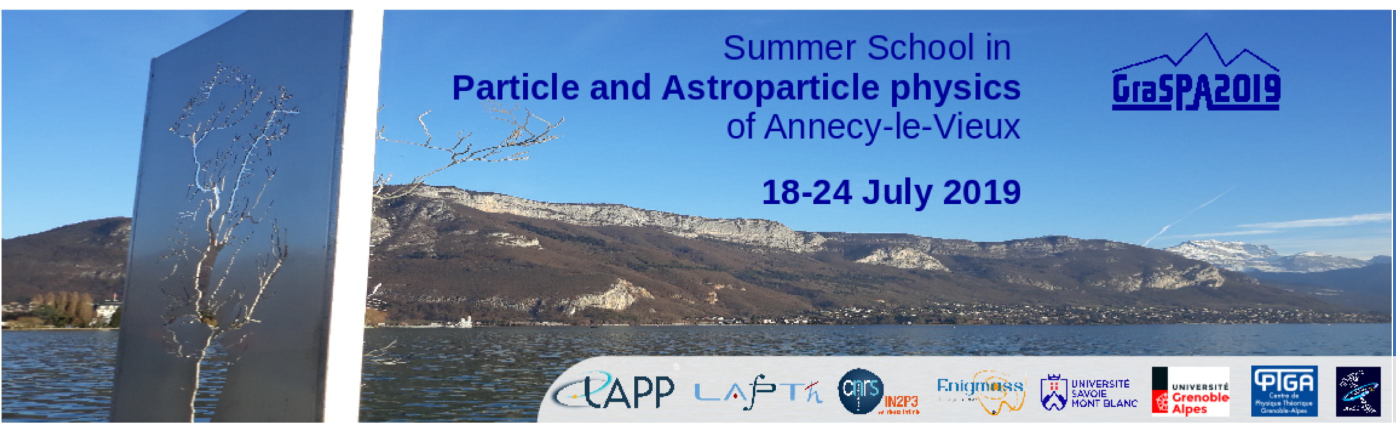
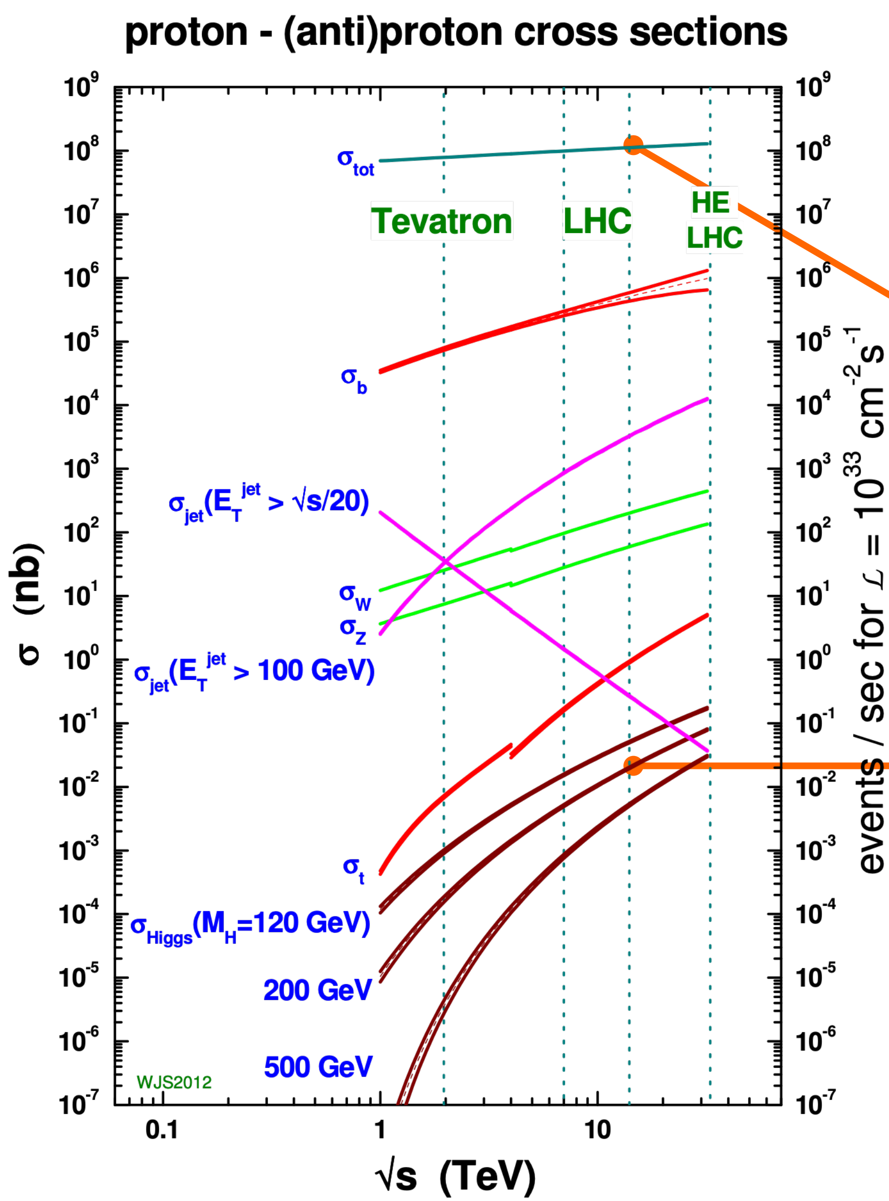
(experimental) LHC physics



2. { how to search for a new particle }

Marco Delmastro

Interesting processes are rare!



1 nb = 10^{-33} cm^2

σ_{tot} (13 TeV) = 10^8 nb

σ_H (13 TeV) = 0.05 nb

LHC instantaneous luminosity L = 1×10^{34} cm^{-2}s^{-1}

inelastic *pp* collisions

10^9 events/s

$\sim10^{10}$

10^{-1} events/s

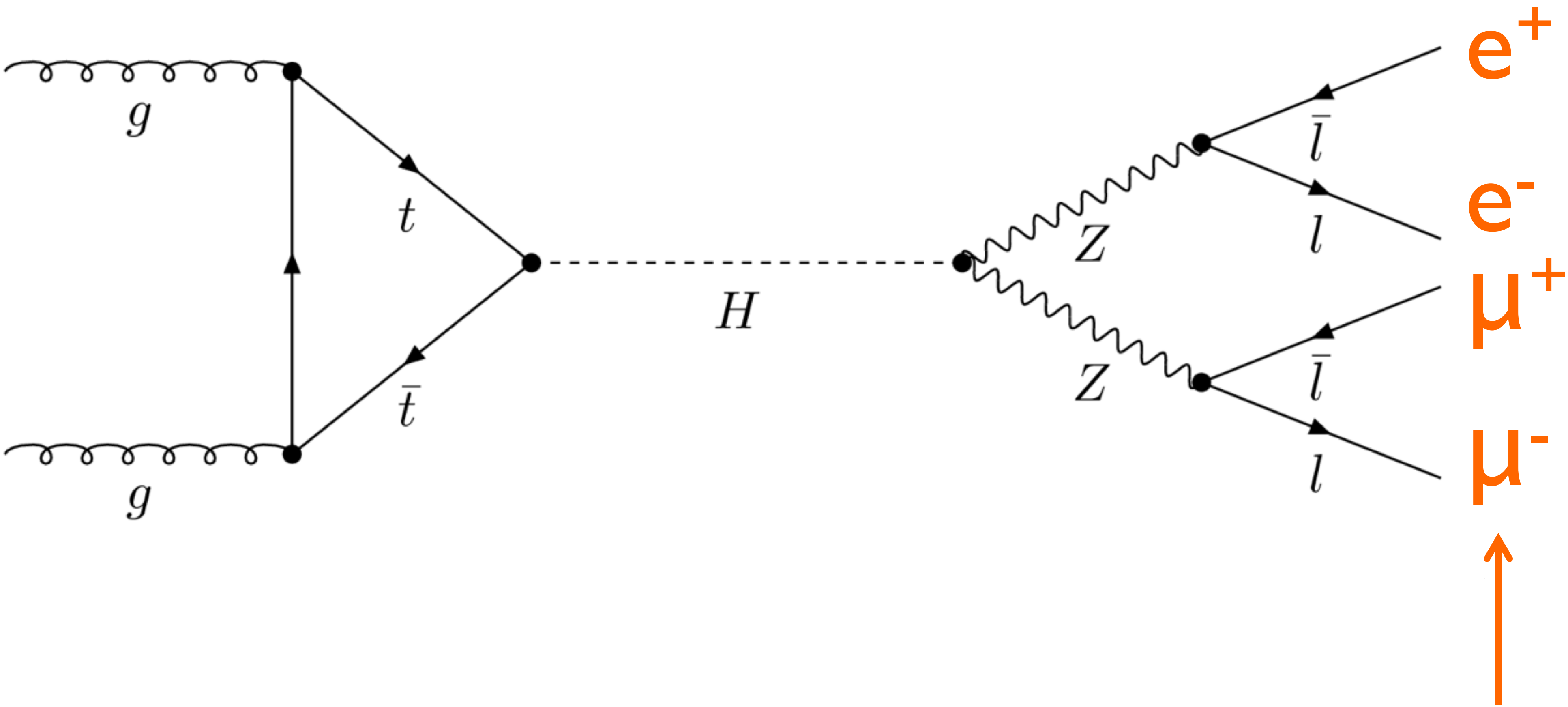
~ 1 Higgs boson every 2 seconds

[m_H ~ 125 GeV]

0.2% H → γγ

1.5% H → ZZ

There is no Higgs-boson detector!

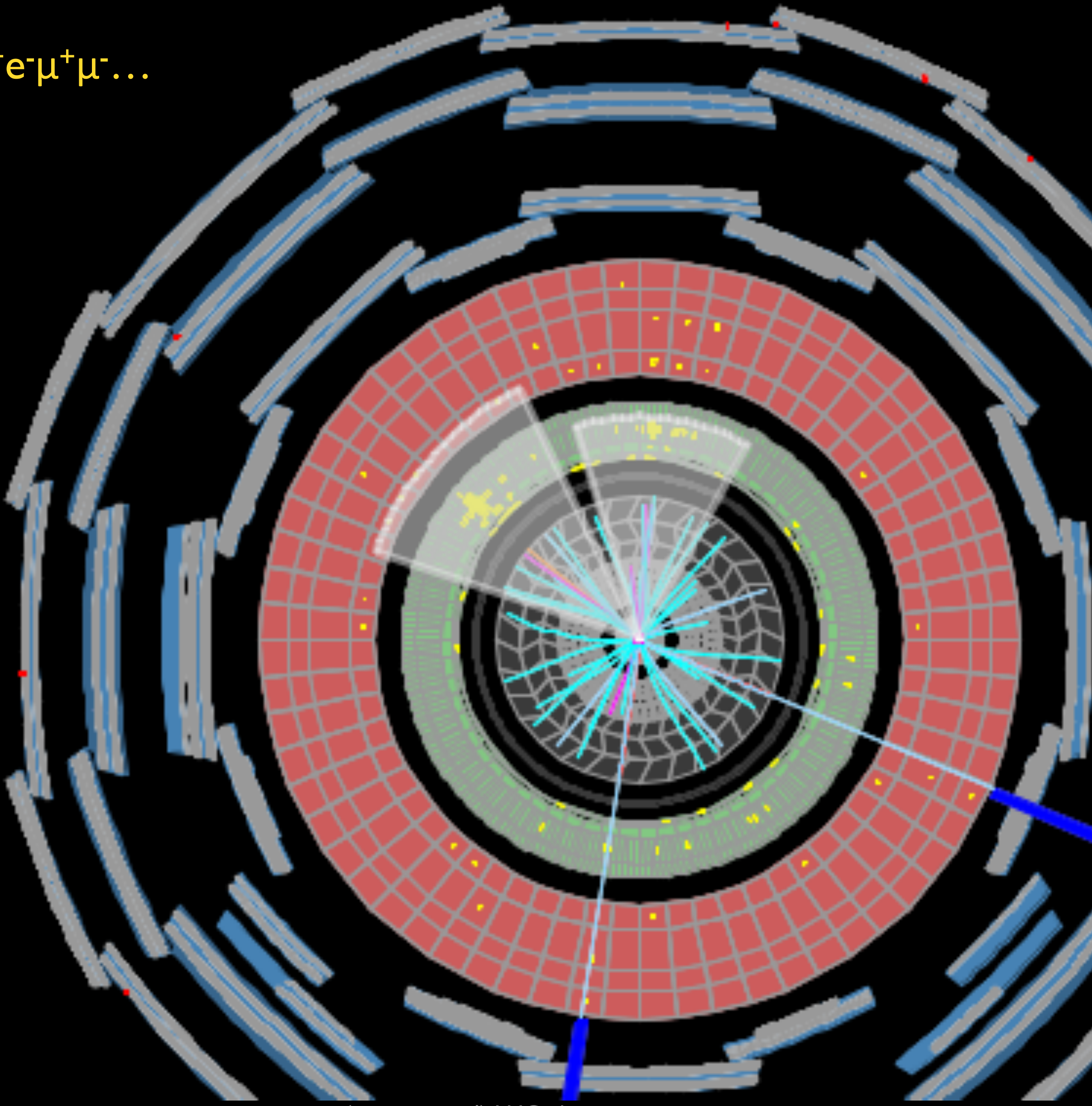


this is what we are looking for…

Step 1: find events with the right ingredients

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

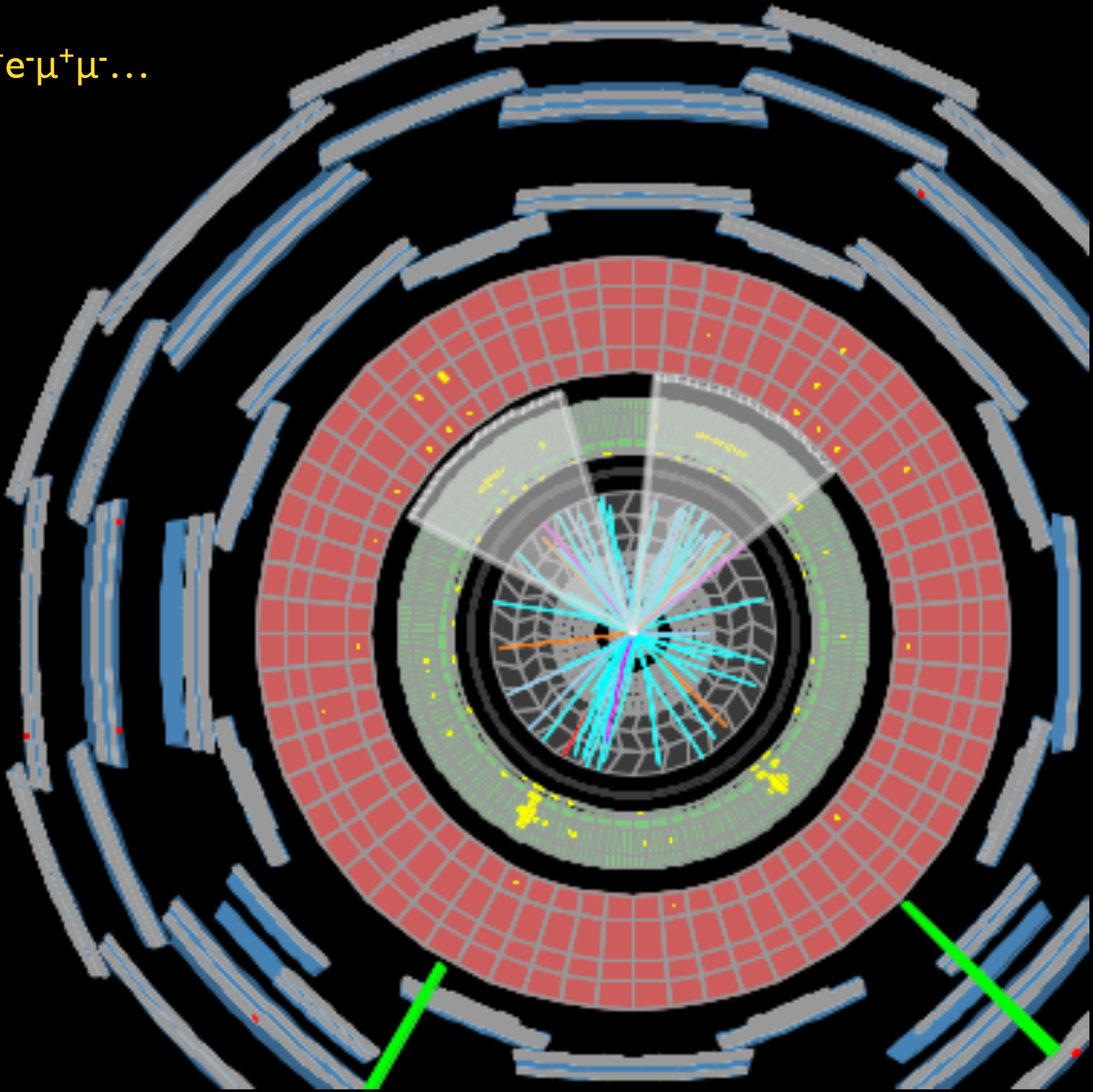
Is this event ok?



Step 1: find events with the right ingredients

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

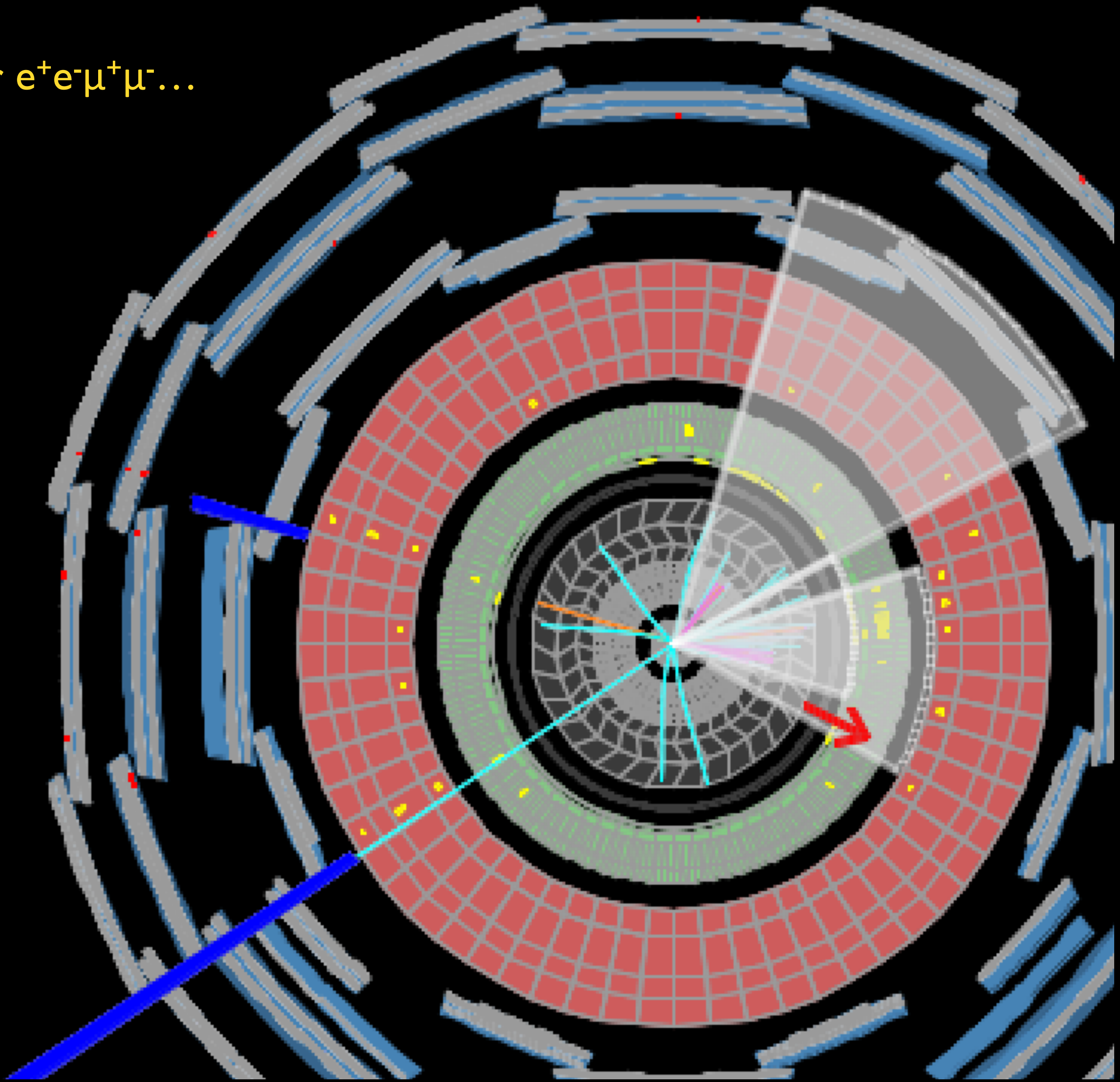
What about this one?



