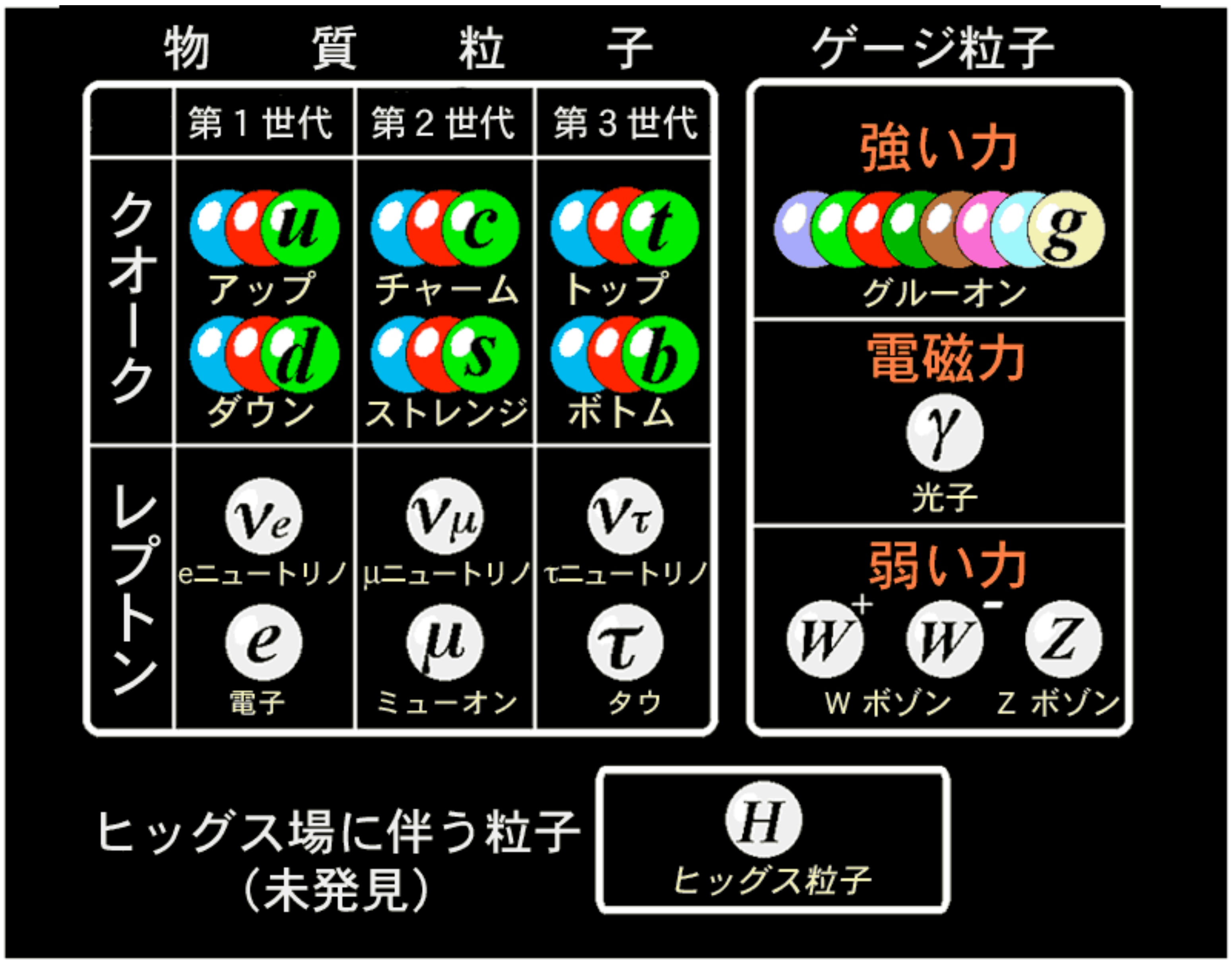
Particle Physics

Dr Victoria Martin, Spring Semester 2013

Lecture 20: The Final Lecture



- ★Higgs boson discovery
- ★Test of the Standard Model
- ★Supersymmetry...

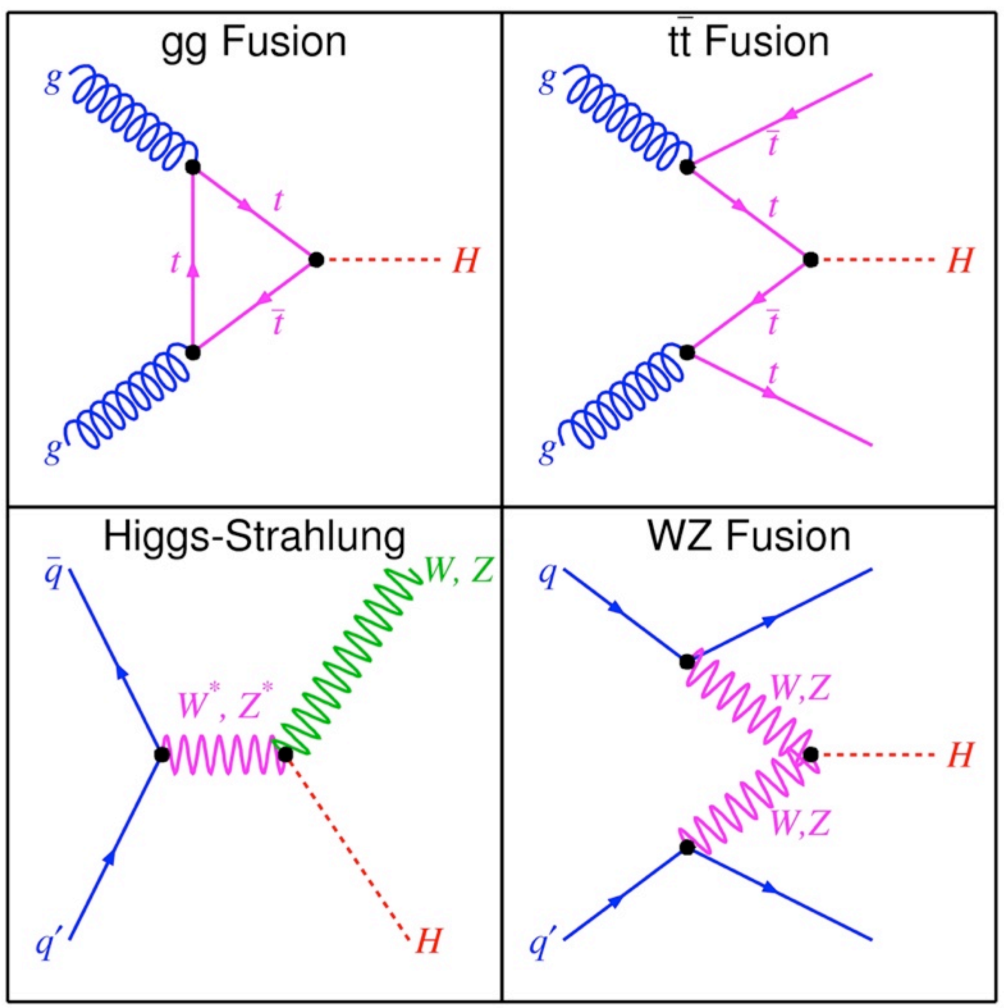
- Today is the last lecture

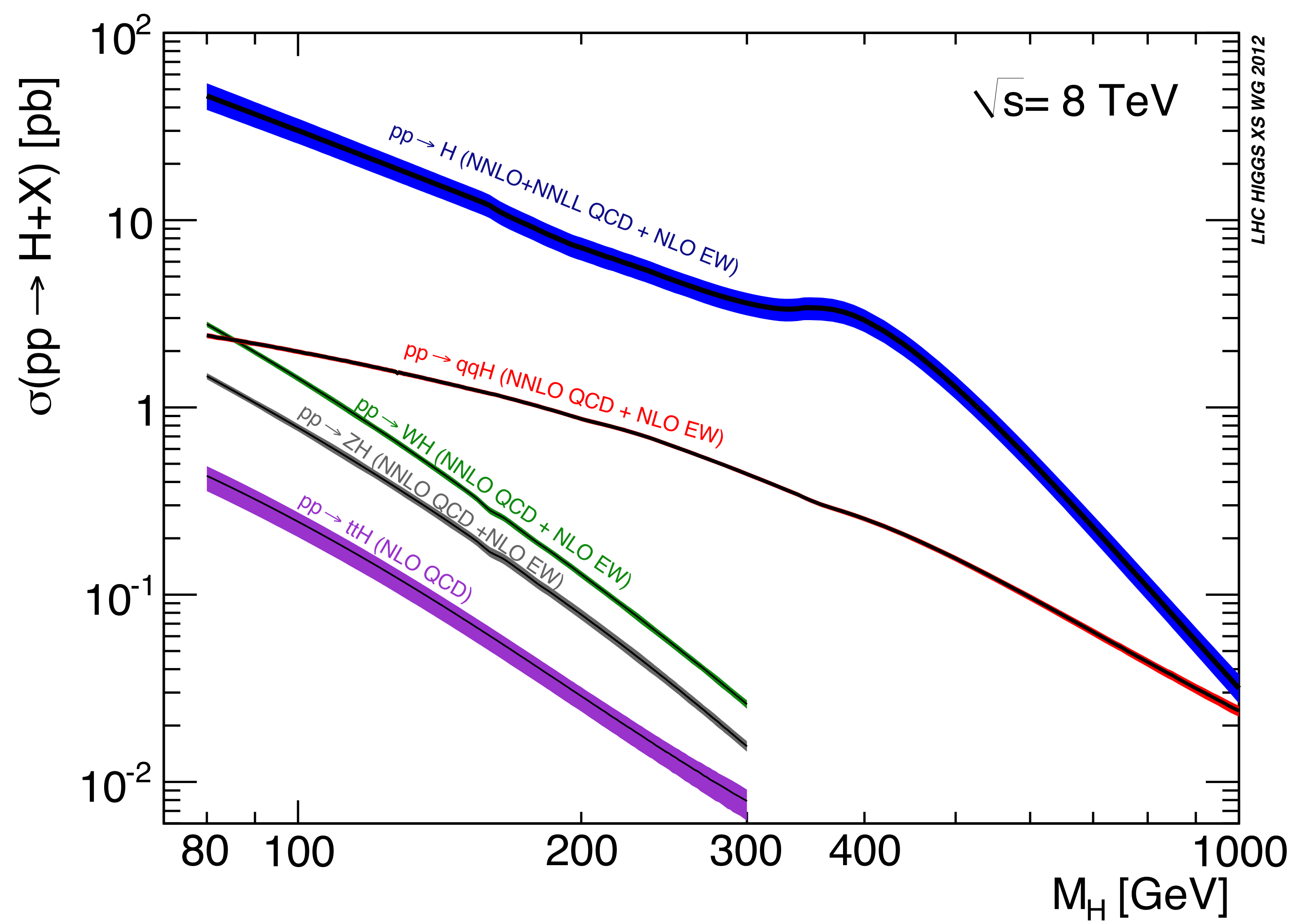
- Revision Session:
  - With me: week of 22 - 26 April??
  - With a tutor week of 13 - 17 May??
  - Both??

