# FYST17 Lecture 10
# The Higgs discovery

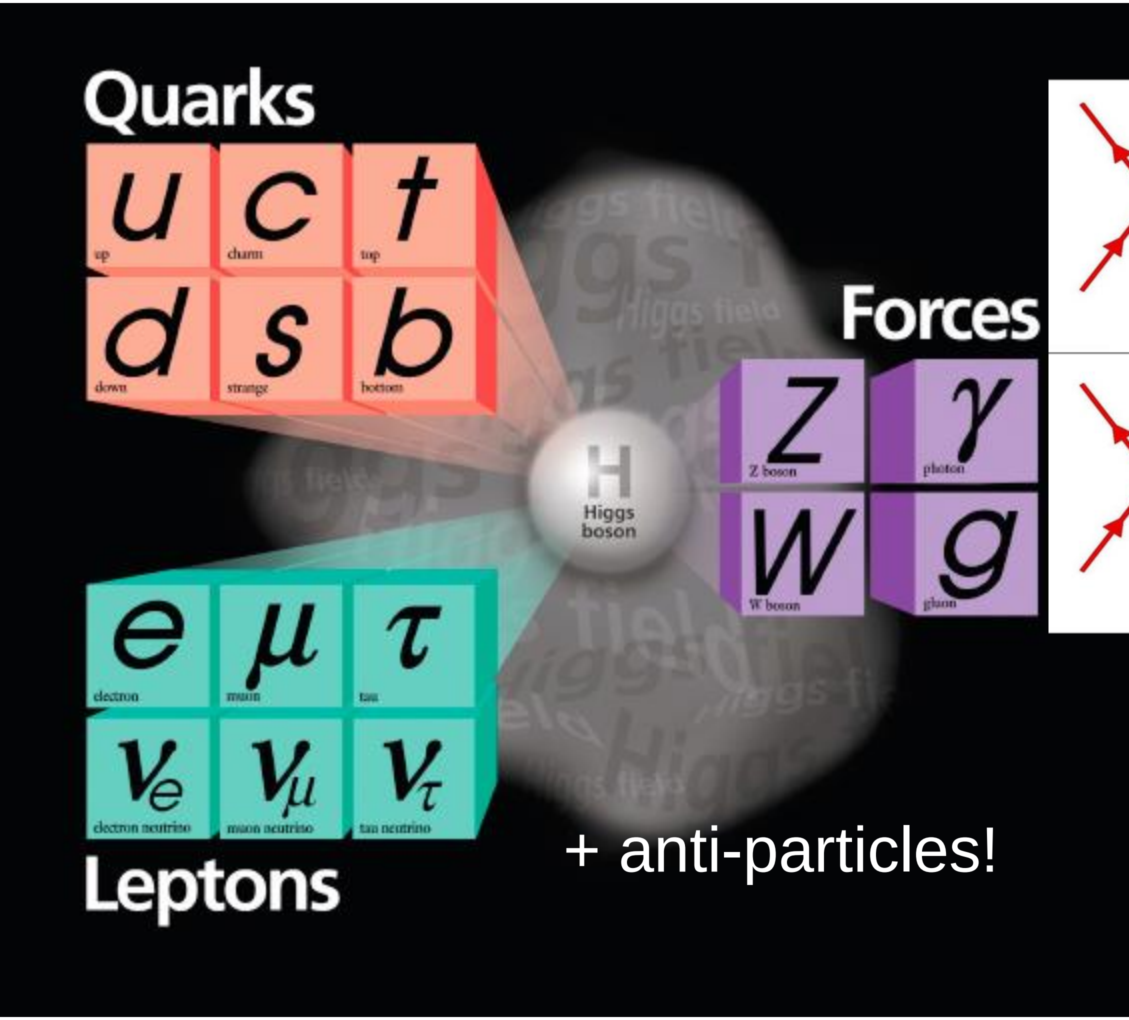
Thanks to A. Hoecker, F. Gianotti, J. Incandela

Suggested reading: chapter 12 in G. Barr et al.

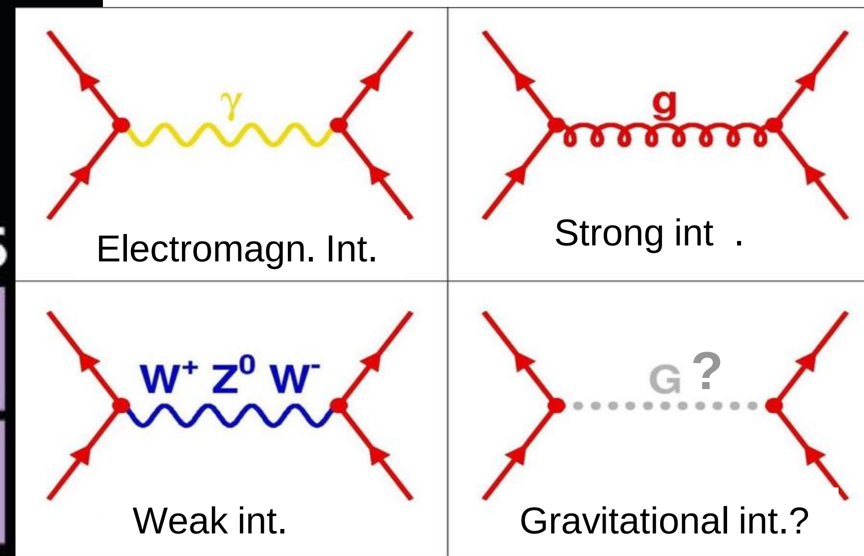
# Outline

- The Higgs boson and the Standard Model
- Production and decay modes at the LHC
- Elements in the analysis
- The 2012 ”discovery”
- Latest status

# The Standard Model in one slide



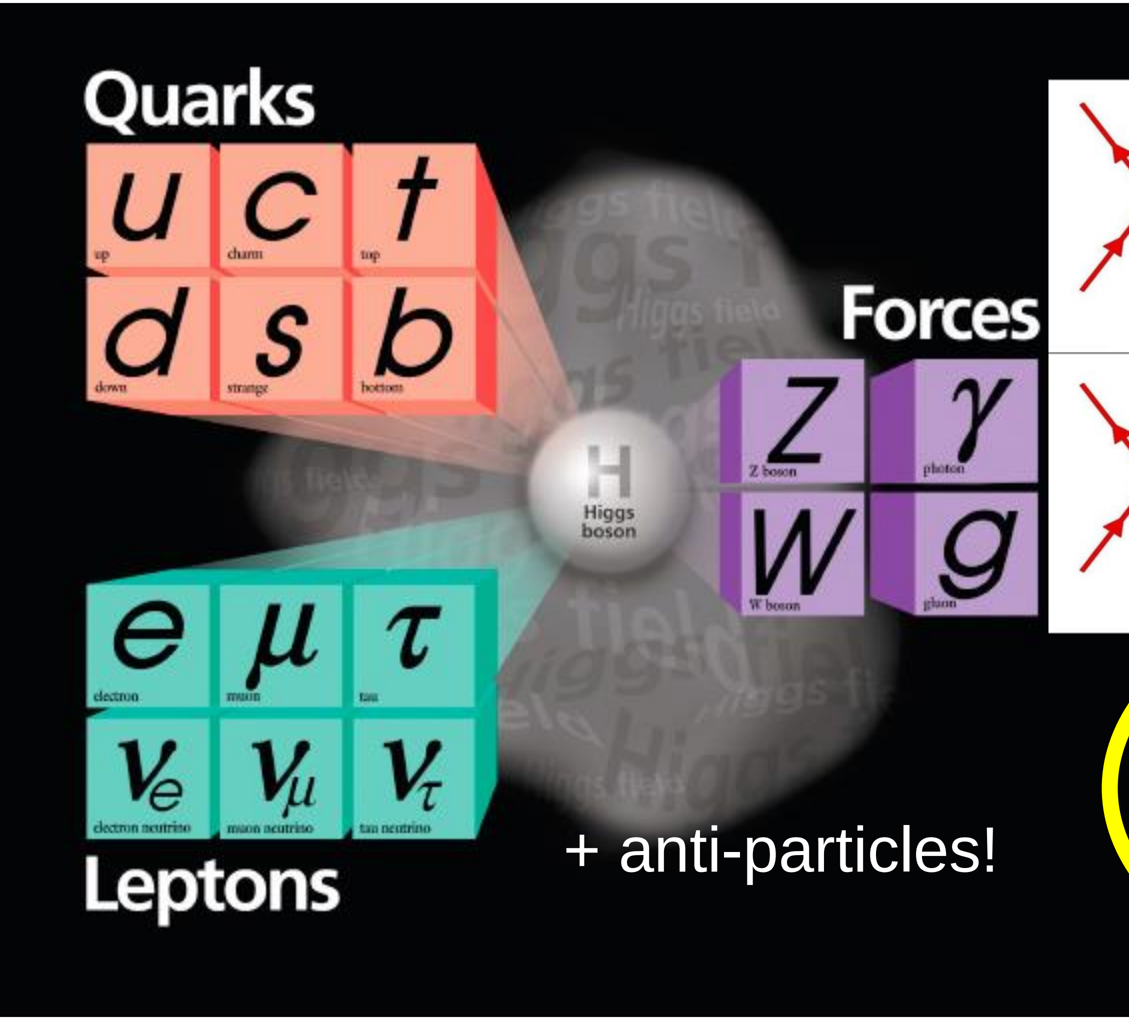

+ anti-particles!

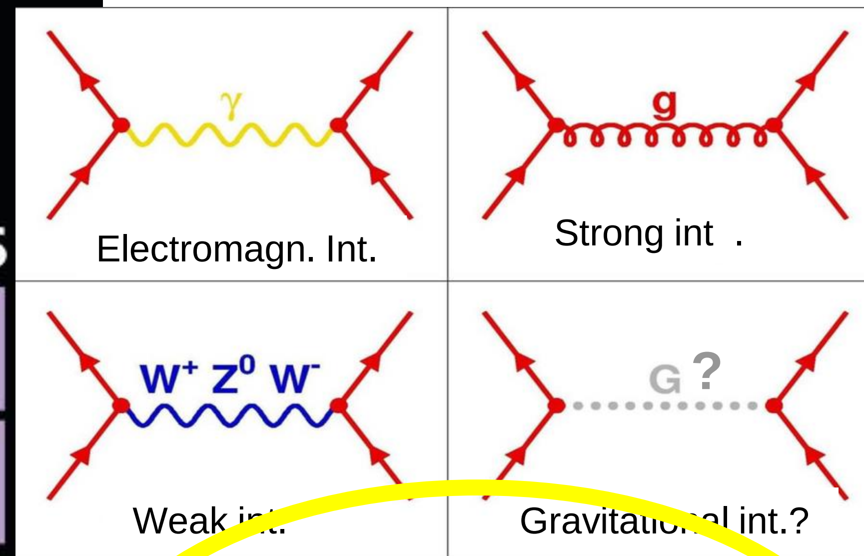



The **Higgs boson** gives mass to the other particles

2. and 3. generation unstable
Decay via weak interaction

# The Standard Model in one slide




The **Higgs boson** gives mass to the other particles

2. and 3. generation unstable
Decay via weak interaction

4

# The Standard Model

**Elementary particle physics is successfully described by local gauge theories**

*A problem*: local gauge symmetry requires massless spin-1 "gauge" (=force) boson

This has been well verified for QED, with a massless photon (= infinite range)

However, the *W*, *Z* bosons are massive (= finite range ~$10^{-18}$ m)

Only way to break gauge symmetry consistently is to spontaneously break the symmetry of the vacuum:

$$M_{Z,W} \neq 0 \quad \Leftrightarrow \quad \langle 0 | \phi | 0 \rangle = \upsilon \neq 0$$ [ non-zero vacuum expectation value ]

$\phi$ is a complex doublet field with non-zero vacuum expectation value.
3 d.o.fs become $Z$, $W^{\pm}$ masses, remaining d.o.f is massive scalar Higgs boson

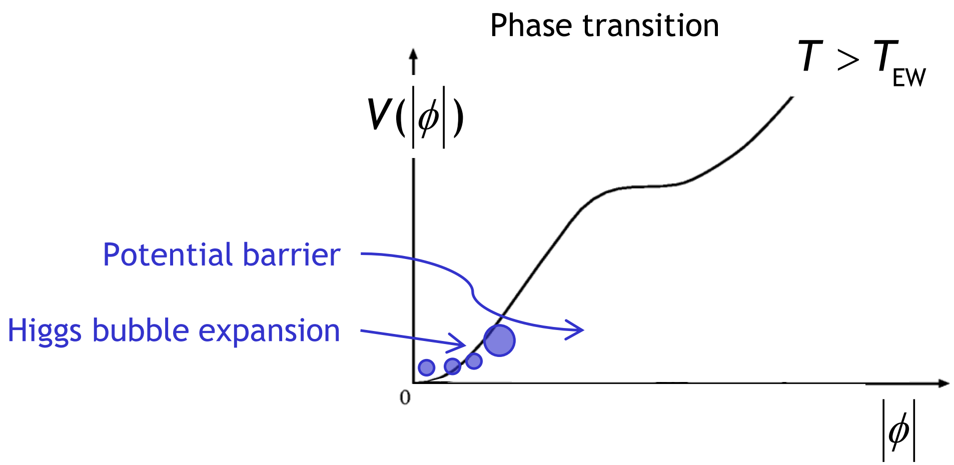
This is known as the **"Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism"**

or simply **the Higgs mechanism**

# The Standard Model

## Englert-Brout-**Higgs**-Guralnik-Hagen-Kibble **mechanism**

The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ ($10^{-10}$ s after big bang) led to $|\phi_{min}| > 0$



# The Standard Model

## Englert-Brout-**Higgs**-Guralnik-Hagen-Kibble **mechanism**

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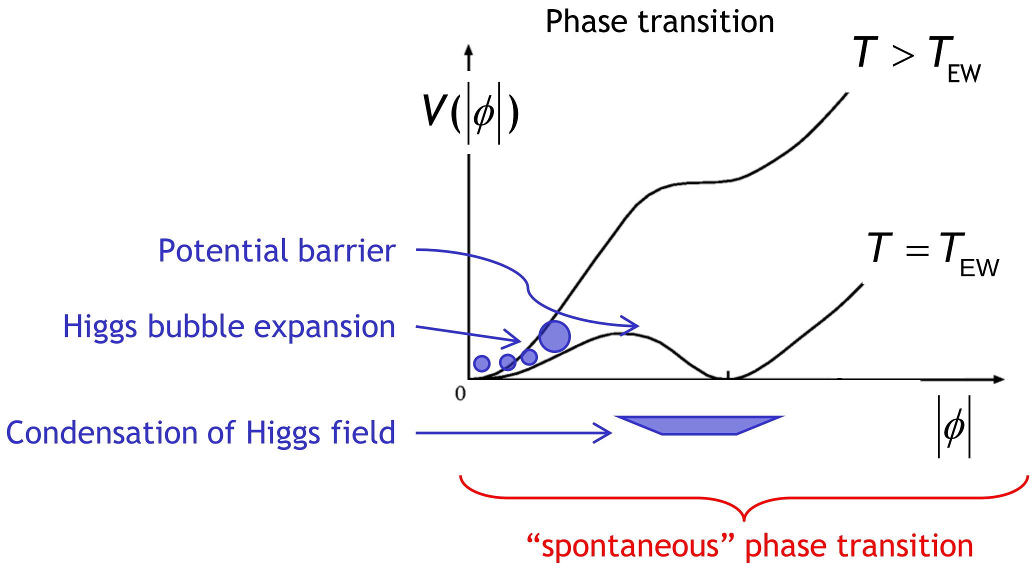



Higgs potential: $V(\phi) = \mu^2_{<0}|\phi|^2 + \lambda|\phi|^4 + Y^{ij}\psi^i_L\psi^j_R\phi$

Yukawa coupling

Simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems.

