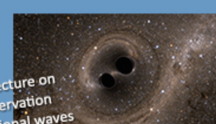
(experimental) LHC physics

GraSPA2016

Summer School in Particle and Astroparticle physics of Annecy-le-Vieux



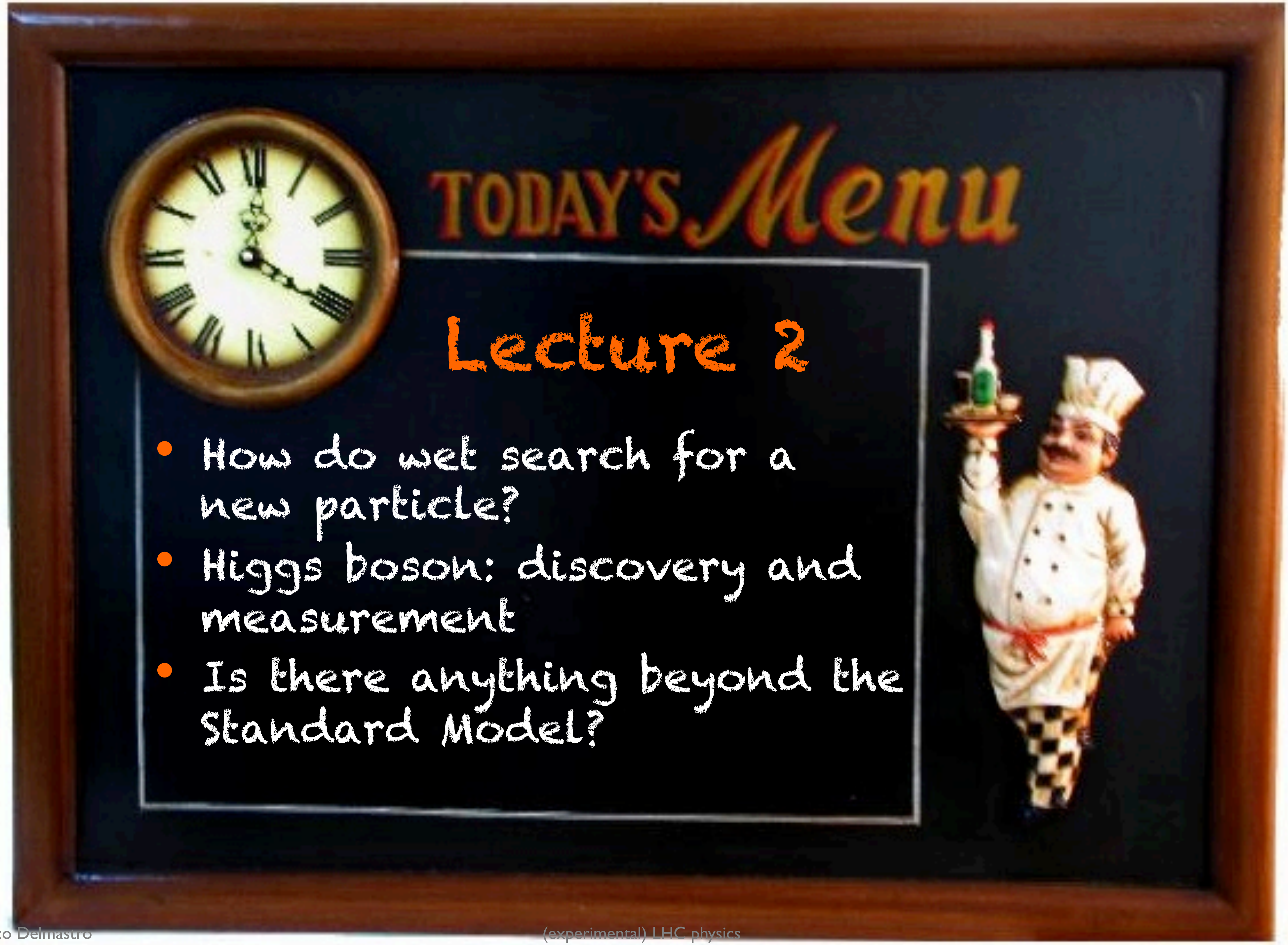
Special lecture on the observation of gravitational waves

21-27 July 2016

LAPP LAPTh CNRS IN2P3 Les deux infinis Enigmass Université Savoie Mont Blanc PTGA Centre de Physique Théorique Grenoble-Alpes IDPASC

2. {on how we search for a new particle}

Marco Delmastro



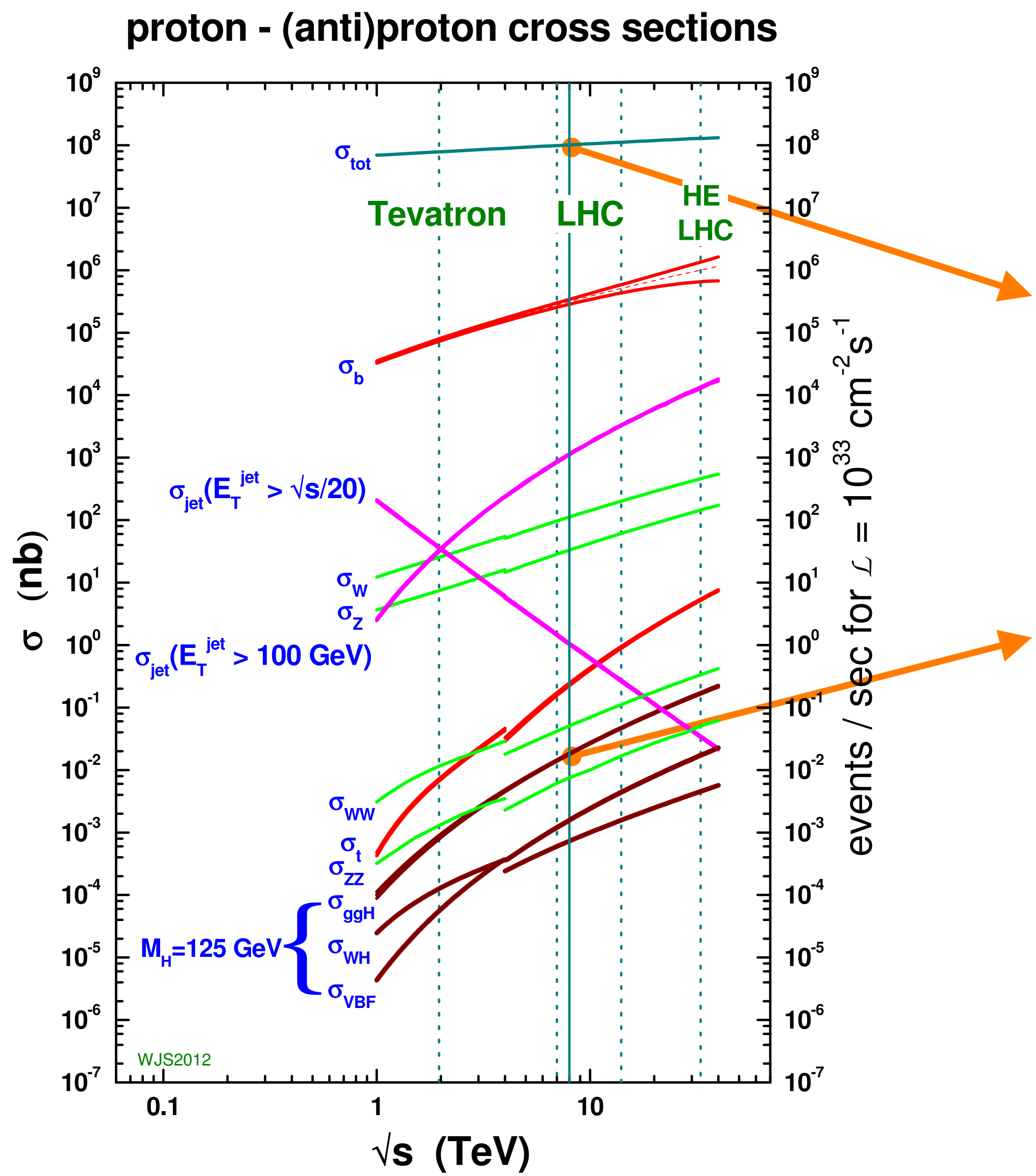
Lecture 2

- How do wet search for a new particle?
- Higgs boson: discovery and measurement
- Is there anything beyond the Standard Model?

How to search for a new particle

and (possibly) find it!

Interesting processes are rare!



10^8 events/s

~10^{10}

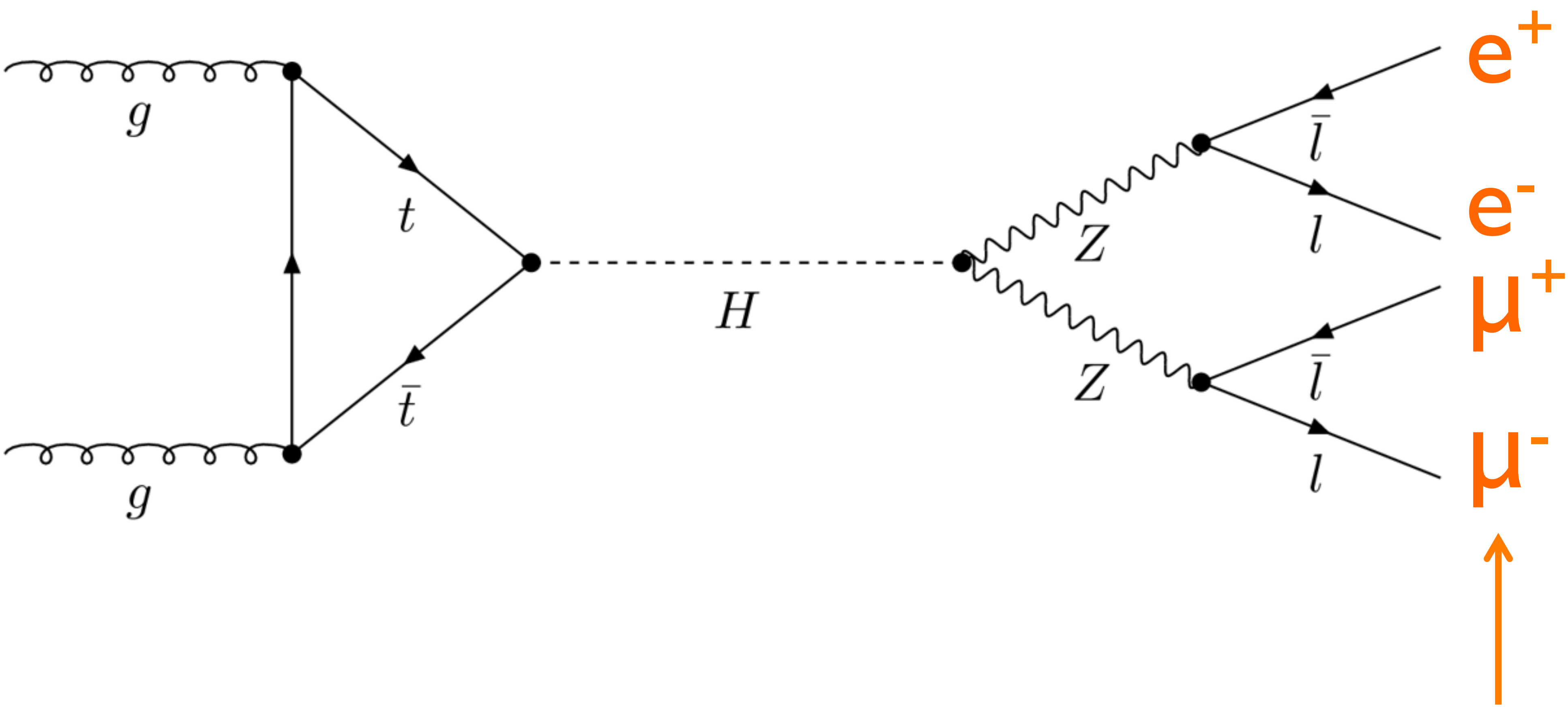
10^{-2} events/s ~

10 events/min

[m_H ~ 125 GeV]

0.2% H → γγ
1.5% H → ZZ

There is no Higgs-boson detector!

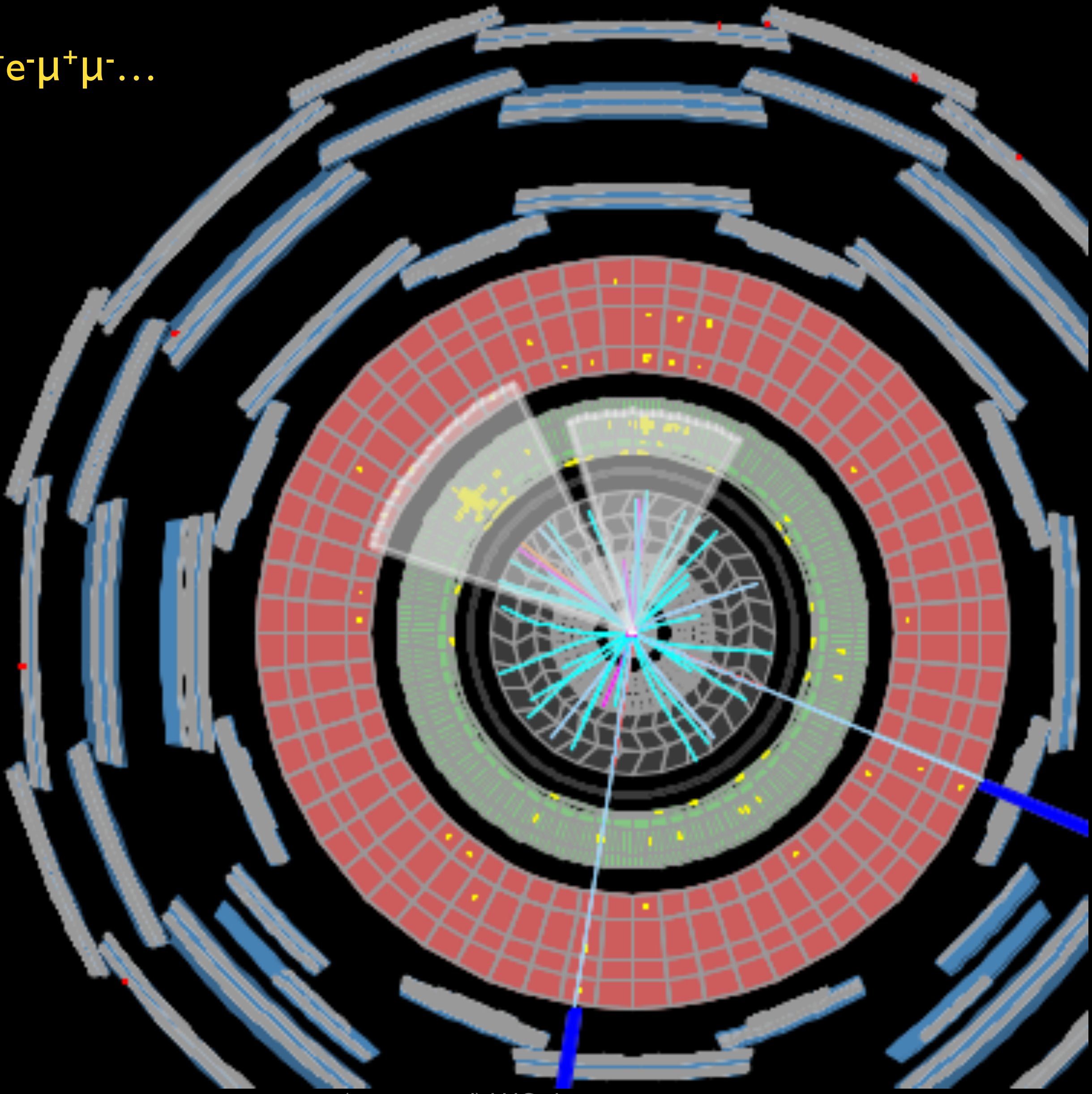


this is what we are looking for…

Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

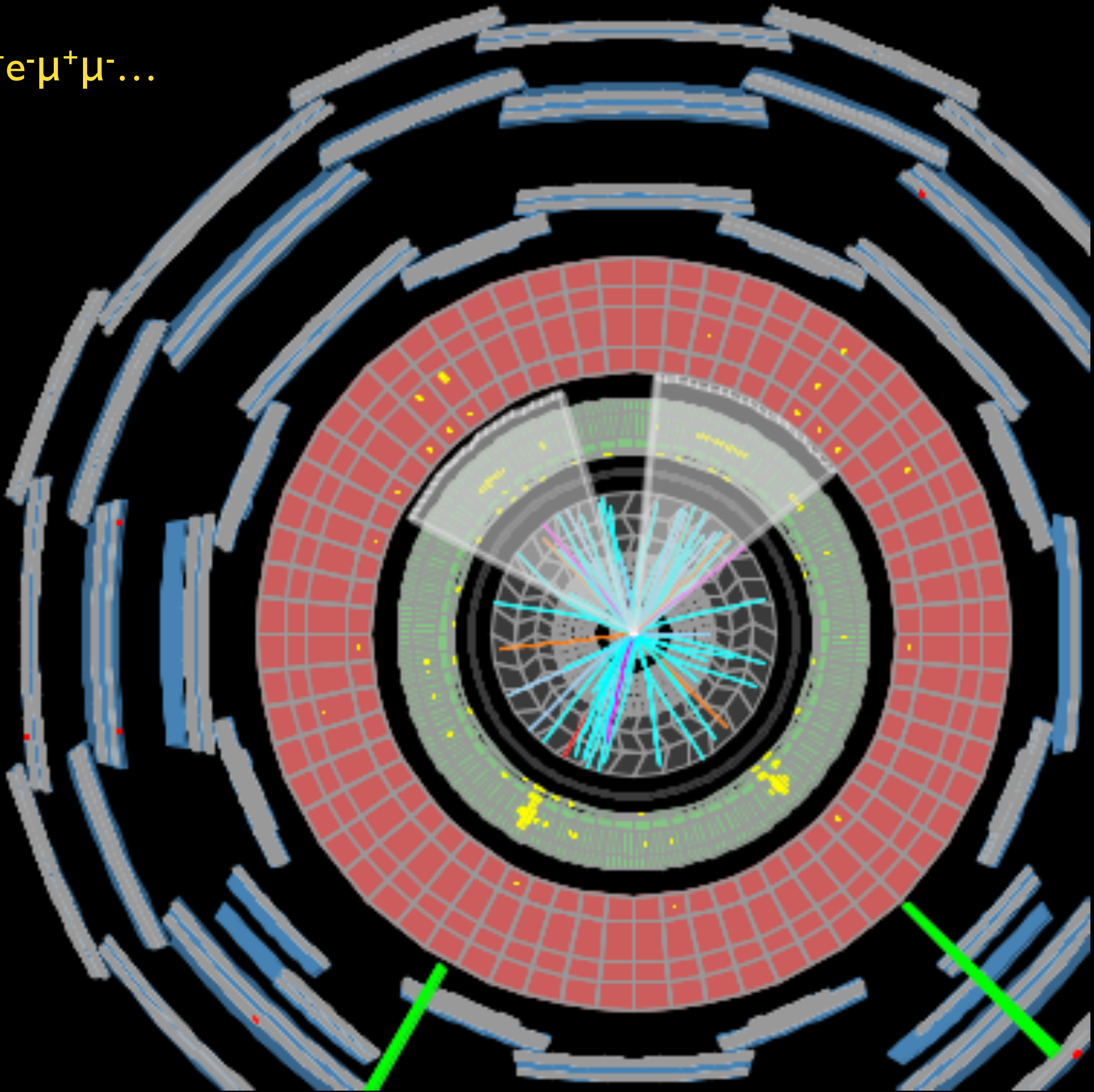
Is this event ok?



Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

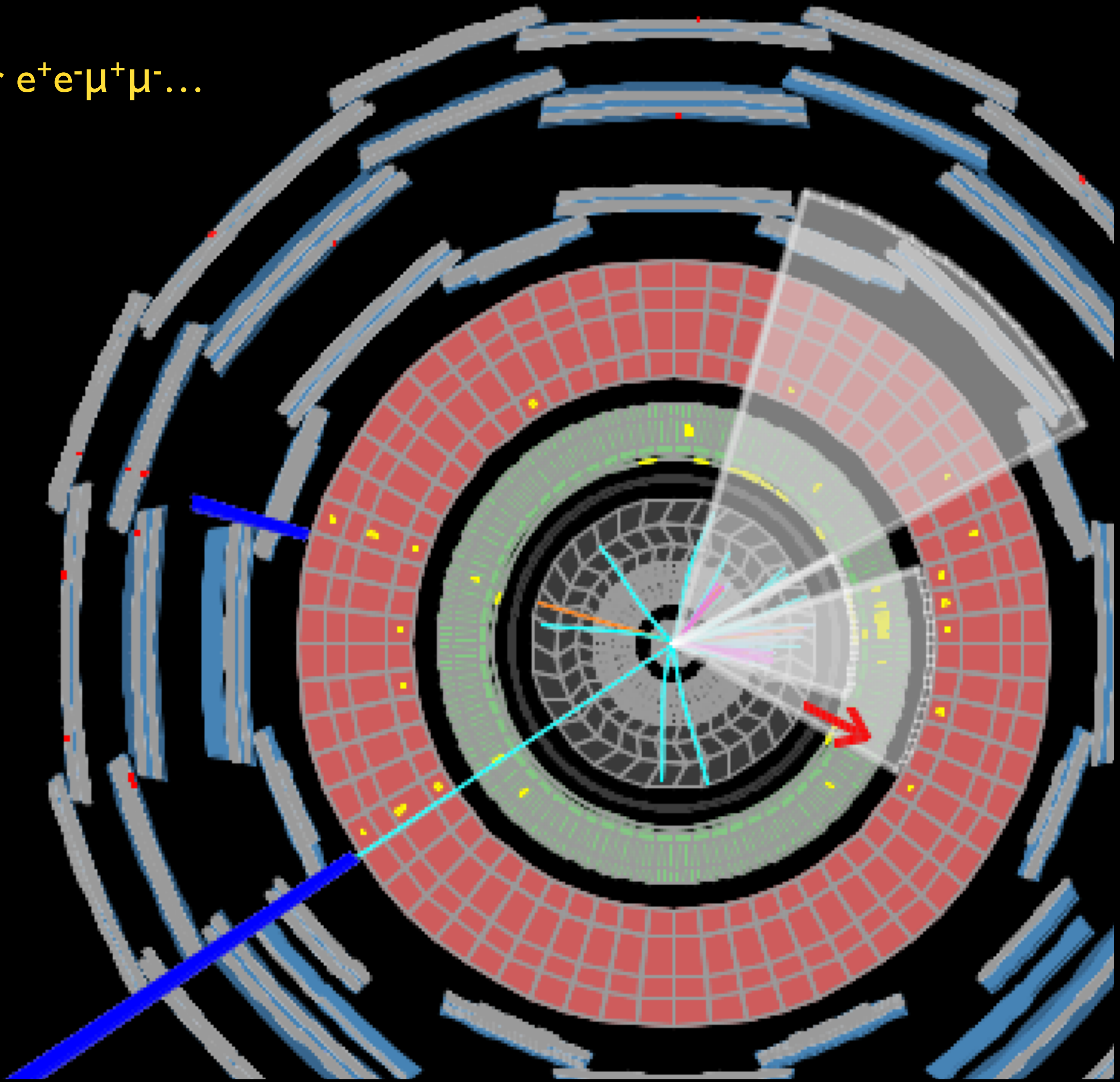
What about this one?



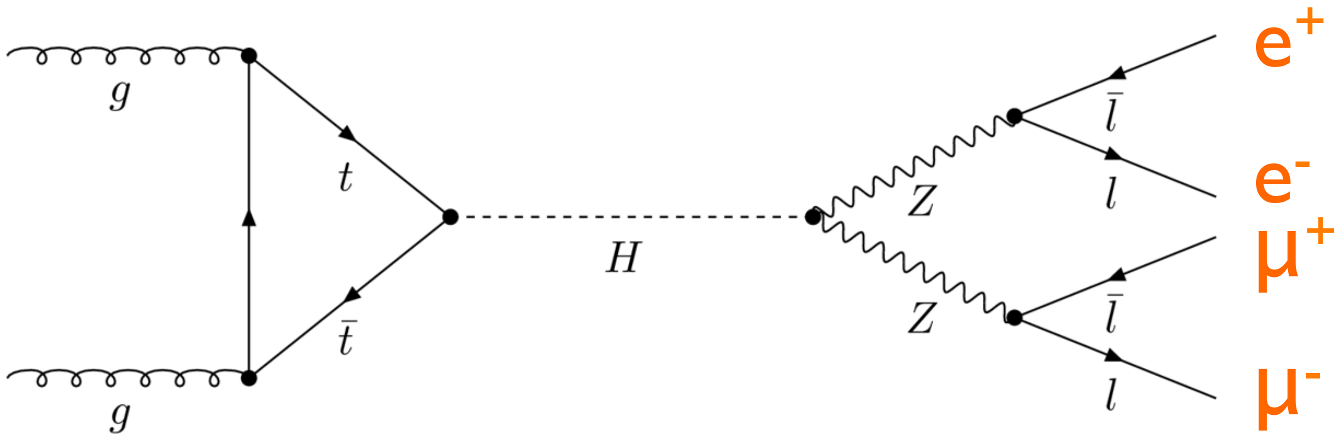
Step 1: find events with the right ingredients

We are looking for $e^+e^-\mu^+\mu^-$…

And this one?

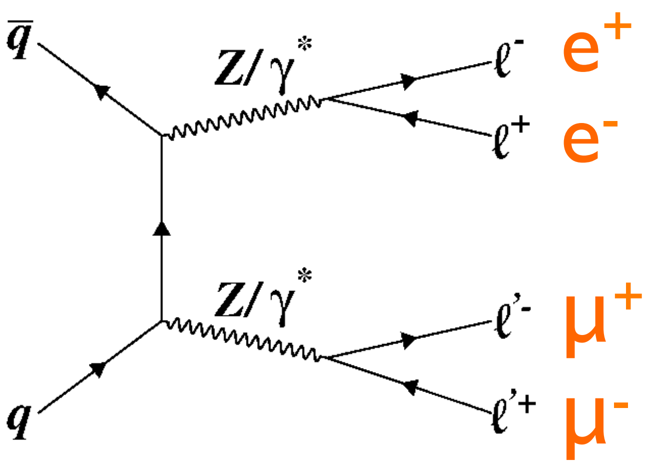


Signal and background



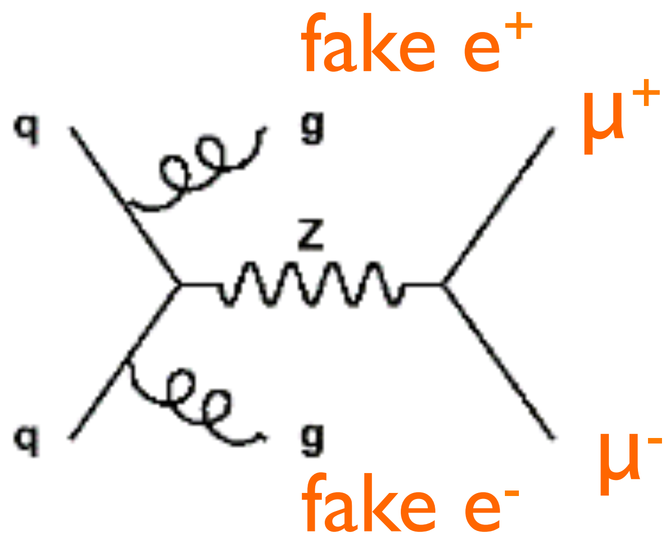
Irreducible background

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



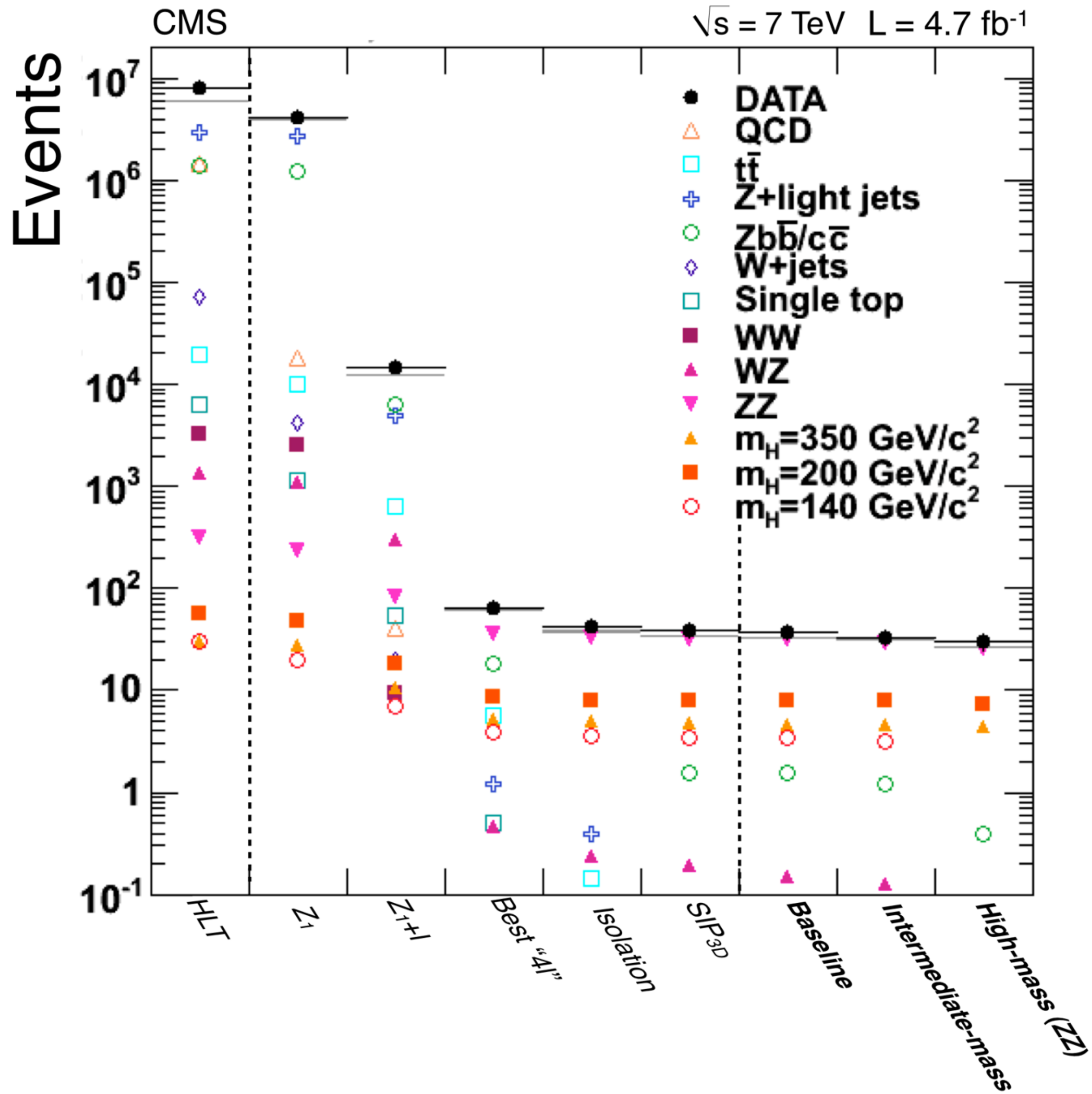
Reducible background

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



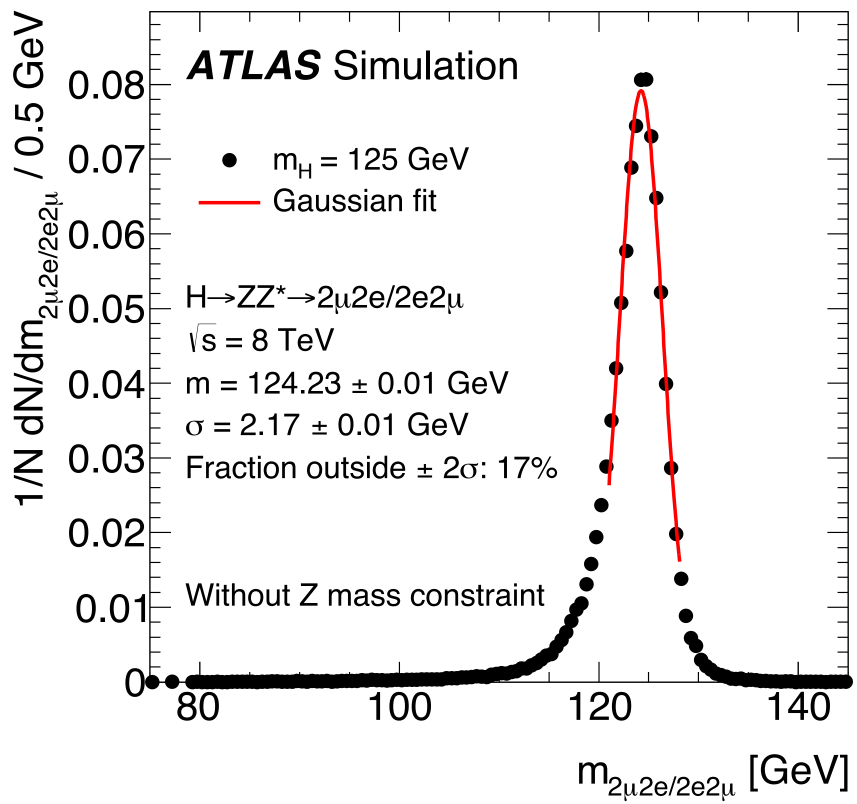
Selections

- Cut on particle properties to reduce reducible background
  - ✓ Shower shapes, track properties, …
- Cut on event properties to distinguish signal from background
  - ✓ Particle kinematics, decay kinematics event shape, …
- Try to keep signal while reducing background!
  - ✓ Increase S/B…



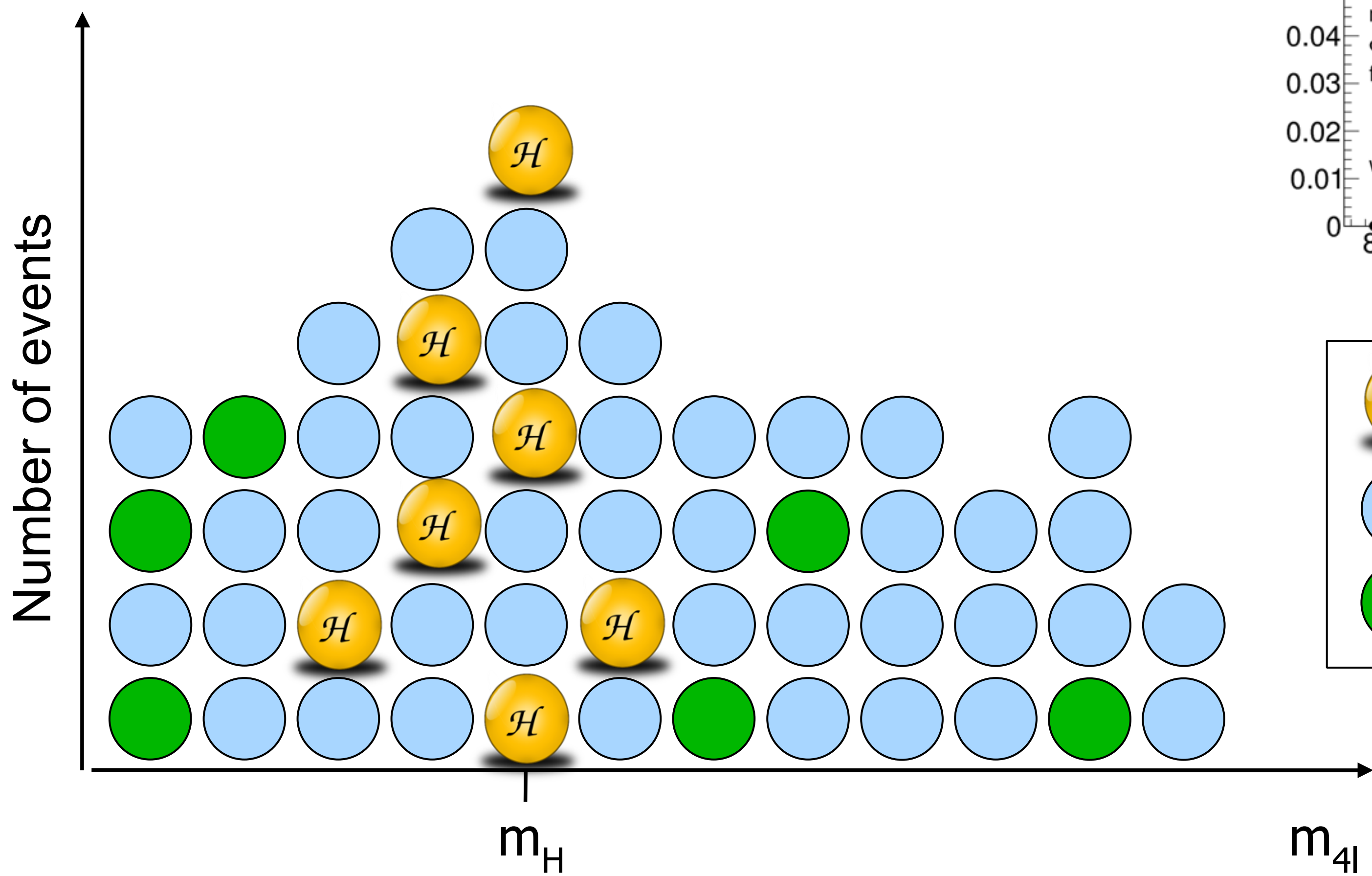
Step 2: reconstruct properties of initial particle

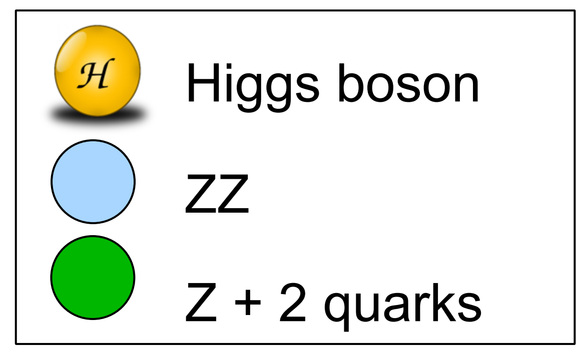
- We have 4 particles…
  - ✓ … with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^+\mu^-$
- Reconstruct invariant mass from the 4 particles $M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$

