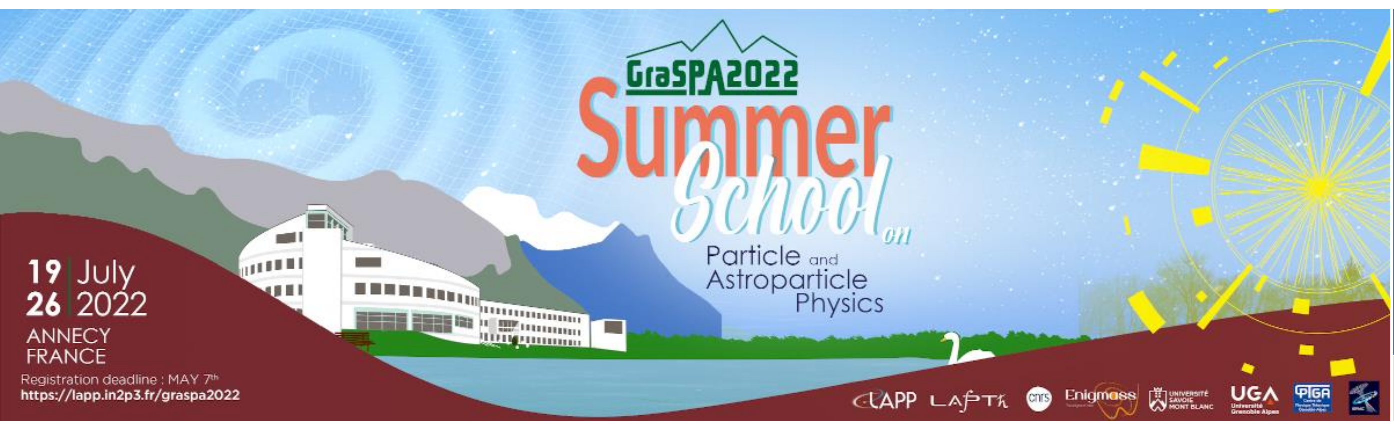
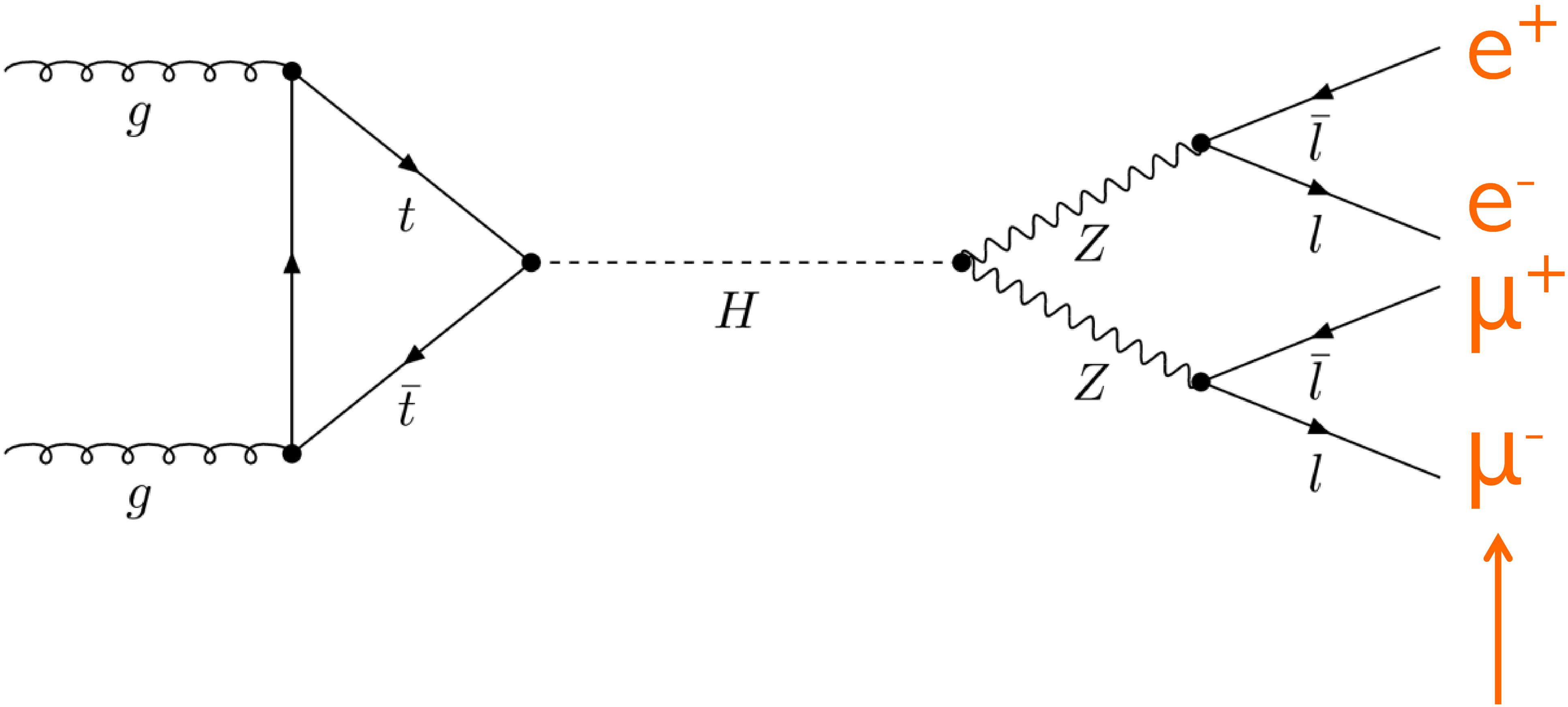
(experimental) LHC physics



2. { how to search for (and measure) a new particle }

Roberto Covarelli

There is no Higgs-boson detector!

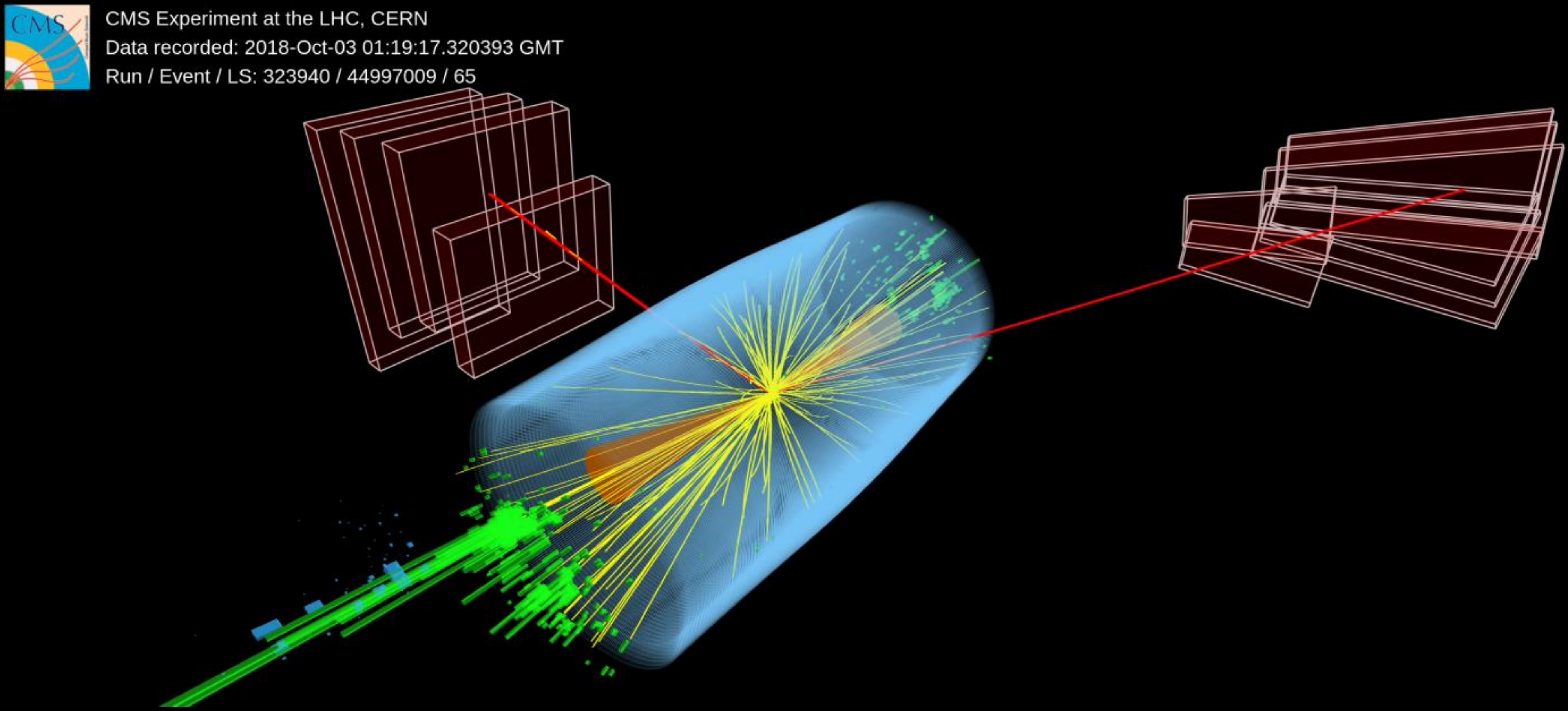


this is what we are looking for…

Step 1: find events with the right ingredients

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

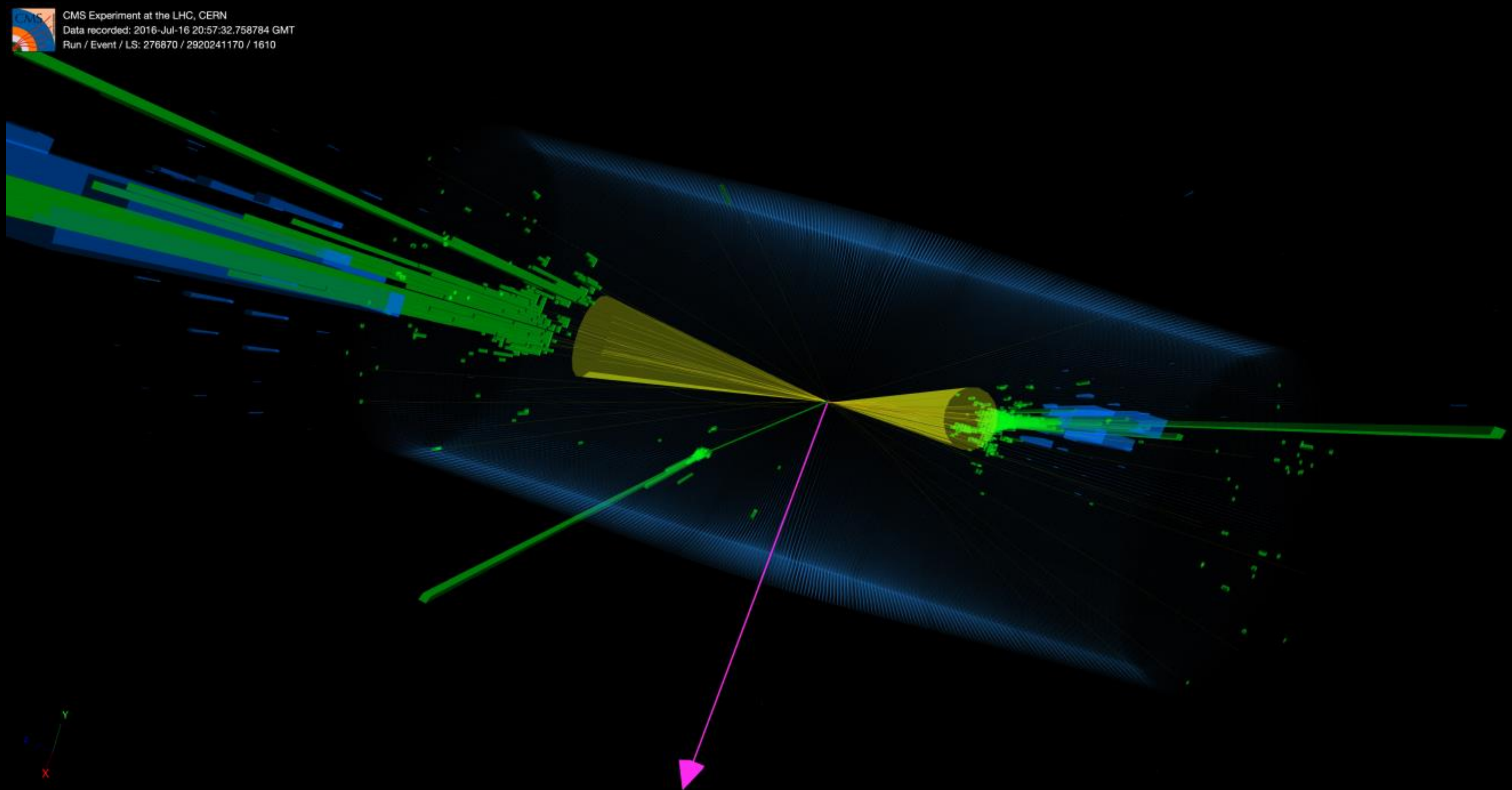
Is this event OK?



Step 1: find events with the right ingredients

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

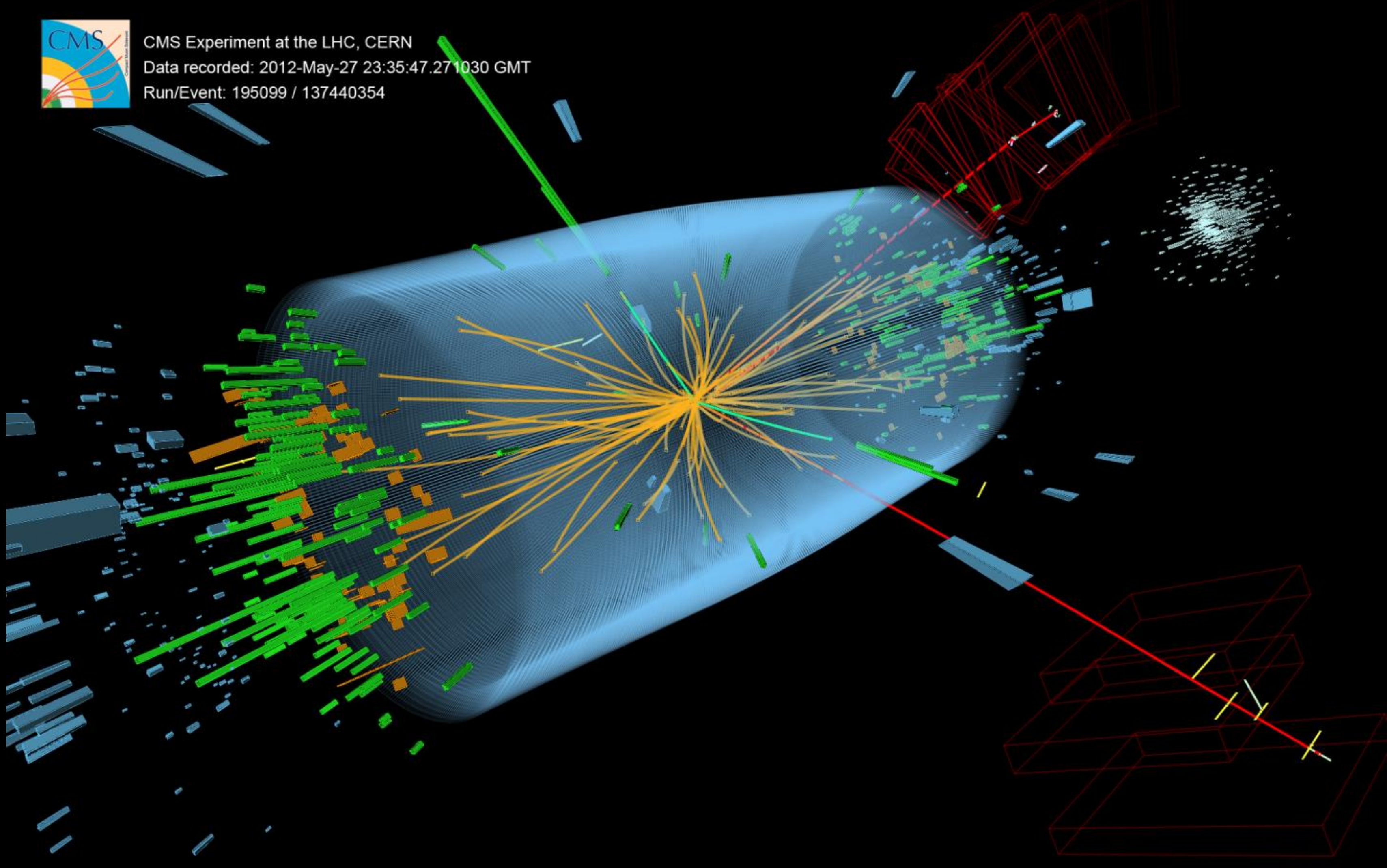
What about this one?



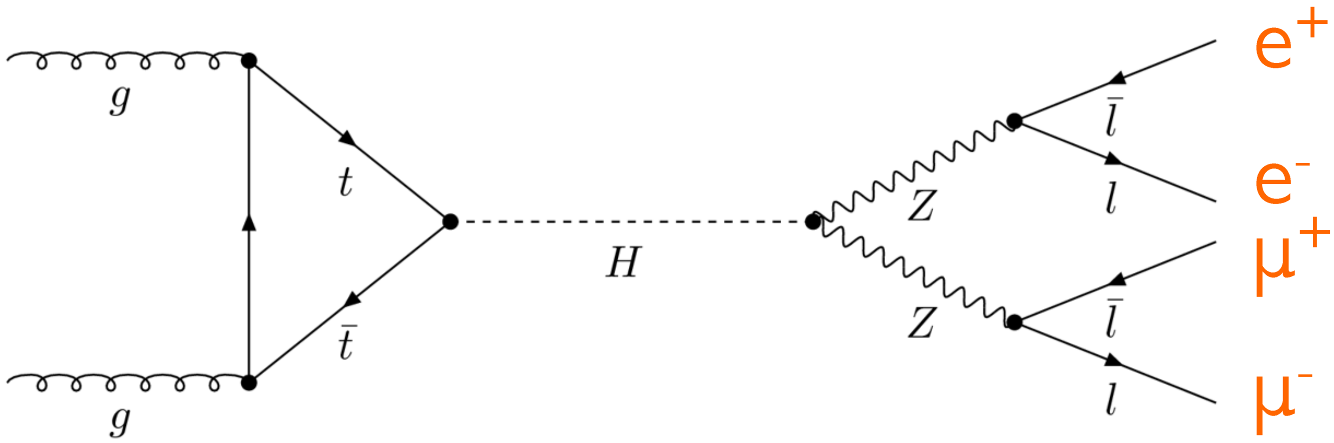
Step 1: find events with the right ingredients

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

And this one?

