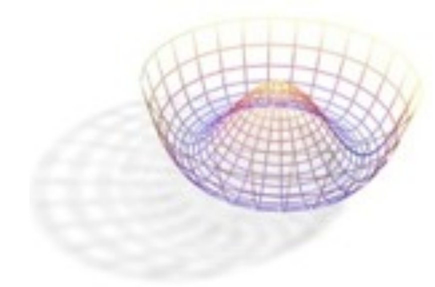
The discovery of the Higgs boson

Frank Filthaut
Radboud Universiteit Nijmegen / Nikhef

- Theory & previous searches
- Discovery
- Next

Theory & previous searches

Higgs mechanism basics



Motivation: hooked on the gauge principle!

- QED is a spectacular success: $(g\text{-}2)_e$, $(g\text{-}e)_\mu$

But a priori the gauge principle is incompatible with massive W, Z

Required: a mechanism to break the EW symmetry spontaneously

- Lagrangian maintains full EW symmetry; the ground state does not

Achieved through the introduction of the (complex scalar) Higgs field

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

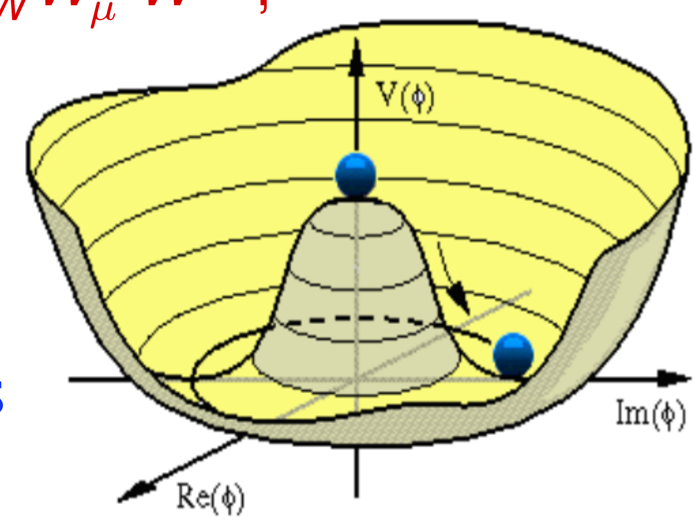
$$D_\mu = \partial_\mu - i\frac{g}{2}\sigma_i W_{i\mu} - \frac{g'}{2} Y_h B_\mu$$

$$\boxed{V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2}$$

$$(D_\mu \Phi)^\dagger (D^\mu \Phi) \rightarrow \frac{1}{2} M_Z^2 Z_\mu Z^\mu + M_W^2 W_\mu^- W^{\mu +},$$

$$M_W = \frac{1}{2} v g,$$

$$M_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}$$



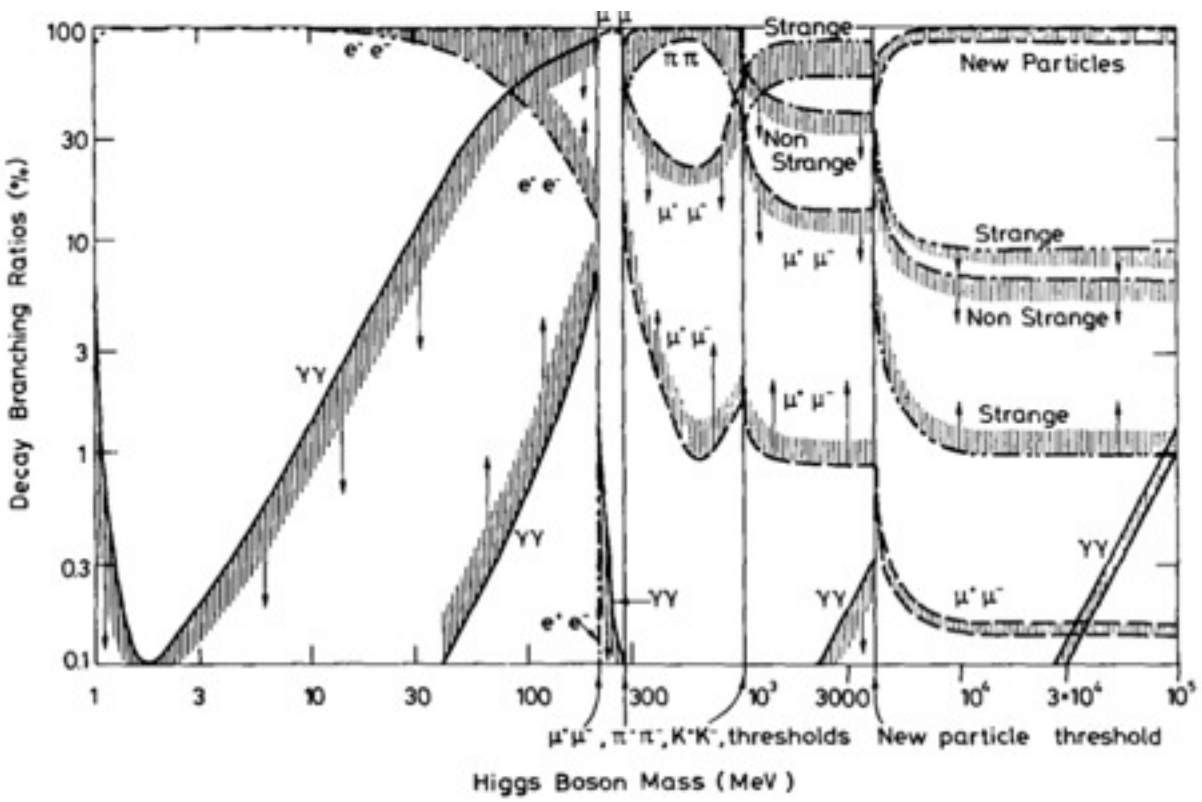
Generation of fermion masses through Yukawa couplings

Phenomenology depends only on (unknown) M_H

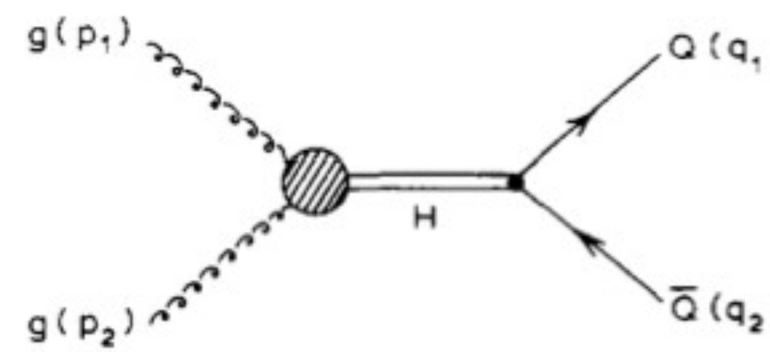
Early Higgs boson phenomenology

A priori any mass is possible...

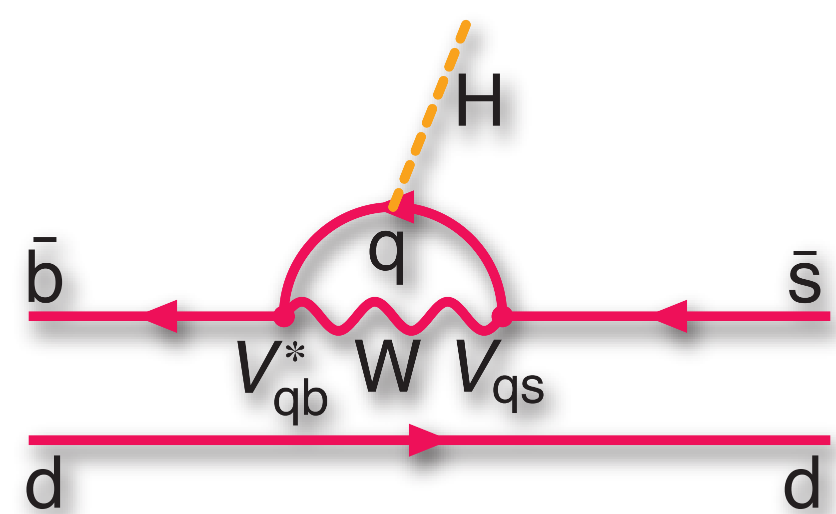
- Ellis, Gaillard, Nanopoulos (1976): decays to e^+e^-, $\gamma\gamma$, $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-, cc



- Gaemers, Hoogeveen (1984): Higgs production at hadron colliders (and decaying to bb, tt(!))



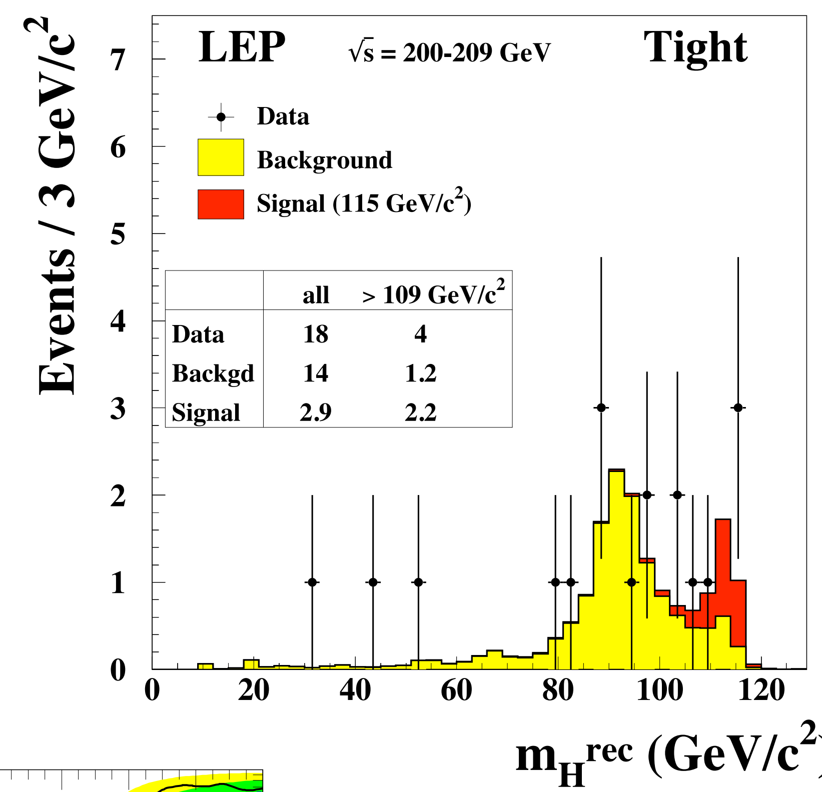
- Haber, Schwartz, Snyder (1987): Higgs production in B decays

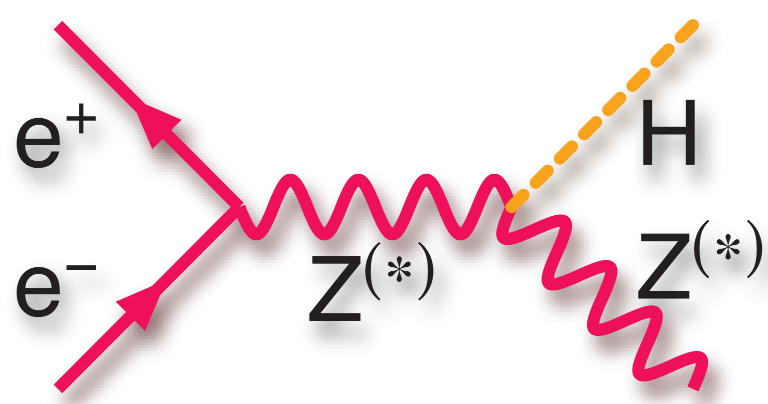


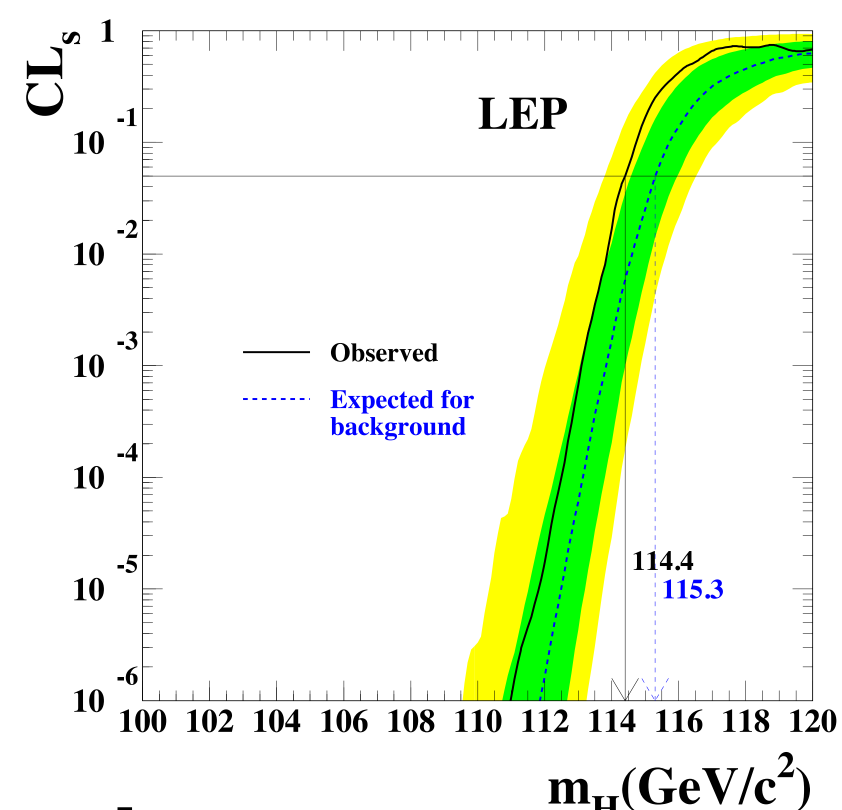
LEP Higgs boson search

Searches at LEP dominated by ZH associated production ("Higgs-strahlung"). Clean!

- LEP 1: profit from large Z production cross section, look for decay to on-shell Higgs boson + off-shell Z decay
  - exclude $M_H \lesssim 30$ GeV (1990), $\lesssim 63$ GeV (1995)
- LEP 2: look for decay of off-shell Z boson to on-shell Higgs boson + on-shell Z boson
  - exclude $M_H \lesssim 114.4$ GeV







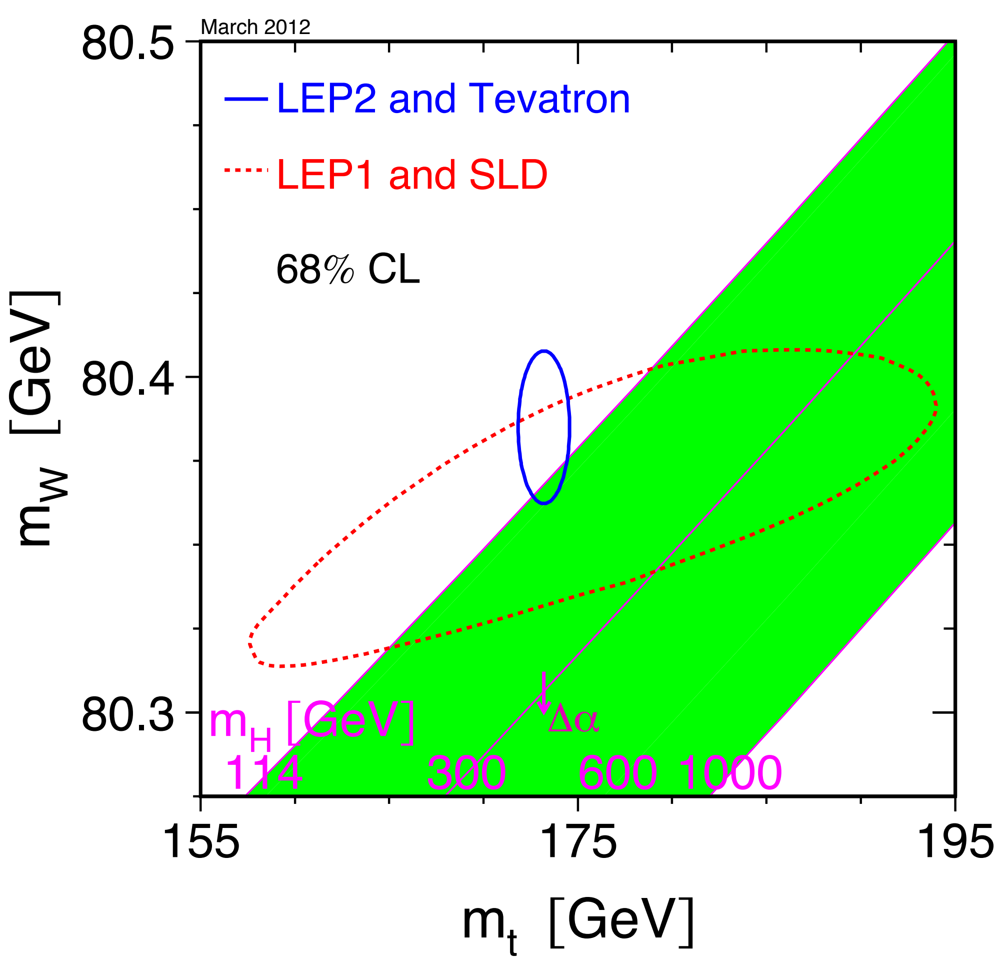
A wealth of electroweak results

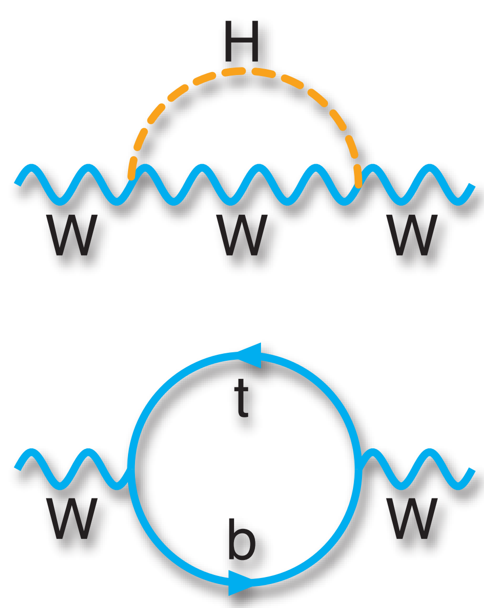
Many precision tests of EW structure carried out (LEP, SLD, Tevatron)

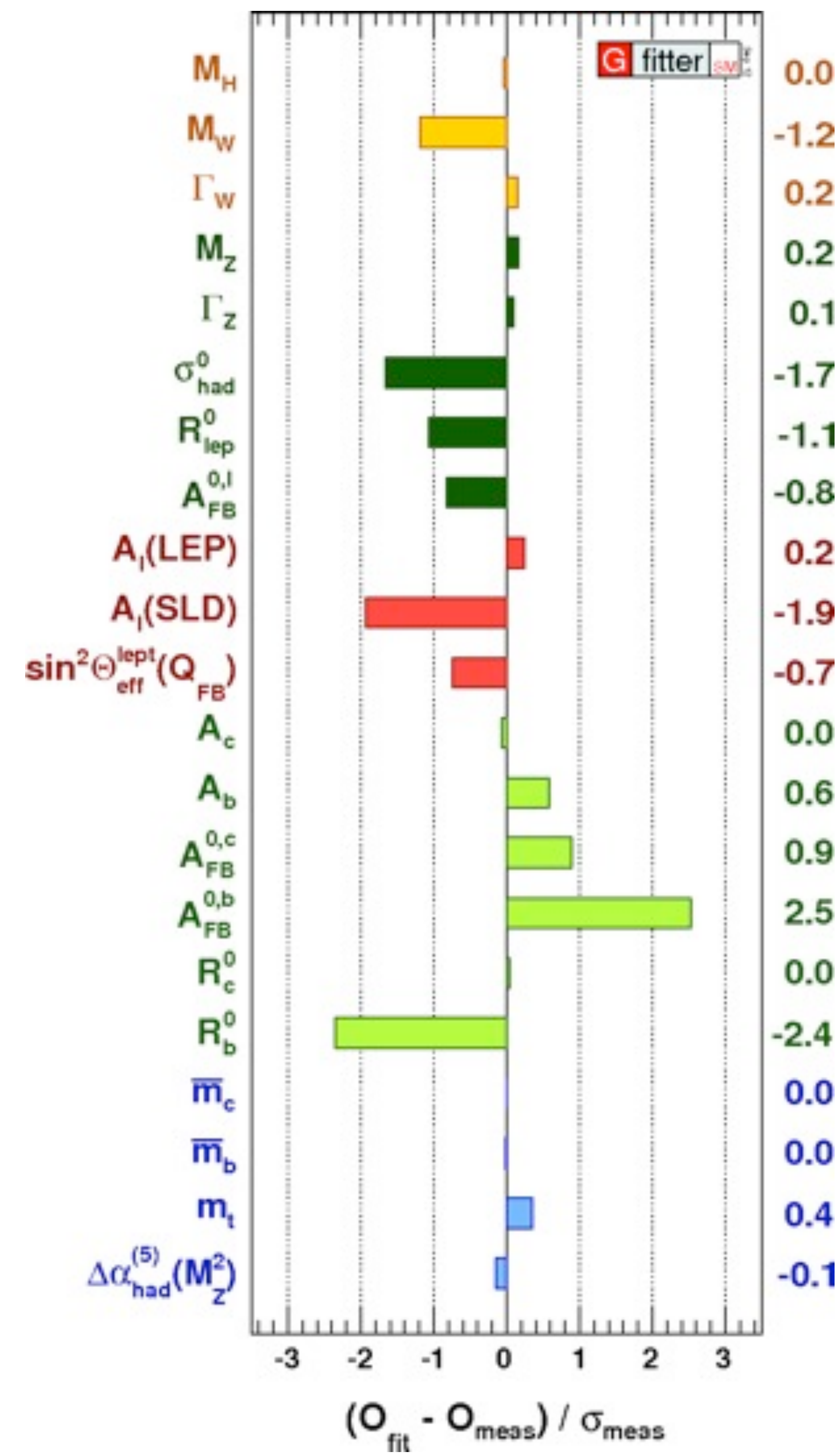
- good internal consistency fitting to pseudo-observables (M_Z, M_H, $\Delta\alpha^{(5,had)}(M_Z^2)$, $\alpha_s(M_Z^2)$, m_t, m_b, m_c)

Constraints on M_H dominated by M_W, m_t measurements

➠ prefer low M_H!