- I will make a complete, corrected copy of the notes and study guide for the webpage, and email to let you know it's ready.

Higgs Boson Production at the LHC

- Four main production modes at the LHC:
  - 2 induced by (virtual) top quarks
  - 2 induced by ***W*** or ***Z*** bosons
- Different production modes have different backgrounds and are used in different searches





Higgs Boson Discovery

- The Higgs boson was discovered by ATLAS and CMS in July 2012 with a mass, $m_H \sim 125$ GeV
- Main search modes:
  - $H \rightarrow b\bar{b}$ $H \rightarrow W^+W^-$ $H \rightarrow \tau^+\tau^-$ $H \rightarrow ZZ$ $H \rightarrow \gamma\gamma$

- The W and Z bosons are searched for through their decays to leptons:
  - ➡ $Z \rightarrow \mu\mu$ (3.3%) $Z \rightarrow ee$ (3.3%)
  - ➡ $W \rightarrow \mu\nu$ (10%) $W \rightarrow e\nu$ (10%)

- The invariant mass of the decay products is used to look Higgs boson production. Expect a ~gaussian bump at m_H

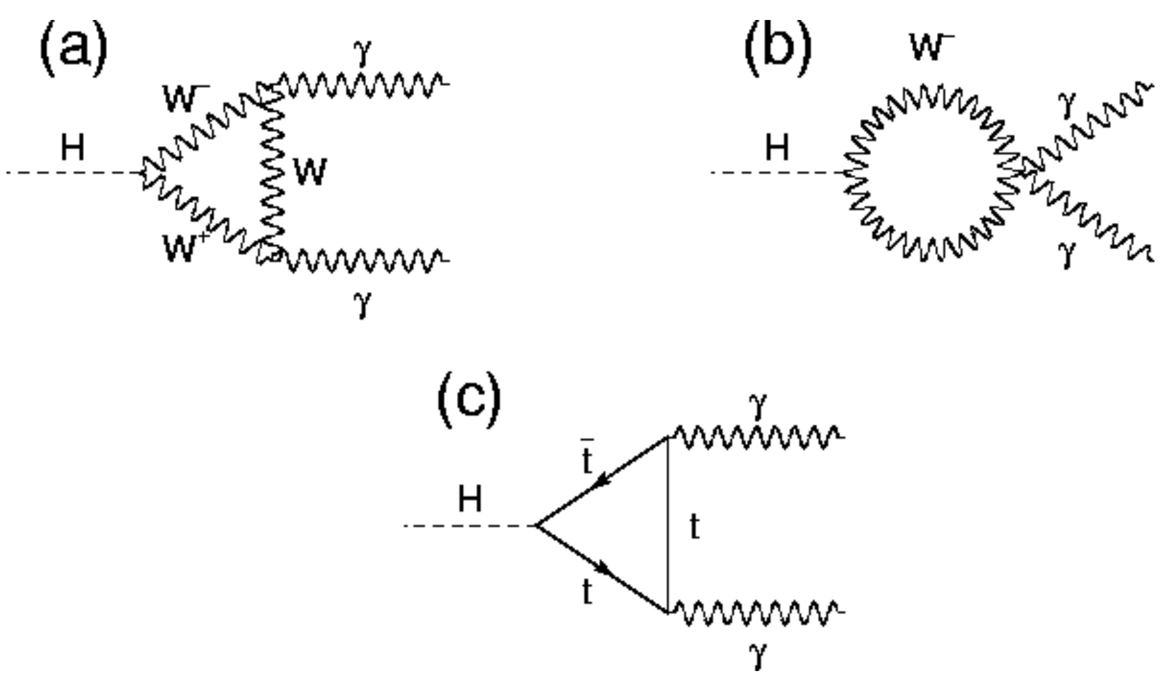
- The following results are all taken from the ATLAS experiment. The CMS experiment have similar results.

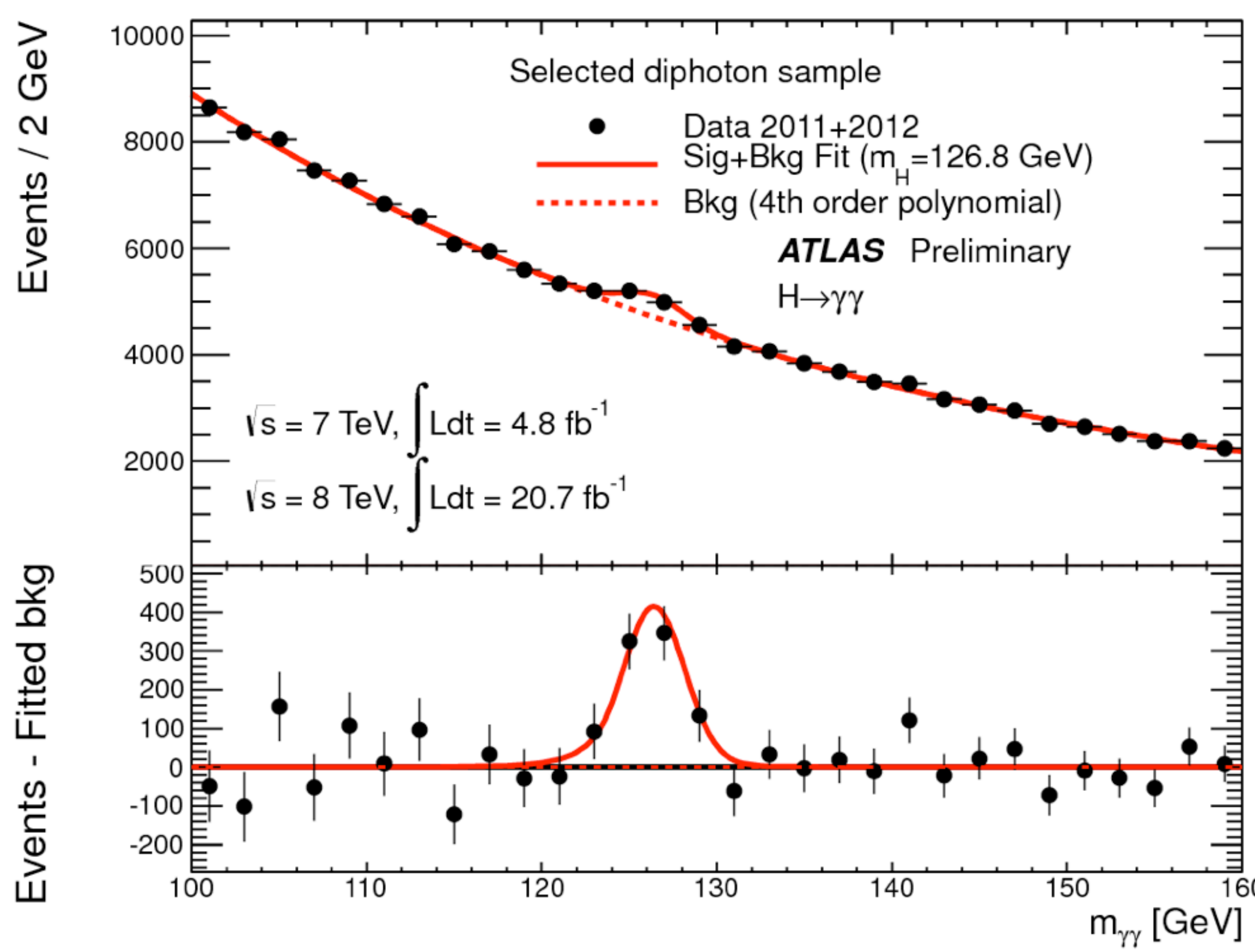
http://atlas.ch/

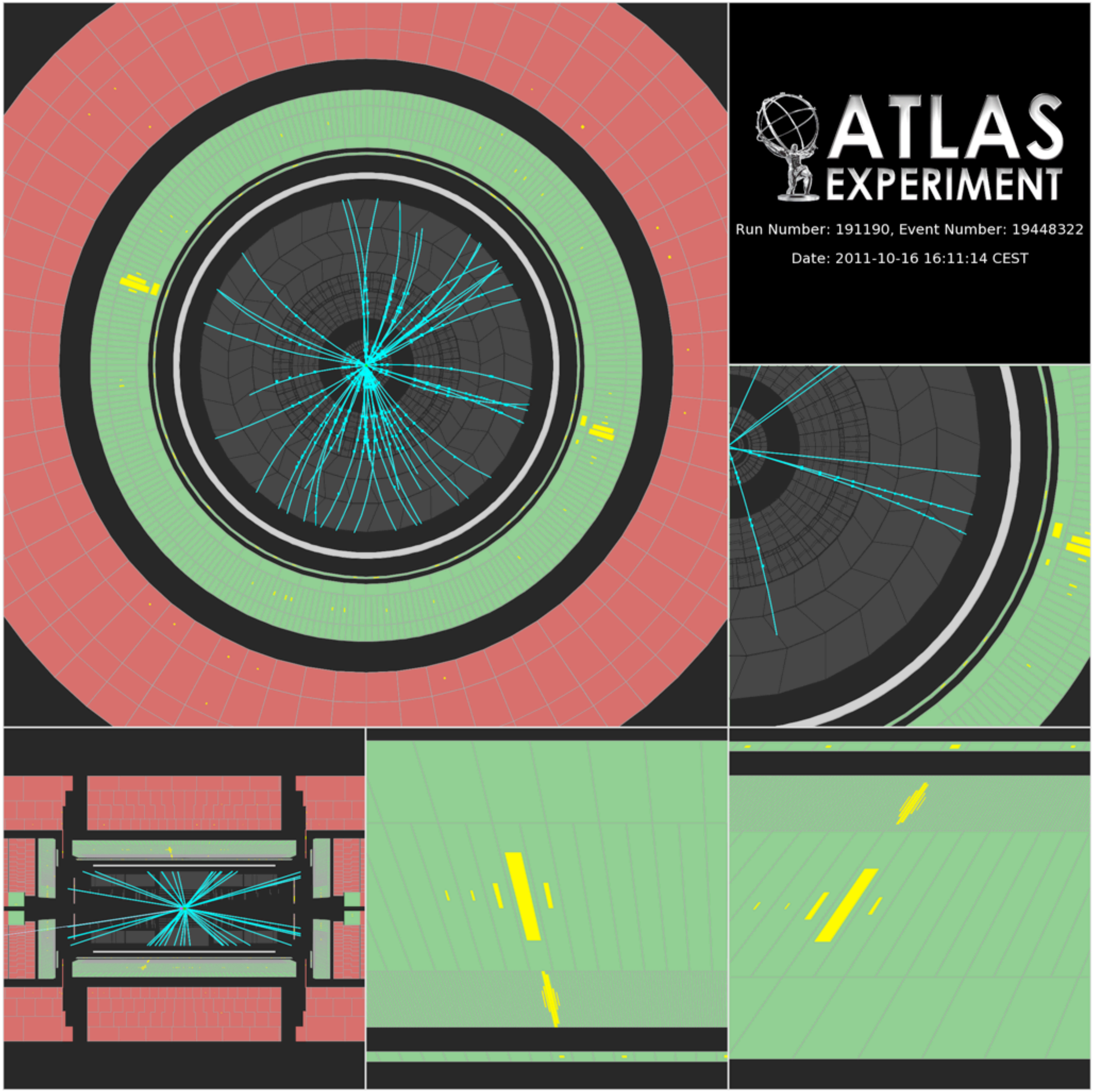
http://cms.web.cern.ch/

Higgs Boson Searches: $H \to \gamma\gamma$

- $H \to \gamma\gamma$ proceeds through loop diagrams
- The search uses all Higgs boson production modes: $gg \to H$ is the largest
- Look for diphoton invariant mass bump