**Carries the seeds for new physics …**

# The Standard Model

**Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism**

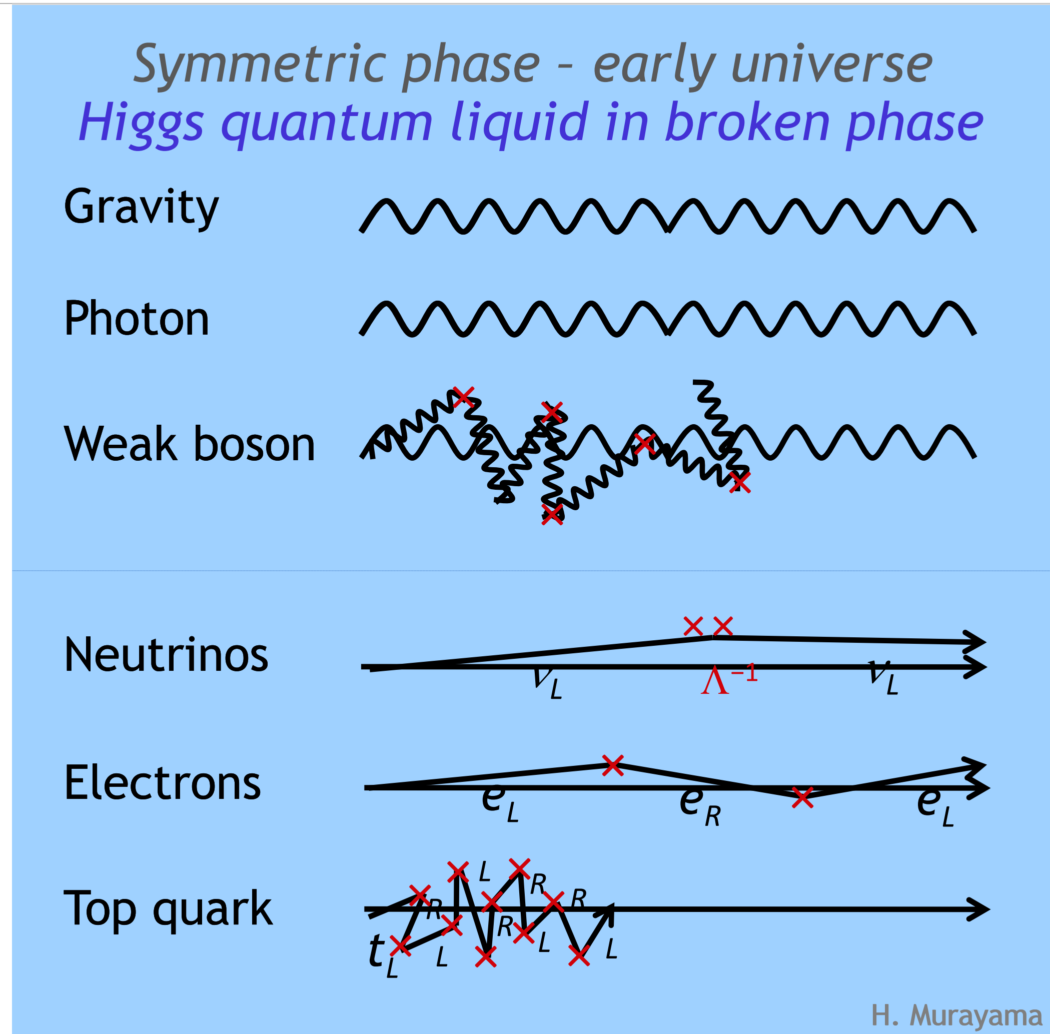
Early universe: symmetric phase, fundamental particles are massless
⇒ gauge symmetry is respected

A **Higgs field** displaces ground state breaking gauge symmetry

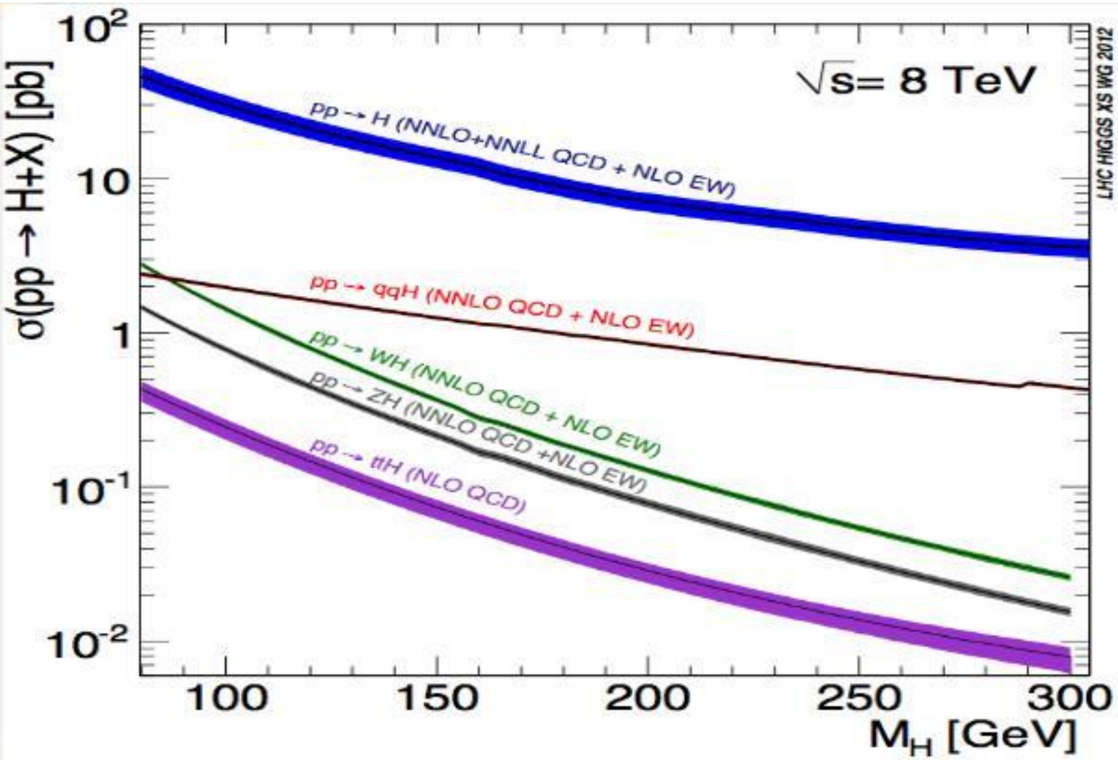
**It fills all space time** (but w/o orientation as spin=0)

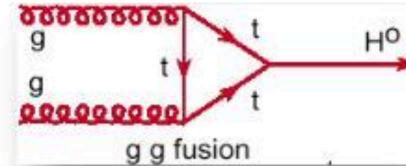
Particles interact with the Higgs field and reduce their velocity.
**They acquire a mass proportional to interaction strength**

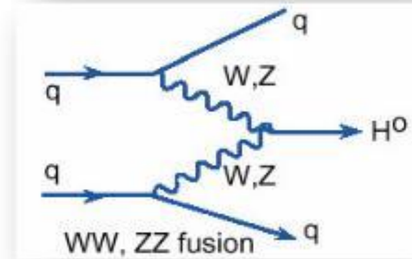
⇒ Action of the Higgs field creates a ***vacuum viscosity***

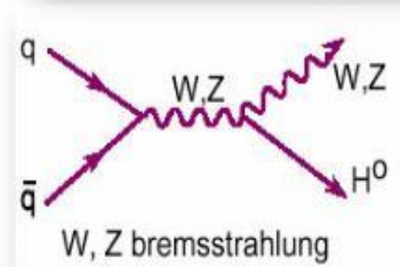


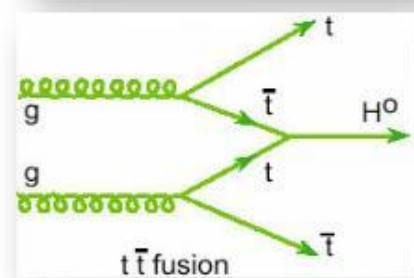
# Higgs production at the LHC



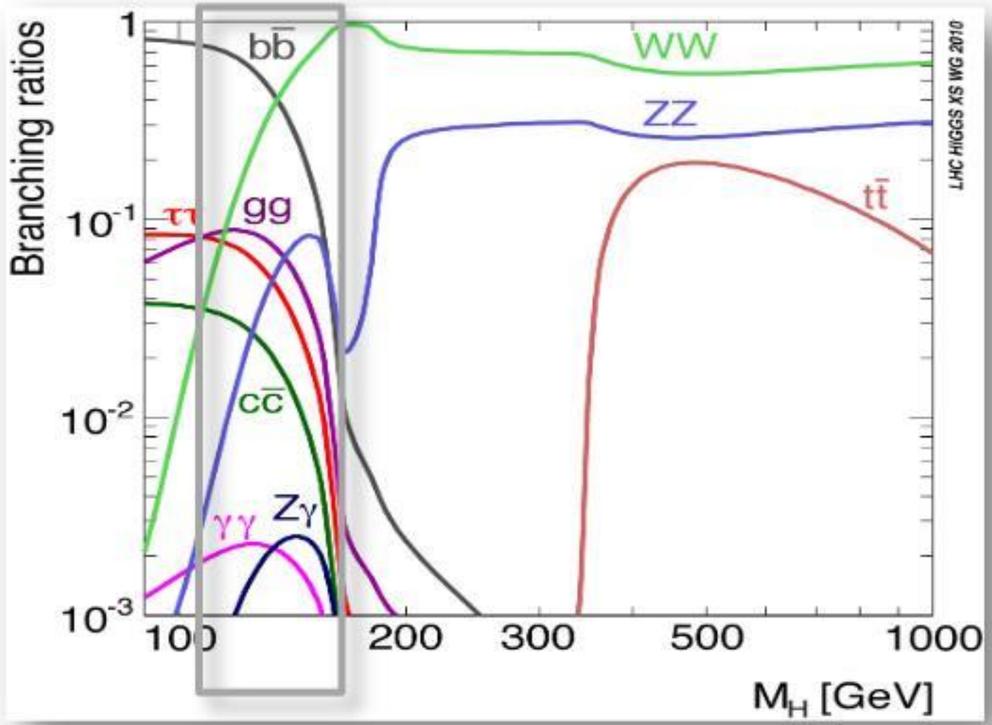




- $\sqrt{s}$=8 TeV: 25-30% higher $\sigma$ than $\sqrt{s}$=7 TeV at low $m_H$
- All production modes to be exploited
  - gg VBF VH ttH
  - Latter 3 have smaller cross sections but better S/B in many cases

# Most important decay modes

5 decay modes exploited

- High mass: WW, ZZ
- Low mass: $b\bar{b}$, ττ, WW, ZZ, γγ
- Low mass region is very rich but also very challenging:
  main decay modes ($b\bar{b}$, ττ) are hard to identify in the huge background
- Very good mass resolution (1%): H→γγ and H→ZZ→4l



# 4th of July, 2012 – Higgs-day at CERN

# Trigger on Higgs bosons?

Several triggers in use:

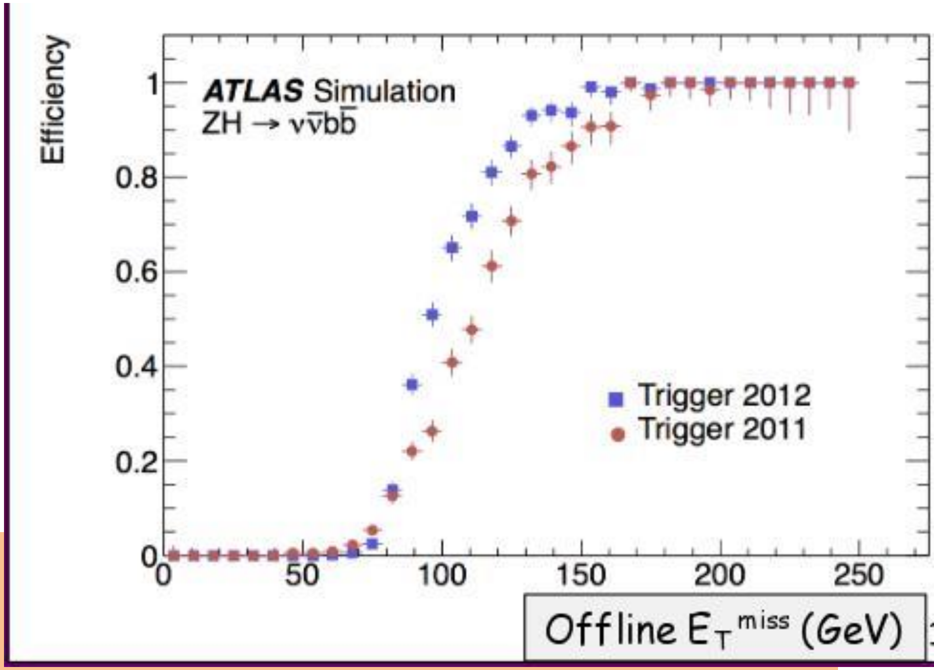
**Main triggers: lepton/photon triggers**

but even tau (had) triggers

jet triggers and a trigger

on "missing $E_T$" (for the

$ZH \rightarrow \upsilon\bar{\upsilon}\, b\bar{b}$



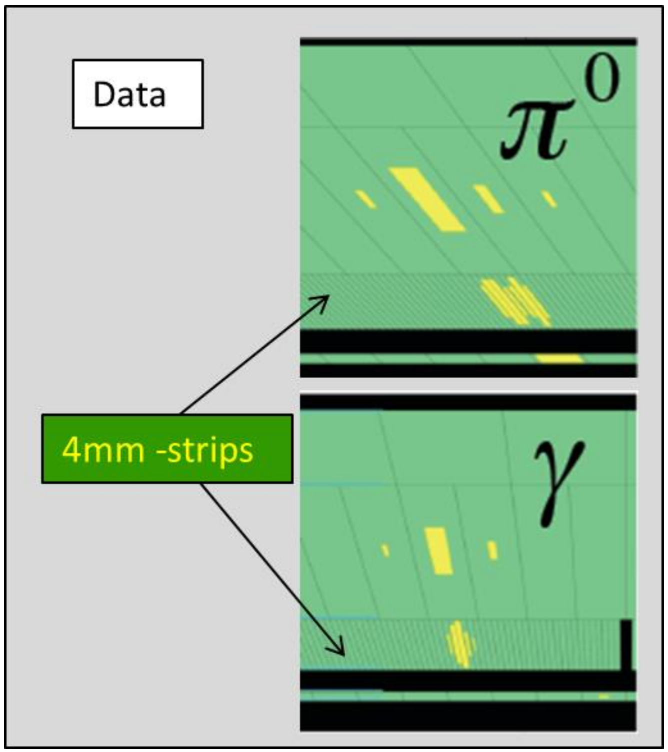

Final analysis uses a combination of several triggers, several "channels" for maximal sensitivity

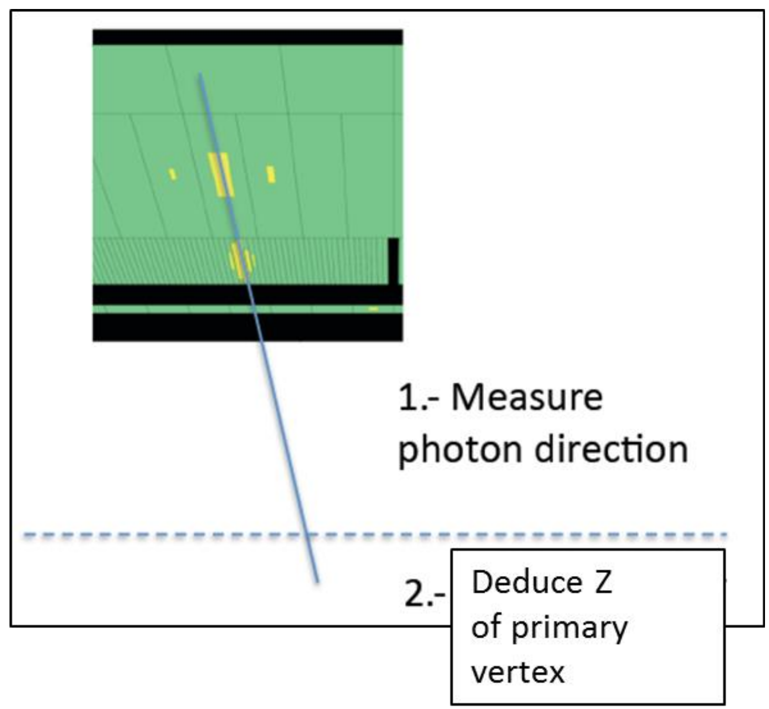
# Reconstructing photons

Without a track, can we tell the difference between $\gamma$ and $\pi^0$?

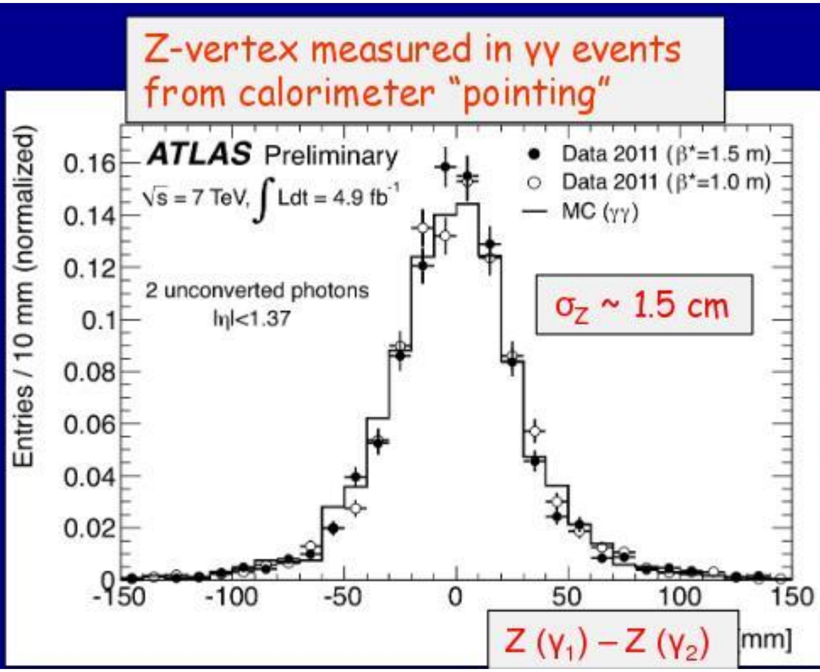
*Crucial for $H \rightarrow \gamma\gamma$ search!*

ATLAS uses the fine segmentation of the EM calorimeter to measure $\gamma$ direction



# Reconstructing photons




Note:

- ❑ Calorimeter pointing alone reduces vertex uncertainty from beam spot spread of ~ 5-6 cm to ~ 1.5 cm and is robust against pile-up
  → good enough to make contribution to mass resolution from angular term negligible
- ❑ Addition of track information (less pile-up robust) needed to reject fake jets from pile-up in 2j/VBF category

