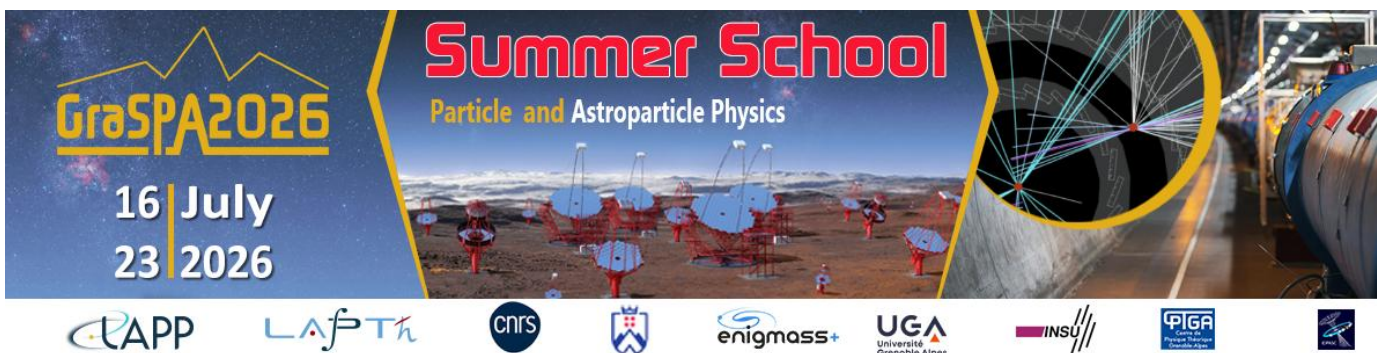


(experimental) LHC physics



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

Roberto Covarelli

Step 1: find events with the right ingredients

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

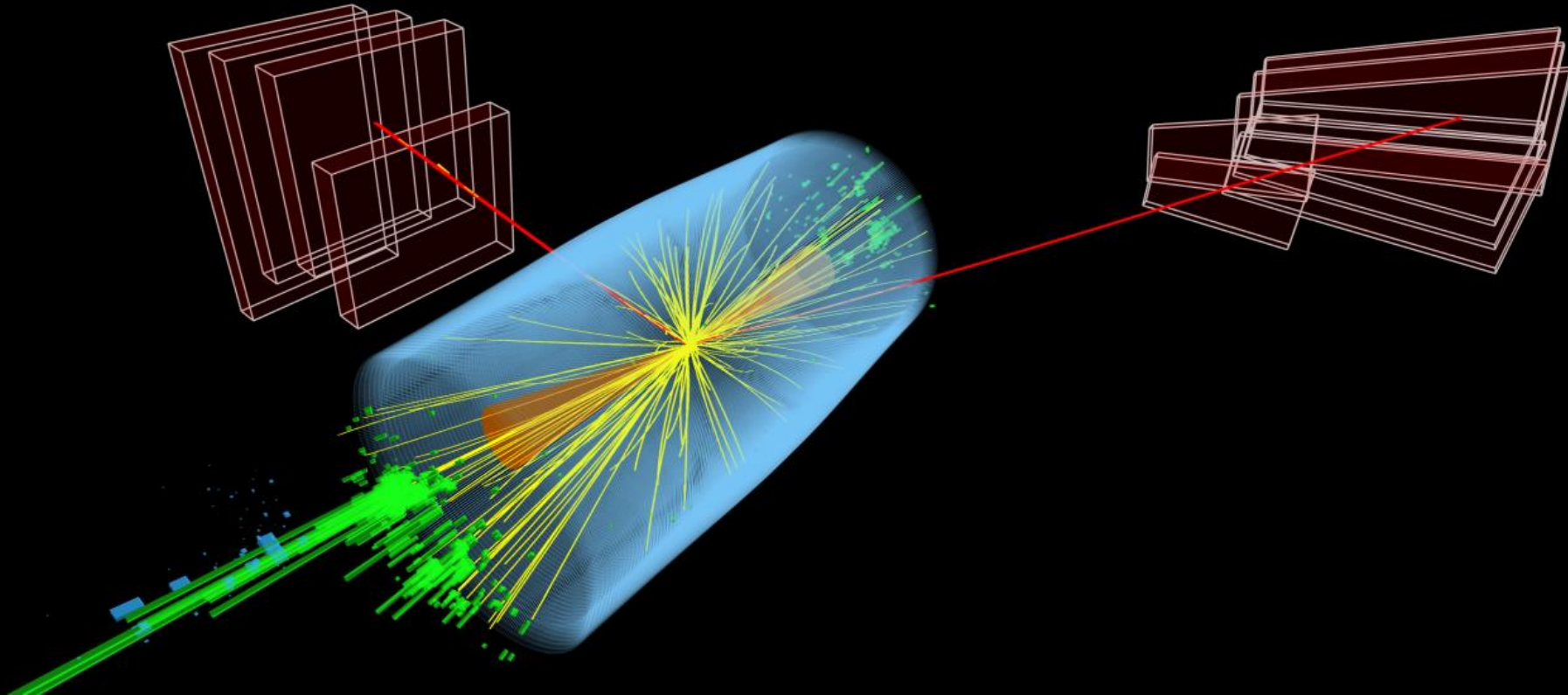
Is this event OK?



CMS Experiment at the LHC, CERN

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

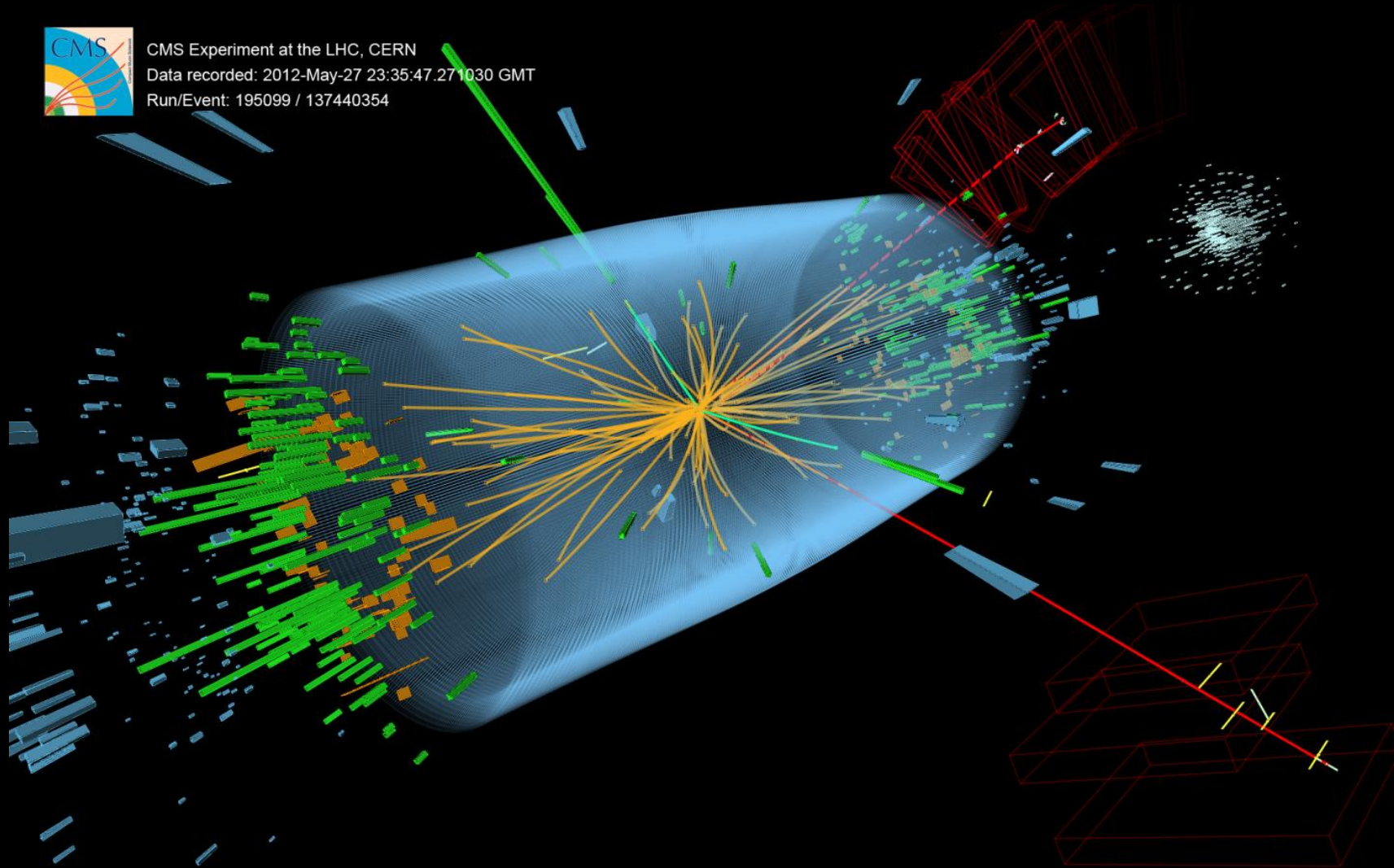
Run / Event / LS: 323940 / 44997009 / 65



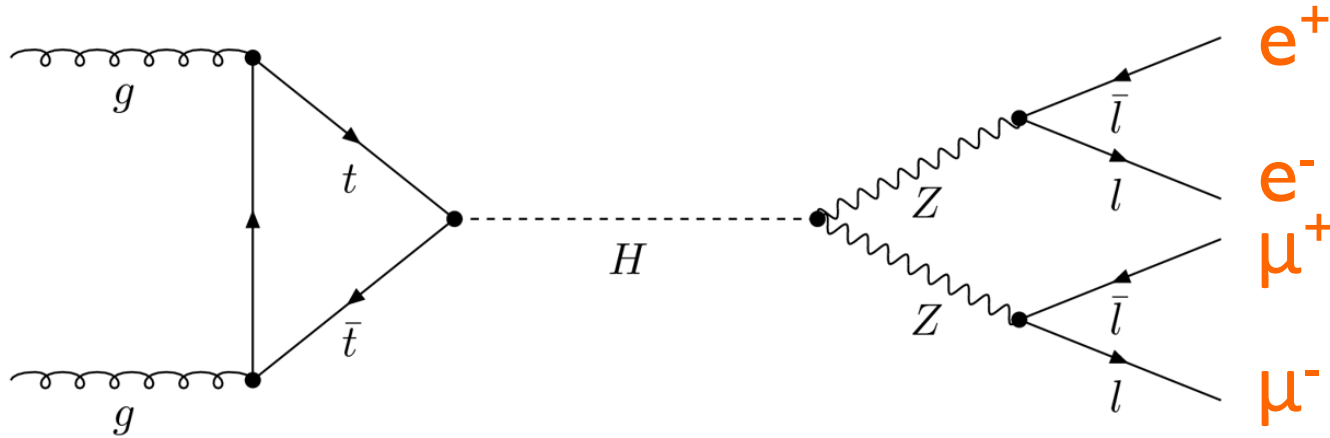
Step 1: find events with the right ingredients

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

And this one?

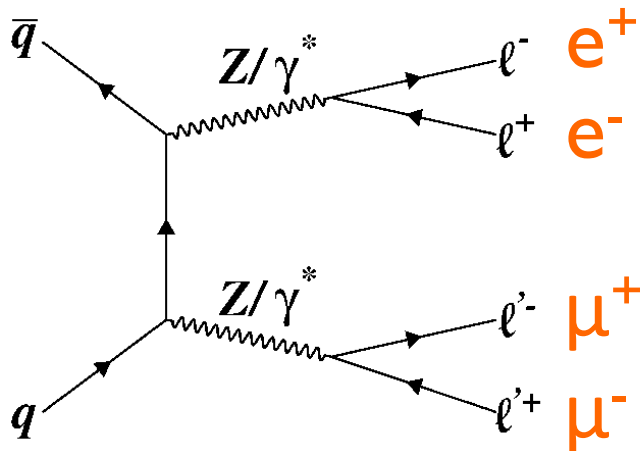


Step 2: signal and background



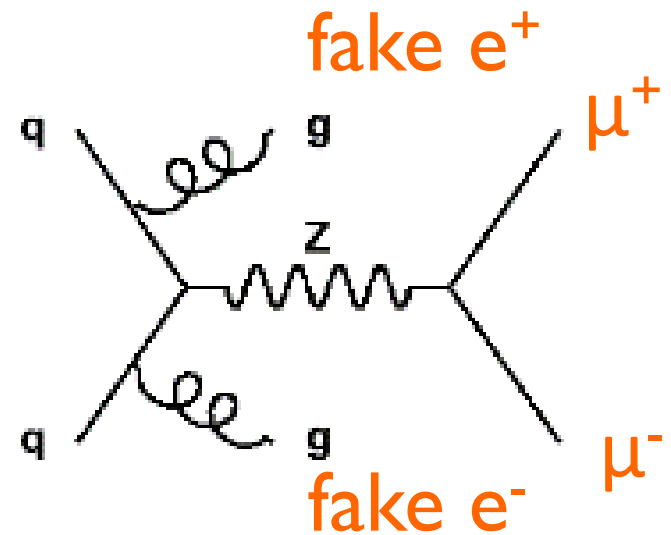
Irreducible background

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

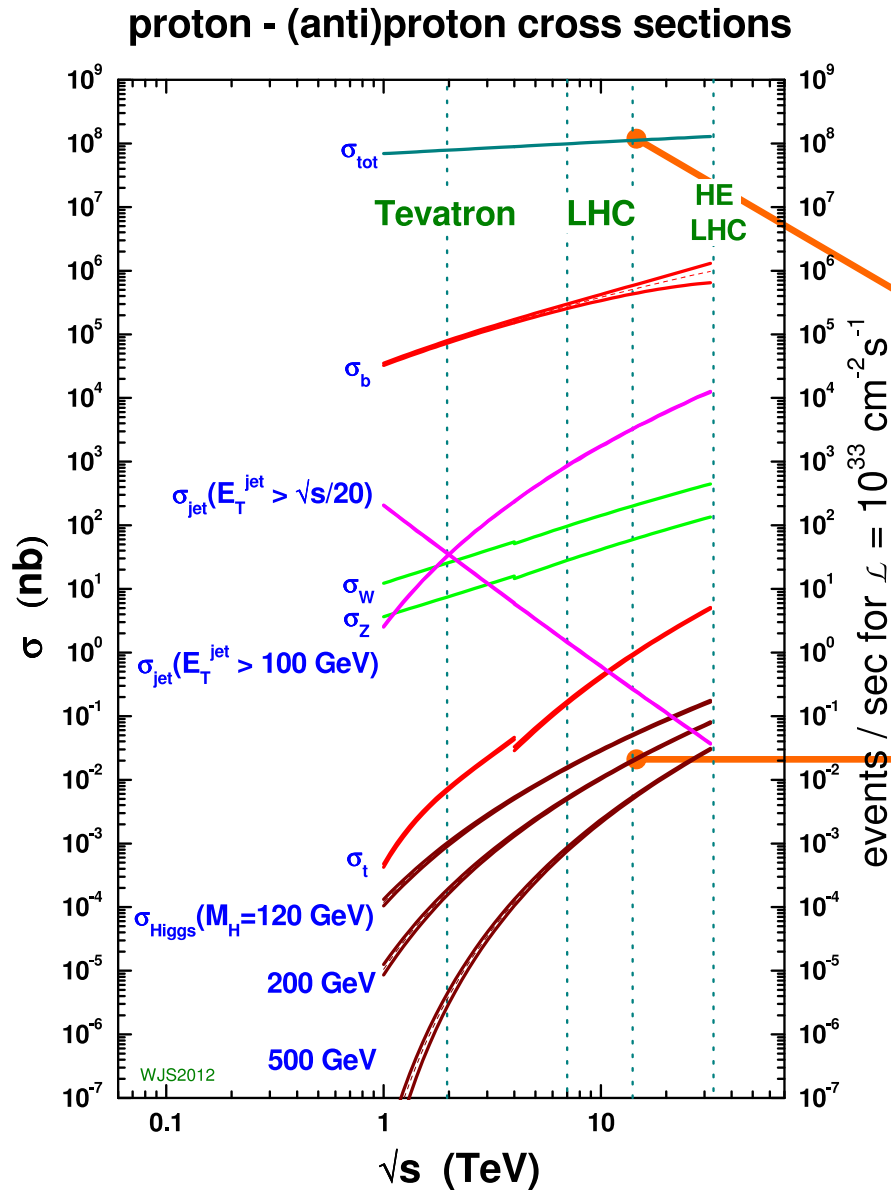


Reducible background

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



Interesting processes are rare!



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

$$\sigma_{\text{tot}} (13.6 \text{ TeV}) \sim 10^8 \text{ nb}$$

$$\sigma_H (13.6 \text{ TeV}) \sim 0.05 \text{ nb}$$

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

inelastic pp collisions

10^9 events/s

$\sim 10^{10}$

10^{-1} events/s

~ 1 Higgs boson
every 2 seconds

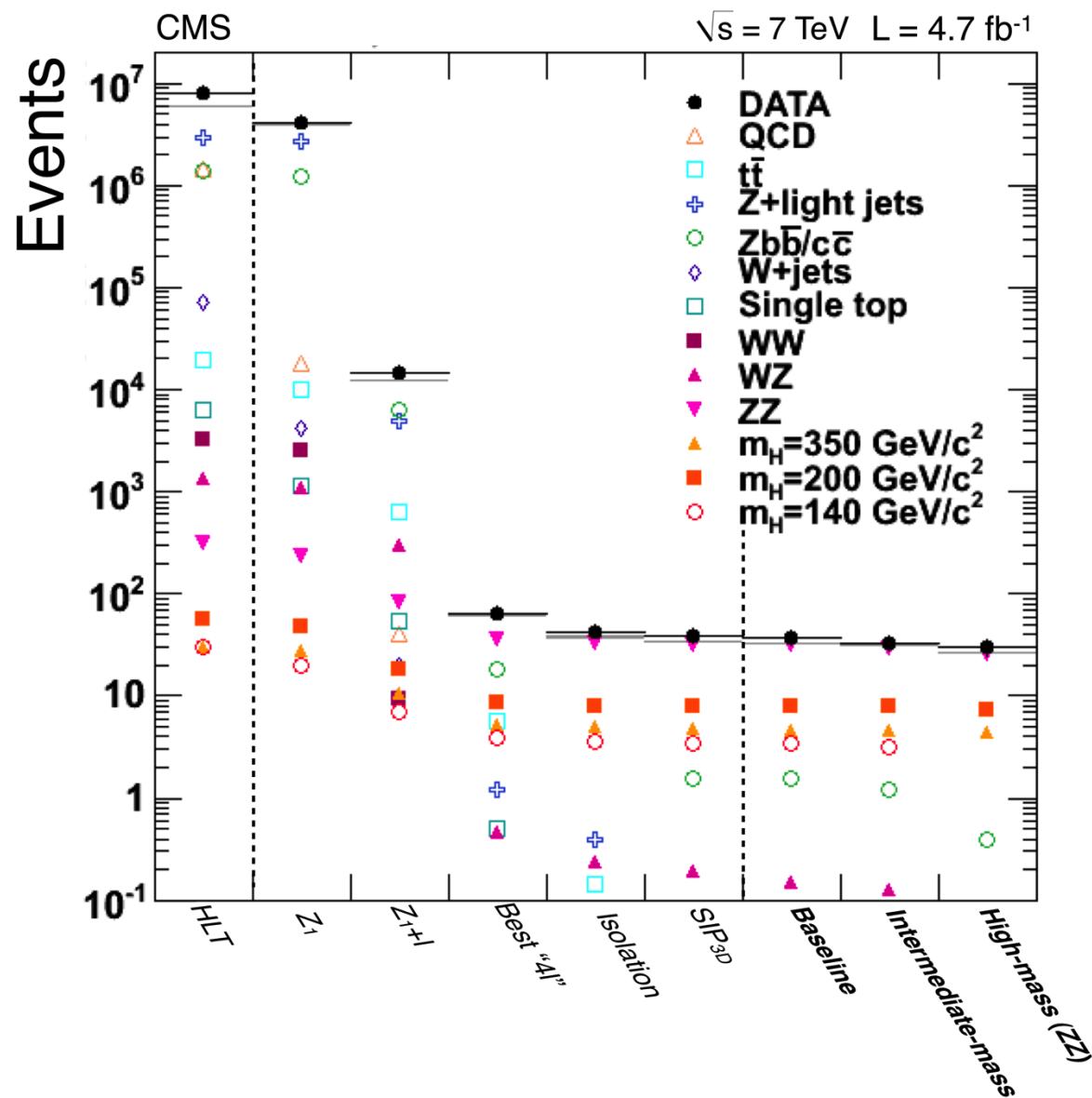
$[m_H \sim 125 \text{ GeV}]$

0.2% $H \rightarrow \gamma\gamma$

0.01% $H \rightarrow ZZ$

Lose some signal, suppress backgrounds...