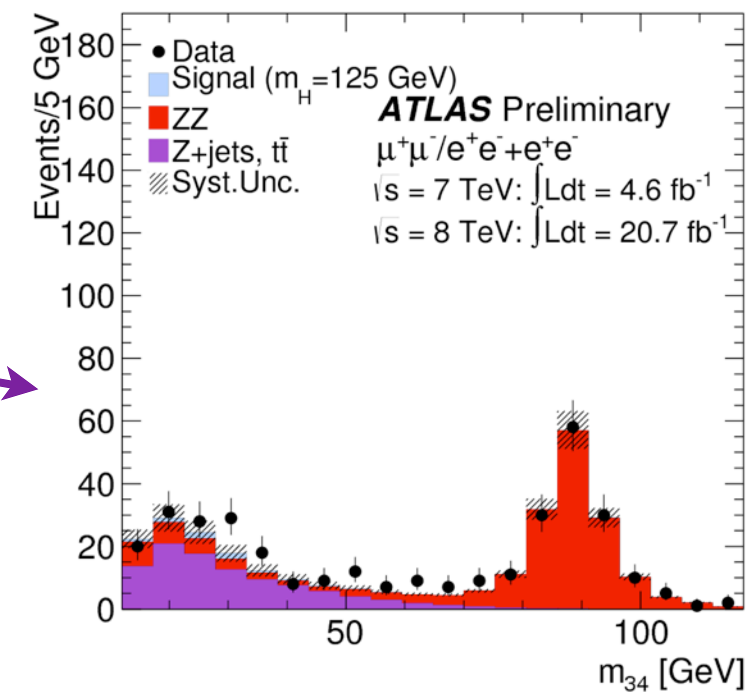




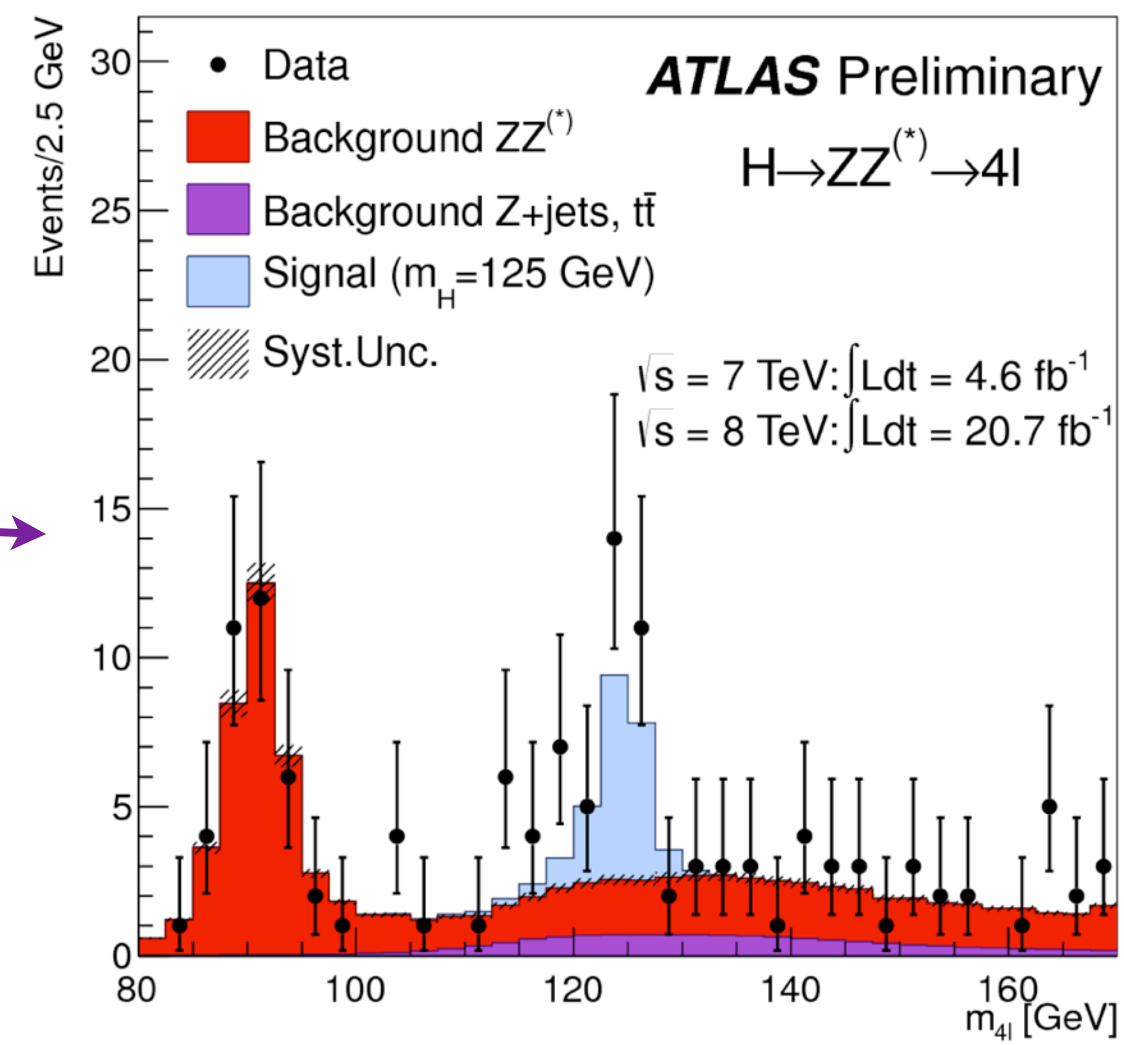
$H \rightarrow \gamma\gamma$ Candidate Event

Higgs Boson Searches: $H \rightarrow ZZ^*$

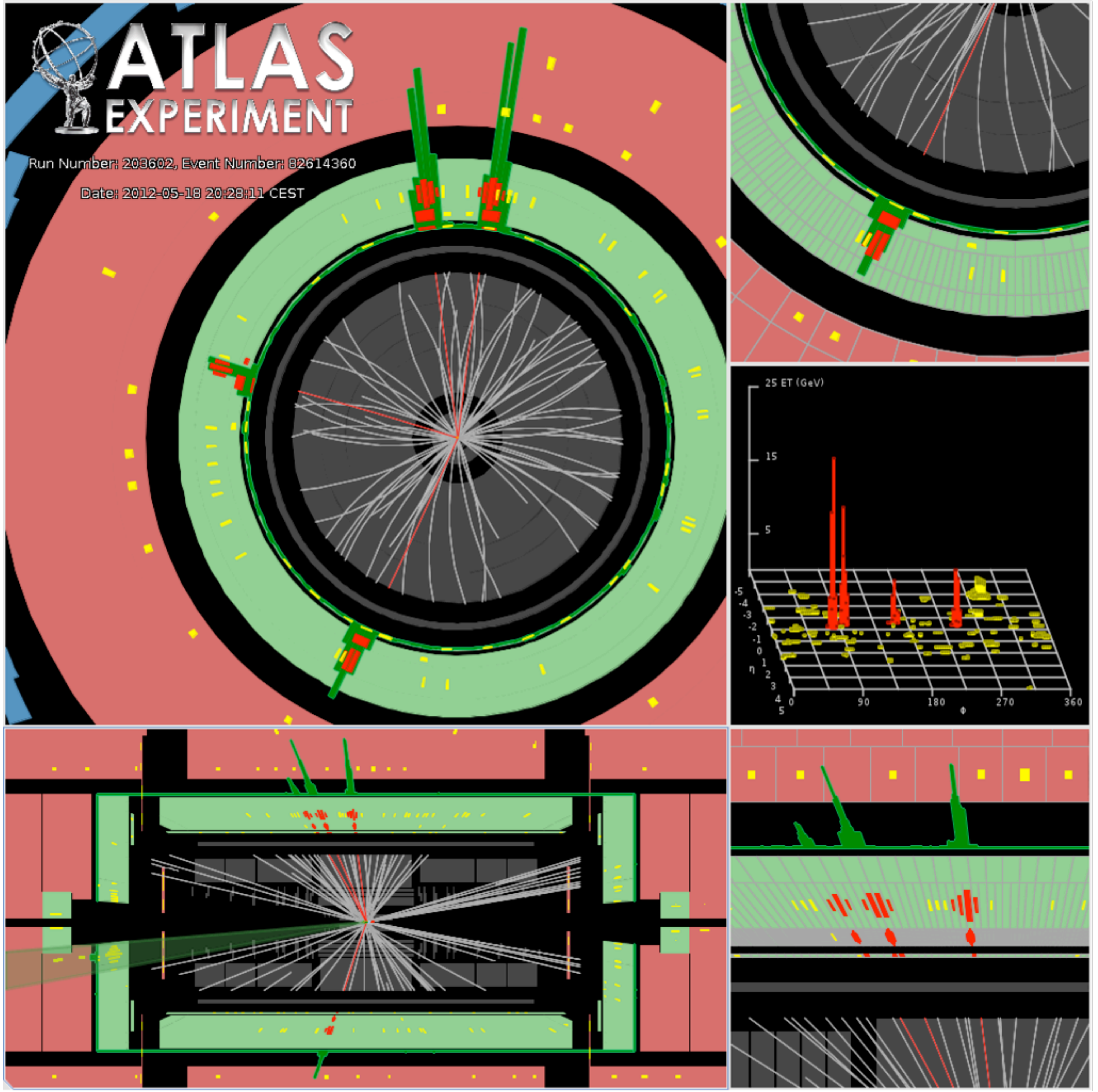
- At $m_H \sim 125$ **GeV** at least one of the Z bosons must be virtual.