In addition of course also mass resolution is crucial

$m_{\gamma\gamma}^2 = 2\, E_1 E_2\, (1 - \cos\alpha)$

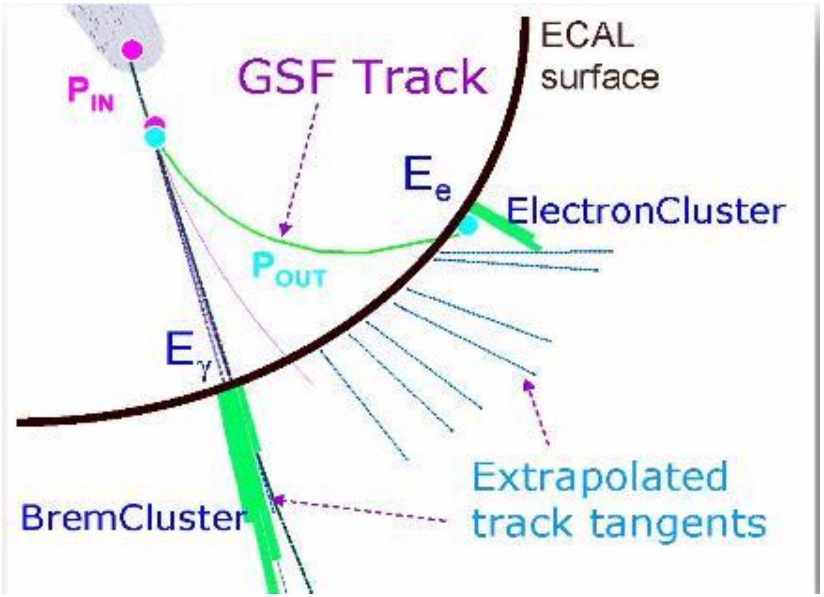
Resolution 1.6 GeV (linearity + uniformity terms ~1%)

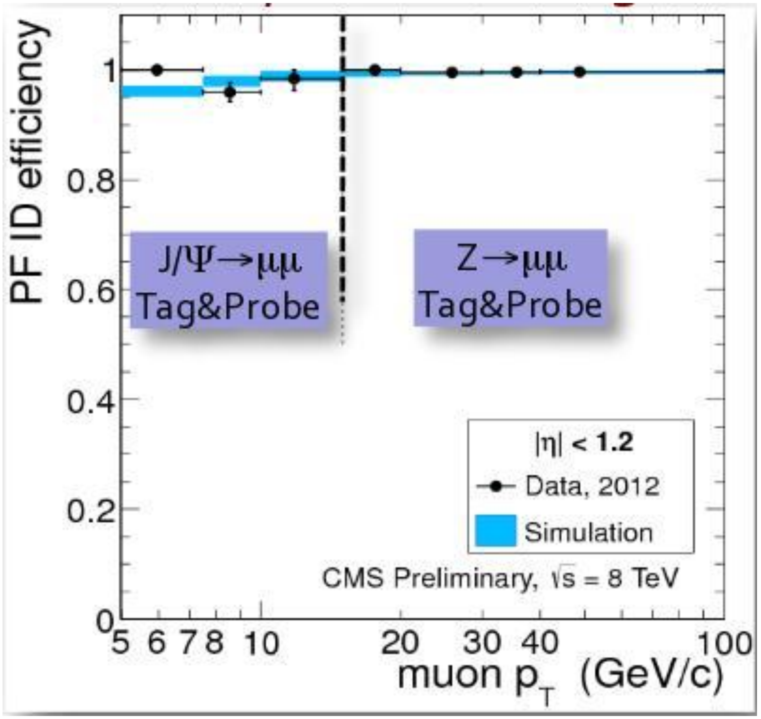
# Reconstructing leptons (e,μ)

Typically reconstructed with high efficiency

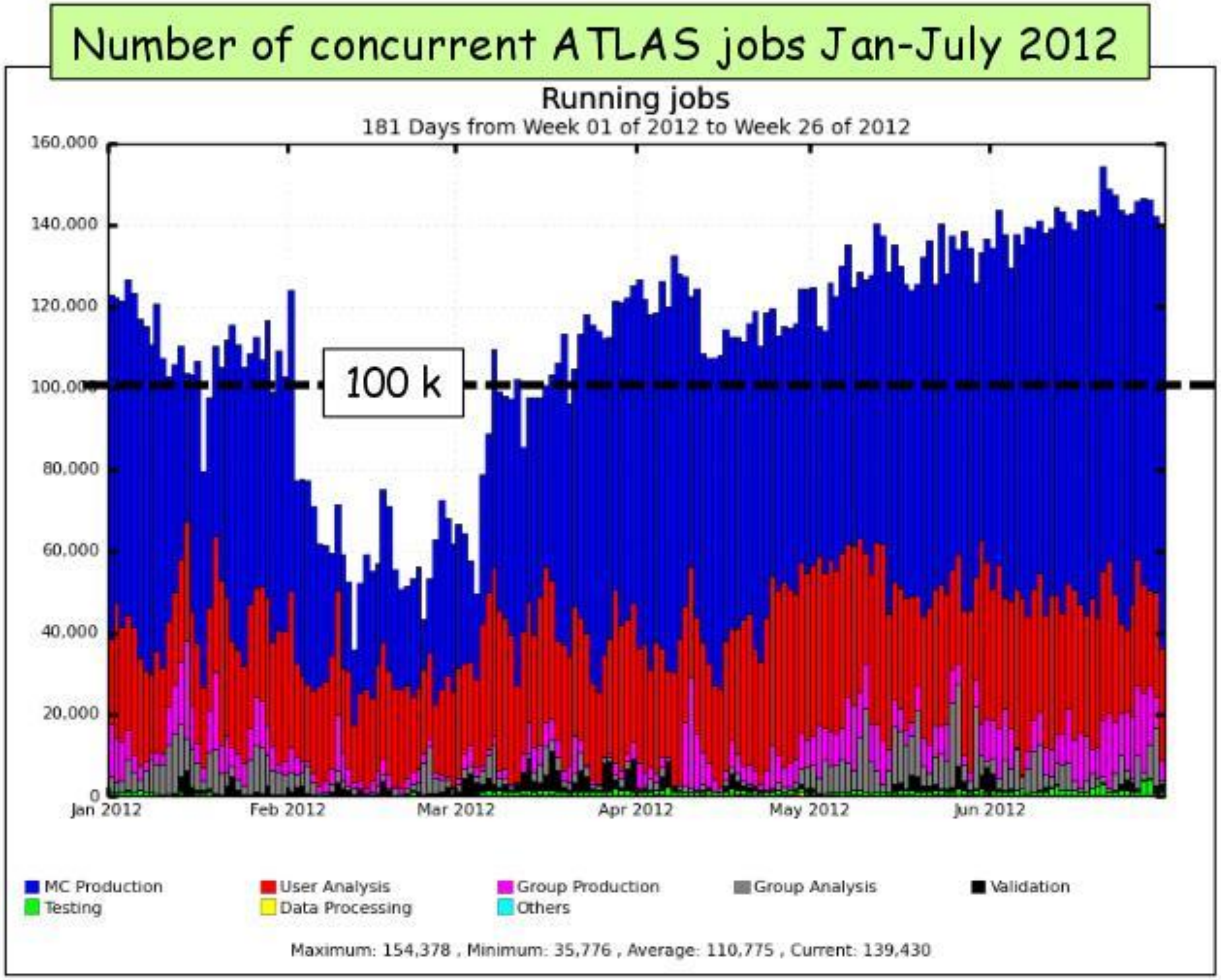
- electron selection based on likelihoods and multivariate techniques to reduce backgrounds

Gaussian Sum Filter allows for reconstruction of e tracks with large bremsstrahlung



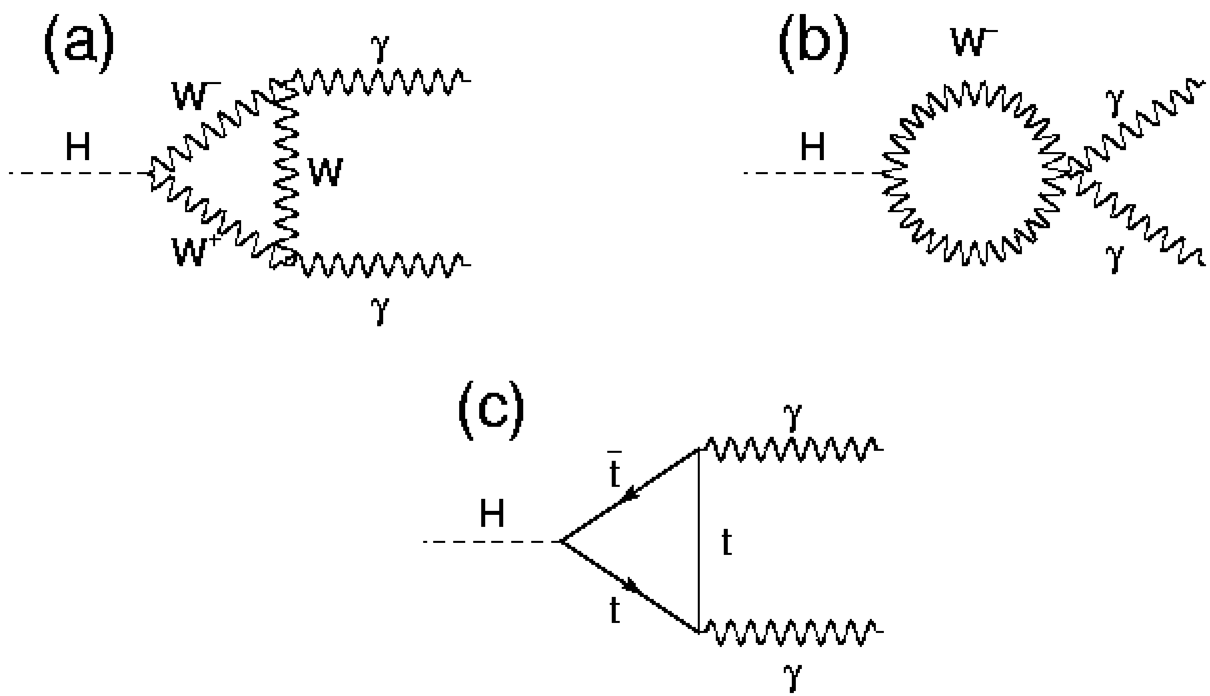
# Computing

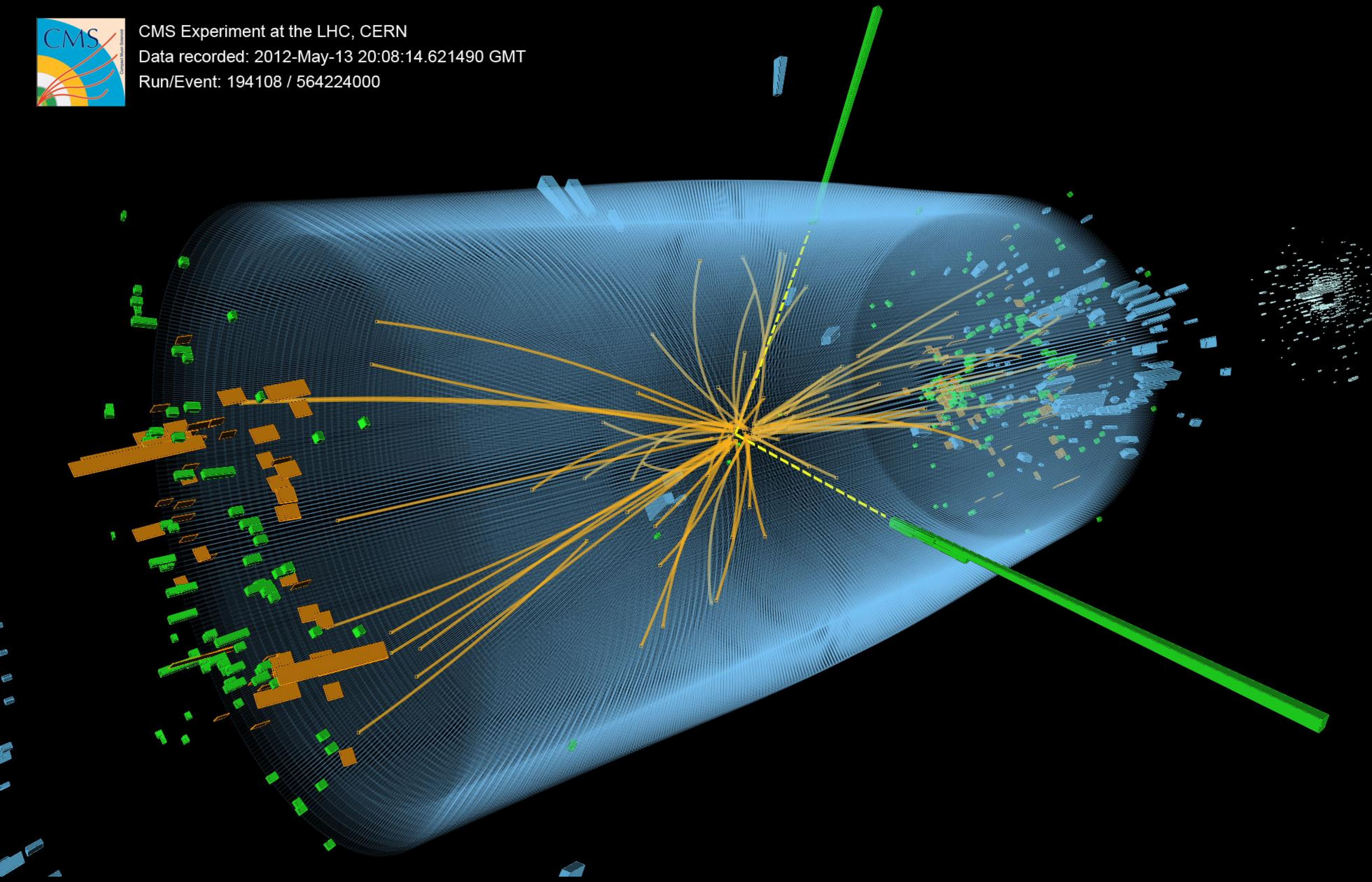

Number of concurrent ATLAS jobs Jan-July 2012
Running jobs
181 Days from Week 01 of 2012 to Week 26 of 2012
160,000
140,000
120,000
100,000
100 k
80,000
60,000
40,000
20,000
0
Jan 2012
Feb 2012
Mar 2012
Apr 2012
May 2012
Jun 2012
MC Production
User Analysis
Group Production
Group Analysis
Validation
Testing
Data Processing
Others
Maximum: 154,378 , Minimum: 35,776 , Average: 110,775 , Current: 139,430

# $H \rightarrow \gamma\gamma$

Most important channel for Higgs masses below 150 GeV!

Simple topology but large backgrounds $\Rightarrow$ requires excellent energy resolution