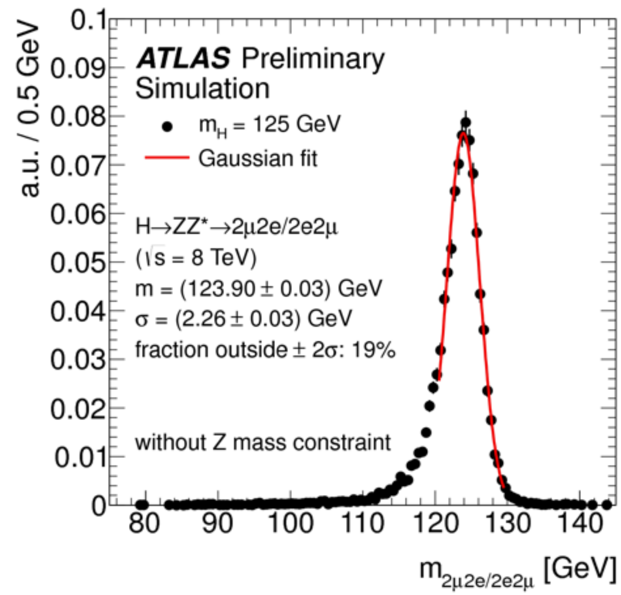


Extract signal from background

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

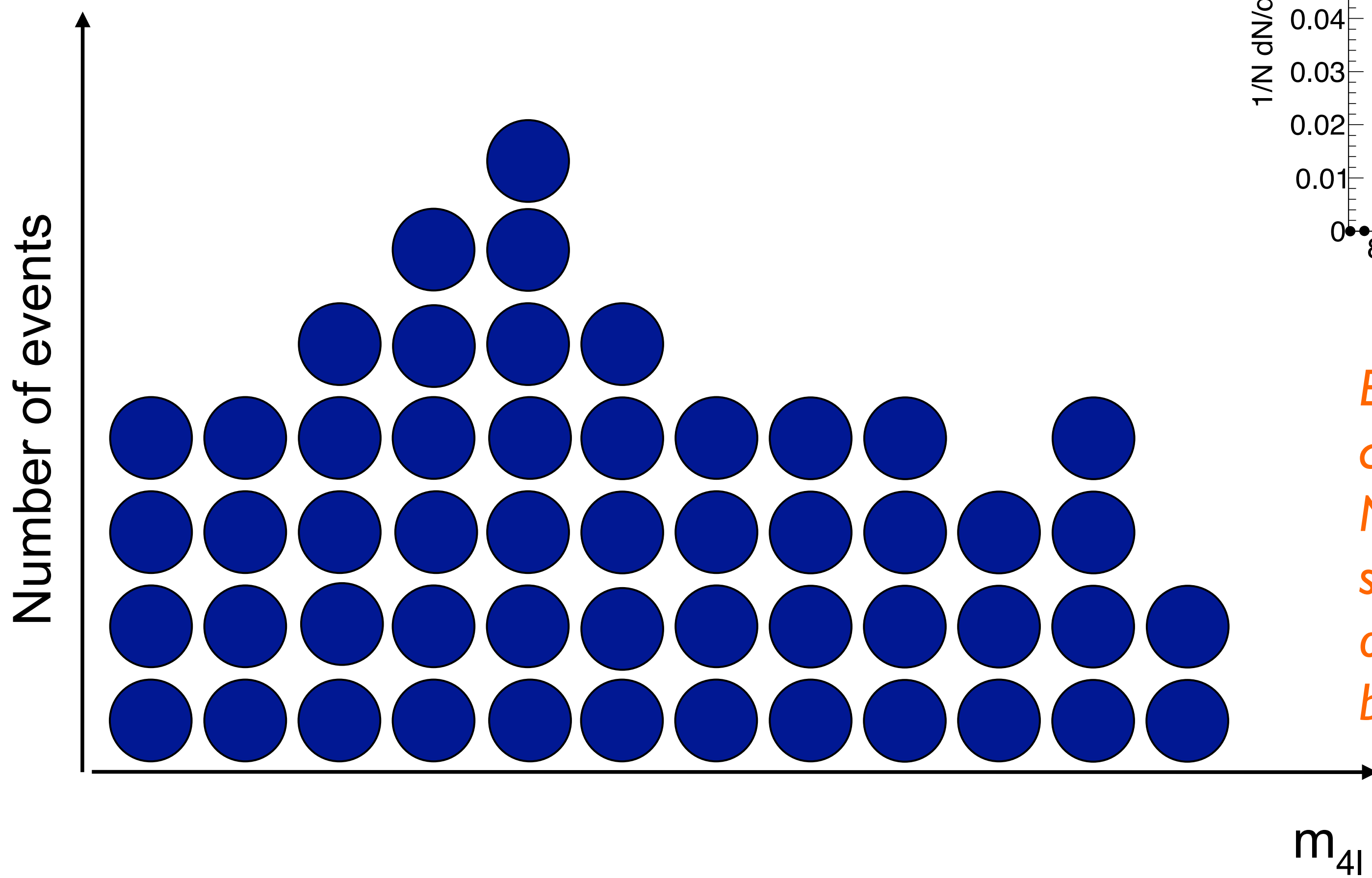


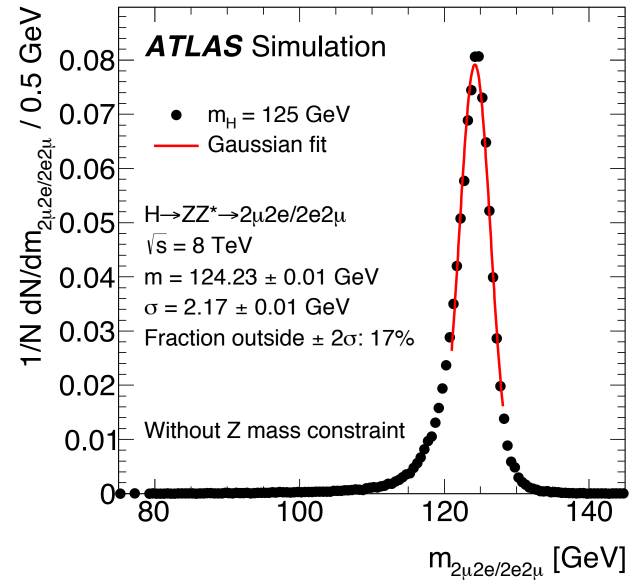




Extract signal from background

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

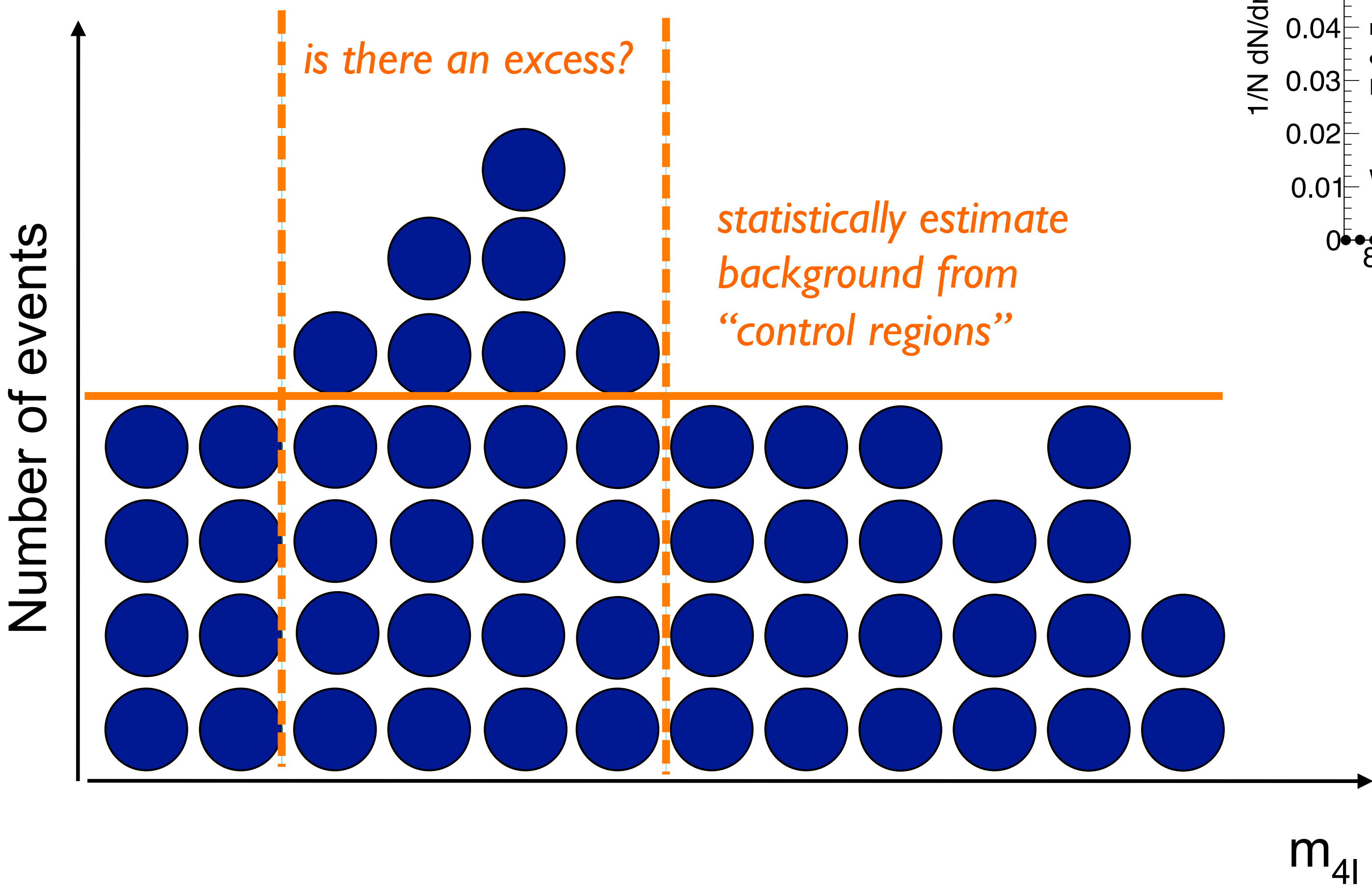


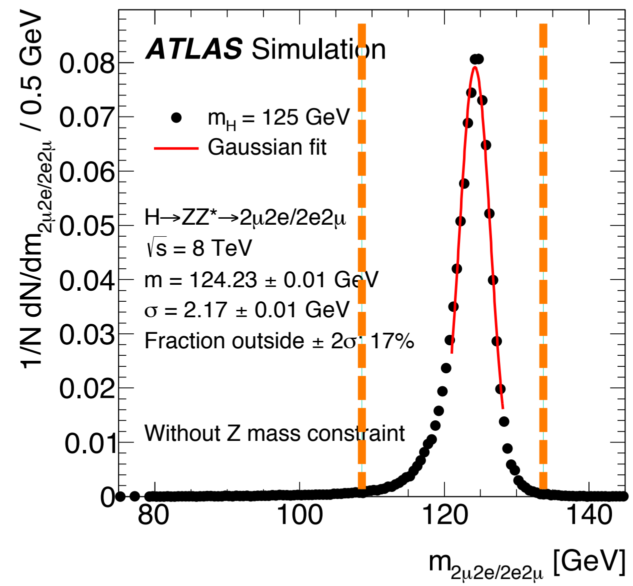


Events in real life do not come with a label!
No way to distinguish signal from background on an event-by-event base…

Extract signal from background

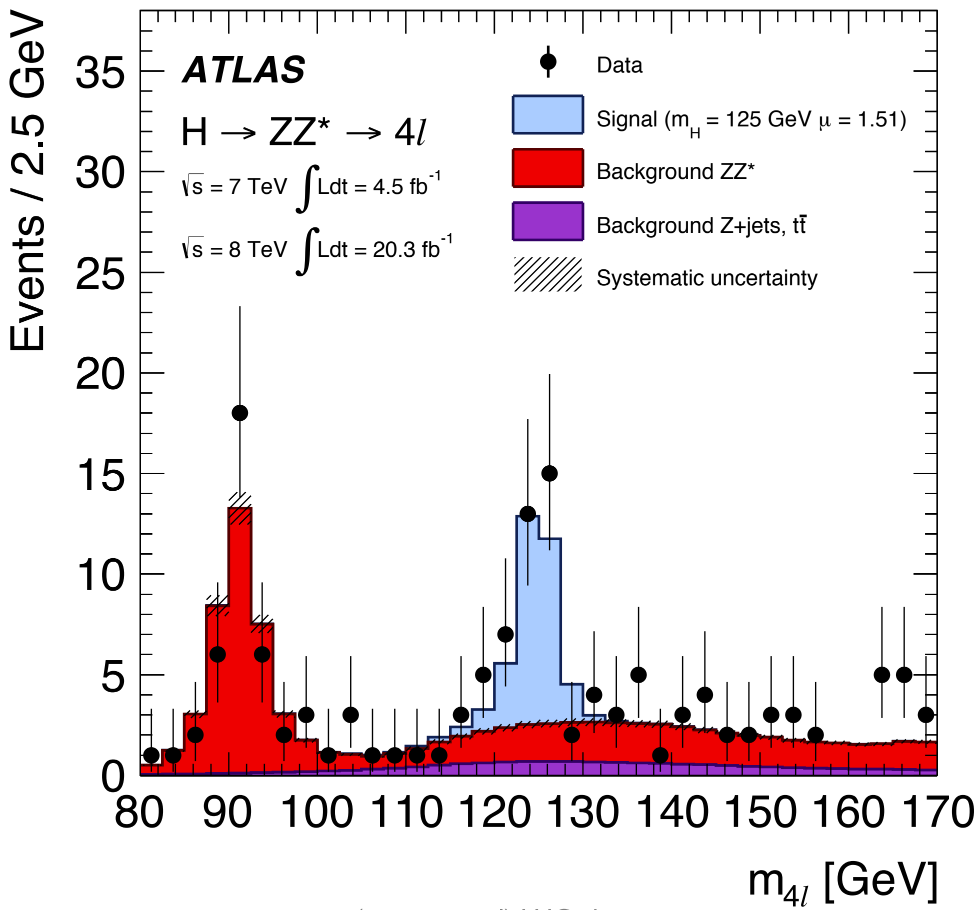
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$





Extract signal from background

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

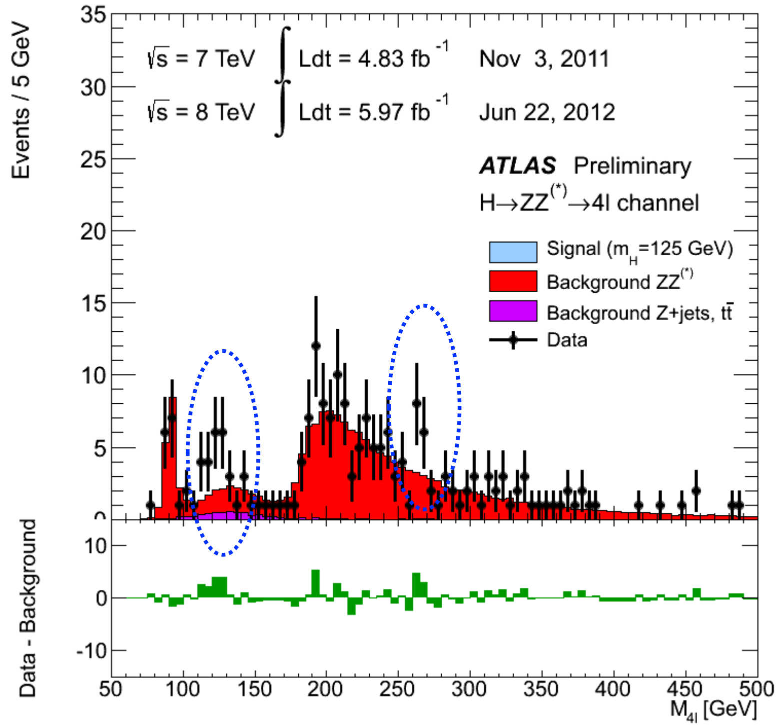


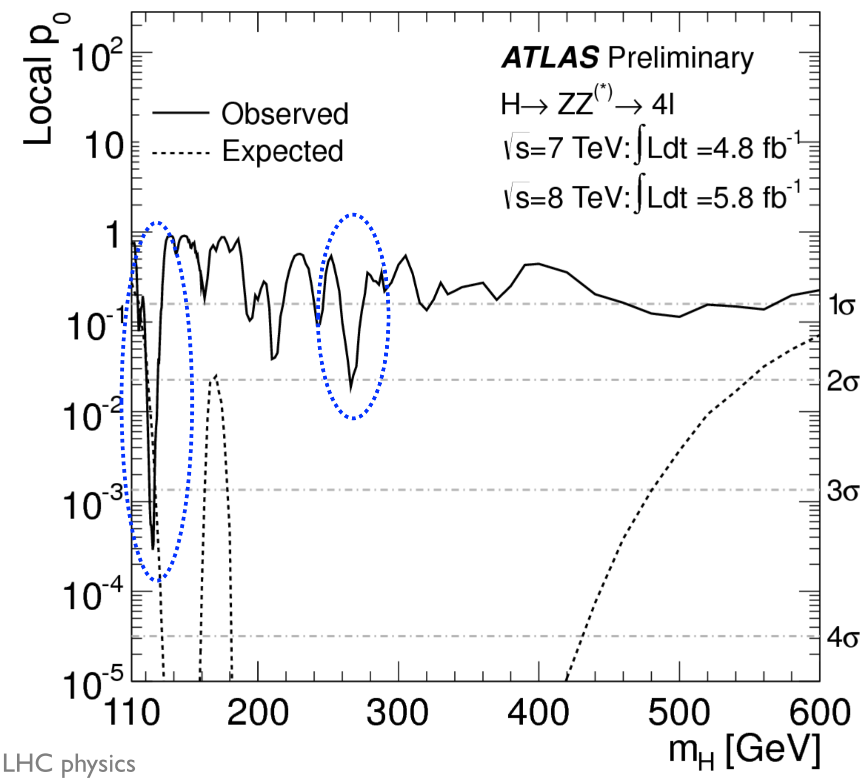
How significant is an excess?

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

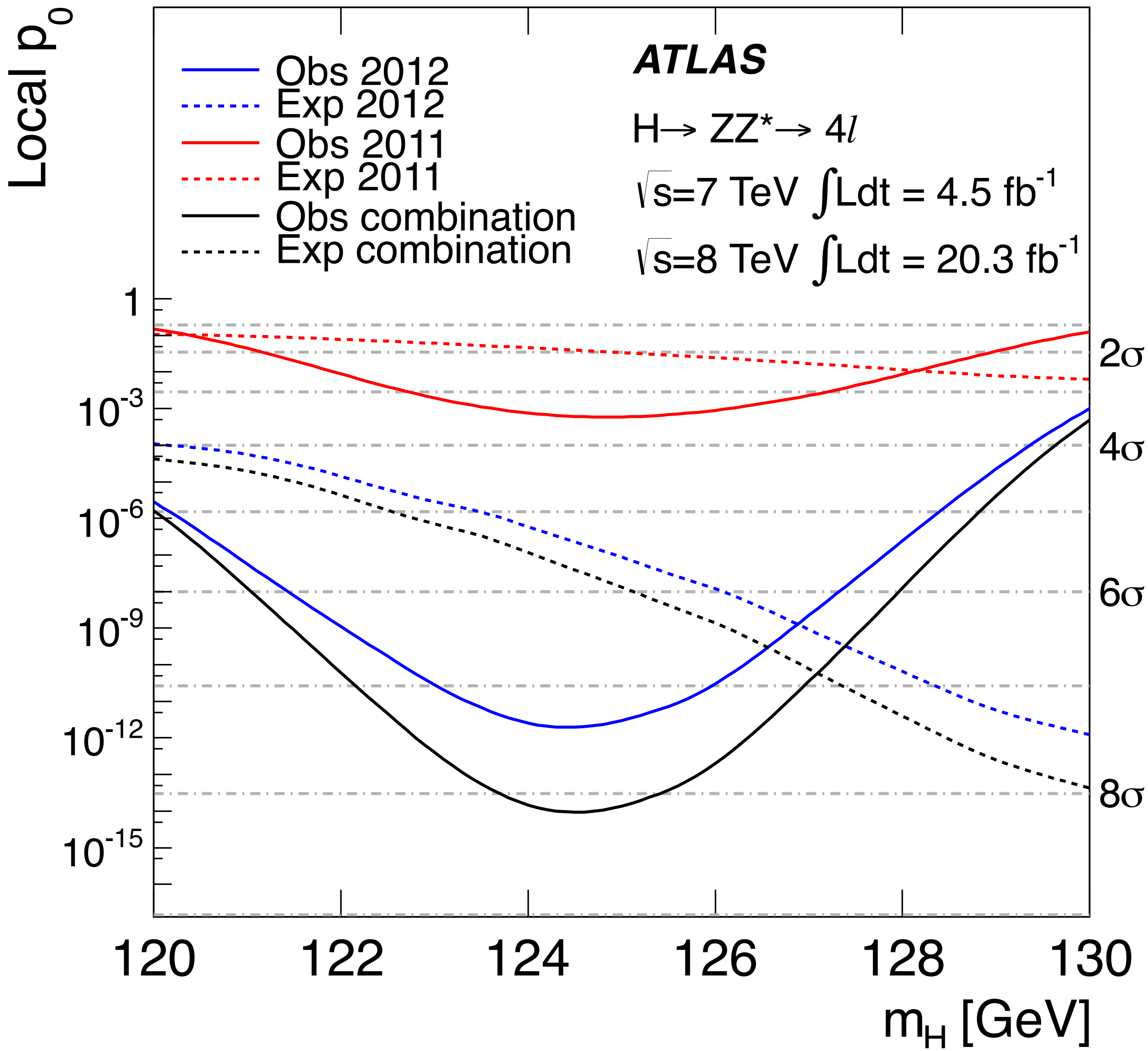
$$Z \sim \frac{S}{\sqrt{B}} \qquad p_0 = 1 - \mathrm{Erf}\left(\frac{Z}{\sqrt{2}}\right)$$