- Z boson are searched for through their decays to leptons:
  - ➡ $Z \rightarrow \mu\mu$ (3.3%) $Z \rightarrow ee$ (3.3%)
- Four final states: $e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, $\mu^+\mu^-\mu^+\mu^-$
- Look for bump in m(**4 leptons**) invariant mass distribution



$H \to ZZ^* \to e^+e^-e^+e^-$ candidate event

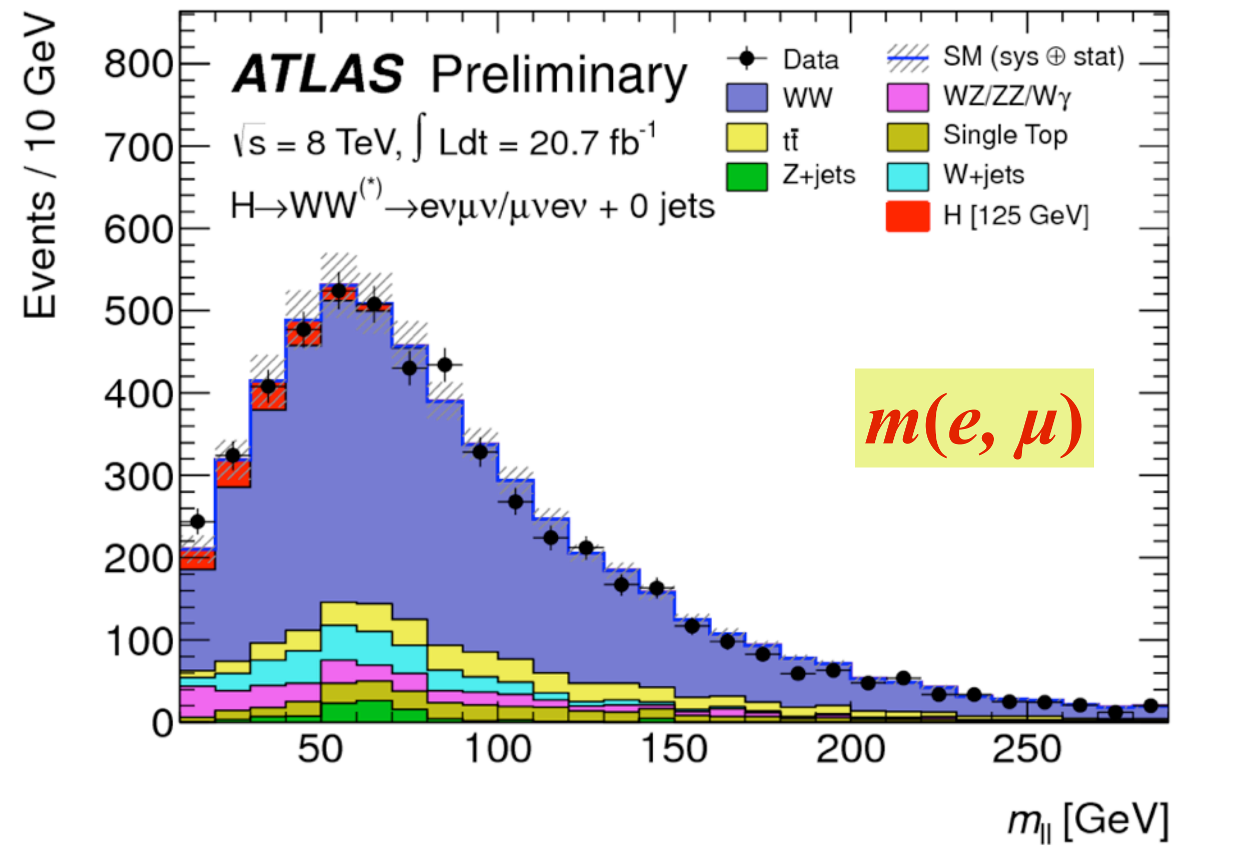


Higgs Boson Searches: $H \to W^+W^-$

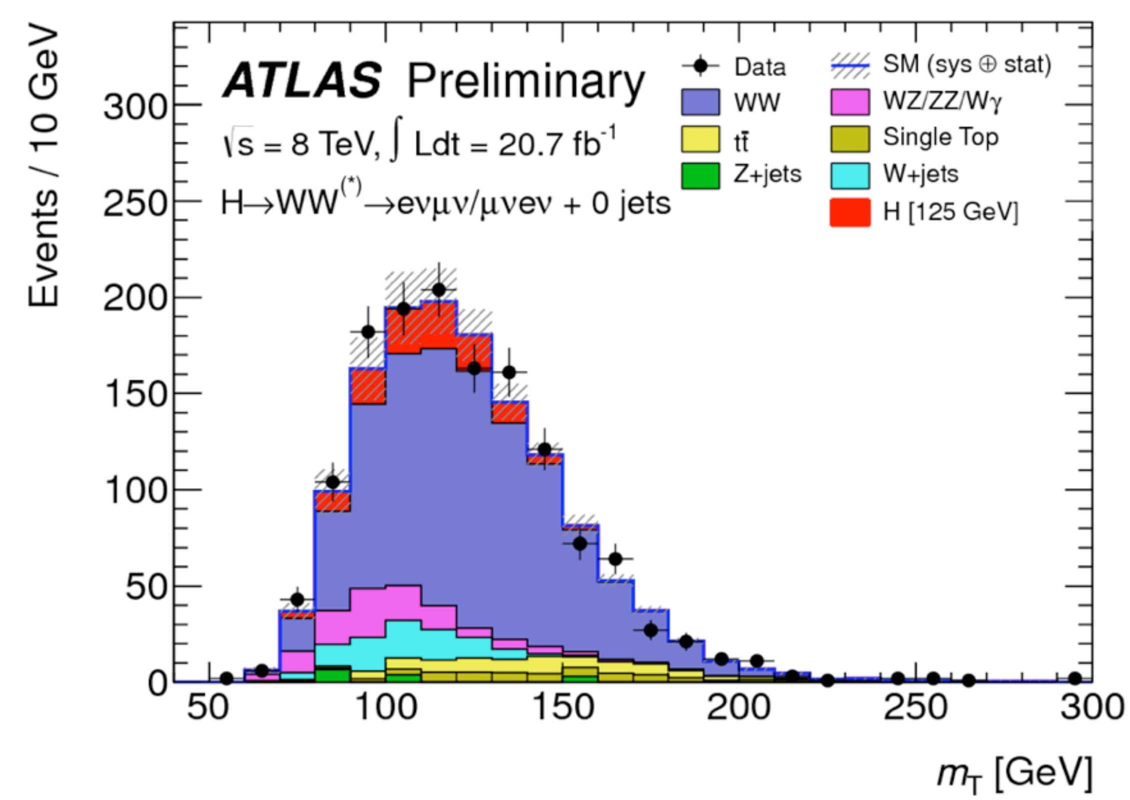
- W bosons are searched for through their decays to leptons:
  - $W \to \mu\nu$ (10%) $W \to e\nu$ (10%)

- The individual momentum of the two neutrinos cannot be measured: cannot reconstruct the mass of the Higgs boson.

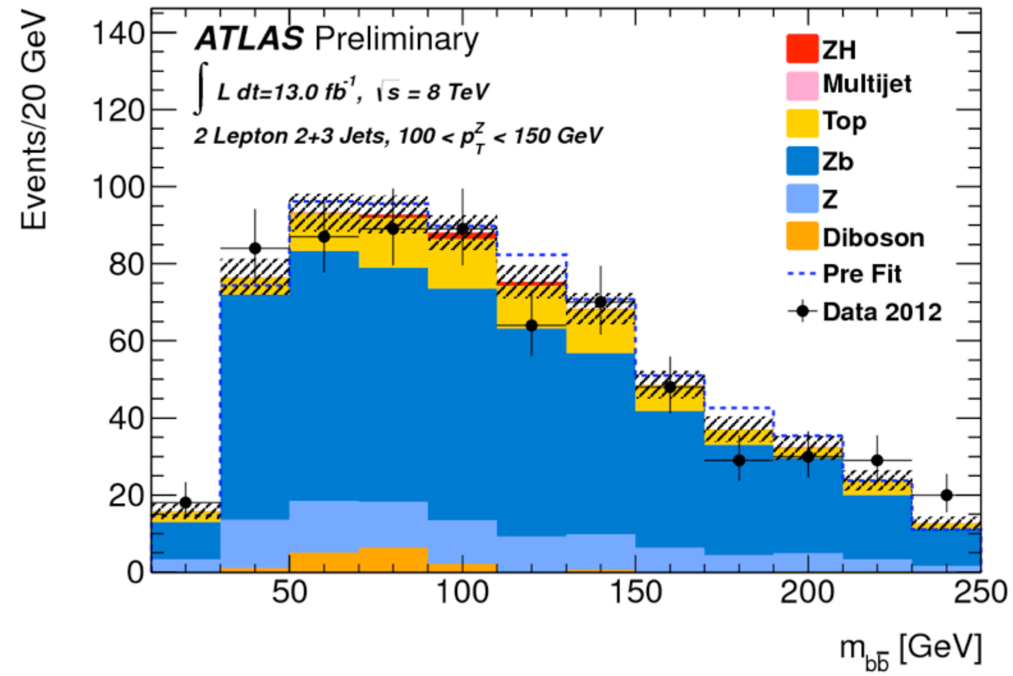
- Instead examine other combinations of the measured momentum of the charged leptons (e, μ) and the missing transverse energy.



$\sqrt{(p_x^{(e,\mu,MET)})^2 + (p_y^{(e,\mu,MET)})^2}$



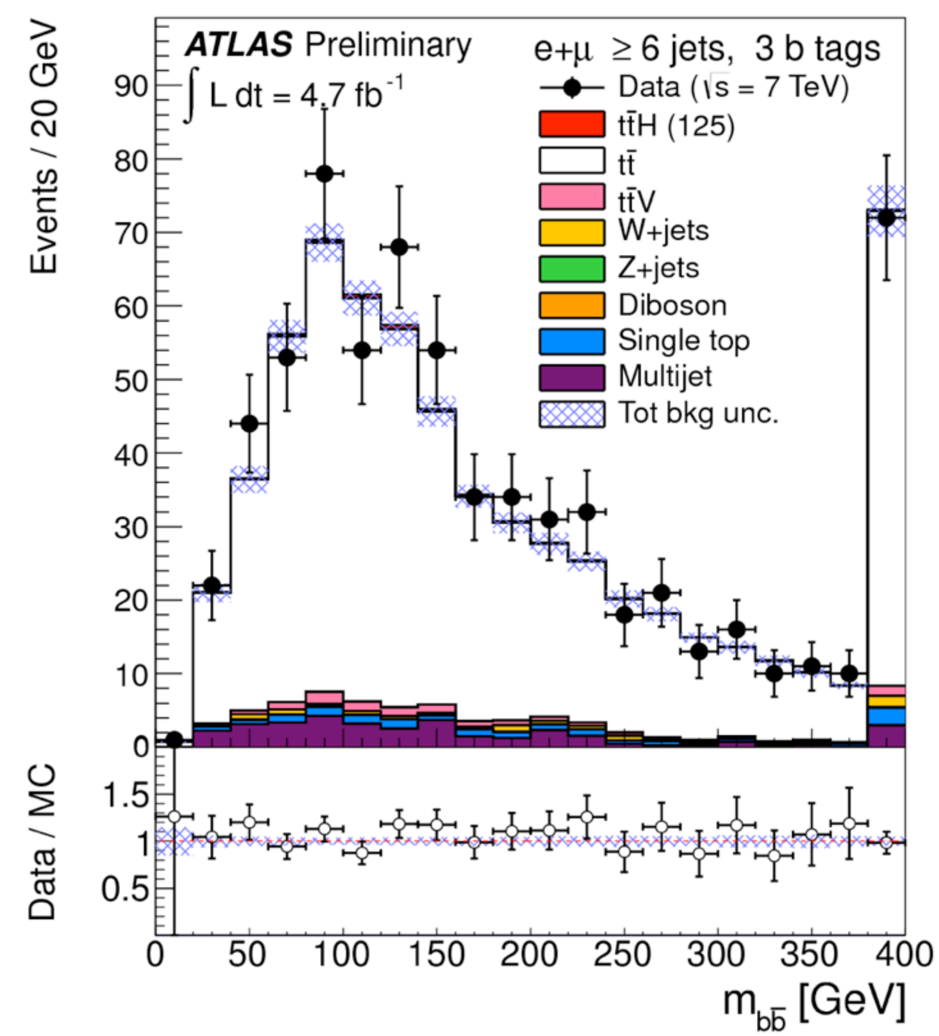
Higgs Boson Searches: $H \rightarrow b\bar{b}$



- The background from QCD processes producing b-quarks at the LHC is huge!

