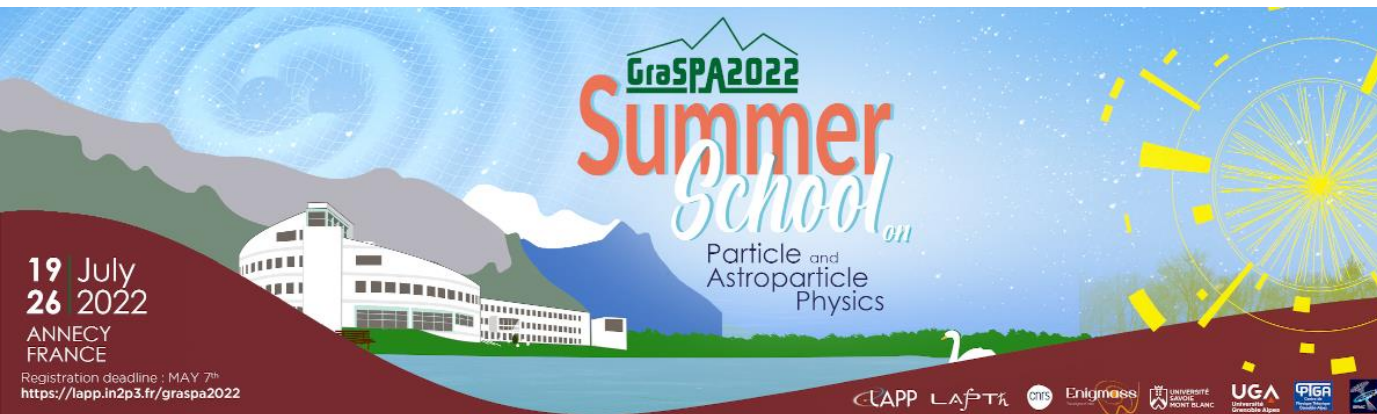


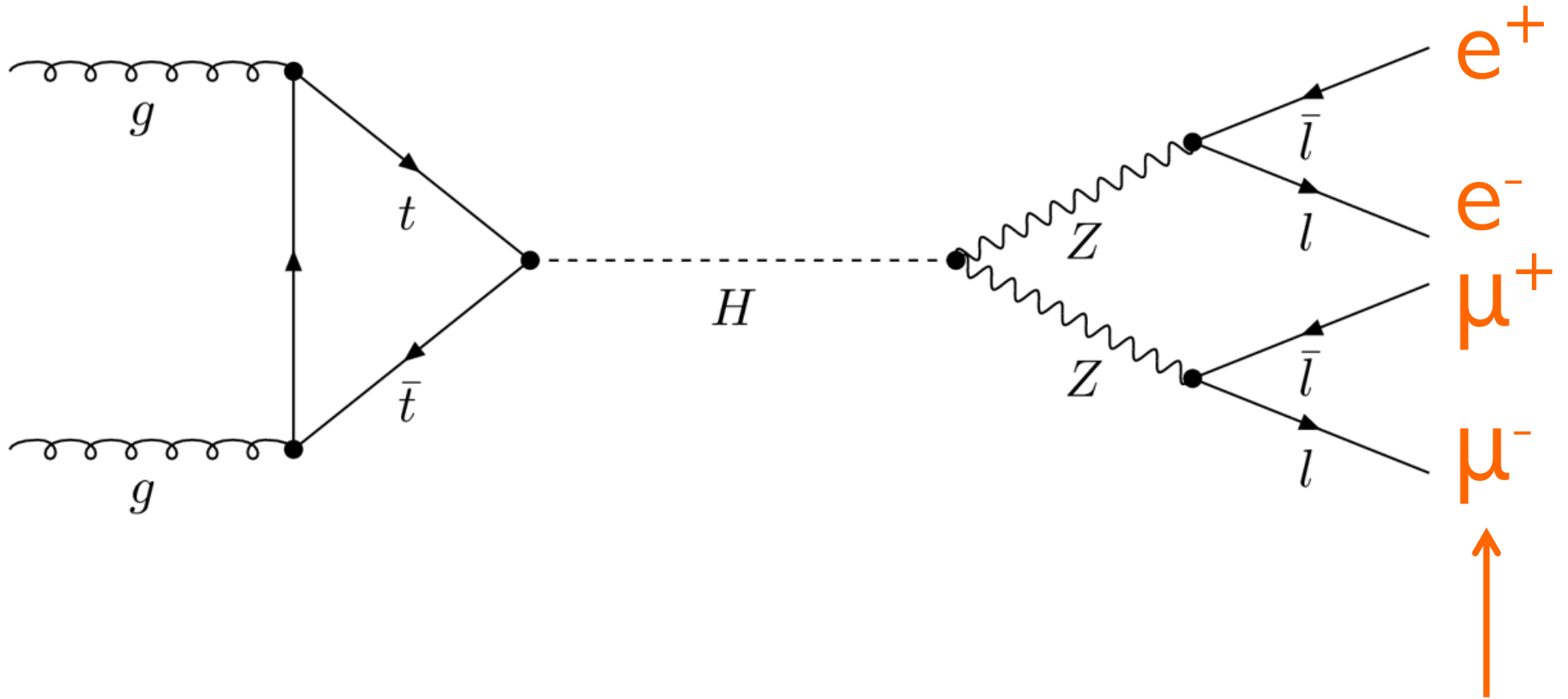
(experimental) LHC physics



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 I: find events with the right ingredients

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

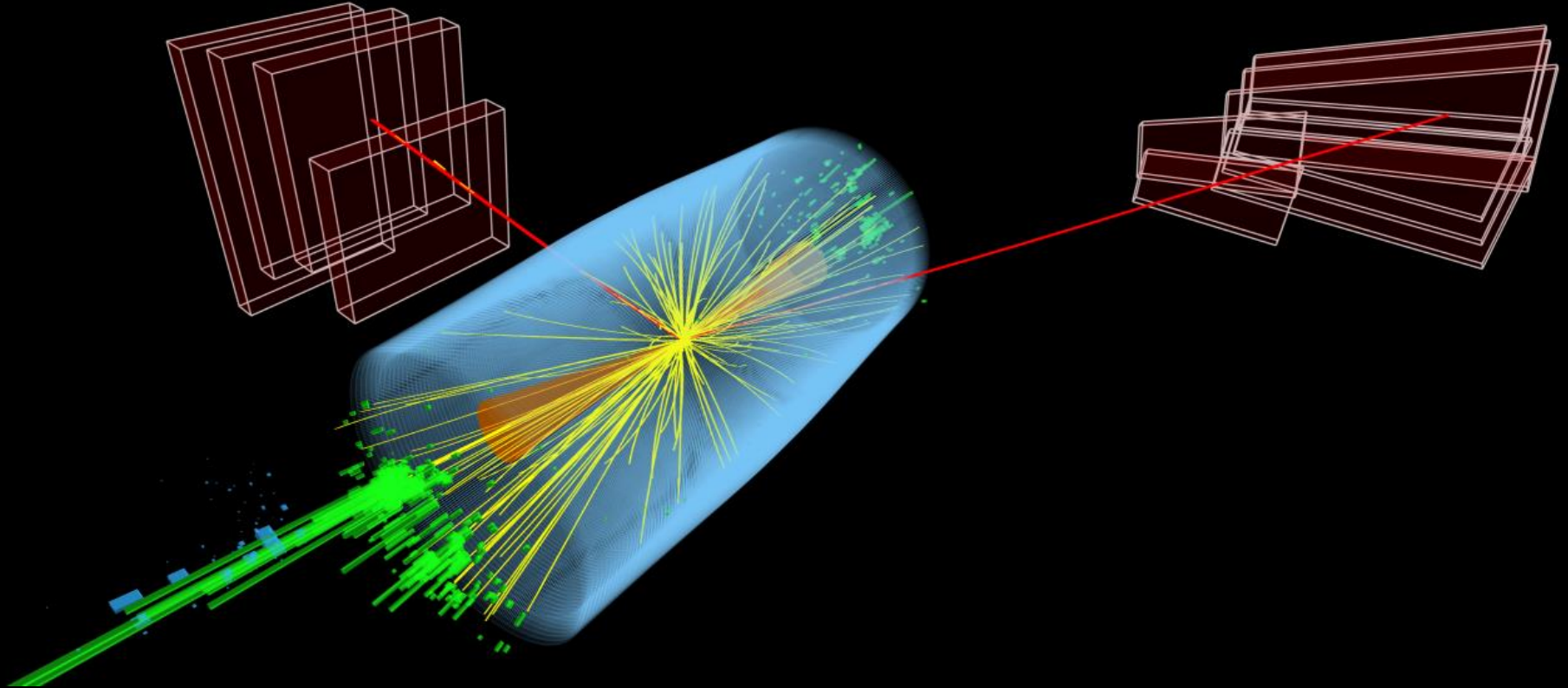
Is this event OK?



CMS Experiment at the LHC, CERN

Data recorded: 2018-Oct-03 01:19:17.320393 GMT

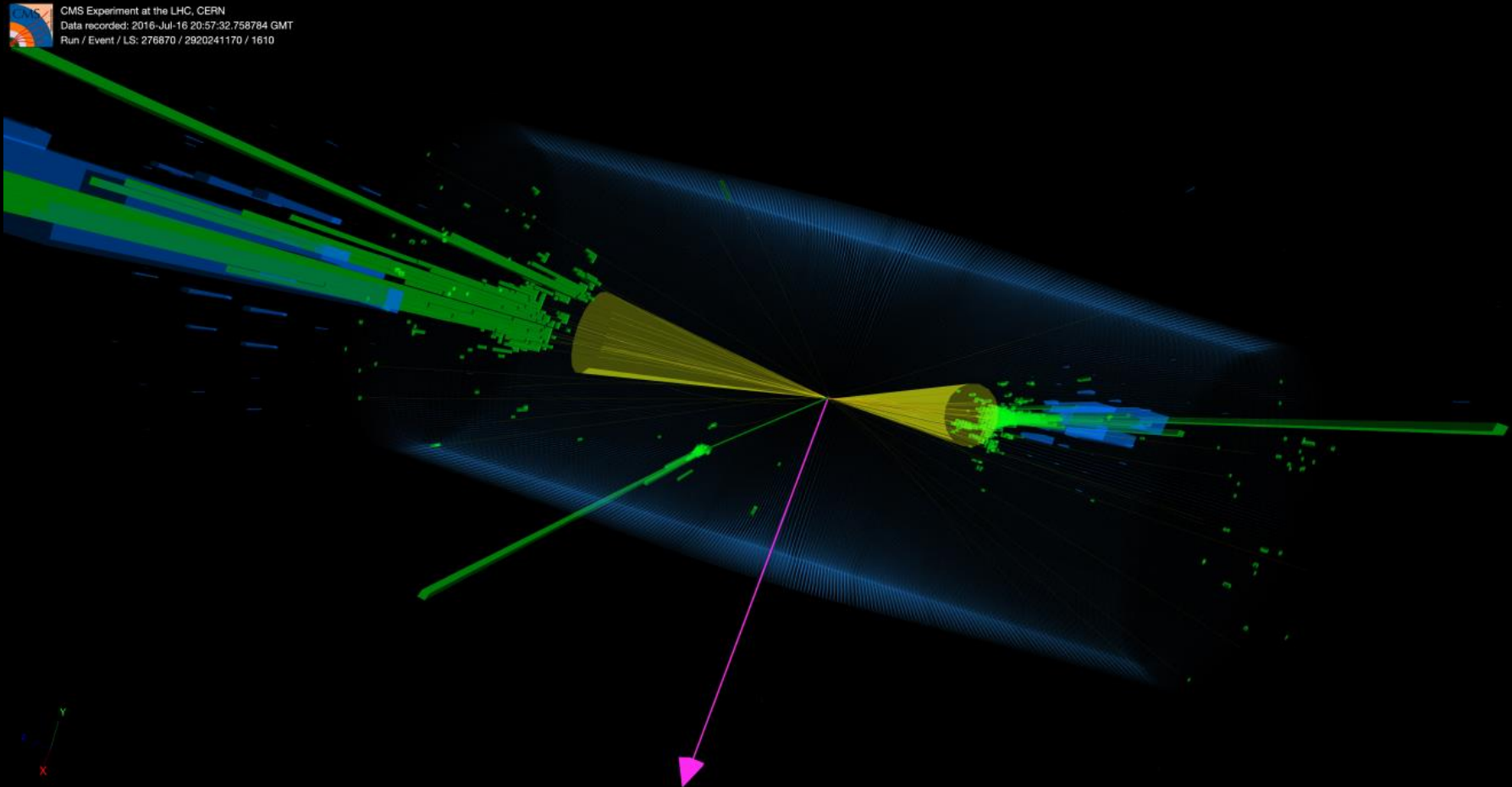
Run / Event / LS: 323940 / 44997009 / 65



Step I: find events with the right ingredients

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

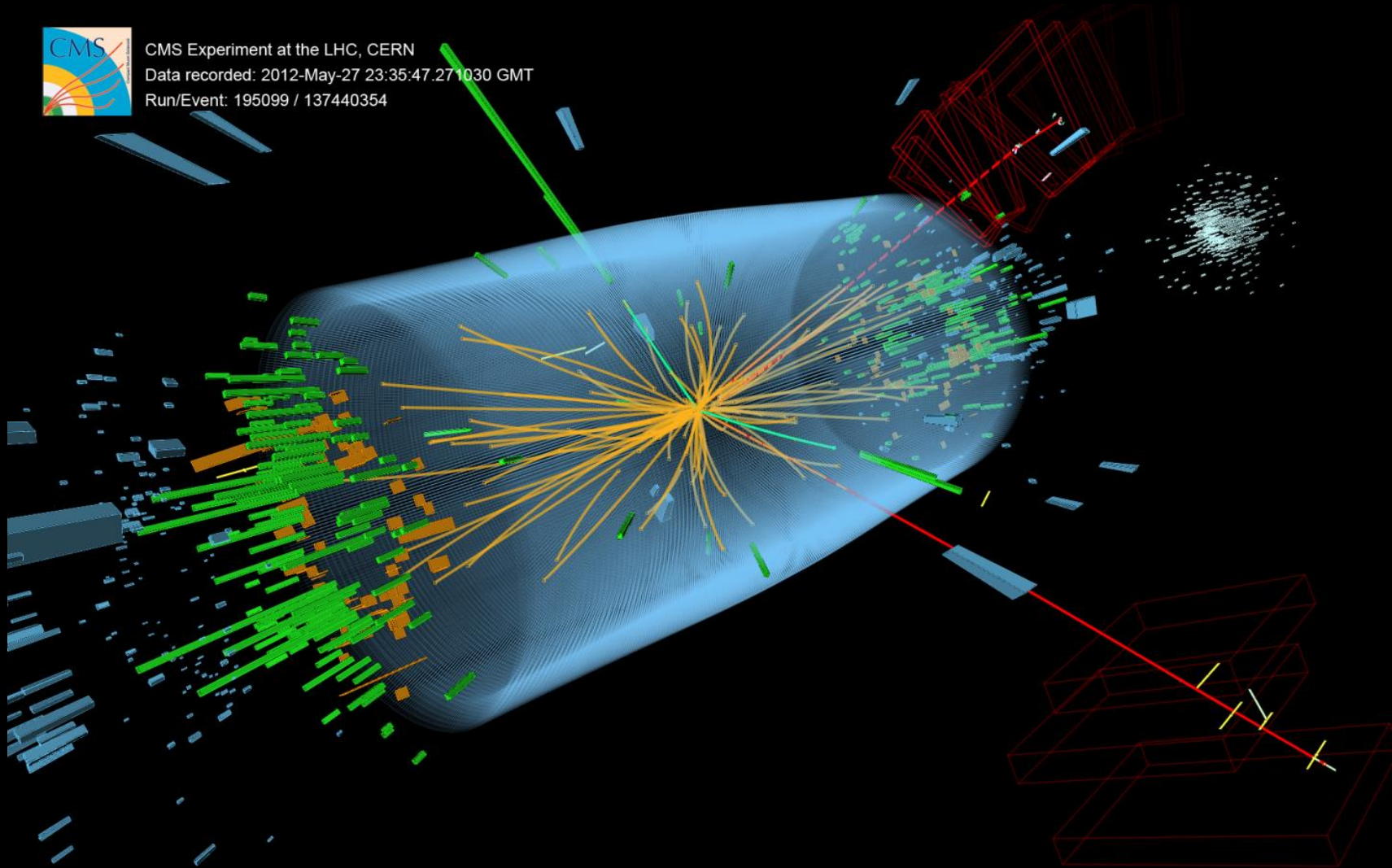
What about this one?