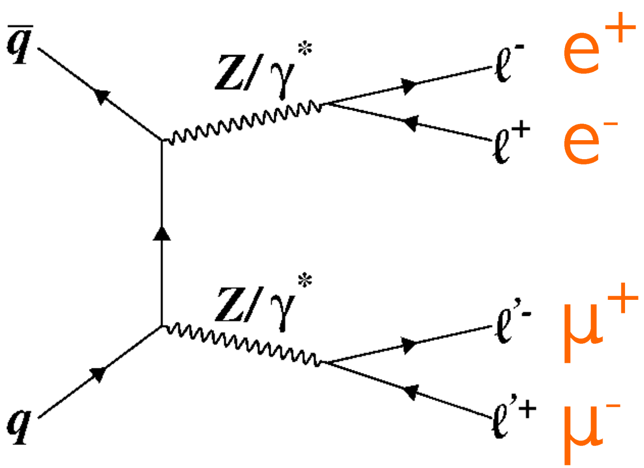


Step 2: signal and background



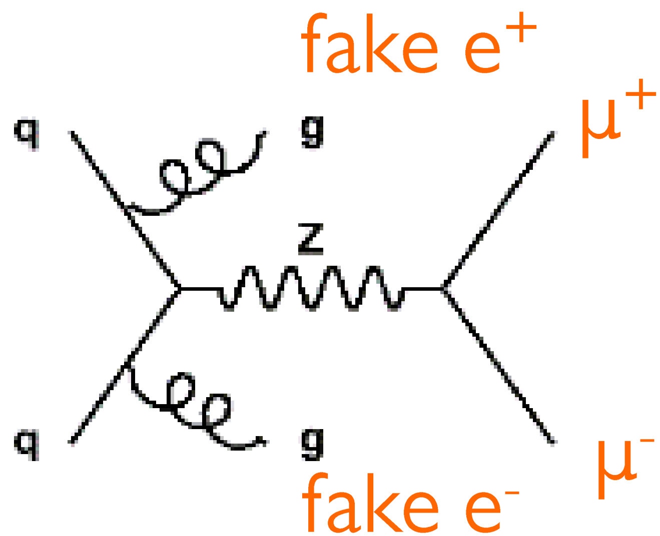
Irreducible background

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

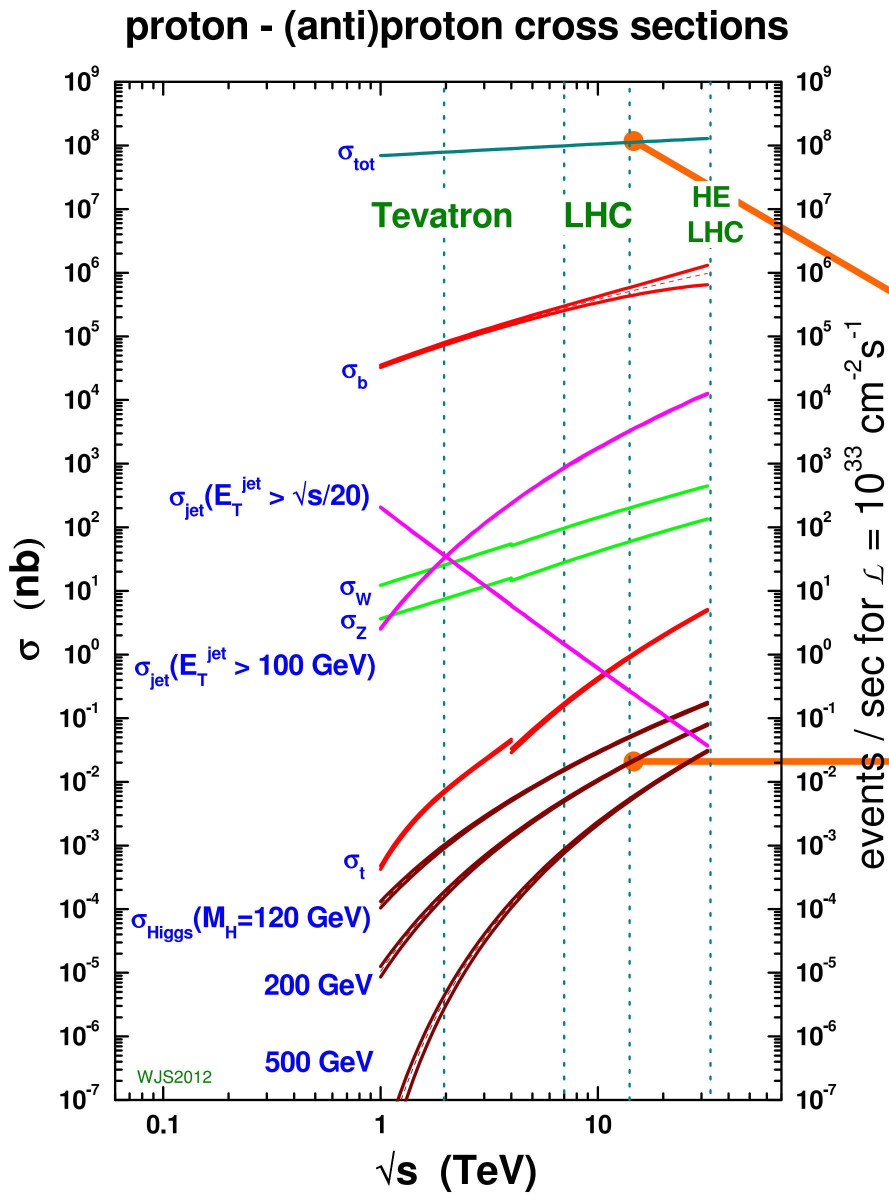


Reducible background

The final state looks like the same because some of the particles fake what you are looking for



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

$\sim 10^{10}$

10^{-1} events/s

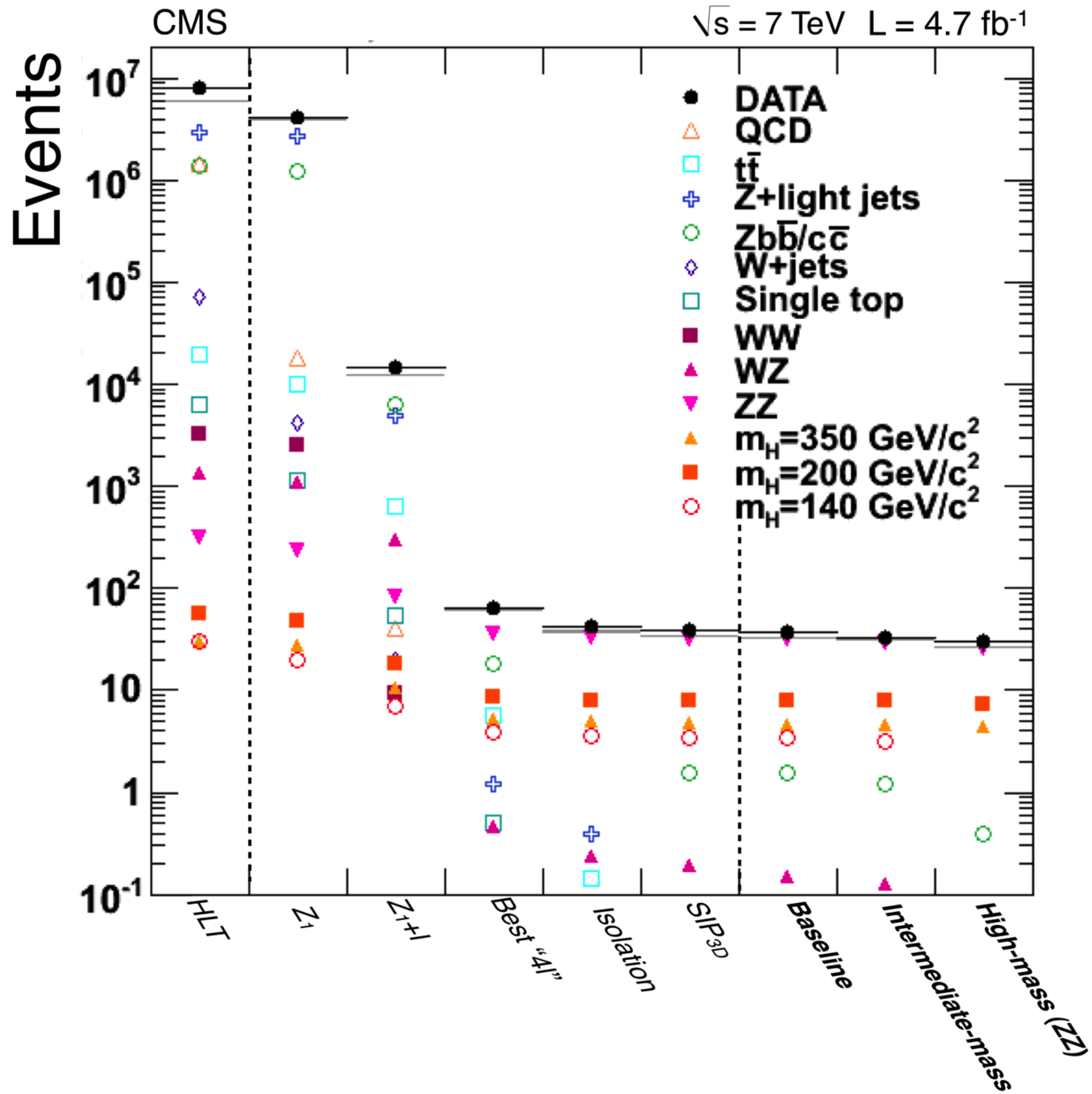
~ 1 Higgs boson every 2 seconds

[m_H ~ 125 GeV]

0.2% H → γγ
0.01% H → ZZ

Lose some signal, suppress backgrounds…

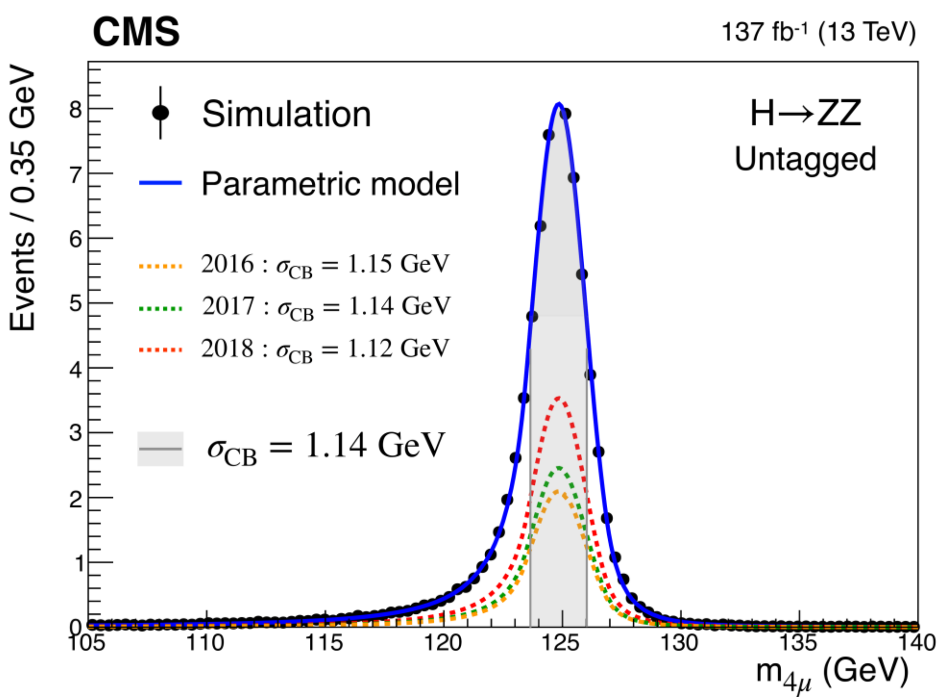
- Selections based on particle properties to reduce reducible background
  - ✓ Shower shapes, track properties, …
- Selections based on event properties to distinguish signal from background
  - ✓ Particle kinematics, decay kinematics event shape, …
- Try to keep signal while reducing background!
  -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



Step 3: 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

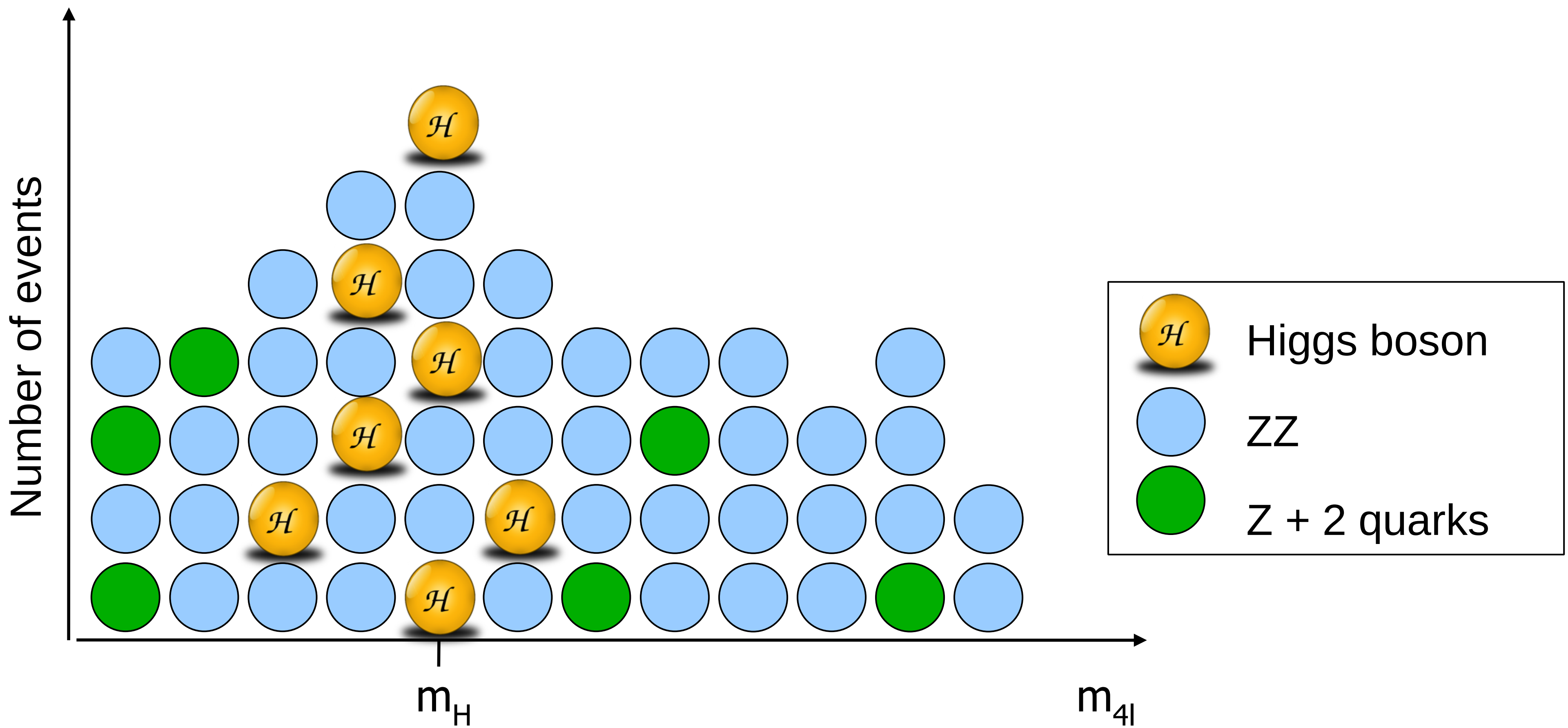
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