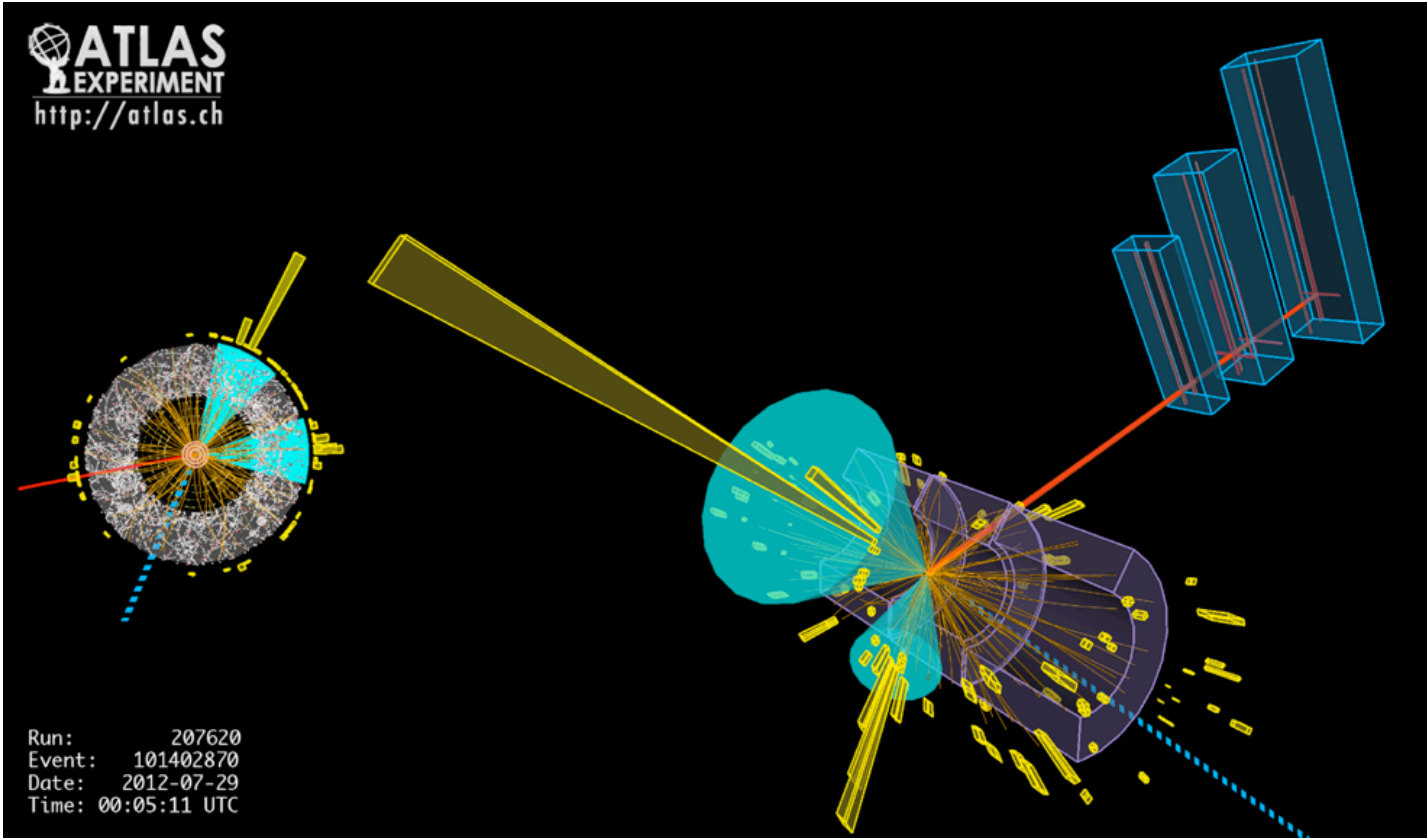
- Impossible to see $H \rightarrow b\bar{b}$ above this QCD background.
  - Look for a $H \rightarrow b\bar{b}$ in the other production modes: WH, ZH, $t\bar{t}H$.

- Look for a bump in $m(b\bar{b})$ distribution



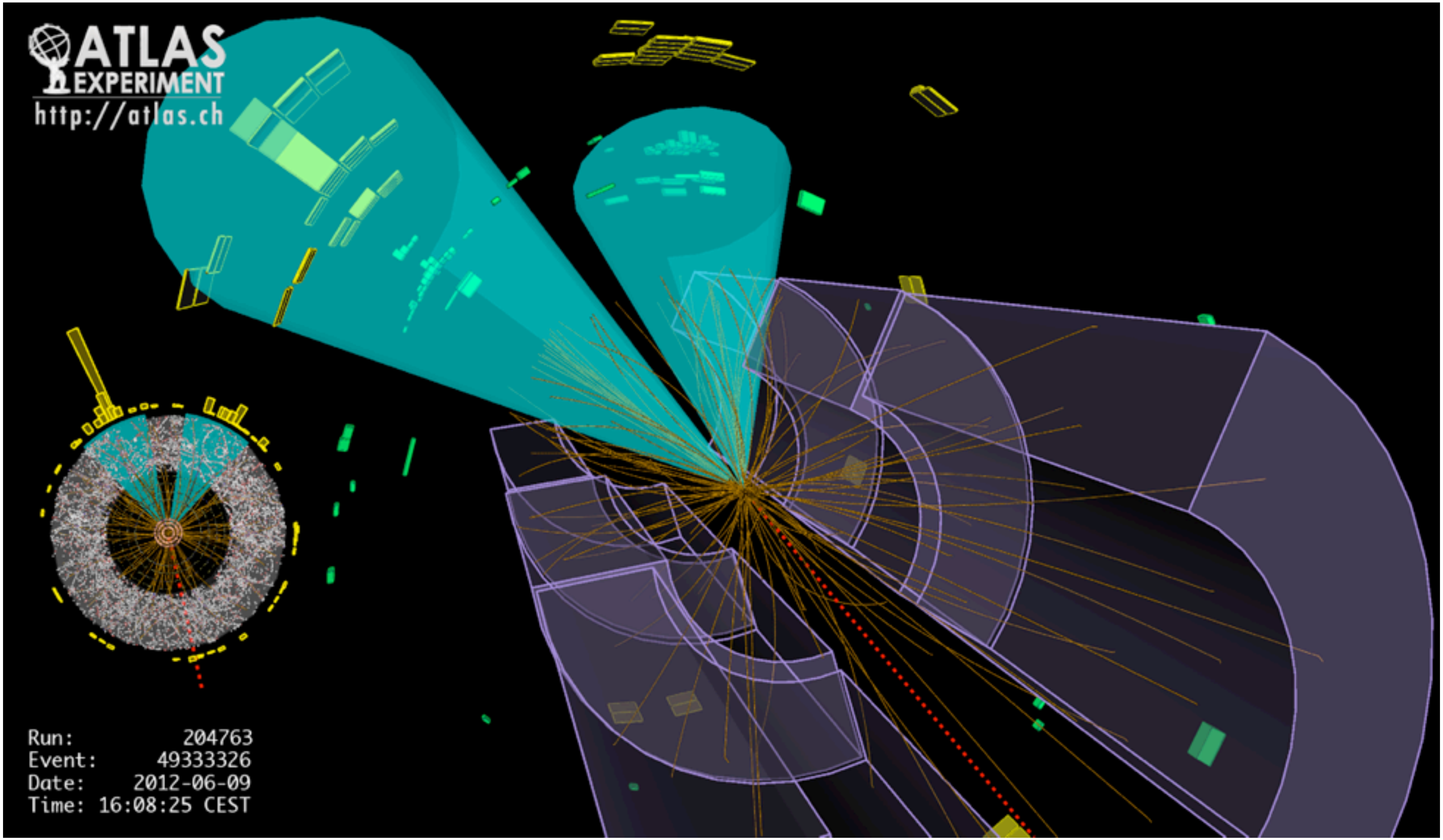
$WH \rightarrow \mu\nu\, b\bar{b}$ candidate event