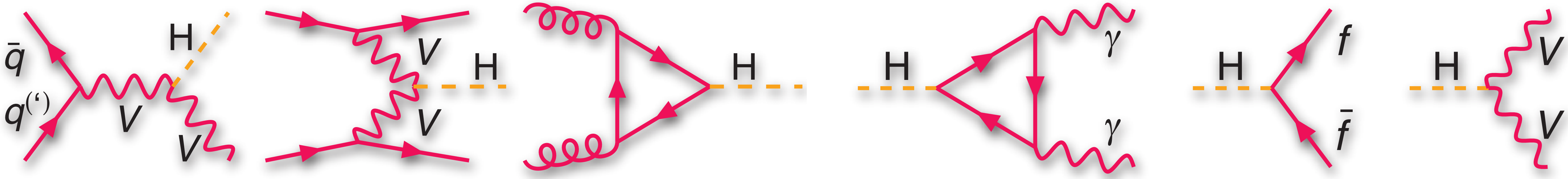


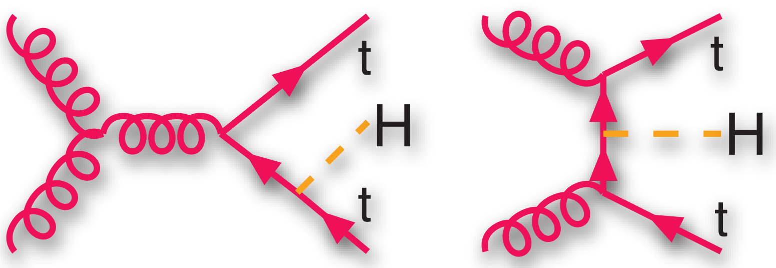




Higgs hunting at the LHC
(and a few words on the Tevatron)

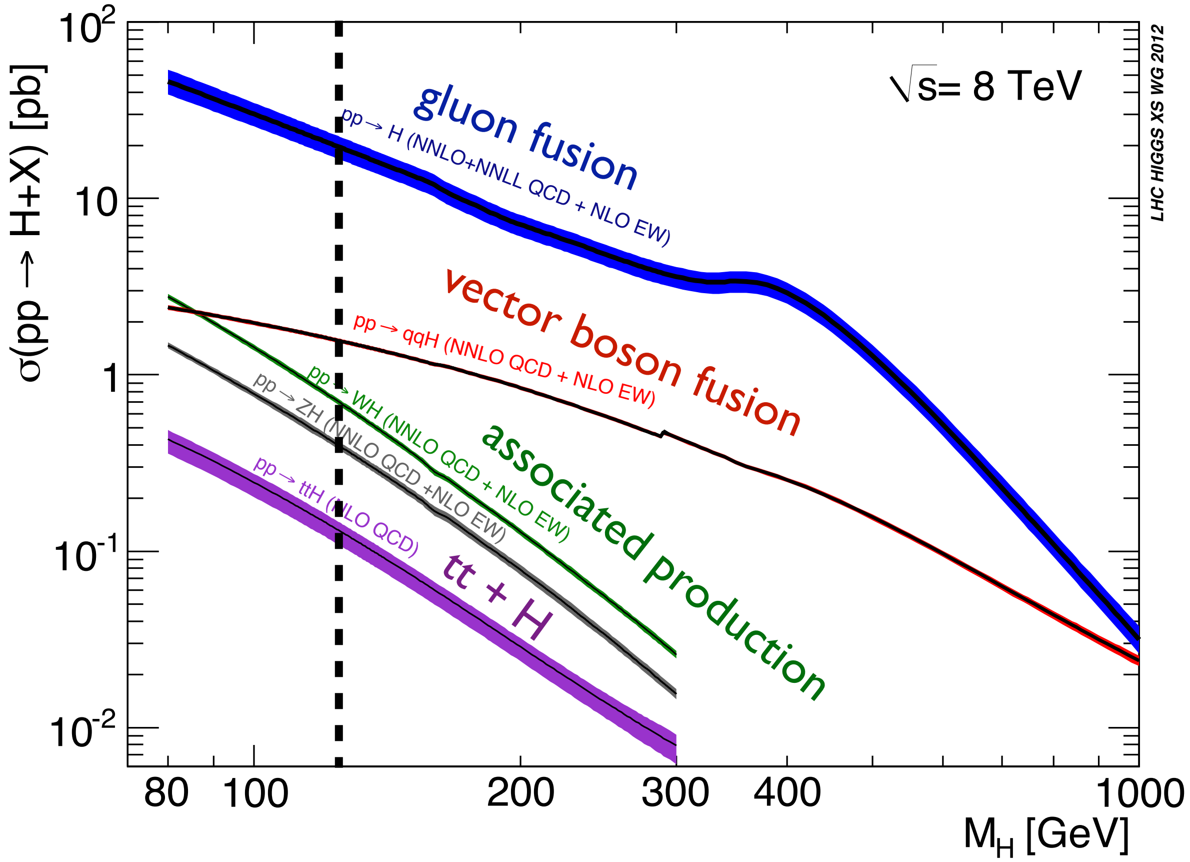
Production & decay at hadron colliders

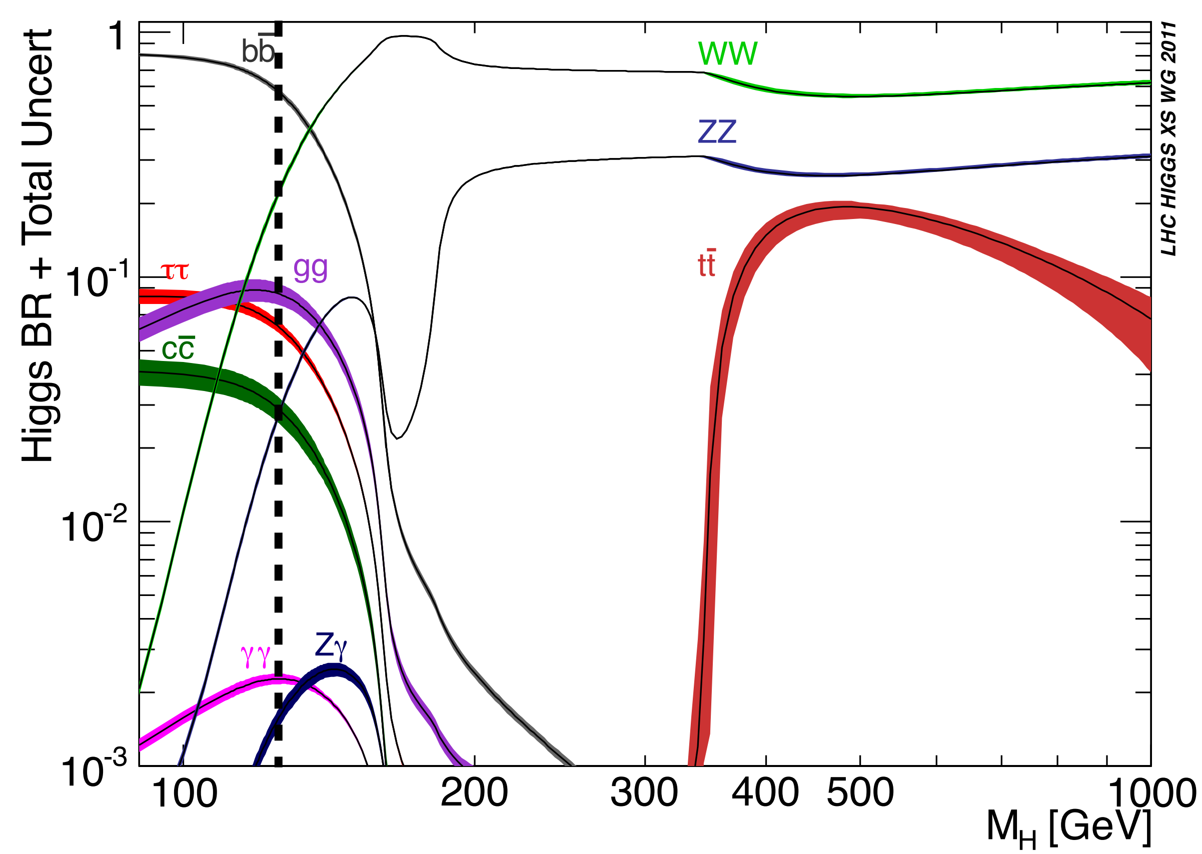




Same processes at the Tevatron as at the LHC, but

- much reduced gluon fusion + VBF cross sections
- sizeable cross section for associated production



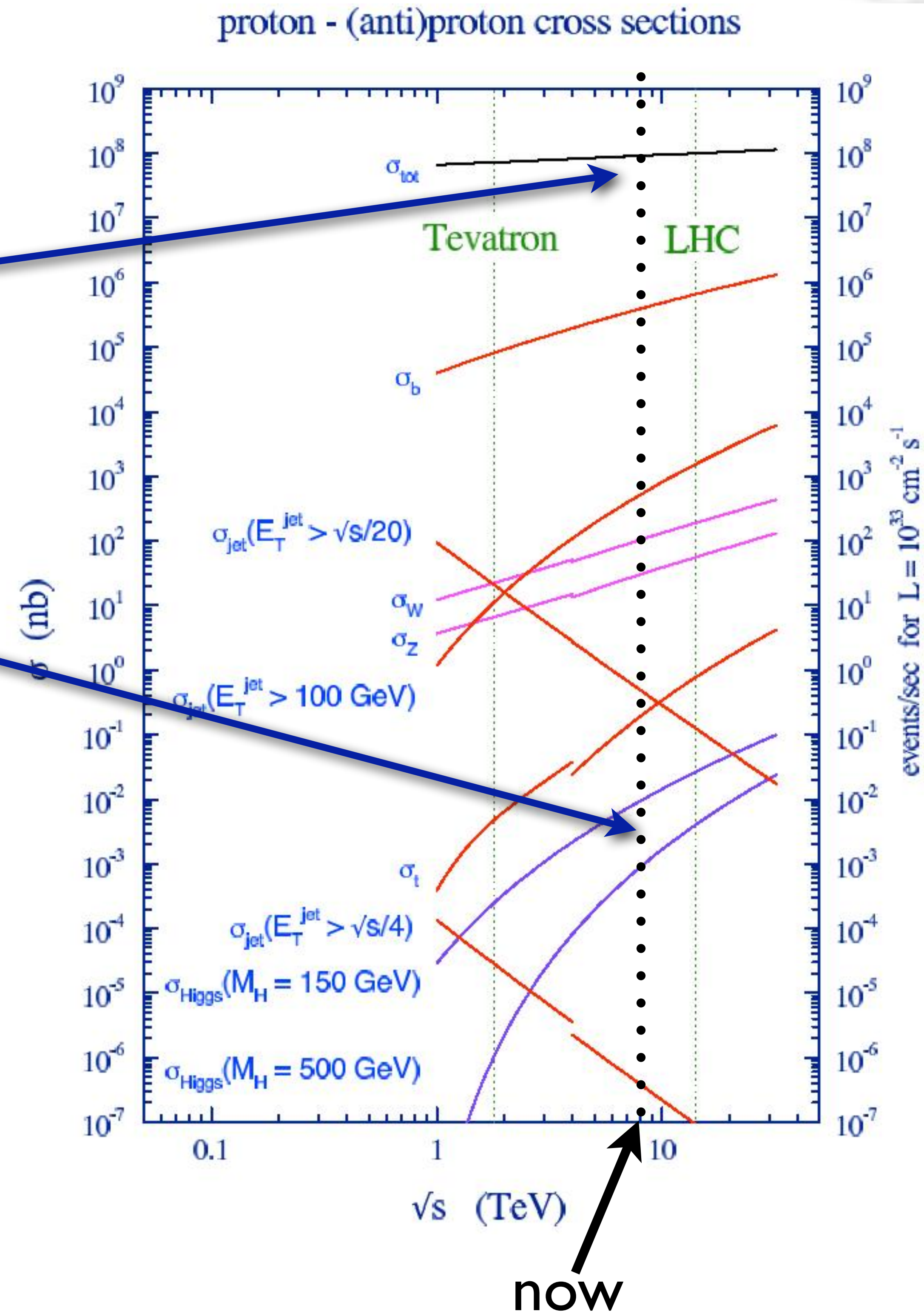


figures from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Experimental conditions

The main issue is not the presence of a signal but the backgrounds!

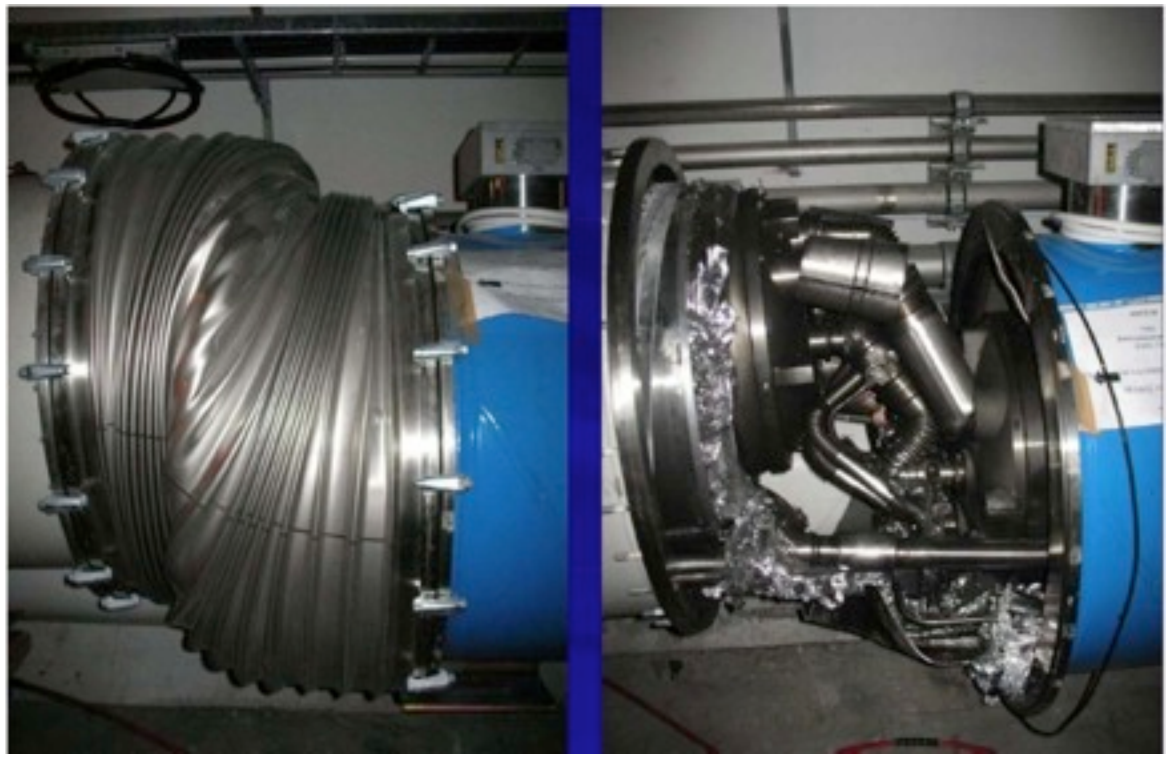
- interactions at hadron colliders dominated by strong interaction
- when searching for Higgs boson production, need to suppress backgrounds by ~ 10^{10}

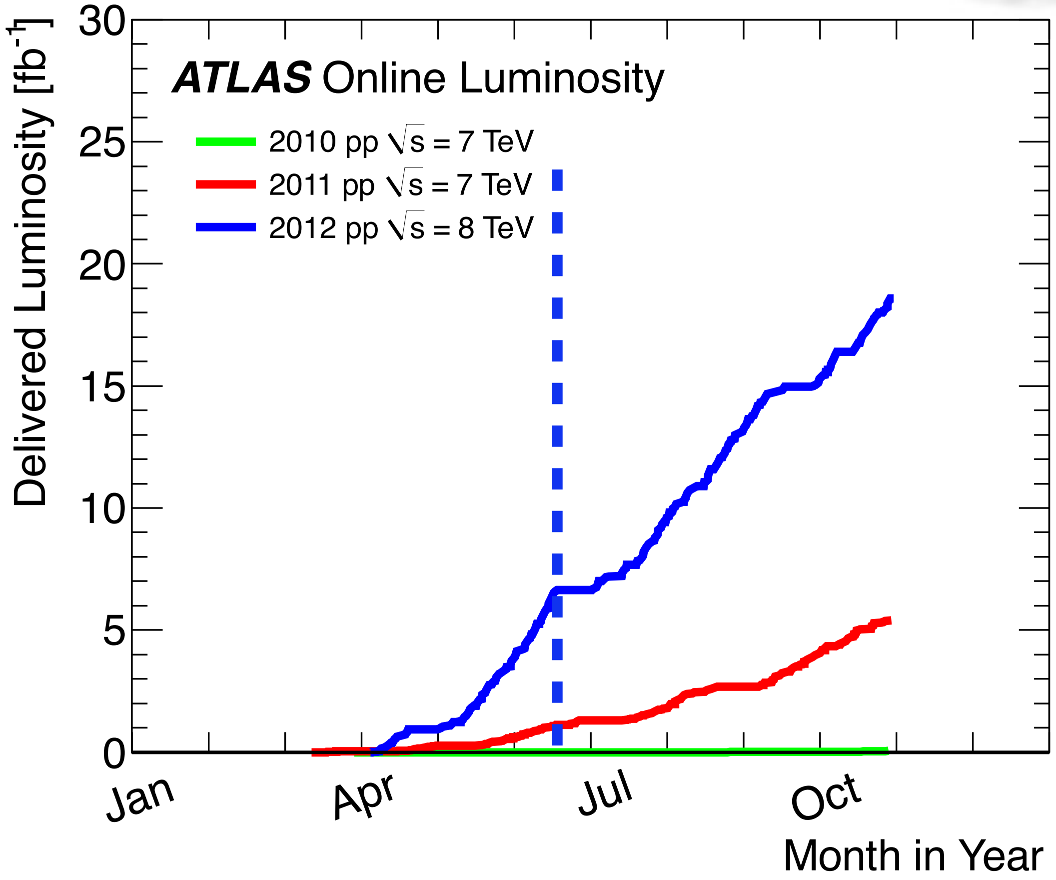


Need to look for striking signatures setting the Higgs boson apart from the (much) more ubiquitous backgrounds

- look for (relatively) rare production / decay modes
- need high luminosity

The LHC & ATLAS: success stories!