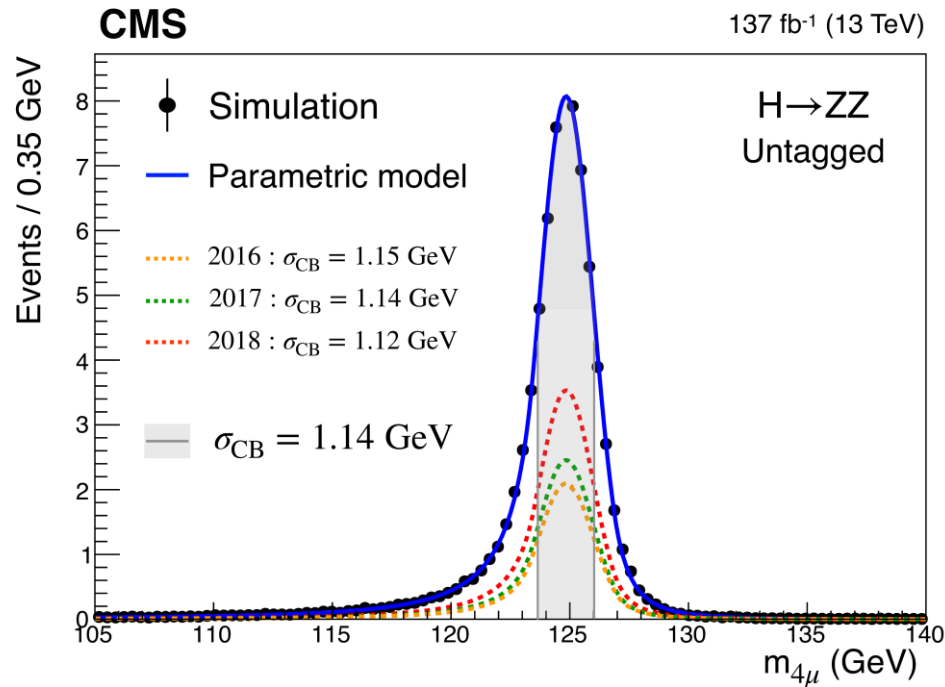
- Selections based on particle properties to reduce reducible background
 - ✓ Shower shapes, track properties, ...
- Selections based on event properties to distinguish signal from background
 - ✓ Particle kinematics, decay kinematics event shape, ...
- Try to keep signal while reducing background!
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

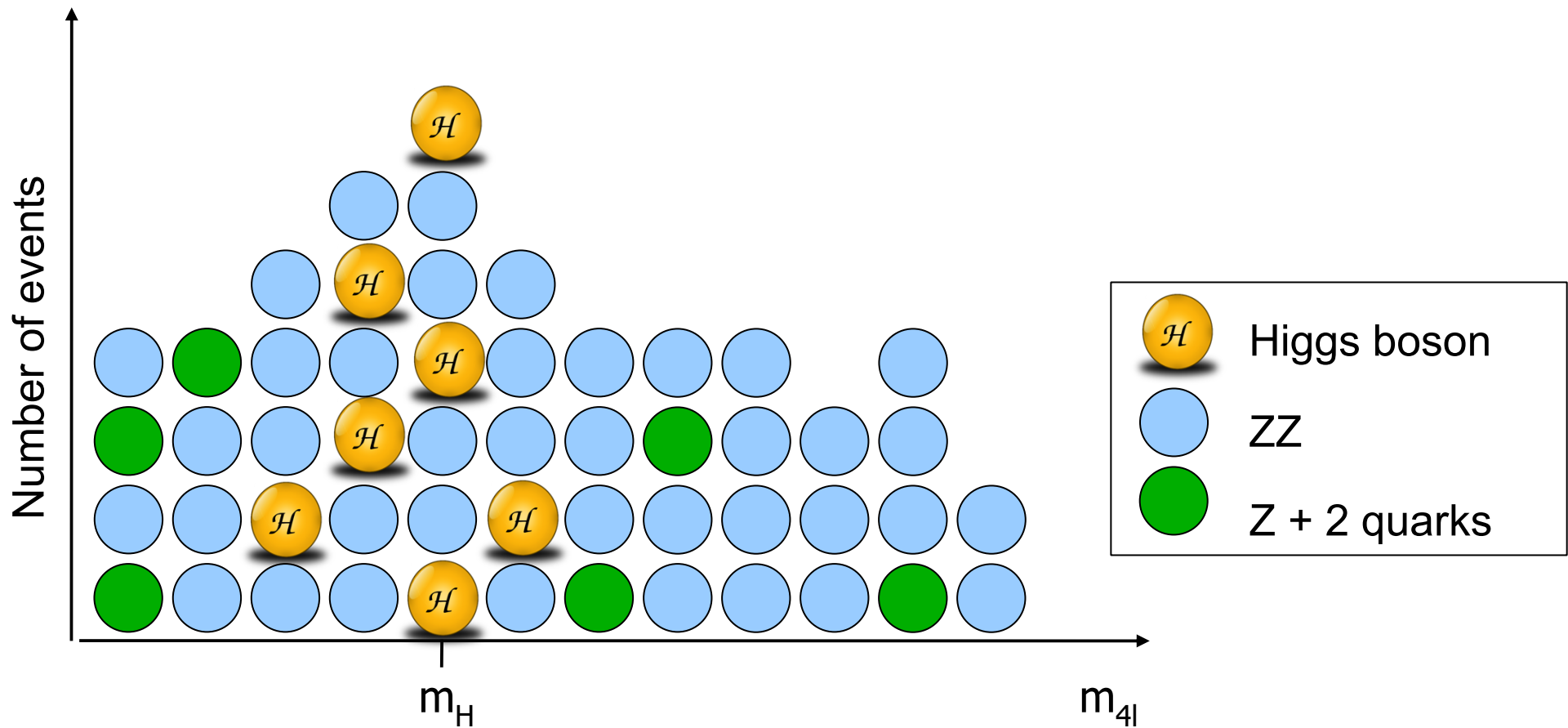
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



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

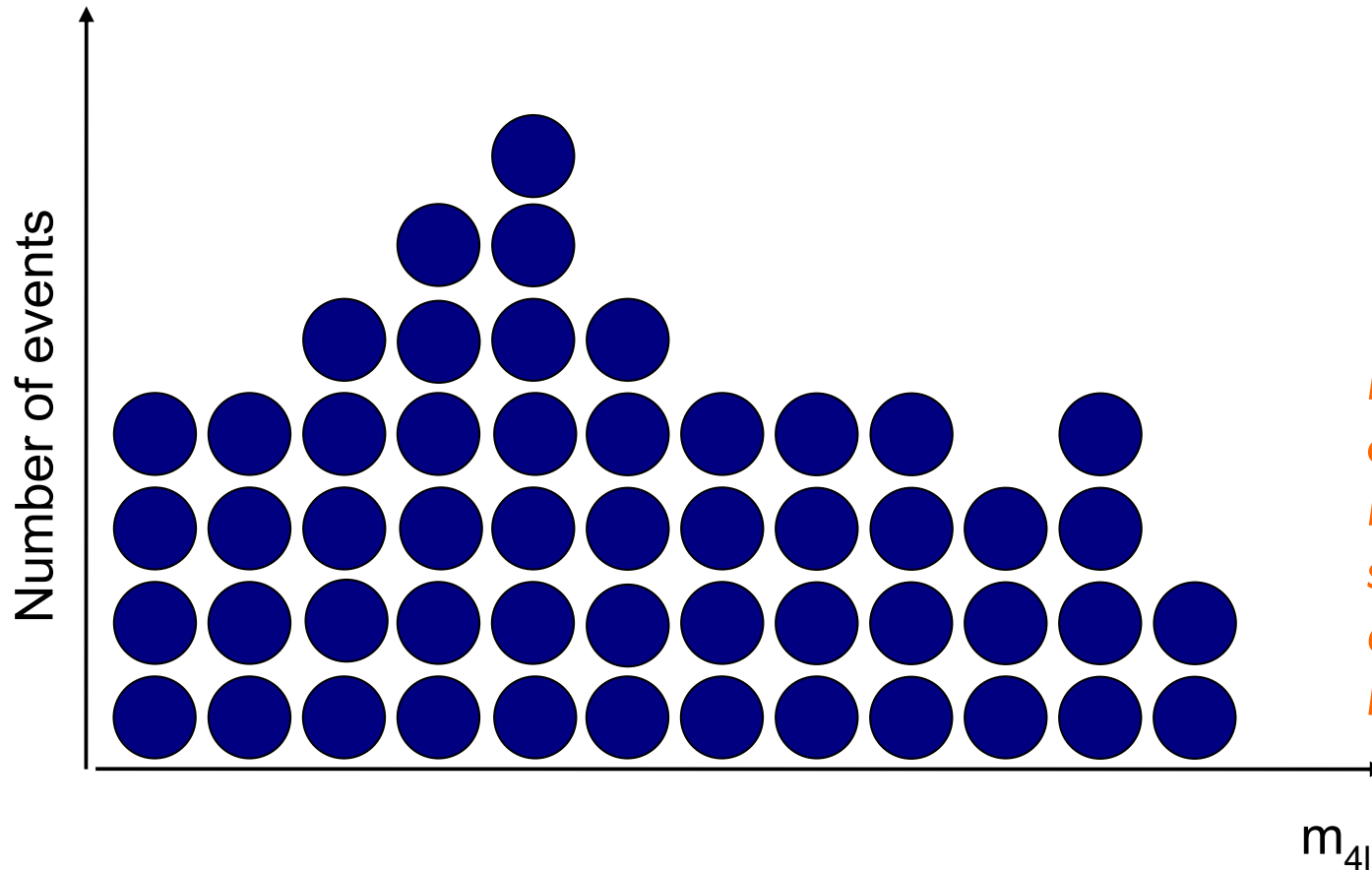
Extract signal from background

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



Extract signal from background

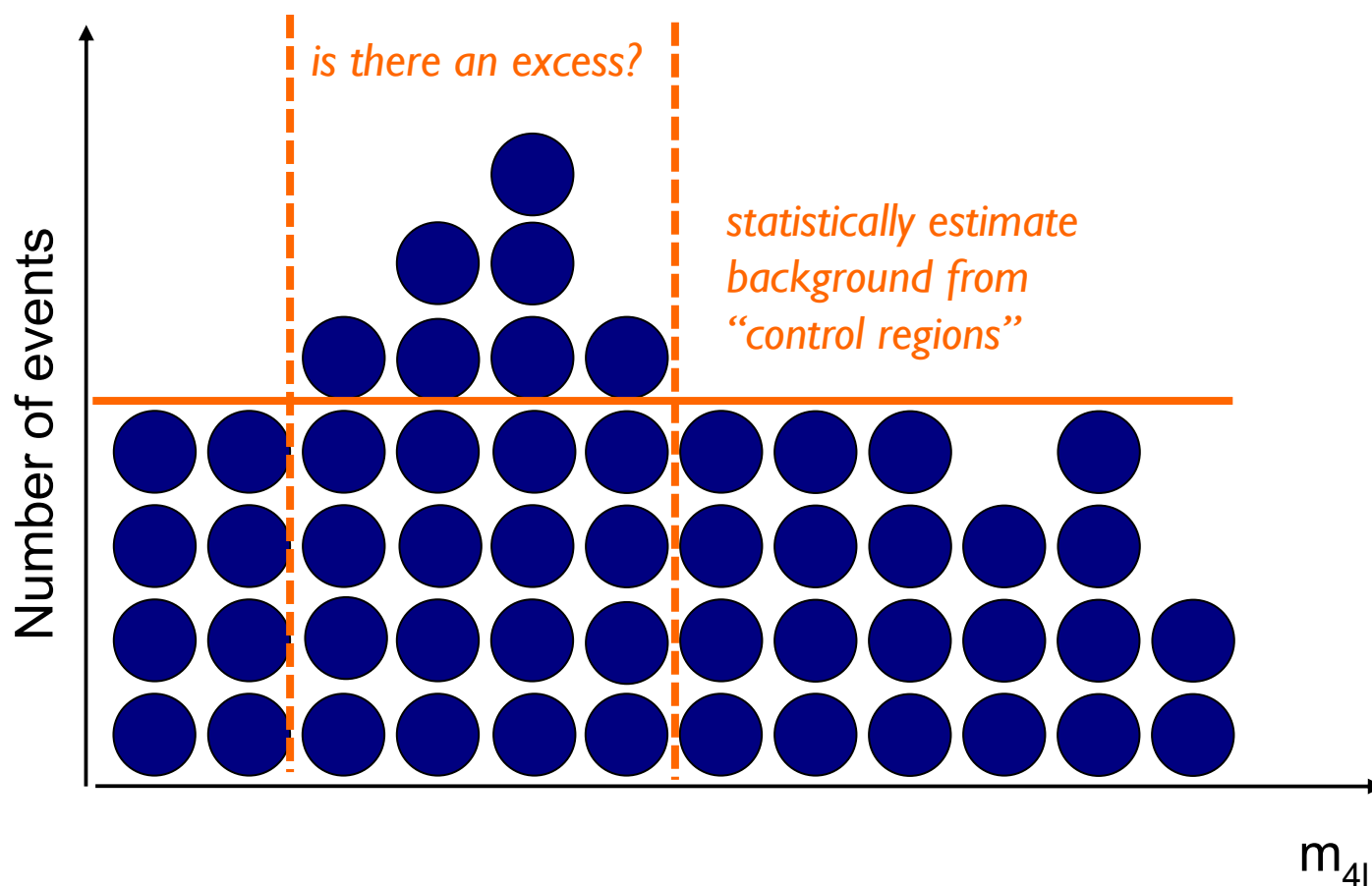
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



*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

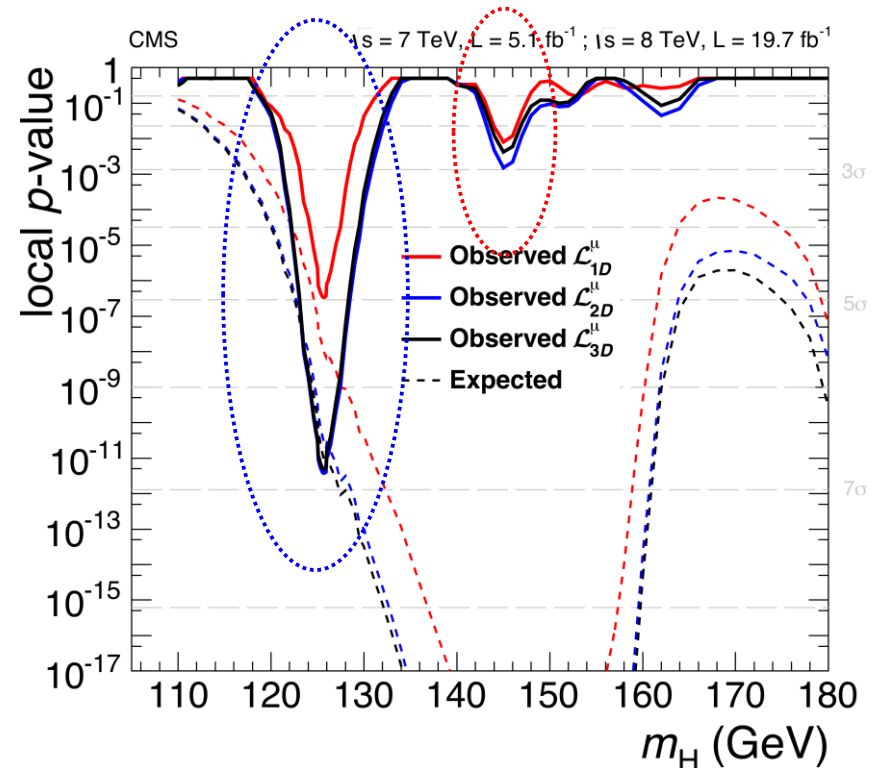
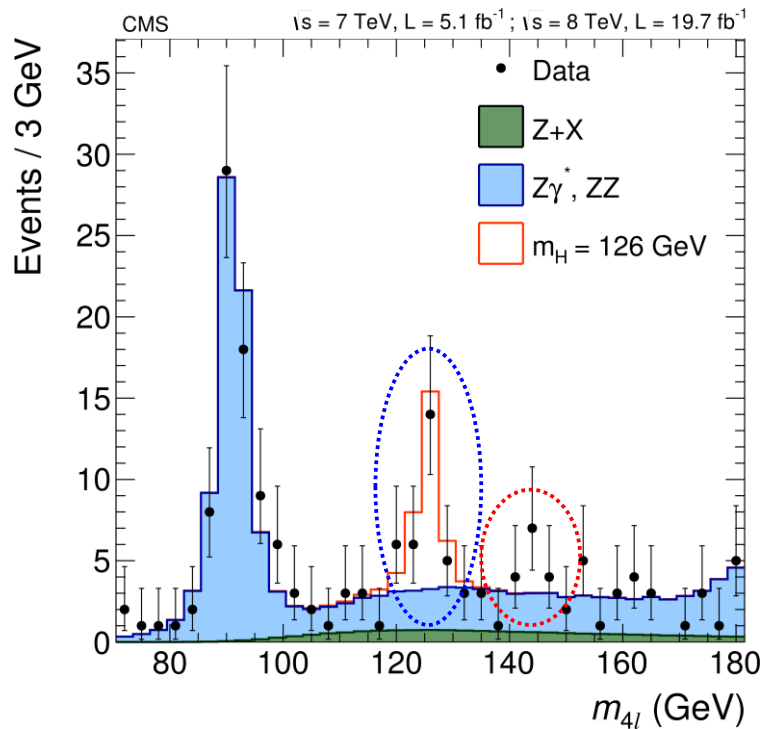
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



