

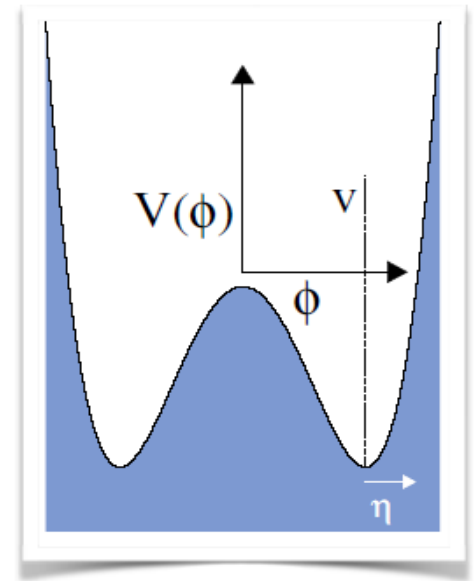
Elementary Particle Physics: theory and experiments

Discovery of the Higgs boson

Measurements: mass, spin, couplings

The Higgs boson in the Standard Model

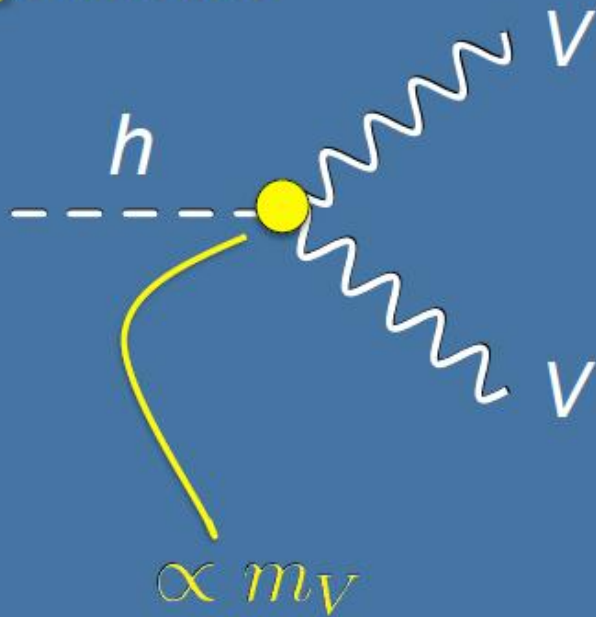
- SM describes all known elementary **particles** and their **interactions**
- **Local gauge invariance** forbids explicit mass terms in the Lagrangian – but experimentally both gauge bosons and fermions have mass
- Introduce a new field with a very specific potential that keeps the full Lagrangian invariant but makes the vacuum not invariant
- **Higgs mechanism** predicts existence of at least one new, neutral boson: the **Higgs boson**
 - SM parameters: mass (μ or m_H) and vacuum expectation value, v
 - Discovered at CERN by the ATLAS and CMS collaborations in 2012 after 40+ years of searching



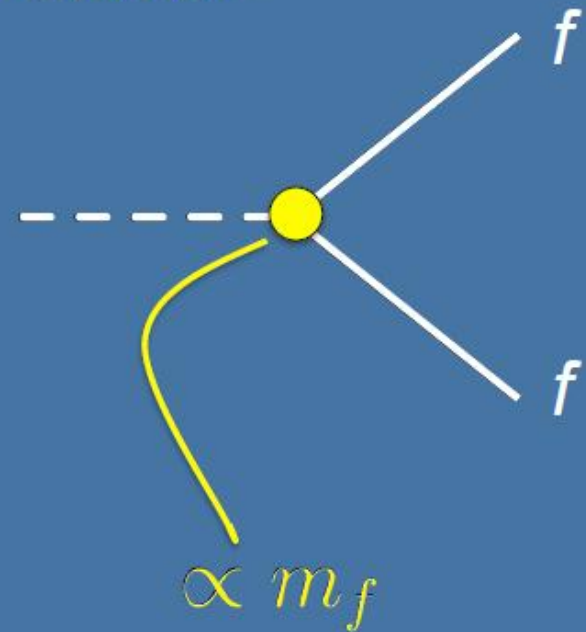
$$\mathcal{L} = |D^\mu \phi|^2 - y_i q_L^i q_R^i \phi - \mu^2 \phi^2 - \lambda \phi^4 + \dots \quad \mu^2 < 0$$