Step I: find events with the right ingredients

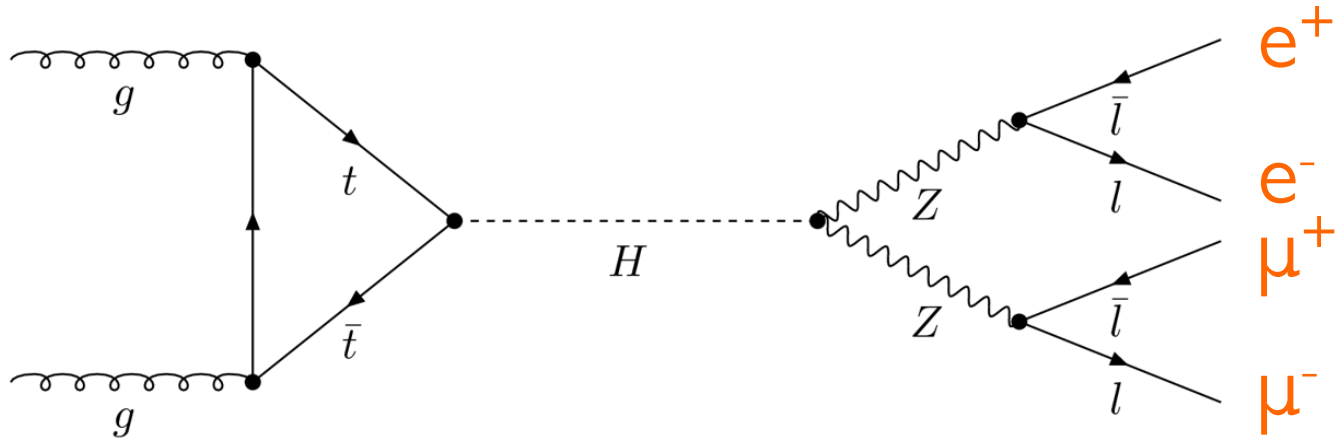
We are looking for $e^+e^-\mu^+\mu^-$...

And this one?



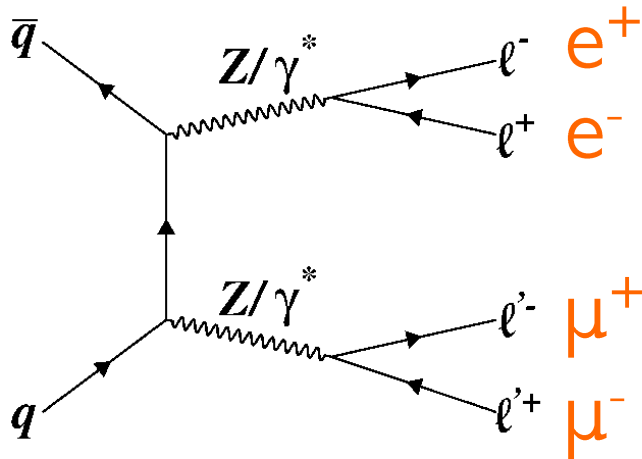
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

Step 2: signal and background



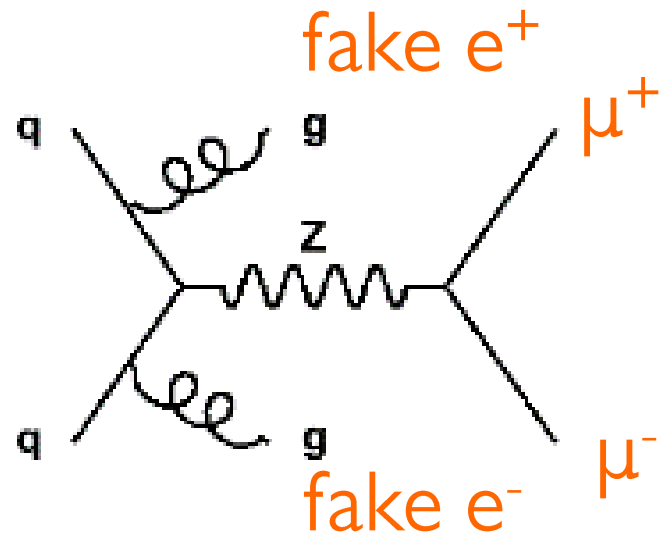
Irreducible background

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

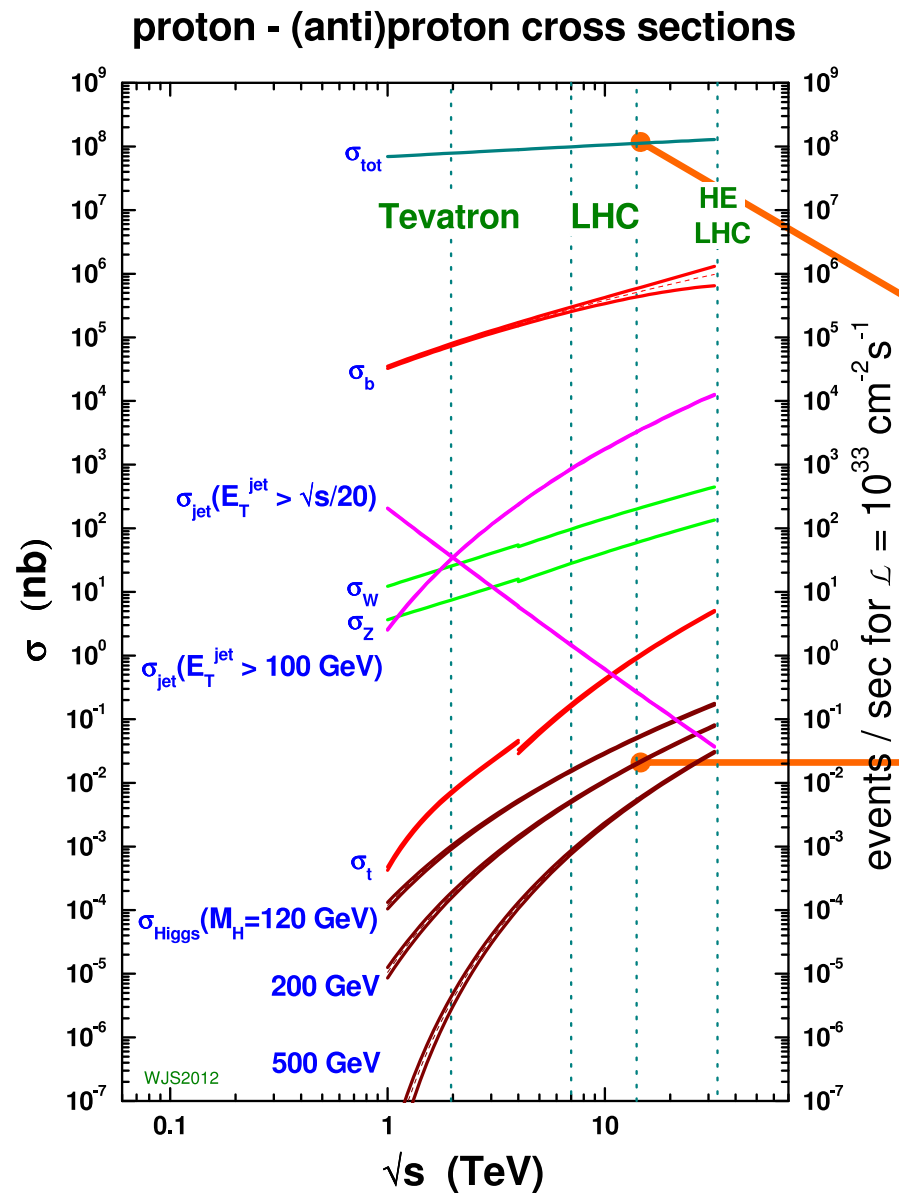


Reducible background

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



Interesting processes are rare!



$1 \text{ nb} = 10^{-33} \text{ cm}^2$

$\sigma_{\text{tot}}(13 \text{ TeV}) = 10^8 \text{ nb}$

$\sigma_H(13 \text{ TeV}) = 0.05 \text{ nb}$

LHC instantaneous luminosity $L = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

inelastic pp collisions

10^9 events/s

$\sim 10^{10}$

10^{-1} events/s

~ 1 Higgs boson every 2 seconds

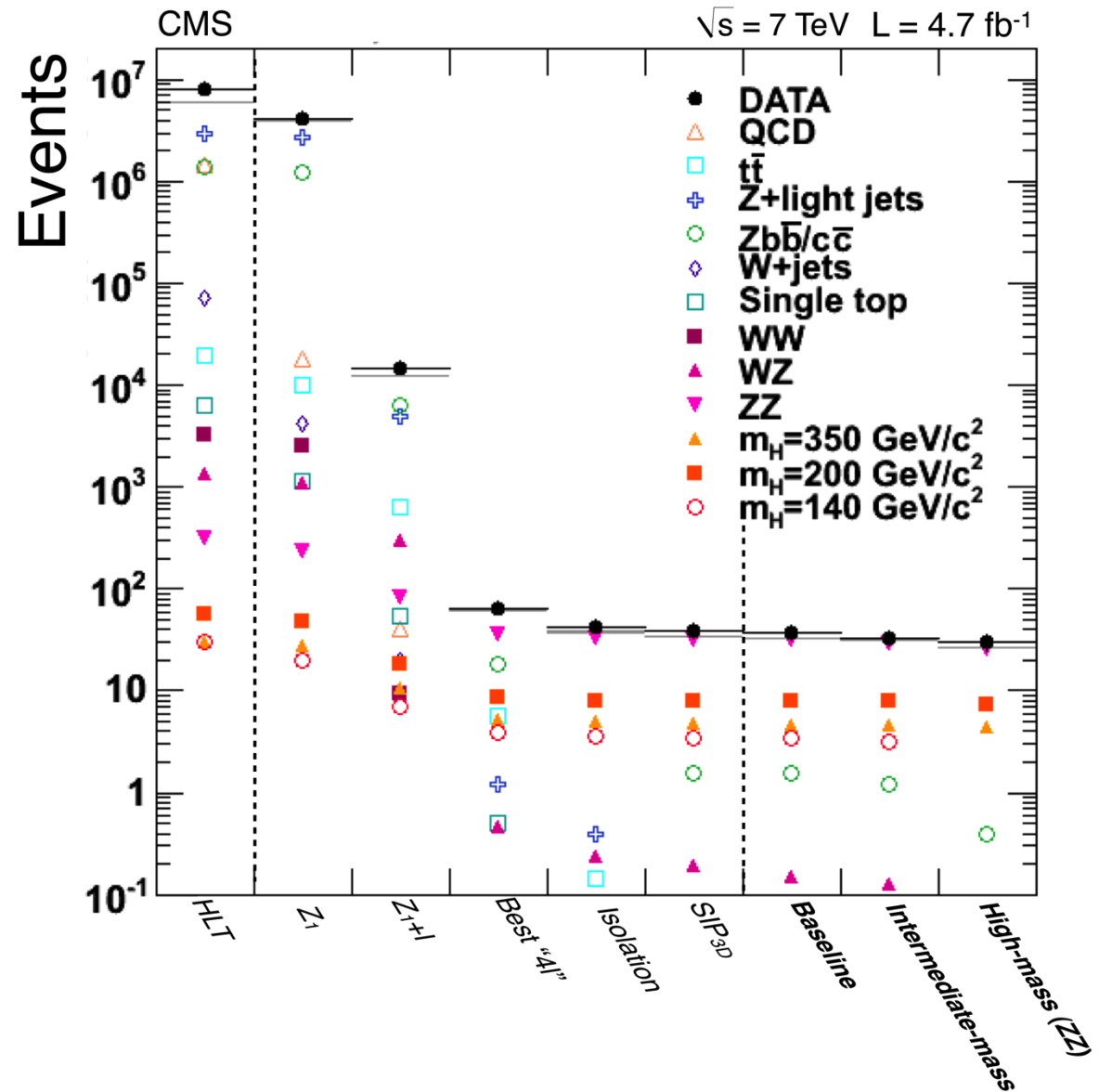
$[m_H \sim 125 \text{ GeV}]$

$0.2\% H \rightarrow \gamma\gamma$

$0.01\% H \rightarrow ZZ$

Lose some signal, suppress backgrounds...

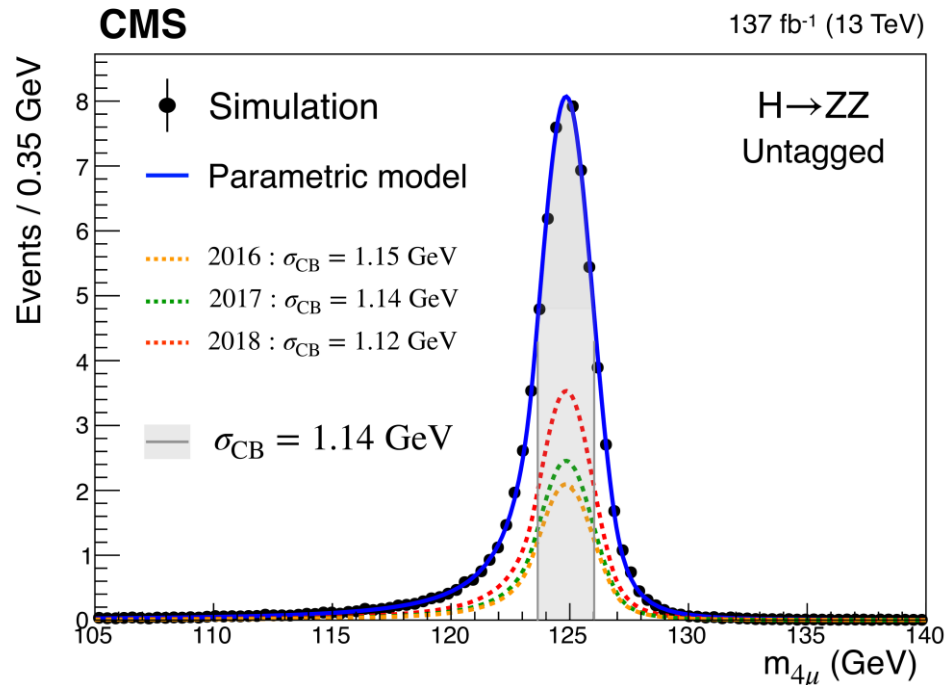
- Selections based on particle properties to reduce reducible background
 - ✓ Shower shapes, track properties, ...
- Selections based on event properties to distinguish signal from background
 - ✓ Particle kinematics, decay kinematics event shape, ...
- Try to keep signal while reducing background!
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

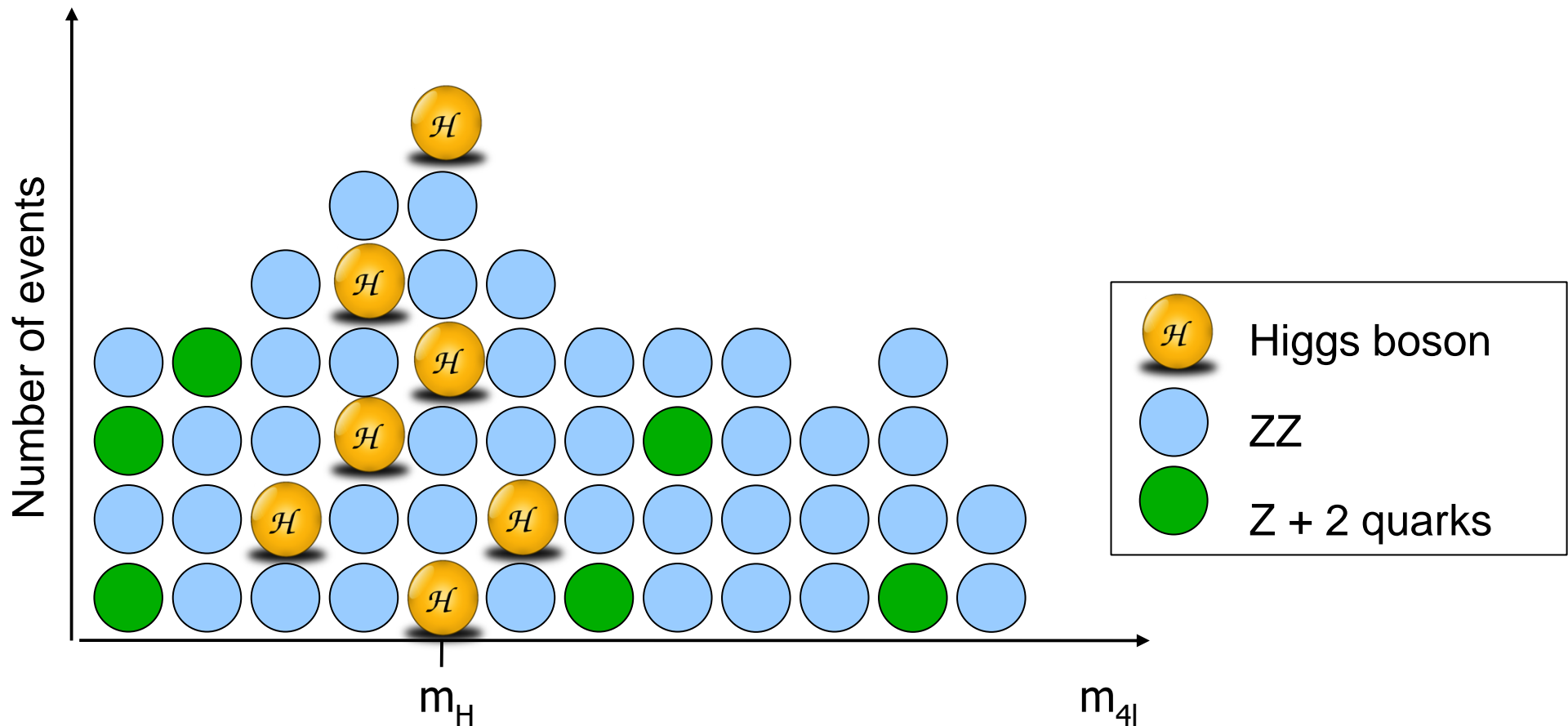
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