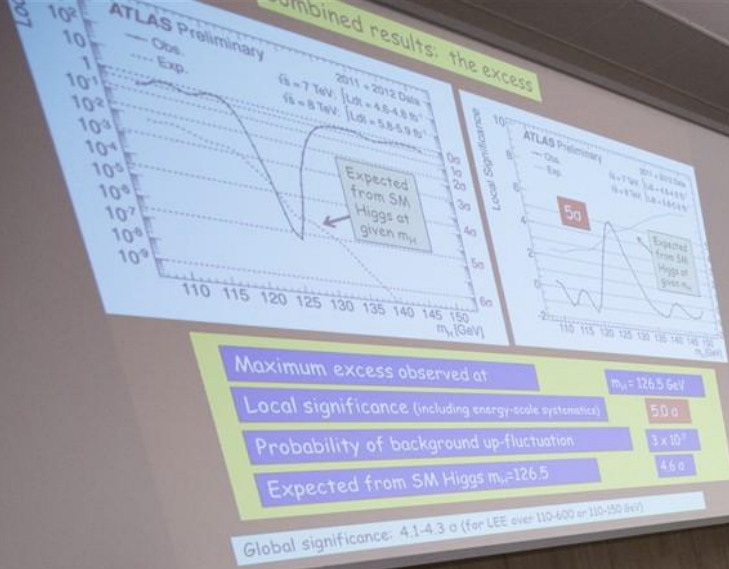
- Background gets estimated...
 - ✓ ... from simulation (normalized to data)
 - ✓ ... directly from data (“control regions”, enriched in background events)

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** ($p_0 = 5.7 \cdot 10^{-7}$)



CERN Auditorium, July 4th 2012



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

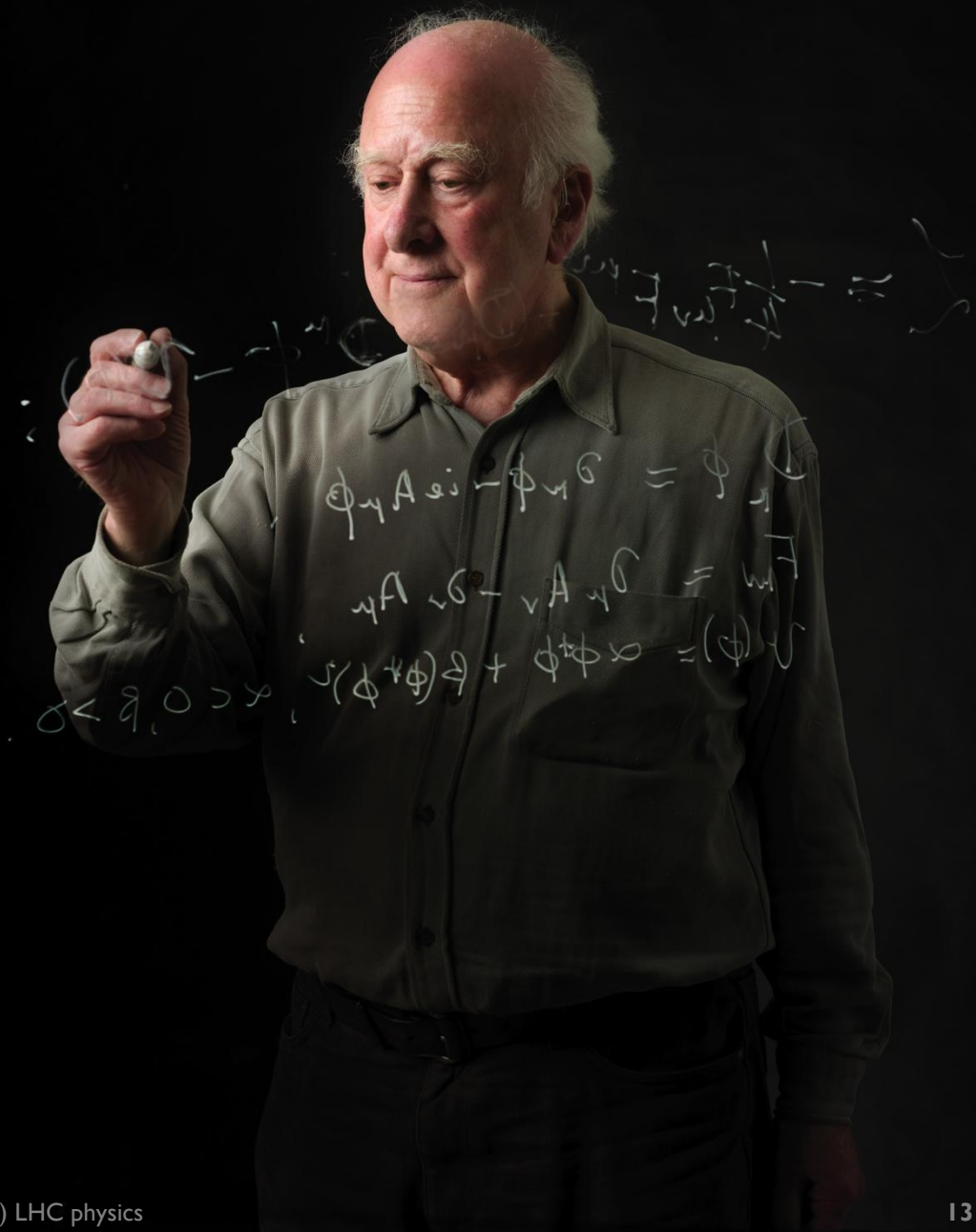
ATLAS 2011-12 $\sqrt{s} = 7-8 \text{ TeV}$

www.elsevier.com/locate/physletb

10 years HIGGS boson discovery

CERN Auditorium, July 4th 2012

Is it a
scalar
boson?



Spin!

What's a particle spin?

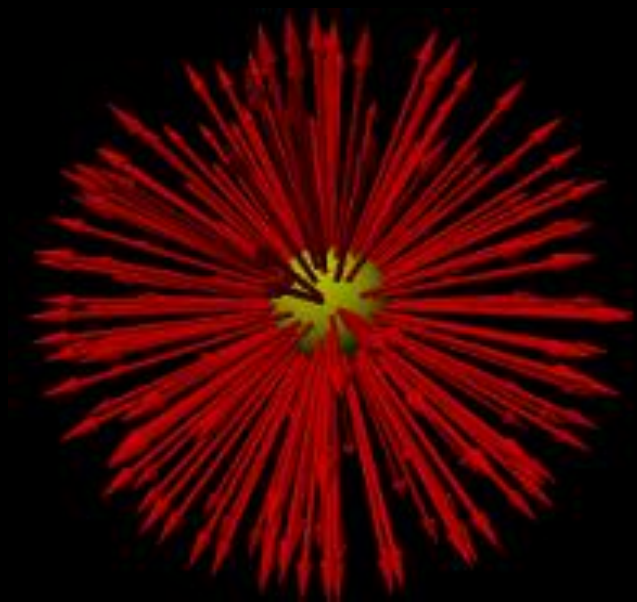
“An *amount of rotation* that is quantized”

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 ($-\frac{1}{2} \hbar$)



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

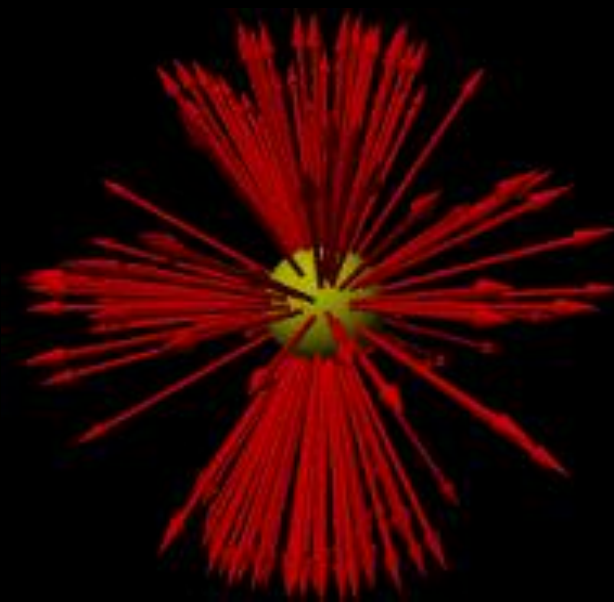
How can we recognize spin?



spin 0



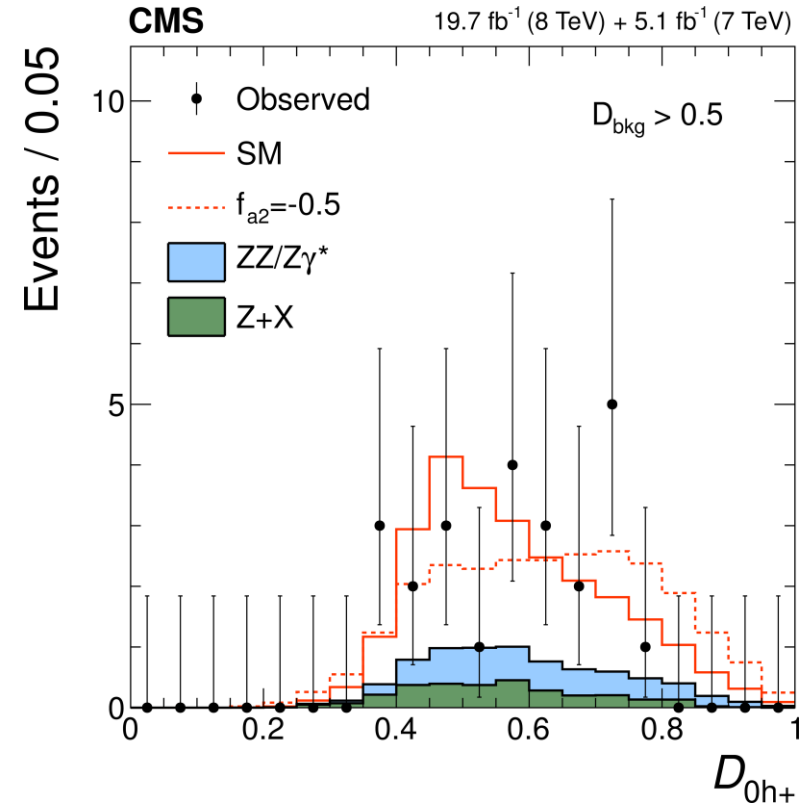
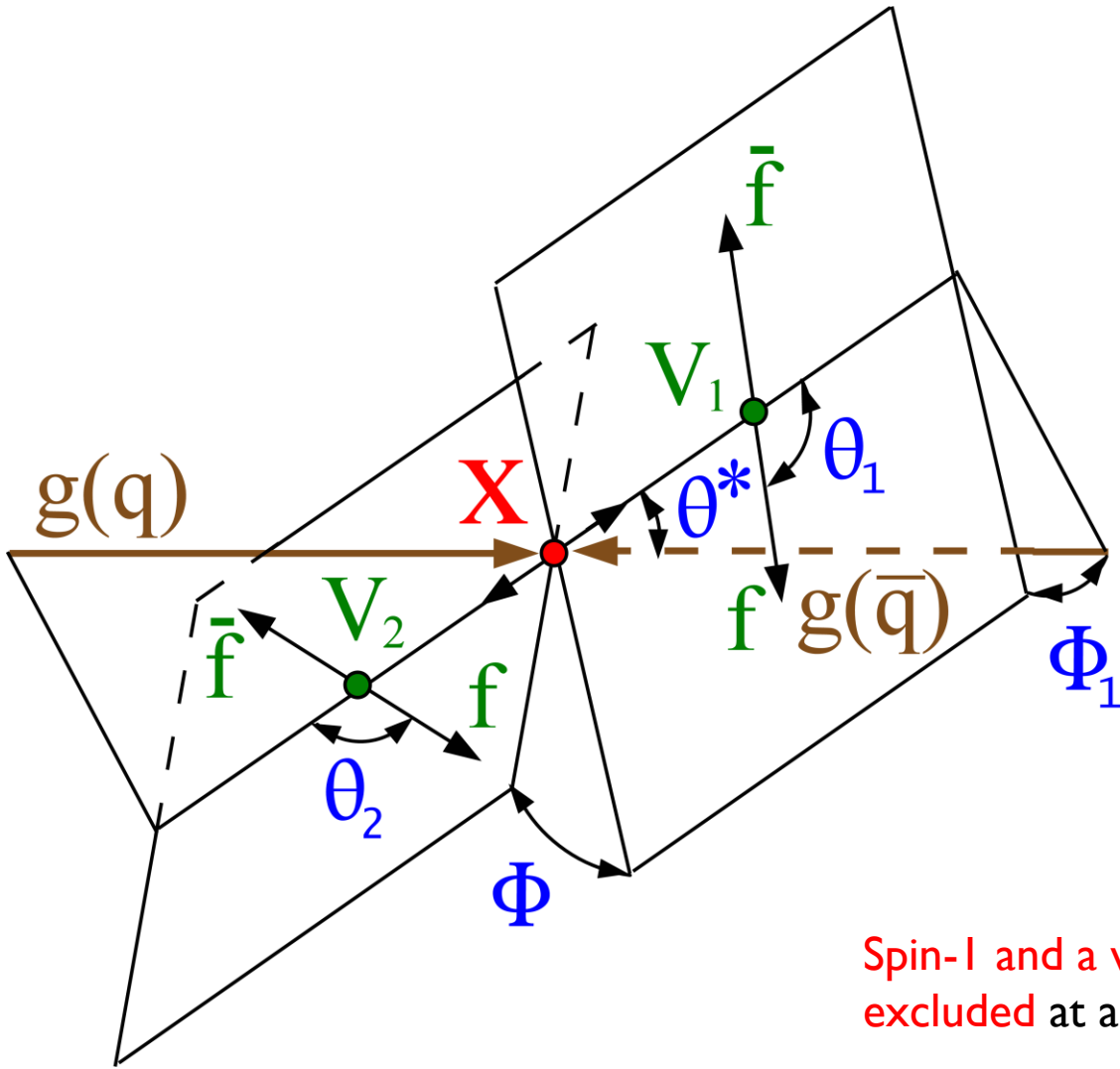
spin 1



spin 2

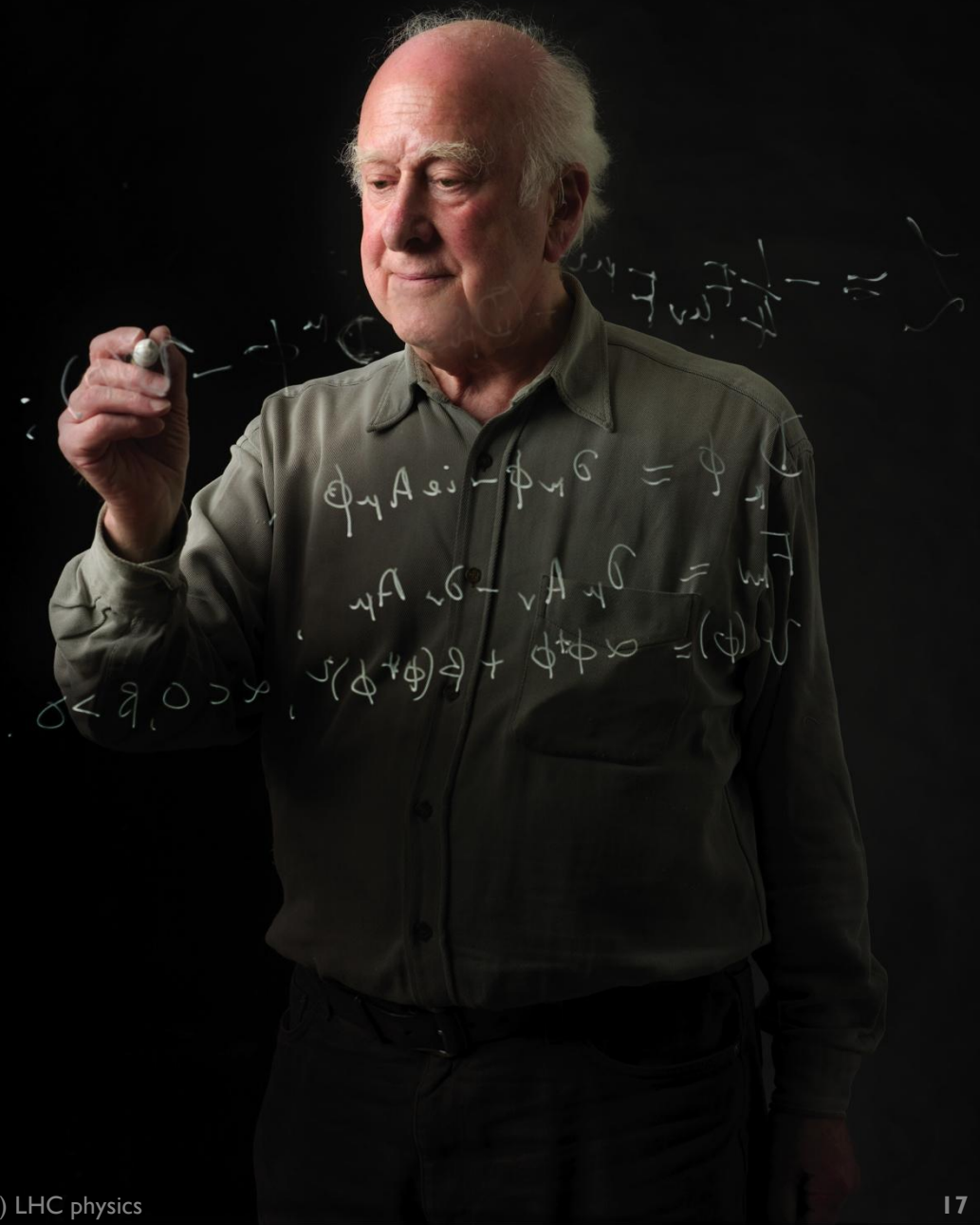
Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

Spin with $H \rightarrow 4$ 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

- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow WW^* \rightarrow 2l2\nu$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $H \rightarrow c\bar{c}$
- $H \rightarrow b\bar{b}$
- $pp \rightarrow t\bar{t}H$
- ...



