

(experimental) LHC physics



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

Roberto Covarelli

Step I: find events with the right ingredients

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

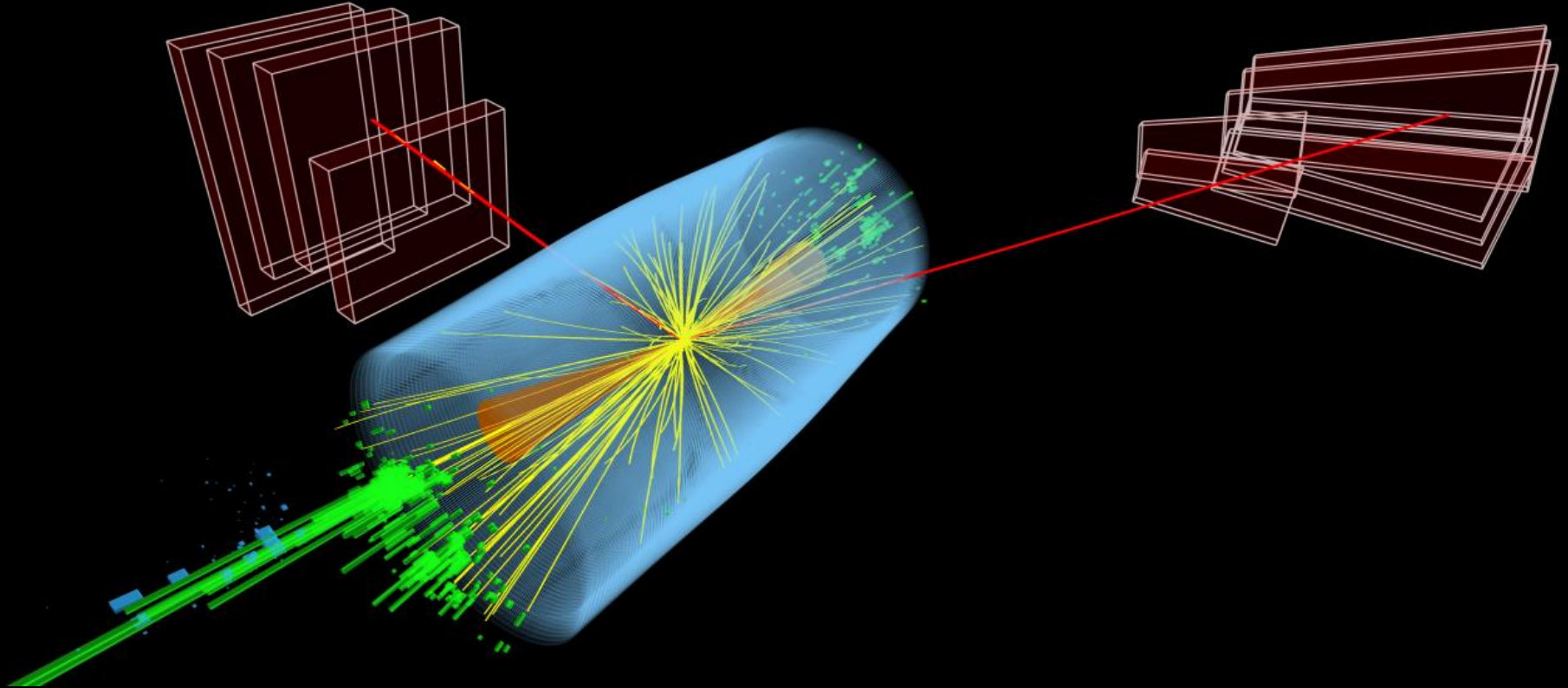
Is this event OK?



CMS Experiment at the LHC, CERN

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

Run / Event / LS: 323940 / 44997009 / 65

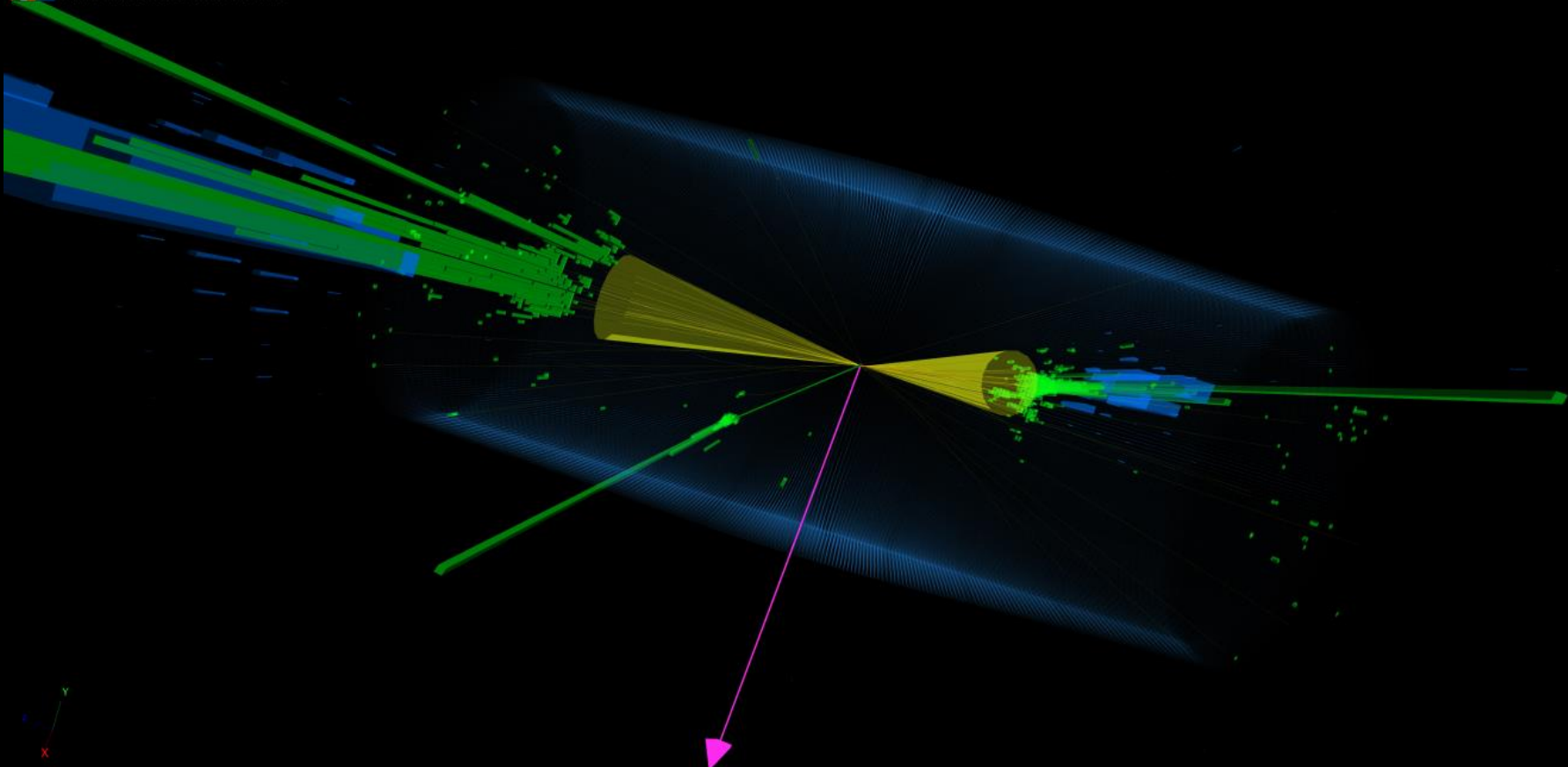


Step I: find events with the right ingredients

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

What about this one?

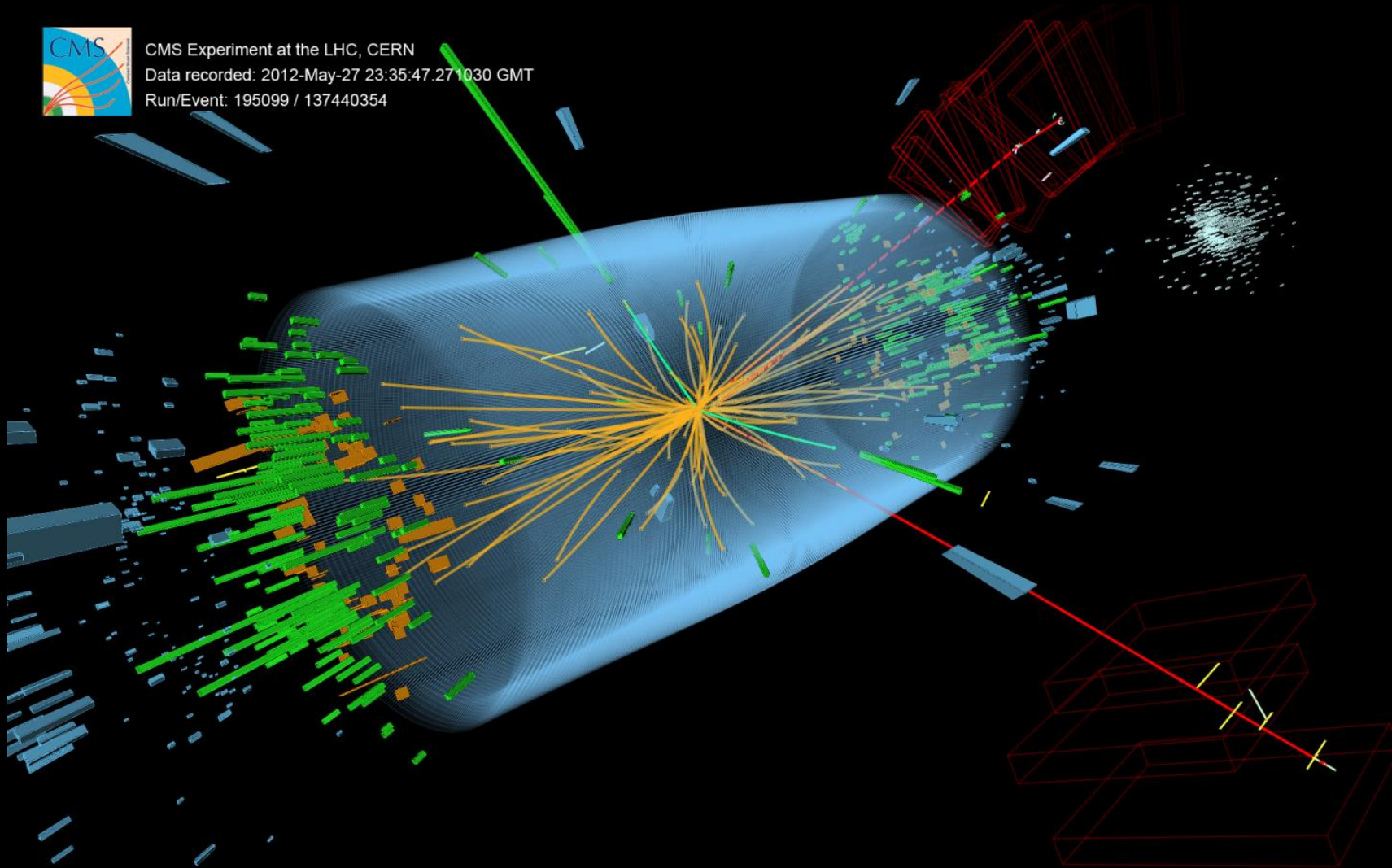
CMS Experiment at the LHC, CERN
Data recorded: 2016-Jul-16 20:57:32.758784 GMT
Run / Event / LS: 276670 / 2920241170 / 1610



Step I: find events with the right ingredients

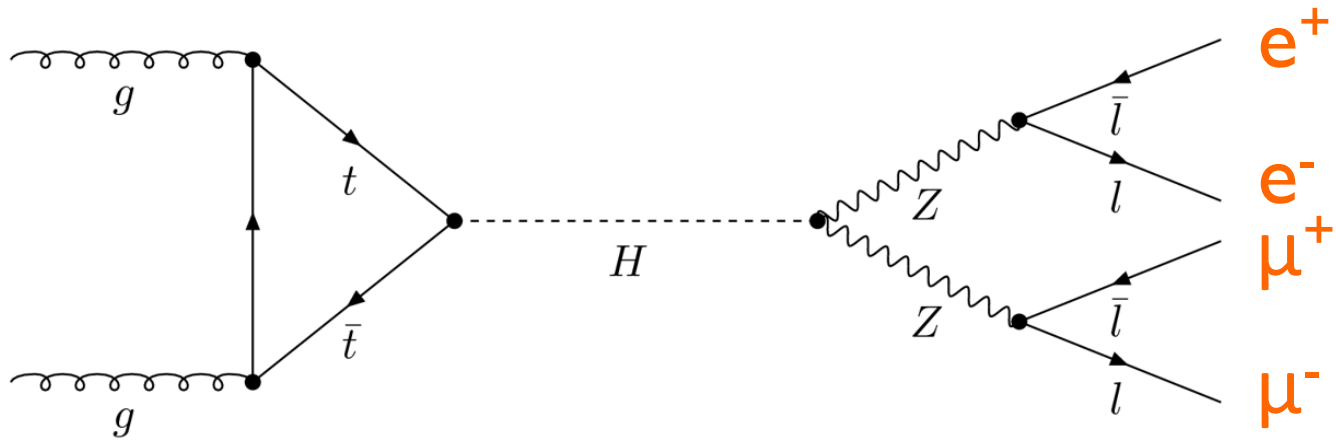
We are looking for $e^+e^-\mu^+\mu^-$...

And this one?



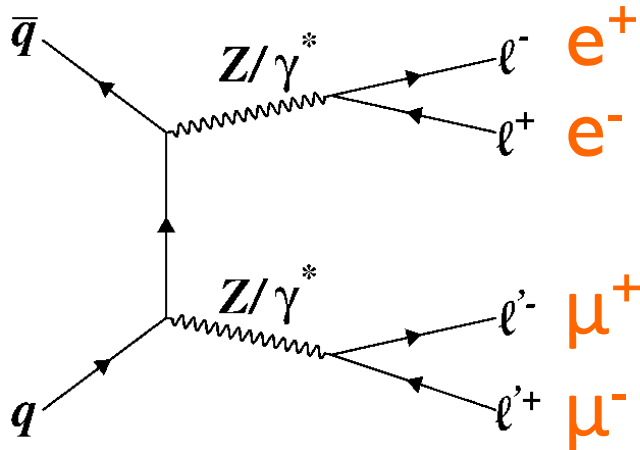
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

Step 2: signal and background



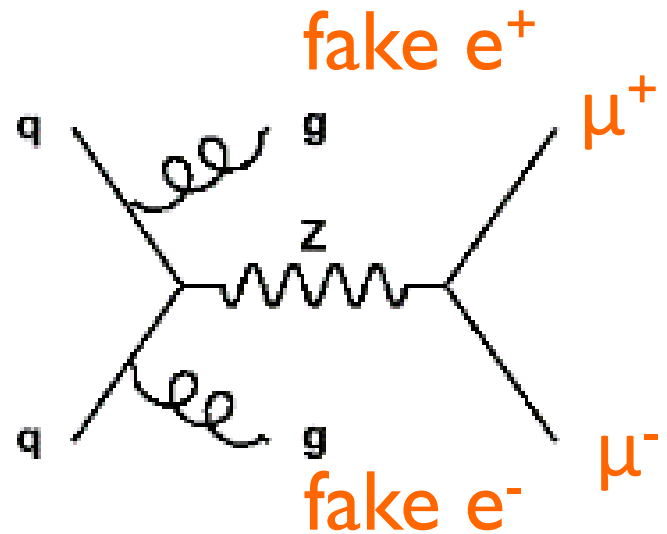
Irreducible background

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

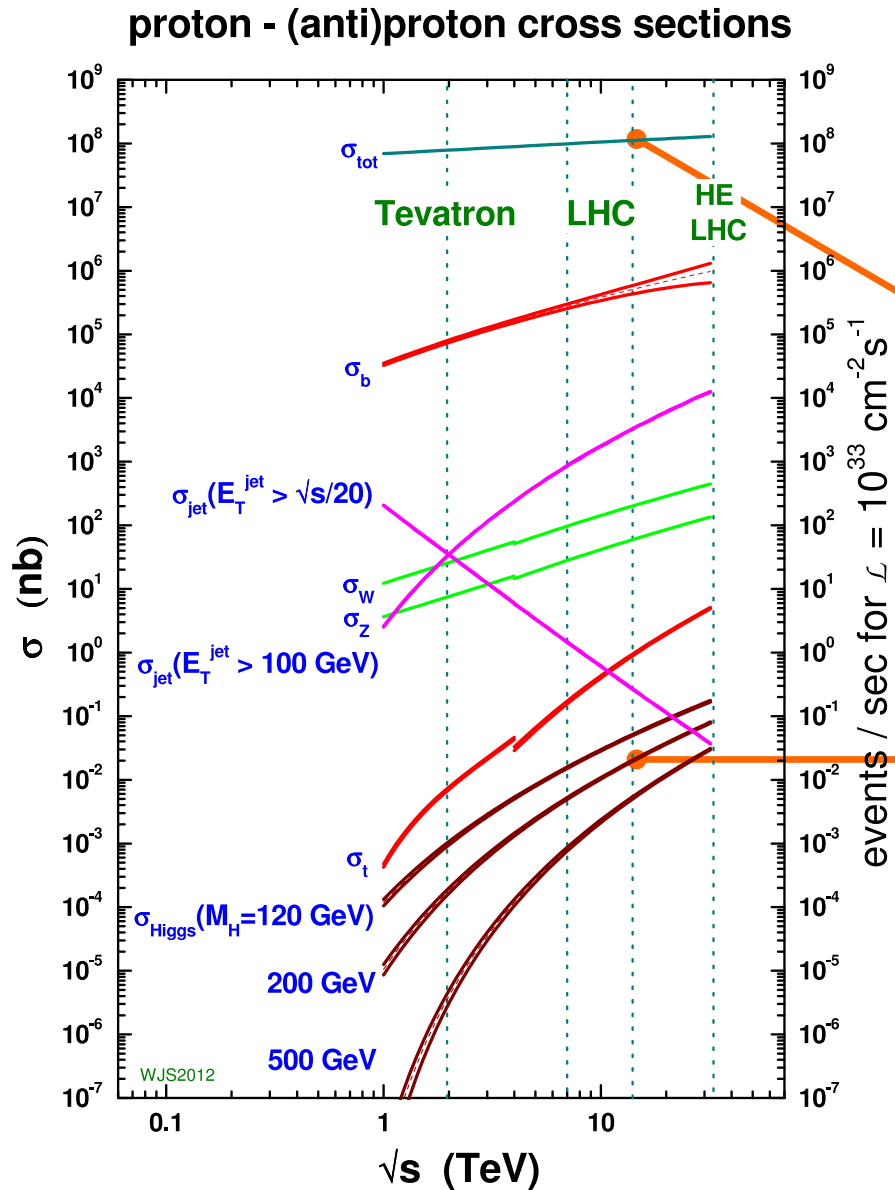


Reducible background

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



Interesting processes are rare!