- But, even after selection, we don't have just true Higgs bosons left…

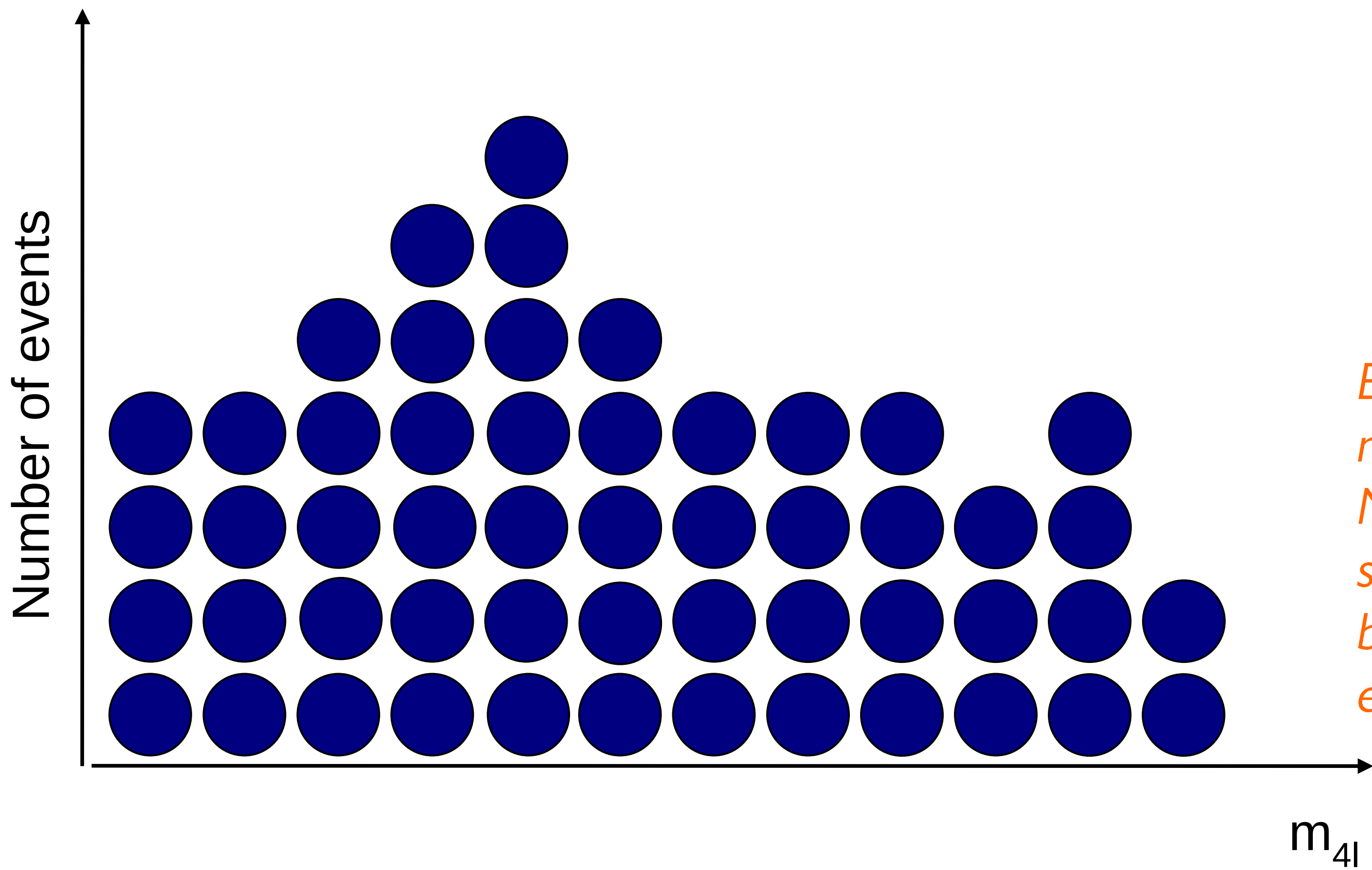
Extract signal from background

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



Extract signal from background

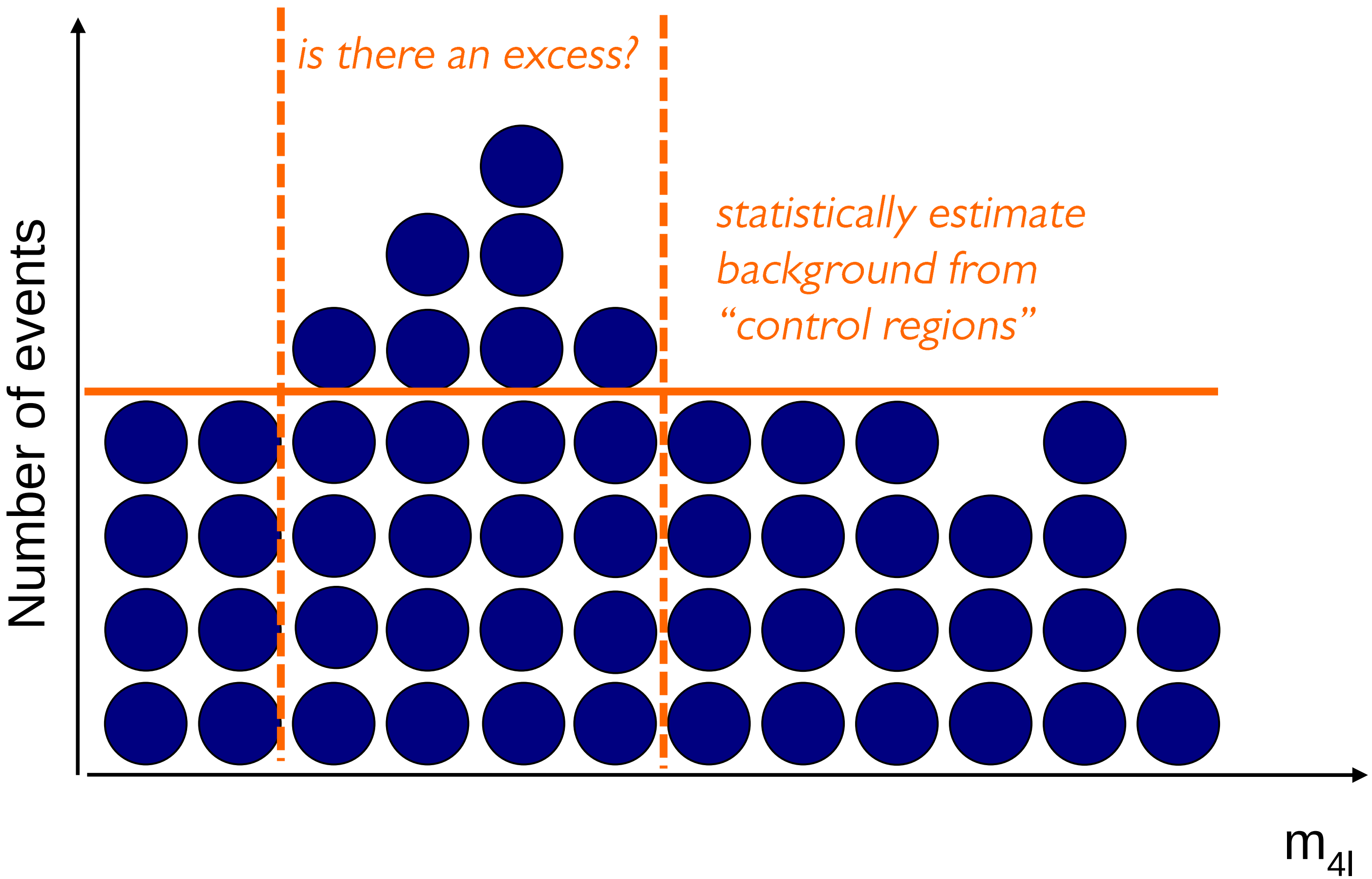
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



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

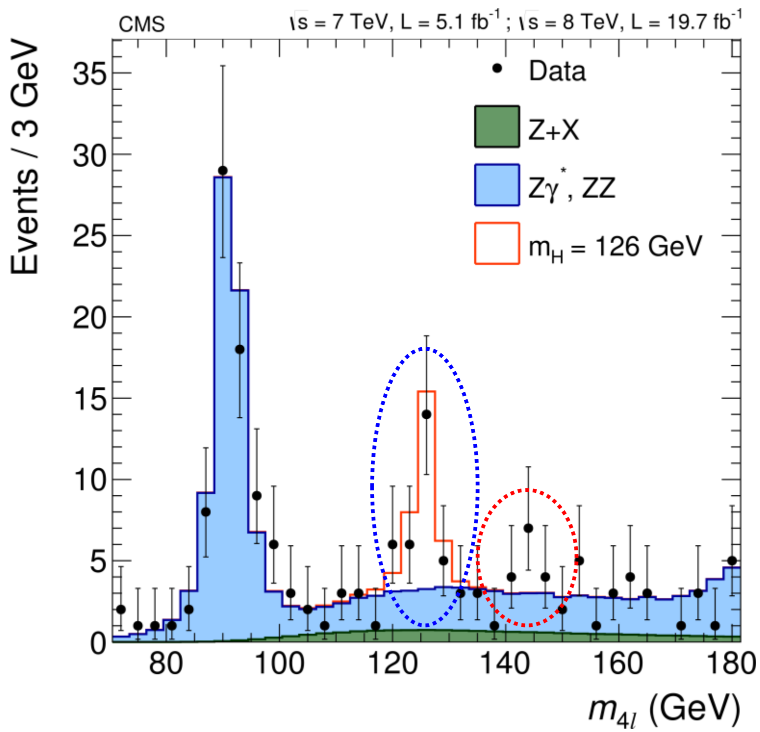
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

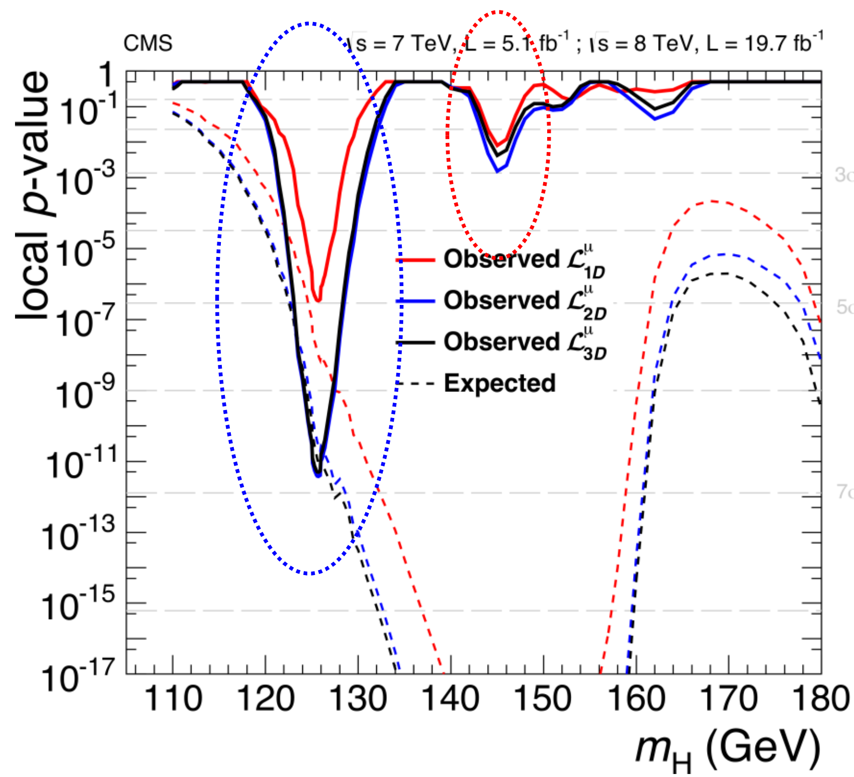


- Background gets estimated…
  - ✓ … from simulation (normalized to data)
  - ✓ … directly from data ("control regions", enriched in background events)

How significant is an excess?

- p_0: 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 ($p_0 = 5.7.10^{-7}$)



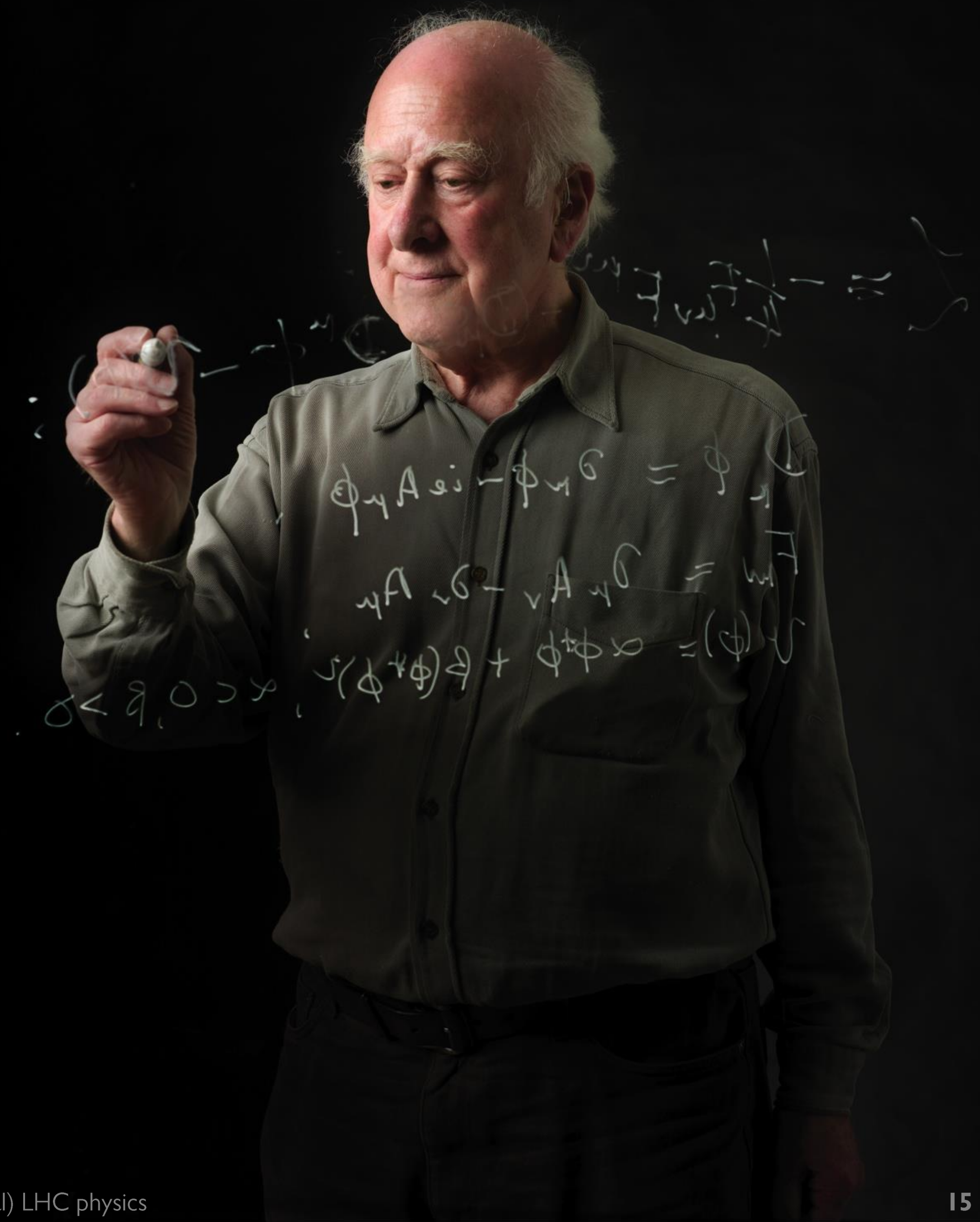


CERN Auditorium, July 4th 2012

CERN | 10 years HIGGS boson discovery

CERN Auditorium, July 4th 2022

Is it a *scalar* boson?



Spin!

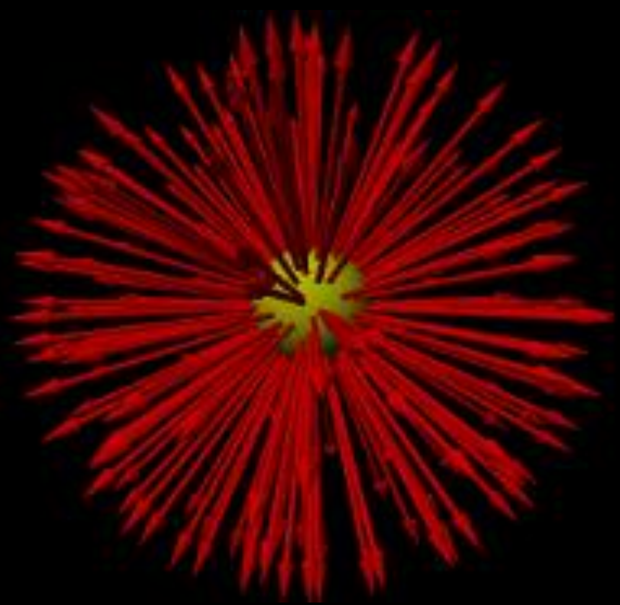
What's a particle spin?

"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)

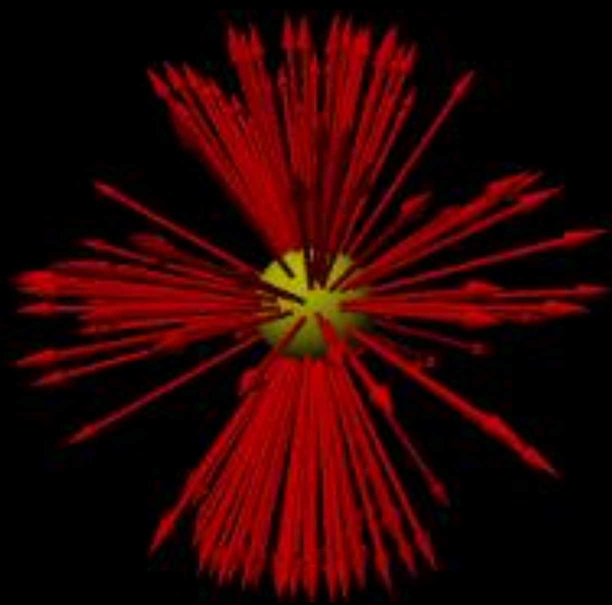
$\hbar = 1.0545 \times 10^{-34}\ \mathrm{J \cdot s}$

How can we recognize spin?