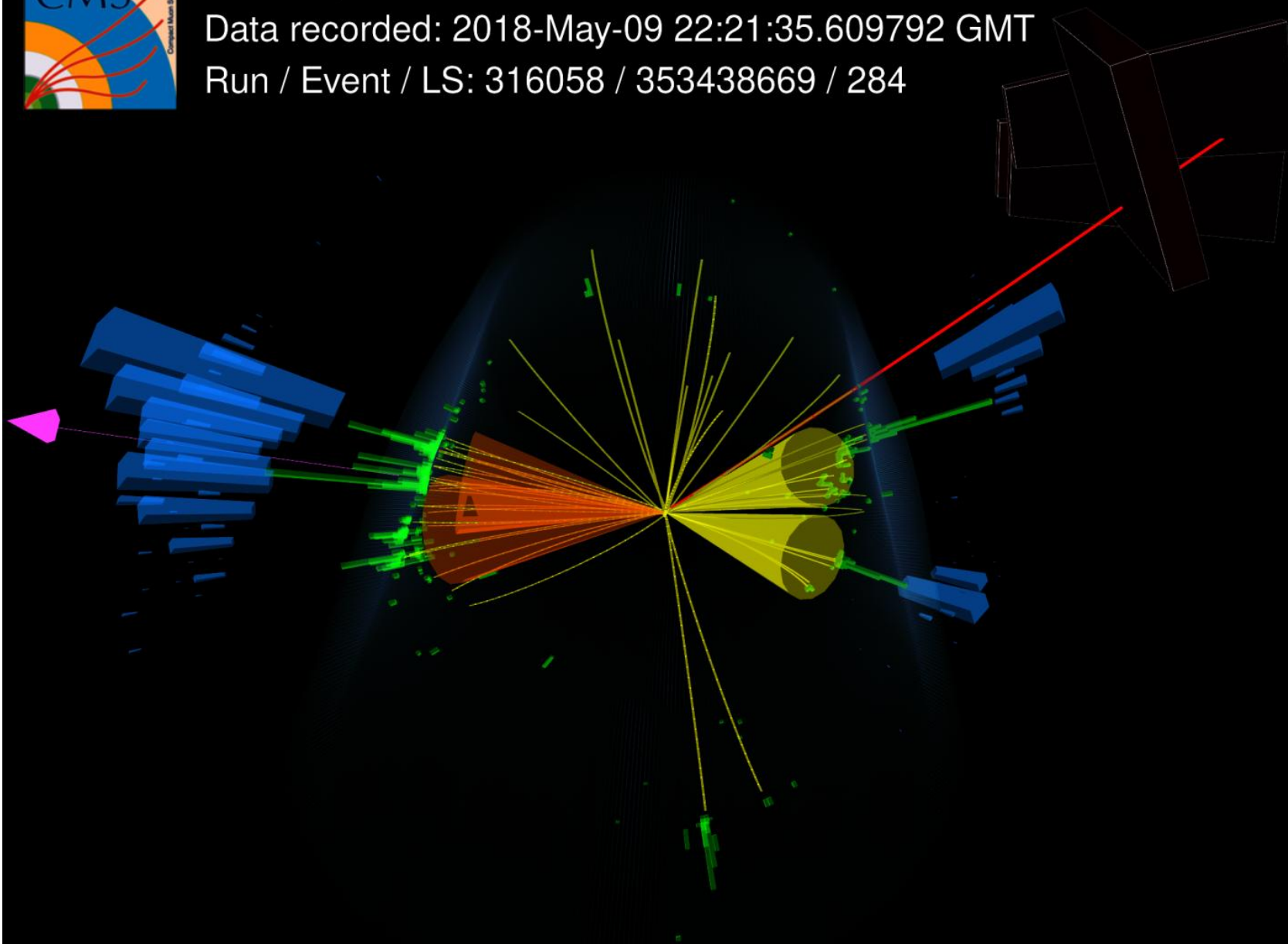
- If the Higgs boson is responsible for masses, we expect each of these cross-sections / decay rates to be **proportional to m_F^2** , where F is the final state particle



CMS Experiment at the LHC, CERN

Data recorded: 2018-May-09 22:21:35.609792 GMT

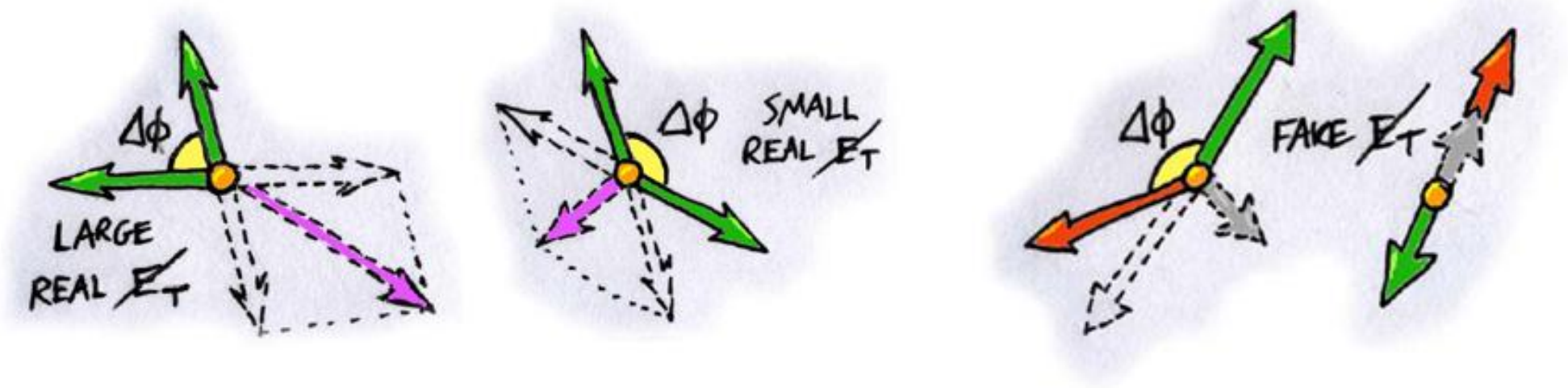
Run / Event / LS: 316058 / 353438669 / 284



Neutrino (and other invisible particles) at colliders



- Interaction length $\lambda_{\text{int}} = A / (\rho \sigma N_A)$
- Cross section $\sigma \sim 10^{-38} \text{ cm}^2 \times E [\text{GeV}]$
 - ✓ This means 10 GeV neutrinos can pass through more than a million km of rock
- Neutrinos are usually detected in HEP experiments through *missing (transverse) energy*

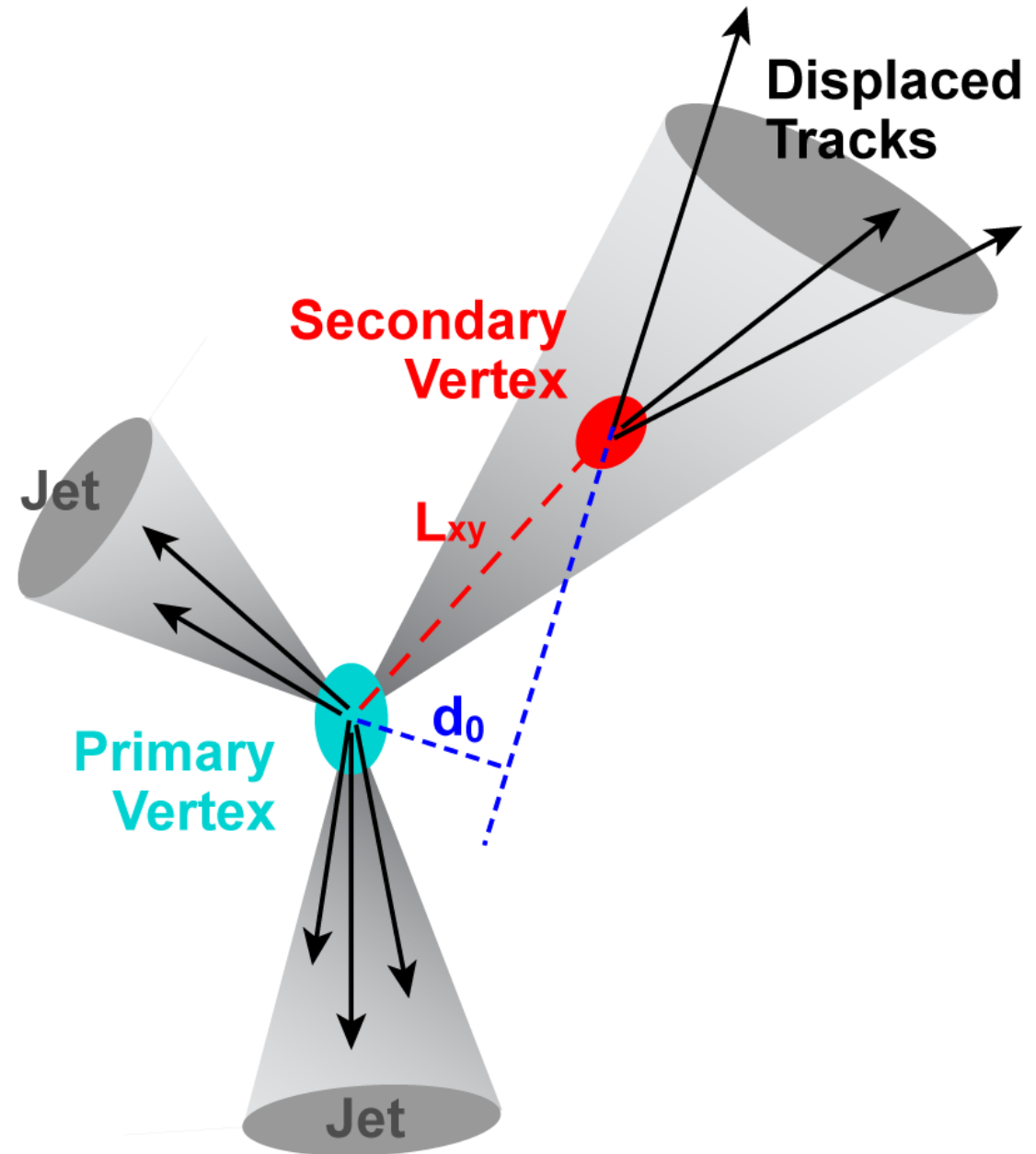


- Missing energy resolution depends on
 - ✓ Detector acceptance
 - ✓ Detector noise and resolution (e.g. calorimeters)

B-tagging



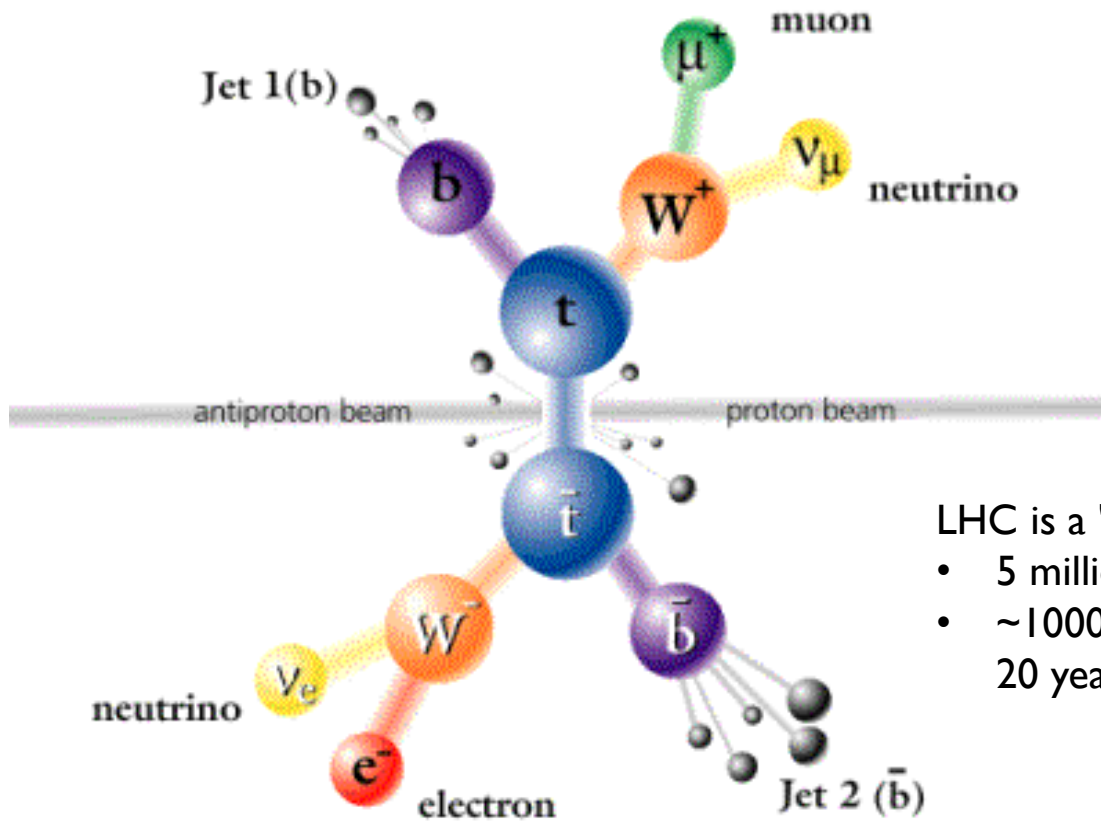
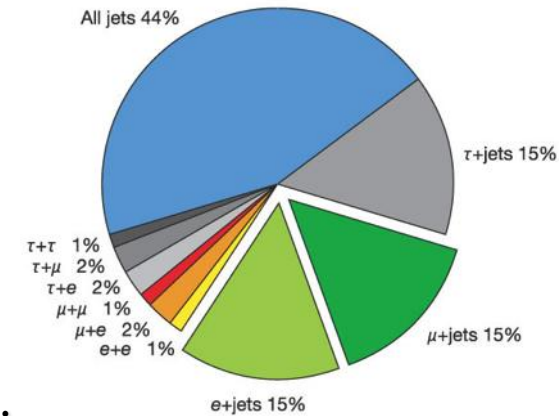
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
 - ✓ ~ 1.6 ps
 - ✓ They will travel away from collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark content
- Similar procedure for c quark...



top quark

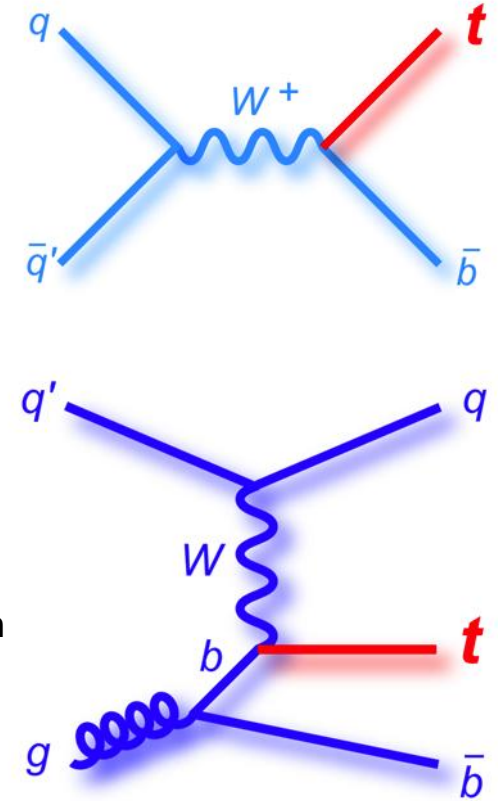


- Mean lifetime $\sim 5 \times 10^{-13}$ ps
 - ✓ Shorter than time scale at which QCD acts: no time to hadronize!
 - ✓ It decays as $t \rightarrow Wb$
- Events with top quarks are very rich in (b) jets...



LHC is a "top factory"!

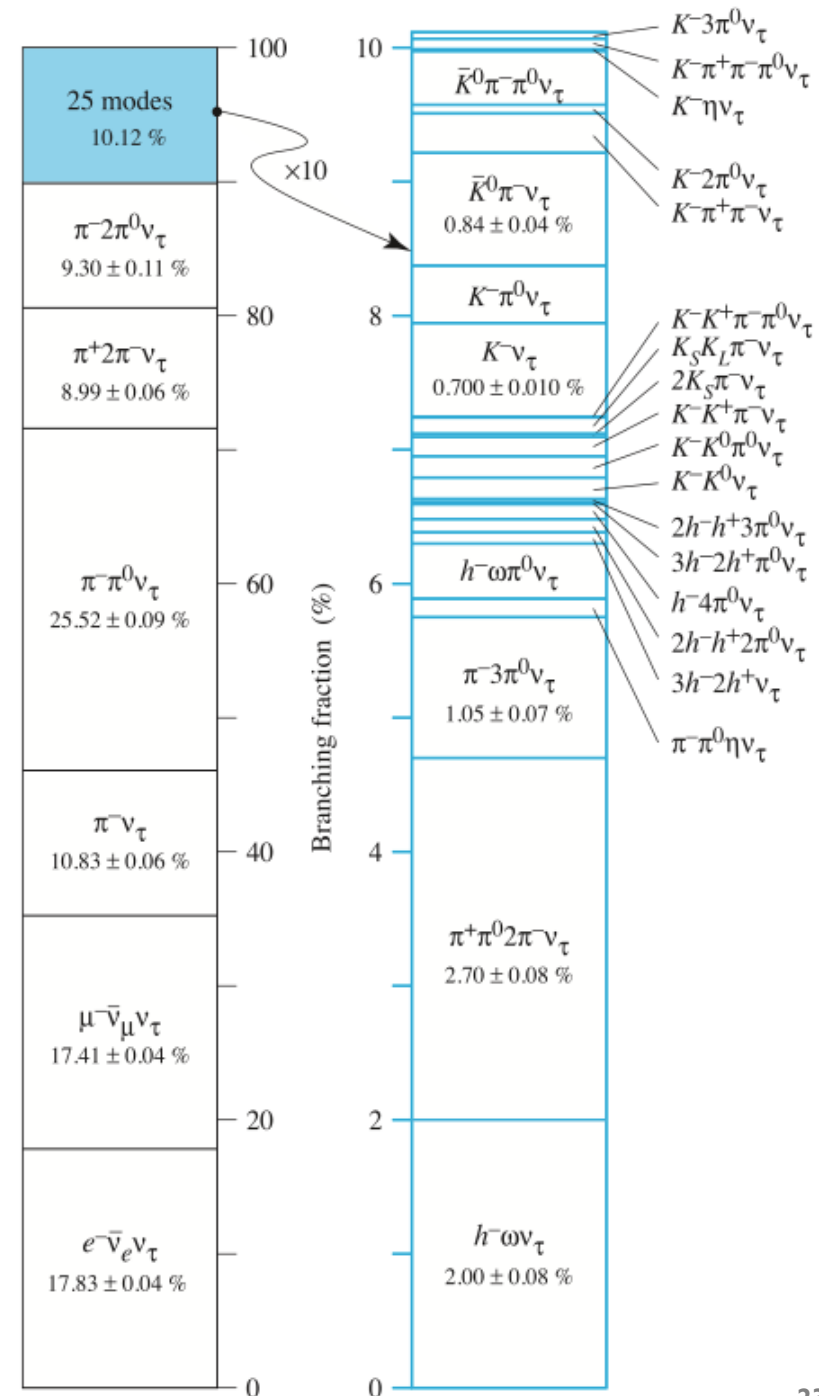
- 5 millions of $t\bar{t}$ pairs
- ~ 100000 in Tevatron in 20 years



Tau

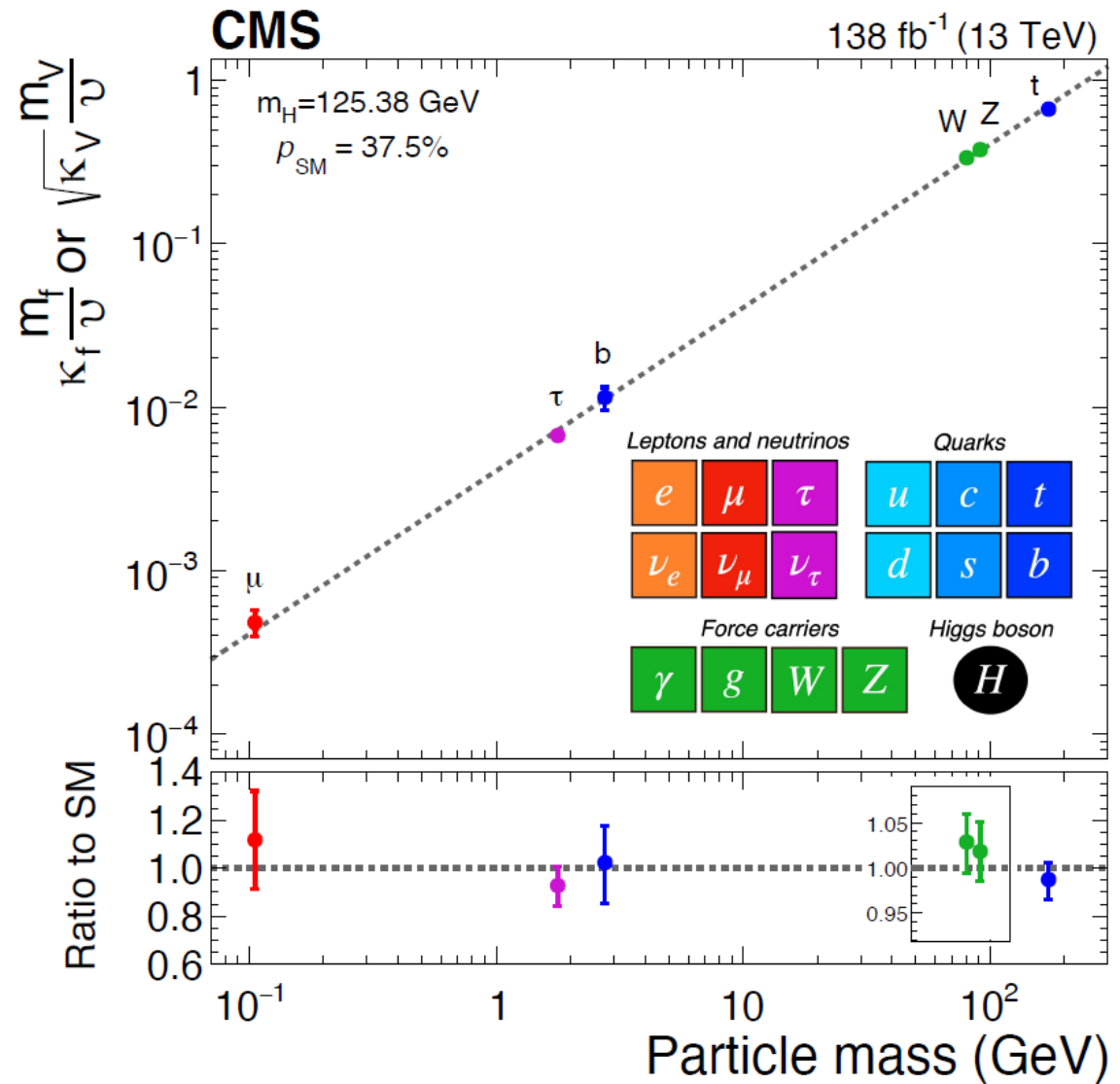


- Tau are heavy enough that they can decay in several final states
 - ✓ Several of them with hadrons
 - ✓ Sometimes neutral hadrons
- Mean lifetime ~ 0.29 ps
 - ✓ 10 GeV tau flies ~ 0.5 mm
 - ✓ Too short to be directly seen in the detectors
- Tau needs to be identified by their decay products
- Accurate vertex detectors can detect that they do not come exactly from the interaction point



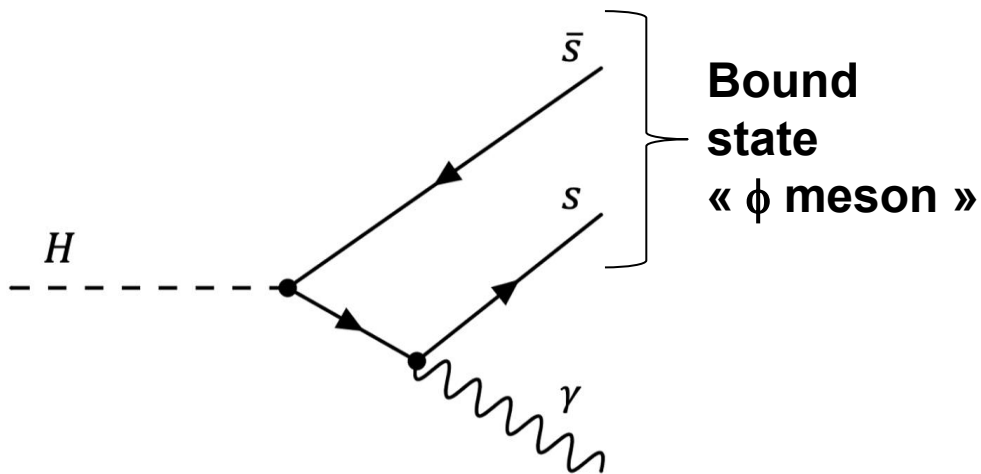
Combine many other decay modes

- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow WW^* \rightarrow 2l2\nu$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $H \rightarrow c\bar{c}$
- $H \rightarrow b\bar{b}$
- $pp \rightarrow t\bar{t}H$
- ...

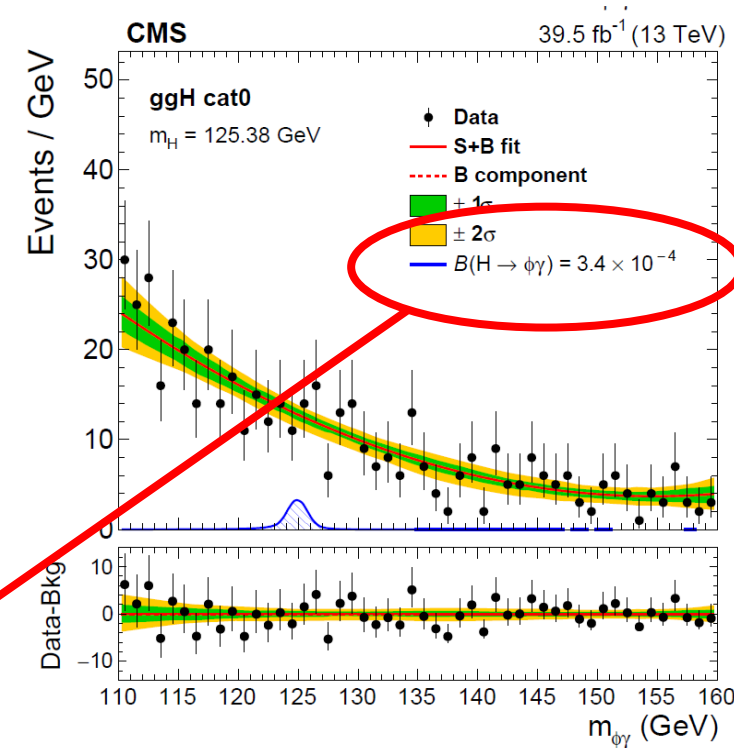


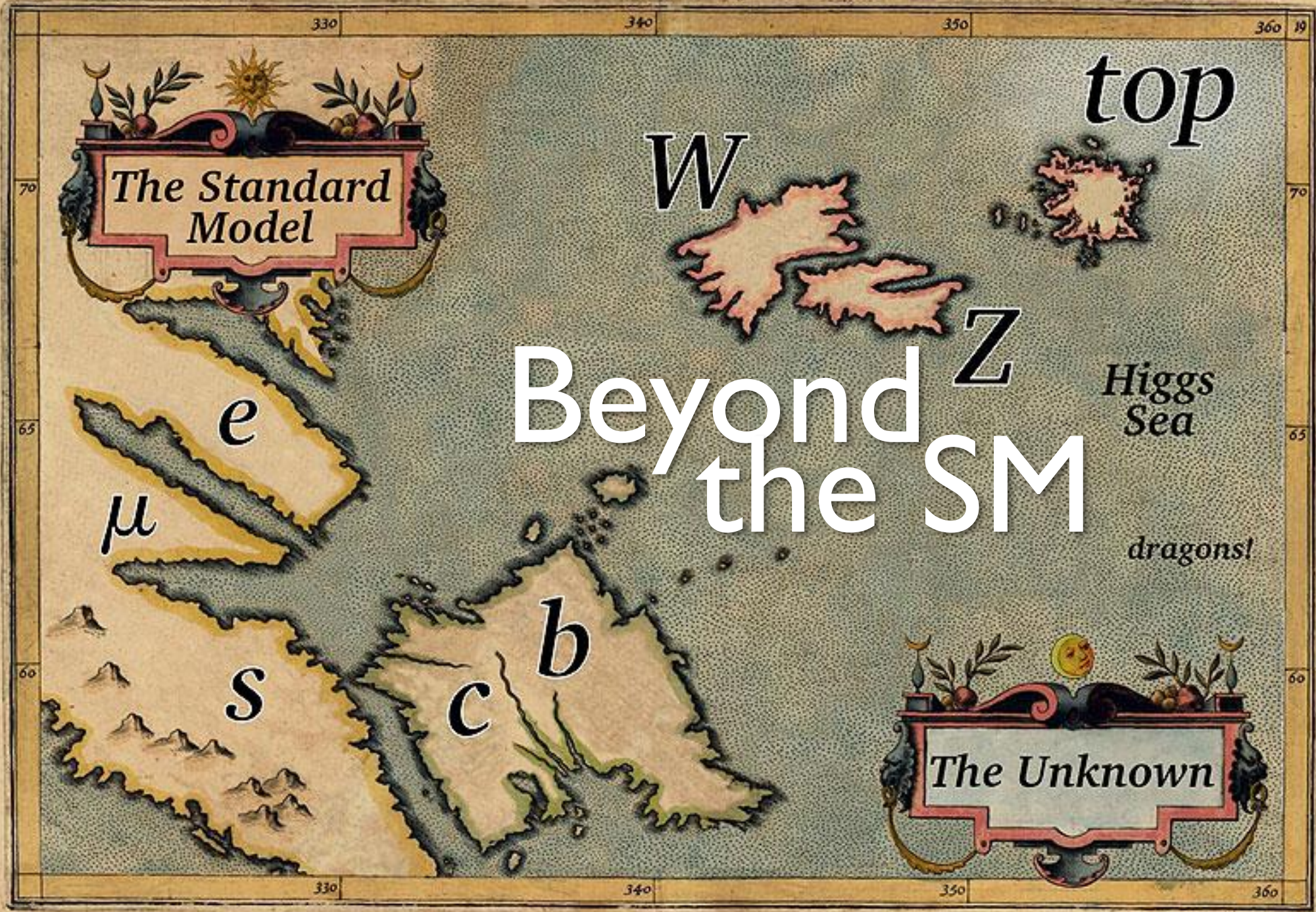
What about couplings to LIGHT quarks?

- $H \rightarrow u\bar{u}$
- $H \rightarrow s\bar{s} \dots$
- **Not feasible**
 - *Even using invariant mass, overwhelming background from QCD jets*
- **Solution: use very rare Higgs decays**



SM $\sim 10^{-6}$





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?

Are there more forces?

What keeps the Higgs mass so small?

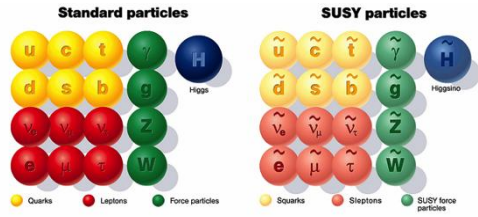
1968: SLAC <i>u</i> up quark	1974: Brookhaven & SLAC <i>c</i> charm quark	1995: Fermilab <i>t</i> top quark	1979: DESY <i>g</i> gluon
1968: SLAC <i>d</i> down quark	1947: Manchester University <i>s</i> strange quark	1977: Fermilab <i>b</i> bottom quark	1923: Washington University* γ photon
1956: Savannah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

How do we incorporate gravity?

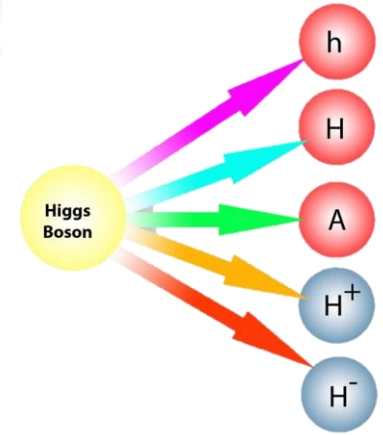
What is Dark Matter?

... as many possible answers to probe!

Super-symmetry?

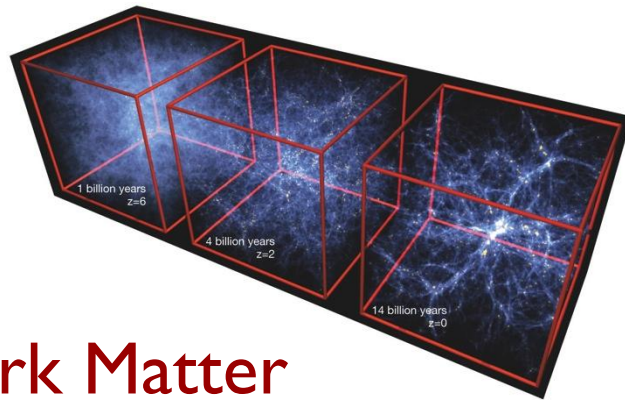


Extended Higgs sector?



New heavy bosons?

Composite quark and leptons?

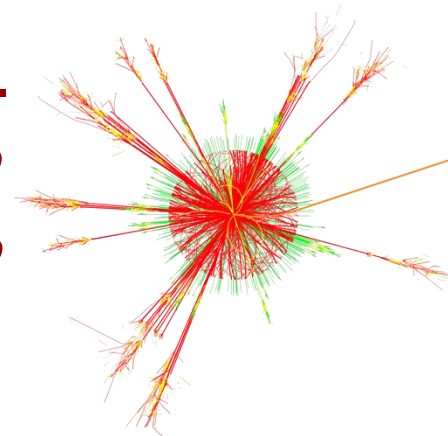


Dark Matter particles?

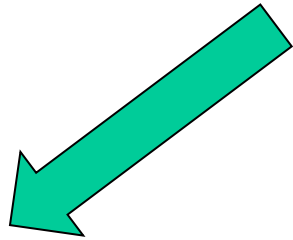
up quark	charm quark	top quark	gluon
down quark	strange quark	bottom quark	photon
electron neutrino	muon neutrino	tau neutrino	W boson
electron	muon	tau	Z boson

Any new theory needs to agree with the SM!

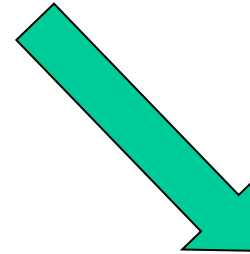
Large extra-dimensions?
Black holes?
Gravitons?



Where is Beyond-the-SM Physics?