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

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

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

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

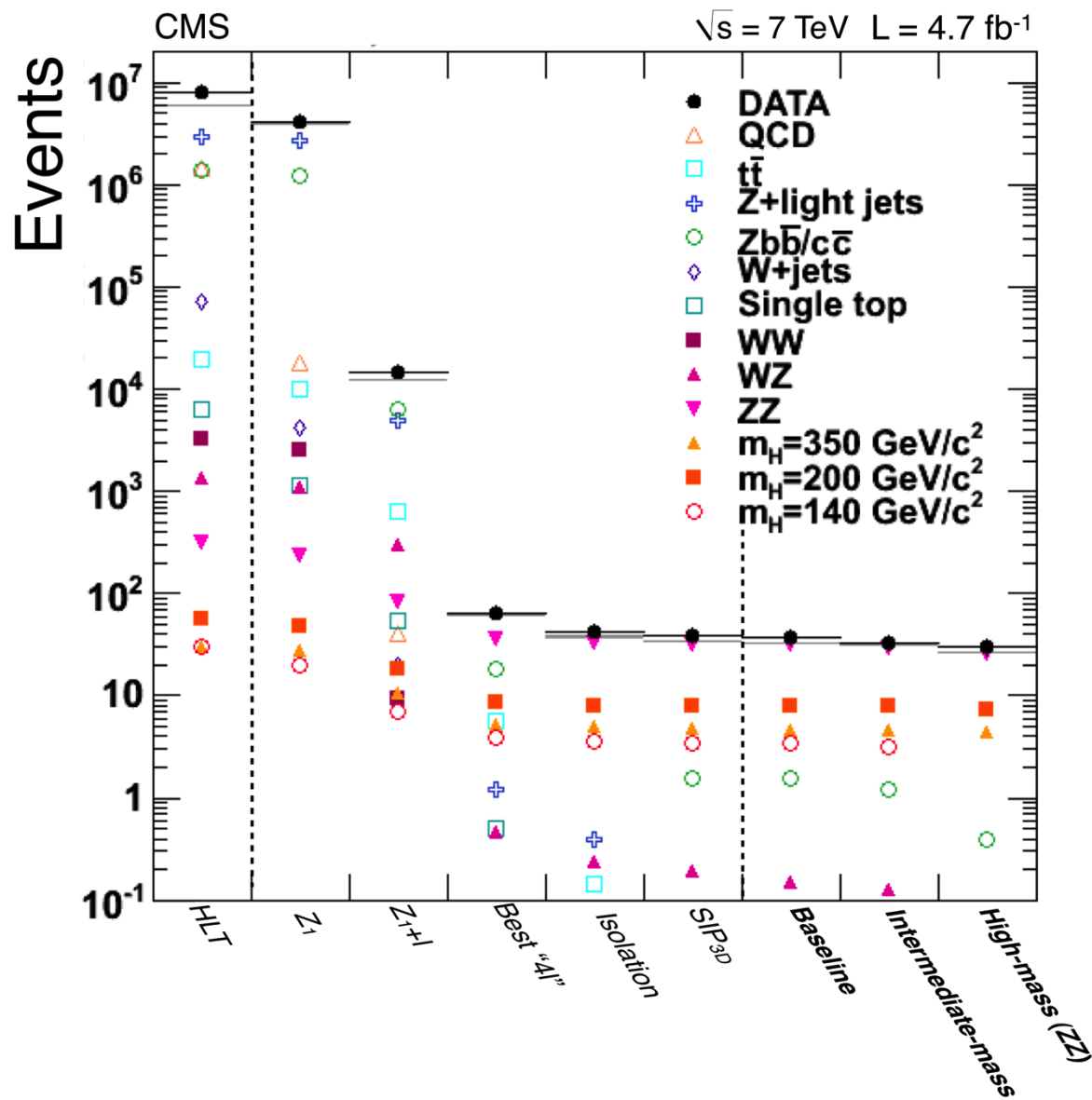
$[m_{\text{H}} \sim 125 \text{ GeV}]$

0.2% $\text{H} \rightarrow \gamma\gamma$

0.01% $\text{H} \rightarrow \text{ZZ}$

Lose some signal, suppress backgrounds...

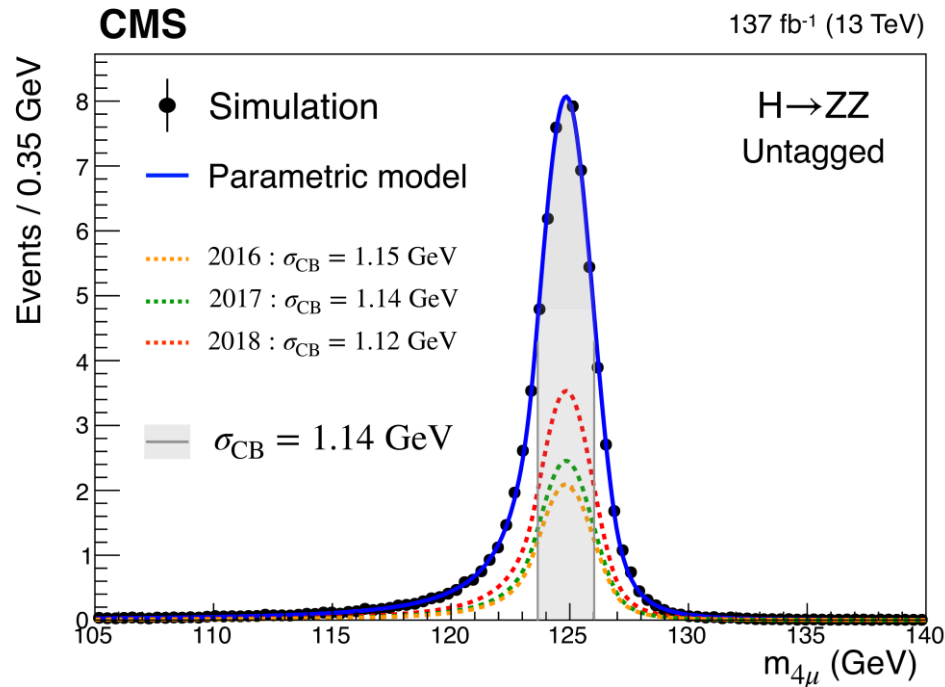
- Selections based on particle properties to reduce reducible background
 - ✓ Shower shapes, track properties, ...
- Selections based on event properties to distinguish signal from background
 - ✓ Particle kinematics, decay kinematics event shape, ...
- Try to keep signal while reducing background!
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

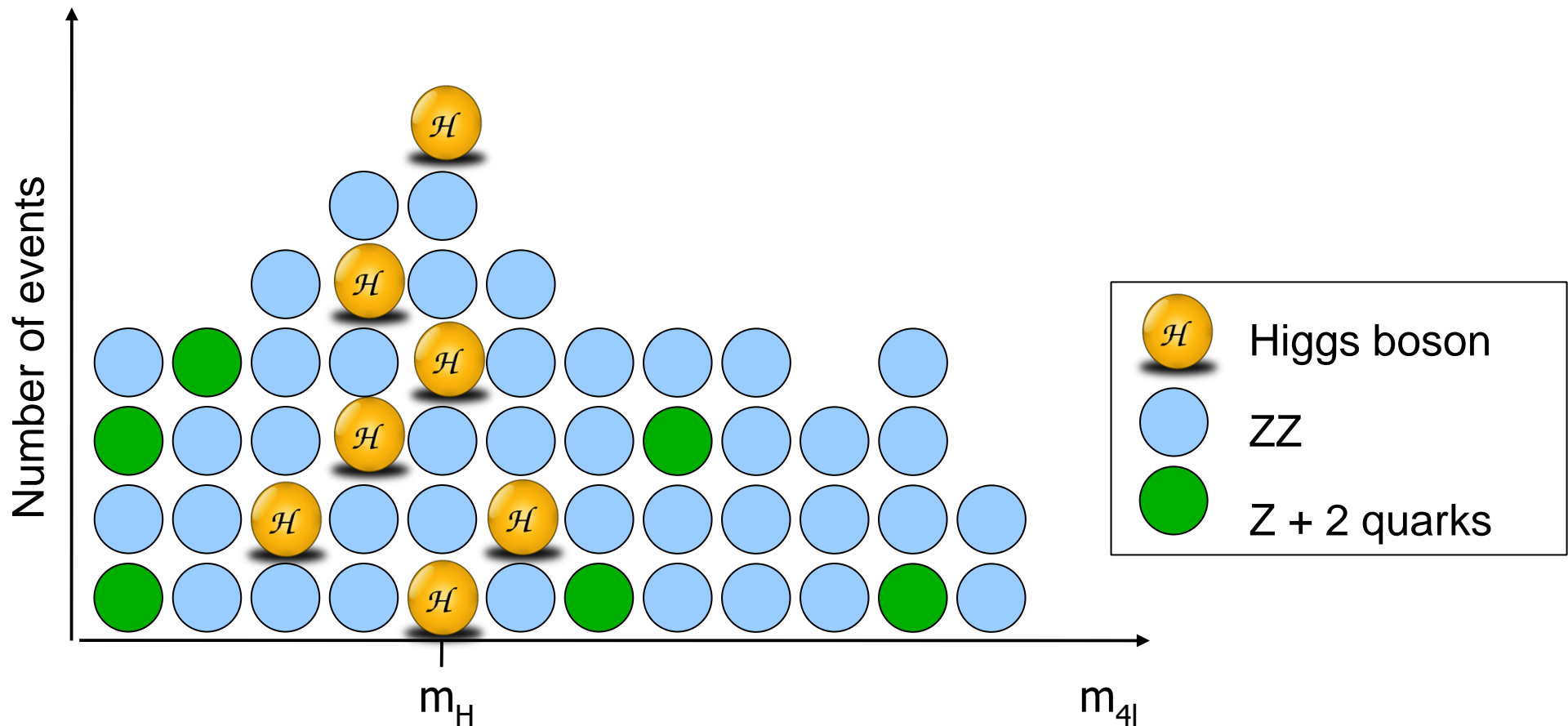
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



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

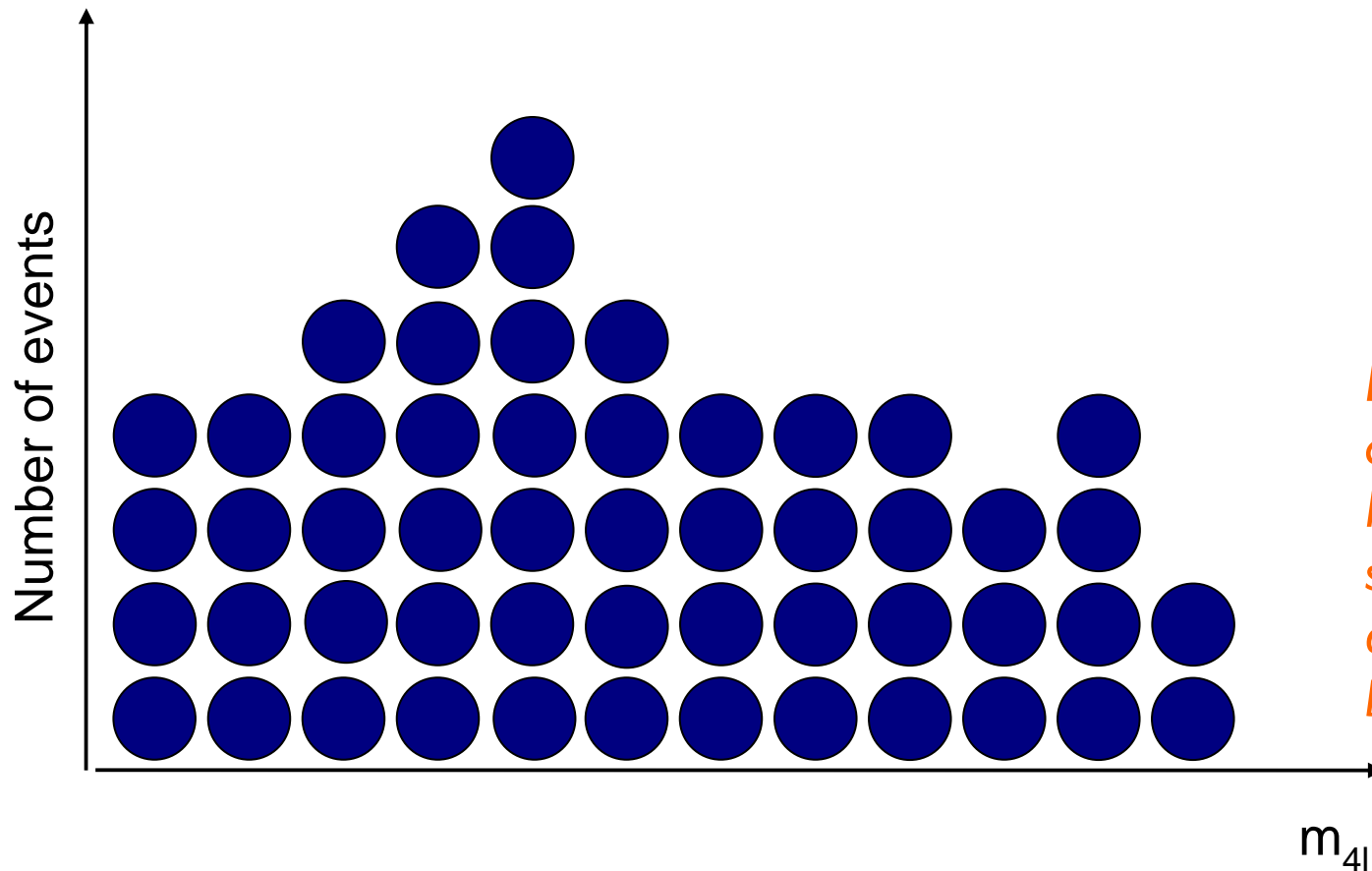
Extract signal from background

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



Extract signal from background

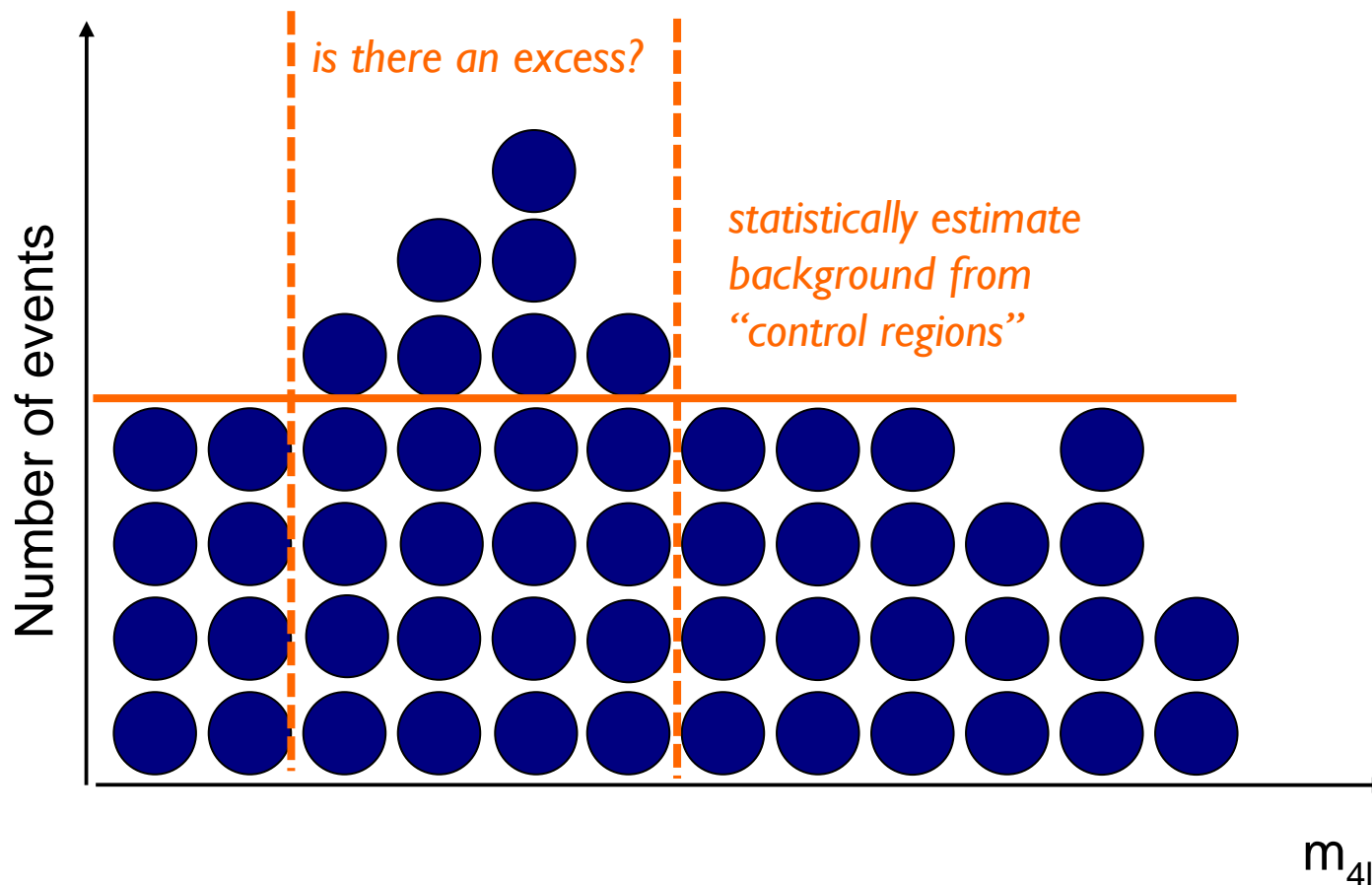
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



*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

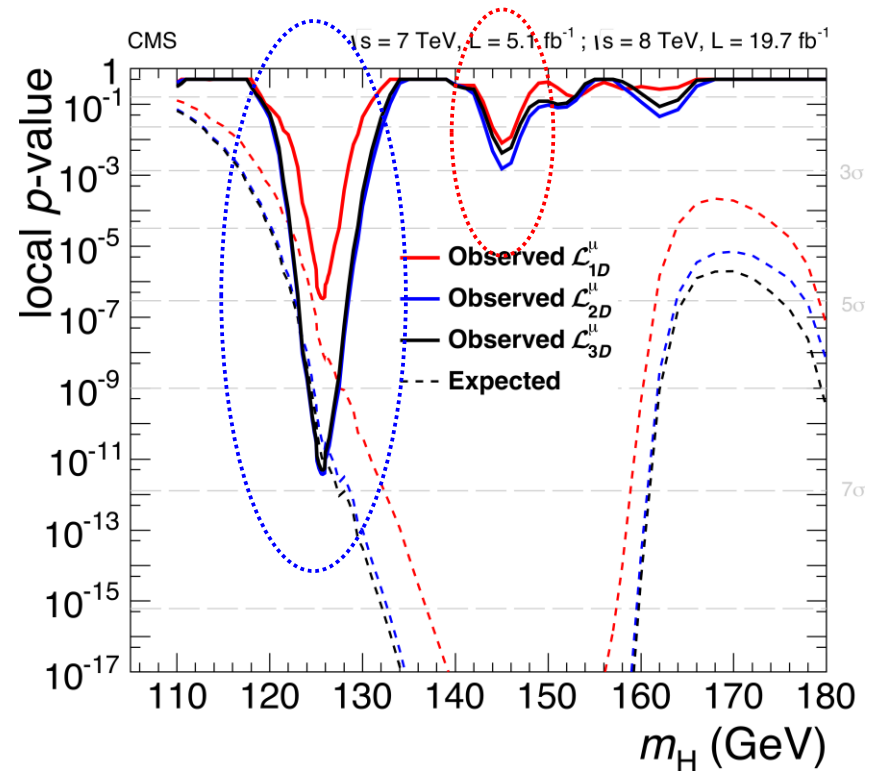
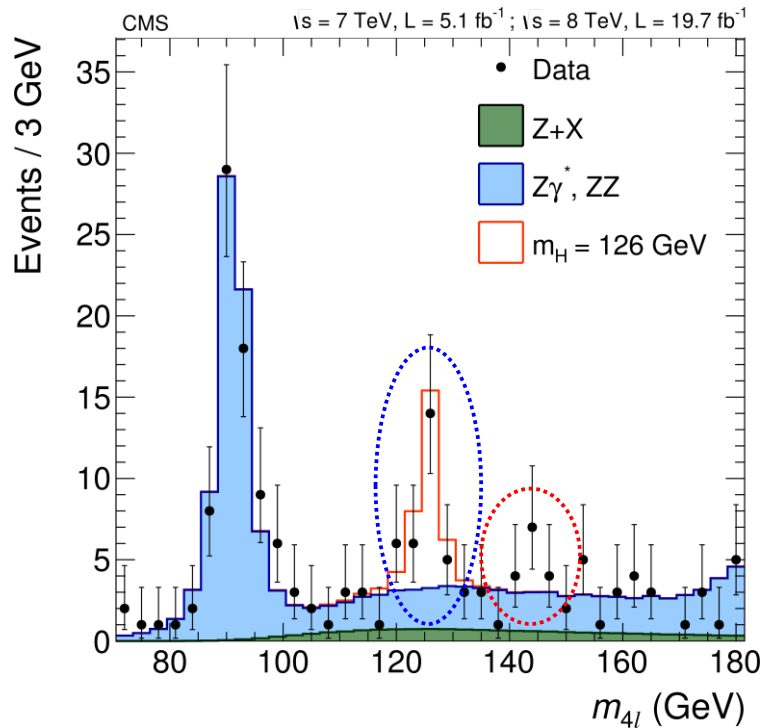
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

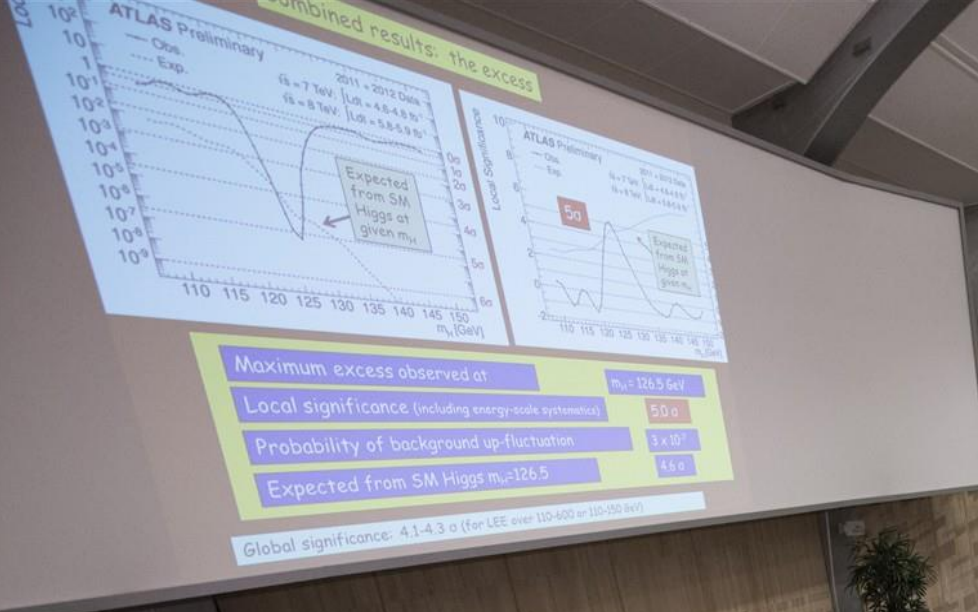


- Background gets estimated...
 - ✓ ... from simulation (normalized to data)
 - ✓ ... directly from data ("control regions", enriched in background events)

How significant is an excess?