spin 0

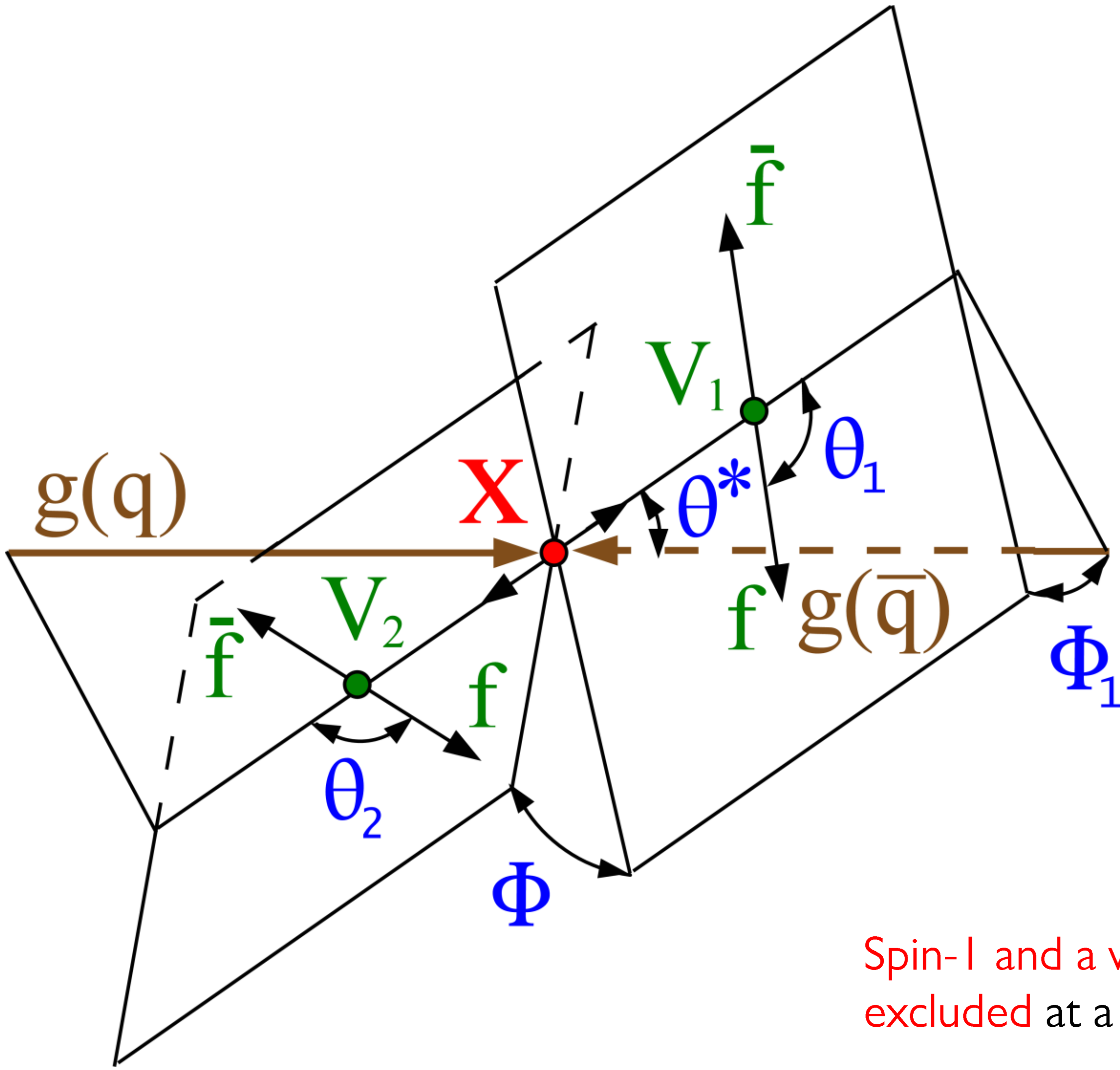
spin 1

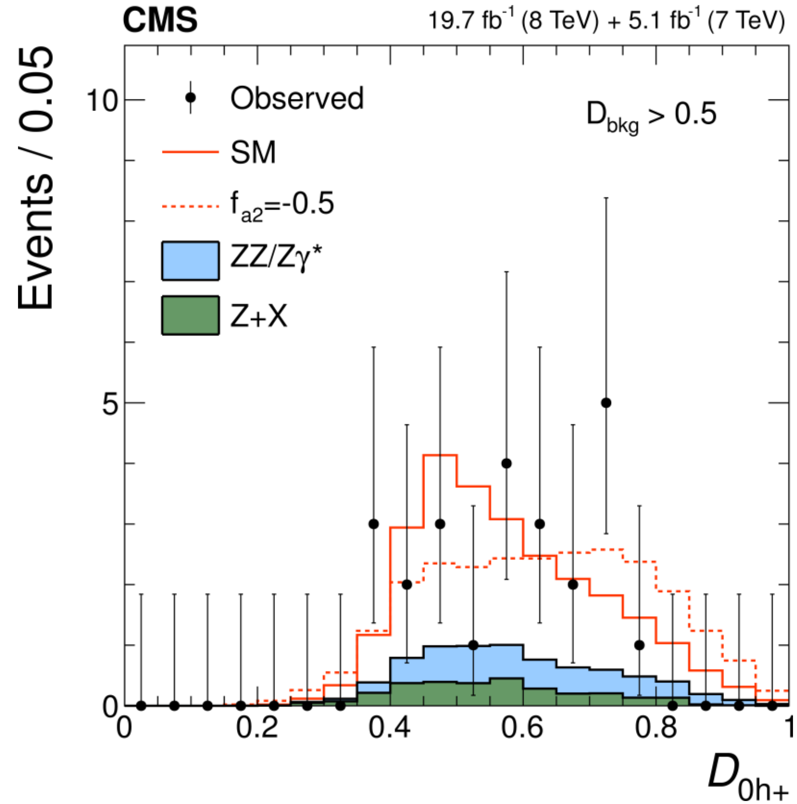


spin 2

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.

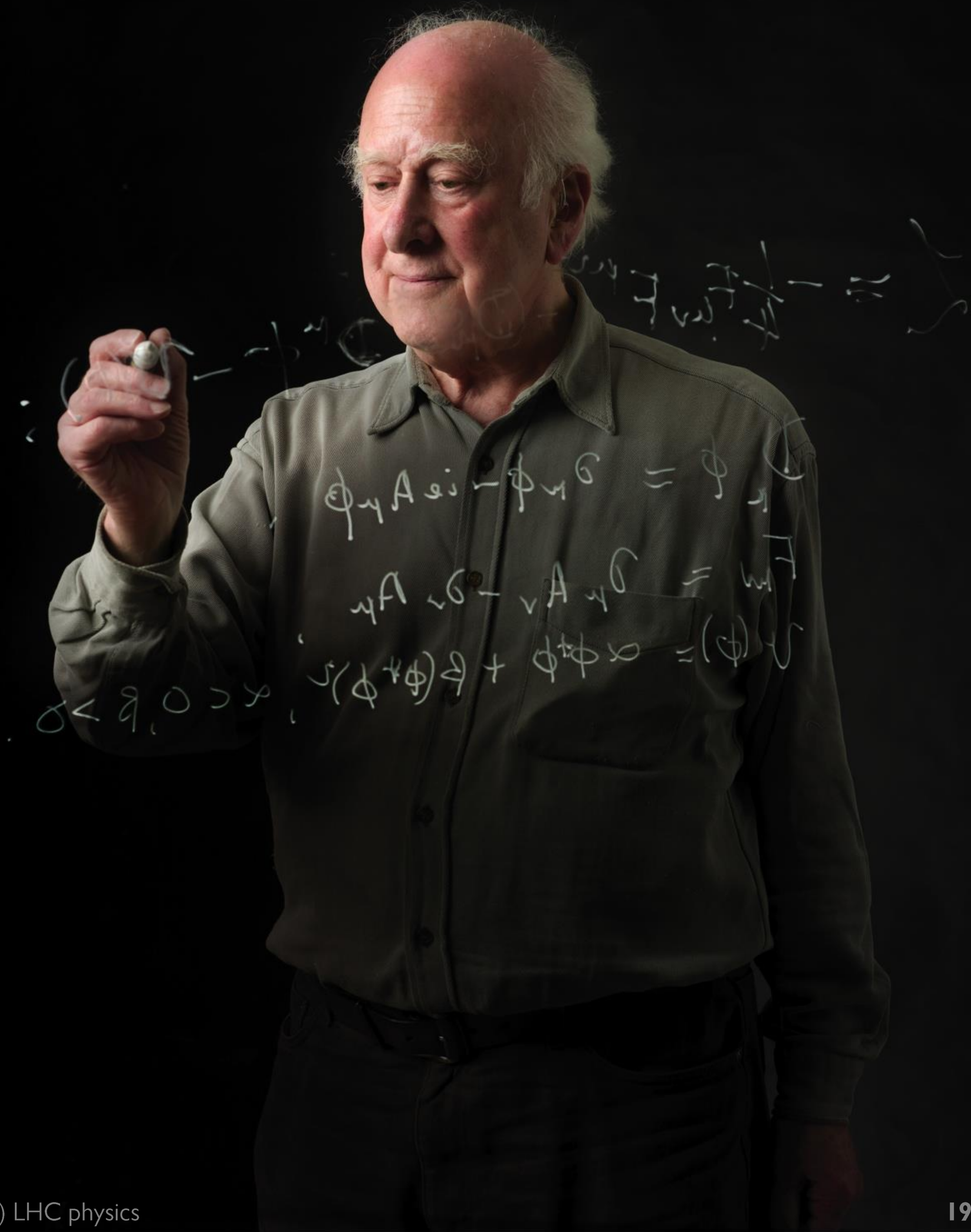
Spin with H → 4 leptons





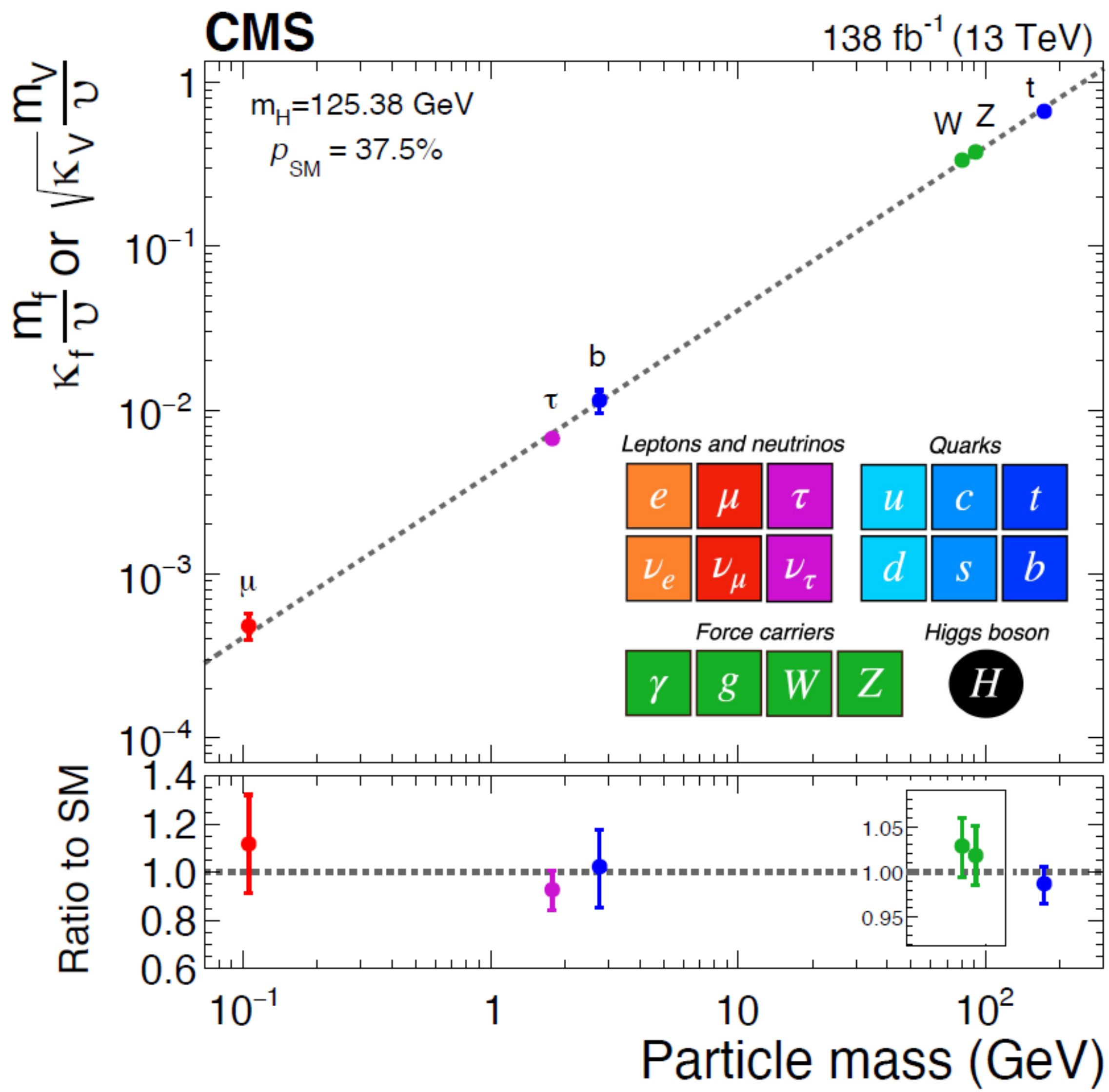
Spin-1 and a wide range of spin-2 models is excluded at a 99% confidence level or higher

Is it responsible for masses?

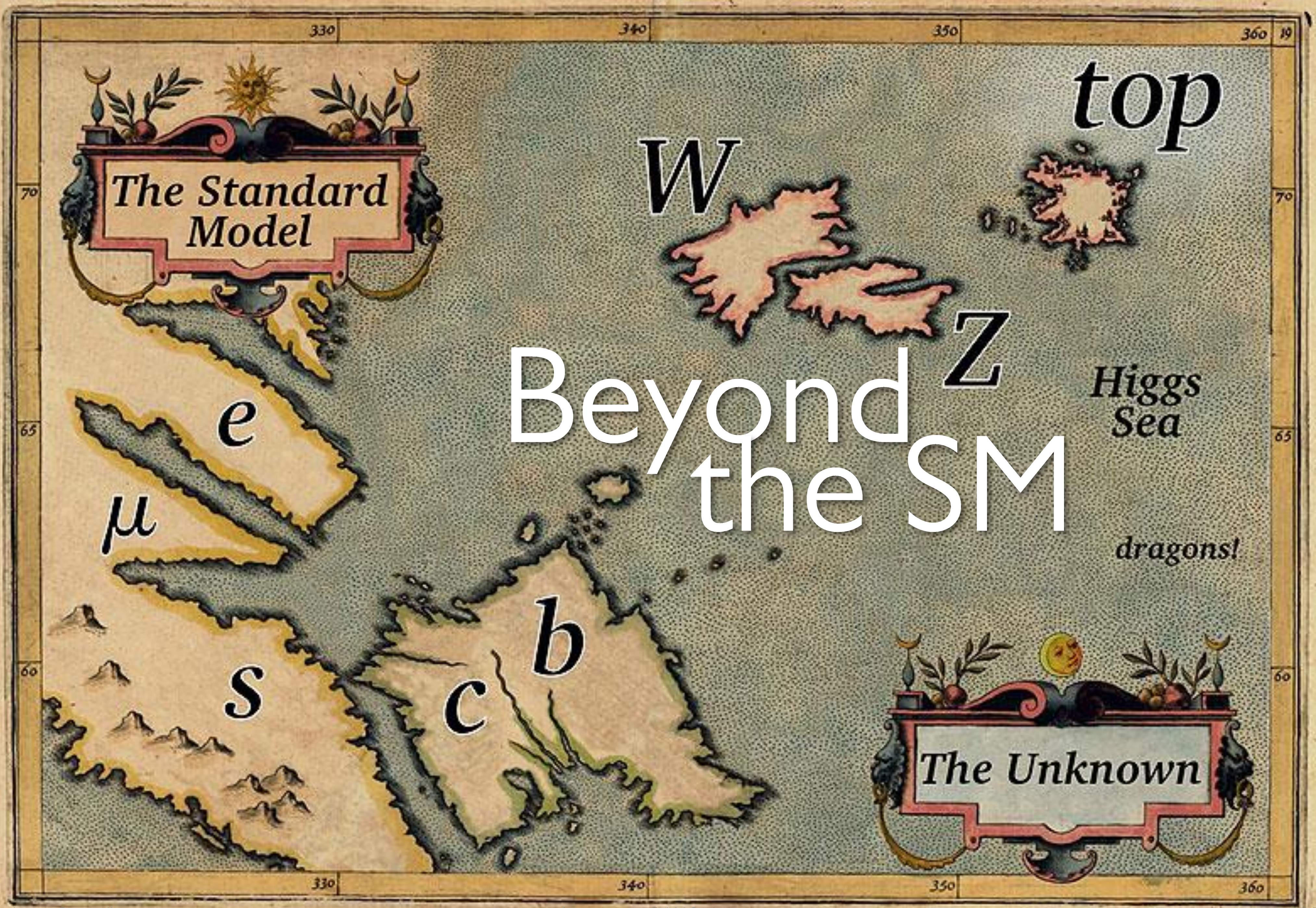


Combine many other decay modes

- ***H→ZZ****
- ***H→WW****
- ***H→γγ***
- ***H→ττ***
- ***H→μμ***
- ***H→cc***
- ***VH, H→bb***
- ***ttH***
- ***…***



Beyond the SM

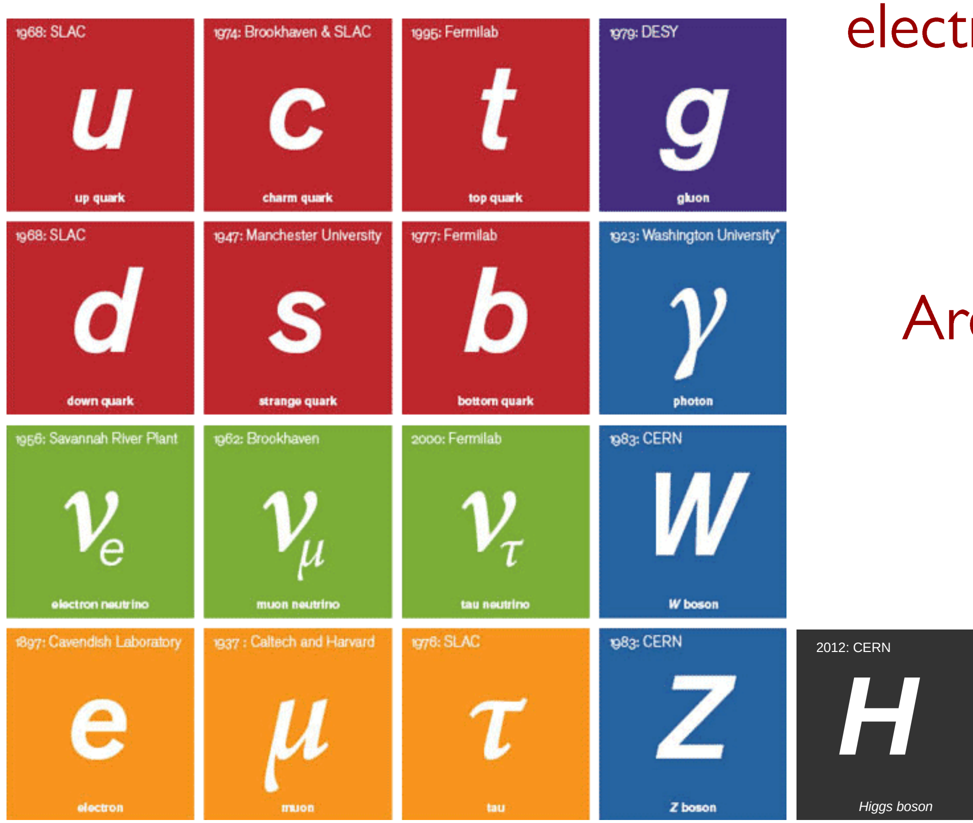


Many unanswered questions…

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

Why is there a hierarchy of masses (top quark mass >> electron mass)?