Higgs boson couplings

Gauge bosons

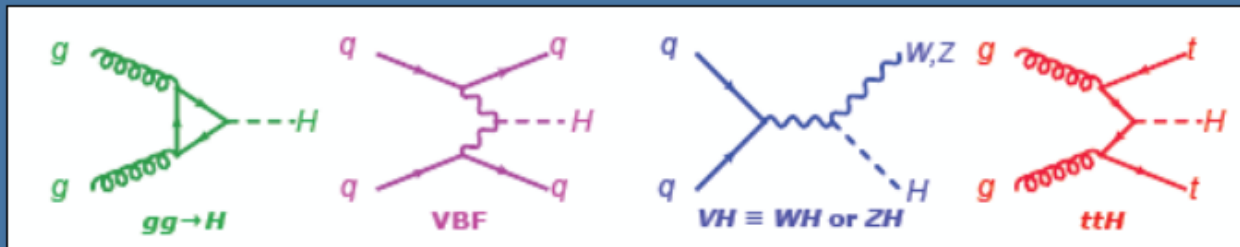


Fermions

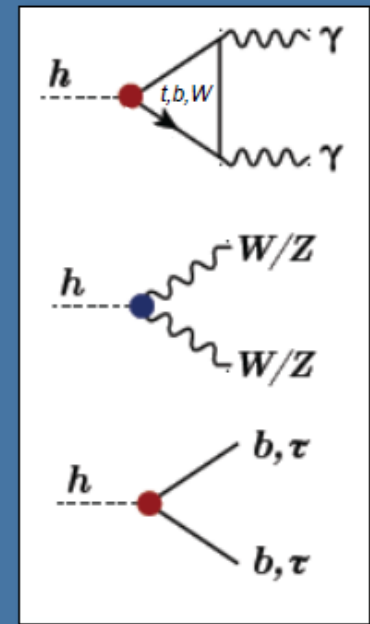


Higgs boson properties are fixed in the Standard Model (m_h)

Higgs boson phenomenology

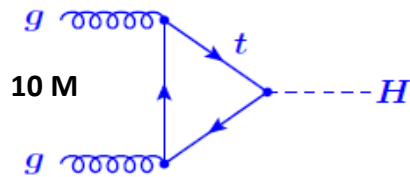


‘production & decay matrix’
sensitivity to different Higgs properties

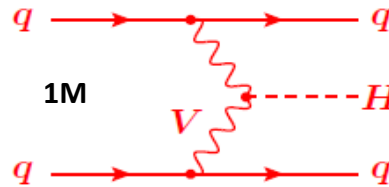


The Higgs Boson at the LHC

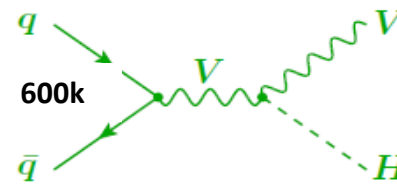
Production



Main production channel

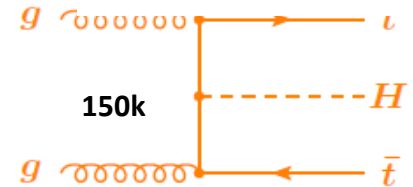


2 forward jets,
little central
hadronic activity



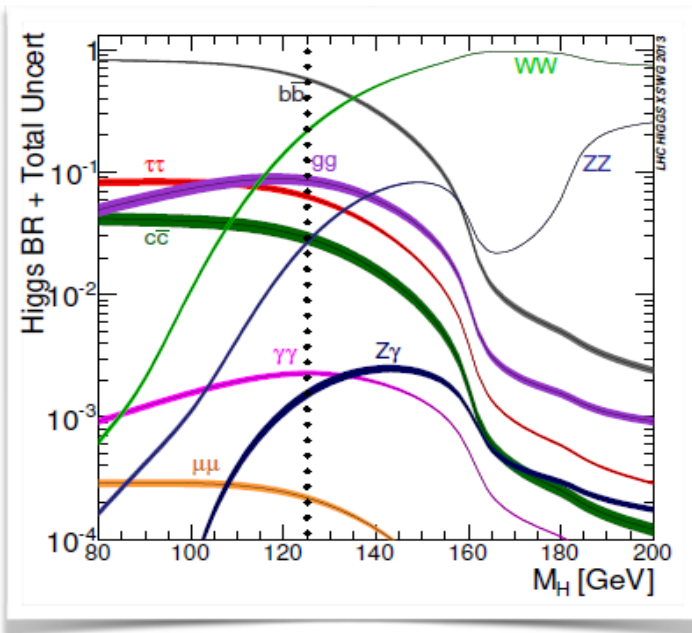
Tag W and Z
decays

#Higgs produced at
13 TeV (2015-2017)



