FYST17 Lecture 10
The Higgs discovery

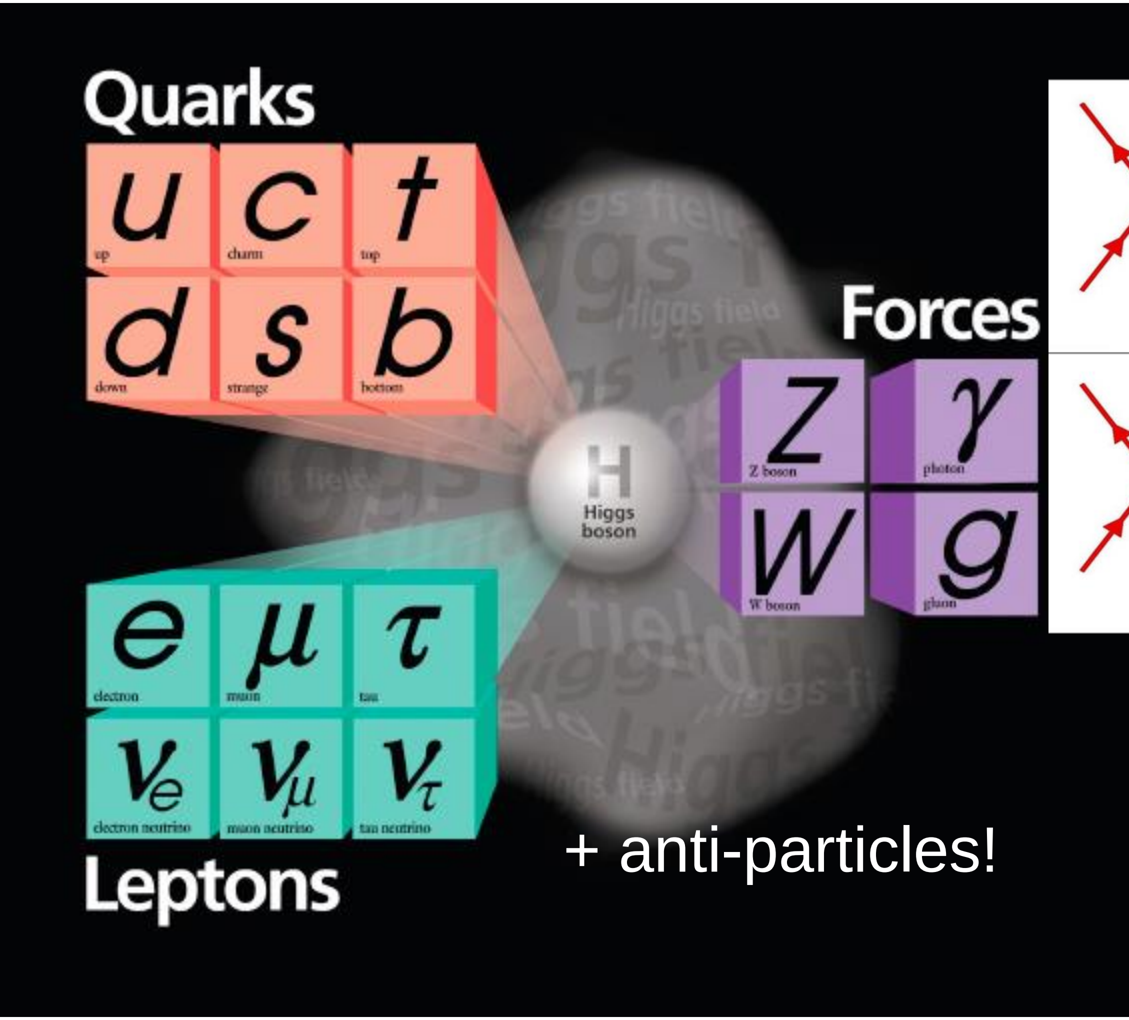
Thanks to A. Hoecker, F. Gianotti, J. Incandela

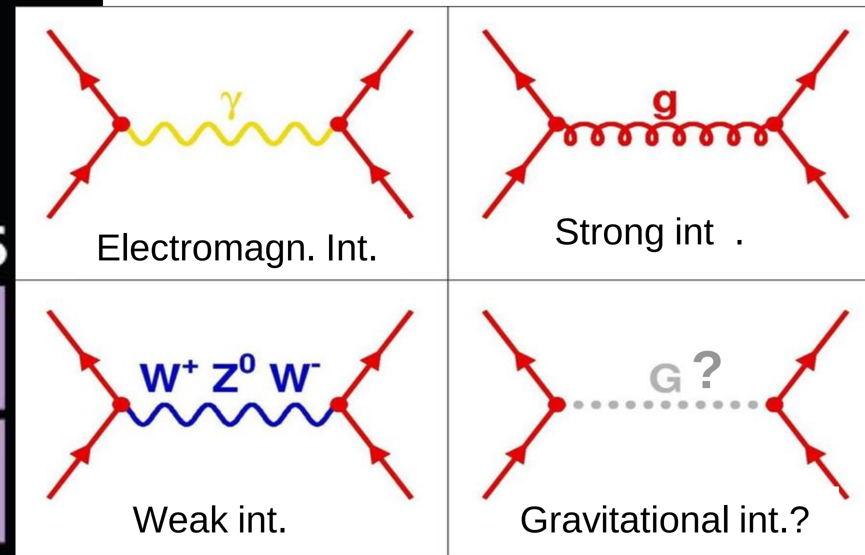
Suggested reading: chapter 12 in G. Barr et al.

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

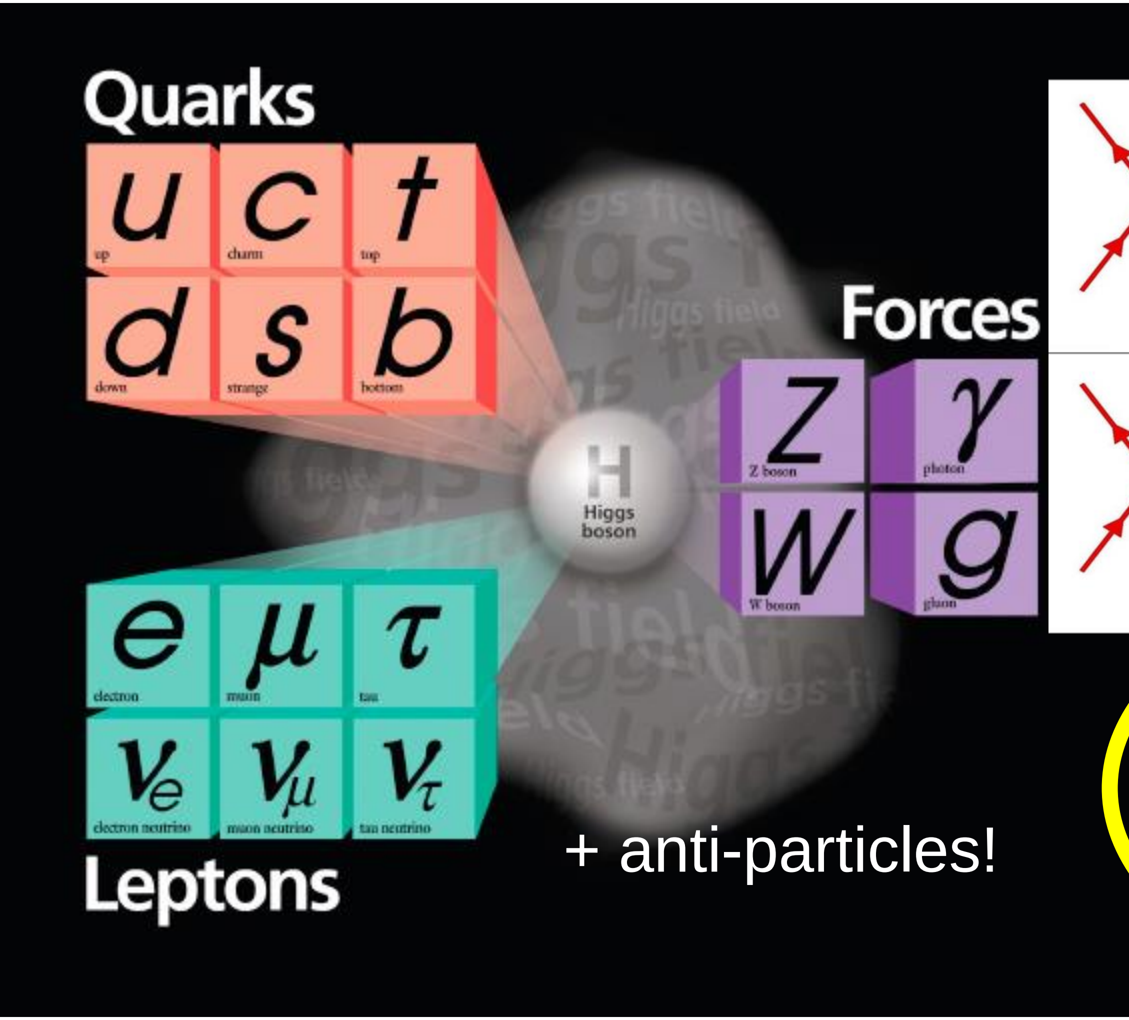


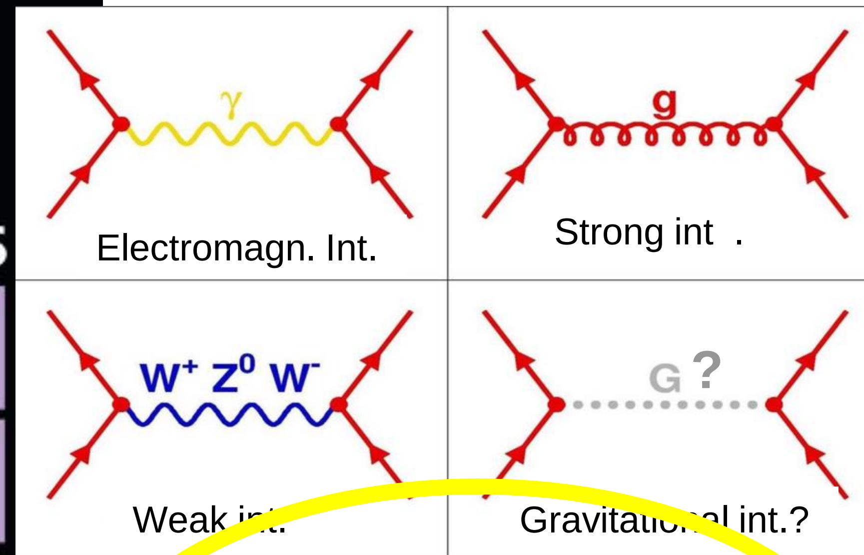


The **Higgs boson** gives mass to the other particles

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

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]

ϕ 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

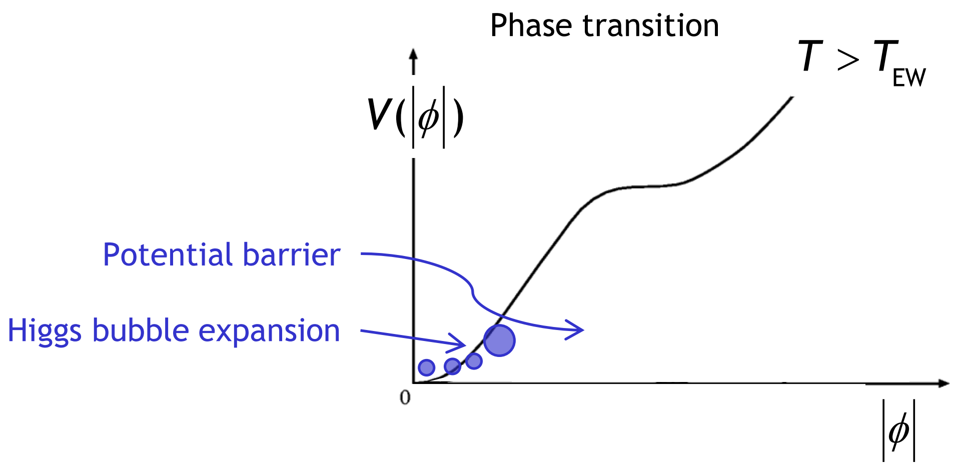
This is known as the **"Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism"**

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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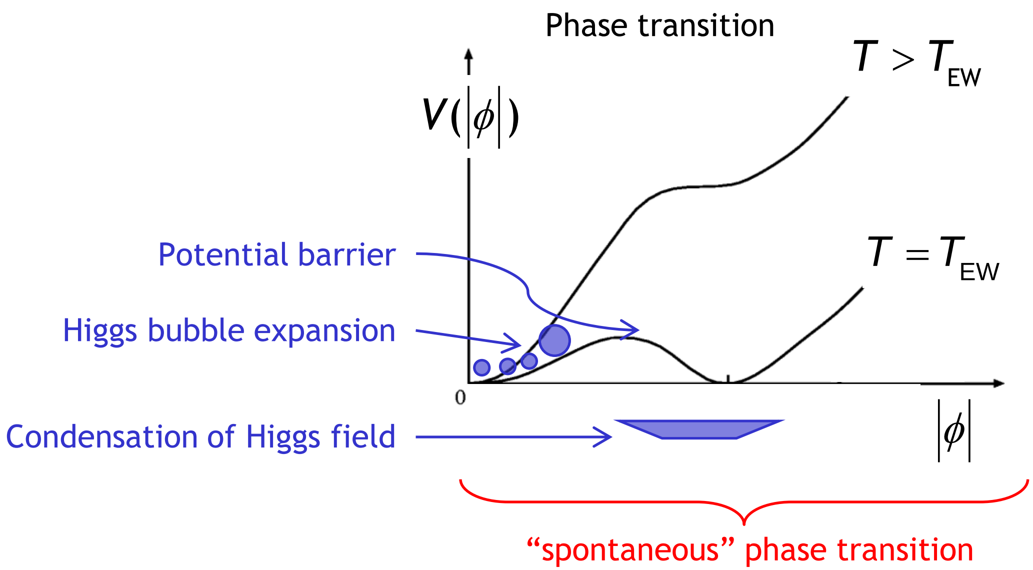


Higgs potential: $V(\phi) = \mu^2_{<0} |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi^i_L \psi^j_R \phi$

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

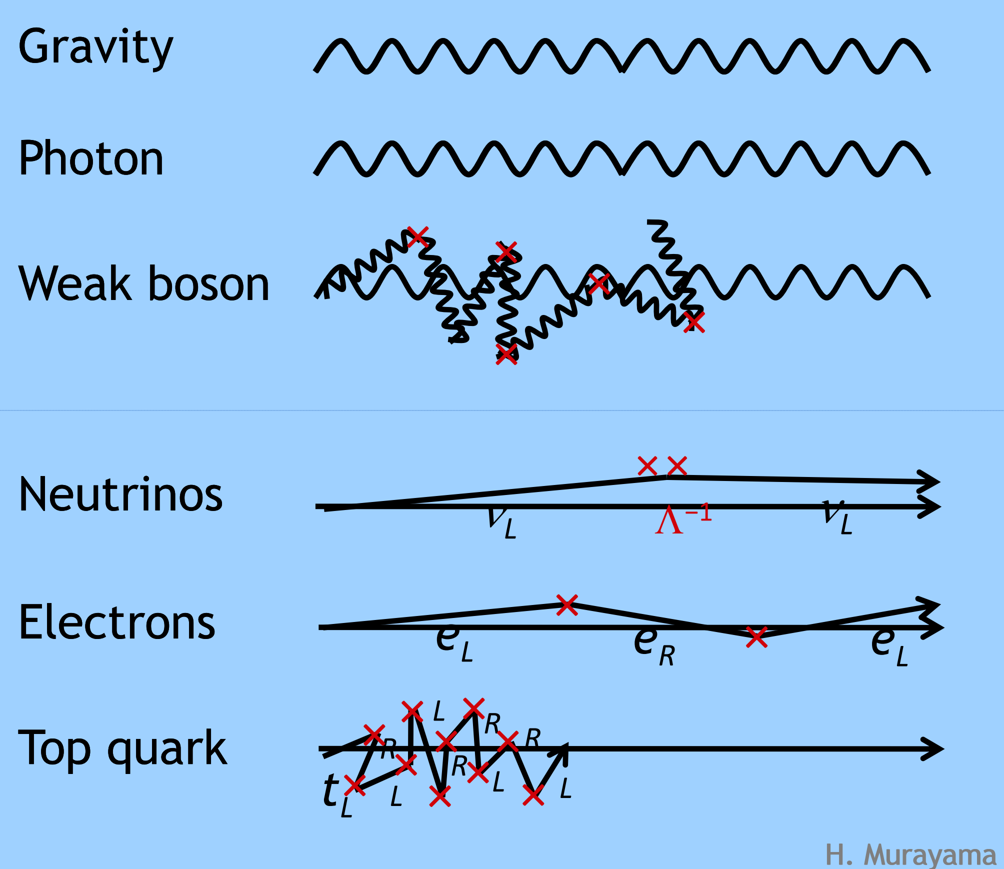
A **Higgs field** displaces ground state breaking gauge symmetry