Why there's more matter than anti-matter?



Are there more forces?

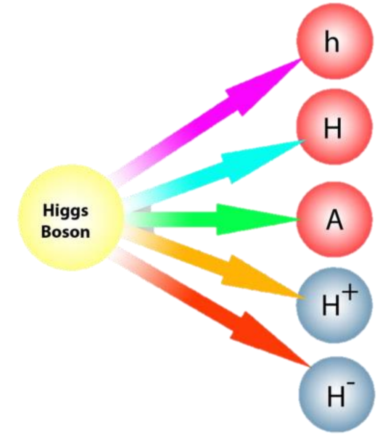
How do neutrinos get mass?

What keeps the Higgs mass so small?

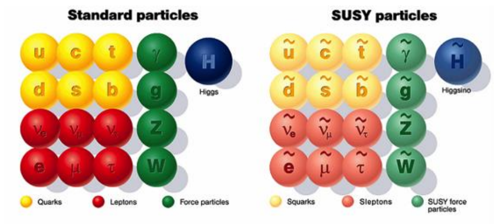
How do we incorporate gravity?

What is Dark Matter?

… as many possible answers to probe!



Super-symmetry?

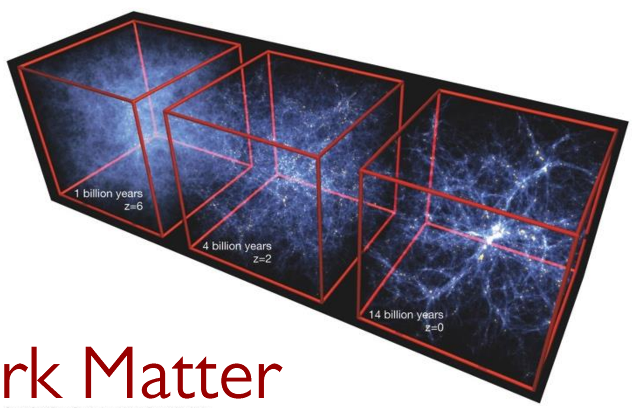


Extended Higgs sector?

New heavy bosons?

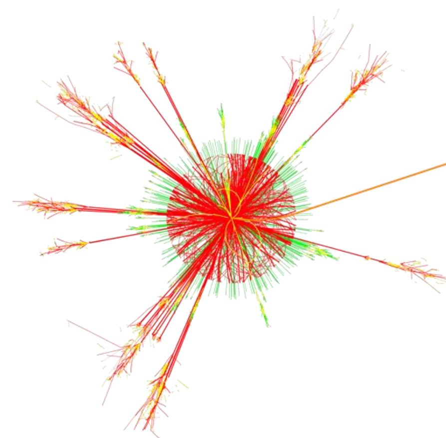
Any new theory needs to agree with the SM!

Composite quark and leptons?



Dark Matter particles?

Large extra-dimensions? Black holes? Gravitons?



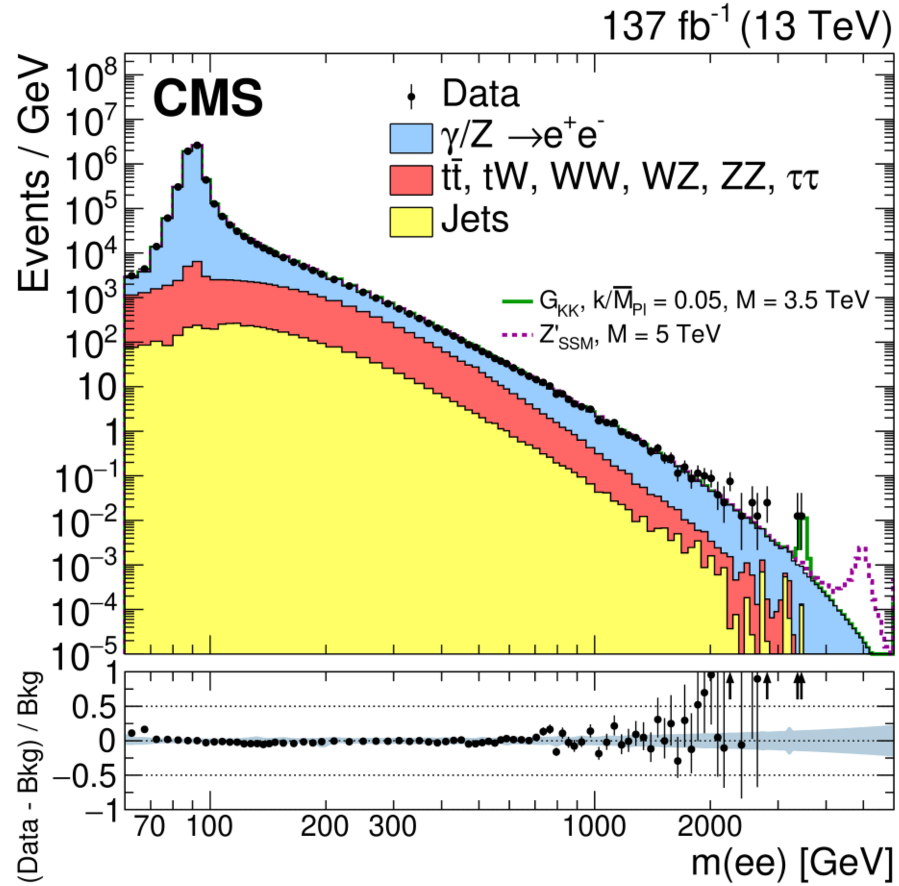
Where is Beyond-the-SM Physics?

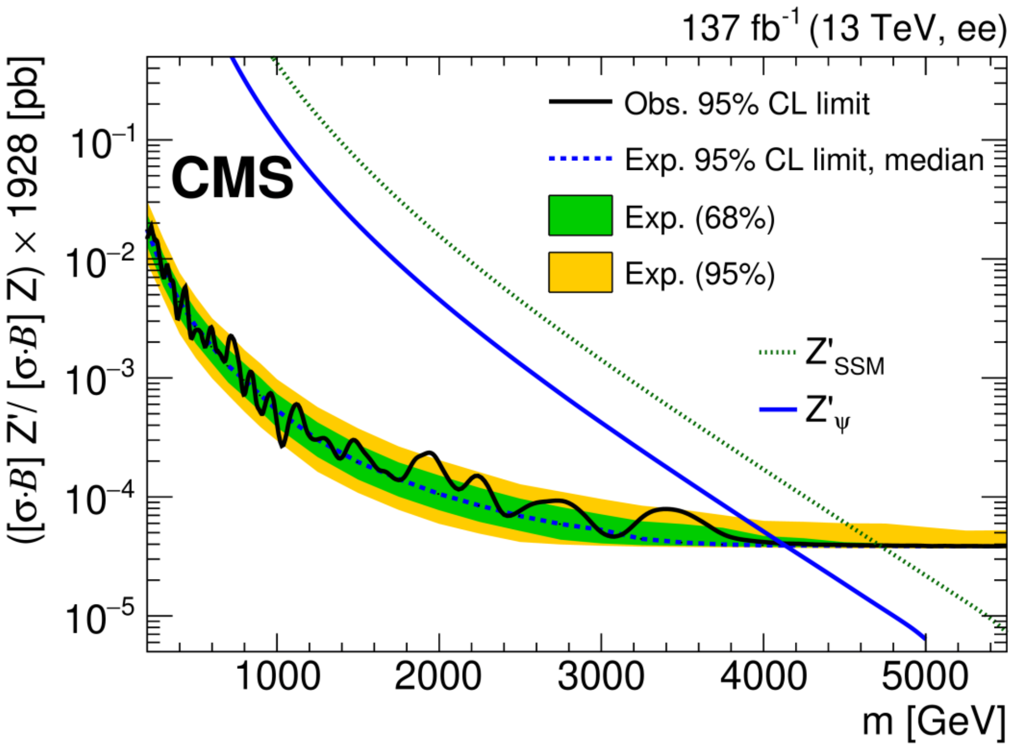
Masses of new particles within the LHC reach

Masses of new particles **not** within the LHC reach

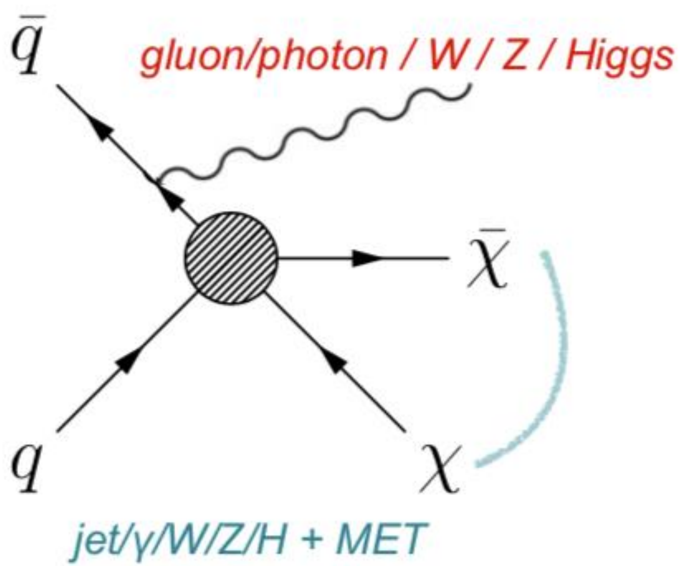
Simple example: heavy Z' boson

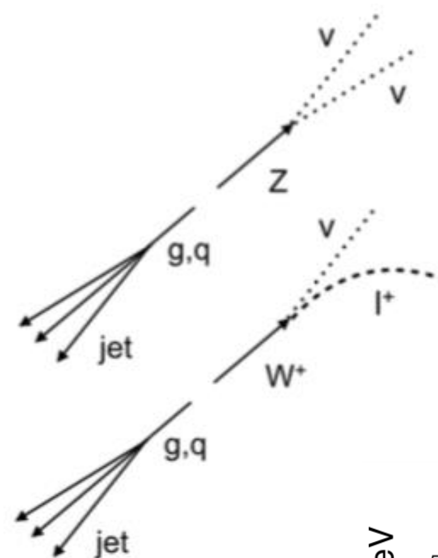
- Use very clear dilepton decay channel
  - ✓ e.g. electron-positron
  - ✓ Drell-Yan modeling important, but clear peak over a continuum ("bump hunting")
- Result expressed as a 95% confidence-level excluded (upper) cross-section

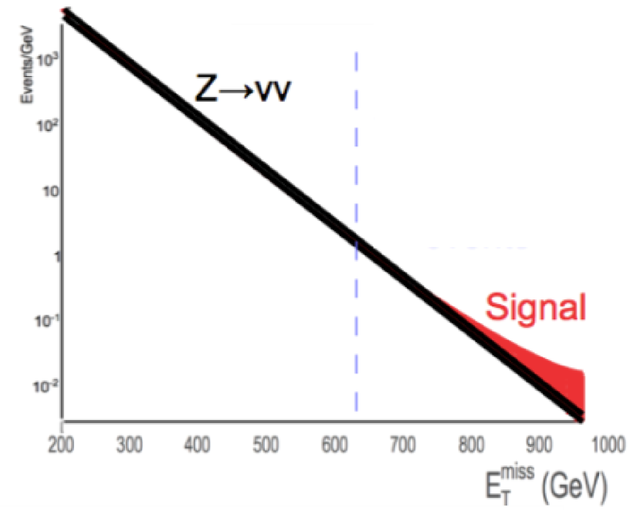


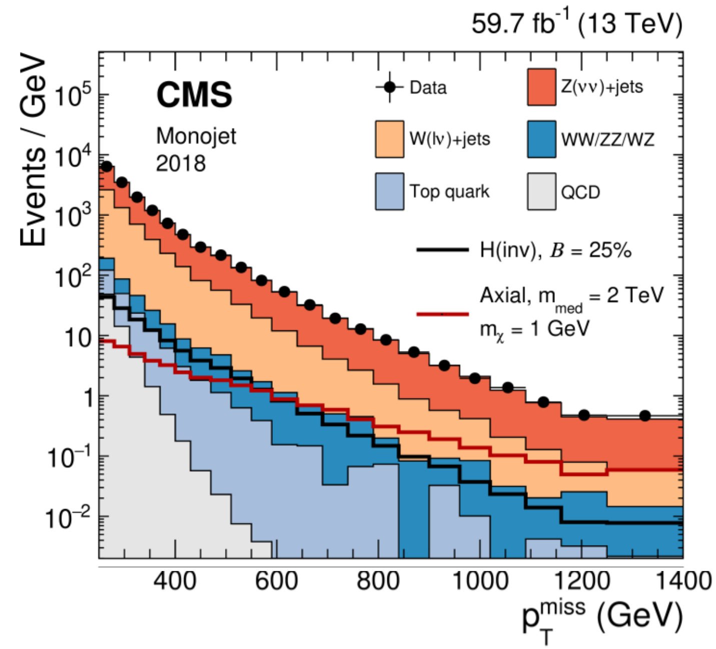


More complex example: Dark Matter searches





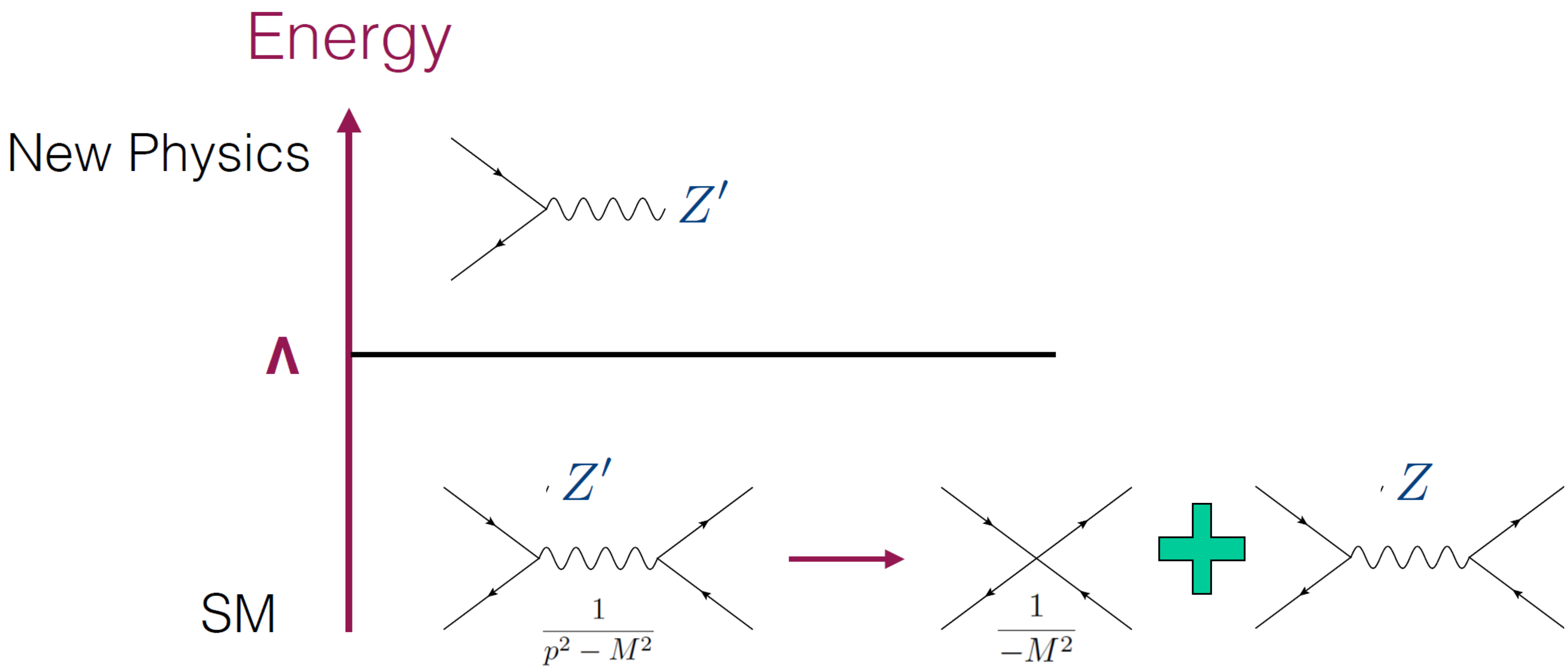




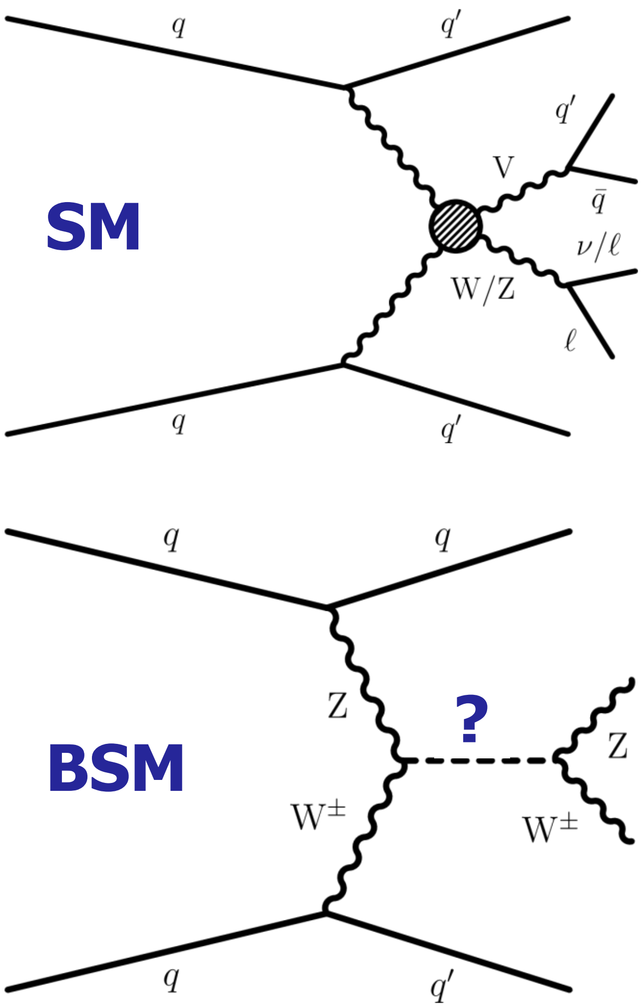
- Use MET shape to extract signal contribution
  - ✓ Similar shape for signal and background
  - ✓ Background modeling very important
- Main contributions (monojet example)
  - ✓ Z(νν)+jet
  - ✓ W(lν)+jet, where charged lepton is not reconstructed