- p_0 : probability that the excess is due to a fluctuation of background
- Significance: $Z \sim \frac{S}{\sqrt{B}}$ $p_0 = 1 - \text{Erf} \left(\frac{Z}{\sqrt{2}} \right)$
- Convention:
 - 3σ is an **evidence** ($p_0 = 0.27\%$)
 - 5σ is a **discovery** ($p_0 = 5.7 \cdot 10^{-7}$)





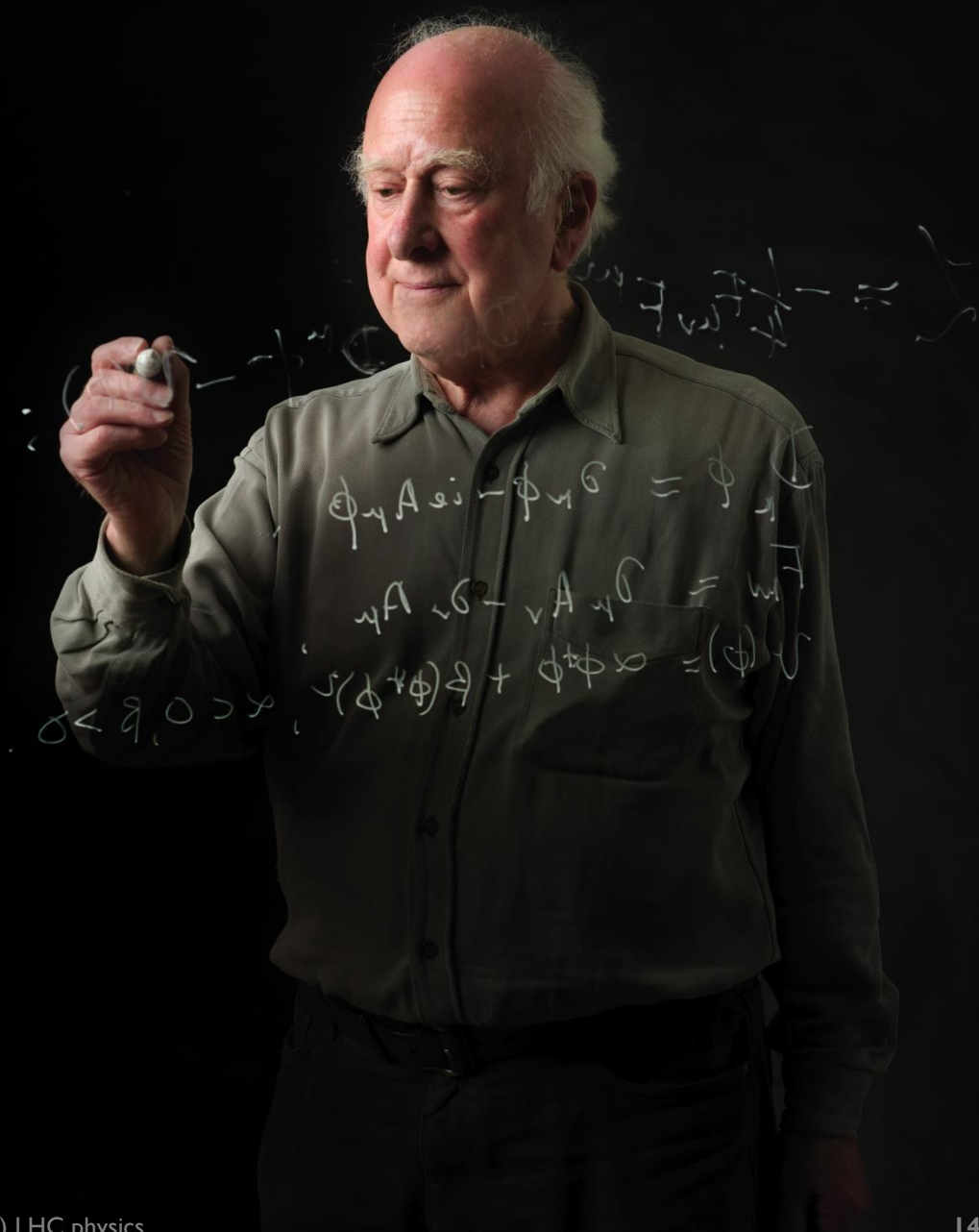
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

www.elsevier.com/locate/physletb

CERN

10 years HIGGS boson discovery

Is it a scalar boson?



Spin!

What's a particle spin?

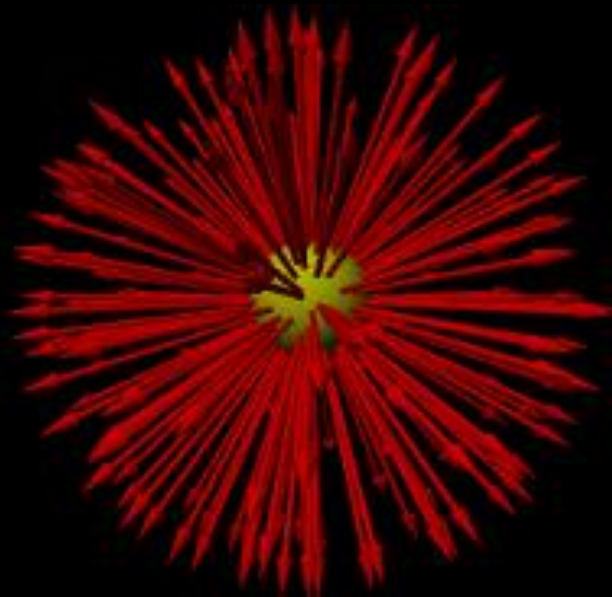
“An *amount of rotation* that is quantized”

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

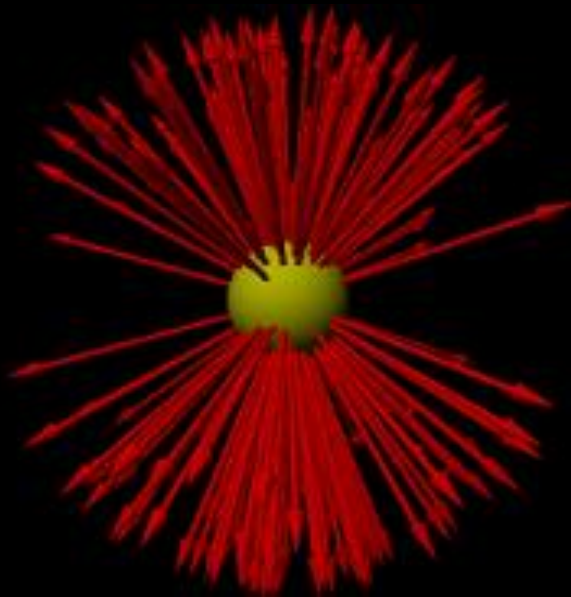


$$\hbar = 1.0545 \times 10^{-34} \text{ J} \cdot \text{s}$$

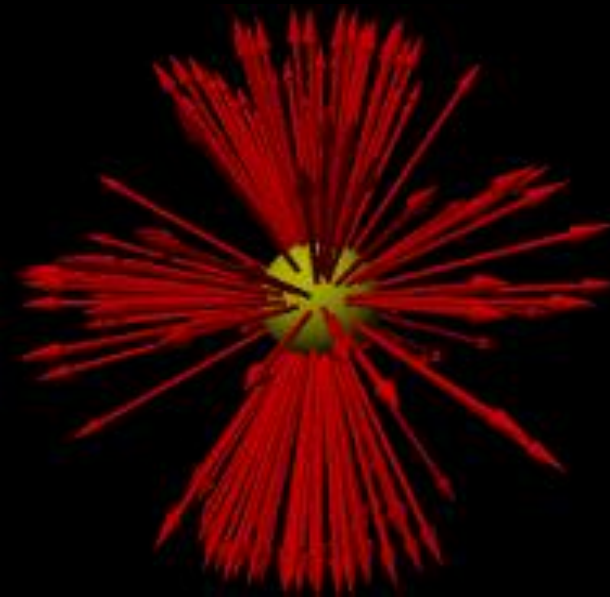
How can we recognize spin?



spin 0



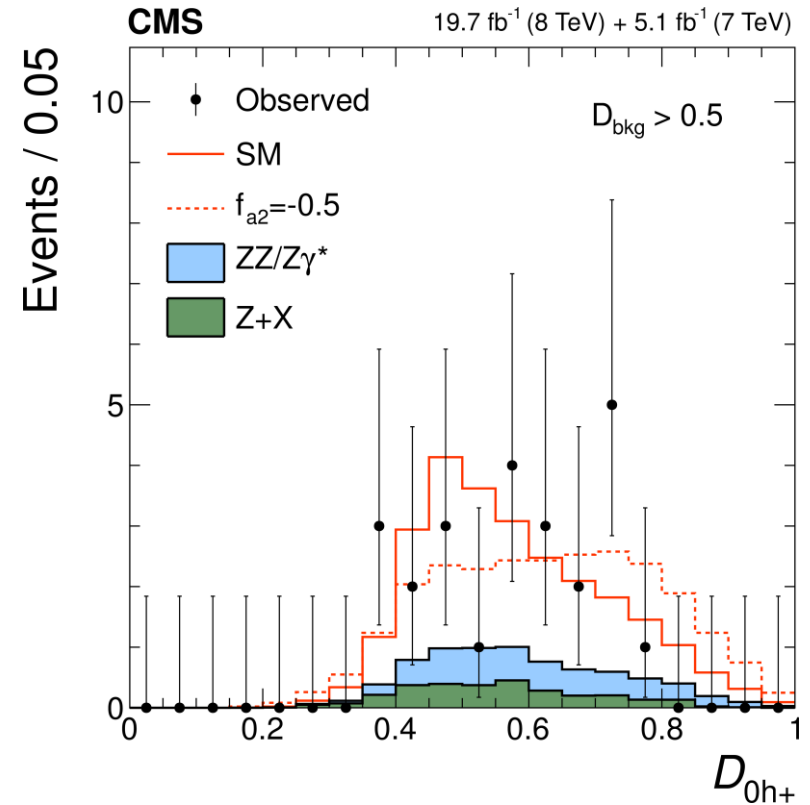
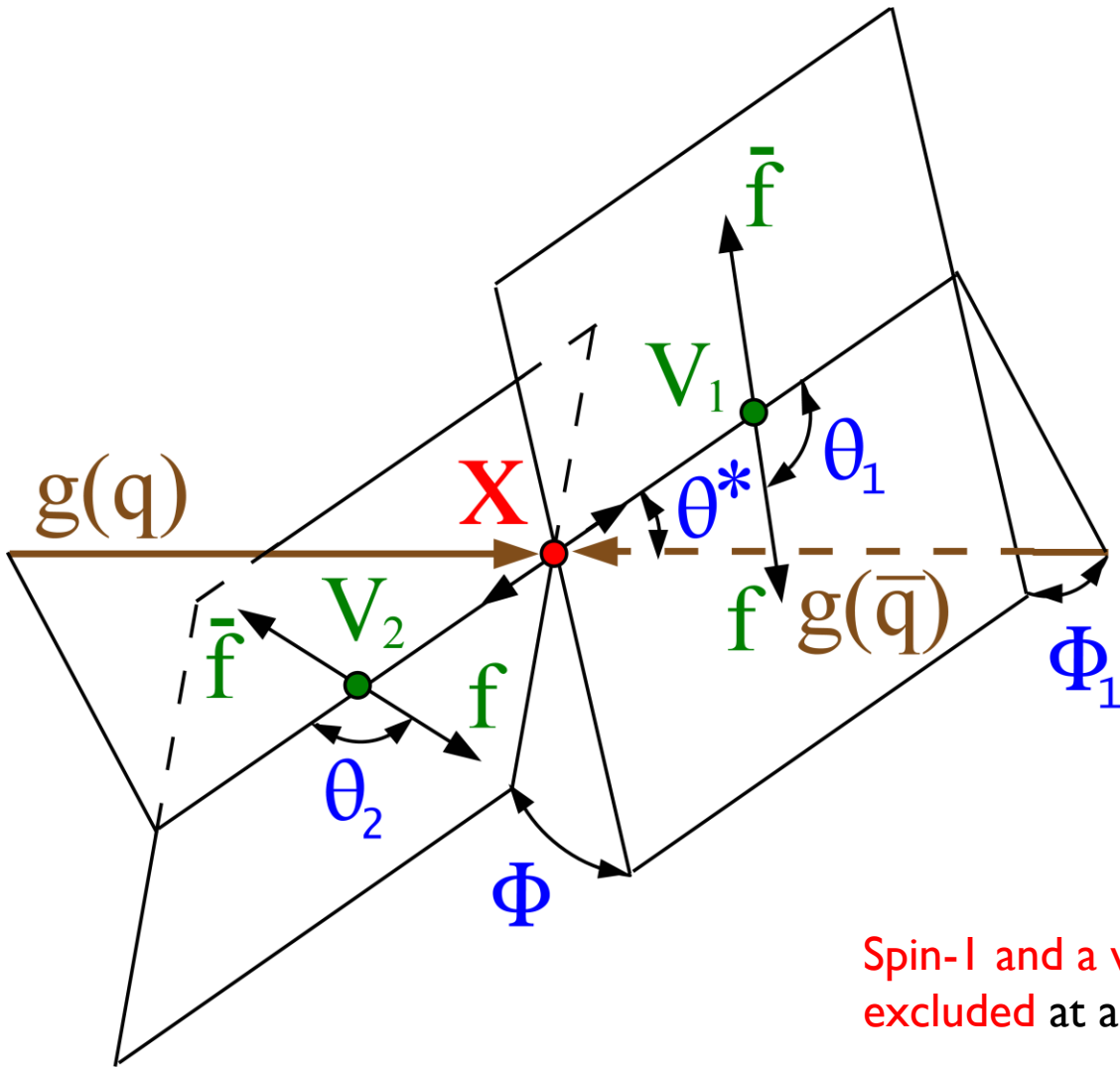
spin 1



spin 2

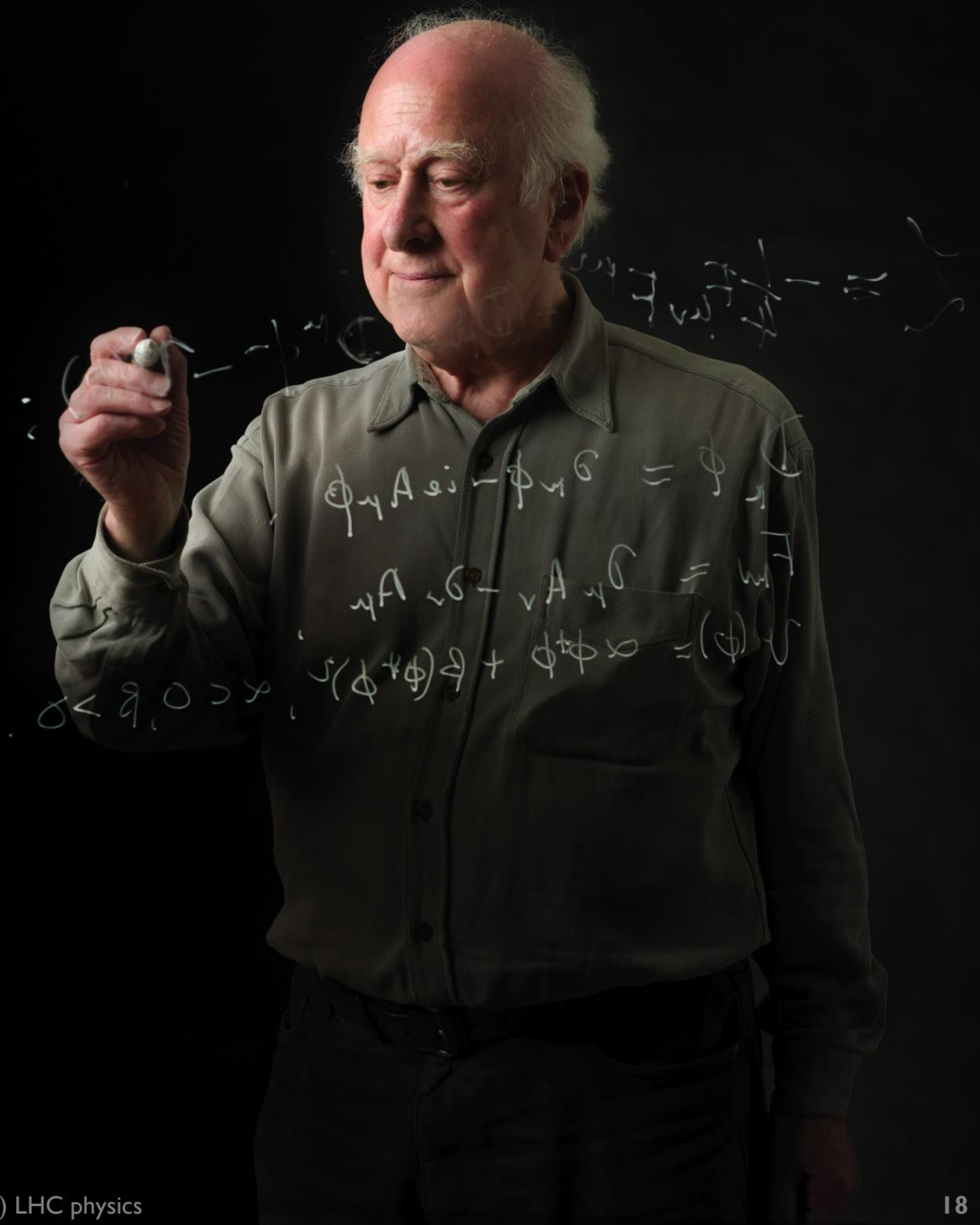
Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

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

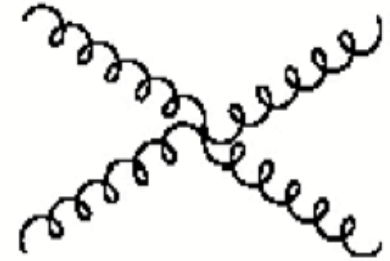
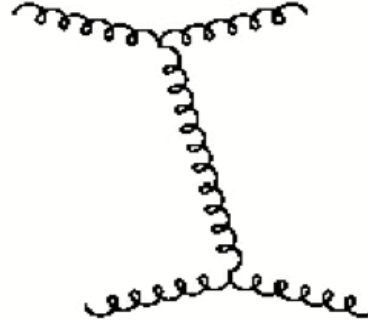
- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow WW^* \rightarrow 2l2\nu$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $H \rightarrow c\bar{c}$
- $H \rightarrow b\bar{b}$
- $pp \rightarrow t\bar{t}H$
- ...