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**

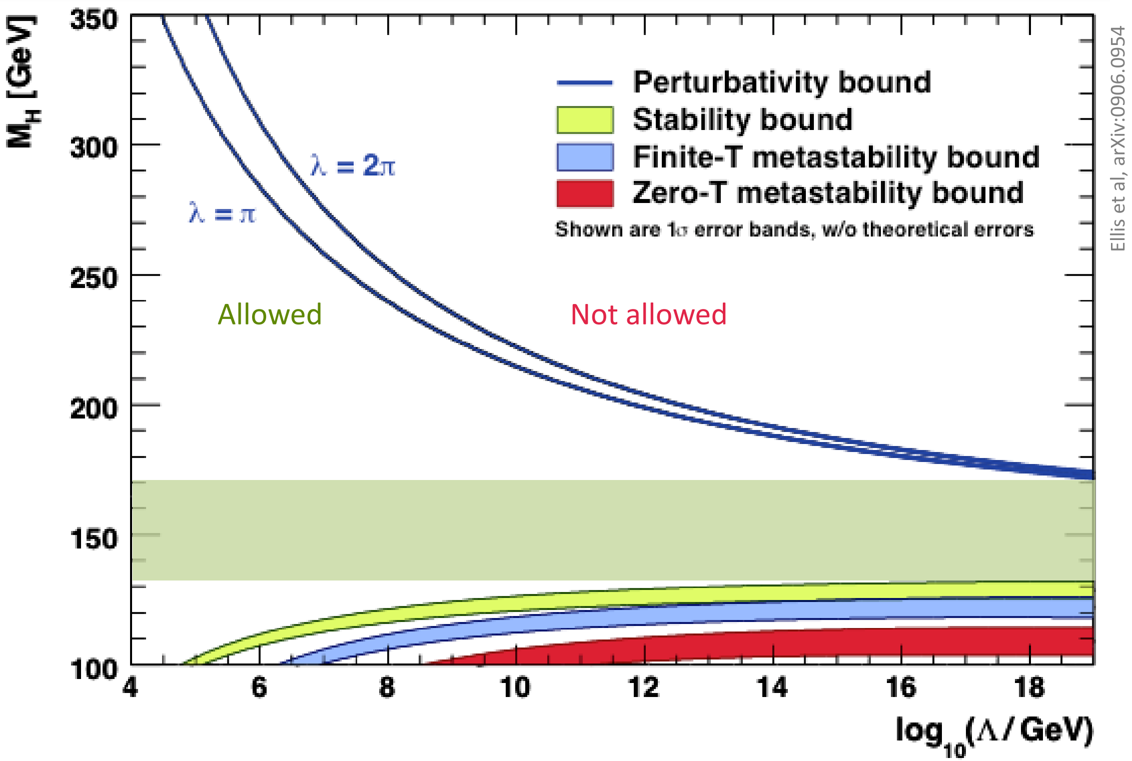
⇒ Action of the Higgs field creates a ***vacuum viscosity***

Symmetric phase - early universe
Higgs quantum liquid in broken phase



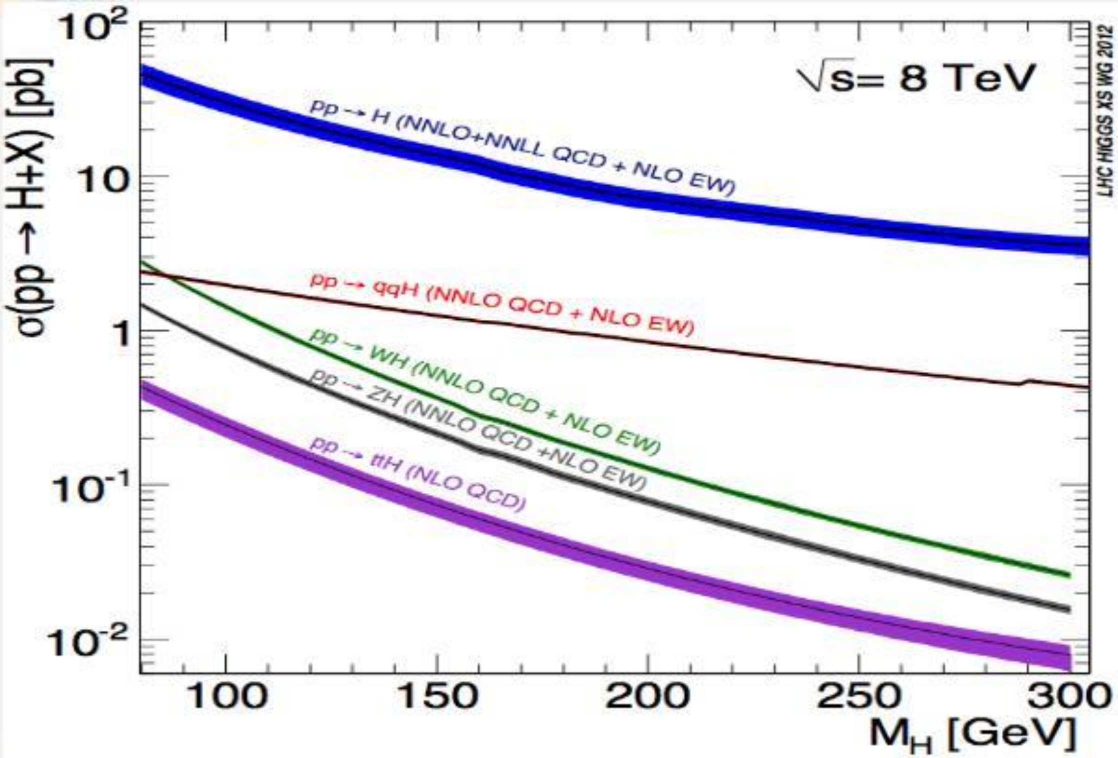
The Higgs boson should not be too light, and not too heavy…

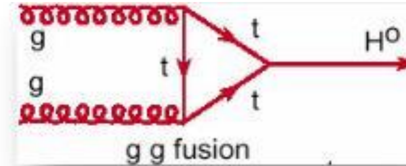
Perturbativity and (meta)stability bounds versus the SM cut-off scale Λ

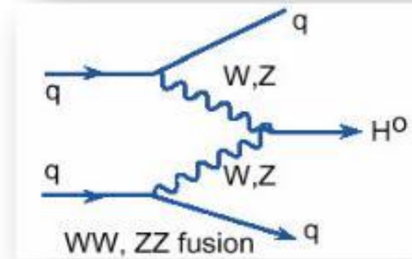


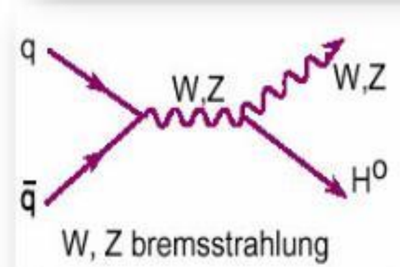
The SM Higgs must steer a narrow course between two disastrous situations if the SM is to survive up to the Planck scale $M_P \sim 2\times10^{18}$ GeV

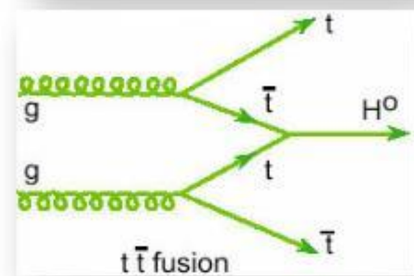
Higgs production at the LHC









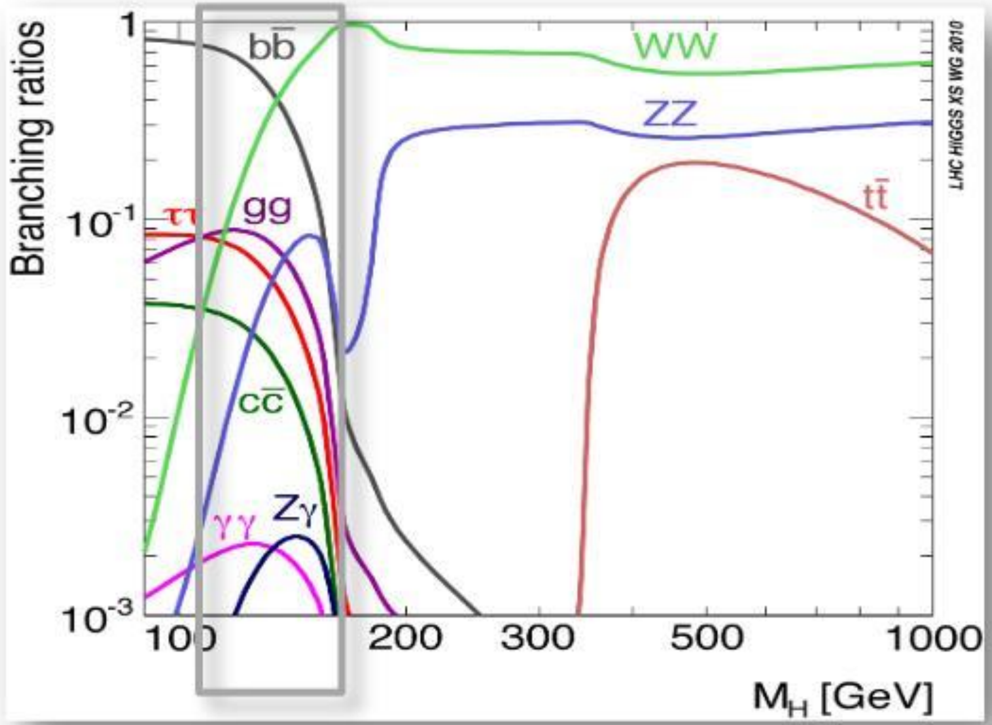


- $\sqrt{s}$=8 TeV: 25-30% higher σ than $\sqrt{s}$=7 TeV at low m_H
- All production modes to be exploited
  - gg VBF VH ttH
  - Latter 3 have smaller cross sections but better S/B in many cases

Most important decay modes

5 decay modes exploited

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



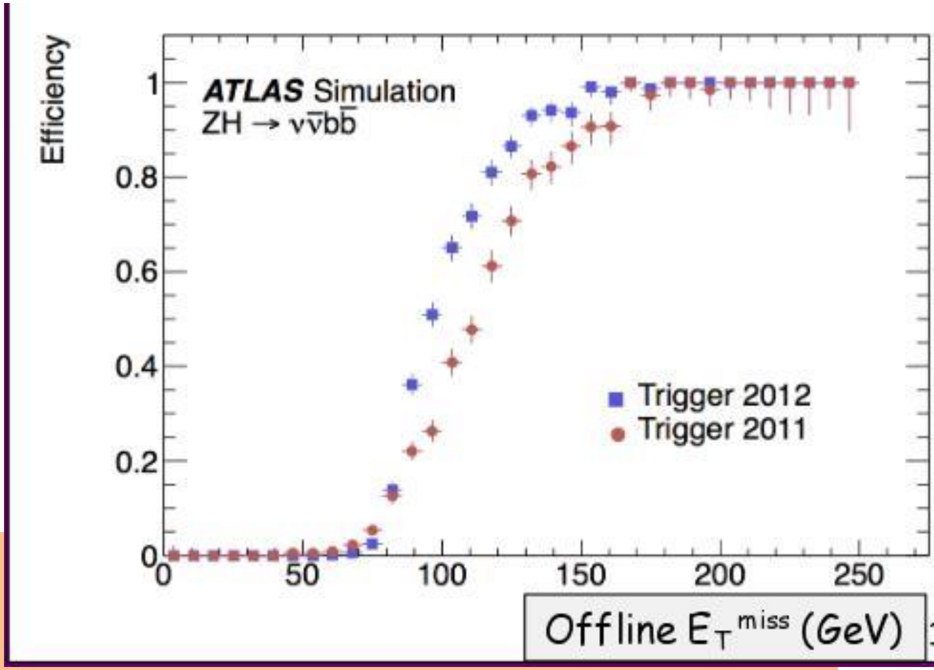
4th of July, 2012 — Higgs-day at CERN

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



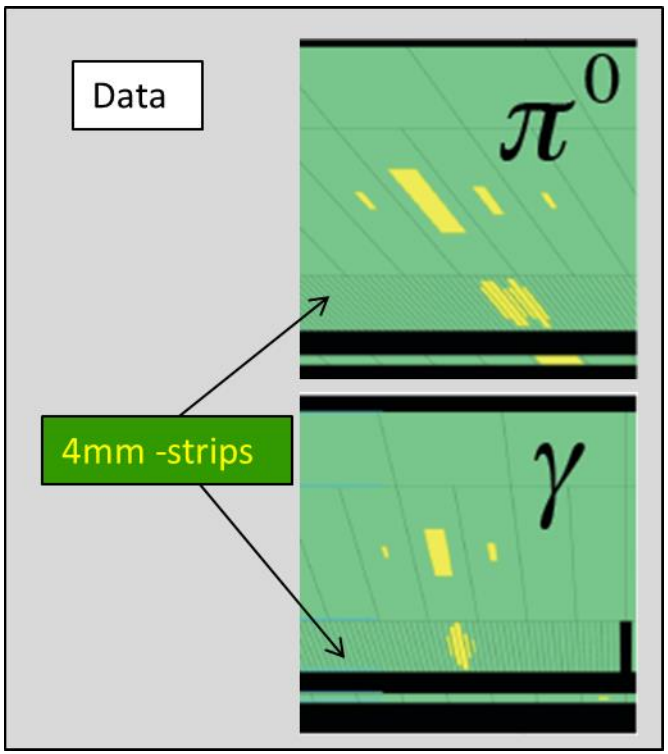
Final analysis uses a combination of several triggers, several "channels" for maximal sensitivity

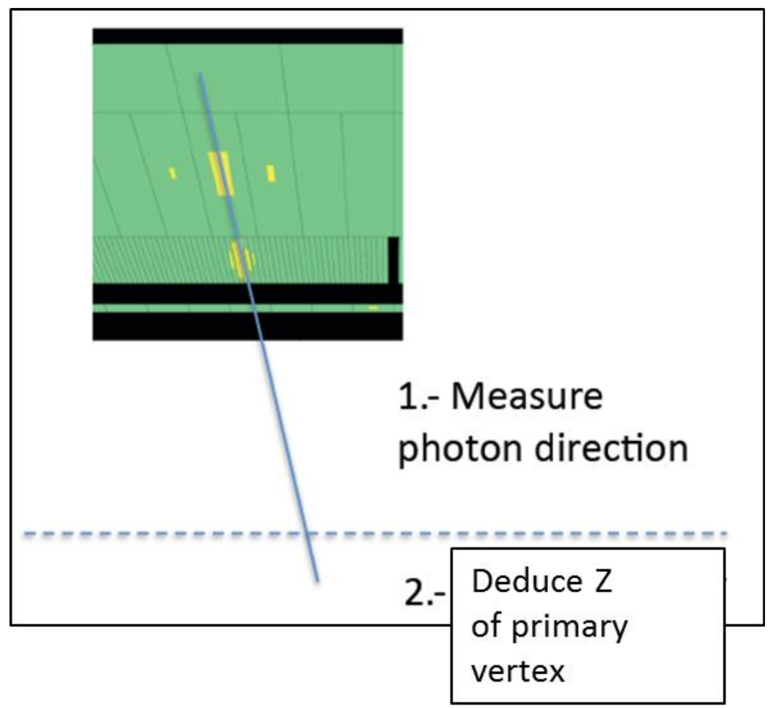
Reconstructing photons

Without a track, can we tell the difference between γ and π^0?