Masses not within LHC reach

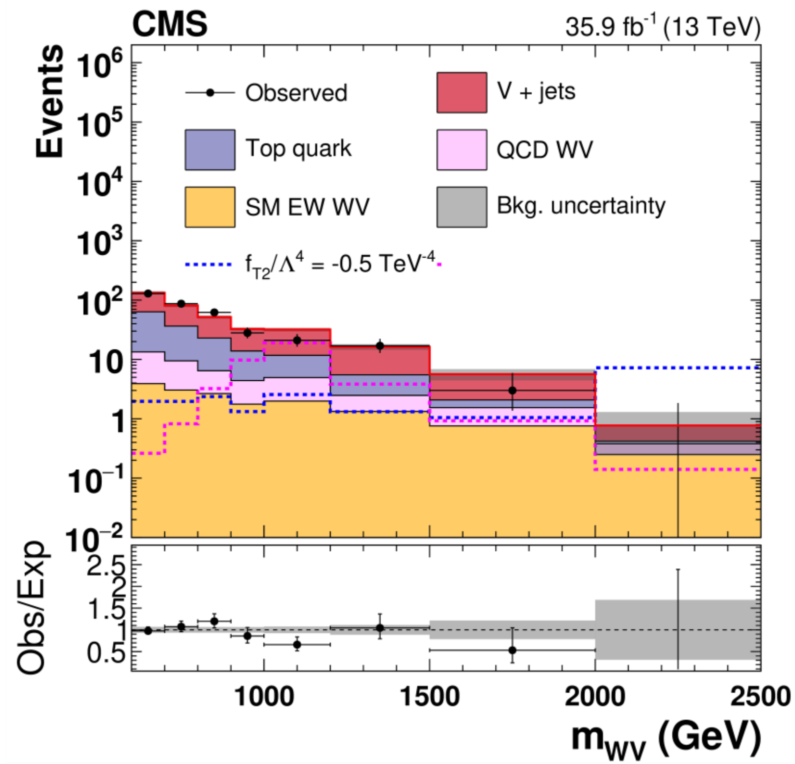
- Search for indirect effects on cross-sections of known processes



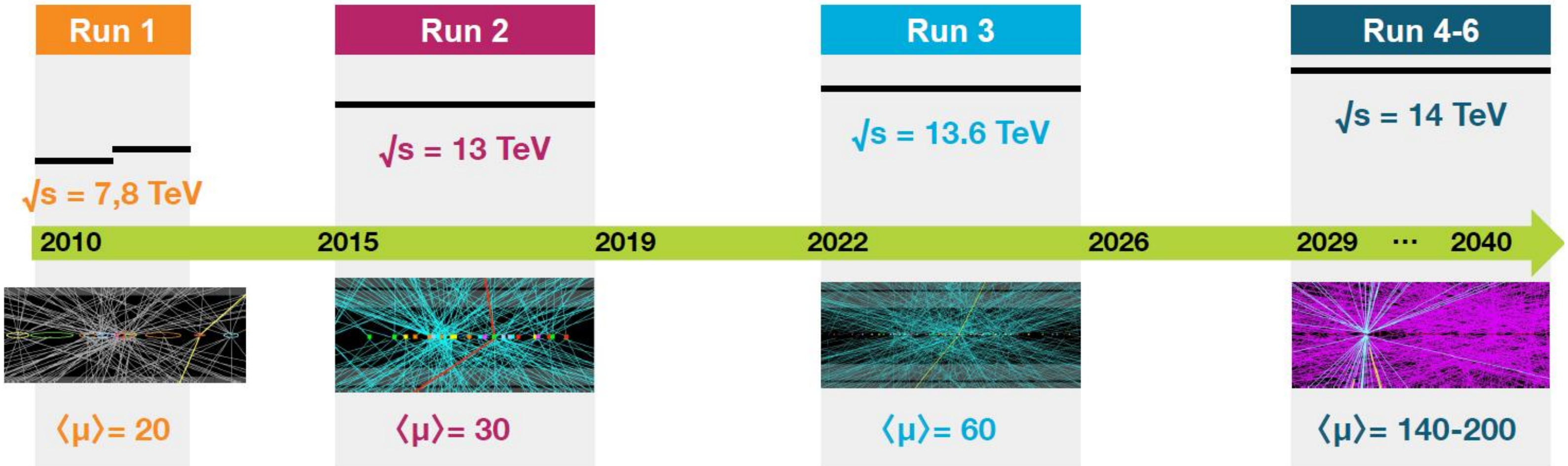
Example: di-boson production

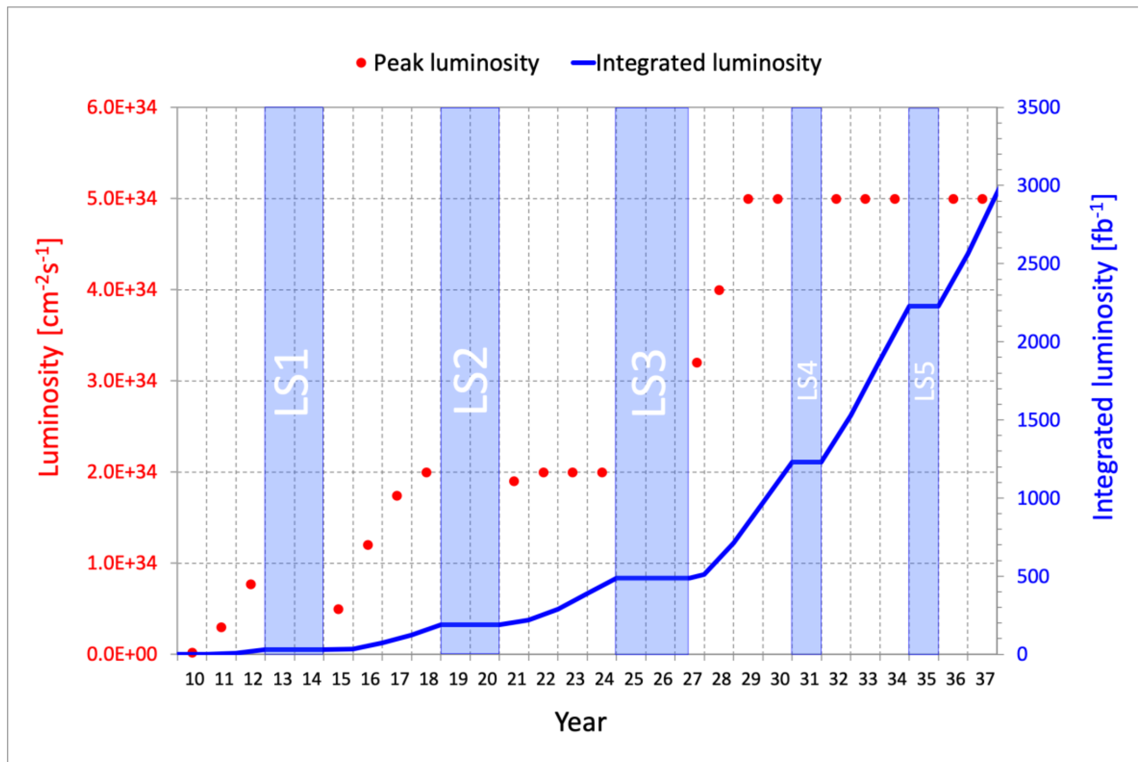


- Search for small deviations in the predicted cross-section in the high-energy tails of the invariant mass distributions
- Exclude/find energy scales at which BSM physics could pop up



The LHC will run for a long time…



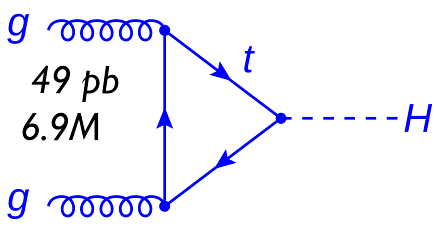


Additional information

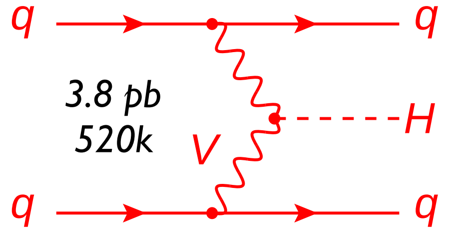
(I find you lack of faith disturbing)

Probing Higgs couplings at the LHC

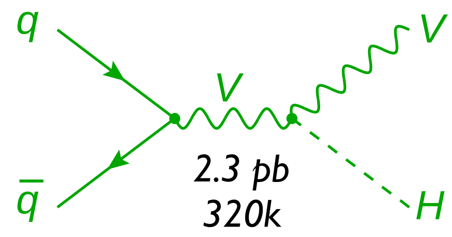
σ[pb] @ 13 TeV
 # Higgs produced in 140 fb^{-1} in one experiment



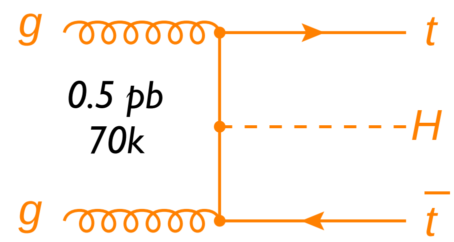
gluon-gluon fusion: main production mode at LHC



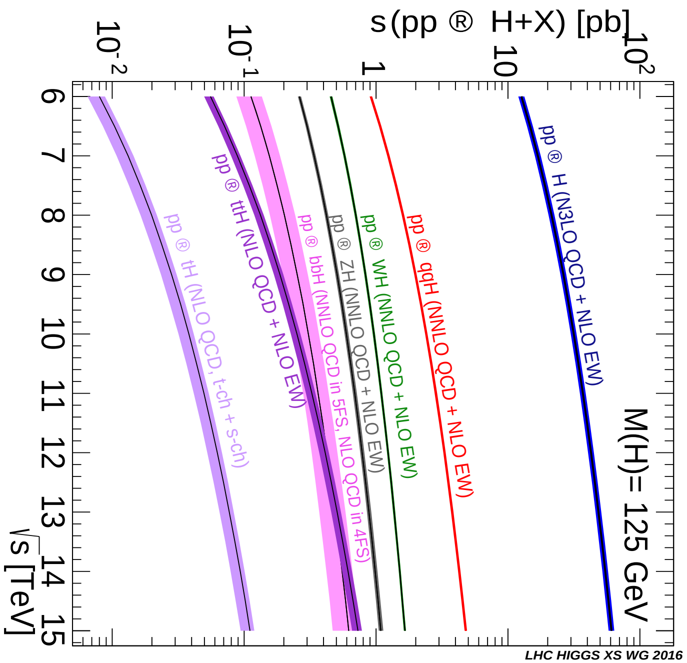
Vector Boson Fusion
2 well-separated forward jets

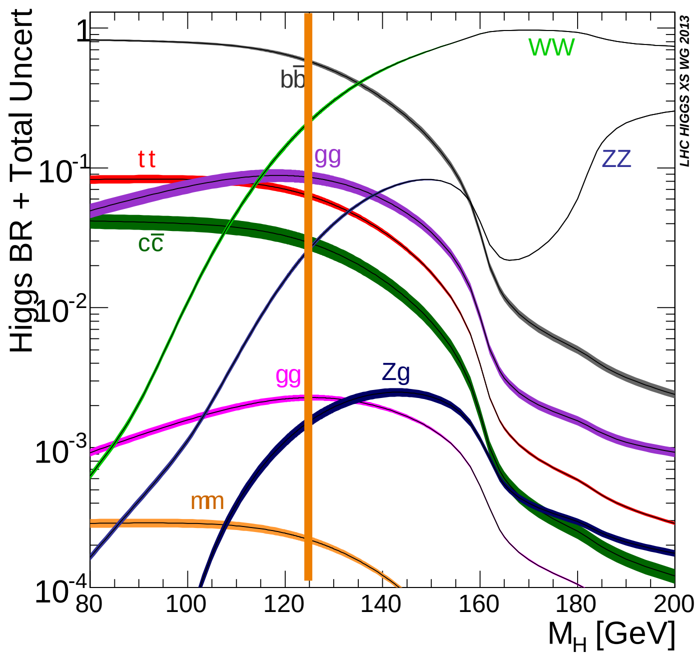


VH
tag W and Z boson decays



ttH
tag 2 top quarks

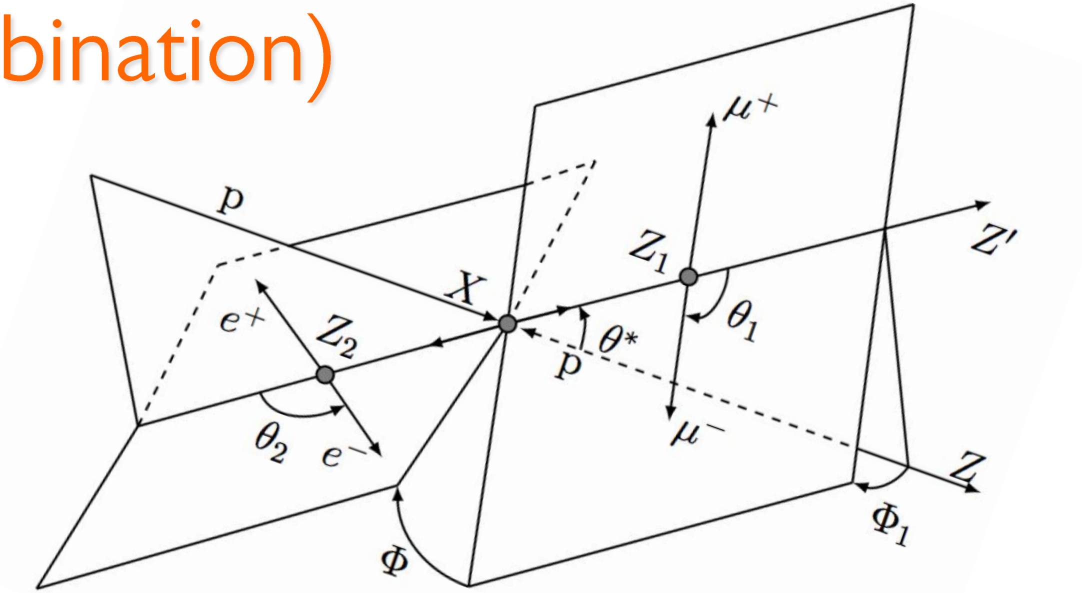


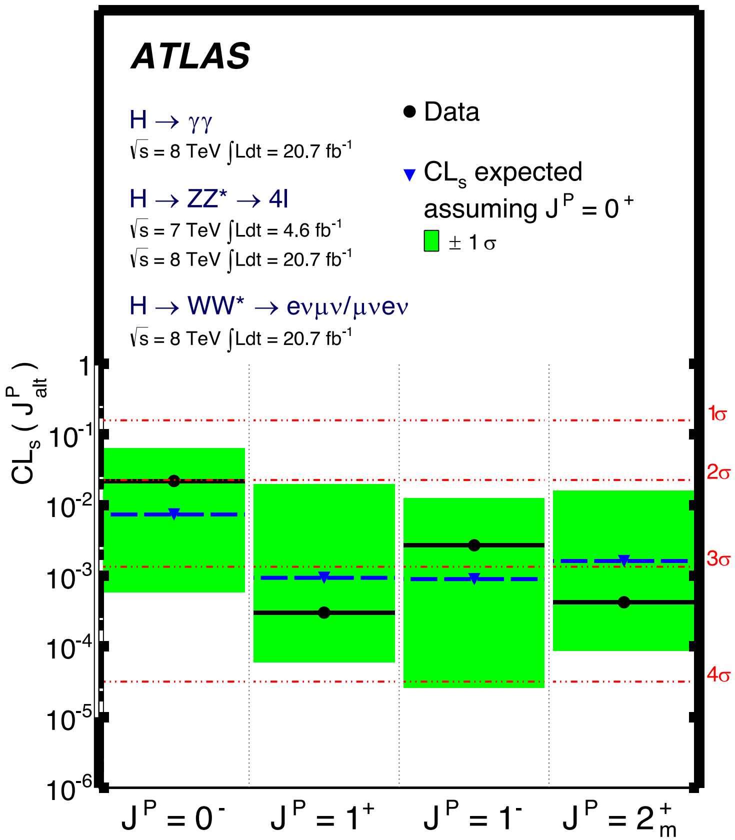


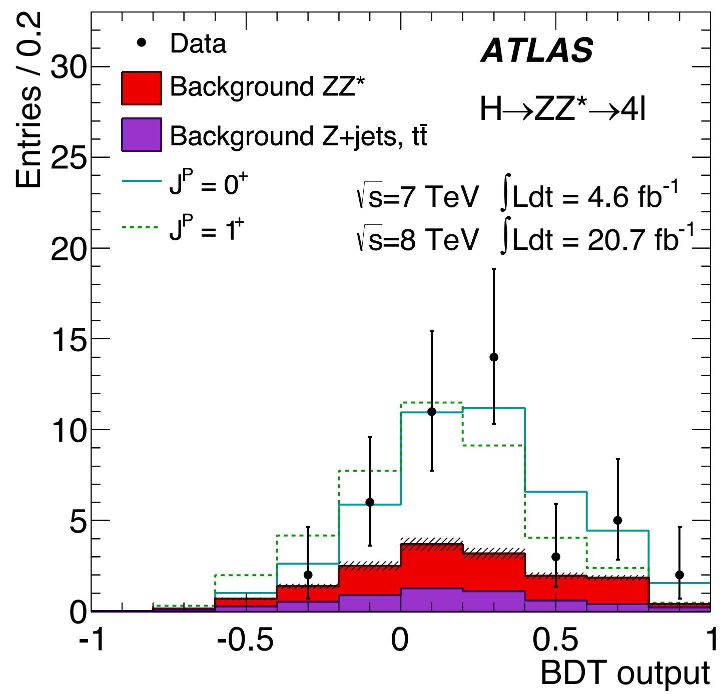
decay	SM BR [%] m_H = 125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→γγ	0.23