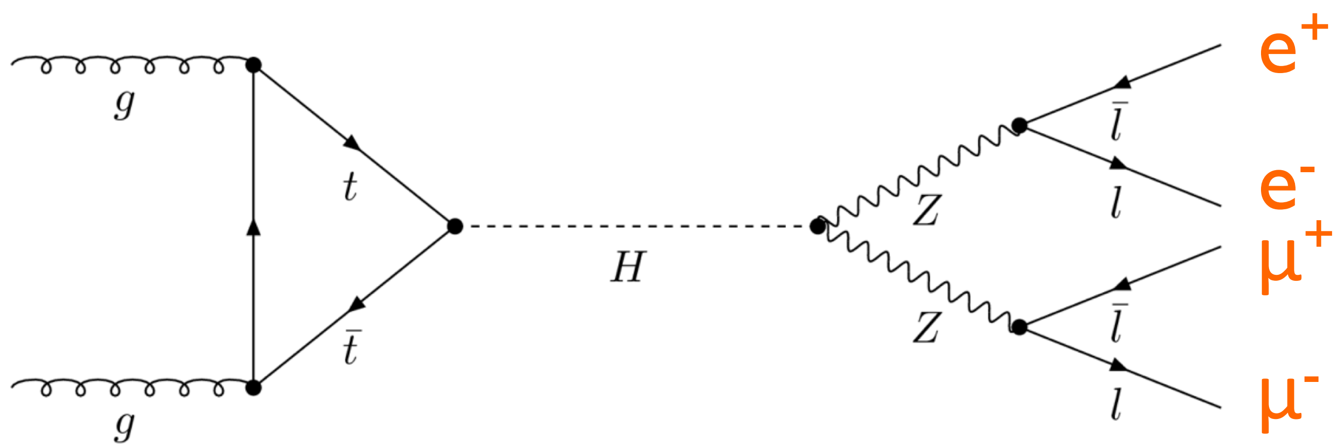
Step 1: find events with the right ingredients

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

And this one?

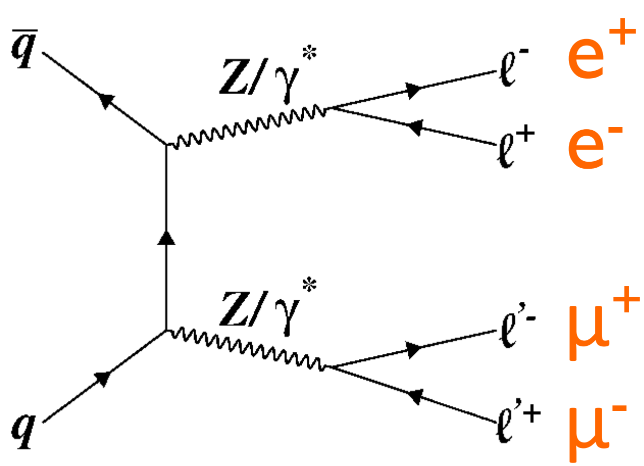


Signal and background



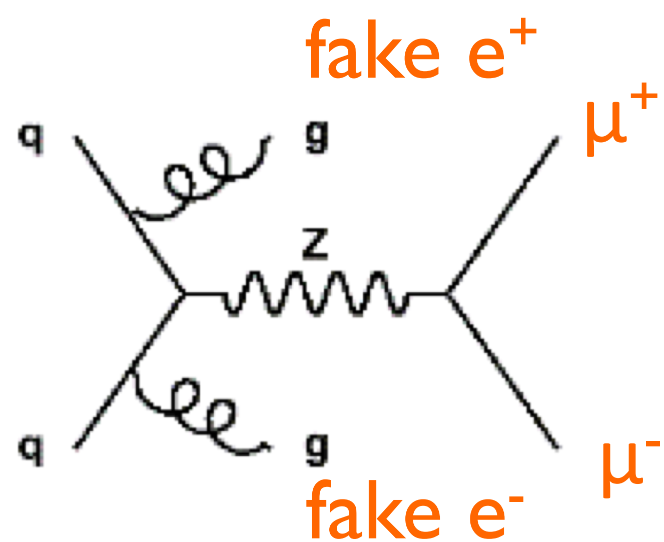
Irreducible background

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



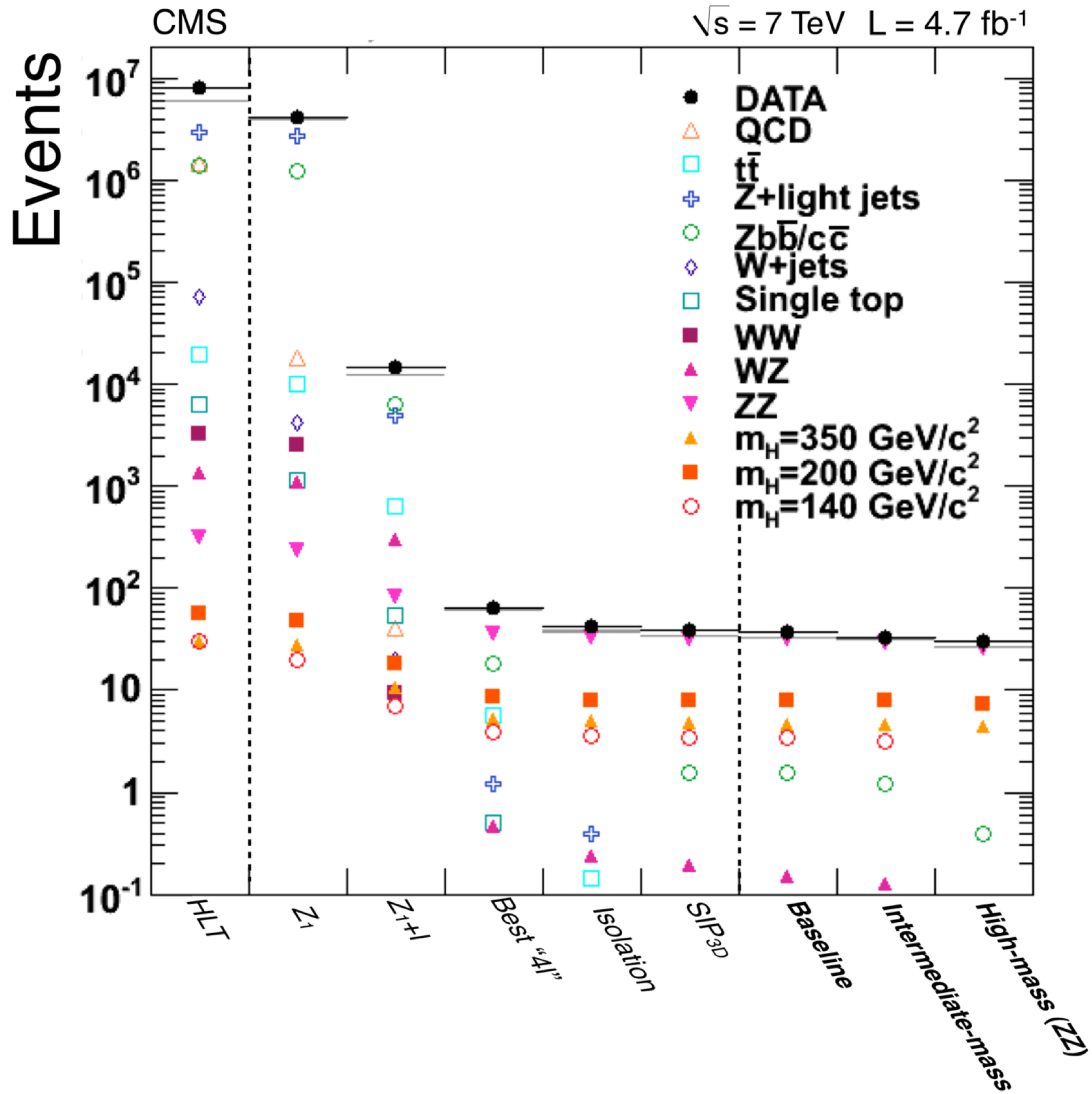
Reducible background

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



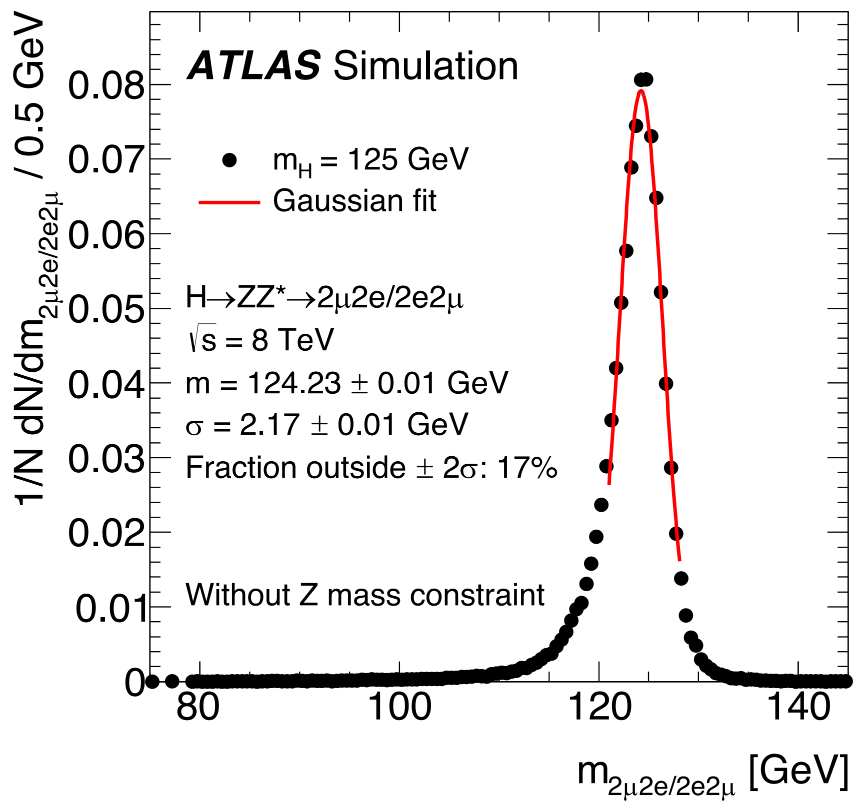
Loose some signal, suppress backgrounds…

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



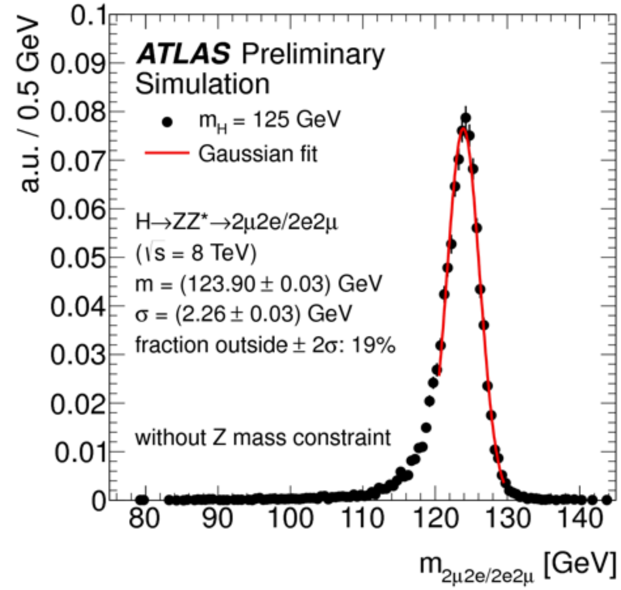
Step 2: reconstruct properties of initial particle

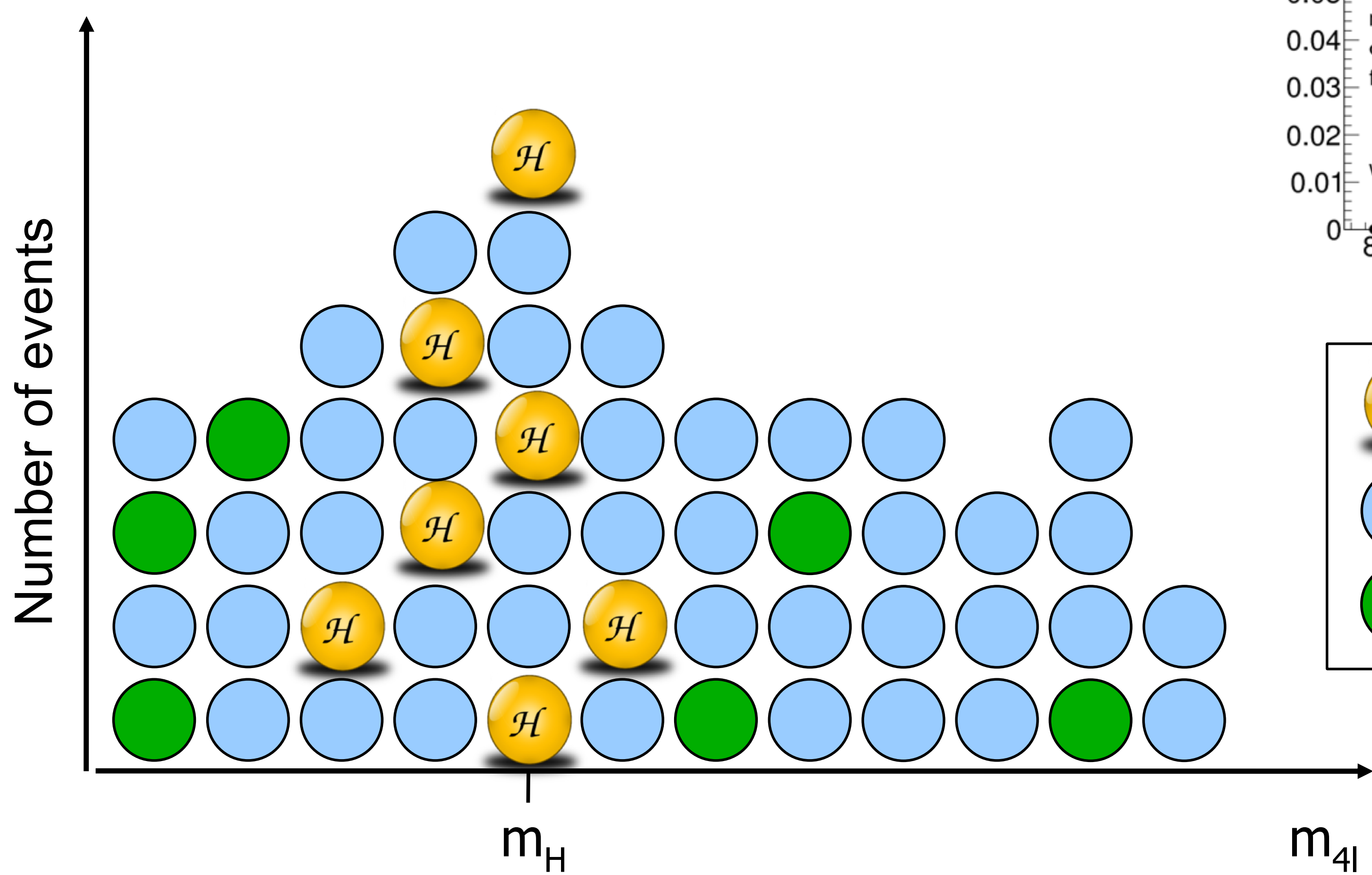
- We have 4 particles…
  - ✓ … with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^+\mu^-$
- Reconstruct invariant mass from the 4 particles $M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$

