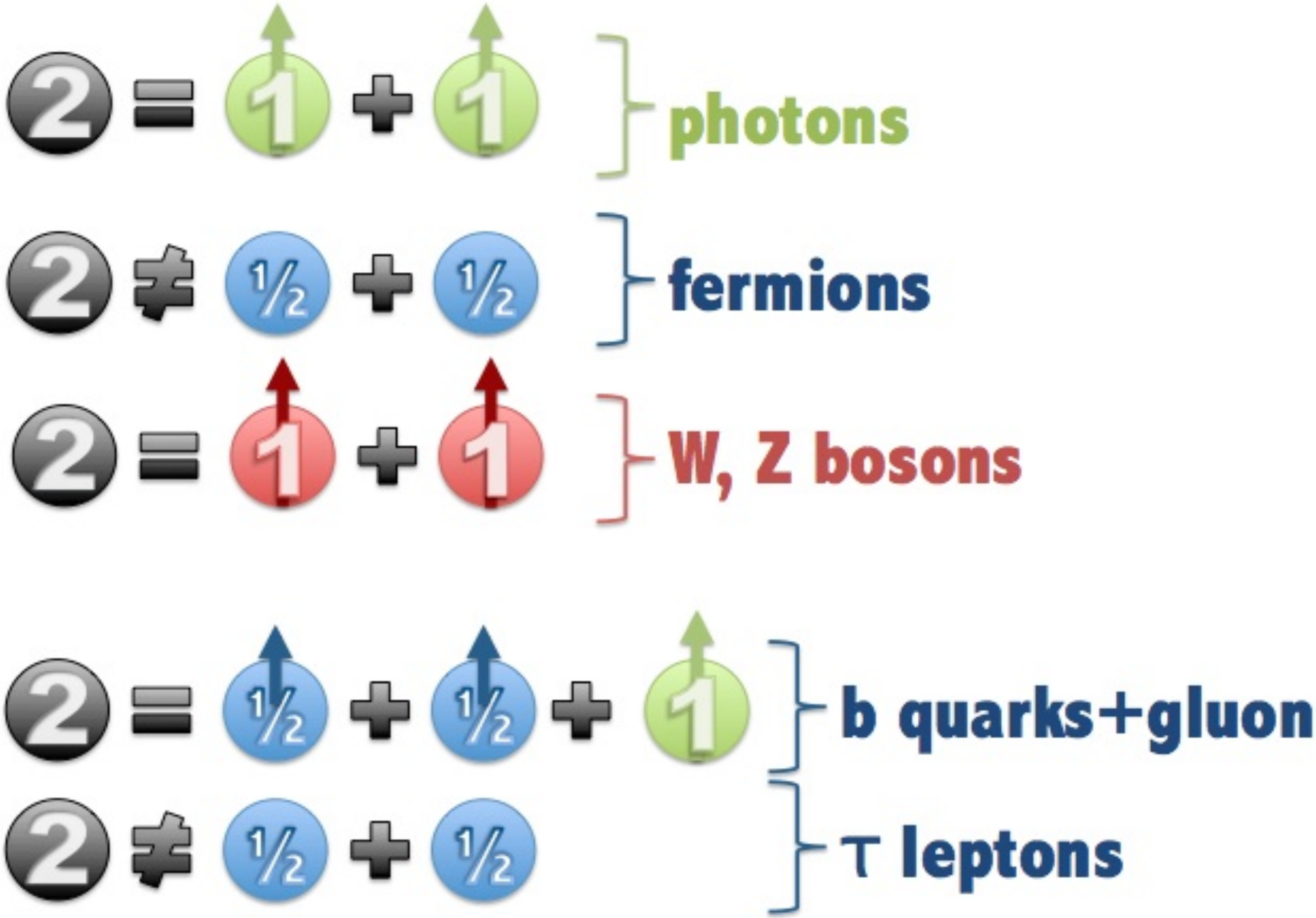
What can a spin 0 particle decay to?



What can a spin 1 particle decay to?



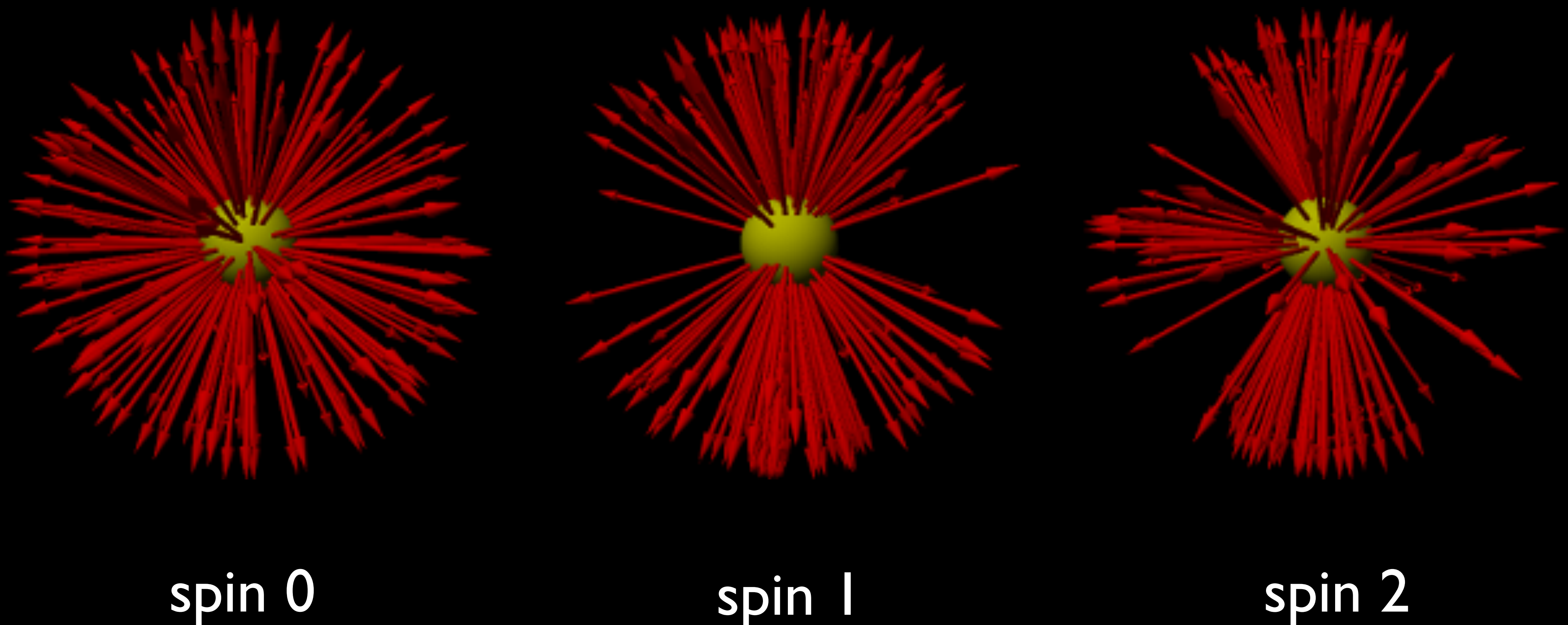
What can a spin 2 particle decay to?



So, what spin has our Higgs-like particle?

Spin of particle	γγ	ZZ*
Spin 0	☺	☺
Spin 1	☹	☺
Spin 2	☺	☺

How can we recognize spin?