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

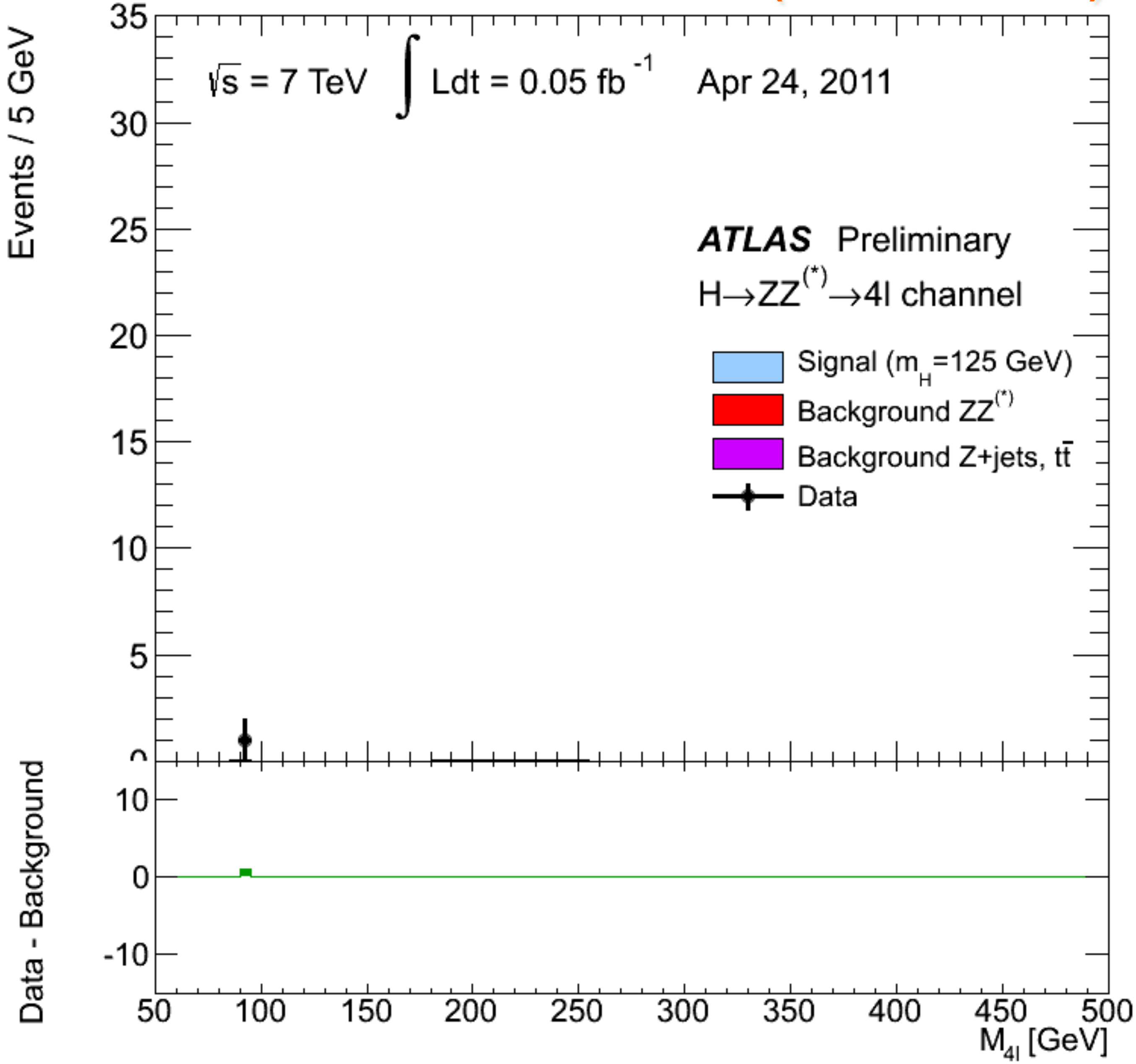




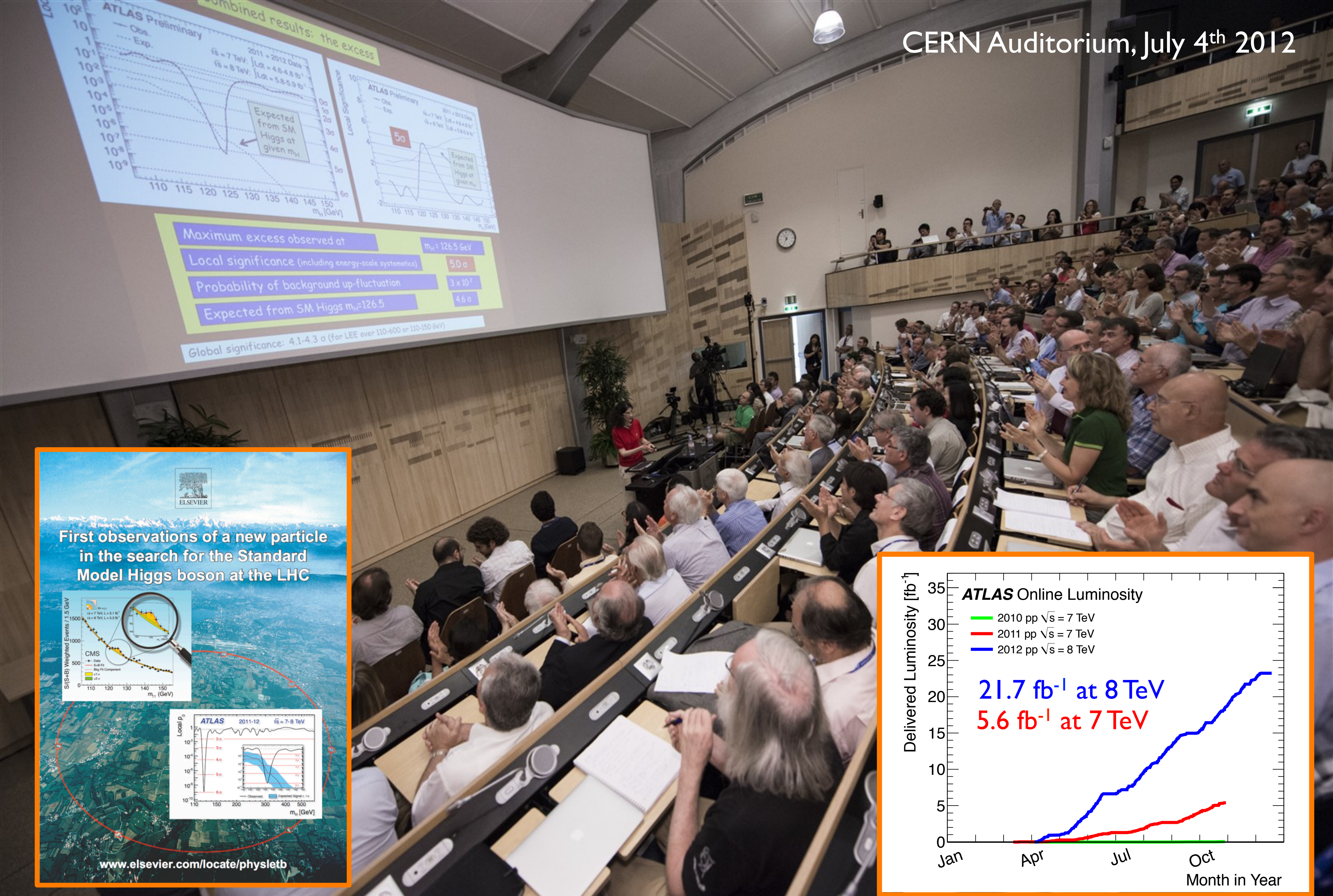
How significant is an excess?



Significance increase with data (and time!)



