LHC physics (experimental side) part 2

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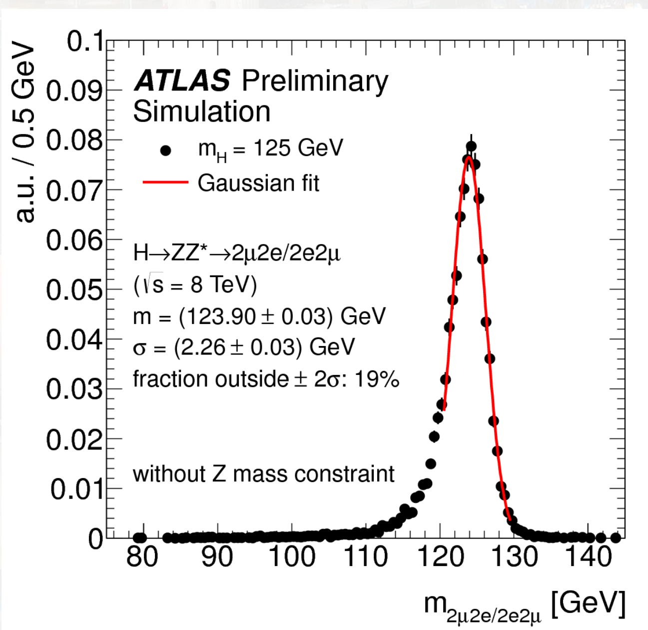
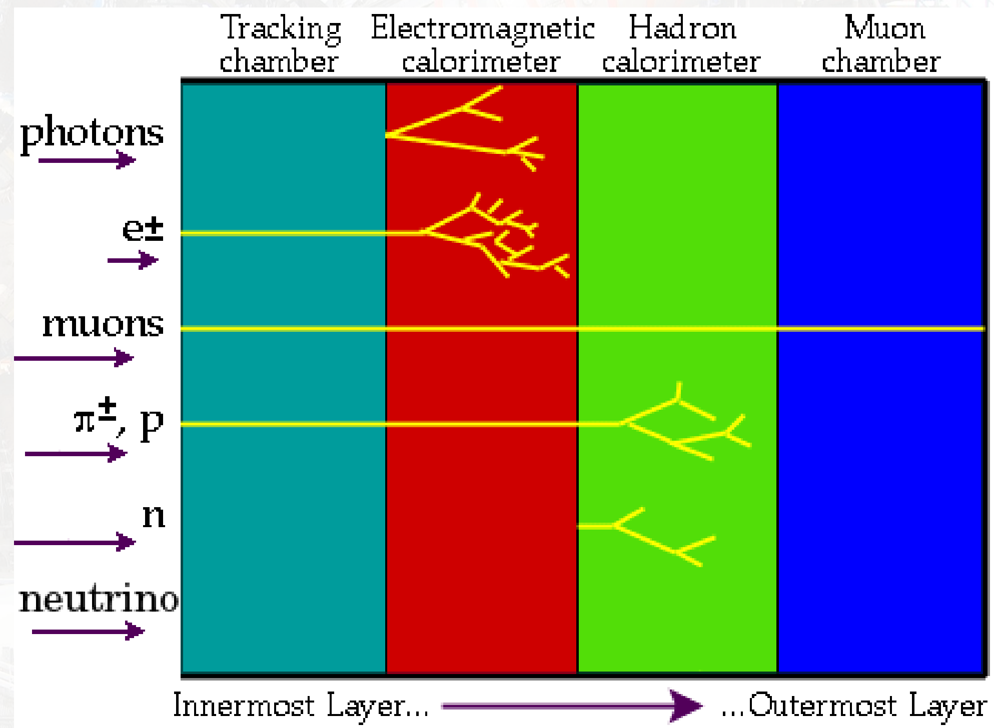
Reminders from first lesson

- Collide beams of particles to create new ones ($E_{collision}$ ~ M of particle)
- Huge detectors to reconstruct and identify decay products
- Selection of interesting events and reconstruction of initial state





Building

Maintenance

Detector calibration

Data acquisition

Data quality

Data processing

Analysis

Approbation procedures

Scientific result

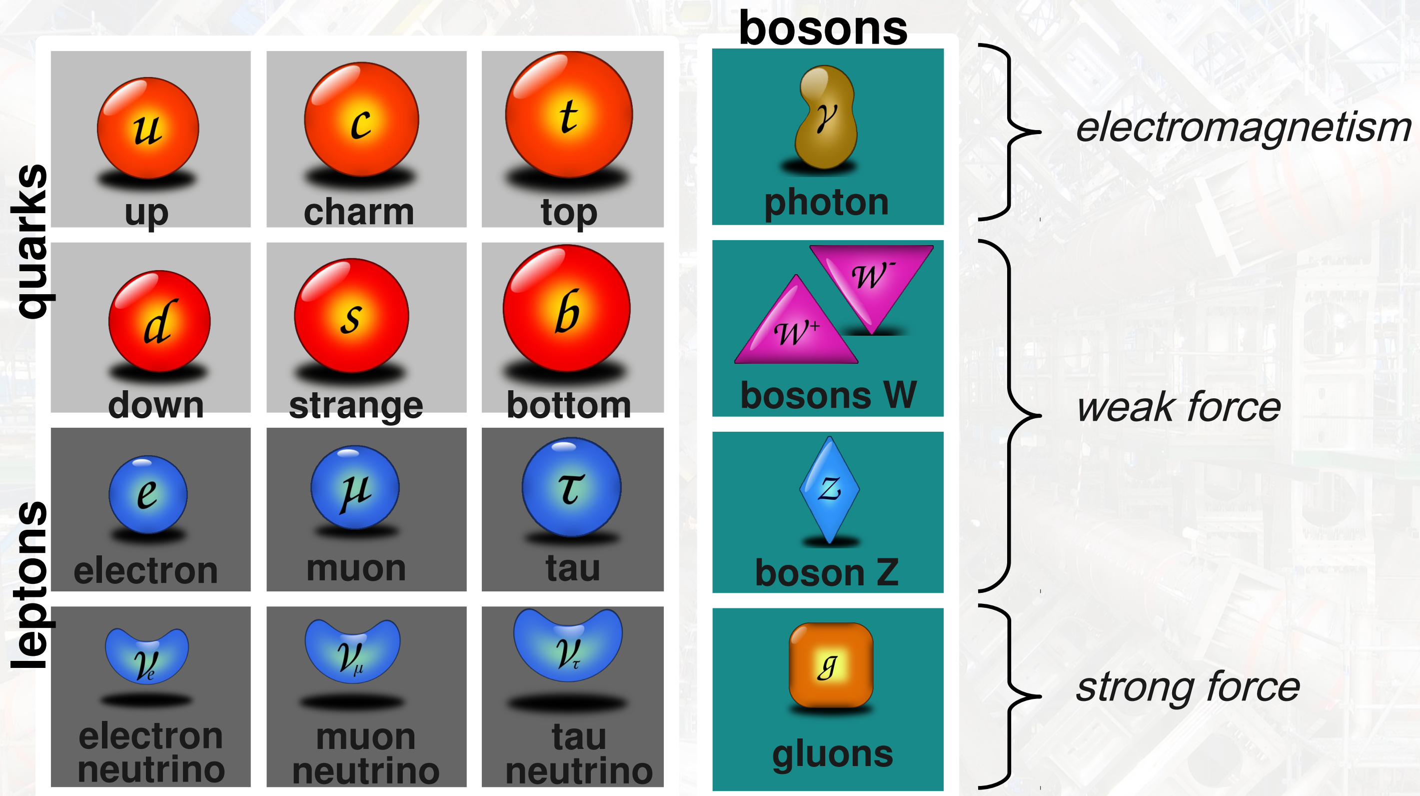
image : http://www.lhc-france.fr

ATLAS and CMS research program

- Precision measurements of the Standard Model
  - W boson mass, top quark properties, etc
  - indirect sensitivity to Beyond SM physics
- Search and study of the Higgs boson
  - observed last year
- Direct search for Beyond SM physics
  - supersymmetry
  - heavy gauge bosons, excited quarks, etc
- (Heavy ions)

Part I: Standard model measurements (1)

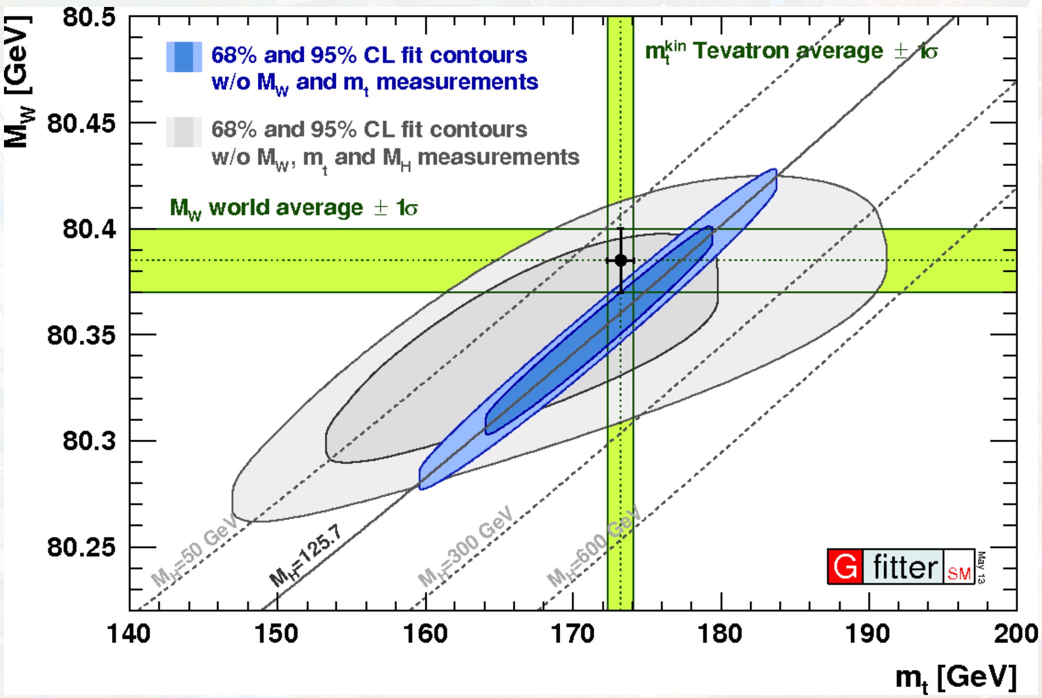
- Theory to describe elementary particles + forces

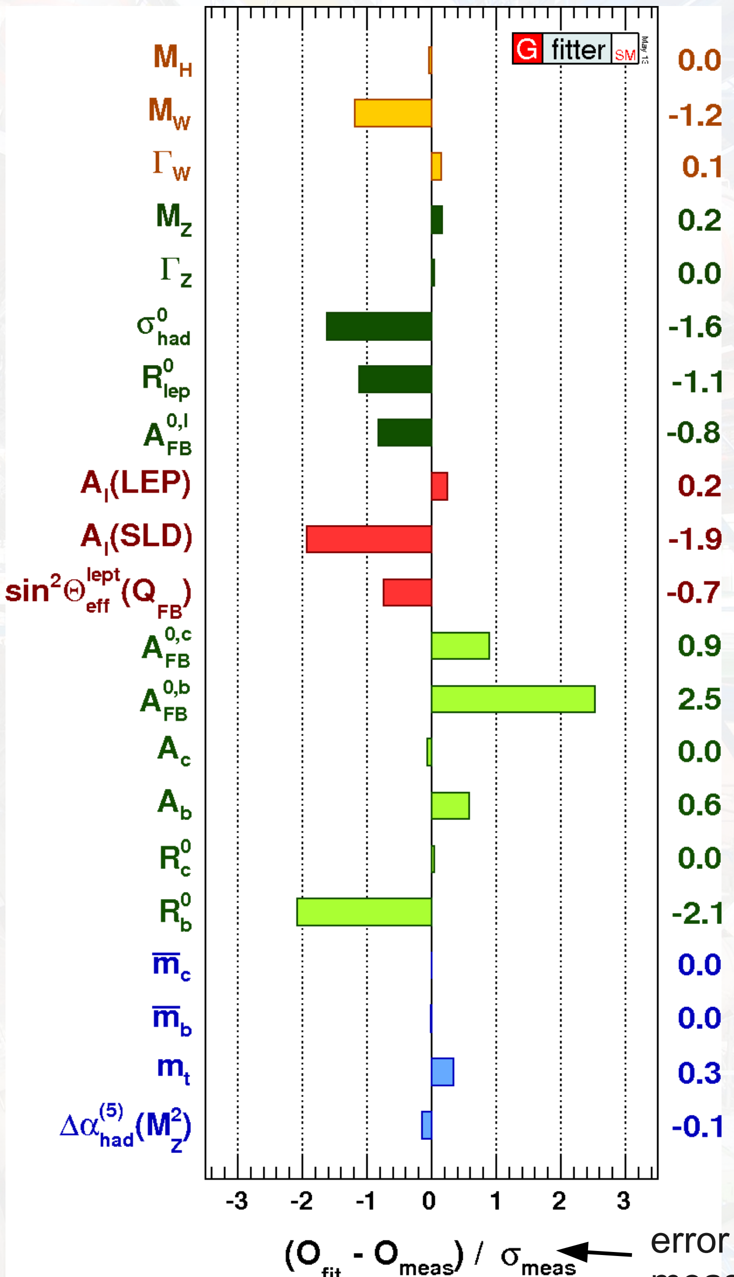


- Predicts:
  - production cross sections
  - branching ratios
  - etc

Part I: Standard model measurements (2)

- Very accurate predictions from the SM
  - all measurements in less than 3 standard deviations
- Predictions to be tested at LHC centre-of-mass energies
- Precise measurements possible
  - ex.: W mass, top mass