LHC expectations for 2011 exceeded by a factor 5

- even if at $\sqrt{s}$ = 7 TeV

2012 integrated luminosity by end June exceeded that at end of 2011

- and yet more to come..

Experiments coping very well with increased pile-up

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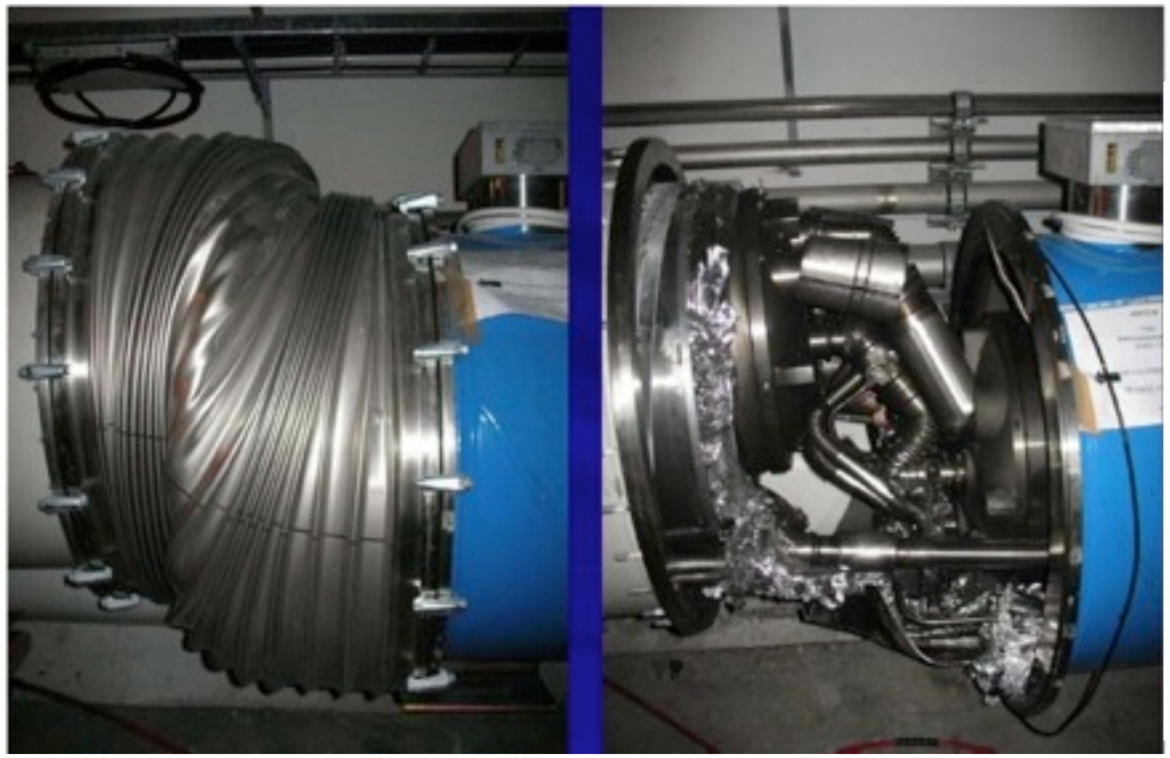

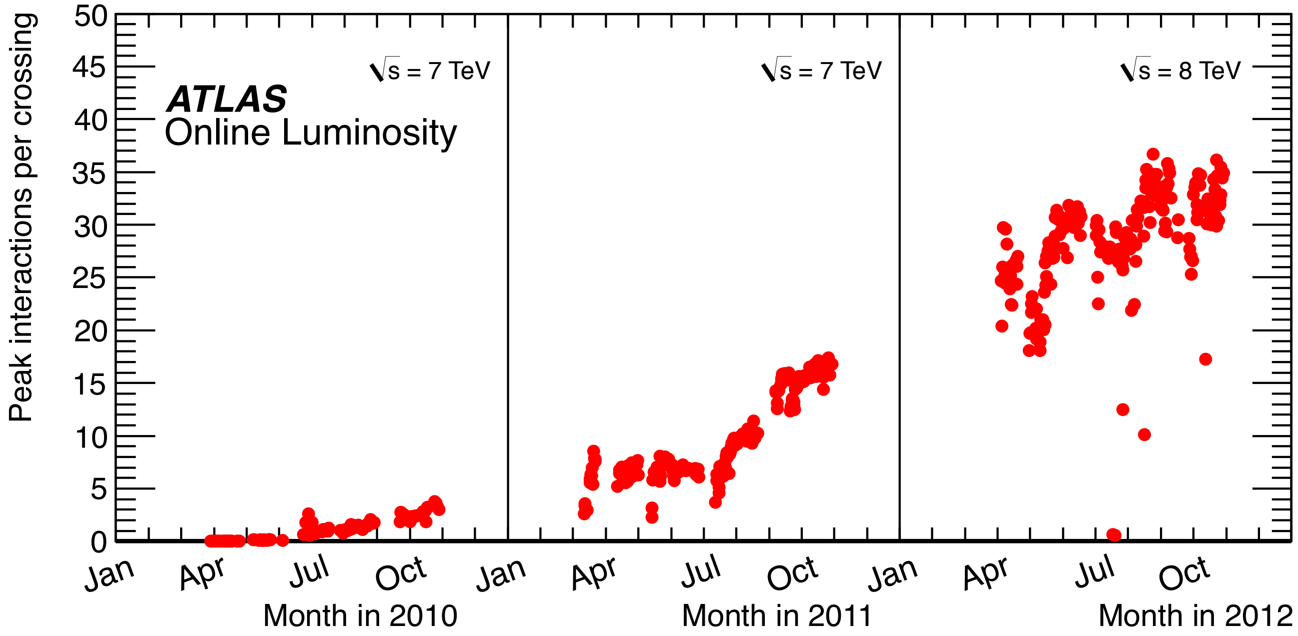

increased pile-up: up to 35 interactions / crossing

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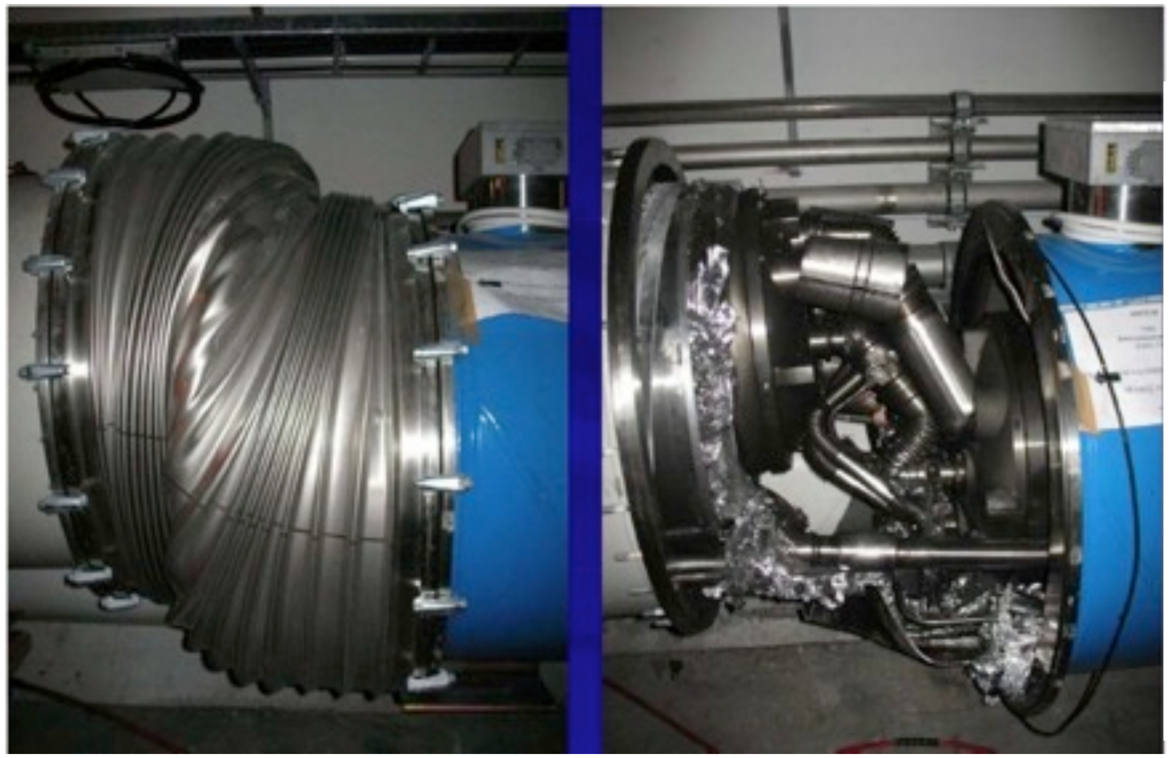

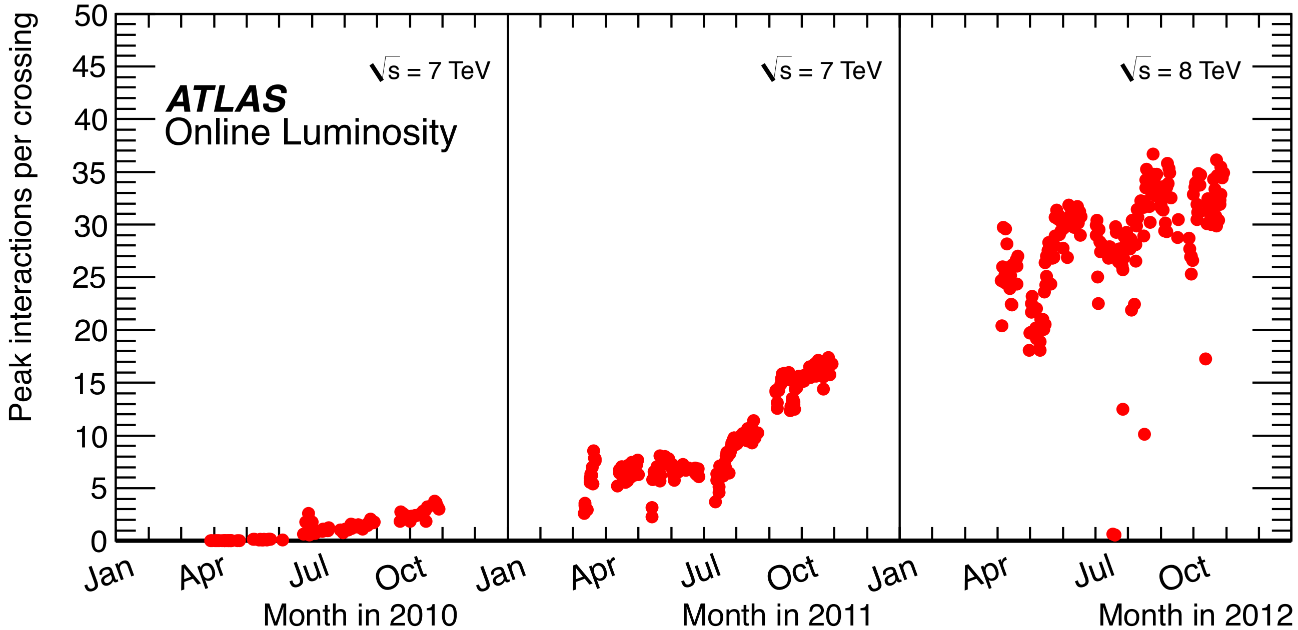

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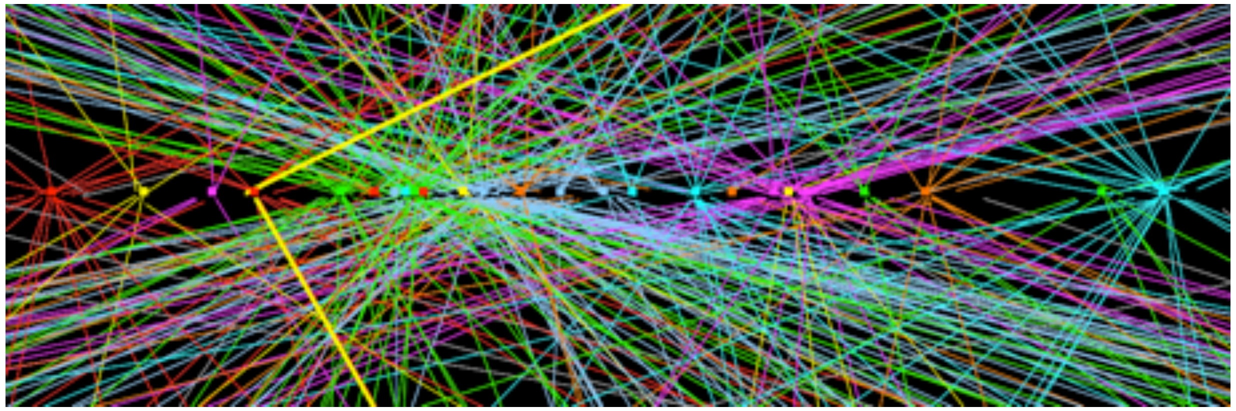
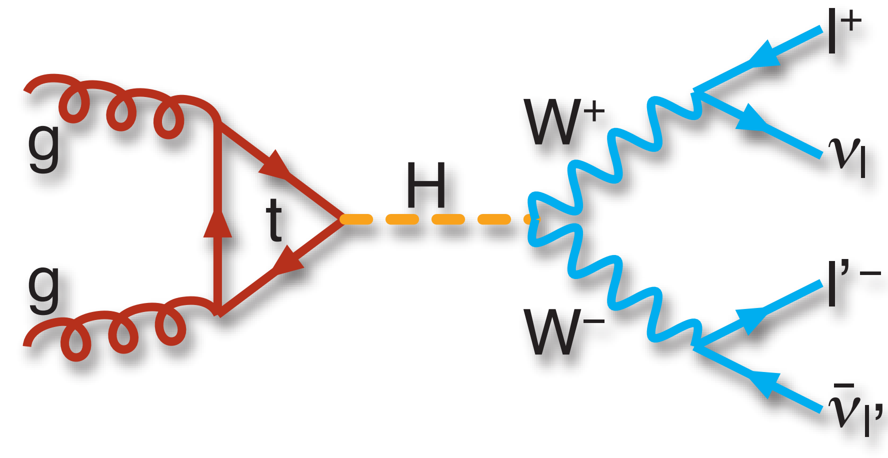
$Z \to \mu\mu$ candidate with 25 reconstructed primary vertices

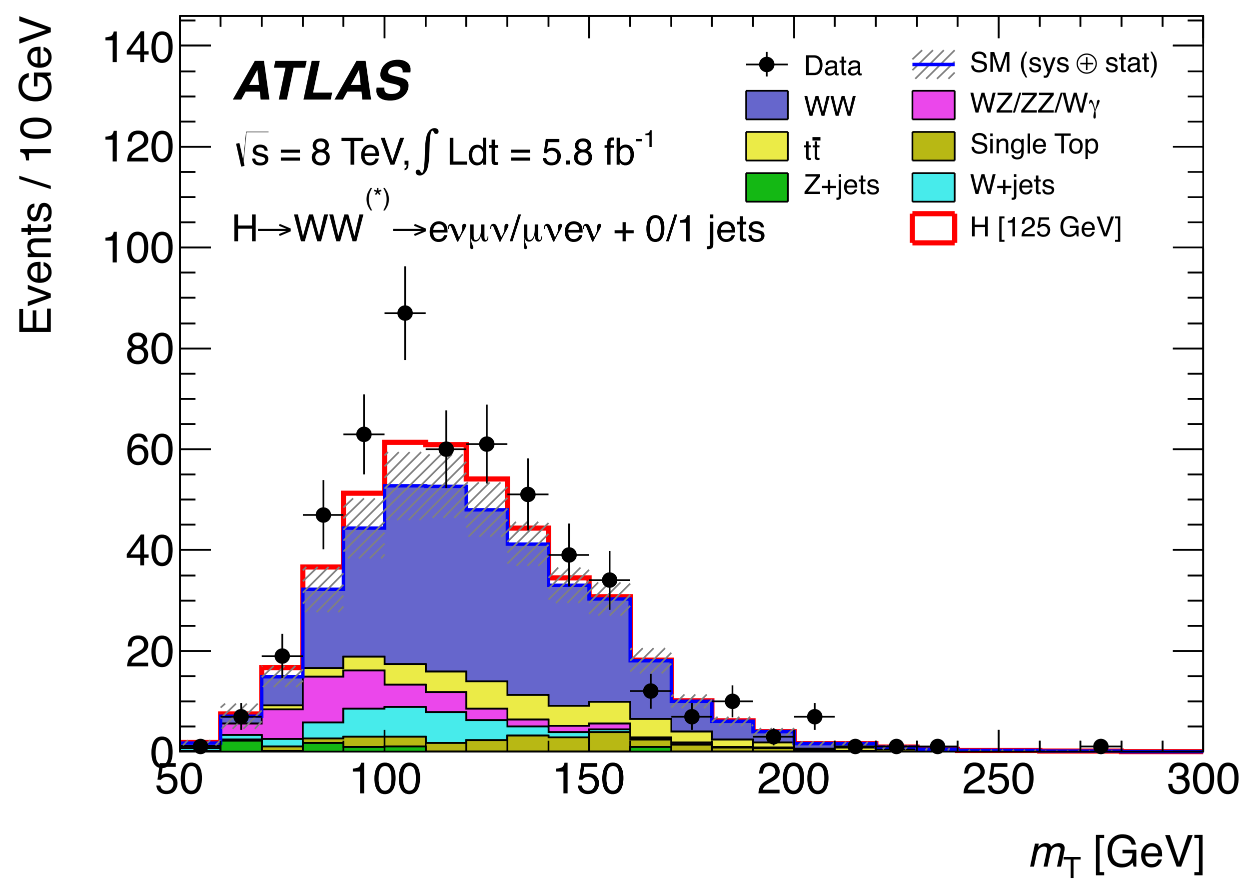


Higgs Boson discovery channels

Many possible production and decay modes! Here, focus on channels relevant in the most "interesting" mass range:



- $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$: relatively large event rate but cannot reconstruct mass of event candidates due to escaping neutrinos
  - rely on shapes of kinematic variables
  - also substantial backgrounds



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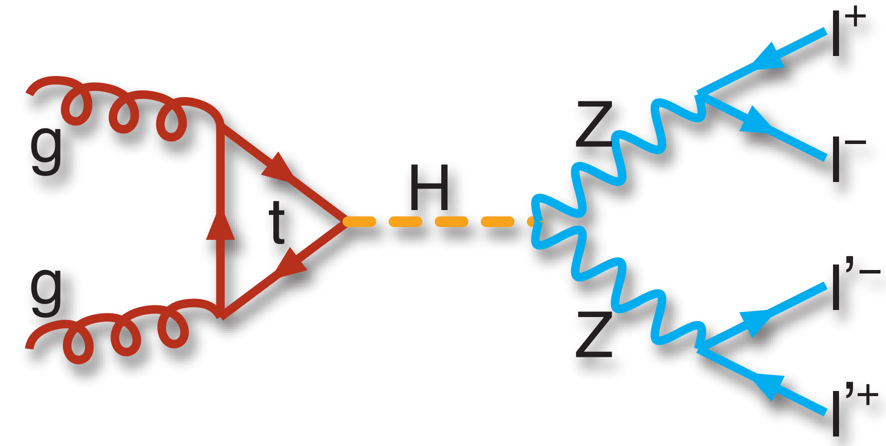