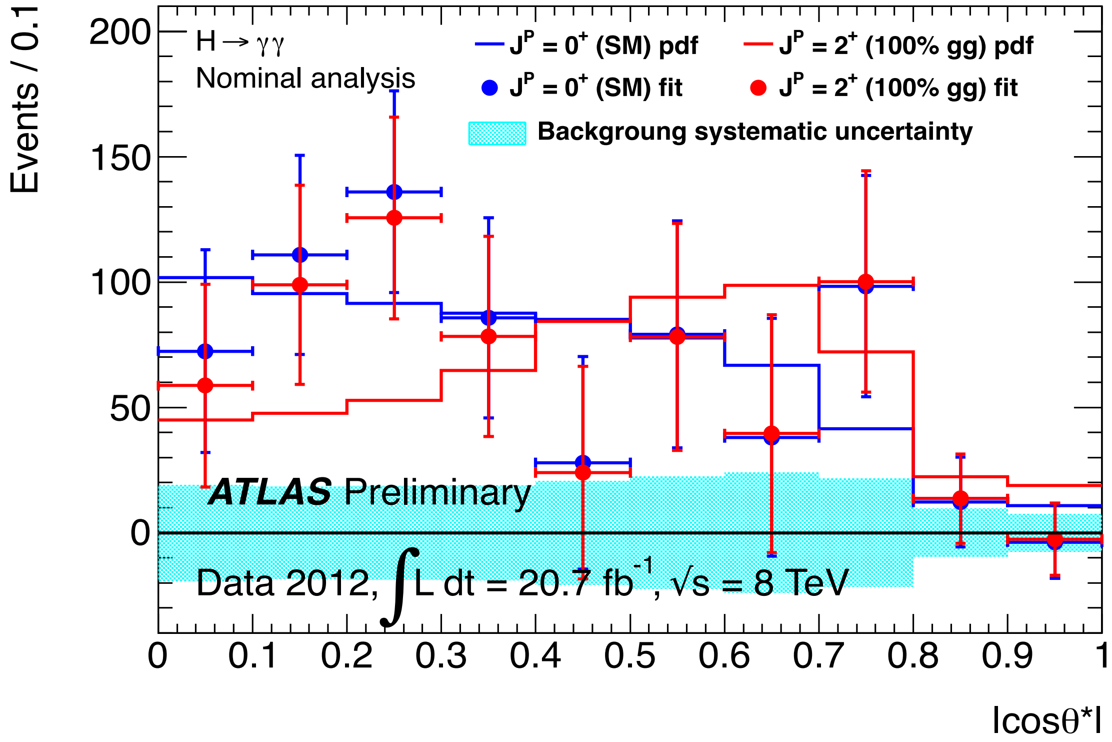


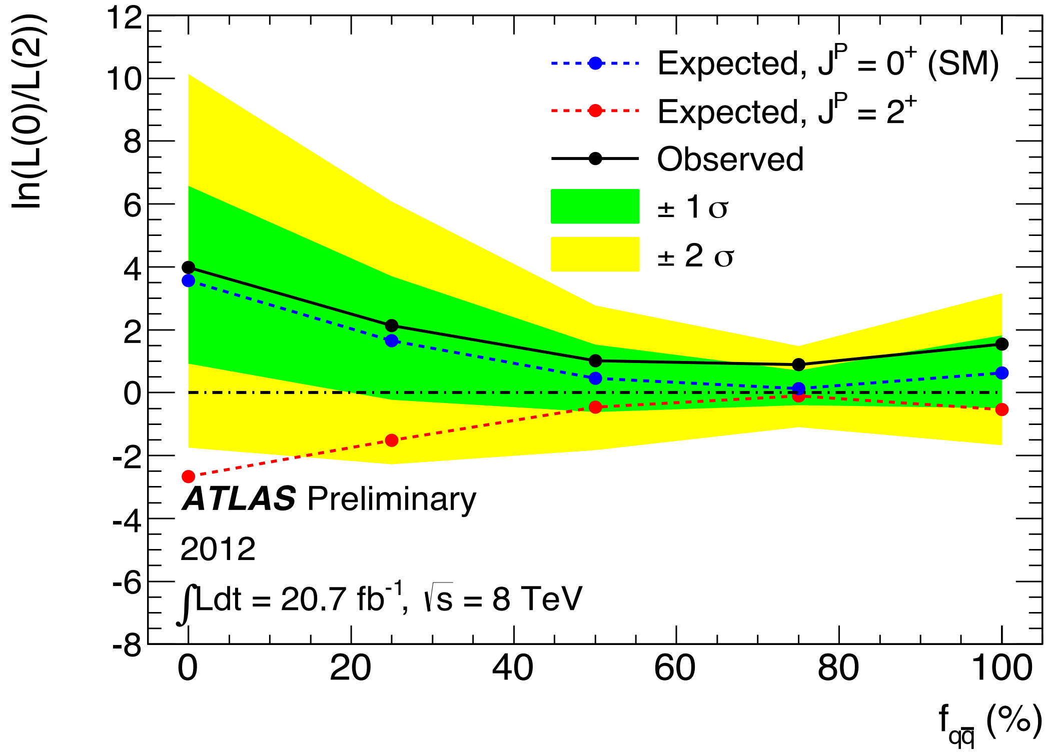
Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

Spin study with H→γγ

*γγ polar angle θ**
with respect to Z-axis
in Colin-Sopper frame

$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



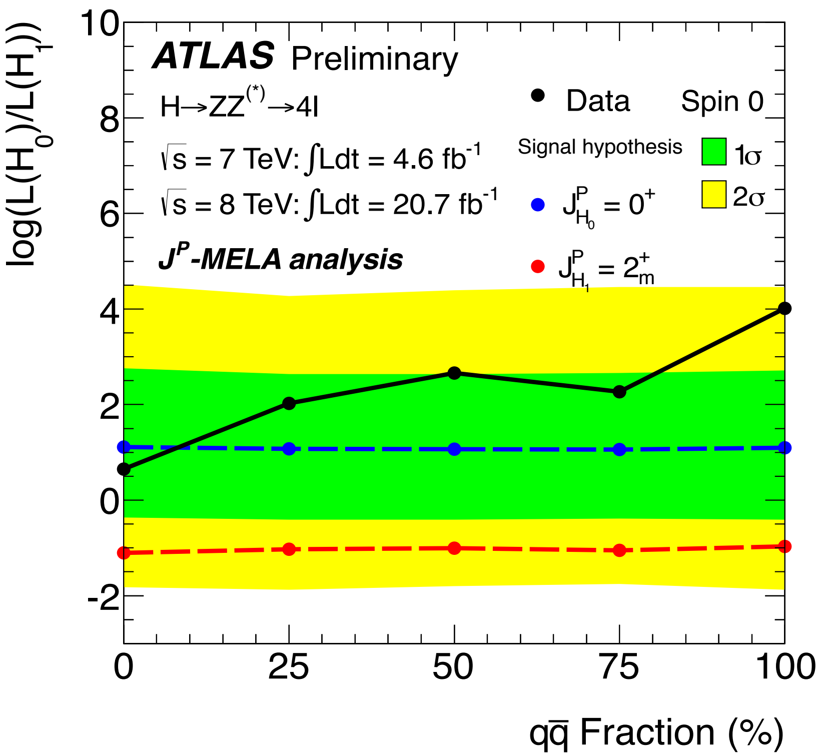


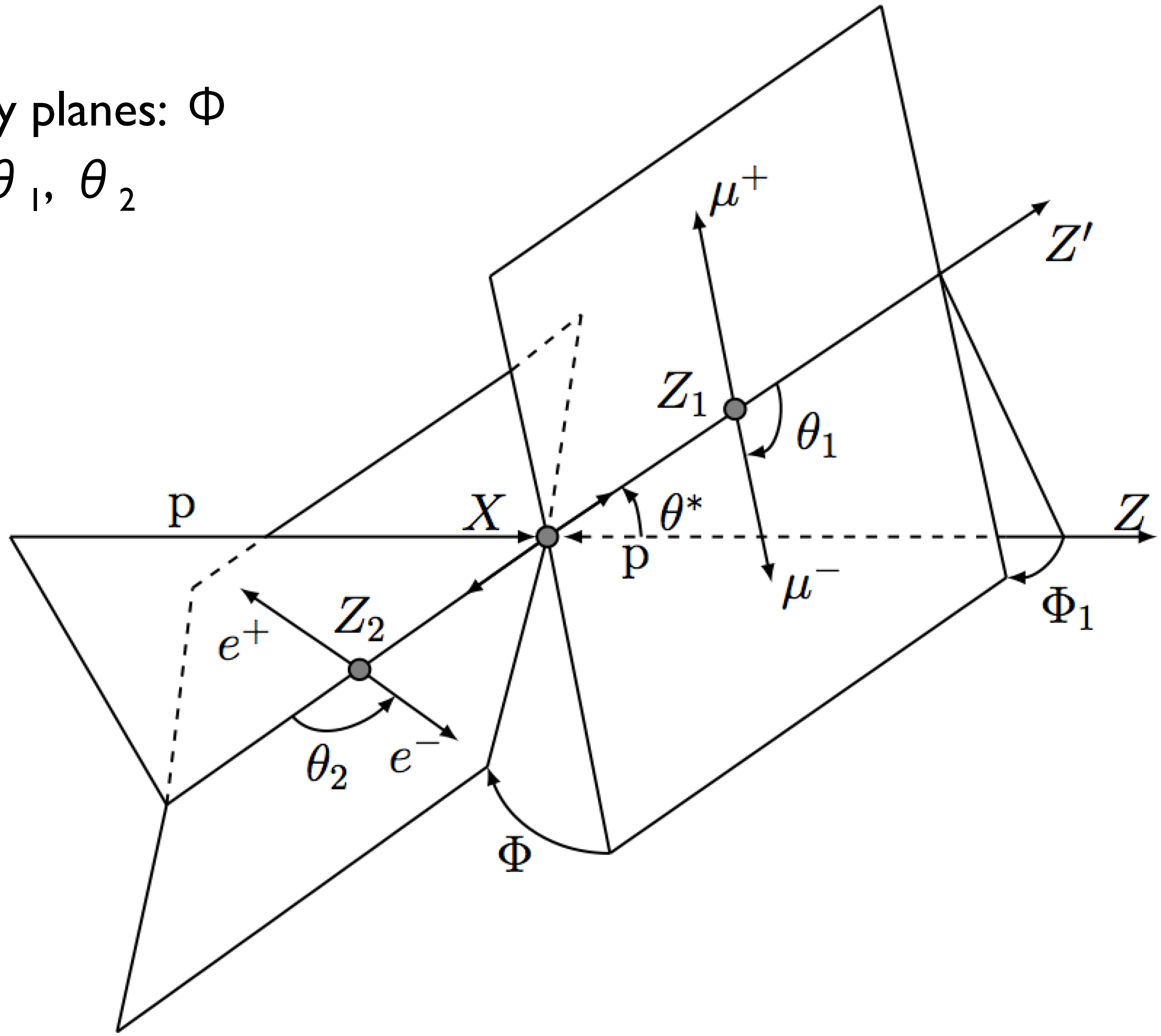
- If spin-2 resonance is produced 100% by gluon fusion, observed *rejection* p-values are:
  - ✓ spin-0 → 58.8% (1.2% expected) → good agreement with spin-0 hypothesis
  - ✓ spin-2 → 0.3% (0.5% expected) → spin-2 excluded at 99.3% CL

Spin study with H→4l

- Sensitive variables
  - ✓ Intermediate boson masses: m_{Z1}, m_{Z2}
  - ✓ Z_1 production angle: θ^*
  - ✓ Z_1 decay plane angle: Φ_1
  - ✓ Angle between the Z_1 and Z_2 decay planes: Φ
  - ✓ Decay angles of negative leptons: θ_1, θ_2

- Expected separation >2.5 σ, except for 2+m (~1.5 σ)
  - ✓ New boson compatible with SM 0+ Higgs hypothesis when compared pair-wise with 0-, 1-, 1+, 2+m





The Higgs boson or *a* Higgs boson?