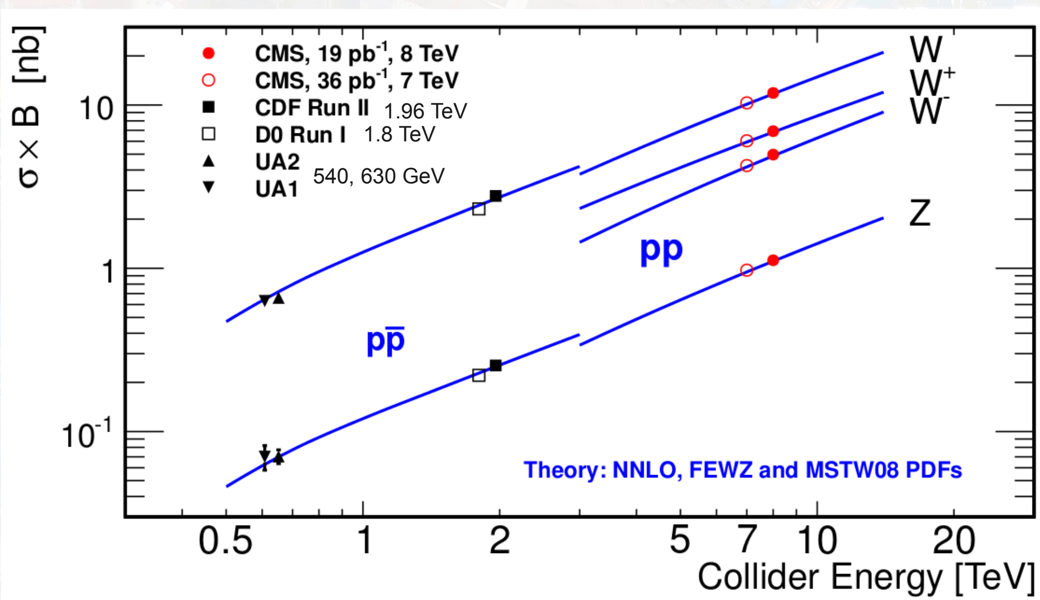


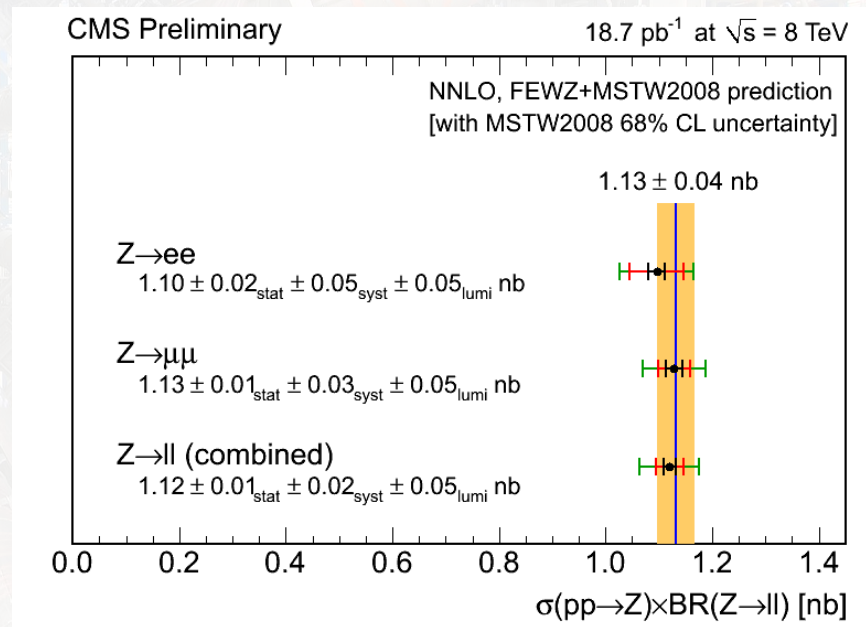


error on measurement
prediction
measurement

Cross sections (1)

- Production cross section σ = probability of a particle to be produced
- Number of produced particle: N = σ.L
- Example: production cross section of $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$

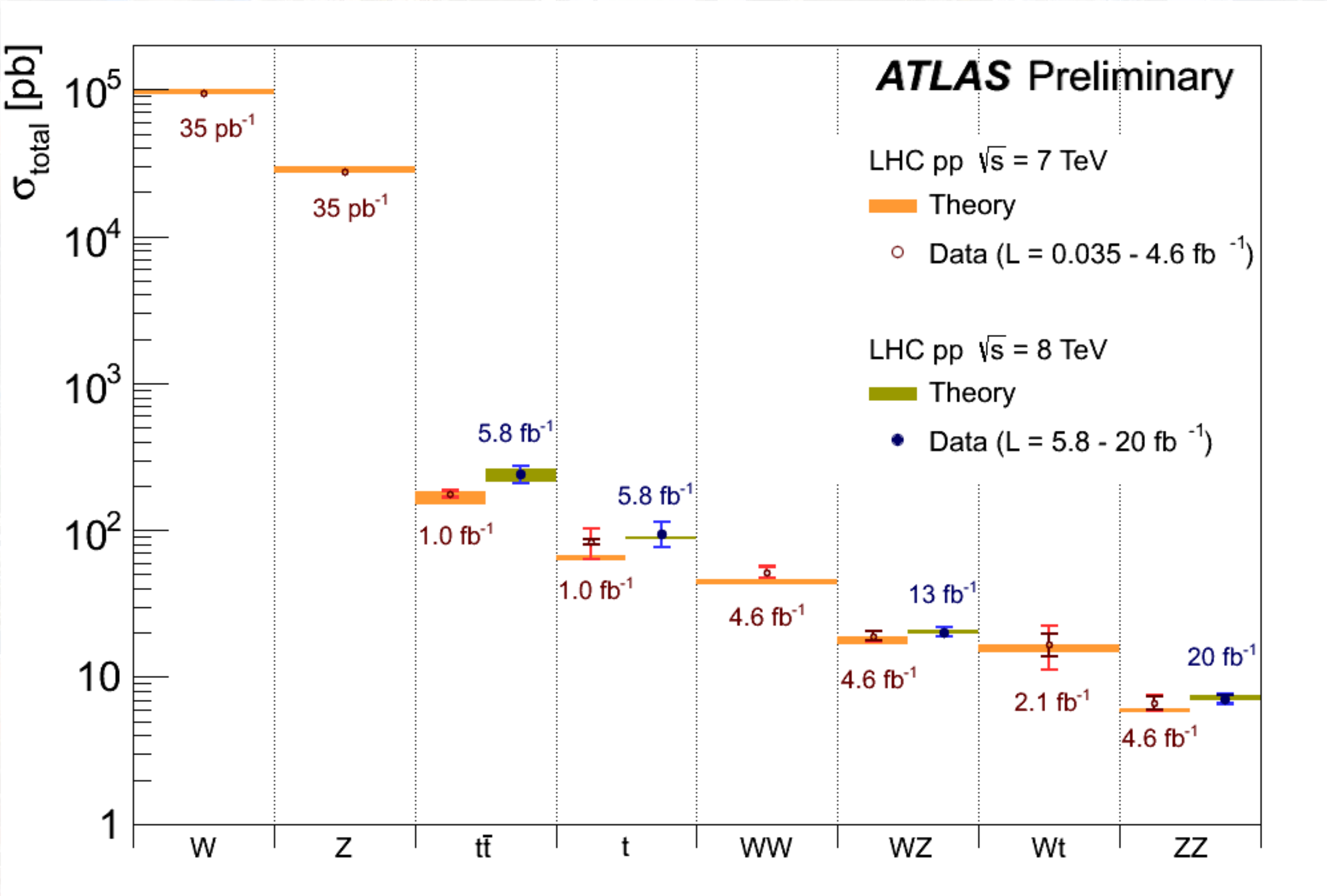




- Precision of the prediction: 3.5%
- Precision of the measurement: 4.8% (mainly to due to luminosity)

Cross sections (2)

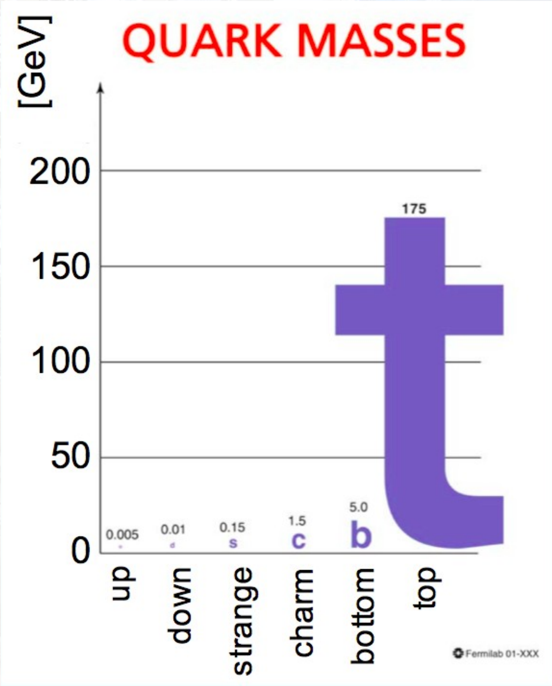
- Summary of cross section measurements:



- Once again, perfect agreement with SM predictions

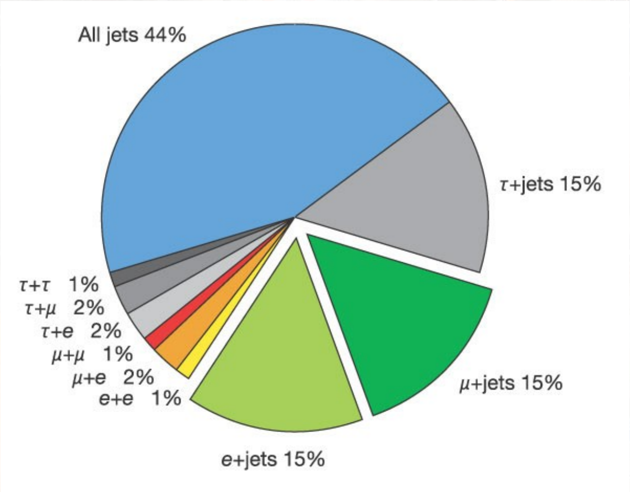
Top quark

- ♦ A very special quark
  - very massive
  - very short lifetime
    - decay in Wb ~ exclusively
  - discovered in 1995 at Tevatron



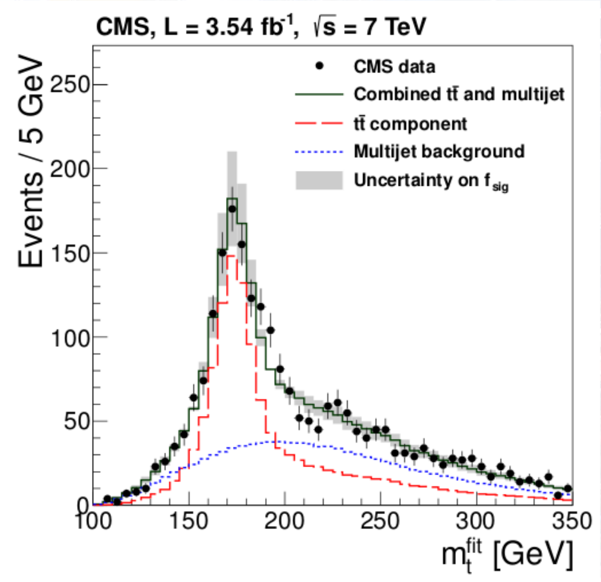
- ♦ Often produced by pairs of top-antitop
  - W can decay to eν, μν, τν or $q\bar{q}$

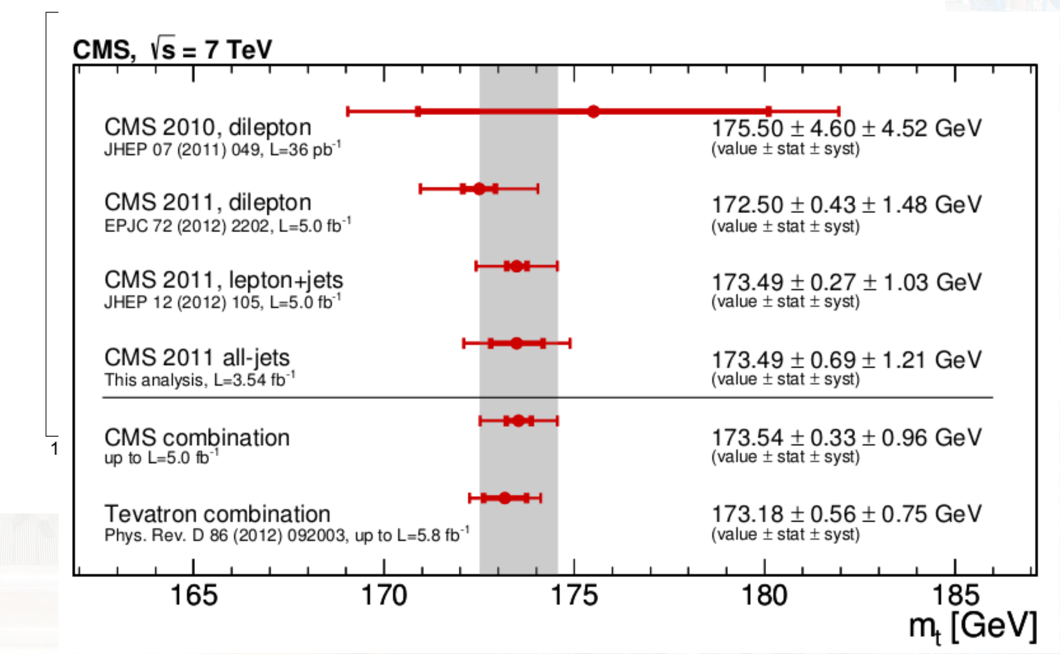
- ♦ LHC is a "top factory"
  - 5 millions of $t\bar{t}$ pairs
  - ~100000 in Tevatron in 20 years

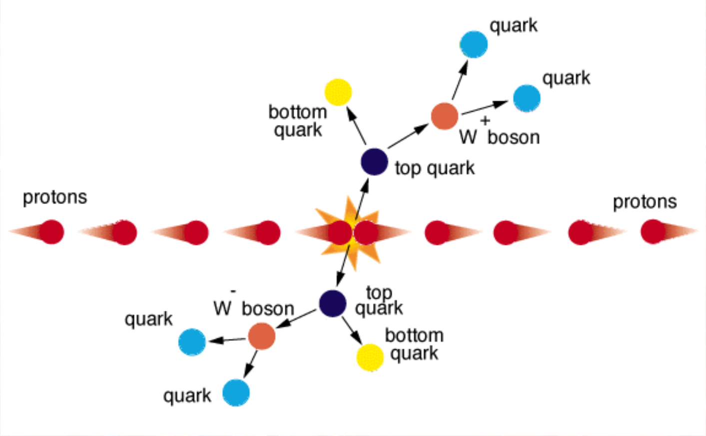


Top mass

- Mass several orders of magnitude larger than u and d quarks
- Best precise measurement at Tevatron
  - uncertainty of 0.5%
- Best precise measurement at the LHC:
  - reconstructed from 6 quarks
  - uncertainty of 0.6%





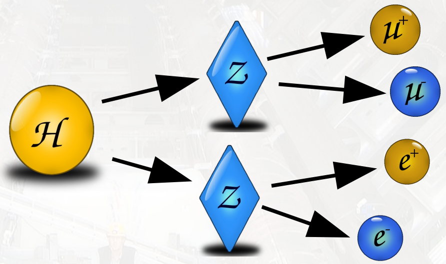


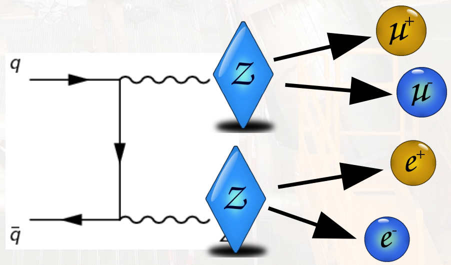
Interlude: search for a particle

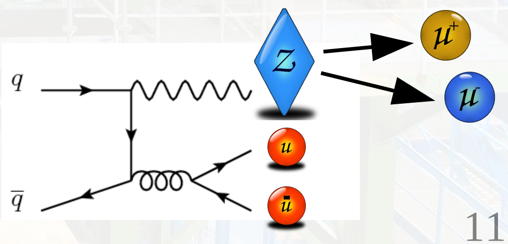
- LHC: 40 millions of collisions/s
- Interesting processes are very rare:

	mass (GeV)	cross section	Events (millions)
2 quarks/gluons		500 μb	100000000
W→lν	80.4	10 nb	300
Z→ll	91.2	0.9 nb	30
$t\bar{t}$	173.1	165 pb	5
Higgs	125	22 pb	0.7
Z'→ll	1000	95 fb	0.003