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

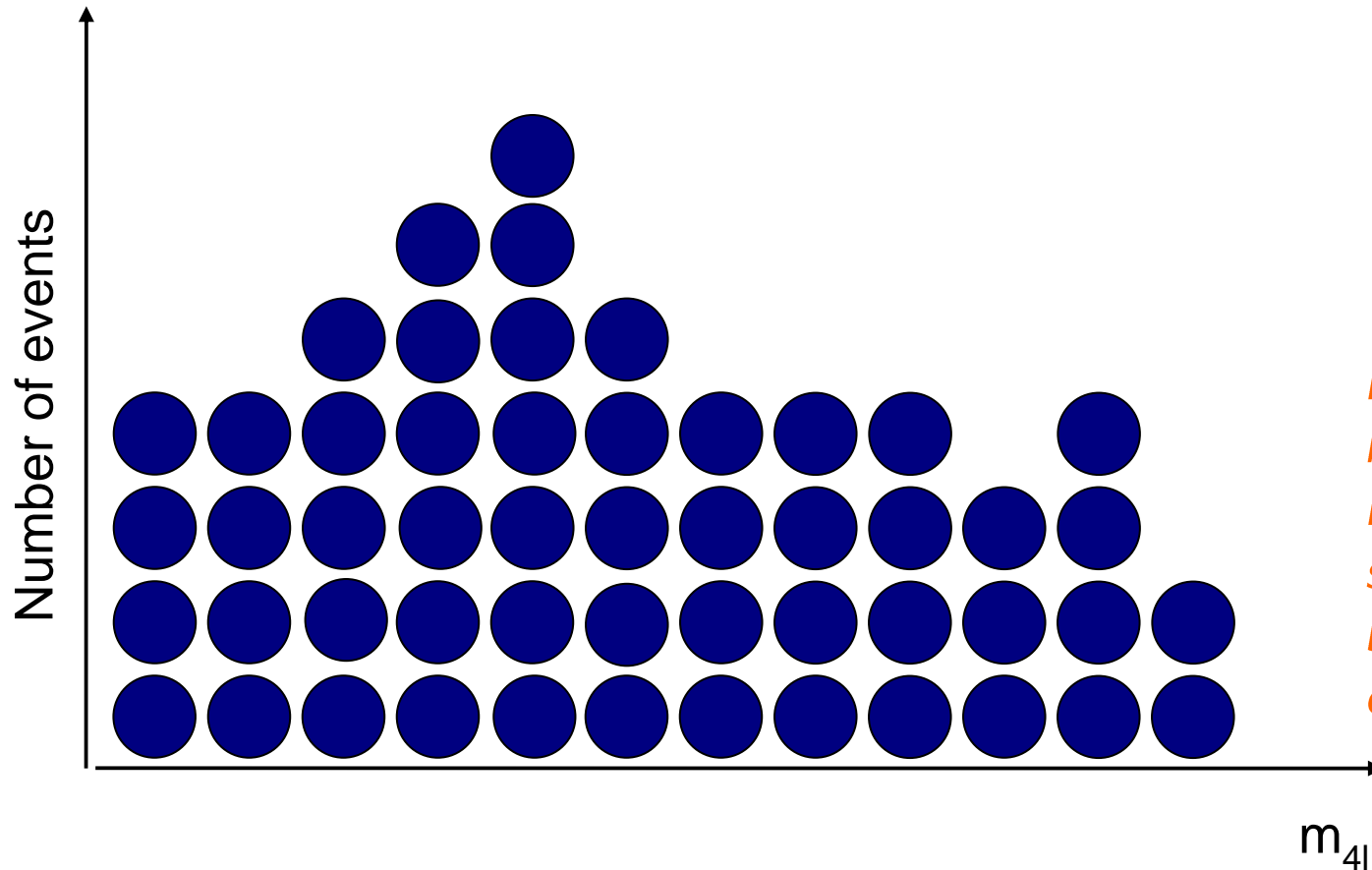
Extract signal from background

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



Extract signal from background

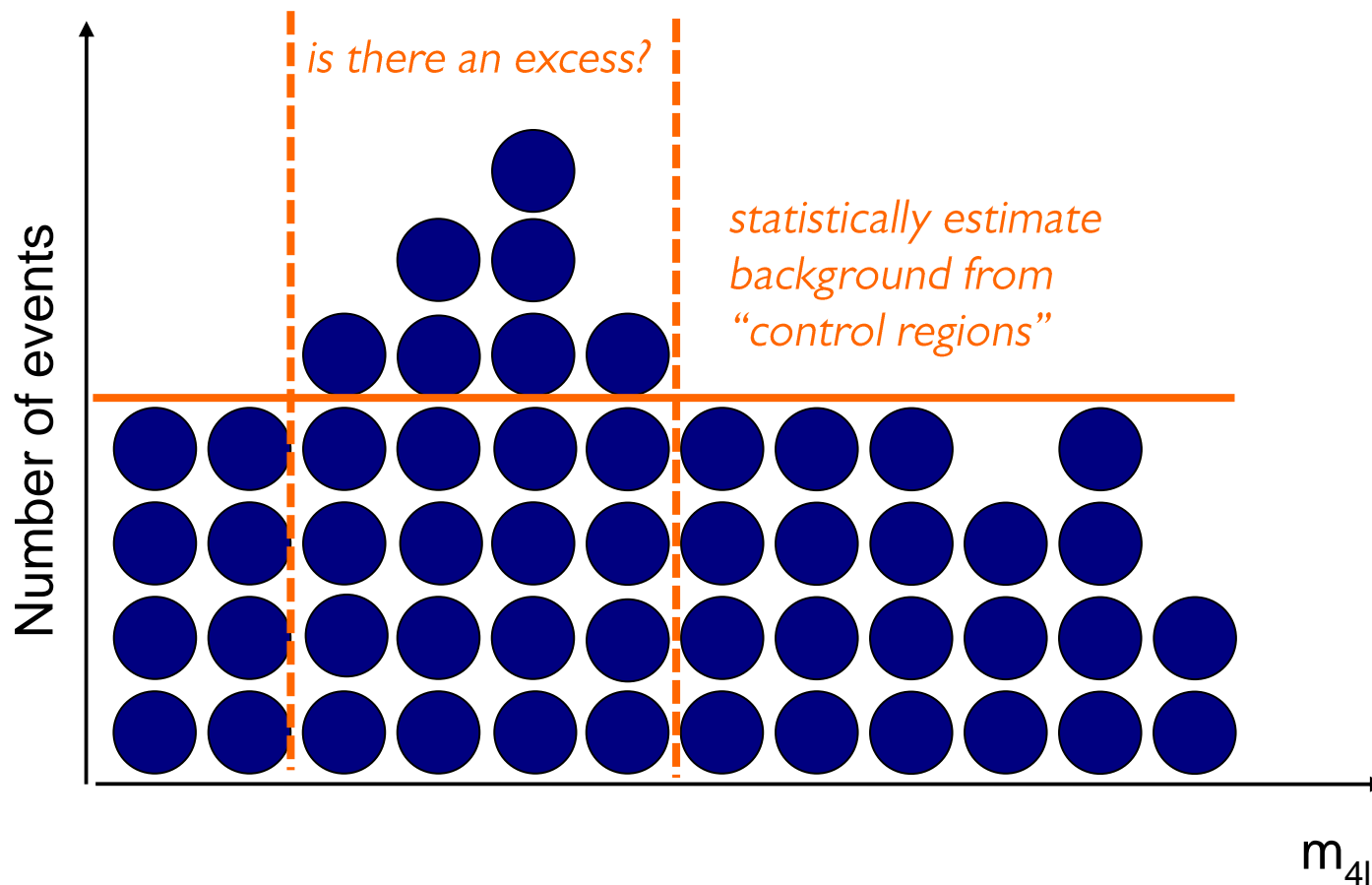
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



*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)

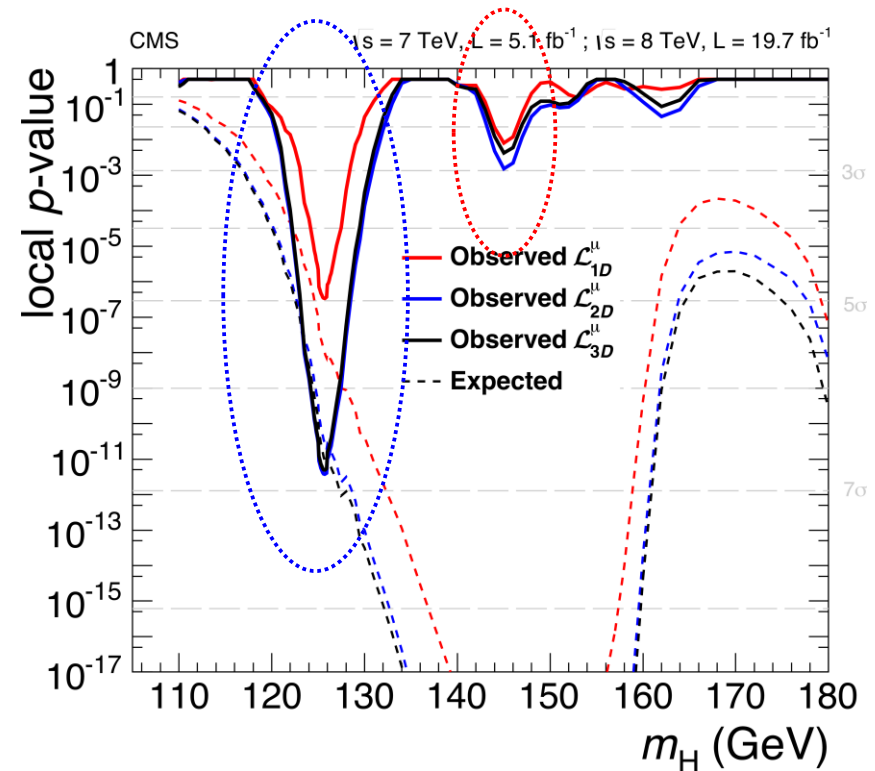
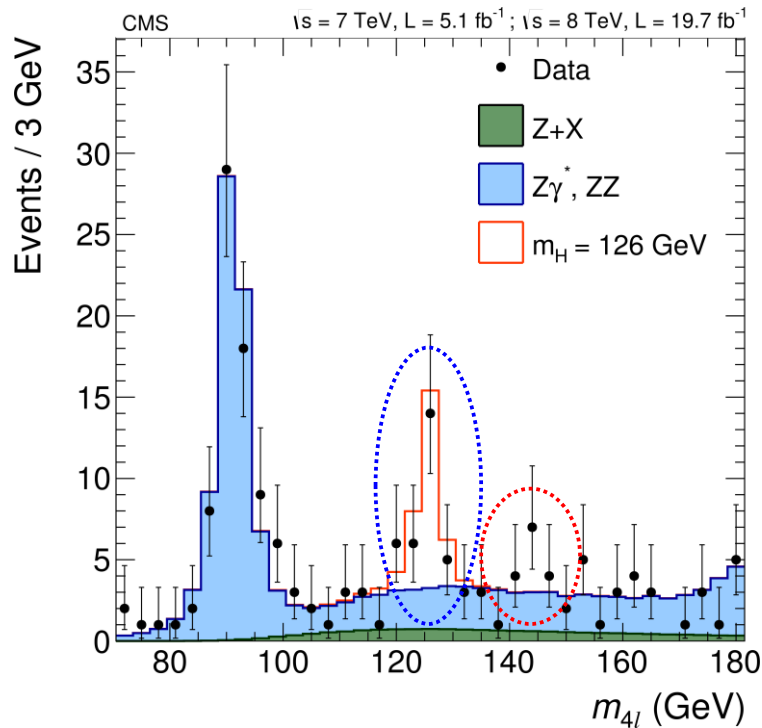
How significant is an excess?

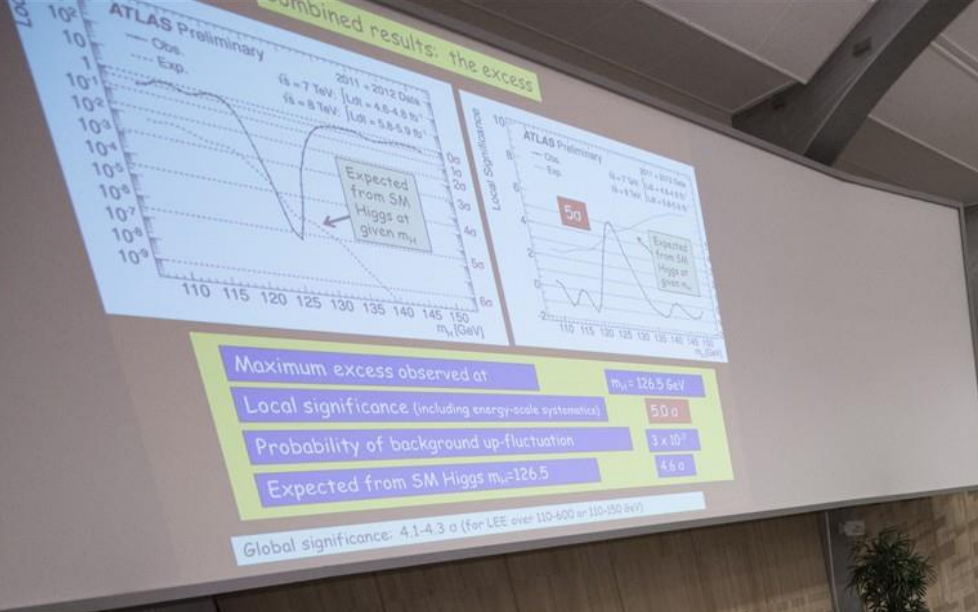
- p_0 : probability that the excess is due to a fluctuation of background

- Significance:
$$Z \sim \frac{S}{\sqrt{B}} \quad p_0 = 1 - \text{Erf} \left(\frac{Z}{\sqrt{2}} \right)$$

- Convention:

- 3σ is an **evidence** ($p_0 = 0.27\%$)
- 5σ is a **discovery** ($p_0 = 5.7 \cdot 10^{-7}$)





ELSEVIER

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

S(μ) Weighted Events / 1.5 GeV

1500
1000
500
0

110 120 130 140 150

m_H (GeV)

CMS

Obs. Exp. 1.5 σ 1.5 σ 1.5 σ 1.5 σ

110 120 130 140 150

m_H (GeV)

ATLAS

2011-12 $\sqrt{s} = 7-8 \text{ TeV}$

Local P_0

10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹

110 150 200 300 400 500

m_H (GeV)