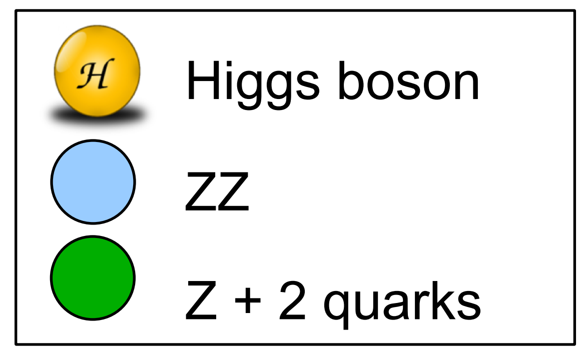


Extract signal from background

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

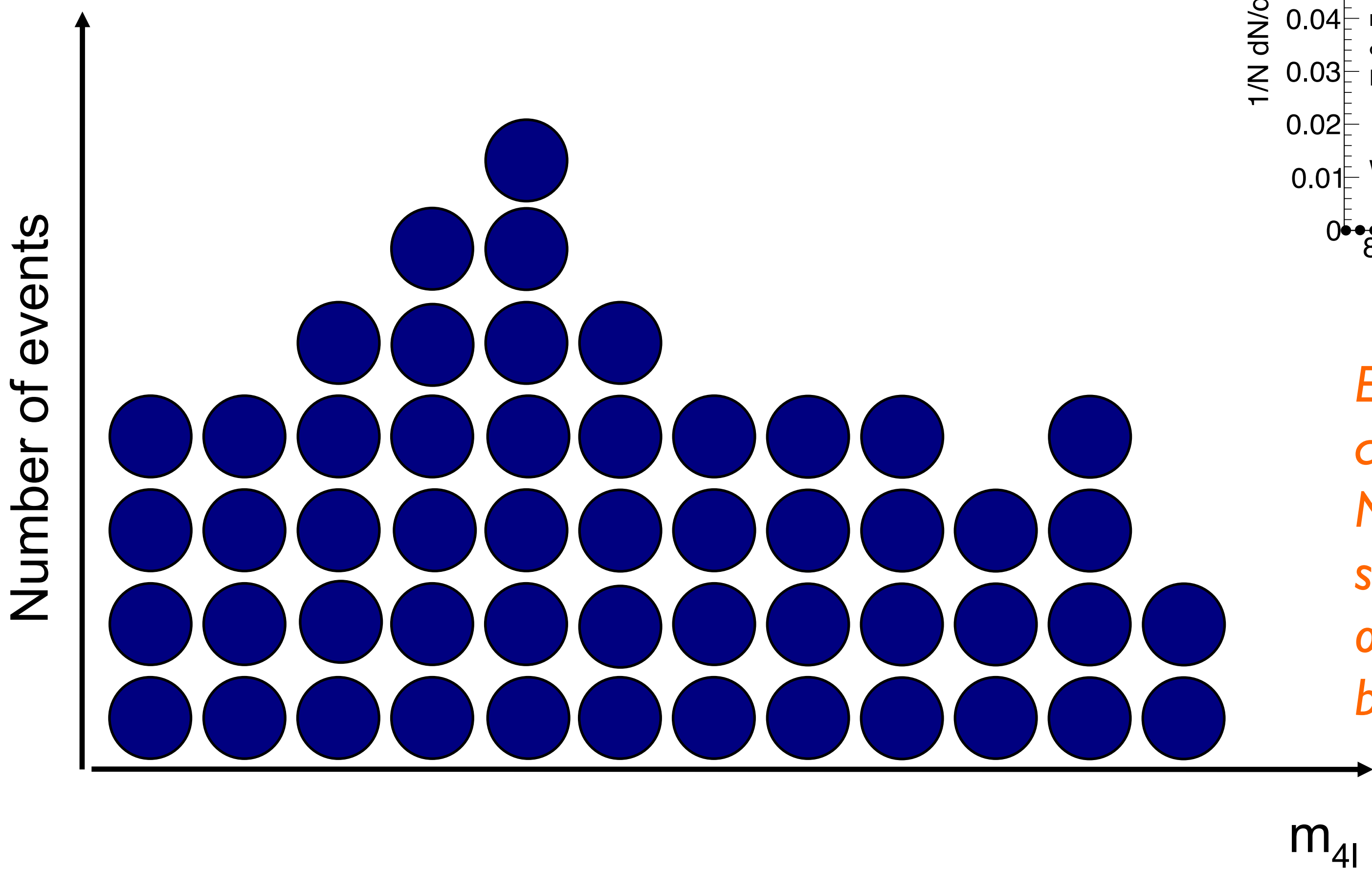


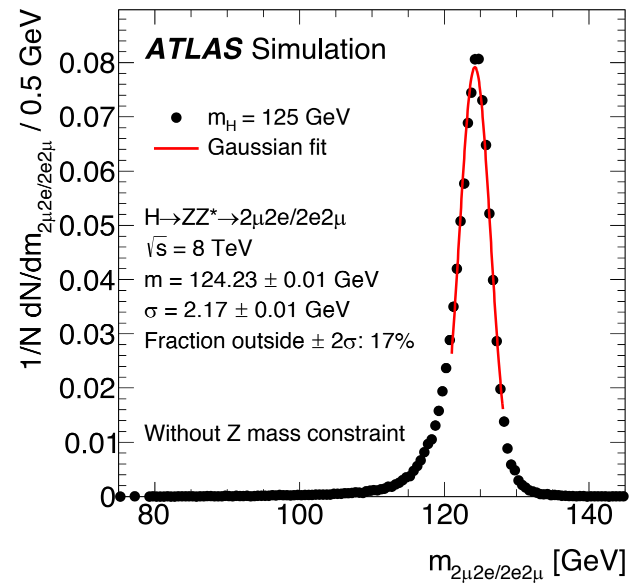




Extract signal from background

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

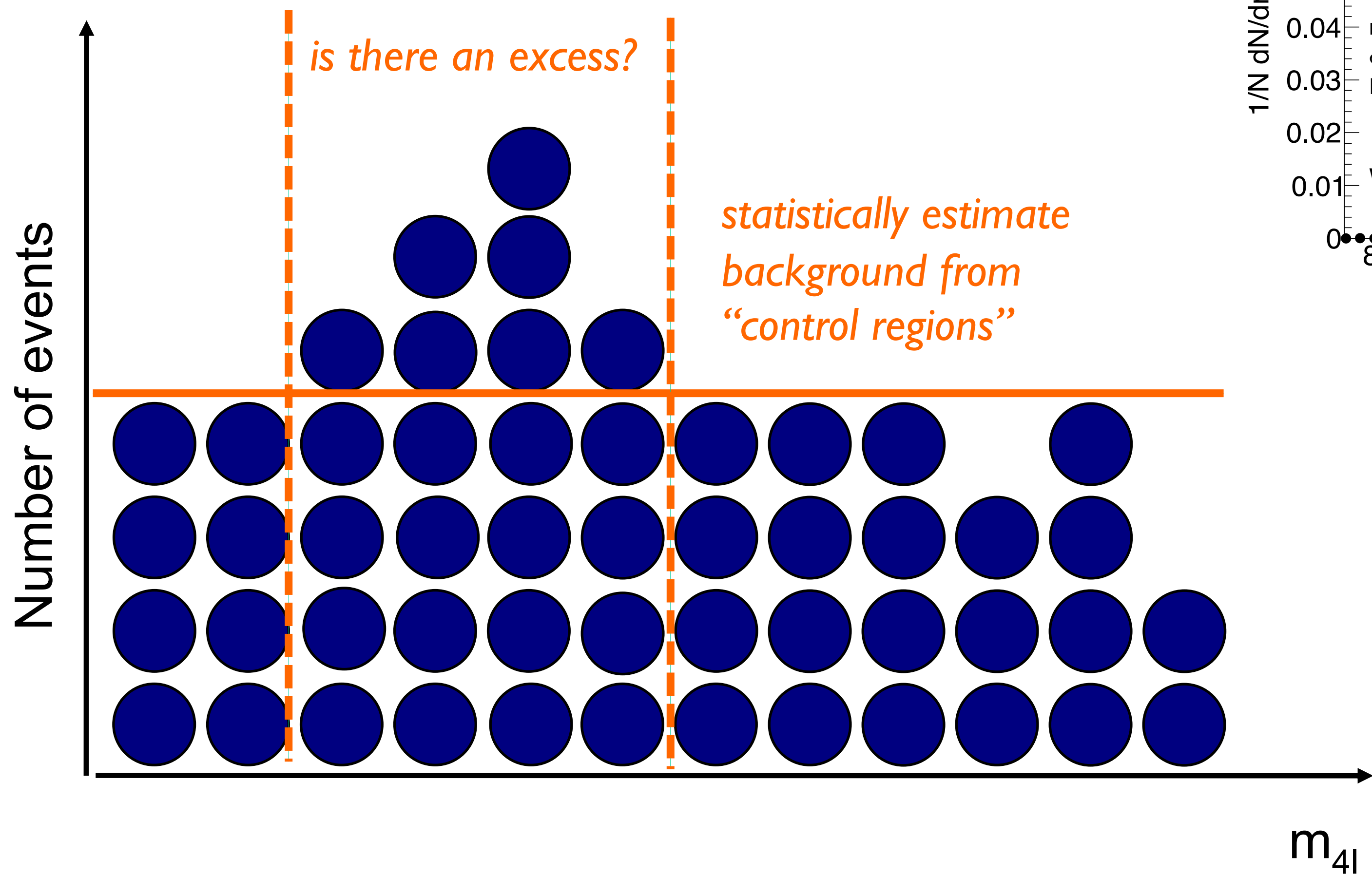


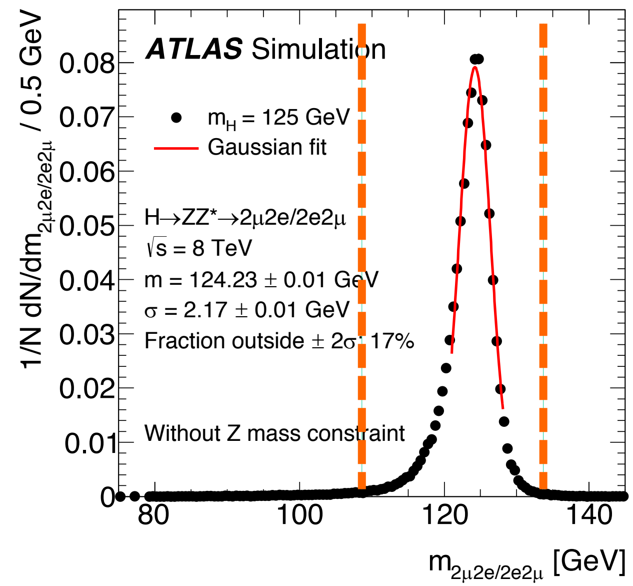


Events in real life do not come with a label!
No way to distinguish signal from background on an event-by-event base…

Extract signal from background

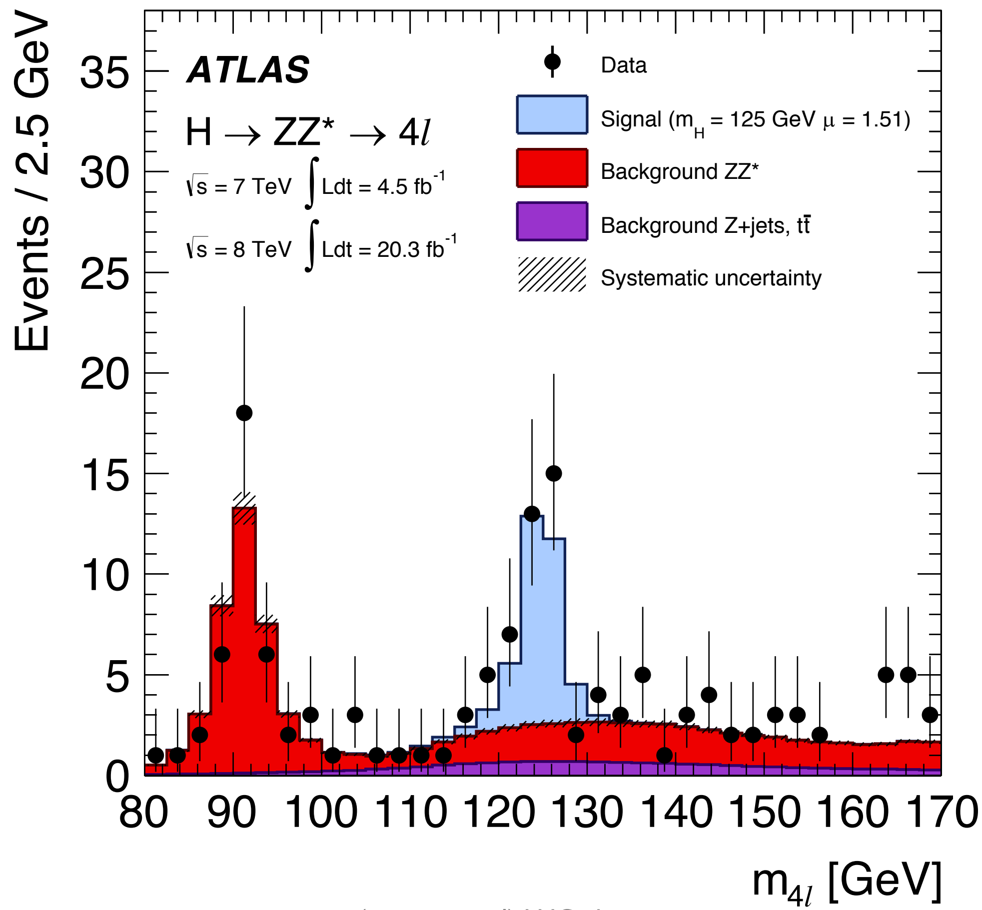
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$





Extract signal from background

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

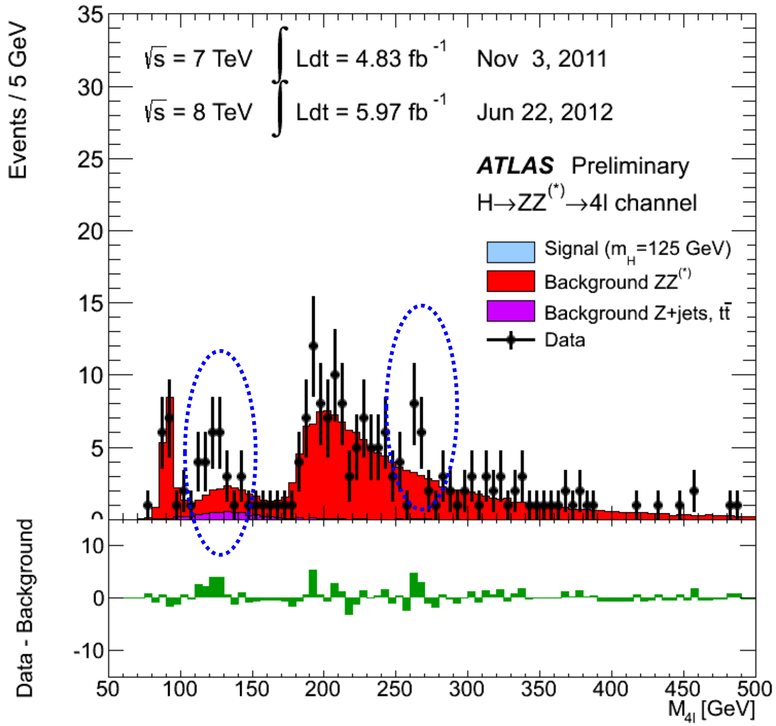


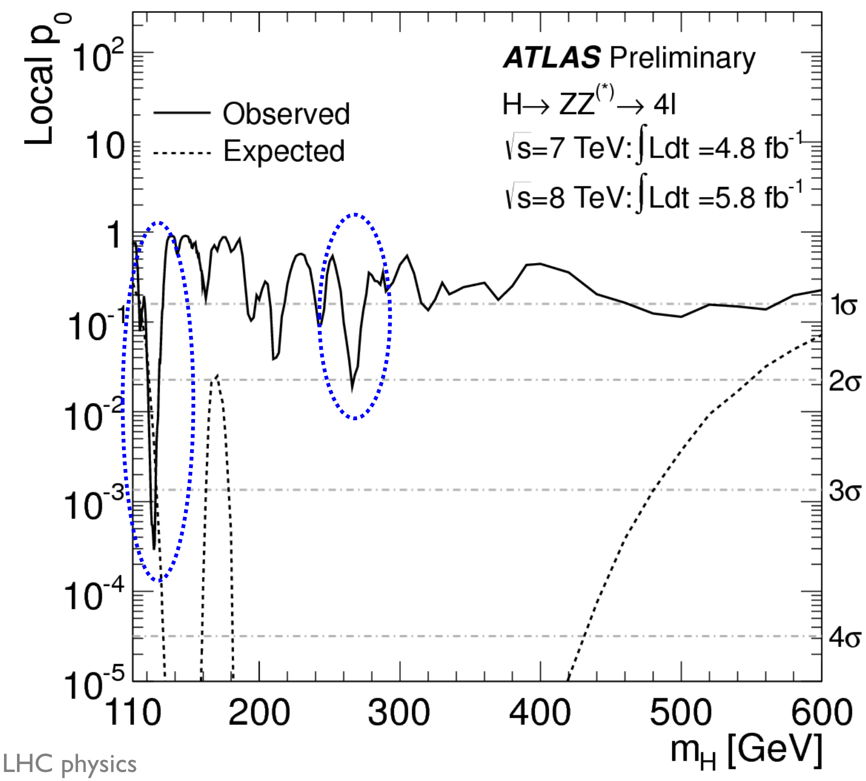
How significant is an excess?

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

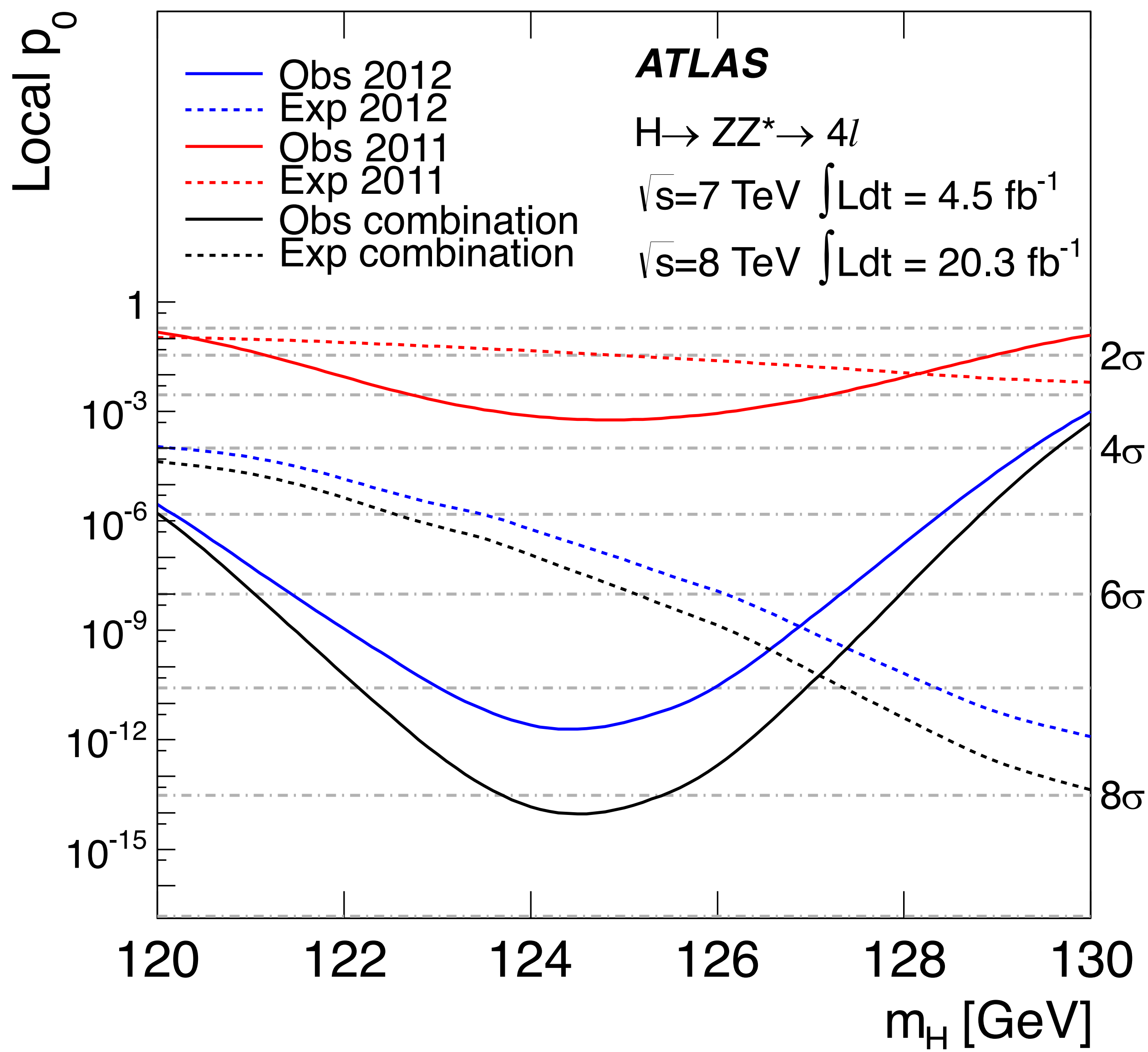
$$Z \sim \frac{S}{\sqrt{B}} \qquad p_0 = 1 - \mathrm{Erf}\left(\frac{Z}{\sqrt{2}}\right)$$