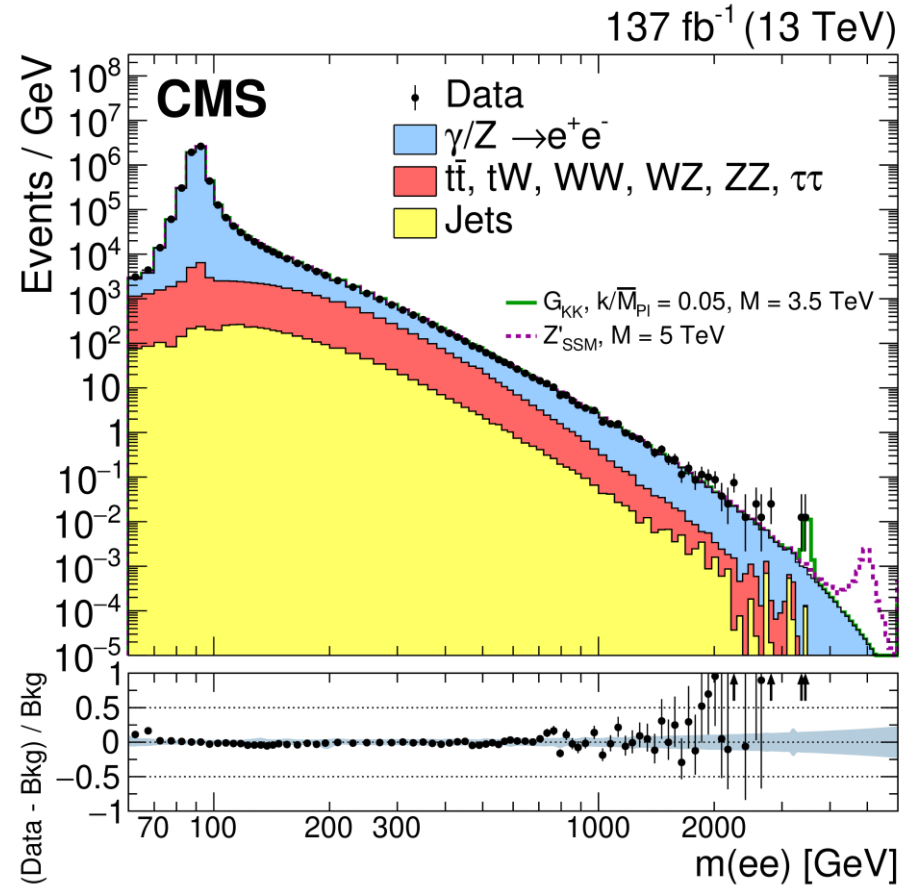
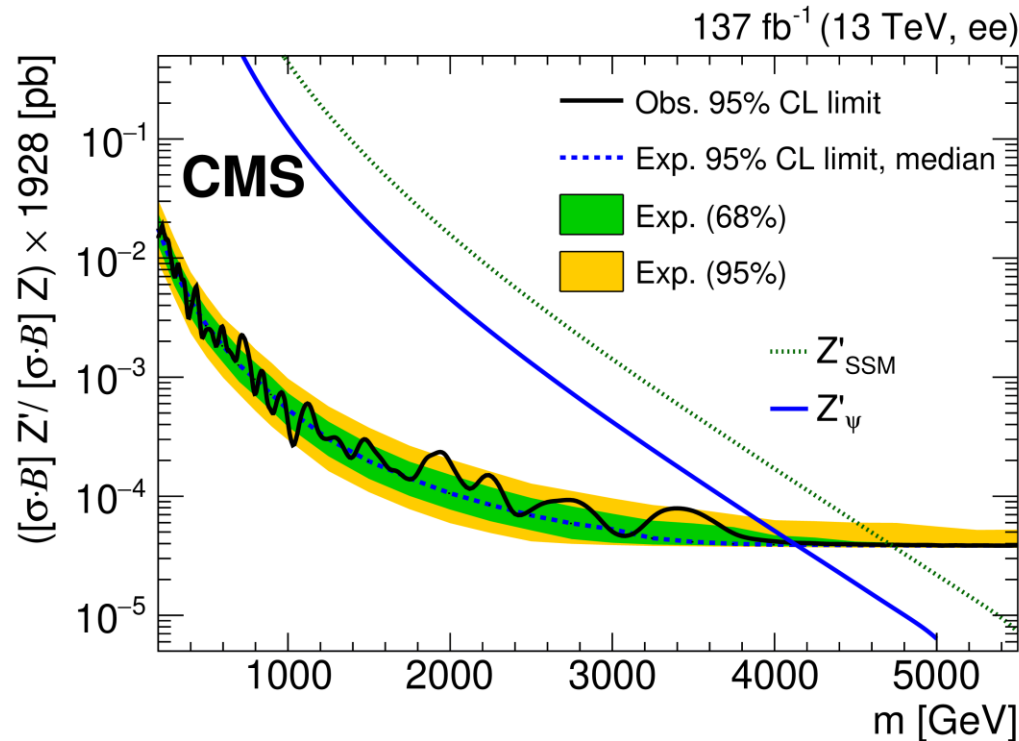
Masses of new
particles
within the
LHC reach



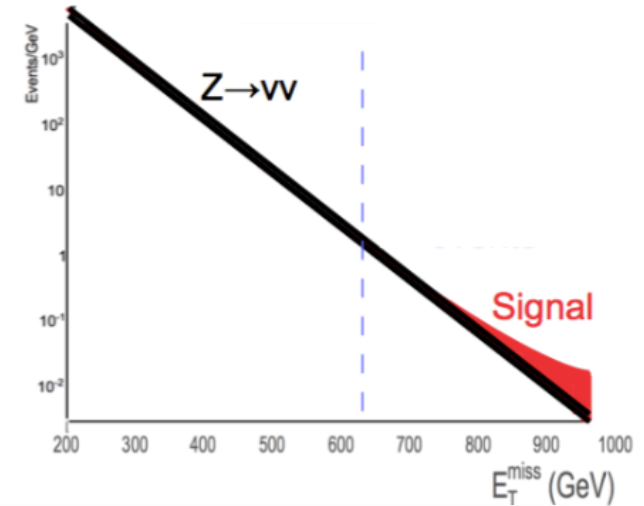
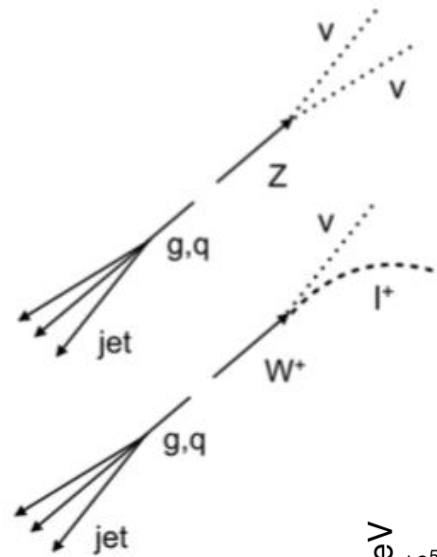
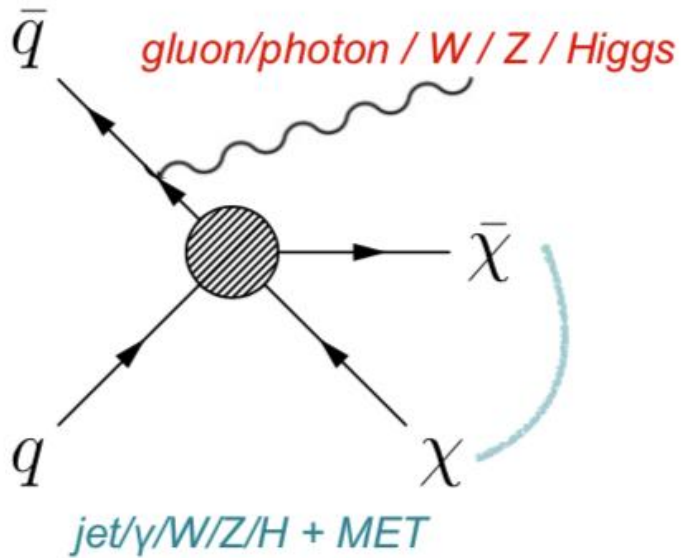
Masses of new
particles
not within the
LHC reach

Simple example: heavy Z' boson

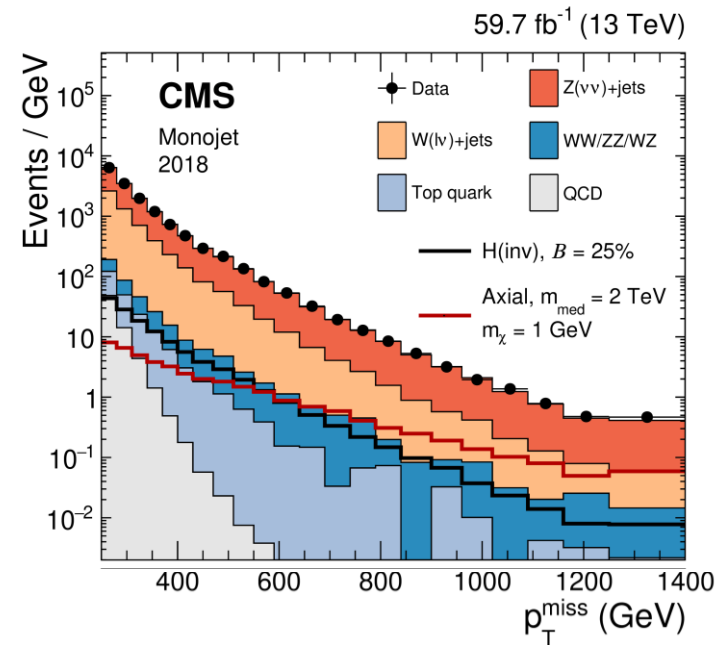
- Use very clear dilepton decay channel
 - ✓ e.g. electron-positron
 - ✓ Drell-Yan modeling important, but clear peak over a continuum (“bump hunting”)
- Result expressed as a 95% confidence-level excluded (upper) cross-section



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)
 - ✓ $Z(\nu\nu)$ +jet
 - ✓ $W(l\nu)$ +jet, where charged lepton is not reconstructed



The Effective-Field Theory approach

BSM searches:

2010 $\Rightarrow$ 2023

$\Rightarrow$ New physics is heavy

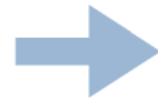
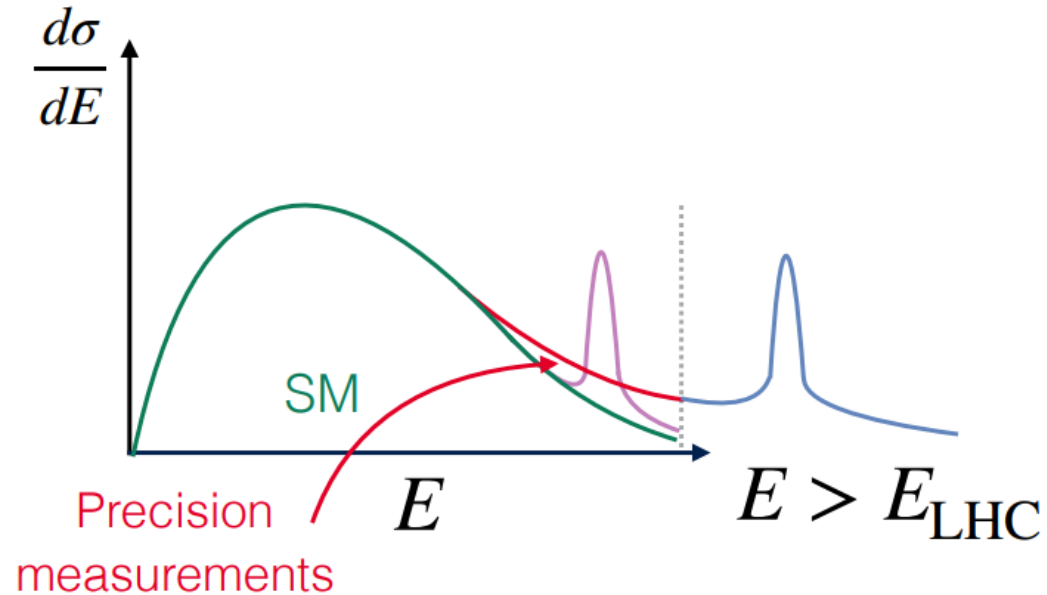
Direct (bumps)

Indirect (tails)

Heavy new physics

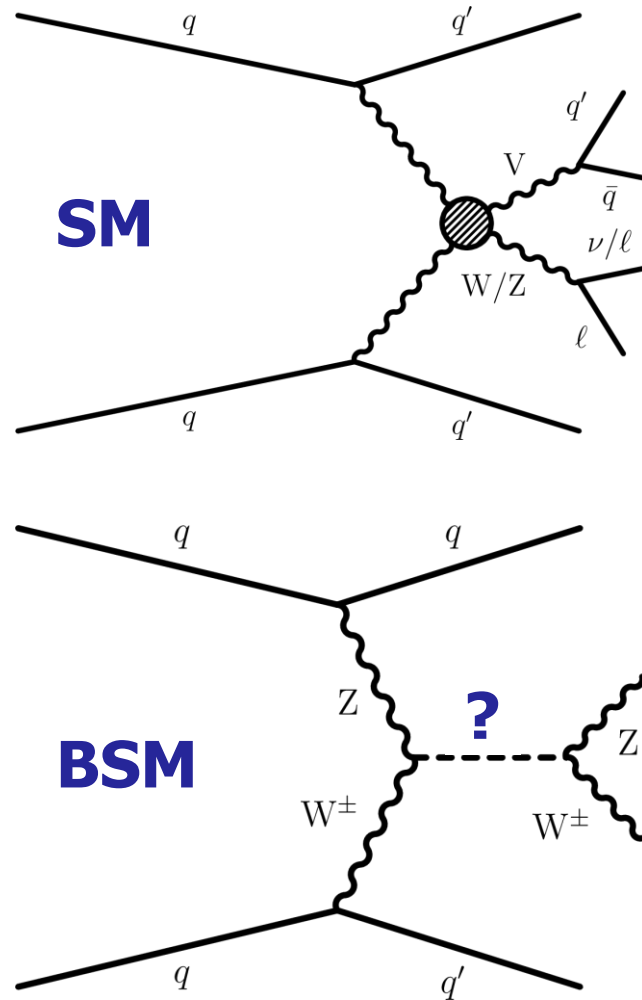
Precision measurements

High energy

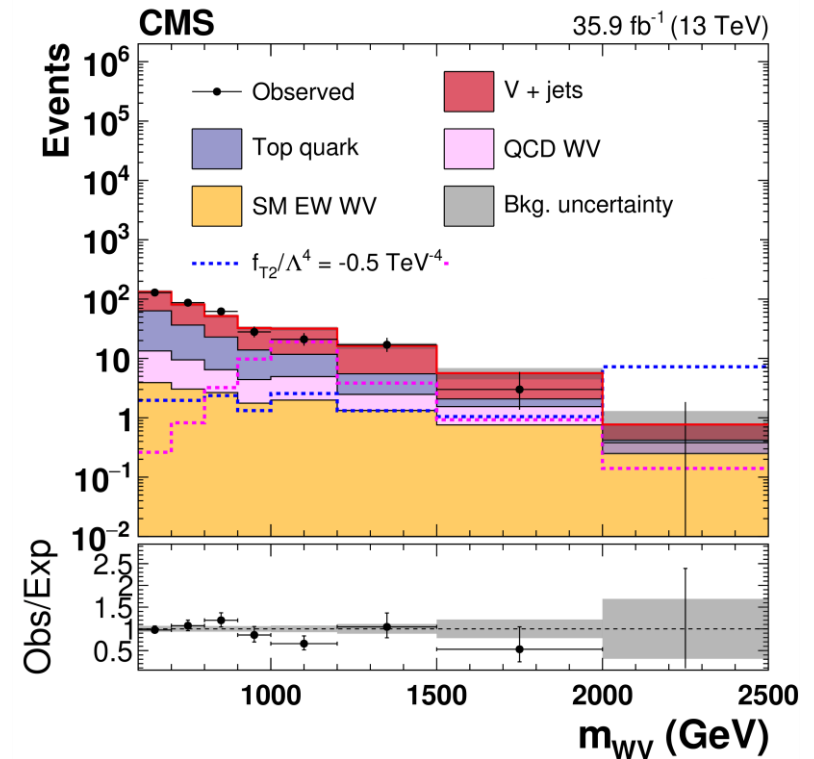


Effective Field Theory (EFT)

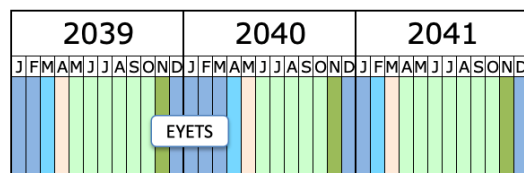
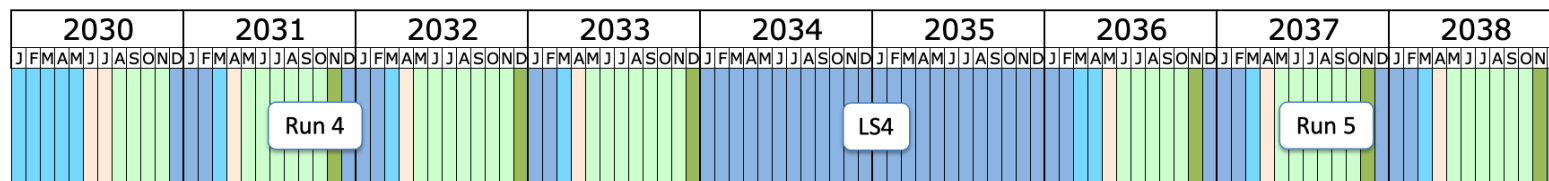
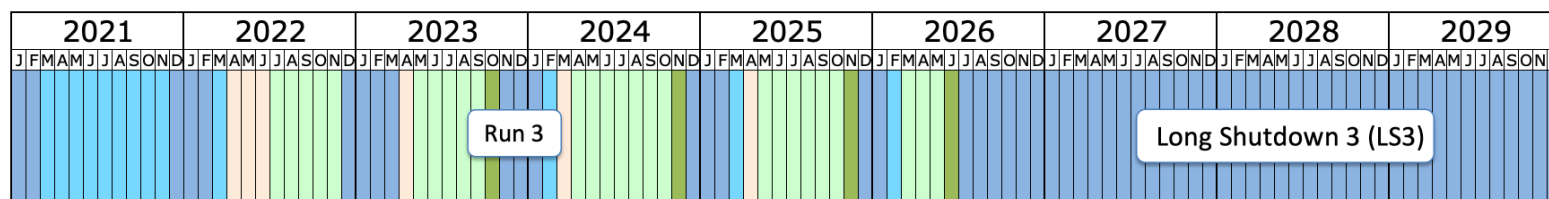
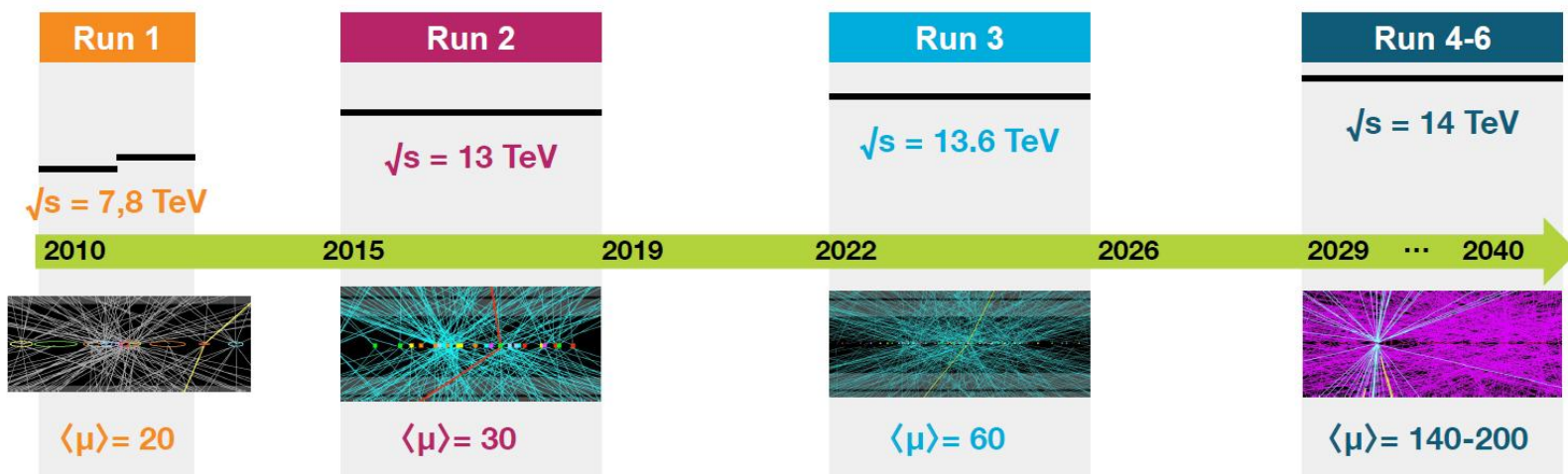
Example: di-boson production



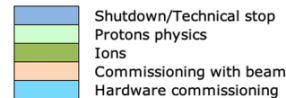
- Search for small deviations in the predicted cross-section in the high-energy tails of the invariant mass distributions
- Exclude/find energy scales at which BSM physics could pop up



The LHC will run for a long time...