Observed Expected Signal: 1.5 σ

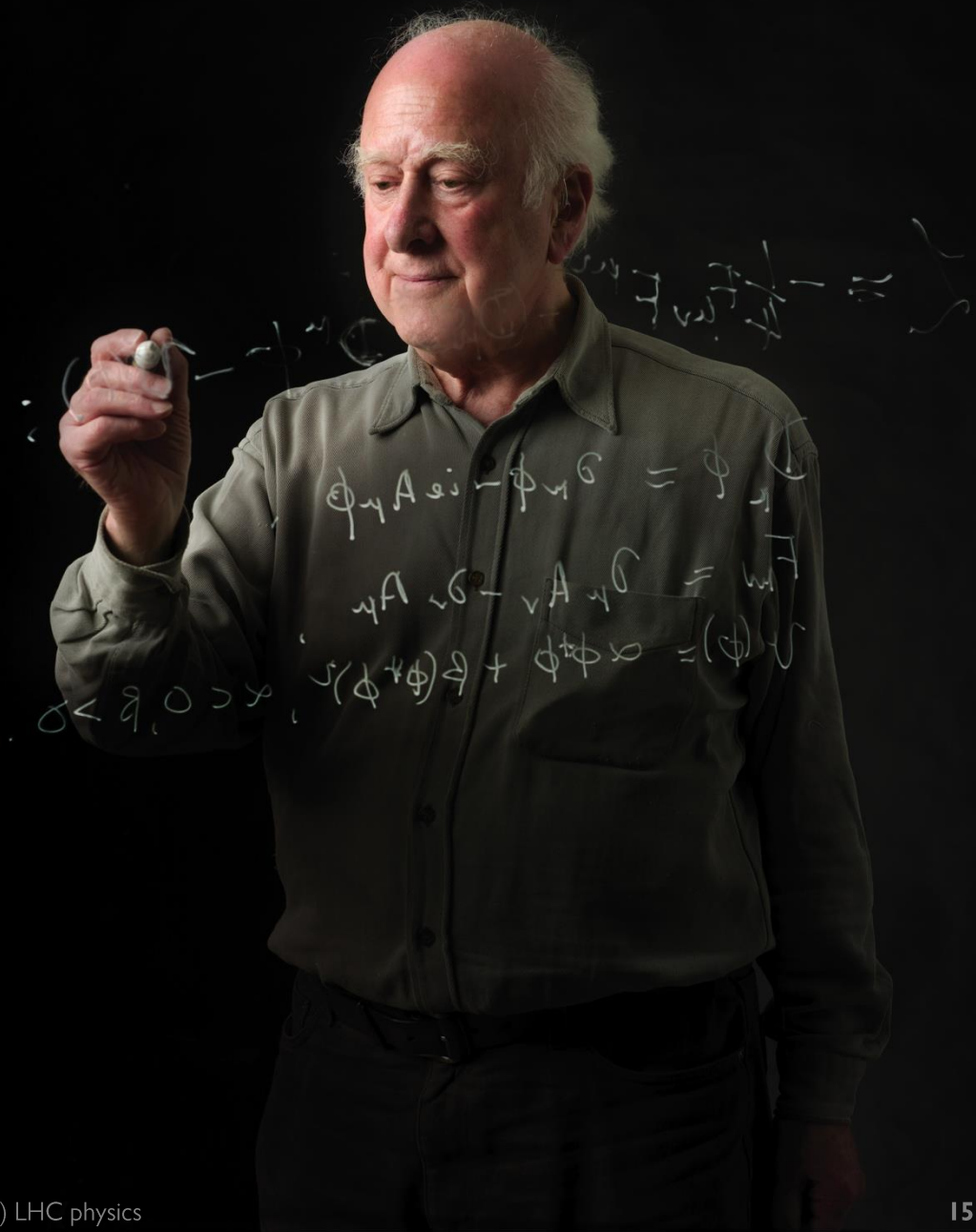
www.elsevier.com/locate/physletb

CERN

10 years HIGGS boson discovery

CERN Auditorium, July 4th 2012

Is it a *scalar* boson?



Spin!

What's a particle spin?

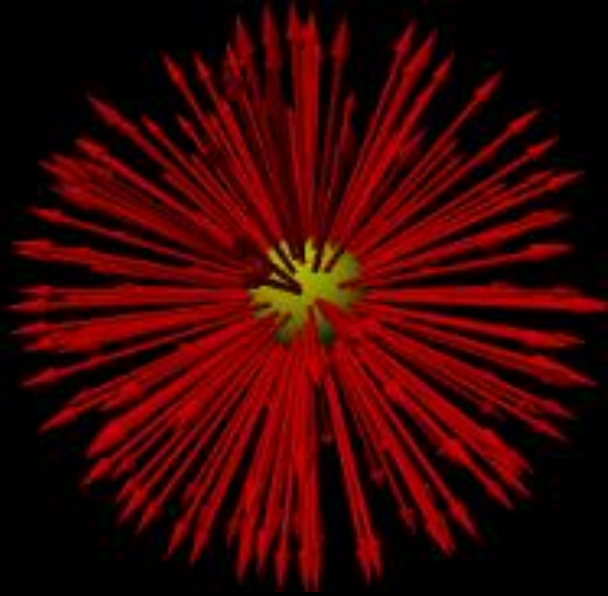
“An *amount of rotation* that is somehow quantized”

An electron has always an angular momentum of $\frac{1}{2} \hbar$ either in its direction of travel ($+\frac{1}{2} \hbar$) or opposite to it ($-\frac{1}{2} \hbar$)

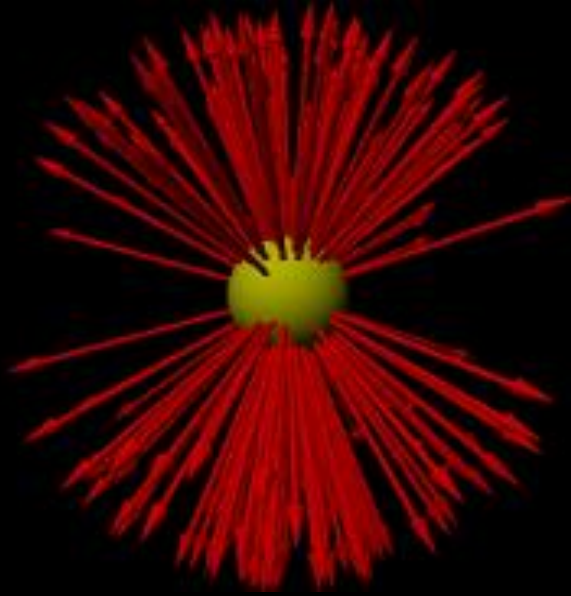


$$\hbar = 1.0545 \times 10^{-34} \text{ J} \cdot \text{s}$$

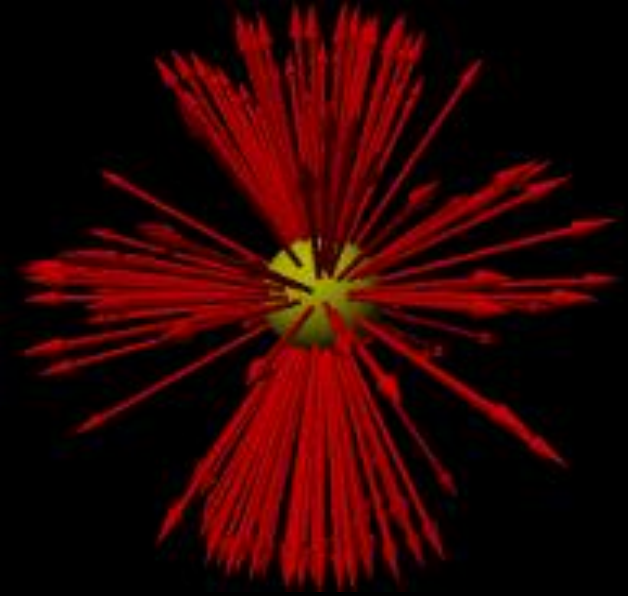
How can we recognize spin?



spin 0



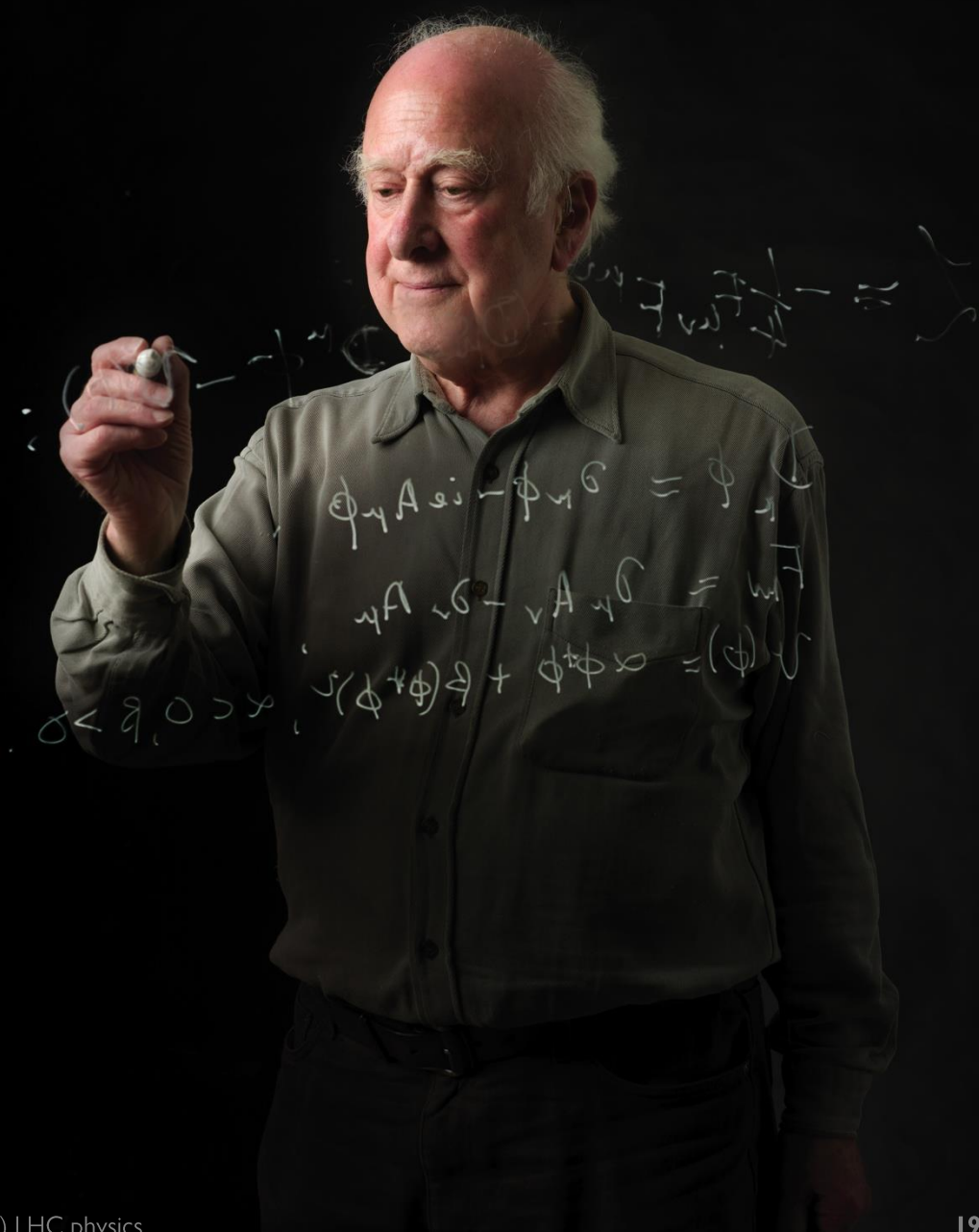
spin 1



spin 2

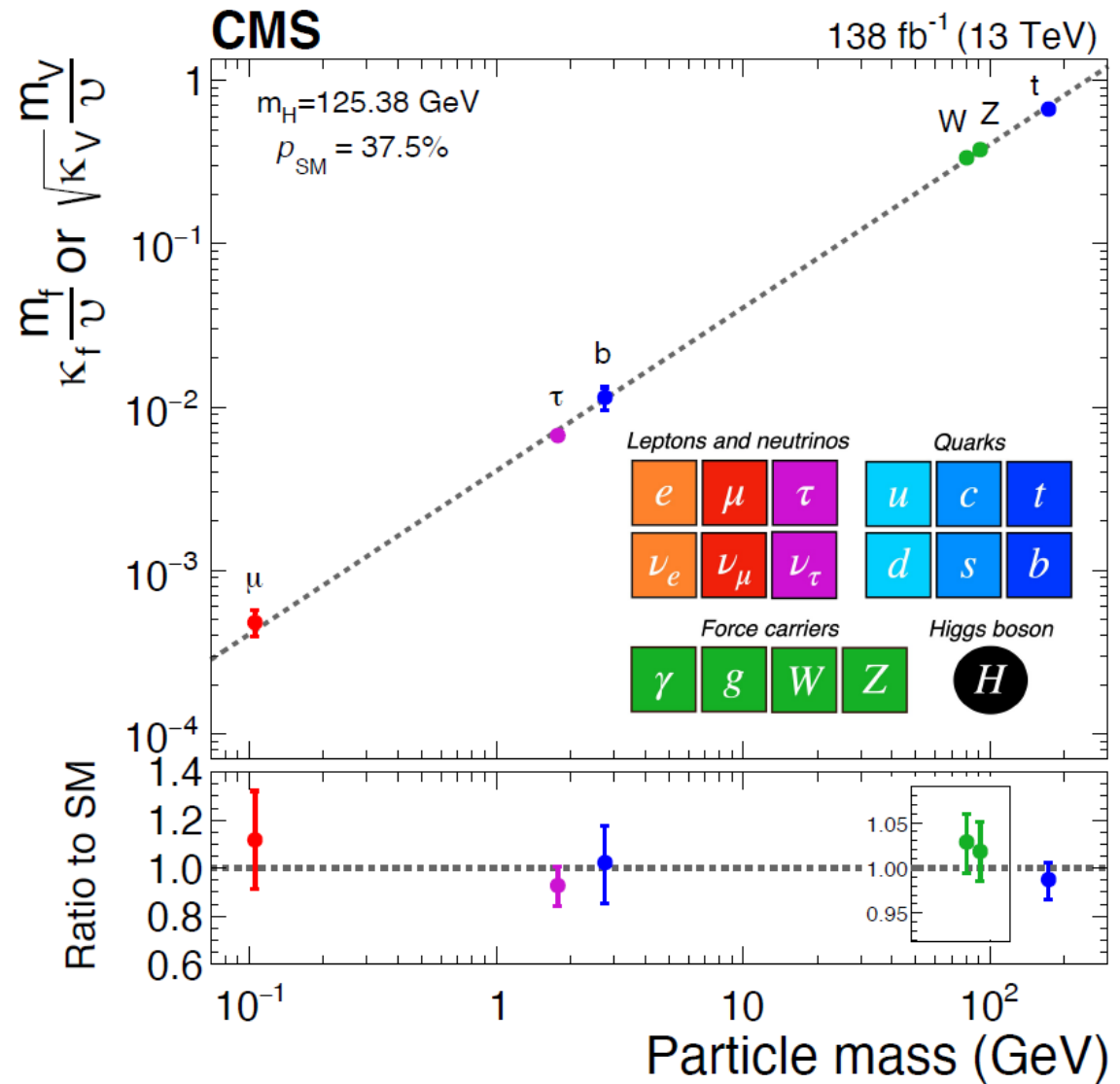
Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

Is it responsible for masses?



Combine many other decay modes

- $H \rightarrow ZZ^*$
- $H \rightarrow WW^*$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $H \rightarrow cc$
- $VH, H \rightarrow bb$
- ttH
- ...



330

340

350

360 19

top

W

Z

Beyond the SM

Higgs Sea

dragons!



The Standard Model



The Unknown

70

70

65

65

60

60

330

340

350

360

Many unanswered questions...

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

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

Why there's more matter than anti-matter?

How do neutrinos get mass?

1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: DESY g gluon
1968: SLAC d down quark	1947: Manchester University s strange quark	1977: Fermilab b bottom quark	1923: Washington University* γ photon
1956: Savannah River Plant ν_e electron neutrino	1962: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W W boson
1997: Cavendish Laboratory e electron	1937: Caltech and Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson
			2012: CERN H Higgs boson

Are there more forces?

What keeps the Higgs mass so small?

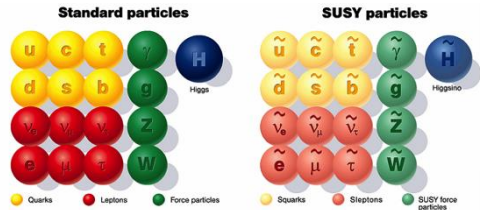
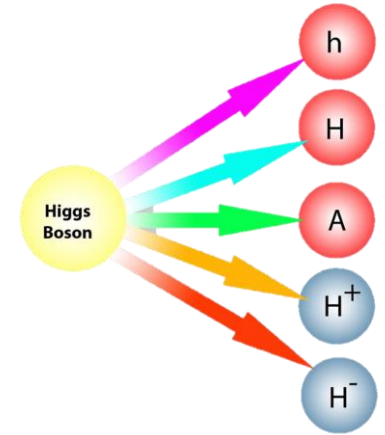
How do we incorporate gravity?

What is Dark Matter?

... as many possible answers to probe!