- Reminder from lesson 1:
  - signal
  - background: similar final state
  - select interesting events
  - reconstruct invariant mass

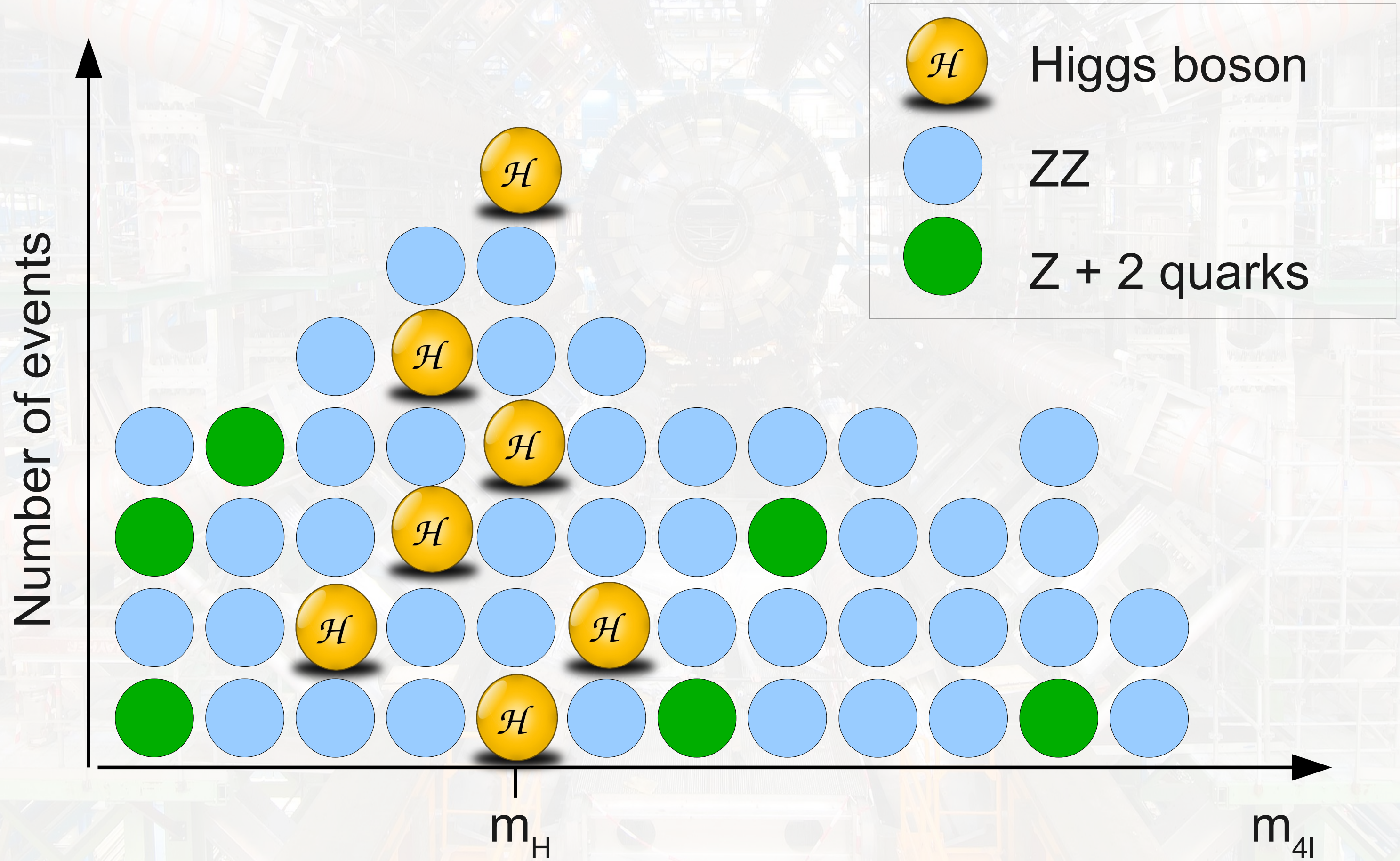






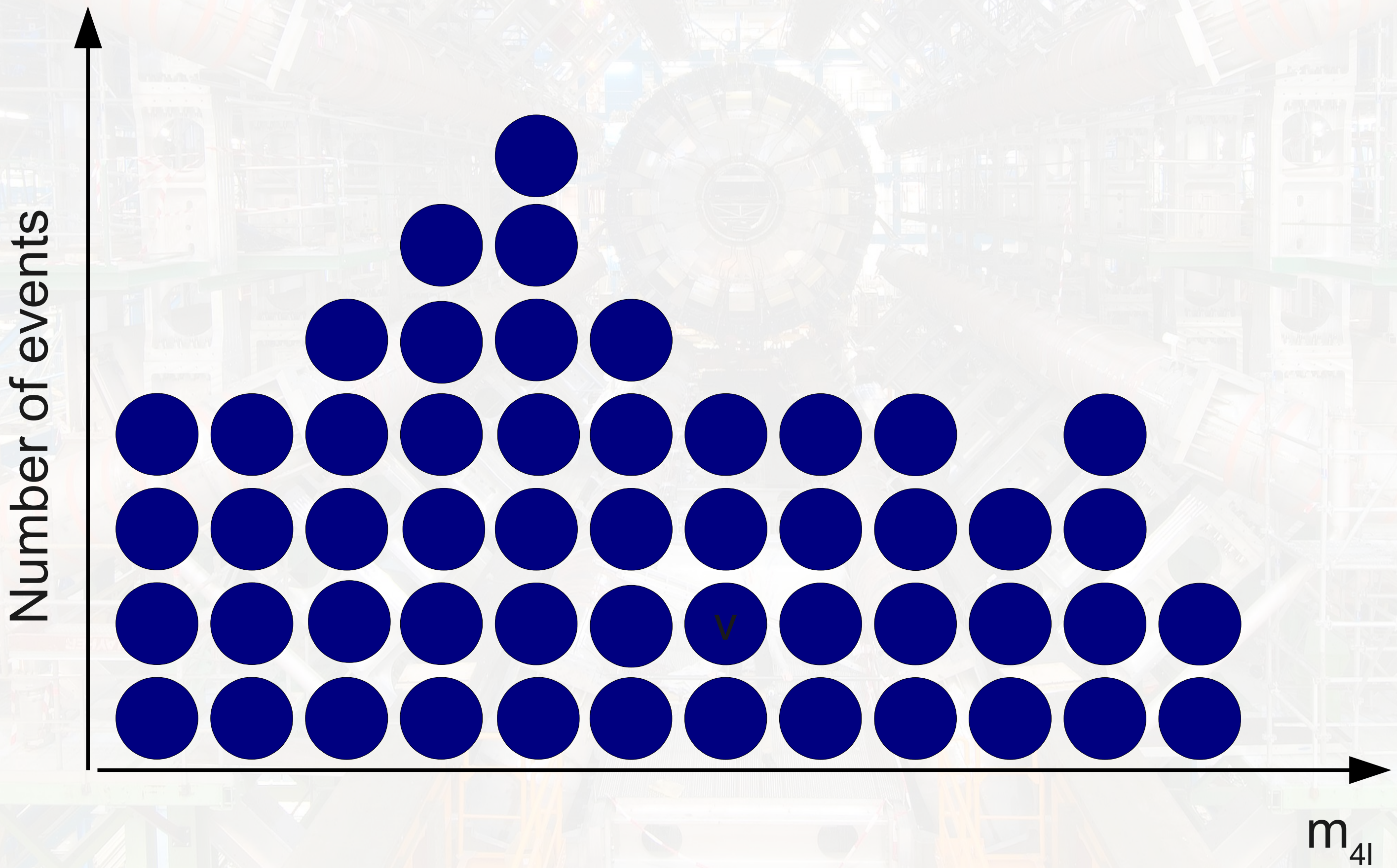
Extract signal from background (1)

- Signal is at a given invariant mass (unknown)
  - background can have any mass (no resonance)
- Example:



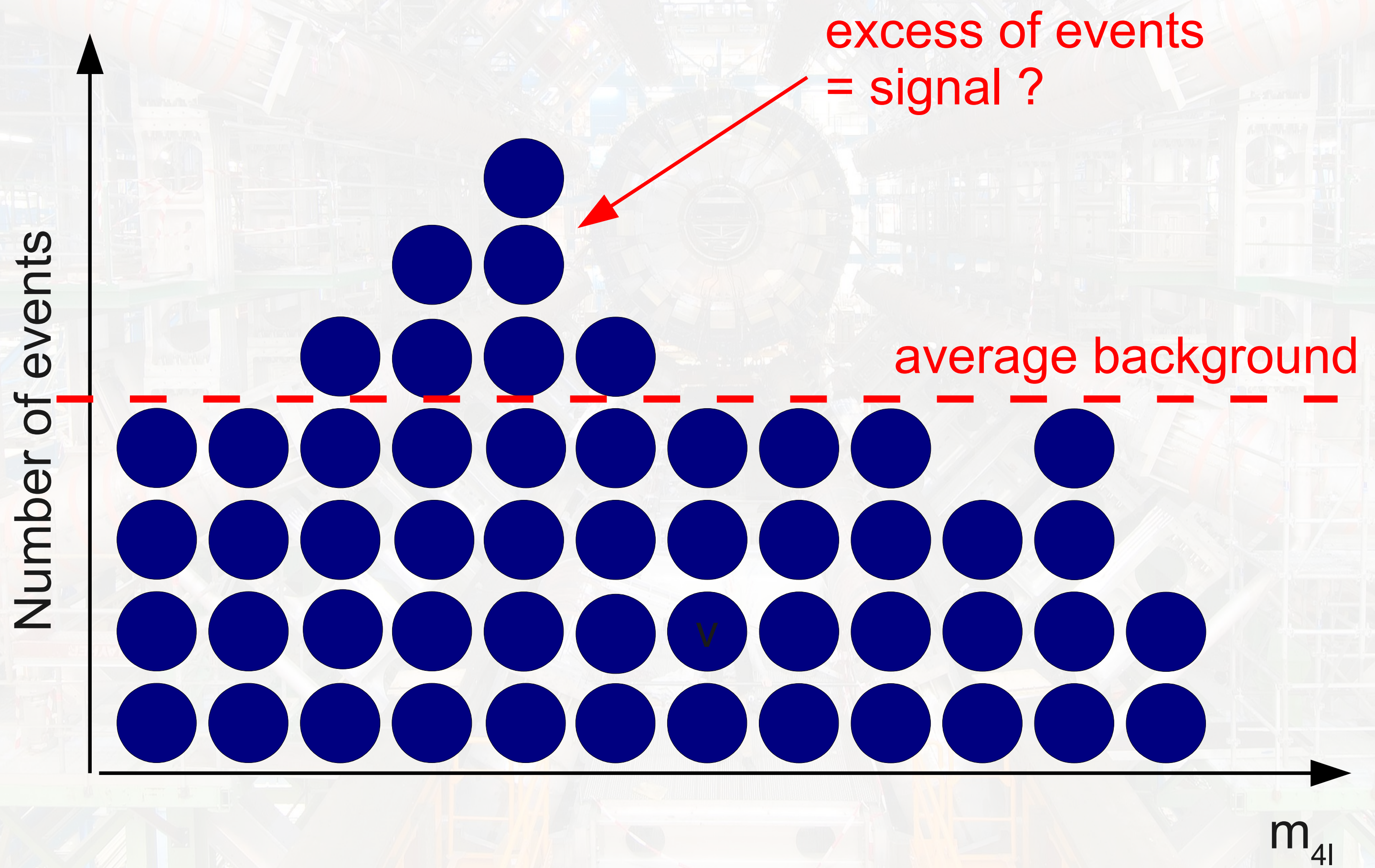
Extract signal from background (2)

- But can't distinguish signal from background events:



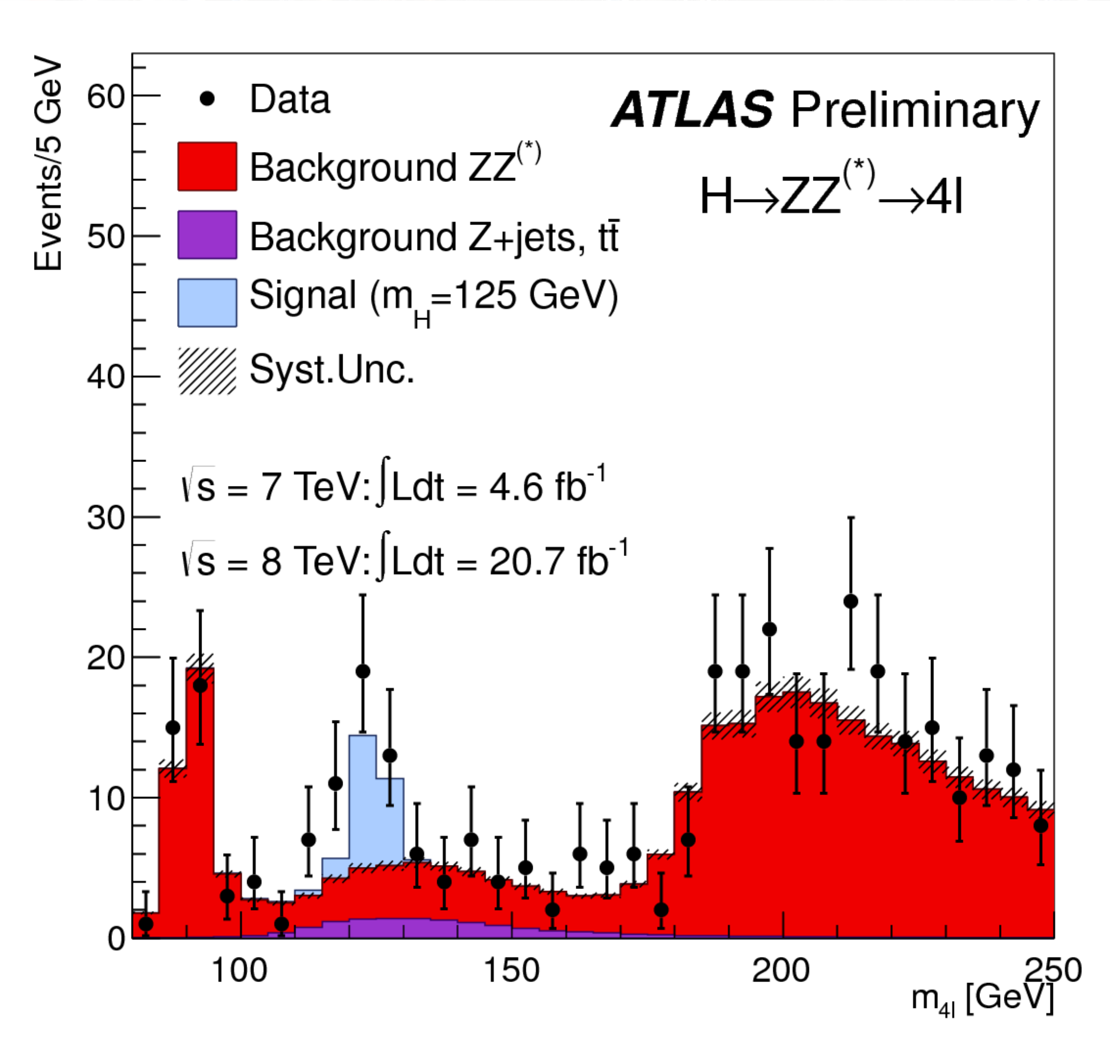
Extract signal from background (3)