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

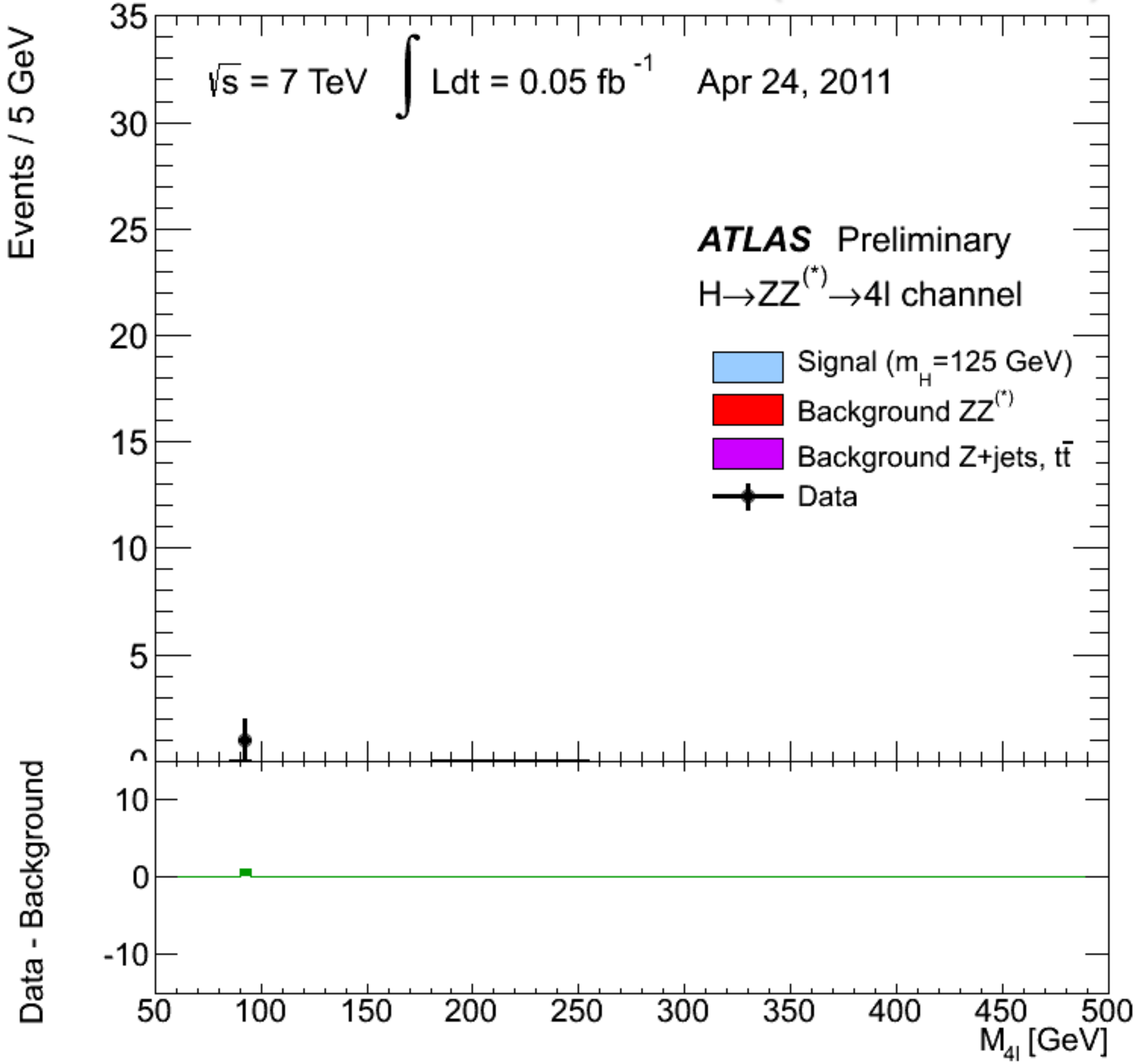




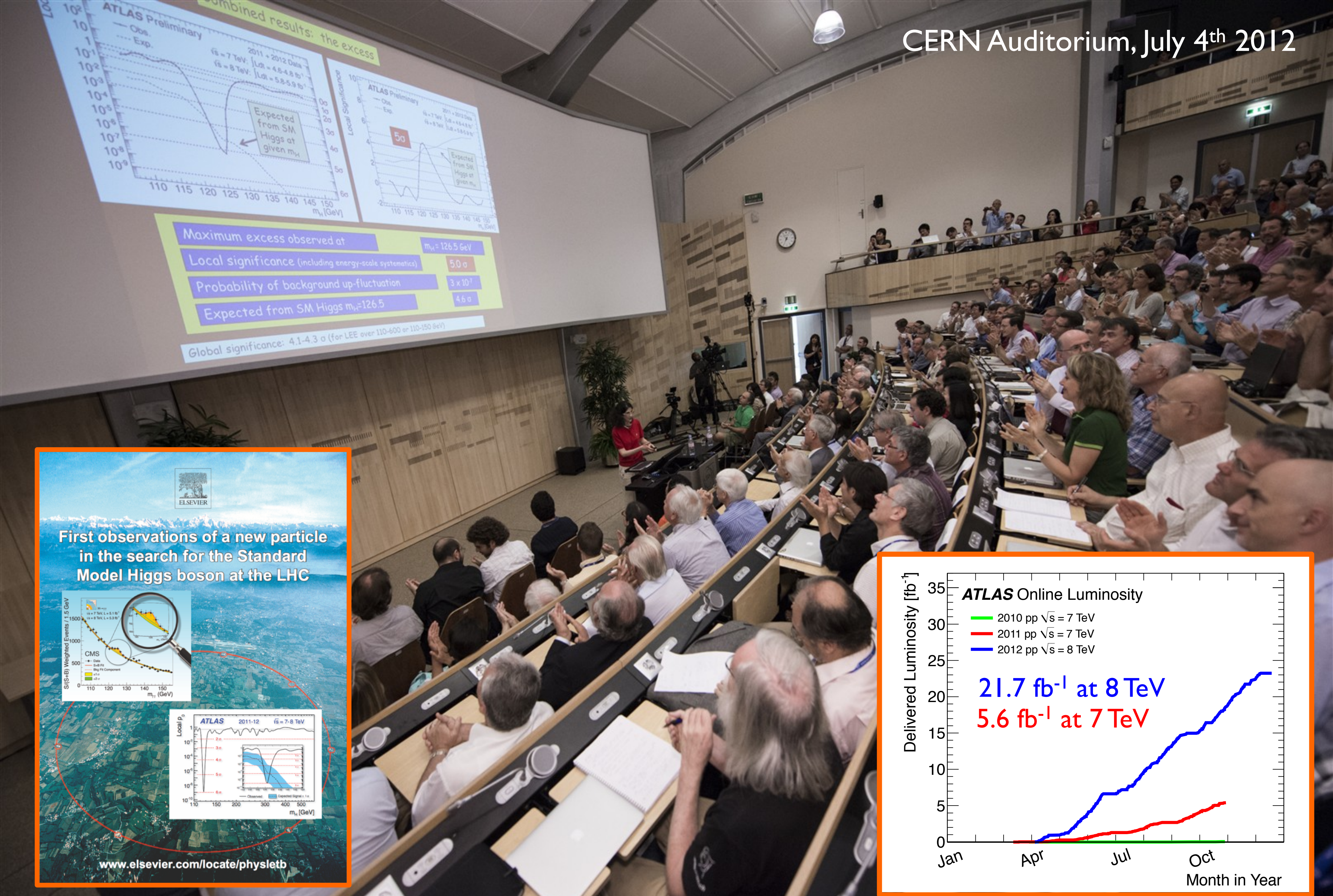
How significant is an excess?



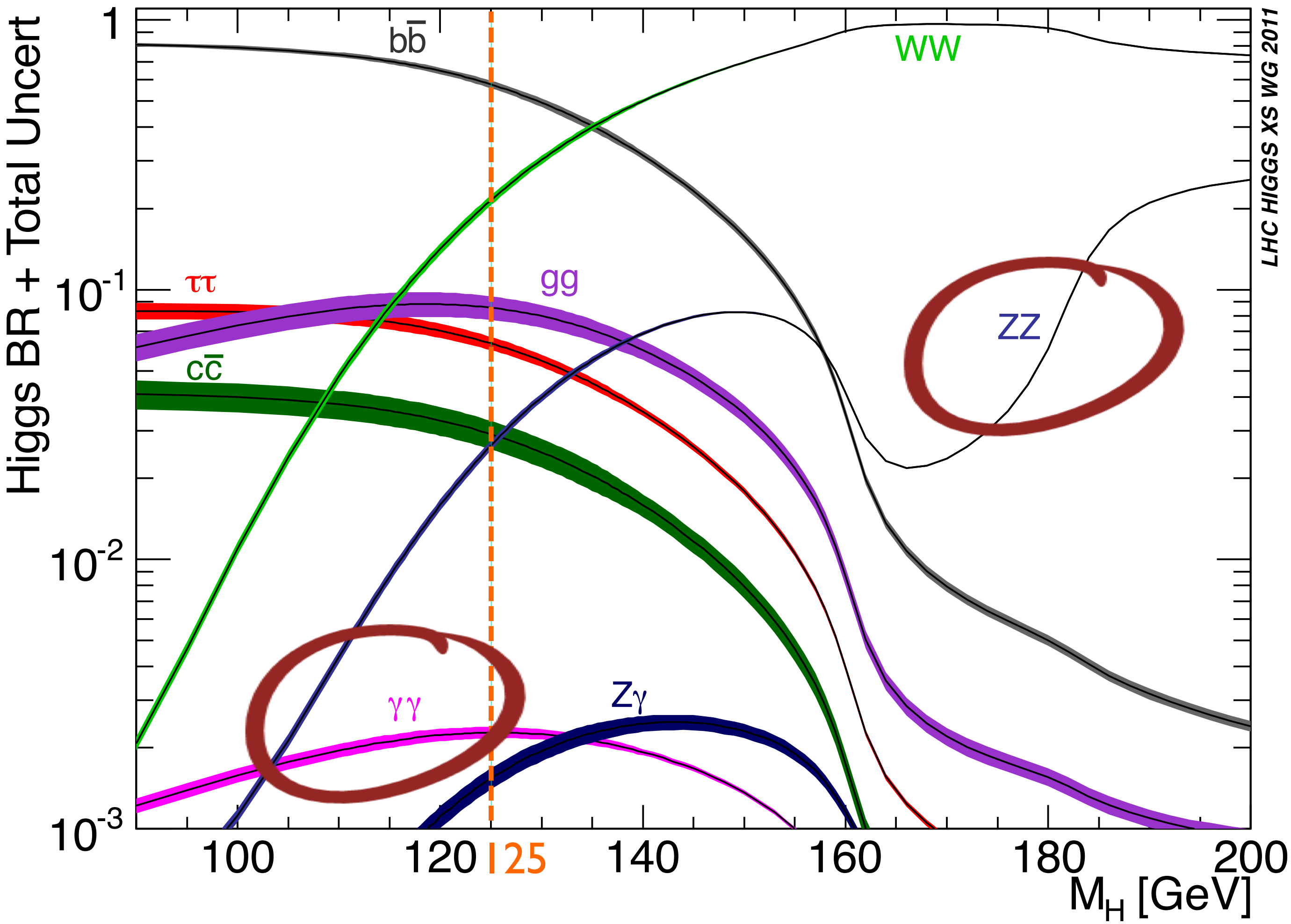
Significance increase with data (and time!)



CERN Auditorium, July 4th 2012



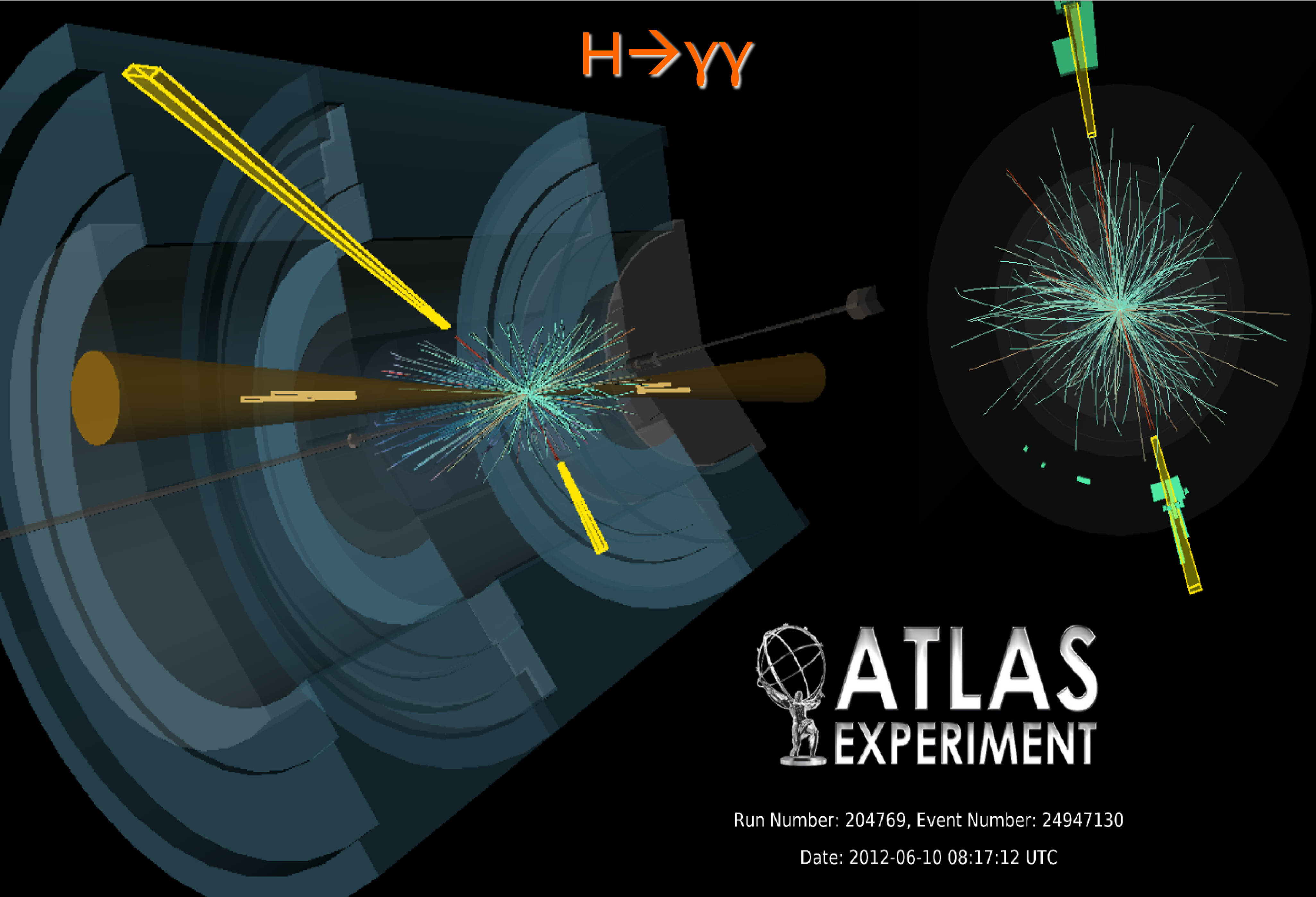
Standard Model Higgs decays

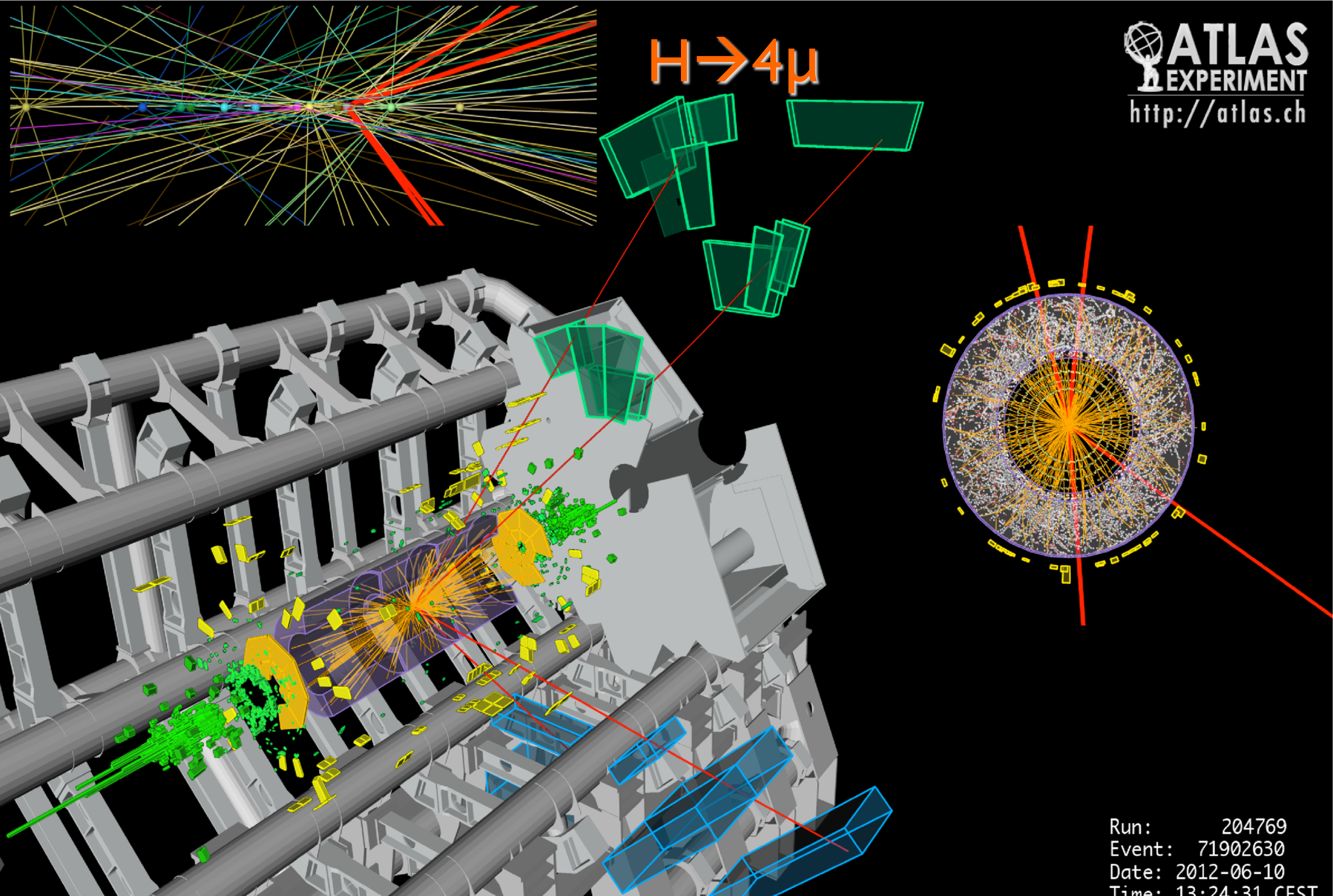


decay	SM BR [%] m_H = 125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→γγ	0.23