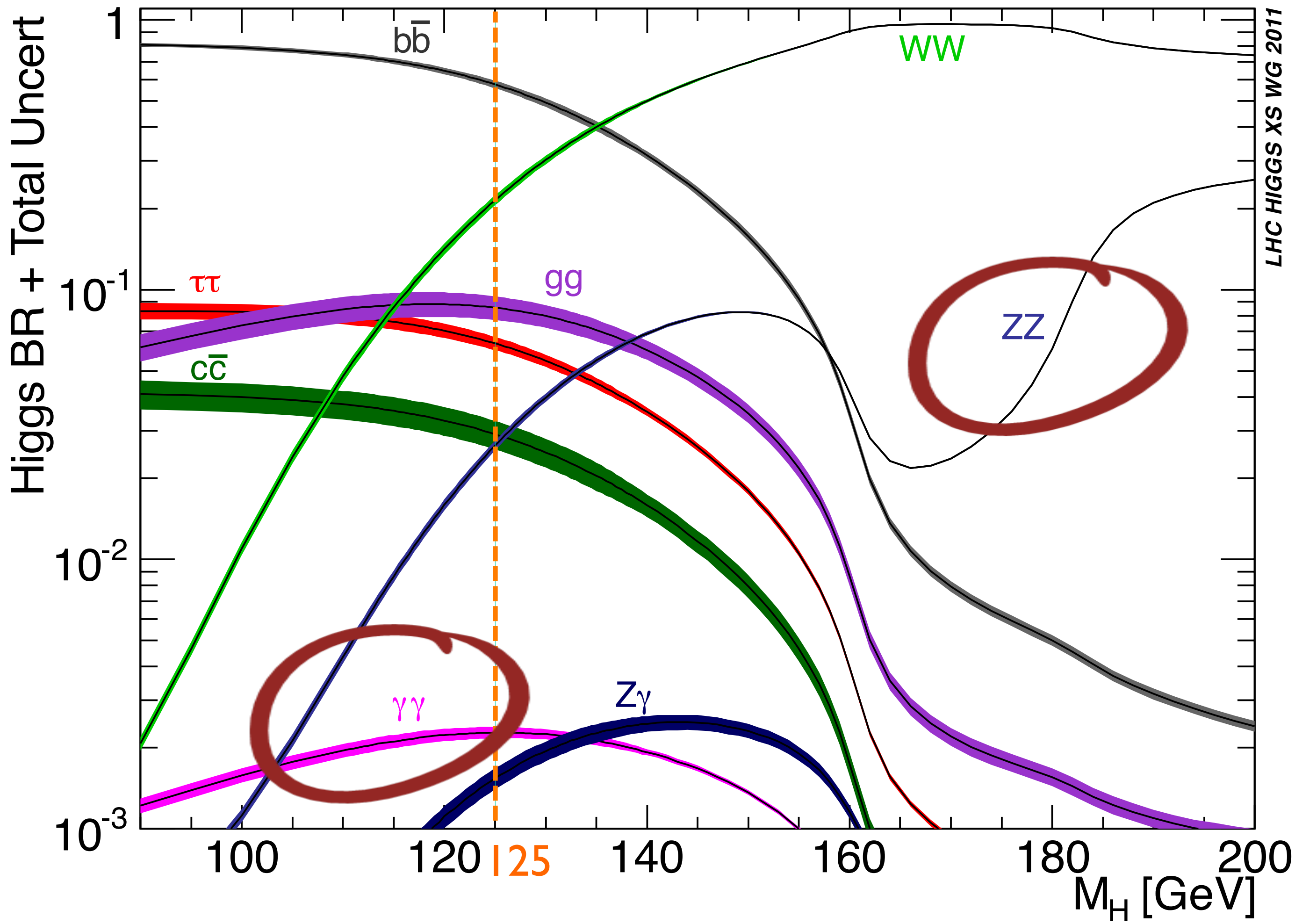
CERN Auditorium, July 4th 2012



Higgs boson

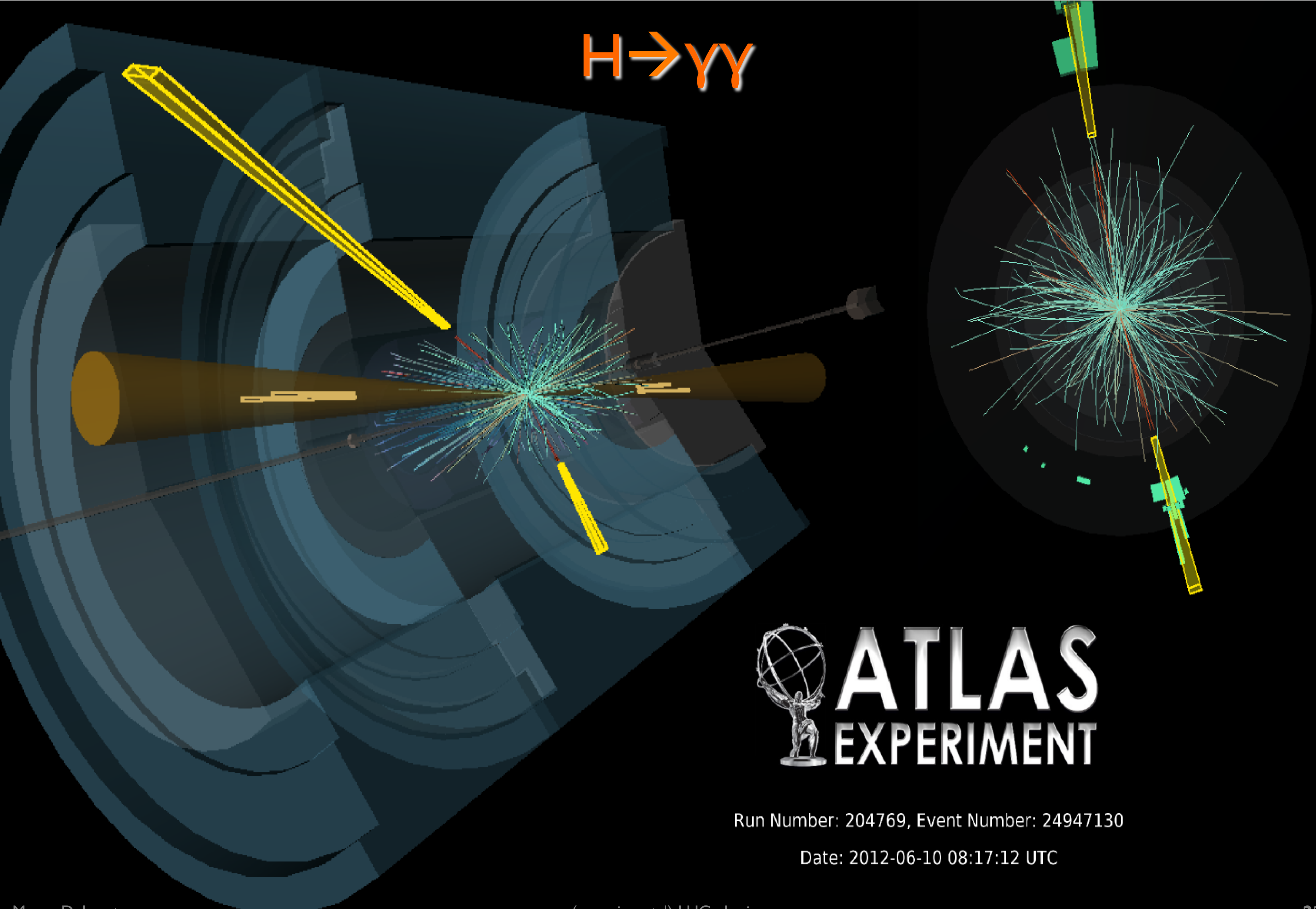
discovery & properties

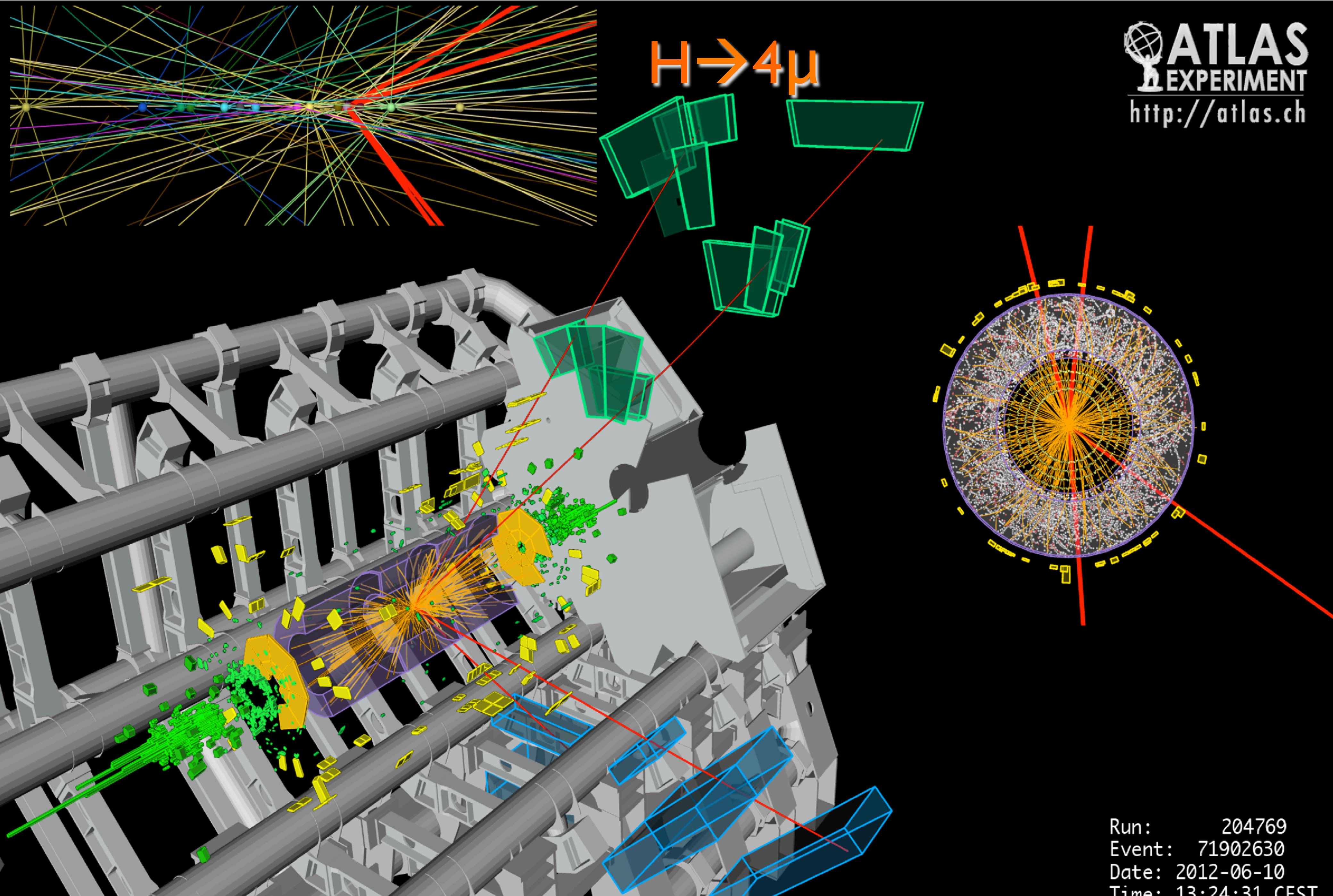
Standard Model Higgs decays



- 1 Higgs every 10 s
- 1 H→γγ every 1.5 h
- 1 H→ZZ→4ℓ(ℓ= e or μ) every 2 days

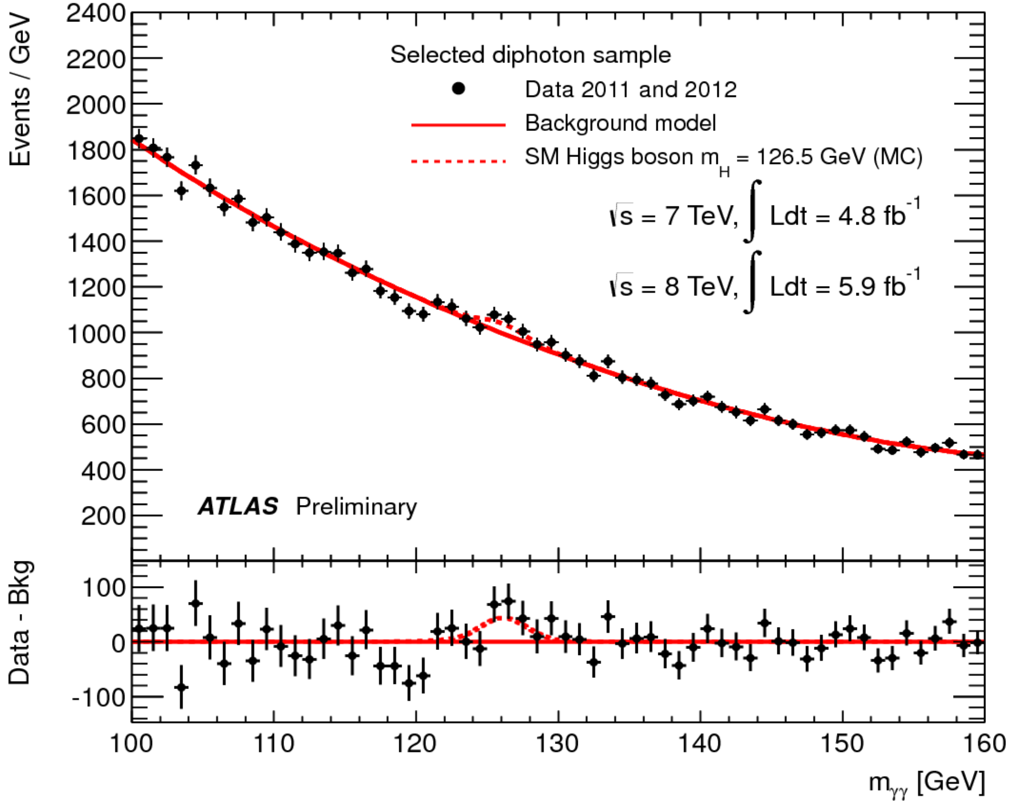
$H \rightarrow \gamma\gamma$



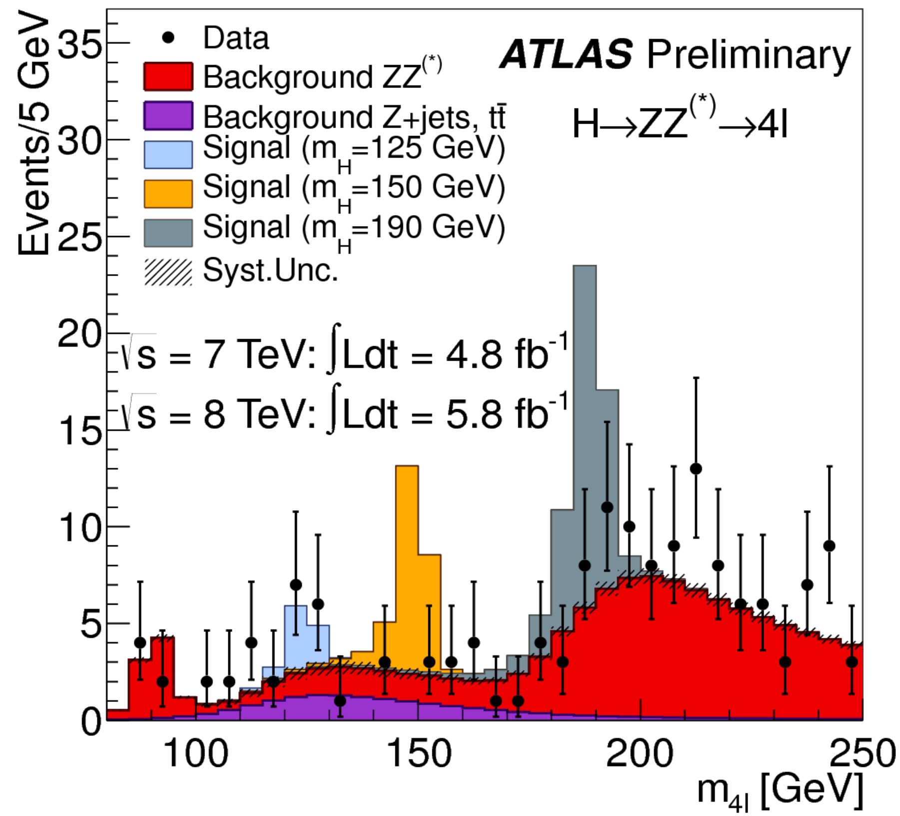

H→4μ
ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

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

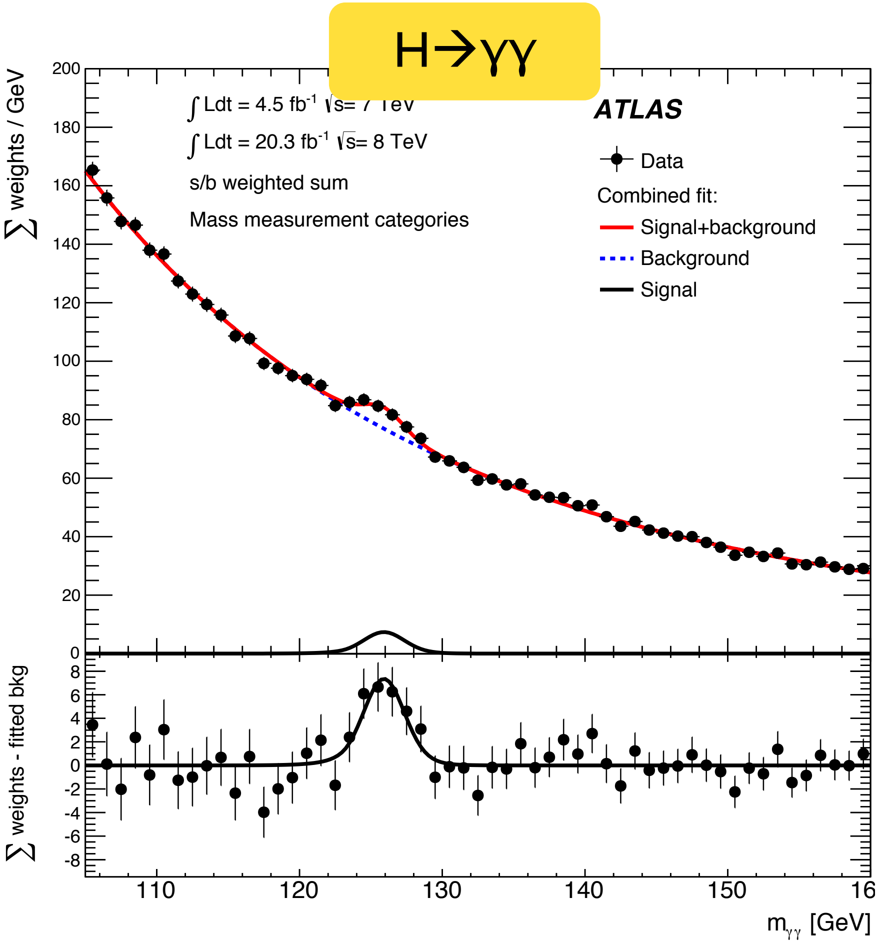
H→γγ

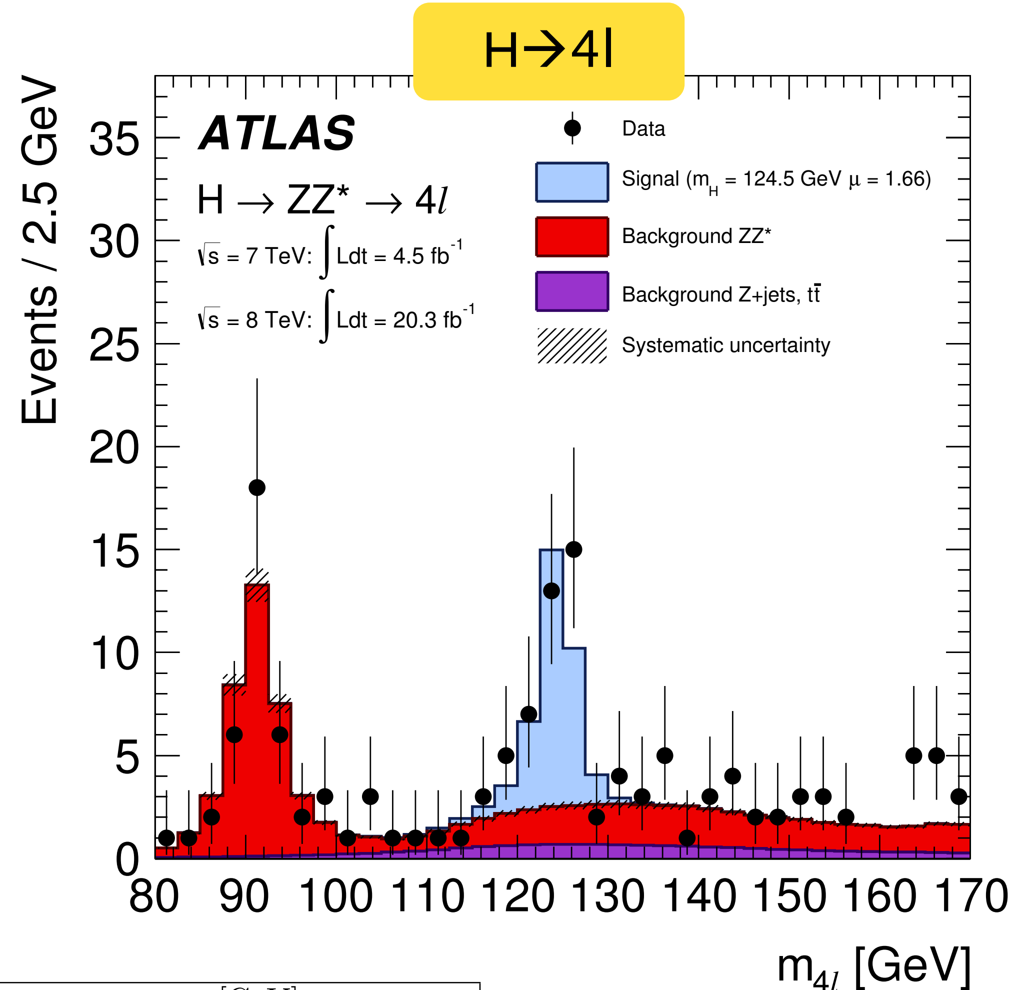


H→4l



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



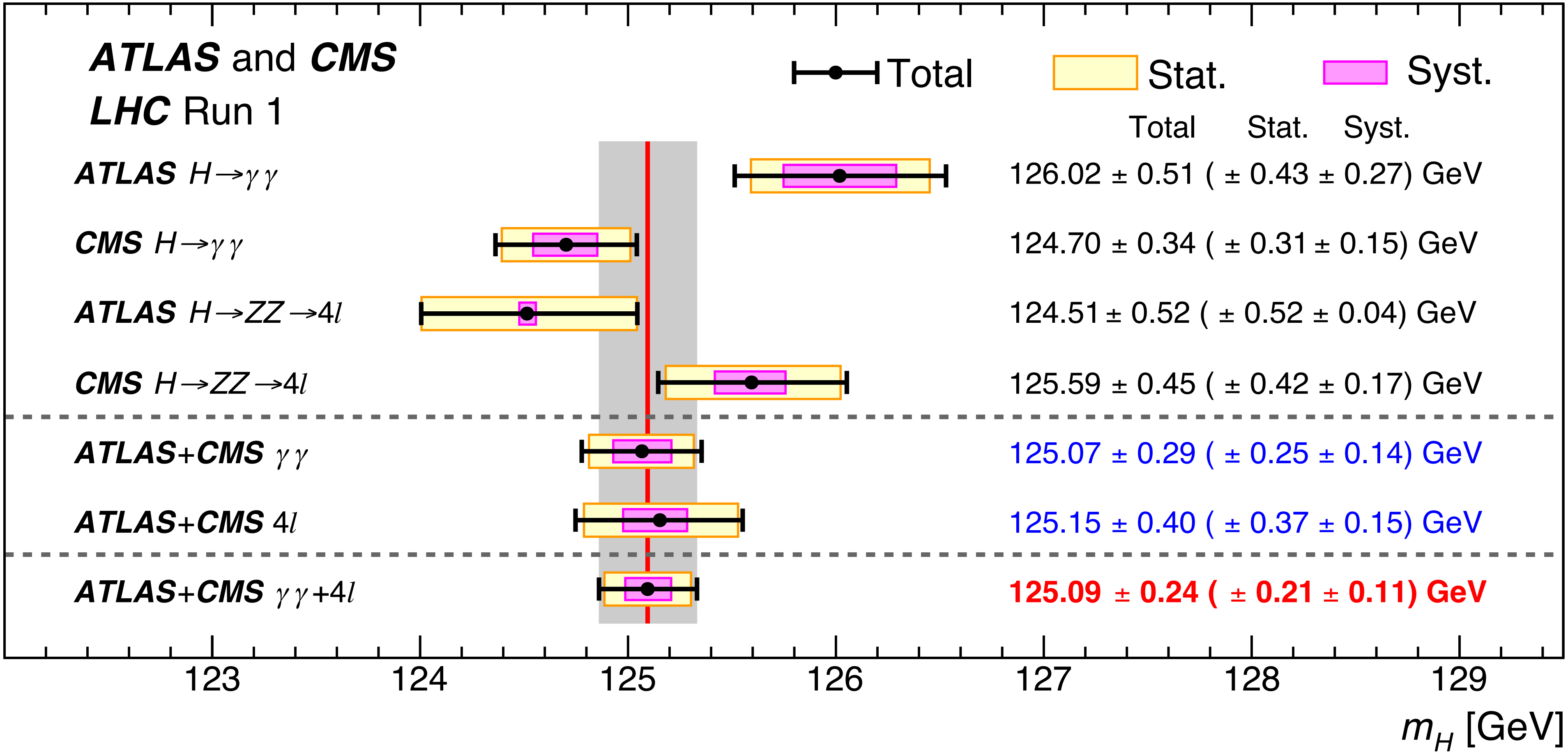


- Signal significance ~ 7 σ
- μ = 1.29 ± 0.30

Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZllll$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

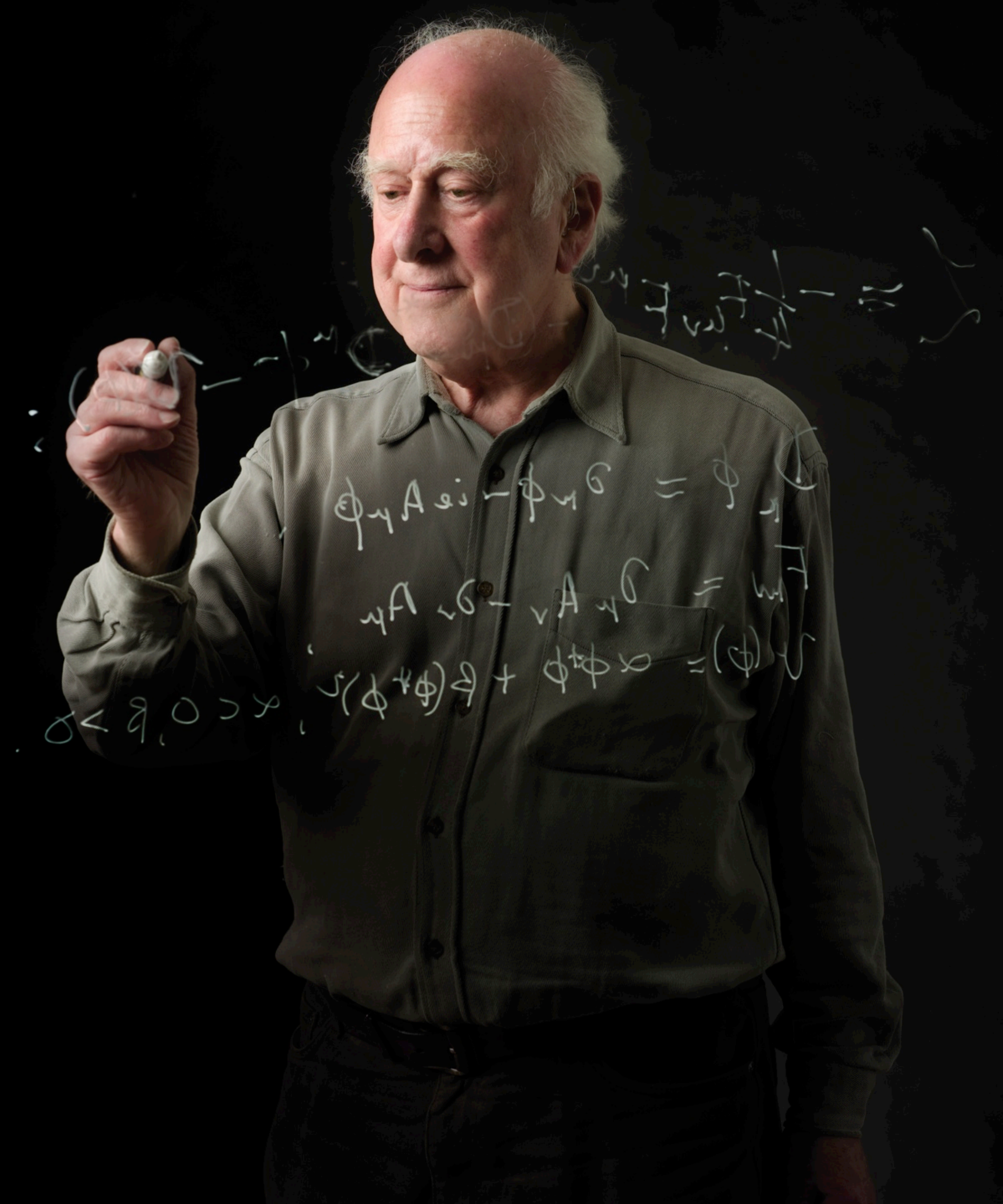
- Signal significance ~ 7 σ
- $\mu = 1.66\ ^{+0.45}_{-0.38}$

Higgs mass



ATLAS and CMS
LHC Run 1
Total
Stat.
Syst.
Total Stat. Syst.
ATLAS H→γγ
126.02 ± 0.51 (± 0.43 ± 0.27) GeV
CMS H→γγ
124.70 ± 0.34 (± 0.31 ± 0.15) GeV
ATLAS H→ZZ→4l
124.51 ± 0.52 (± 0.52 ± 0.04) GeV
CMS H→ZZ→4l
125.59 ± 0.45 (± 0.42 ± 0.17) GeV
ATLAS+CMS γγ
125.07 ± 0.29 (± 0.25 ± 0.14) GeV
ATLAS+CMS 4l
125.15 ± 0.40 (± 0.37 ± 0.15) GeV
ATLAS+CMS γγ+4l
125.09 ± 0.24 (± 0.21 ± 0.11) GeV
123
124
125
126
127
128
129
m_H [GeV]

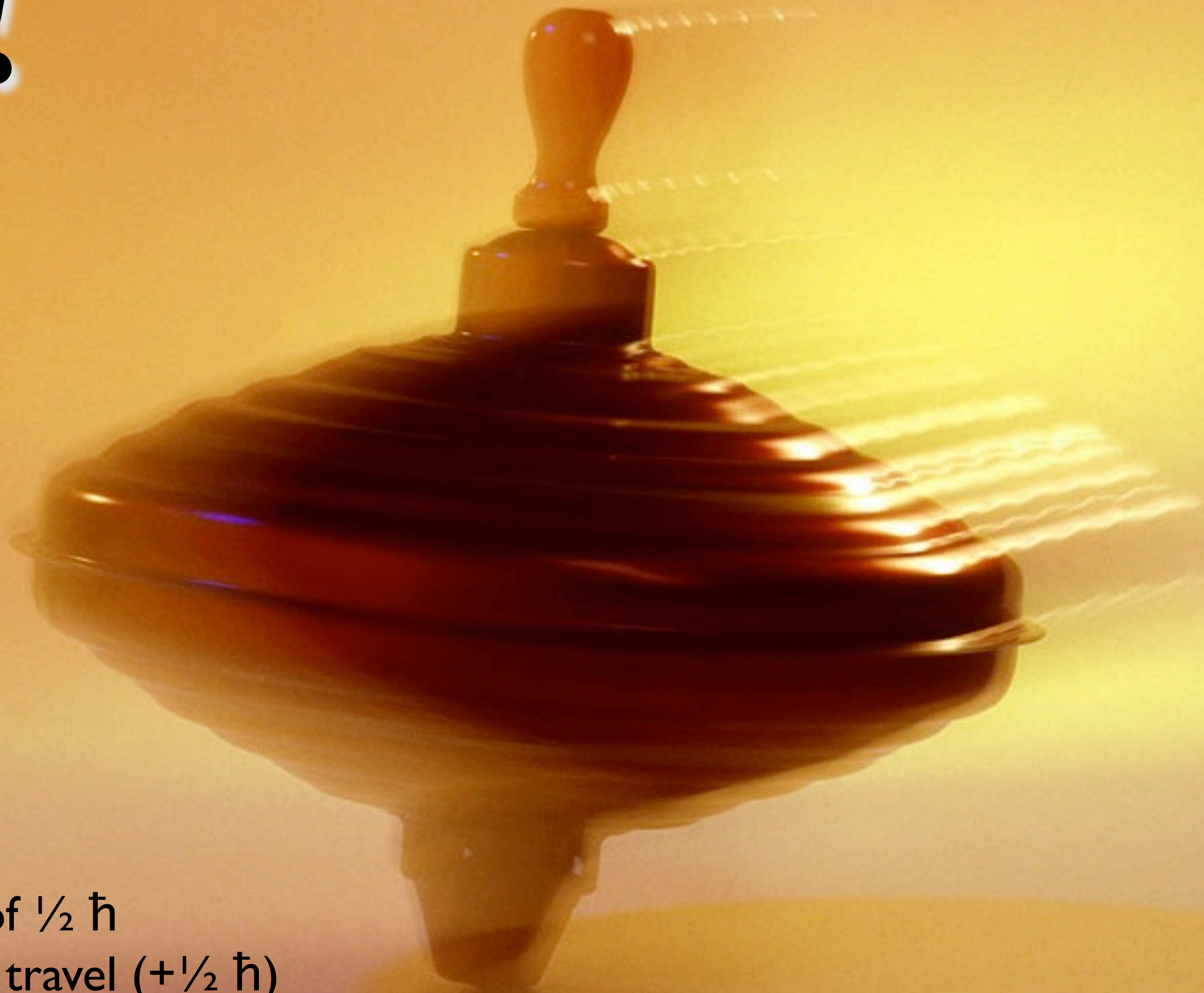
is it the Higgs boson?



Spin!

What's a particle spin?