- Look for an excess of events over the background:



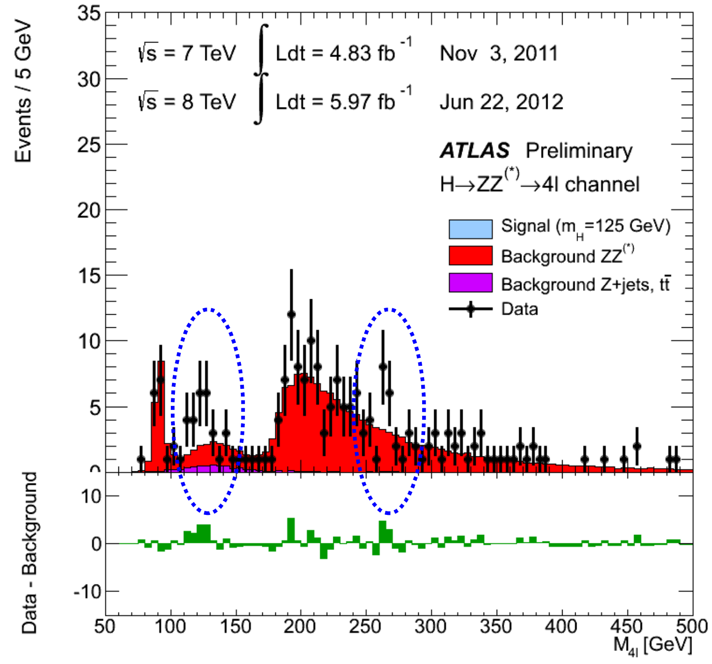
Extract signal from background (4)

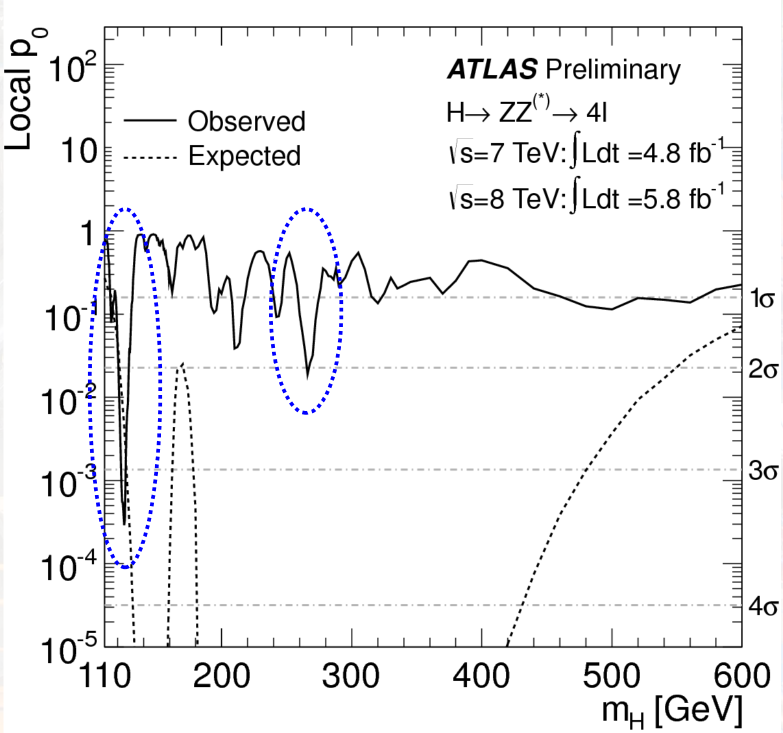
- Background estimate
  - from simulation
  - from data (samples enriched in background events)



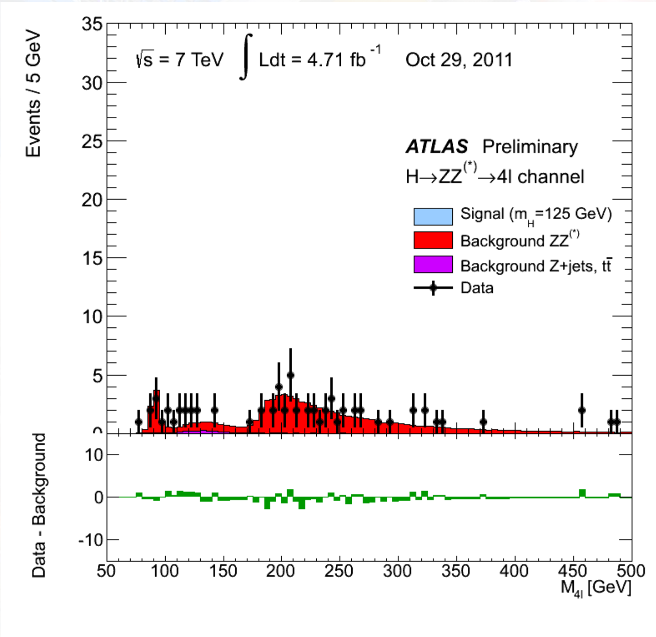
Statistical analysis

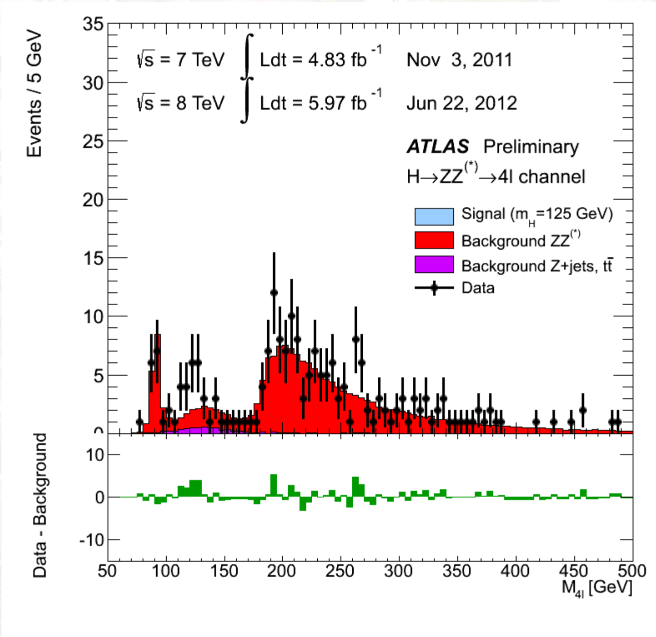
- p0: probability that the excess is due to a fluctuation of background
- Significance:
  - $Z \sim S/\sqrt{B}$
  - $p_0 = 1 - \mathrm{Erf}\left(\frac{Z}{\sqrt{2}}\right)$
- Convention in HEP:
  - 3σ is an evidence (↔ p0 = 0.27%)
  - 5σ is a discovery (↔ p0 = $5.7.10^{-7}$)
- If no signal, put a limit on the cross section

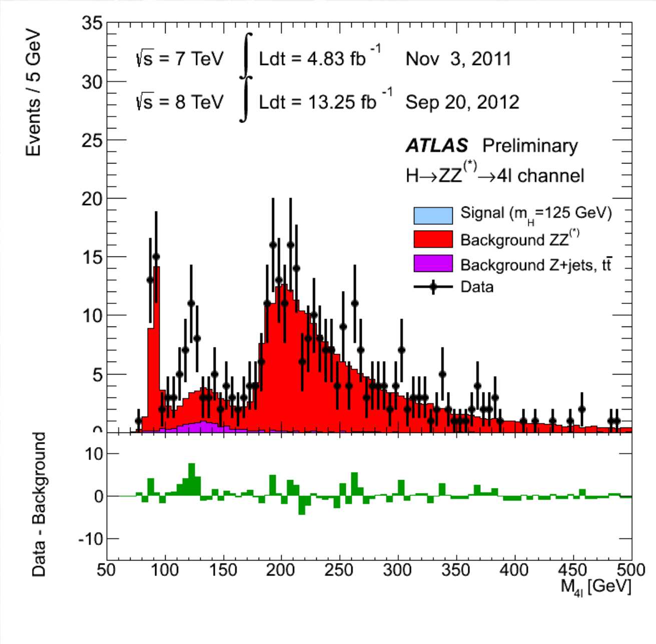


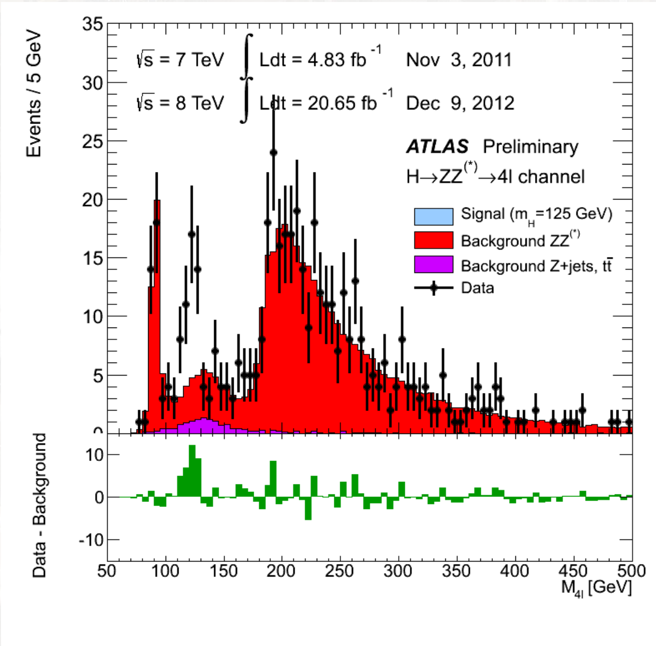


Need for a lot of data



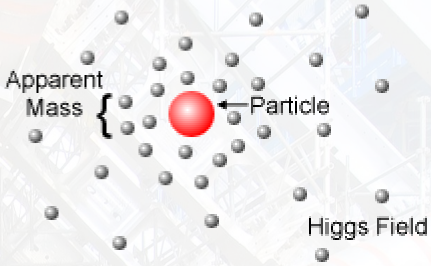






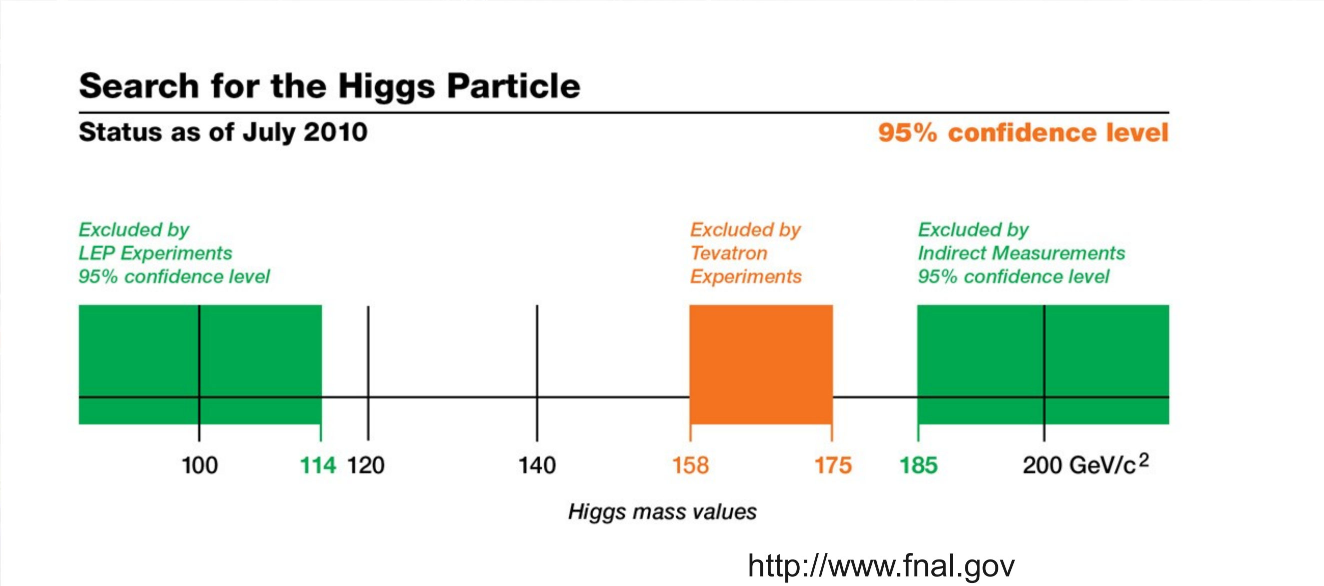
Part II: Higgs boson

- Interaction of the particles with the Higgs field give them mass



- Theory does not predict the Higgs boson mass!
  - but would prefer a "light" Higgs

- Masses excluded before LHC:



History of Higgs boson search

- 1964 Brout & Englert, Higgs, Guralnik, Hagen & Kibble,
  - not taken too seriously until...
- 1967 Used in the formulation of the Standard Model
  - proven to be self-consistent in 1971