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

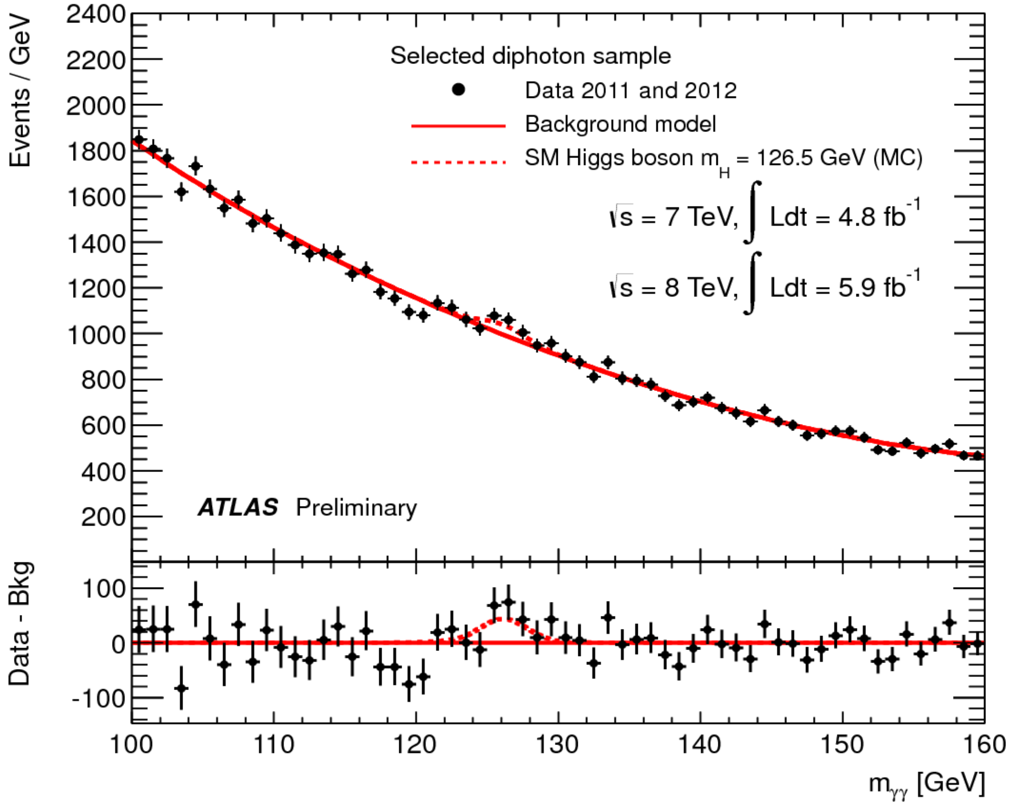
H→γγ


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

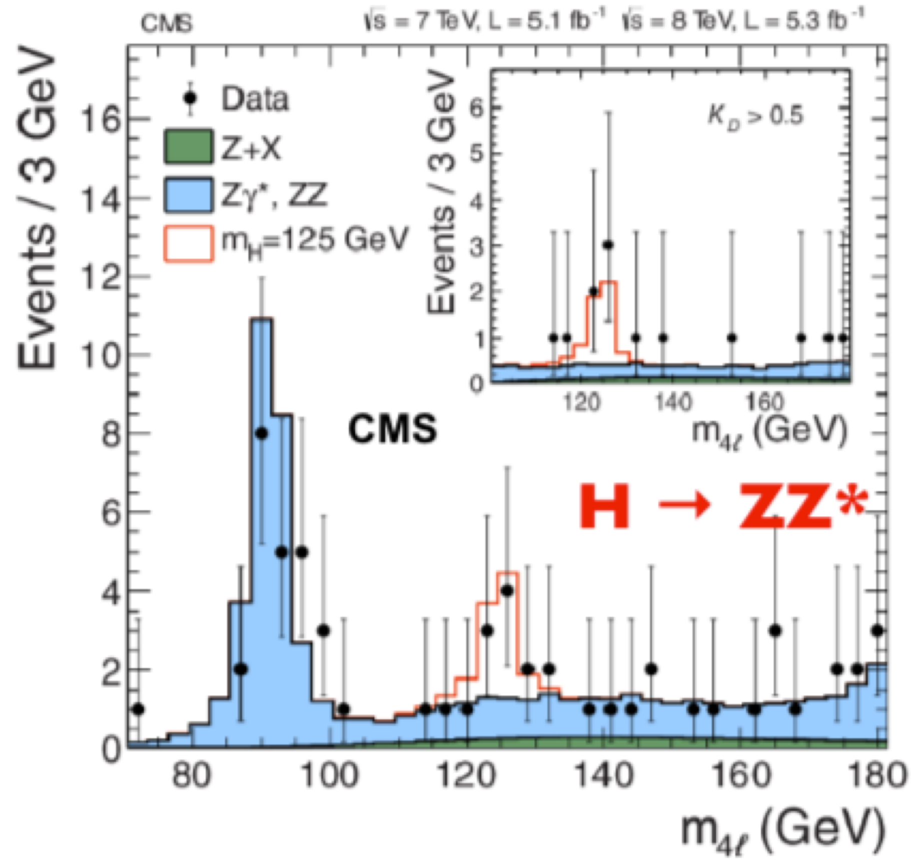

H→4μ
ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs signals on July 4th 2012

H→γγ

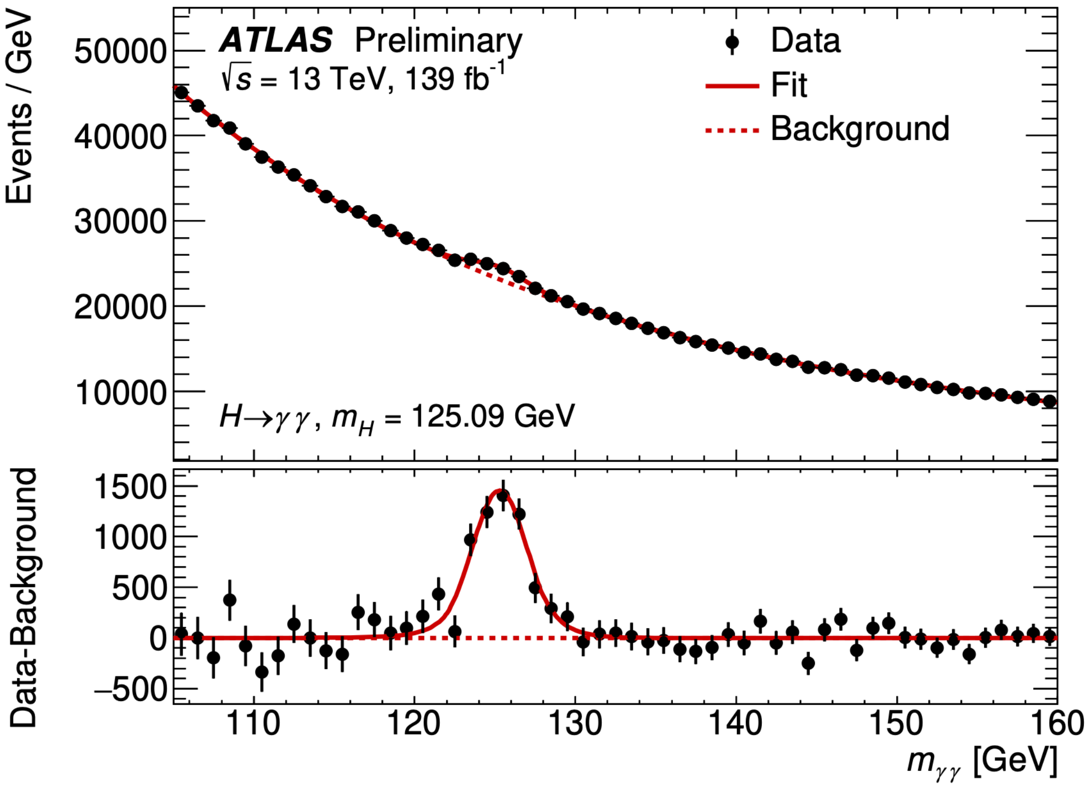


H→4l

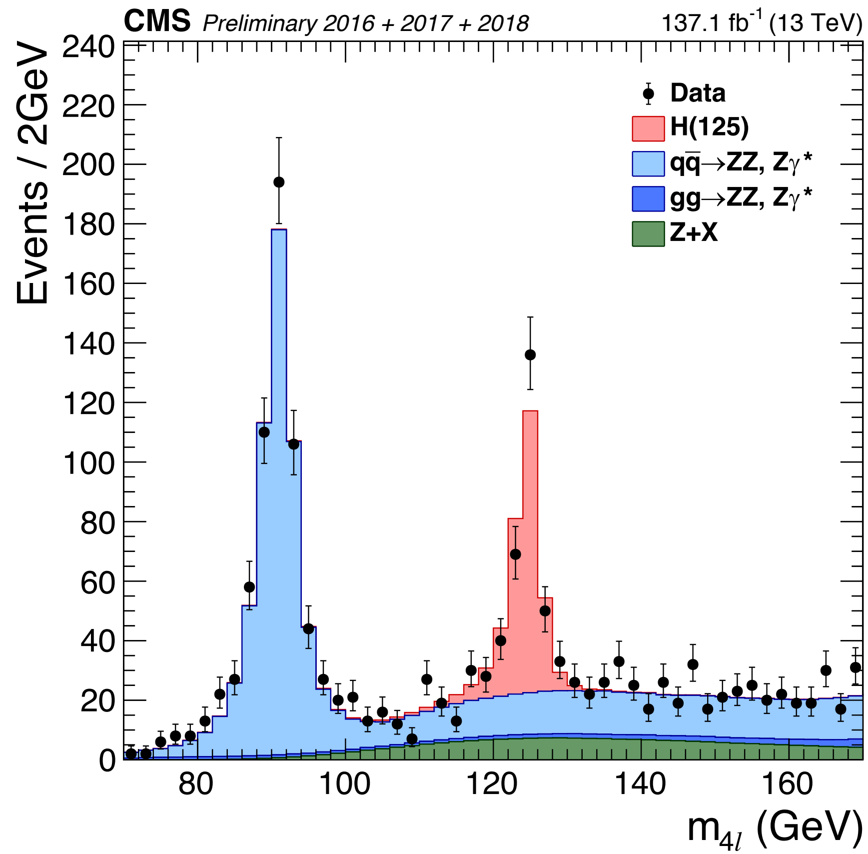


Higgs signals with the *latest* 13 TeV data…

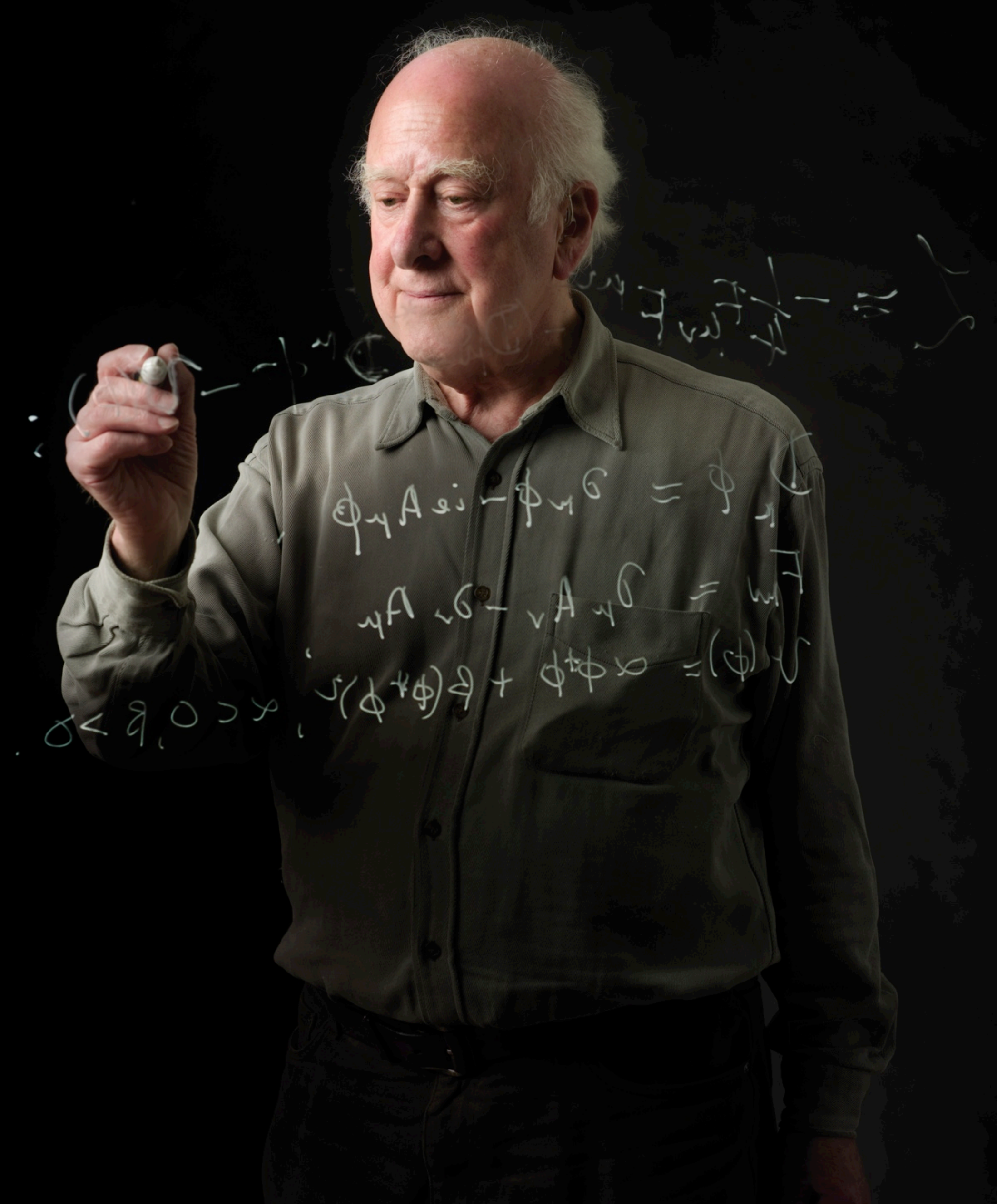
H→γγ



H→4l



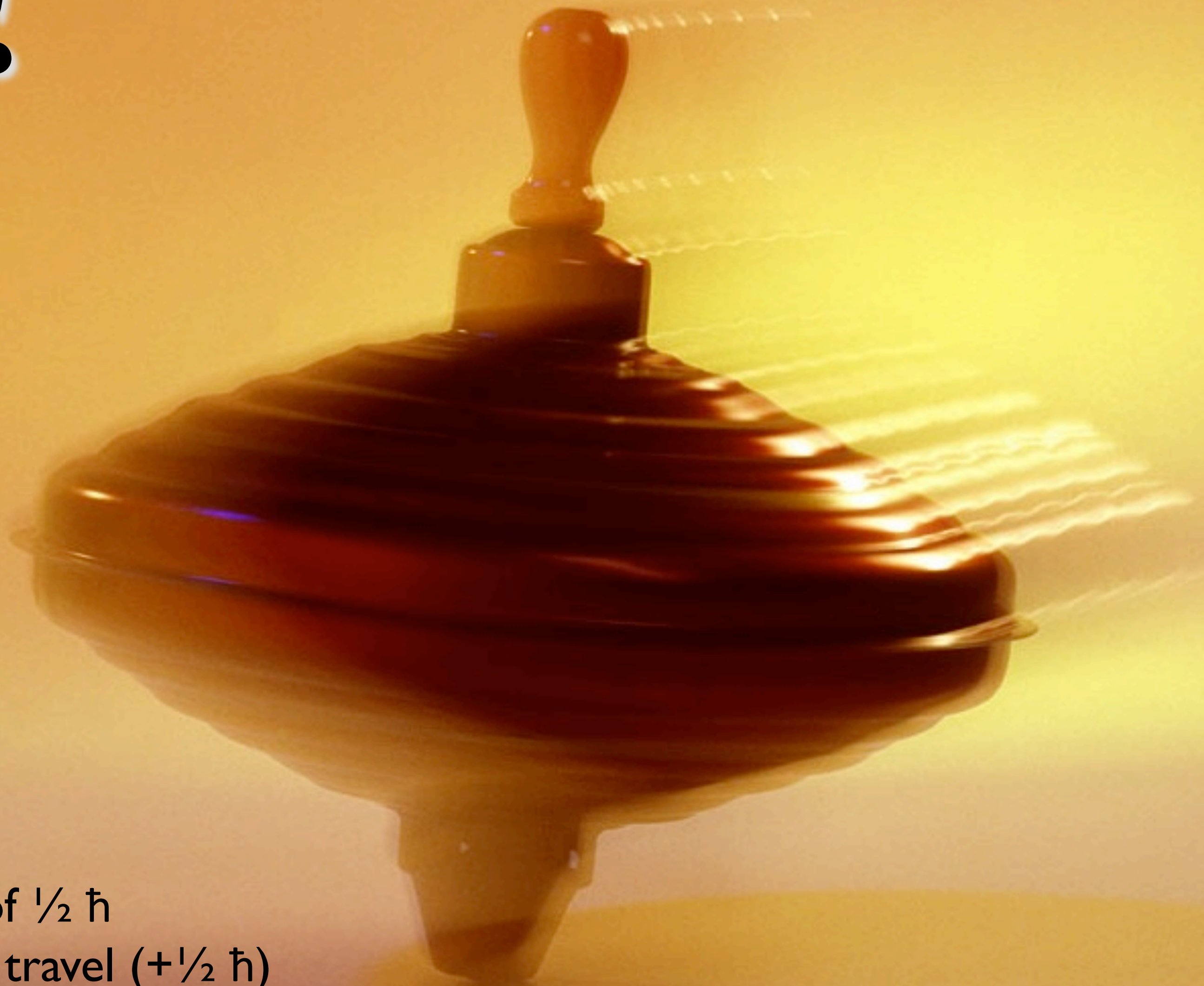
is it *the* Higgs boson?



Spin!

What's a particle spin?

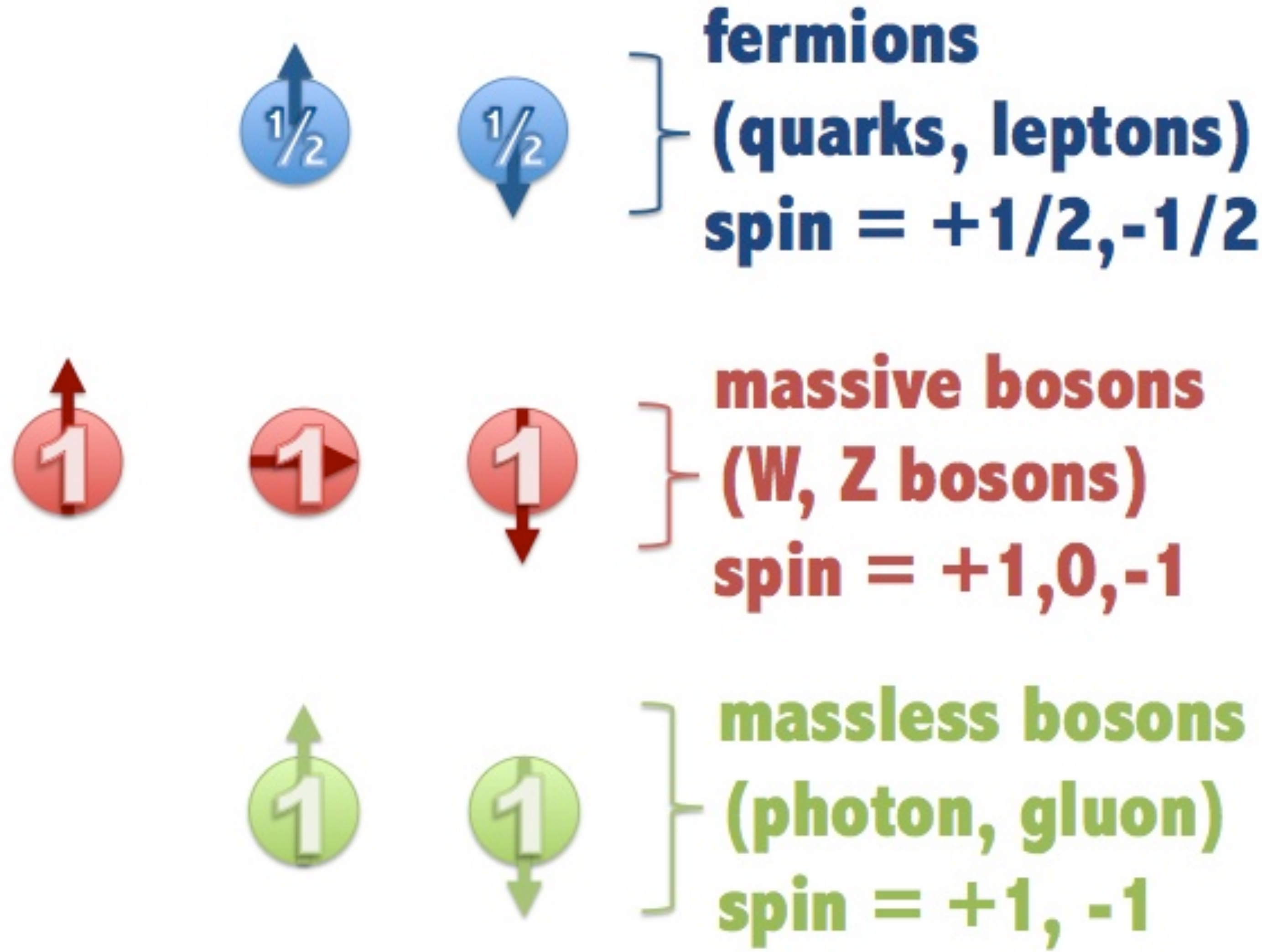
"An *amount of rotation* that is somehow quantized"



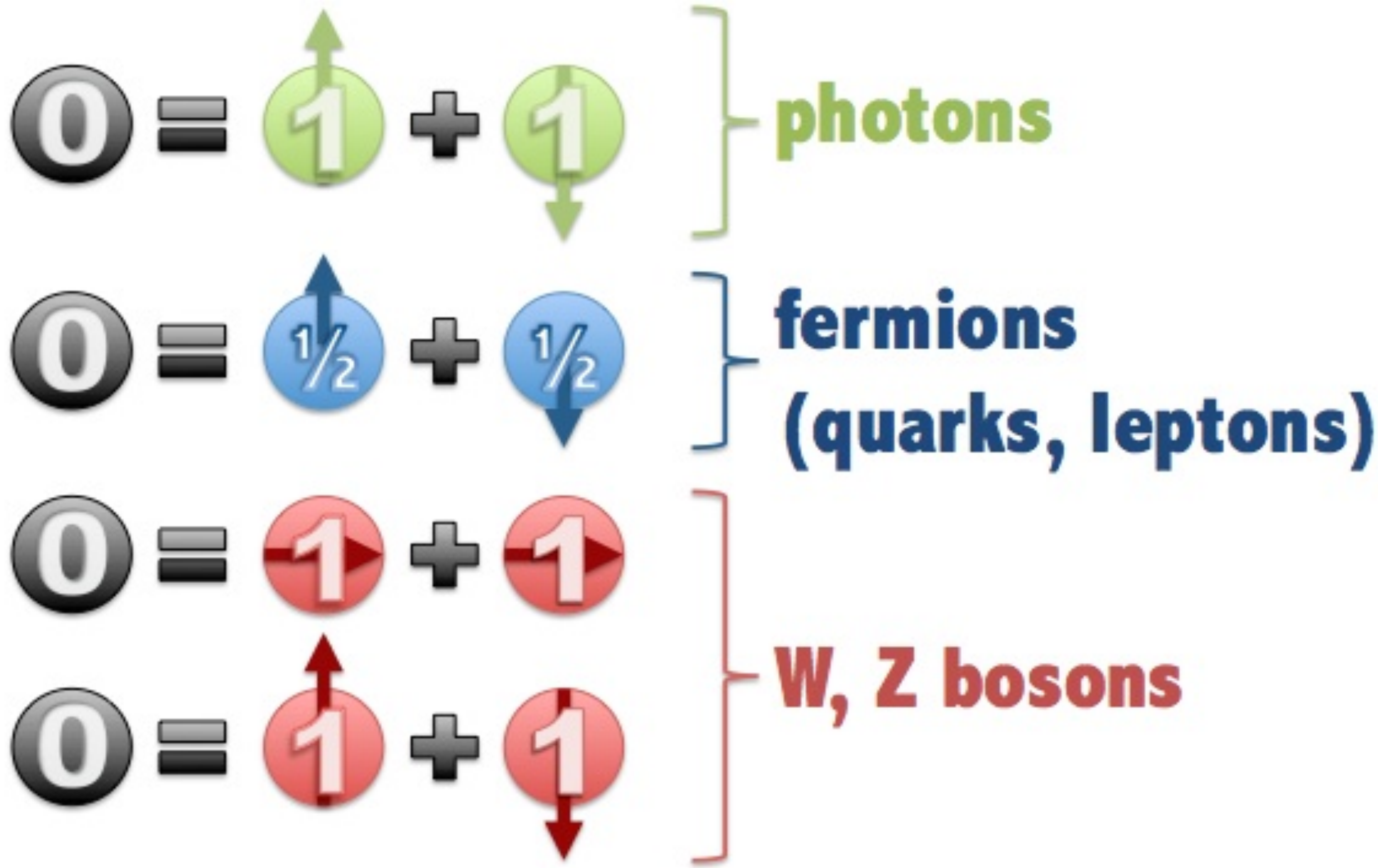
An electron has always an angular momentum of ½ ħ either in its direction of travel (+½ ħ) or opposite to it (-½ ħ)

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

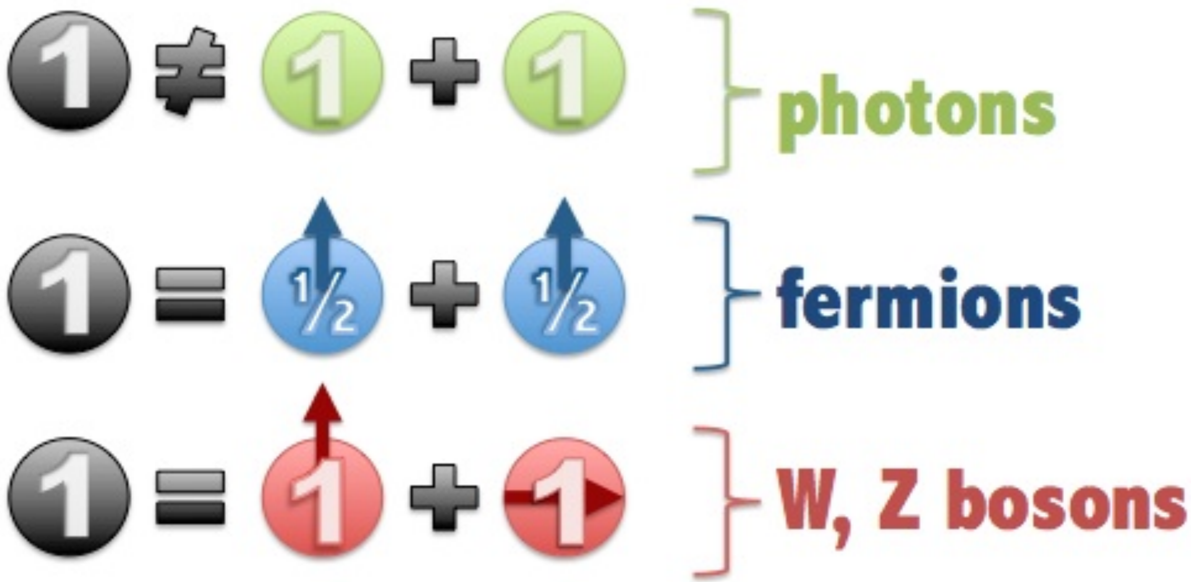
What spin do particles have?



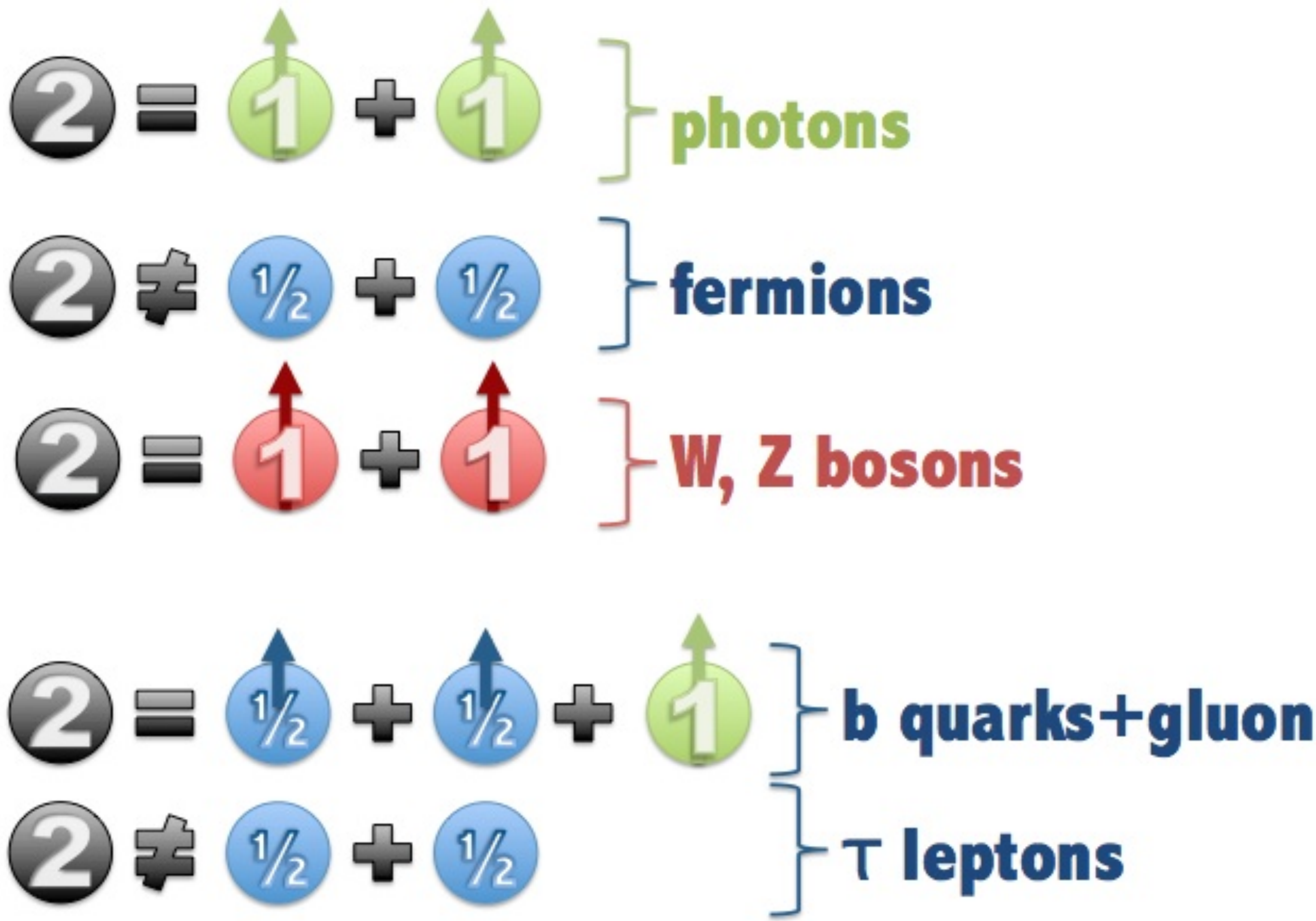
What can a spin 0 particle decay to?



What can a spin 1 particle decay to?



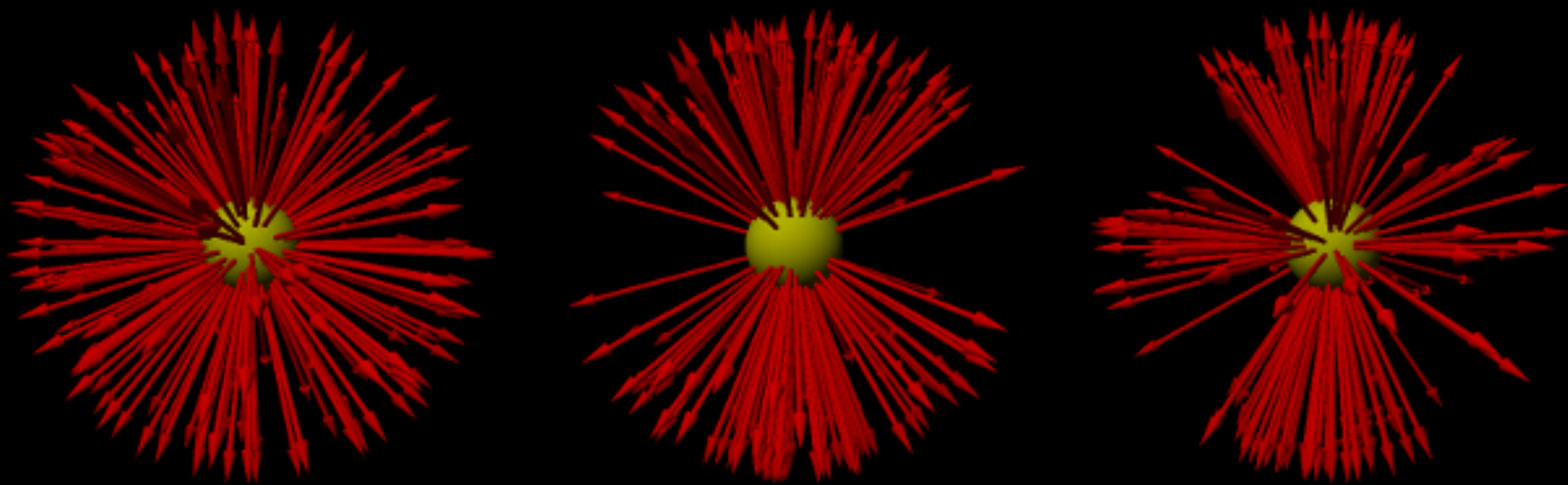
What can a spin 2 particle decay to?



So, what spin has our Higgs-like particle?

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

How can we recognize spin?



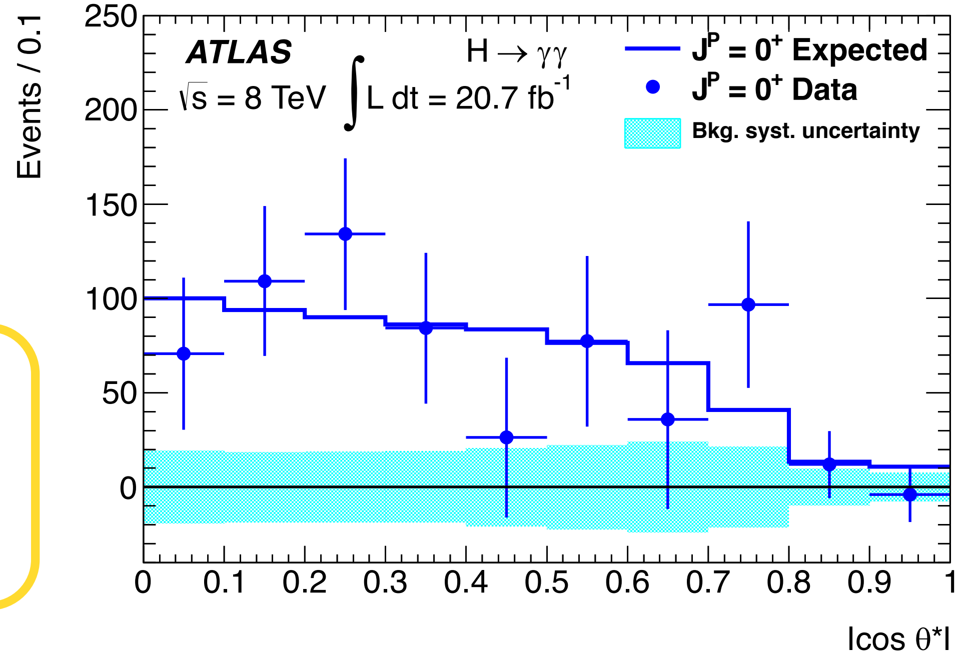
spin 0 spin 1 spin 2

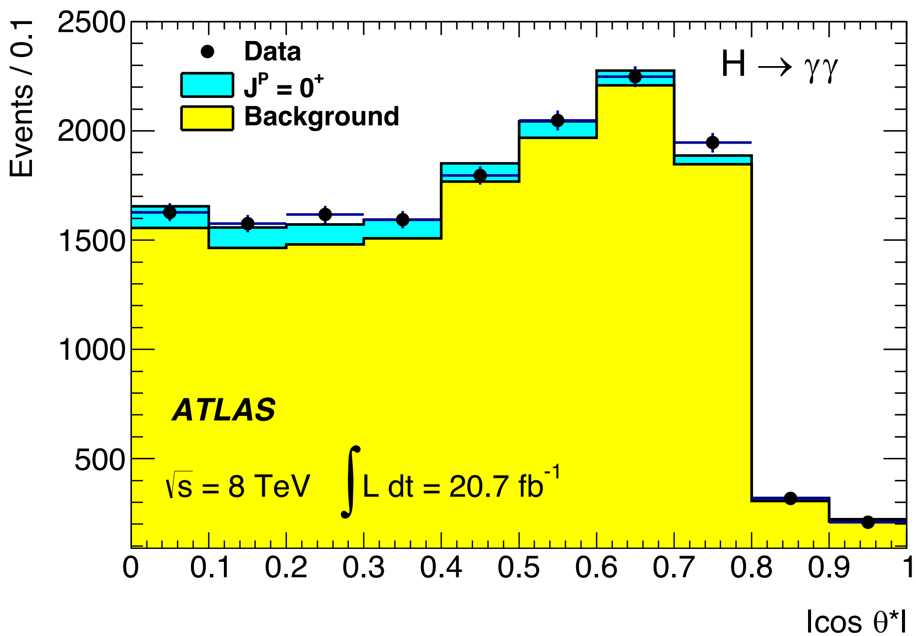
Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

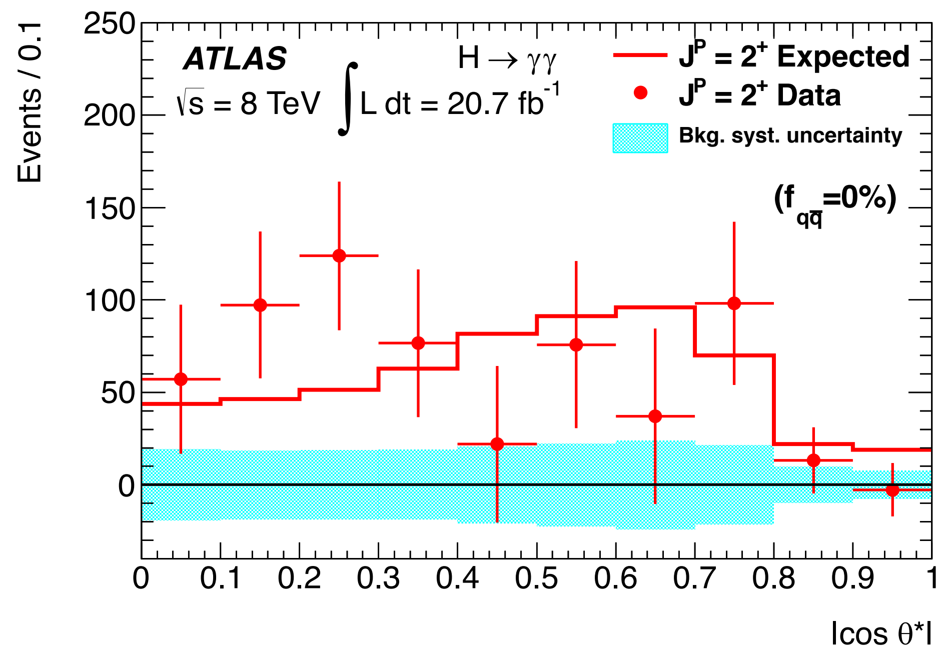
Spin with H→γγ

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

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







The Higgs boson or *a* Higgs boson?