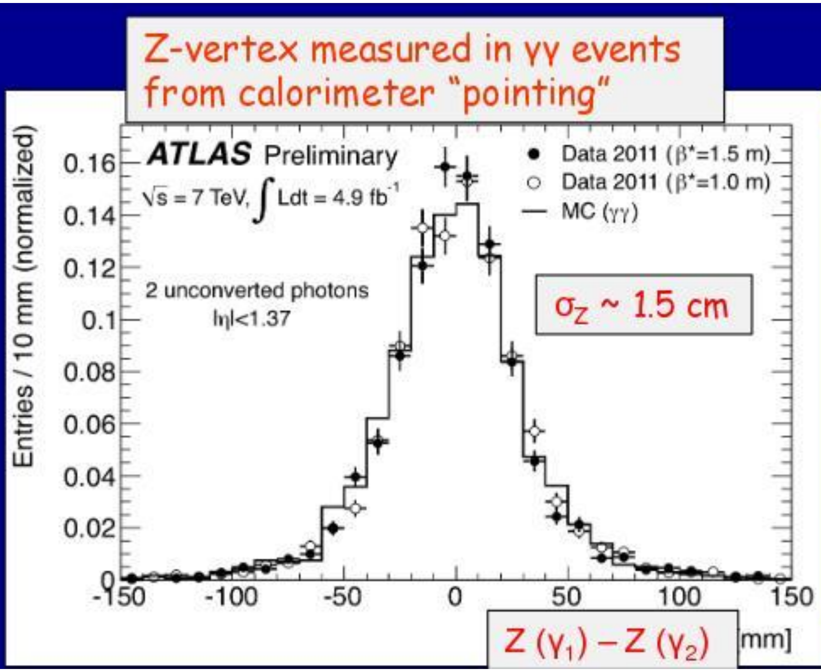
Crucial for $H \rightarrow \gamma\gamma$ search!

ATLAS uses the fine segmentation of the EM calorimeter to measure γ 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

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

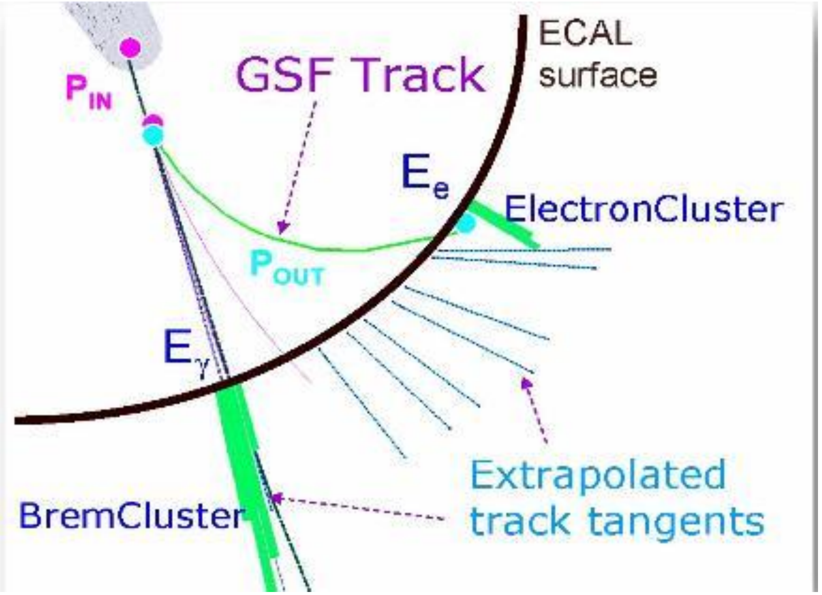
Resolution 1.6 GeV (linearity + uniformity terms ~1%)

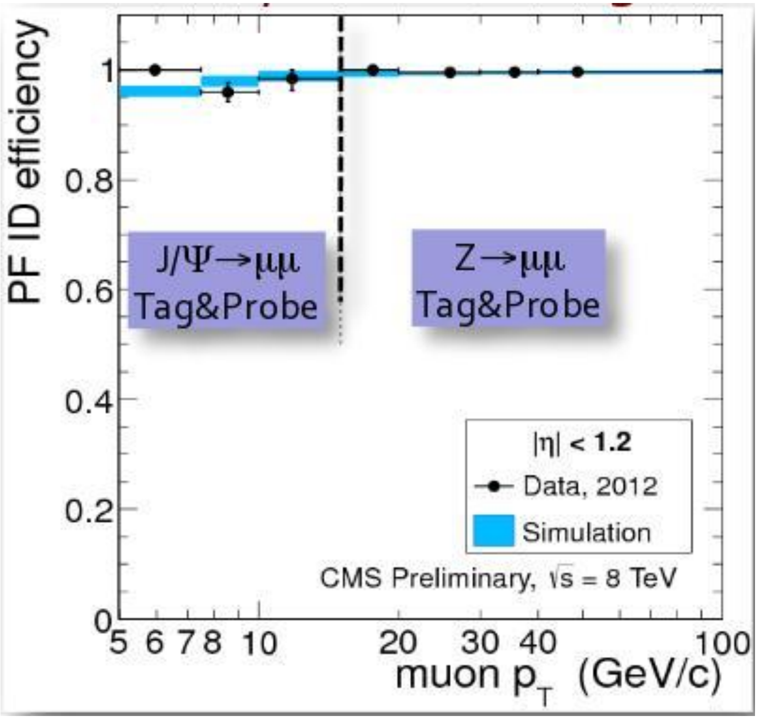
Reconstructing leptons (e,μ)

Typically reconstructed with high efficiency

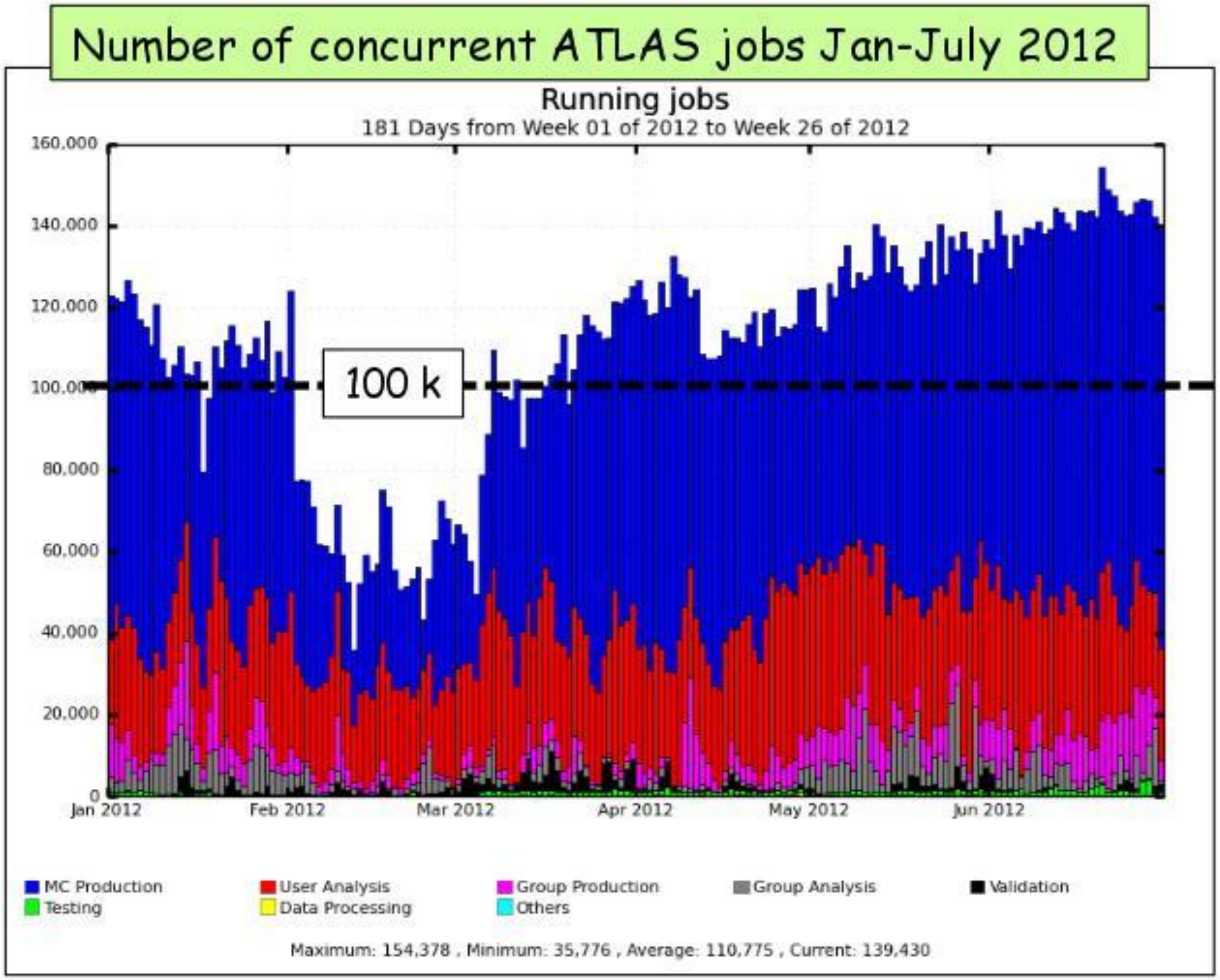
- electron selection based on likelihoods and multivariate techniques to reduce backgrounds

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





Computing

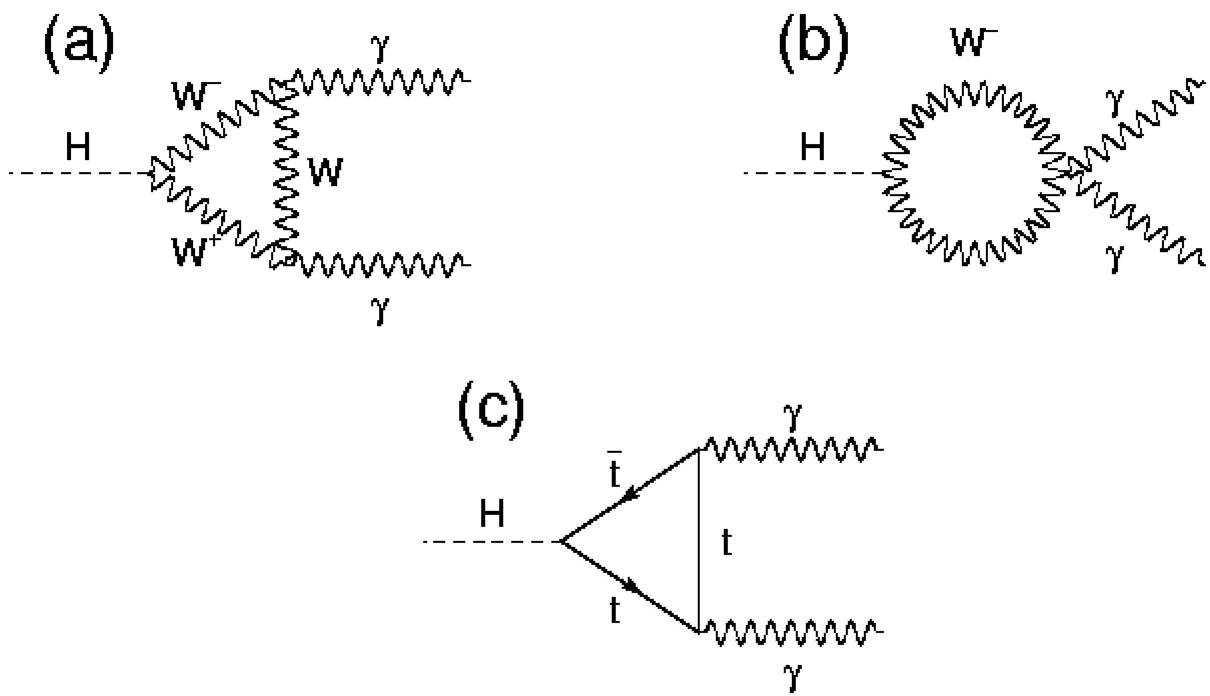


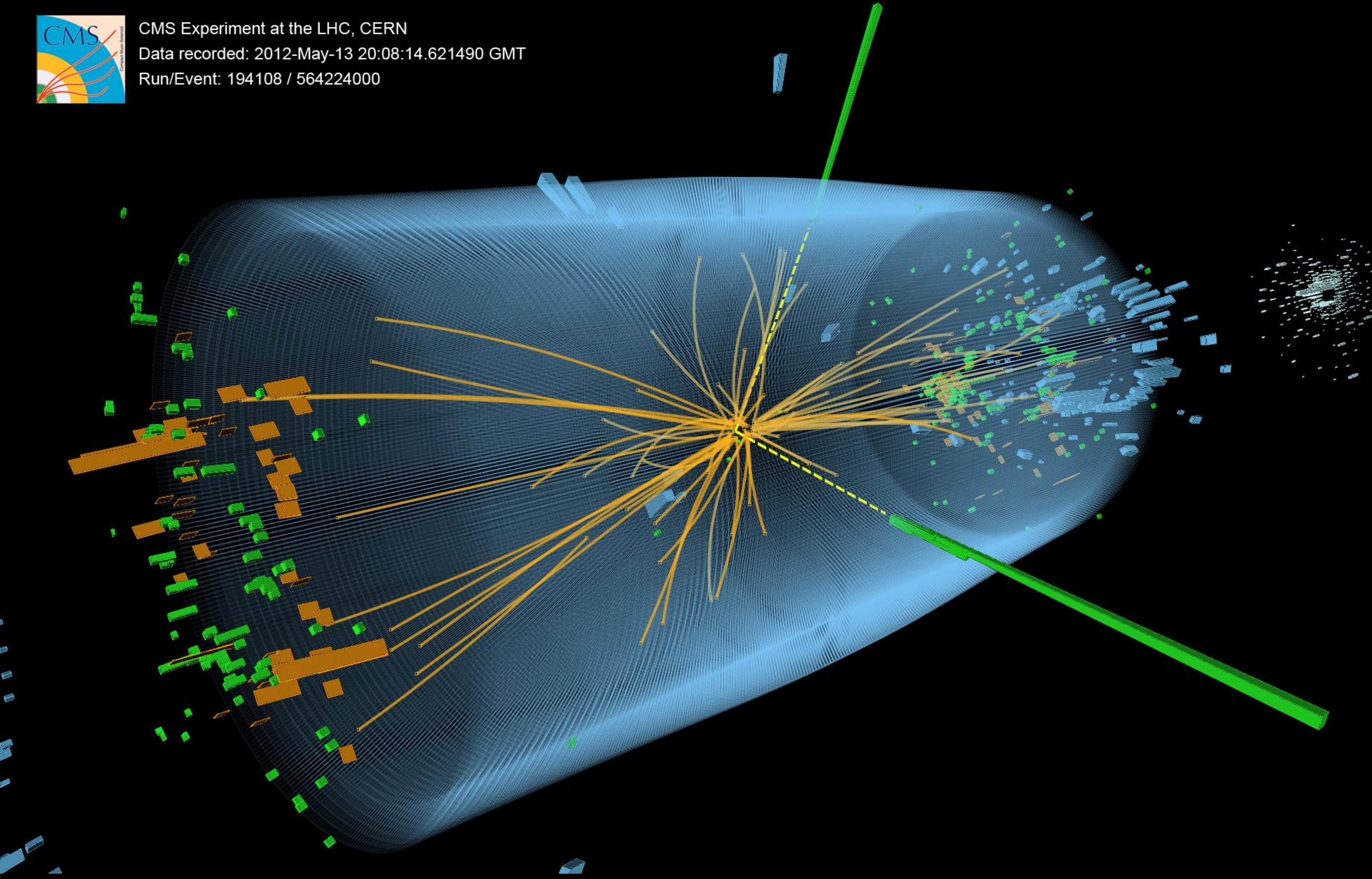
Number of concurrent ATLAS jobs Jan-July 2012
Running jobs
181 Days from Week 01 of 2012 to Week 26 of 2012
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
Jan 2012
Feb 2012
Mar 2012
Apr 2012
May 2012
Jun 2012
100 k
MC Production
User Analysis
Group Production
Group Analysis
Validation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

$H \to \gamma\gamma$

Most important channel for Higgs masses below 150 GeV!