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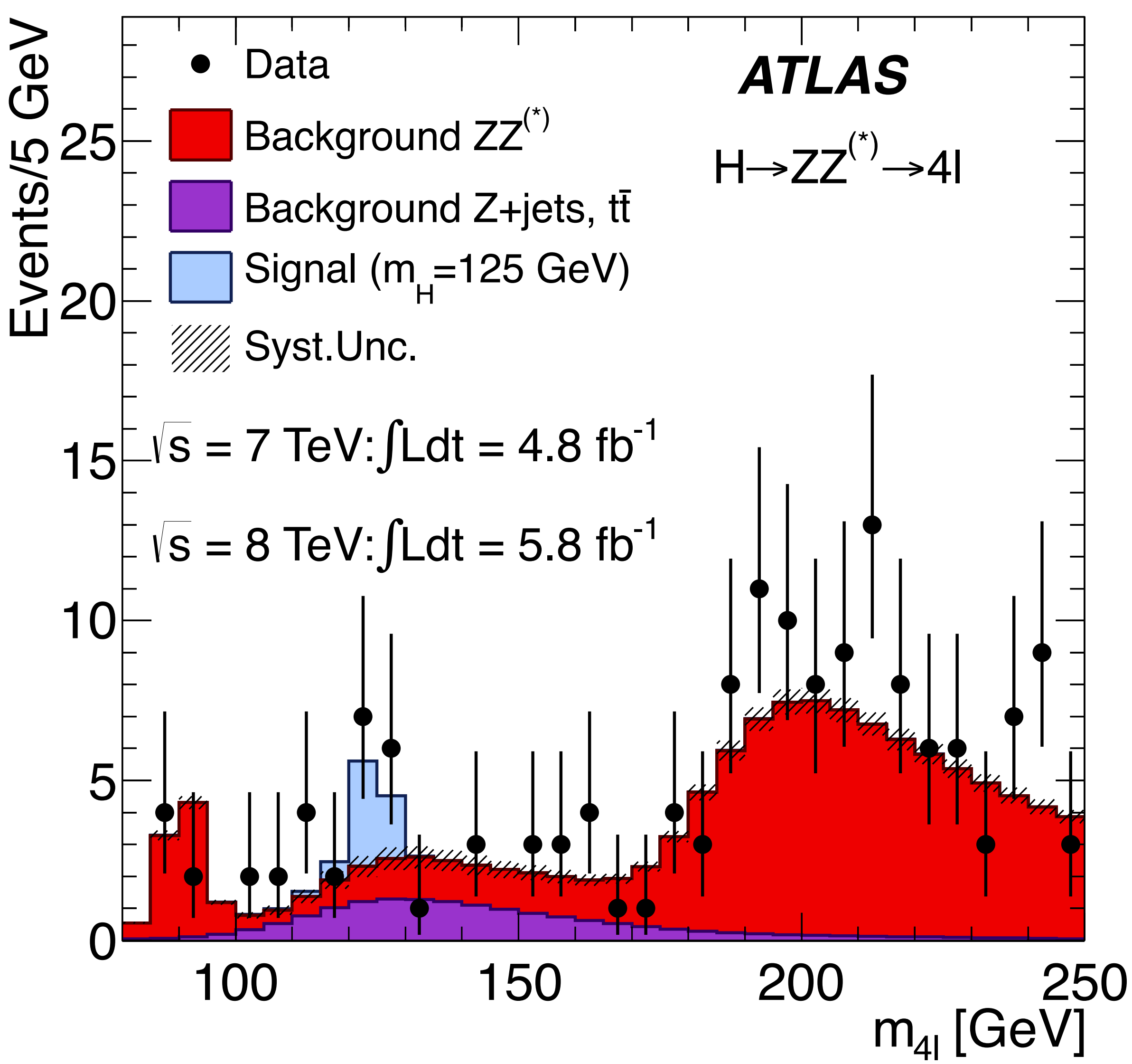
- $H \to ZZ^{(*)} \to l^+l^- \, l'^+l'^-$: precise mass reconstruction, very rare but very pure



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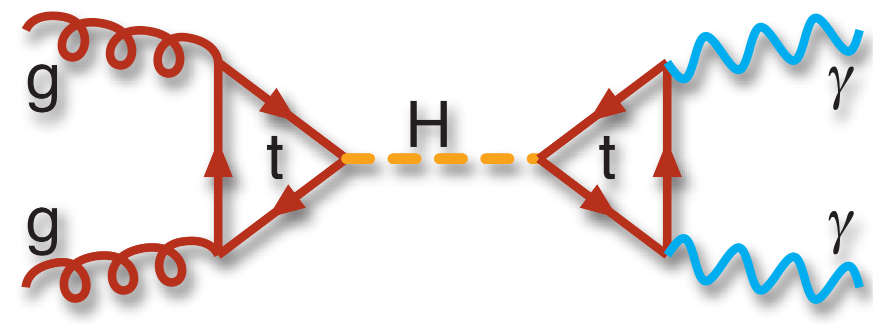

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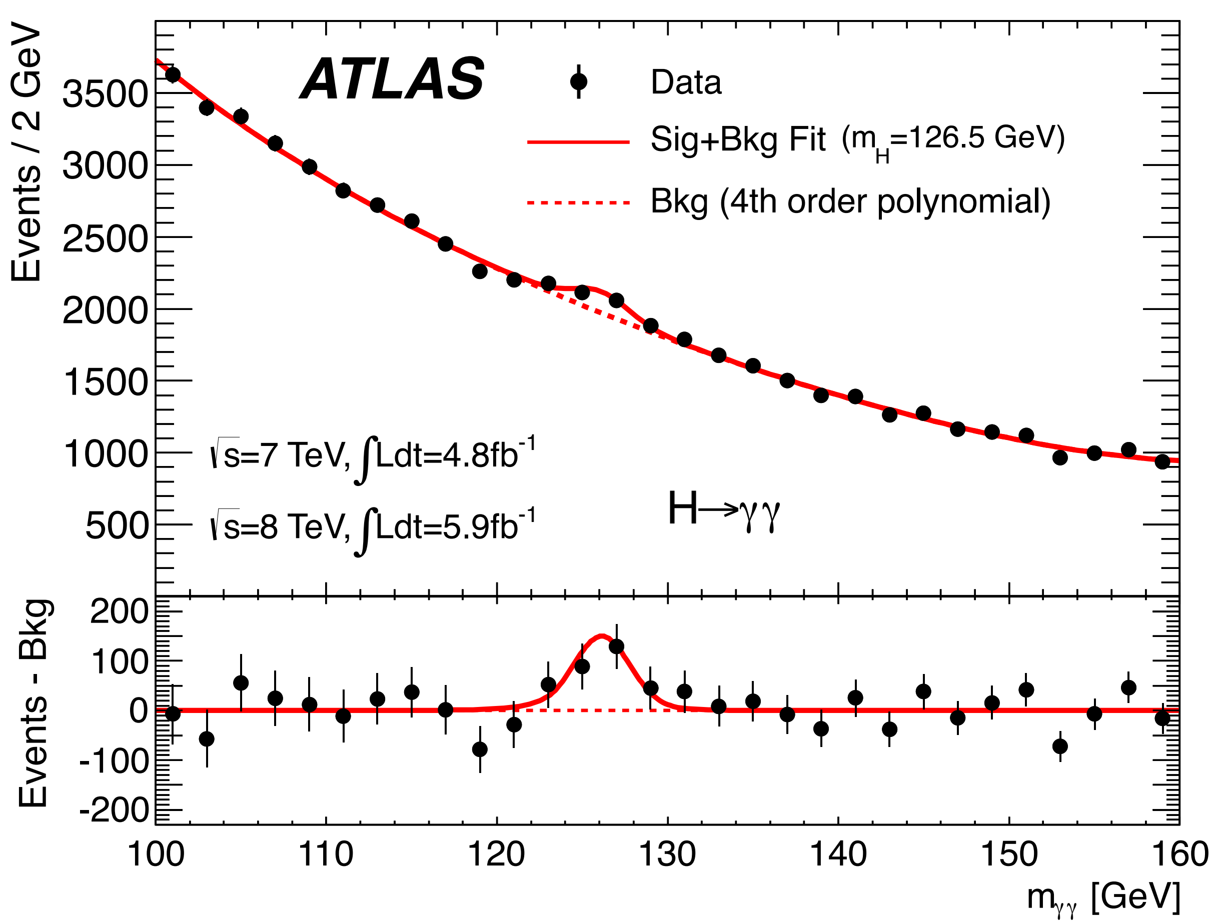
- $H \to \gamma\gamma$: precise mass reconstruction, modest rate but large background



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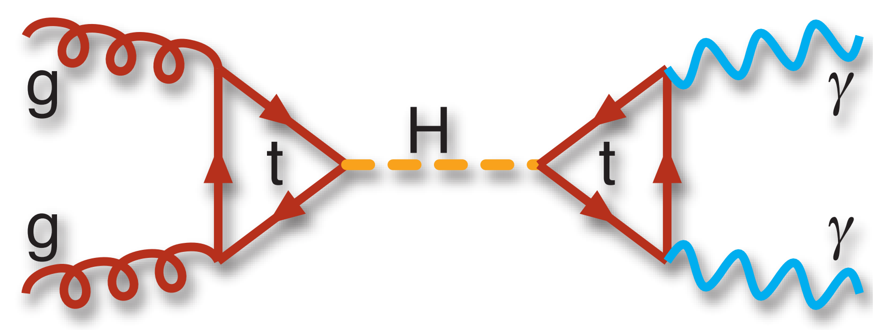

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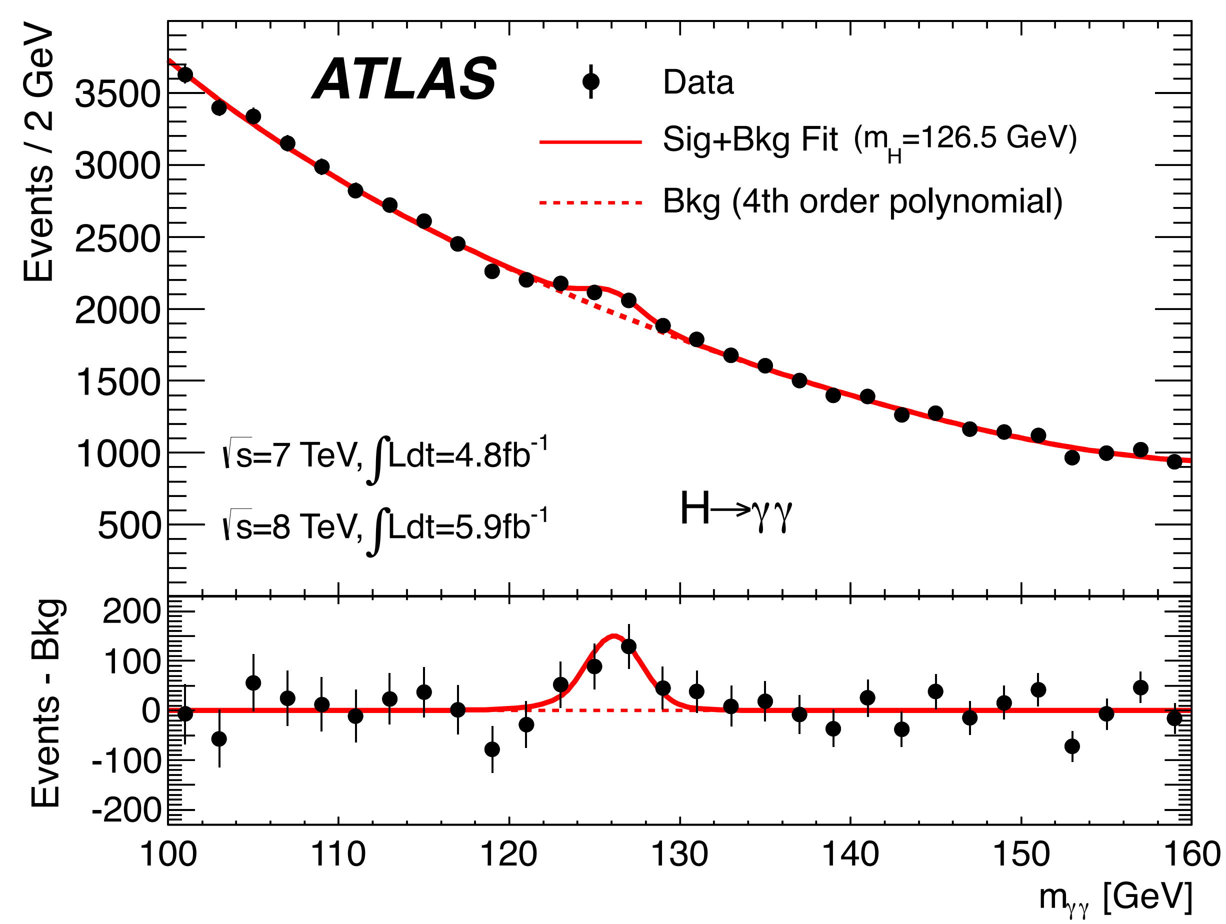
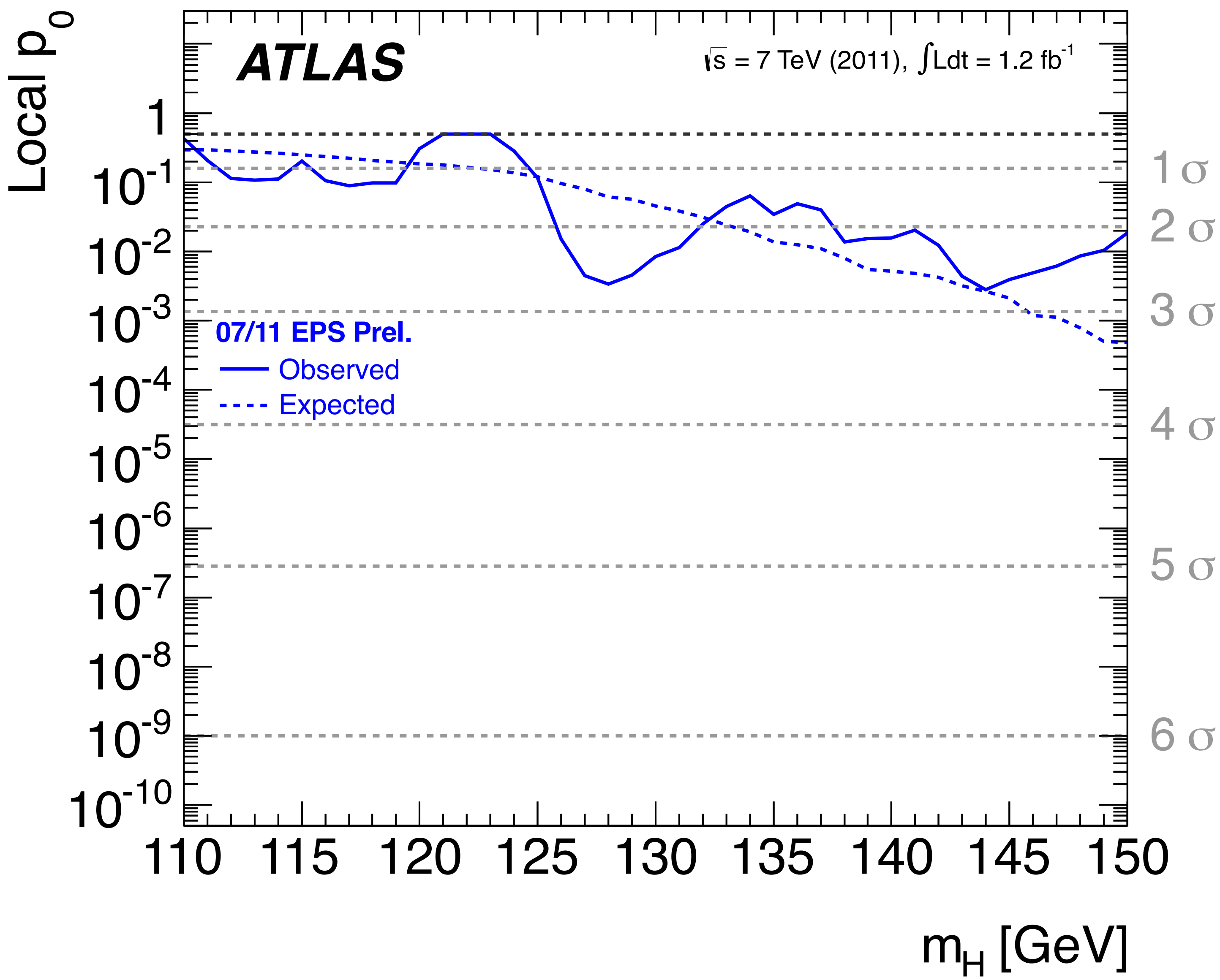


Side note: Higgs boson couples to mass but most promising production modes involve massless gluons...

Chronology of a discovery



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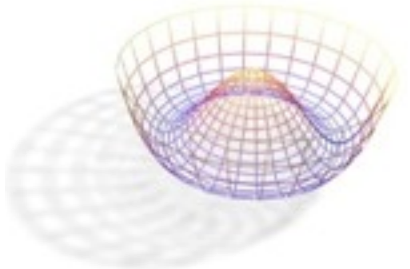

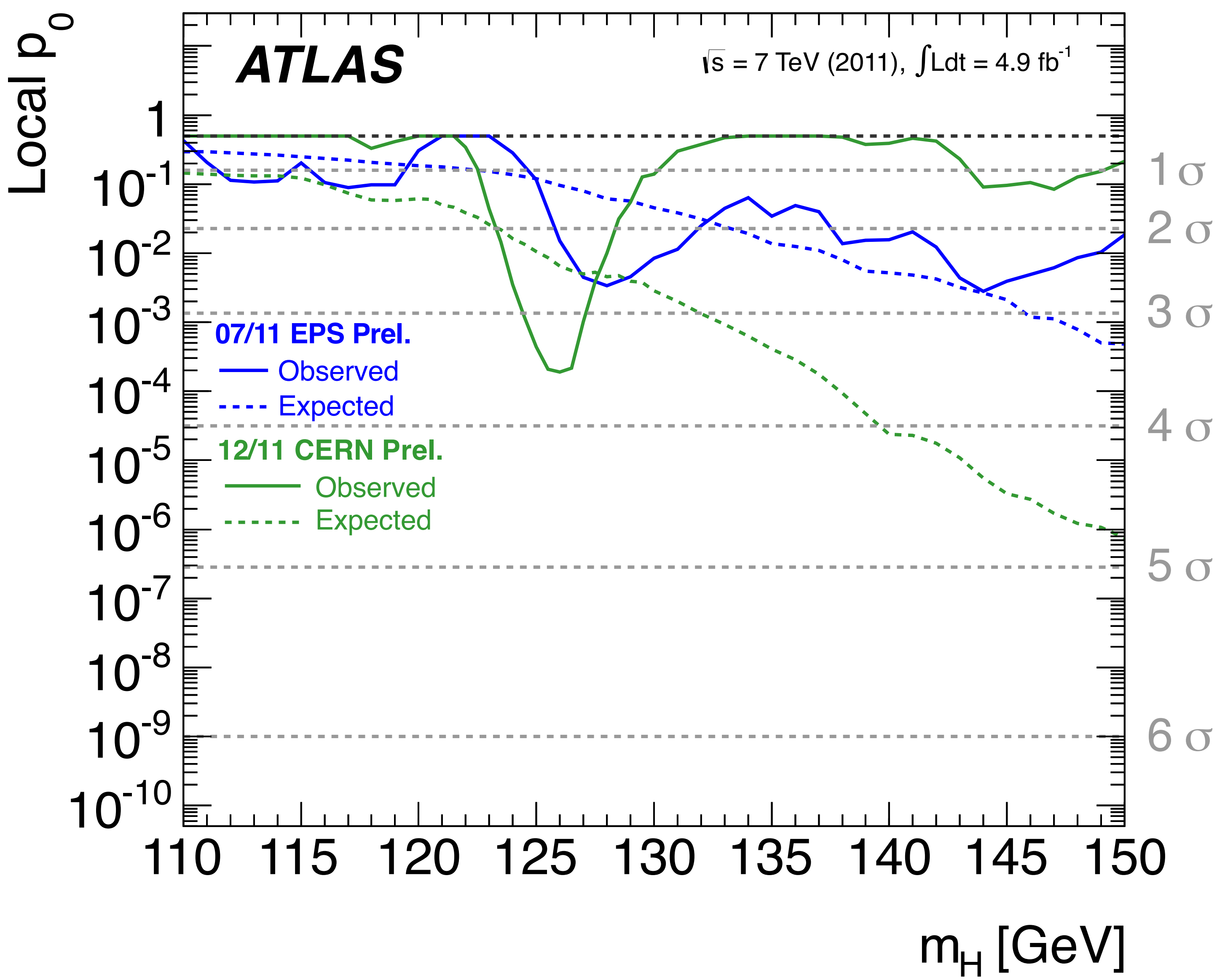

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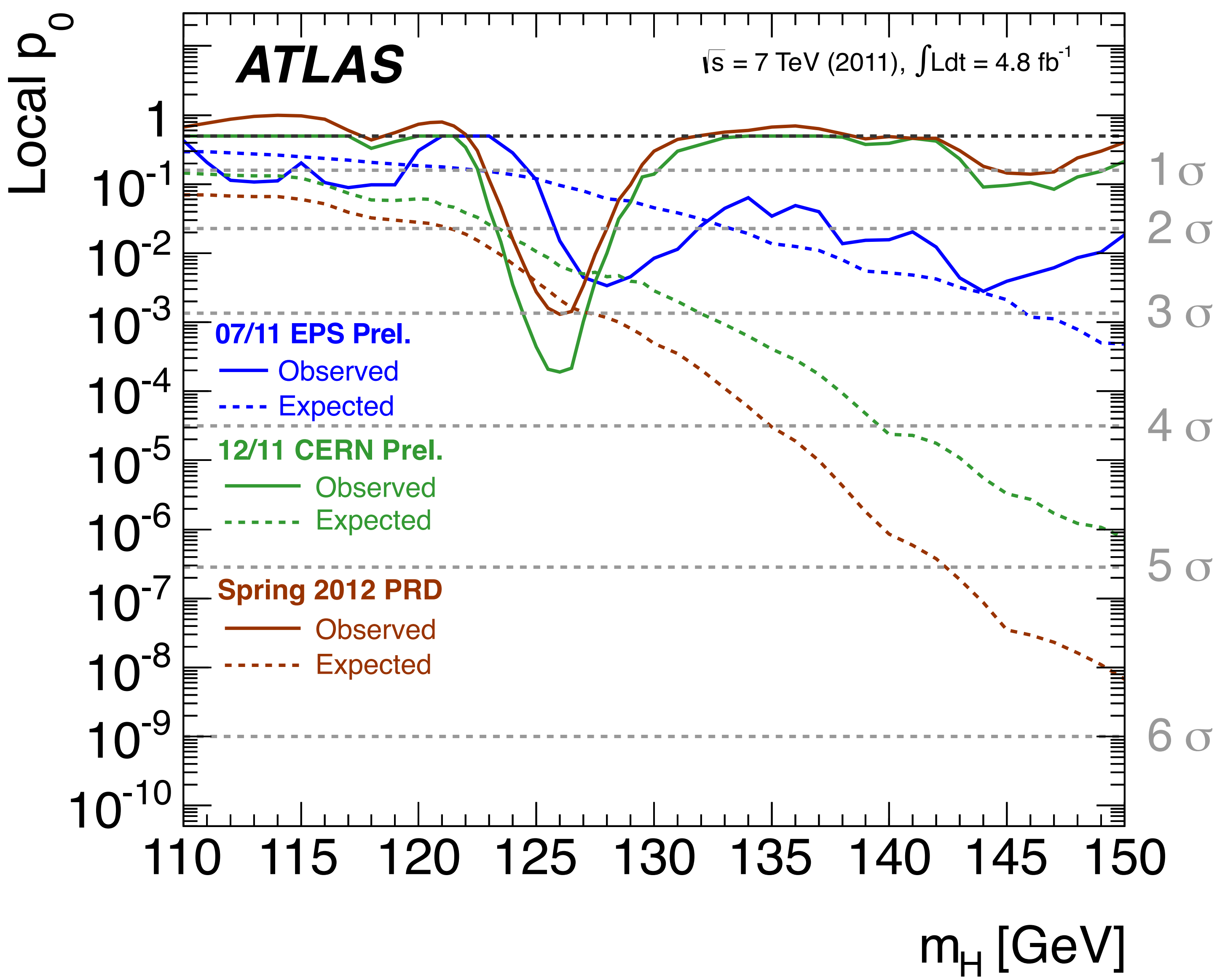

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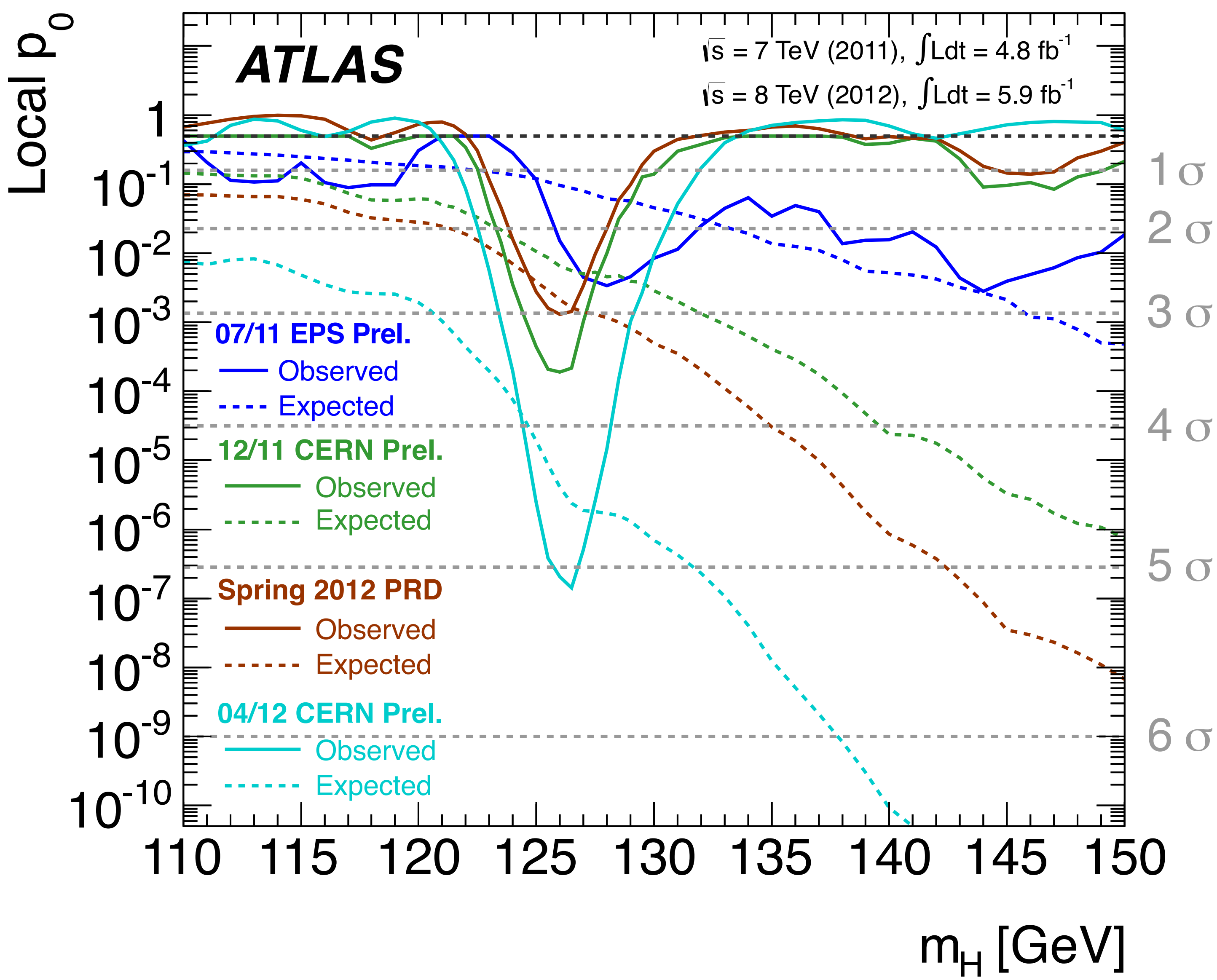

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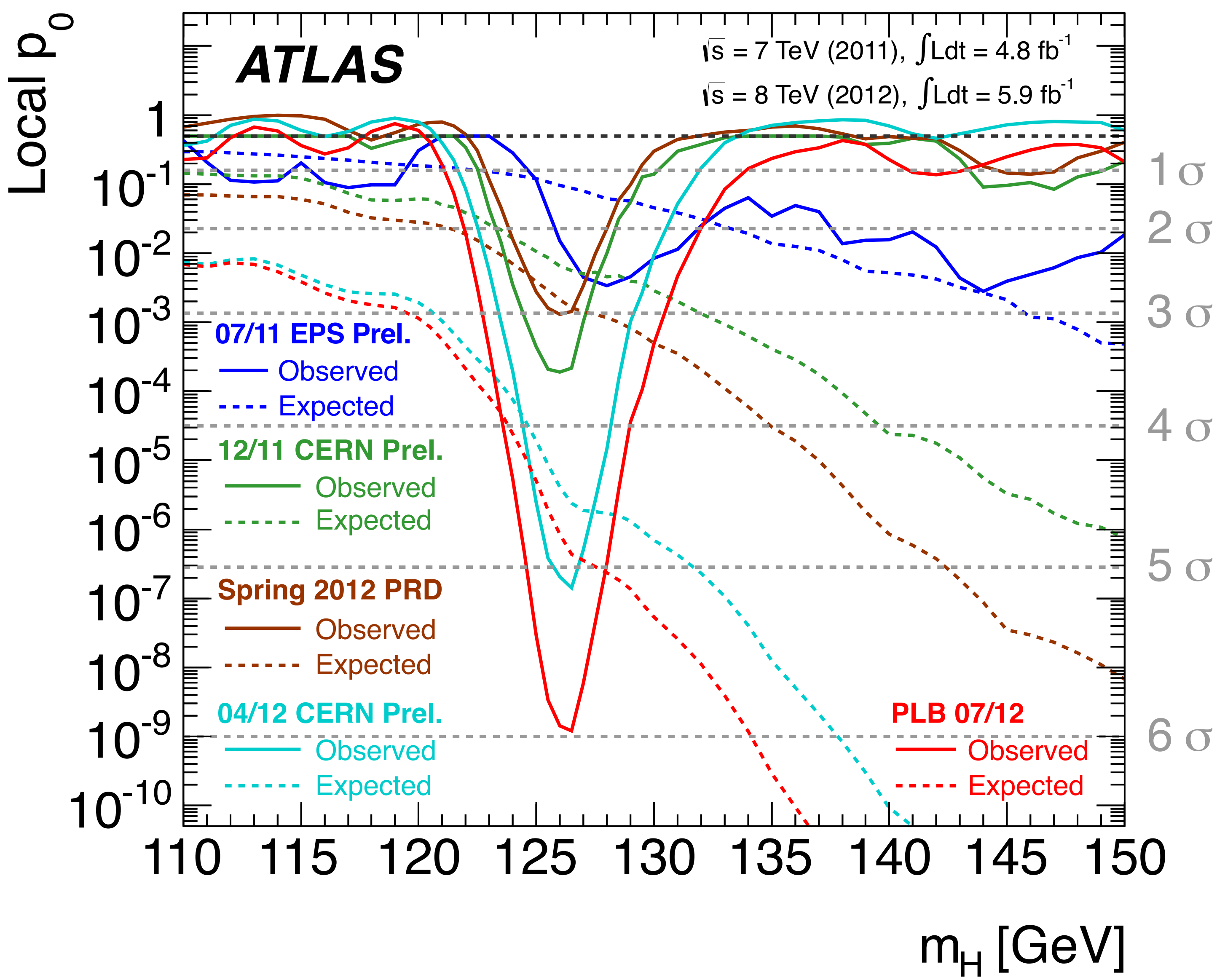

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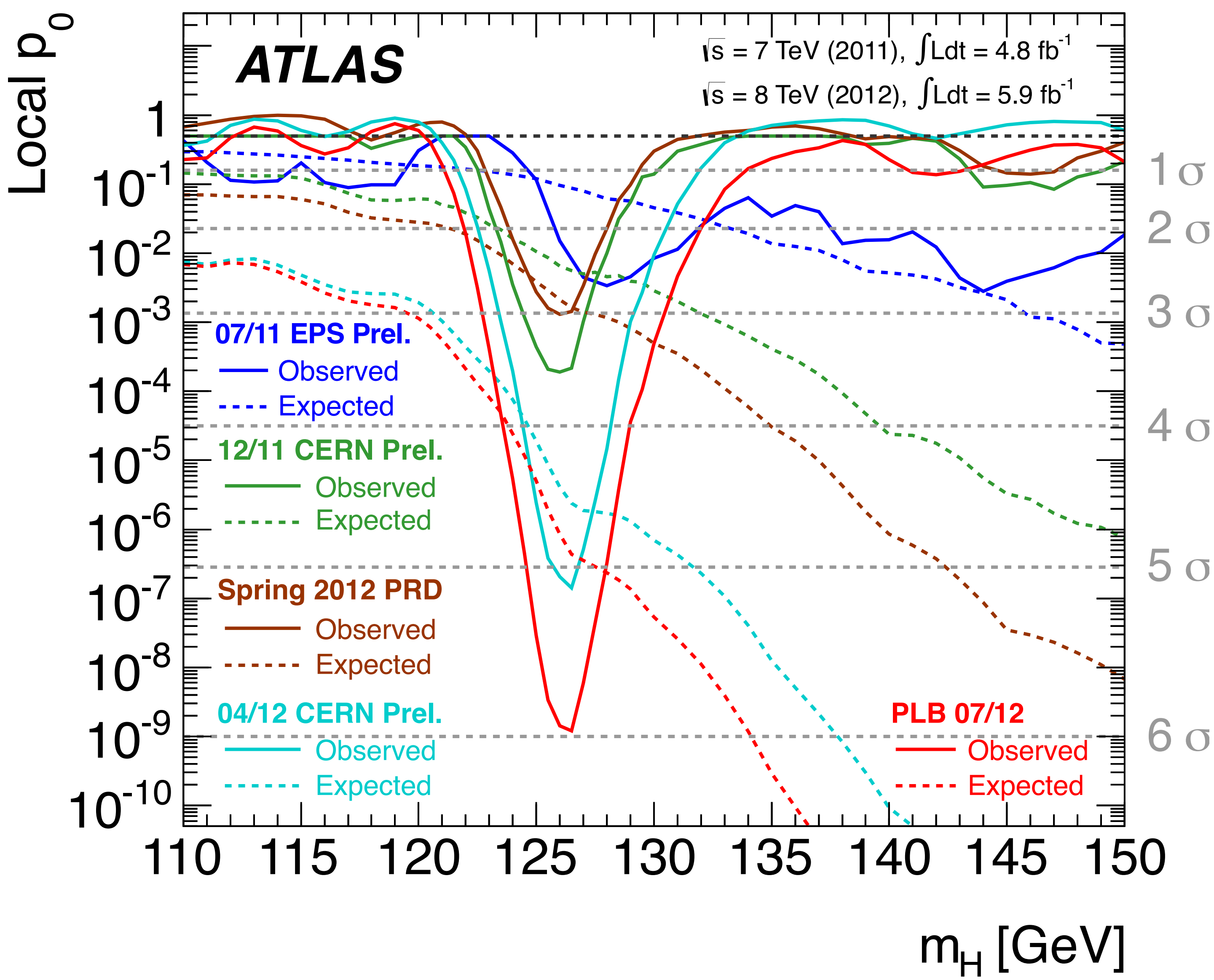

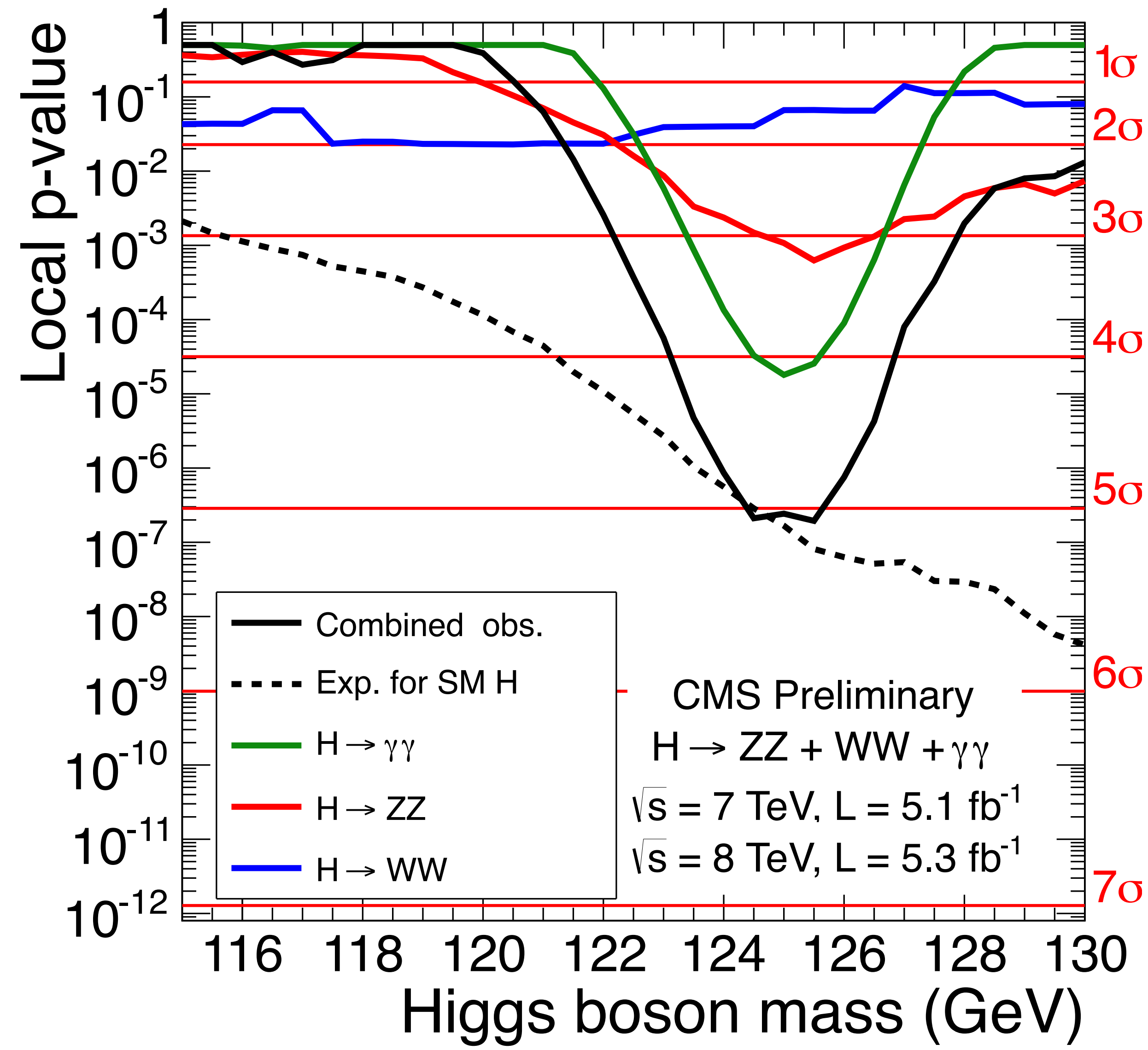

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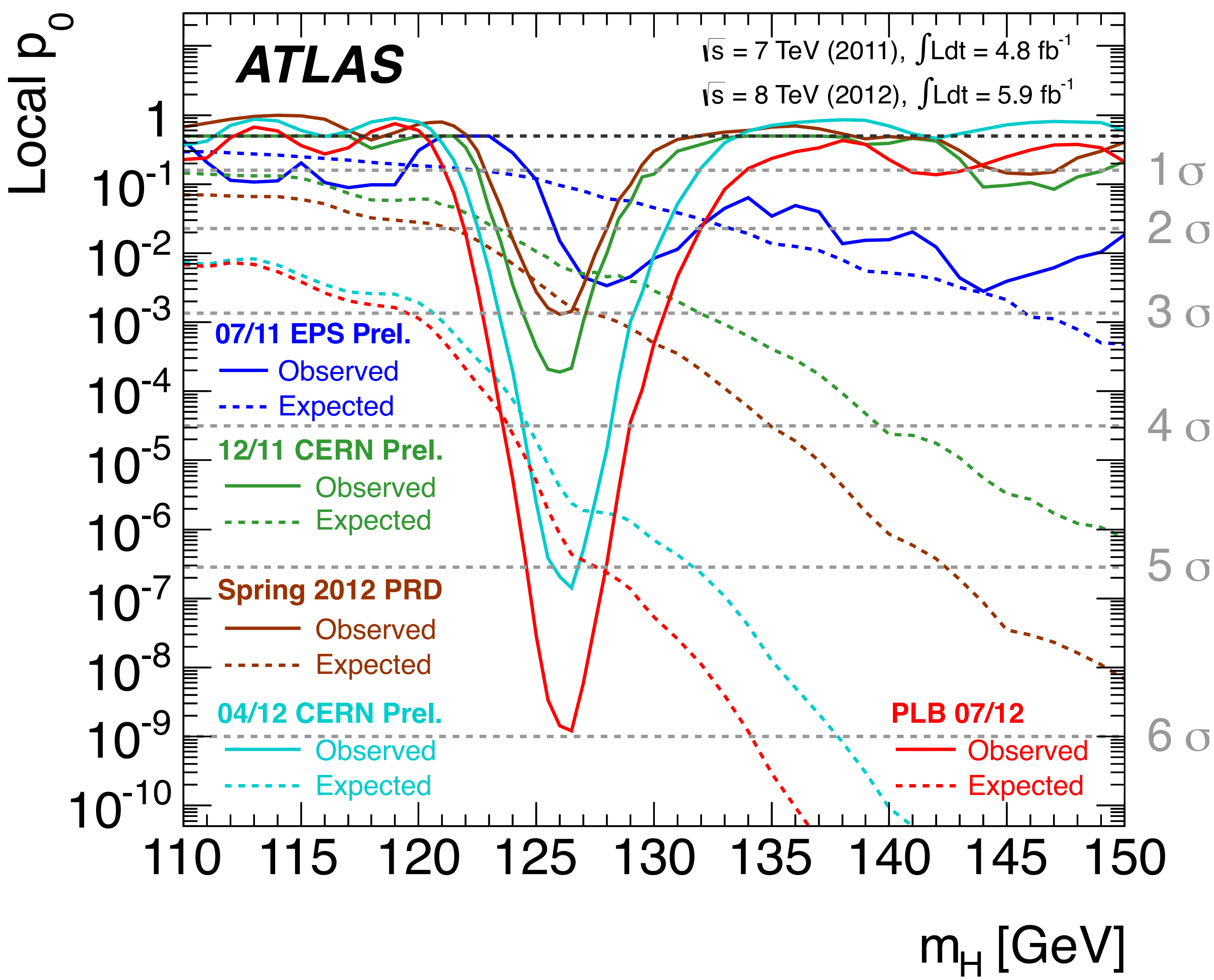
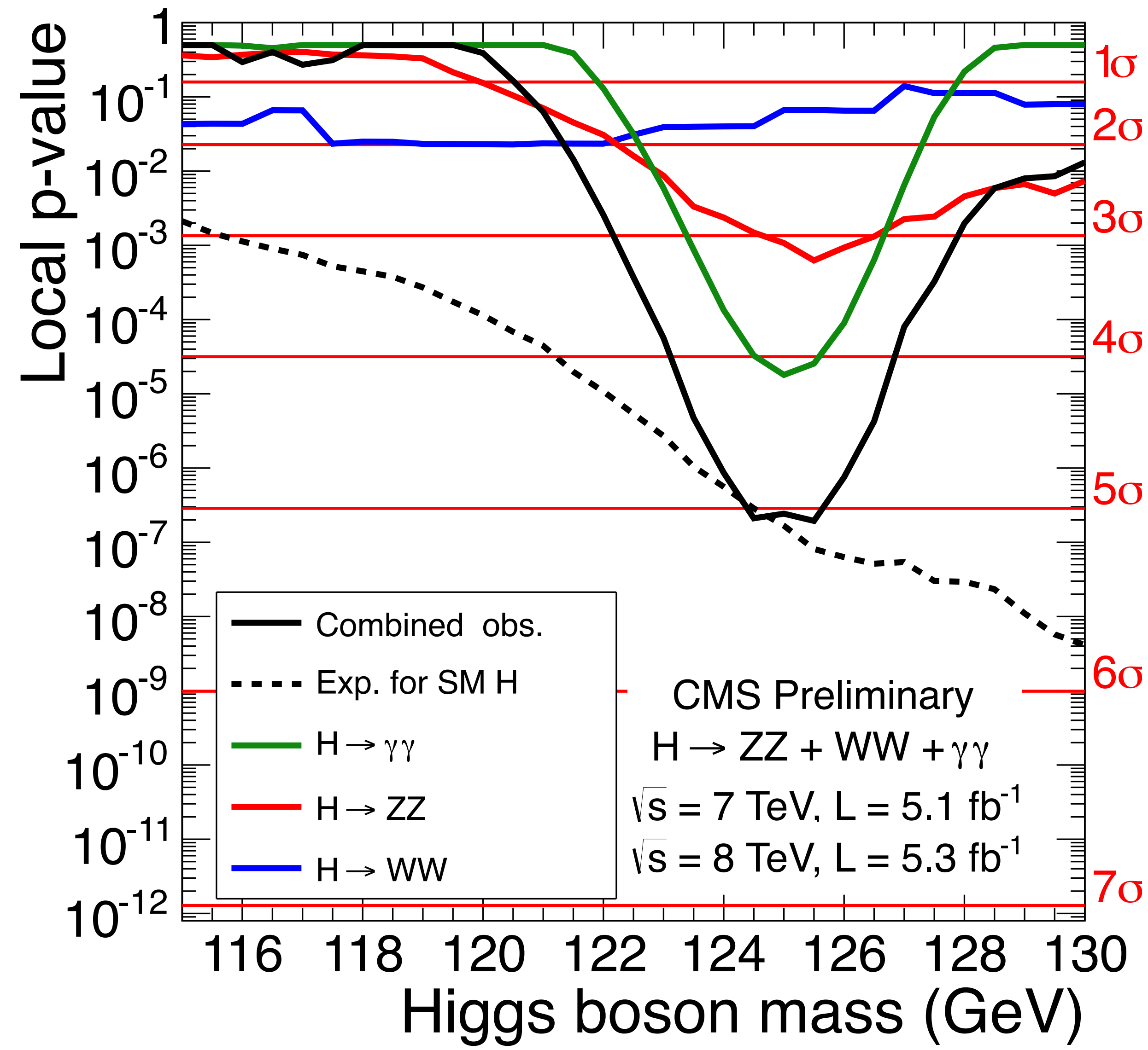




... and corroborated (scooped?) by (less conclusive) Tevatron results

We aren’t done yet!

What did we discover?

Discovered a new particle with $M_H \approx 126$ GeV

- boson: decay to ZZ, WW, $\gamma\gamma$
- spin $\neq$ 1: Landau-Yang theorem would forbid decay to $\gamma\gamma$
  - even if there could be a conspiracy: > 1 new particle

But we have only just scratched the surface! Questions to be addressed:

- does it have the expected quantum numbers $J^{PC} = 0^{++}$?
- is it a fundamental or a composite particle?
- is it alone or part of a more extended Higgs sector?

Solid answer to the above requires continued searches for BSM physics

- but studying the Higgs will help

Are we done with electroweak physics?

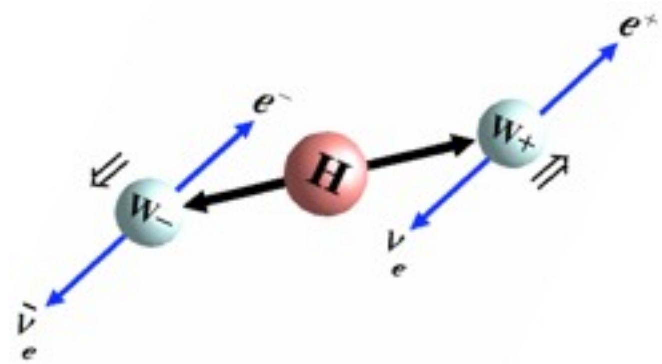
- in the presence of dark matter with a likely particle nature: no!

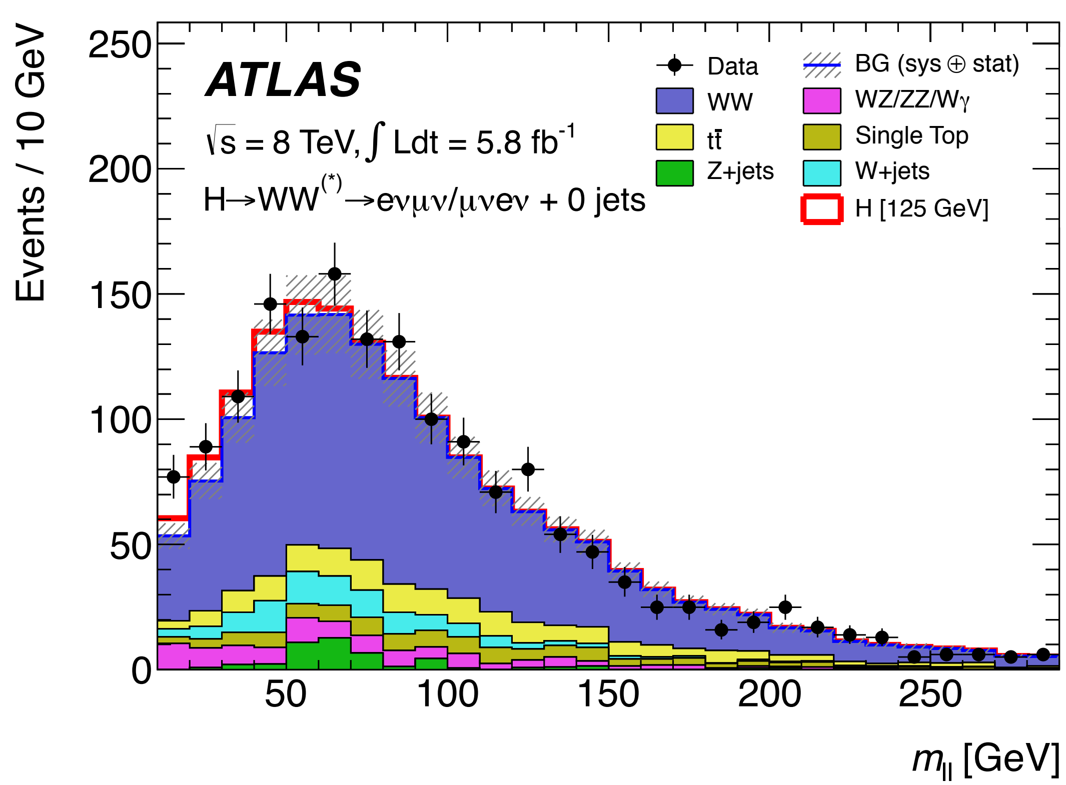
Quantum numbers

Most sensitivity to different J^{CP} in case of (parity-violating) decays of Higgs decay products: H → WW, ZZ

- ongoing efforts, but $J^{CP} = 0^{++}$ assumption used in event selections

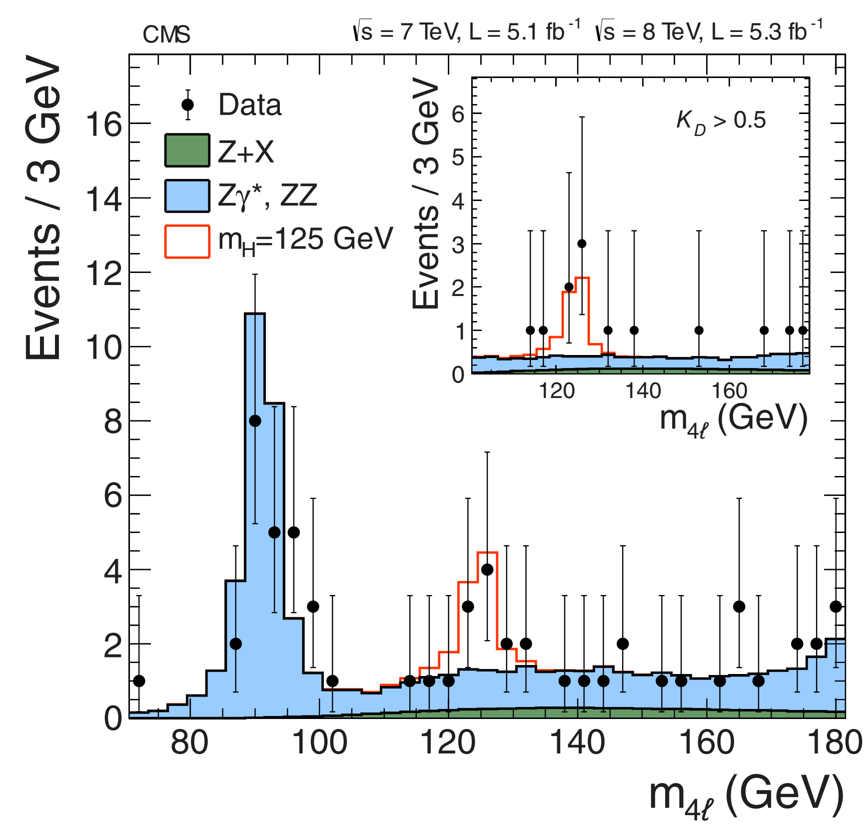
ATLAS H→WW





CMS H→ZZ

Cut on matrix element discriminant using decay angular variables

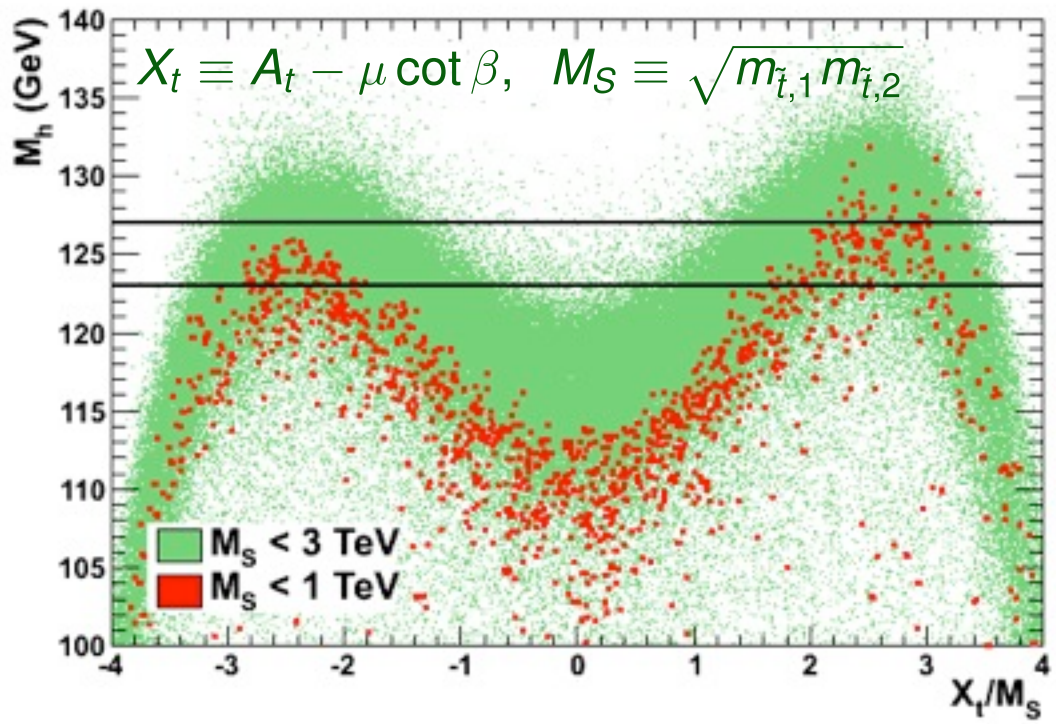


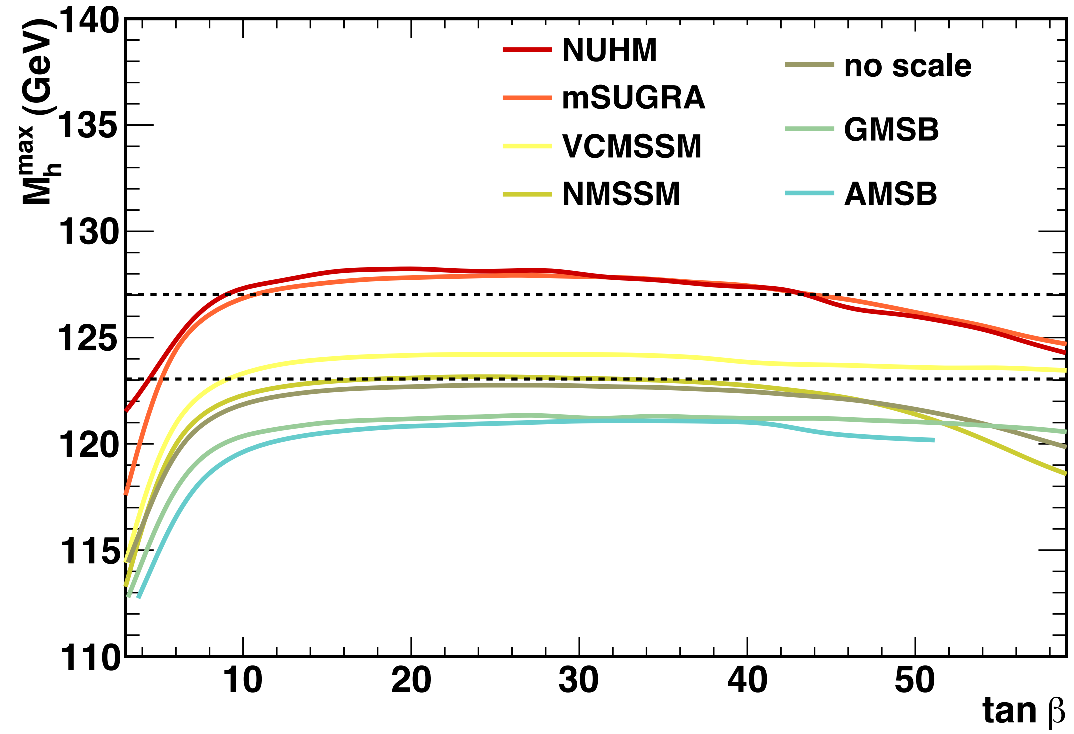
Mass

In the MSSM, $M_h \approx M_Z |\cos 2\beta|$ + radiative corrections

- significant dependence on SUSY breaking scenario

Arbey et al. ('12)