Last update: November 24

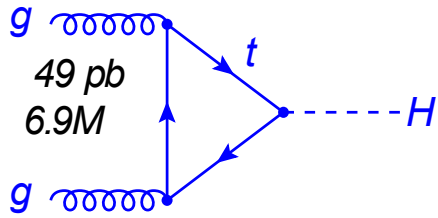


Additional information

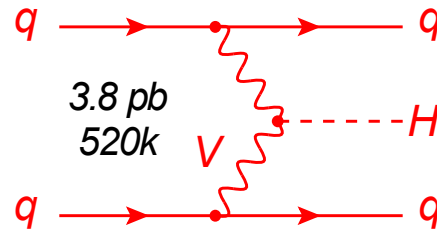
(I find you lack of faith disturbing)

Probing Higgs couplings at the LHC

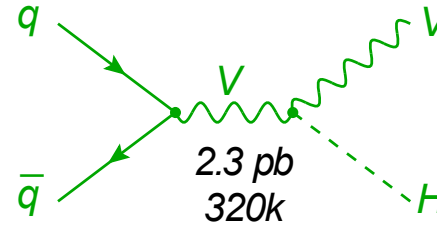
$\sigma[\text{pb}]$ @ 13 TeV
Higgs produced in 140 fb⁻¹
in one experiment



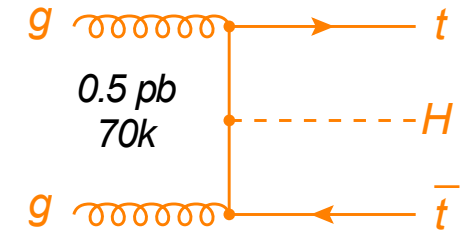
gluon-gluon fusion:
main production mode at
LHC



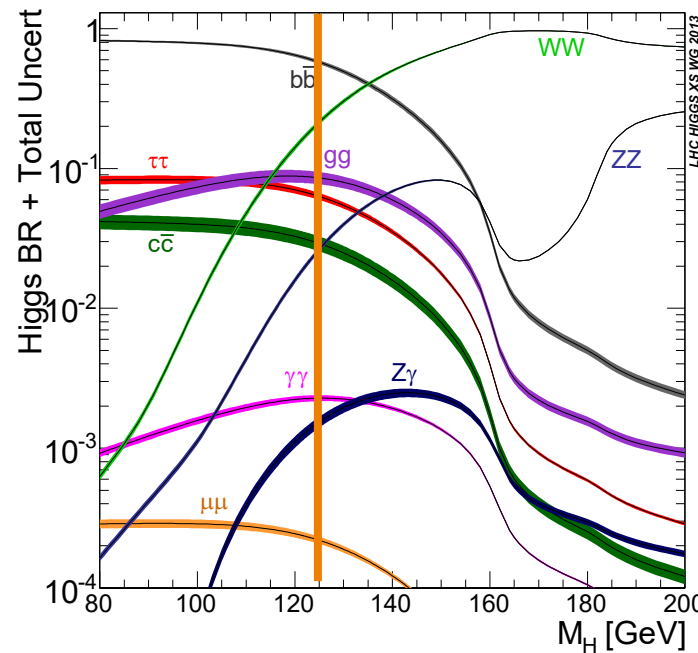
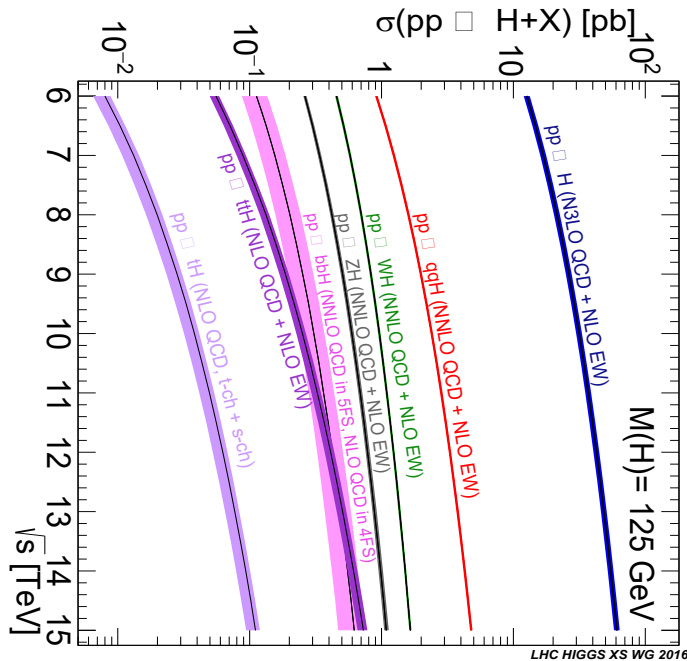
Vector Boson Fusion
2 well-separated forward
jets



VH
tag V and Z
boson decays



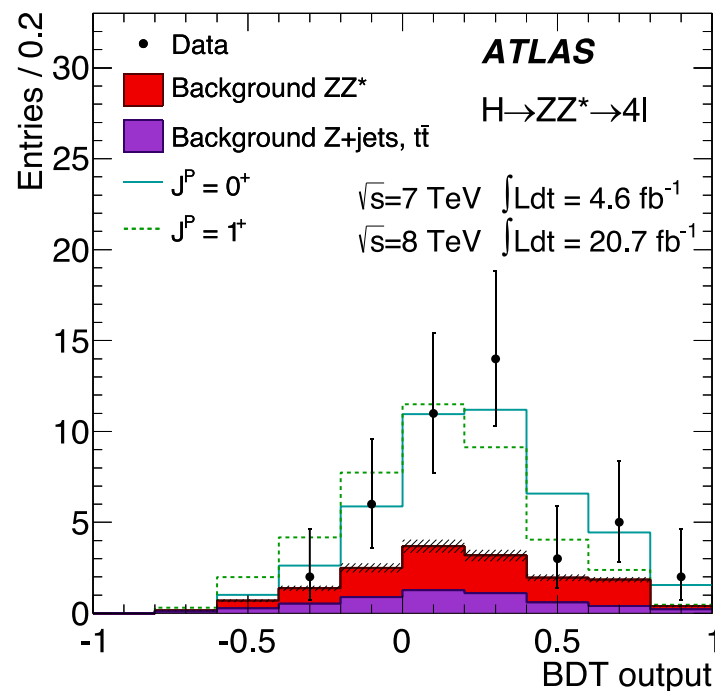
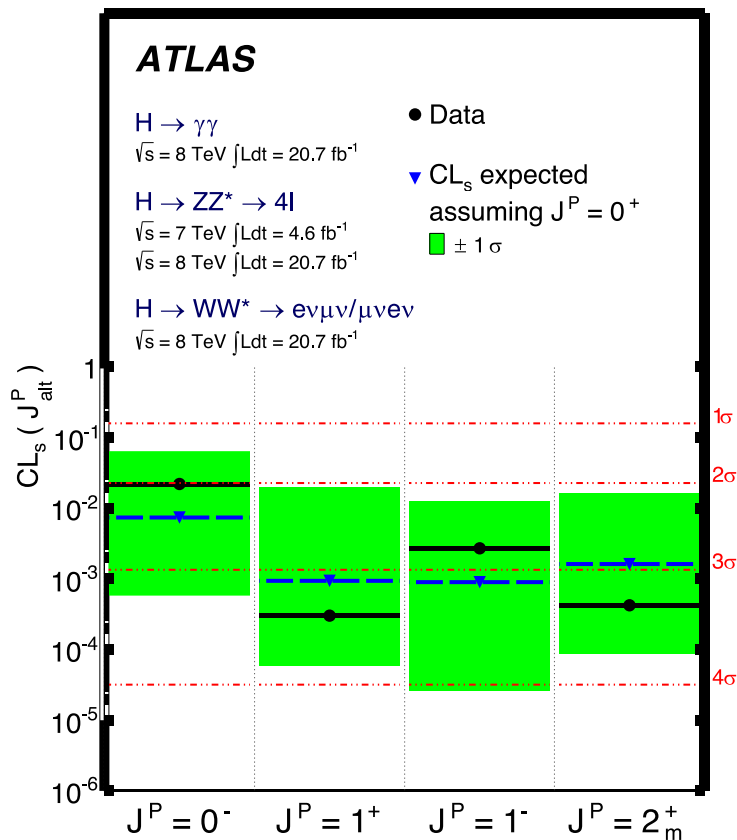
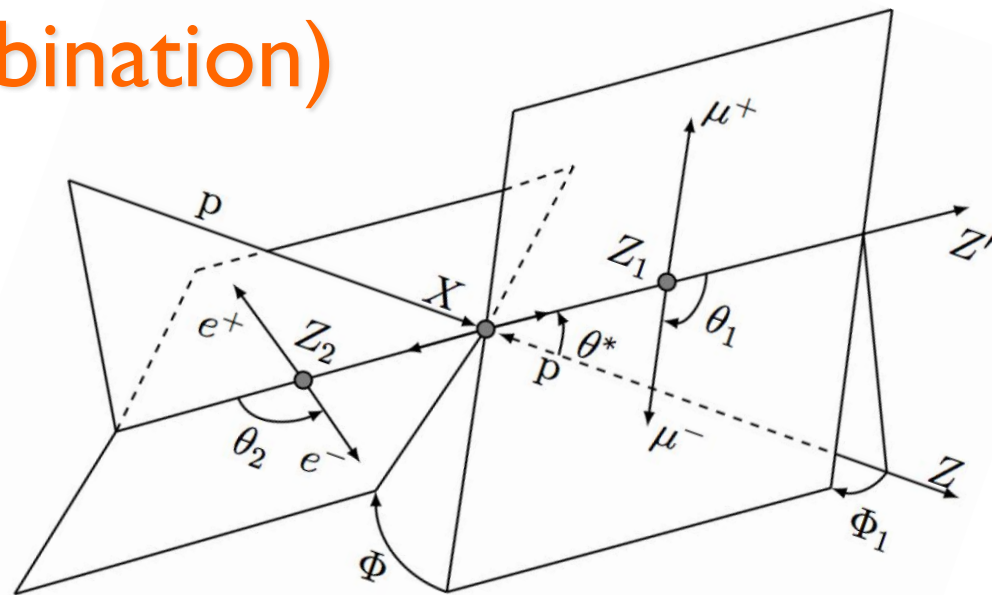
ttH
tag 2 top quarks



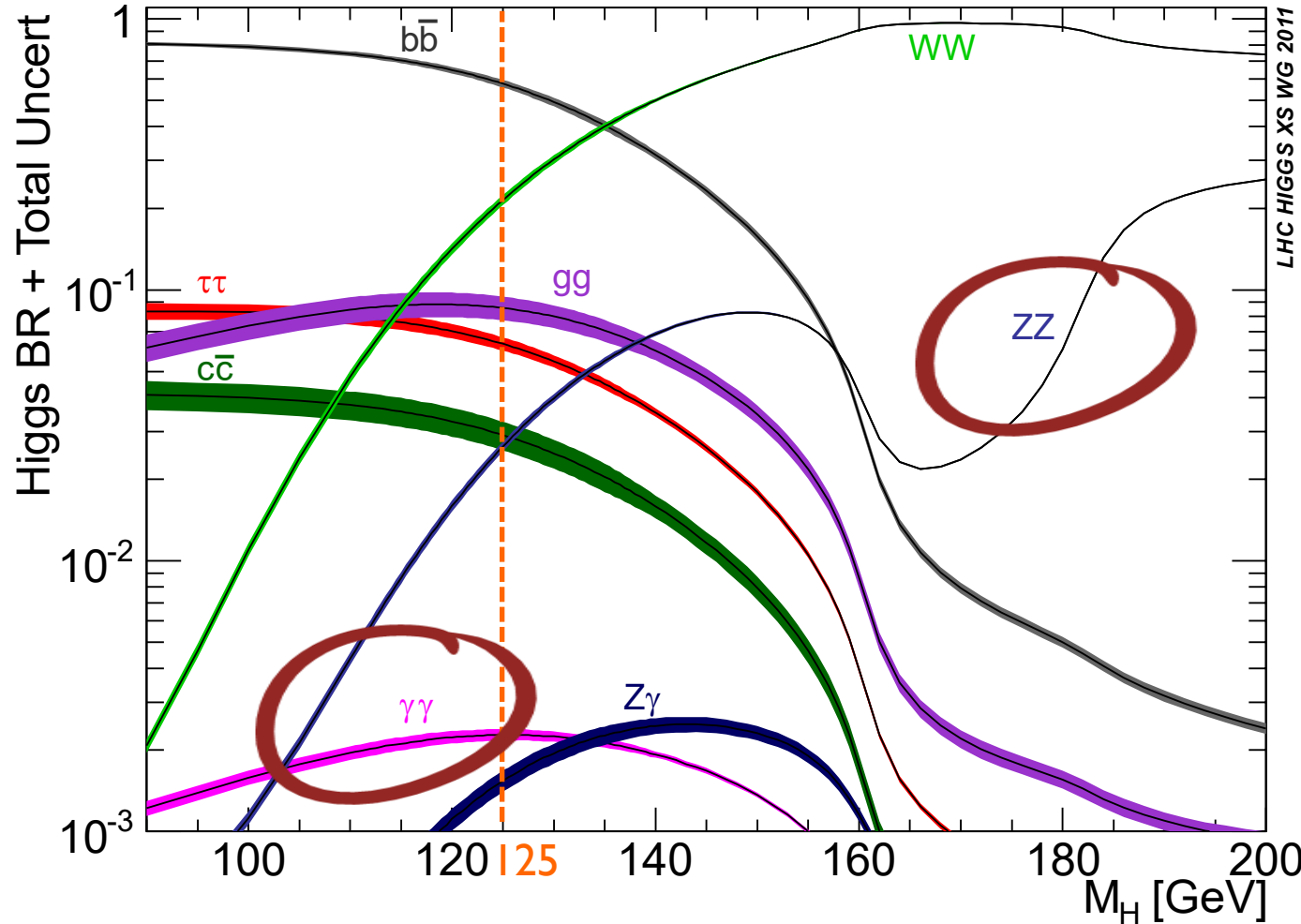
decay	SM BR [%] $m_H = 125.09 \text{ GeV}$
$H \rightarrow b\bar{b}$	58.1
$H \rightarrow W\bar{W}$	21.5
$H \rightarrow \tau\bar{\tau}$	6.26
$H \rightarrow Z\bar{Z}$	2.64
$H \rightarrow \gamma\gamma$	0.23

Spin with $H \rightarrow 4l$ (& 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



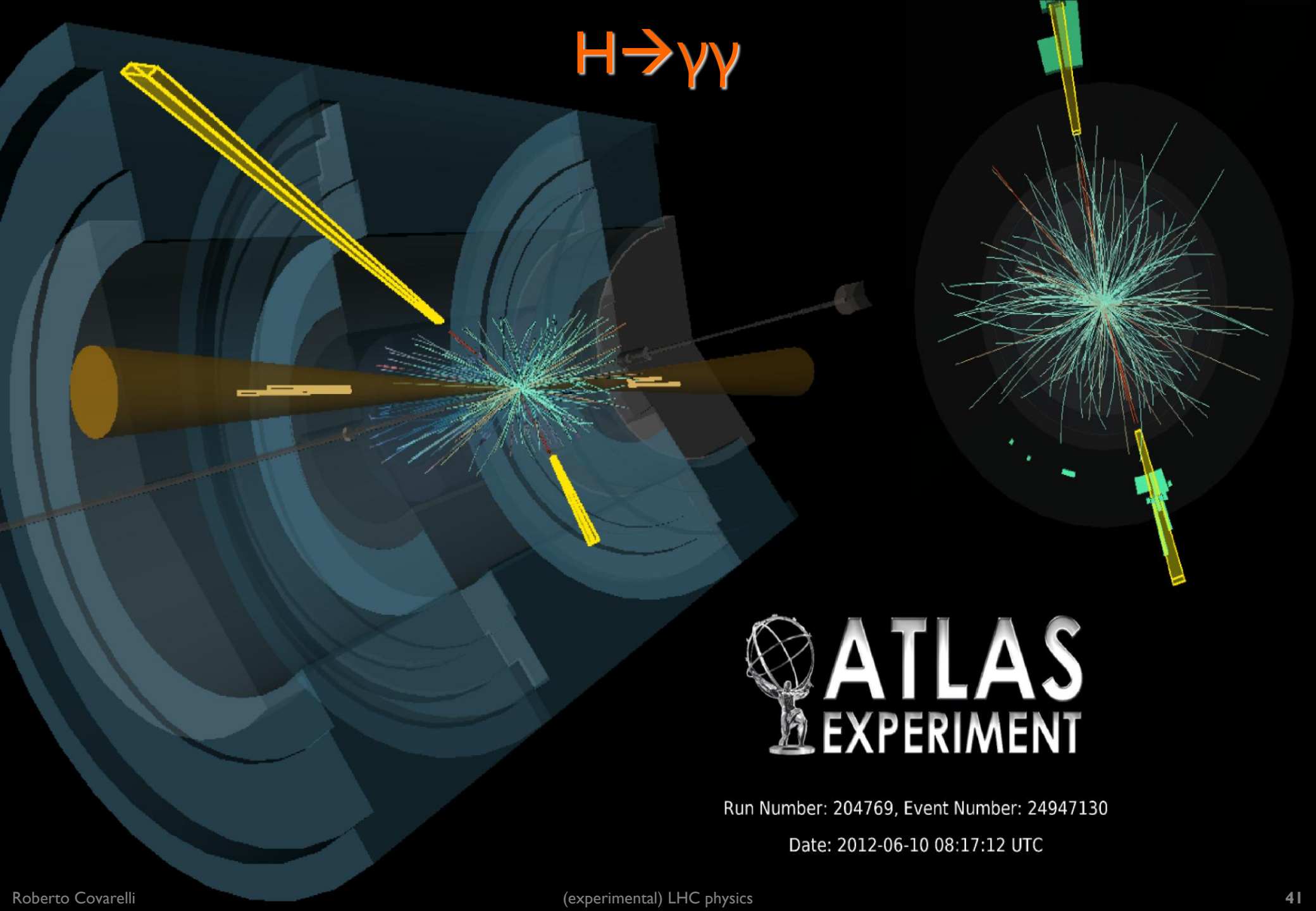
Standard Model Higgs decays



decay	SM BR [%] $m_H = 125.09 \text{ GeV}$
$H \rightarrow b\bar{b}$	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