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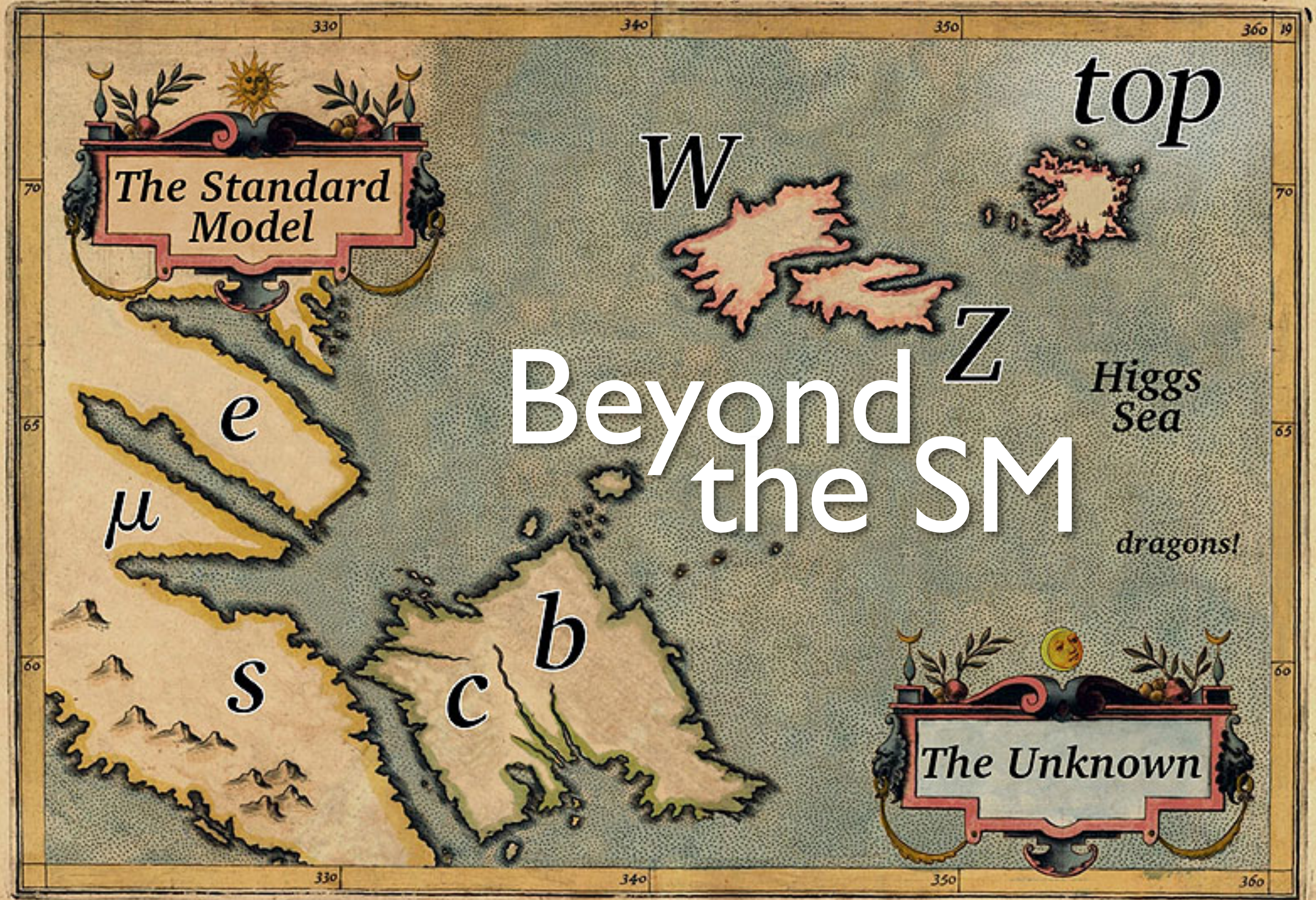
New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

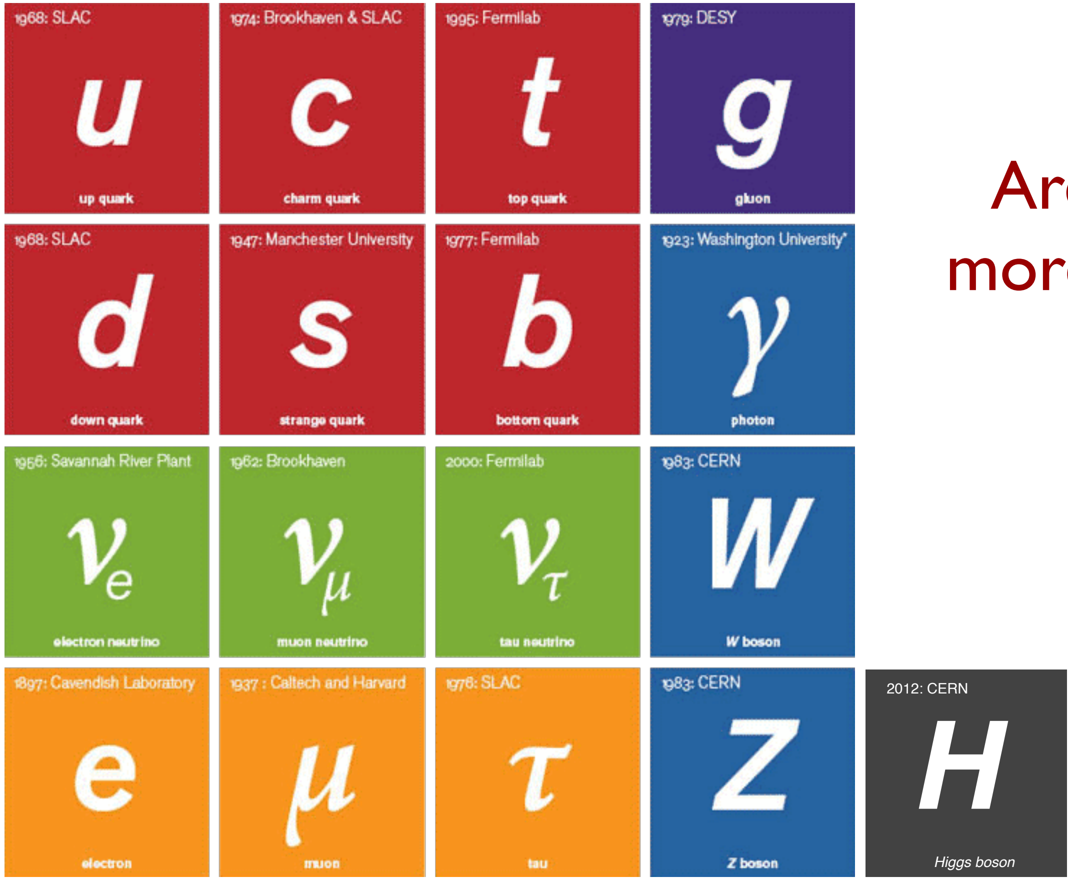

The Standard Model
top
W
Z
Beyond the SM
Higgs Sea
e
μ
dragons!
b
s
c
The Unknown
330
340
350
360
70
65
60

Many unanswered questions…

Why there are 3 families of particles? Are there more?

Why is the top quark so heavy?

Why there's more matter then anti-matter?



Are there more forces?

How do neutrinos get mass?

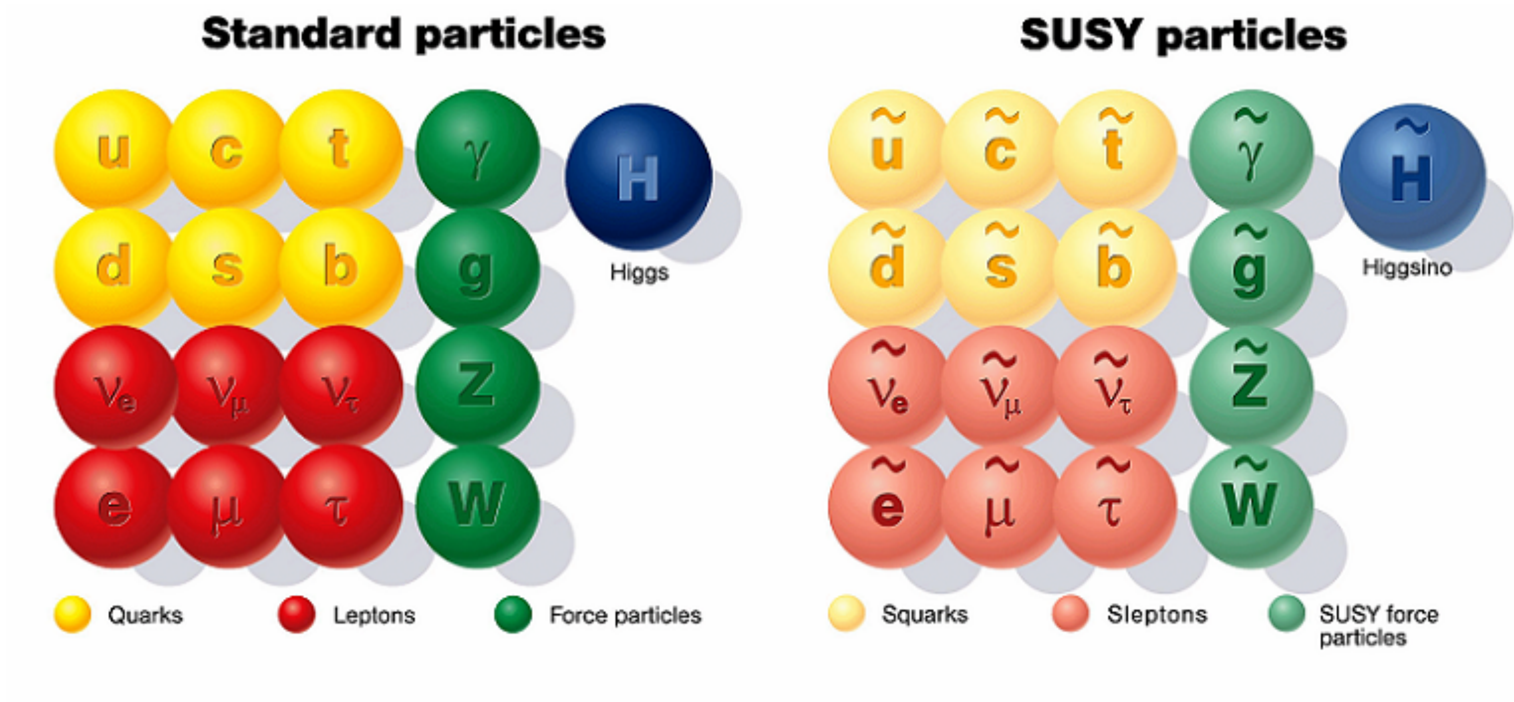
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

… as many possible answers to probe!

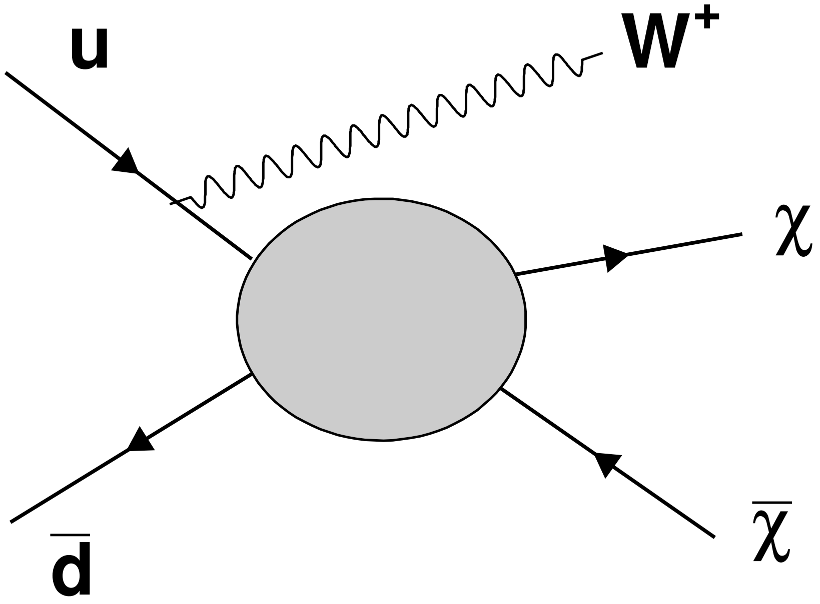
- Super-symmetry?