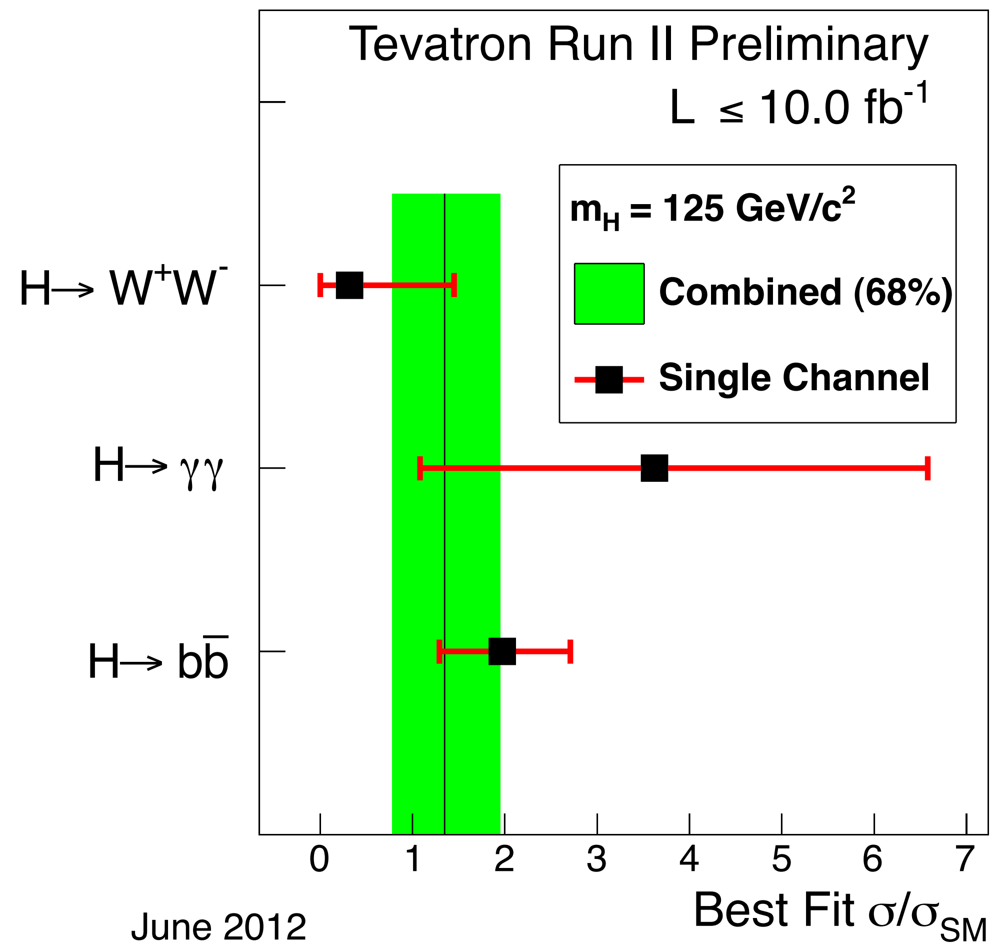
- rule out multiple SUSY breaking mechanisms, more exotic scenarios being considered
  - e.g. split SUSY: heavy scalars, m(fermions) ~ M_Z; heavy SUSY

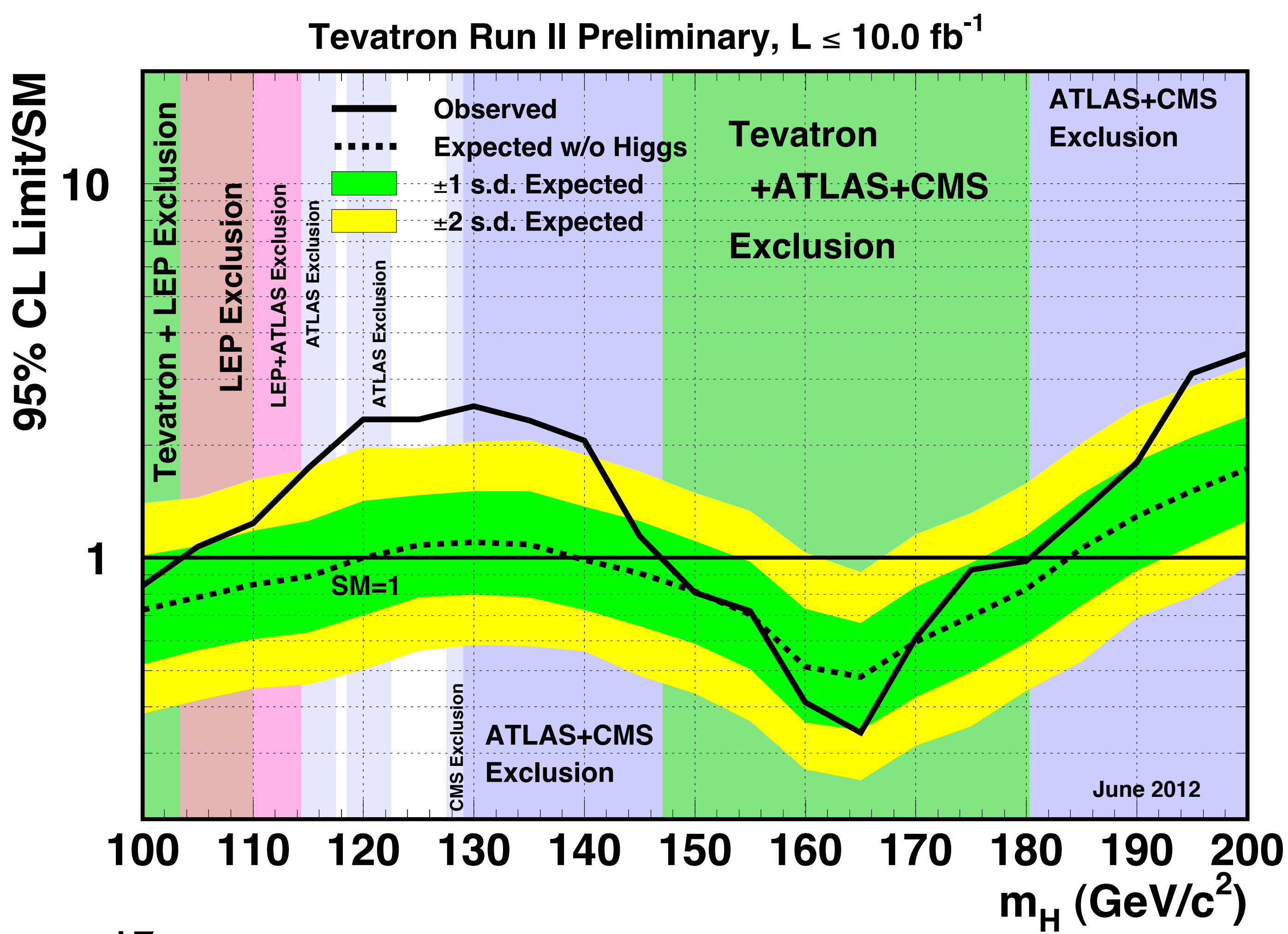
The mass relations change when going beyond the MSSM...

Coupling strengths

Information available thus far from Higgs boson searches:

- inclusive signal strengths for H → bb, H → WW, H → γγ: LHC, Tevatron





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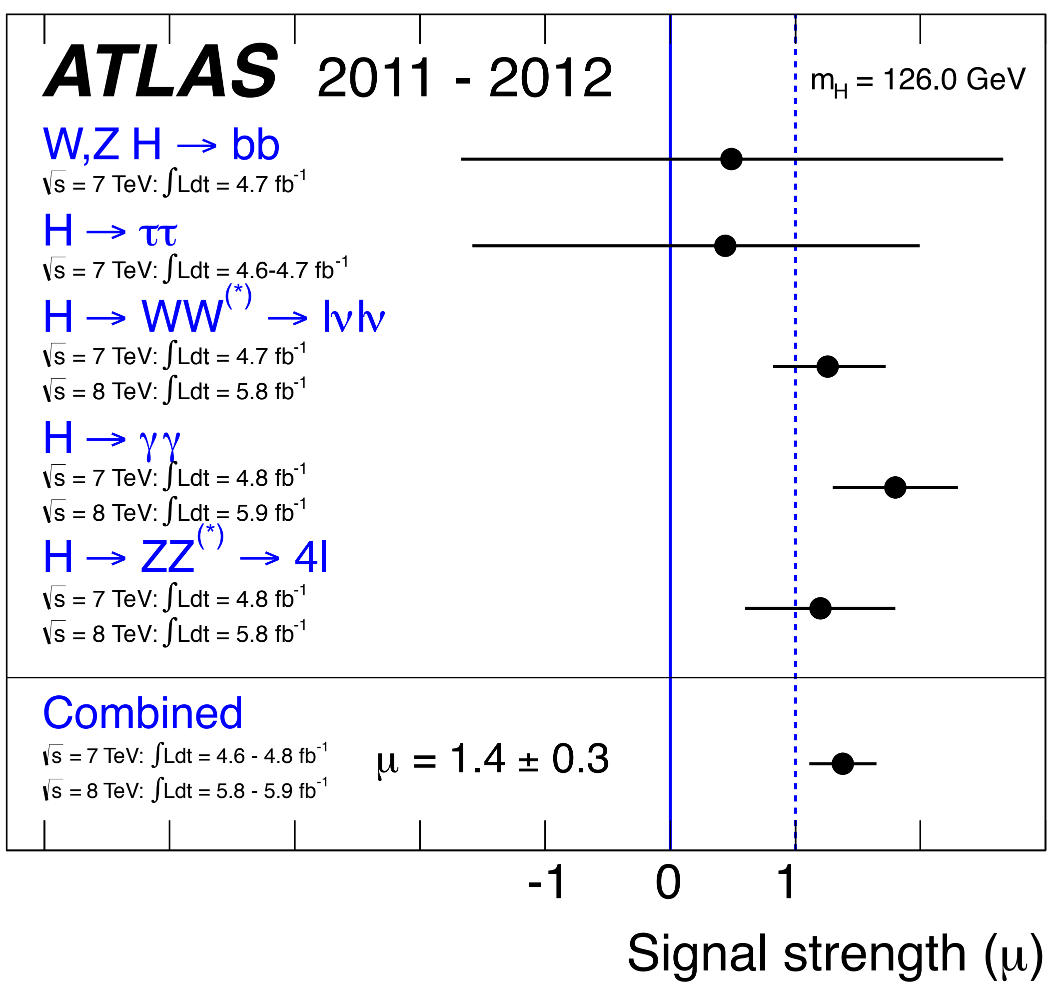
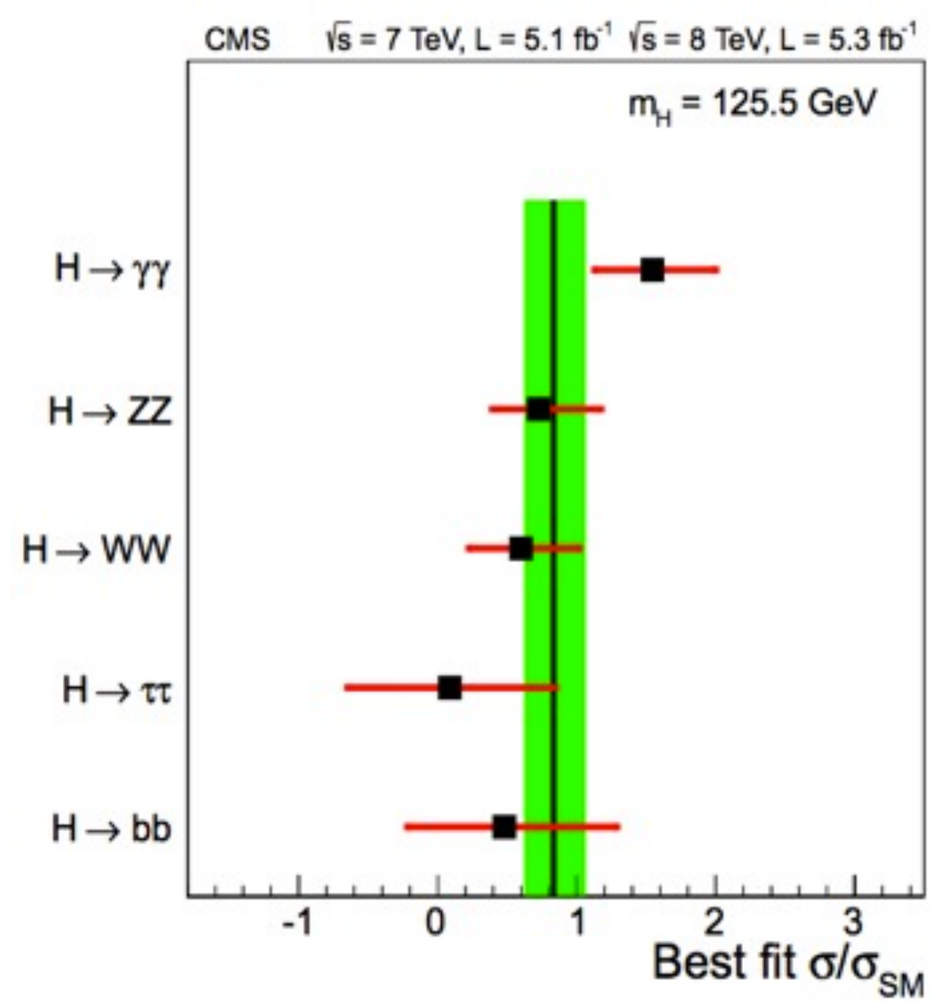
- $H \to ZZ$, $H \to \tau\tau$ inclusive signal strength: ATLAS, CMS





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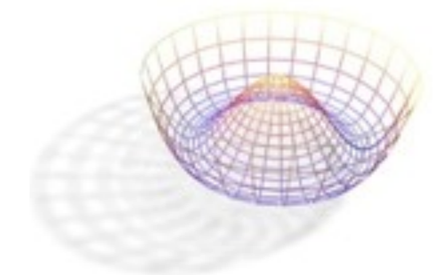

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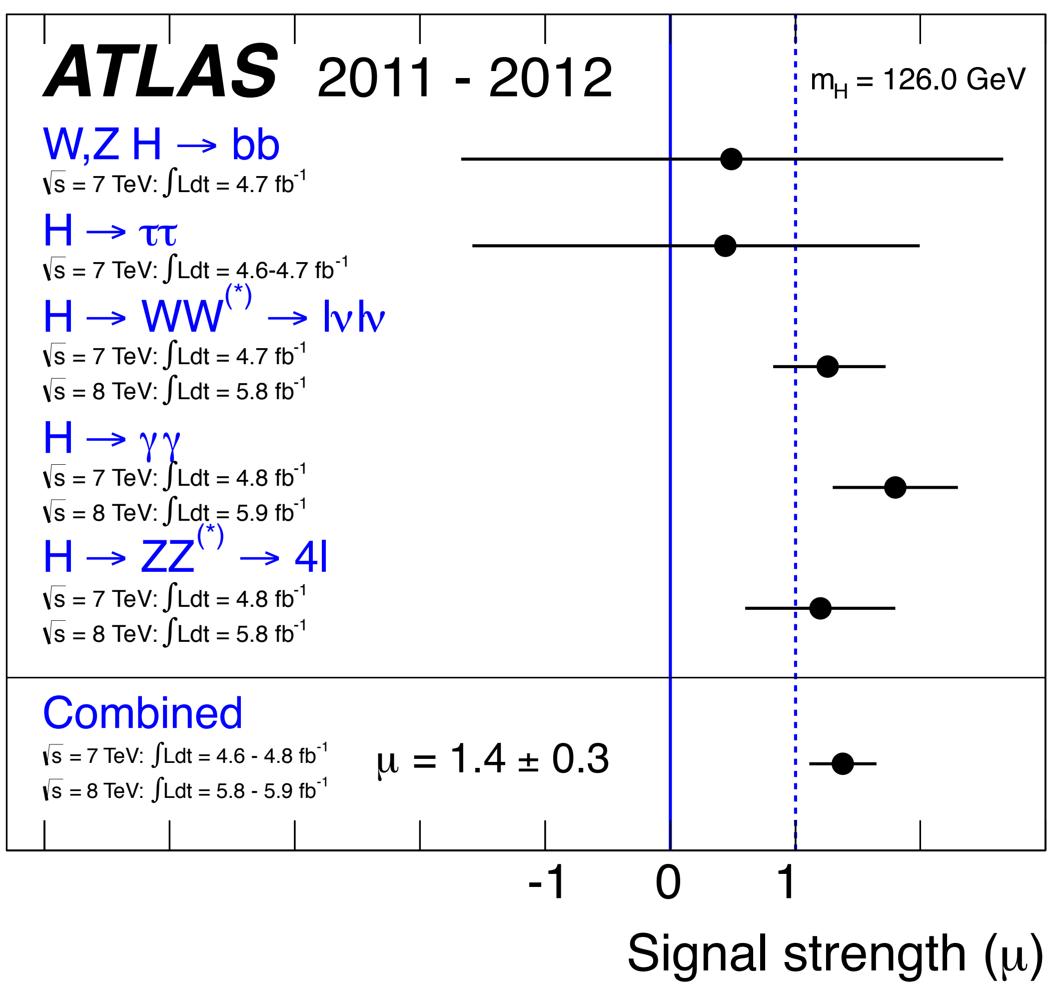
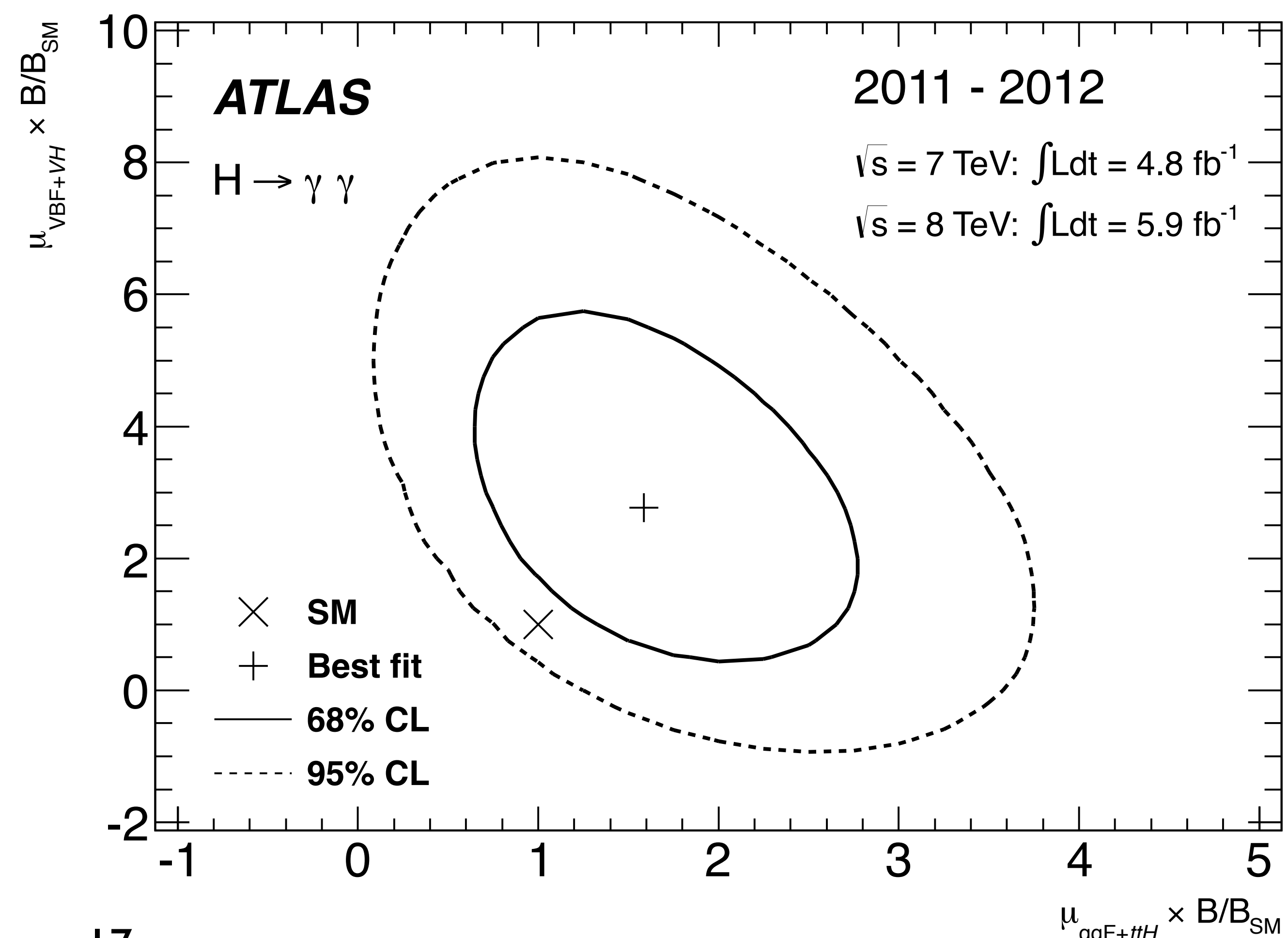
- $H \to ZZ$, $H \to \tau\tau$ inclusive signal strength: ATLAS, CMS
- VBF+VH exclusive signal strength measurement: ATLAS
  - VBF, VH both rely on VVH couplings

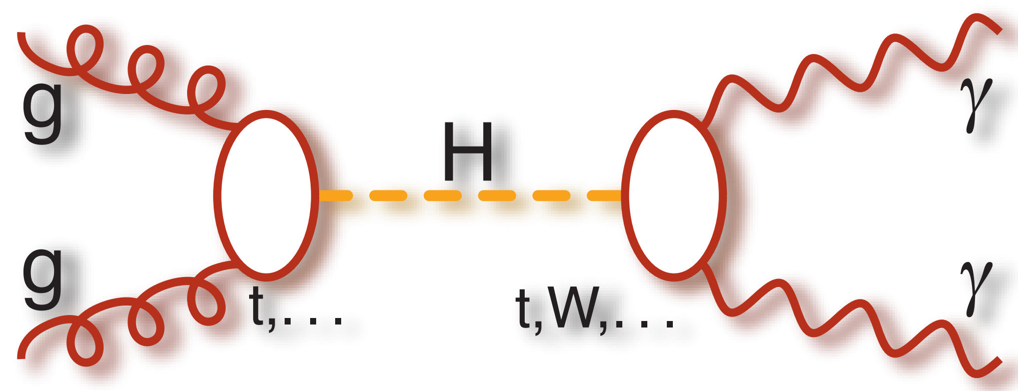




$H \to \gamma\gamma$ and implications for models

A lot of attention for somewhat large strength parameter observed in the $H \to \gamma\gamma$ channel

- loops in both production and decay
  ➠ sensitive to new physics!
  - MSSM, general 2HDM, ...