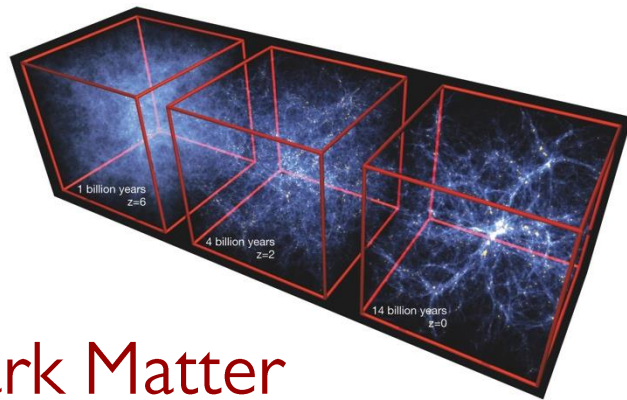
Super-symmetry?

Extended Higgs sector?



New heavy bosons?

Composite quark and leptons?

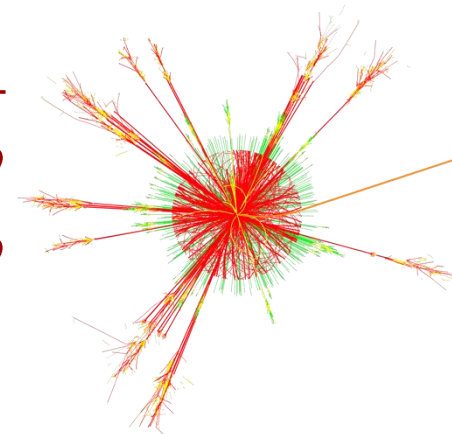


Dark Matter particles?

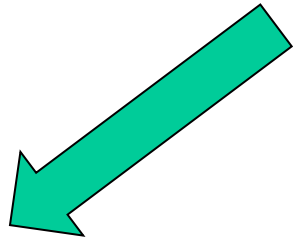
1981 SLAC u up quark	1978 Brookhaven & SLAC c charm quark	1975 Fermilab t top quark	1995 DESY g gluon
1981 SLAC d down quark	1971 Manchester University s strange quark	1971 Fermilab b bottom quark	1991 Washington University γ photon
1981 Savannah River Plant ν_e electron neutrino	1981 Brookhaven ν_μ muon neutrino	2000 Fermilab ν_τ tau neutrino	1983 CERN W W boson
1957 Cavendish Laboratory e electron	1947 Caltech and Harvard μ muon	1975 SLAC τ tau	1983 CERN Z Z boson

Any new theory needs to agree with the SM!

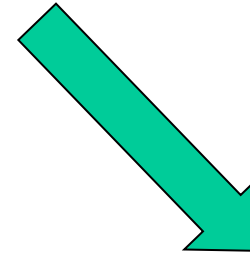
Large extra-dimensions?
Black holes?
Gravitons?



Where is Beyond-the-SM Physics?



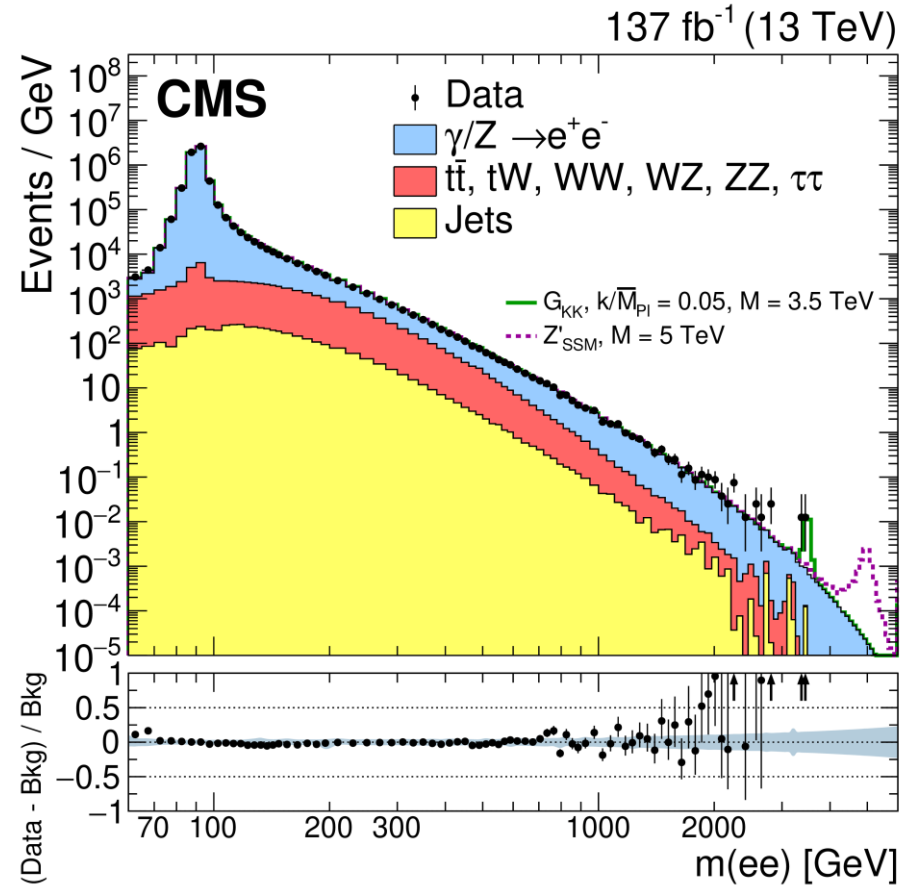
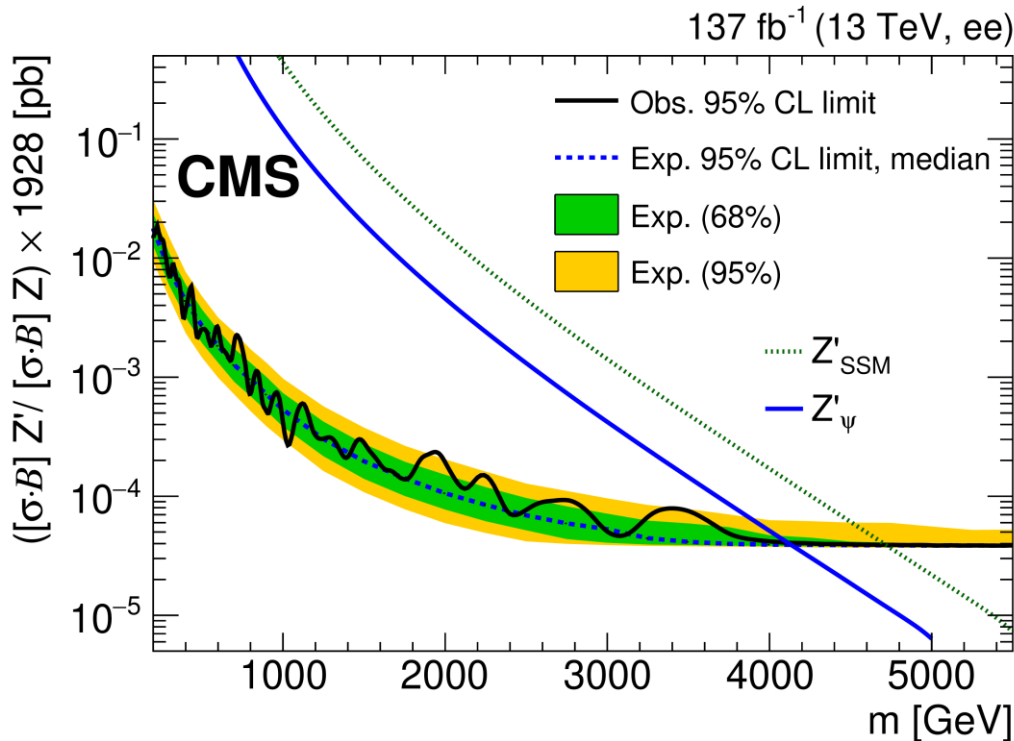
Masses of new
particles
within the
LHC reach



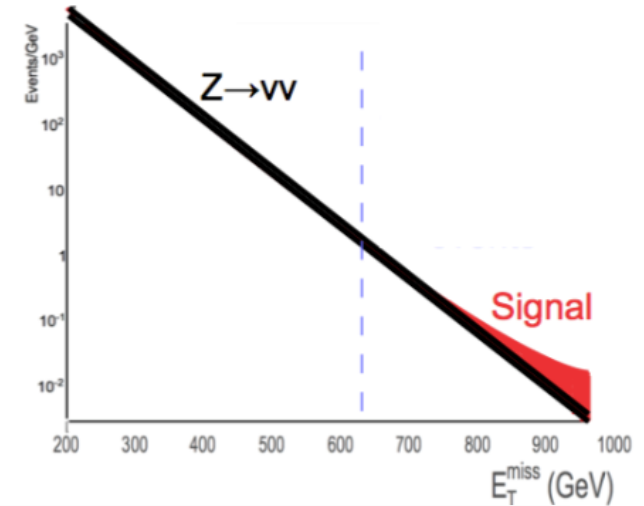
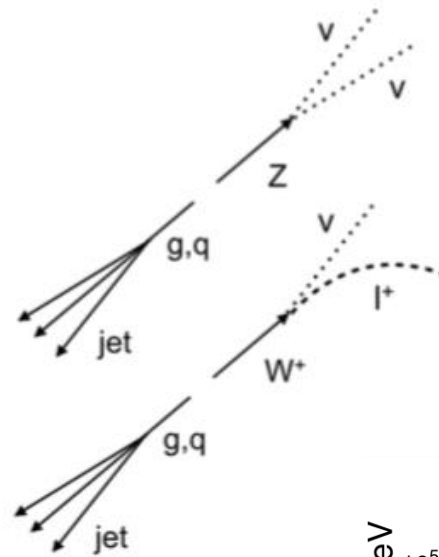
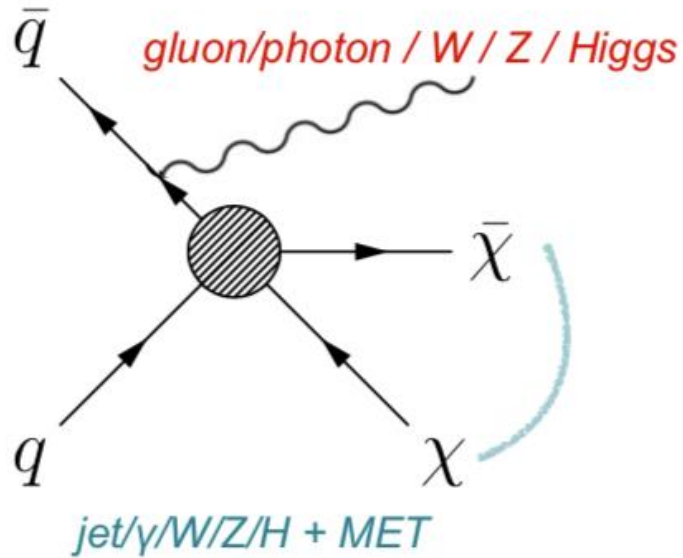
Masses of new
particles
not within the
LHC reach

Simple example: heavy Z' boson

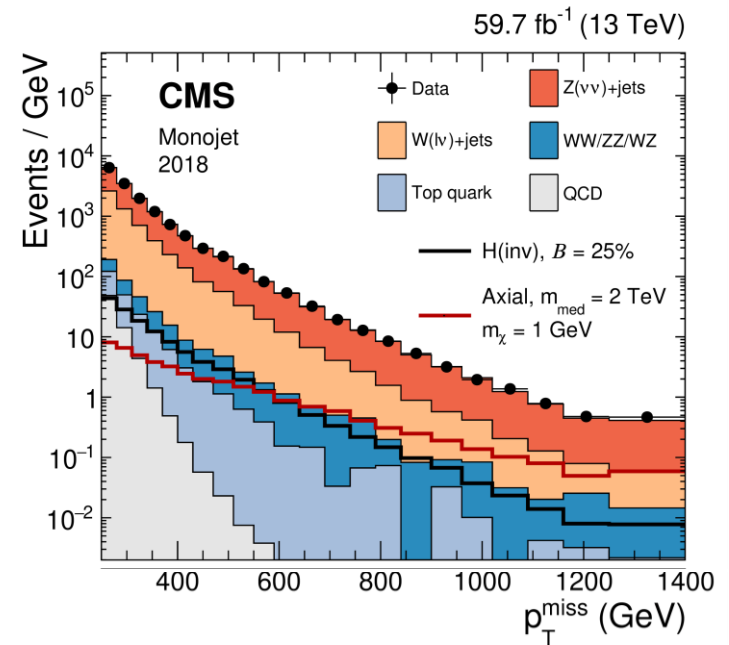
- Use very clear dilepton decay channel
 - ✓ e.g. electron-positron
 - ✓ Drell-Yan modeling important, but clear peak over a continuum (“bump hunting”)
- Result expressed as a 95% confidence-level excluded (upper) cross-section



More complex example: Dark Matter searches

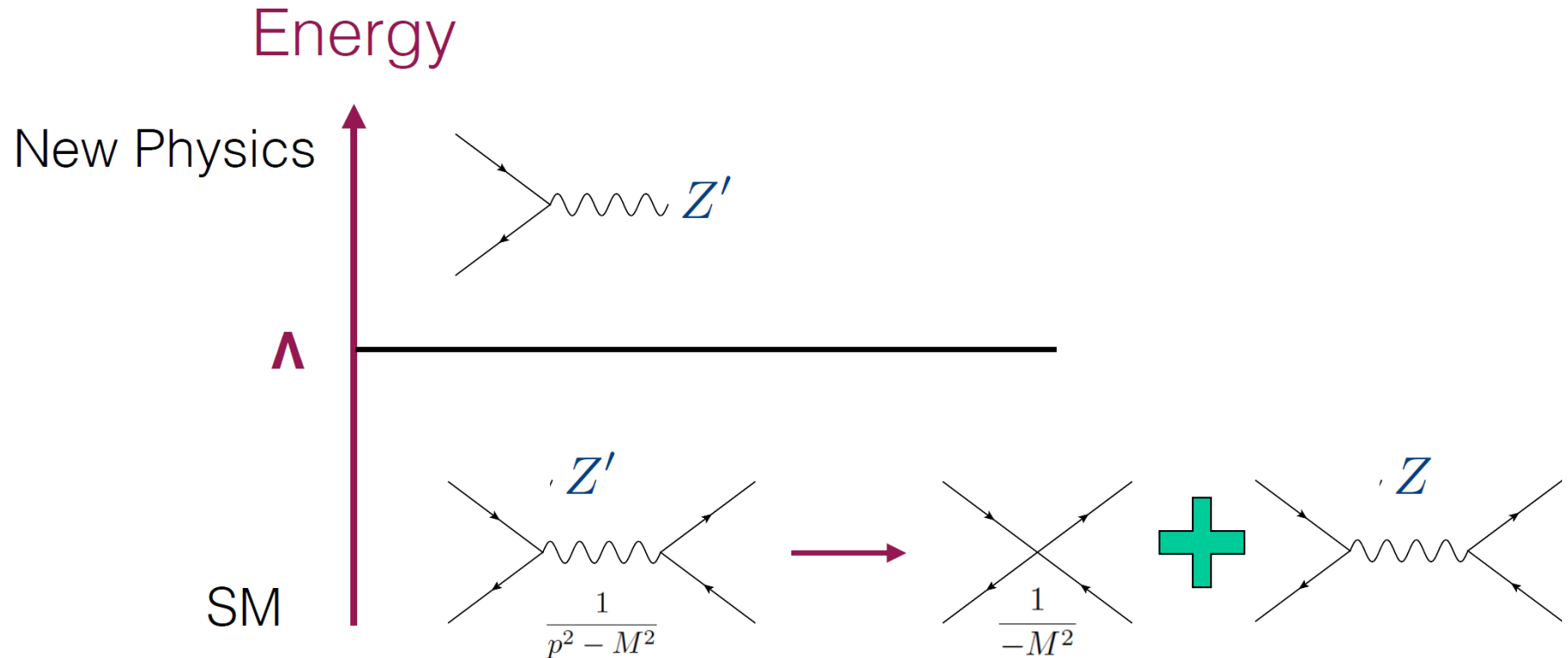


- Use MET shape to extract signal contribution
 - ✓ Similar shape for signal and background
 - ✓ Background modeling very important
- Main contributions (monojet example)
 - ✓ $Z(\nu\nu)+\text{jet}$
 - ✓ $W(l\nu)+\text{jet}$, where charged lepton is not reconstructed