Tag 2 top quarks

Decays



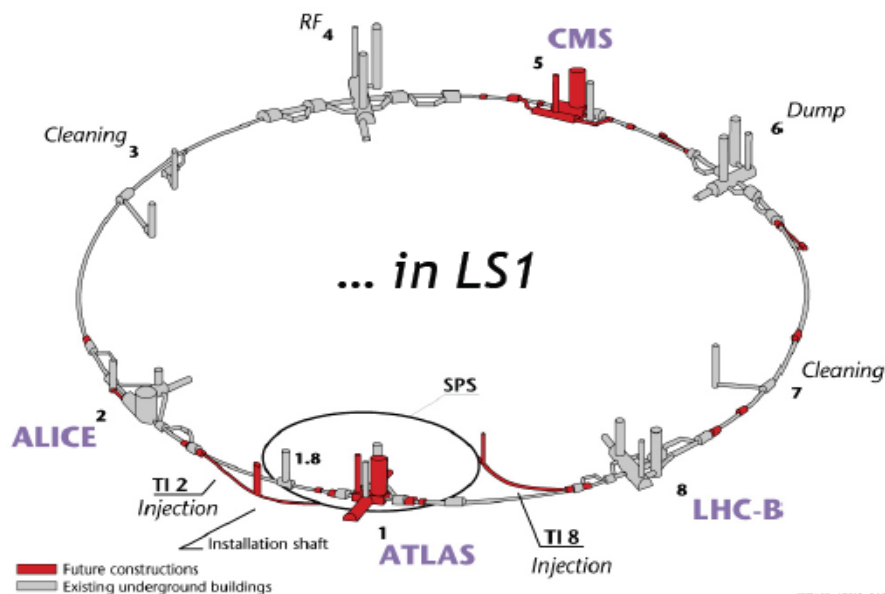
5 main channels at the LHC

Decay branching fractions for
 $m_H = 125 \text{ GeV}$

- $H \rightarrow bb$: 58 %
- $H \rightarrow WW^*$: 21%
- $H \rightarrow \tau^+\tau^-$: 6.3%
- $H \rightarrow ZZ^*$: 2.6%
- $H \rightarrow \gamma\gamma$: 0.2%

Shown here results based on Run I

Energy frontier



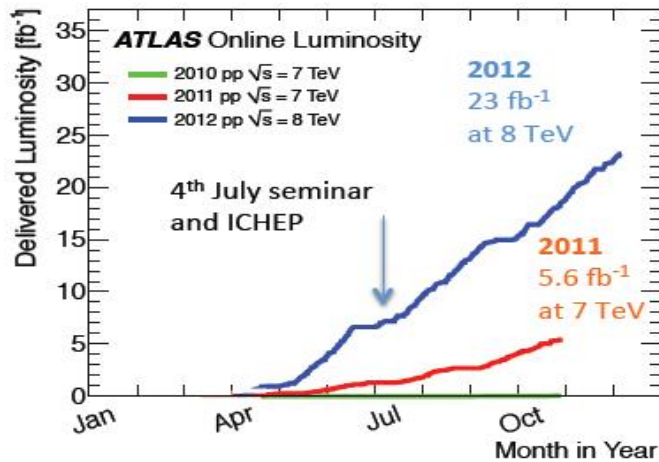
The LHC

- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

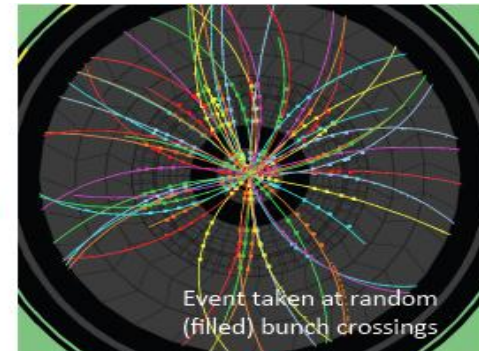
$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns / 1380	25 ns / 2808
ϵ (mm rad)	2.4-4	1.9-2.3	2.5	3.75
β^* (m)	3.5	1.5-1	0.6	0.55
L (cm ⁻² s ⁻¹)	2x10 ³²	3.3x10 ³³	~7x10 ³³	10 ³⁴