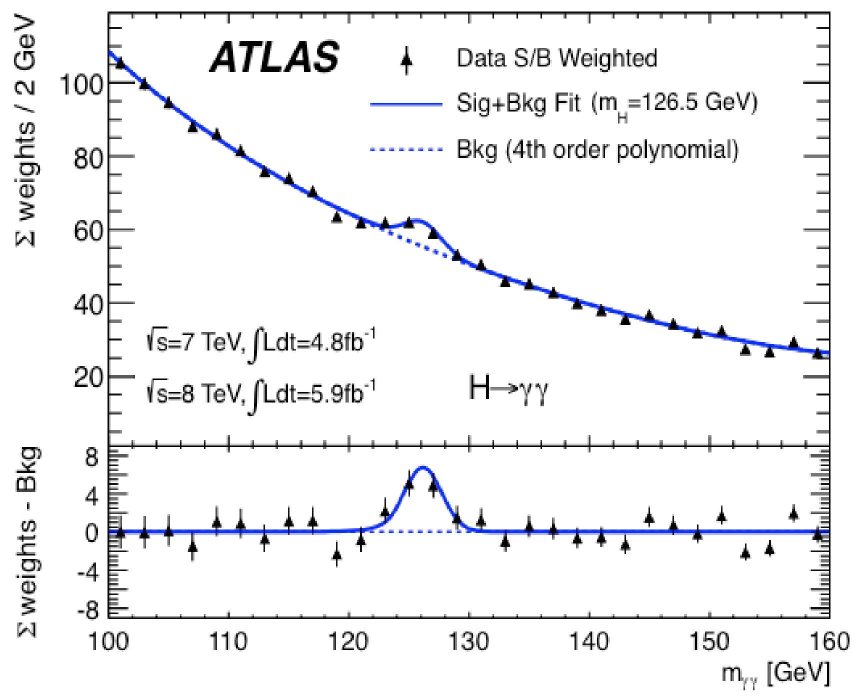

*$H \rightarrow \gamma\gamma$ candidate event (CMS)*

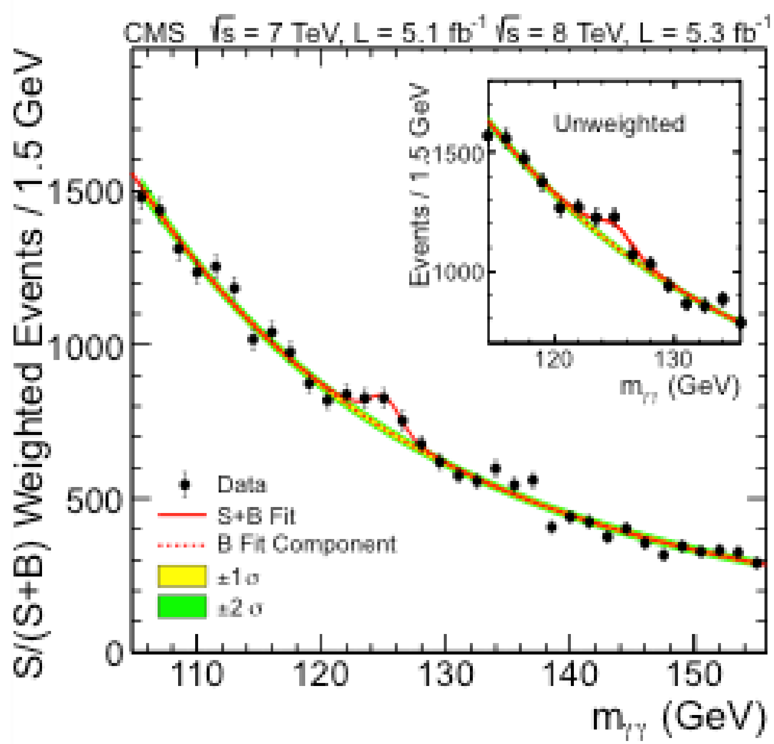
# $H \rightarrow \gamma\gamma$

Clean discovery channels for Higgs, allowing precise mass determination

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB

**Benefit from excellent energy resolution and photon identification capabilities of ATLAS/CMS**

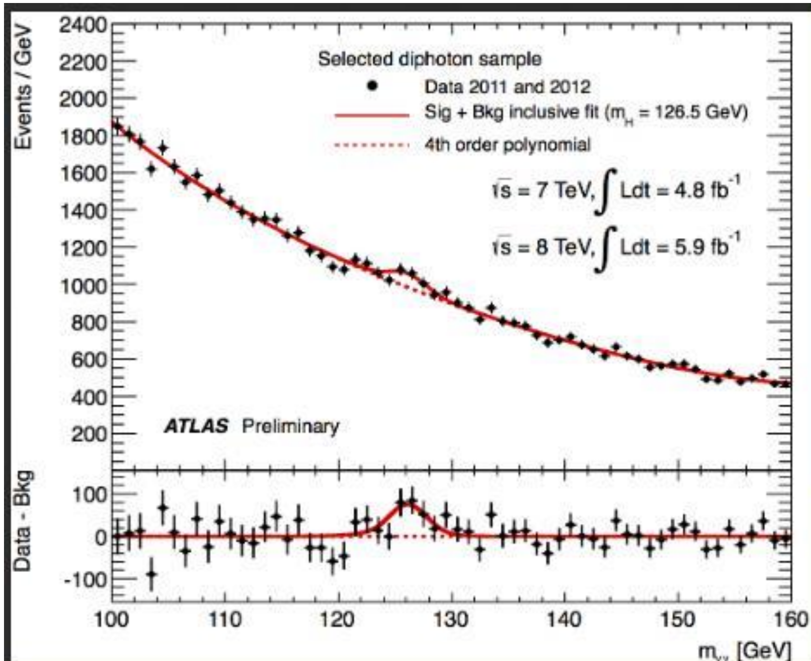



Both experiments classify events according to resolution and topology in ML fit

Maximum excess of 4.5σ (4.1σ) seen by ATLAS (CMS) at 126.5 (125) GeV

# A look at the details




Total after selections: 59059 events

$m_{\gamma\gamma}$ spectrum fit, <u>for each category</u>, with Crystal Ball + Gaussian for signal plus background model optimised (with MC) to minimize biases
Max deviation of background model from expected background distribution taken as systematic uncertainty

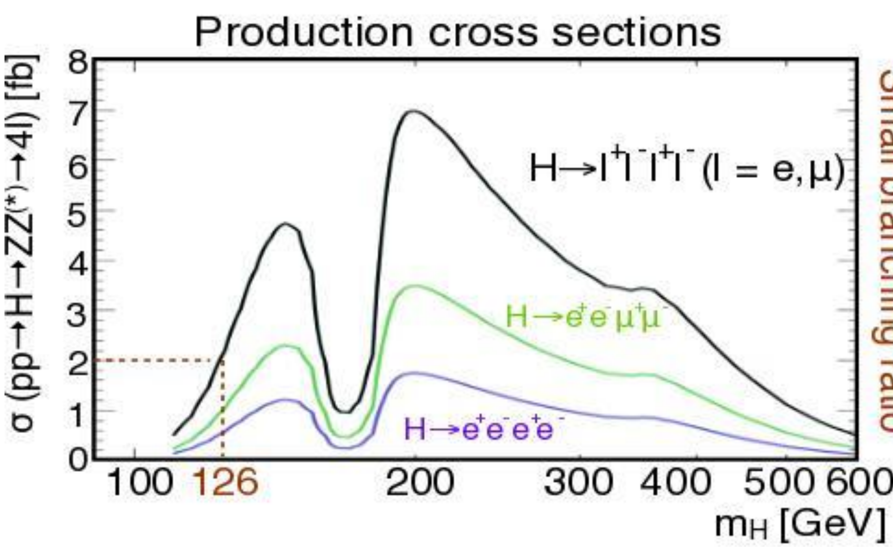
Main systematic uncertainties

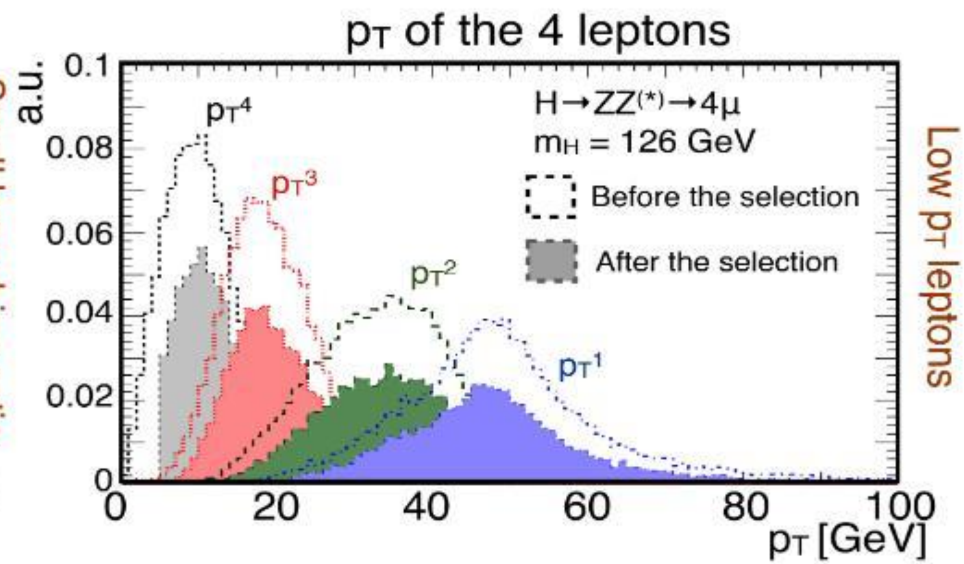
| | |
|---|---|
| Signal yield | |
| Theory | ~ 20% |
| Photon efficiency | ~ 10% |
| Background model | ~ 10% |
| Categories migration | |
| Higgs $p_T$ modeling | up to ~ 10% |
| Conv/unconv $\gamma$ | up to ~ 6% |
| Jet E-scale | up to 20% (2j/VBF) |
| Underlying event | up to 30% (2j/VBF) |
| $H \rightarrow \gamma\gamma$ mass resolution | ~ 14% |
| Photon E-scale | ~ 0.6% |

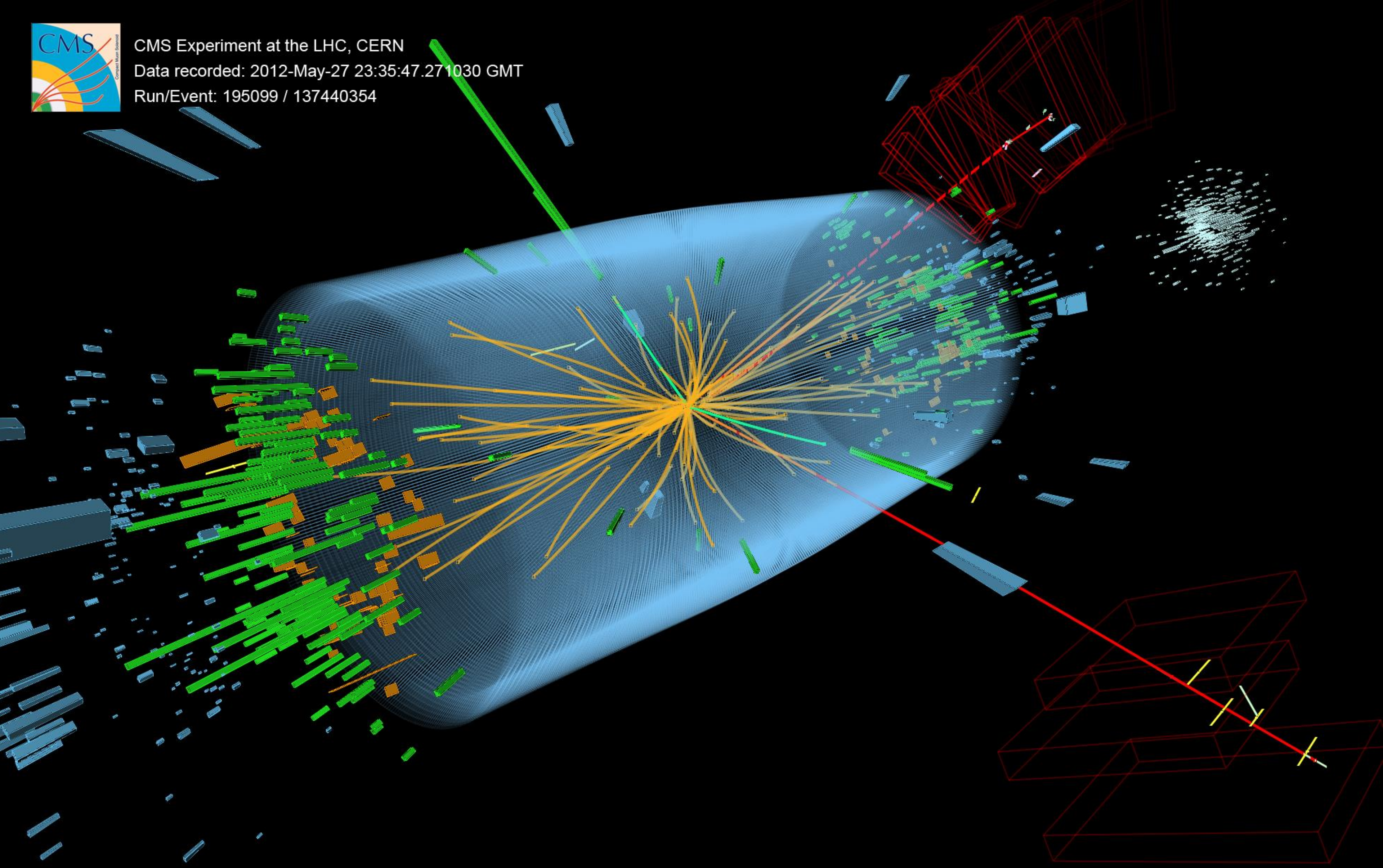
# $H \to ZZ^*$

**One of the best performing channels in the whole mass range …**

**… but extremely demanding channel for selection, requiring the highest possible efficiencies (lepton Reco/ID/Isolation).**





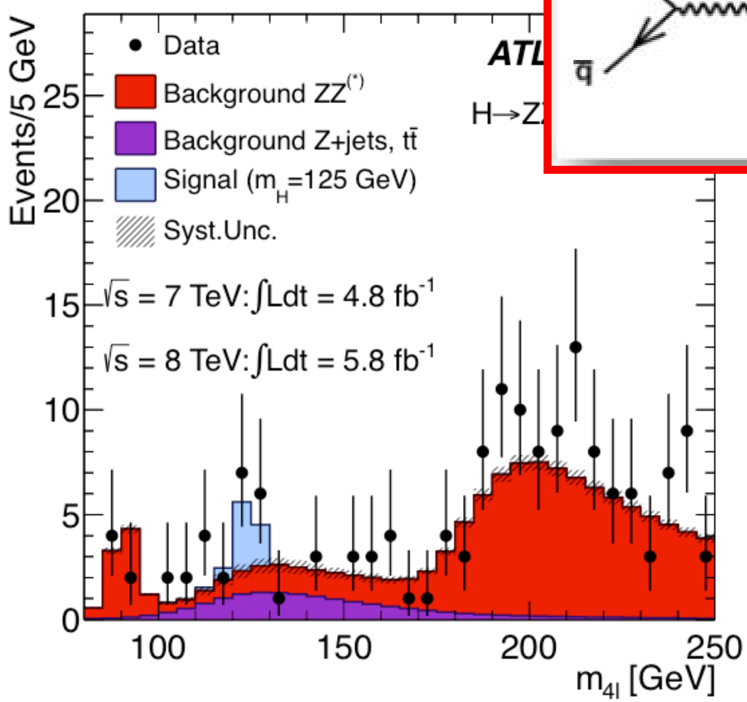

*H → 2e2μ candidate event (CMS)*

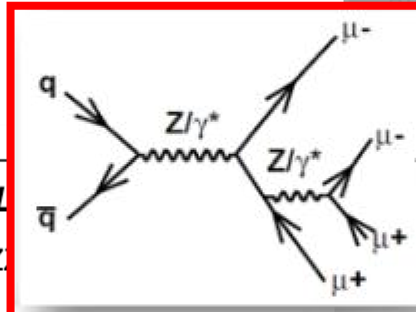
# $H \to ZZ^{(*)} \to 2(e,\mu) + 2(e,\mu)$

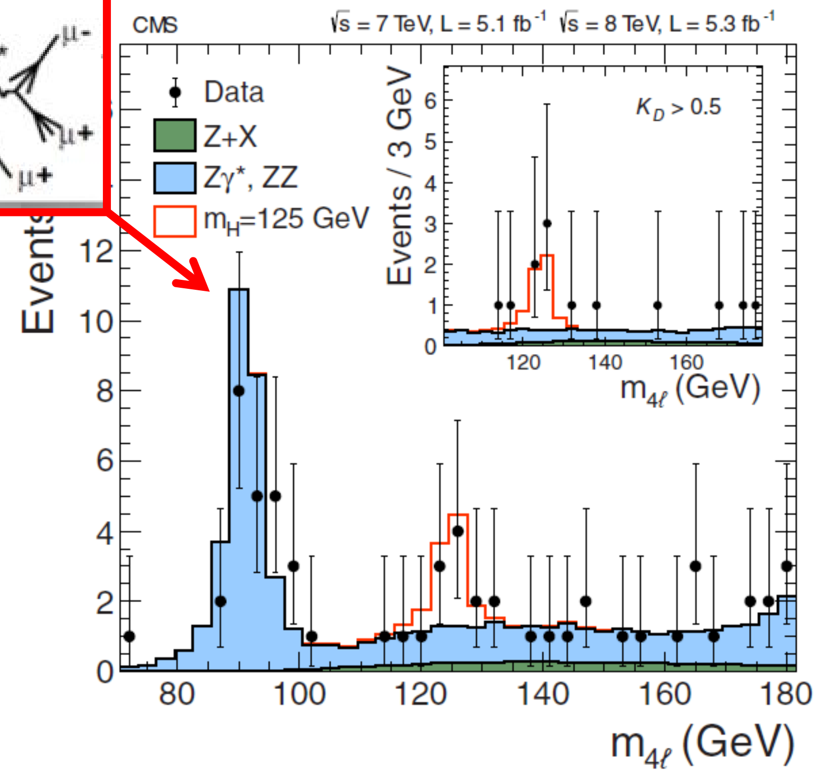
## Clean discovery channels for Higgs, allowing precise mass determination

**Benefit from excellent energy/momentum resolution and identification capabilities at ATLAS/CMS**

ATLAS arXiv:1207.7214, CMS arXiv:1207.7235, both submitted on Aug 1st, 2012 to PLB

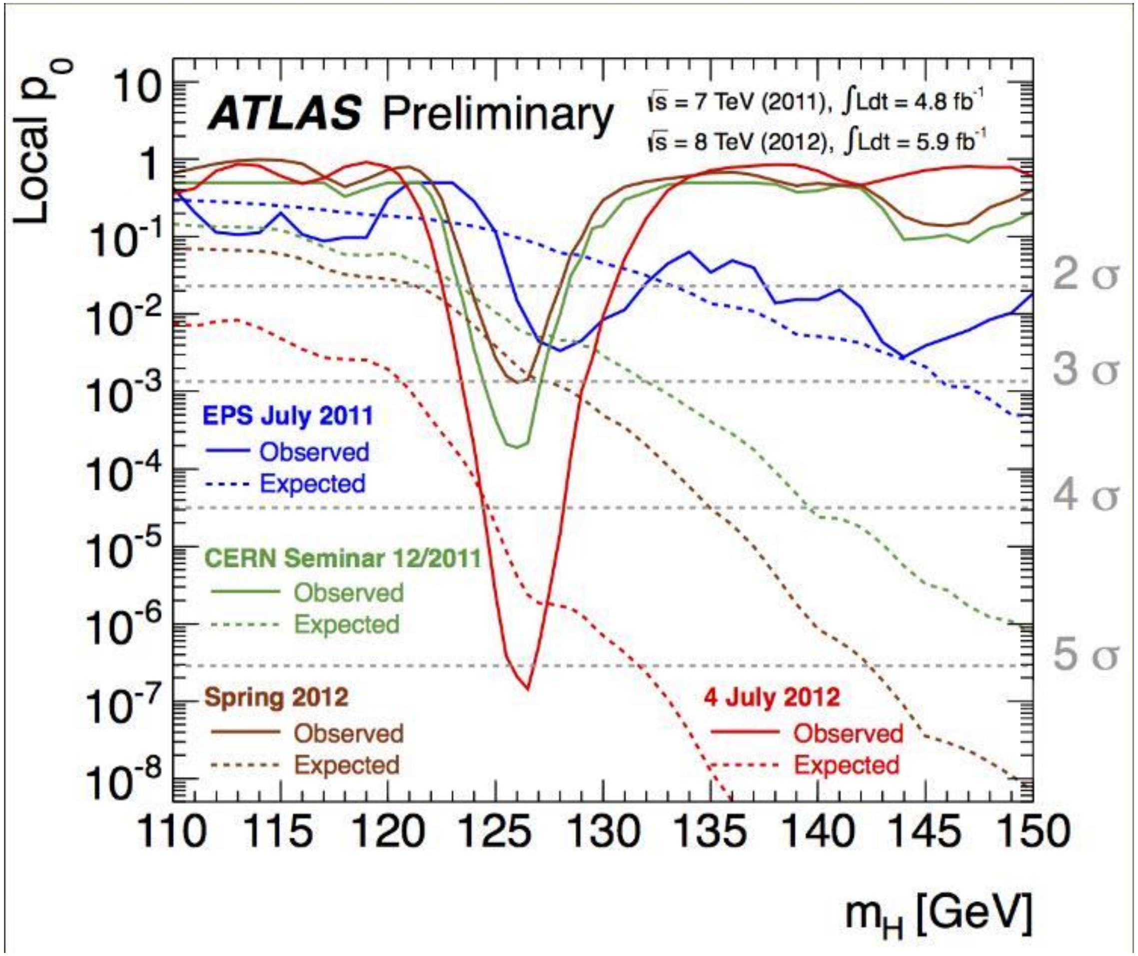



Order one $S/B$ ratio. Maximum excess of 3.6σ (3.2σ) seen by ATLAS (CMS) at 125 (125.6) GeV