- $m_{b\bar{b}}$ = 109 GeV, E_T^{miss} = 139 GeV



$ZH \rightarrow \nu\bar{\nu}\ b\bar{b}$ candidate event

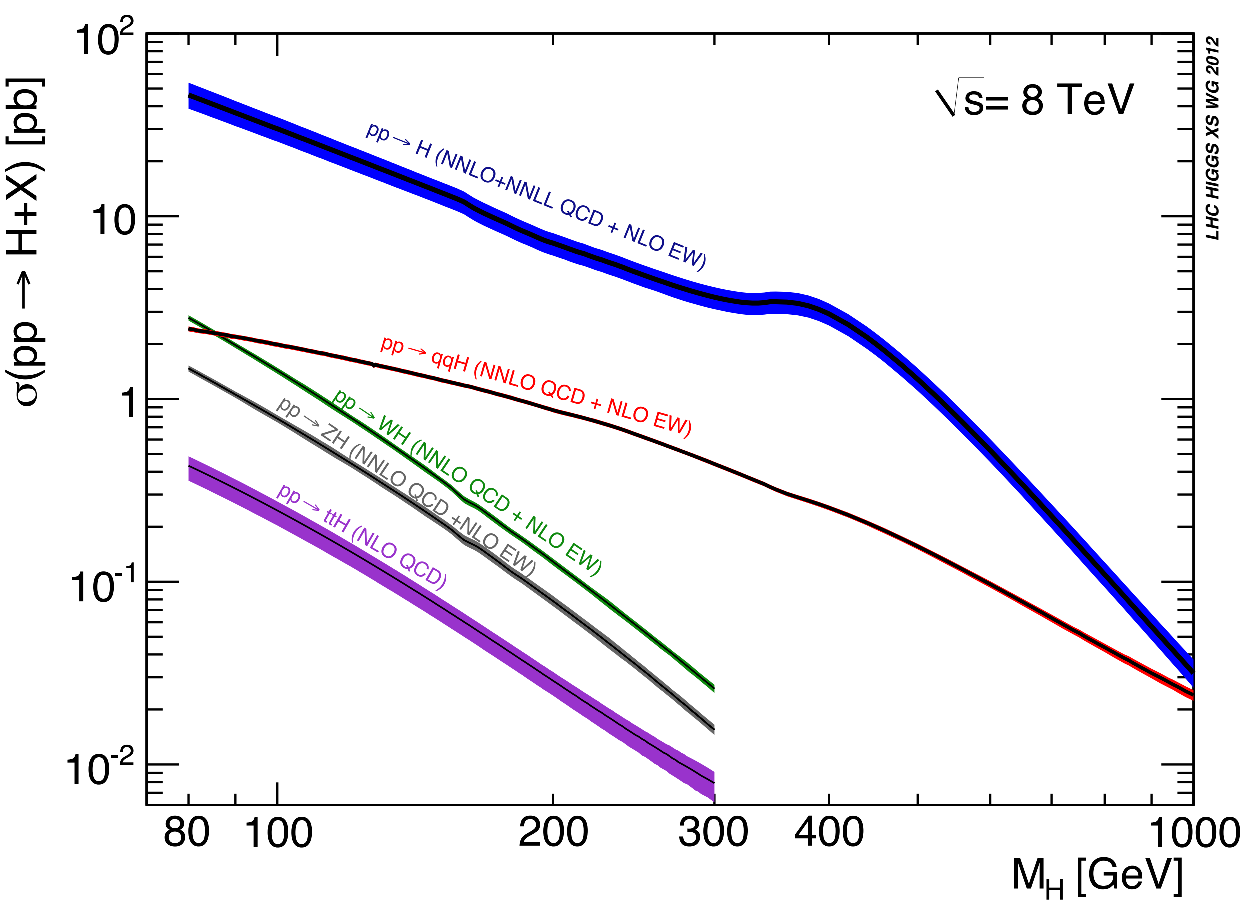
- $m_{b\bar{b}}$ = 123 GeV E_T^{miss} = 271 GeV

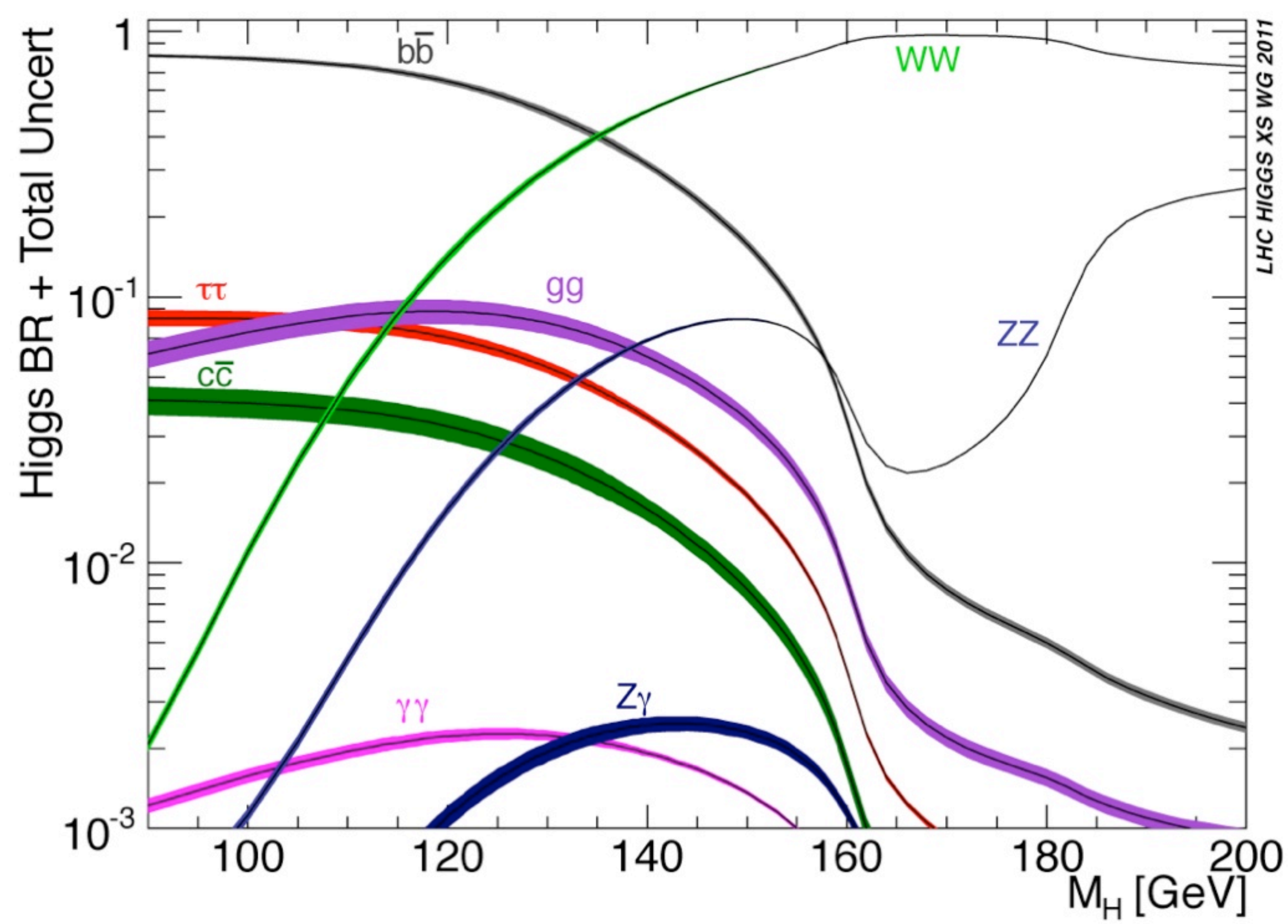


Reminder: Higgs Boson Properties

- In the Standard Model the mass of the Higgs boson is not predicted (λ is not predicted) $m_H = \sqrt{2\lambda}v$
  - m_H must be measured:

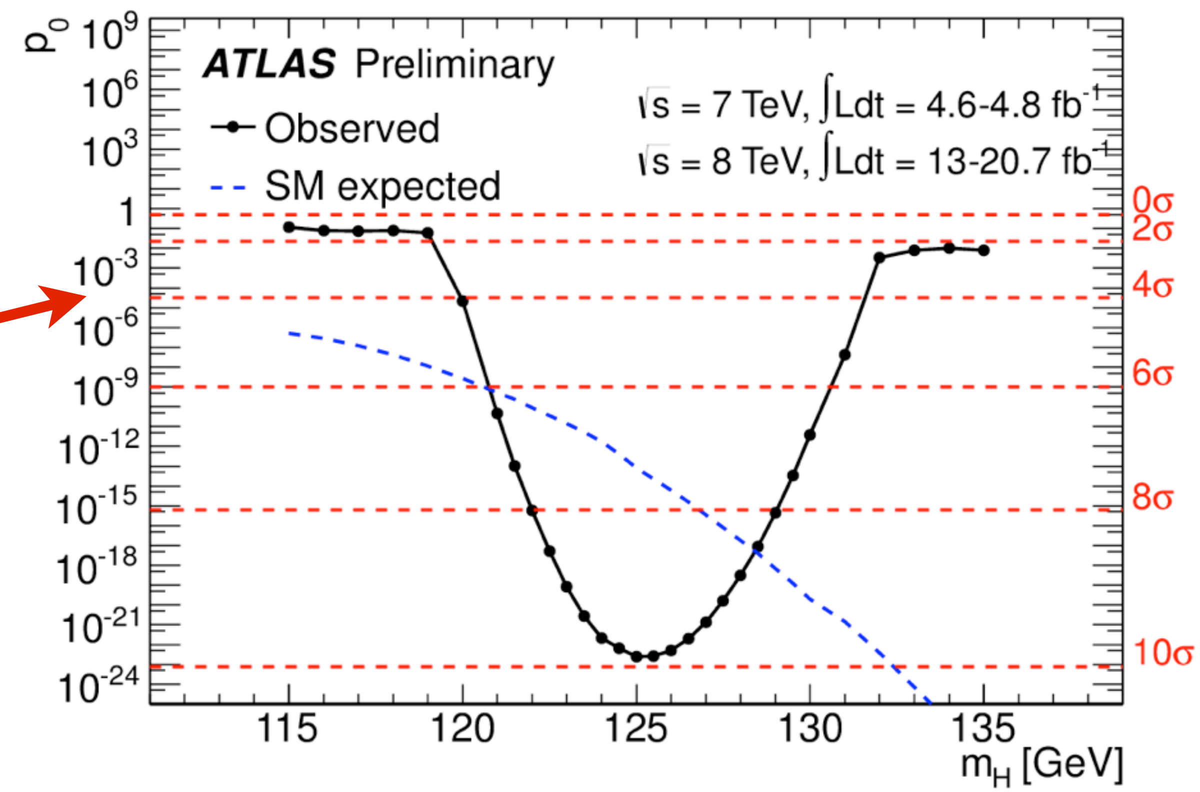
- Once m_H is known, the values of the Higgs boson production cross section and the branching ratios are predicted:

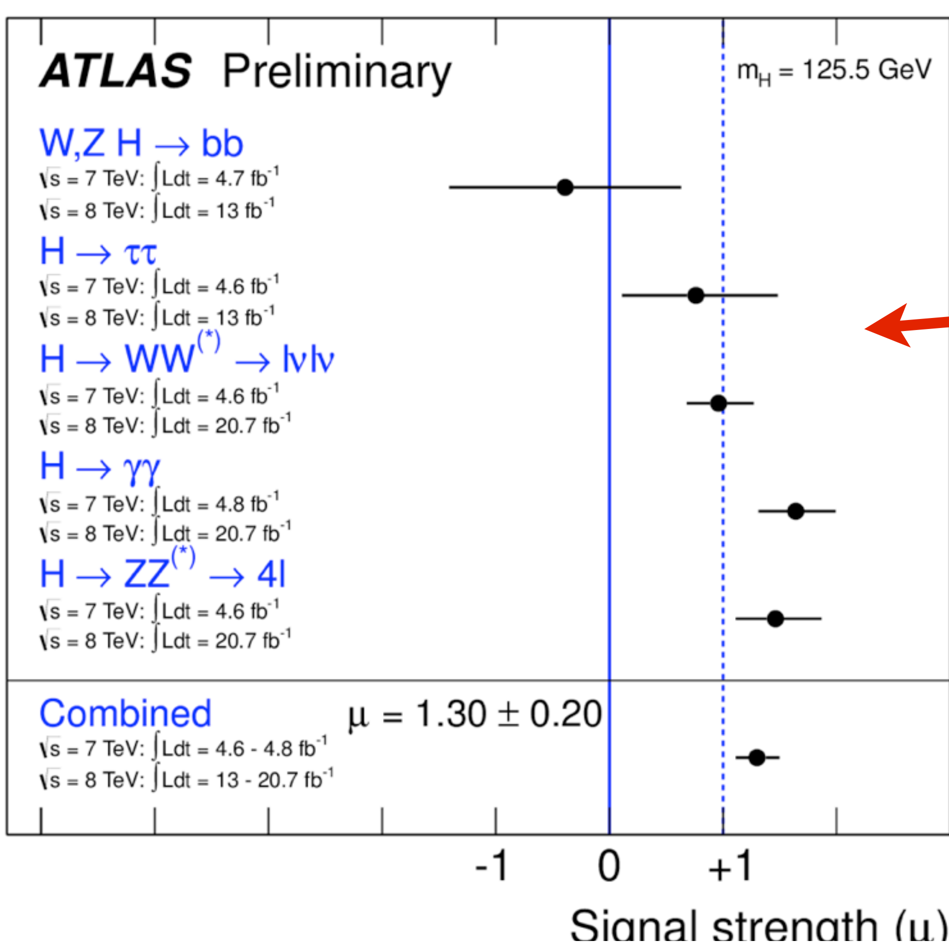




Measured Higgs boson properties

- The ZZ^* and $\gamma\gamma$ channels provide the best measurement of the Higgs boson mass.
  - Measured to be $m_H = 125.5 \pm 0.6$ **GeV**
  - The significance of the observation is ~**10** standard deviations.