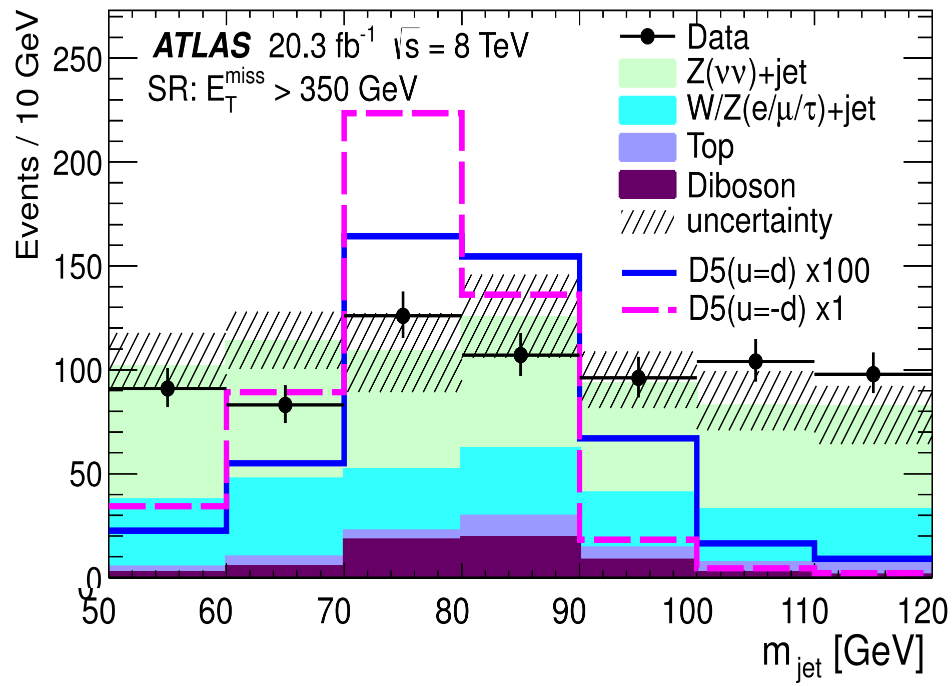


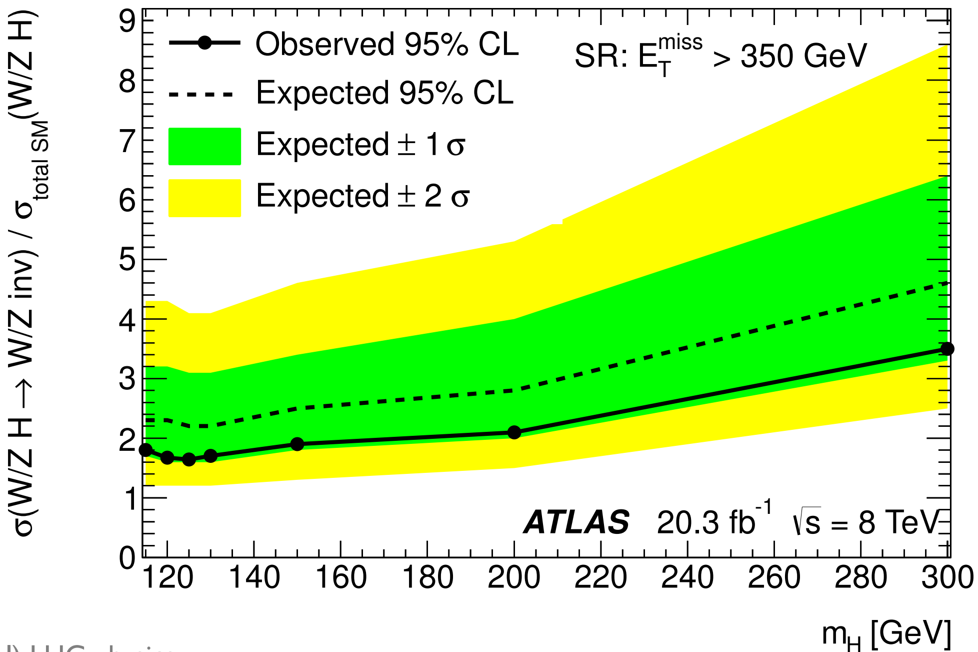
- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- …

Any new theory need to agree with the SM!