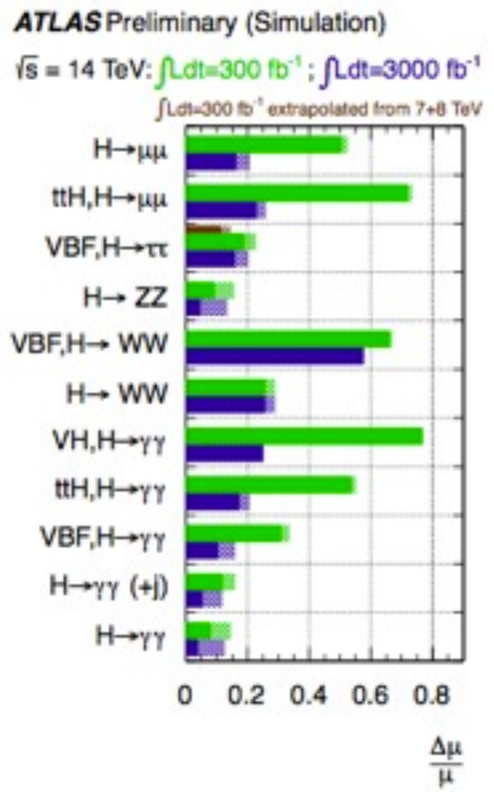
Assuming this persists: need to find out whether the deviation from SM predictions is in production or decay (or both!)

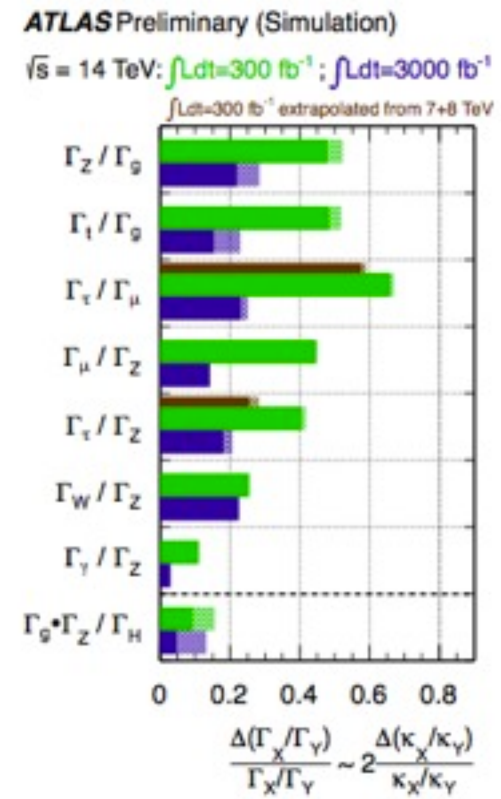
- general: starting to focus more on measurement of exclusive production processes (gluon fusion, VBF, WH, ZH, ttH) in addition to decay modes
- will help test various aspects:
  - custodial symmetry (couplings to W ↔ Z)
  - couplings to up-type (t) versus down-type (b) quarks
  - ...

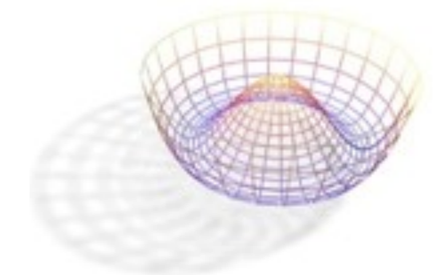
Prospects

Existing analyses will continue! Projections made for LHC high-luminosity phase

- even under extreme LHC pile-up conditions (μ ~ 140), expect continued improvements
- but measurements at a linear collider will be far better
  - determining couplings to ~10% relative accuracy will allow incisive tests of models







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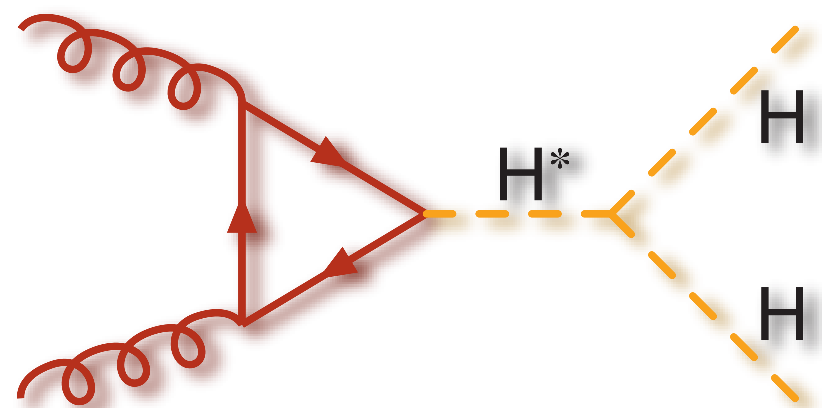

Higgs self-coupling:

- very difficult topic for the LHC
- (simple) studies: may achieve ~ 3σ signal in HH $\rightarrow b b \gamma\gamma$
  - not sufficient by itself: also other diagrams contribute
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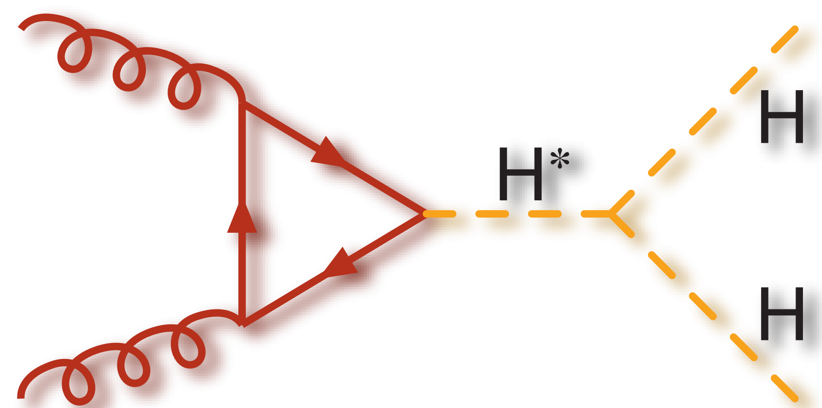

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Don’t hold your breath...

Conclusion & outlook

The LHC and its experiments have been a big success, with the most important discovery in ~ 30 years

The search (for new physics) must go on!

But unless / until we find direct evidence for BSM physics, the Higgs boson is our best portal to new physics

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- determining better its properties will allow us to learn (yet) more

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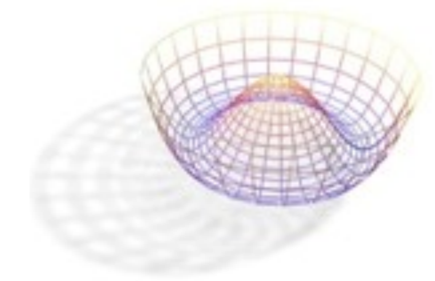

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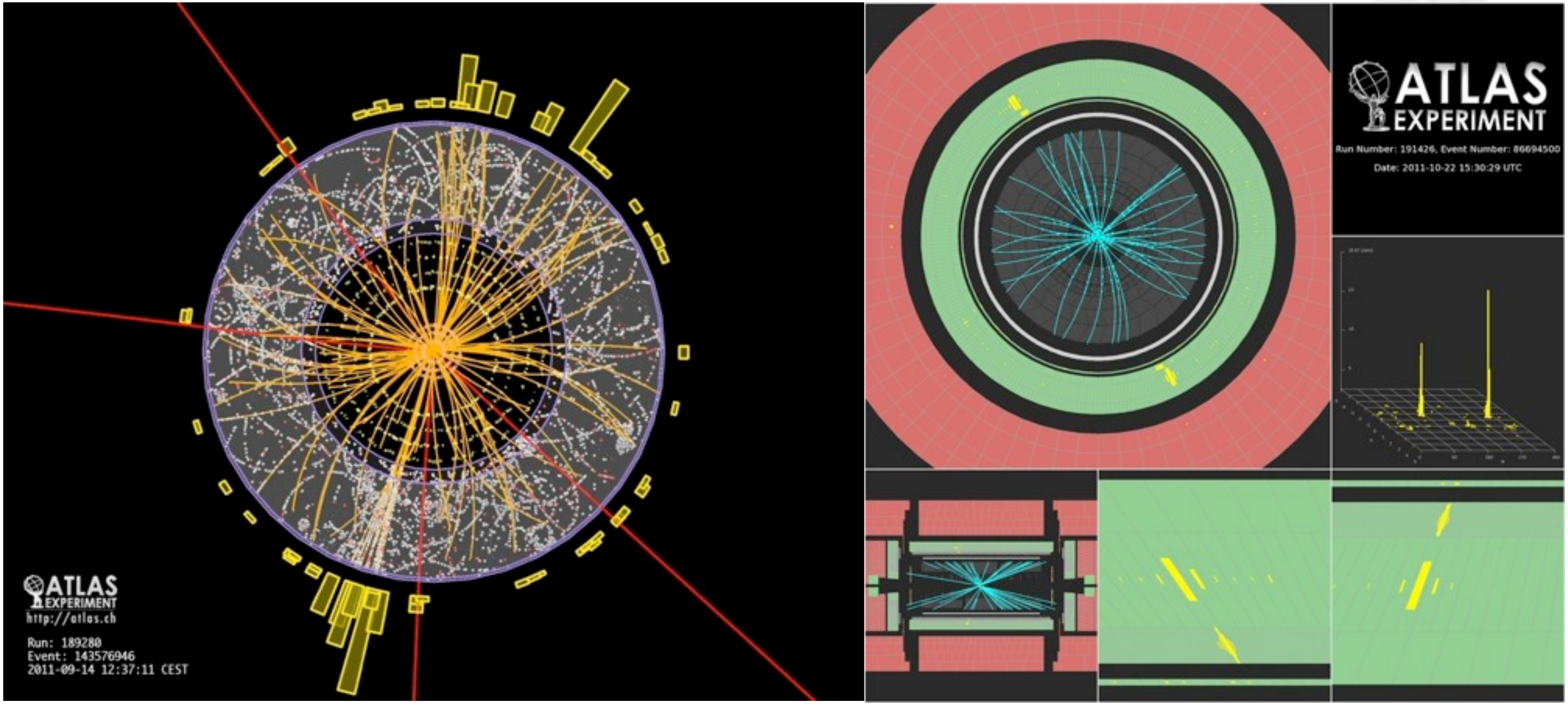
The Higgs portal era is starting!

Thank you!



ATLAS $H \rightarrow ZZ^{*} \rightarrow \mu^{+}\mu^{-}\mu^{+}\mu^{-}$ and $H \rightarrow \gamma\gamma$ candidates

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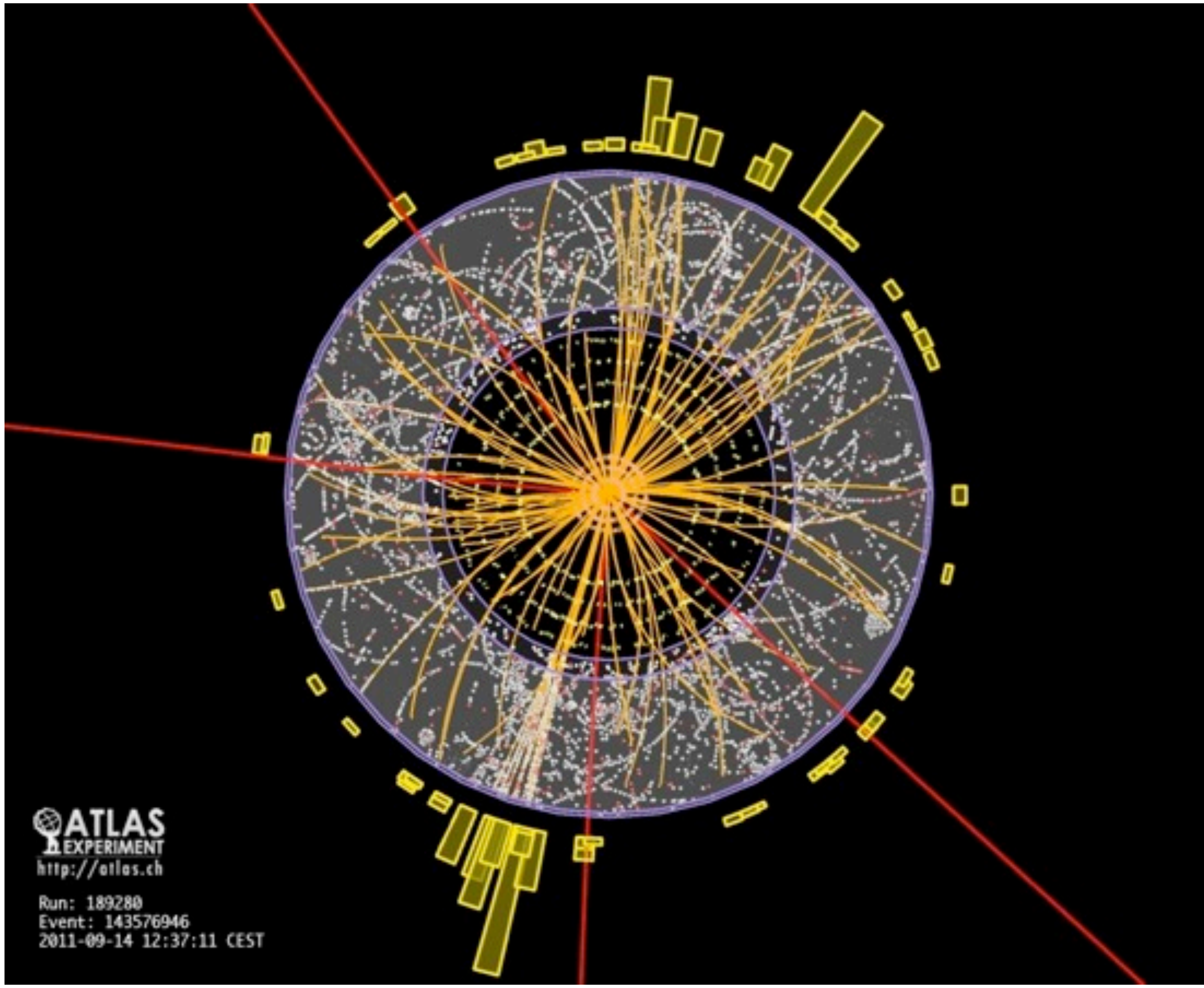

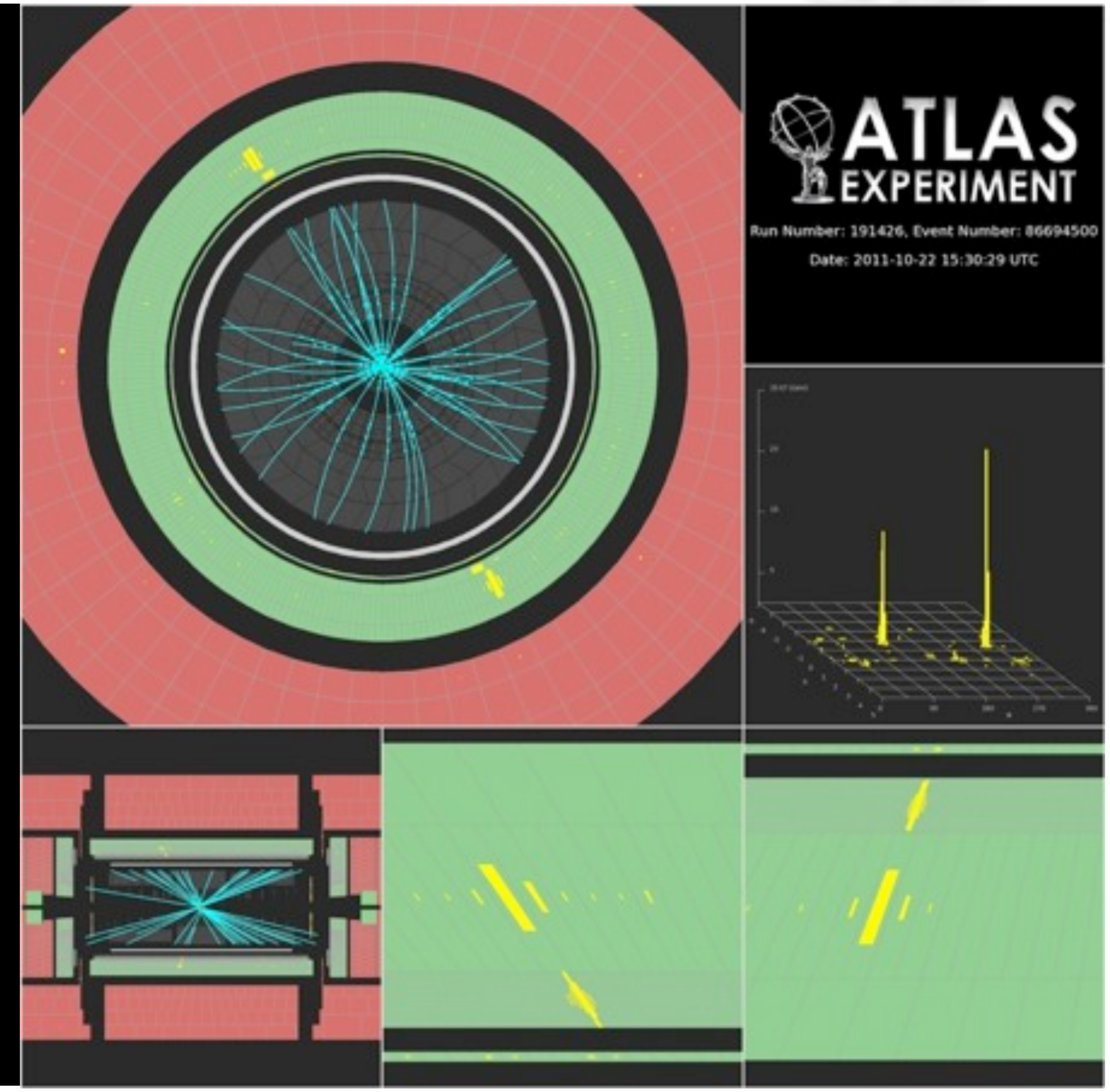

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