Ratio between the predicted and measured **cross section * branching ratio**

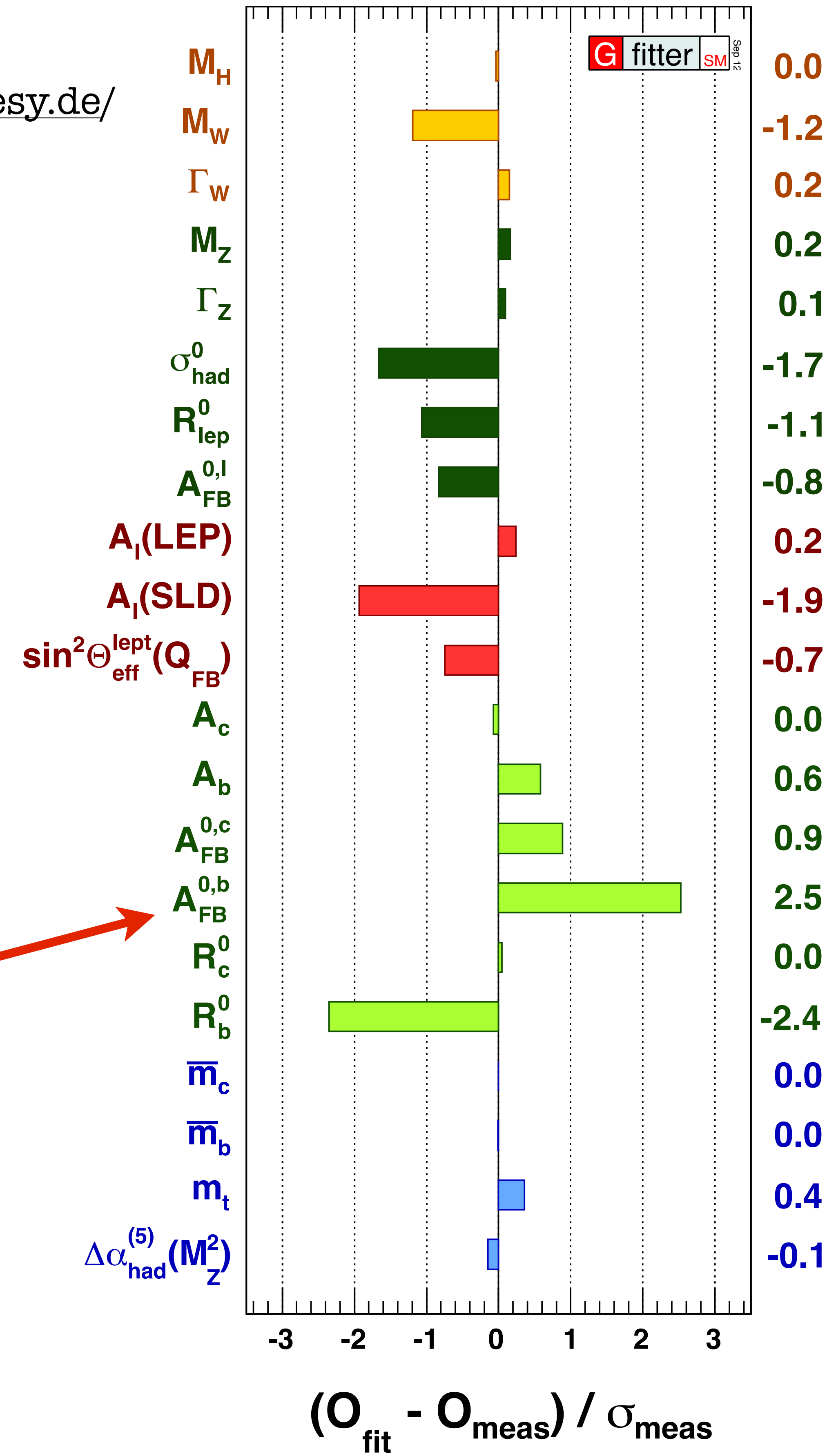
- More data is required before we are sure that what we observe is the Standard Model Higgs boson.

Electroweak Precision Tests

http://gfitter.desy.de/

- Tests can be run to test the consistency of Electroweak theory.
- Check if it is really described by three parameters g_W, g'_W v
  - Plus m_H and the fermion masses

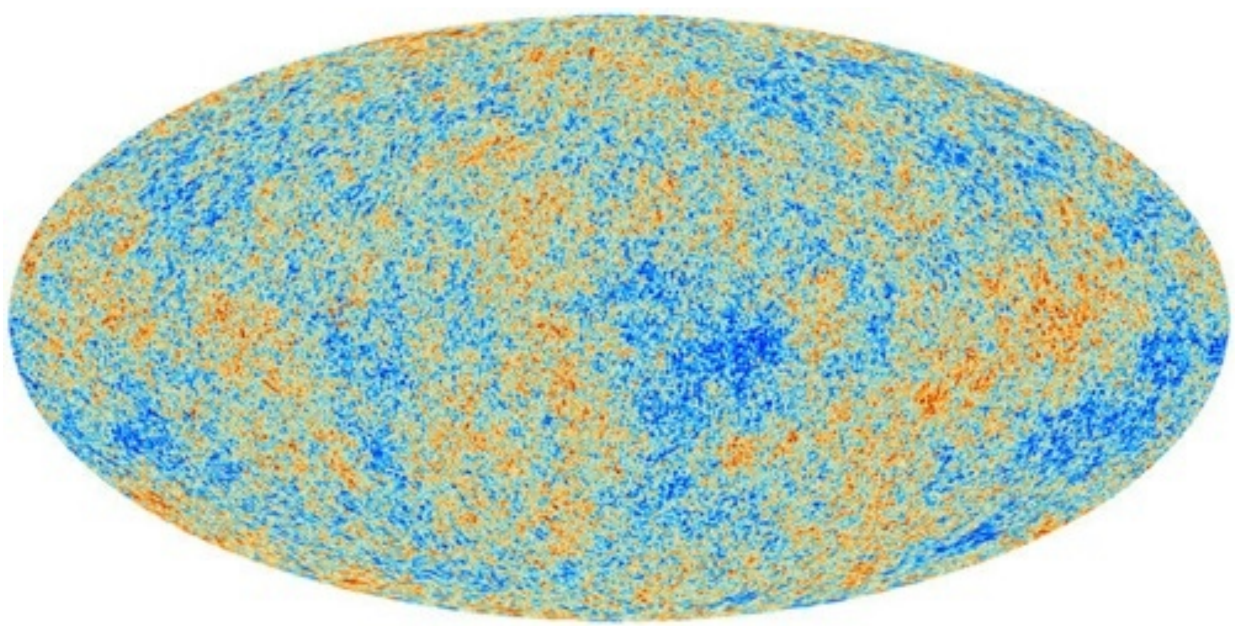
Difference between the predicted and measured parameter divided by the error

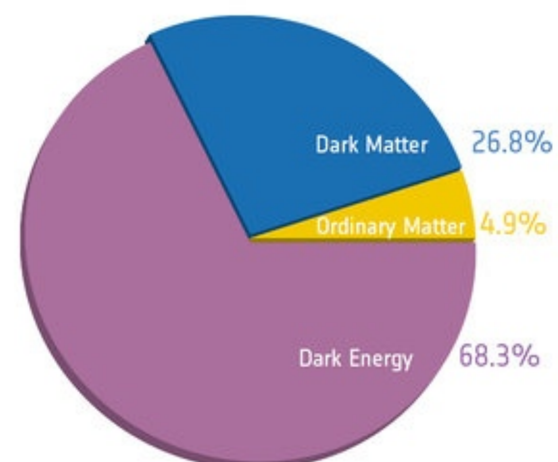


- Electroweak model is consistent within errors

For Fun:

- Finding the Higgs boson doesn't solve everything. For example:
  - The amount of **CP** violation observed in the Standard Model is not consistent with cosmological models.
  - Recent measurements of the cosmic microwave background radiation from the Planck satellite suggest that only 4.9% of the universe is described by Standard Model particles.