The first LHC run

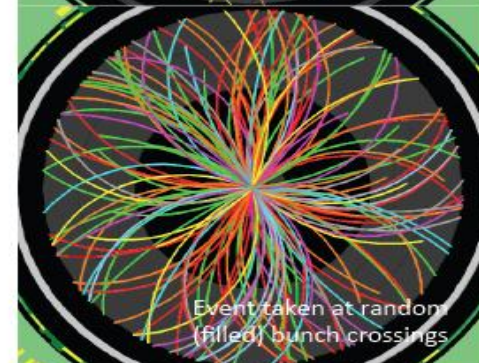


2010
O(2) Pile-up events
150 ns inter-bunch spacing



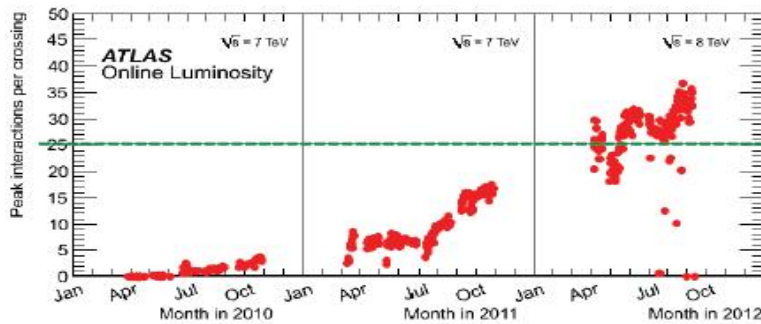
2010
0.05 fb^{-1}
at 7 TeV

2011
O(10) Pile-up events
50 ns inter-bunch spacing



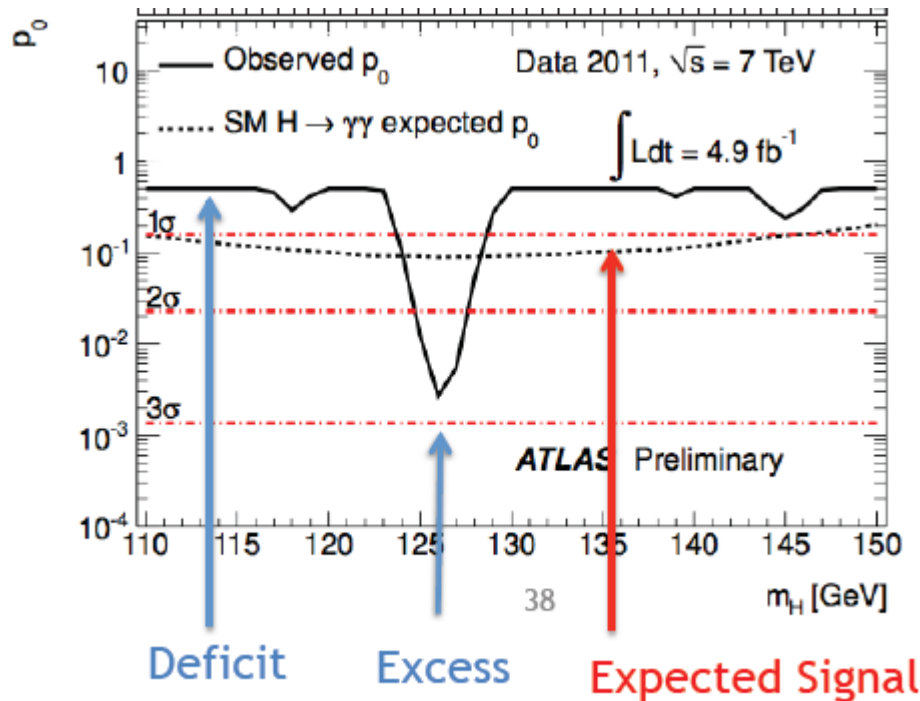
Design value
(expected to be
reached at $L=10^{34}$!)