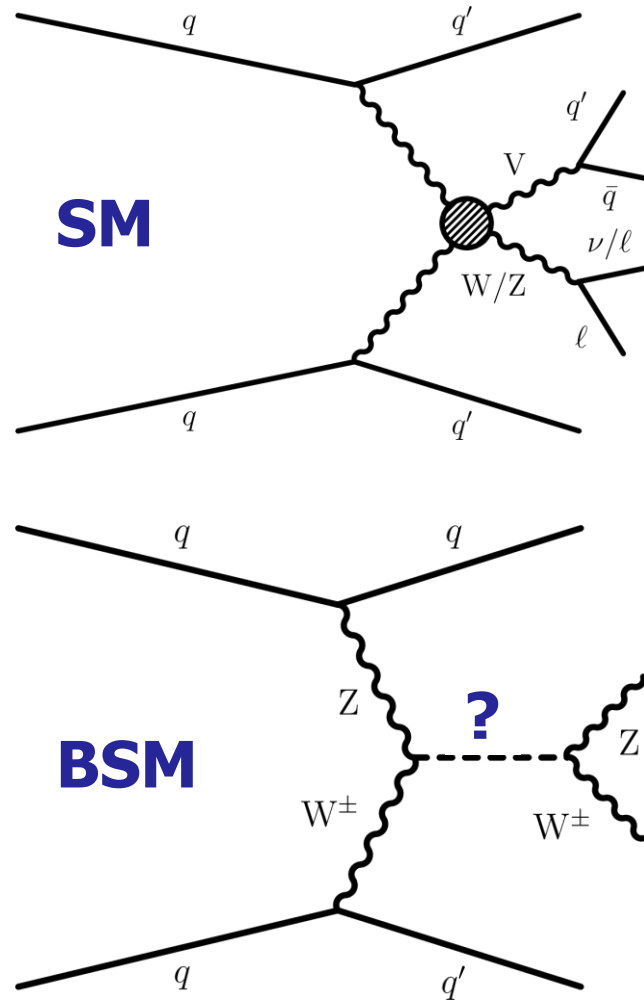


Masses not within LHC reach

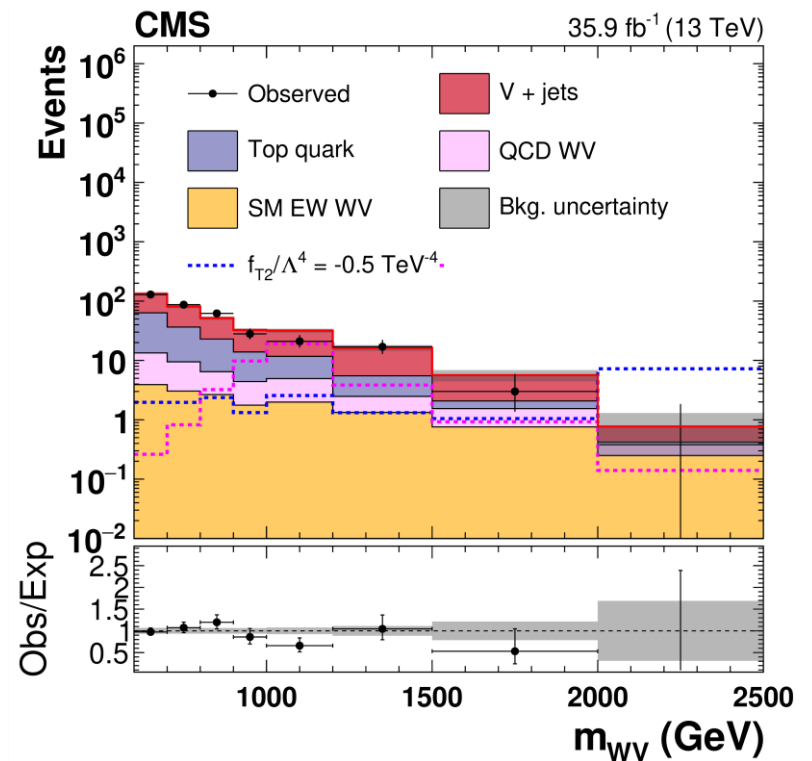
- Search for indirect effects on cross-sections of known processes



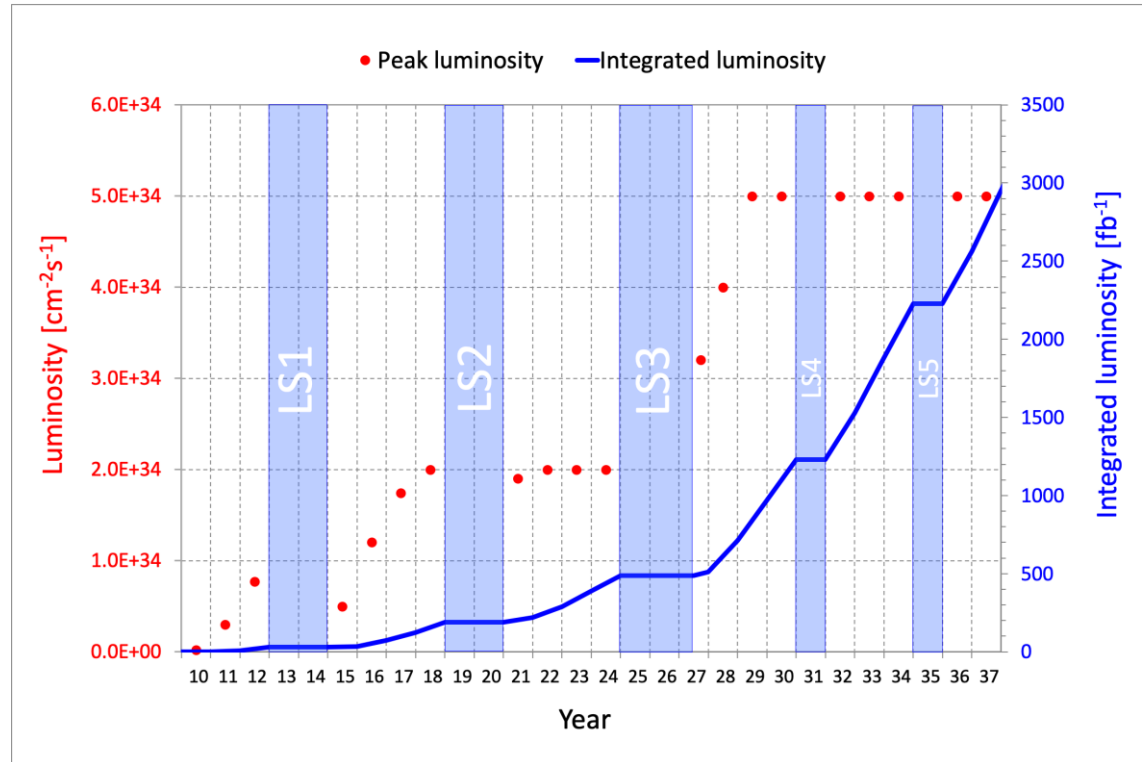
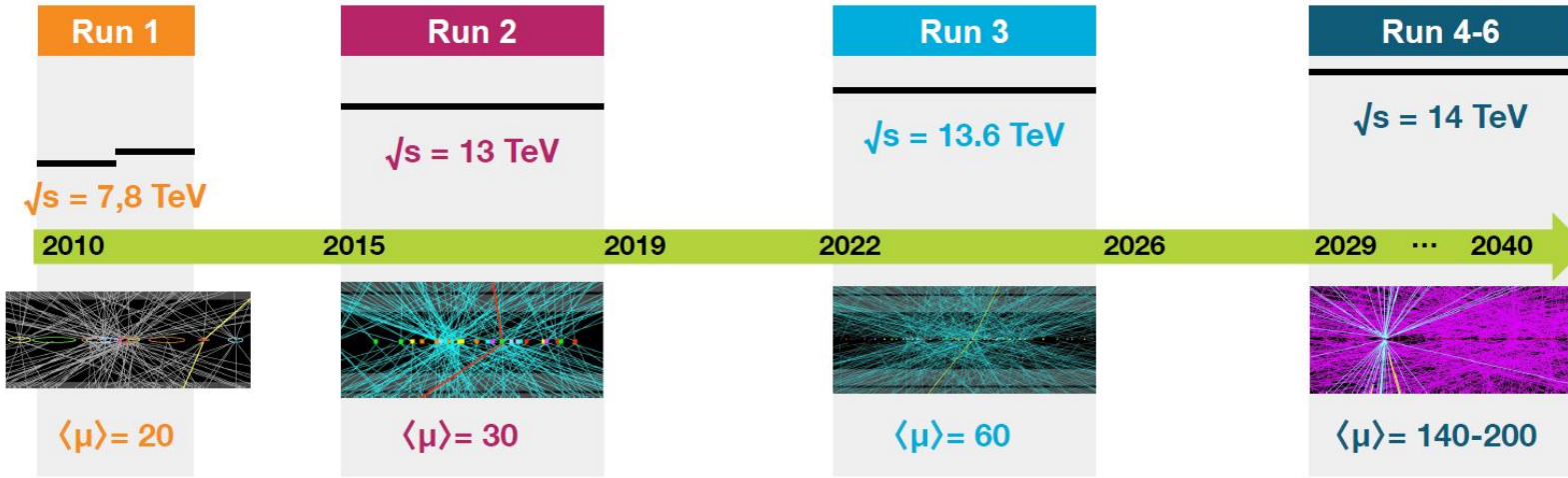
Example: di-boson production



- 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...

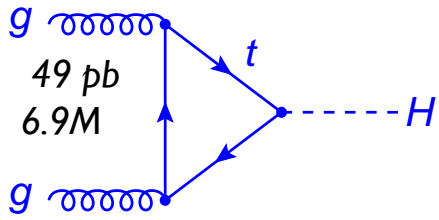


Additional information

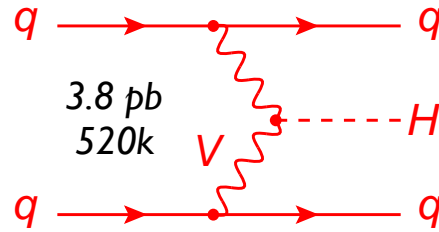
(I find you lack of faith disturbing)

Probing Higgs couplings at the LHC

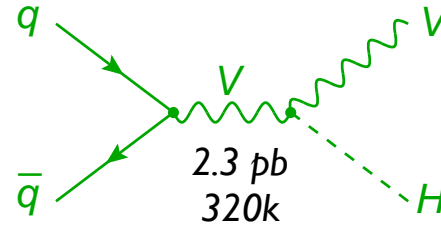
$\sigma[\text{pb}] @ 13 \text{ TeV}$
 # Higgs produced in 140
 fb^{-1} in one experiment



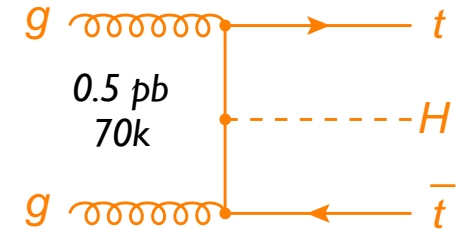
gluon-gluon fusion:
 main production mode at
 LHC



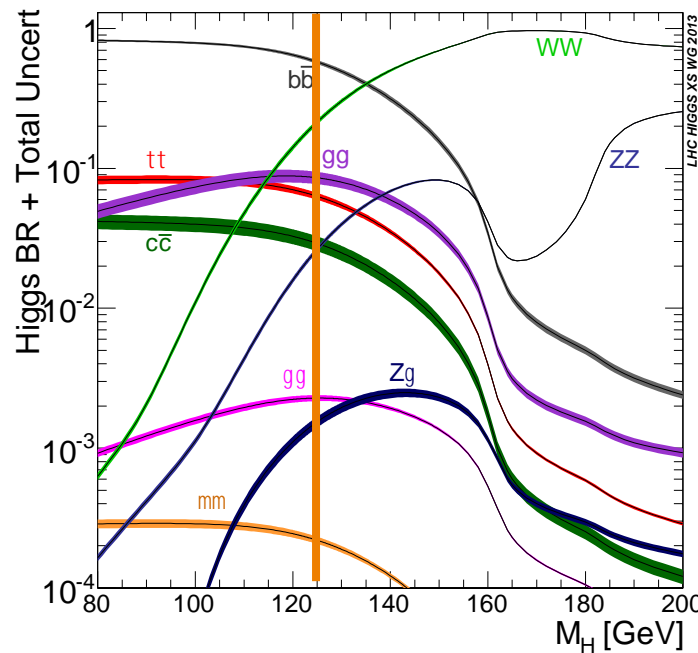
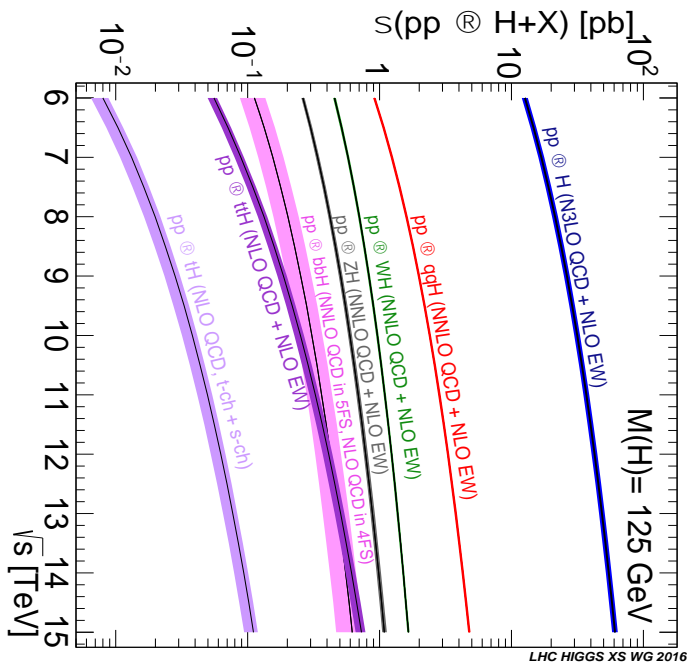
Vector Boson Fusion
 2 well-separated forward
 jets



VH
 tag W and Z
 boson decays



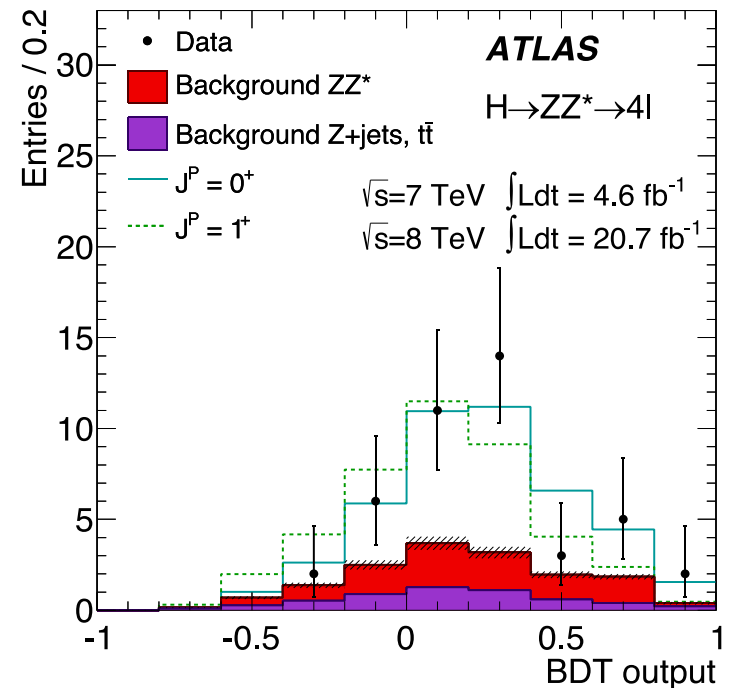
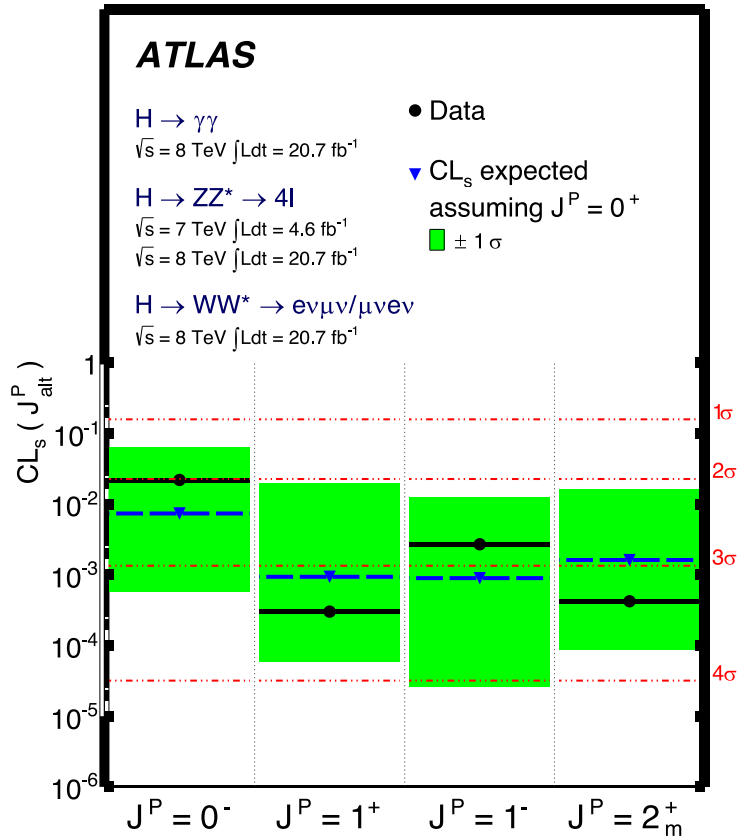
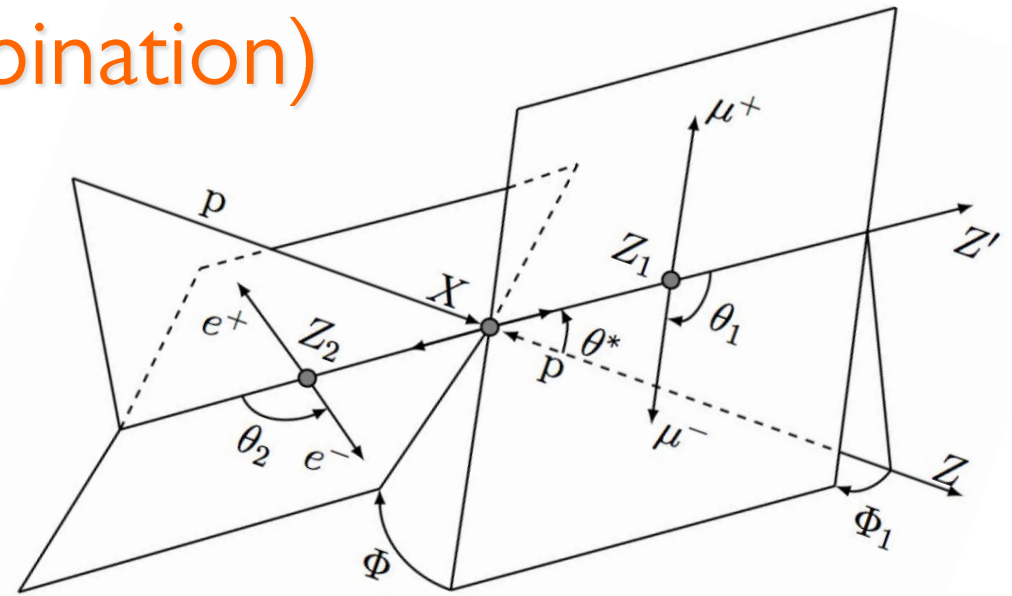
ttH
 tag 2 top quarks