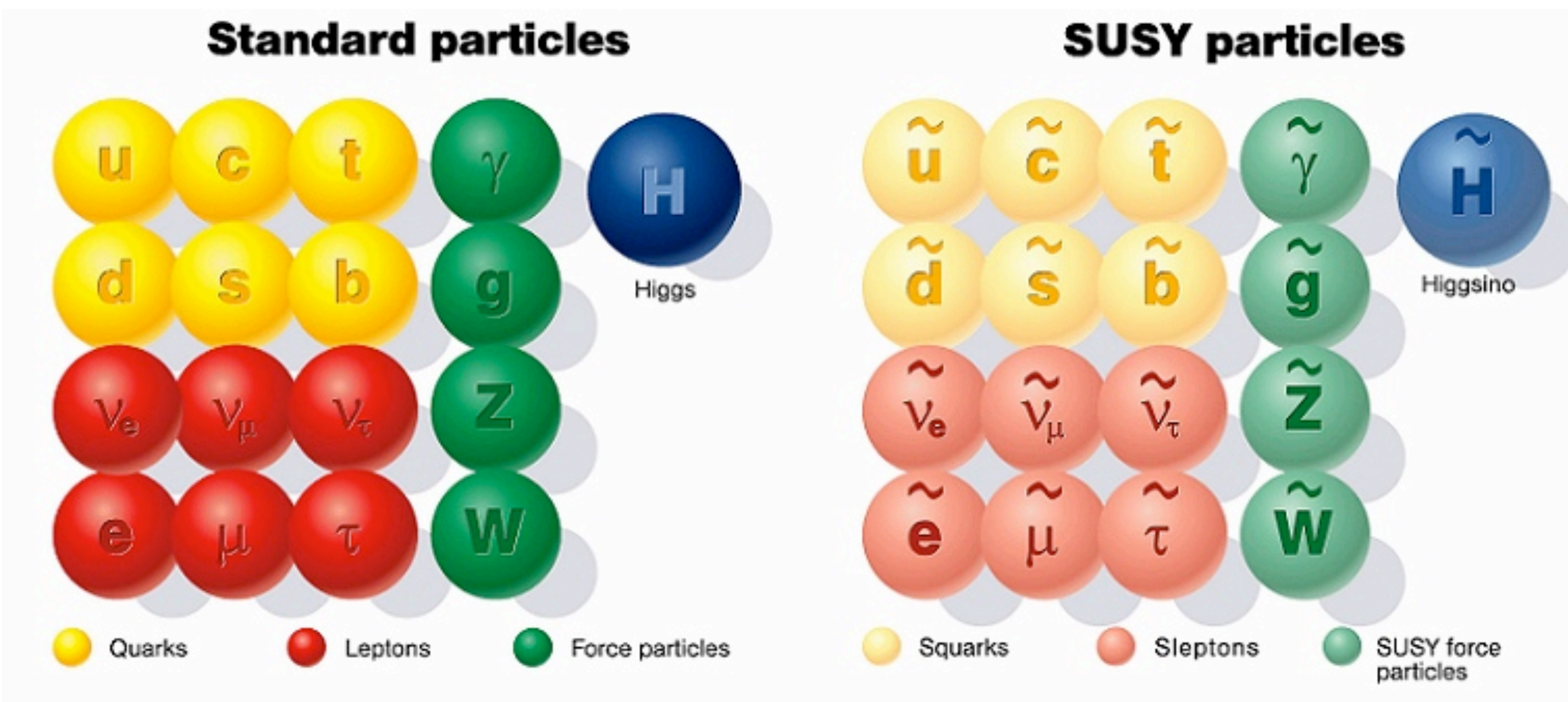


planck.esa.int

  - We have no idea why there are three generations of quarks and leptons
  - No nice theoretical way to give a mass to the neutrinos.
  - Gravity doesn't fit into the Standard Model at all!

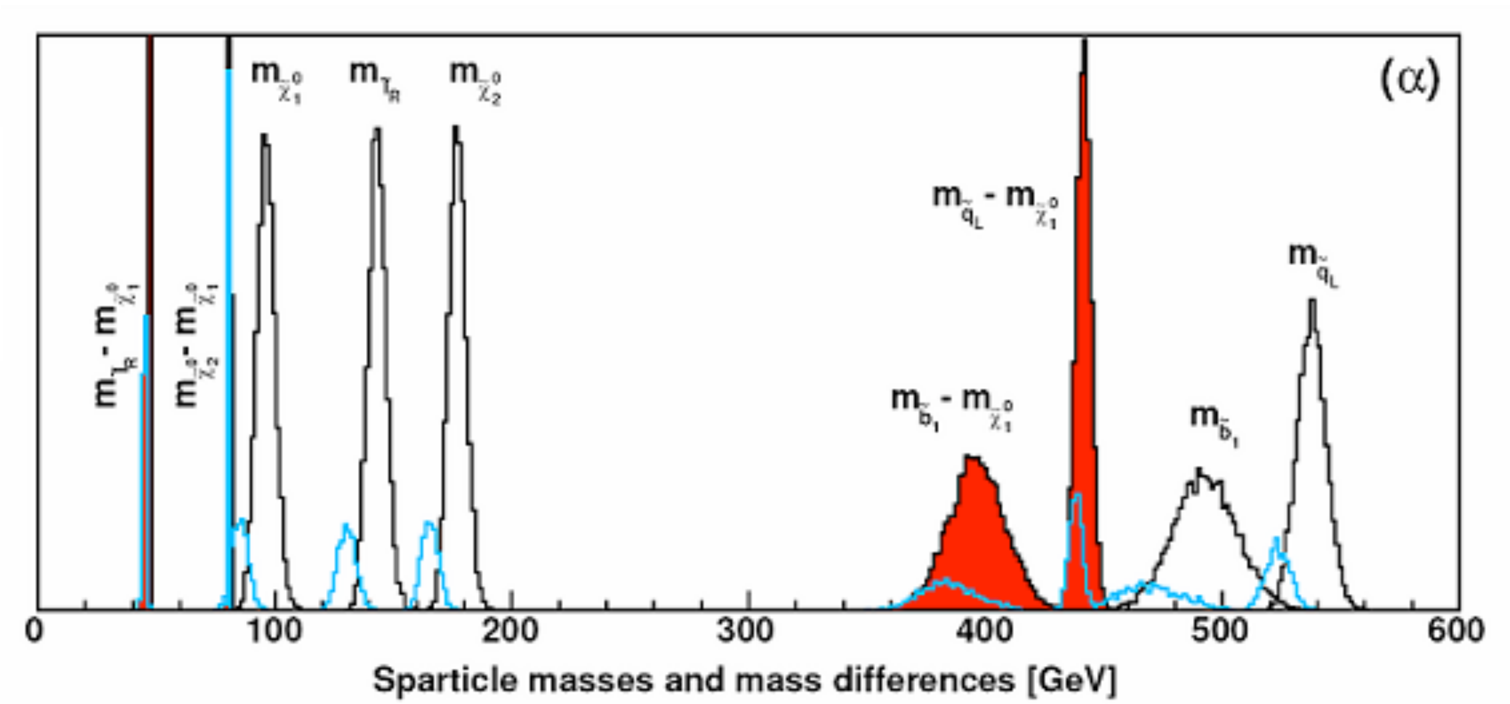
Supersymmetry (SUSY)

- Supersymmetry is a proposed additional symmetry of nature between fermions and bosons.
  - Every fermion will have a bosonic partner
  - Every boson will have a fermionic partner
- The partners should have identical properties (charge, mass) except for the spin.
- This cannot be true: otherwise we would have seen the SUSY particles already. The supersymmetry must be broken.

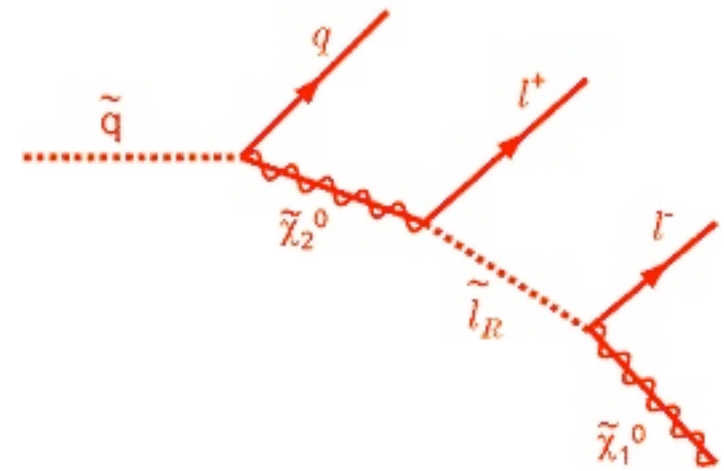


SUSY at the LHC

Measuring mass differences



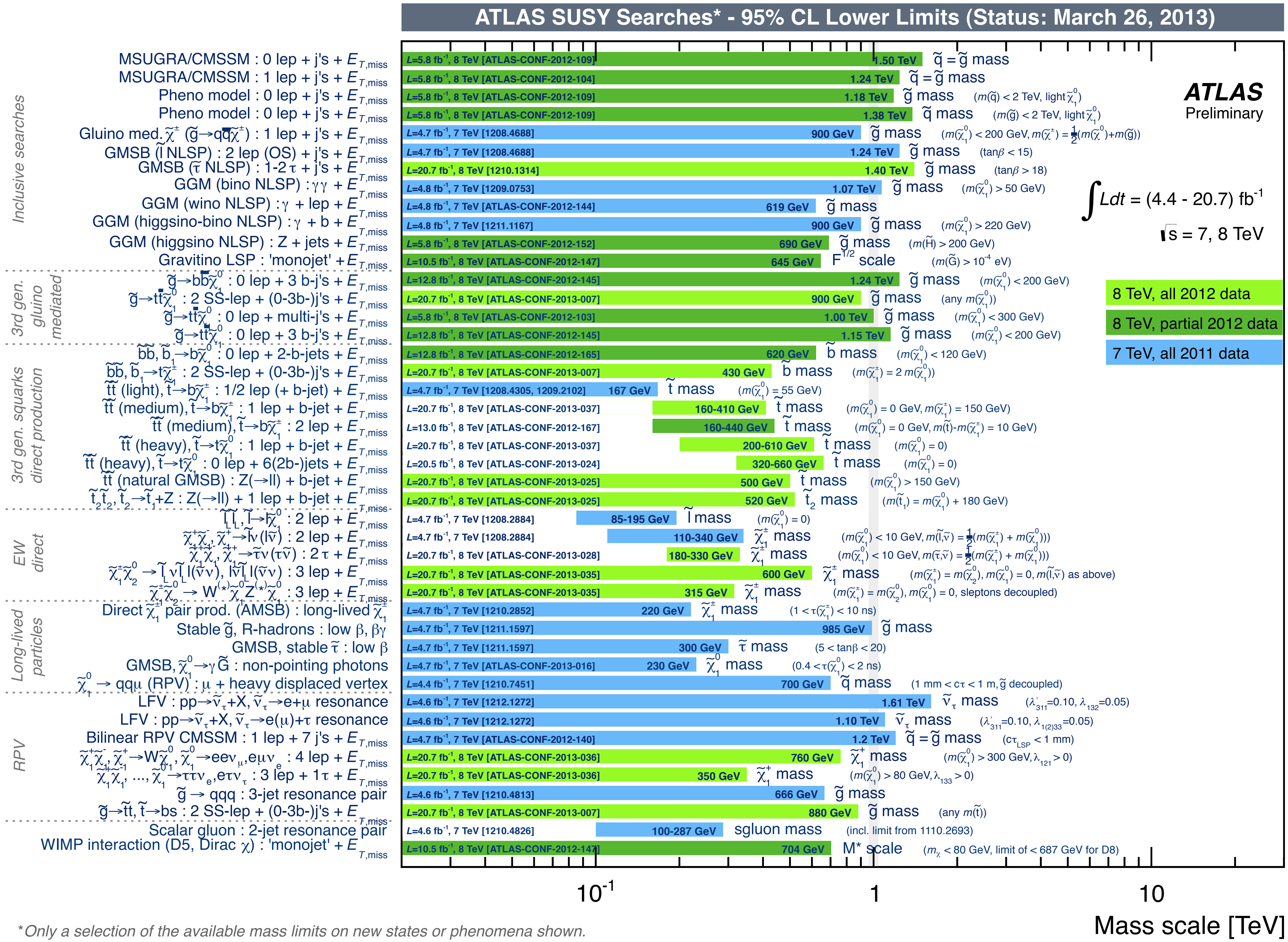
http://www.physics.gla.ac.uk/ppt/bsm.htm



Typical decay of a squark

- The lightest supersymmetric particle is though to be neutral and stable.
- It would appear in an LHC experiment as missing transverse energy.
- Signatures such as these have been searched for at ATLAS and CMS, but nothing has (yet) been observed.

ATLAS (null) results on Supersymmetry



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.