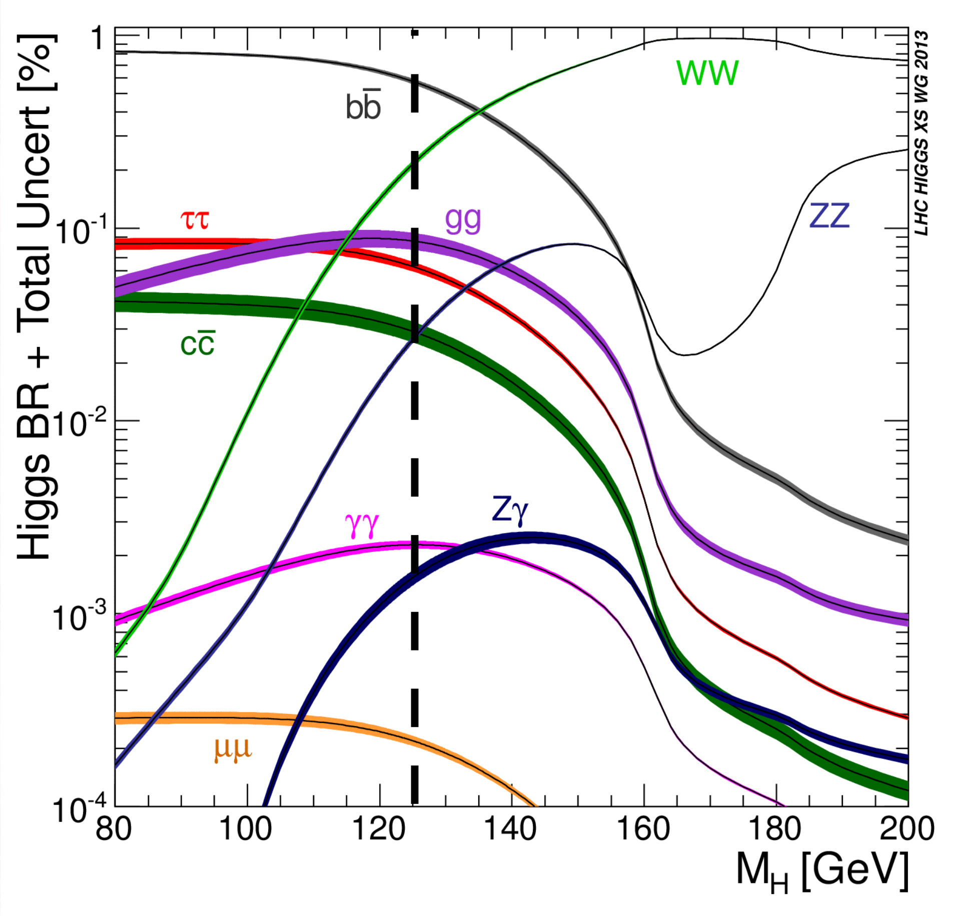
- 1973 Experimental acceptance of the Standard Model
- 1983 Discovery of W and Z bosons
  - closely linked to the Higgs boson

- 1993 LEP studies Z's and rules out m_H<53 GeV
  - and indirectly excludes m_H>300GeV
- 1994 Building of LHC accepted
- 2000 LEP lower limit reaches 114.4 GeV
  - hint of production at 115 GeV?
- 2011 LHC excludes 130-550GeV, Tevatron 156-175 GeV
  - some indications for a particle at 125 GeV?
- 4th July 2012 New particle found at 126GeV

from B. Murray

Higgs boson decay

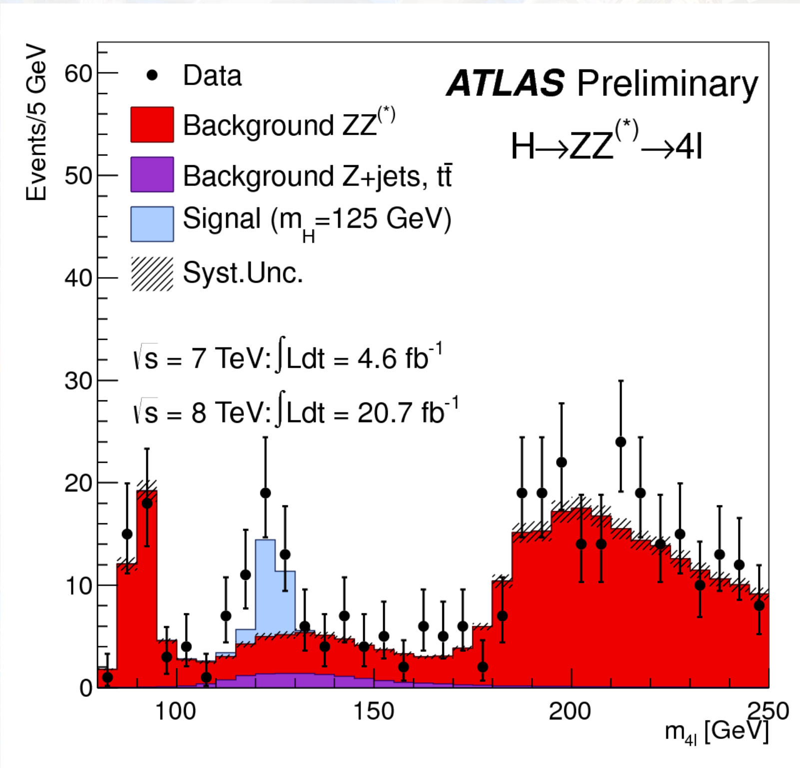
- Predicted branching ratio:



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

Two major decay channels

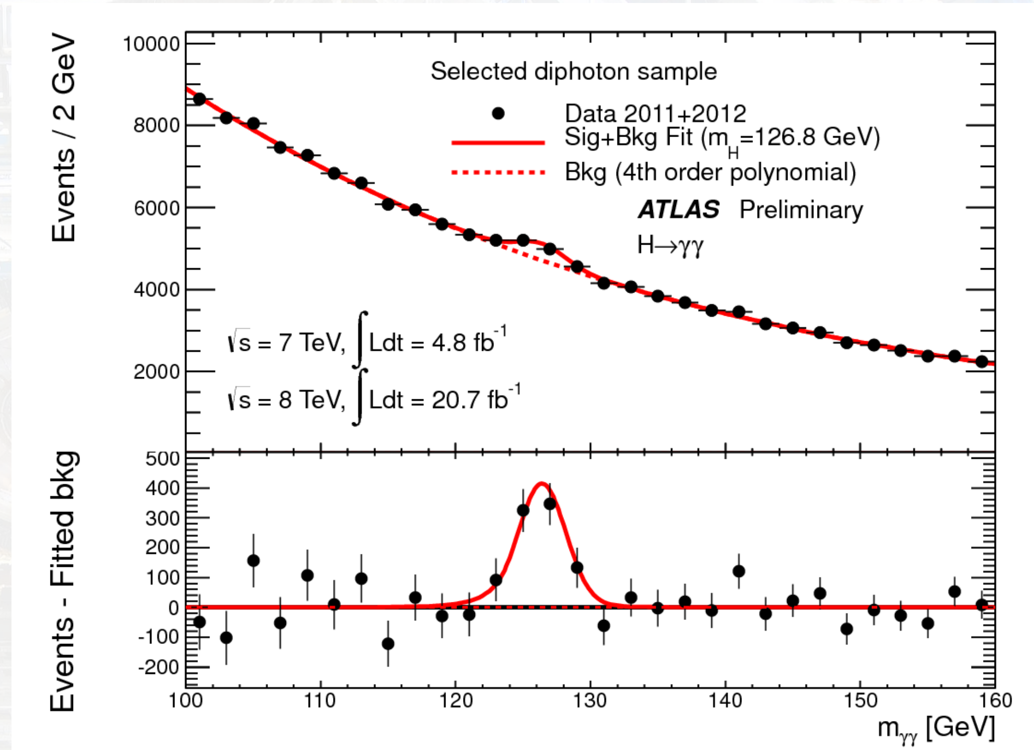
♦ $H \rightarrow ZZ^* \rightarrow 4$ leptons (e, μ)



♦ Signal ≃ 20

♦ S/B ~ 1

♦ $H \rightarrow \gamma\gamma$



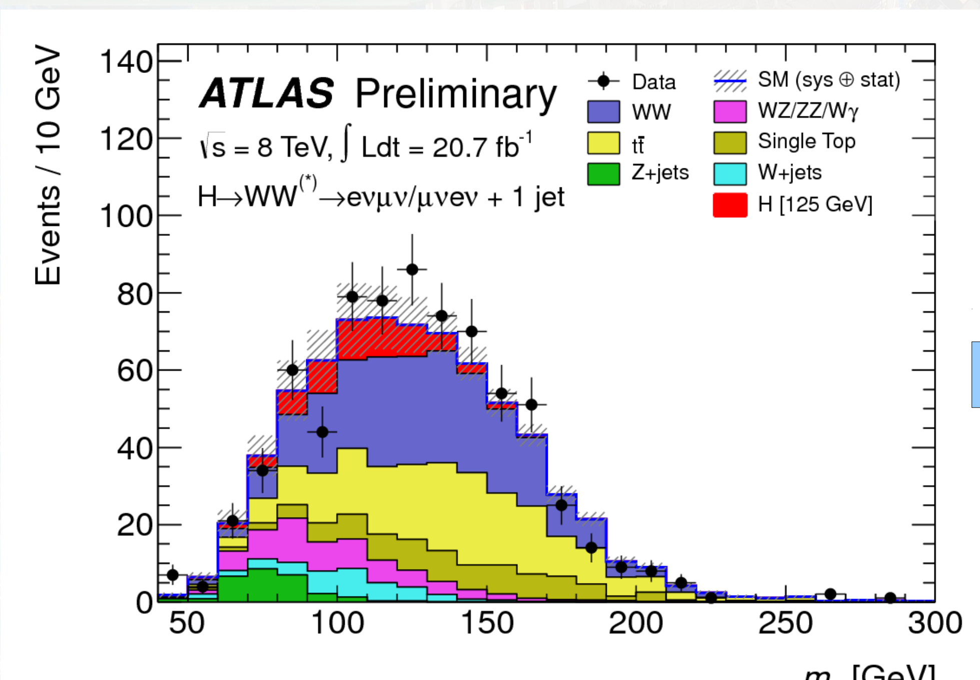
♦ Signal ≃ 400

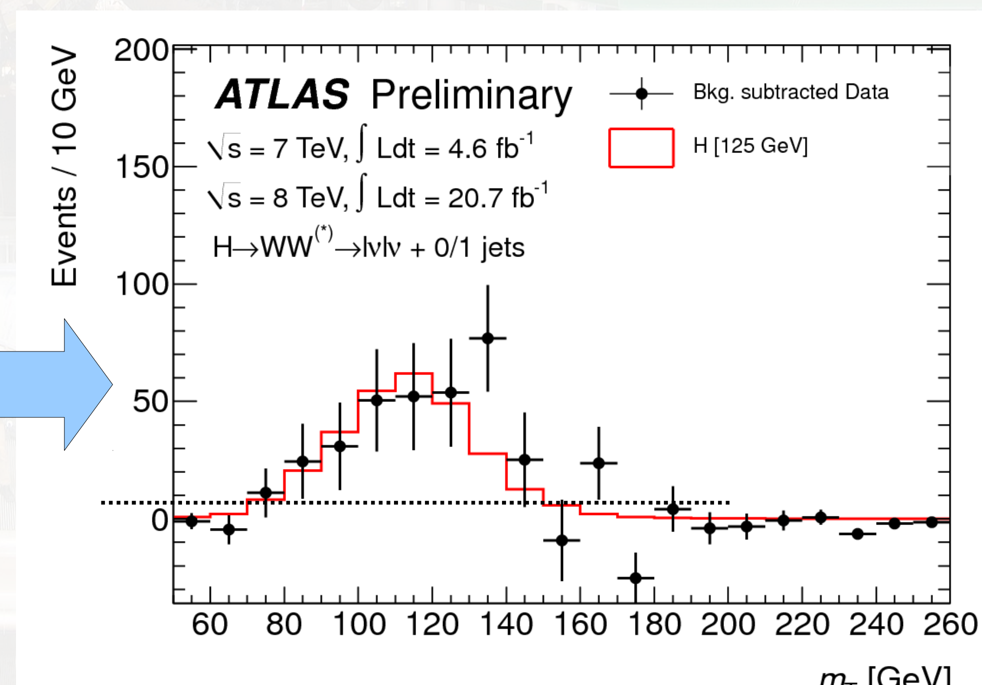
♦ S/B ~ 1%

Example : search for H→WW*

- With decays W → eν et W → μν
- Select events (energy, identification, kinematics of the event, ...)
- Background
  - reducible: tt, WZ, Z+jets, ...
  - irreducible: WW
- Background estimate and data:

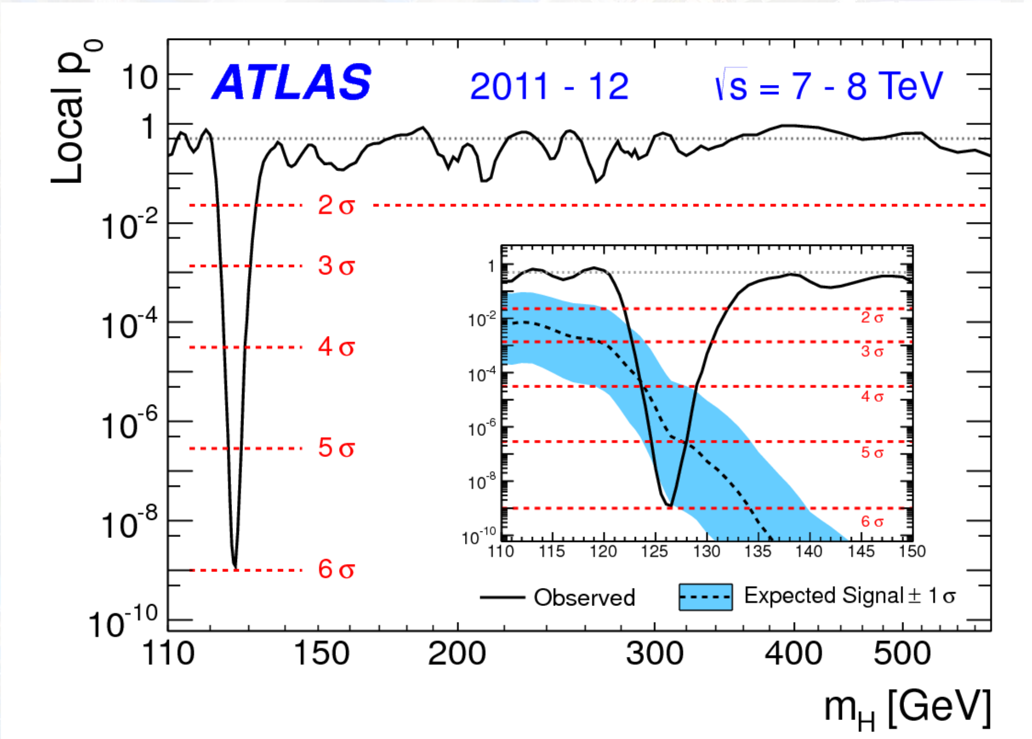
} cf lesson 1

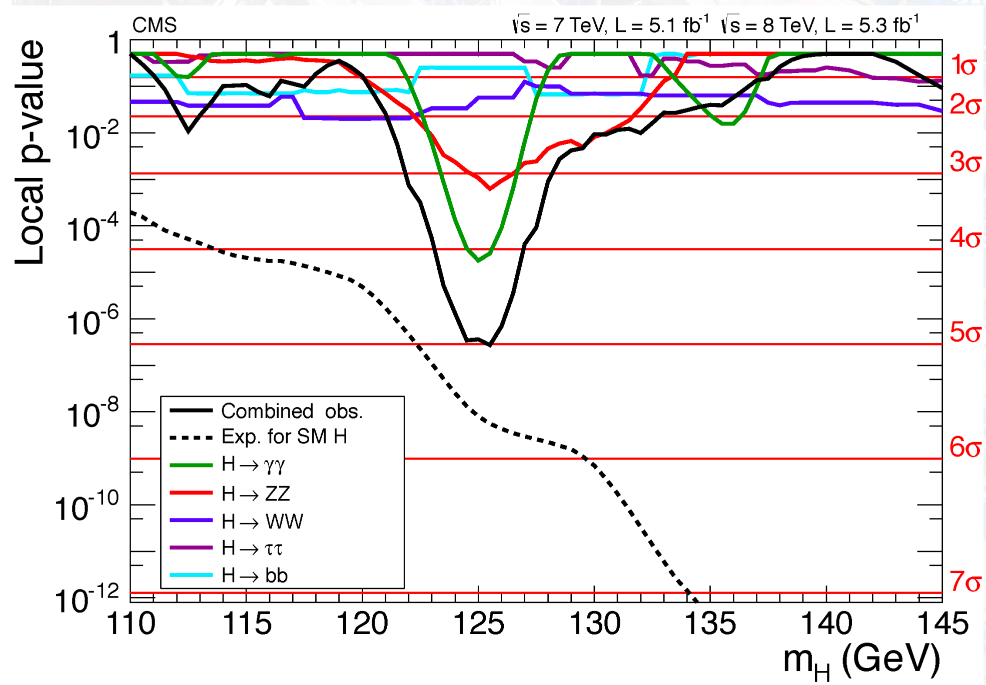




Higgs boson discovery

- In July 2012





- More than 5σ in each experiment !
  - confidence level > 99.999994 %
- Since then: discovery in γγ, ZZ* and WW* decay channels alone

After the discovery

- We know that it is A Higgs boson

  but is it really THE Higgs boson from Standard Model?