$H \rightarrow \gamma\gamma$

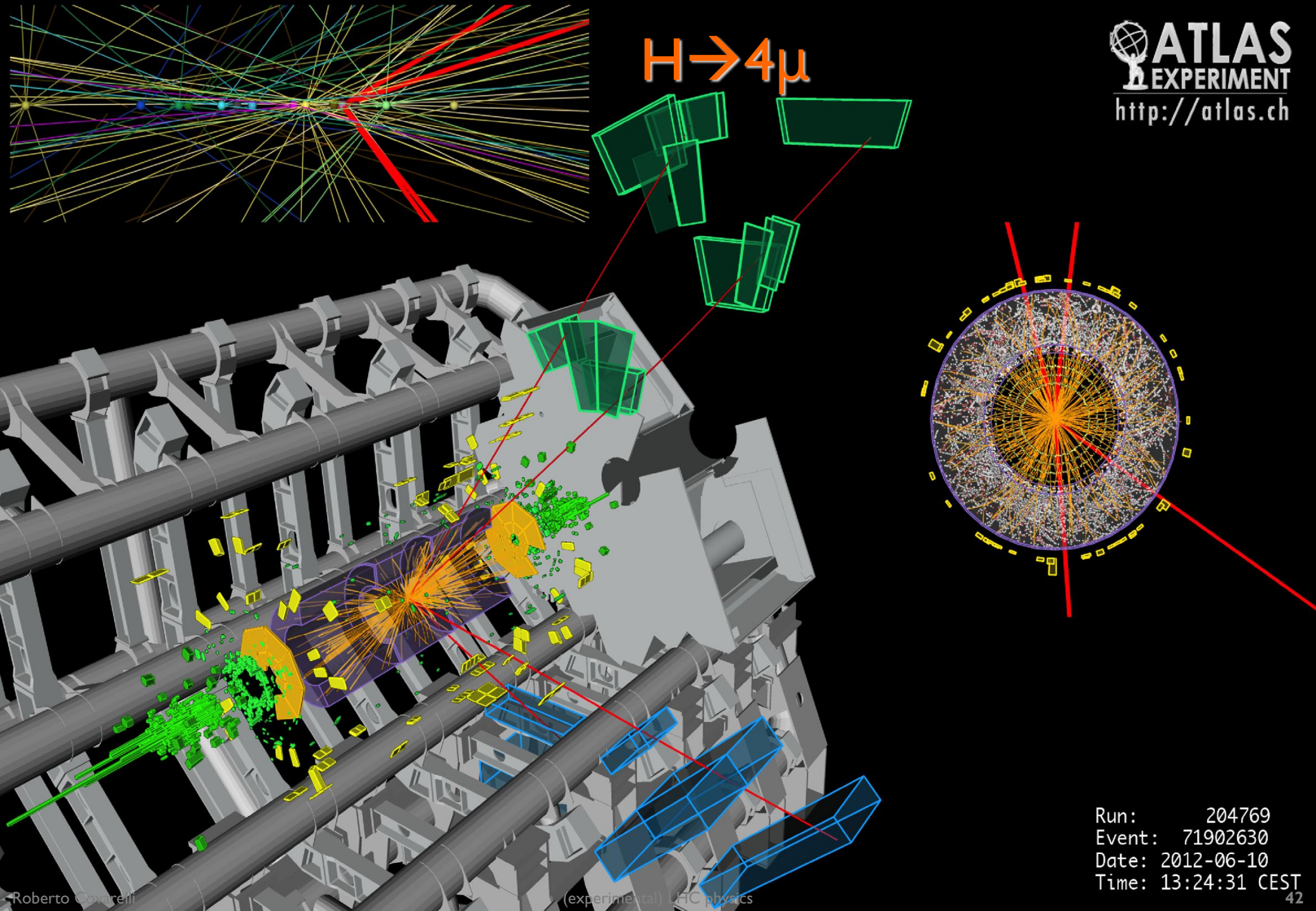


 **ATLAS**
EXPERIMENT

Run Number: 204769, Event Number: 24947130

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

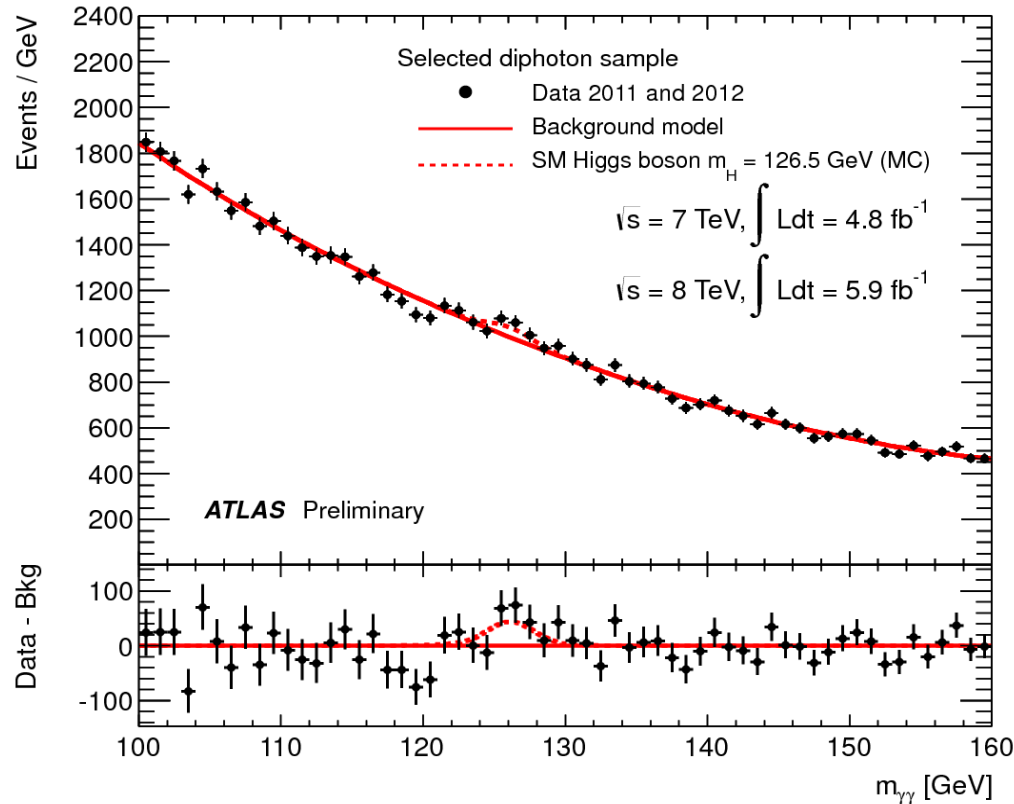
$H \rightarrow 4\mu$



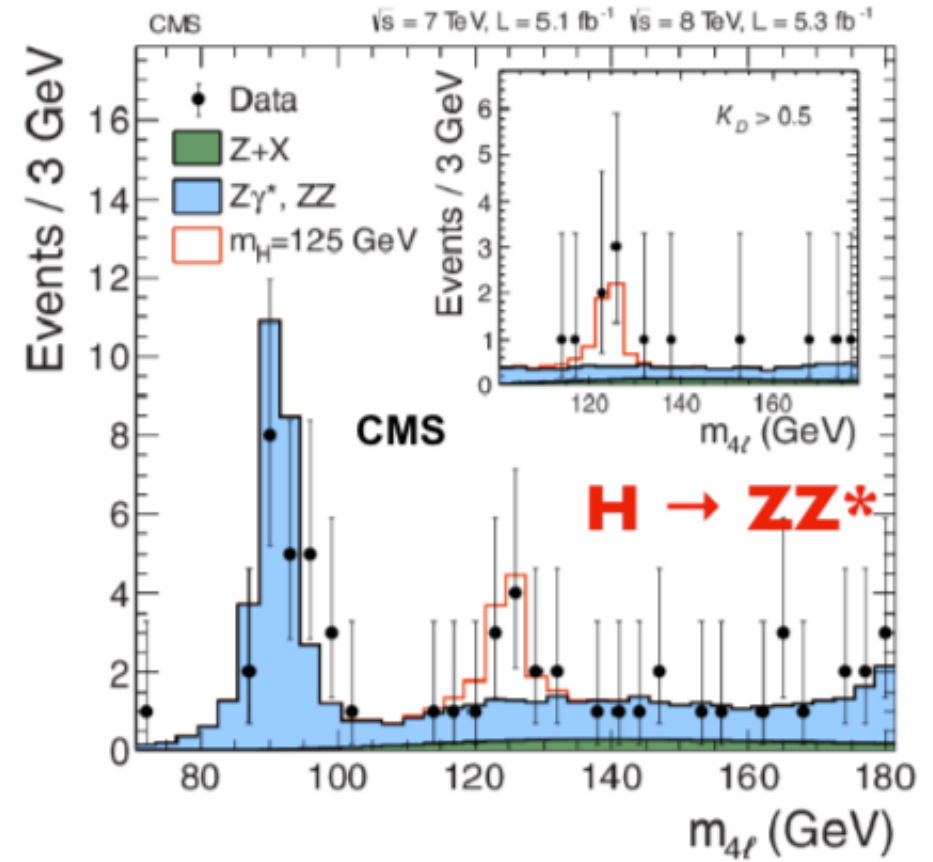
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs signals on July 4th 2012

$H \rightarrow \gamma\gamma$



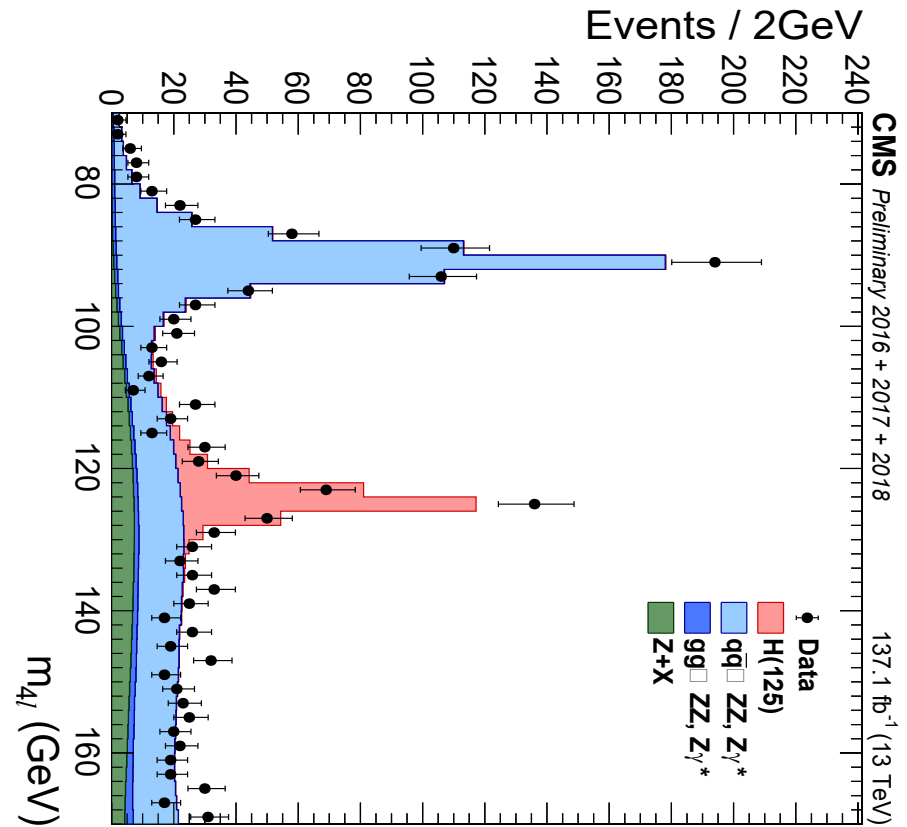
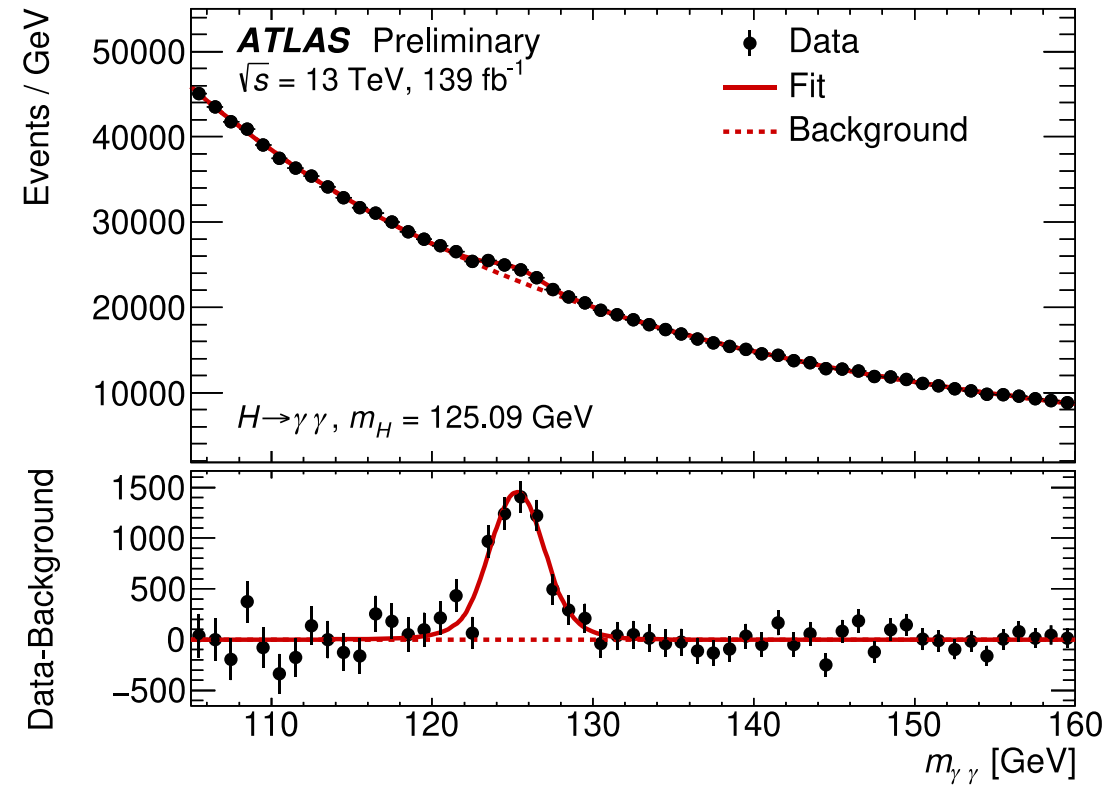
$H \rightarrow 4\ell$



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

$H \rightarrow \gamma\gamma$

$H \rightarrow 4l$



What spin do particles have?



fermions
(quarks, leptons)
spin = $+\frac{1}{2}, -\frac{1}{2}$

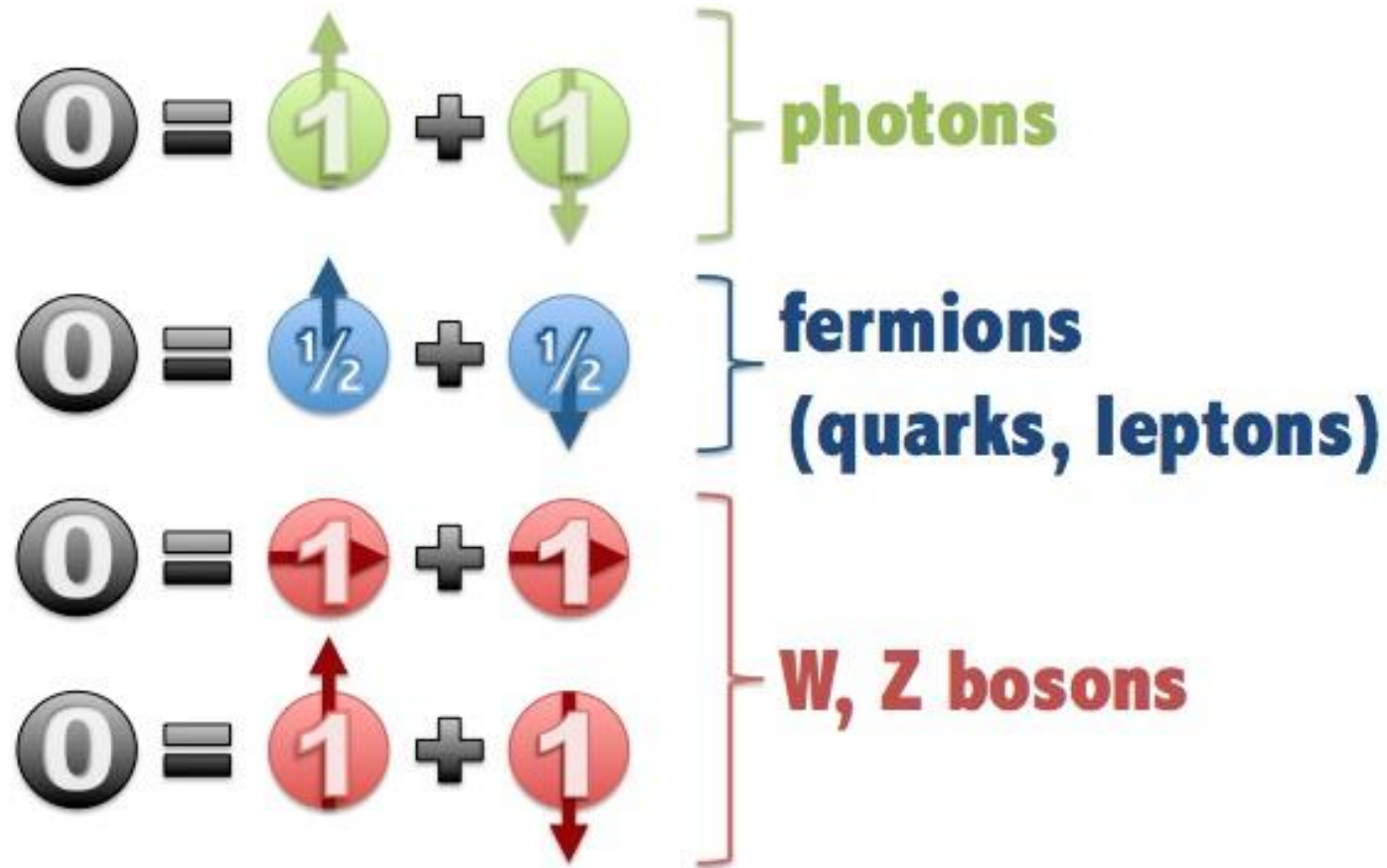


massive bosons
(W, Z bosons)
spin = $+1, 0, -1$



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

What can a spin 0 particle decay to?



What can a spin 1 particle decay to?

$$\begin{array}{lcl} \textcircled{1} \neq \textcircled{1} + \textcircled{1} & \left. \vphantom{\textcircled{1} \neq \textcircled{1} + \textcircled{1}} \right\} & \text{photons} \\ \textcircled{1} = \textcircled{\frac{1}{2}} + \textcircled{\frac{1}{2}} & \left. \vphantom{\textcircled{1} = \textcircled{\frac{1}{2}} + \textcircled{\frac{1}{2}}} \right\} & \text{fermions} \\ \textcircled{1} = \textcircled{1} + \textcircled{1} & \left. \vphantom{\textcircled{1} = \textcircled{1} + \textcircled{1}} \right\} & \text{W, Z bosons} \end{array}$$

What can a spin 2 particle decay to?

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

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

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

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

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

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-Sopner frame

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