- 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

A few more words on QCD

- QCD (strong) interactions are carried out by massless spin-1 particles called gluons
 - ✓ Gluons are massless
 - Long range interaction
 - ✓ Gluons couple to color charges
 - ✓ Gluons have color themselves
 - They can couple to other gluons



- **Principle of asymptotic freedom**

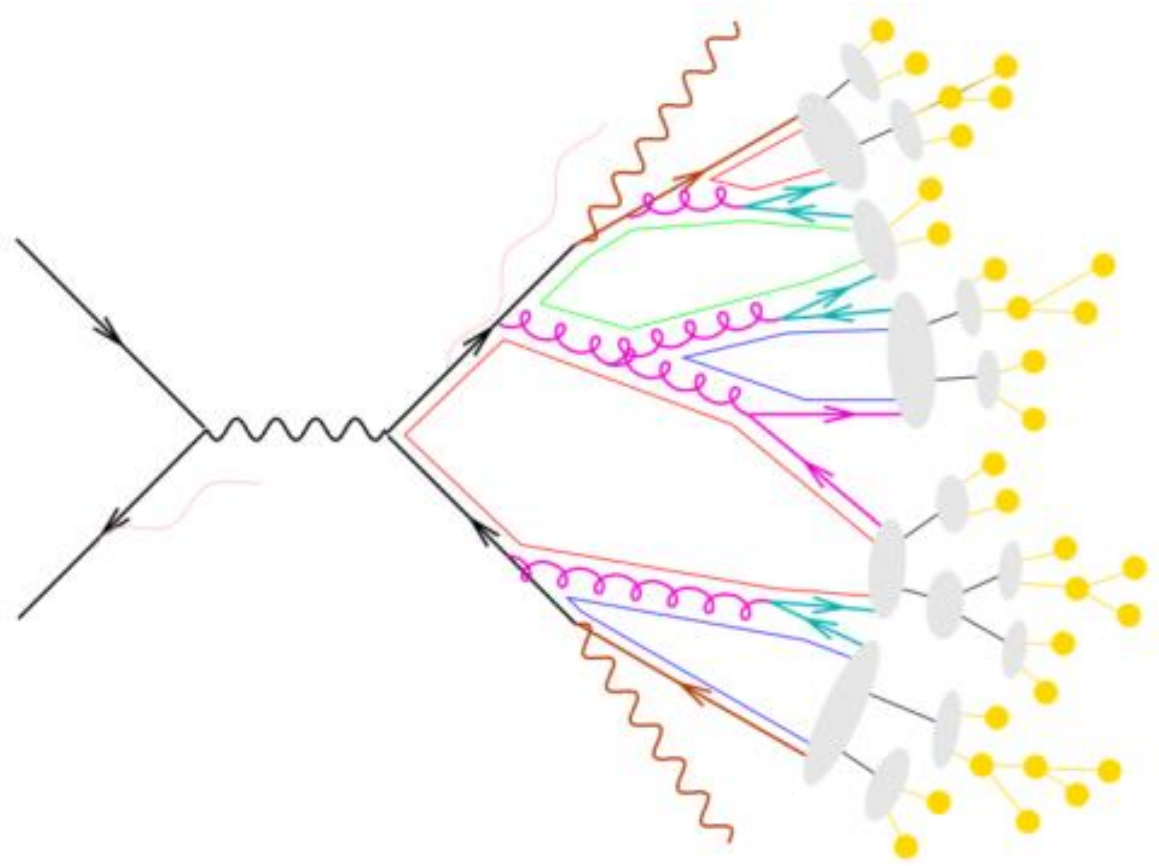
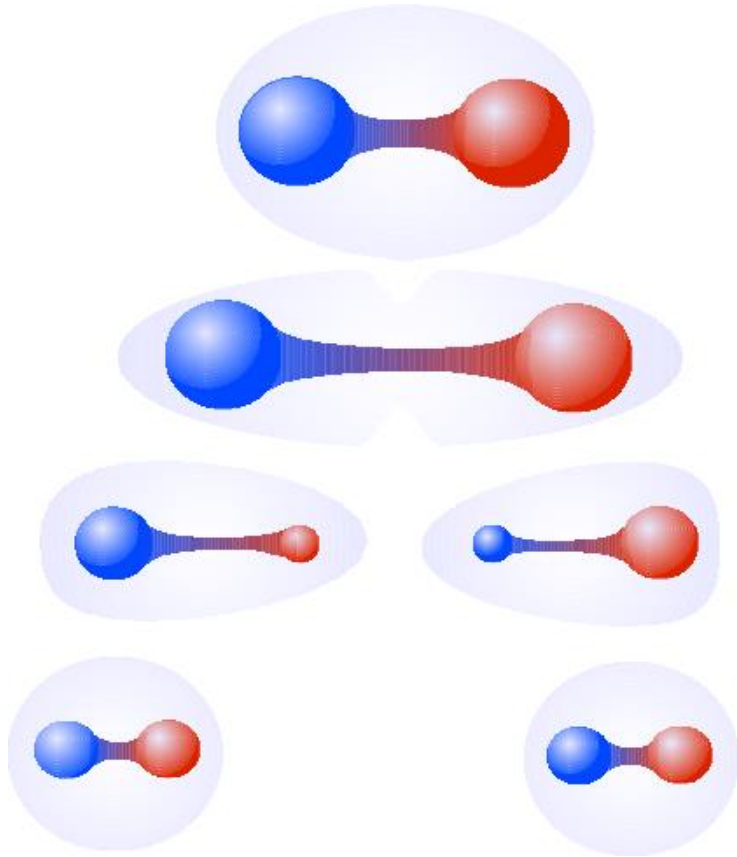
- ✓ At short distances strong interactions are weak
 - Quarks and gluons are essentially free particles
 - Perturbative regime (can calculate!)
- ✓ At large distances, higher-order diagrams dominate
 - Interaction is very strong
 - Perturbative regime fails, have to resort to effective models

quark-quark effective potential

$$V_s = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$

$\underbrace{\hspace{10em}}$ $\underbrace{\hspace{5em}}$
single gluon exchange confinement

Confinement, hadronization, jets

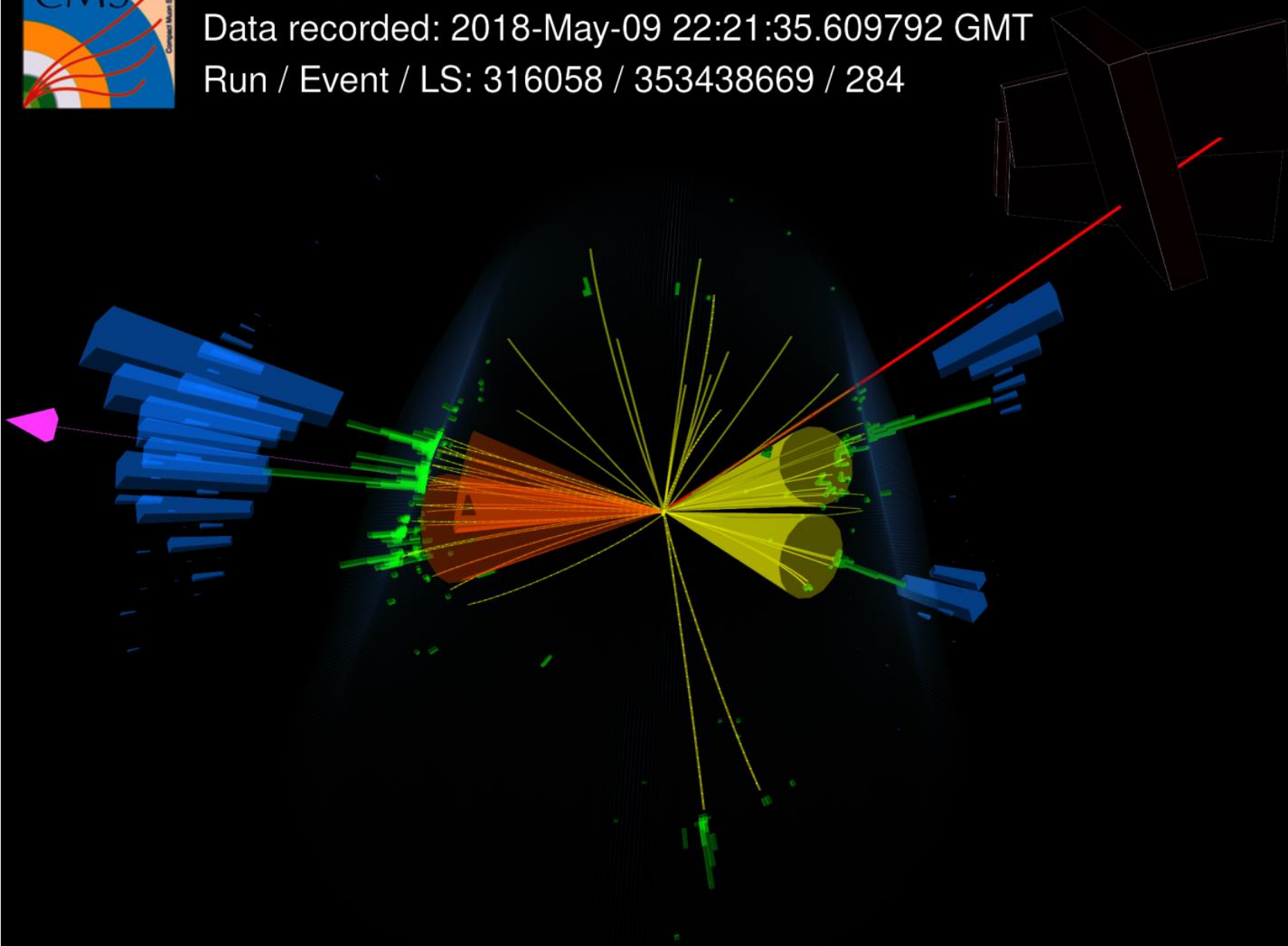




CMS Experiment at the LHC, CERN

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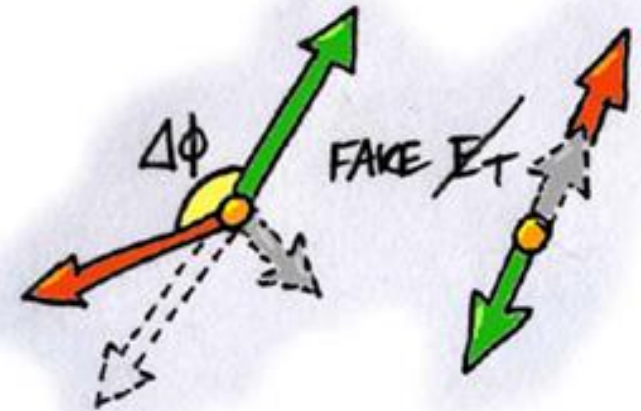
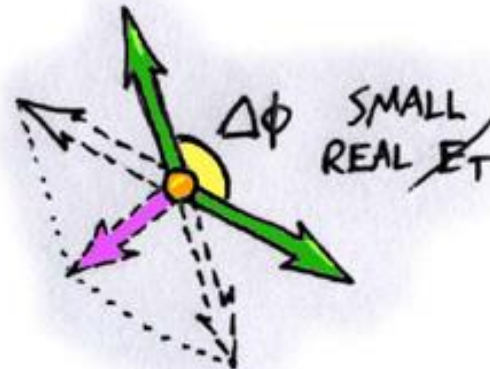
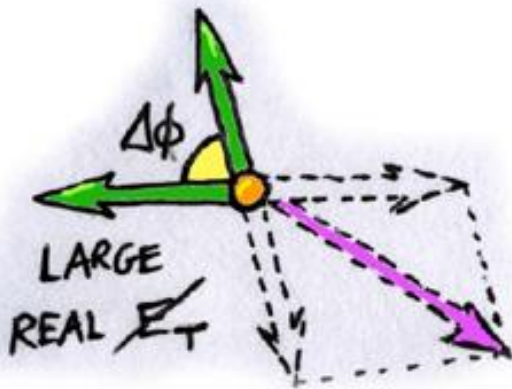
Run / Event / LS: 316058 / 353438669 / 284



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*

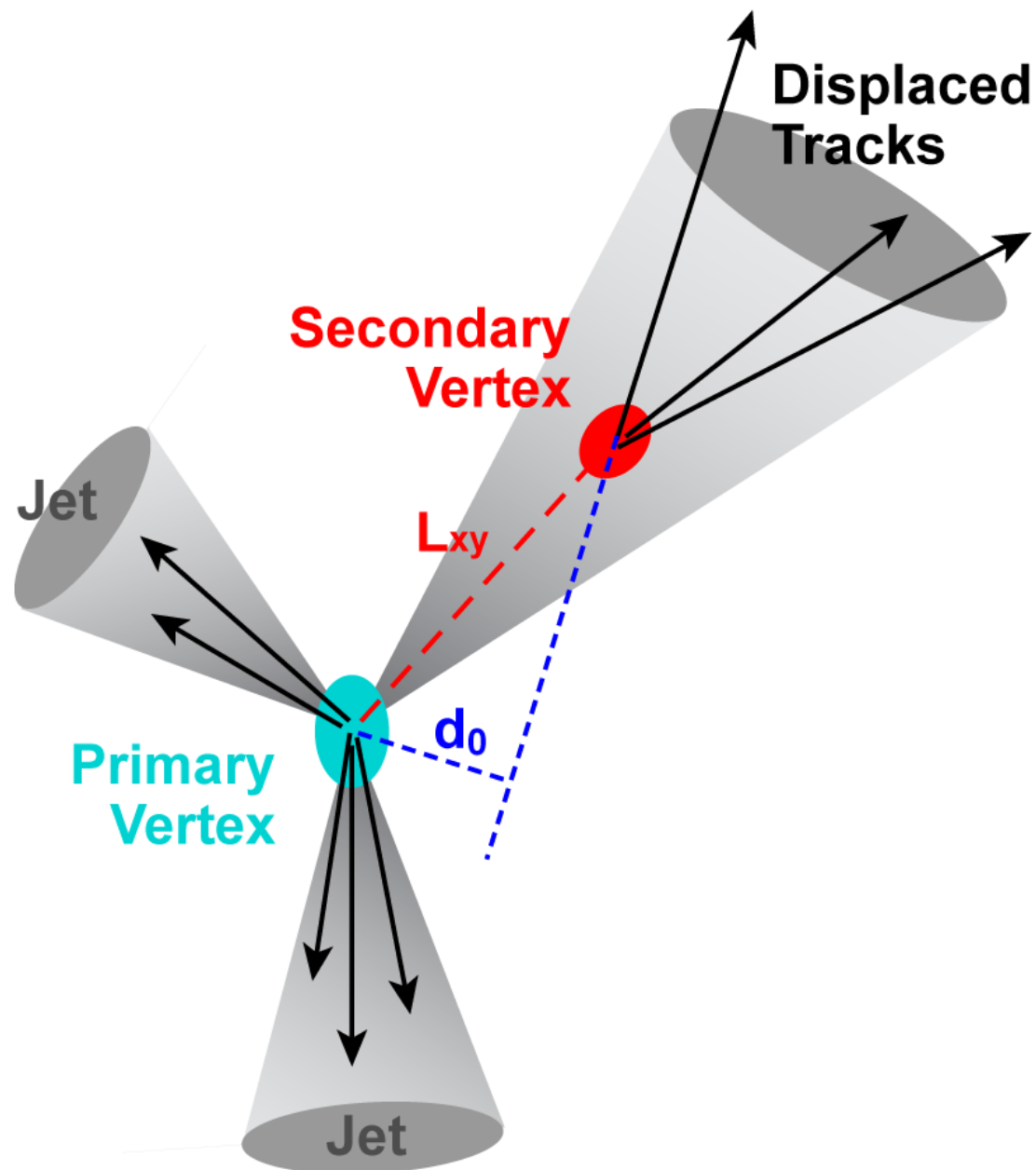


- Missing energy resolution depends on
 - ✓ Detector acceptance
 - ✓ Detector noise and resolution (e.g. calorimeters)

B-tagging



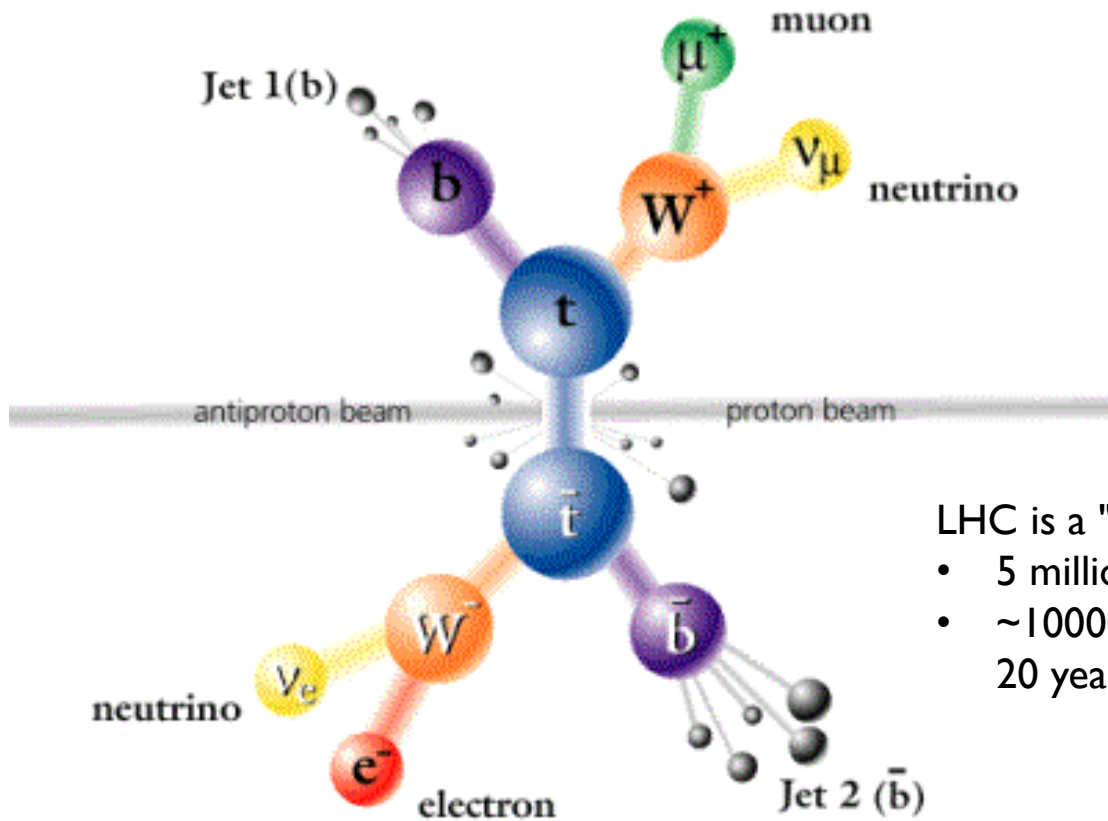
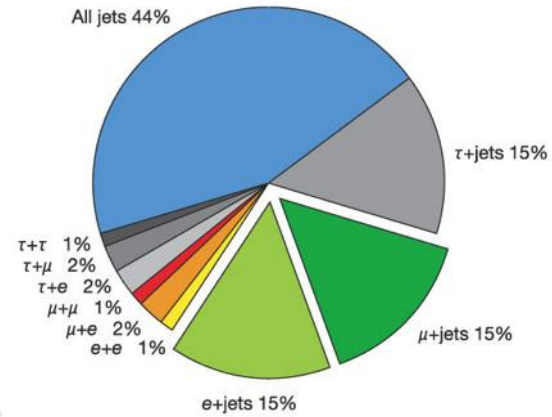
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
 - ✓ ~ 1.6 ps
 - ✓ They will travel away from collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark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



top quark

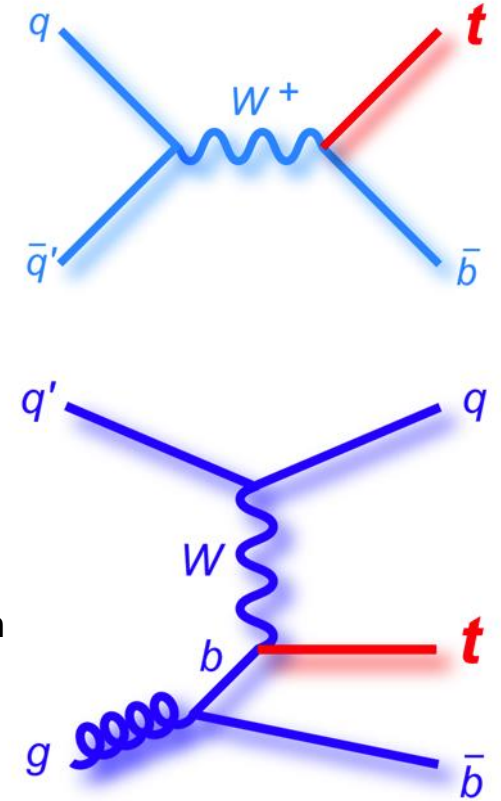


- Mean lifetime $\sim 5 \times 10^{-13}$ ps
 - ✓ Shorter than time scale at which QCD acts: no time to hadronize!
 - ✓ It decays as $t \rightarrow Wb$
- Events with top quarks are very rich in (b) jets...