- Measure mass of this particle
  - not predicted by theory

- Production rate, branching ratio and couplings

- Spin

Mass measurement

ATLAS

- $H \rightarrow ZZ^* \rightarrow 4$ leptons
  - $124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\,\text{GeV}$
- $H \rightarrow \gamma\gamma$
  - 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
- Combined mass:

$124.3 \pm 0.2\ (\text{stat})\ ^{+0.6}_{-0.5}\ (\text{syst})\ \text{GeV}$

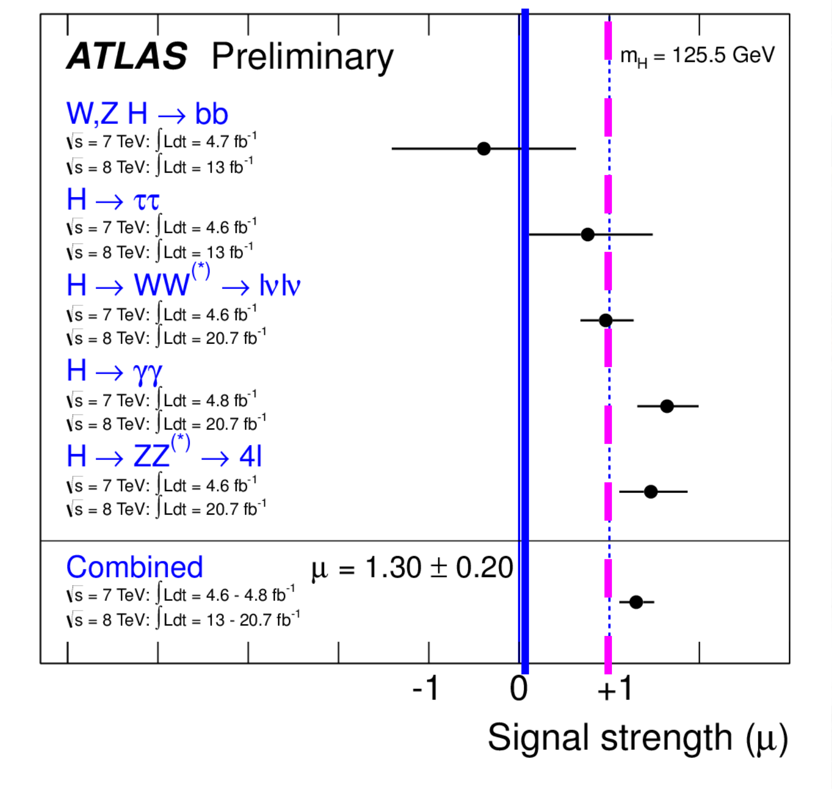
CMS

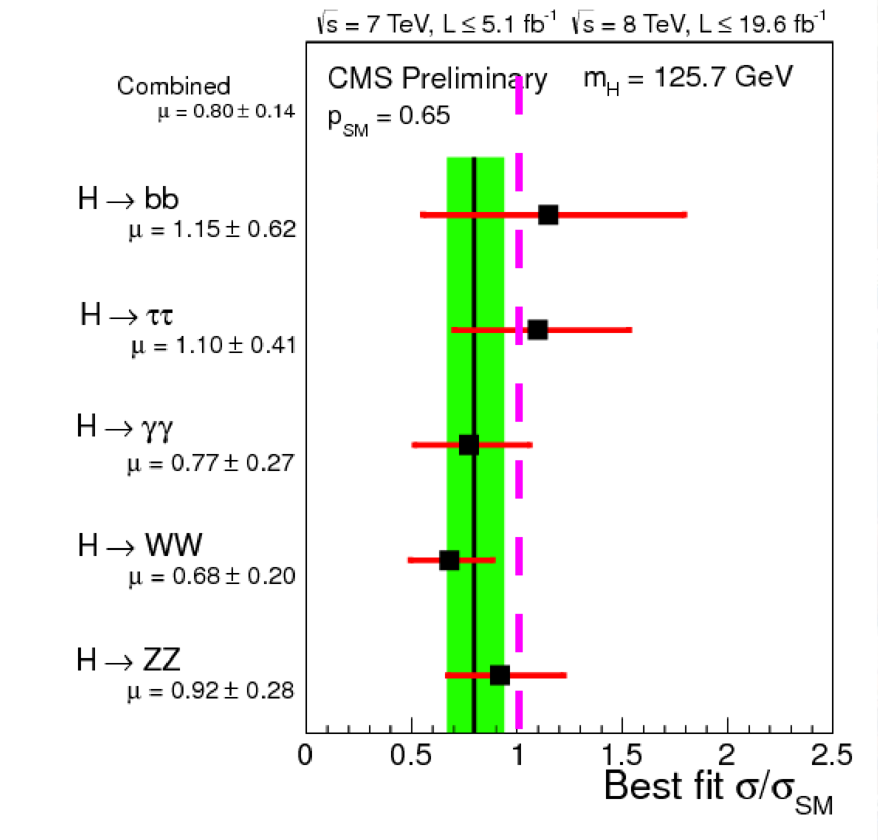
- $H \rightarrow ZZ^* \rightarrow 4$ leptons
  - 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV
- $H \rightarrow \gamma\gamma$
  - 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV
- Combined mass:

125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

Production rate

- Signal strength: $\mu = \frac{N_{observed}}{N_{SM\,Higgs}}$
  - = 0: background only
  - = 1: SM Higgs boson





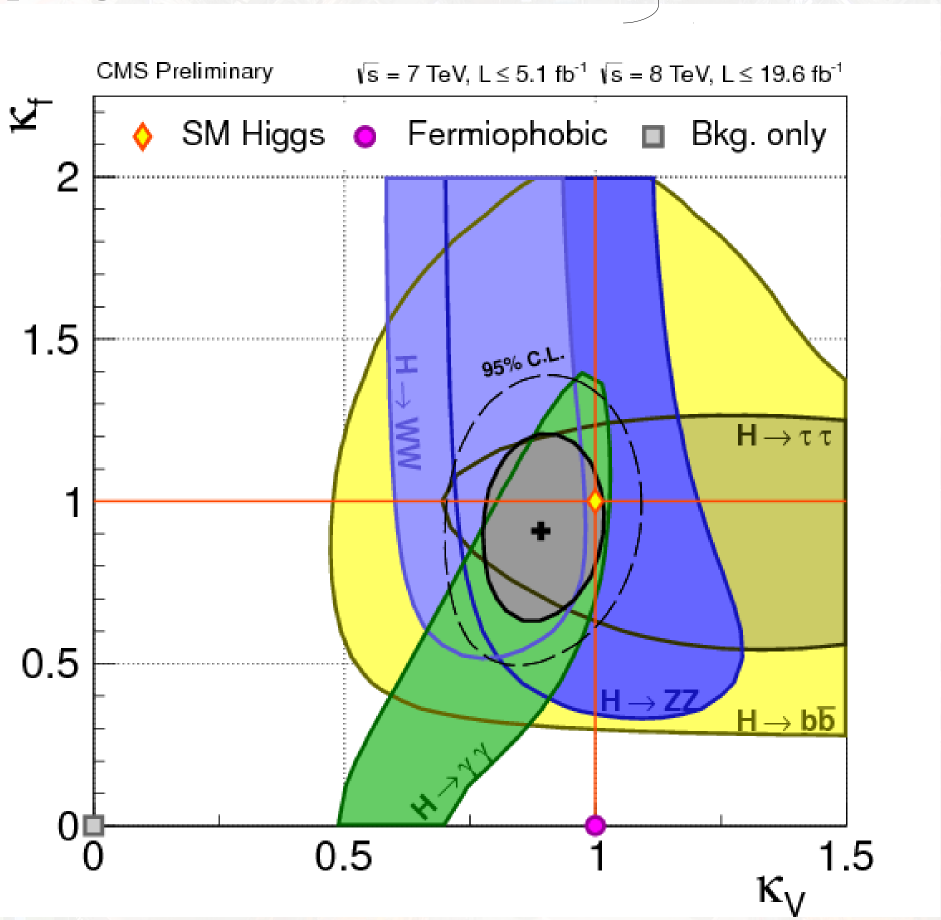
combination : 0.80 ± 0.14

- All measurements compatible with 1
  - biggest deviation: 2.4σ (H → γγ ATLAS)

First coupling measurements (1)

- Comparison to couplings predicted by SM
  - κ_V : couplings to W, Z bosons
  - κ_F : couplings to fermions

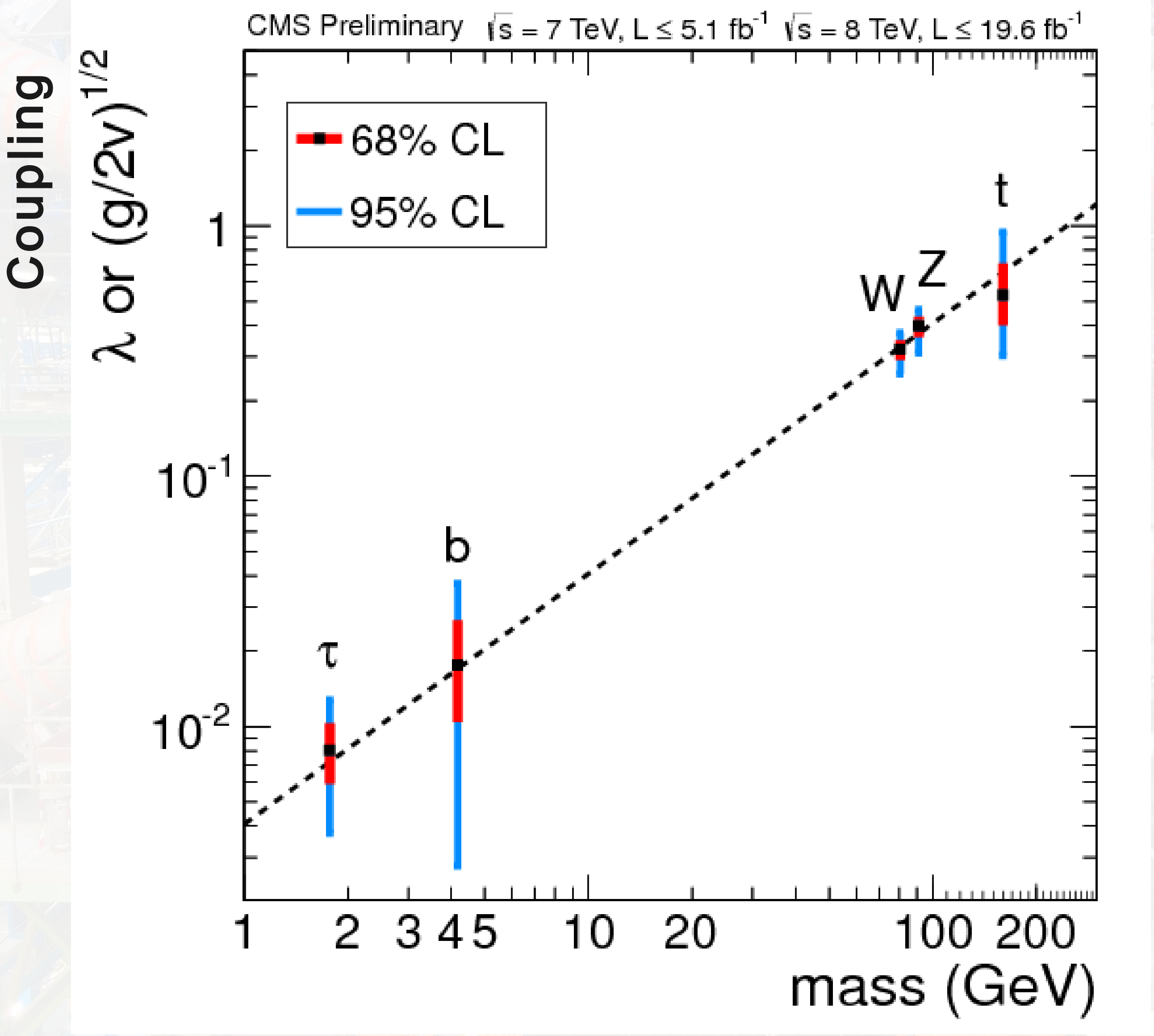
  } ratio with respect to Standard Model



- For the moment, couplings compatible with predictions

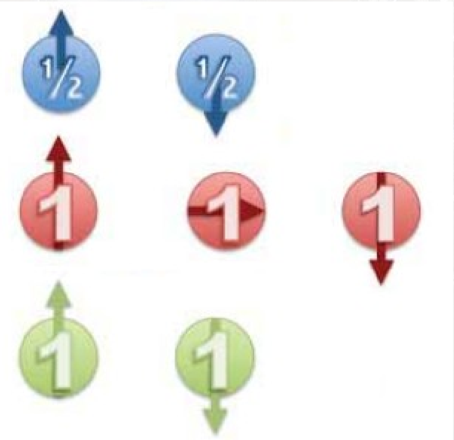
First coupling measurements (2)

- Higgs boson couplings to particules ∝ their mass



Spin measurement (1)