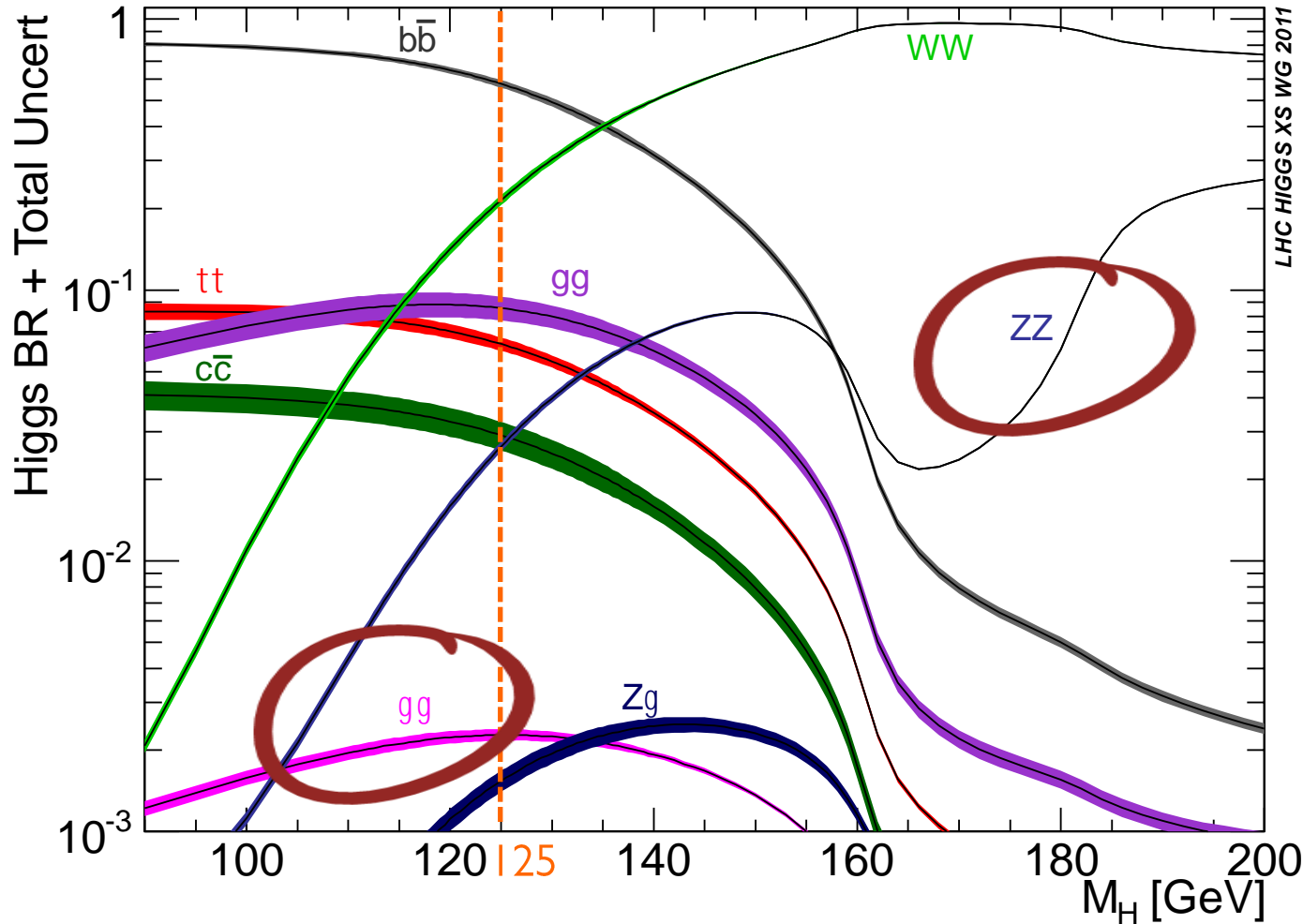
decay	SM BR [%] $m_H = 125.09 \text{ GeV}$
$H \rightarrow bb$	58.1
$H \rightarrow WW$	21.5
$H \rightarrow \tau\tau$	6.26
$H \rightarrow ZZ$	2.64
$H \rightarrow \gamma\gamma$	0.23

Spin with $H \rightarrow 4l$ (& combination)

- Sensitive variables combined in BDT score
 - ✓ Intermediate boson masses: m_{Z_1}, m_{Z_2}
 - ✓ 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



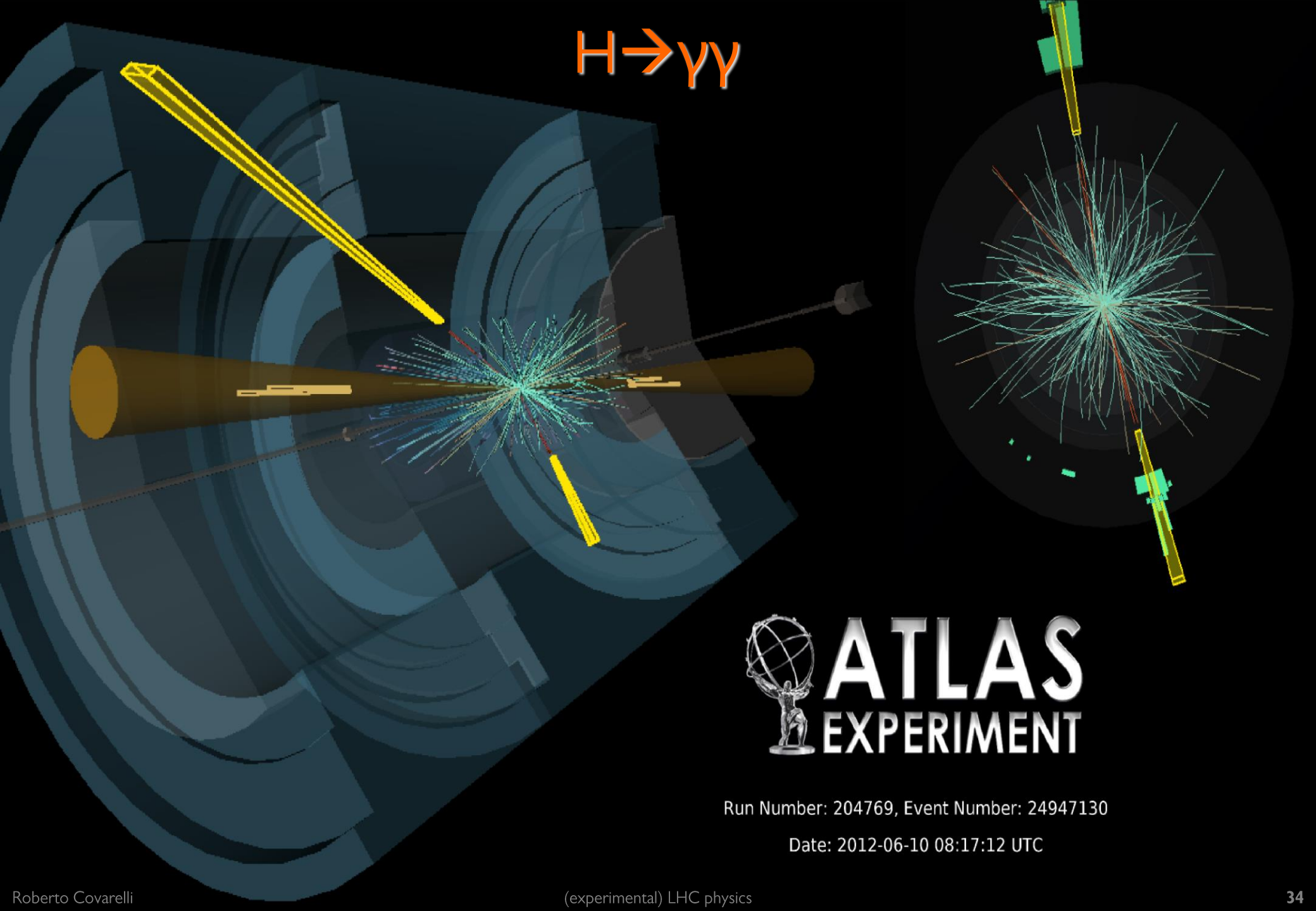
Standard Model Higgs decays



decay	SM BR [%] $m_H = 125.09 \text{ GeV}$
$H \rightarrow b\bar{b}$	58.1
$H \rightarrow WW$	21.5
$H \rightarrow \tau\tau$	6.26
$H \rightarrow ZZ$	2.64
$H \rightarrow \gamma\gamma$	0.23