Spin with H→4l (& combination)

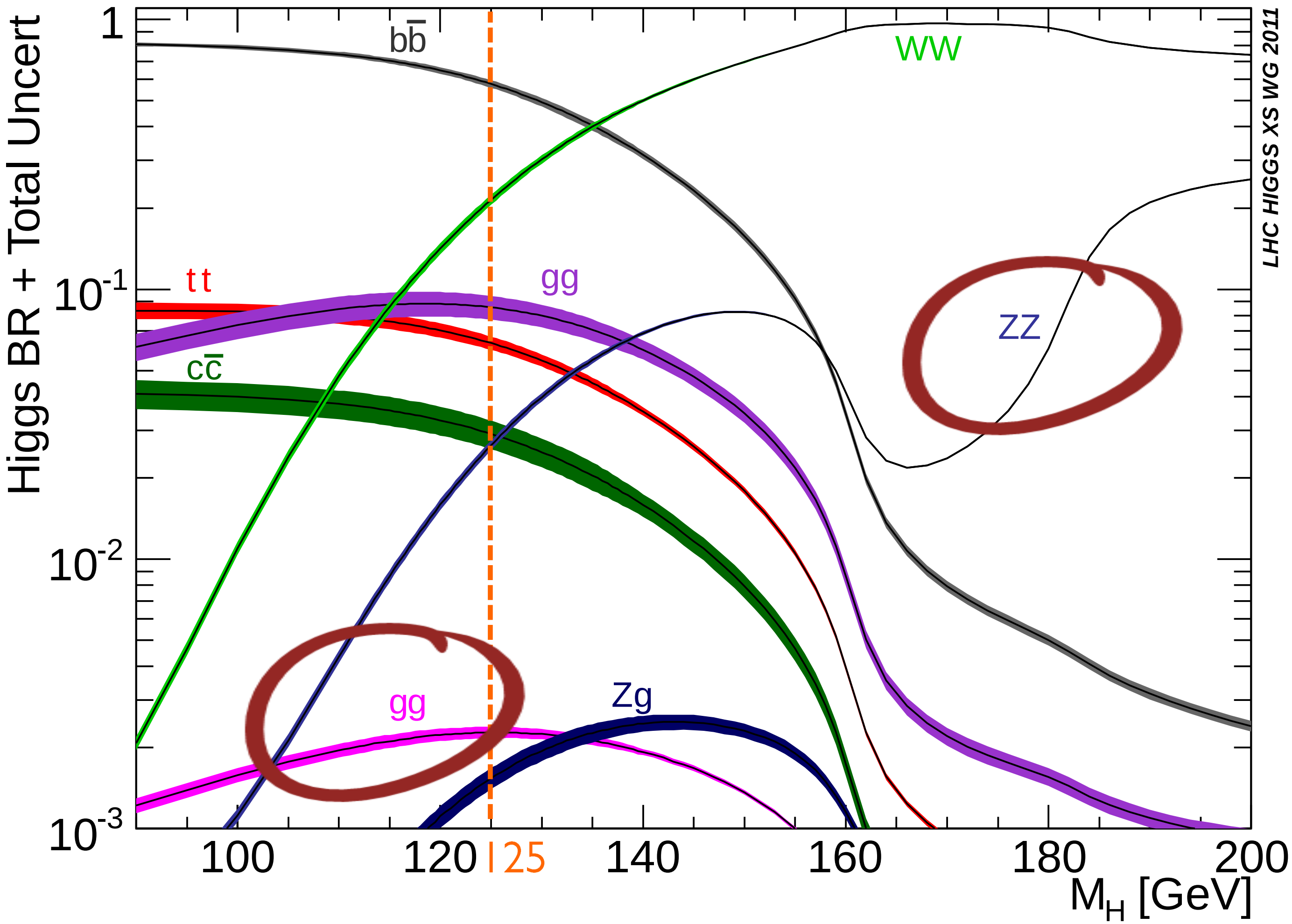
- Sensitive variables combined in BDT score
  - ✓ Intermediate boson masses: m_{Z1}, m_{Z2}
  - ✓ Z_1 production angle: θ*
  - ✓ Z_1 decay plane angle: Φ_1
  - ✓ Angle between the Z_1 and Z_2 decay planes: Φ
  - ✓ Decay angles of negative leptons: θ_1, θ_2







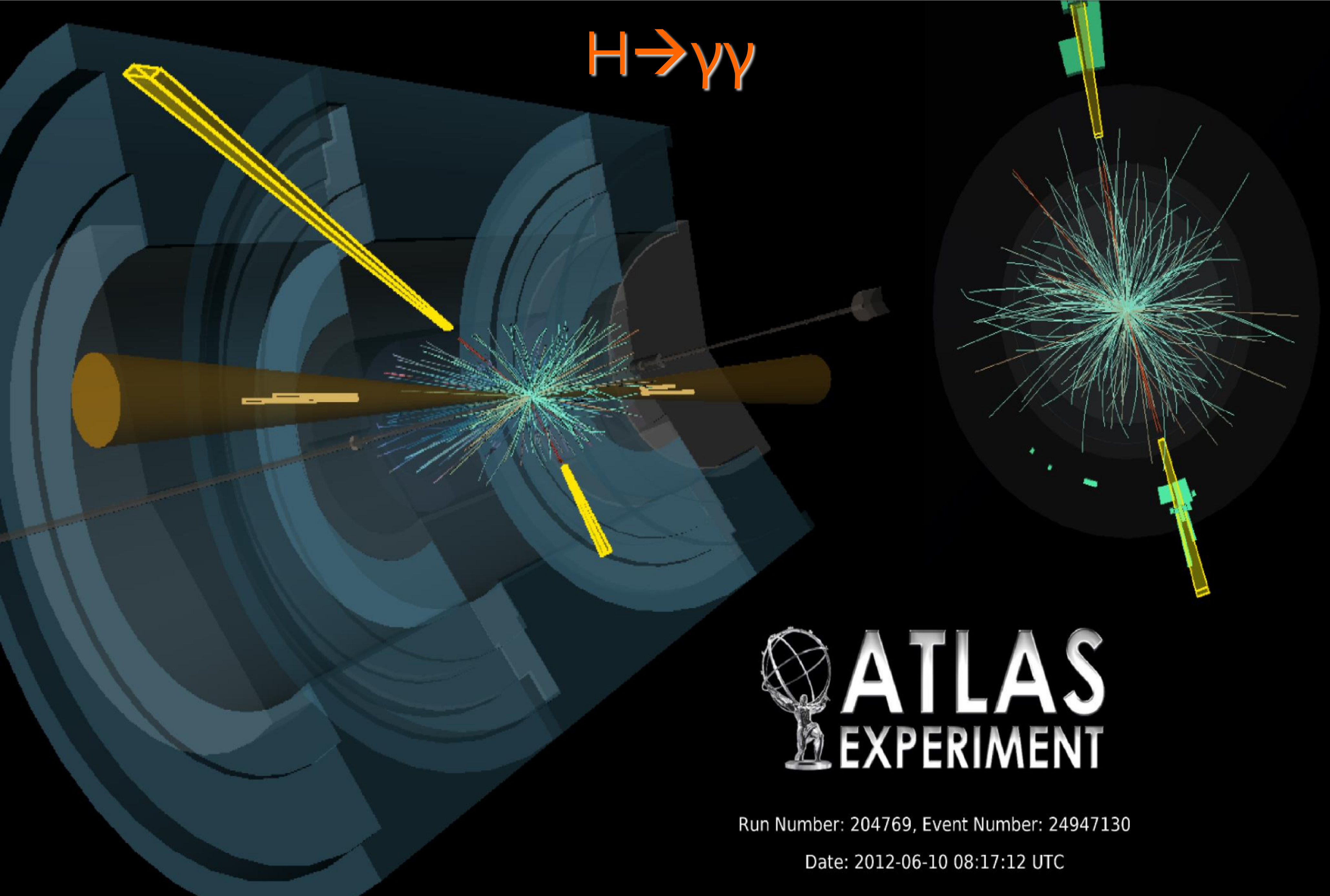
Standard Model Higgs decays



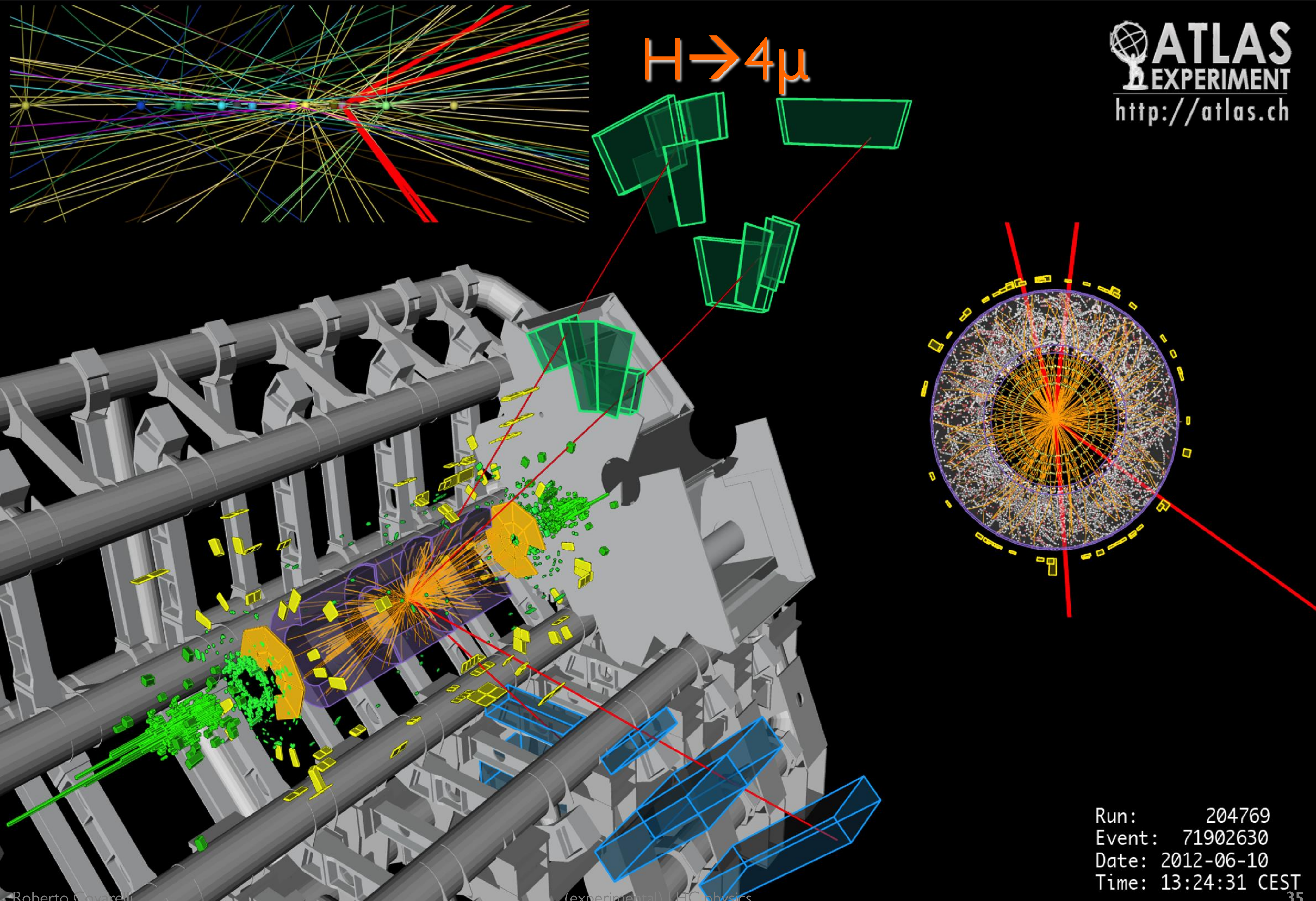
decay	SM BR [%] m_H = 125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→γγ	0.23