- Higgs boson: spin 0
- Spin of other particules :
  - leptons, quarks : +1/2, -1/2
  - W, Z : +1, 0, -1
  - γ : +1, -1



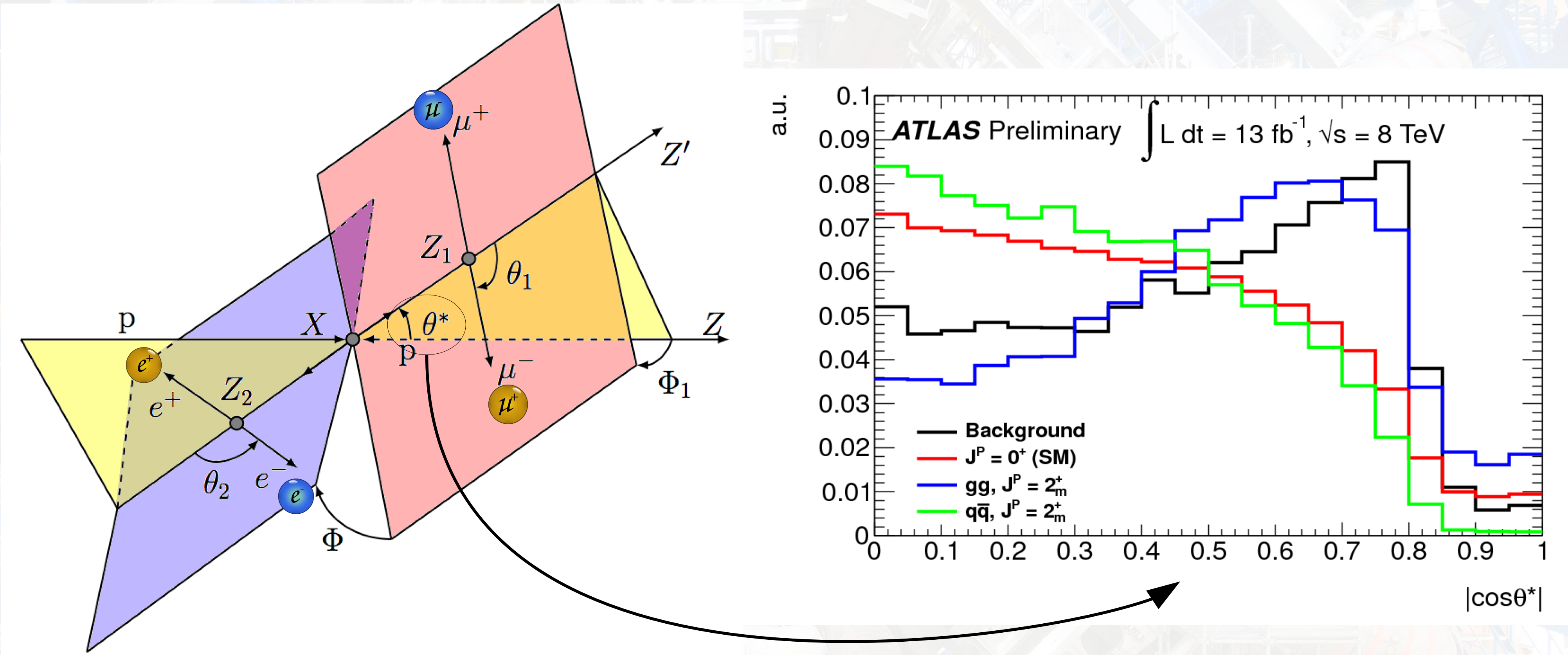
- Values permitted for the different decay modes::

	spin 0	spin 1	spin 2
H→W W, H→ZZ	✔	✔	✔
γγ	✔	✘	✔
H→ττ, H→b$\bar{b}$	✔	✔	✘

← not observed yet

Spin measurement (2)

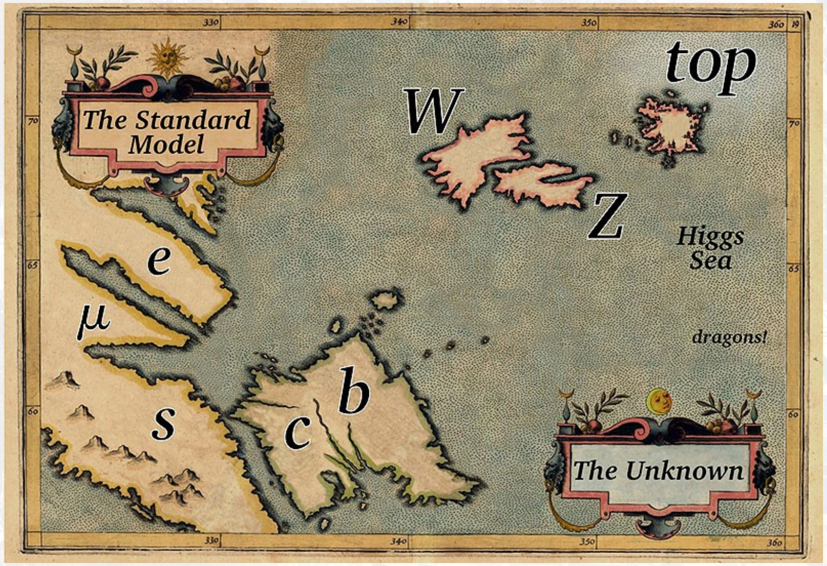
- Tests various spin hypotheses using angular variables:



- Results:
  - spin 2 excluded at >99.9%
  - compatible with spin 0

Part III: search for new physics

- Very accurate predictions of the Standard Model, but...
  - why we have 3 families of particles
  - why is the top quark that heavy?
  - where is gravity?
  - how do neutrinos have mass?
  - ...

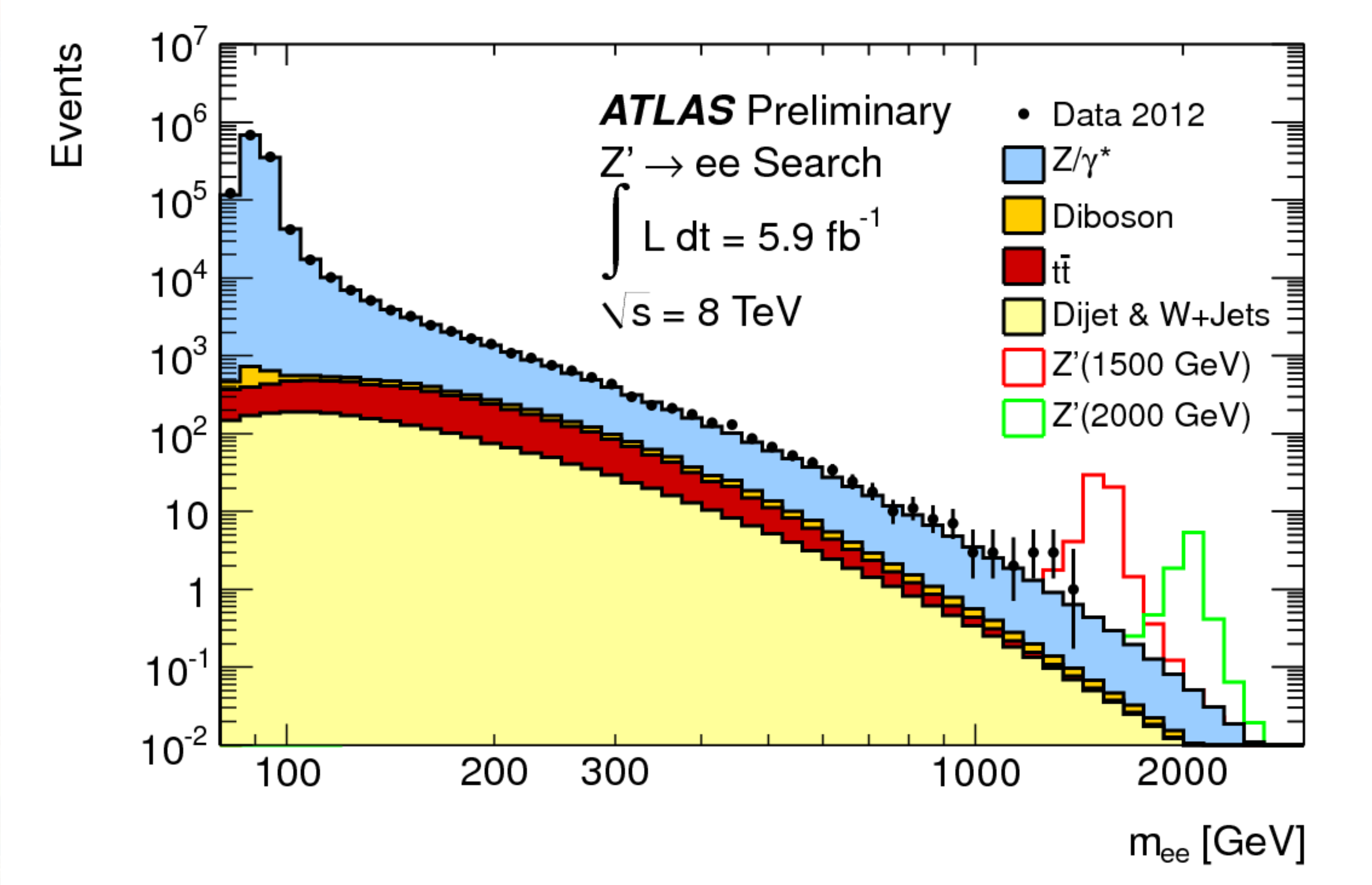


http://www.fnal.gov

- A lot of theories to explain that
  - first they have to have as good predictions as the Standard Model
  - supersymmetry
  - excited quarks
  - heavy bosons W' and Z'
  - many more

Example: heavy Z boson (1)

- Look for particle similar to Z boson, but heavier
  - ex.: Z' → ee
  - main background: Z → ee



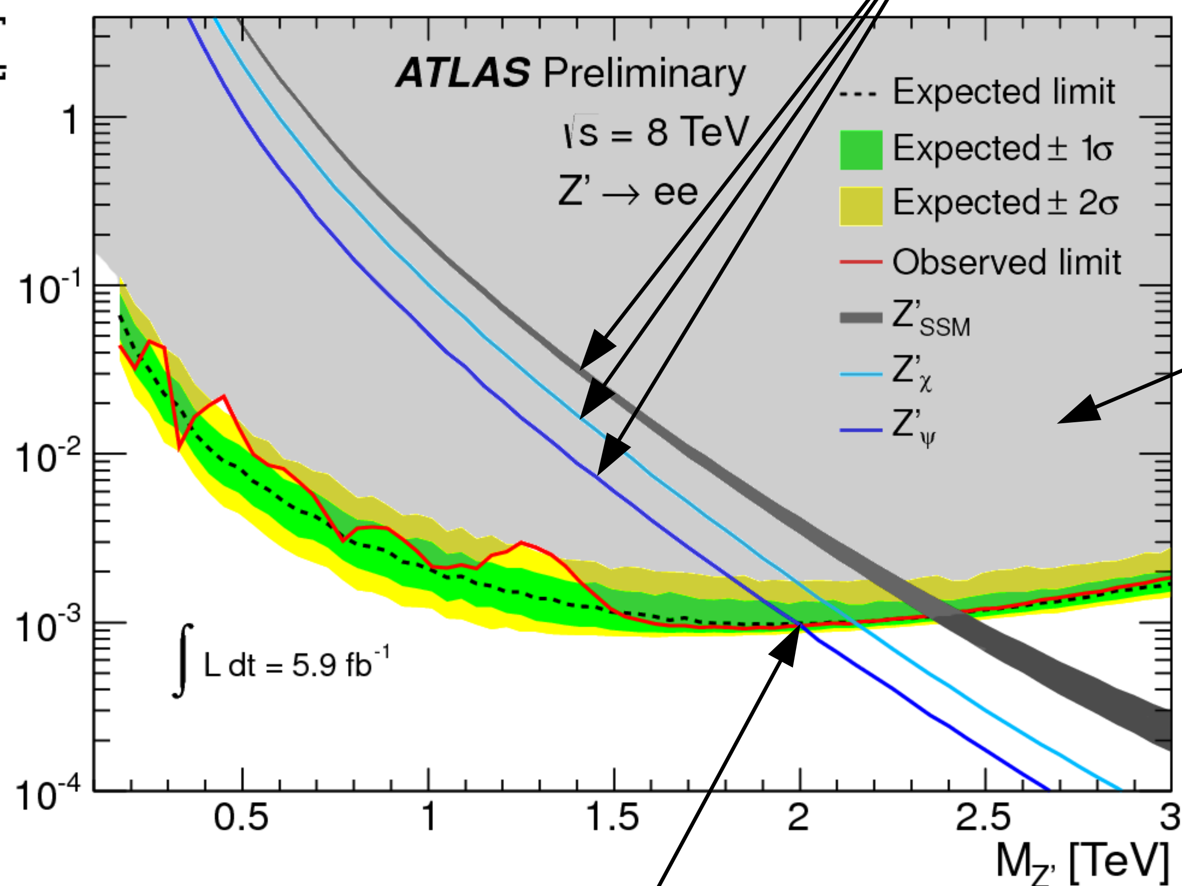
Example: heavy Z boson (2)