An example: ATLAS dark matter search

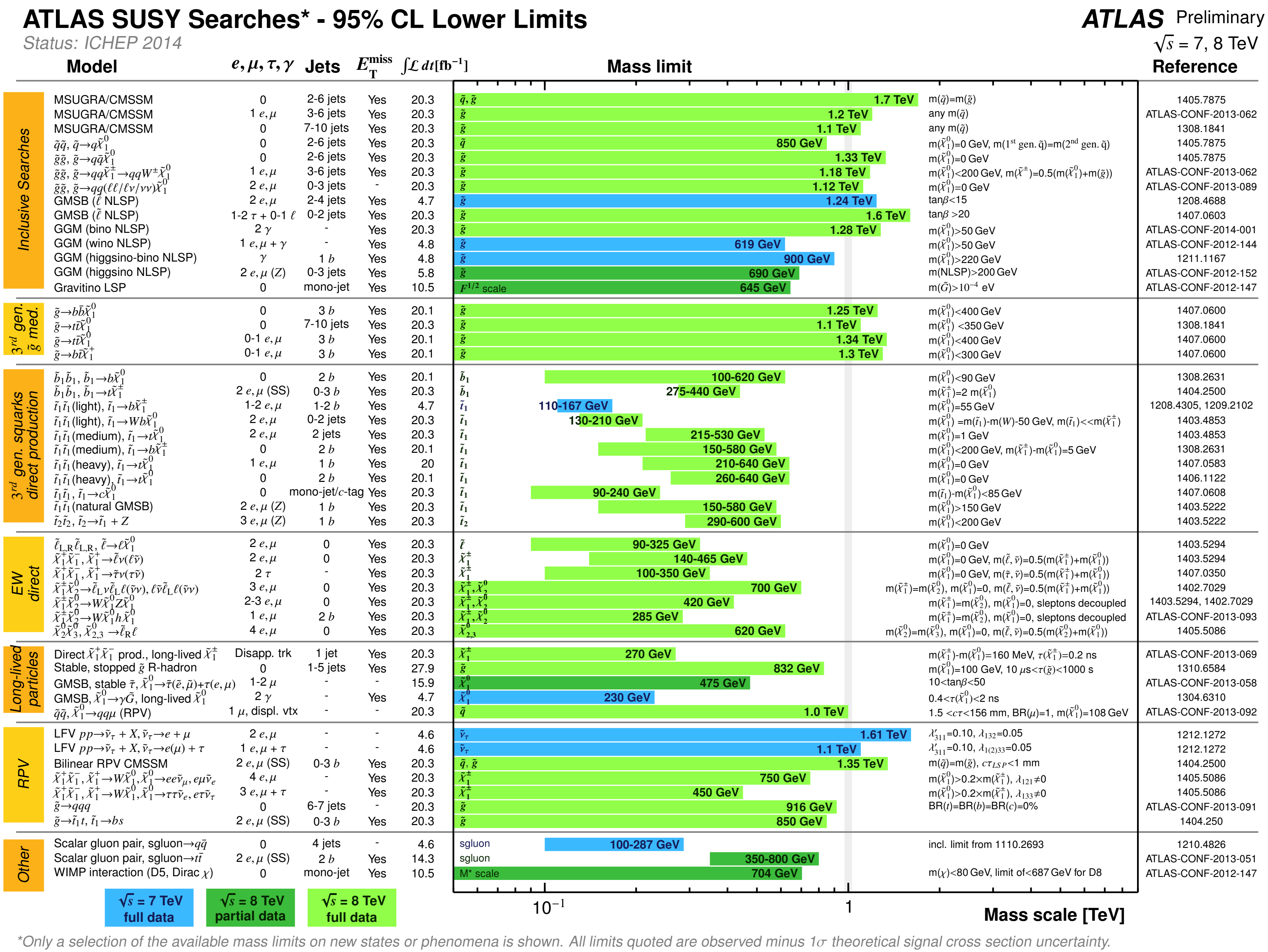




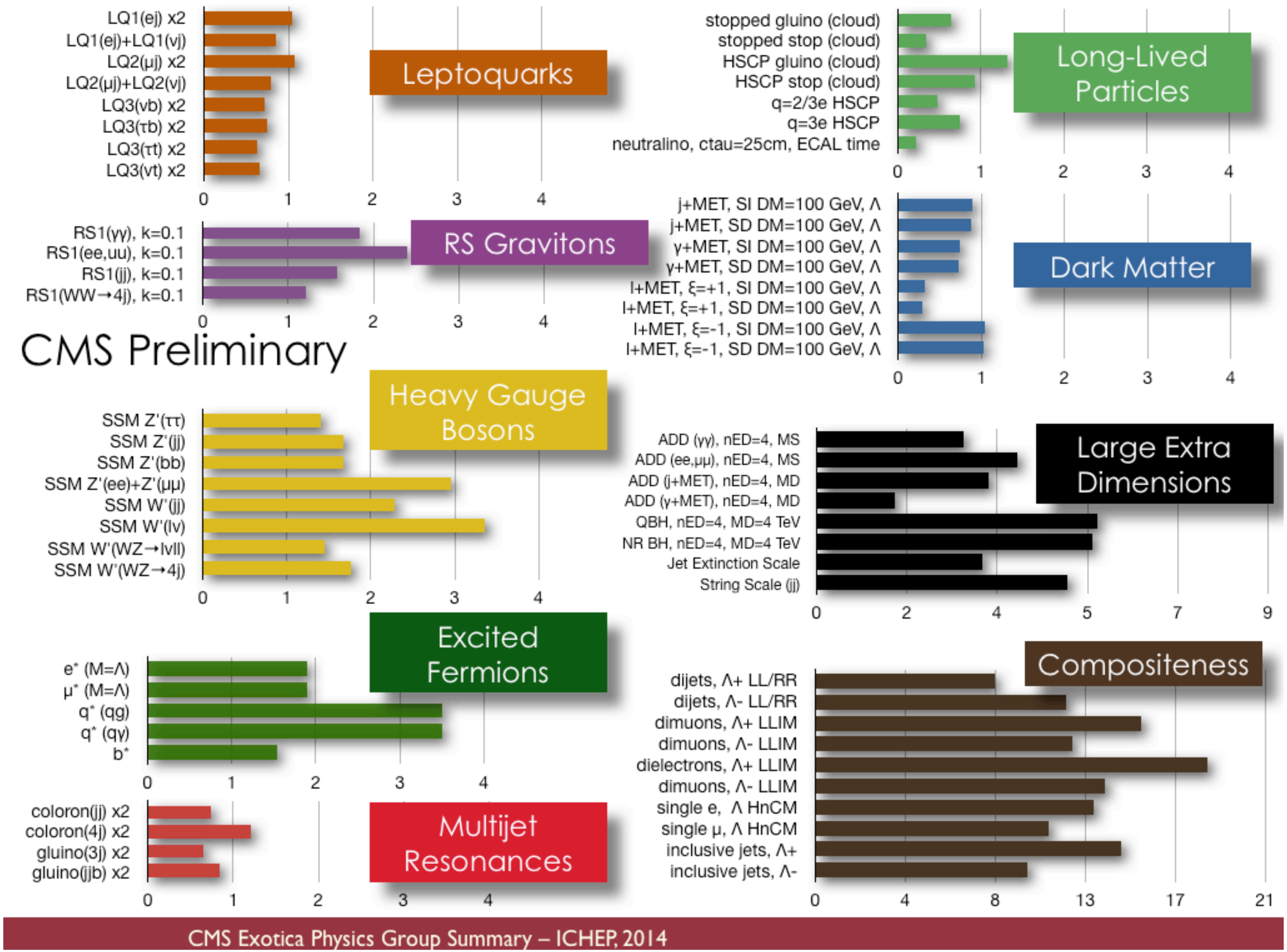


- Pair production of WIMPs plus W or Z bosons decaying and reconstructed as a single massive jet in association with large missing transverse momentum from the undetected WIMPS particles
- The interaction is unknown…
  - ✓ But this doesn't stop the search!

SUSY summary (ATLAS)



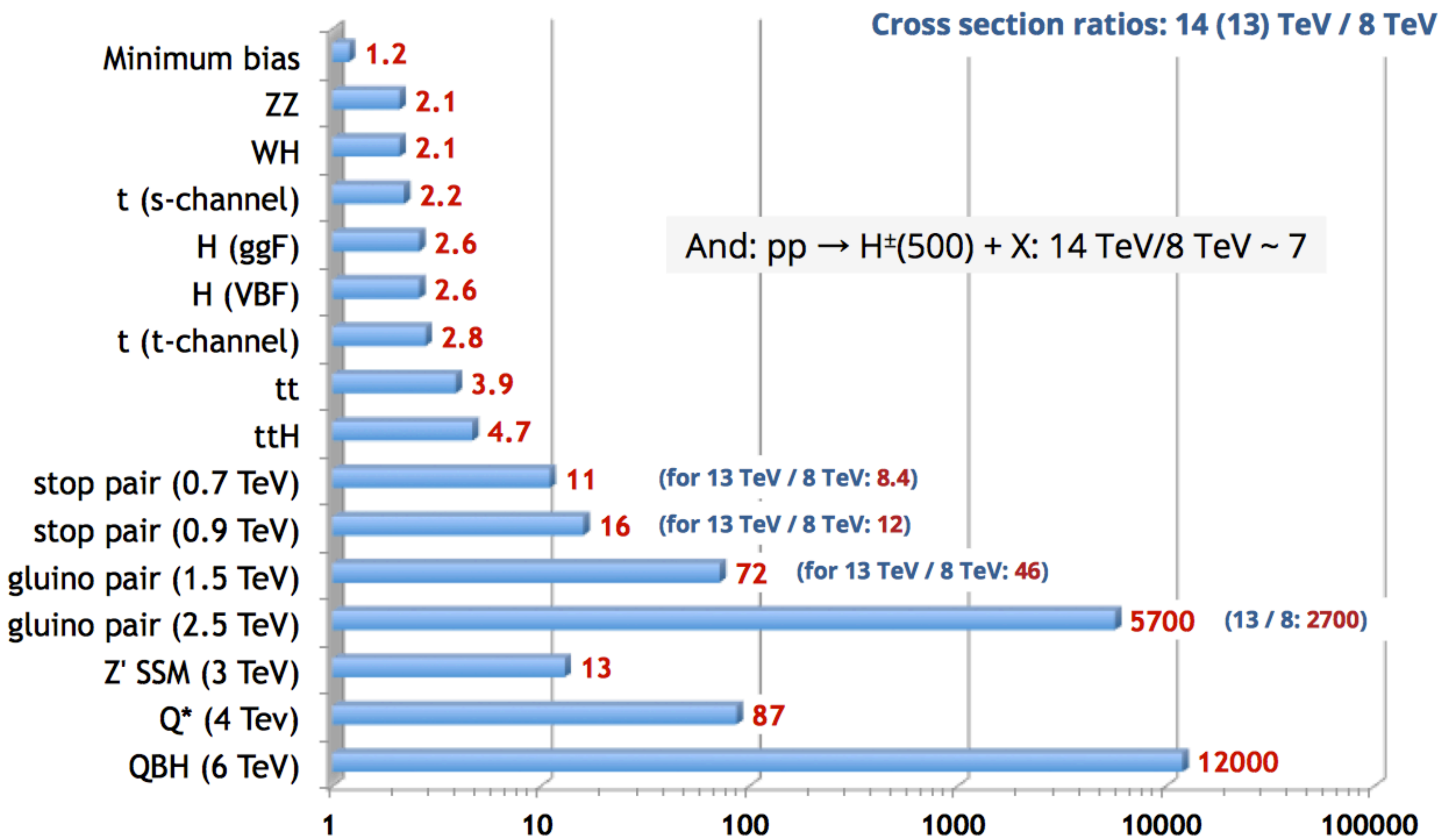
Exotics Summary (CMS)



LHC Run 2 is approaching!

Hugely increased potential for discovery of heavy particles at 13 TeV

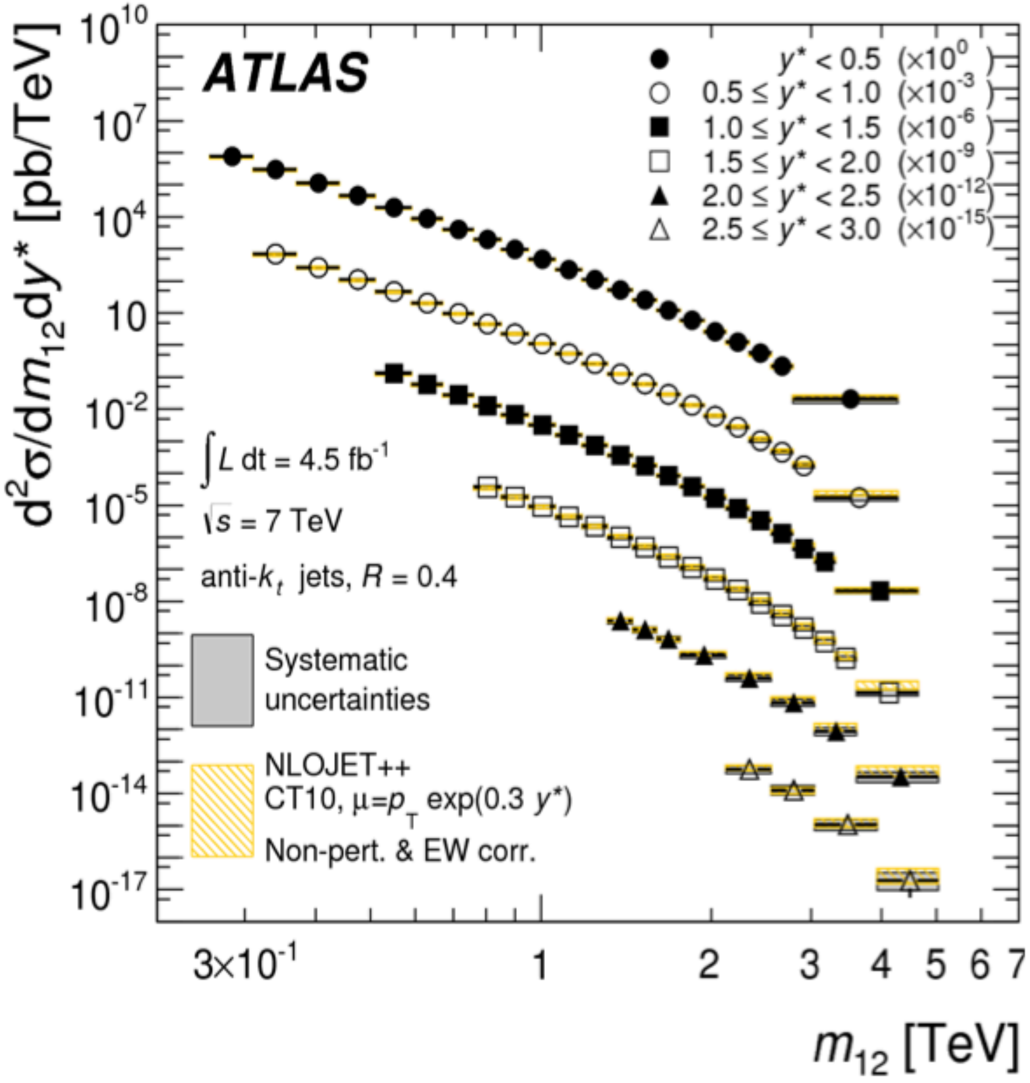
Perfect occasion for young motivated physicists: join the search!