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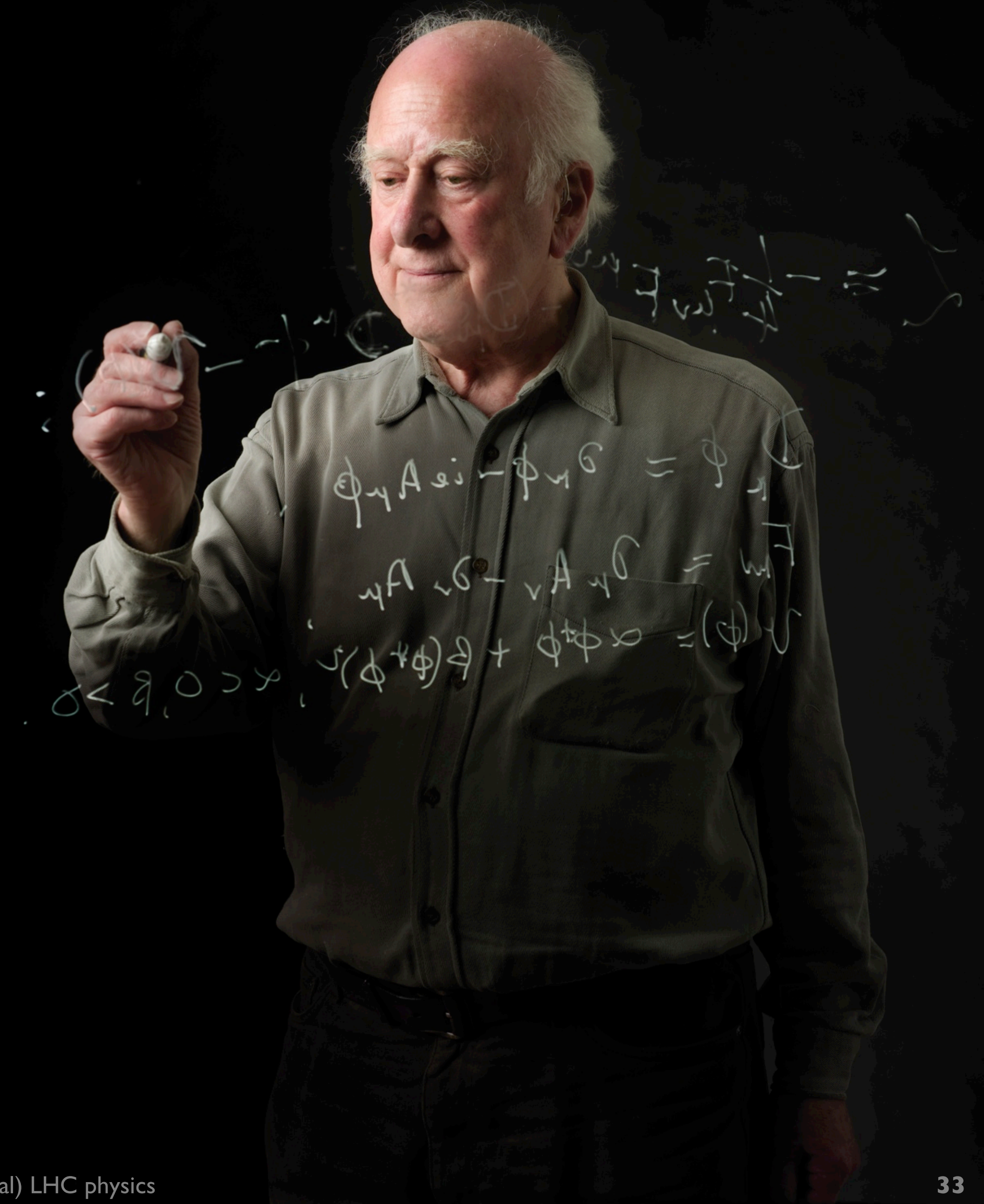
New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

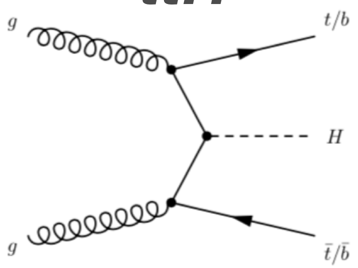
Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery 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.

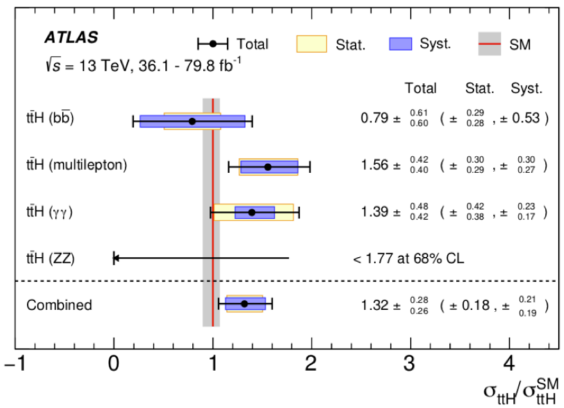
is it responsible for fermion masses?

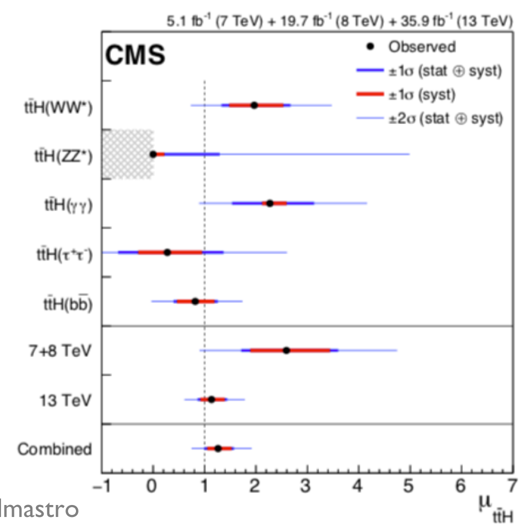


The Higgs boson definitively couples to fermions!

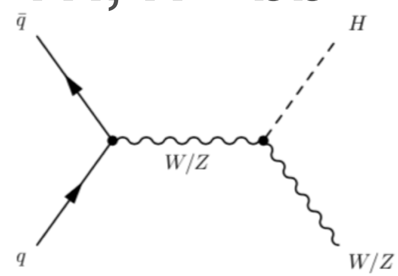
ttH

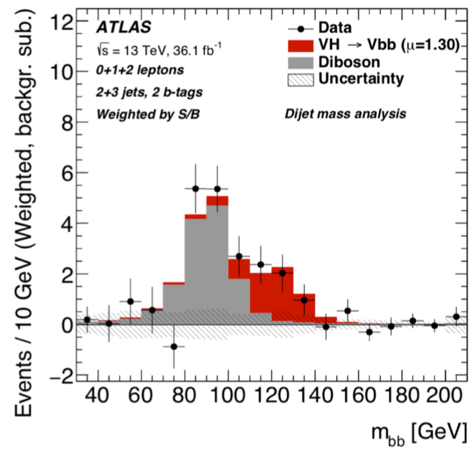


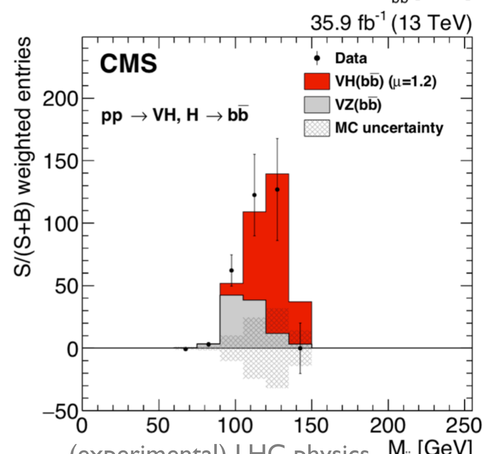




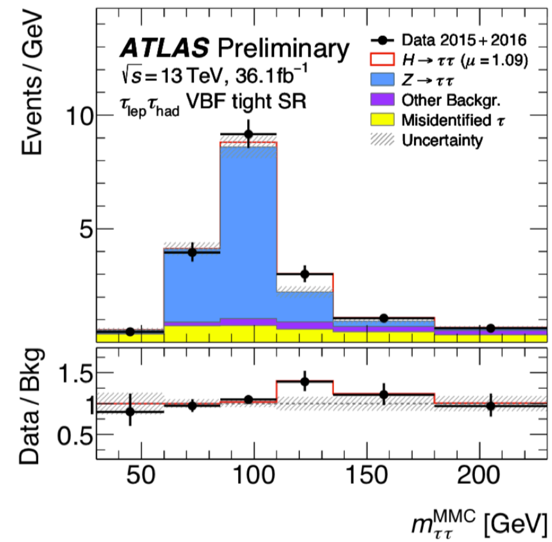
VH, H→bb

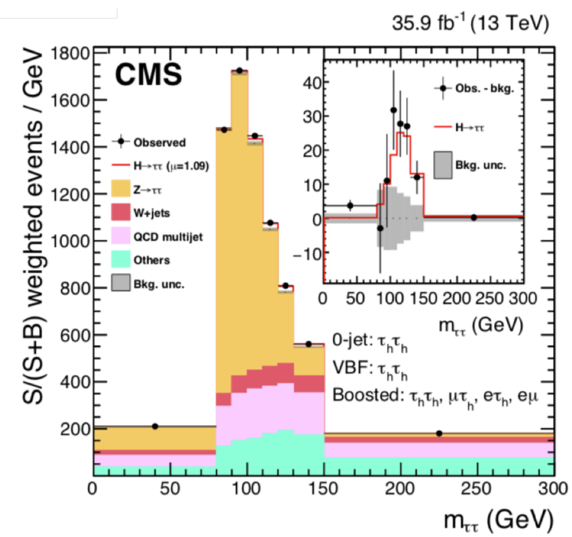




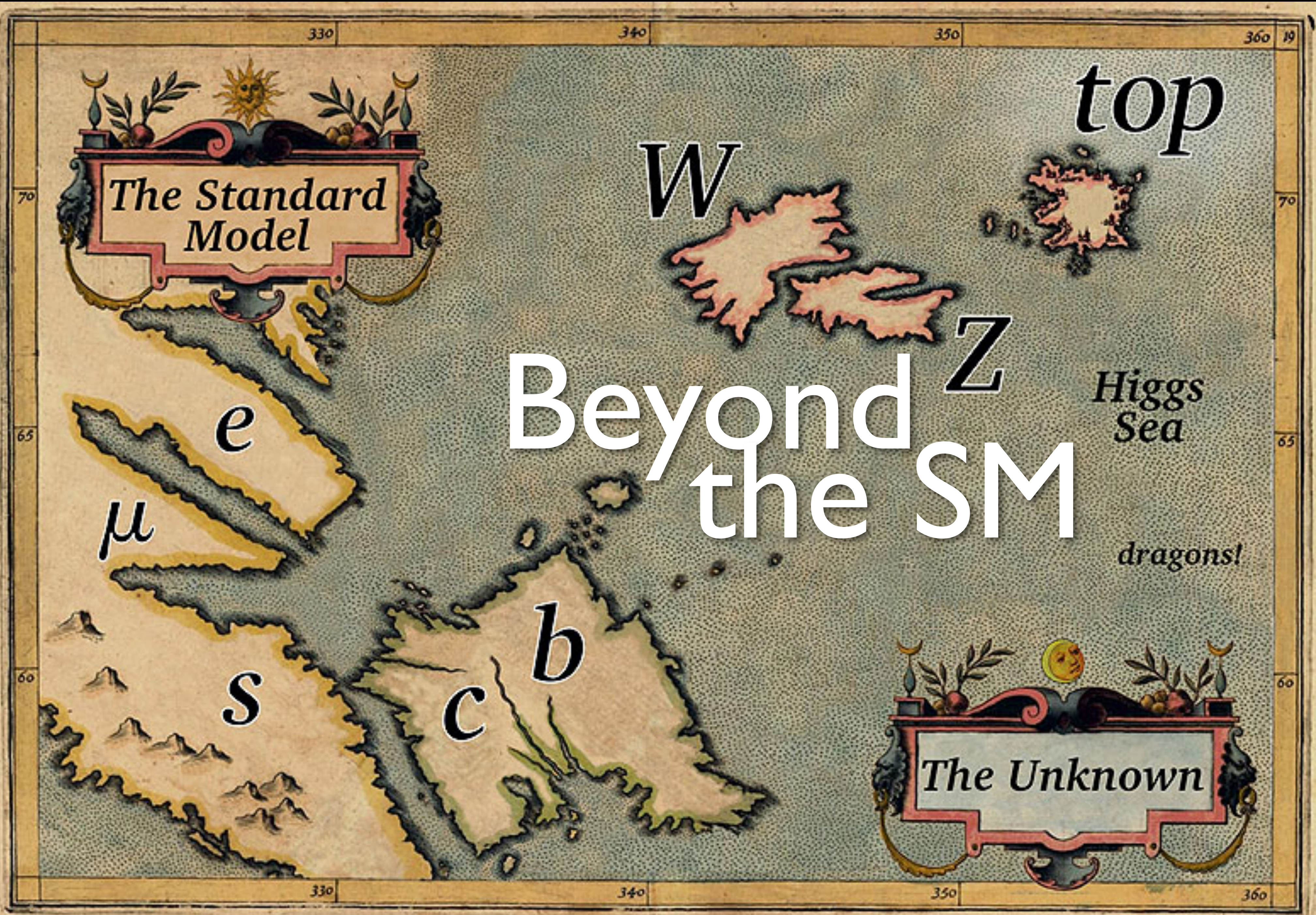


H→ττ





Beyond the SM

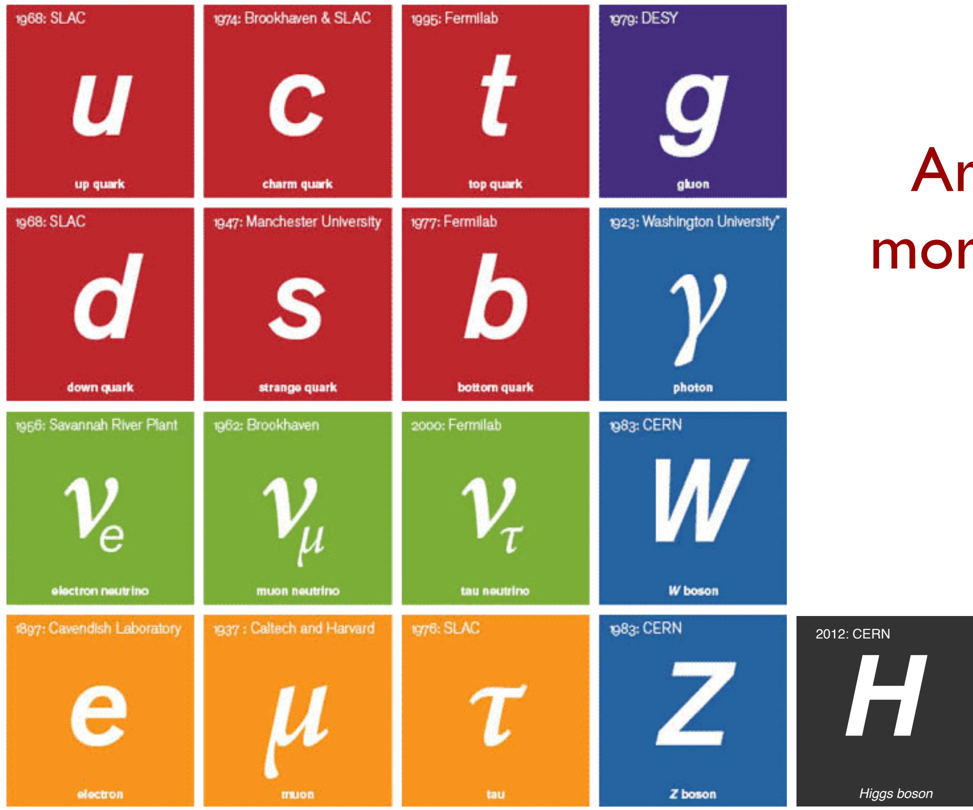


Many unanswered questions…

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?

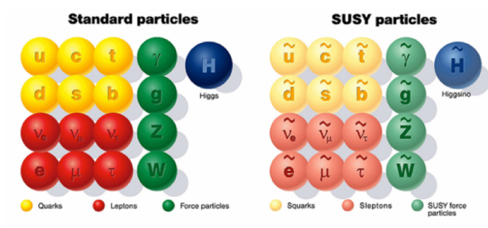
What keeps the Higgs mass so small?

How do we incorporate gravity?

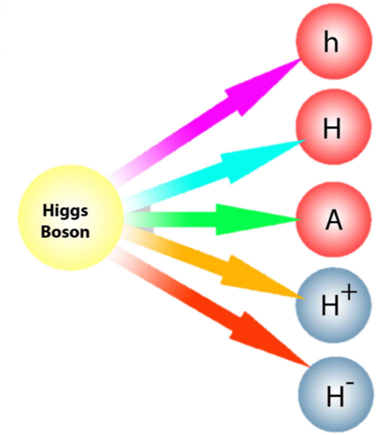
What is Dark Matter?

… as many possible answers to probe!

Super-symmetry?



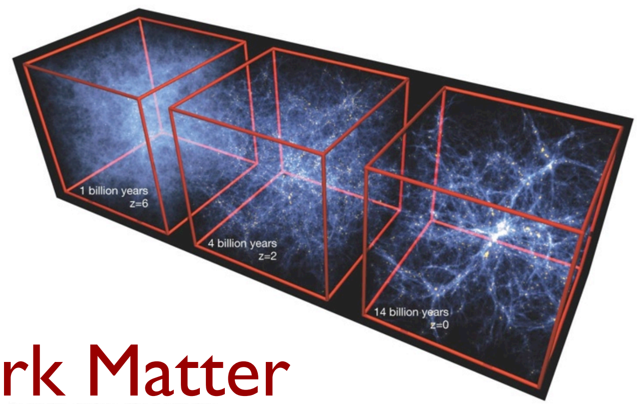
Extended Higgs sector?



New heavy bosons?

Any new theory need to agree with the SM!

Composite quark and leptons?

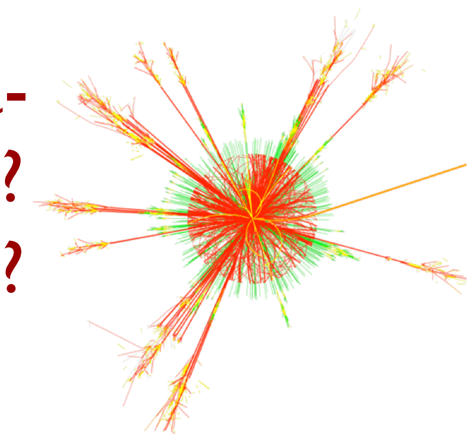


Dark Matter particles?

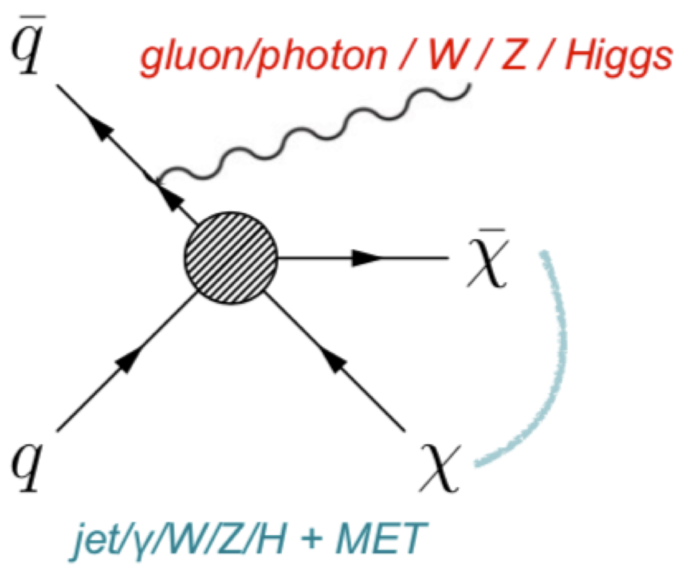
Large extra-dimensions?