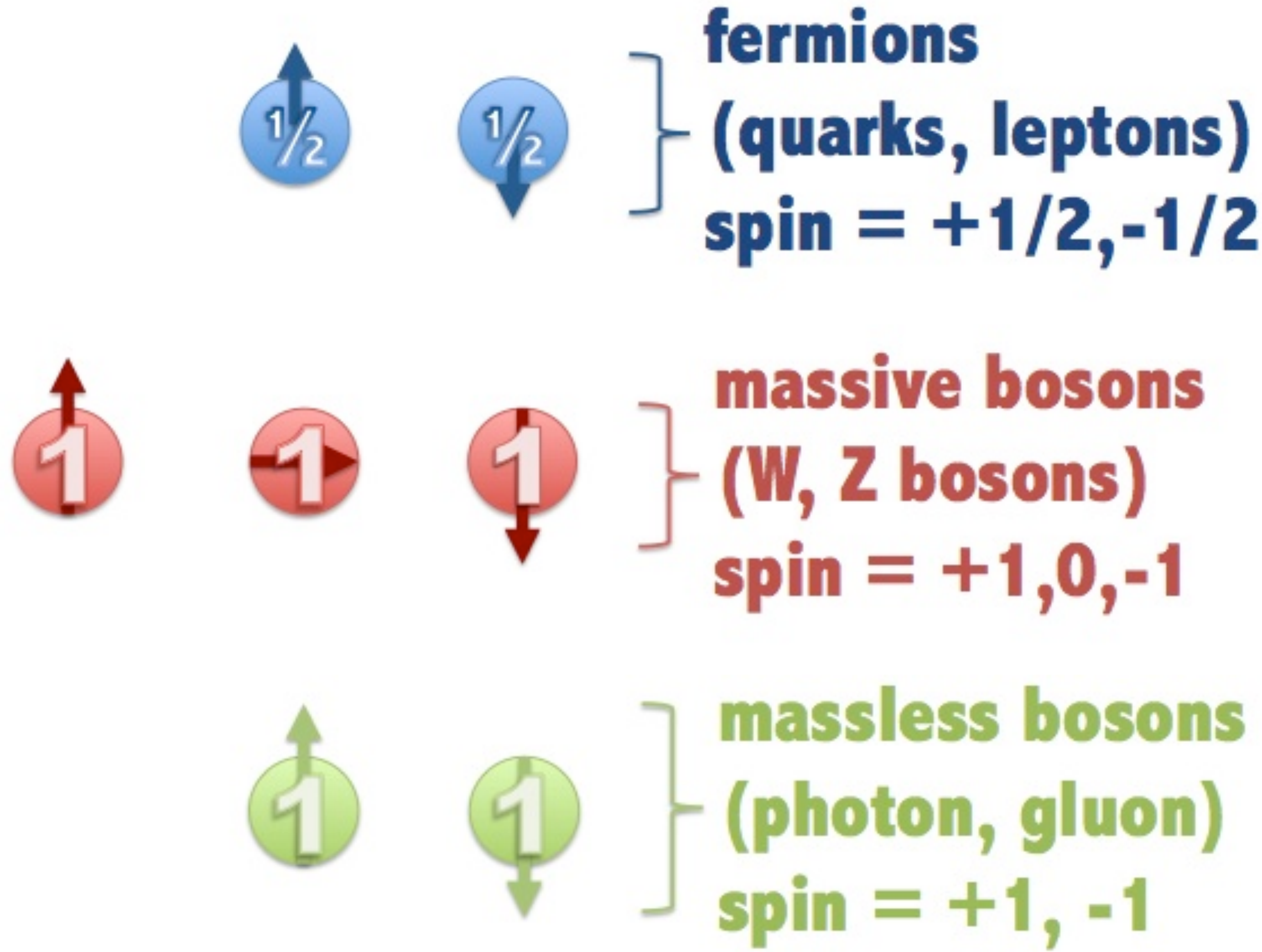
"An *amount of rotation* that is somehow quantized"



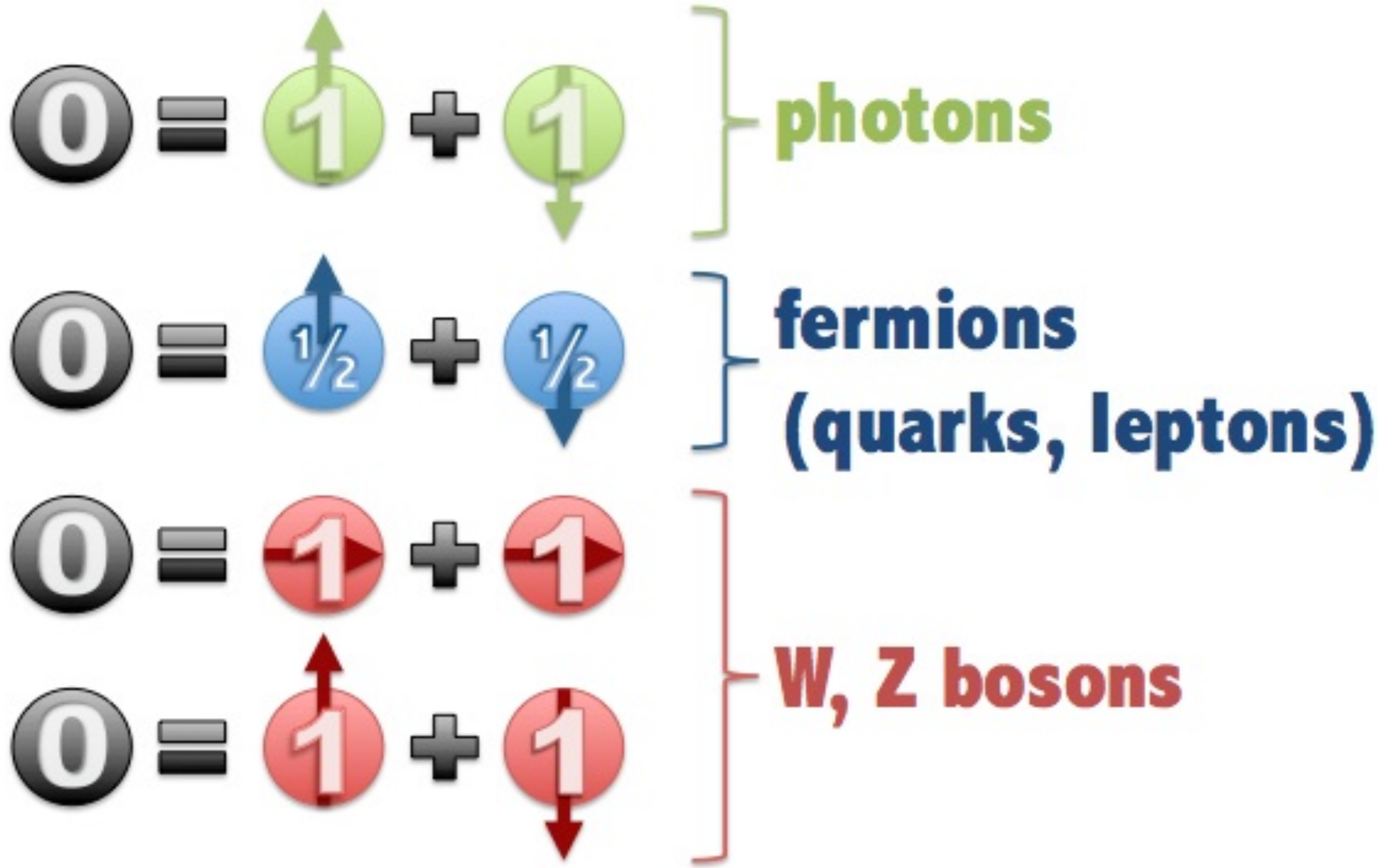
An electron has always an angular momentum of ½ ħ either in its direction of travel (+½ ħ) or opposite to it (-½ ħ)

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

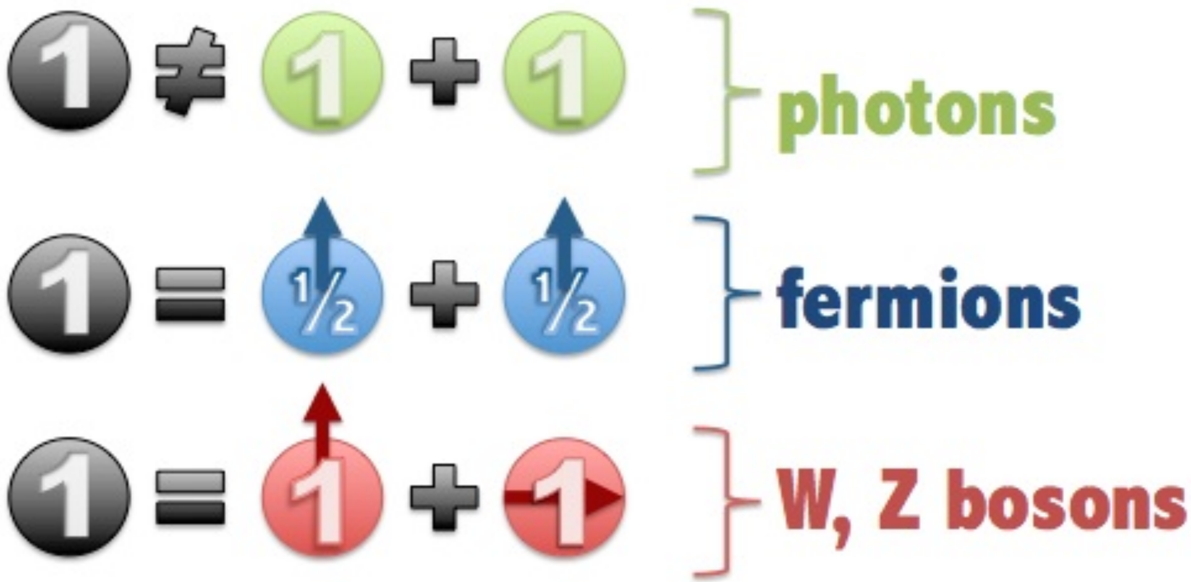
What spin do particles have?



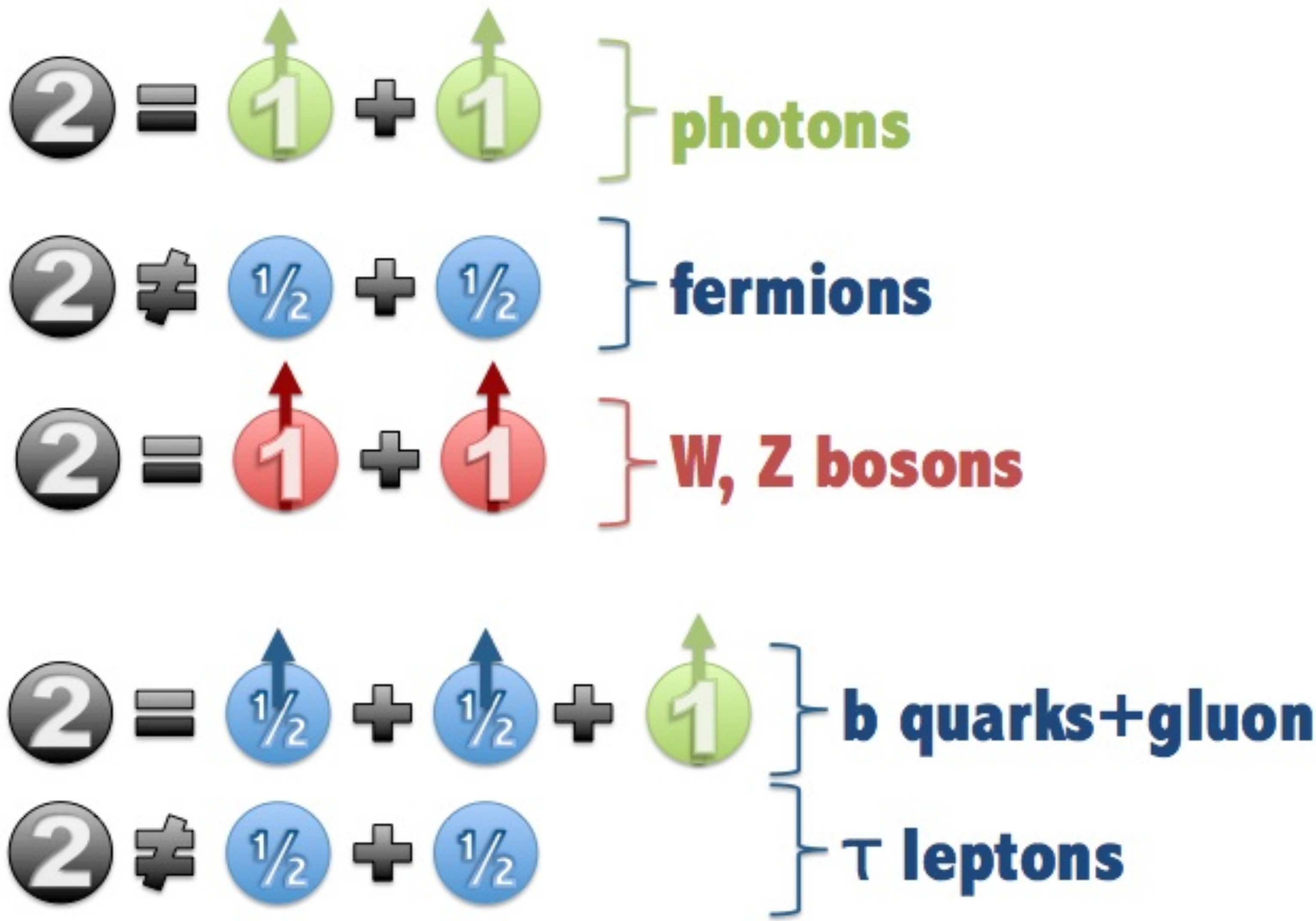
What can a spin 0 particle decay to?



What can a spin 1 particle decay to?



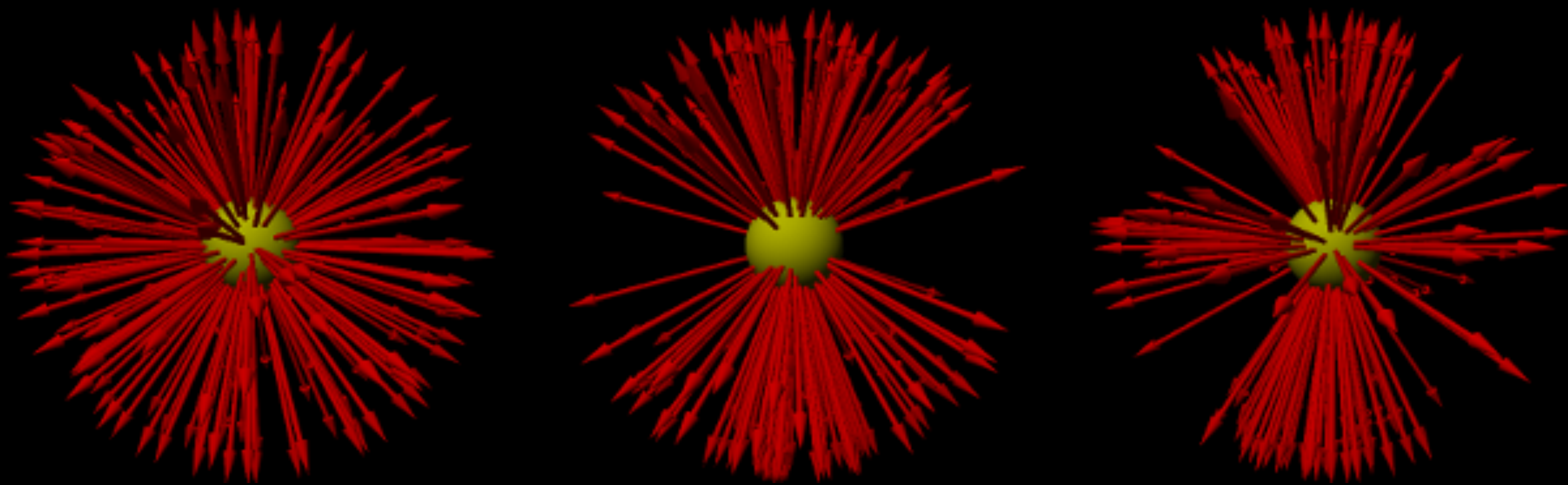
What can a spin 2 particle decay to?



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 spin 1 spin 2

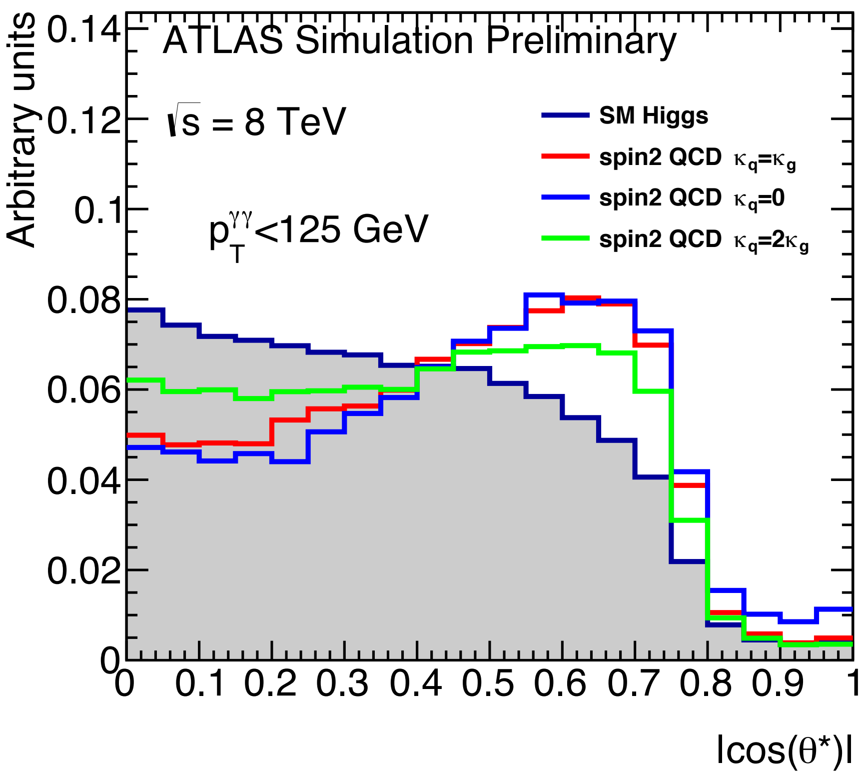
Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

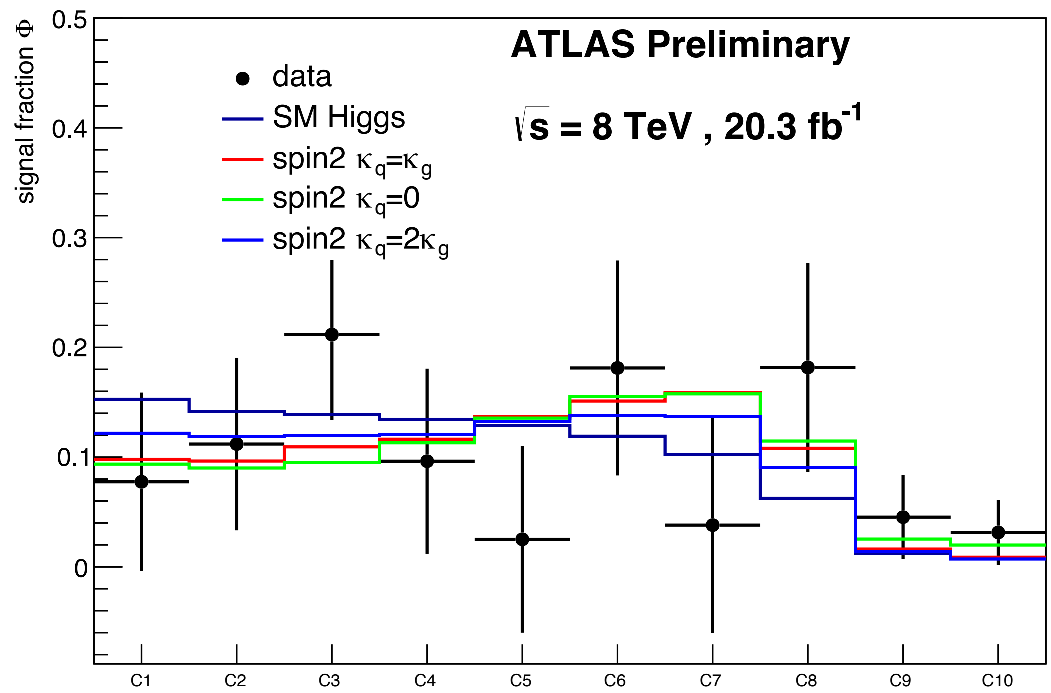
Spin study with H→γγ

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

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

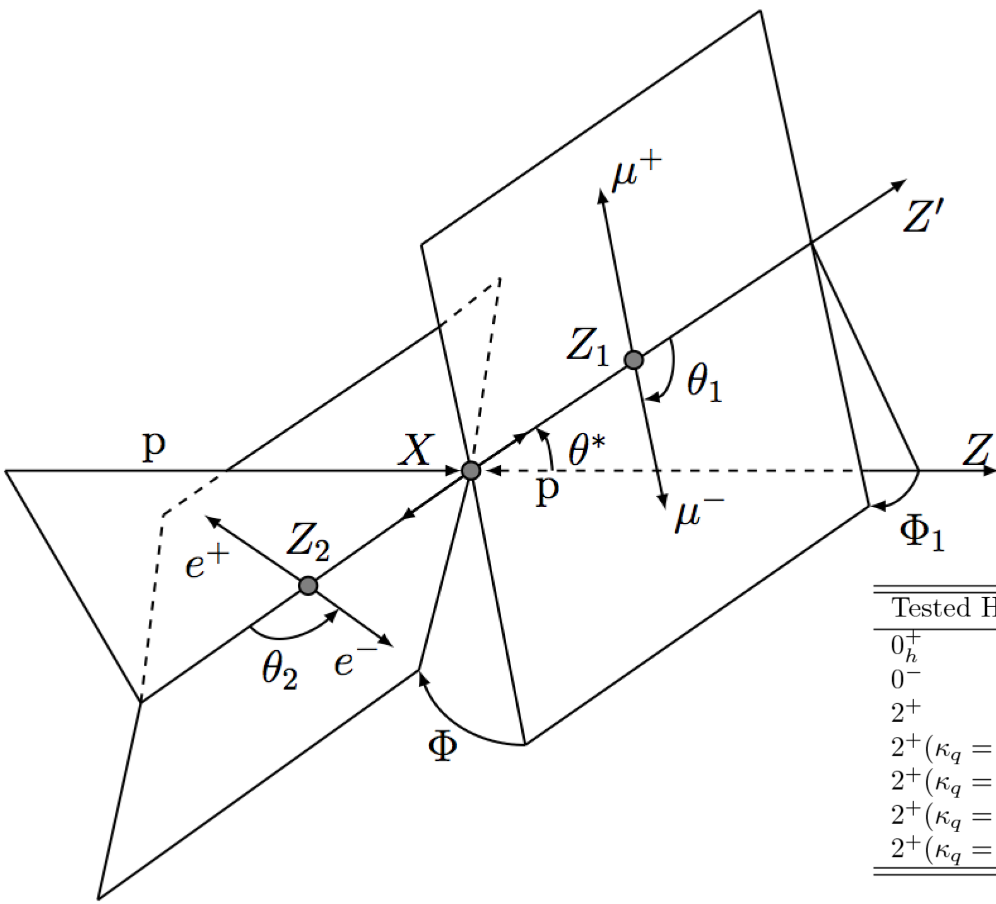
Name	Definition	
C1		$0.0 \leq \lvert\cos\theta^*\rvert < 0.1$
C2		$0.1 \leq \lvert\cos\theta^*\rvert < 0.2$
C3		$0.2 \leq \lvert\cos\theta^*\rvert < 0.3$
C4		$0.3 \leq \lvert\cos\theta^*\rvert < 0.4$
C5	$p_T^{\gamma\gamma} < 125\text{GeV}$ and	$0.4 \leq \lvert\cos\theta^*\rvert < 0.5$
C6		$0.5 \leq \lvert\cos\theta^*\rvert < 0.6$
C7		$0.6 \leq \lvert\cos\theta^*\rvert < 0.7$
C8		$0.7 \leq \lvert\cos\theta^*\rvert < 0.8$
C9		$0.8 \leq \lvert\cos\theta^*\rvert < 0.9$
C10		$0.9 \leq \lvert\cos\theta^*\rvert < 1.0$