LHC is a "top factory"!

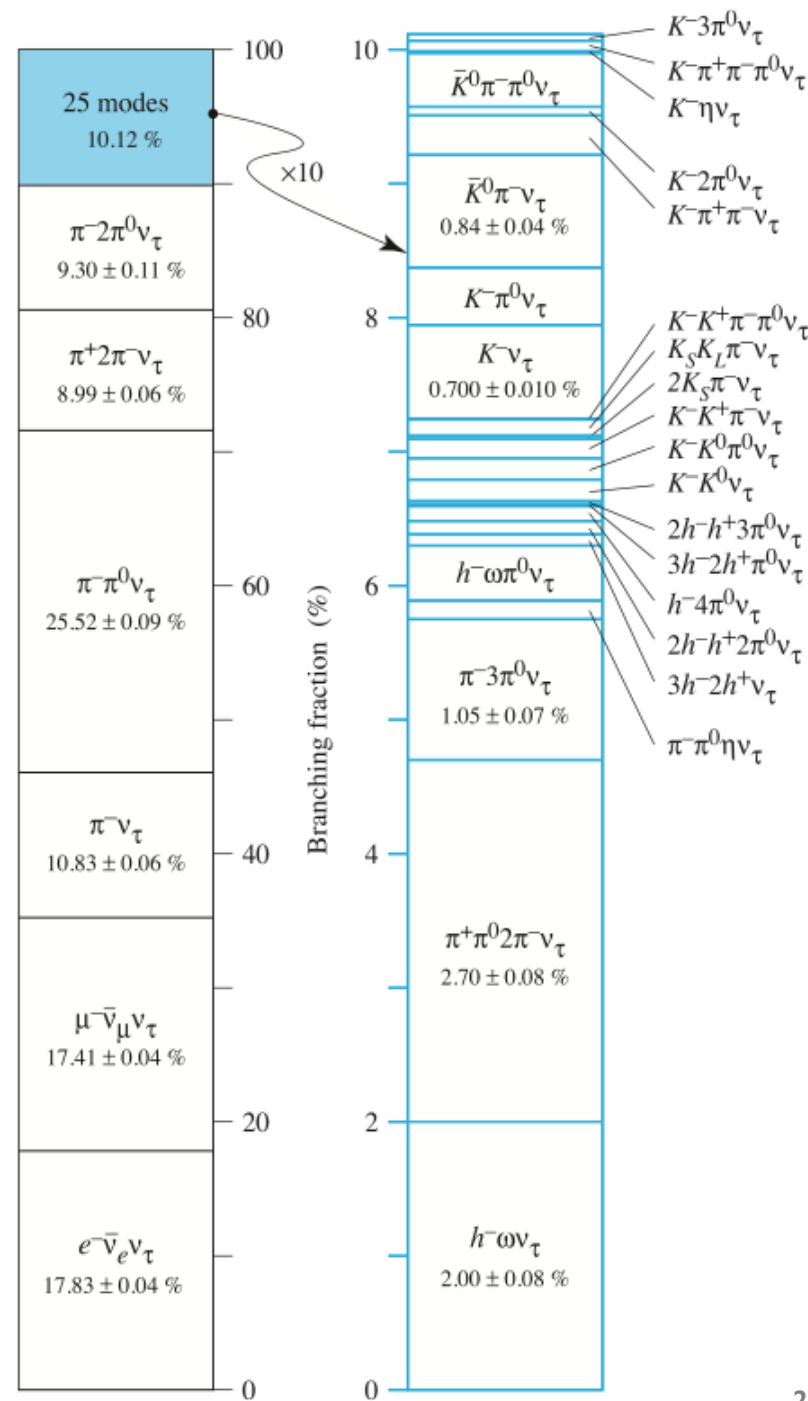
- 5 millions of $t\bar{t}$ pairs
- ~ 100000 in Tevatron in 20 years



Tau

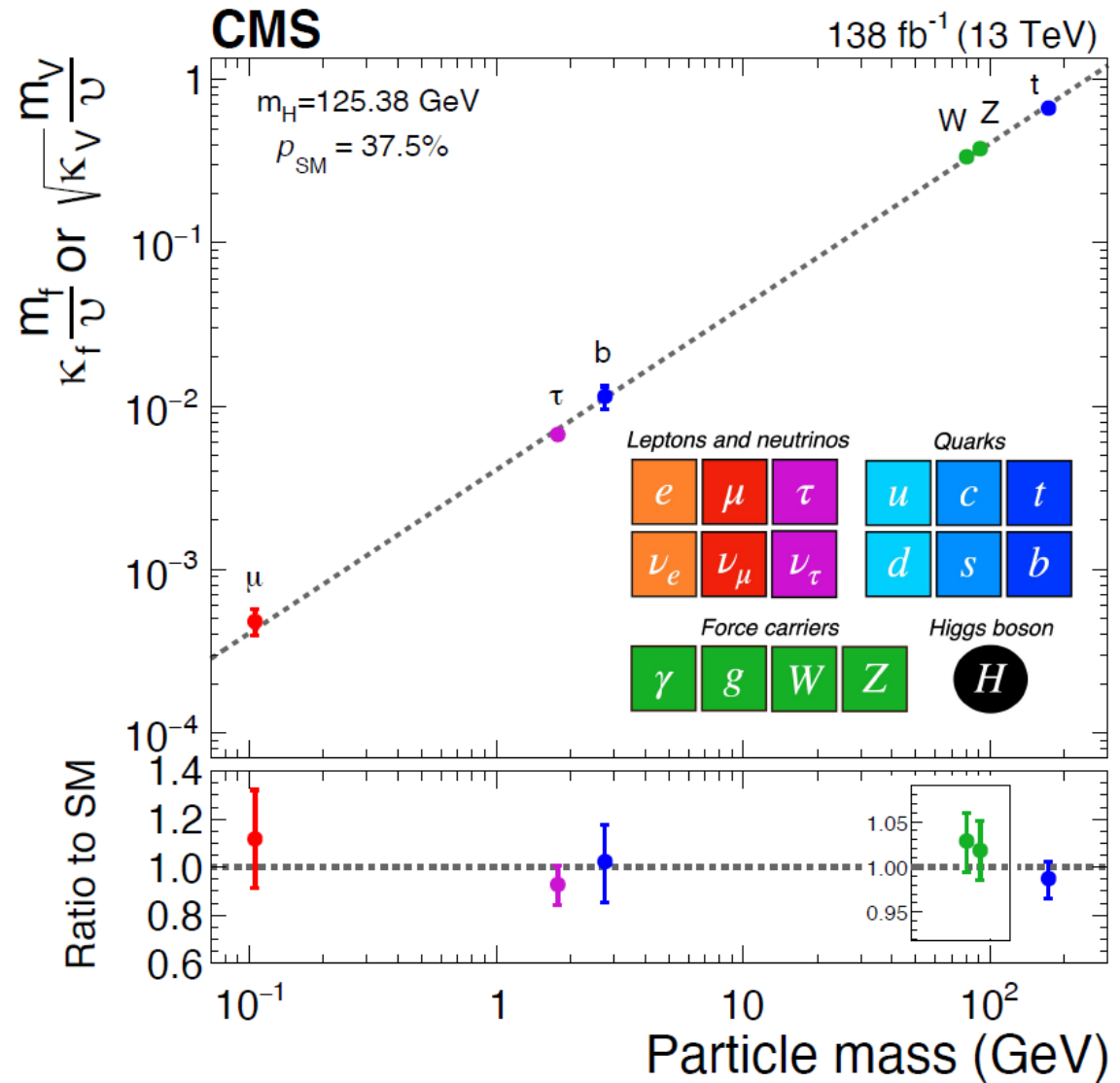


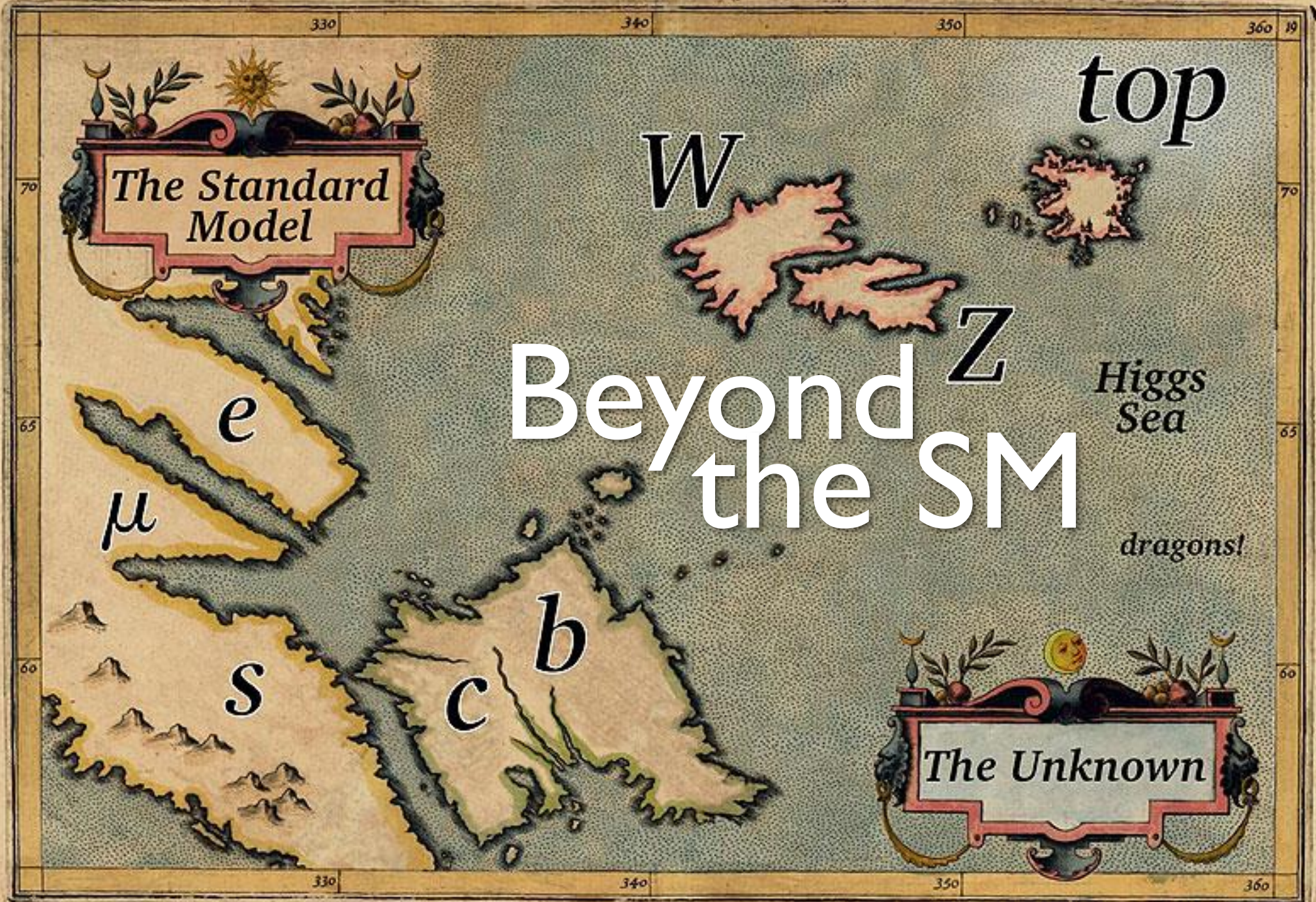
- Tau are heavy enough that they can decay in several final states
 - ✓ Several of them with hadrons
 - ✓ Sometimes neutral hadrons
- Mean lifetime ~ 0.29 ps
 - ✓ 10 GeV tau flies ~ 0.5 mm
 - ✓ Too short to be directly seen in the detectors
- Tau needs to be identified by their decay products
- Accurate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



Combine many other decay modes

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





The Standard Model

Beyond the SM

The Unknown

top

W

Z

Higgs Sea

dragons!

e

μ

s

c

b

330

340

350

360

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 | 1974: 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?

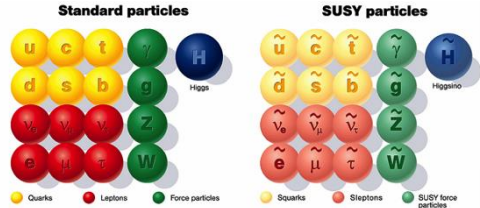
What keeps the Higgs mass so small?

How do we incorporate gravity?

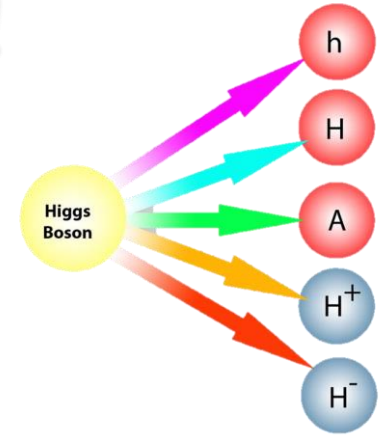
What is Dark Matter?

... as many possible answers to probe!

Super-symmetry?

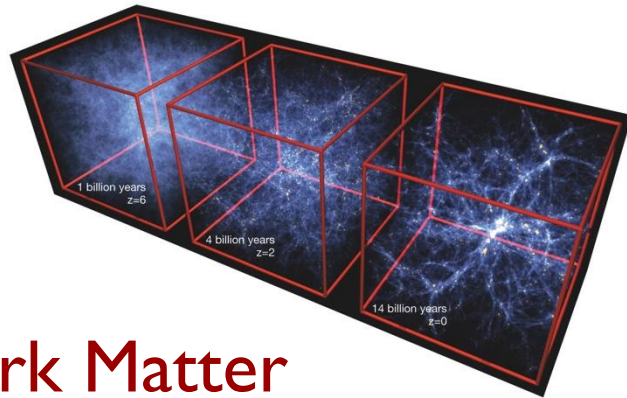


Extended Higgs sector?



New heavy bosons?

Composite quark and leptons?

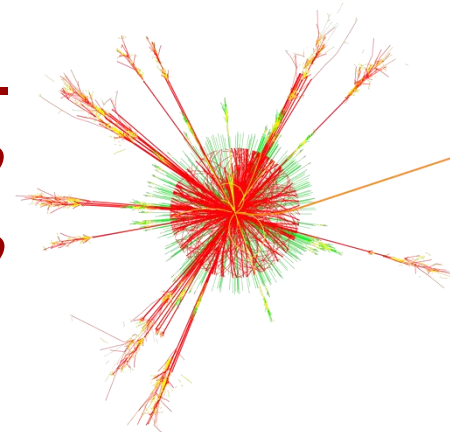


Dark Matter particles?

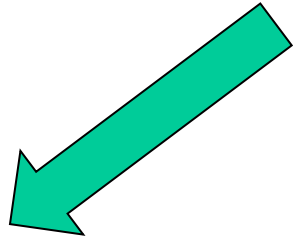
| | | | |
|--|--|---|--|
| 1981 SLAC u up quark | 1976 Brookhaven & SLAC c charm quark | 1976 Fermilab t top quark | 1979 DESY g gluon |
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| 1957 Cavendish Laboratory e electron | 1937 Caltech and Harvard μ muon | 1975 SLAC τ tau | 1973 CERN Z Z boson |

Any new theory needs to agree with the SM!

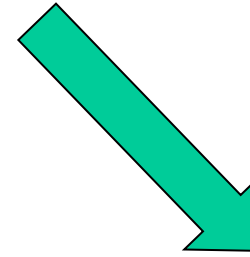
Large extra-dimensions?
Black holes?
Gravitons?



Where is Beyond-the-SM Physics?



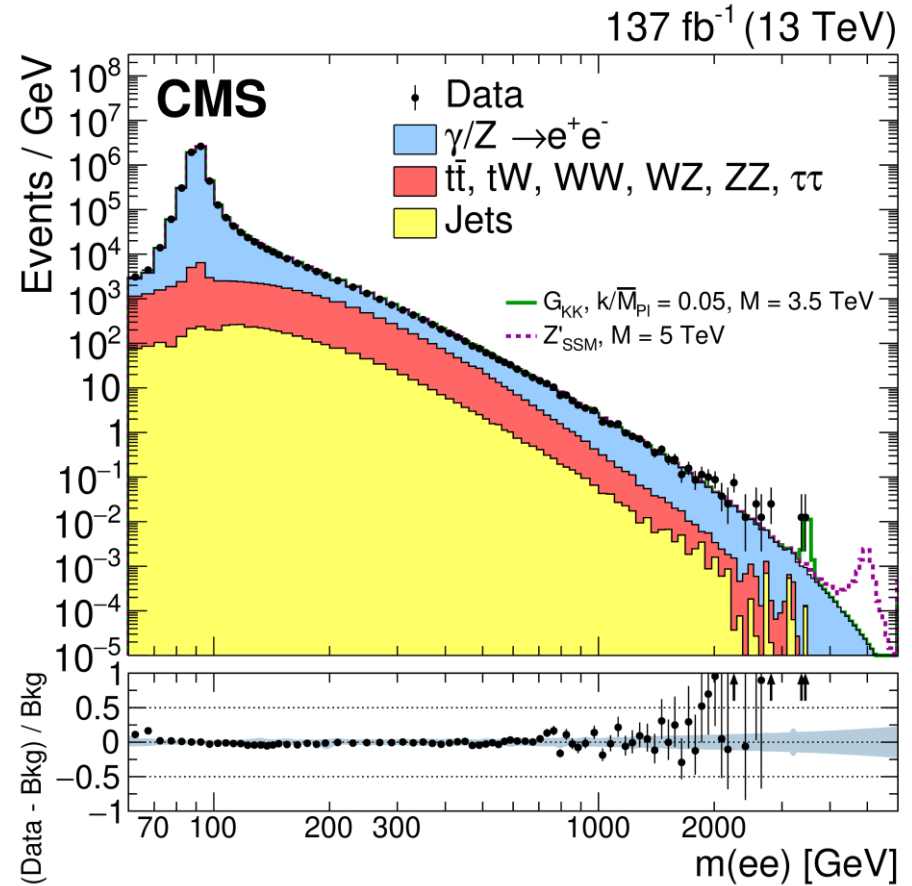
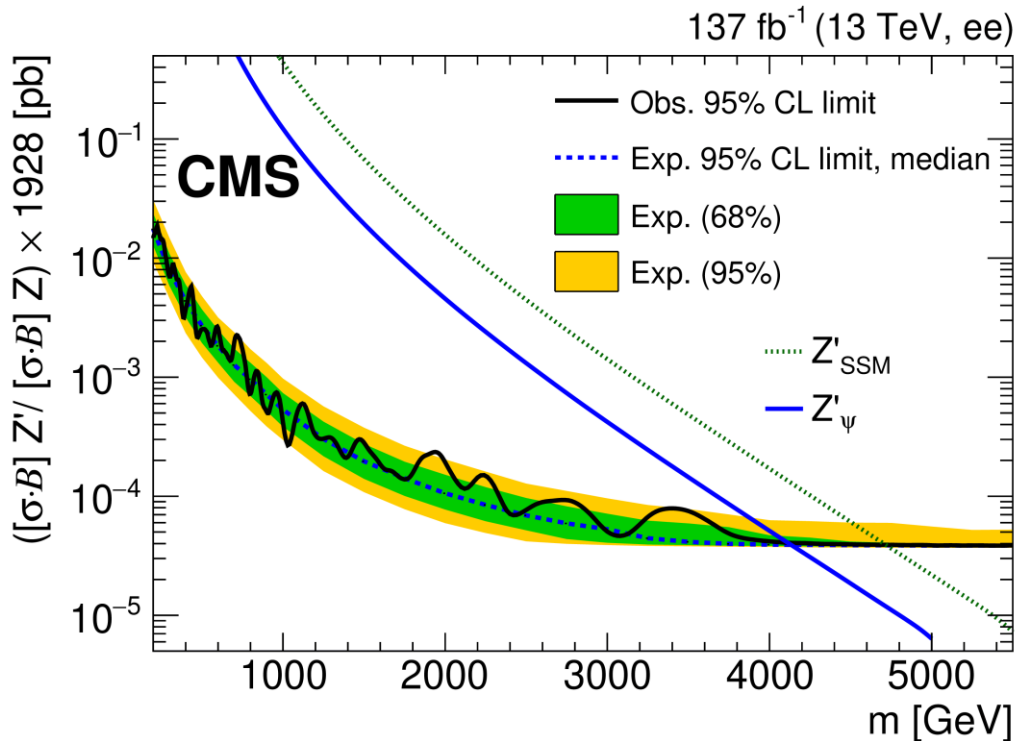
Masses of new
particles
within the
LHC reach