# ATLAS combined July 2012




Max excess

@ 126.5 GeV

Local significance:

5 sigma

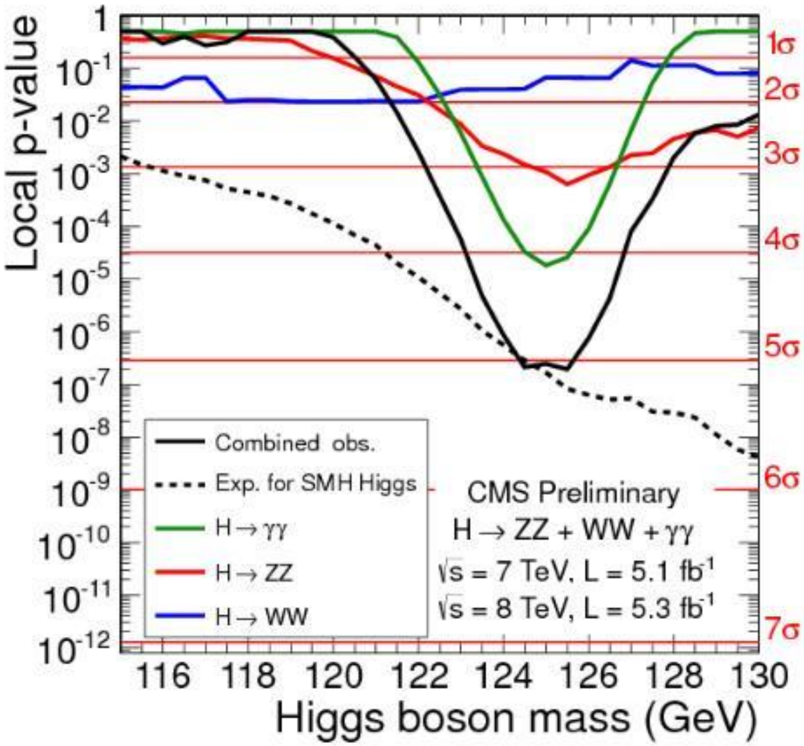
p-value: $3 \times 10^{-7}$

Global significance:

4.1-4.3 sigma

I.e. an "observation" not discovery

# CMS combined July 2012




**adding high sensitivity, but low mass resolution WW**

**comb. significance: 5.1 σ**

**expected significance for SM Higgs: 5.2 σ**

Global significance similar to ATLAS's, i.e. observation only

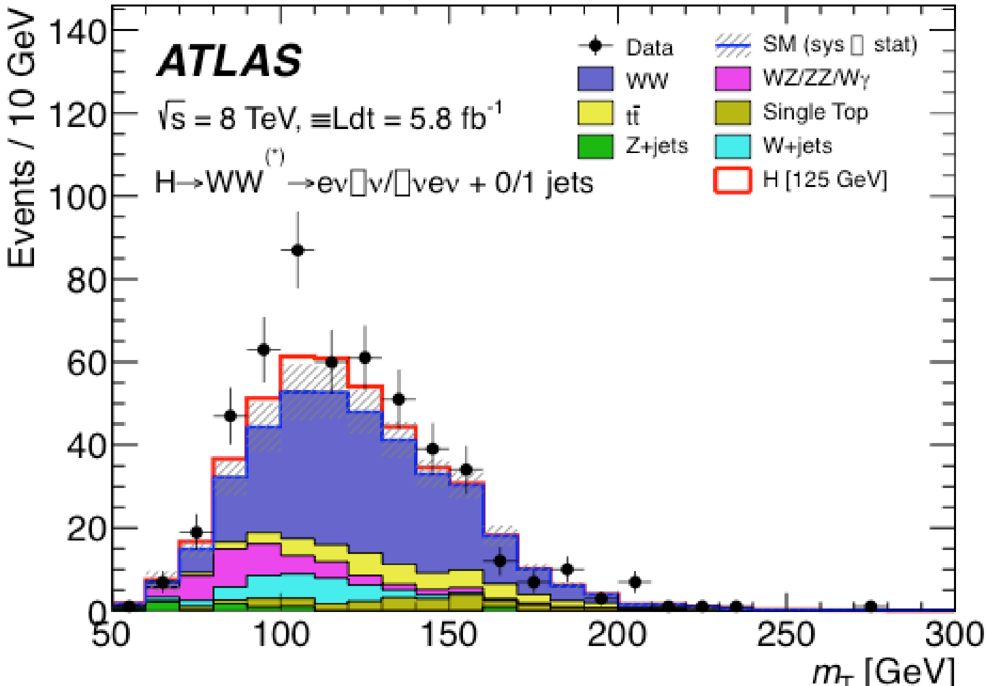
# Other channels

- **H → WW → lνlν**

Less clean, little mass sensitivity but abundant

Result:

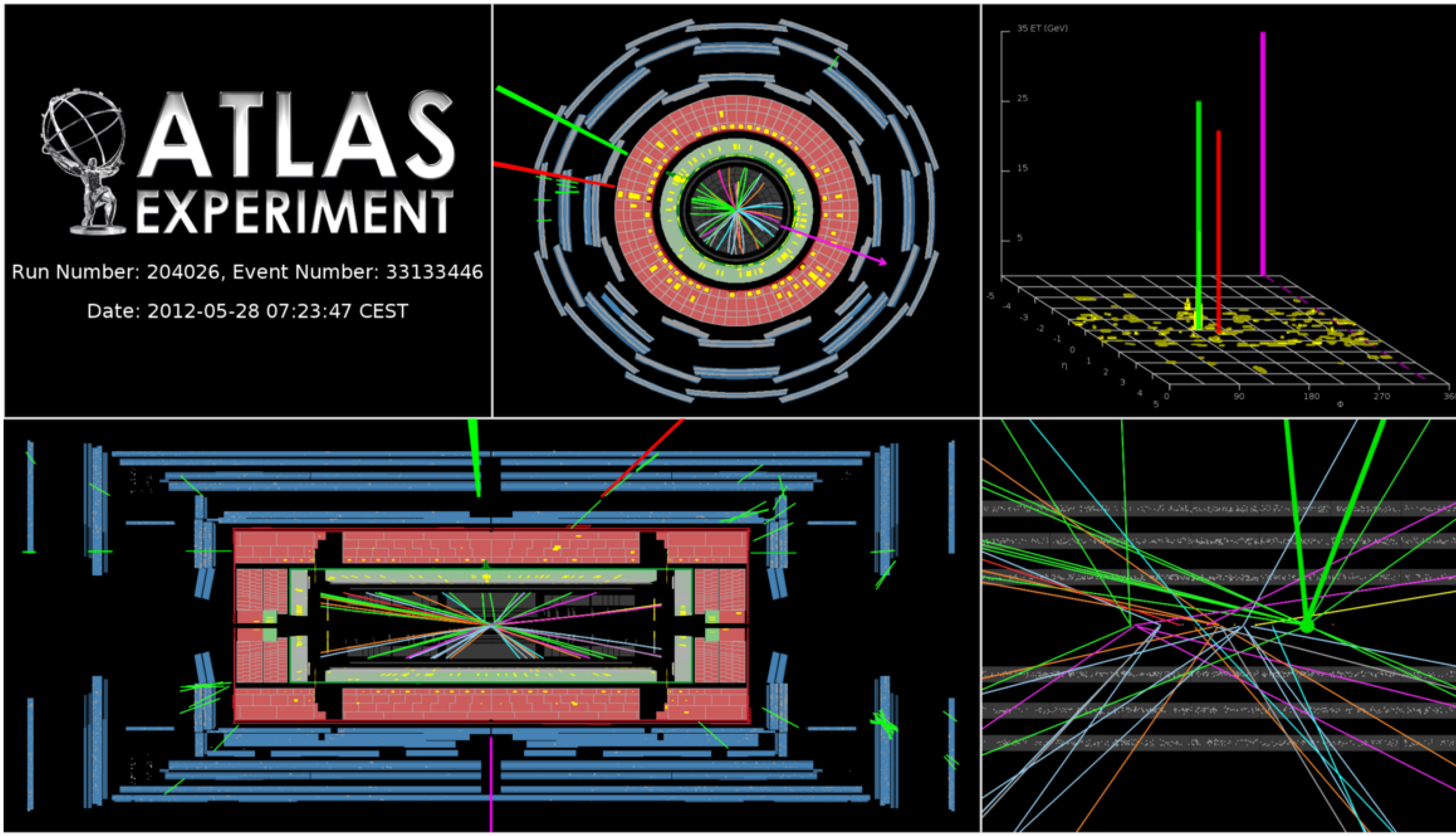
roughly 2σ/experiment



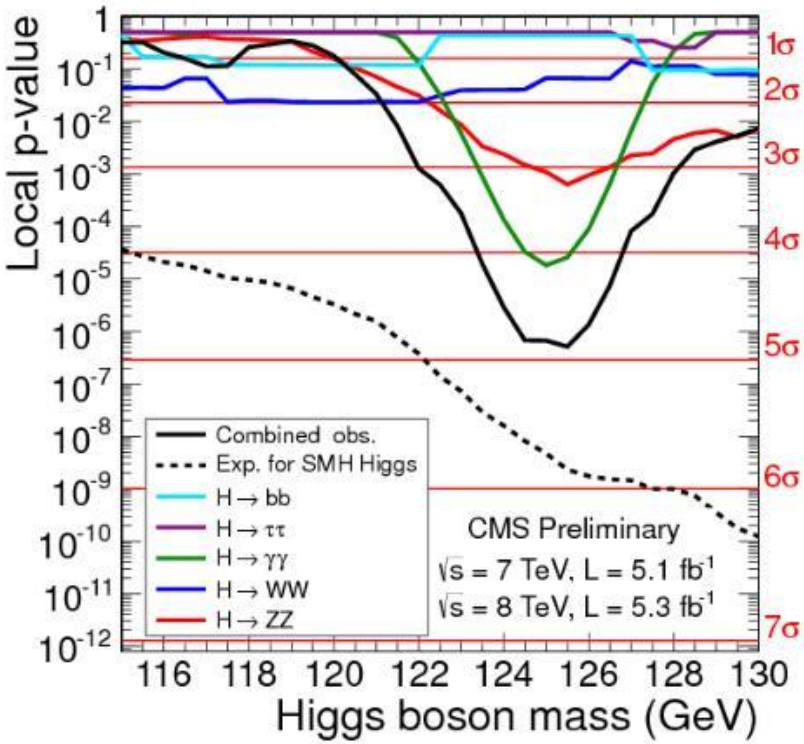

- **Associated production WH, ZH**
- **H →ττ**

Little sensitivity in first analysis

# H → WW candidate



# CMS combined July 2012



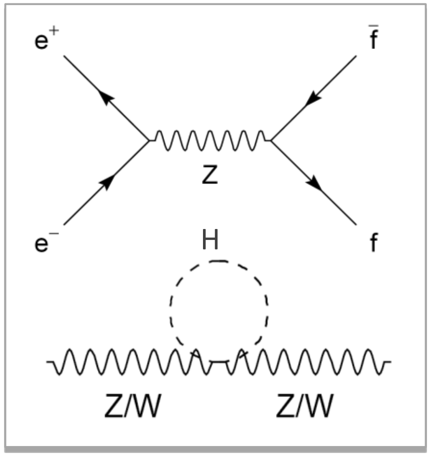

- **all channels together: comb. significance: 4.9 σ**
- **expected significance for SM Higgs: 5.9 σ**

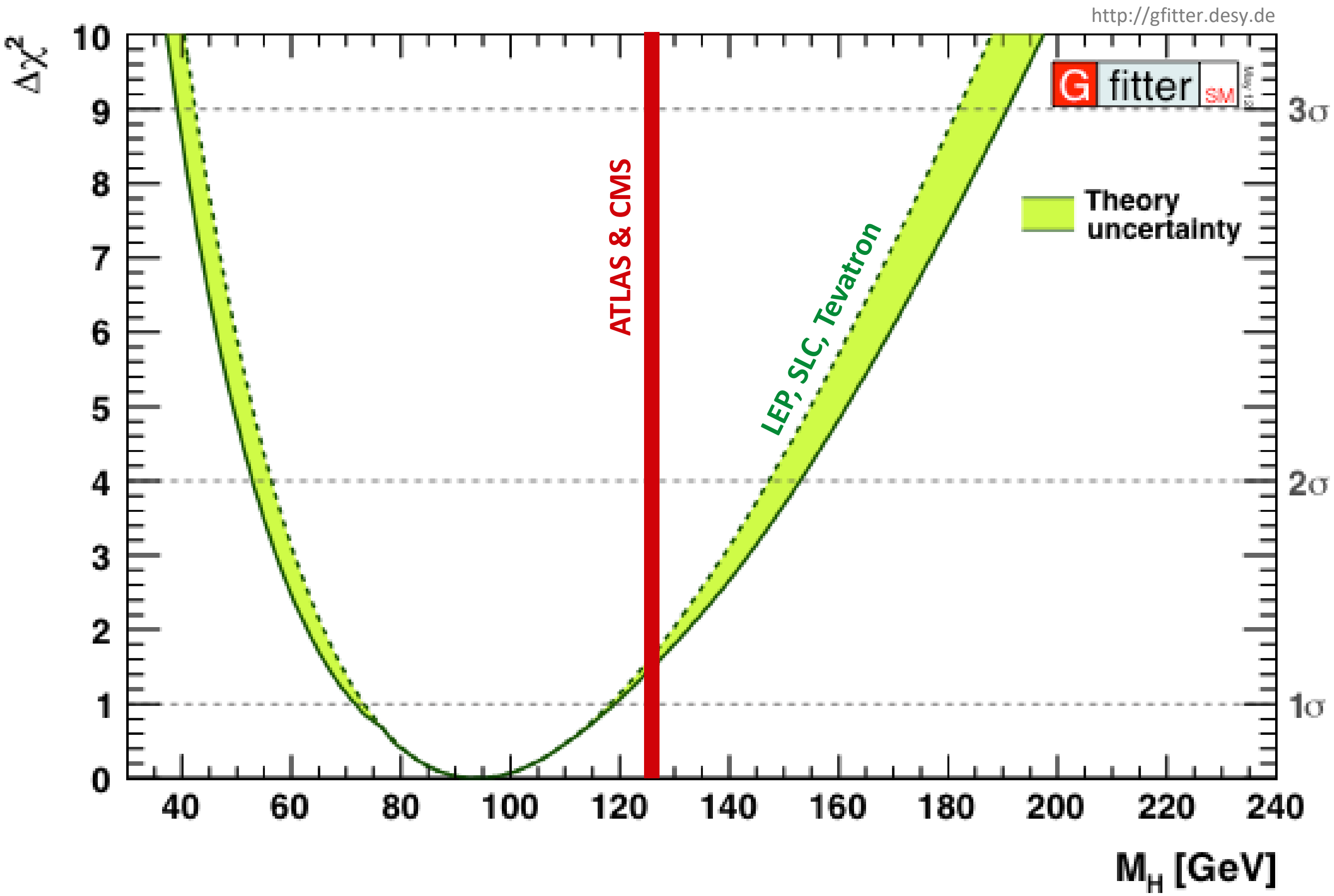
Some times adding more channels means a smaller observation!