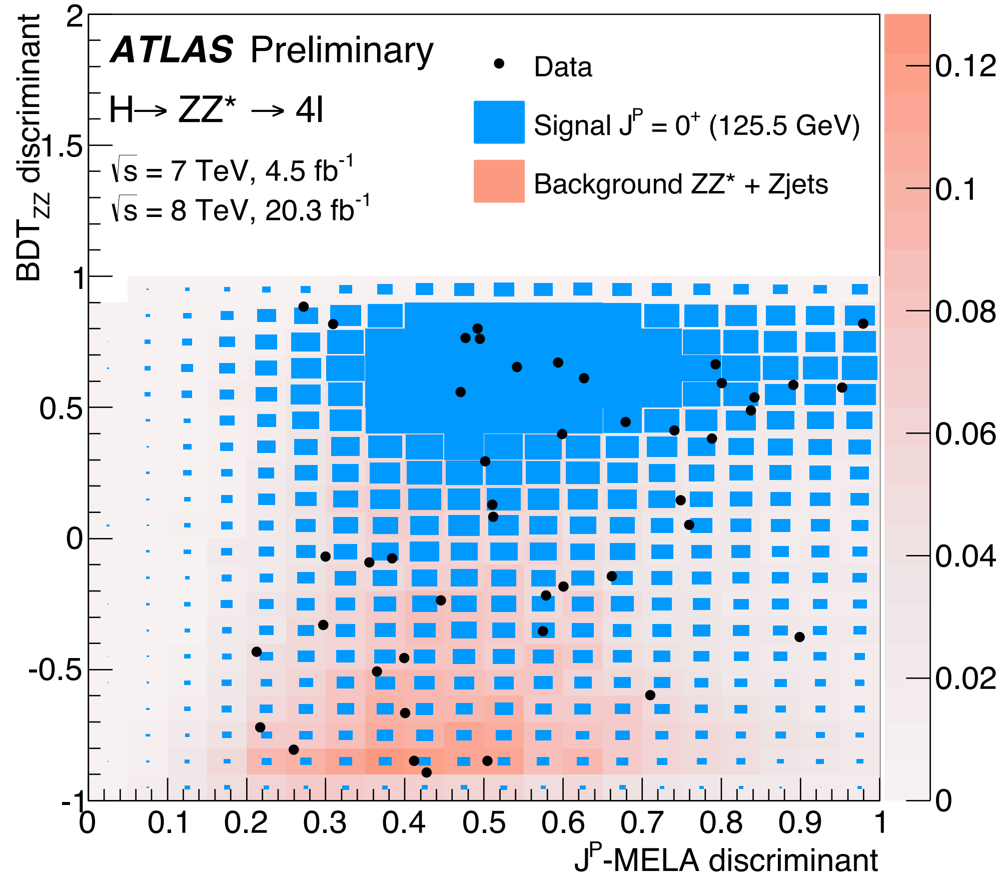




Spin study with H→4l

- Sensitive variables
  - ✓ Intermediate boson masses: m_{Z1}, m_{Z2}
  - ✓ Z_1 production angle: $\theta*$
  - ✓ 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





Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

The Higgs boson or *a* Higgs boson?

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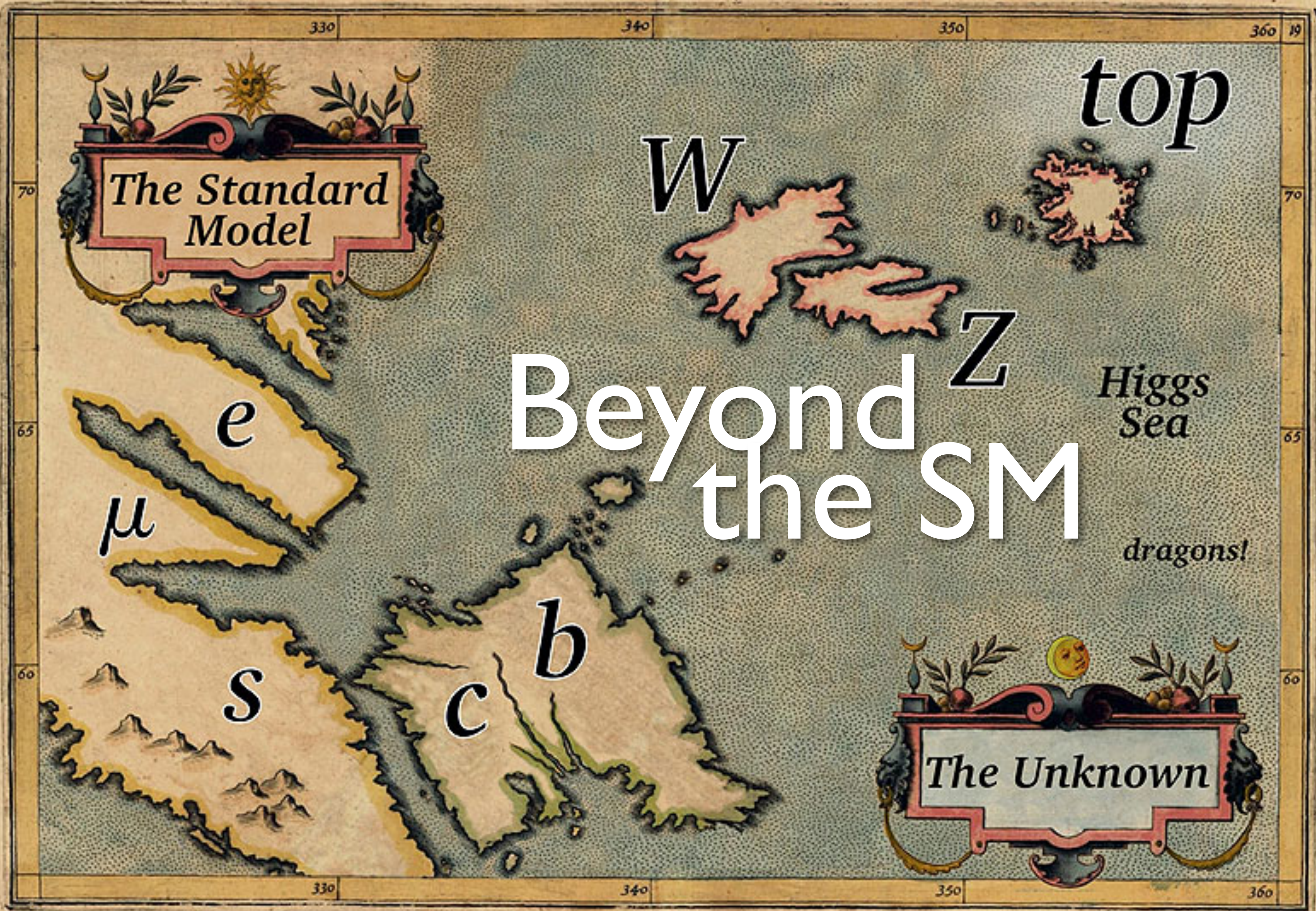
New results indicate that particle discovered at CERN is a Higgs boson

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.


330
340
350
360
19
The Standard Model
top
W
Z
Higgs Sea
Beyond the SM
e
μ
dragons!
b
s
c
The Unknown
70
65
60

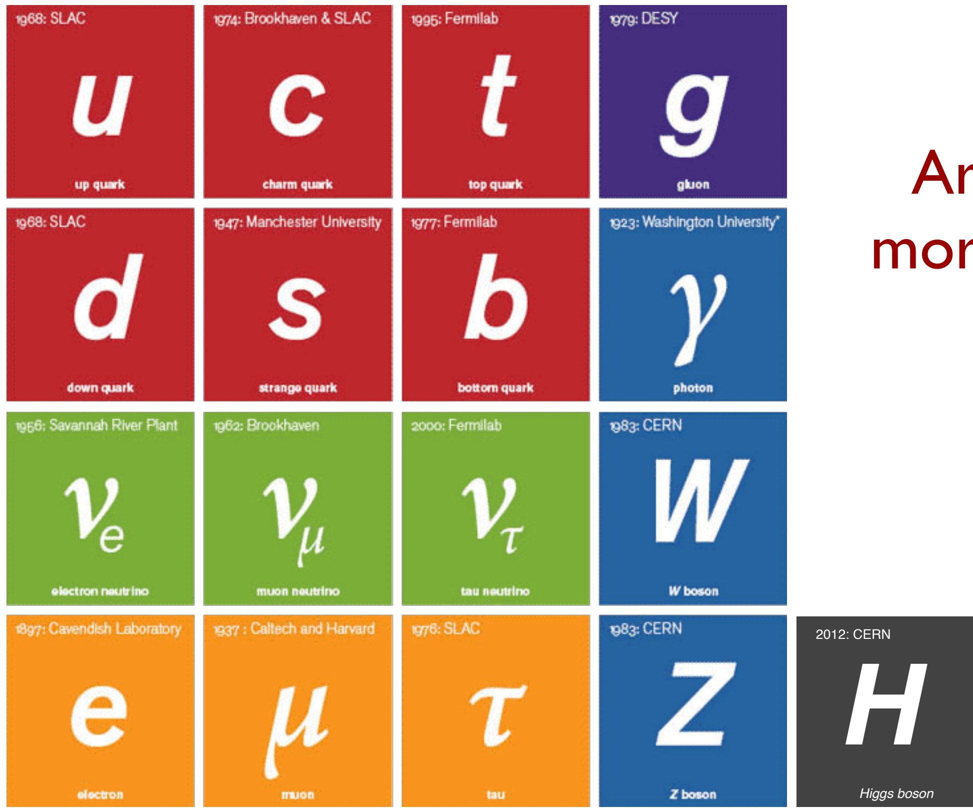
Many unanswered questions…

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?

How do neutrinos get mass?



Are there more forces?

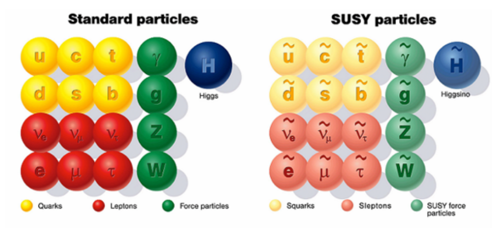
What keeps the Higgs mass so small?

How do we incorporate gravity?

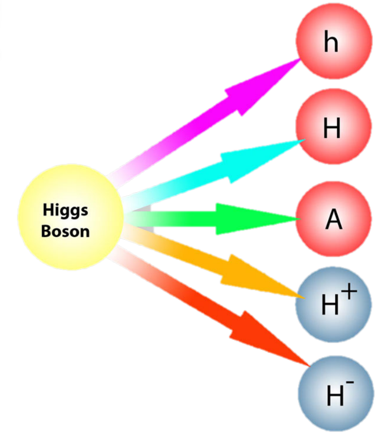
What is Dark Matter?

… as many possible answers to probe!

Super-symmetry?



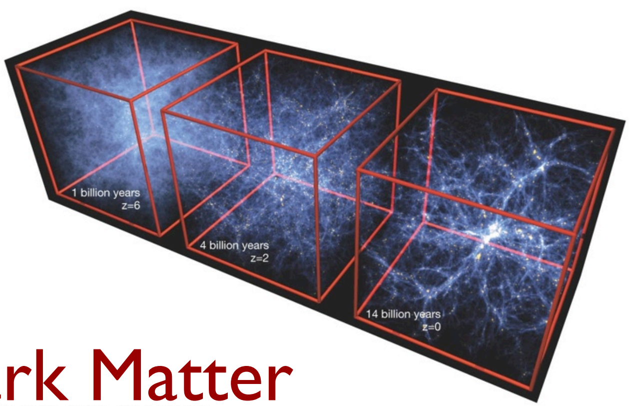
Extended Higgs sector?



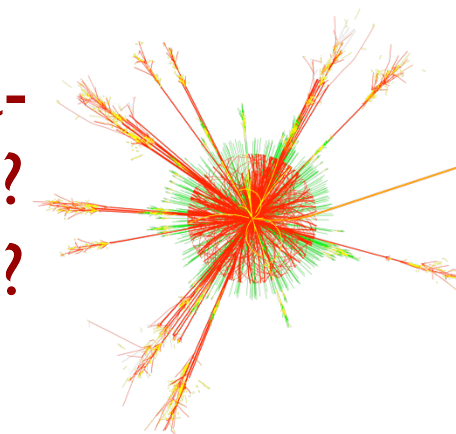
New heavy bosons?

Any new theory need to agree with the SM!

Composite quark and leptons?

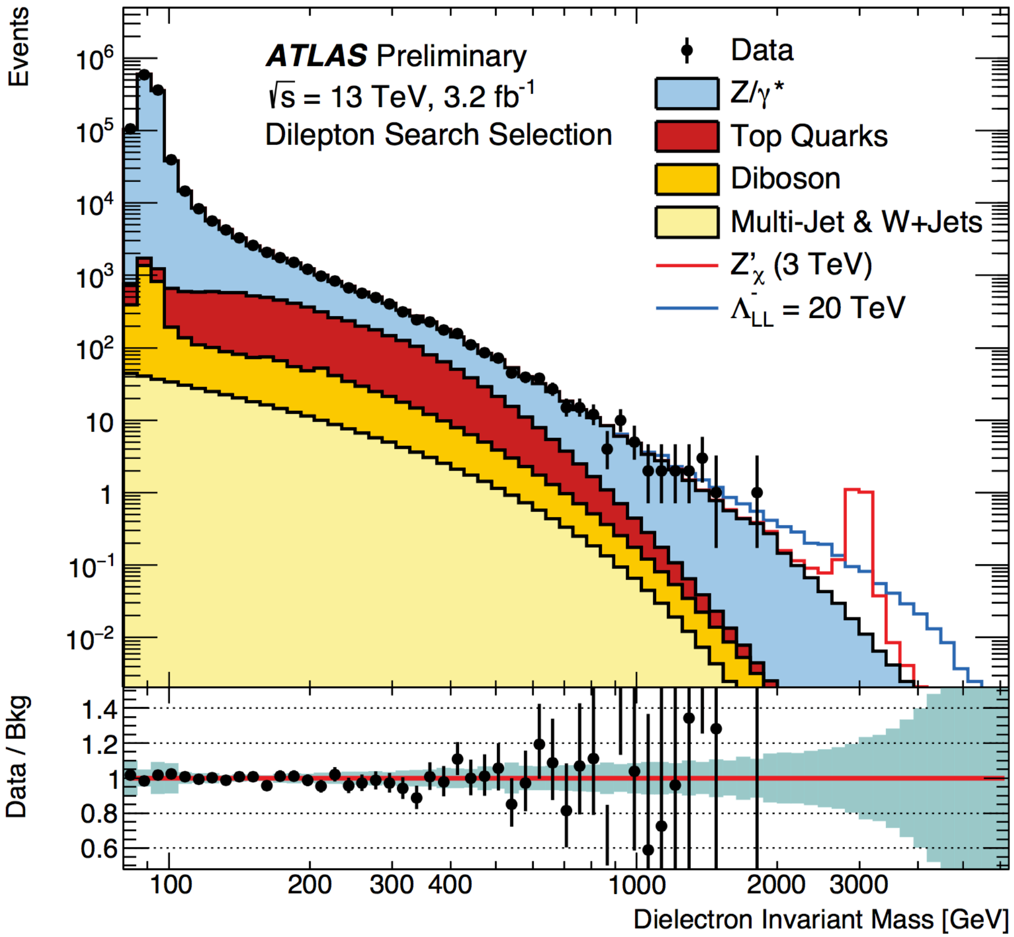


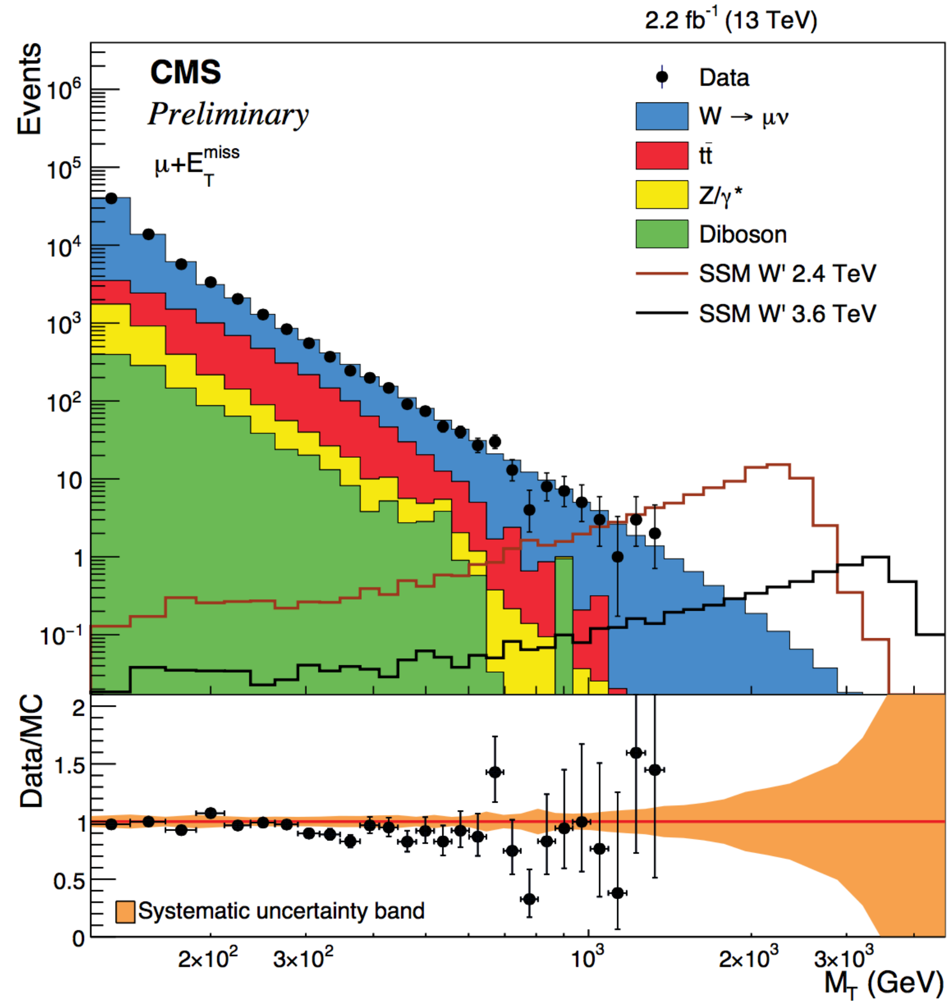
Dark Matter particles?



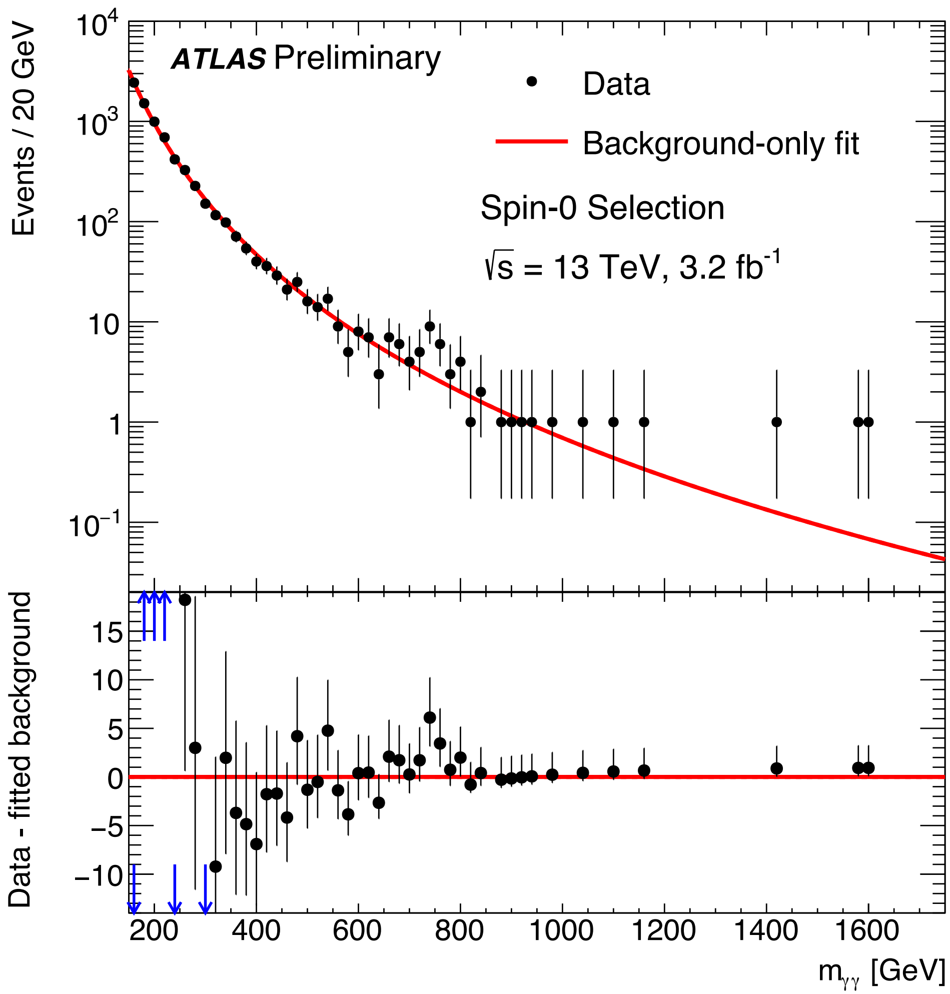
Large extra-dimensions? Black holes? Gravitons?