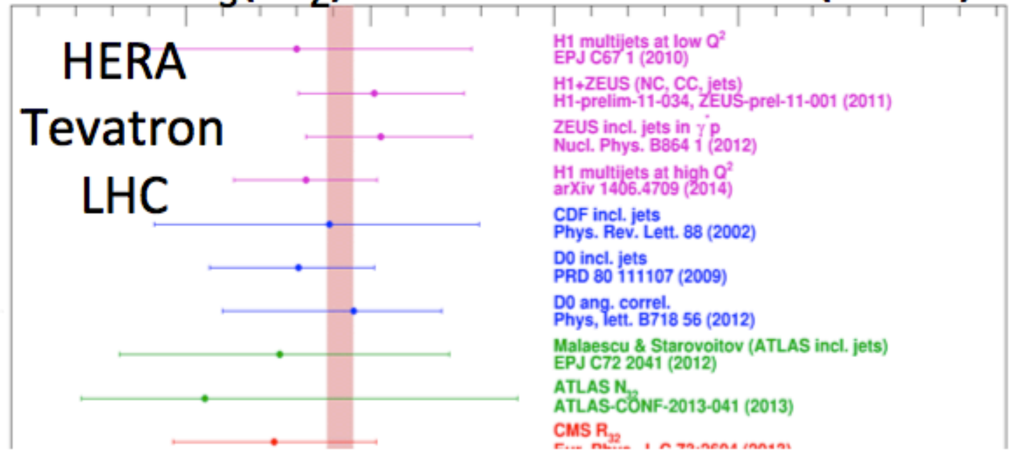
Testing QCD

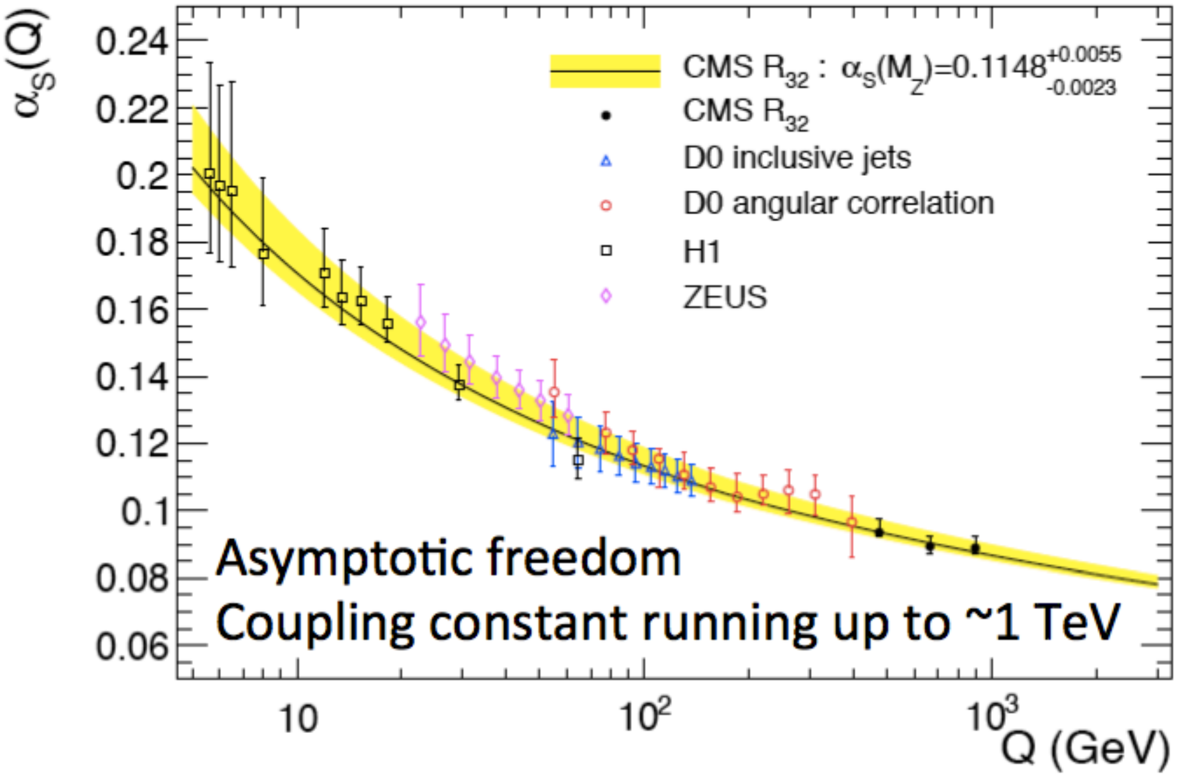
Double Differential Di-jet cross section

$\Lambda_{compositeness}$ > 7 TeV



2014 $\alpha_s(M_Z)$ = 01185 ± 0.0006 (0.5%)