# What can we conclude from this discovery

## Recall: light Higgs was predicted from SM fit to precision measurements

**Discovery of light Higgs boson is a *huge success* of the Standard Model**



# What can we conclude from this discovery

## Is the electroweak vacuum stable or metastable (if SM holds) ?

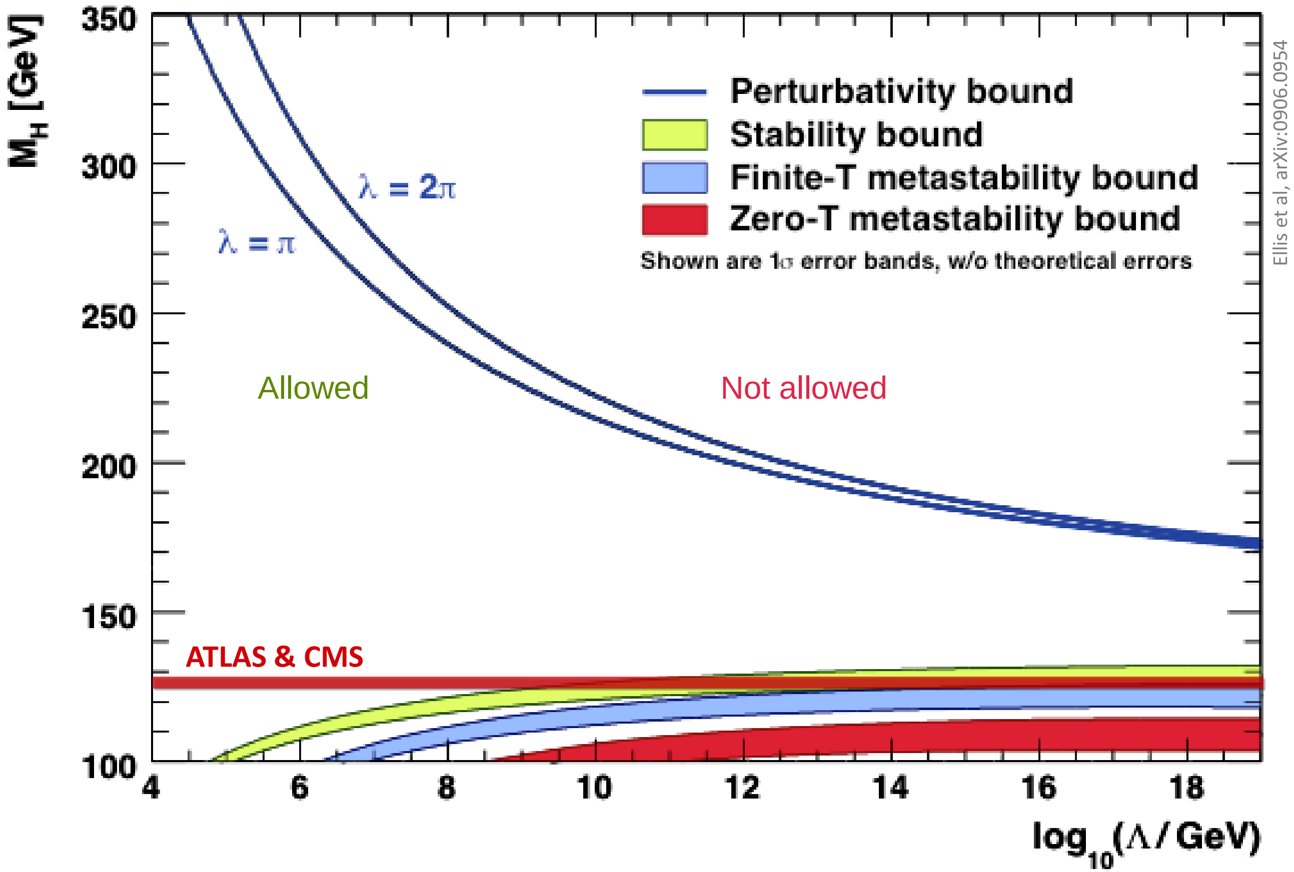
**Barely stable ?**

But: prediction of the stability bound suffers from theoretical uncertainties …

Newest full NNLO result moves up stability bound at Planck mass by +0.8 GeV and reduces uncertainty

→ **barely stable or metastable, but certainly the Higgs self coupling would become very weak at $M_{Pl}$**

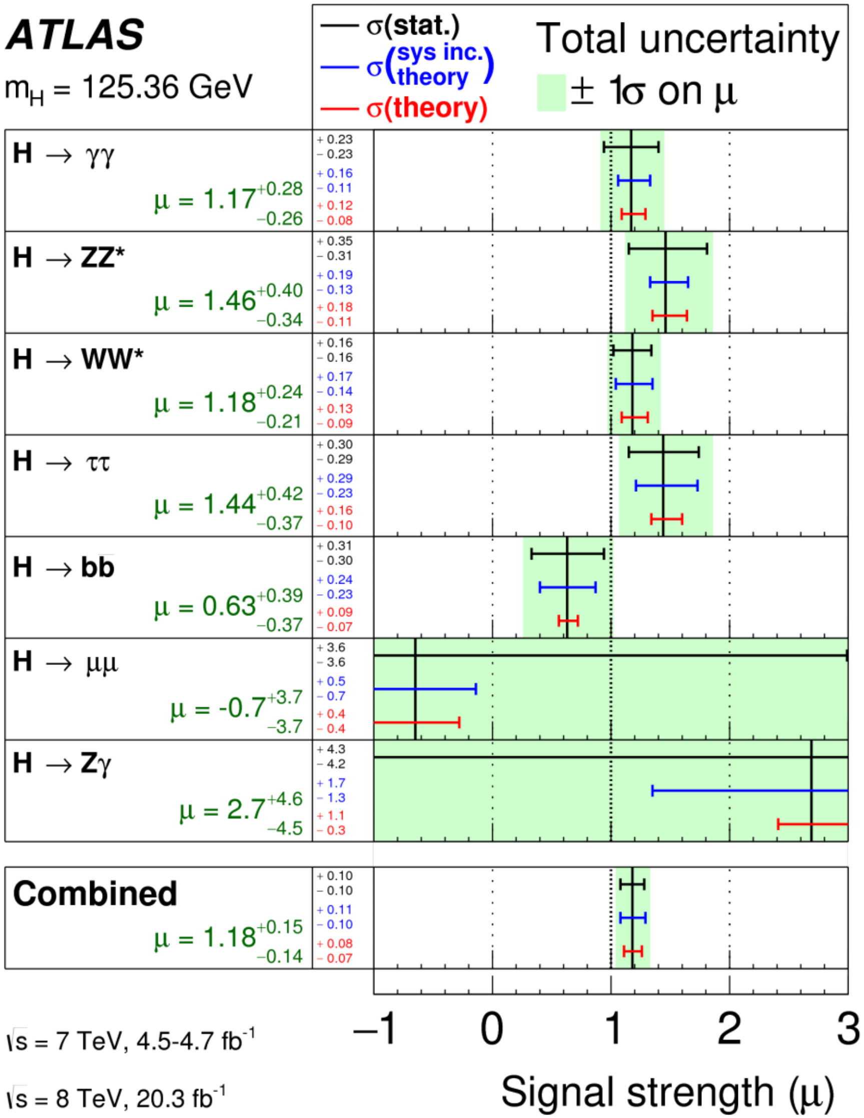
Degrassi *et al*, arXiv:1205.6497

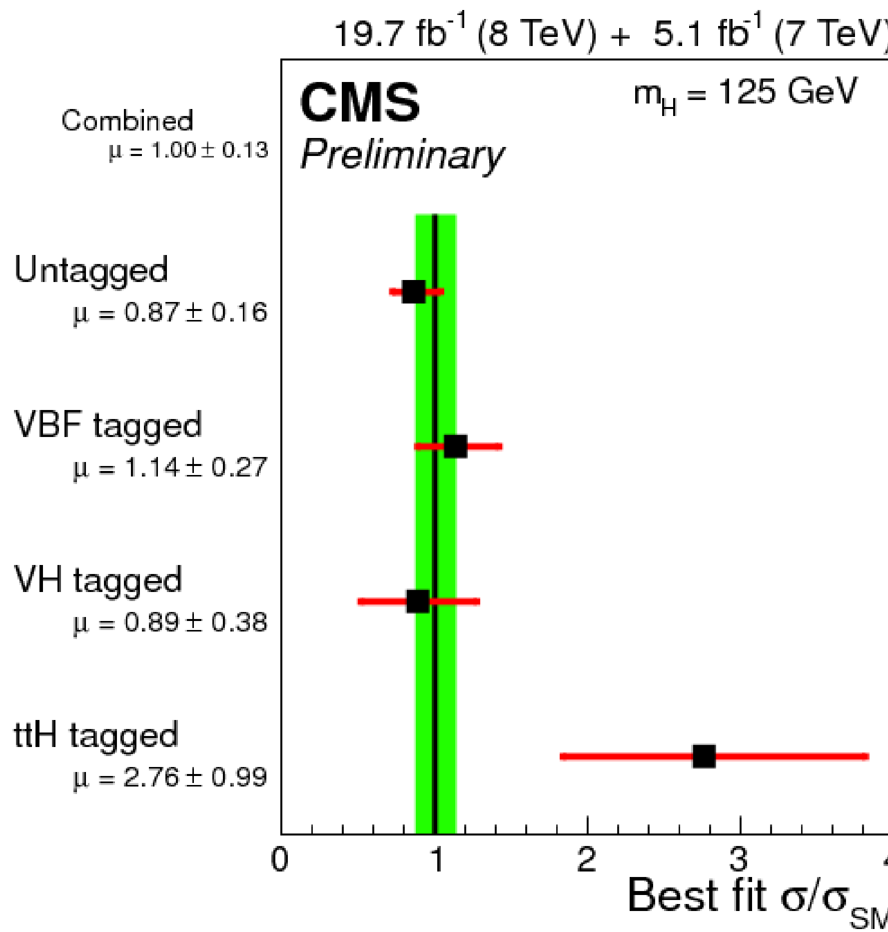


# Current status

What have we learned about the Higgs boson and the Higgs mechanism since then?

# Lots of measurements in more channels



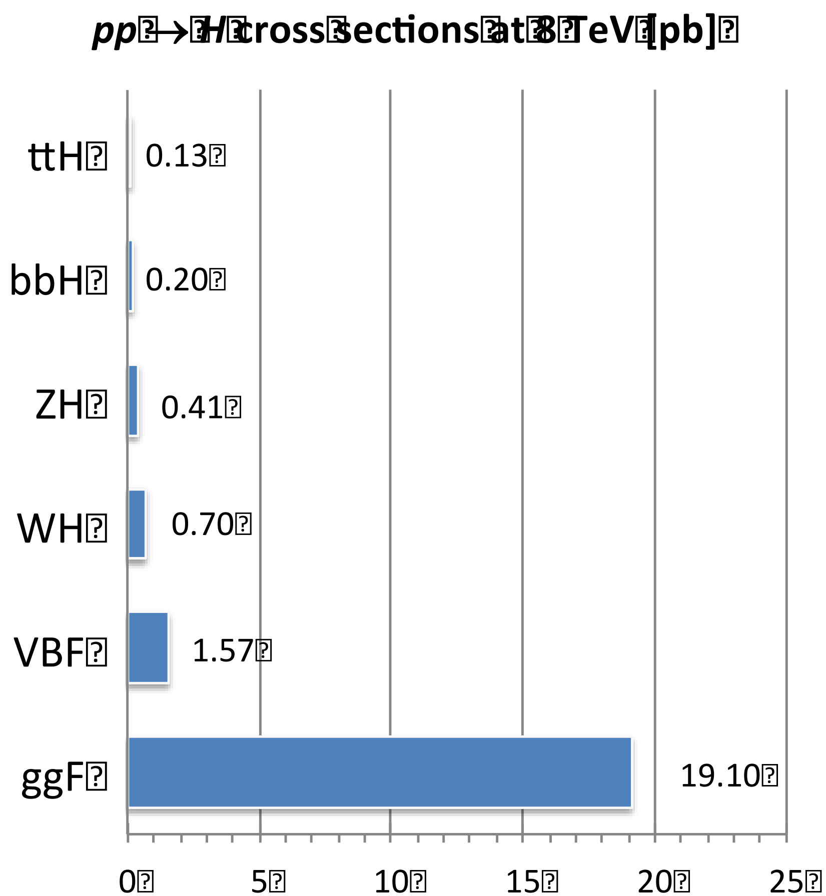



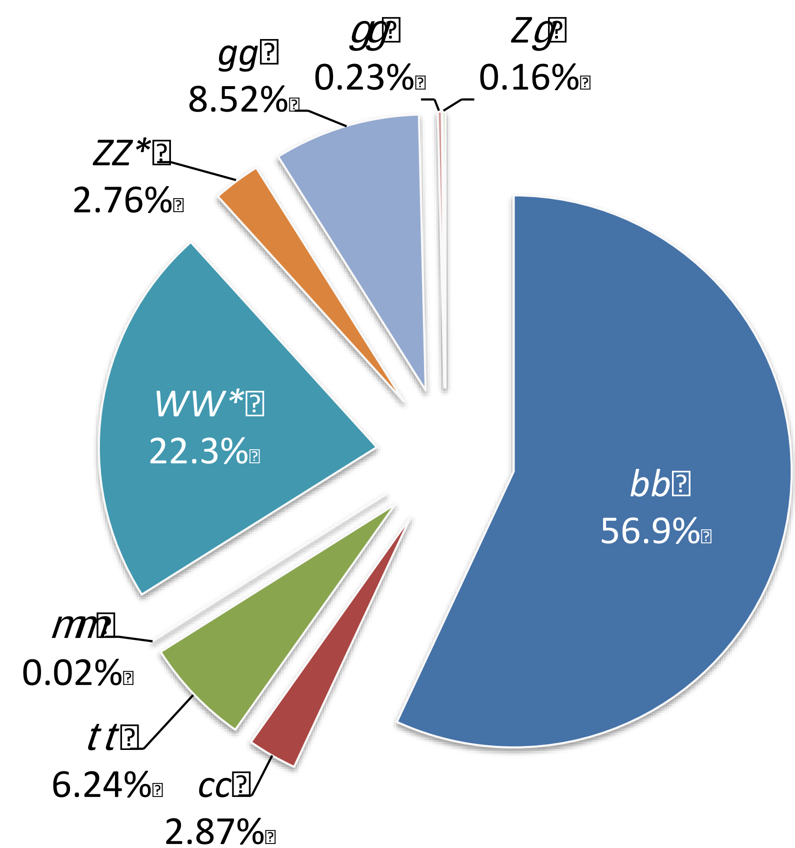
# Higgs and Flavour Physics

125.5 GeV Higgs boson — SM properties

[ LHCPhysics/CrossSections ]

Cross sections and branching fractions precisely predicted ($m_H$ = 125.5 GeV)




Uncertainties 3~12%

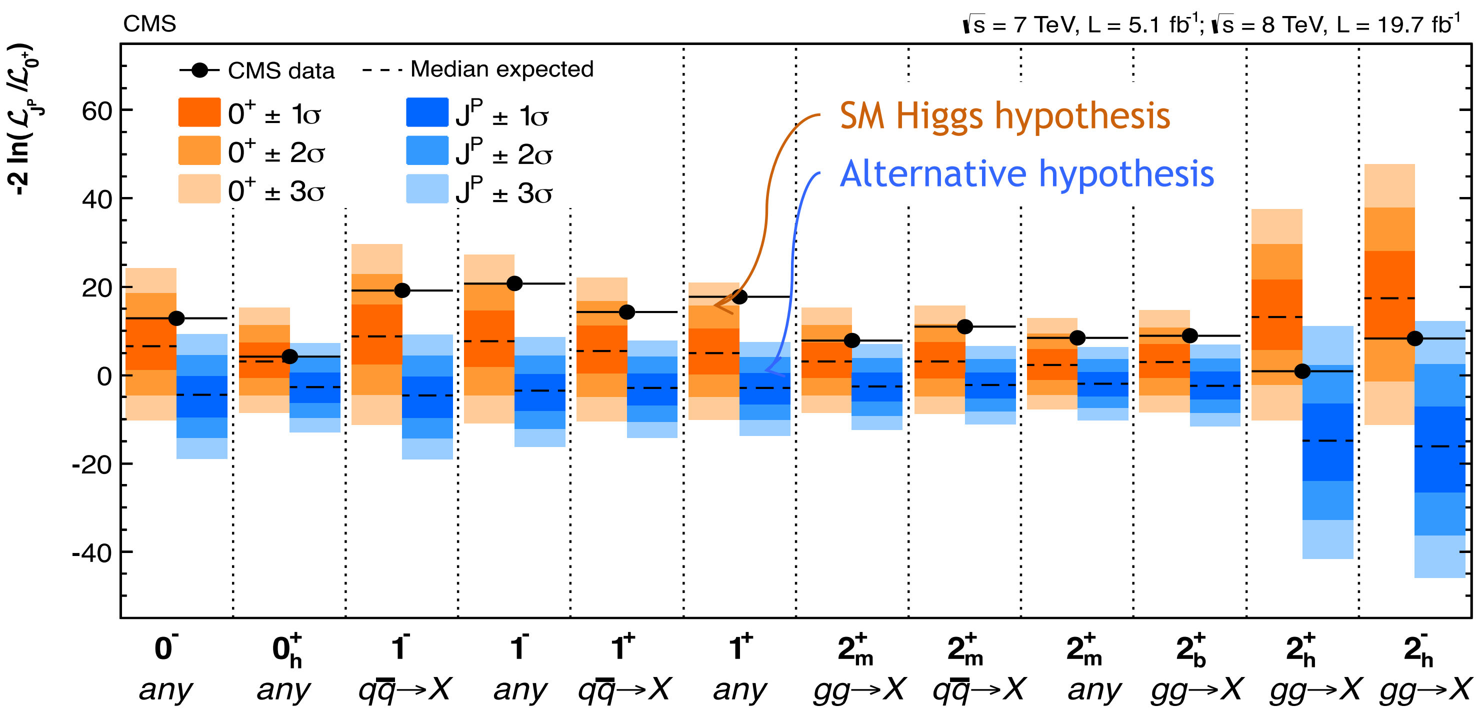
# Higgs spin and CP

Higgs boson appears to be SM-like: $J^P = 0^+$

[ CMS: 1312.5353
See also PDG ]

## From most powerful spin/*CP* analyser: $H \to$ 4-lepton

- $0^-$ excluded at 3.6σ; *CP*-odd fraction in decay amplitude: $f_{a3} < 0.51$ (95% CL)
- Spin-1, 2 hypotheses excluded >> 95% CL