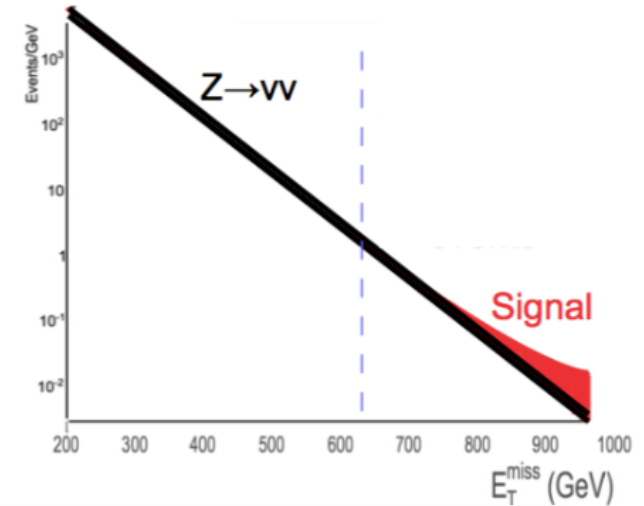
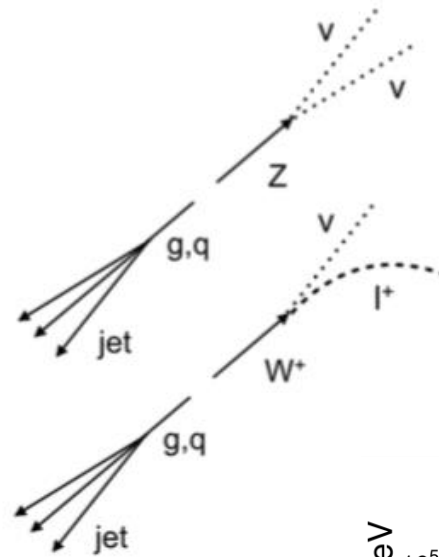
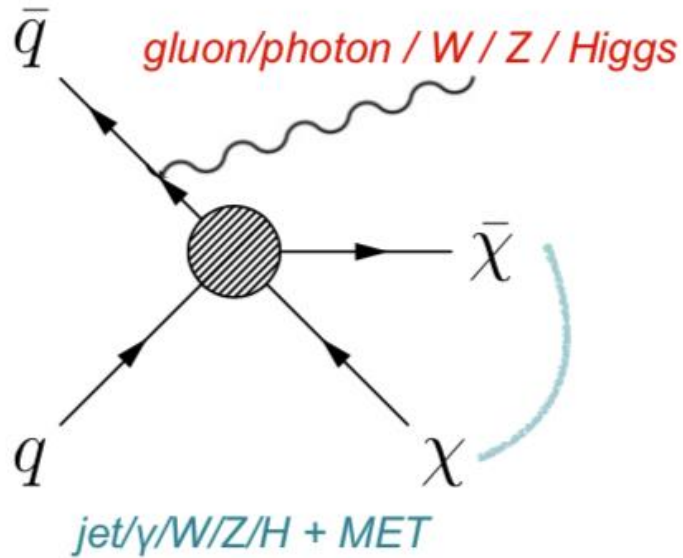
Masses of new
particles
not within the
LHC reach

Simple example: heavy Z' boson

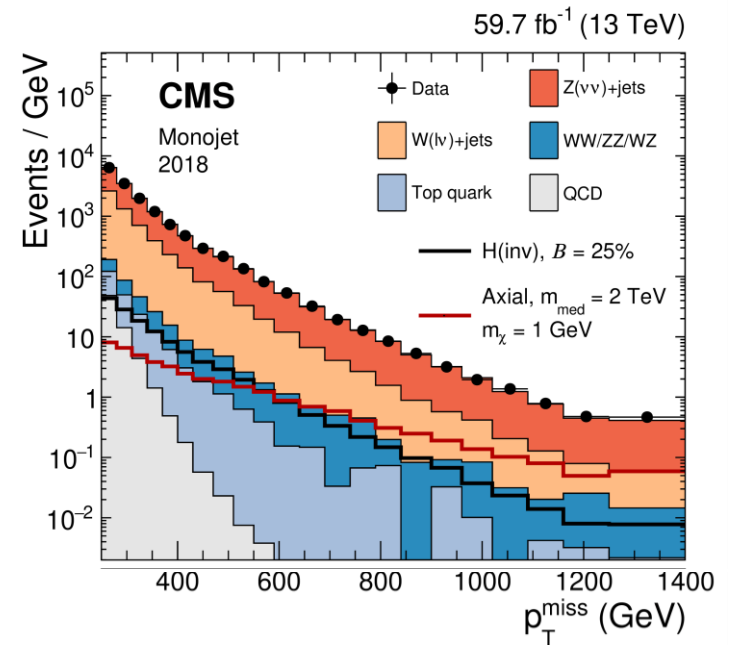
- Use very clear dilepton decay channel
 - ✓ e.g. electron-positron
 - ✓ Drell-Yan modeling important, but clear peak over a continuum (“bump hunting”)
- Result expressed as a 95% confidence-level excluded (upper) cross-section



More complex example: Dark Matter searches

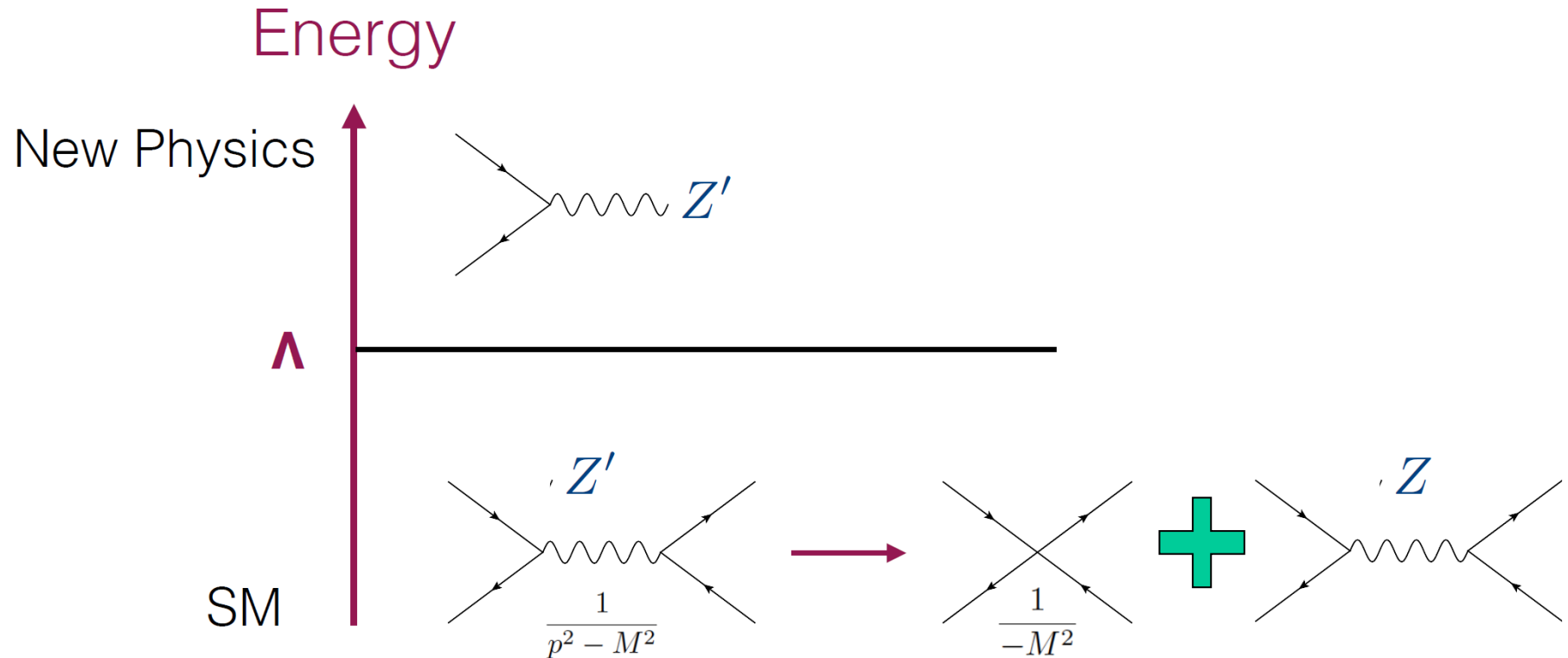


- Use MET shape to extract signal contribution
 - ✓ Similar shape for signal and background
 - ✓ Background modeling very important
- Main contributions (monojet example)
 - ✓ Z($\nu\nu$)+jet
 - ✓ W($l\nu$)+jet, where charged lepton is not reconstructed



Masses not within LHC reach

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



The Effective-Field Theory approach

BSM searches:

2010 \Rightarrow 2023

\Rightarrow New physics is heavy

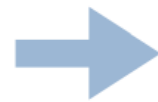
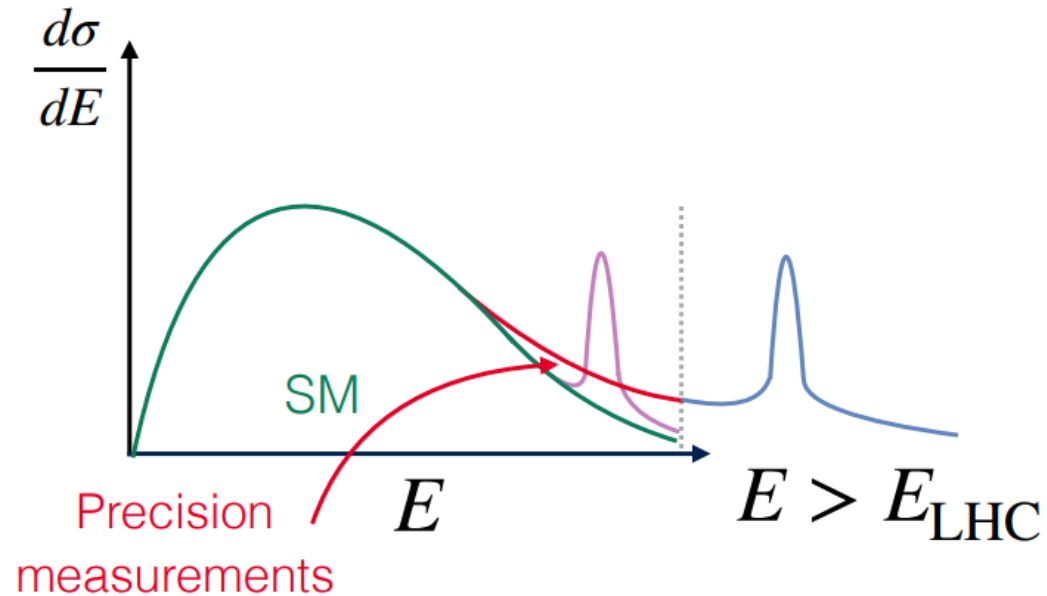
Direct (bumps)

Indirect (tails)

Heavy new physics

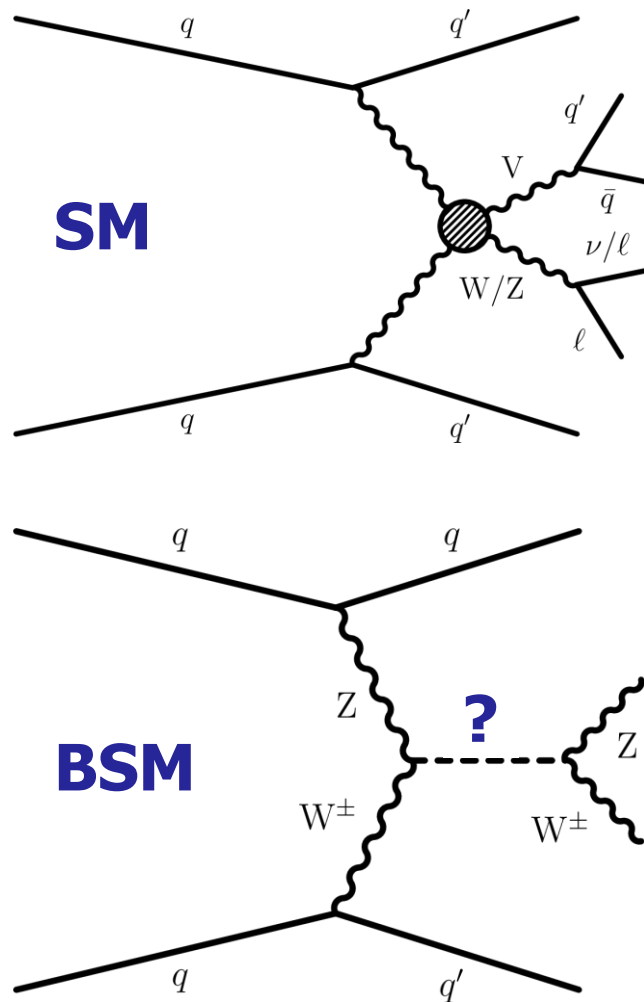
Precision measurements

High energy

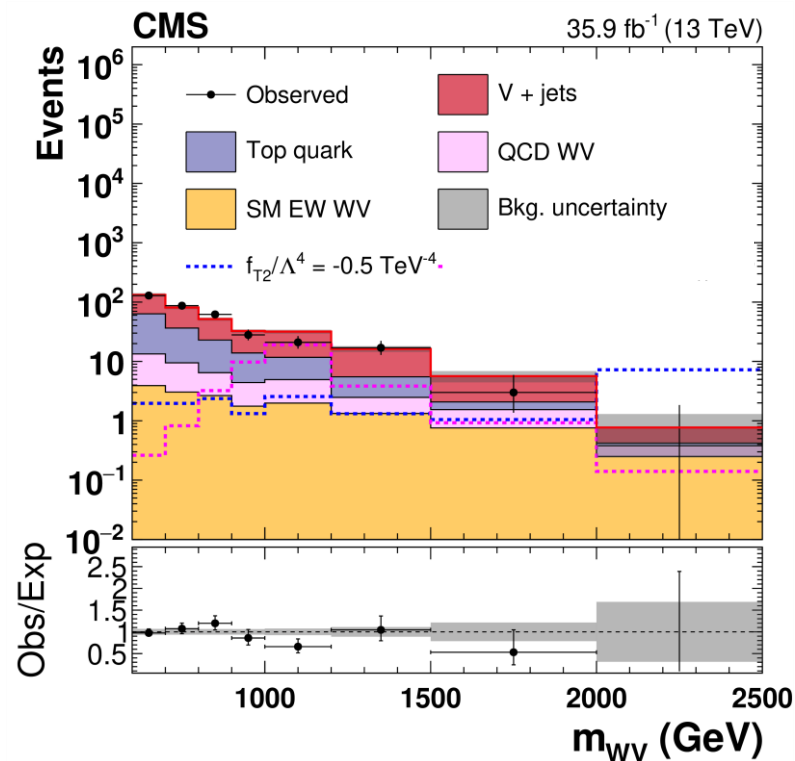


Effective Field Theory (EFT)

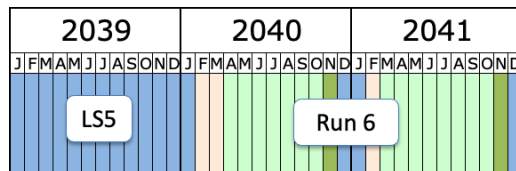
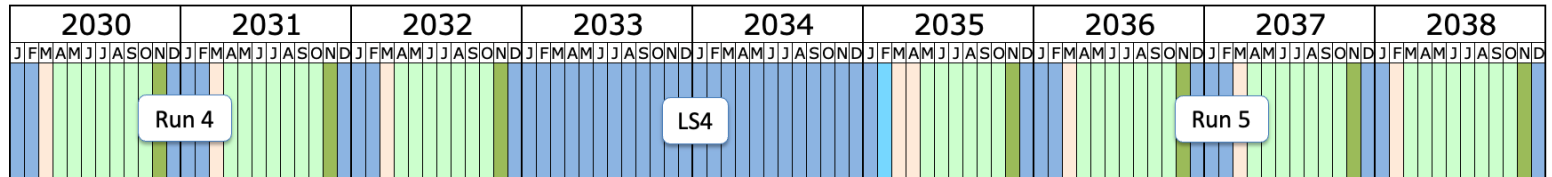
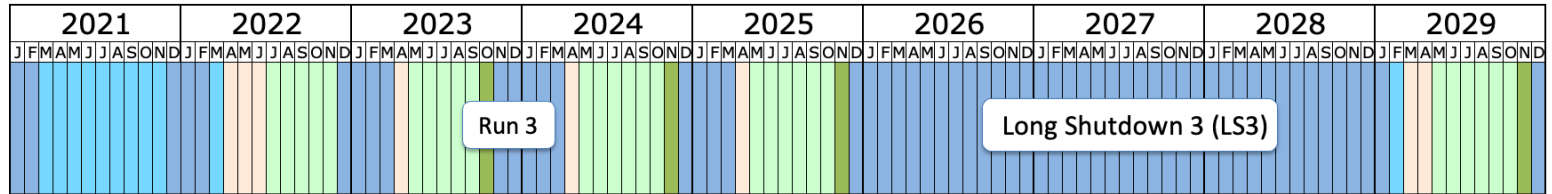
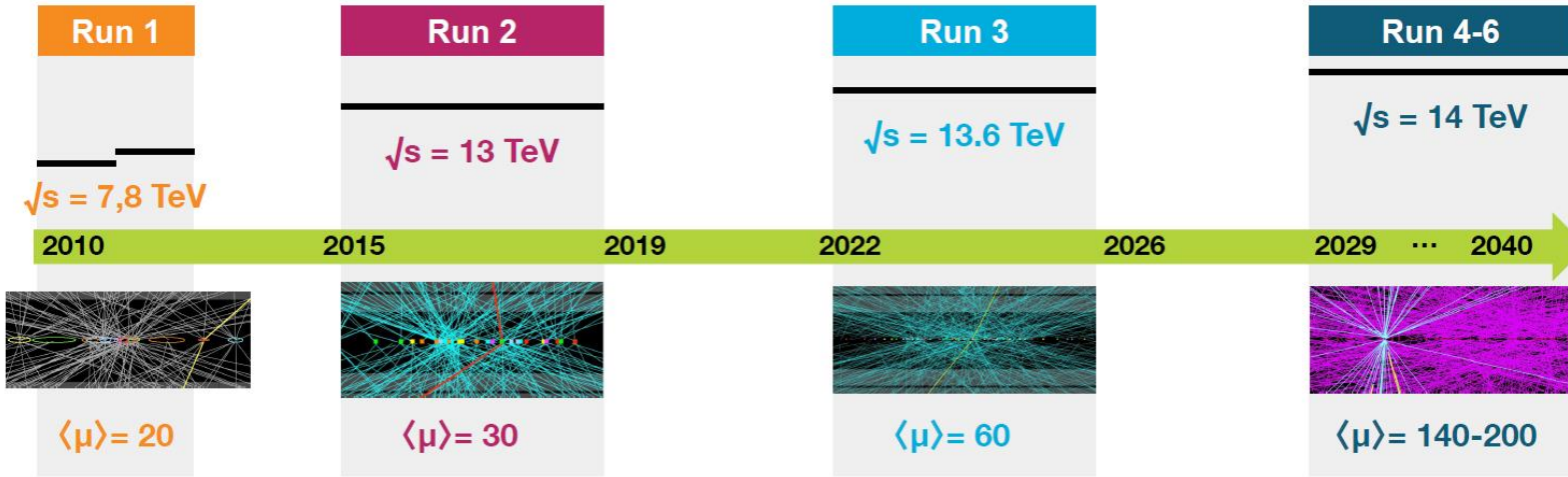
Example: di-boson production



- 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...



- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning

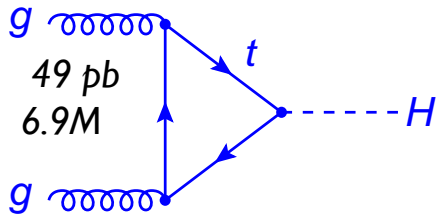
Last update: April 2023

Additional information

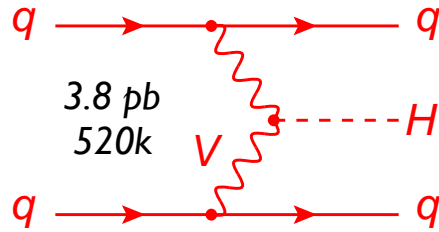
(I find you lack of faith disturbing)

Probing Higgs couplings at the LHC

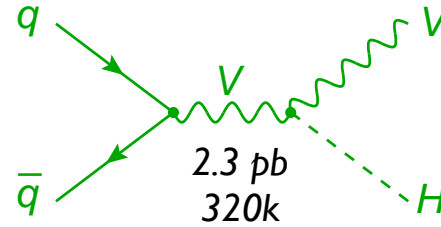
$\sigma[\text{pb}] @ 13 \text{ TeV}$
 # Higgs produced in 140 fb^{-1}
 in one experiment



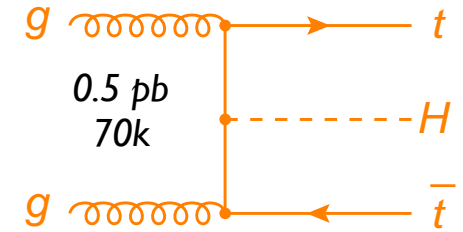
gluon-gluon fusion:
 main production mode at
 LHC



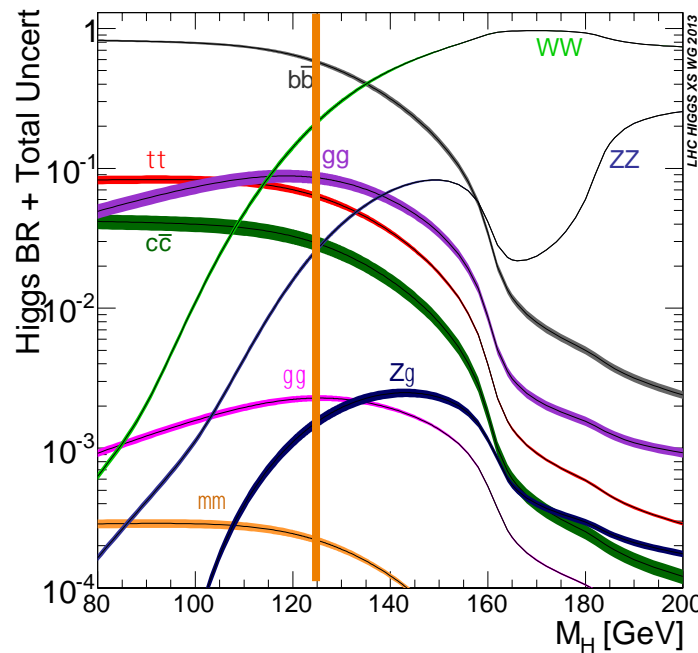
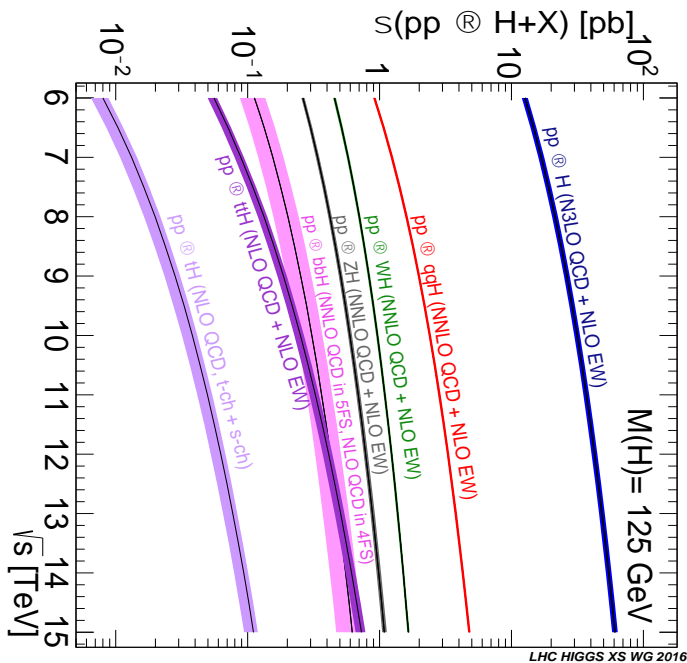
Vector Boson Fusion
 2 well-separated forward
 jets



VH
 tag W and Z
 boson decays



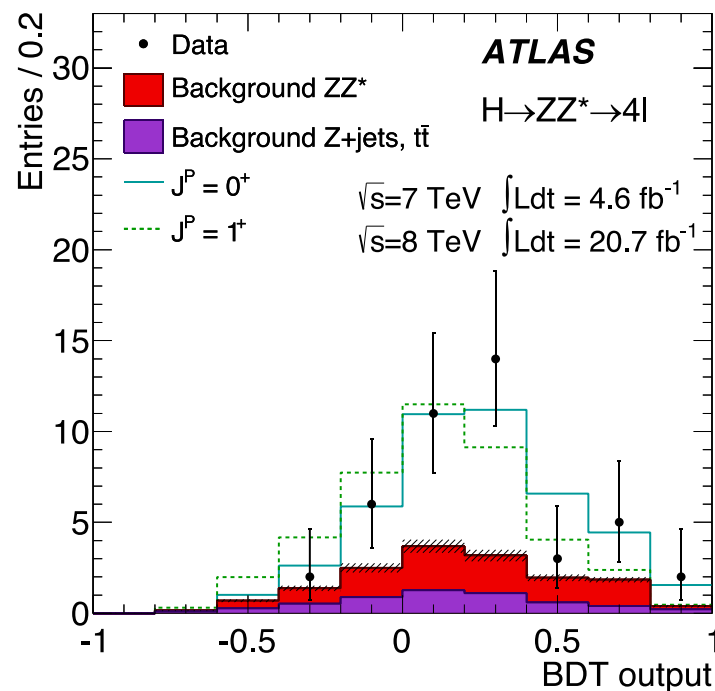
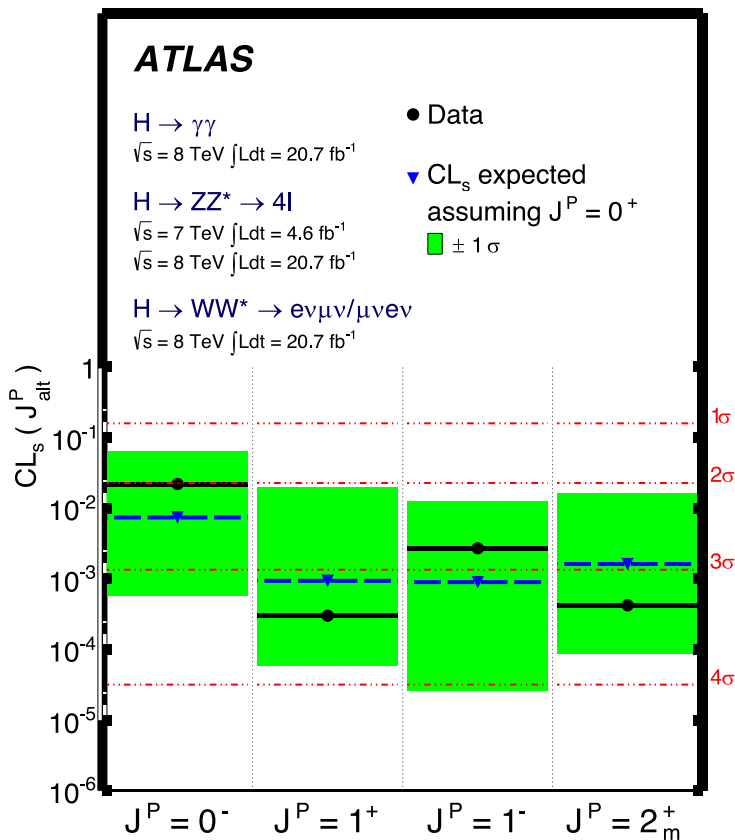
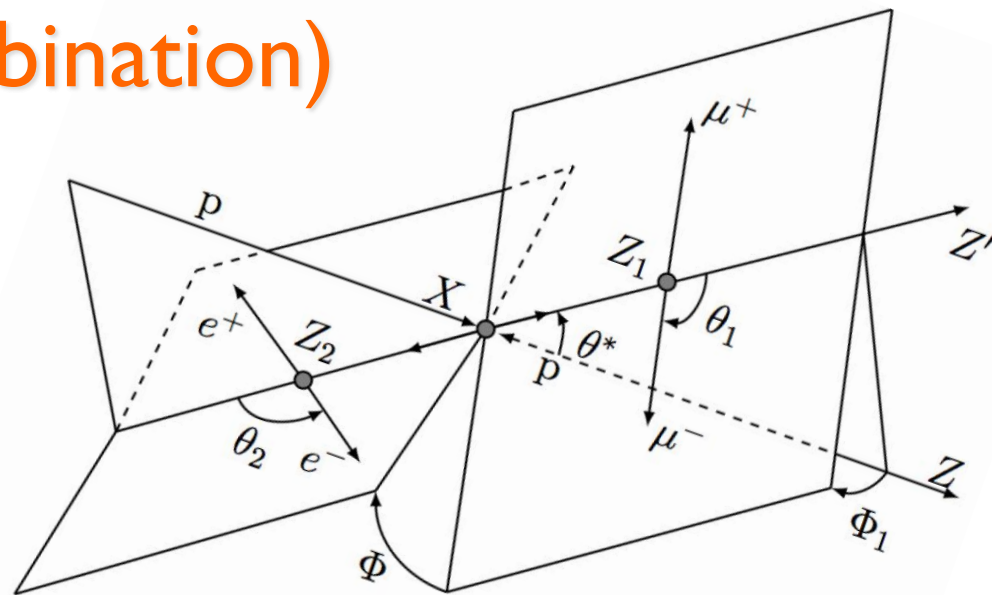
ttH
 tag 2 top quarks



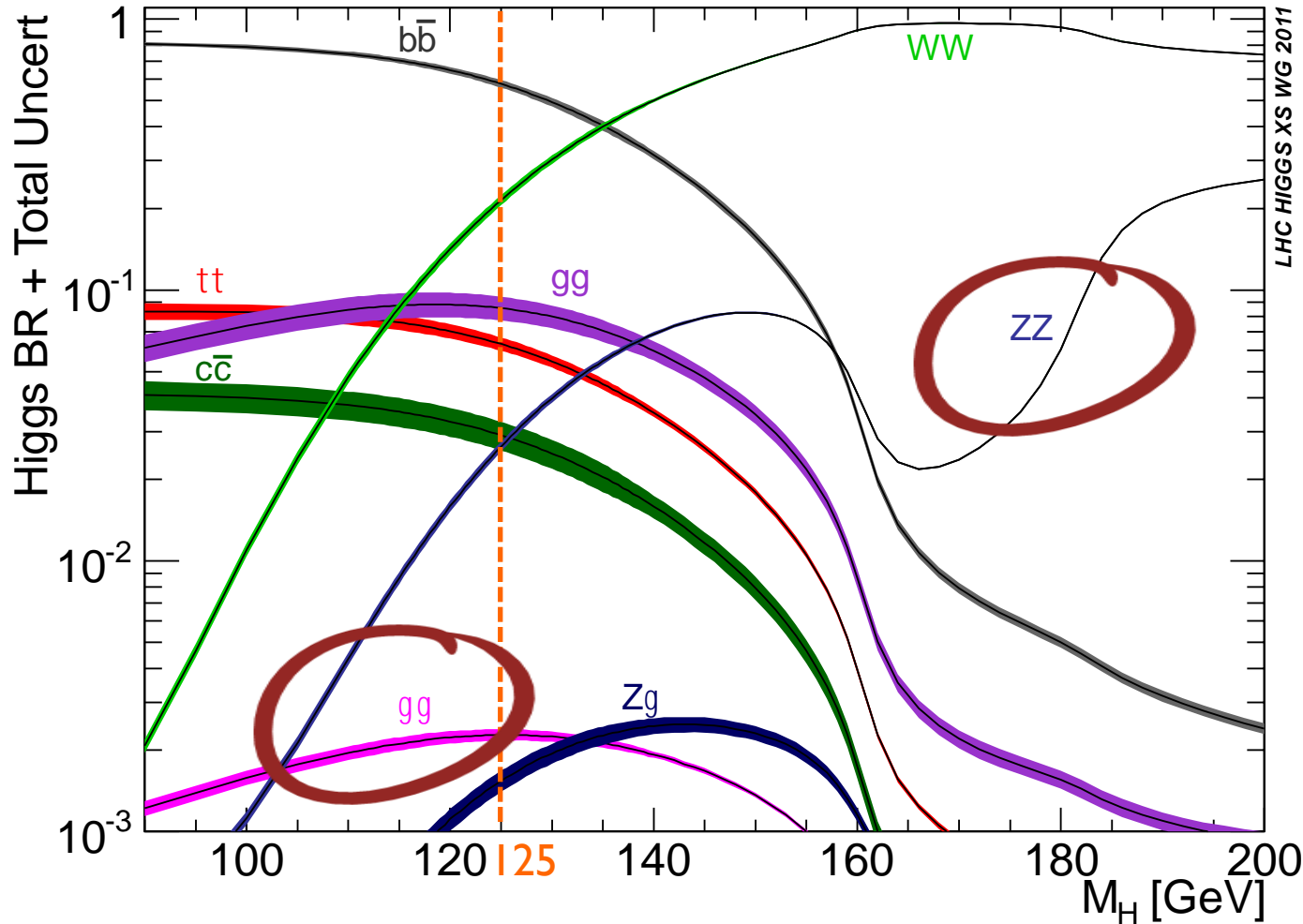
| decay | SM BR [%] $m_H = 125.09 \text{ GeV}$ |
|------------------------------|---|
| $H \rightarrow bb$ | 58.1 |
| $H \rightarrow WW$ | 21.5 |
| $H \rightarrow \tau\tau$ | 6.26 |
| $H \rightarrow ZZ$ | 2.64 |
| $H \rightarrow \gamma\gamma$ | 0.23 |

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



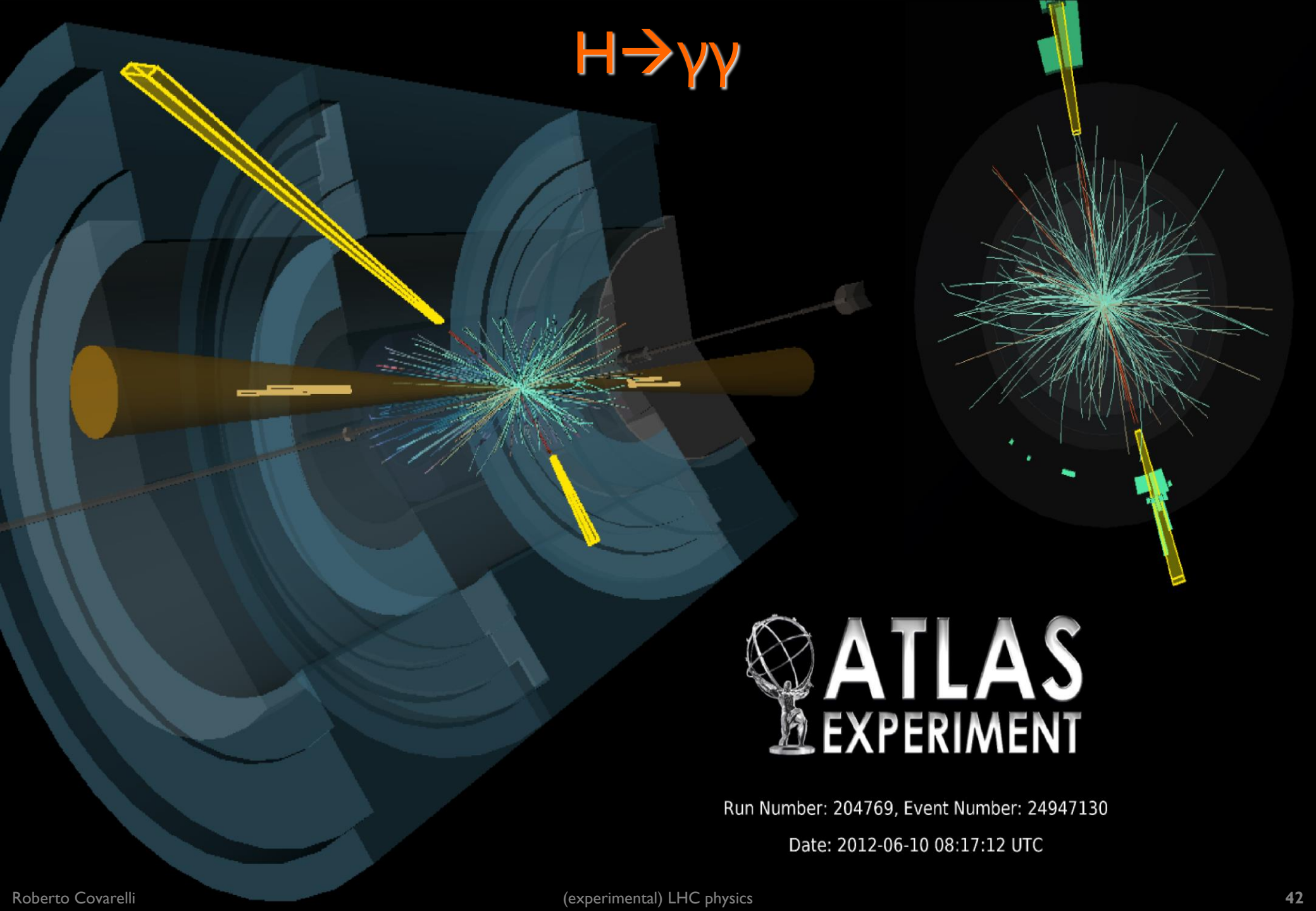
Standard Model Higgs decays



| 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

$H \rightarrow \gamma\gamma$

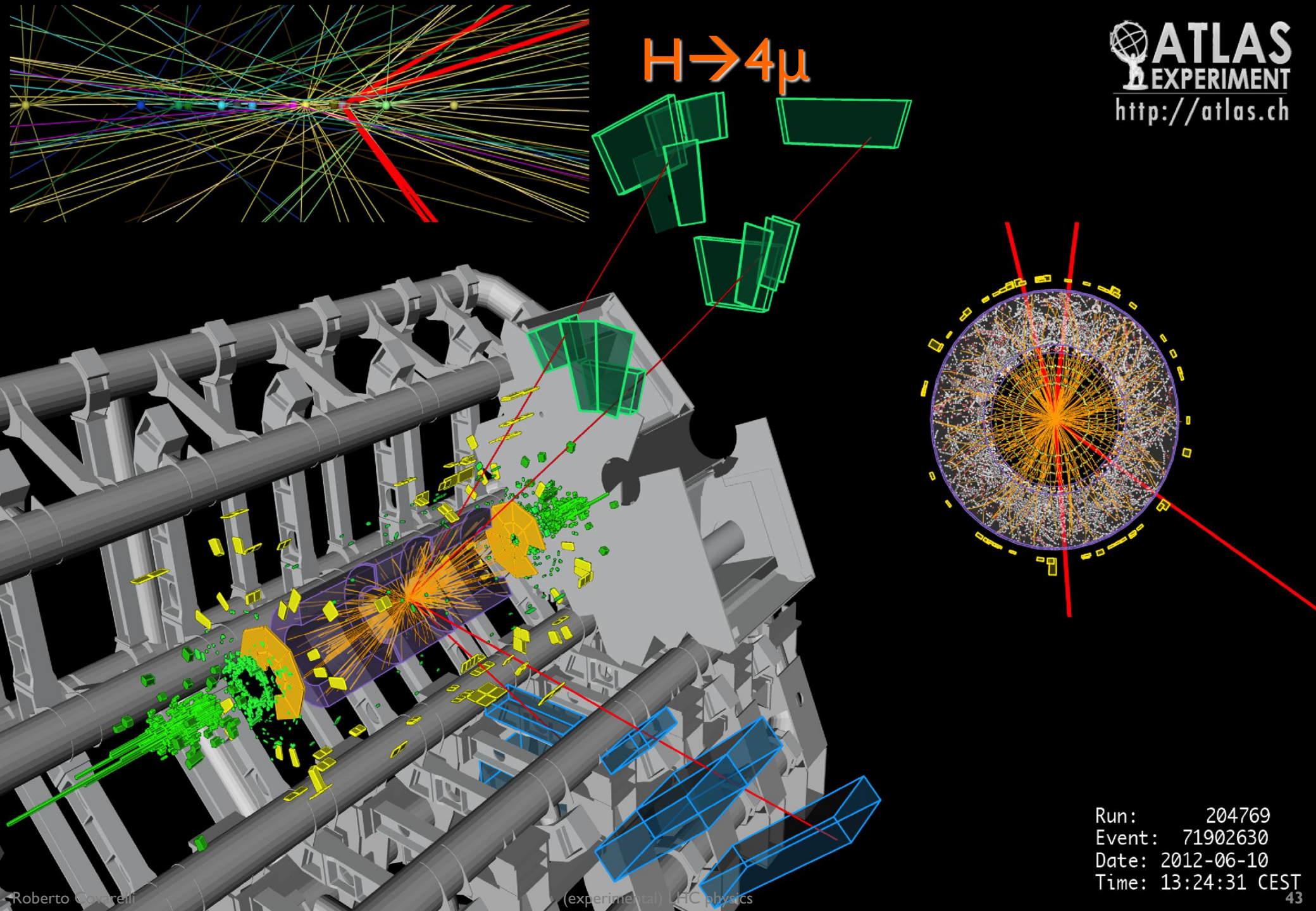


 **ATLAS**
EXPERIMENT

Run Number: 204769, Event Number: 24947130

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

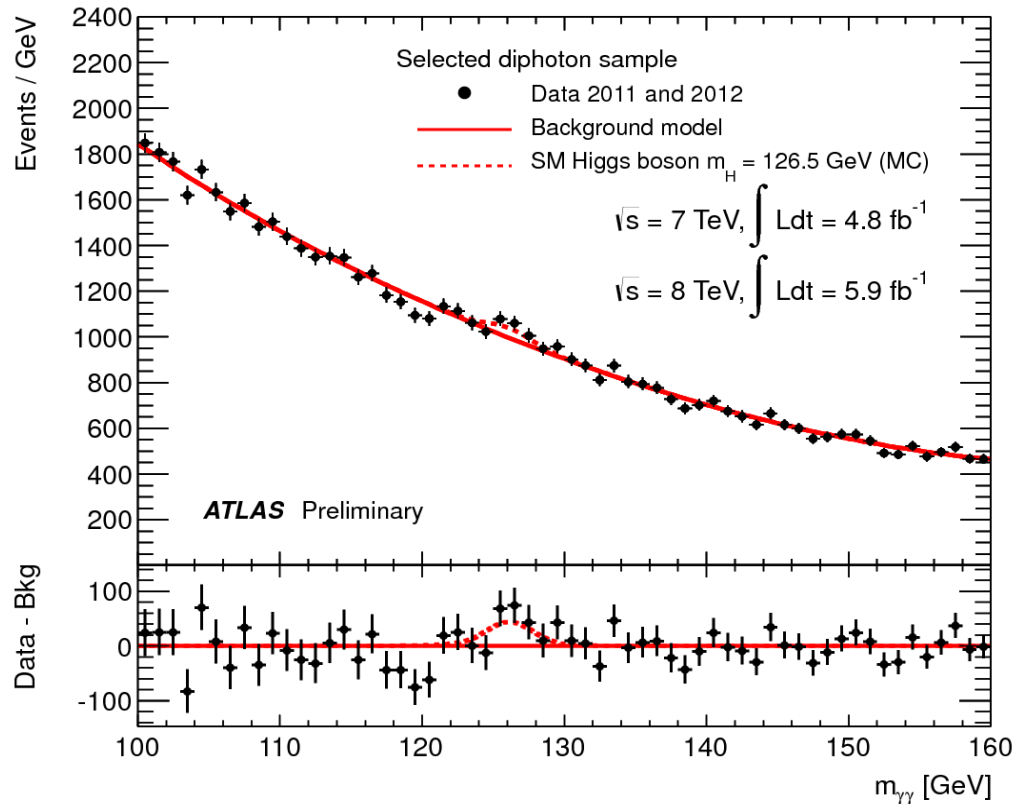
$H \rightarrow 4\mu$



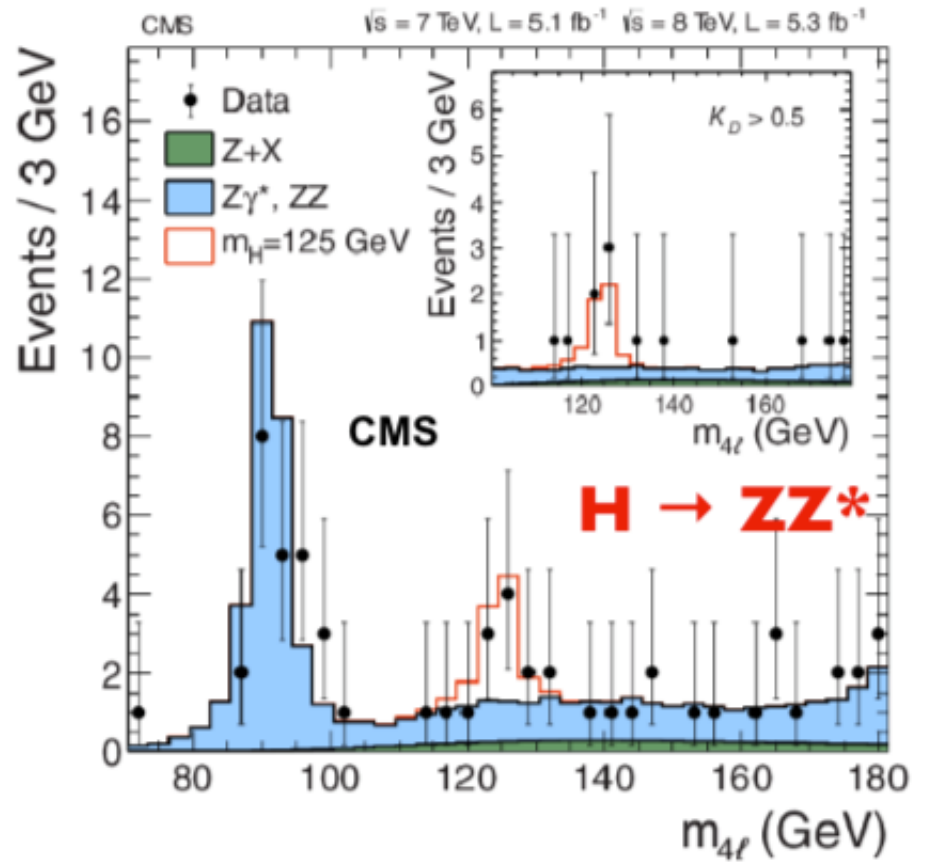
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs signals on July 4th 2012

H → $\gamma\gamma$



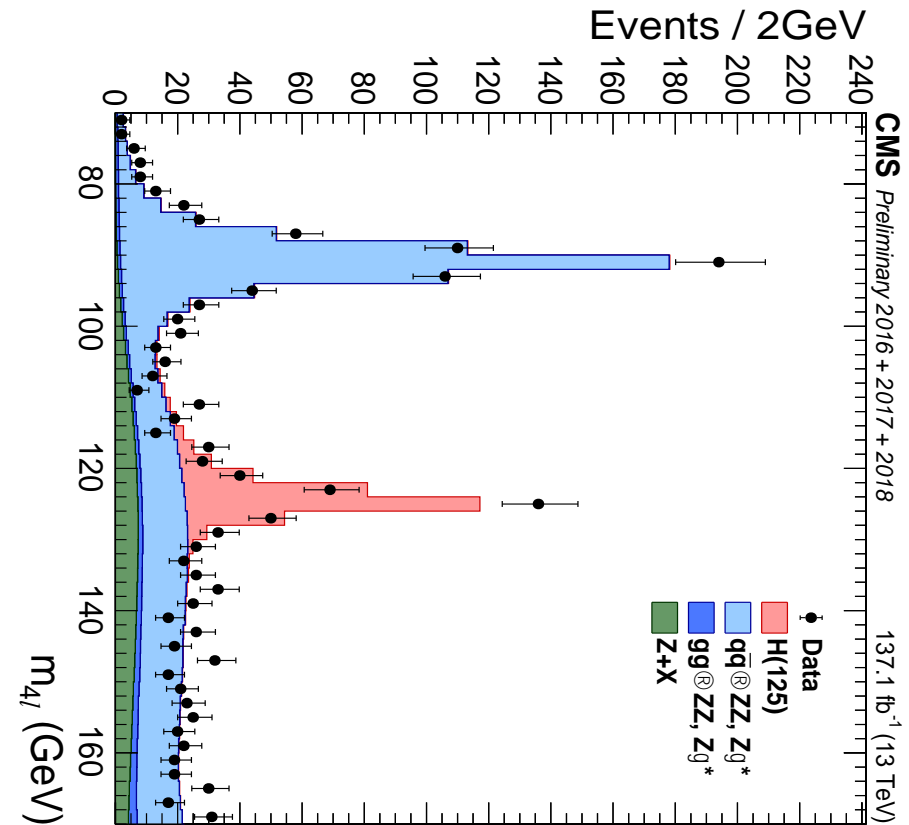
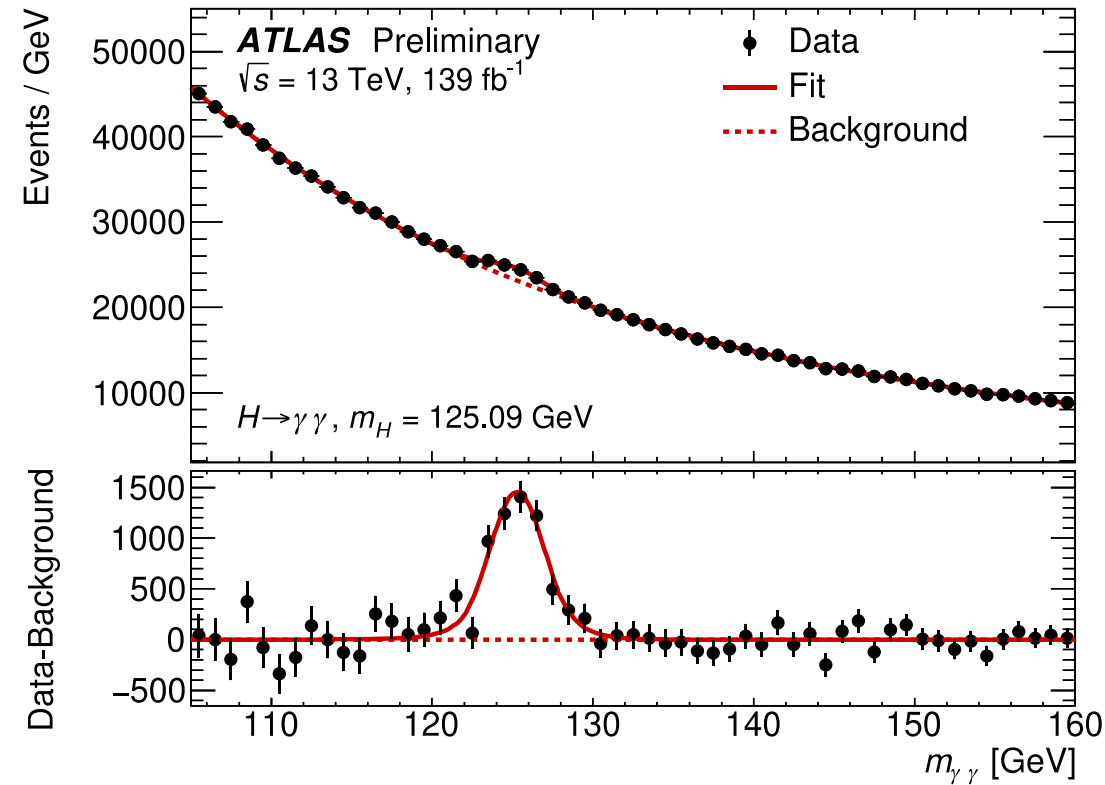
H → 4l



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

$H \rightarrow \gamma\gamma$

$H \rightarrow 4l$



What spin do particles have?



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

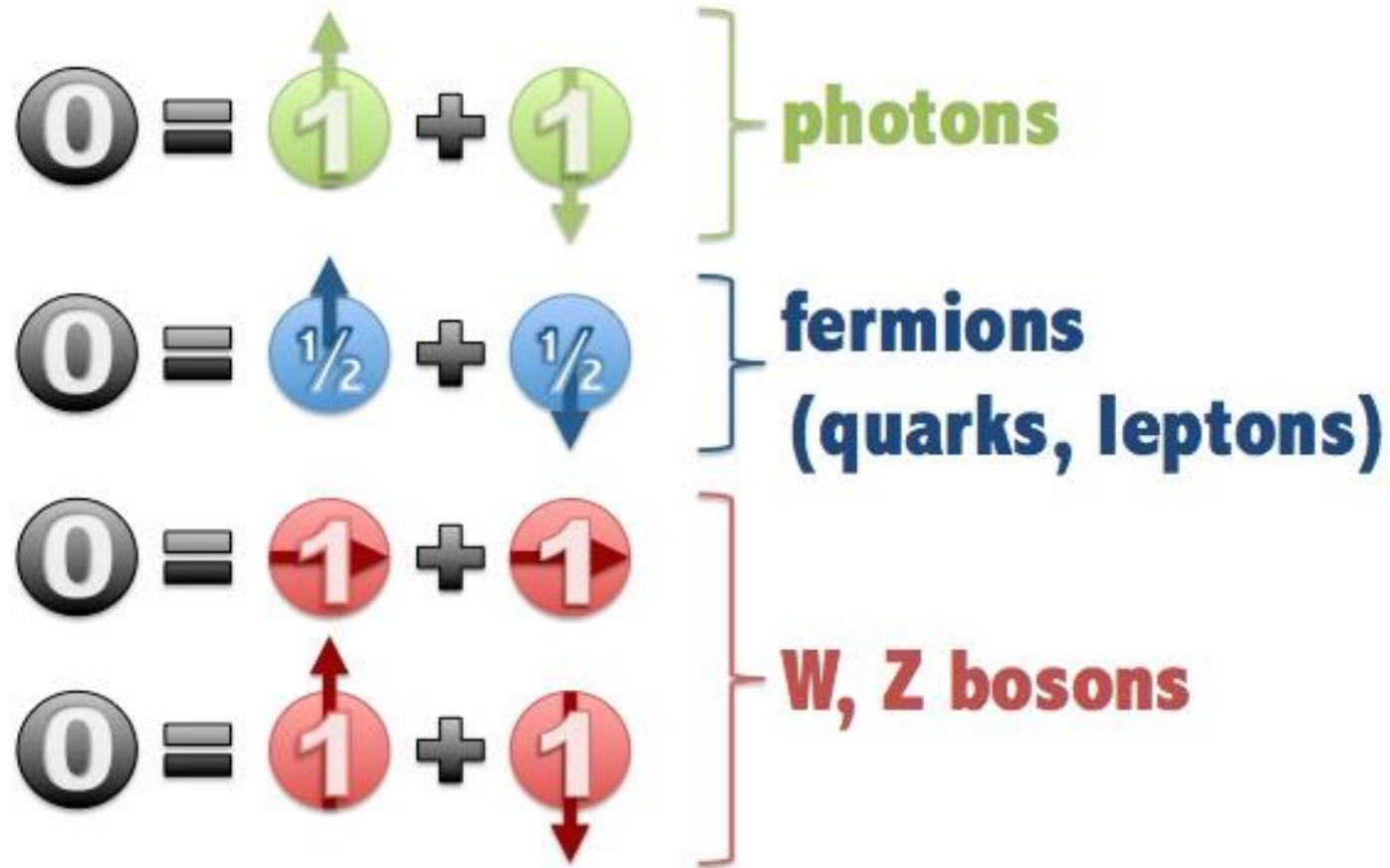


massive bosons
(W, Z bosons)
spin = $+1, 0, -1$

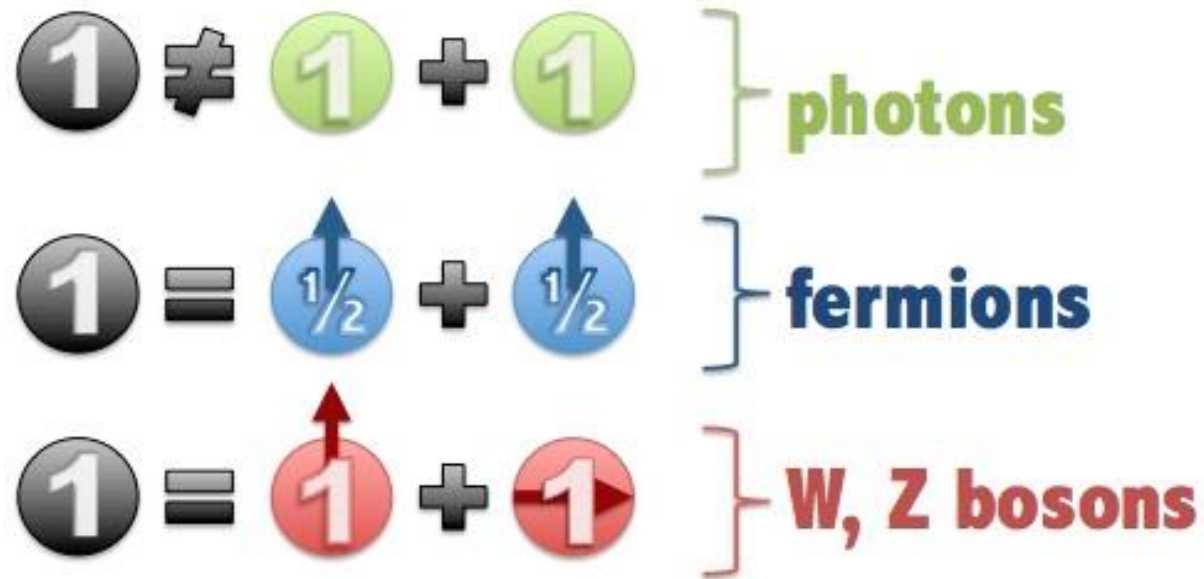


massless bosons
(photon, gluon)
spin = $+1, -1$

What can a spin 0 particle decay to?



What can a spin 1 particle decay to?



What can a spin 2 particle decay to?

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

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

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

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

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

So, what spin has our Higgs-like particle?

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

Spin with $H \rightarrow 4$ leptons

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

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