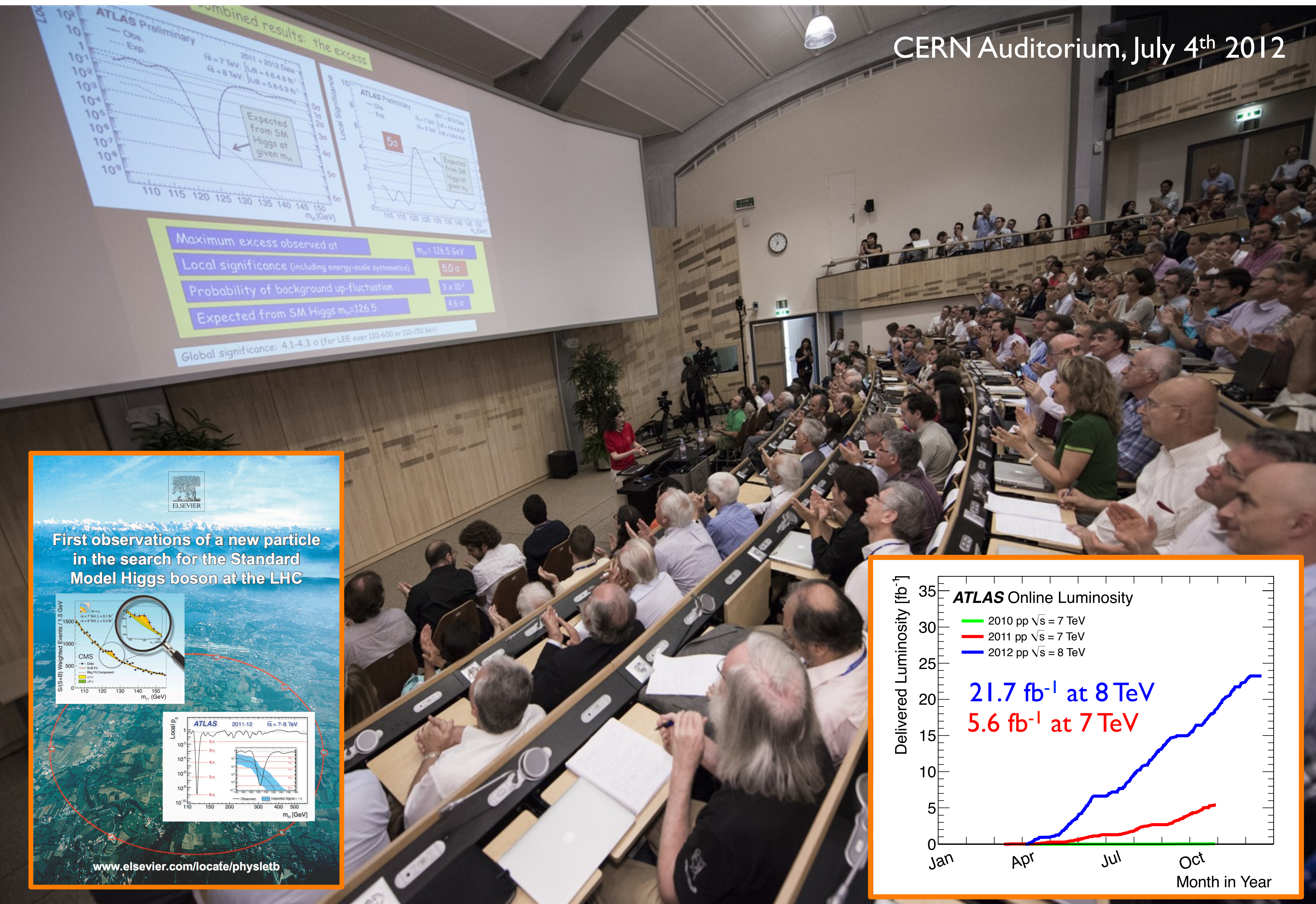




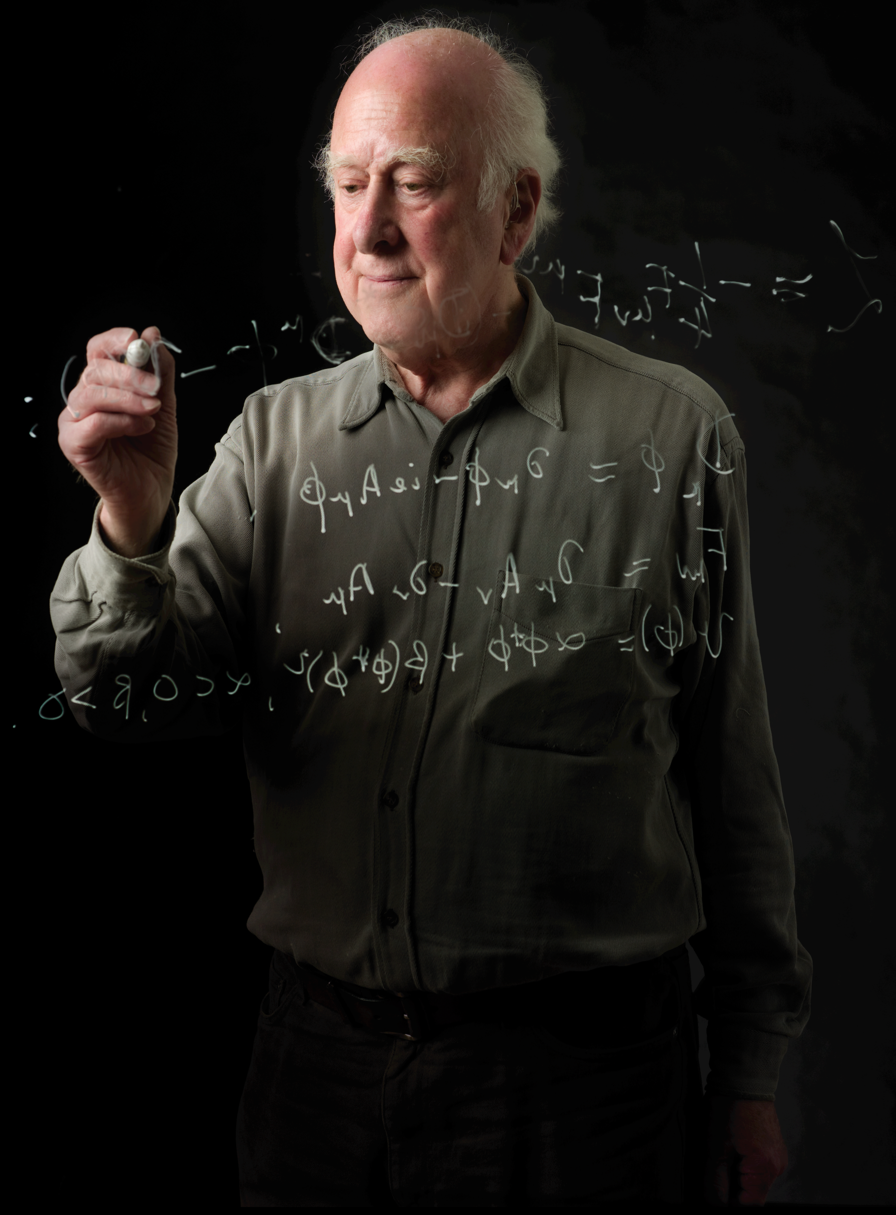
Asymptotic freedom

Coupling constant running up to ~1 TeV

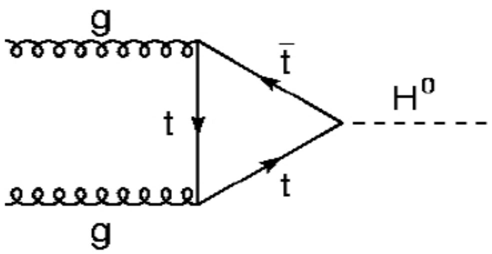
CERN Auditorium, July 4th 2012



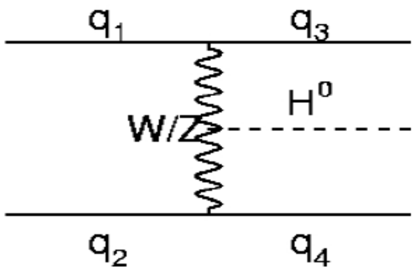
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c + \psi_i y_{ij} \psi_j \phi + h.c + |D_\mu \phi|^2 - V(\phi)$$



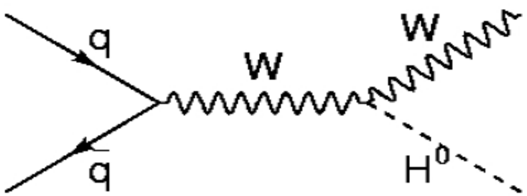
Standard Model Higgs production at the LHC



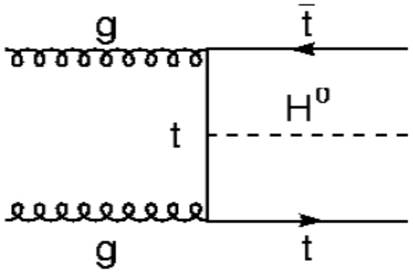
gluon fusion (ggF)



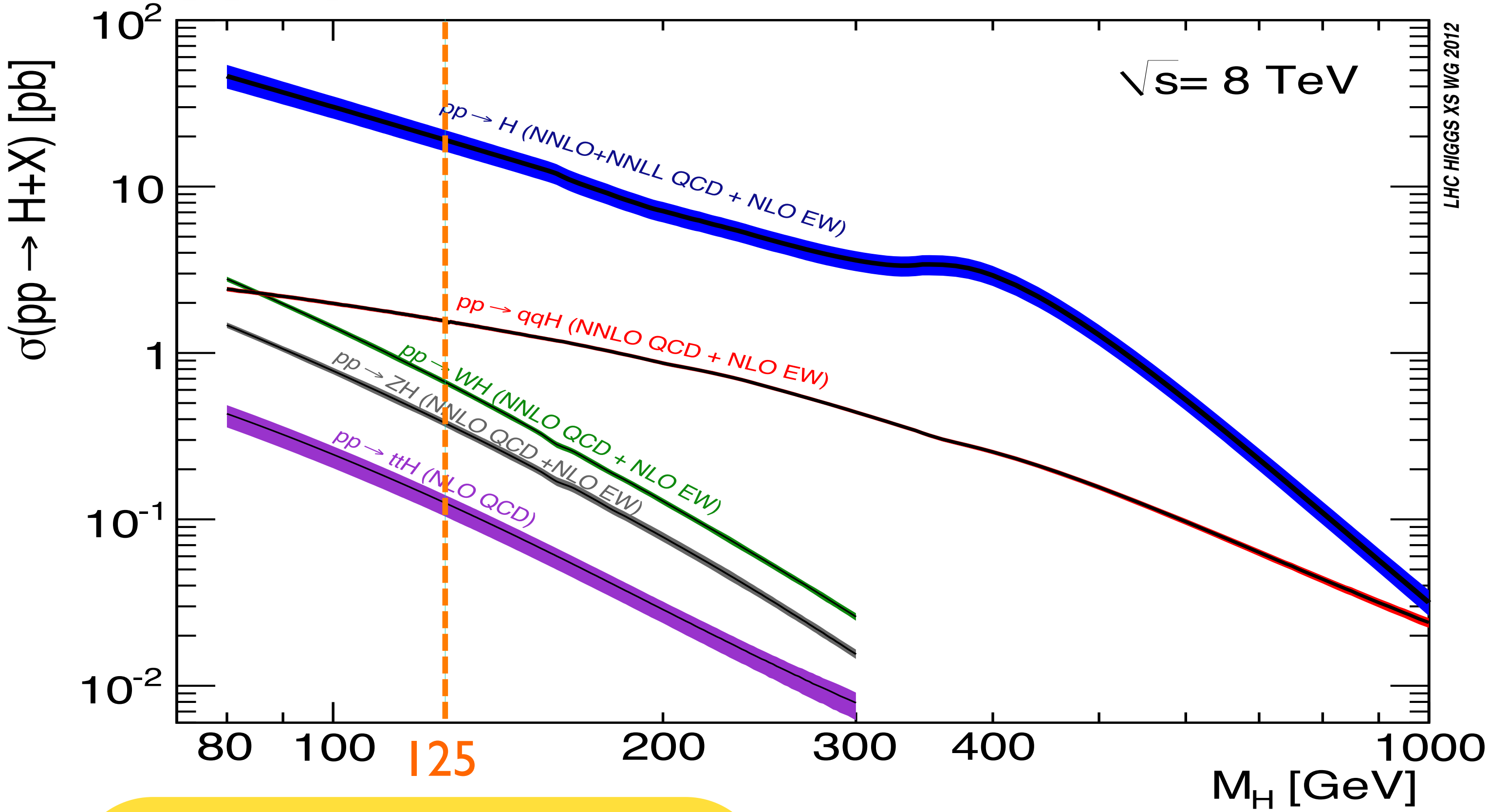
Vector-Boson-Fusion (VBF)



associated production (W, Z)

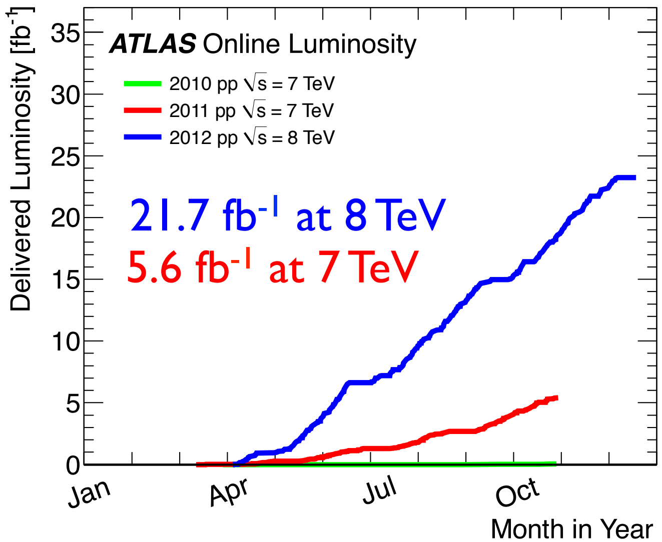


associated production (ttbar)