Discrimination is based on 2D PDFs ($D_{bkg}$, $D_{JP}$)

$J_x^P$ : x represents different coupling scenarios

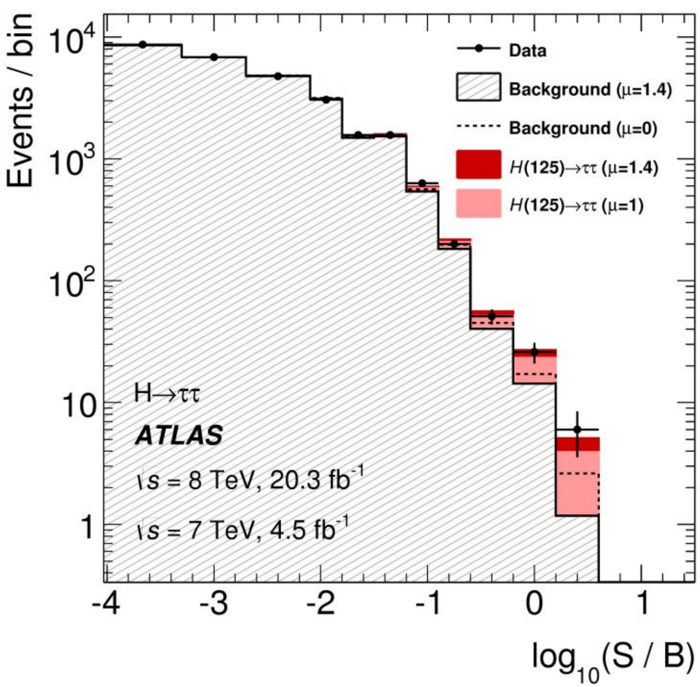
# Higgs and Flavour Physics

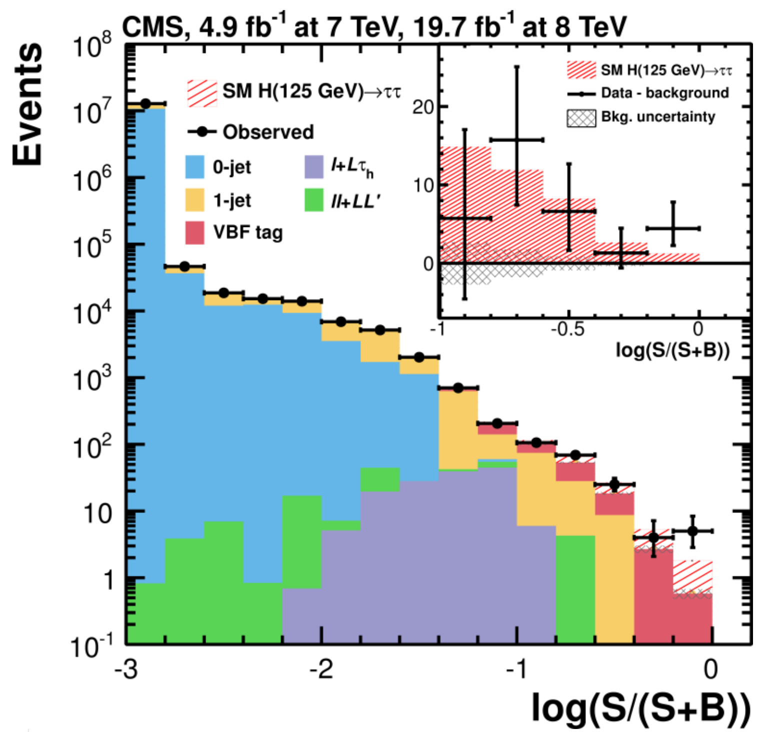
SM Higgs to fermions — $\tau\tau$

[ ATLAS-CONF-2013-108, CMS: 1401.5041 ]

## Higgs to fermion analyses all very challenging (or too low BR)

- Di-tau reconstructed in all lep/had topologies and jets: 0, 1 (boosted or not), 2 (VBF, VH)
- BDT-based tau identification, Higgs discrimination based on $m_{\tau\tau}$
- Likelihood-based calculator to estimate $m_{\tau\tau}$, $\sigma(m_{\tau\tau})$ = 13% ~ 20%, best for boosted $\tau$
- Background dominated by $Z \to \tau\tau$ (use "$\tau$ embedded" $Z \to \mu\mu$), also top and fakes important




**At 125 GeV:**

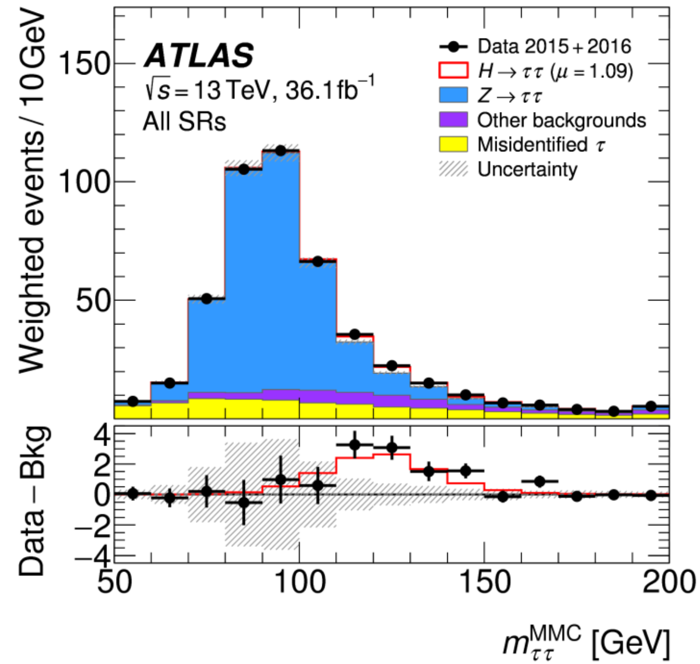
**ATLAS** (8 TeV):
$\mu = 1.4^{+0.5}_{-0.4}$
(4.1 $\sigma$)

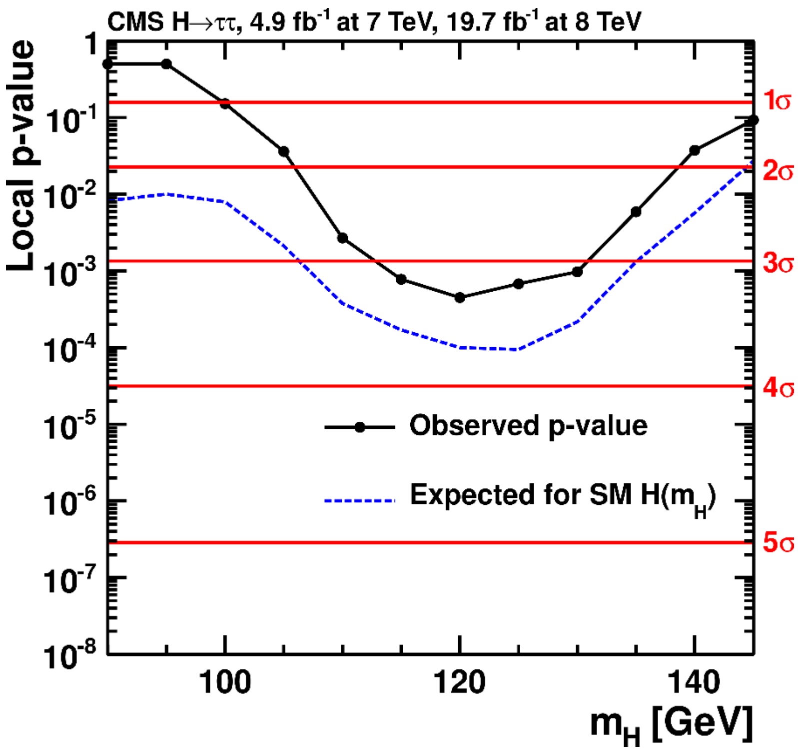
**CMS** (7+8 TeV):
$\mu = 0.78 \pm 0.27$
(3.4 $\sigma$)

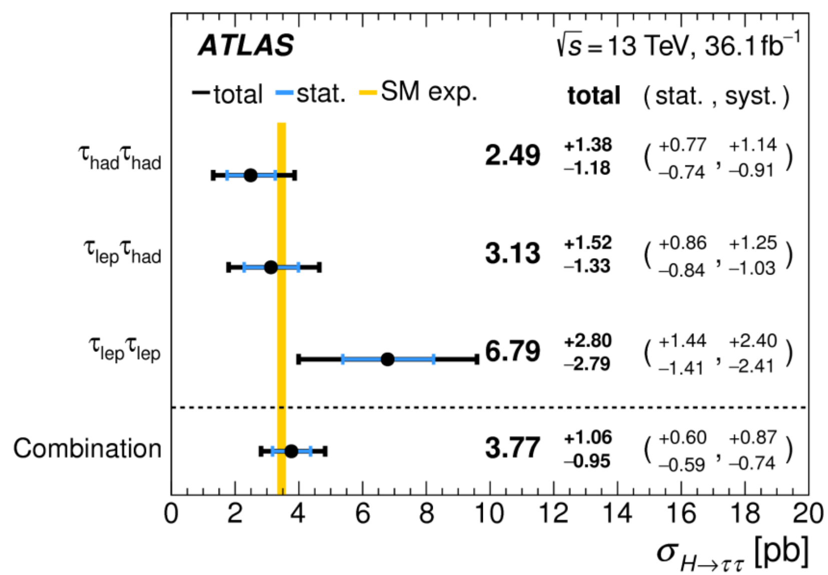
# Higgs and Flavour Physics

SM Higgs to fermions — $\tau\tau$

A closer look at the evidence with more data and higher energies:



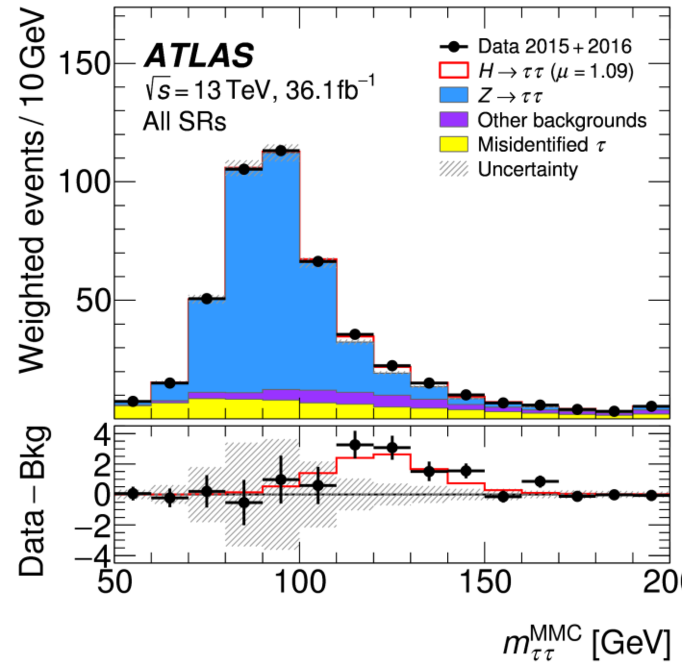



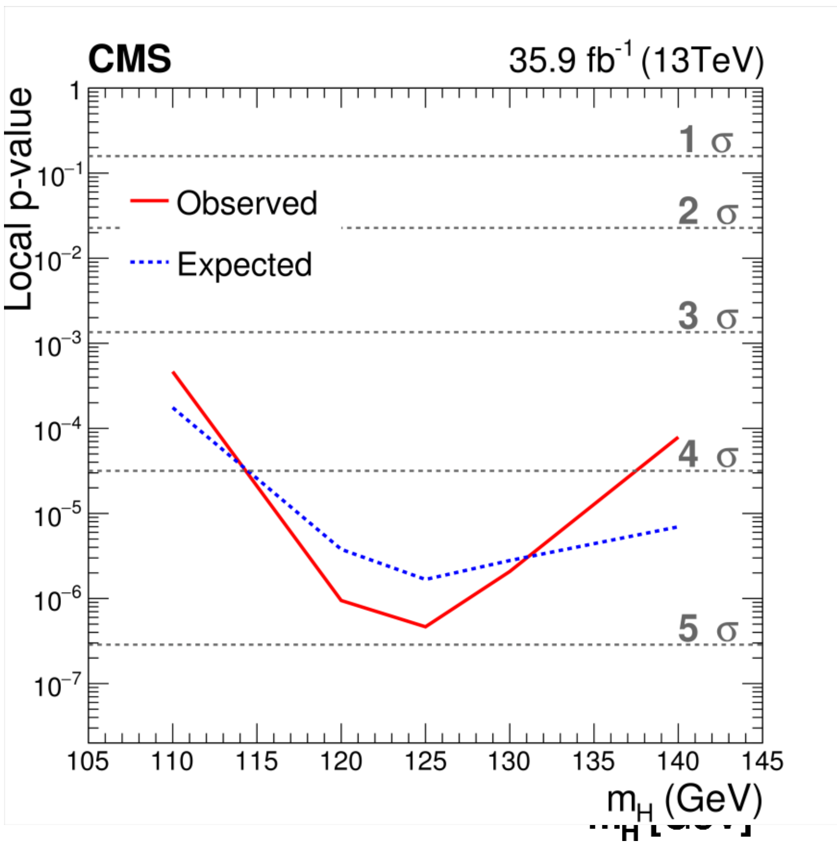



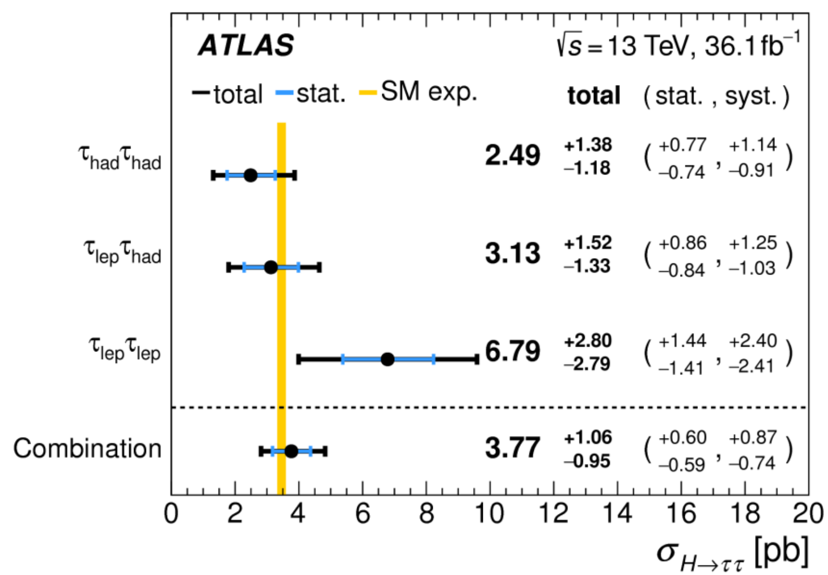
# Higgs and Flavour Physics

SM Higgs to fermions — $\tau\tau$

A closer look at the evidence with more data and higher energies:



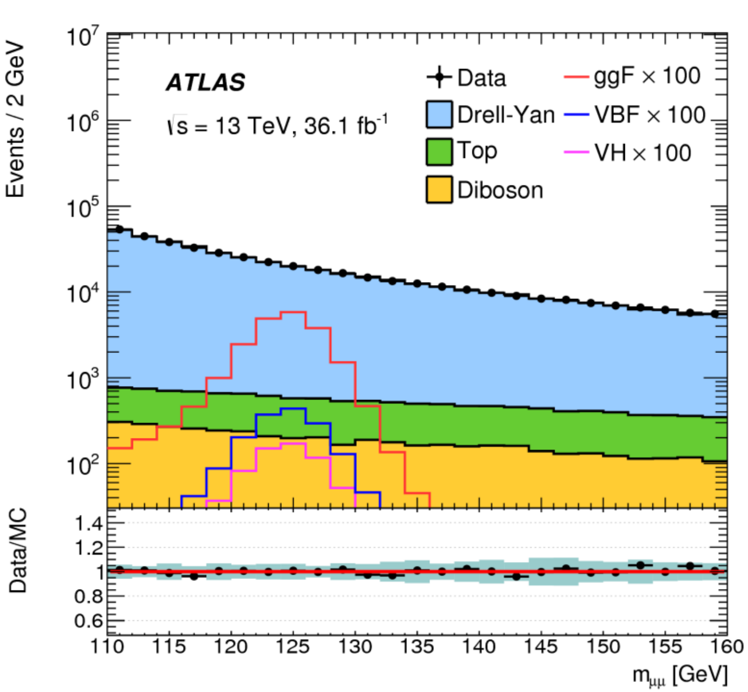
# Higgs and Flavour Physics

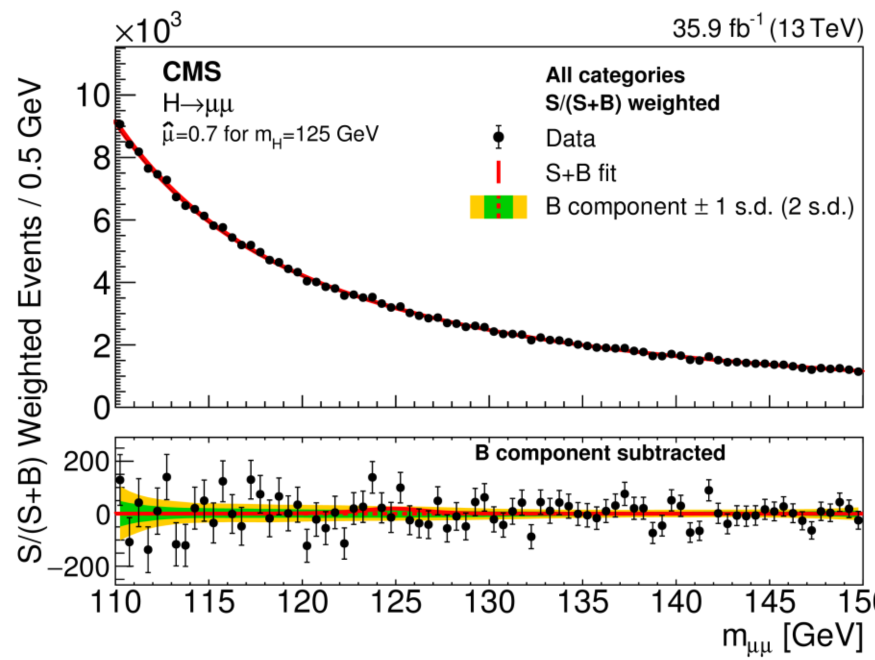
SM Higgs to fermions — $\mu\mu$

[ ATLAS Phys. Rev. Lett. 119 (2017) 051802, CMS-PAS-HIG-17-019 ]