- No excess seen ⇒ set limits

Cross sections predictions

cross section x branching ratio

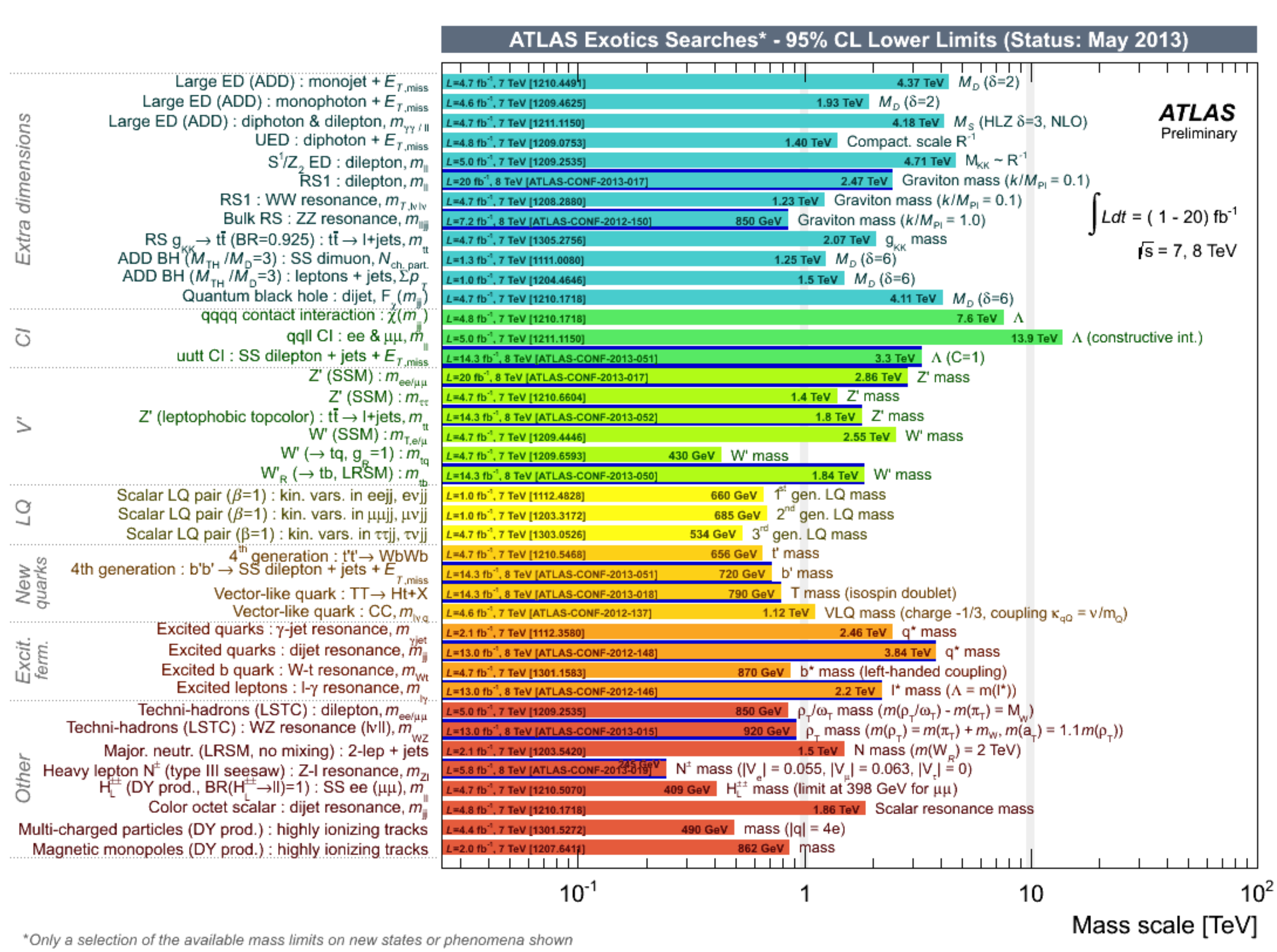
Those cross sections are excluded



This model is excluded for masses > 2 TeV

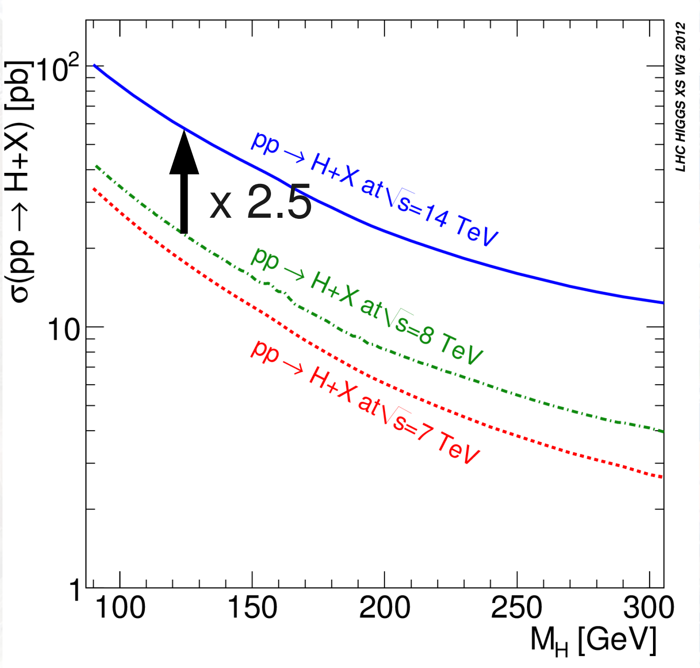
Summary of BSM searches

- Many models excluded with mass < 1 TeV:



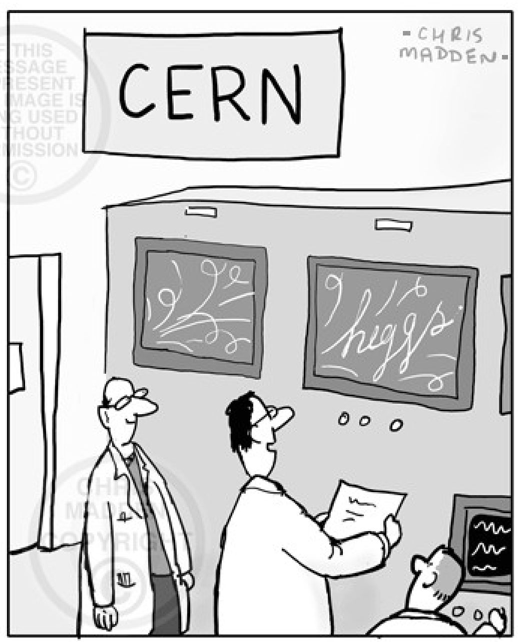
Conclusion

- Physics at LHC quite huge and complicated
  - huge detector, huge collaboration, huge amount of data to analyse



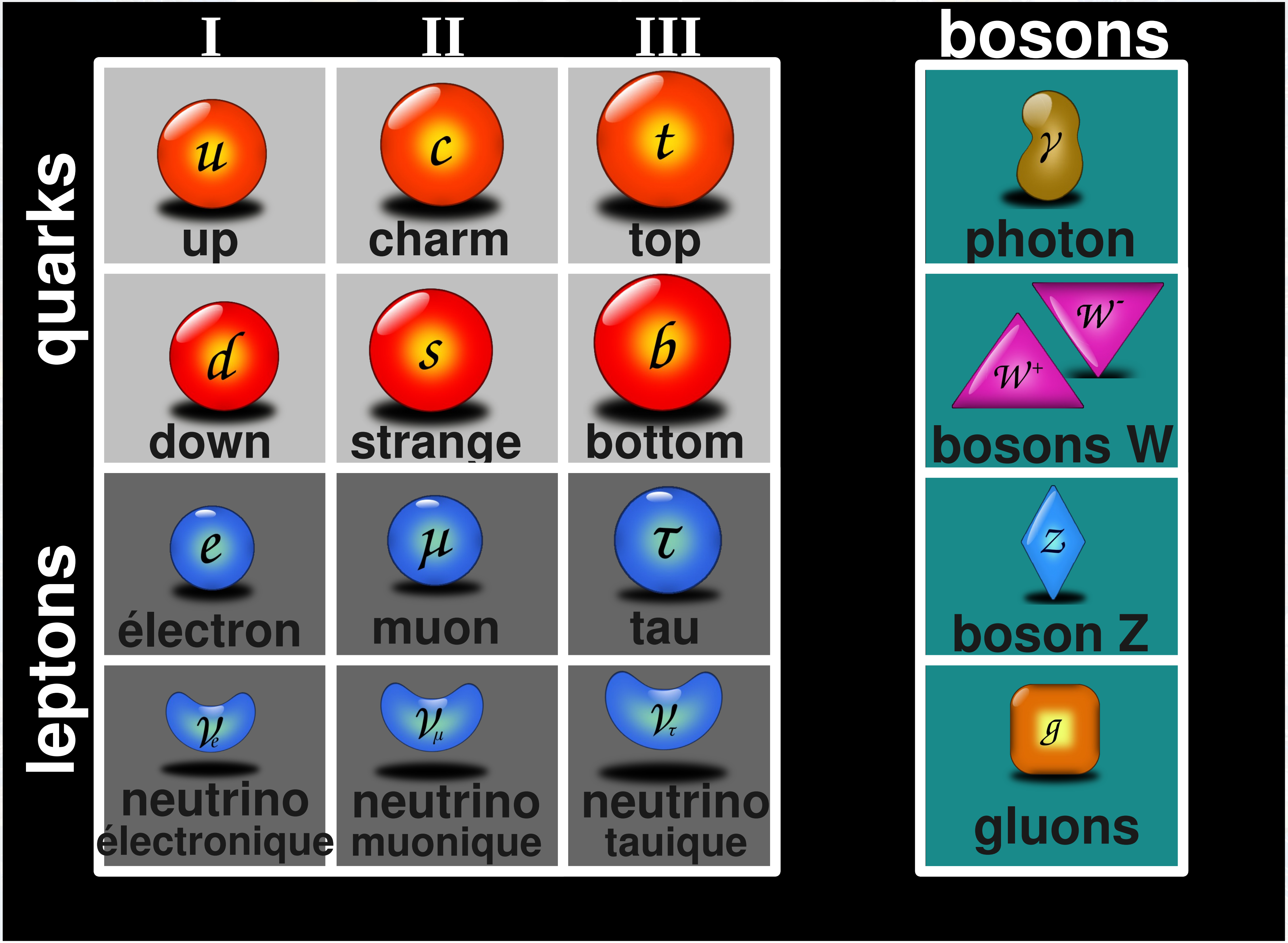
- Many measurements to confirm validity of Standard Model at the LHC energy
- Discovery of the Higgs boson in June 2012
- Look for Beyond Standard Model physics
  - no discovery so far, but...
- In 2015: $\sqrt{s}$ = 13 TeV
  - room left for new particles
- LHC running until ~2023
  - perfect for young, motivated physicists!

Back-up slides



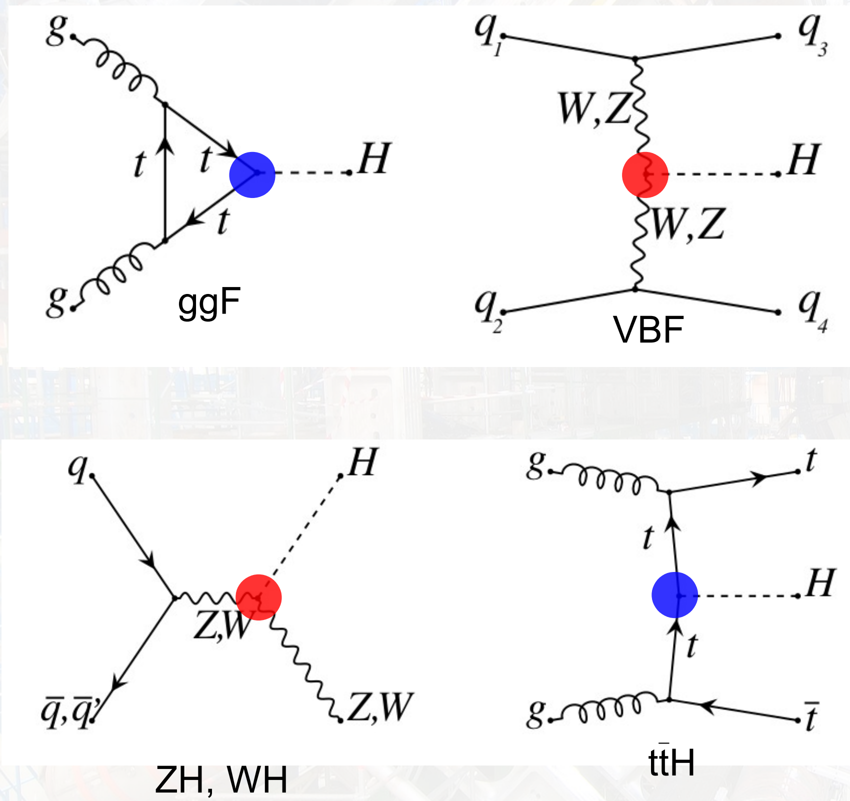
"Take a look at this everyone - it just could be the signature we've been looking for!"

Standard Model of particle physics

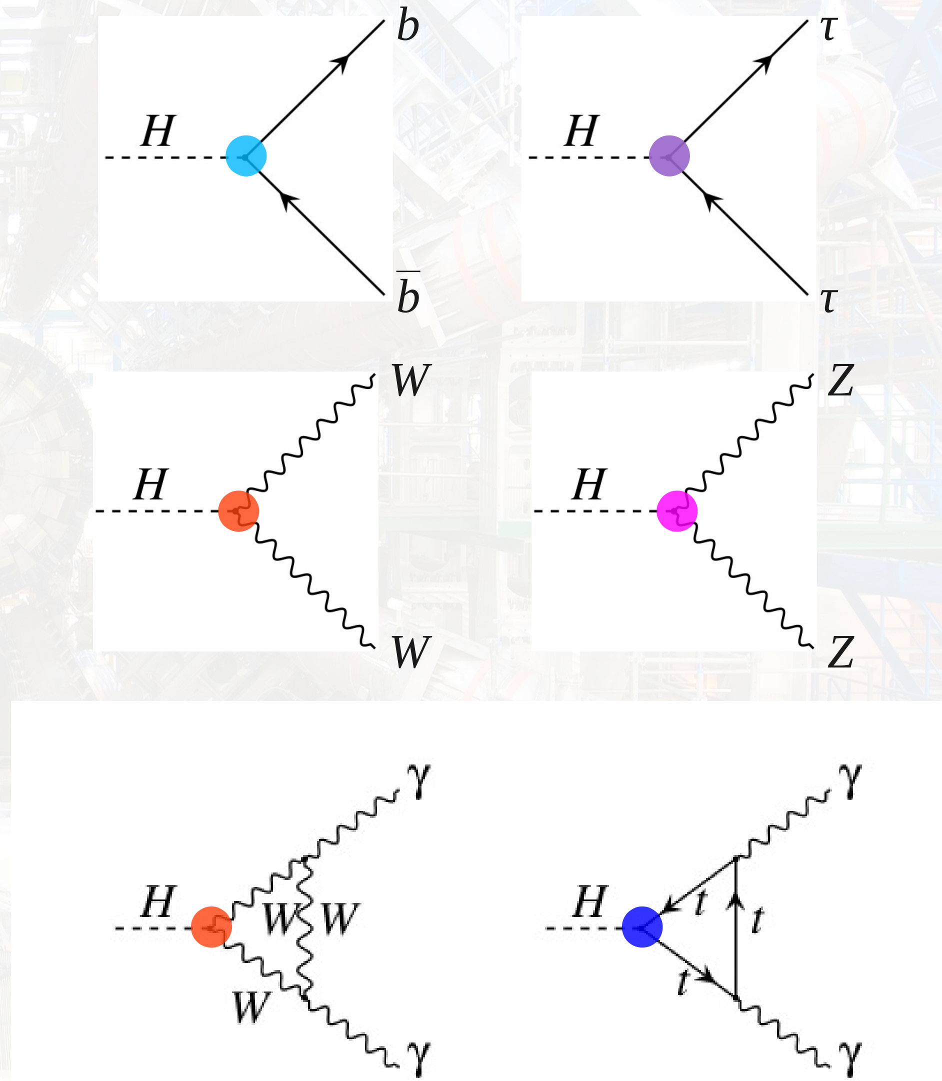


Couplages du boson de Higgs

- Modes de production :



- Canaux de désintégration :



fermions (t, b, τ)
bosons vecteurs (W, Z)

- Mesures des sections efficaces et largeurs partielles de désintégration
  ⇒ remonter aux couplages

♦ LHC schedule: