(experimental) LHC physics

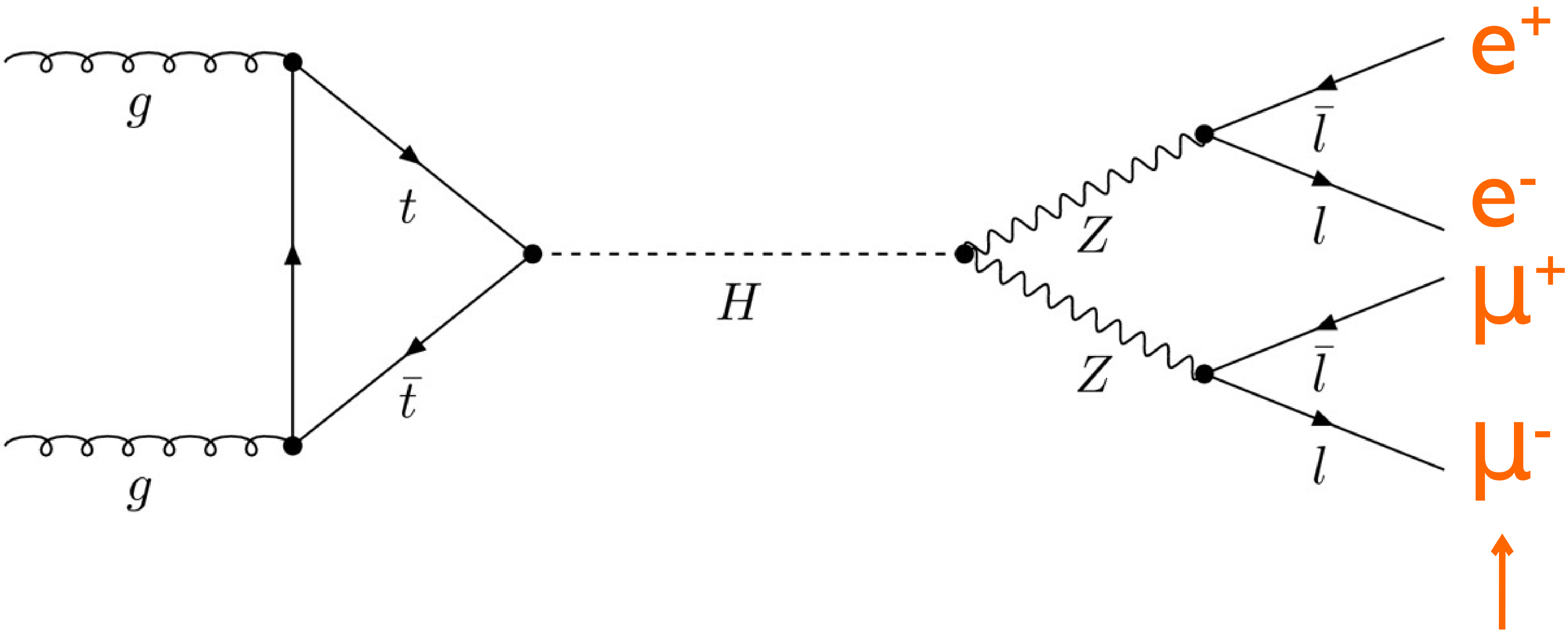
2. { how to search for (and measure) a new particle }

Riccardo Bellan

What do we want to measure?

Example: let's assume a Higgs boson is produced at the LHC …
*It is a **SM particle**, we **can predict** how and how frequently*

… we look for "stable" particles from an unstable particle decays

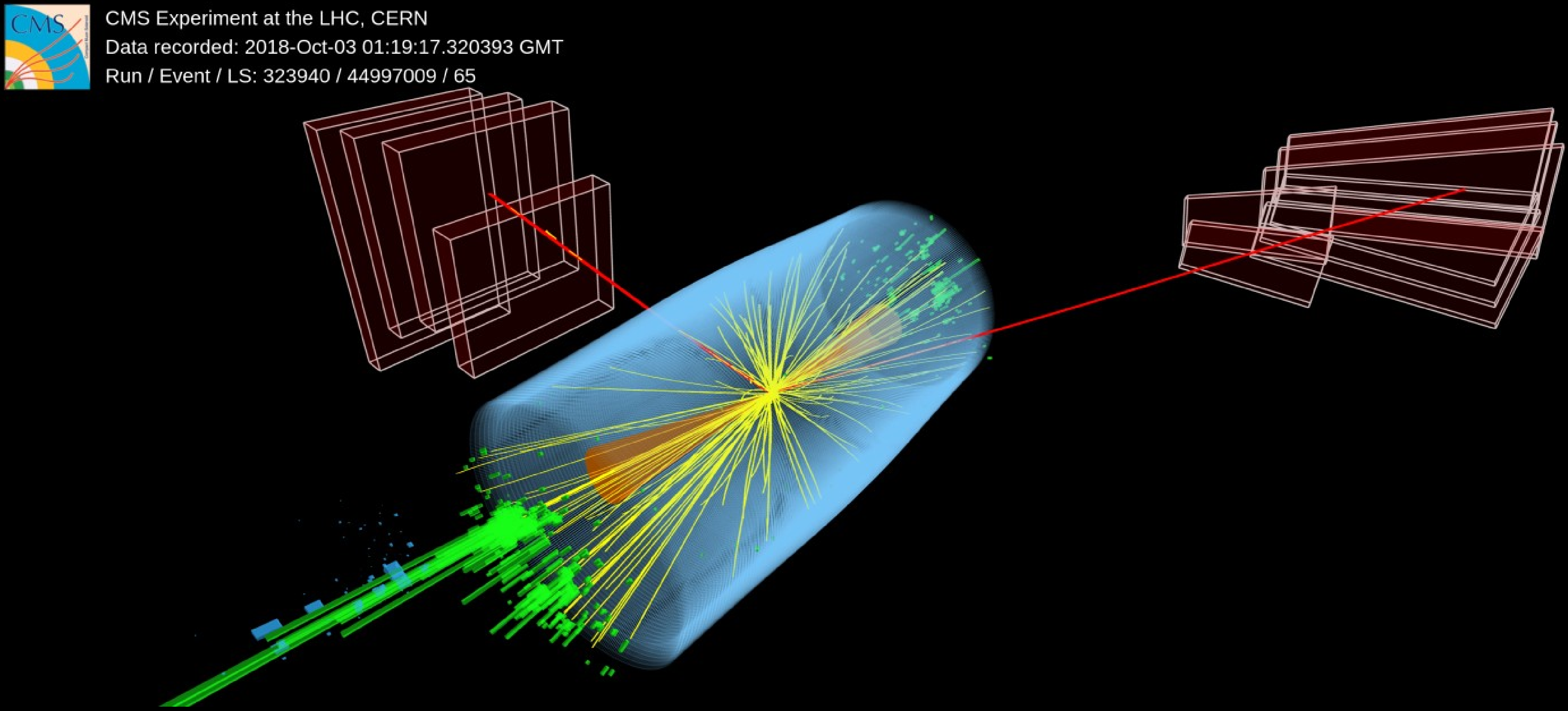


this is what we are looking for…

Step 1: find events with the right ingredients

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

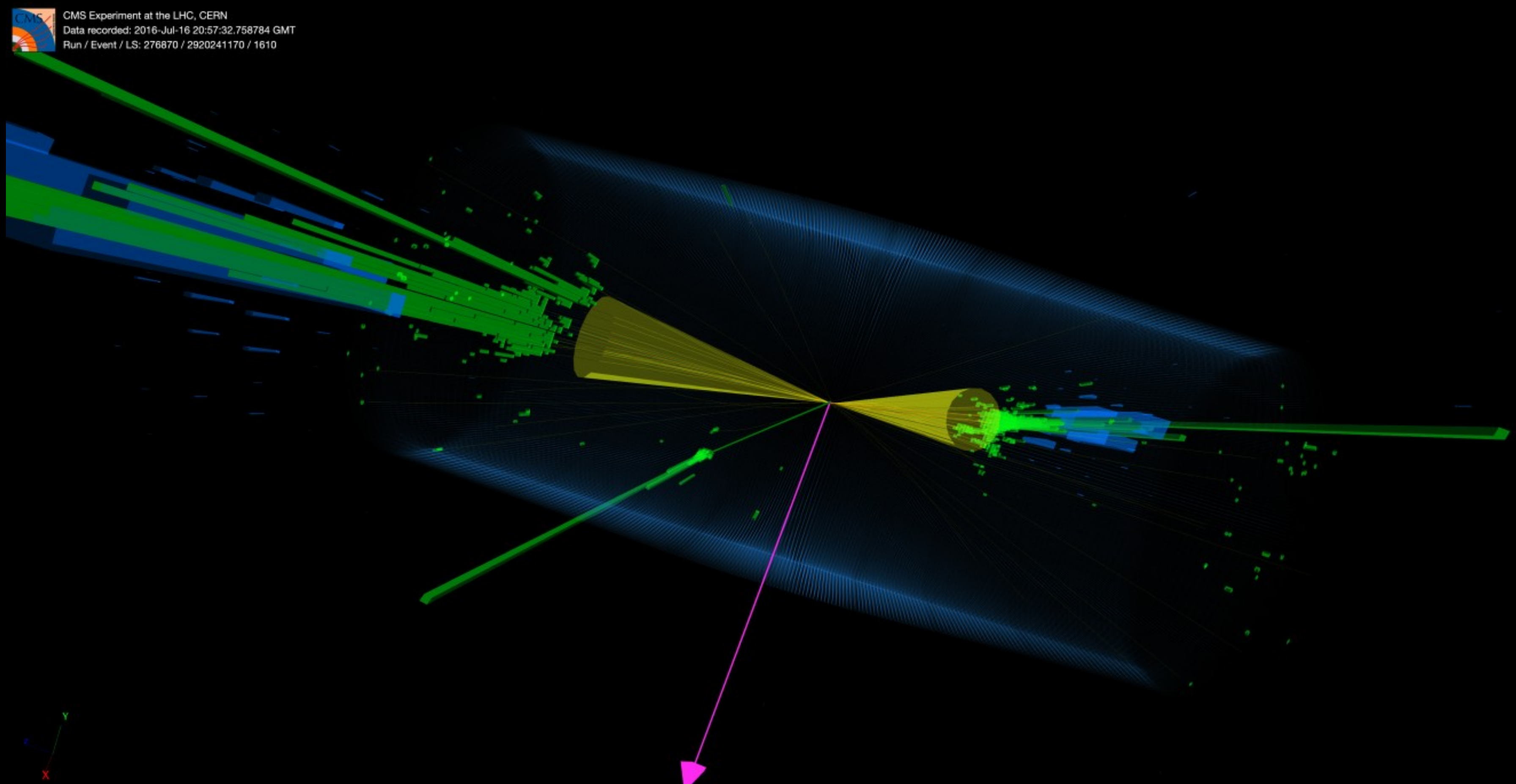
Is this event OK?



Step 1: find events with the right ingredients

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

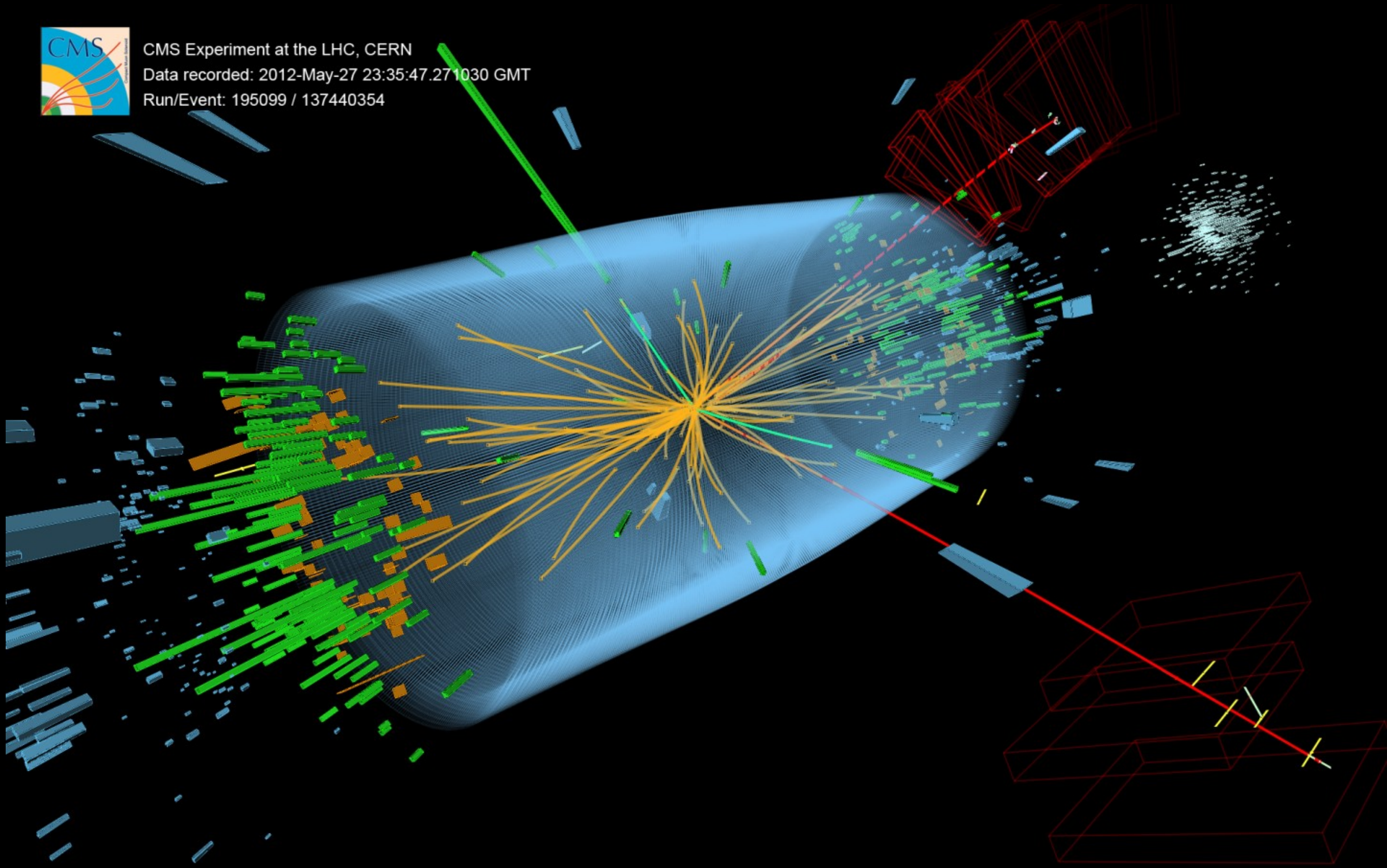
What about this one?



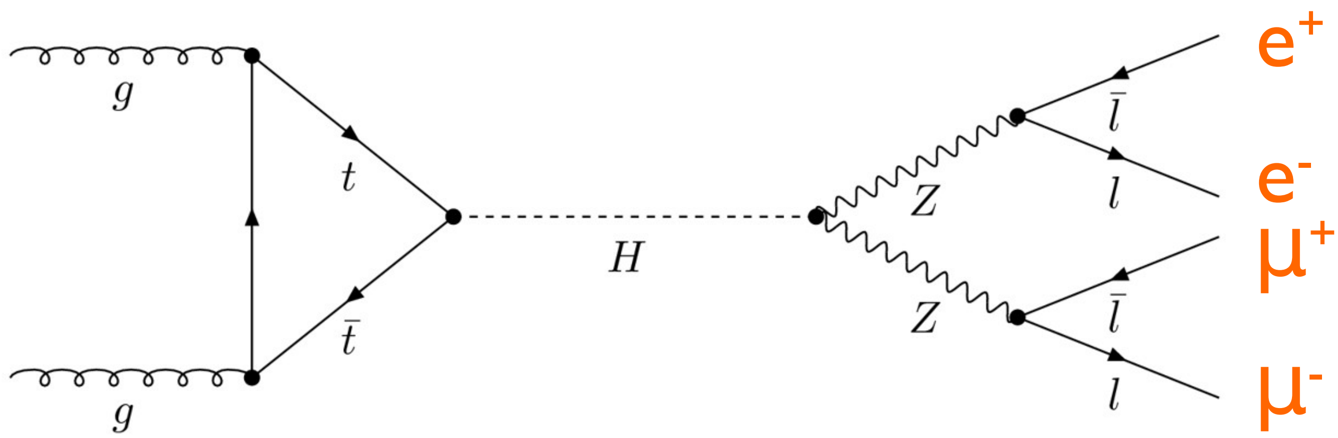
Step 1: find events with the right ingredients

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

And this one?

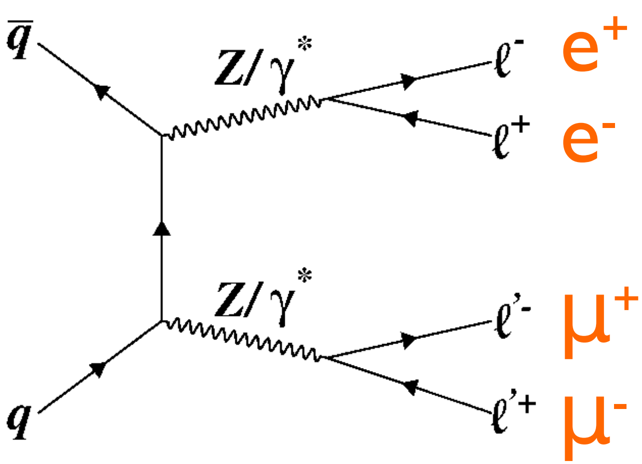


Step 2: signal and background



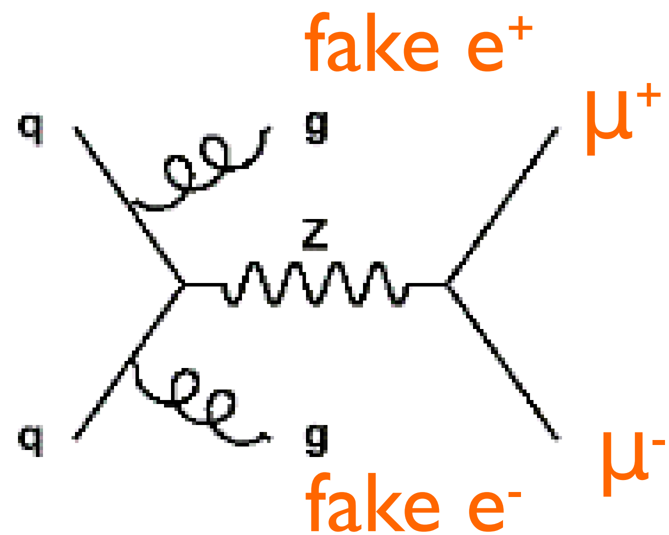
Irreducible background

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

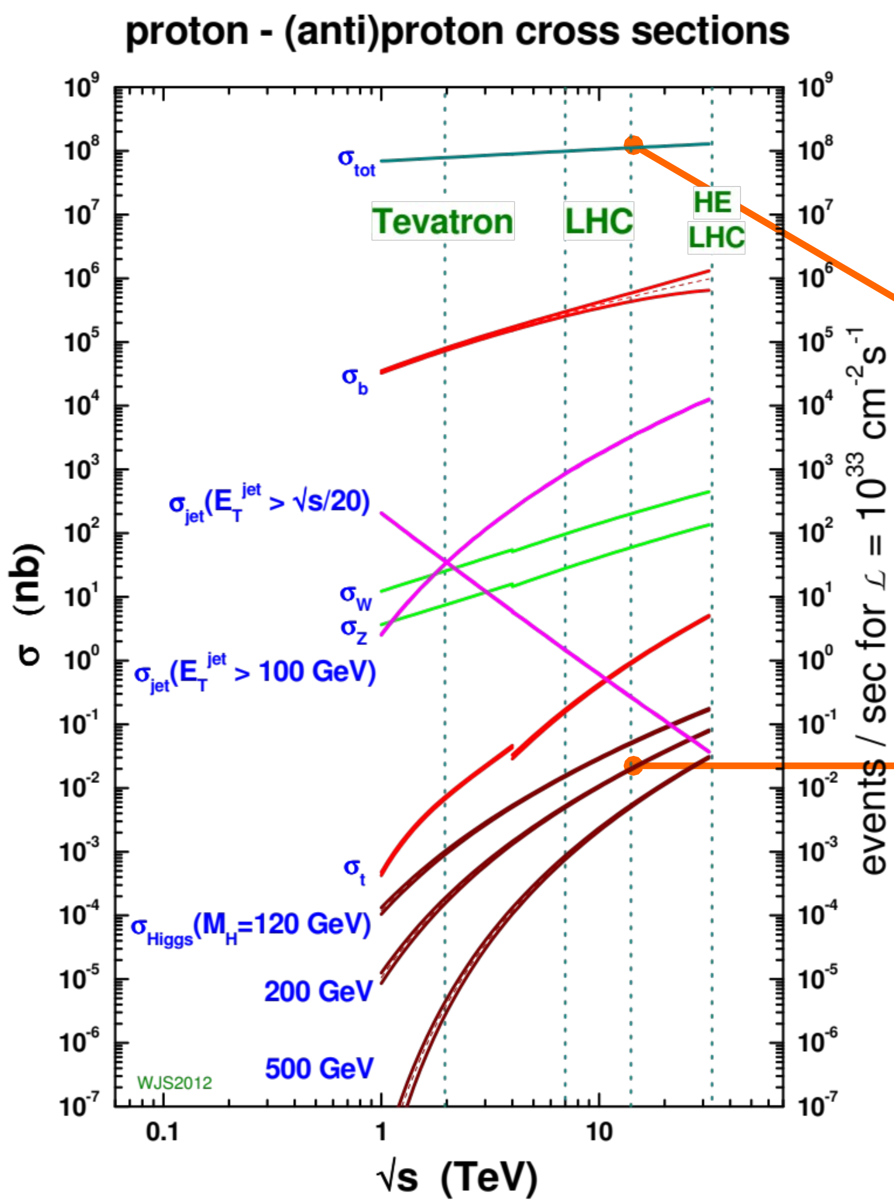


Reducible background

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

~10^{10}

10^{-1} events/s

~ 1 Higgs boson every 2 seconds

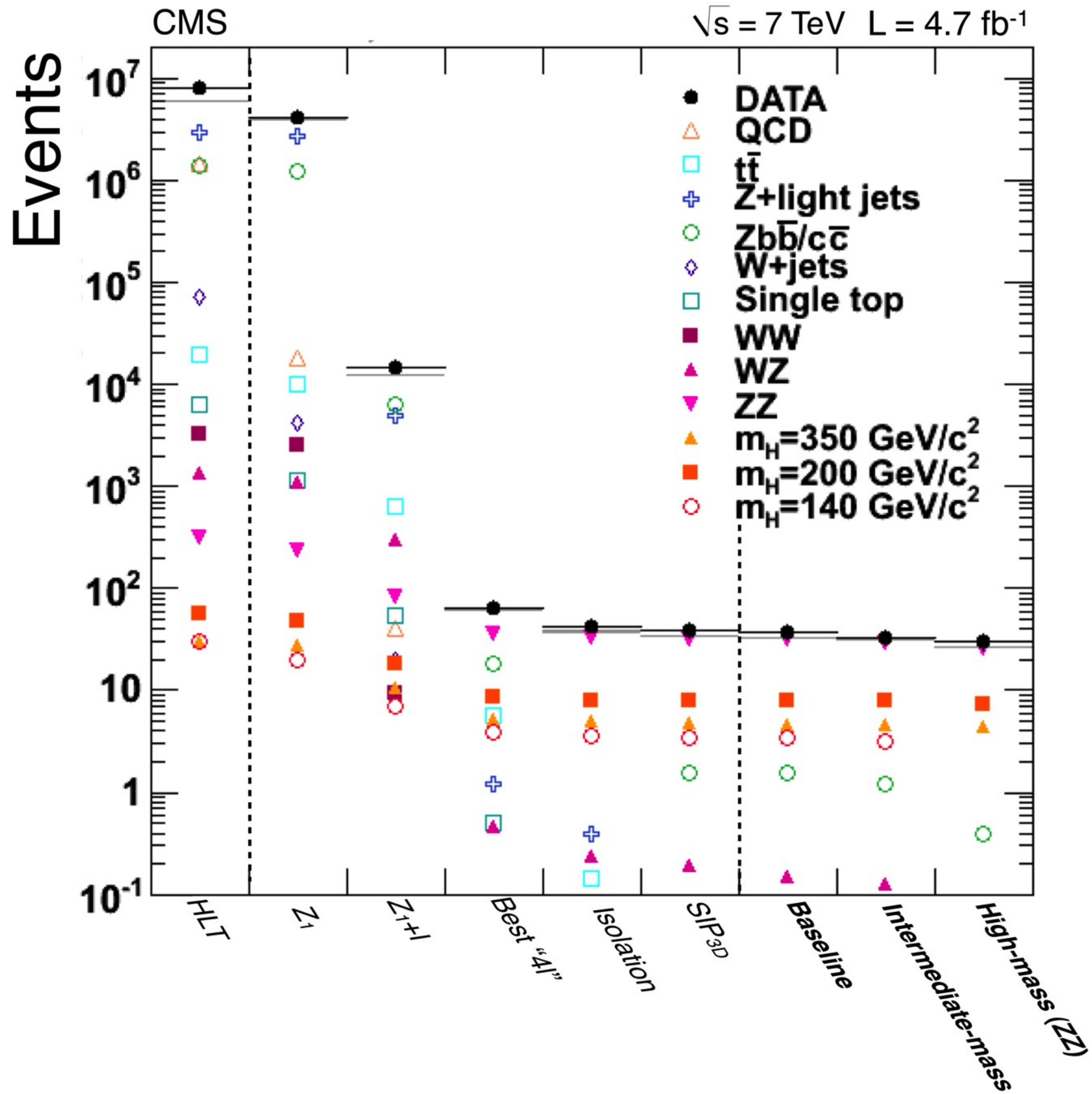
[m_H ~ 125 GeV]

0.2% H → $\gamma\gamma$

0.01% H → ZZ

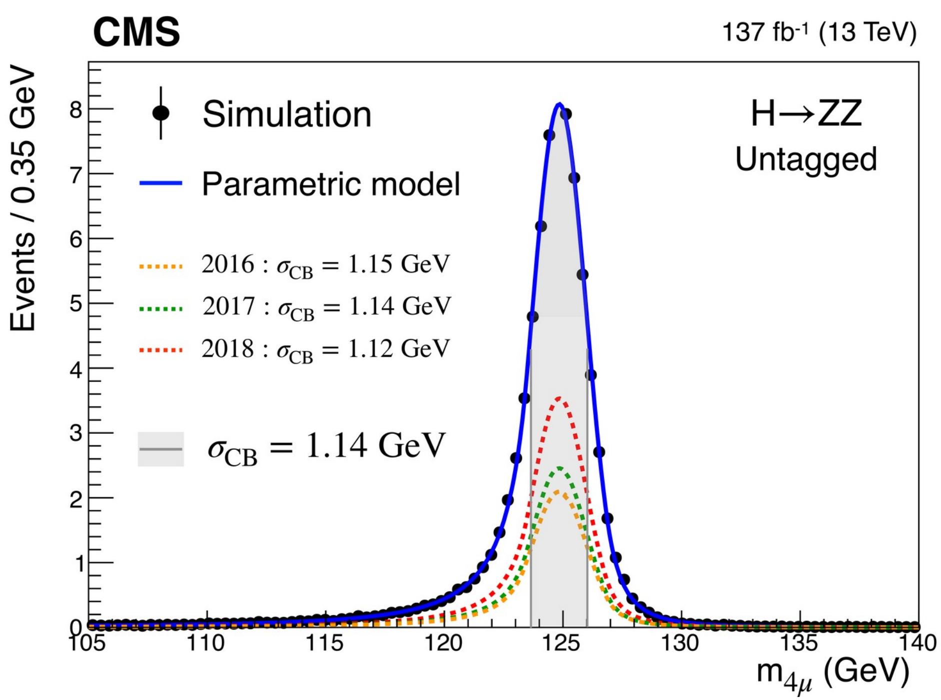
Lose some signal, suppress backgrounds…

- 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

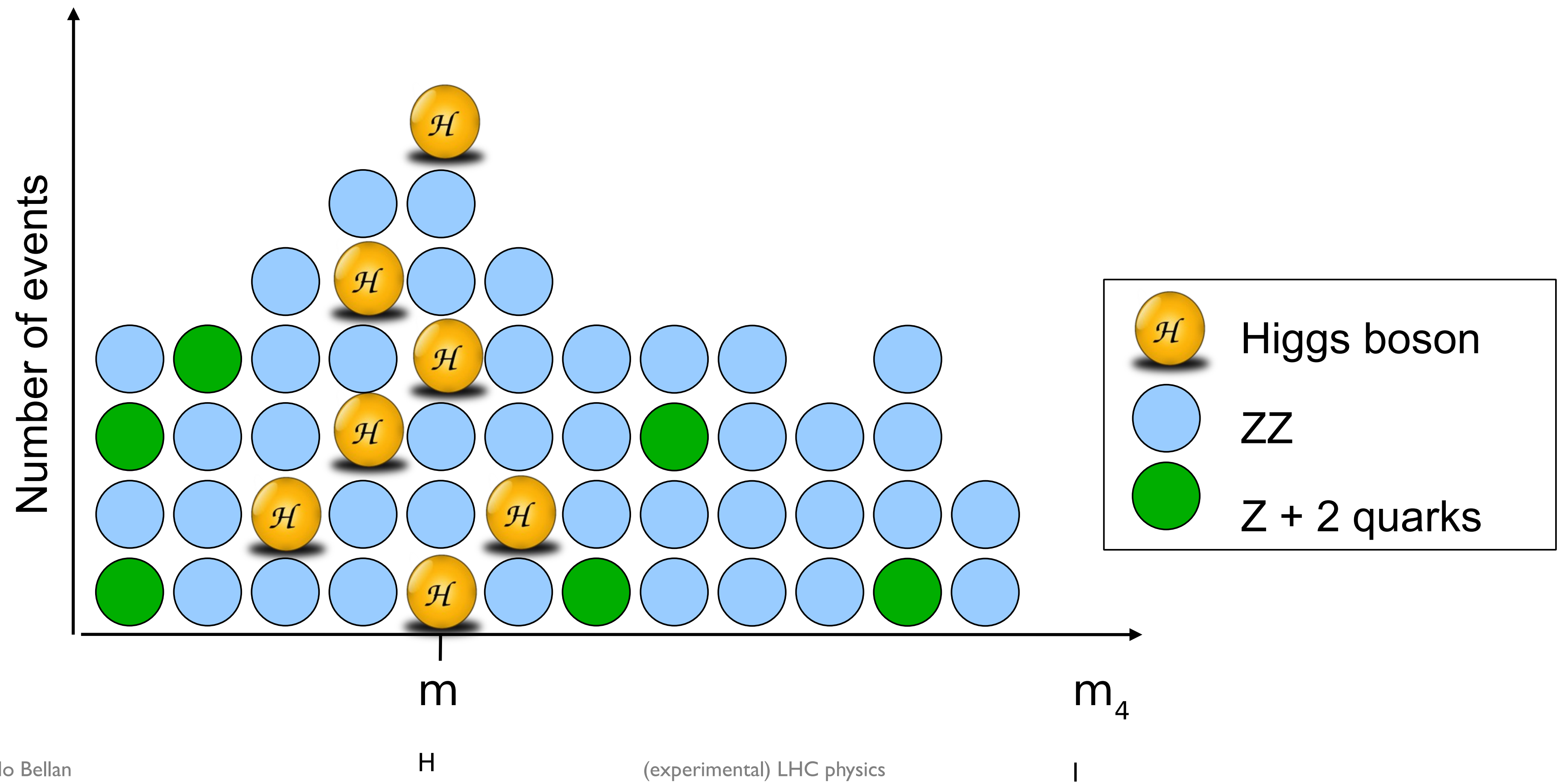
- We have 4 particles…
  - ✓ … with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^+\mu^-$
- Reconstruct invariant mass from the 4 particles $M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$



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

Extract signal from background

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



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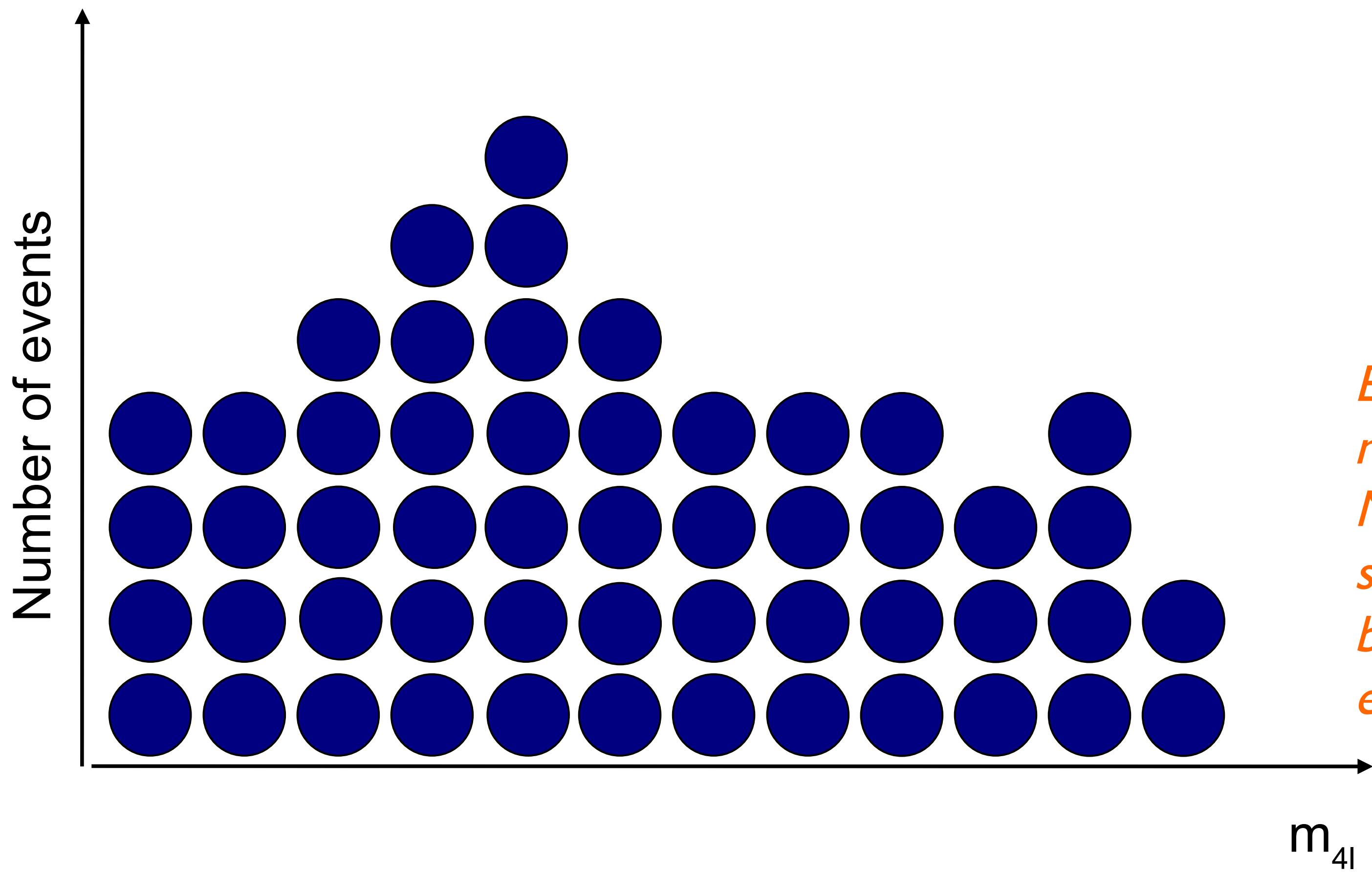
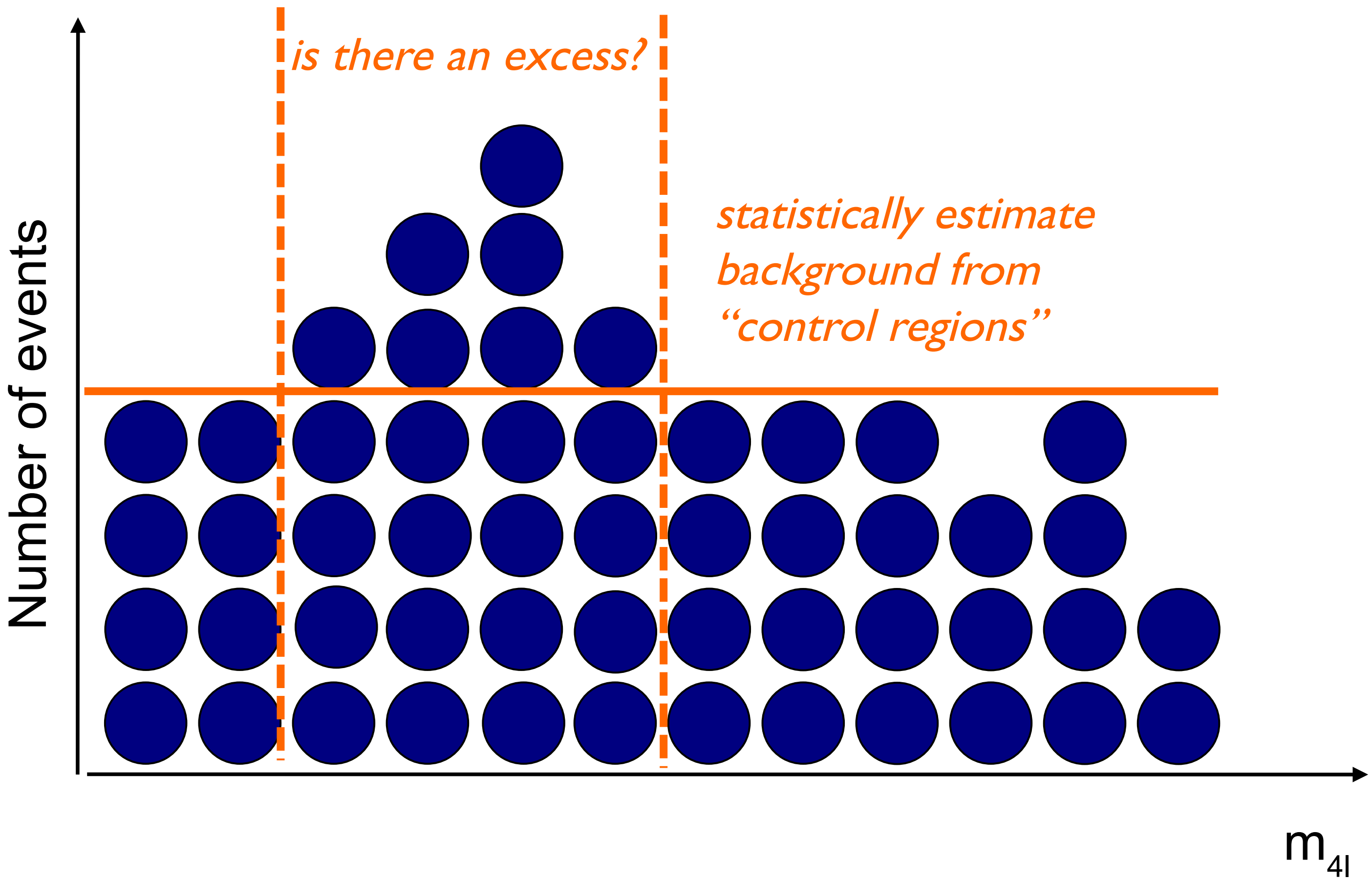


Events in real life do not come with a label! No way to distinguish signal from background on an event-by-event base…

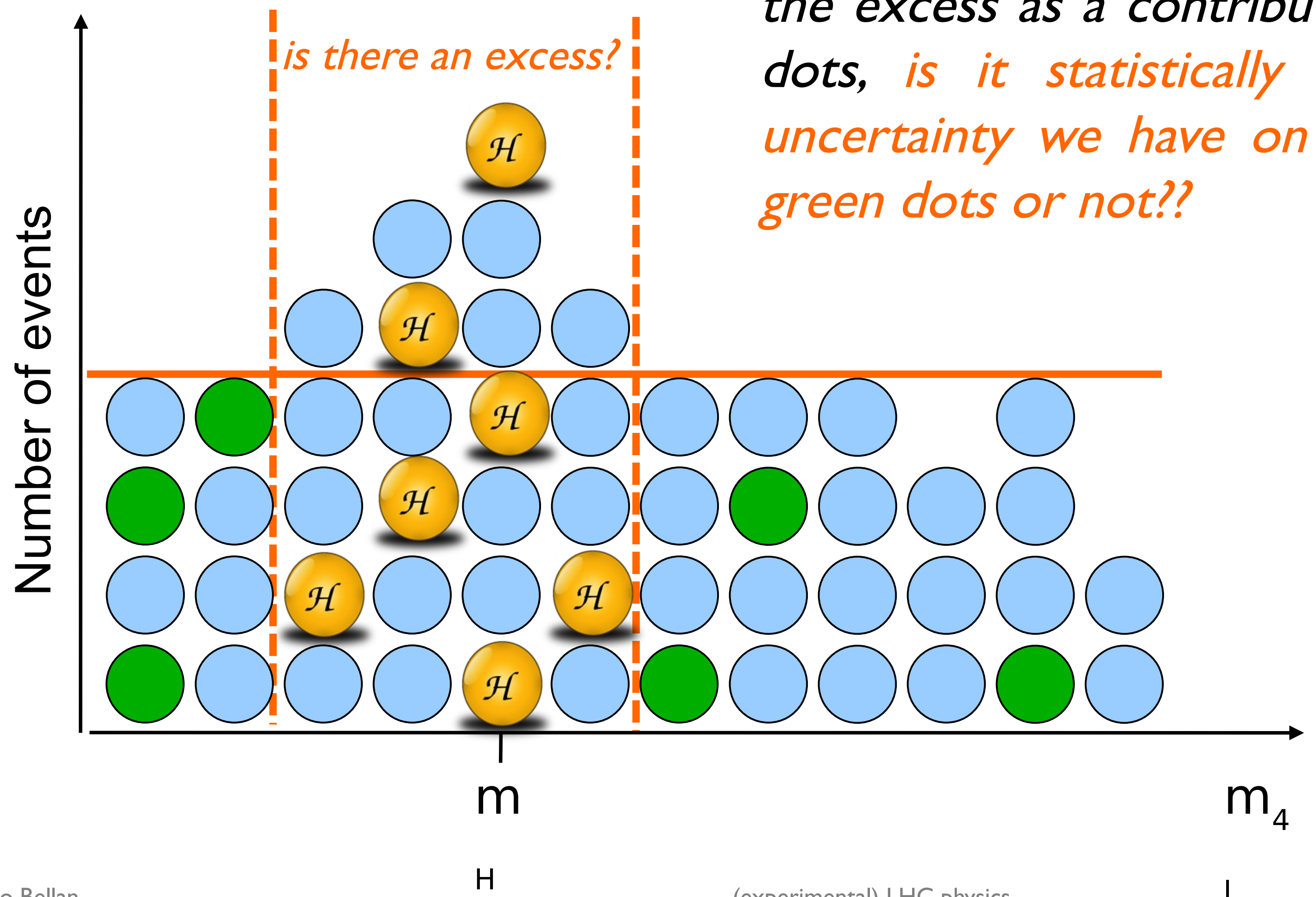
Extract signal from background

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



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

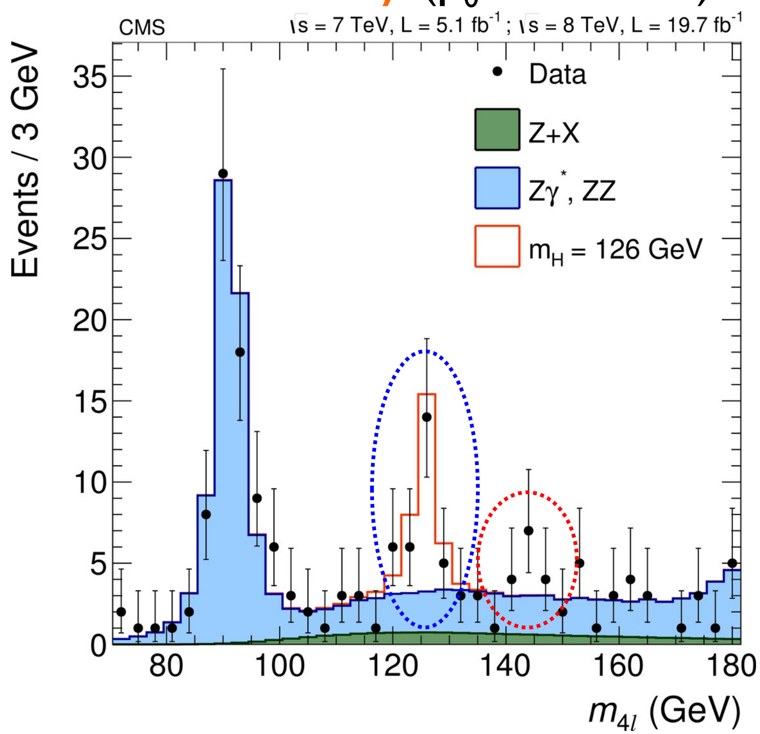
Extract signal from background

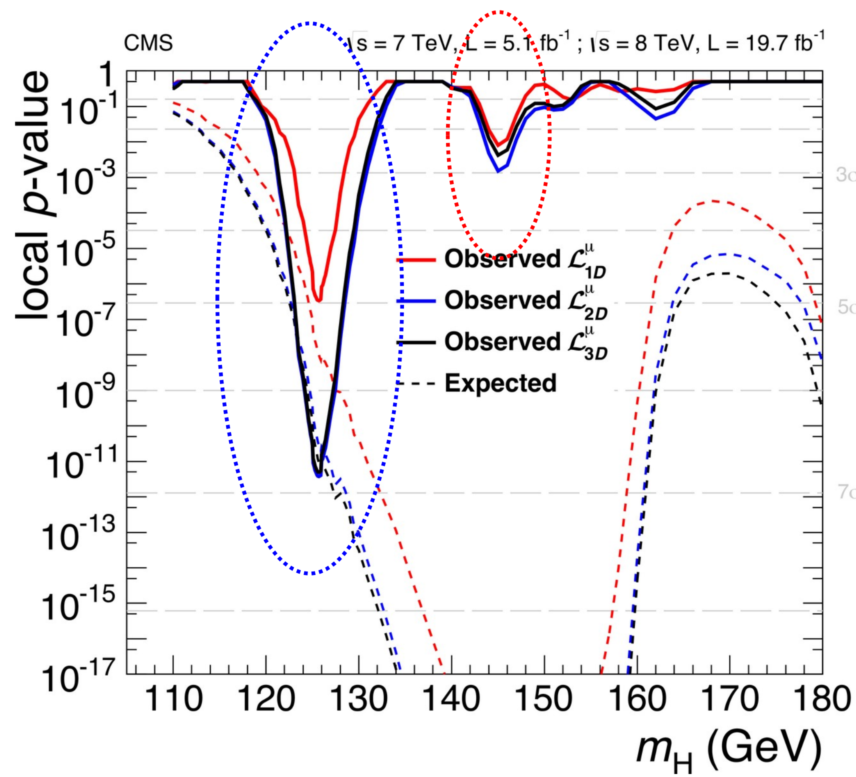


The question we should pose is: *provided that we estimated the # of* ***blue*** *and* ***green*** *dots with a certain precision, the interpretation of the excess as a contribution from the* ***golden*** *dots, is it statistically significant w.r.t. the uncertainty we have on the # of blue and green dots or not??*

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





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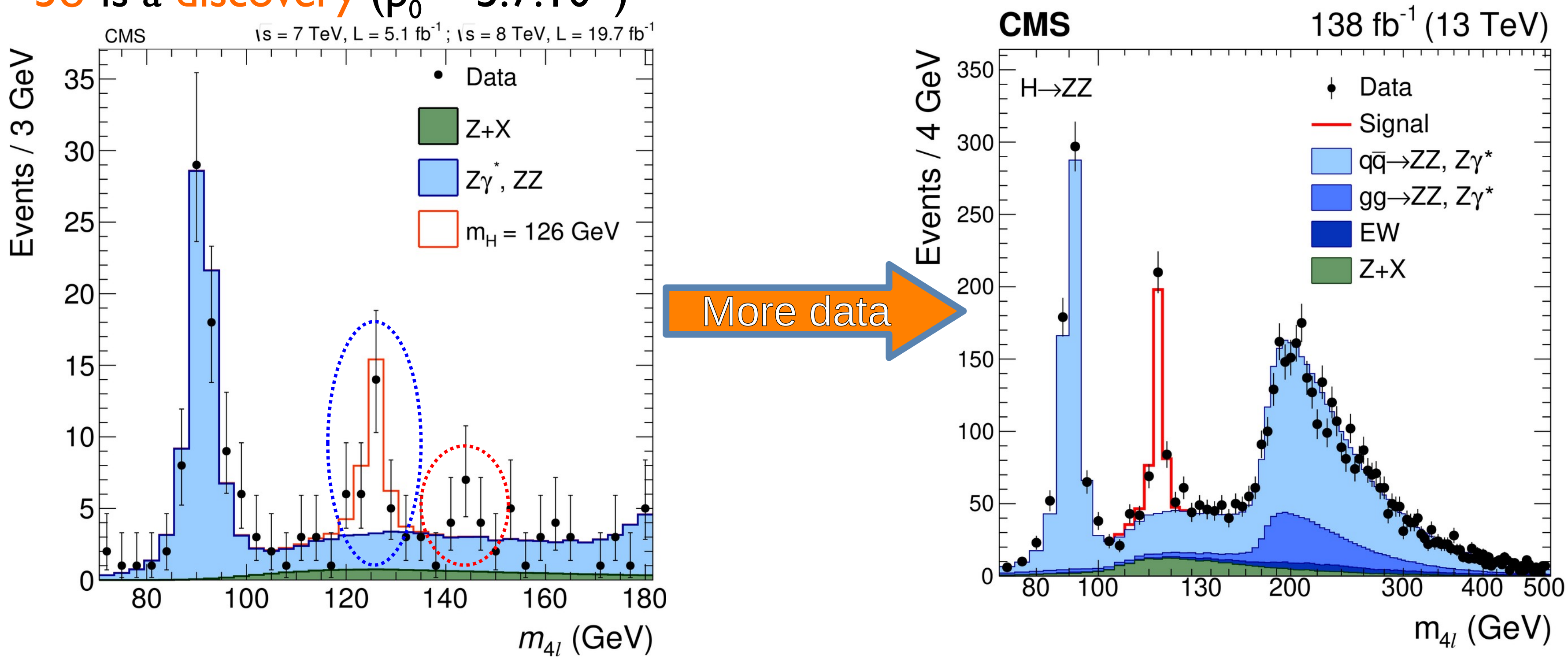
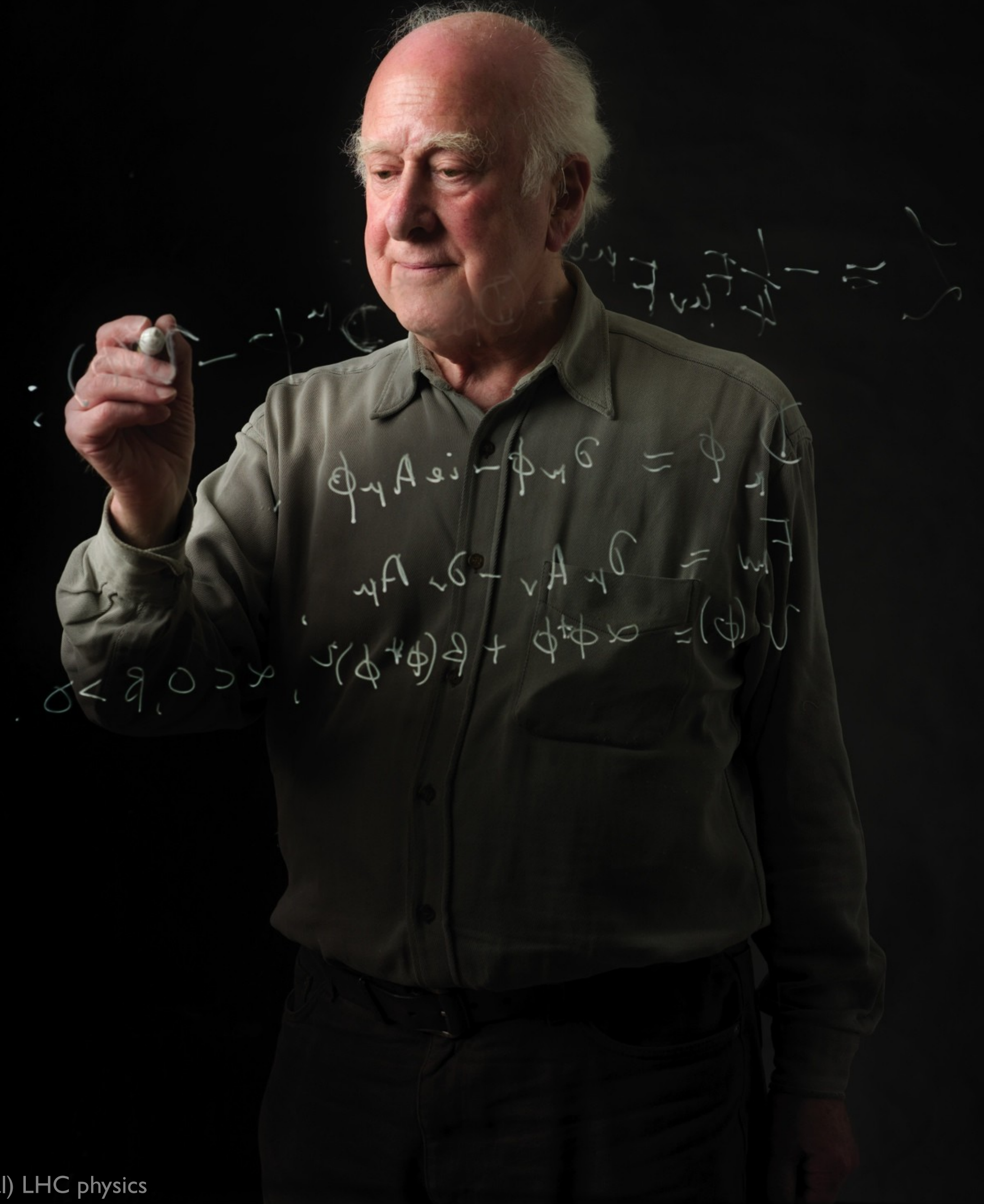


CERN Auditorium, July 4th 2012

CERN 10 years HIGGS boson discovery

CERN Auditorium, July 4th 2022

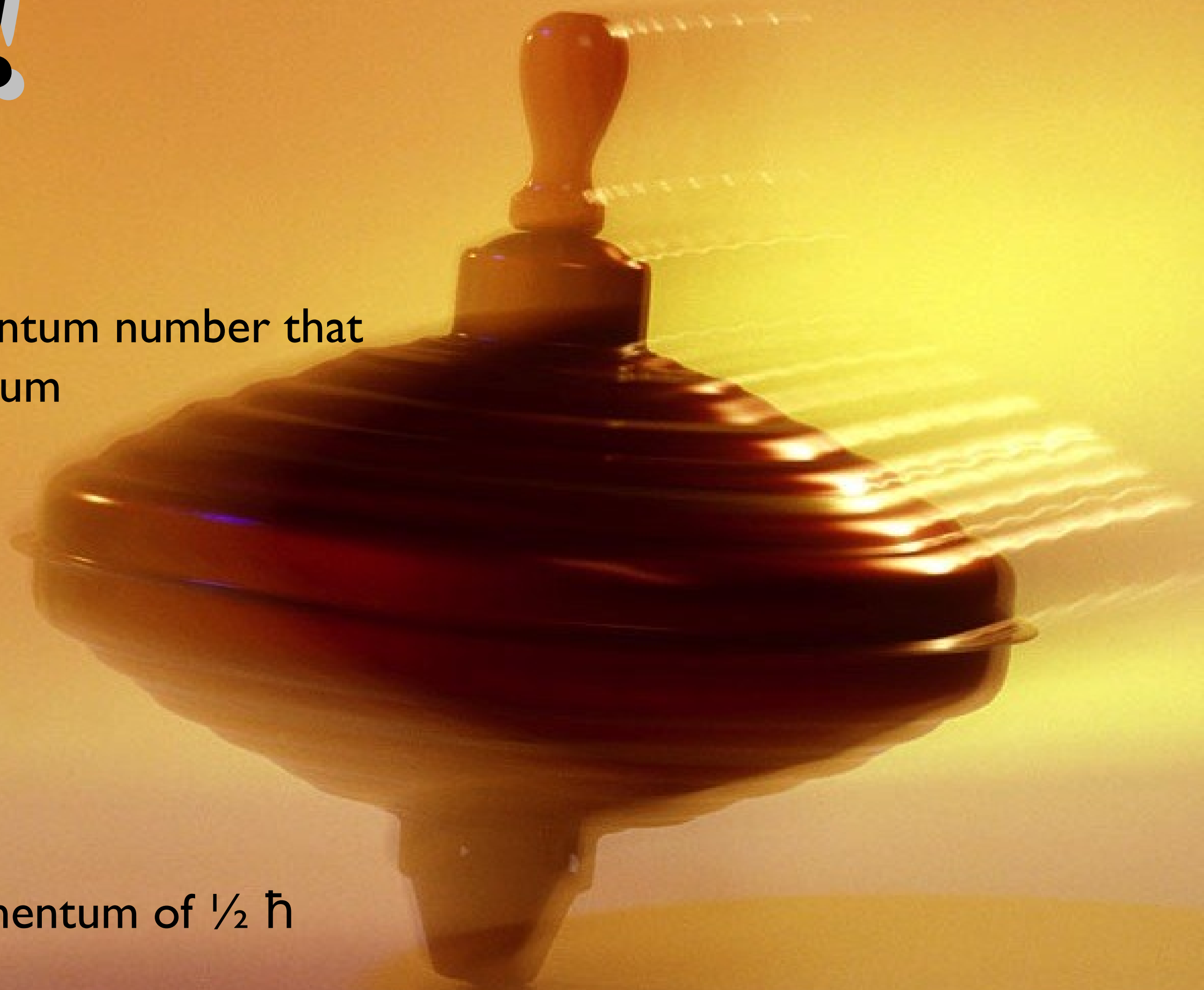
Is it a *scalar* boson?



Spin!

What's a particle spin?

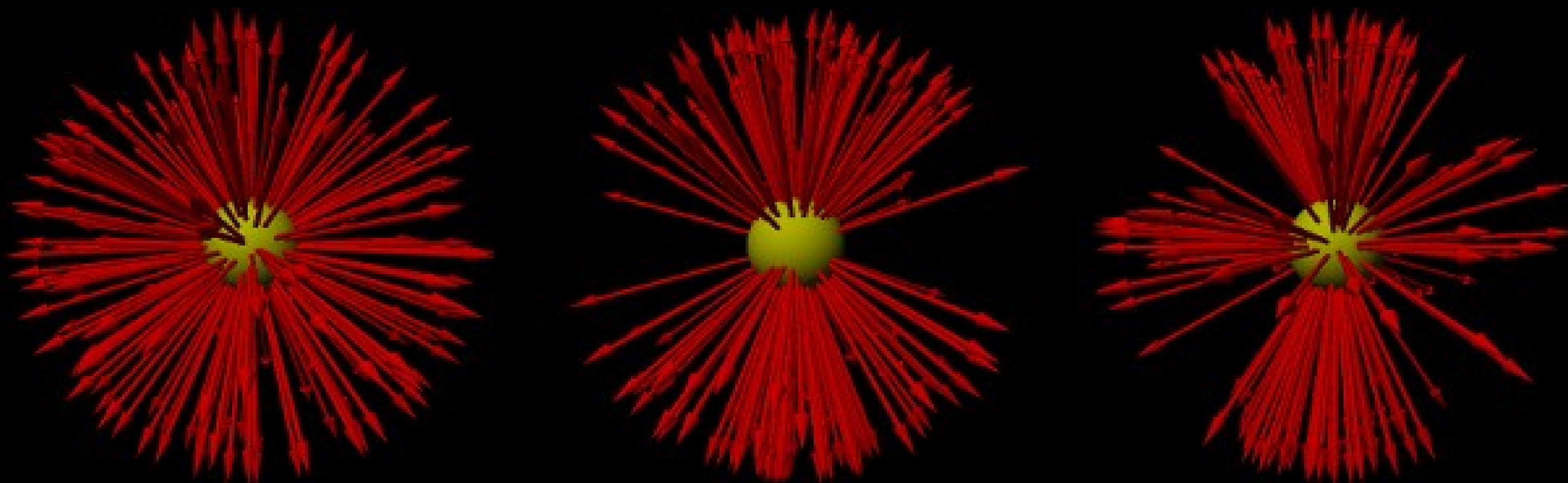
An intrinsic particle quantum number that follows angular momentum algebra



An electron has always an intrinsic angular momentum of ½ ħ

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

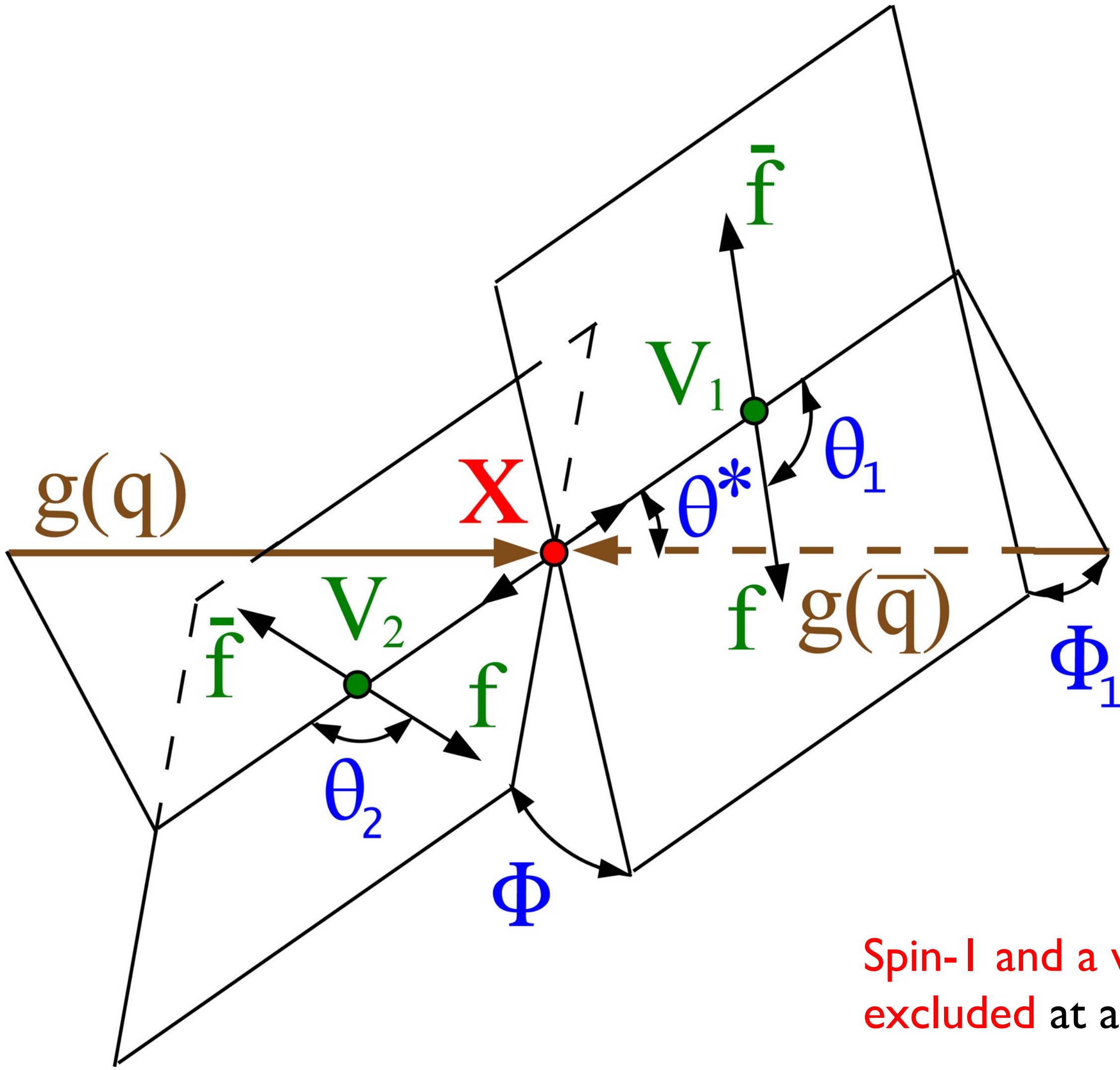
How can we recognize the spin of an unstable particle?

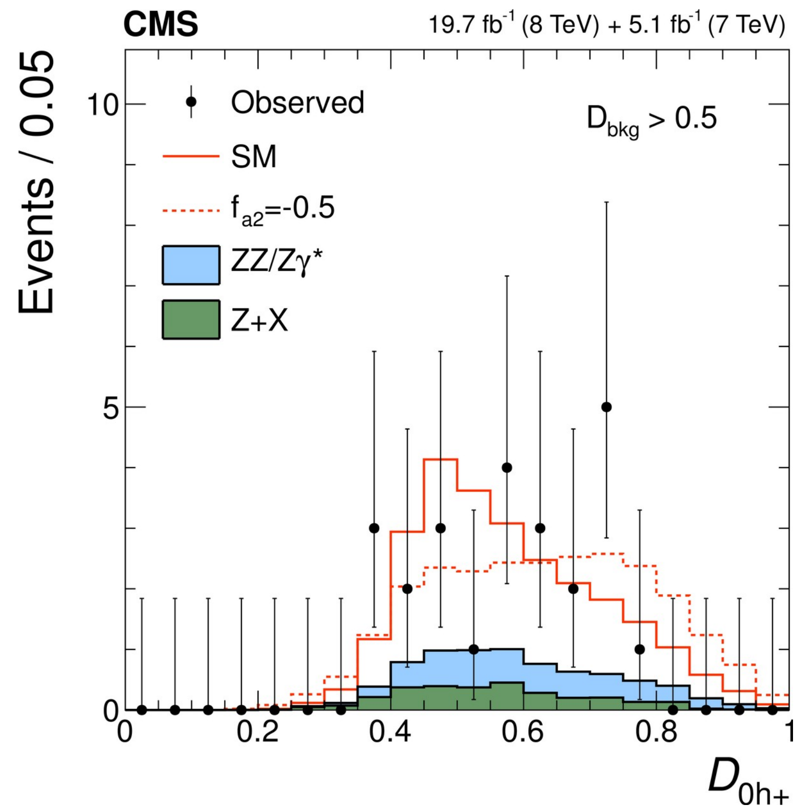


spin 0 spin 1 spin 2

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.

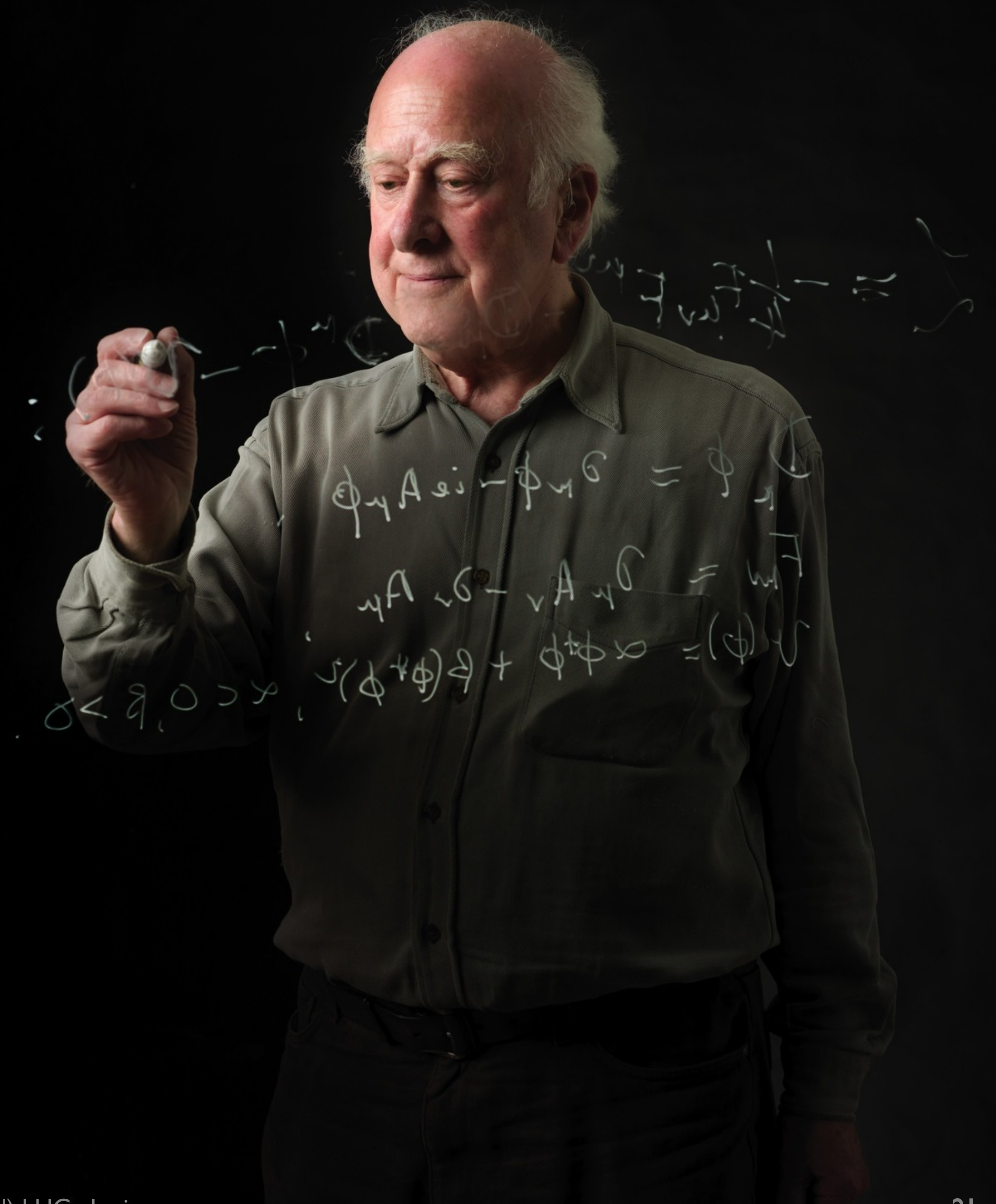
Spin with H → 4 leptons





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

Is it responsible for masses?



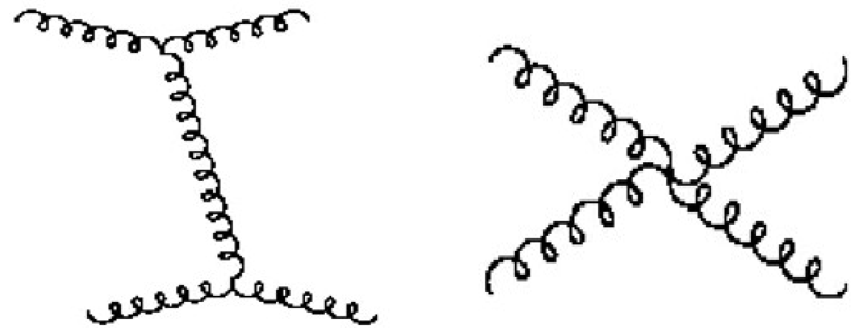
Combine many other decay modes

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

- 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
    - Should imply long range interaction
  - ✓ Gluons couple to color charges
  - ✓ Gluons have color themselves
    - They can couple to other gluons → confinement

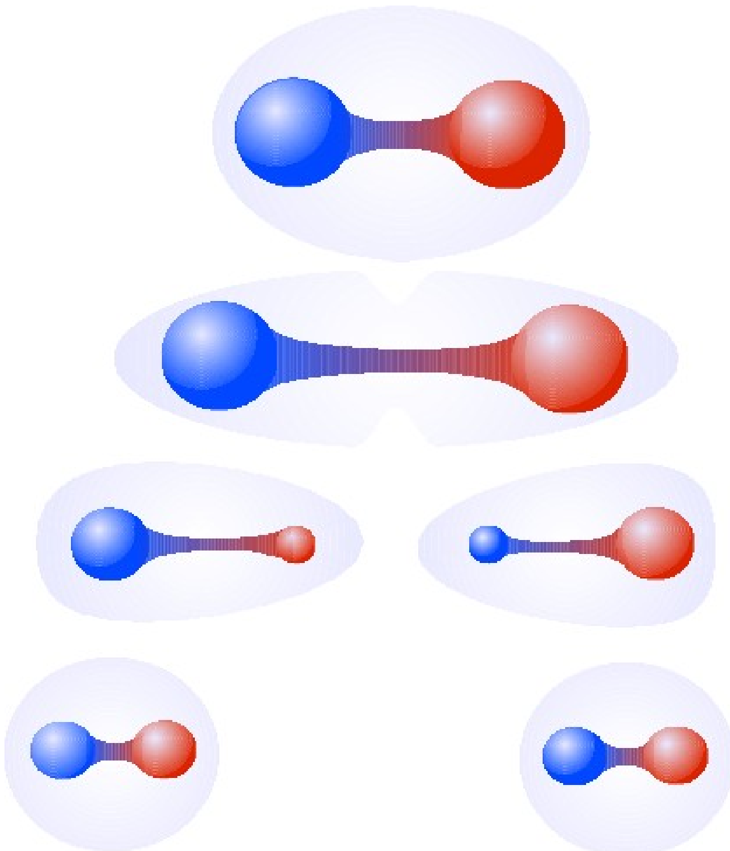


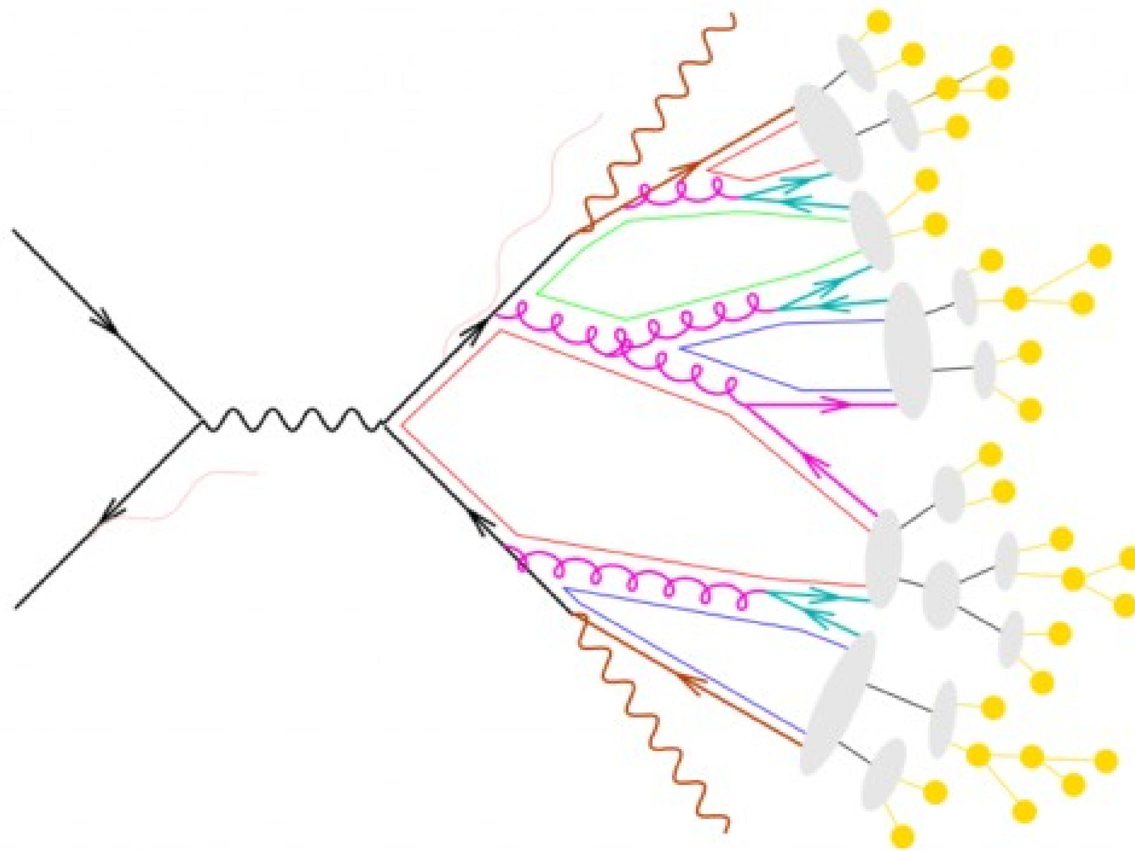
- **Principle of asymptotic freedom**
  - ✓ At short distances strong interactions are weak
    - Quarks and gluons are essentially free particles
    - Perturbative regime (can calculate!)
  - ✓ At large distances, higher-order diagrams dominate
    - Interaction is very strong
    - Perturbative regime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

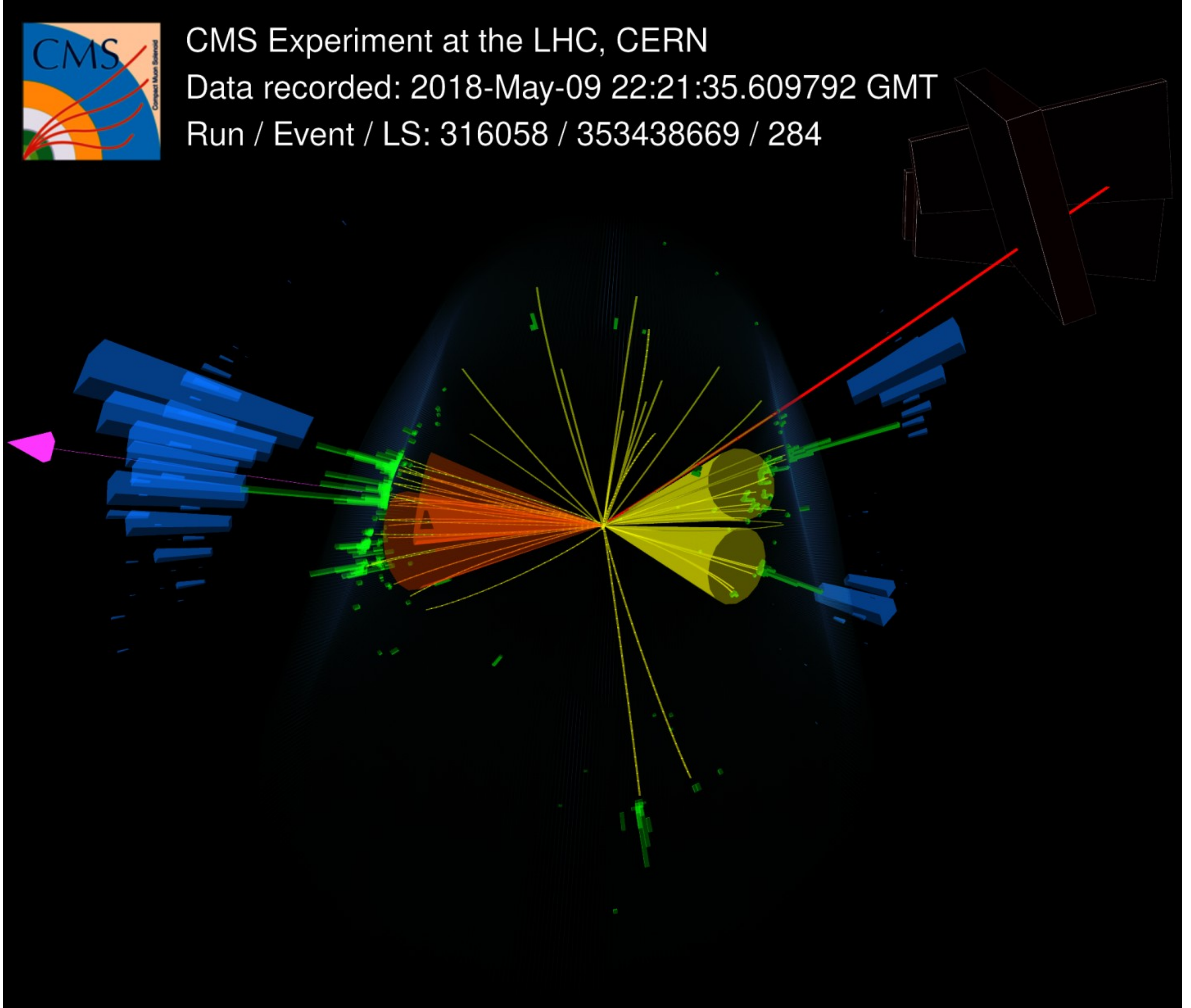
quark-quark effective potential

$$V_s = \underbrace{-\frac{4}{3}\frac{\alpha_s}{r}}_{\text{single gluon exchange}} + \underbrace{kr}_{\text{confinement}}$$

Confinement, hadronization, jets

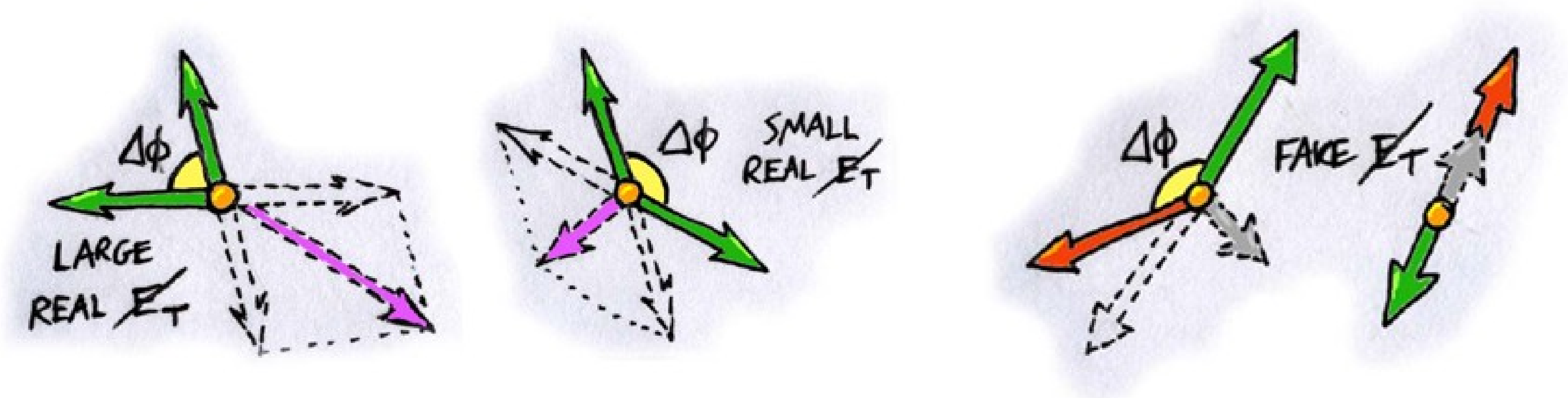





CMS Experiment at the LHC, CERN
Data recorded: 2018-May-09 22:21:35.609792 GMT
Run / Event / LS: 316058 / 353438669 / 284

Neutrino (and other invisible particles) at colliders

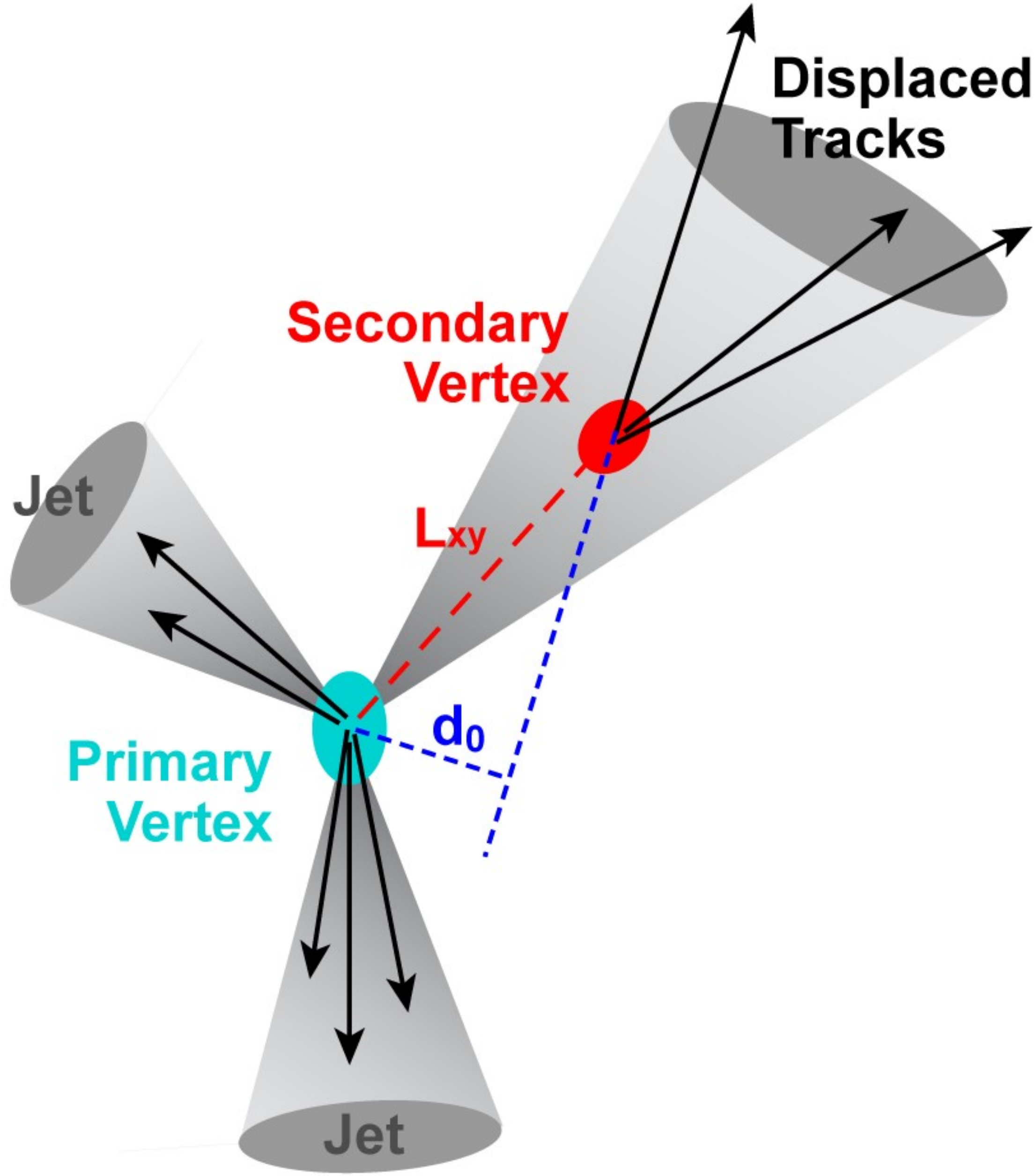
- Interaction length $\lambda_{int} = A / (\rho\ \sigma\ N_A)$
- Cross section $\sigma \sim 10^{-38}$ cm^2
  - ✓ This means 10 GeV neutrinos can pass through more then a million km of rock
- Neutrinos are usually detected in HEP experiments through *missing (transverse) energy, or better, transverse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



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

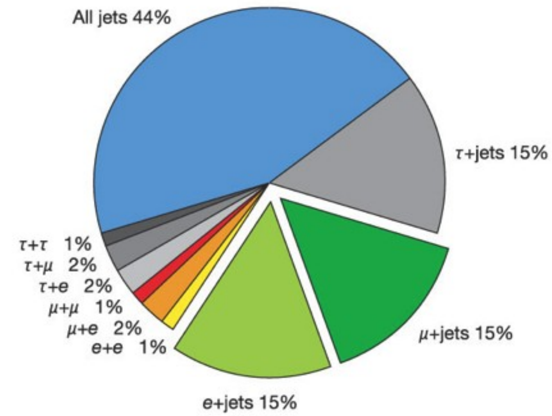
B-tagging

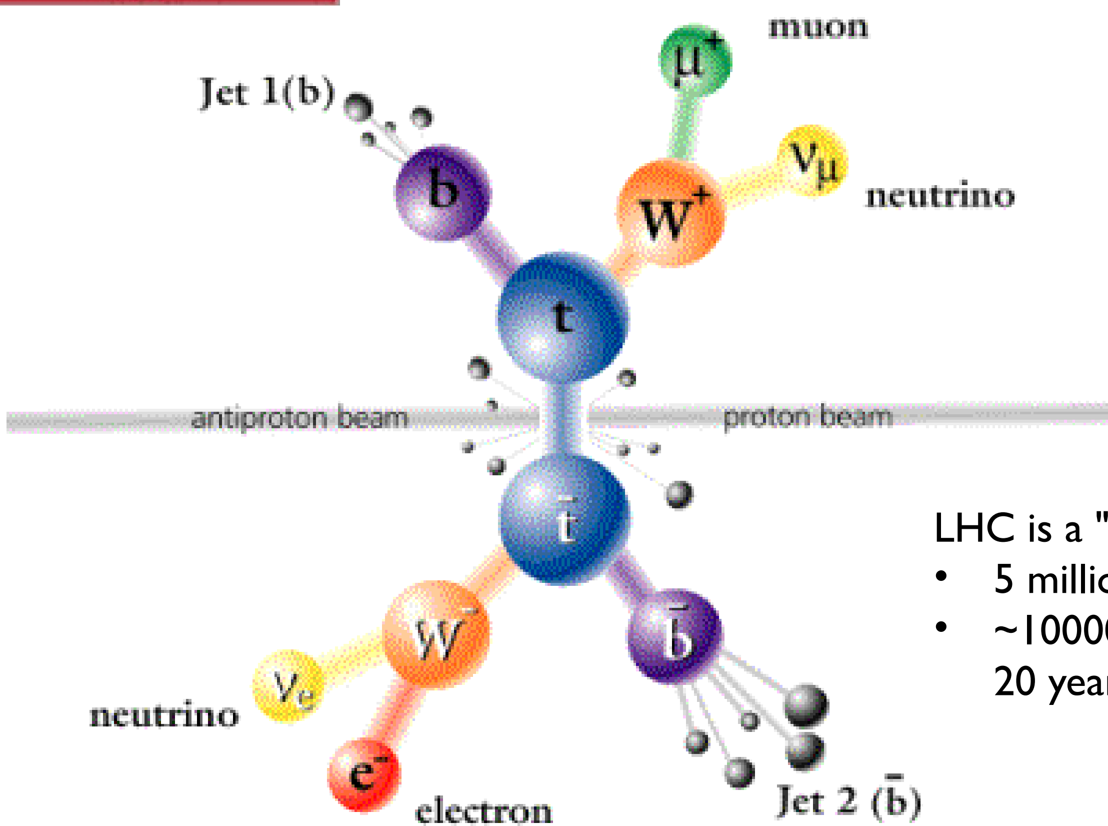
- When a b quark is produced, the associated jet will very likely contain at least one B meson or hadron
- B mesons/hadrons have relatively long lifetime
  - ✓ ~ 1.6 ps
  - ✓ They will travel away form collision point before decaying
- Identifying a secondary decay vertex in a jet allow to tag its quark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

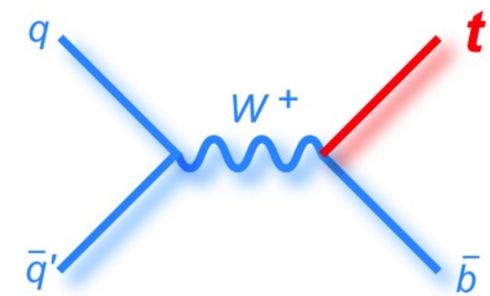


top quark

- Mean lifetime ~ 5×10^{-13} ps
  - ✓ Shorter than time scale at which QCD acts: no time to hadronize!
  - ✓ It decays as **t → Wb**
- Events with top quarks are very rich in (b) jets…

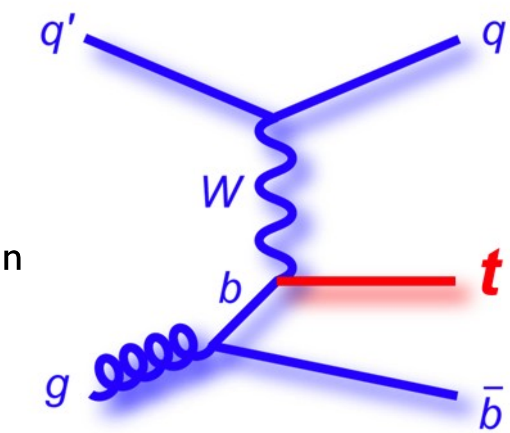






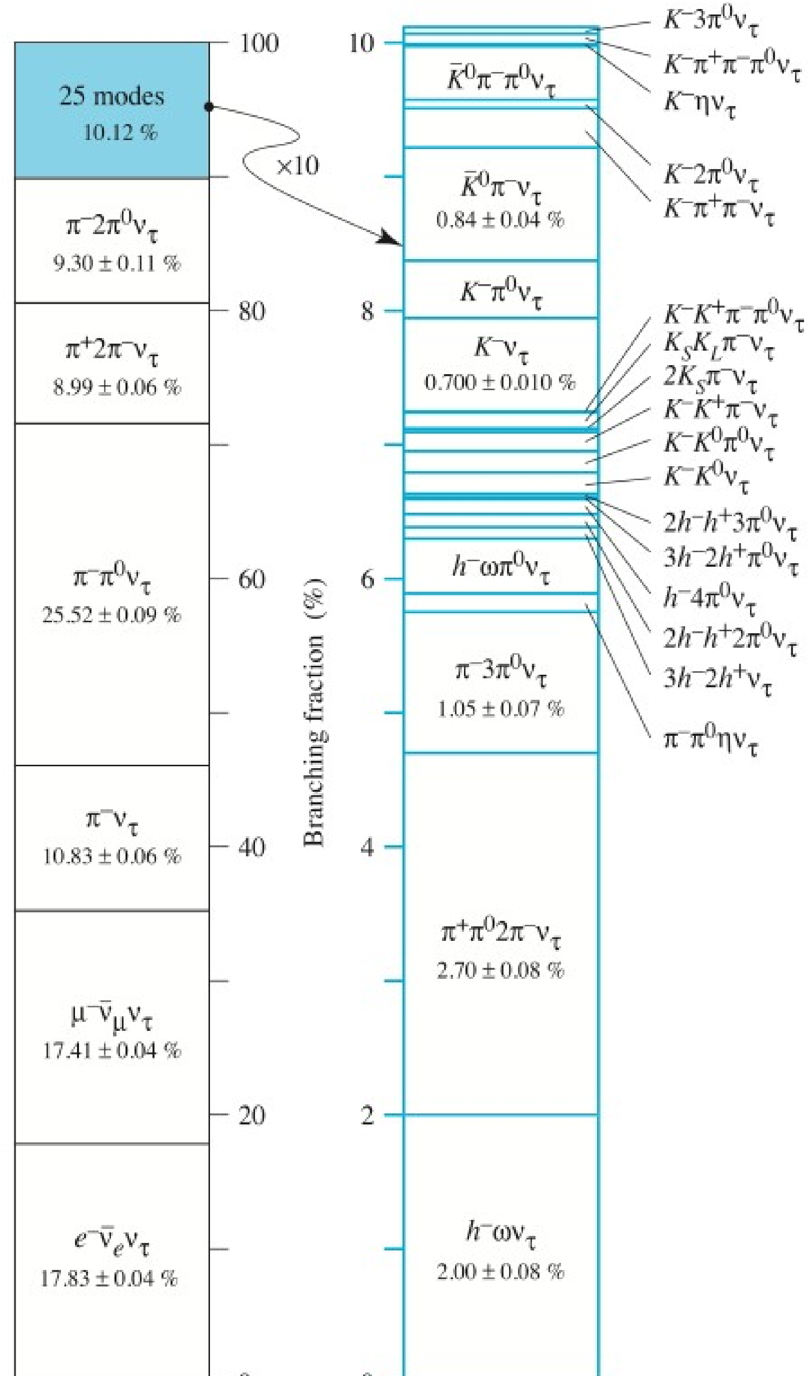
LHC is a "top factory"!

- 5 millions of tt 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 (m_τ =1777 MeV → many accessible final states)
- Accurate vertex detectors can detect that they do not come exactly from the interaction point



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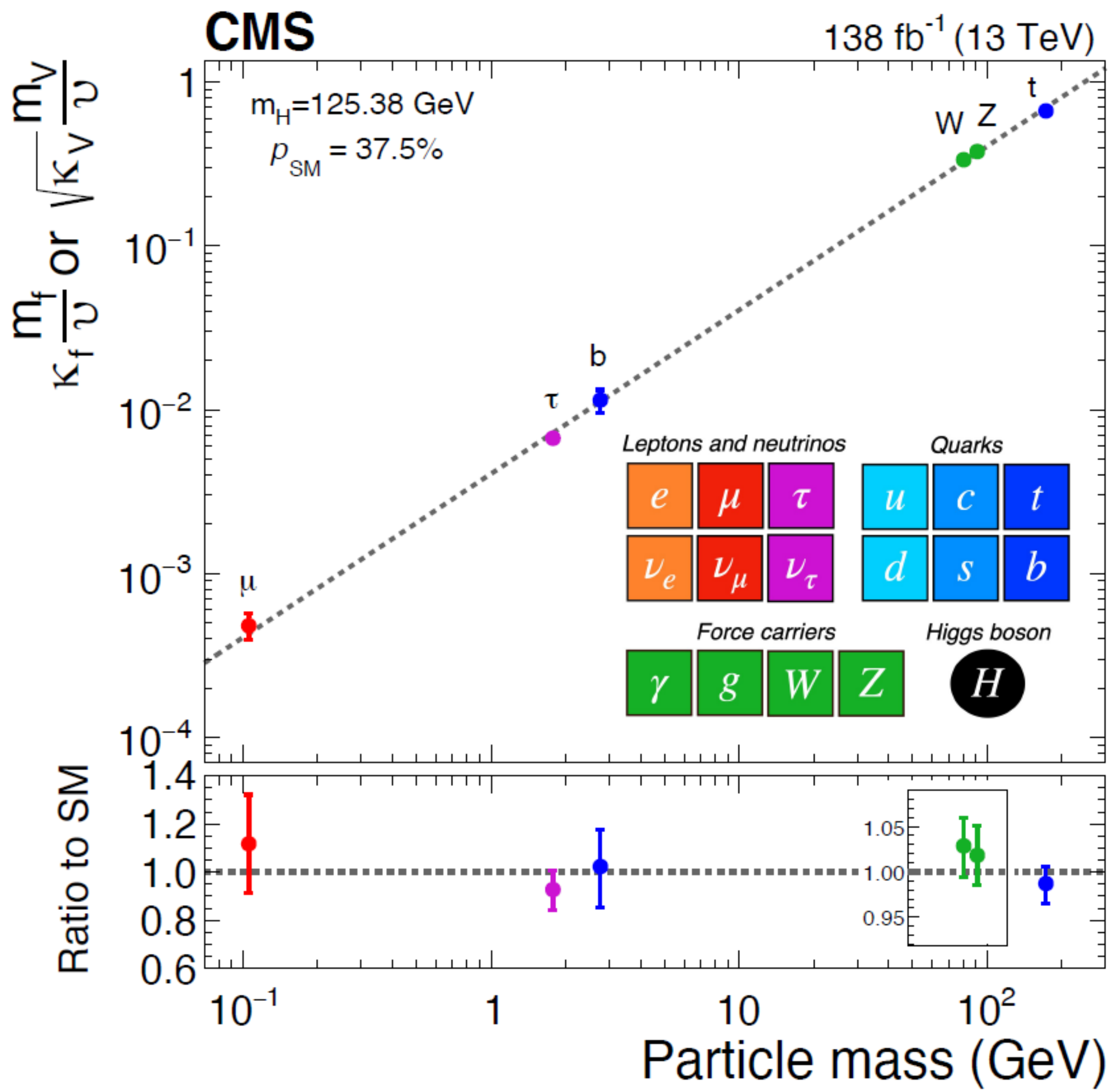
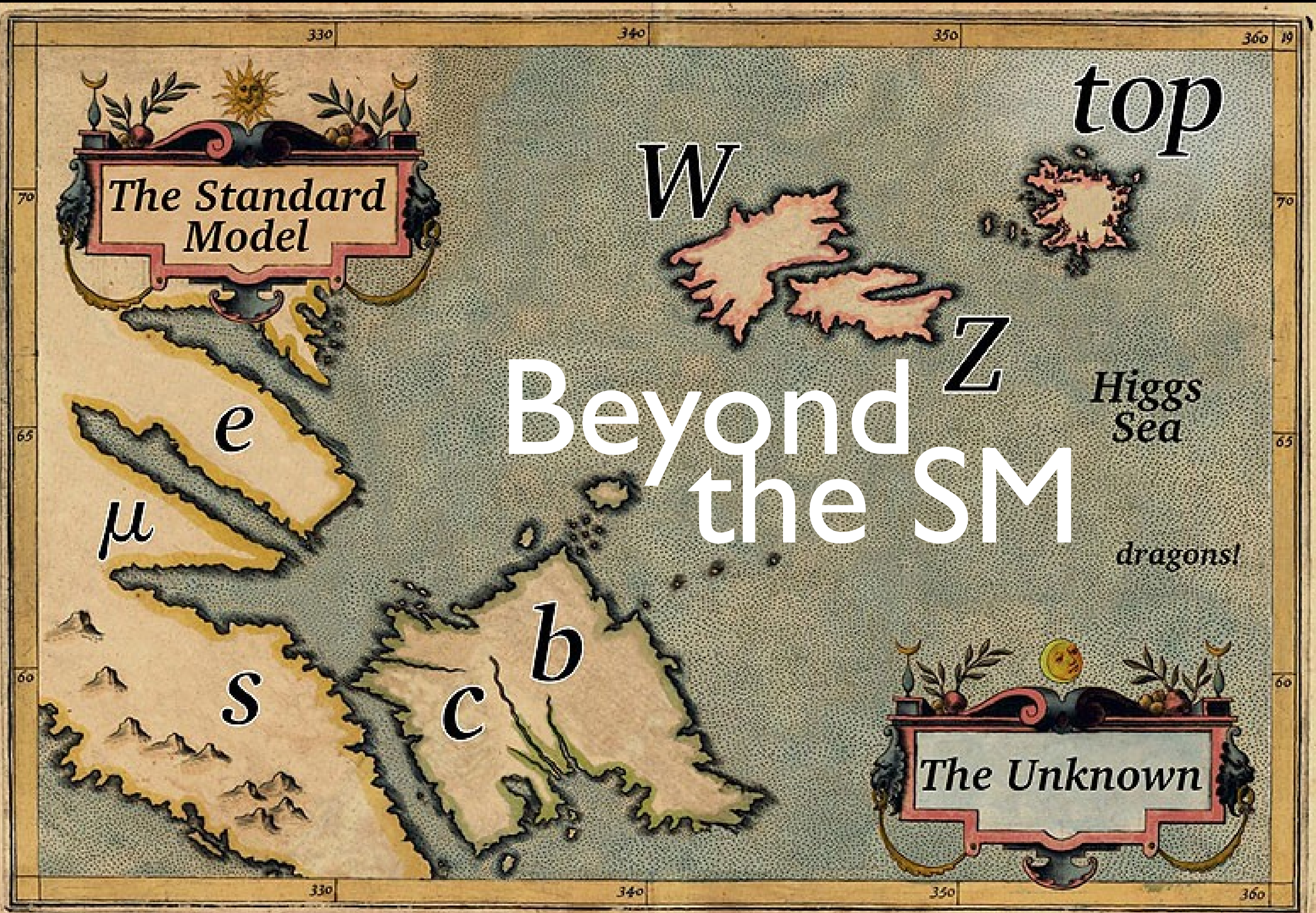
- $H \rightarrow b\bar{b}$
- $pp \rightarrow tt\bar{H}$
- …



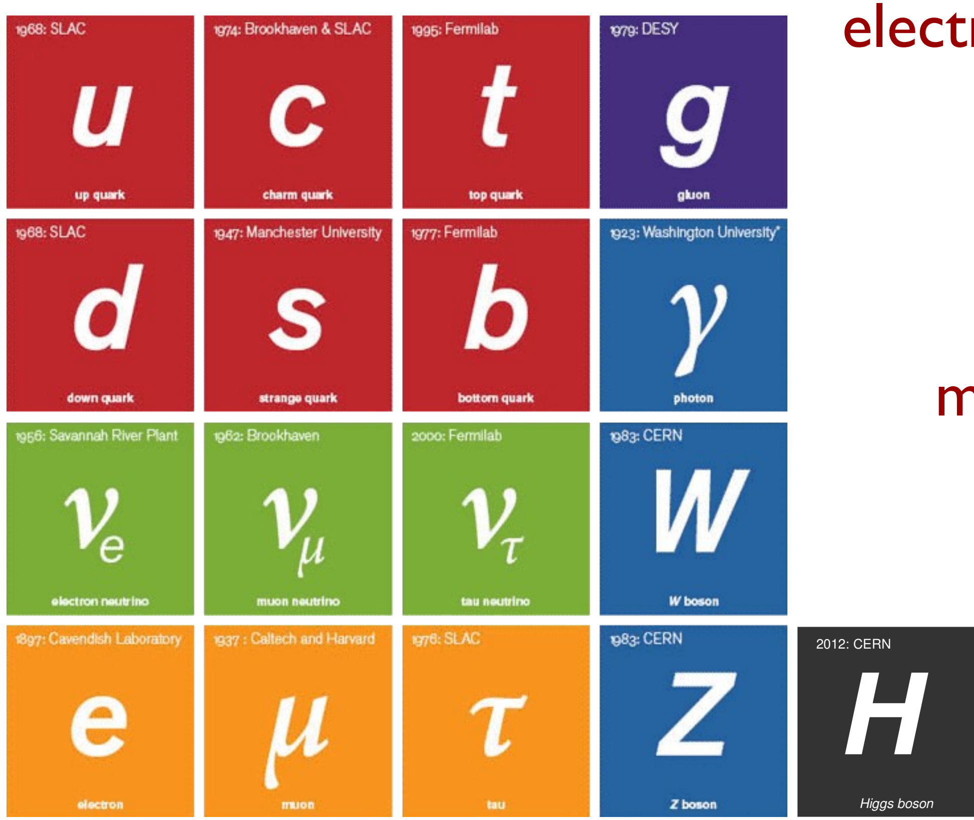

The Standard Model
W
top
Z
Higgs Sea
Beyond the SM
dragons!
e
μ
s
c
b
The Unknown
330
340
350
360
70
65
60

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?

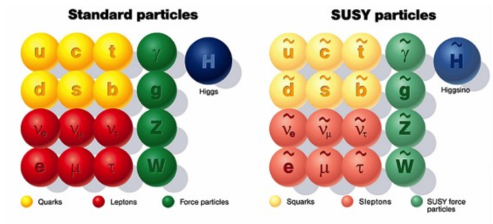
What keeps the Higgs mass so small?

How do we incorporate gravity?

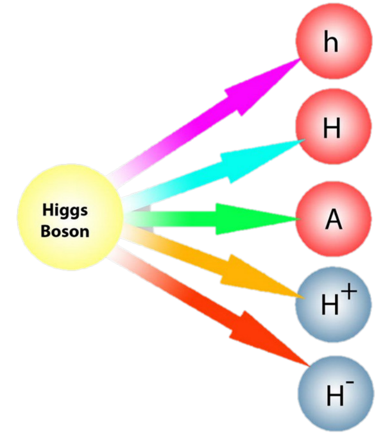
What is Dark Matter?

… as many possible answers to probe!

Super-symmetry?



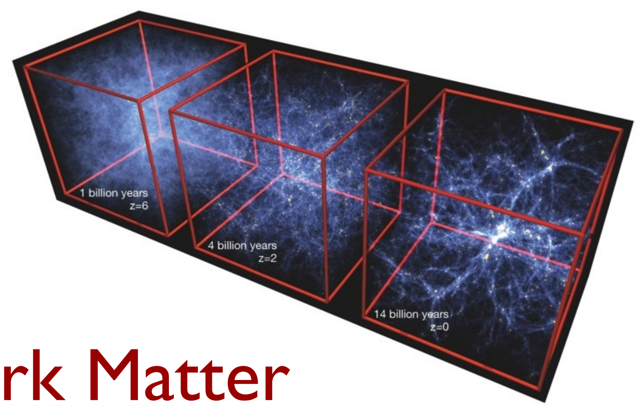
Extended Higgs sector?



New heavy bosons?

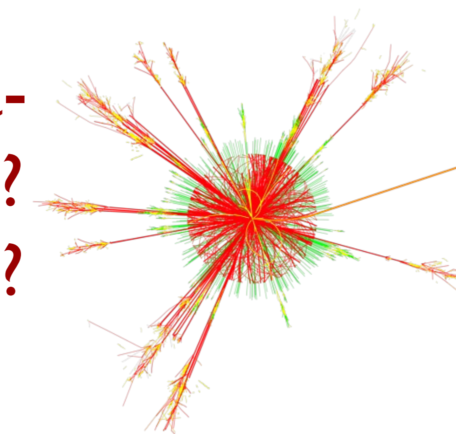
Any new theory needs to agree with the SM!

Composite quark and leptons?



Dark Matter particles?

Large extra-dimensions? Black holes? Gravitons?



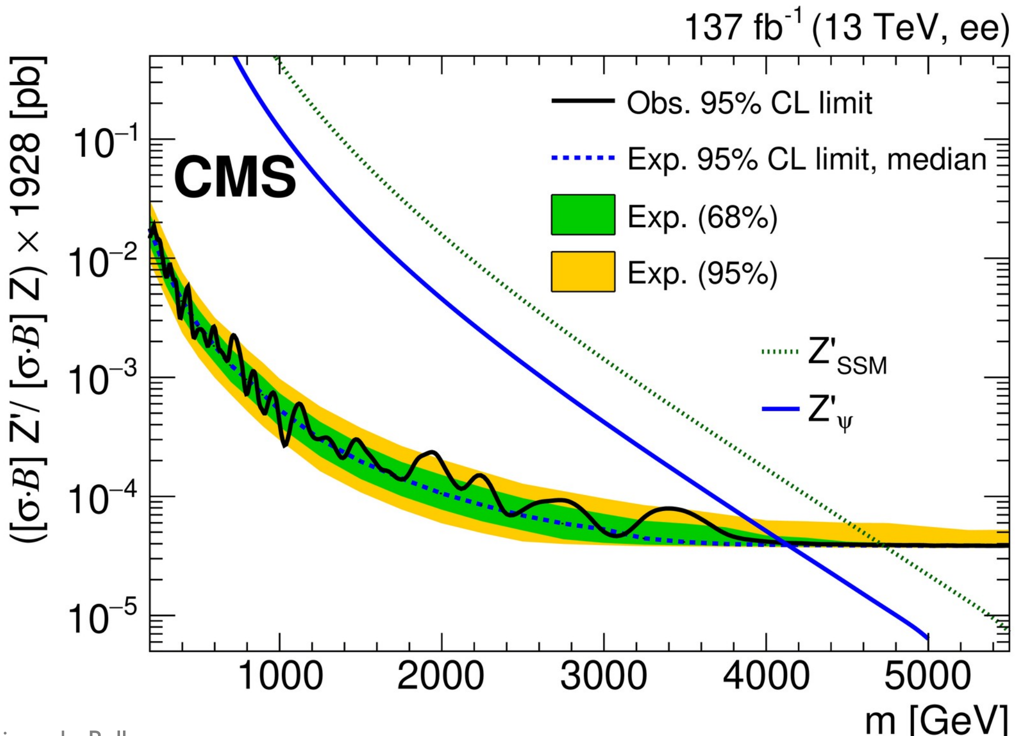
Where is Beyond-the-SM Physics?

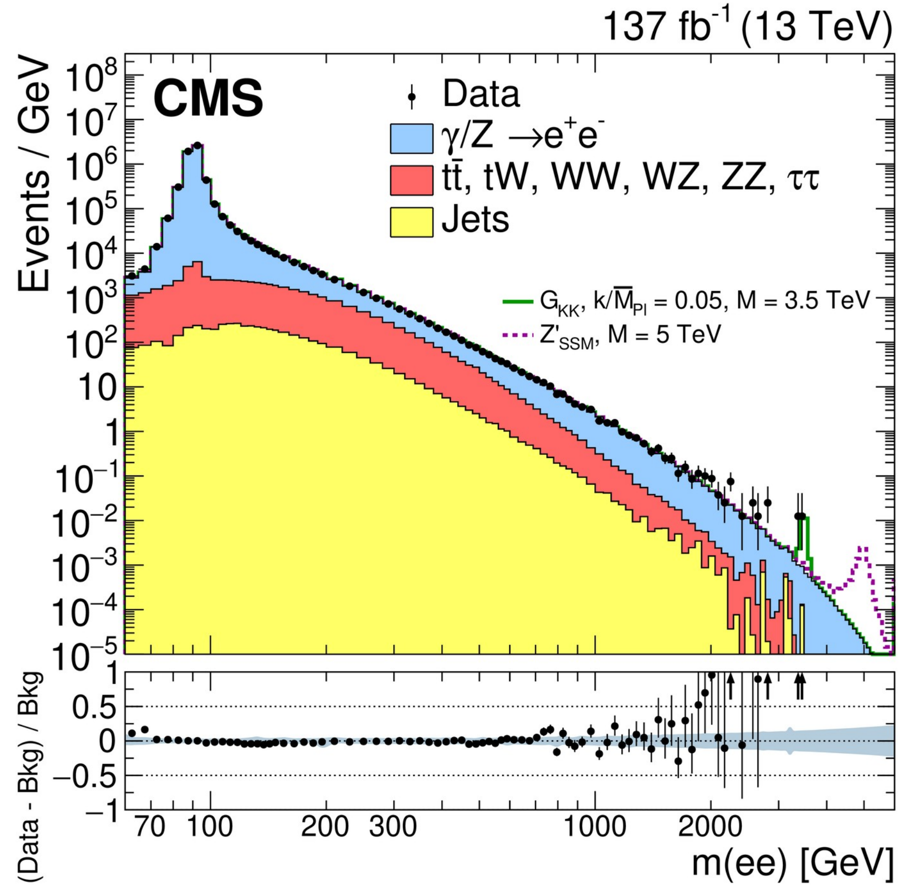
Masses of new particles within the LHC reach

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

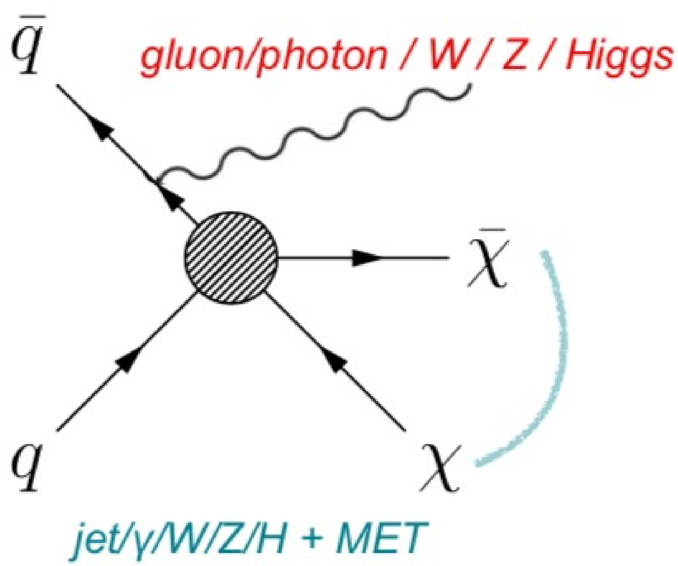
Simple example: heavy Z' boson

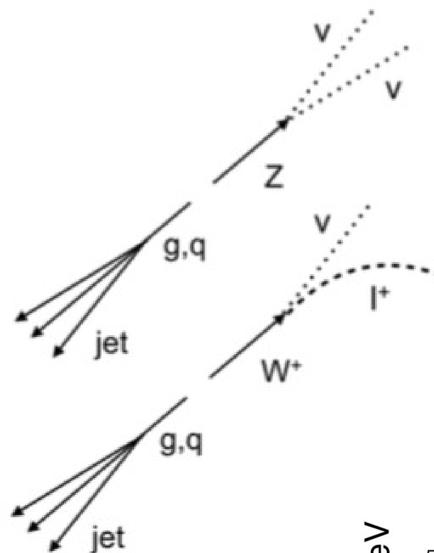
- Use very clean dilepton decay channel
  - ✓ e.g. electron-positron, or $\mu^+\mu^-$.
  - ✓ Drell-Yan modeling important, but clear peak over a continuum ("bump hunting")
    - Control resolution
- Result expressed as a 95% confidence-level excluded (upper) cross-section

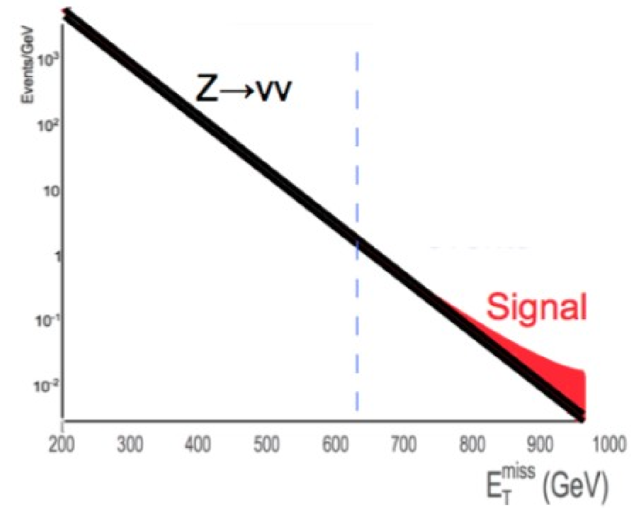


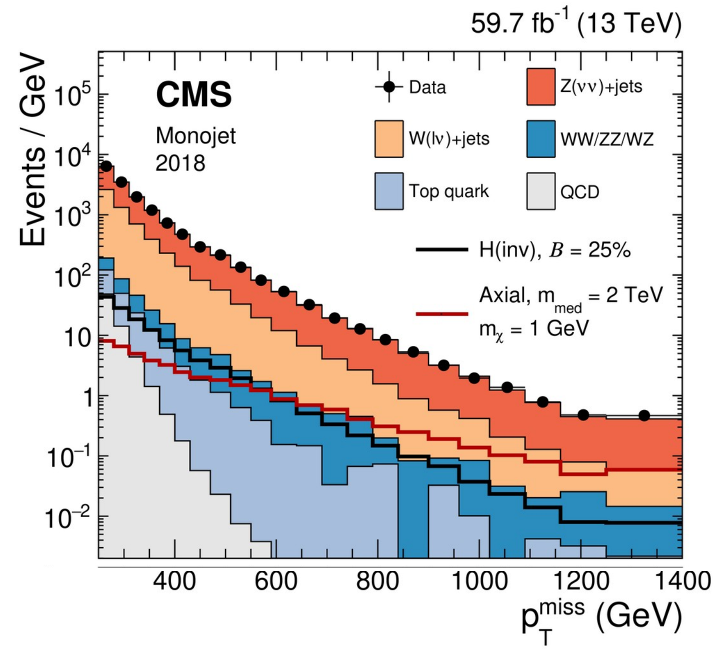


More complex example: Dark Matter searches





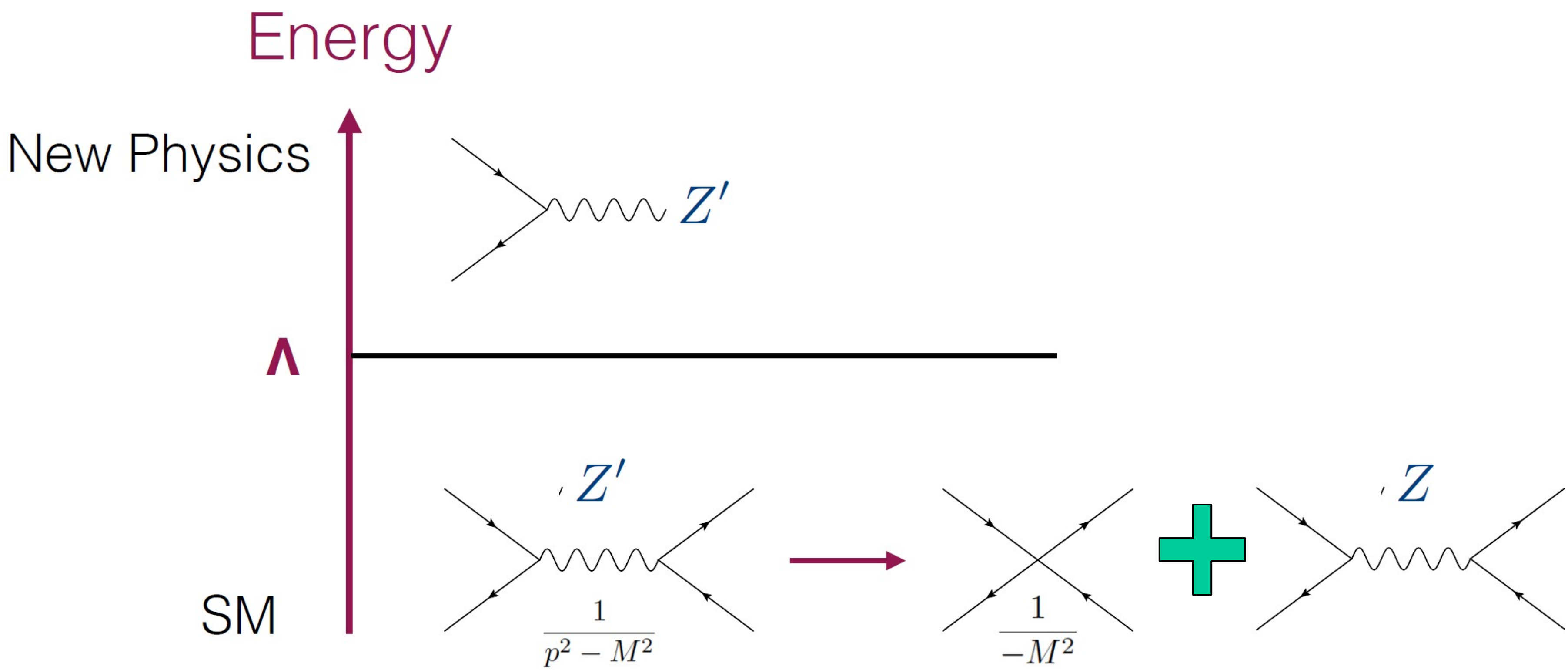




- Use MET shape to extract signal contribution
  - ✓ Similar shape for signal and background
  - ✓ Background modeling very important
- Main contributions (monojet example)
  - ✓ Z(νν)+jet
  - ✓ W(lν)+jet, where charged lepton is not reconstructed

Masses not within LHC reach

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



The Effective-Field Theory approach

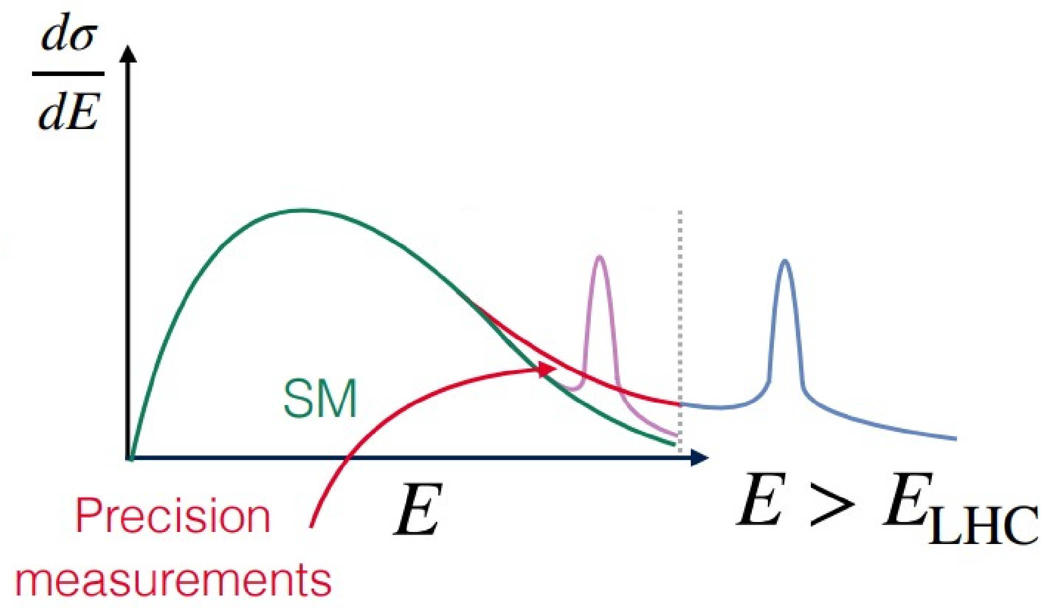
BSM searches:

2010 ⇒ 2023

⇒ New physics is heavy

Direct (bumps)

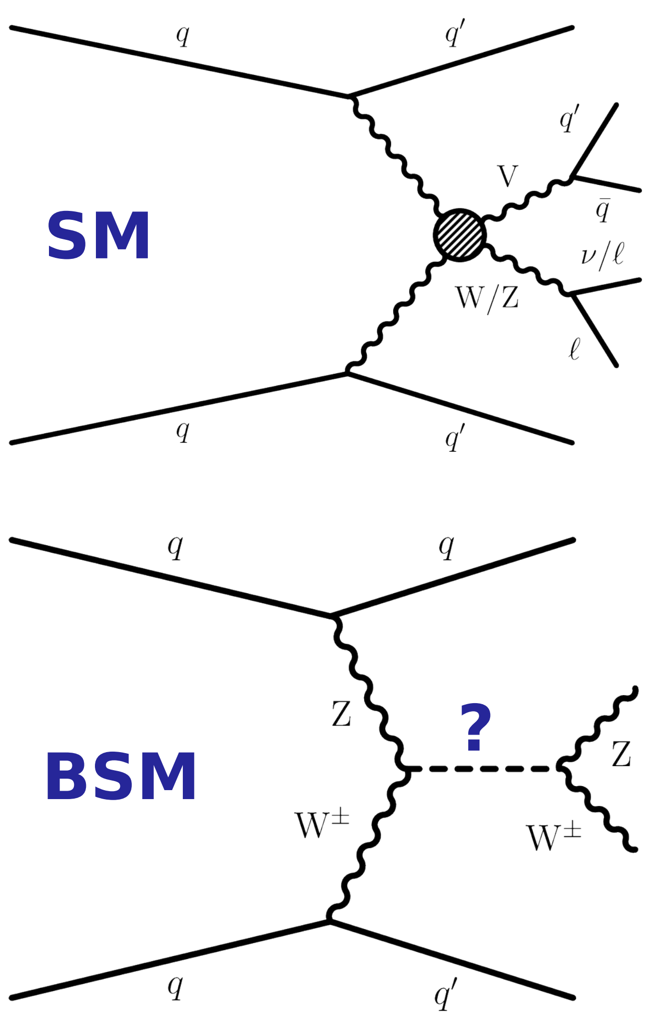
Indirect (tails)



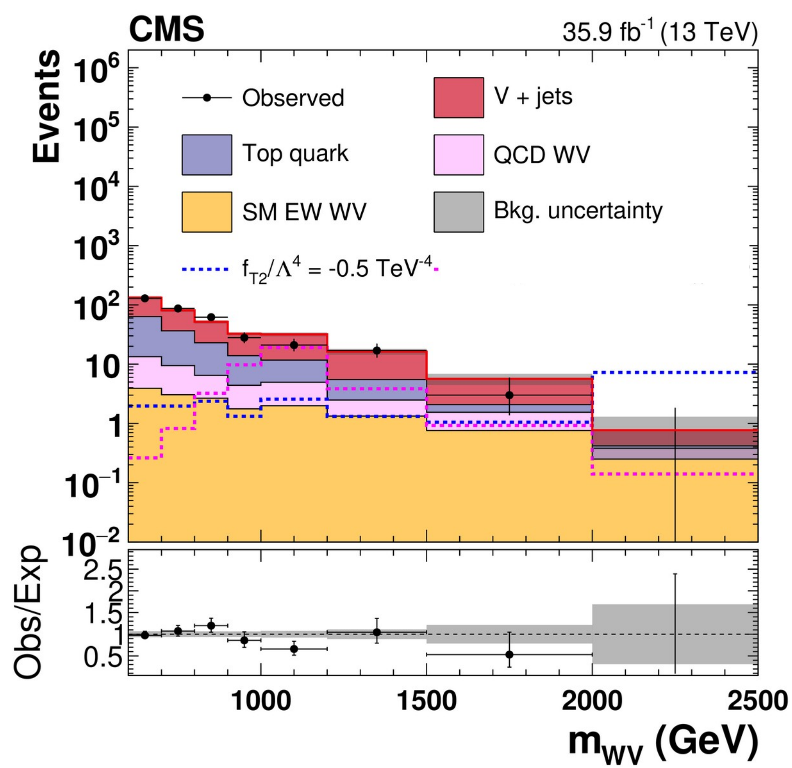
Heavy new physics
Precision measurements
High energy

→ **Effective Field Theory (EFT)**

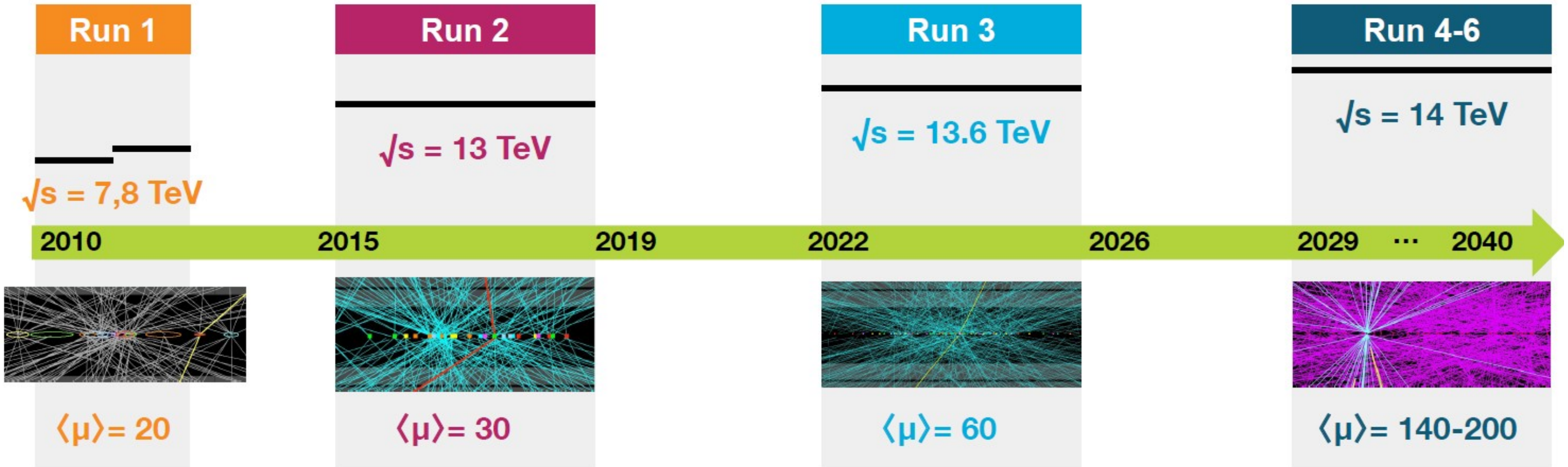
Example: di-boson production



- 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

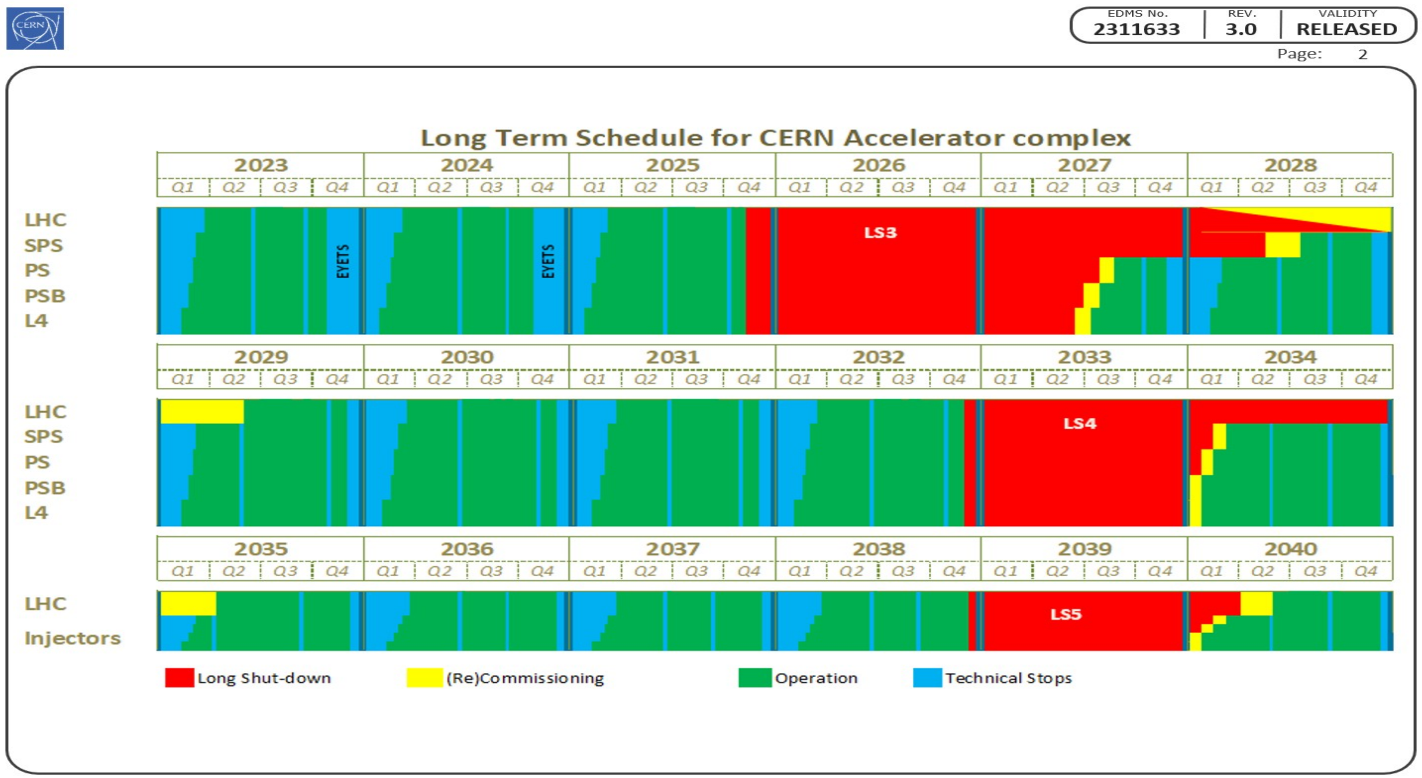


The LHC will run for a long time…



HL-LHC target:

- ❑ Deliver 3000 fb^{-1} pp luminosity to both ATLAS and CMS
- ❑ Programme ends in 2041

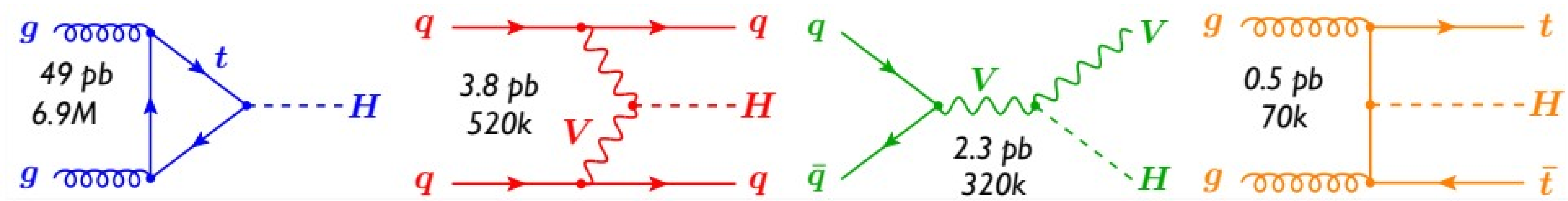


Additional information

(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

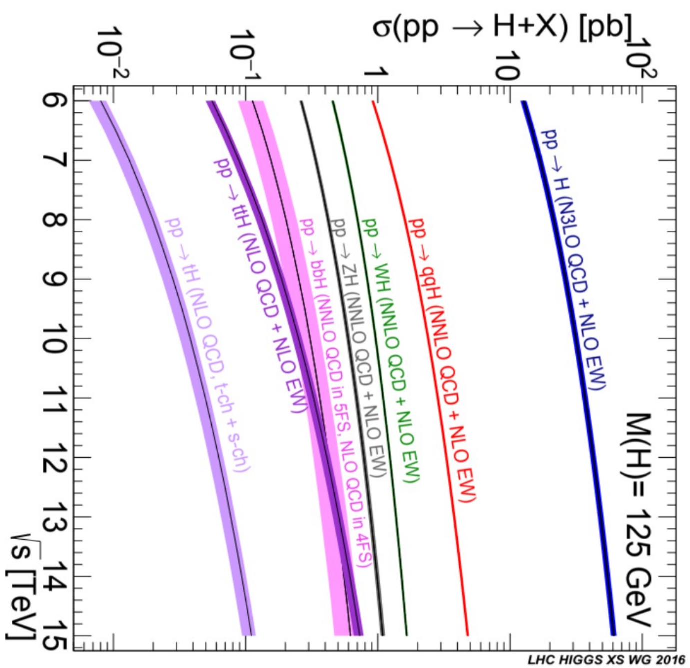


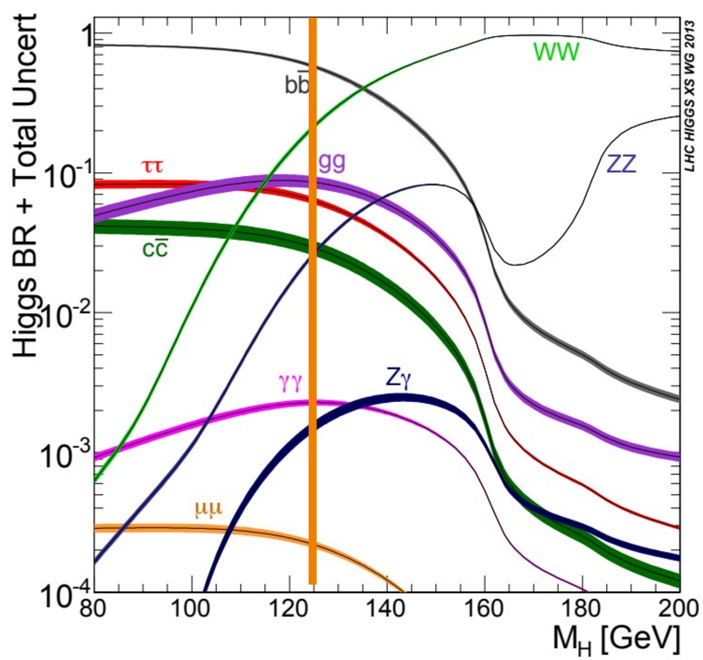
gluon-gluon fusion: main production mode at LHC

Vector Boson Fusion 2 well-separated forward jets

VH tag W and Z boson decays

ttH tag 2 top quarks

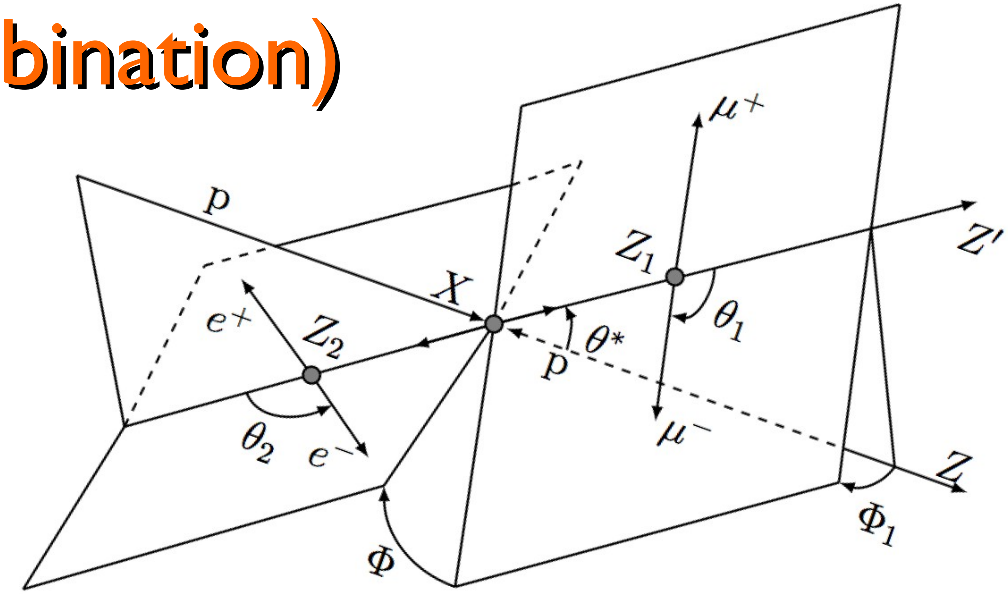


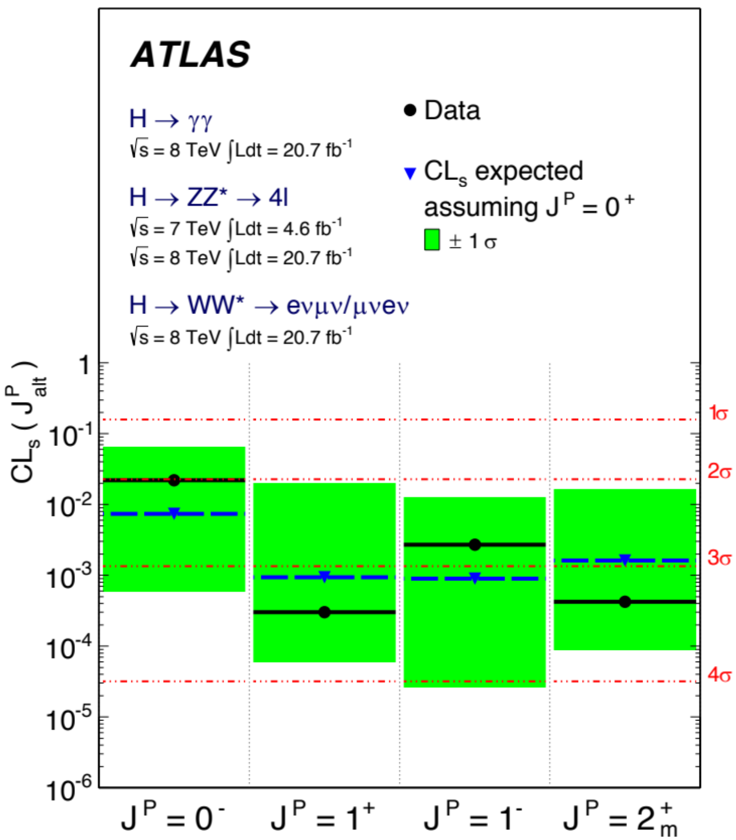


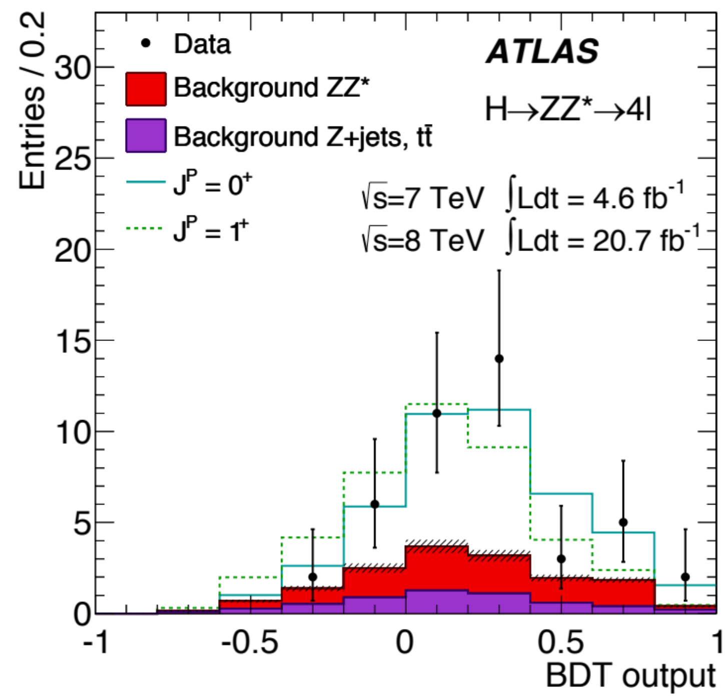
decay	SM BR [%] m_H = 125.09 GeV
H ☾ bb	58.1
H ☾ WW	21.5
H ☾ ττ	6.26
H ☾ ZZ	2.64
H ☾ γγ	0.23

Spin with H→4l (& combination)

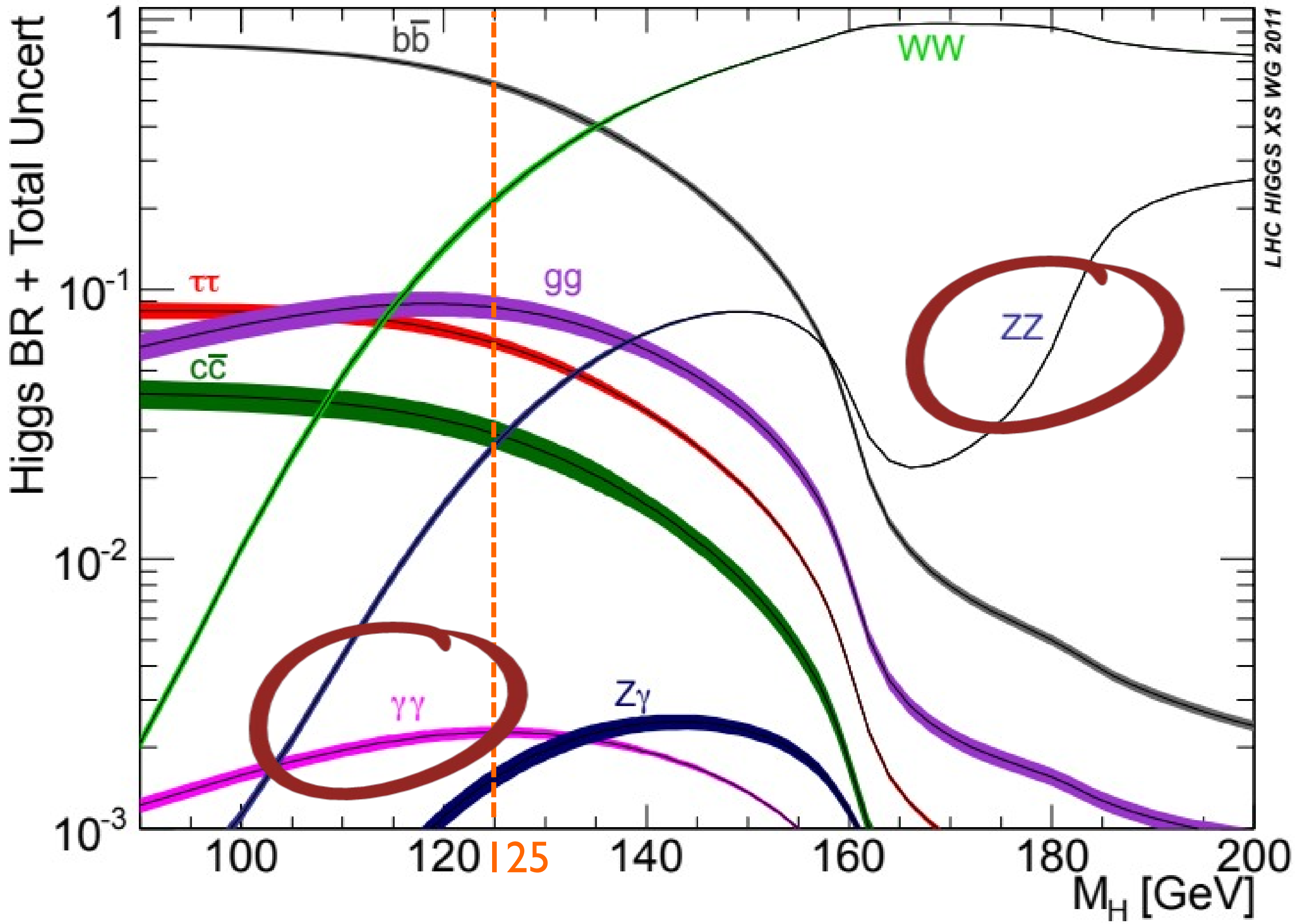
- Sensitive variables combined in BDT score
  - ✓ Intermediate boson masses: m_{Z1}, m_{Z2}
  - ✓ Z_1 production angle: θ^*
  - ✓ Z_1 decay plane angle: Φ_1
  - ✓ Angle between the Z_1 and Z_2 decay planes: Φ
  - ✓ Decay angles of negative leptons: θ_1, θ_2







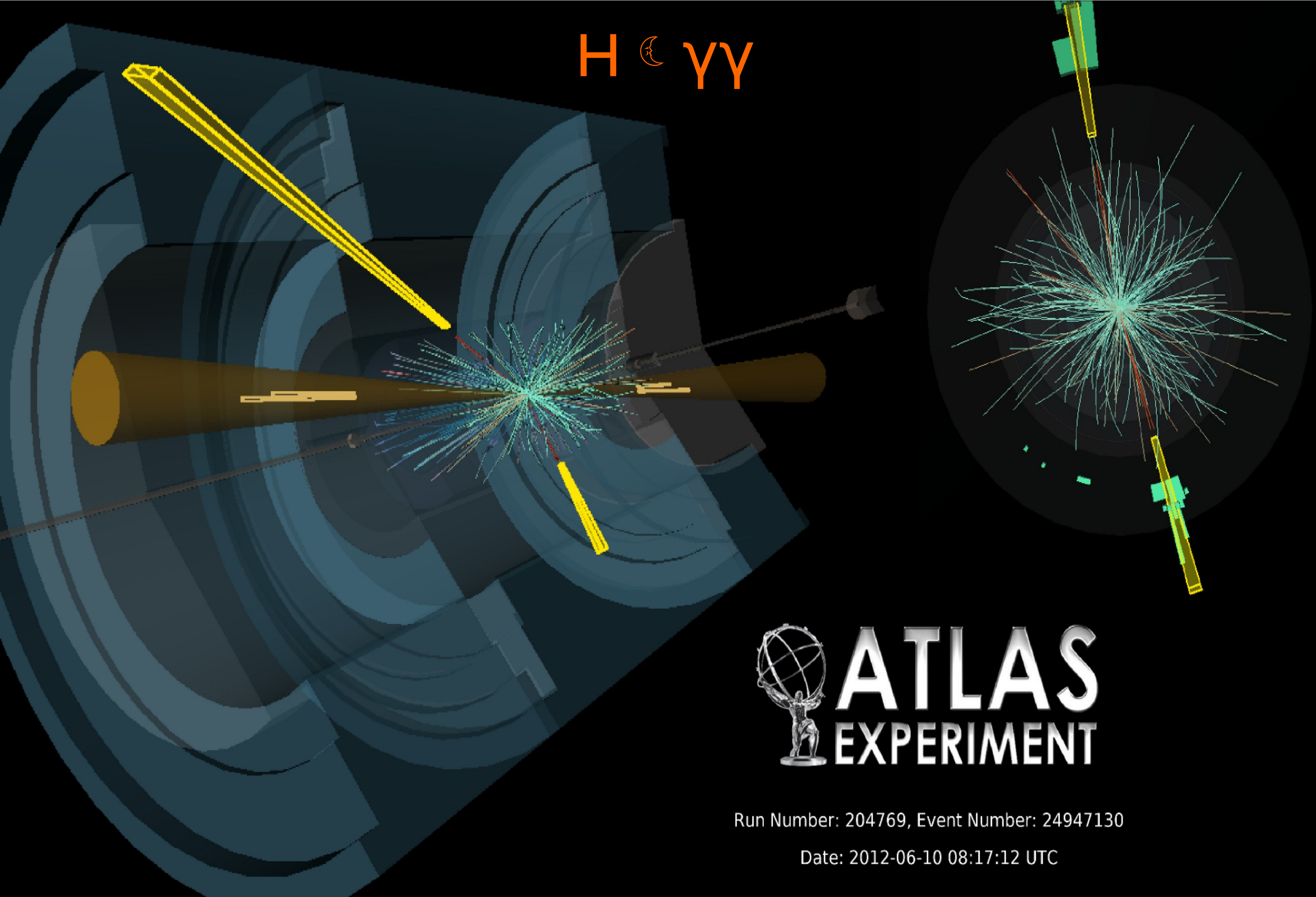
Standard Model Higgs decays



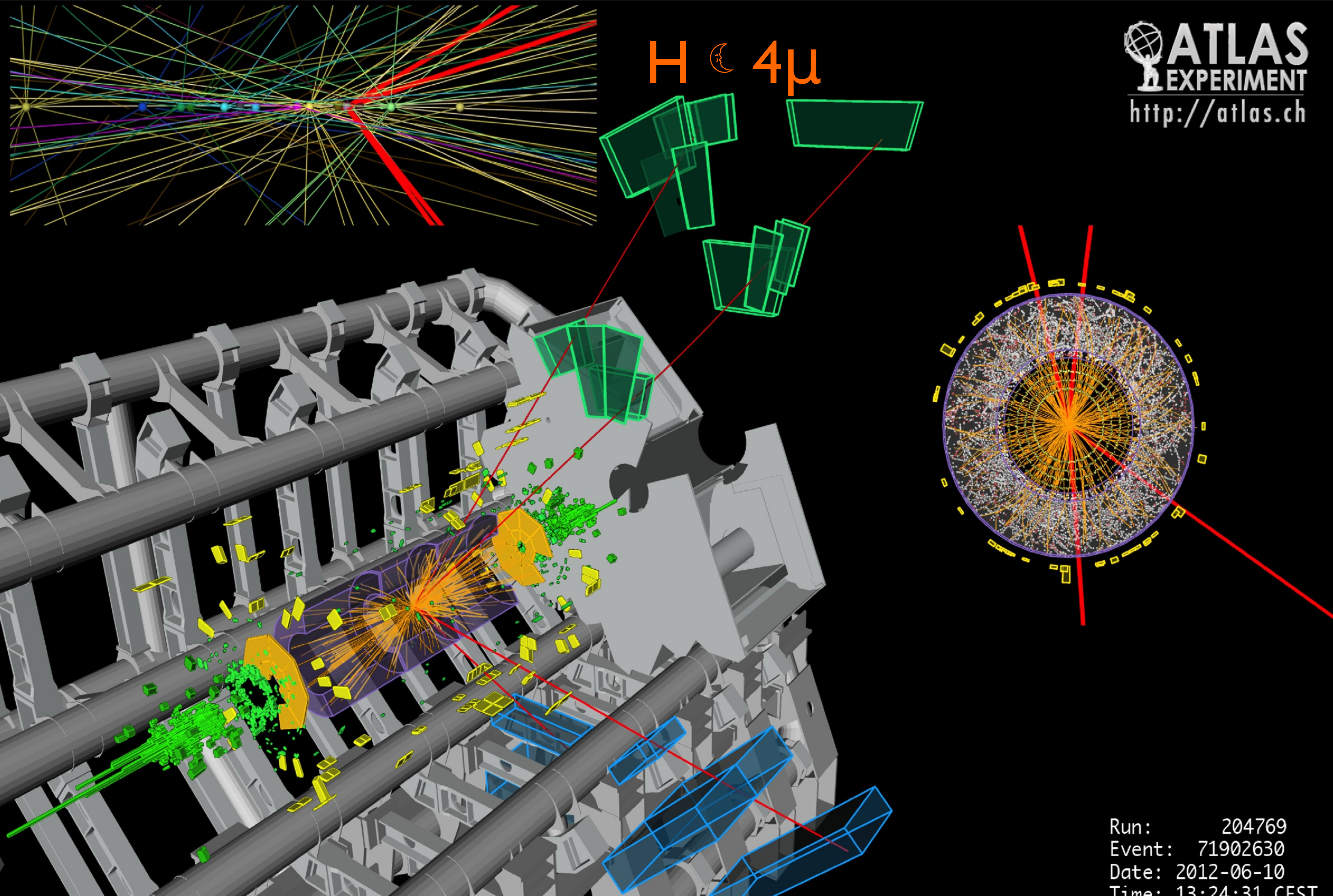
decay	SM BR [%] m_H = 125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→γγ	0.23

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

$H \to \gamma\gamma$

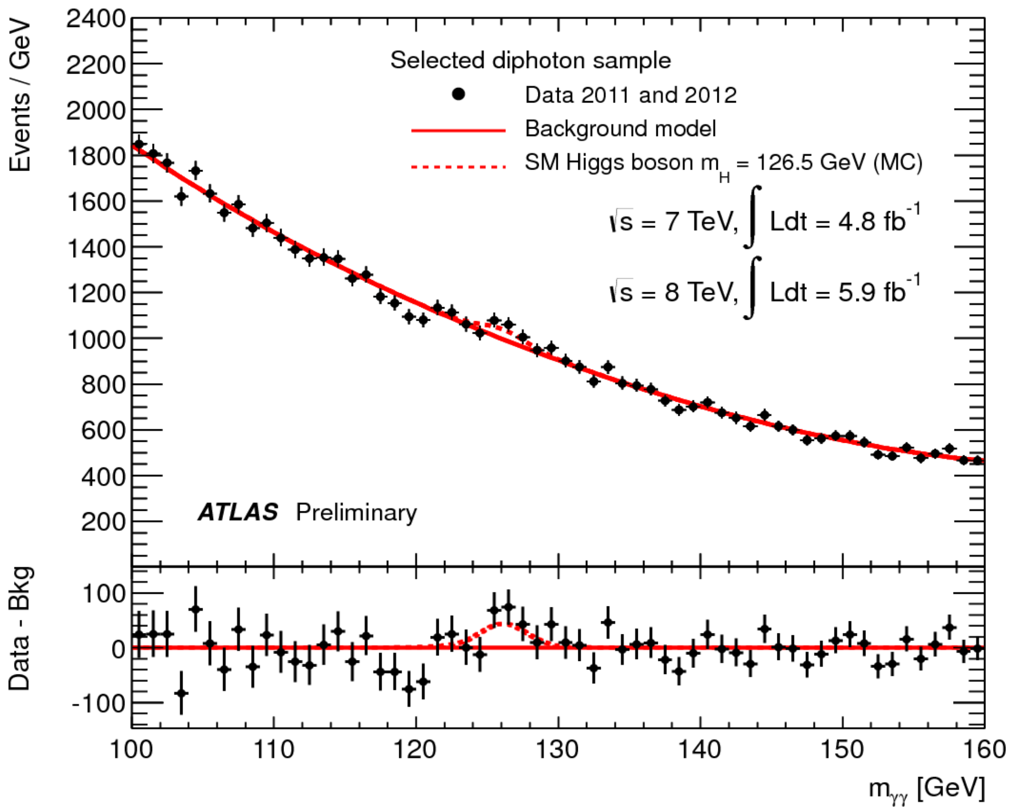


H ☾ 4μ

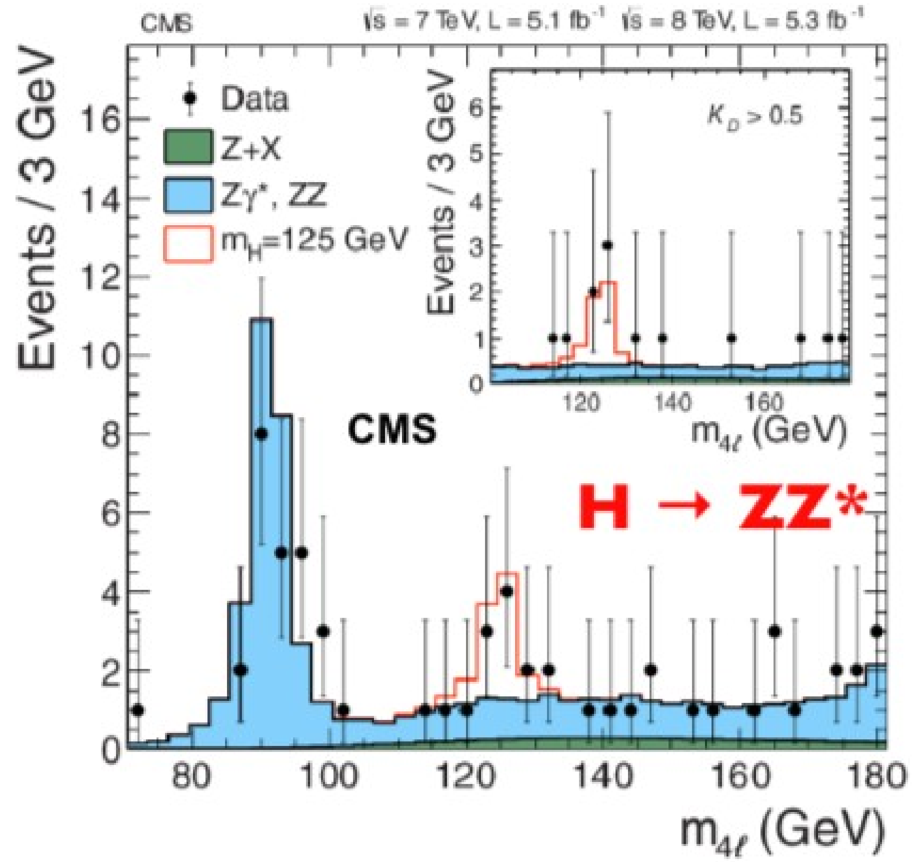

ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs signals on July 4th 2012

H → γγ

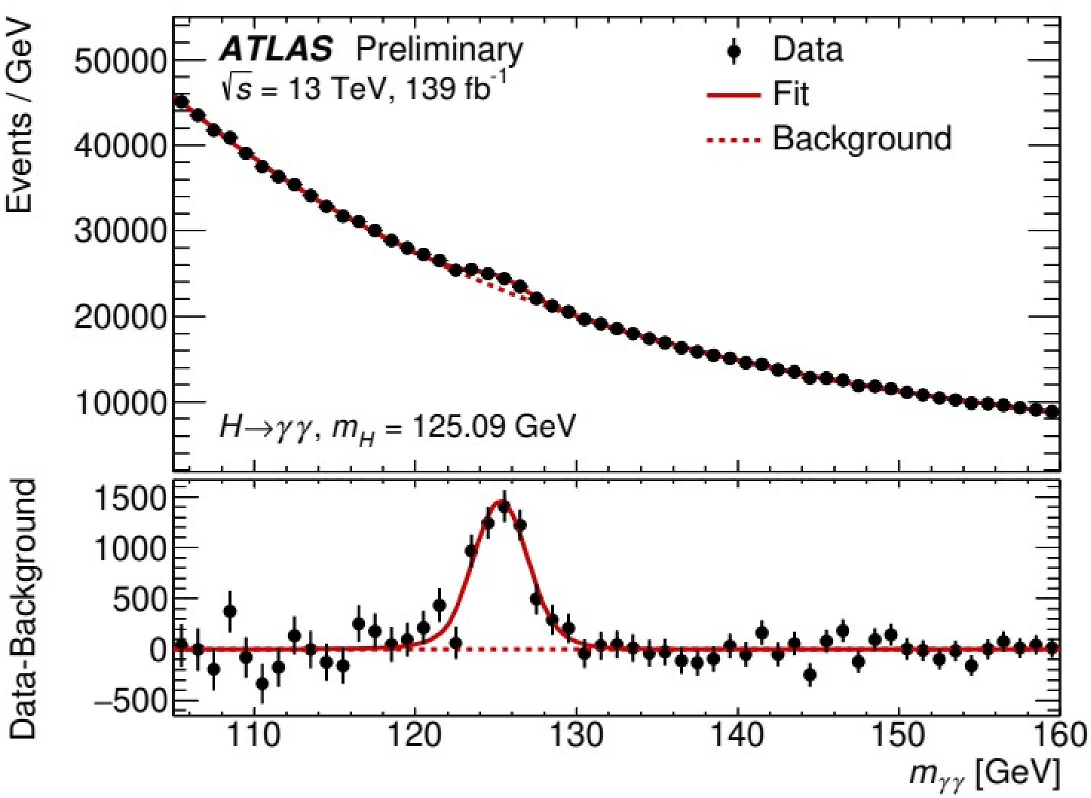


H → 4l

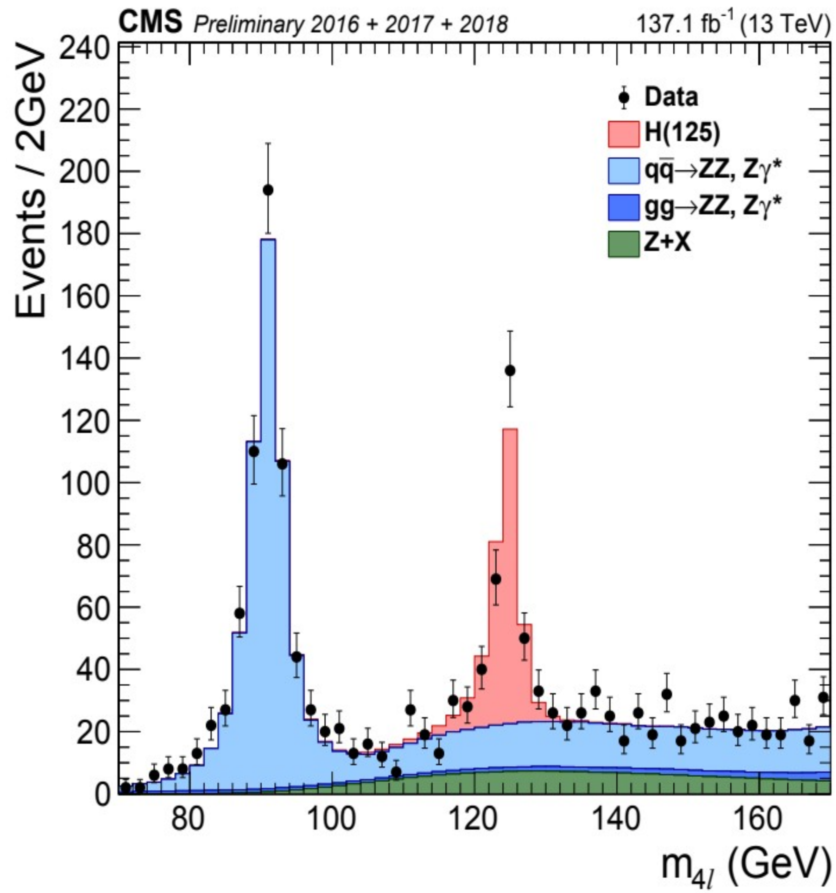


Higgs signals with the *latest* 13 TeV data…

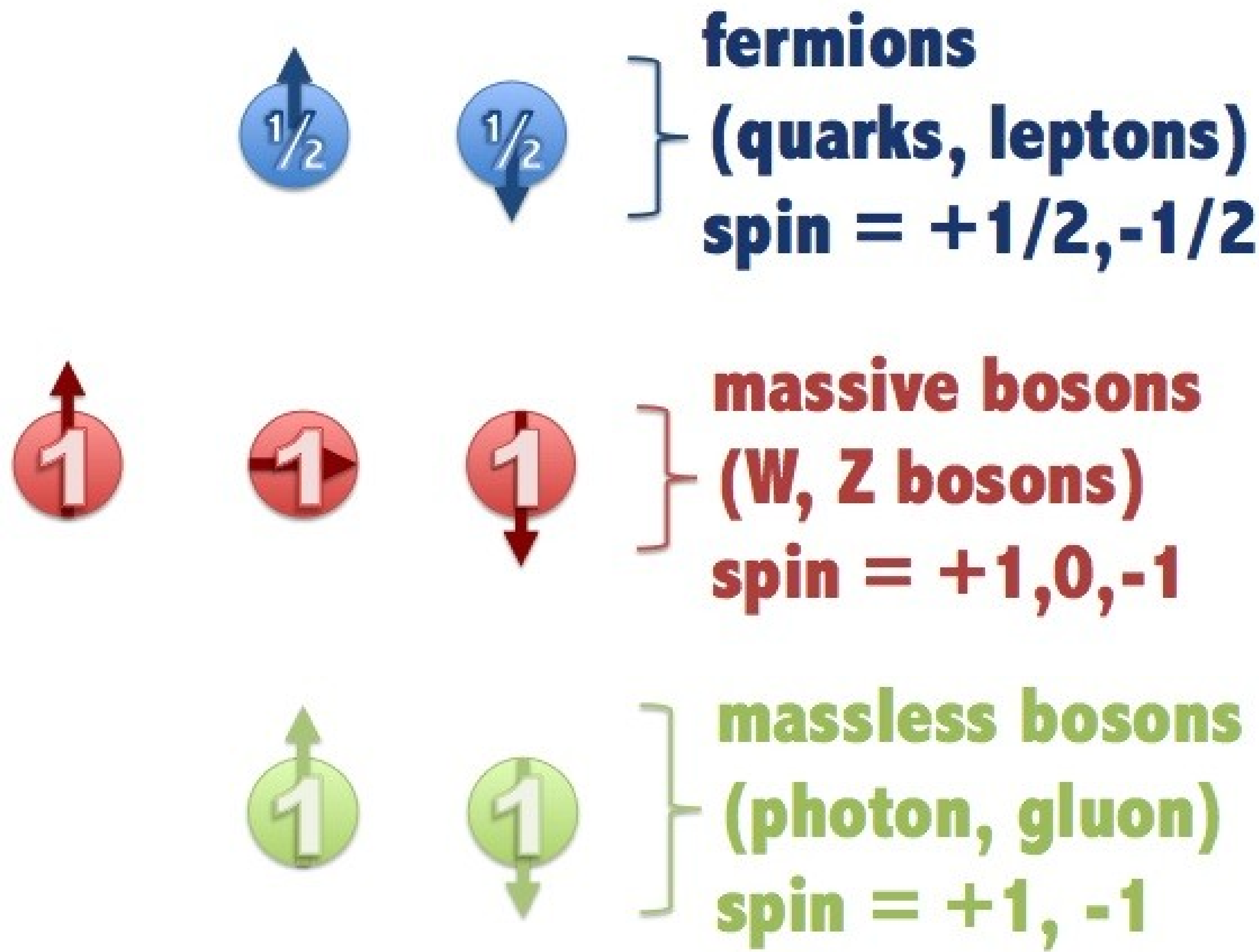
$H \rightarrow \gamma\gamma$



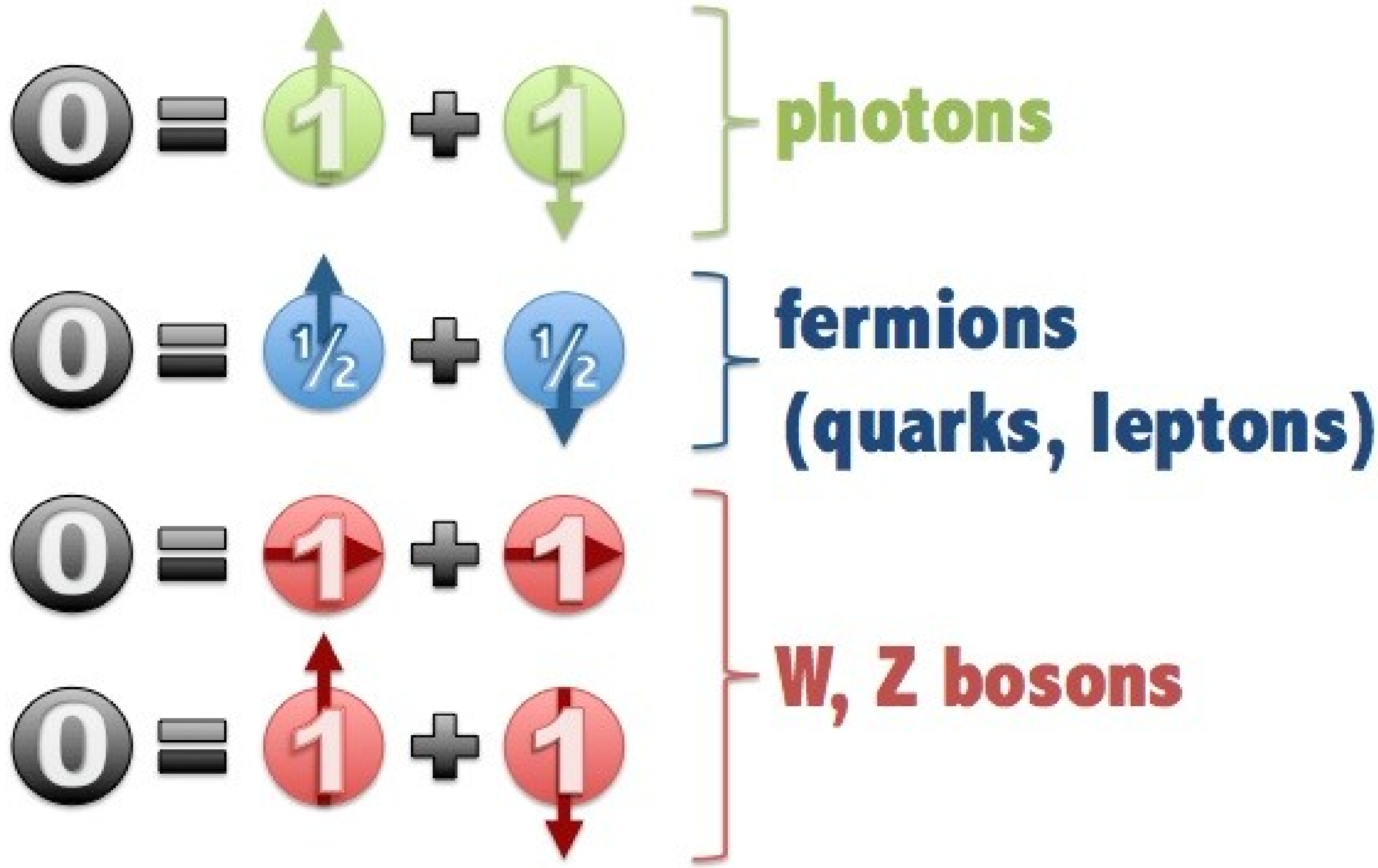
$H \rightarrow 4l$



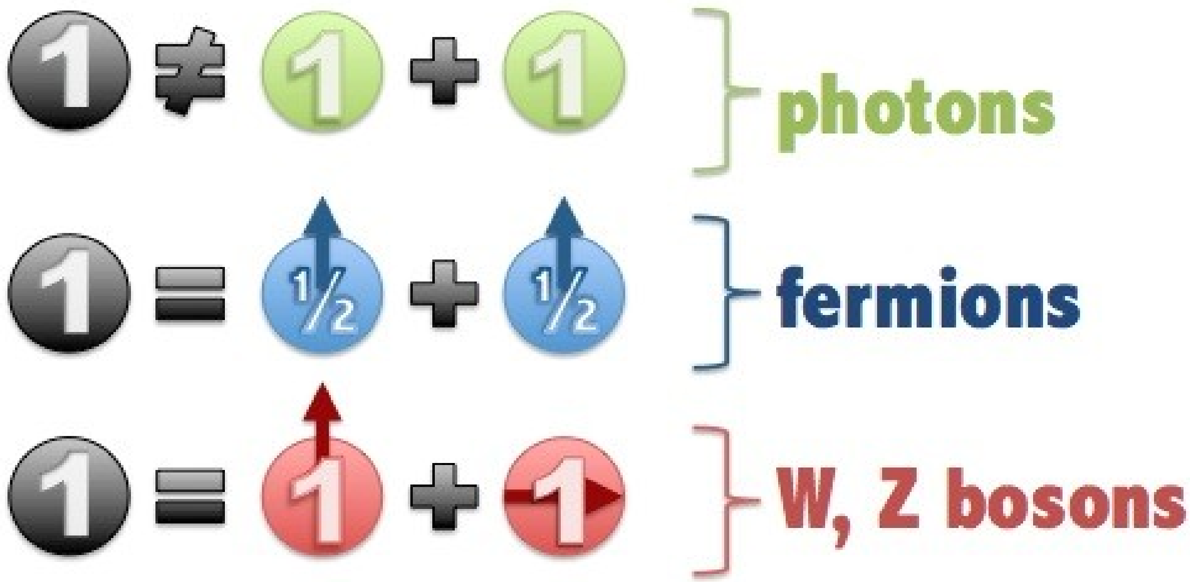
What spin do particles have?



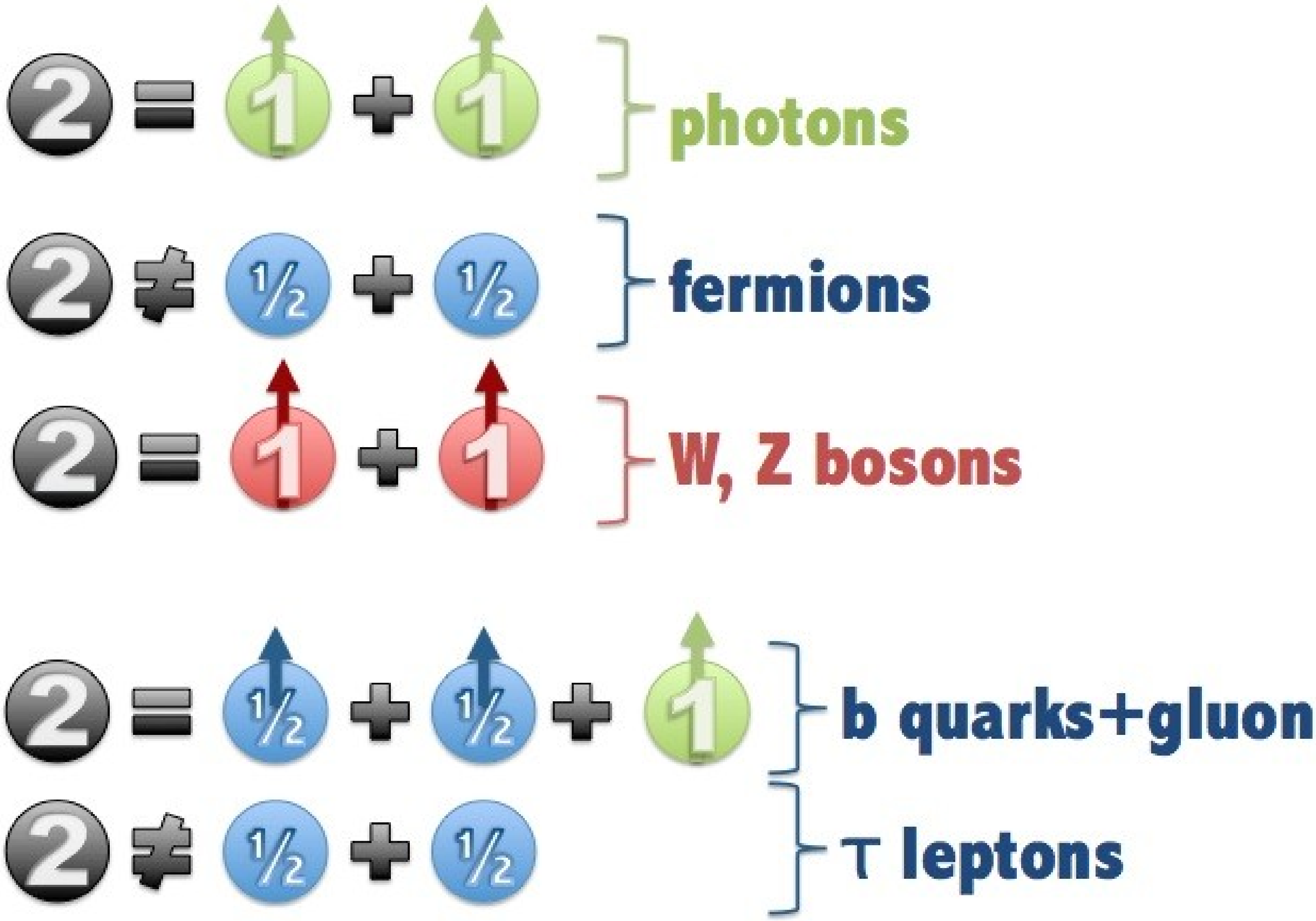
What can a spin 0 particle decay to?



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	$\gamma\gamma$	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*

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