Low branching fraction (ten times smaller than $\gamma\gamma$), mainly data-driven fit akin to $H \rightarrow \gamma\gamma$

- Slight complication due to sum of dominant DY and sub-dominant $tt$, $WW$ backgrounds
- Separation of jet (gluon fusion, VBF), and $S/B$ (central, non-central) categories



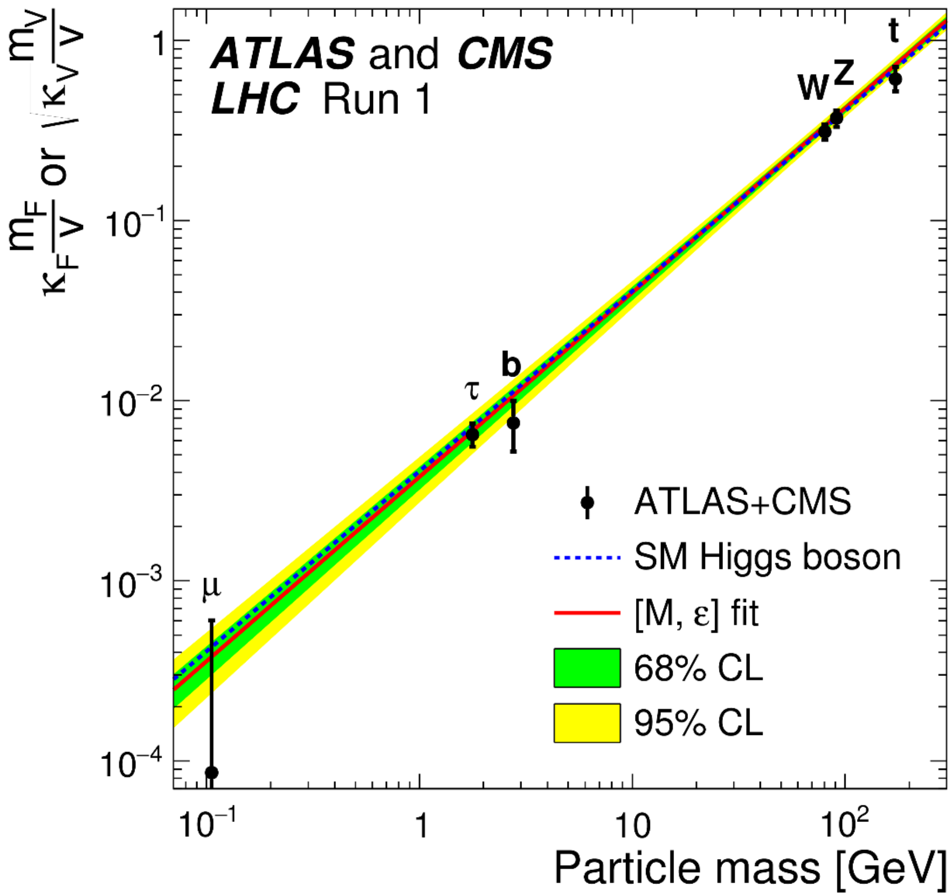

**At 125 GeV:**

**ATLAS** (7+8+13 TeV):
$\mu$ < 2.8 (2.9 exp.) x SM value(95% CL)

CMS (7+8+13 TeV):
$\mu$ < 2.92 (2.16 exp.) x SM value (95% CL)

# Higgs bottom line for Run I (7 + 8 TeV)

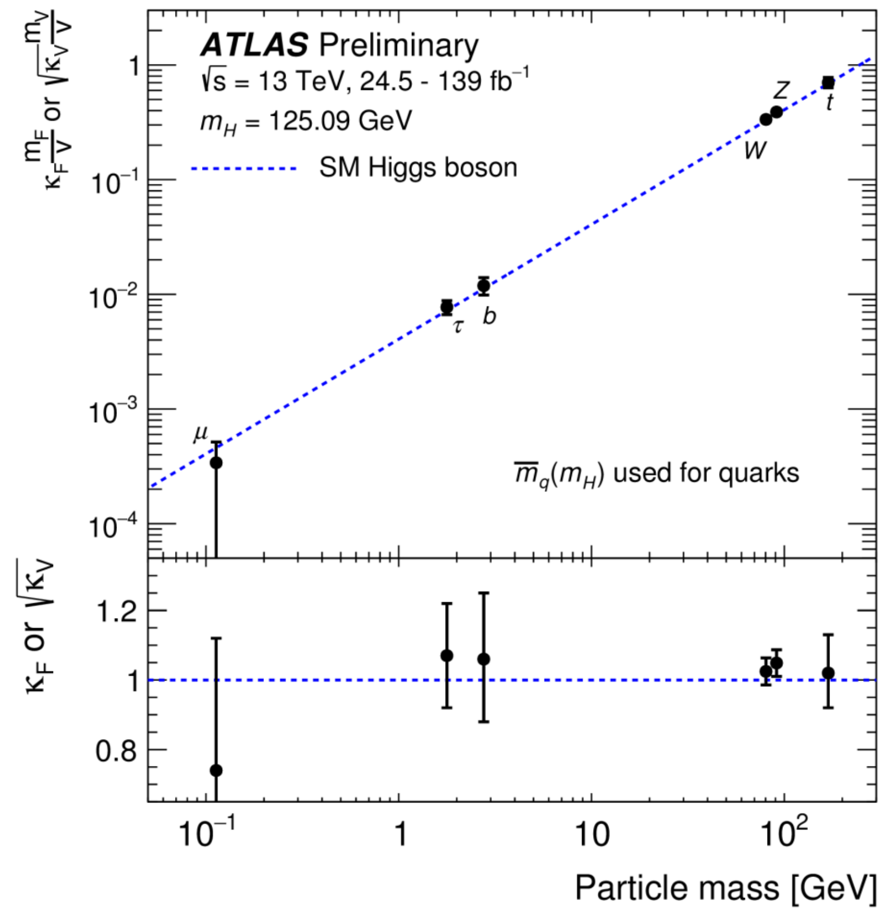
Great measurements — the overall picture is as expected in the SM


***Particle mass proportional to coupling to Higgs field***

# Higgs bottom line for Run 2 (13 TeV)

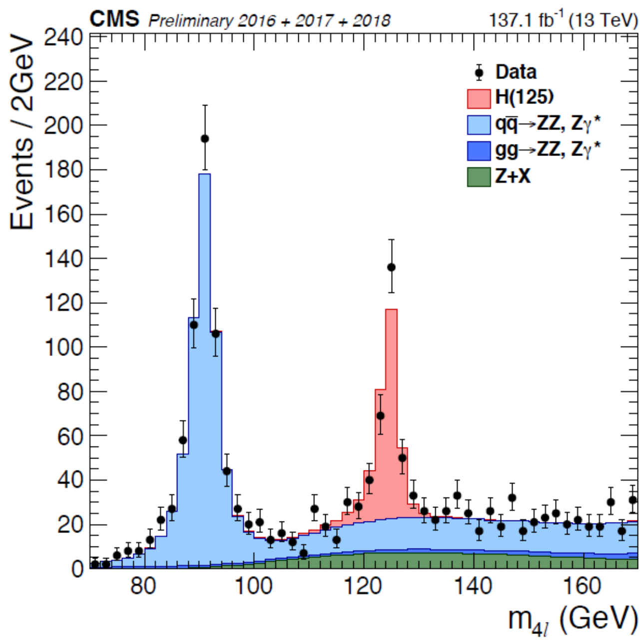
Great measurements — the overall picture is as expected in the SM

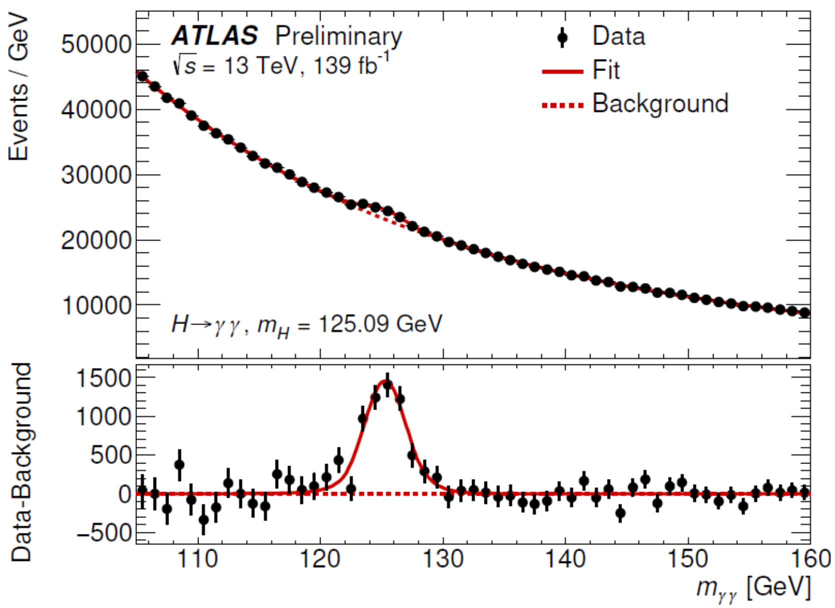

***Particle mass proportional to coupling to Higgs field***

# Full Run 2 results on the ”easy” channels

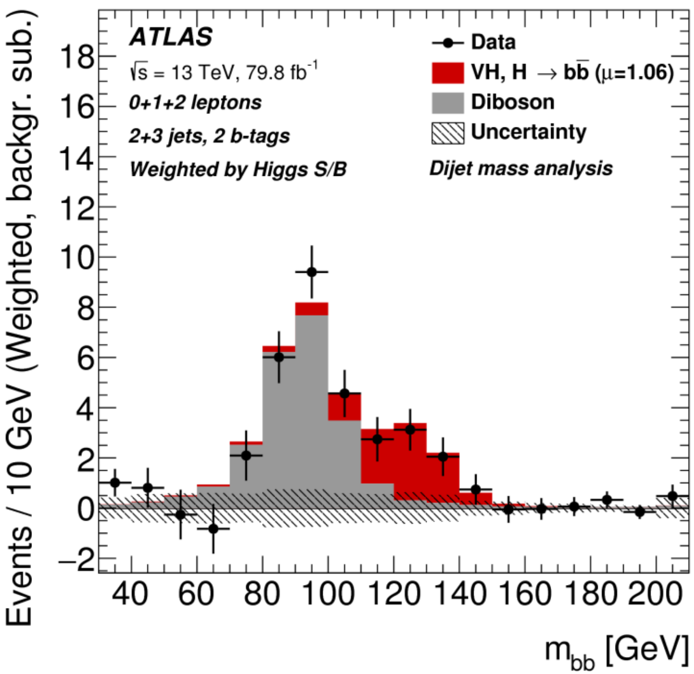
H$\rightarrow$ ZZ $\rightarrow$ 4lep

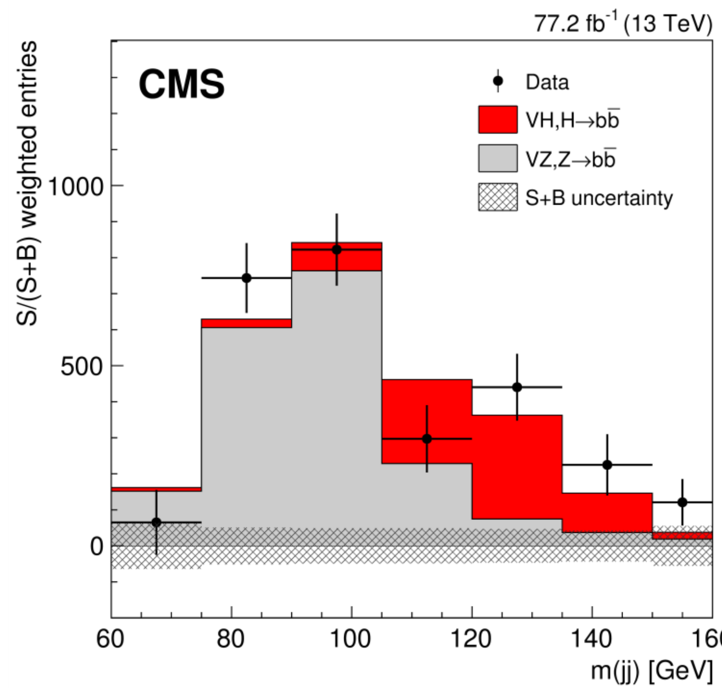



H$\rightarrow$ $\gamma\gamma$



# The most likely decay channel: $b\bar{b}$



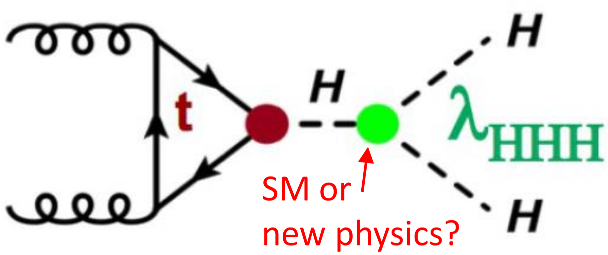



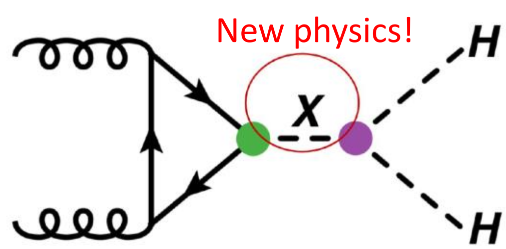

This is only half the Run 2 dataset, so more to come. But it really looks like a SM Higgs ...

# The Higgs potential: di-higgs

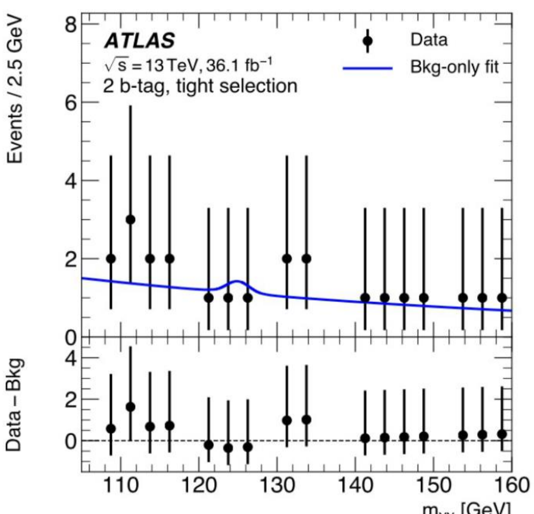
What is the origin of the potential and what does it really look like?

Expand lambda close to origin and get terms depending on Higgs self-couplings (3 or 4 higgs interactions).



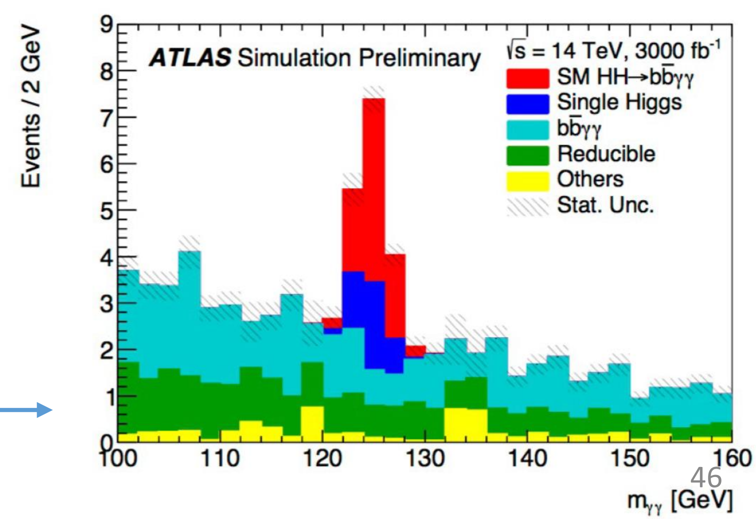




Unfortunately RARE, destructive interference. Showing $bb\gamma\gamma$ as example:




Current sensitivity

Prospects for high luminosity LHC

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# Summary/outlook

- The Higgs field is fundamental for the Standard model
  - *And our Universe!*
- Discovery of the boson took a lot of effort
  - *Needed all parts of the detector, all the ”usual” objects, and with high precision*
  - *It looks like a Standard Model Higgs boson*
- Studying the Higgs boson is another window to find physics beyond the Standard Model
  - *It ”saves” the SM but introduces new problems*
  - *Need to talk about beyond the SM*