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





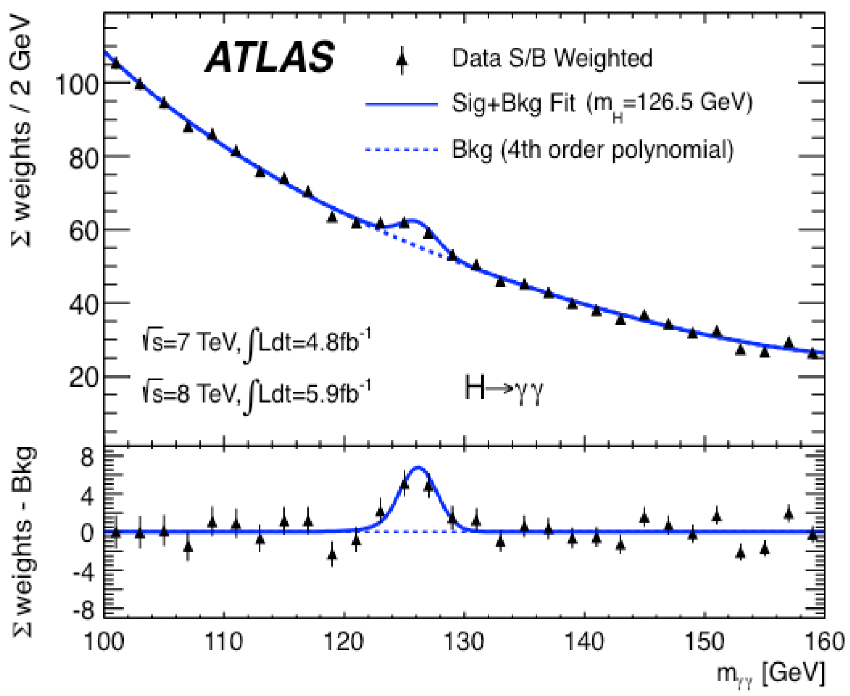
H $\rightarrow \gamma\gamma$ *candidate event (CMS)*

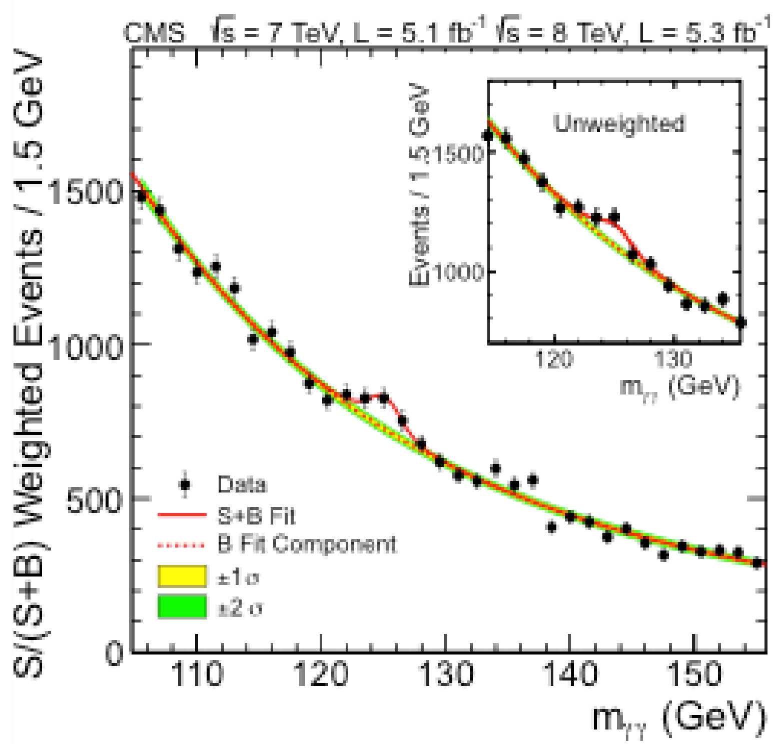
$H \to \gamma\gamma$

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

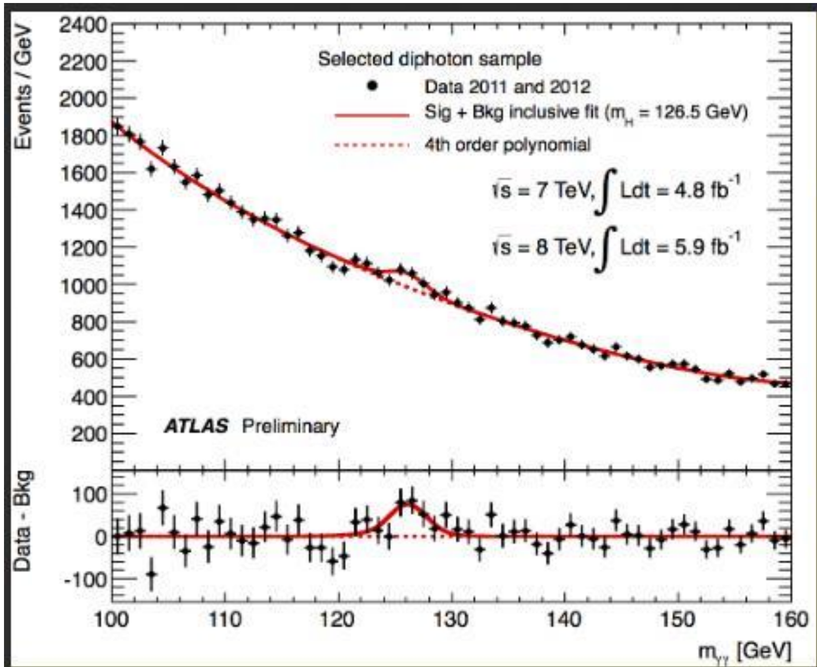




Both experiments classify events according to resolution and topology in ML fit

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

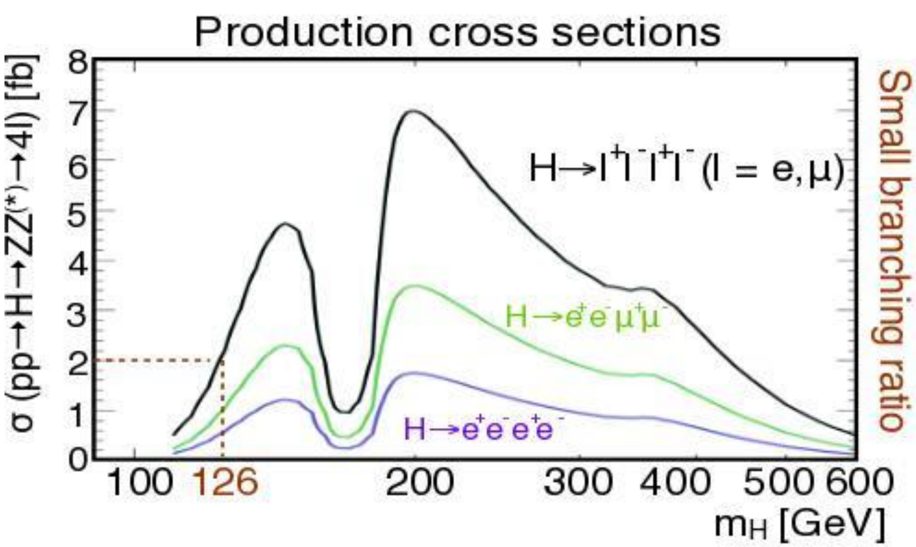
Main systematic uncertainties

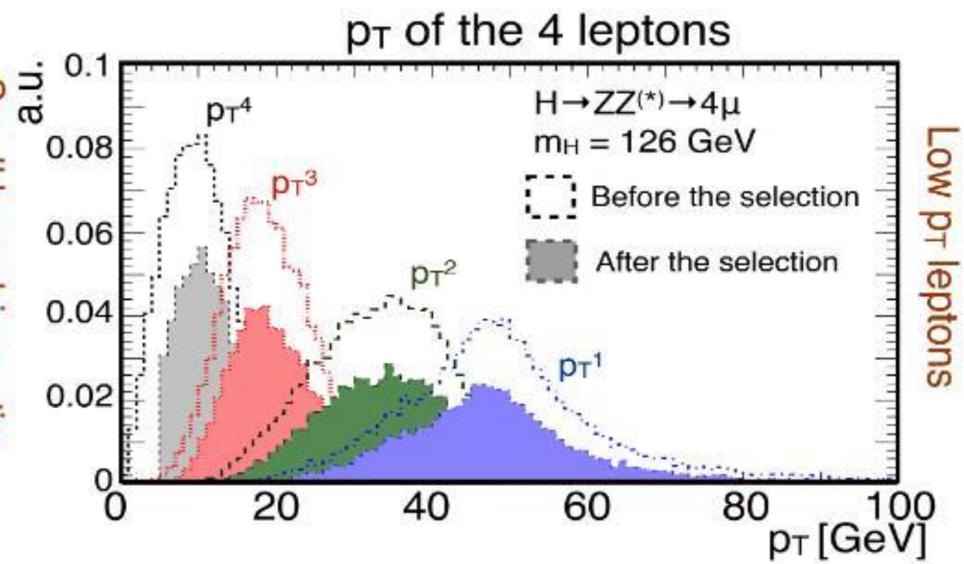
Signal yield	
Theory	~ 20%
Photon efficiency	~ 10%
Background model	~ 10%
Categories migration	
Higgs p_T modeling	up to ~ 10%
Conv/unconv γ	up to ~ 6%
Jet E-scale	up to 20% (2j/VBF)
Underlying event	up to 30% (2j/VBF)
$H \rightarrow \gamma\gamma$ mass resolution	~ 14%
Photon E-scale	~ 0.6%

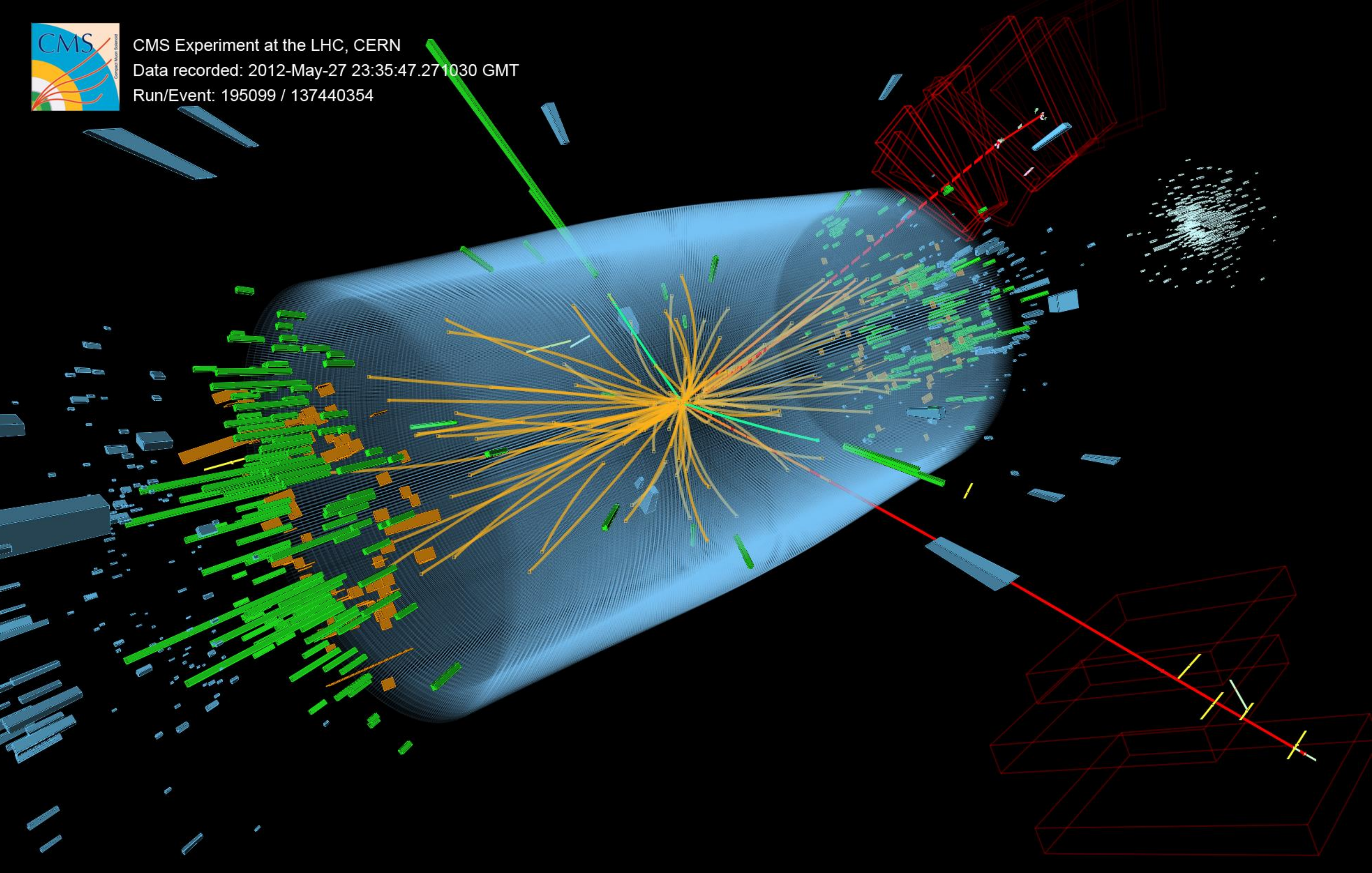
$H \rightarrow ZZ^*$

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).







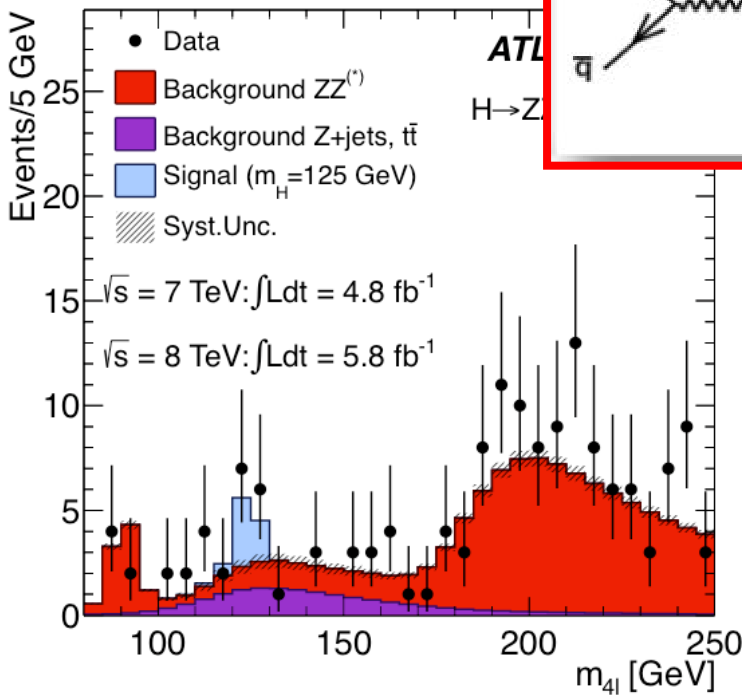
$H \to 2e2\mu$ candidate event (CMS)

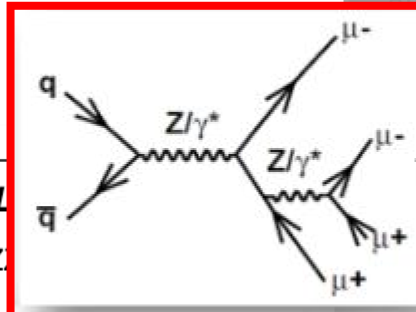
$H \to ZZ^{(*)} \to 2(e, \mu) + 2(e, \mu)$

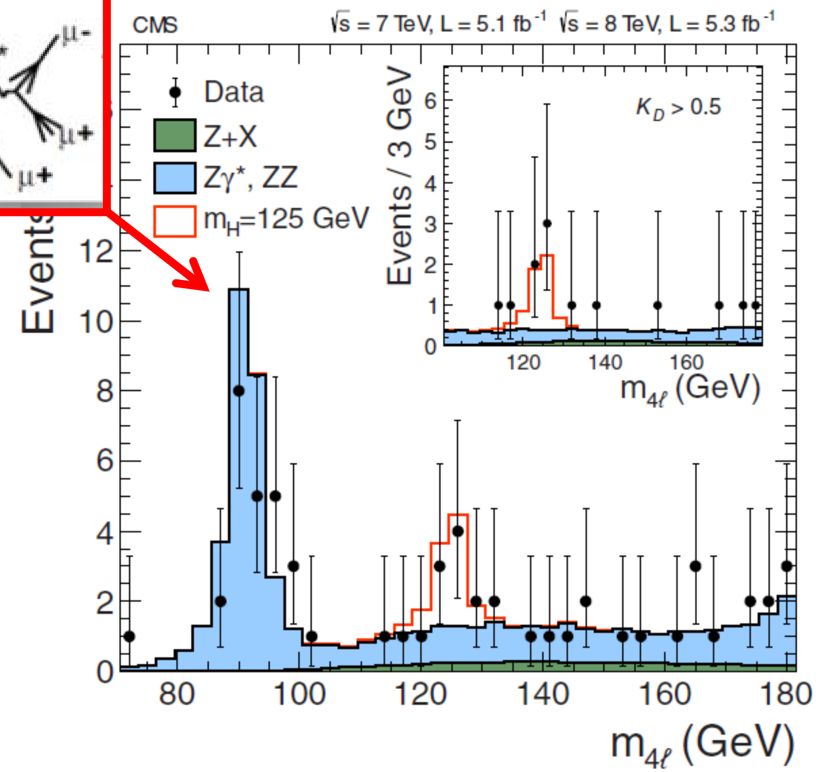
Clean discovery channels for Higgs, allowing precise mass determination

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

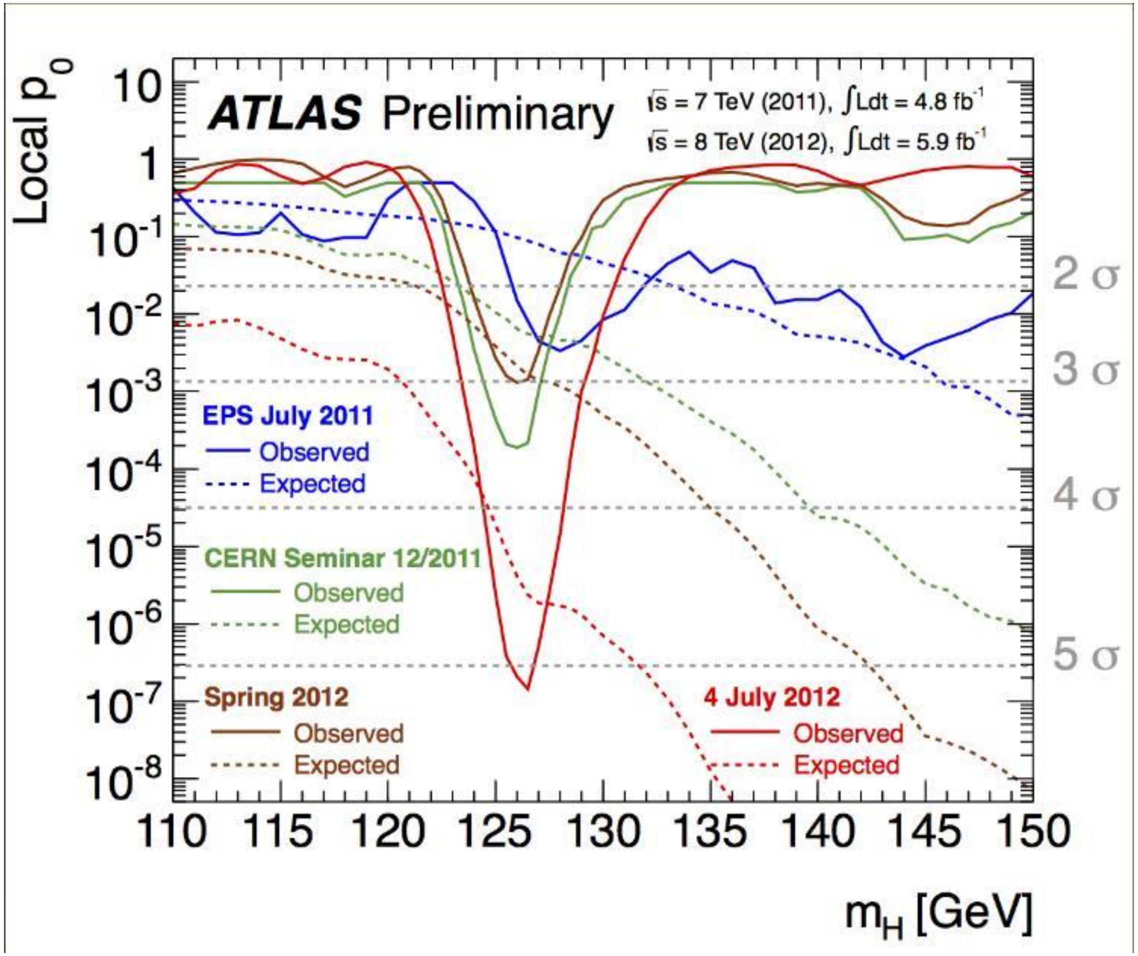






Order one S/B ratio. Maximum excess of 3.6σ (3.2σ) seen by ATLAS (CMS) at 125 (125.6) GeV

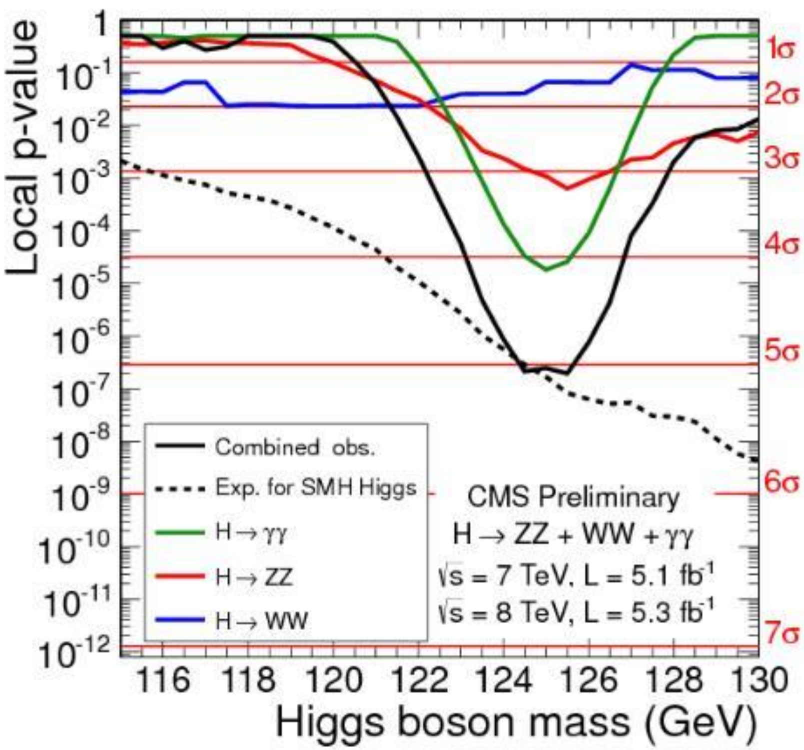
ATLAS combined July 2012



Max excess
@ 126.5 GeV
Local significance:
5 sigma
p-value: 3 x 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

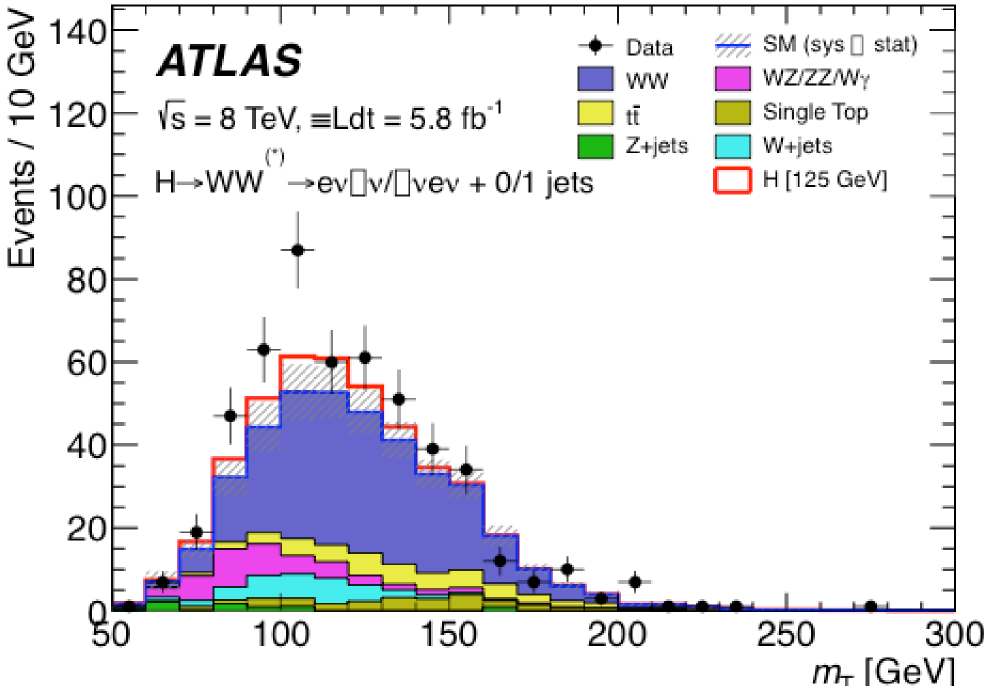
Other channels

- **H → WW → lvlv**

Less clean, little mass sensitivity but abundant

Result:

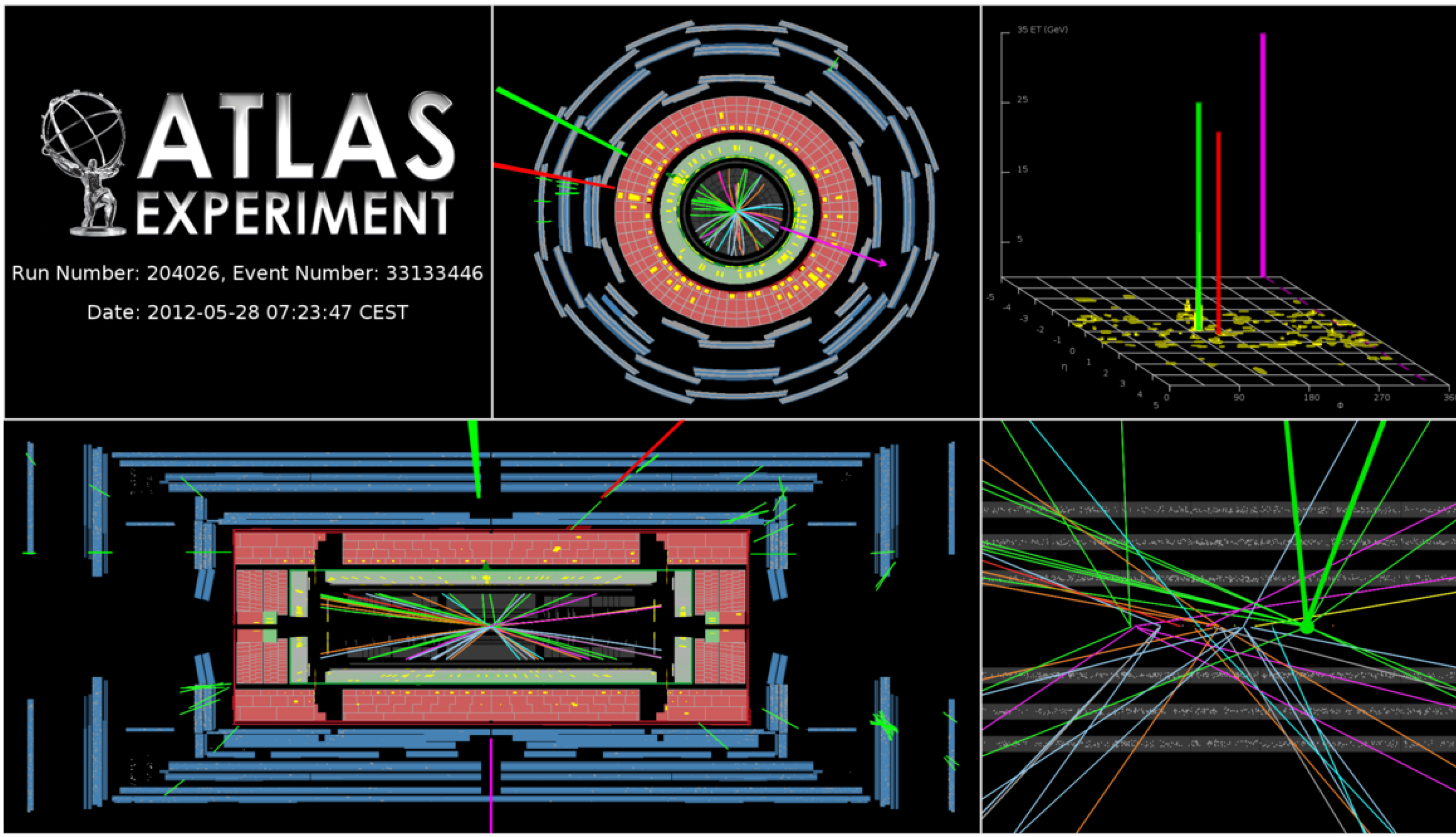
roughly 2σ/experiment



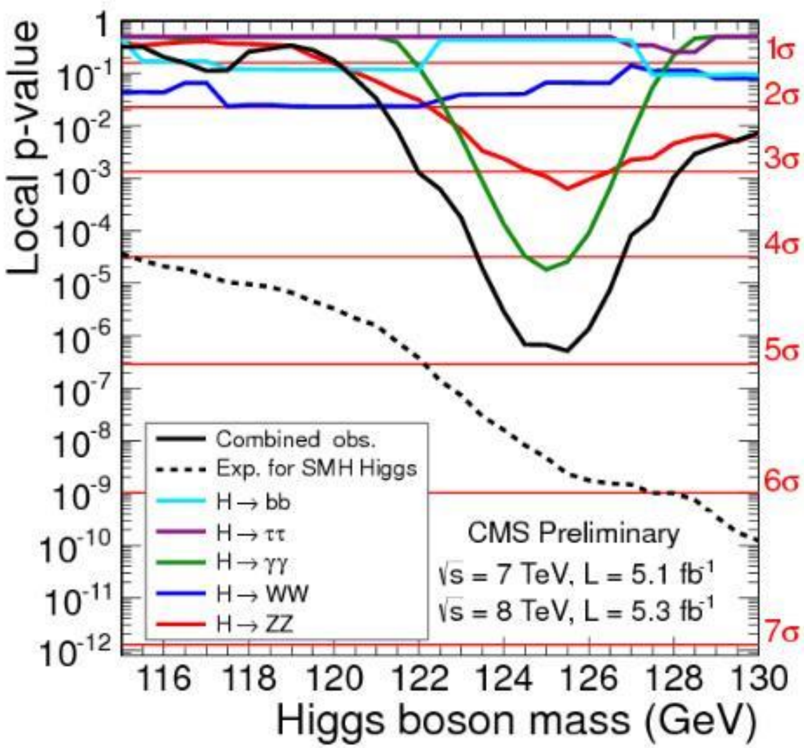
- **Associated production WH, ZH**
- **H →ττ**

Little sensitivity in first analysis

$H \rightarrow WW$ 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!

Combining all the channels

ATLAS: $m_H = (126.0 \pm 0.4 \pm 0.4)$ GeV

CMS: $m_H = (125.3 \pm 0.4 \pm 0.5)$ GeV

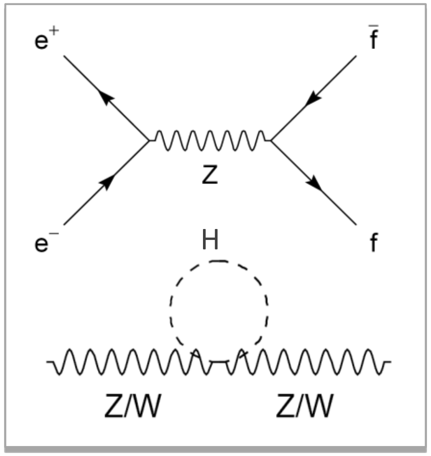
$m_H \sim (125.7 \pm 0.4)$ GeV

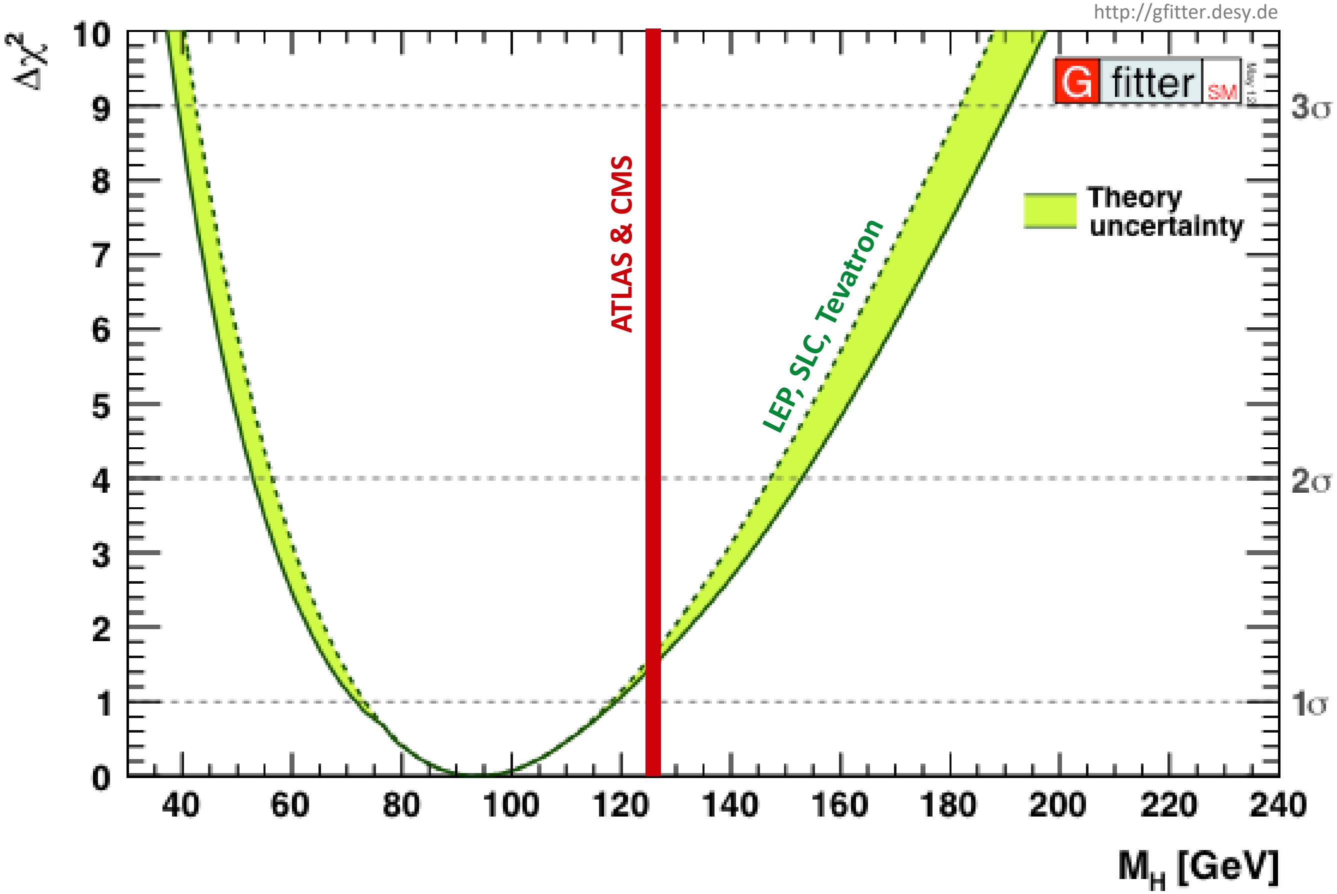
Private average

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

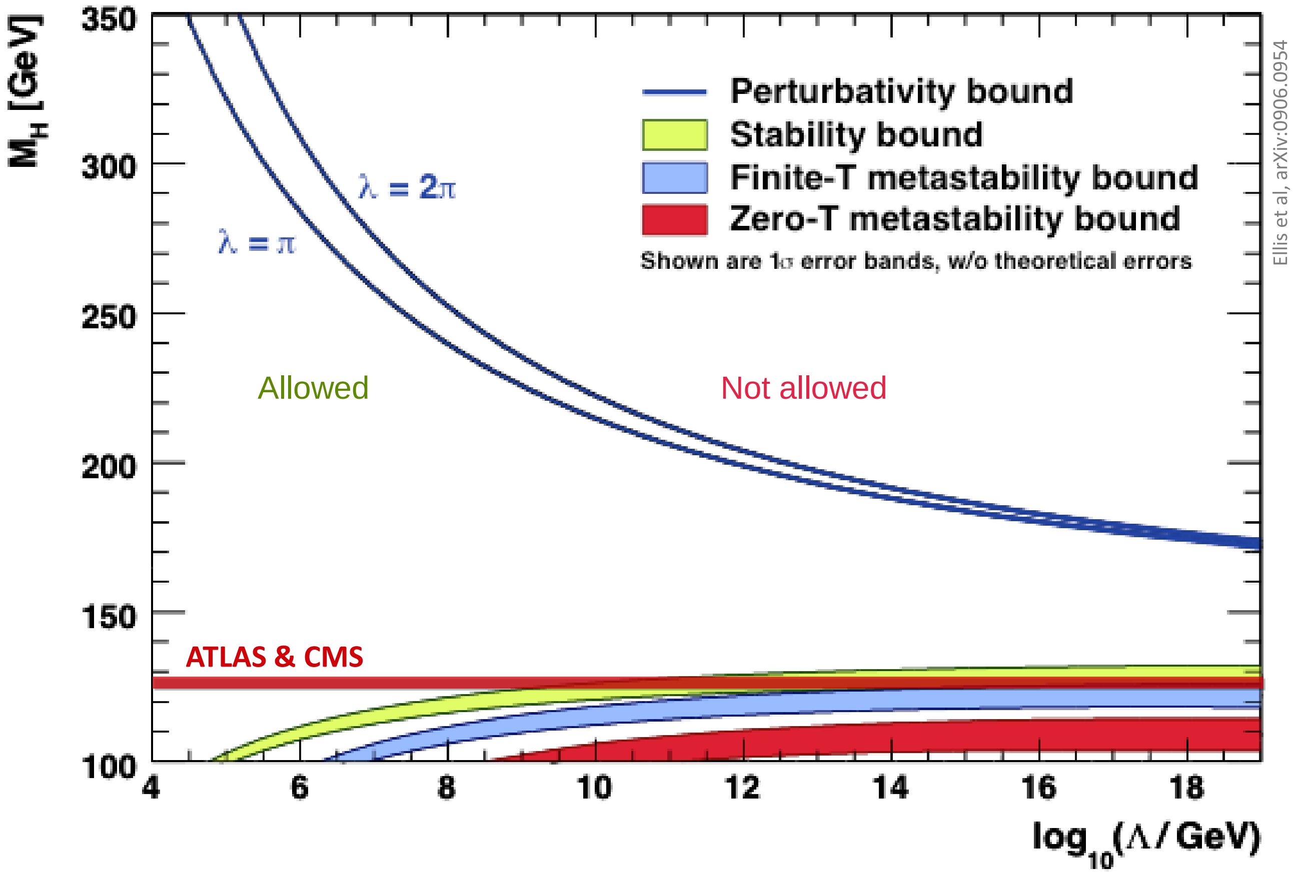
Is the electroweak vacuum stable or metastable (if SM holds) ?

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}**

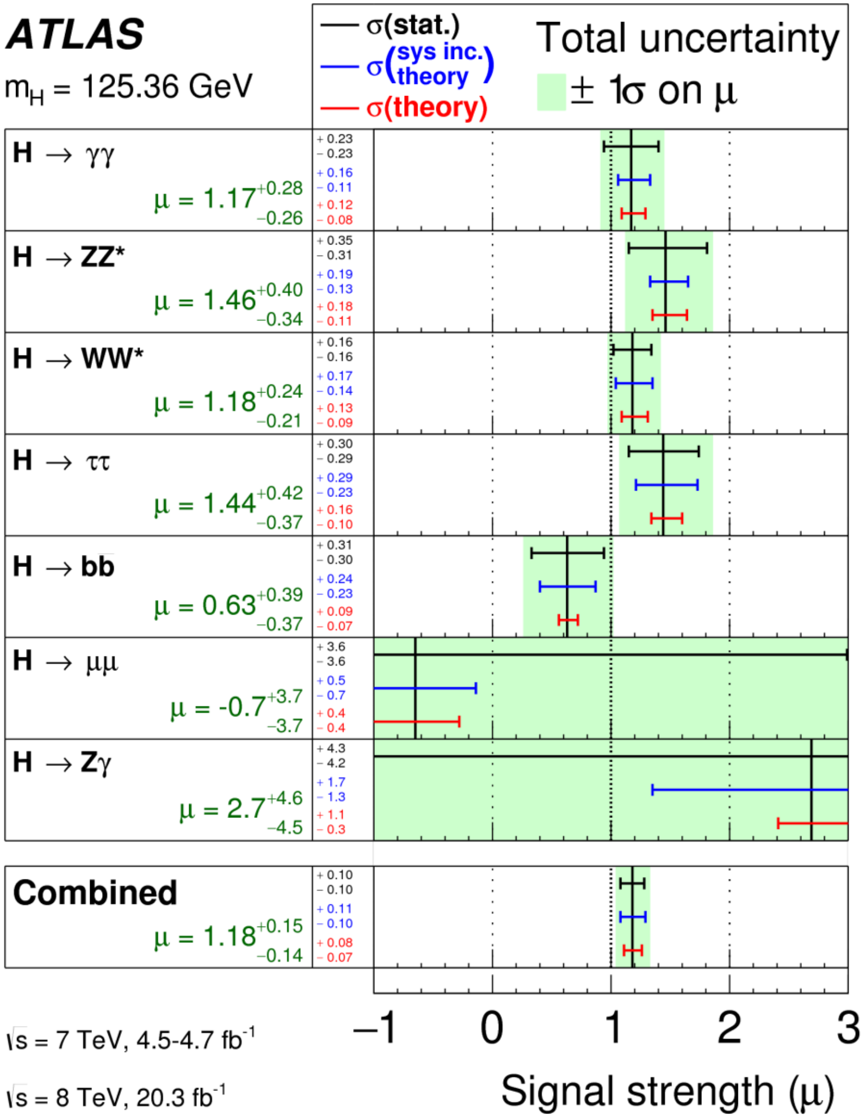


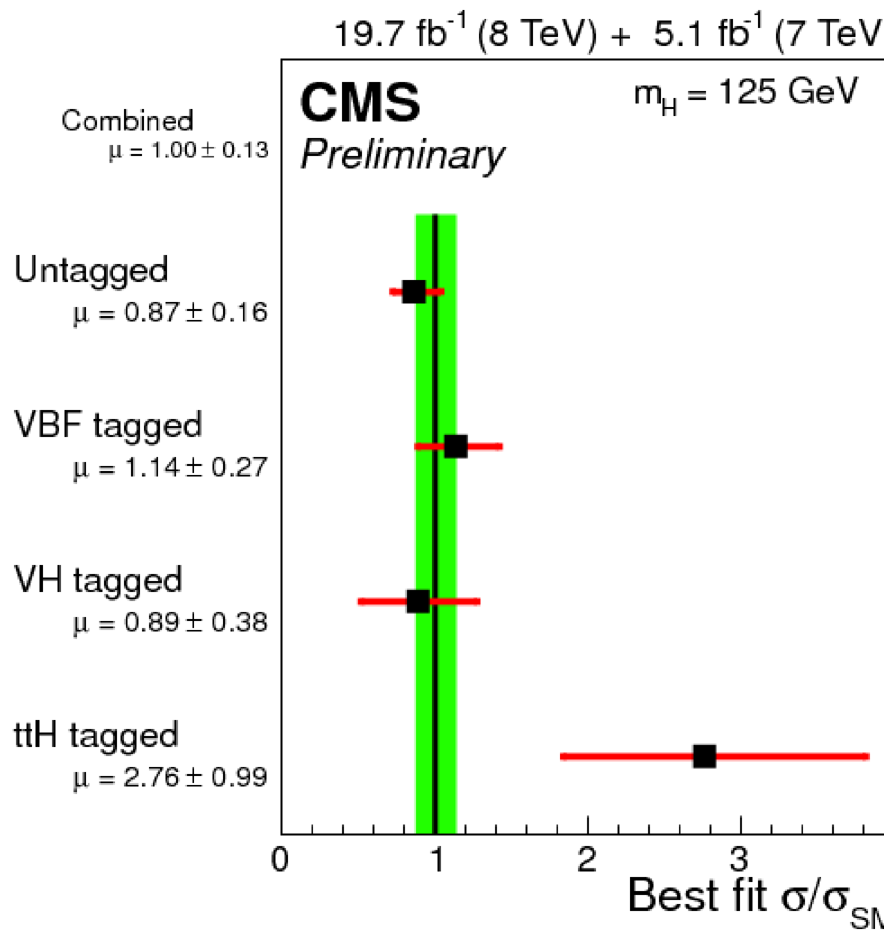
Degrassi *et al*, arXiv:1205.6497

Current status

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

Lots of measurements in more channels



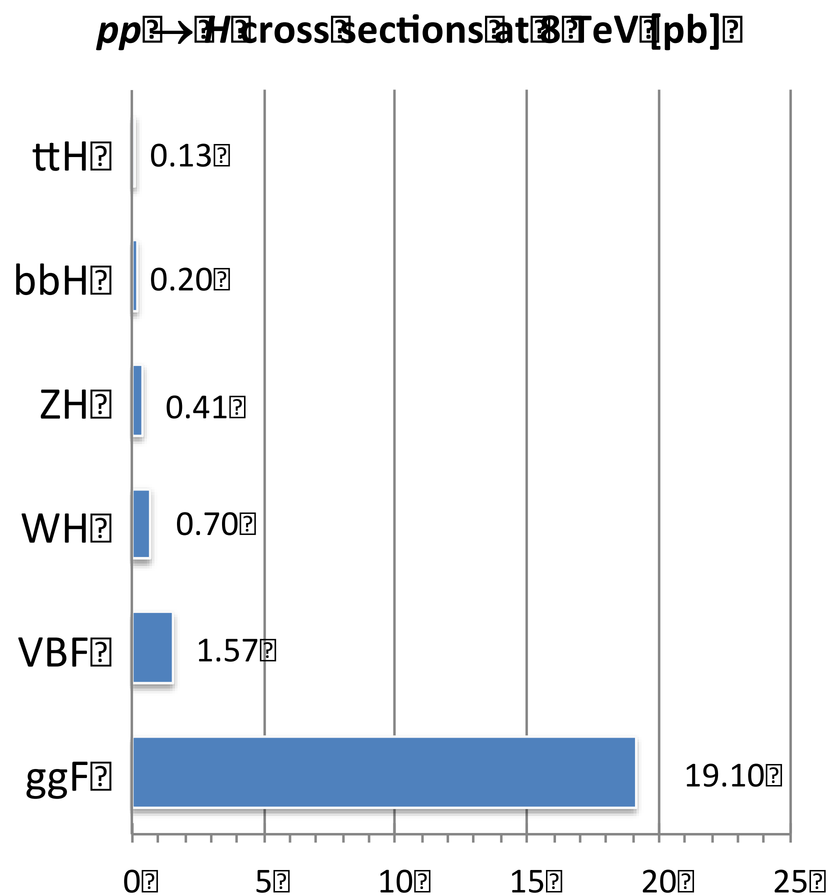


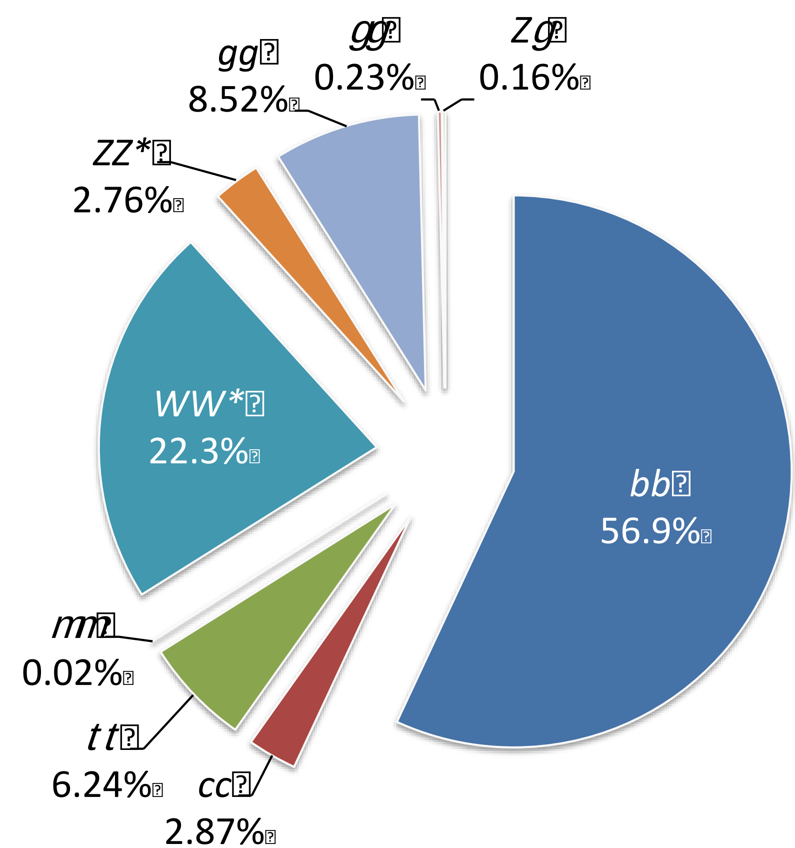
Higgs and Flavour Physics

125.5 GeV Higgs boson — SM properties

[LHCPhysics/CrossSections]