2012
O(20) Pile-up events
50 ns inter-bunch spacing

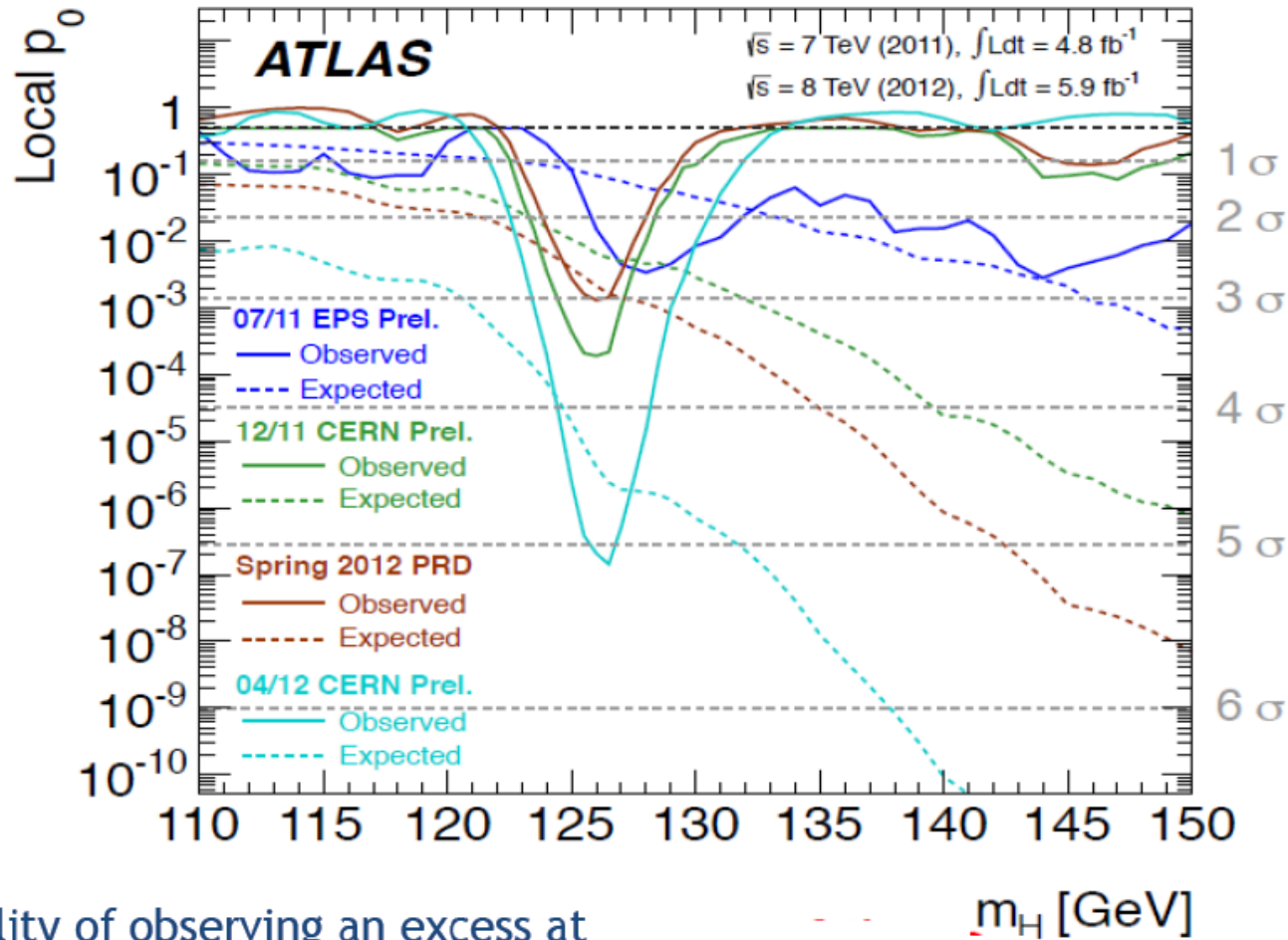


Local p_0

Probability that the background can produce a fluctuation greater than or equal to the excess observed in data. Equivalent in terms of number of standard deviations is called local significance.