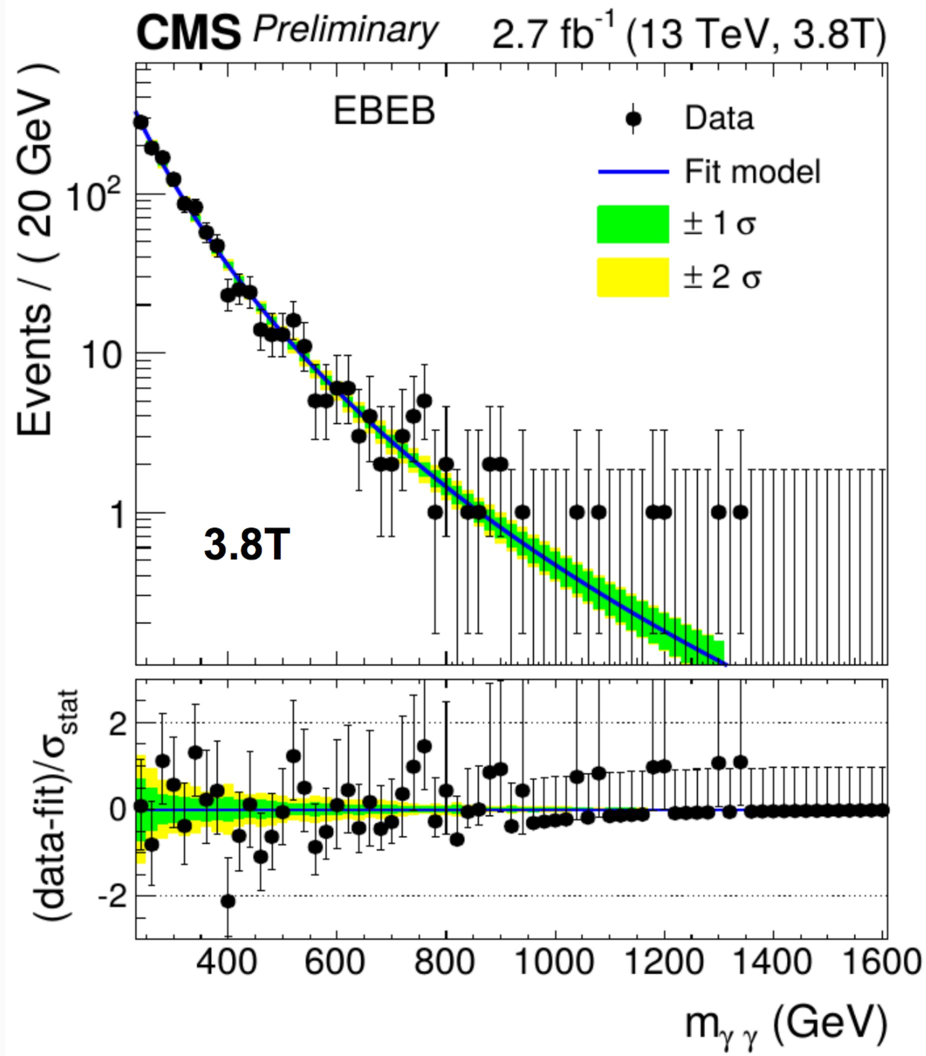
Example: search for a new gauge bosons





Example: search for an heavier Higgs, or for a graviton

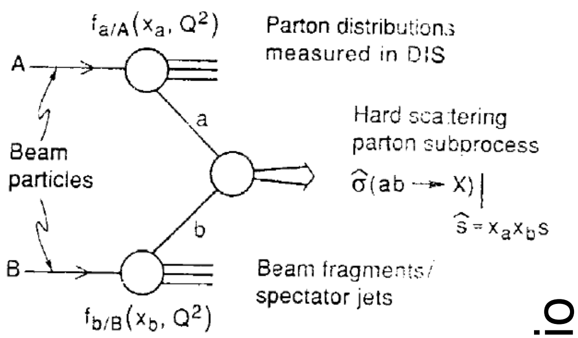


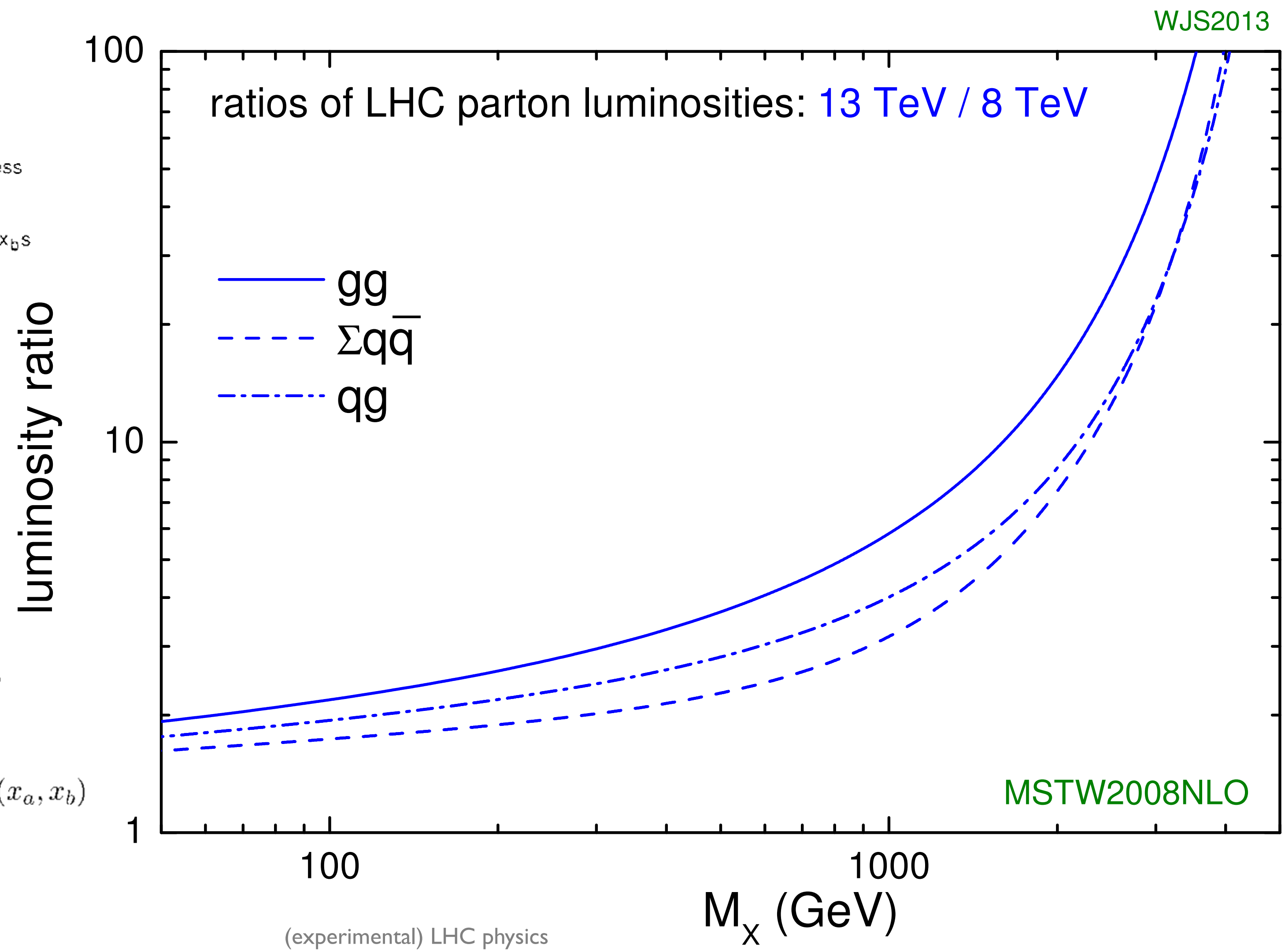


It's the right time to join!

Hugely increased potential for discovery of heavy particles at 13 TeV

Perfect occasion for young motivated physicists: join the search!





$$\sqrt{\hat{s}} = \sqrt{x_a x_b s}$$

$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x, Q^2) f_b(x, Q^2) \hat{\sigma}_{ab}(x_a, x_b)$$

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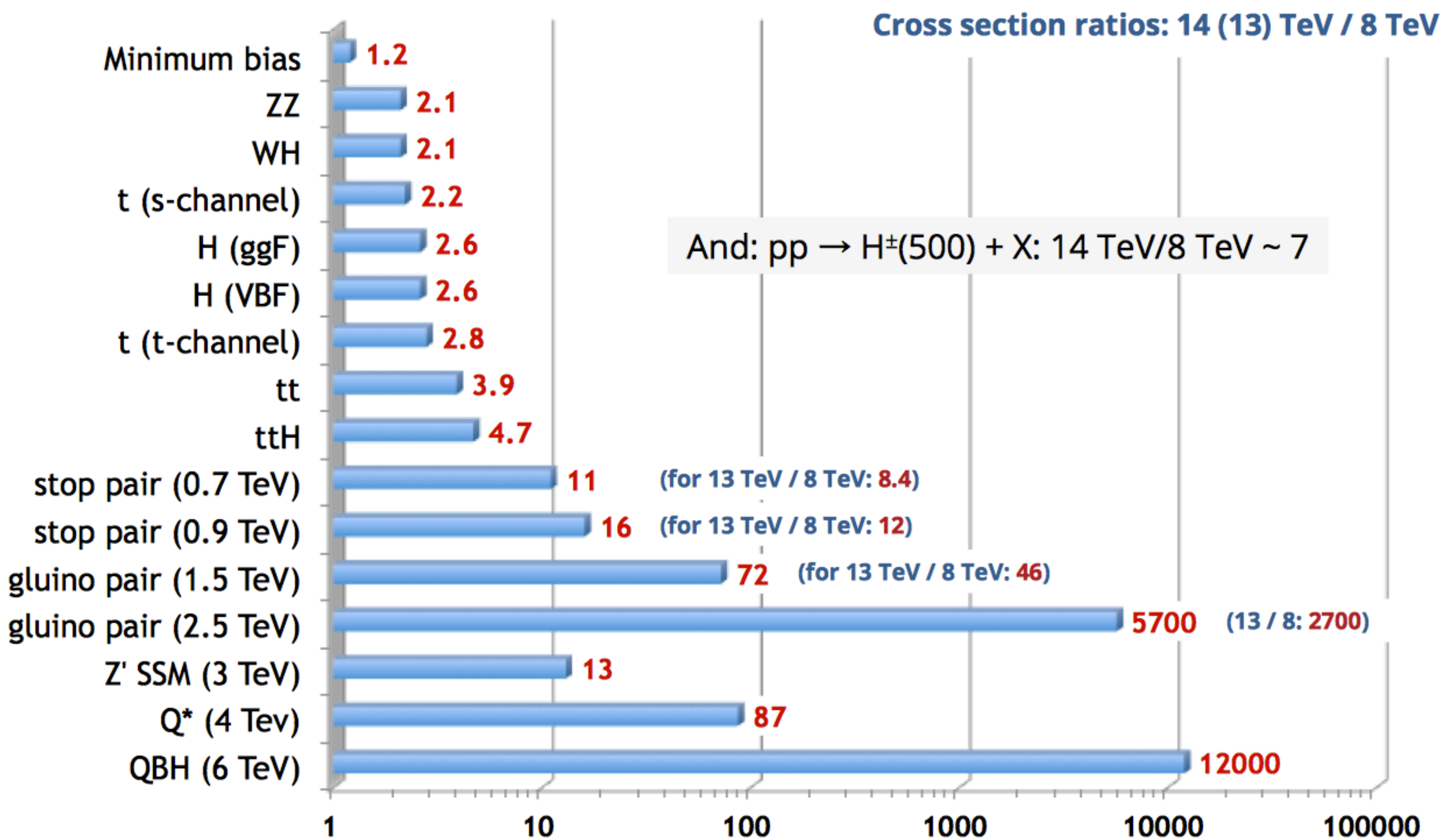
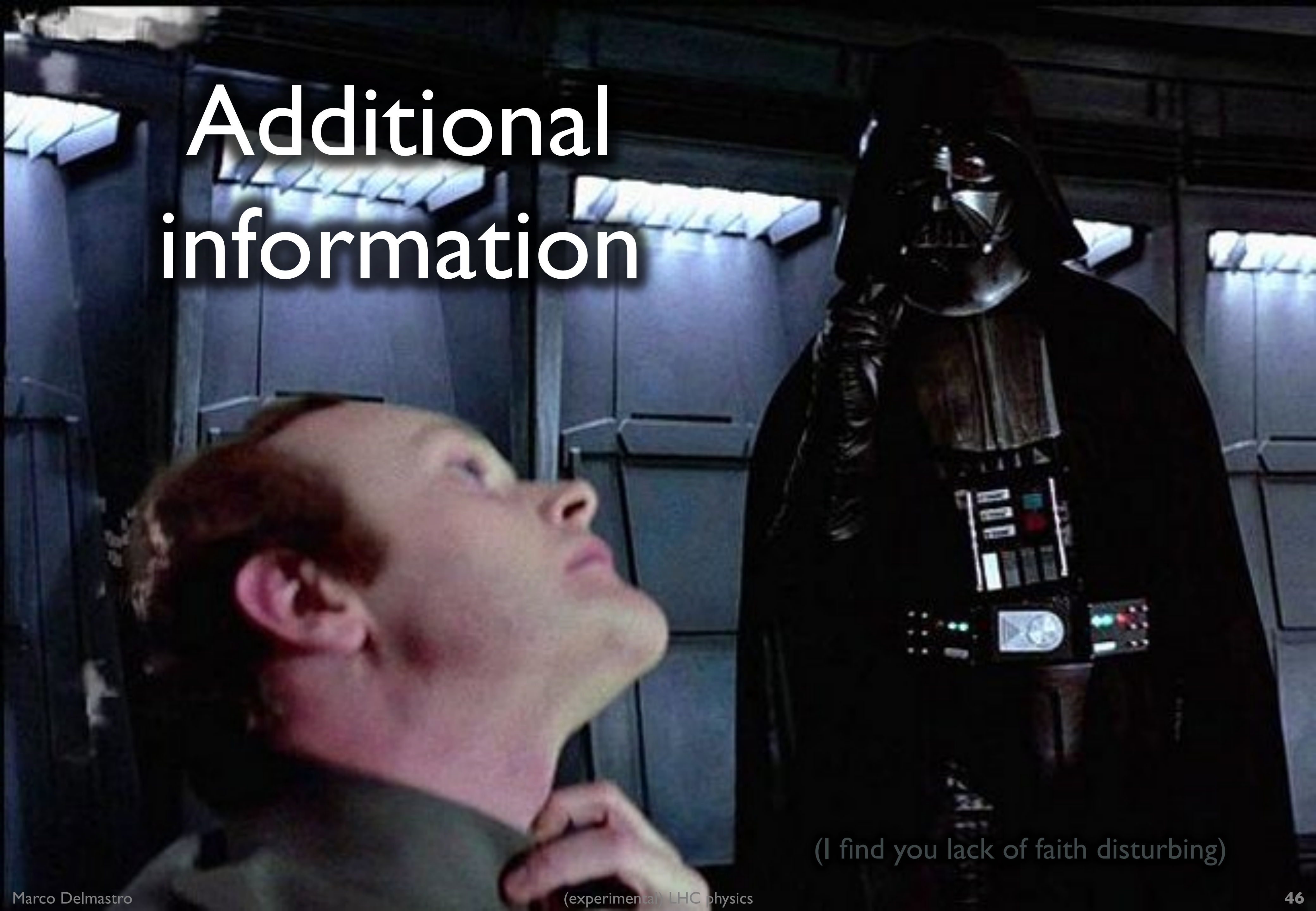


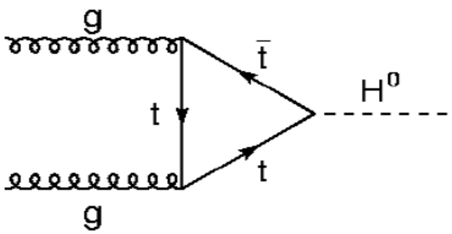

"That's all Folks!"

Additional information

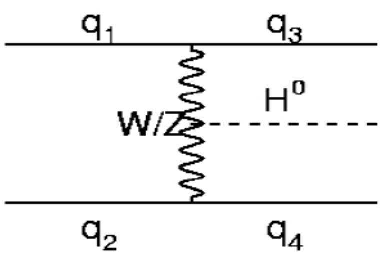


(I find you lack of faith disturbing)

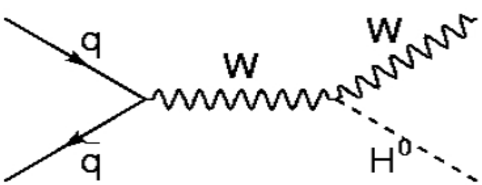
Standard Model Higgs production at the LHC



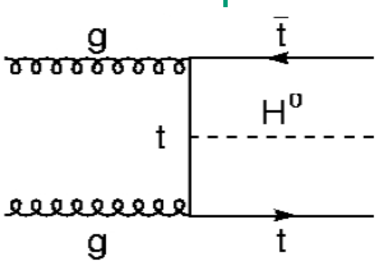
gluon fusion (ggF)



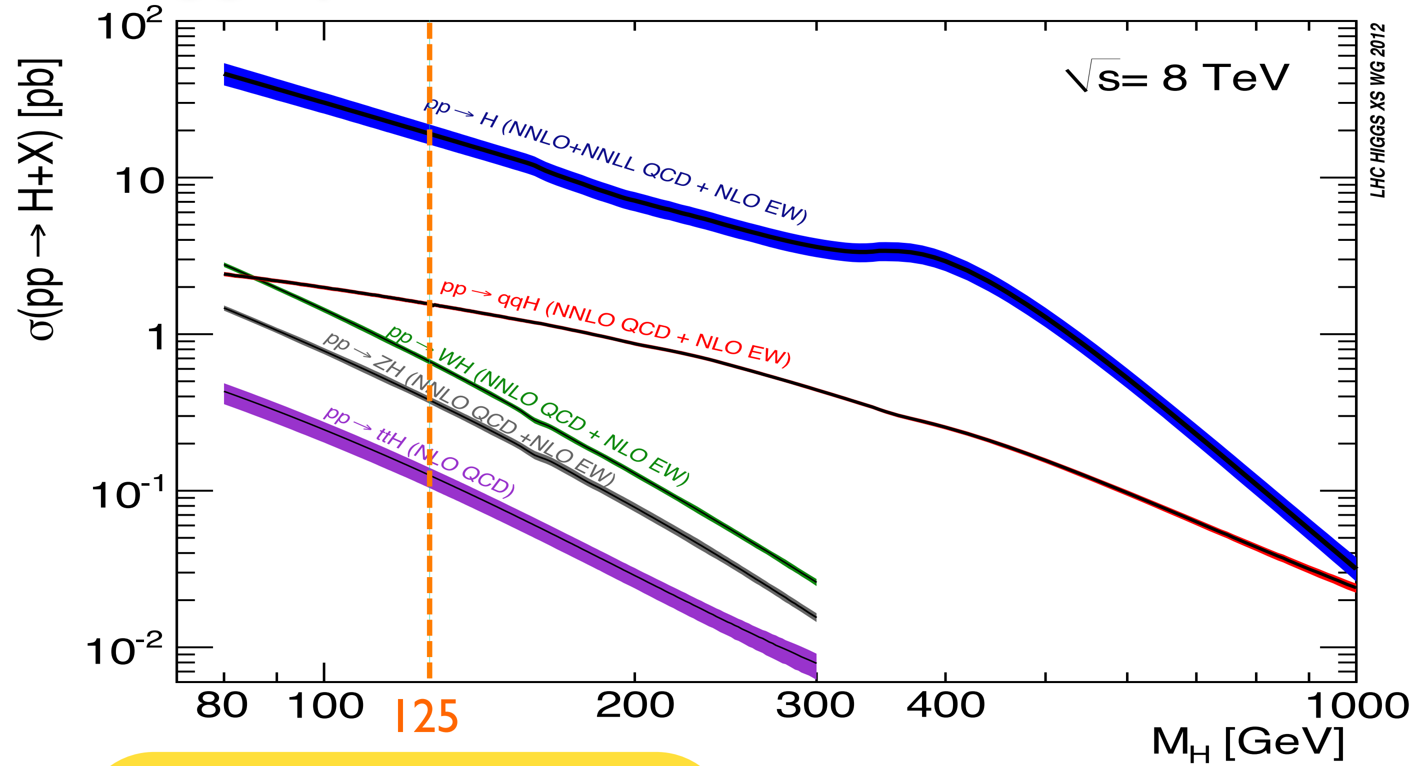
Vector-Boson-Fusion (VBF)



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