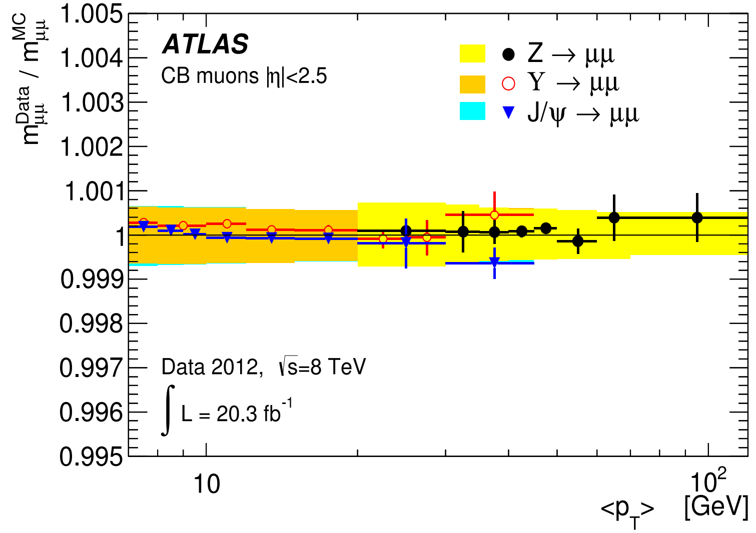
Cross sections and branching fractions precisely predicted (m_H = 125.5 GeV)





Uncertainties 3~12%

Higgs mass



SM predictions can (so far) live without a precision m_H measurement, but as experimentalists we want to do the best possible job

- Recent final Run-1 result be ATLAS after improvement of detector material description and recalibration using all SM candles (Z, W, J/ψ, Υ)

$$125.36 \pm 0.37_{stat} \pm 0.18_{syst}\ \text{GeV}$$

[ATLAS: 1406.3827]

- Perfectly compatible in value and uncertainty with CMS result from 4-lepton channel:

[CMS: 1312.5353]

$$125.6 \pm 0.4_{stat} \pm 0.2_{syst}\ \text{GeV}$$

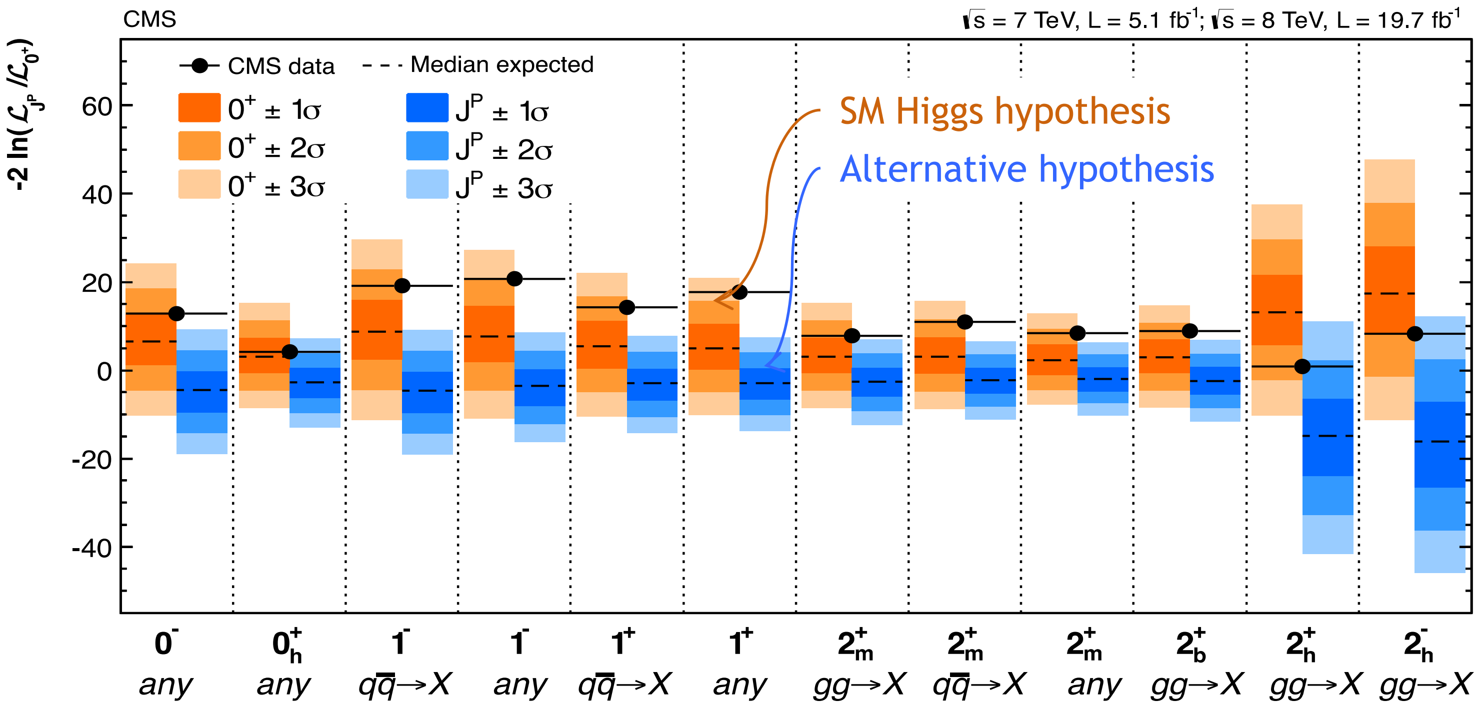
Higgs spin and CP

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

[CMS: 1312.5353]

From most powerful spin/*CP* analyser: $H \rightarrow$ 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

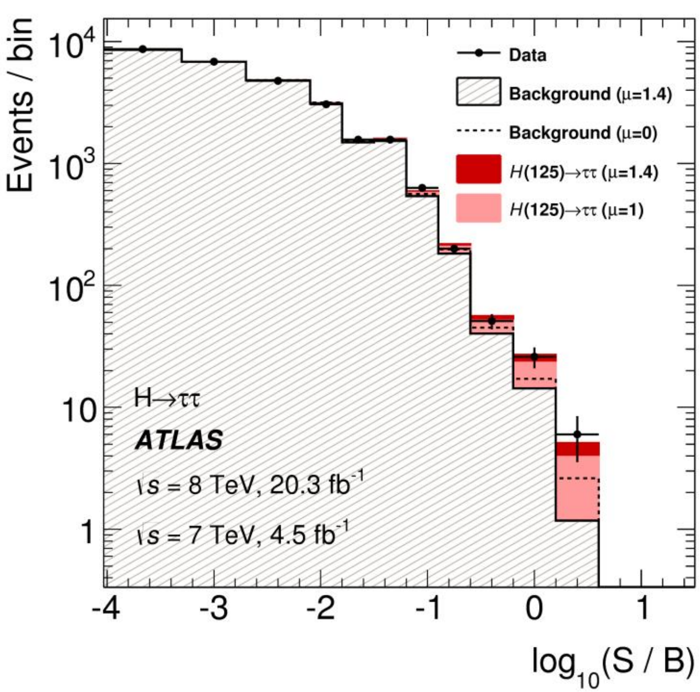
Higgs and Flavour Physics

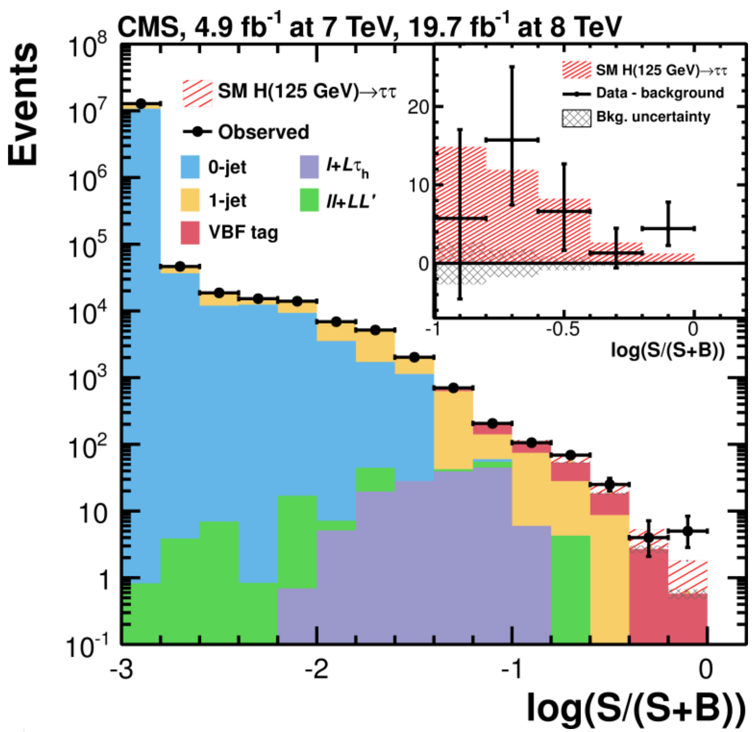
SM Higgs to fermions — $\tau\tau$

[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 τ
- Background dominated by Z $\rightarrow \tau\tau$ (use "τ embedded" $Z \rightarrow \mu\mu$), also top and fakes important





At 125 GeV:

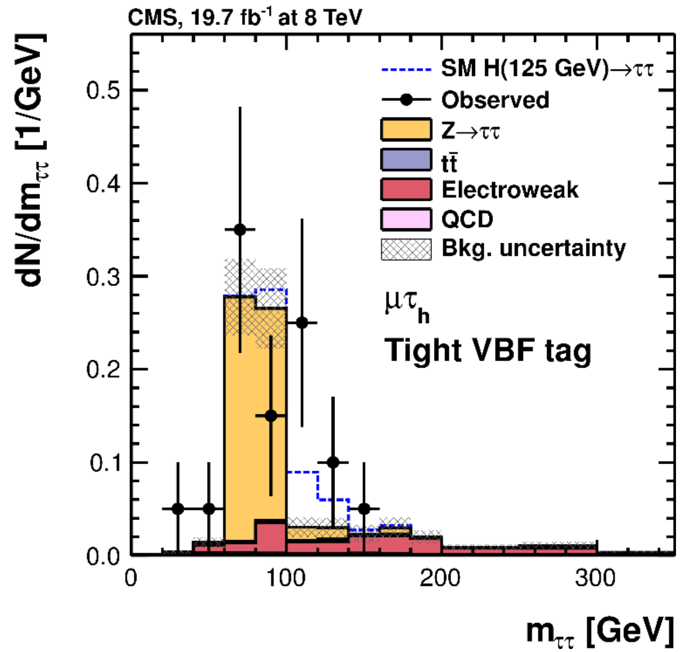
ATLAS (8 TeV):
$\mu = 1.4^{+0.5}_{-0.4}$
(4.1 σ)

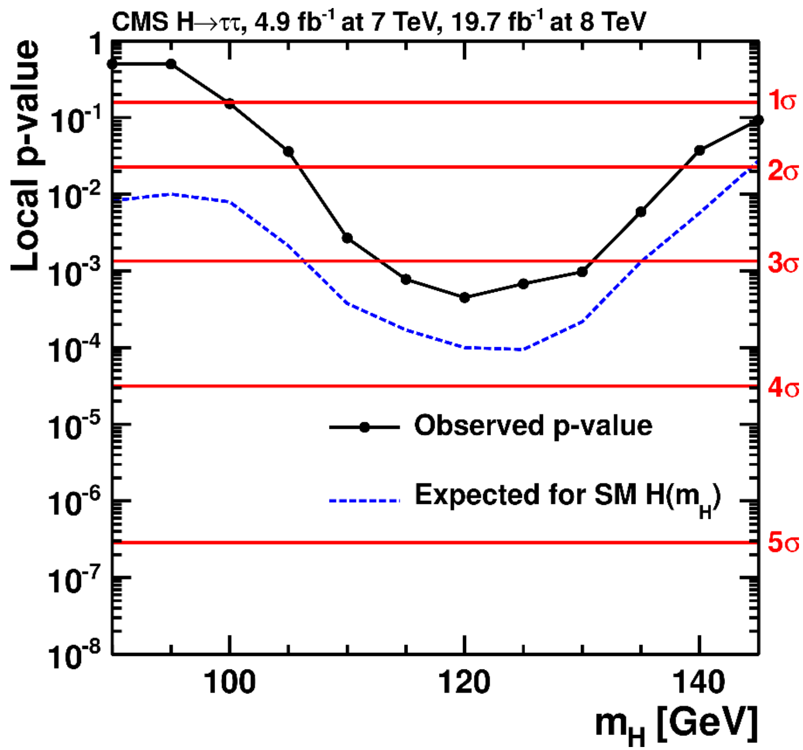
CMS (7+8 TeV):
$\mu = 0.78 \pm 0.27$
(3.4 σ)

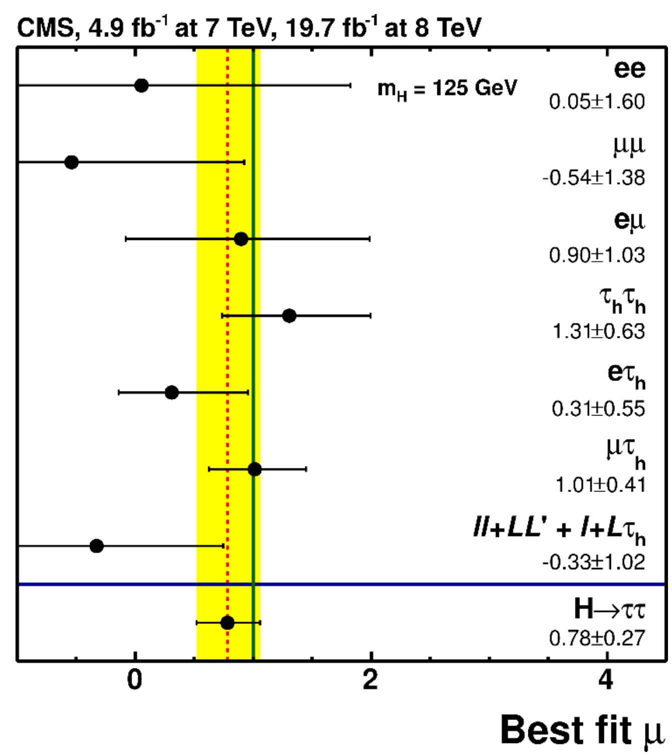
Higgs and Flavour Physics

SM Higgs to fermions — $\tau\tau$

A closer look at the evidence:







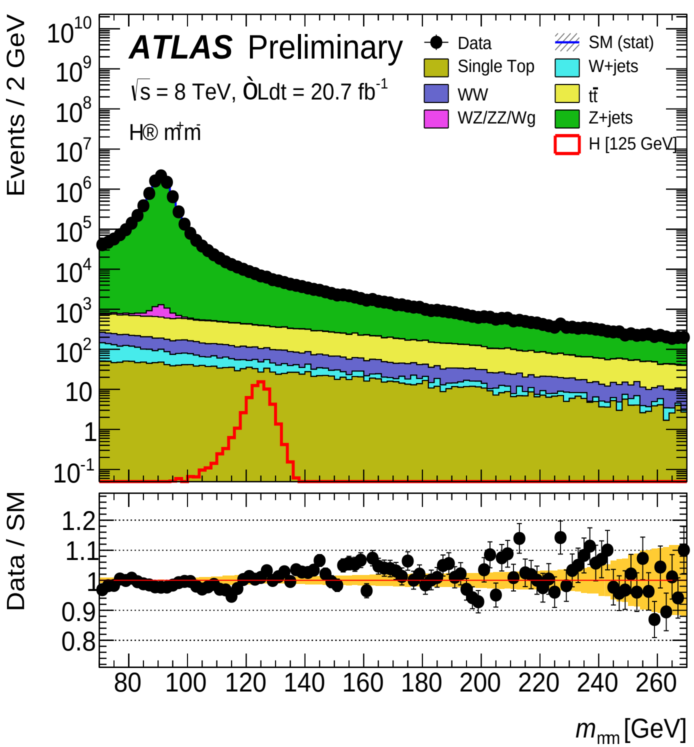
Higgs and Flavour Physics

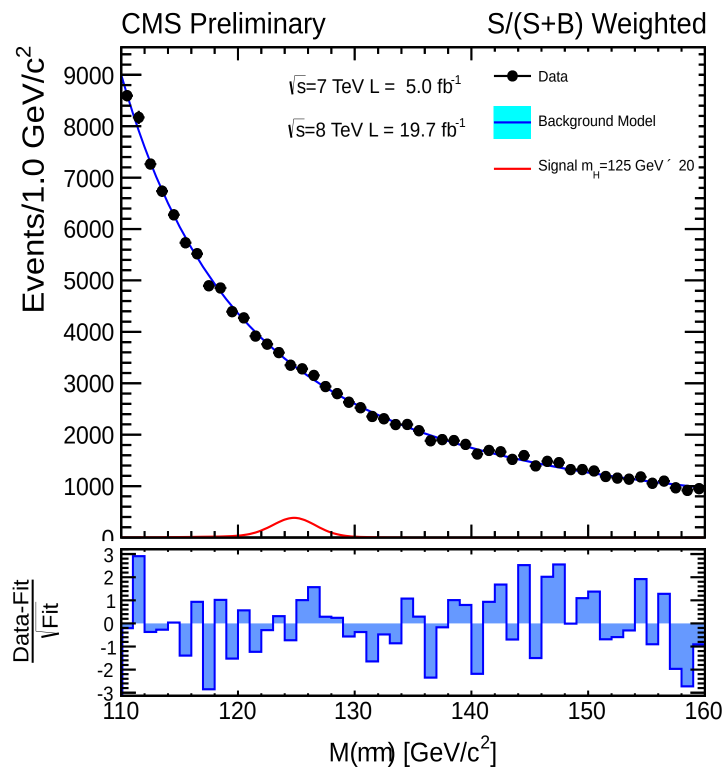
SM Higgs to fermions — $\mu\mu$

[ATLAS-CONF-2013-010, CMS-PAS-HIG-13-007]