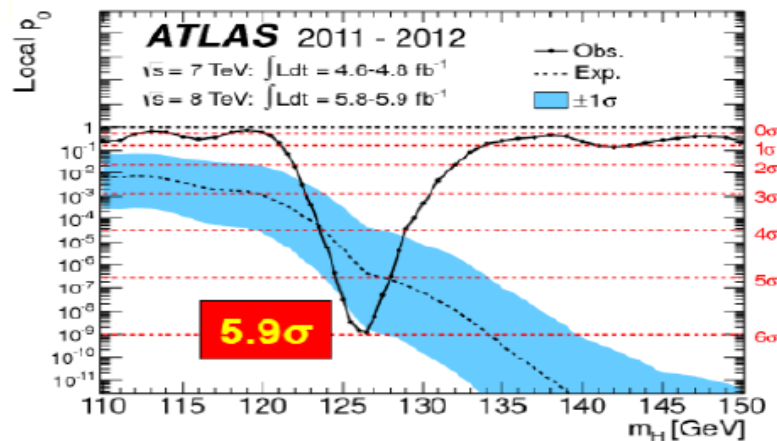
Birth of a particle



Probability of observing an excess at one specific mass (in absence of signal)...

Higgs-like particle – 4 July 2012

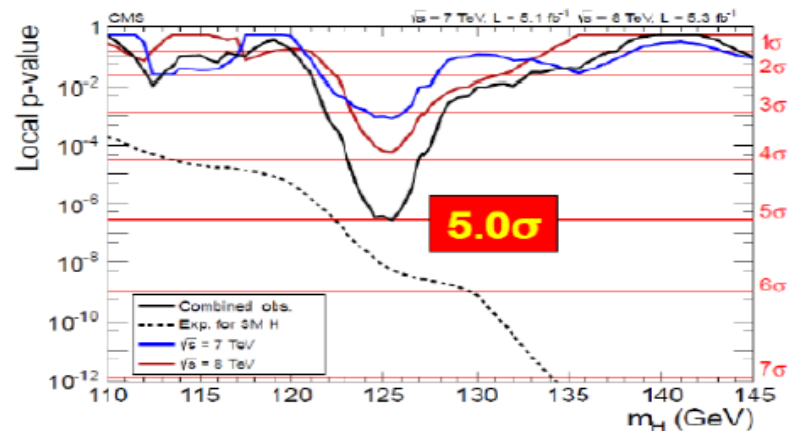
- We are living in a privileged moment in the history of High Energy Physics: **first fundamental scalar**
- The discovery came at half of the design energy, much more severe pile-up and one-third of integrated luminosity than was originally judged as



ATLAS [PLB 716 \(2012\) 1-29](#), Sept 17 (2012)

Largest local excess:
5.9 σ at $m_H = 126.5$ GeV

$H \rightarrow \gamma\gamma, bb, \tau\tau, WW(l\nu l\nu, l\nu q\bar{q}), ZZ(4l, ll\nu\nu, llq\bar{q})$



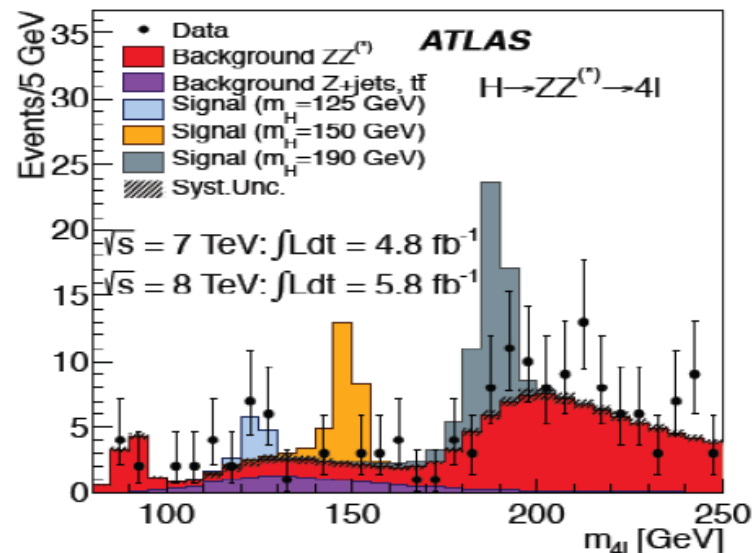
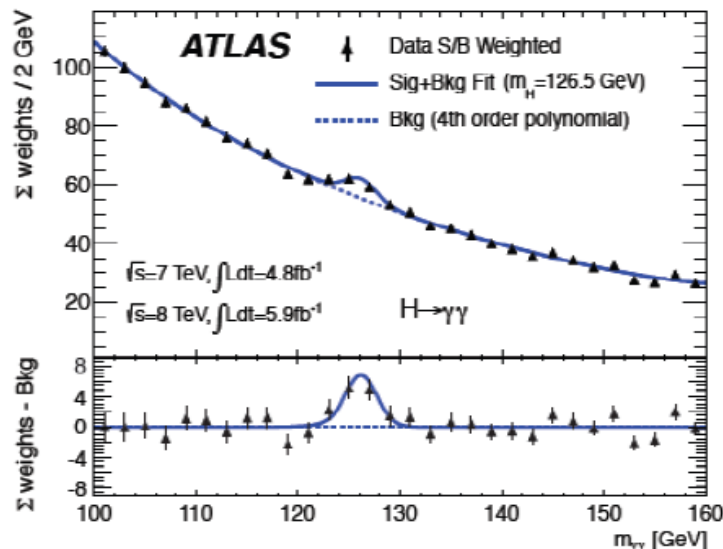
CMS [PLB 716 \(2012\) 30-61](#), Sept 17 (2012)