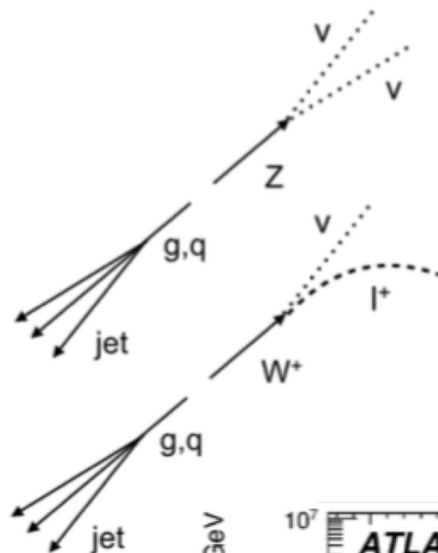
Black holes?

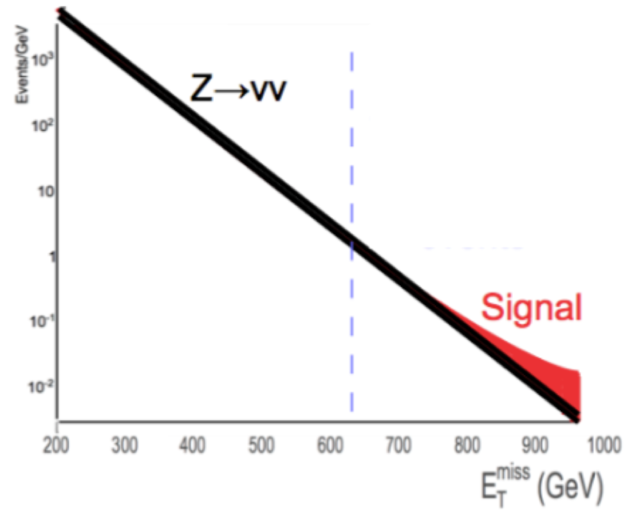
Gravitons?

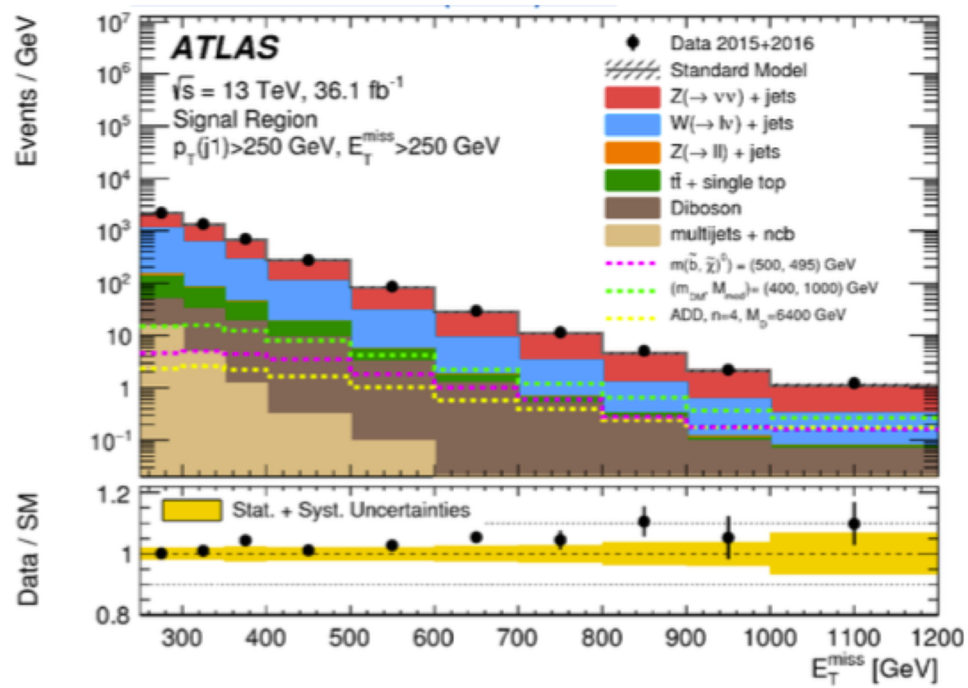


Example: Dark Matter searches at LHC



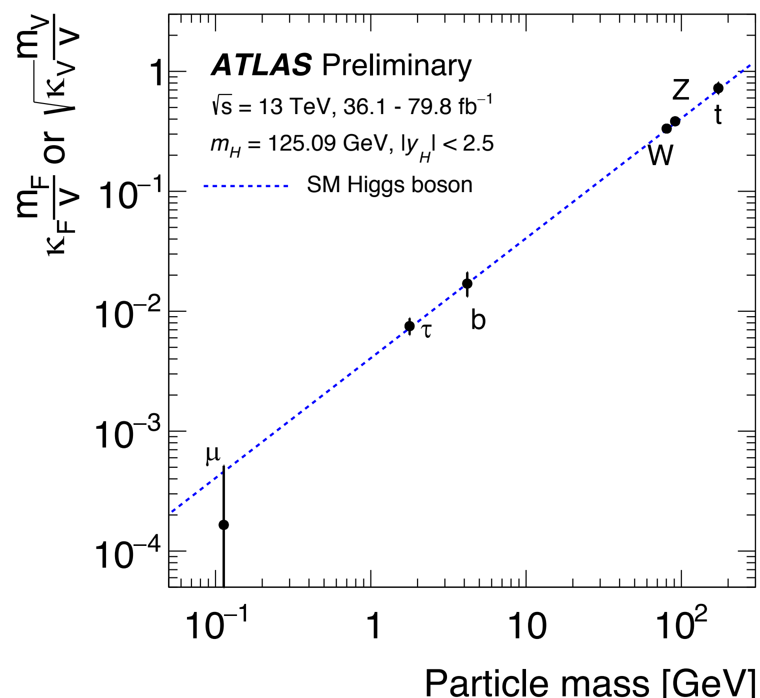


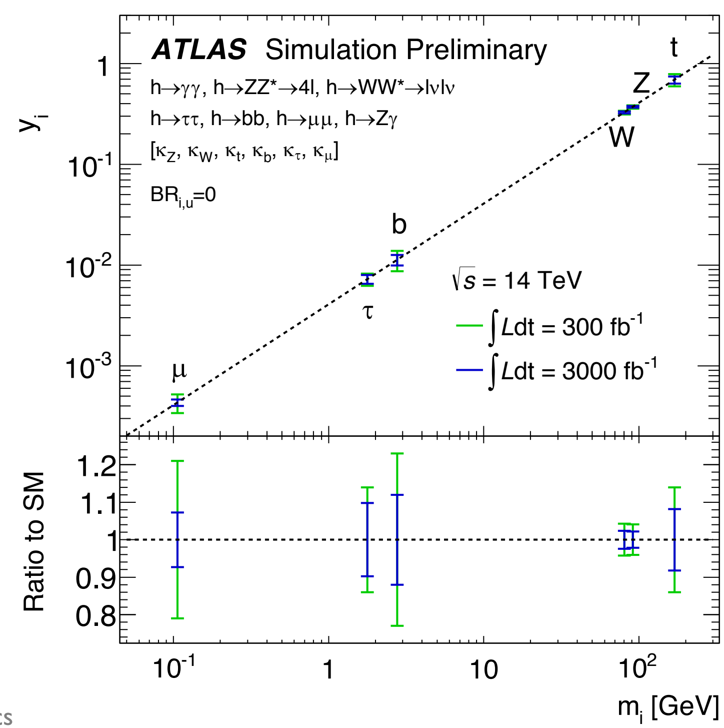


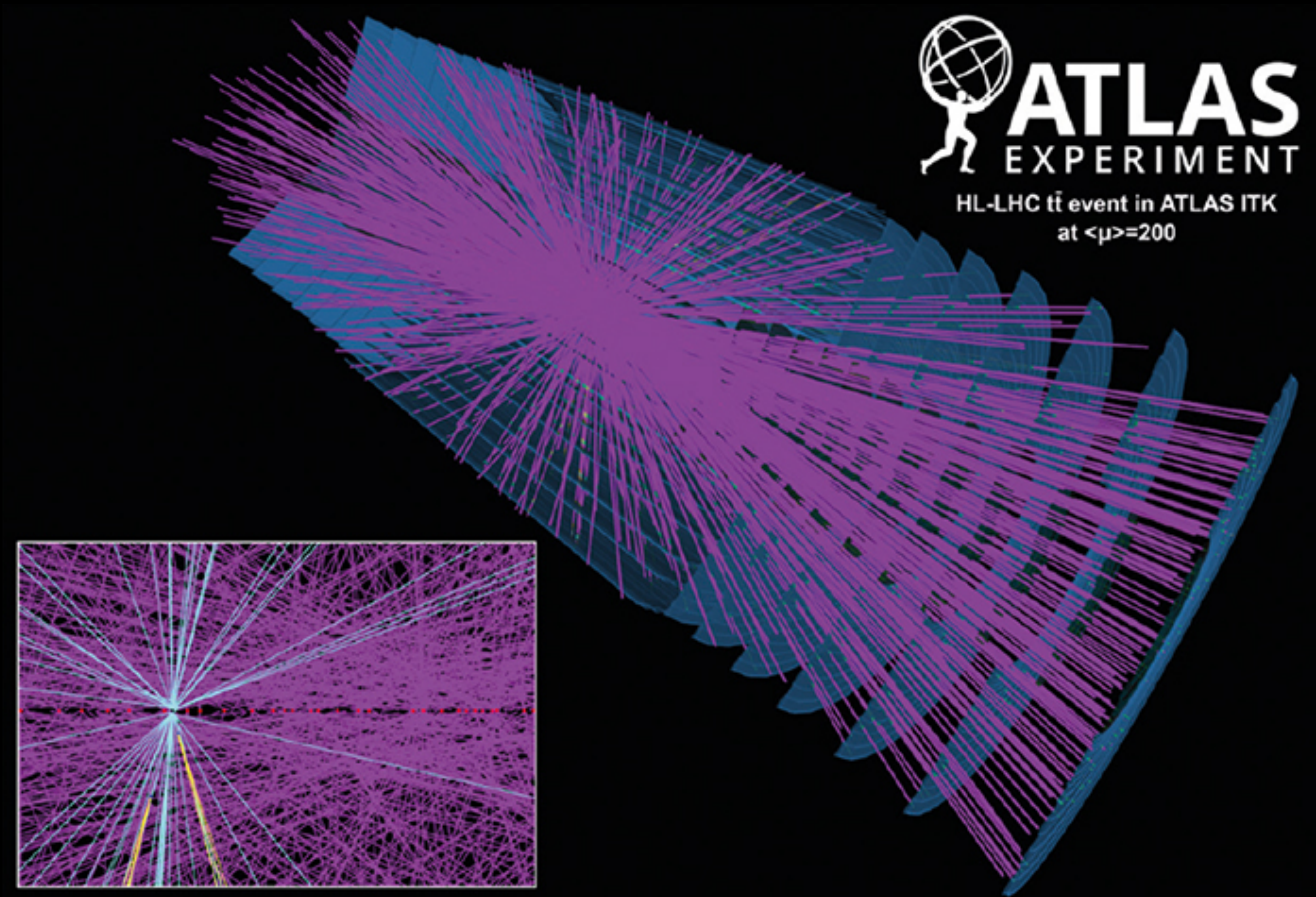


- Use MET shape to extract signal contribution
  - ✓ Similar shape for signal and background
  - ✓ Background modeling very important
- Main contributions (monojet example)
  - ✓ Z(νν)+jet
  - ✓ W(lν)+jet, where charged lepton is not reconstructed

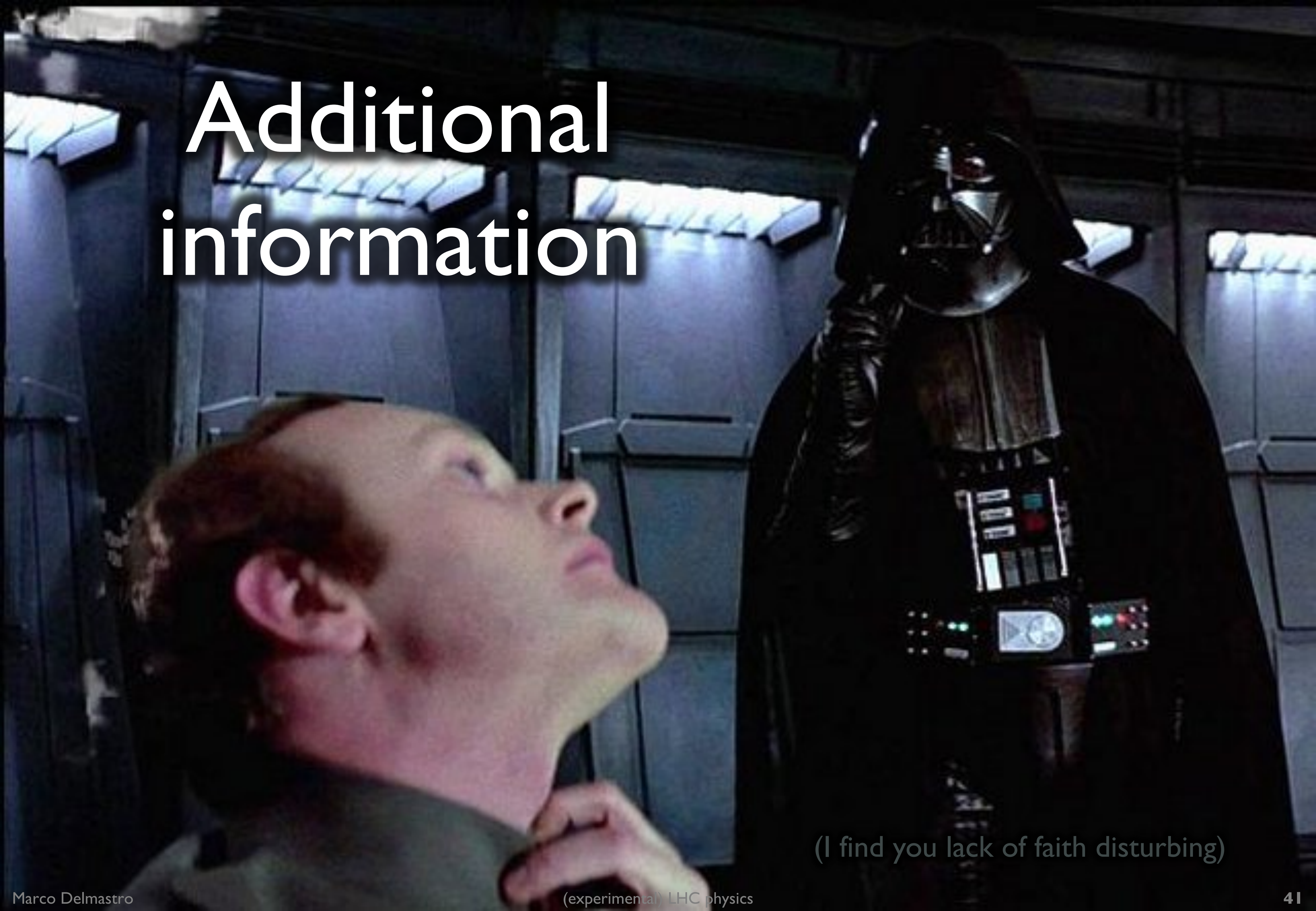
The LHC will run for a long time…






ATLAS
EXPERIMENT
HL-LHC tt̄ event in ATLAS ITK
at <μ>=200

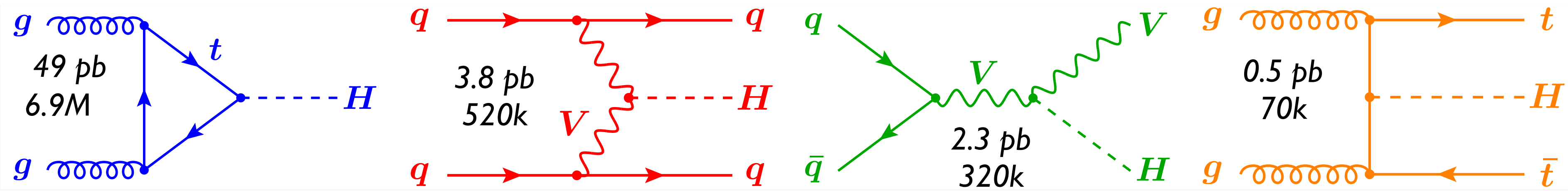
Additional information



(I find you lack of faith disturbing)

Probing Higgs couplings at the LHC

σ[pb] @ 13 TeV
 # Higgs produced in 140 fb⁻¹ in one experiment

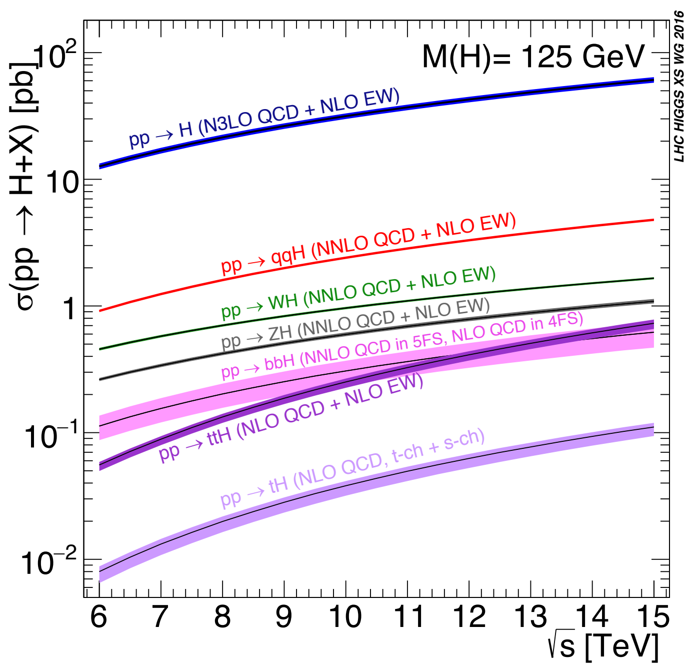


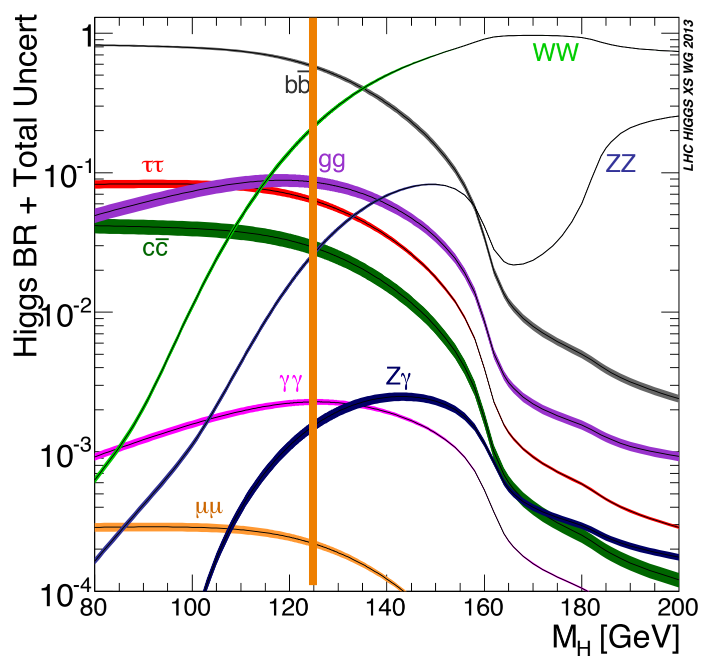
gluon-gluon fusion: main production mode at LHC

Vector Boson Fusion 2 well-separated forward jets

VH tag W and Z boson decays

ttH tag 2 top quarks





decay	SM BR [%] m_H = 125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→γγ	0.23

Spin with H→4l (& combination)

- Sensitive variables combined in BDT score
  - ✓ 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