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

- 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





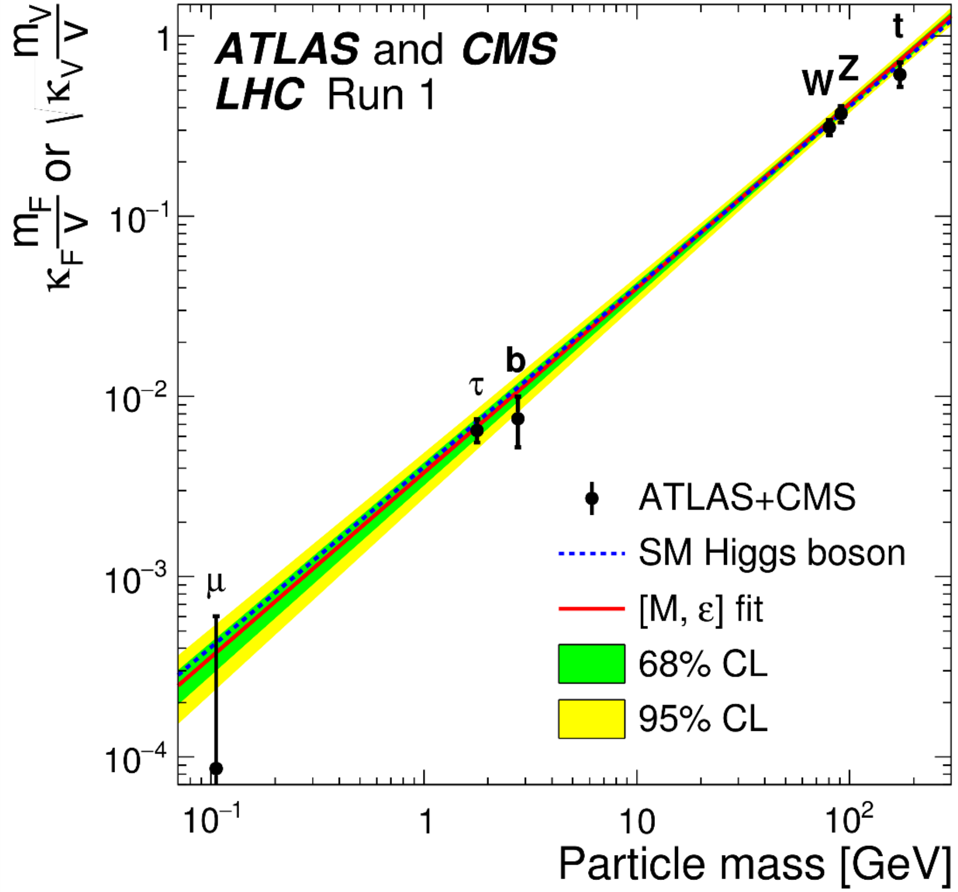
At 125 GeV:

ATLAS (8 TeV):
μ < 9.8 (8.2 exp.) (95% CL)

CMS (7+8 TeV):
μ < 7.4 (5.1 exp.) (95% CL)

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

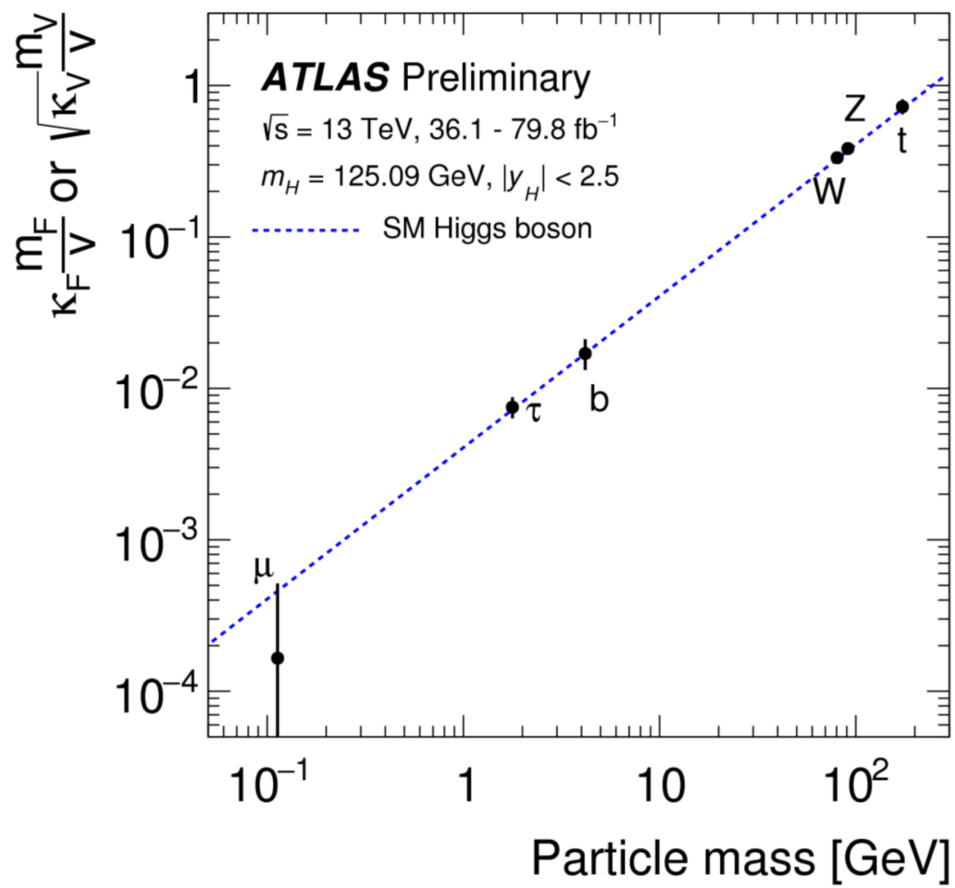
Great measurements — the overall picture is as expected in the SM



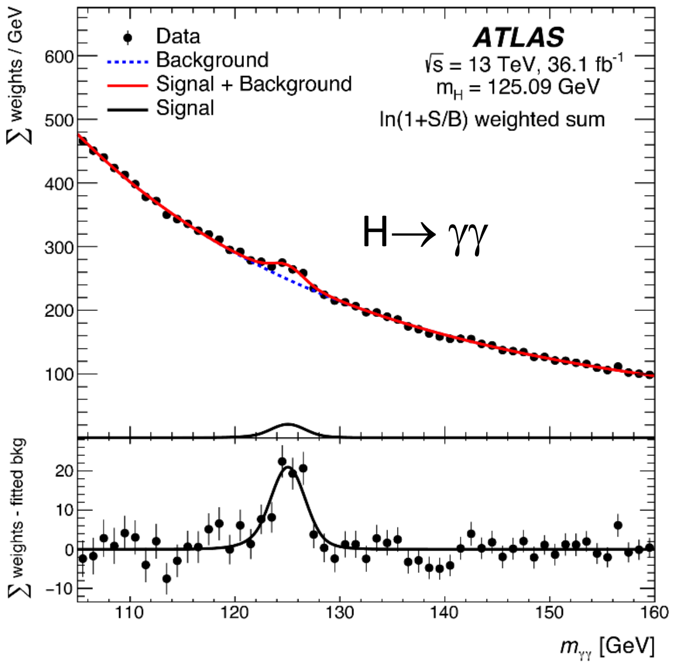
Particle mass proportional to coupling to Higgs field

Higgs bottom line for Run 2 (13 TeV)

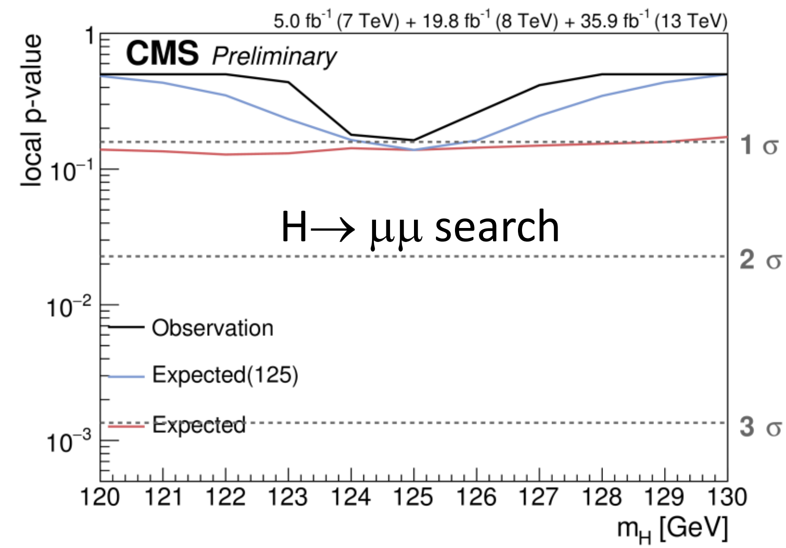
Great measurements — the overall picture is as expected in the SM



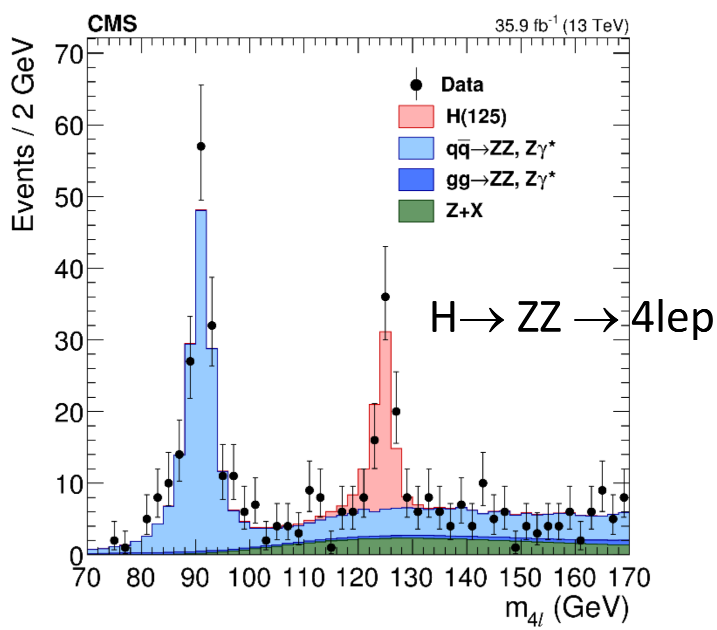
Particle mass proportional to coupling to Higgs field

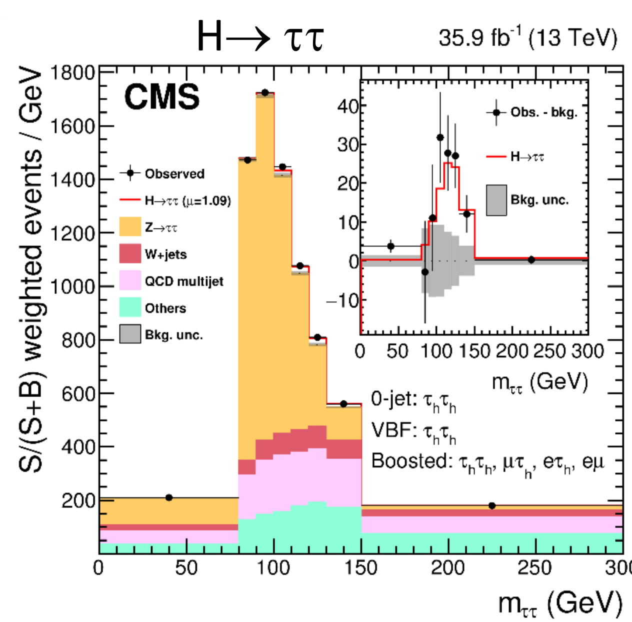


Higgs boson still there ☺ measurement getting more precise

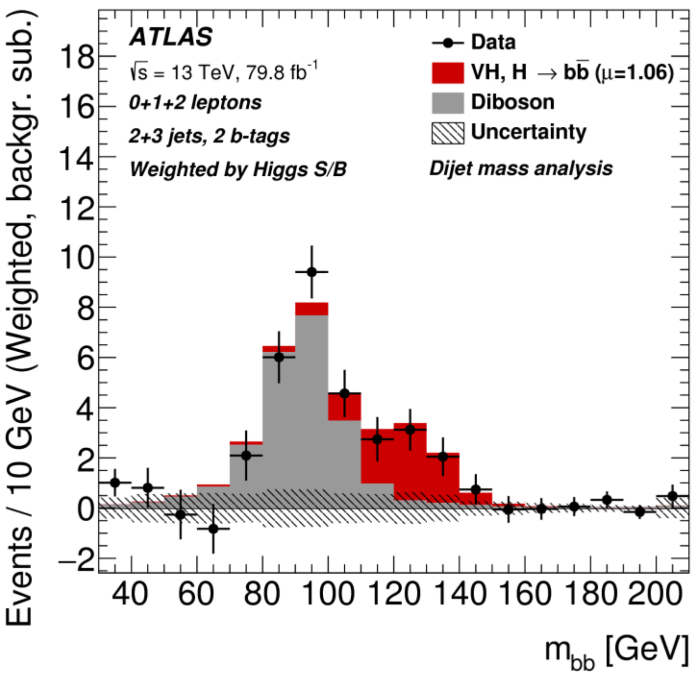


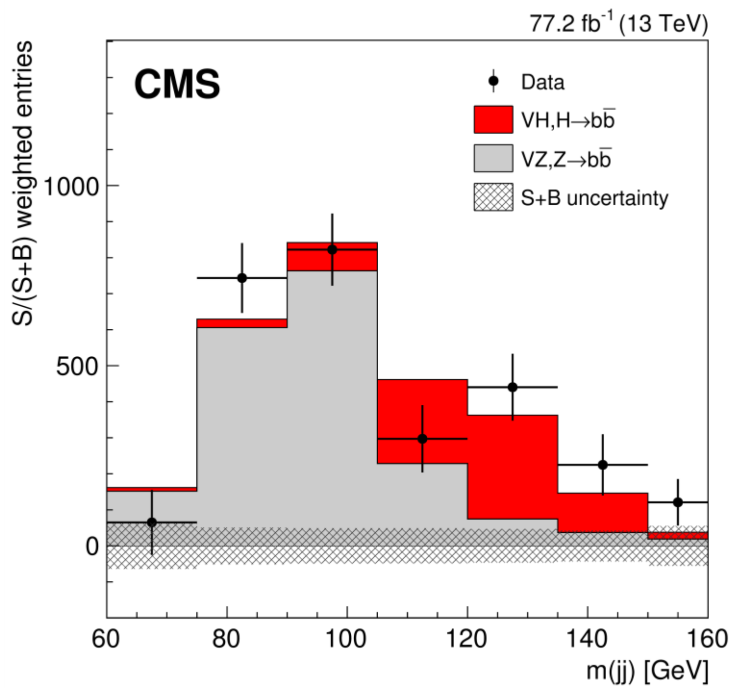
Run 2





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 ...

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*
- 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*