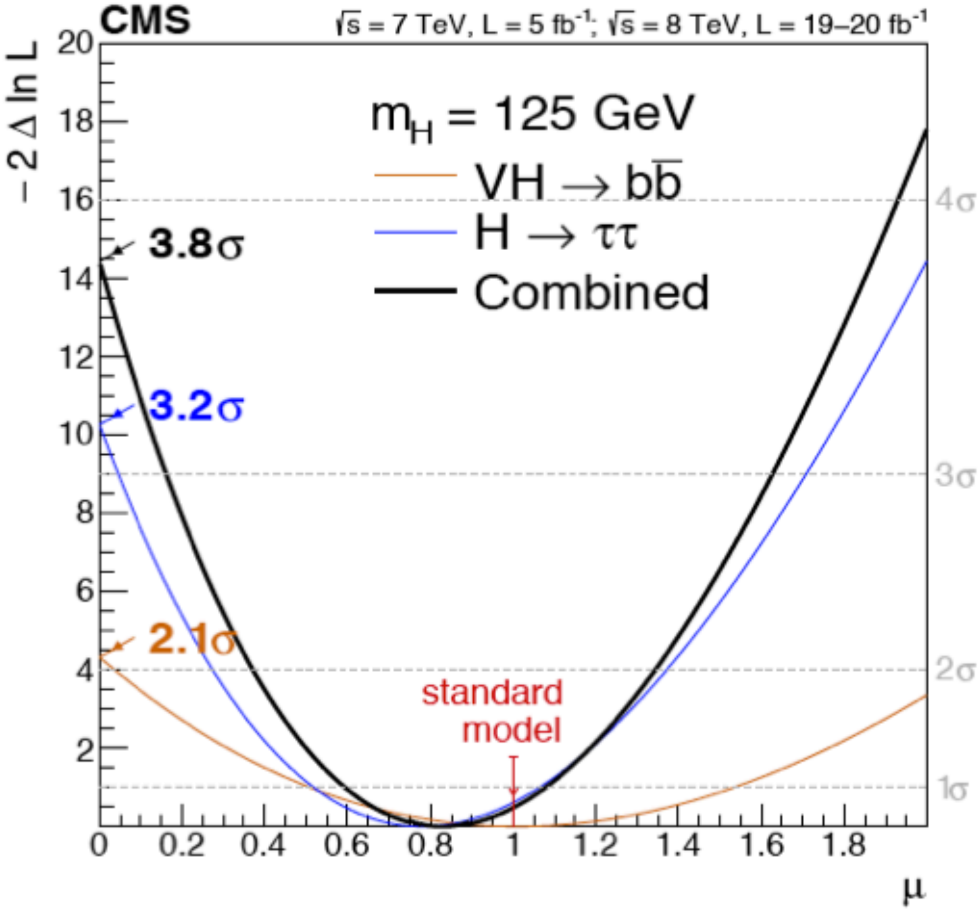
σ(125 GeV) = 22.3 pb

2 Higgs bosons @ m_H 125 GeV produced at LHC in 2012 every 10^{10} pp collisions



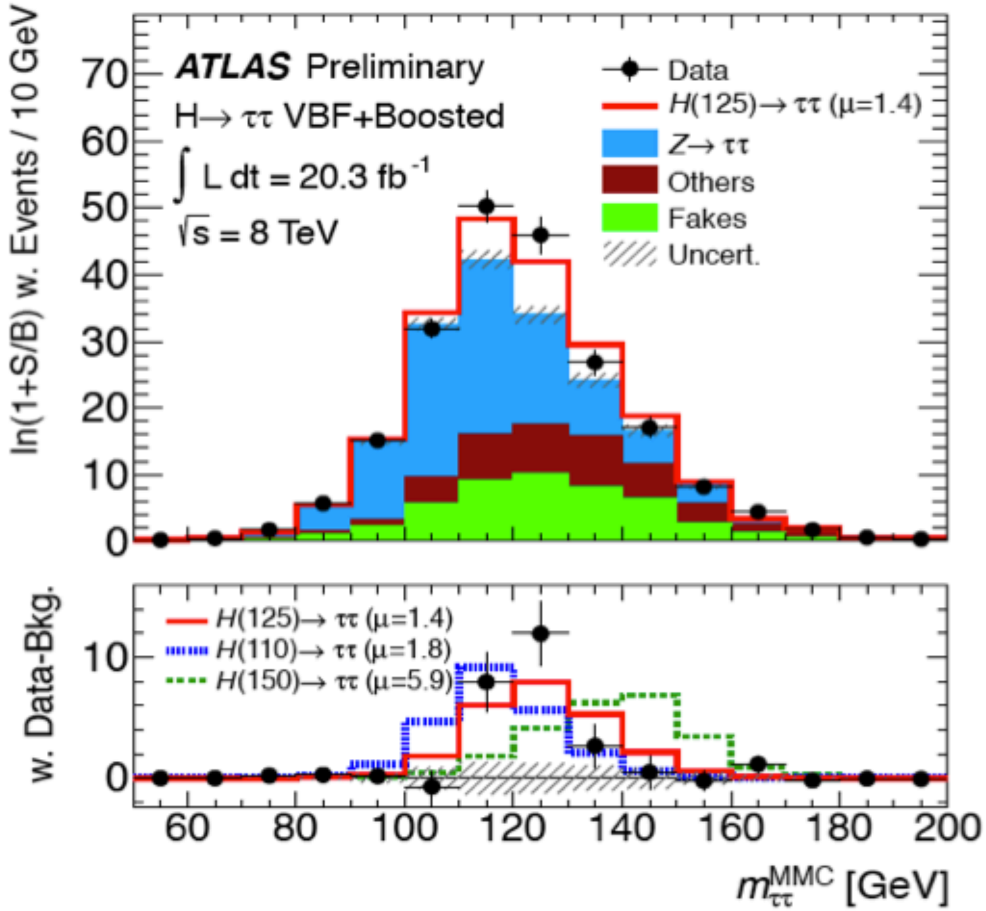
Higgs decays to fermions

CMS: H→ ττ, bb Channels



Significance	Exp	Obs
CMS (ττ)	3.4 σ	3.2 σ
CMS (bb)	2.1 σ	2.1 σ

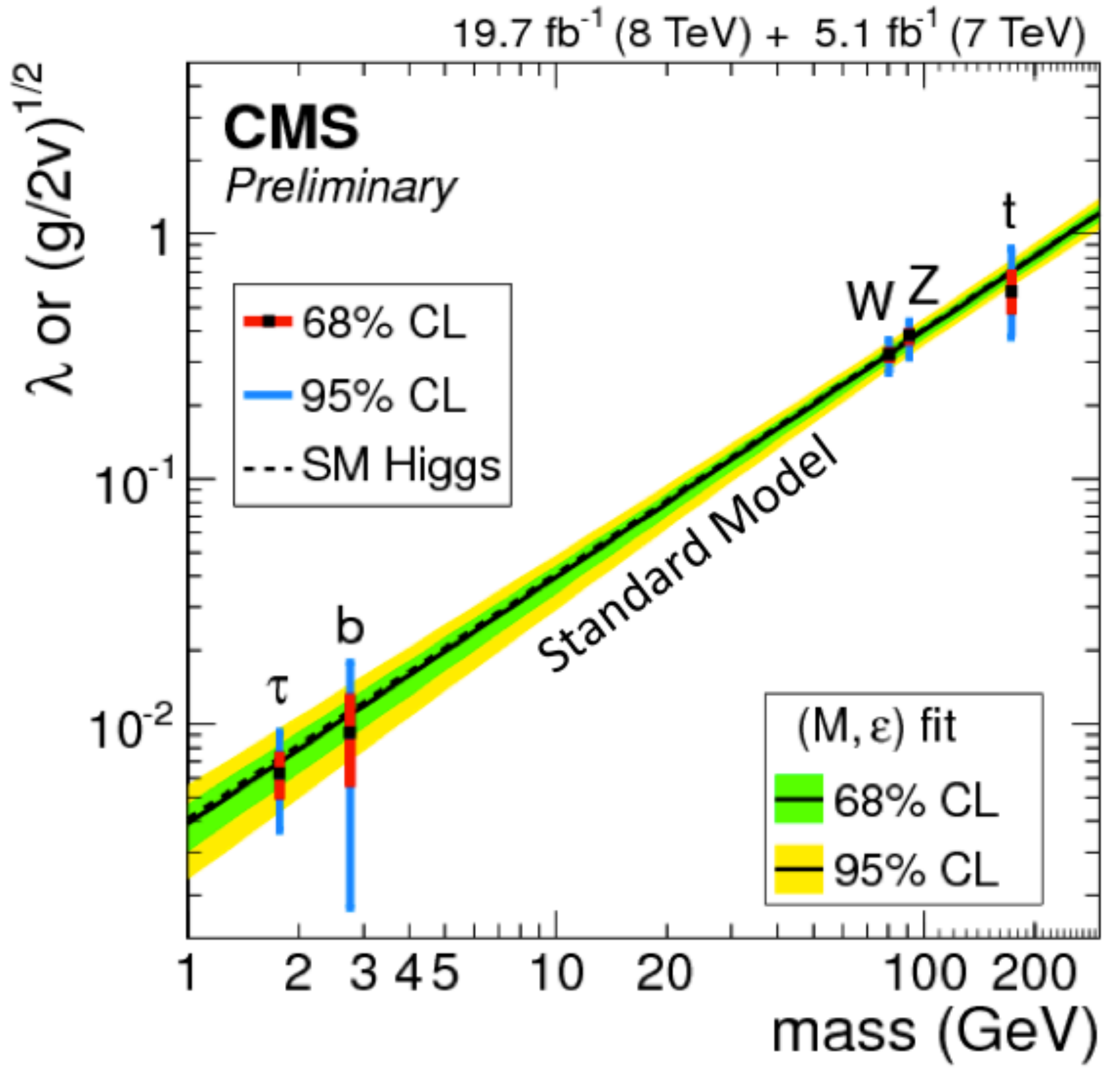
ATLAS: H→ ττ Channel

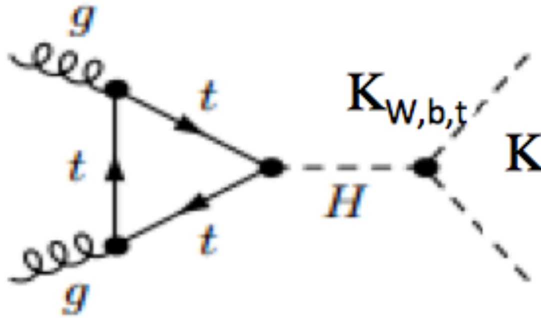


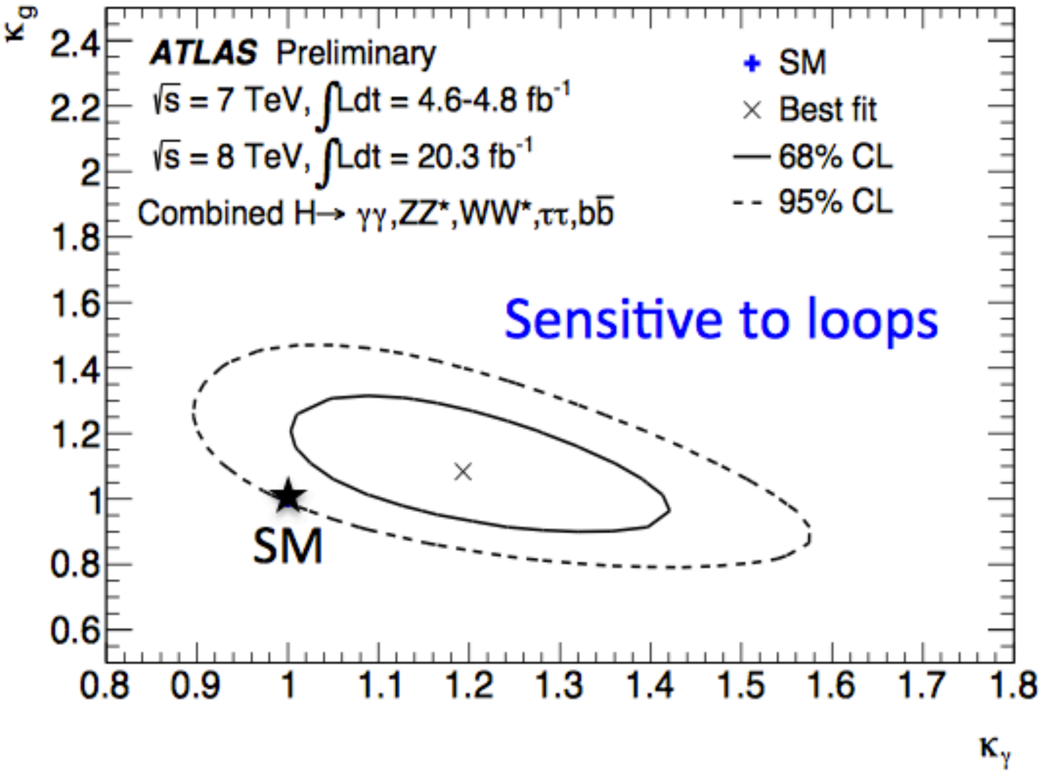
Significance	Exp	Obs
ATLAS (ττ)	3.2 σ	4.1 σ

Tevatron: exp (2.1σ), obs (3.0σ)

Higgs couplings







- All seems consistent with Standard Model predictions…