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

$H \rightarrow \gamma\gamma$

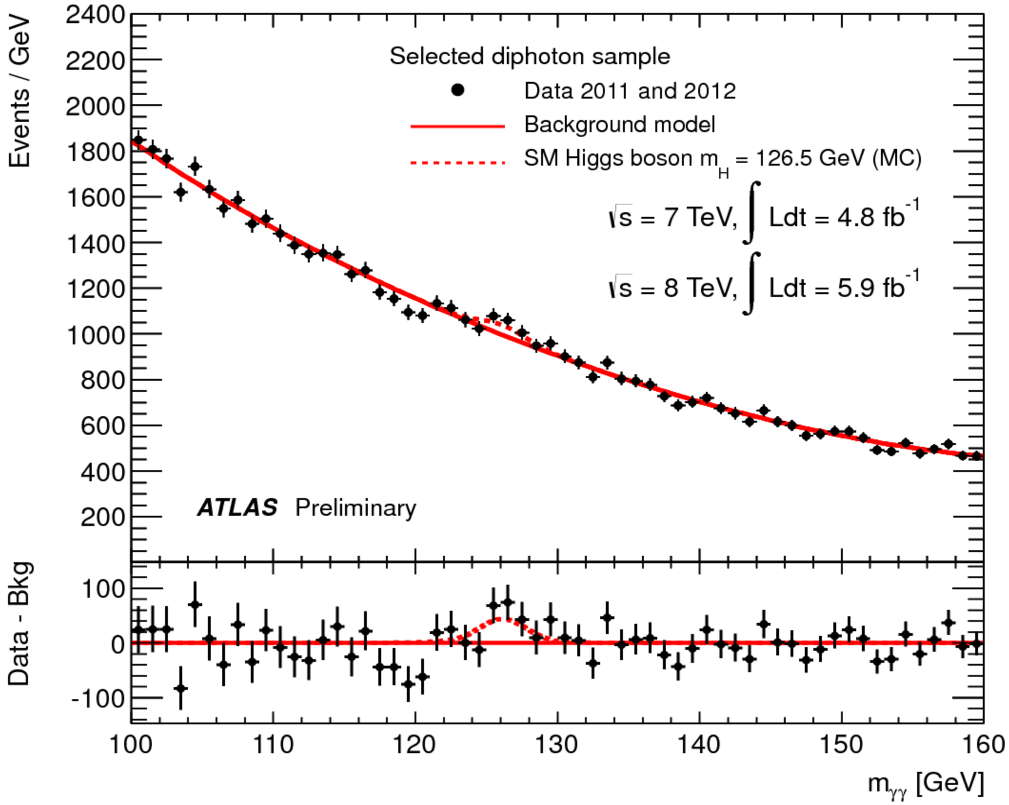


$H \rightarrow 4\mu$

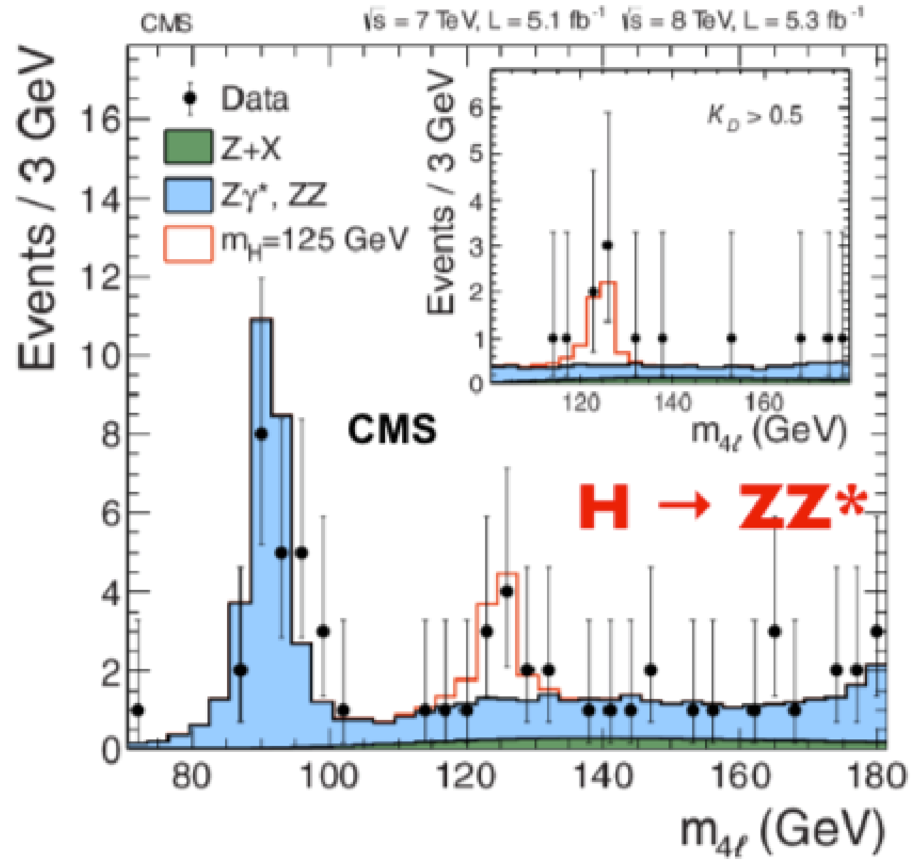


Higgs signals on July 4th 2012

H→γγ

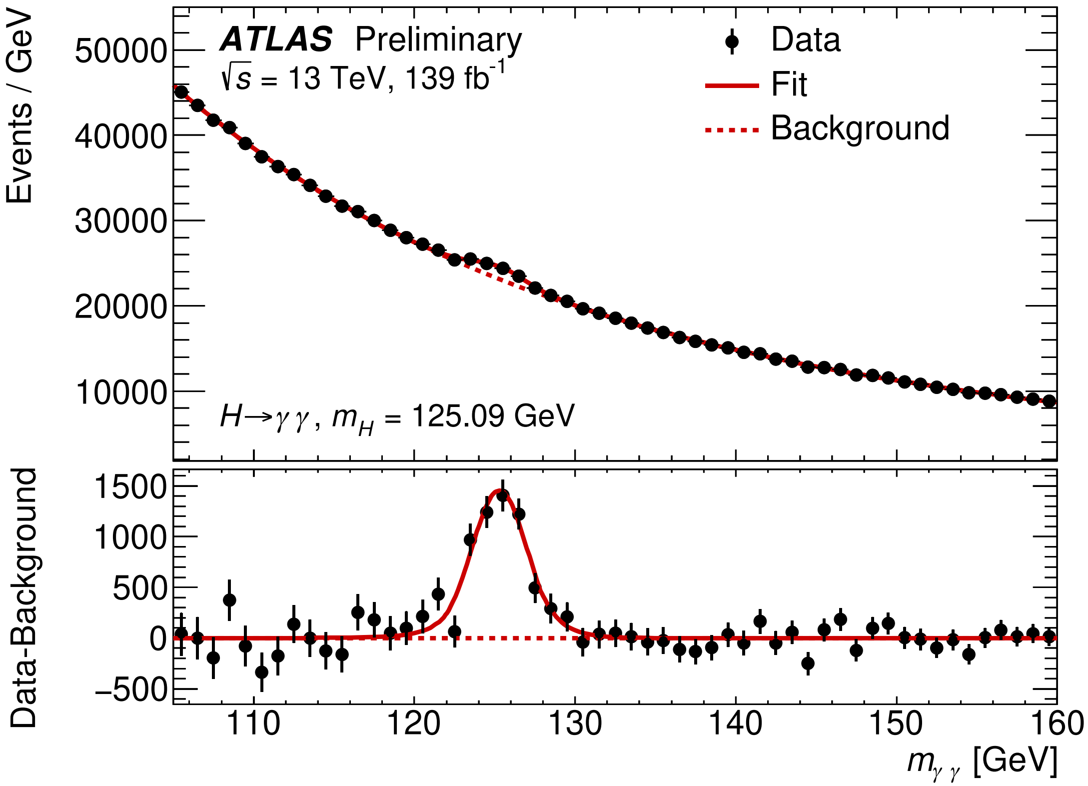


H→4l

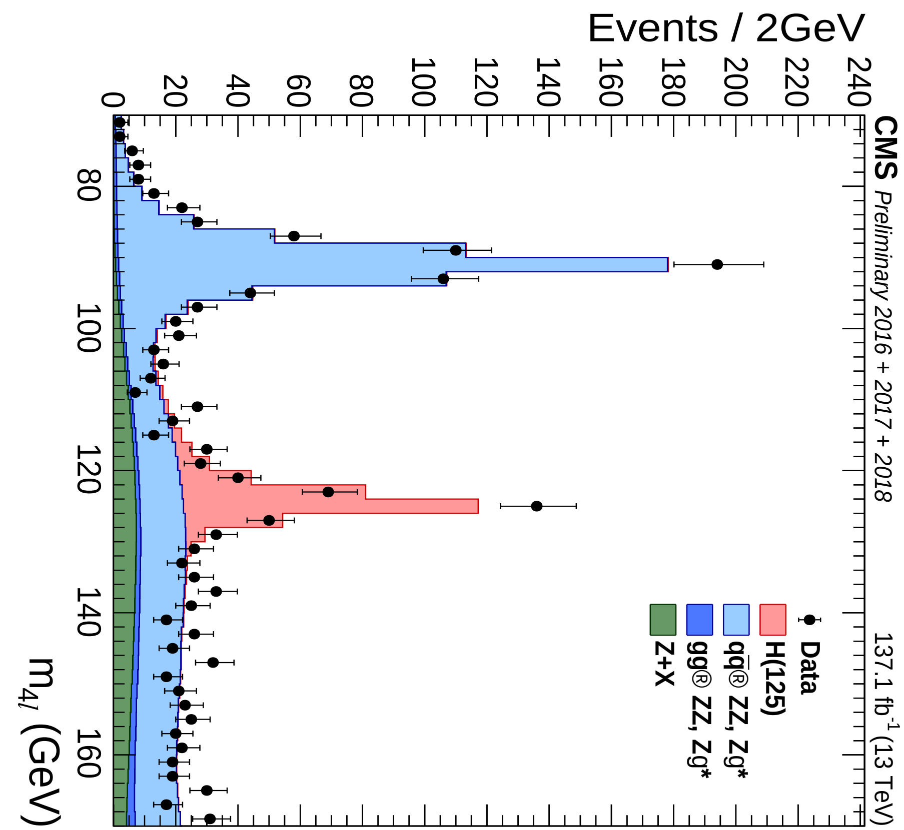


Higgs signals with the *latest* 13 TeV data…

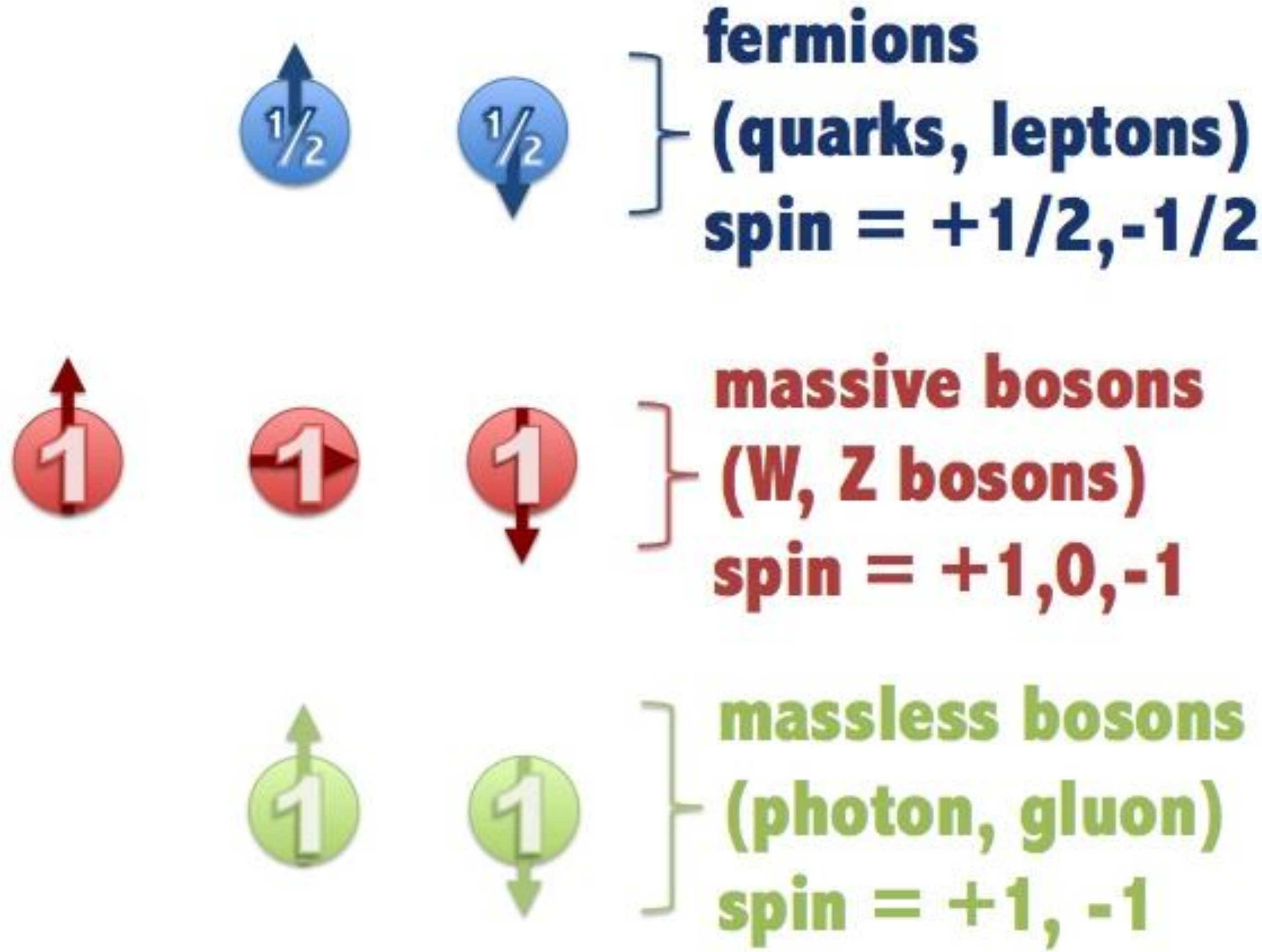
H→γγ



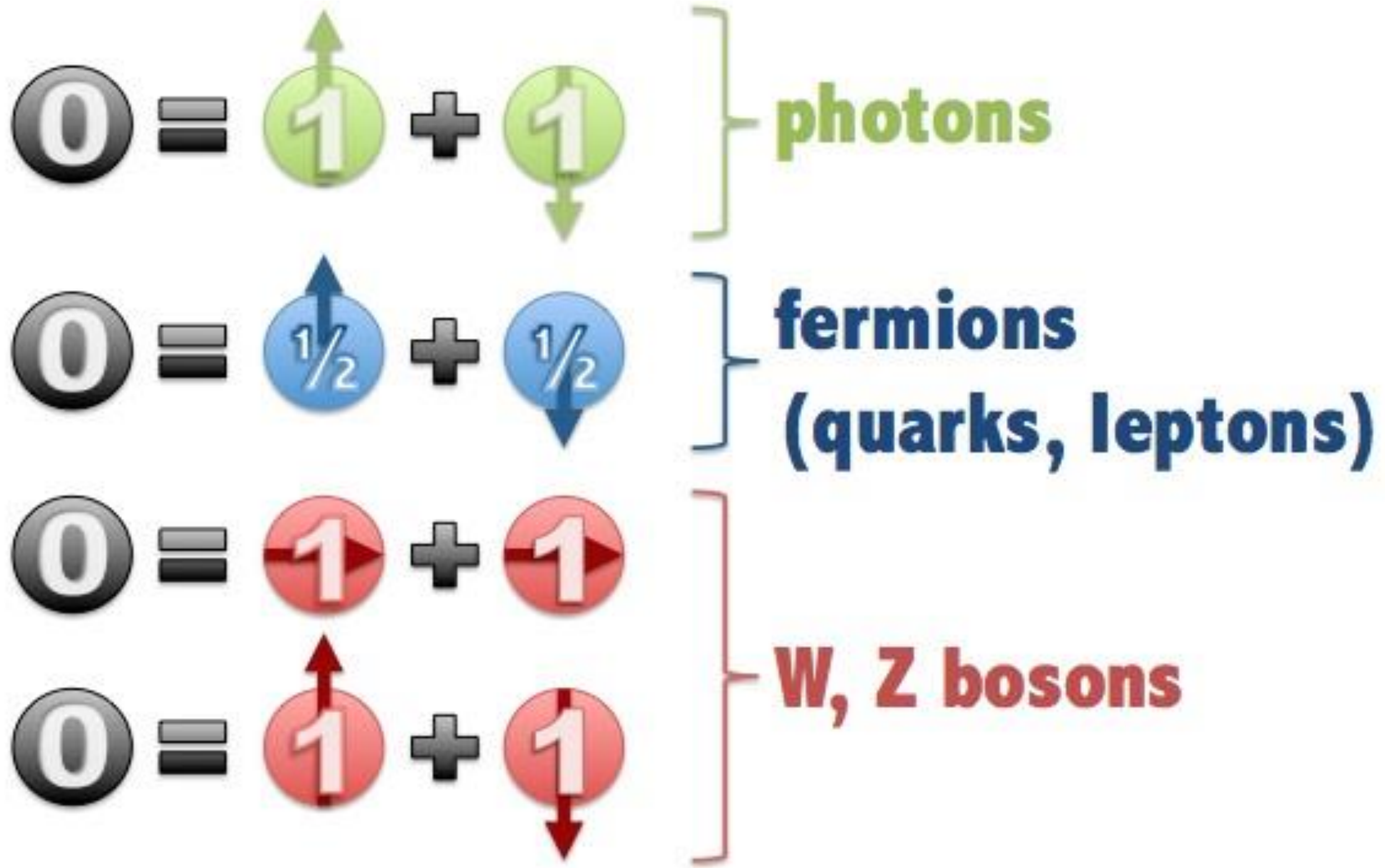
H→4l



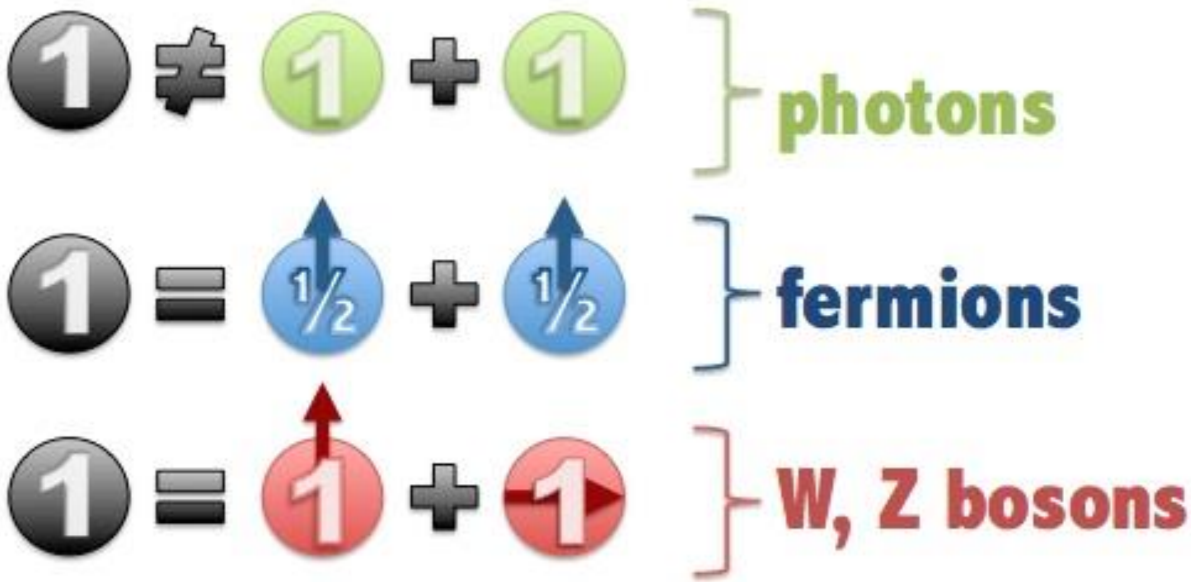
What spin do particles have?



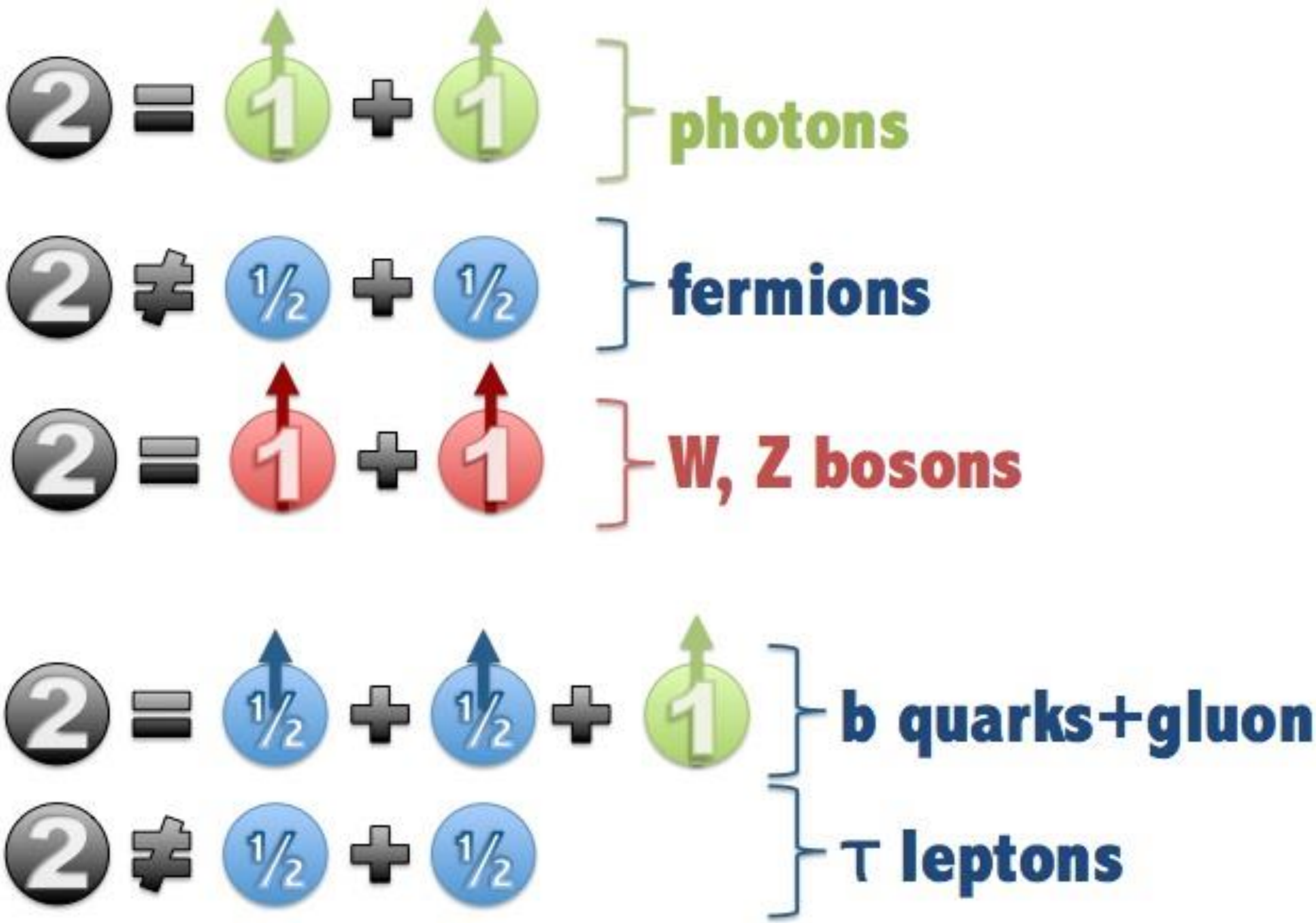
What can a spin 0 particle decay to?



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	☺	☺

Spin with H -> 4 leptons

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

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