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

$H \rightarrow \gamma\gamma$

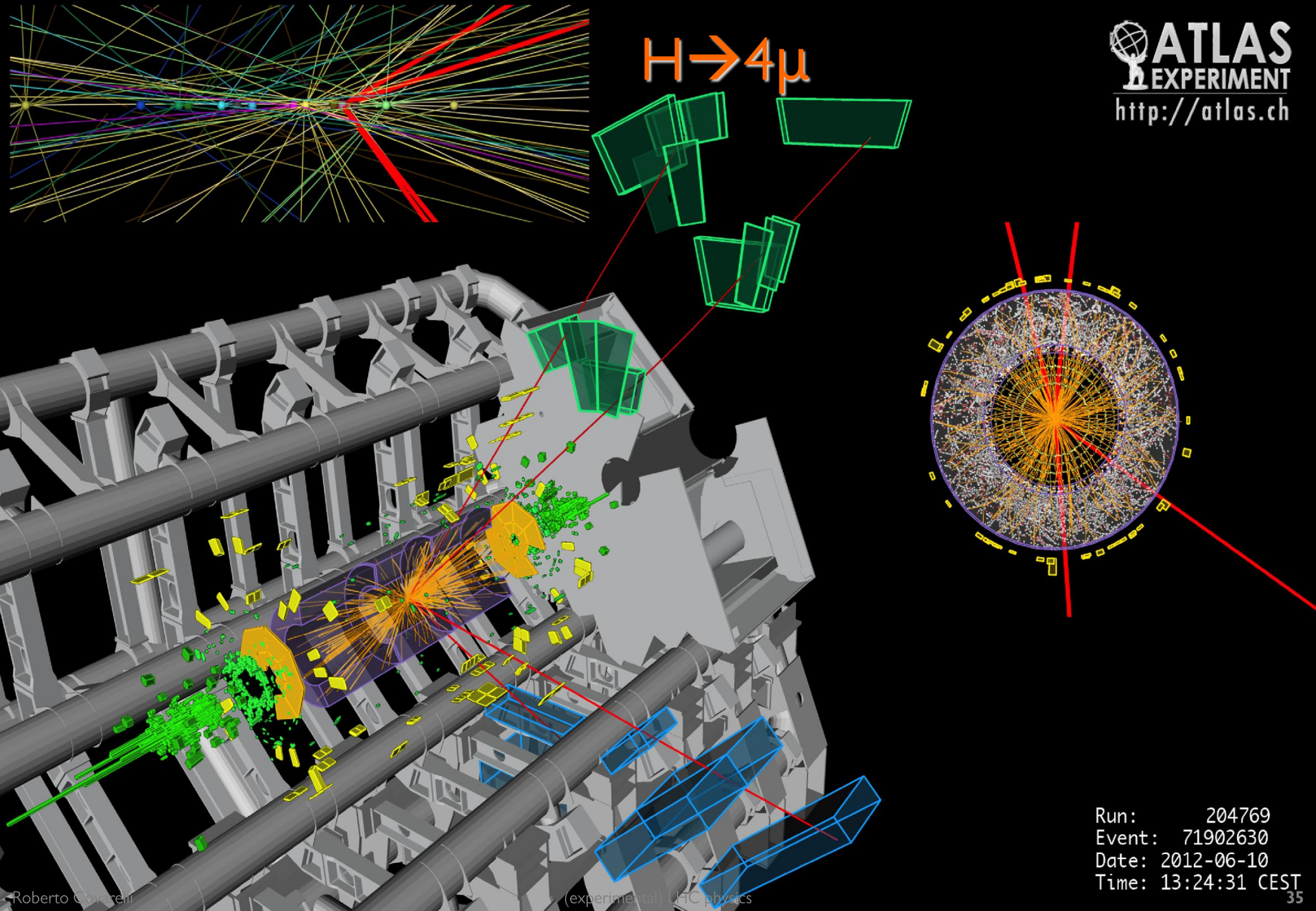


 **ATLAS**
EXPERIMENT

Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

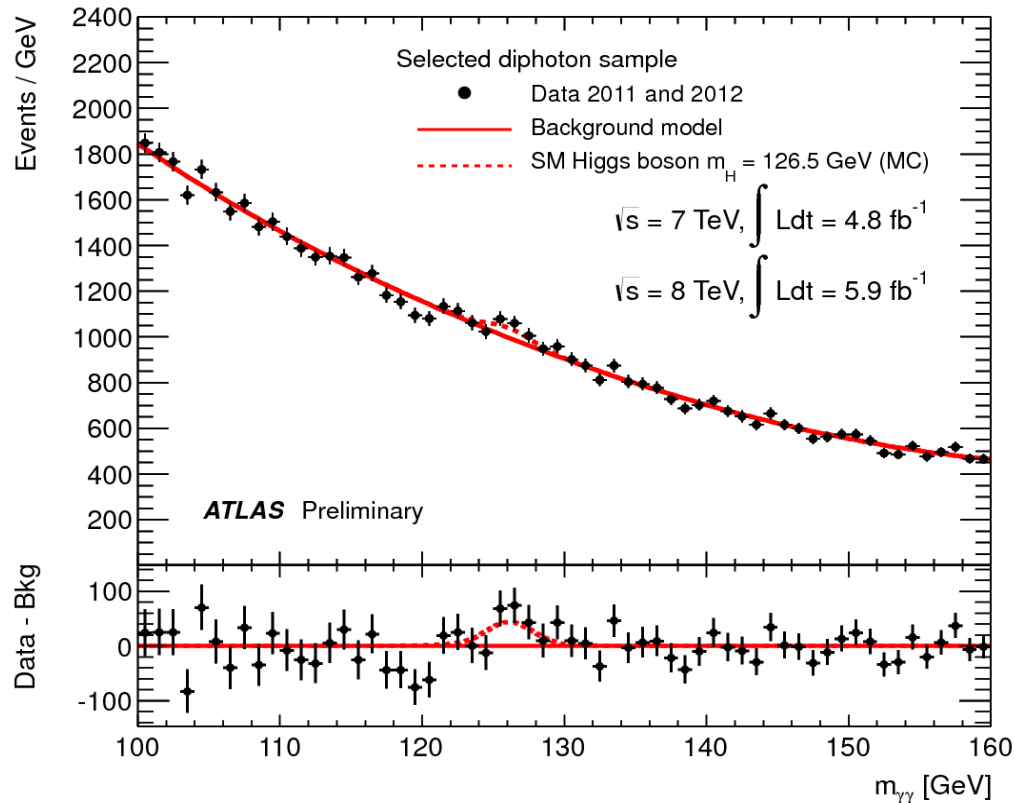
$H \rightarrow 4\mu$



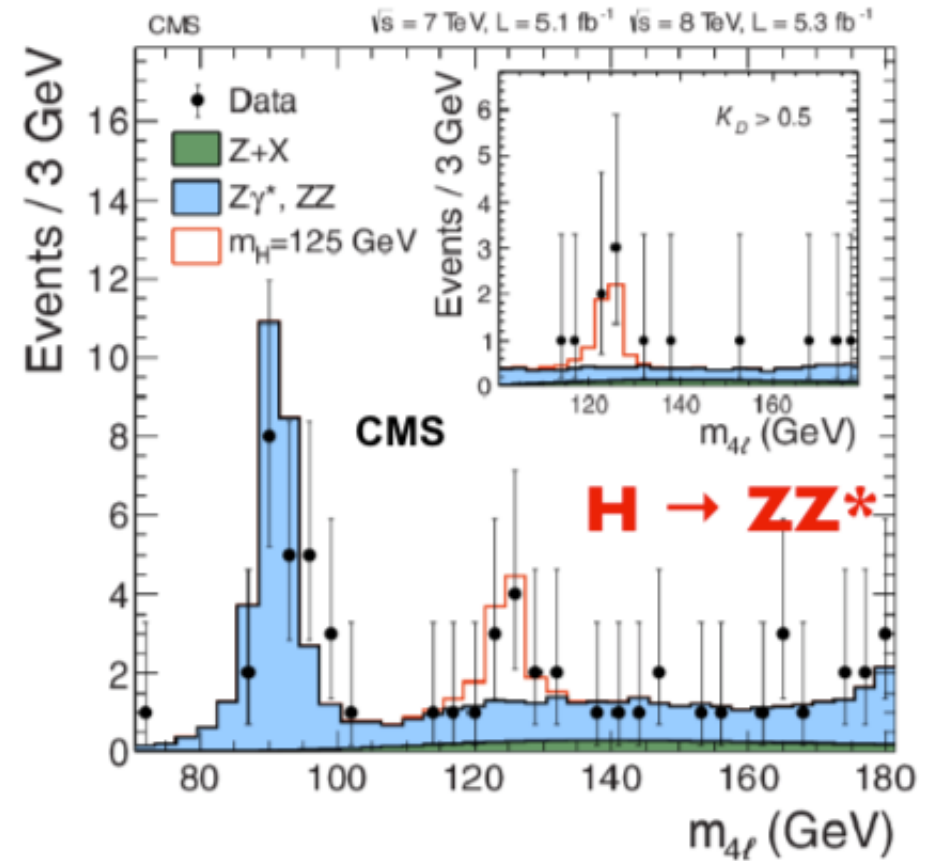
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs signals on July 4th 2012

$H \rightarrow \gamma\gamma$



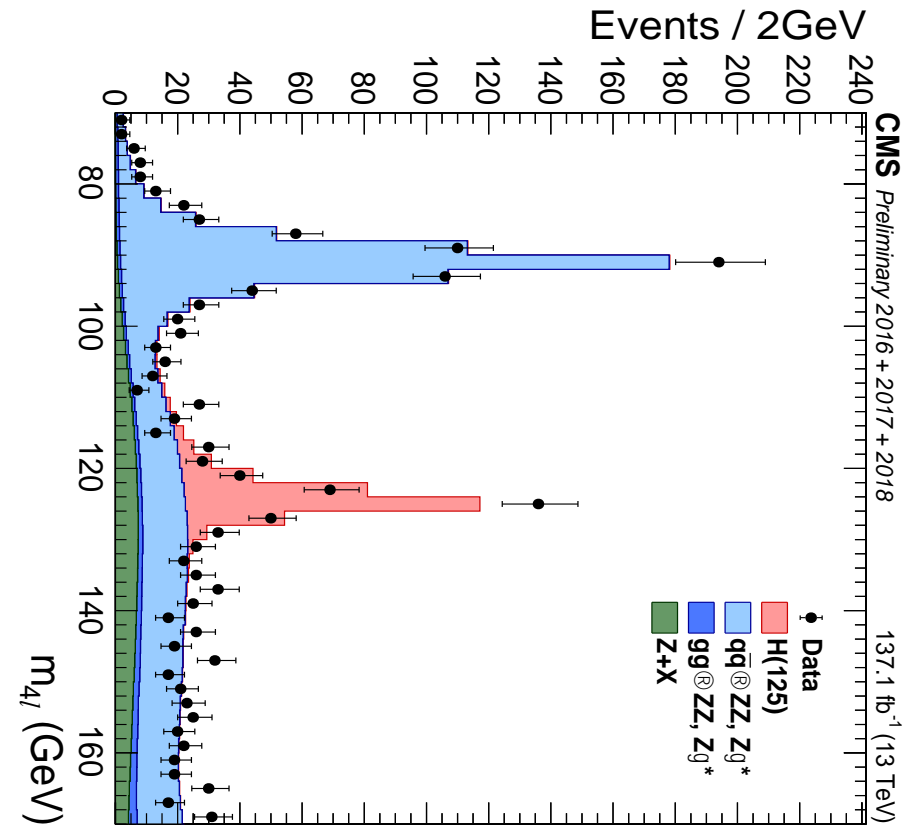
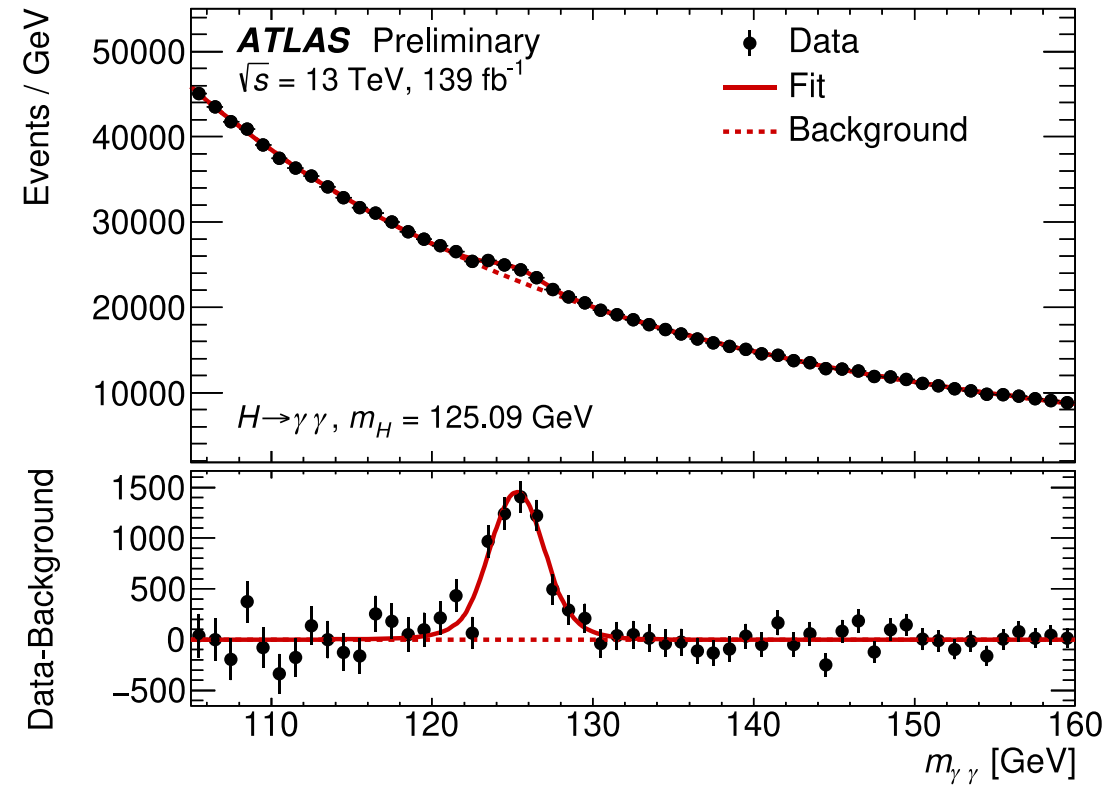
$H \rightarrow 4l$



Higgs signals with the *latest* 13 TeV data...

$H \rightarrow \gamma\gamma$

$H \rightarrow 4l$



What spin do particles have?



fermions
(quarks, leptons)
spin = $+1/2, -1/2$

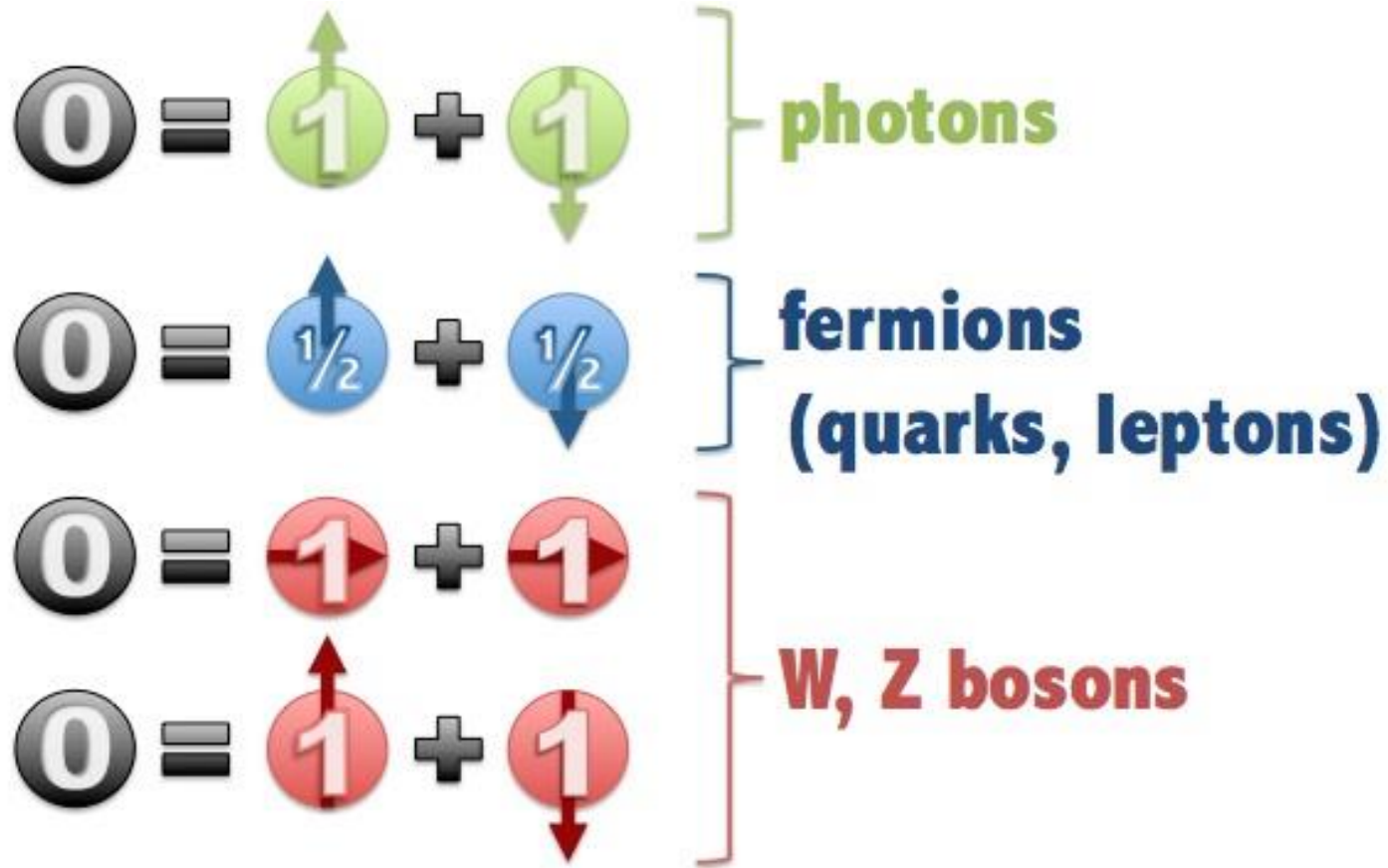


massive bosons
(W, Z bosons)
spin = $+1, 0, -1$

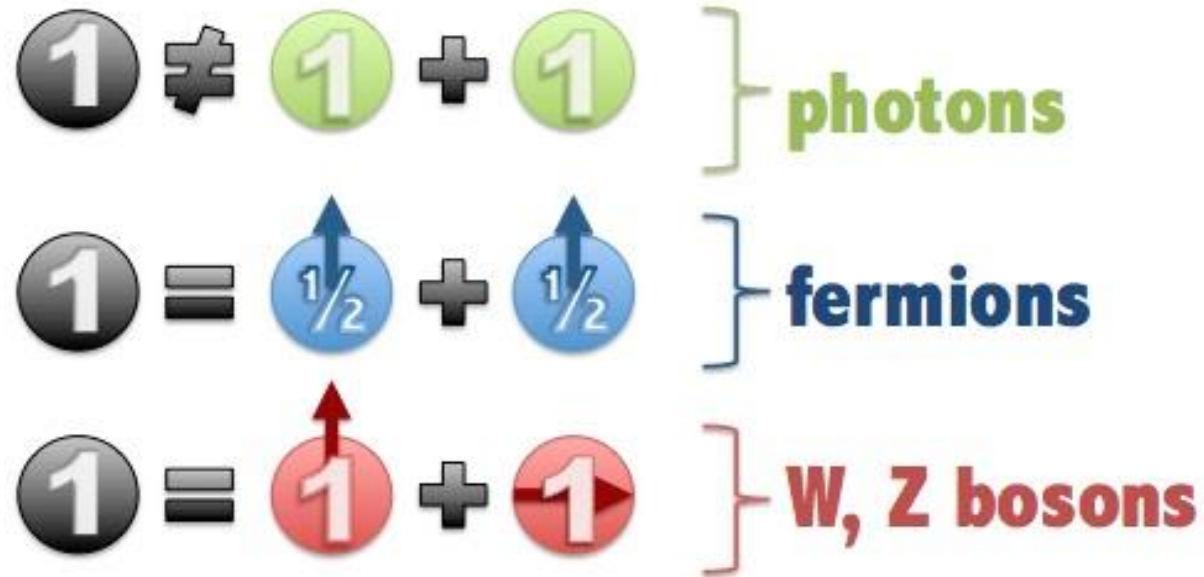


massless bosons
(photon, gluon)
spin = $+1, -1$

What can a spin 0 particle decay to?



What can a spin 1 particle decay to?



What can a spin 2 particle decay to?

$$\textcircled{2} = \textcircled{1}^{\uparrow} + \textcircled{1}^{\uparrow} \quad \left. \vphantom{\textcircled{2}} \right\} \text{photons}$$



$$\textcircled{2} \neq \textcircled{\frac{1}{2}} + \textcircled{\frac{1}{2}} \quad \left. \vphantom{\textcircled{2}} \right\} \text{fermions}$$

$$\textcircled{2} = \textcircled{1}^{\uparrow} + \textcircled{1}^{\uparrow} \quad \left. \vphantom{\textcircled{2}} \right\} \text{W, Z bosons}$$

$$\textcircled{2} = \textcircled{\frac{1}{2}}^{\uparrow} + \textcircled{\frac{1}{2}}^{\uparrow} + \textcircled{1}^{\uparrow} \quad \left. \vphantom{\textcircled{2}} \right\} \text{b quarks+gluon}$$

$$\textcircled{2} \neq \textcircled{\frac{1}{2}} + \textcircled{\frac{1}{2}} \quad \left. \vphantom{\textcircled{2}} \right\} \tau \text{ leptons}$$

So, what spin has our Higgs-like particle?

Spin of particle	$\gamma\gamma$	ZZ^*
Spin 0		
Spin 1		
Spin 2		

Spin with $H \rightarrow 4 \text{ leptons}$

$\gamma\gamma$ polar angle ϑ^* with respect to Z-axis in Colin-Sopper frame

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