Largest local excess:
5.0 σ at $m_H = 125.5$ GeV

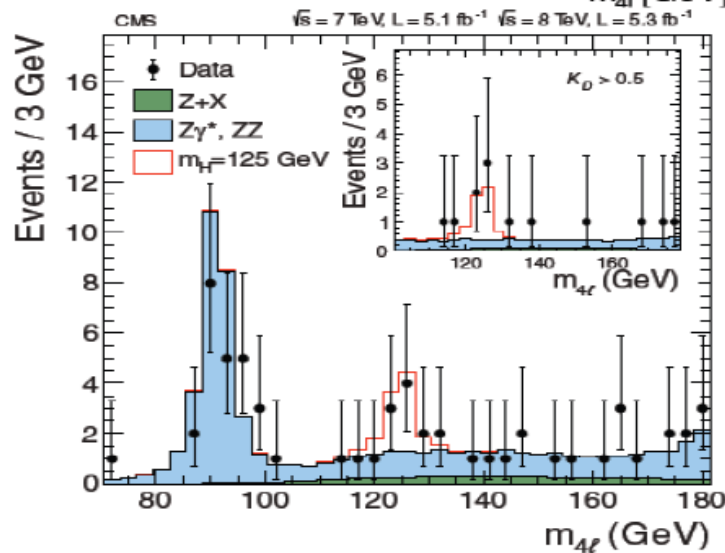
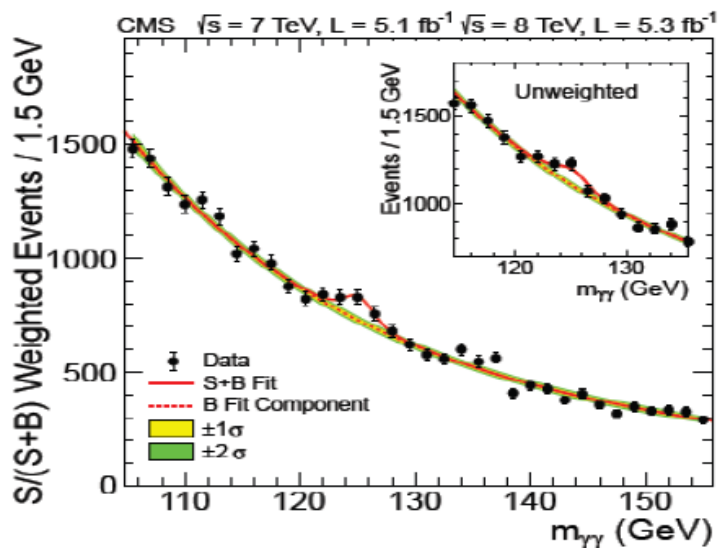
$H \rightarrow \gamma\gamma, bb, \tau\tau, WW(l\nu l\nu), ZZ(4l, ll\tau\tau, ll\nu\nu, llq\bar{q})$

Higgs-like particle – 4 July 2012

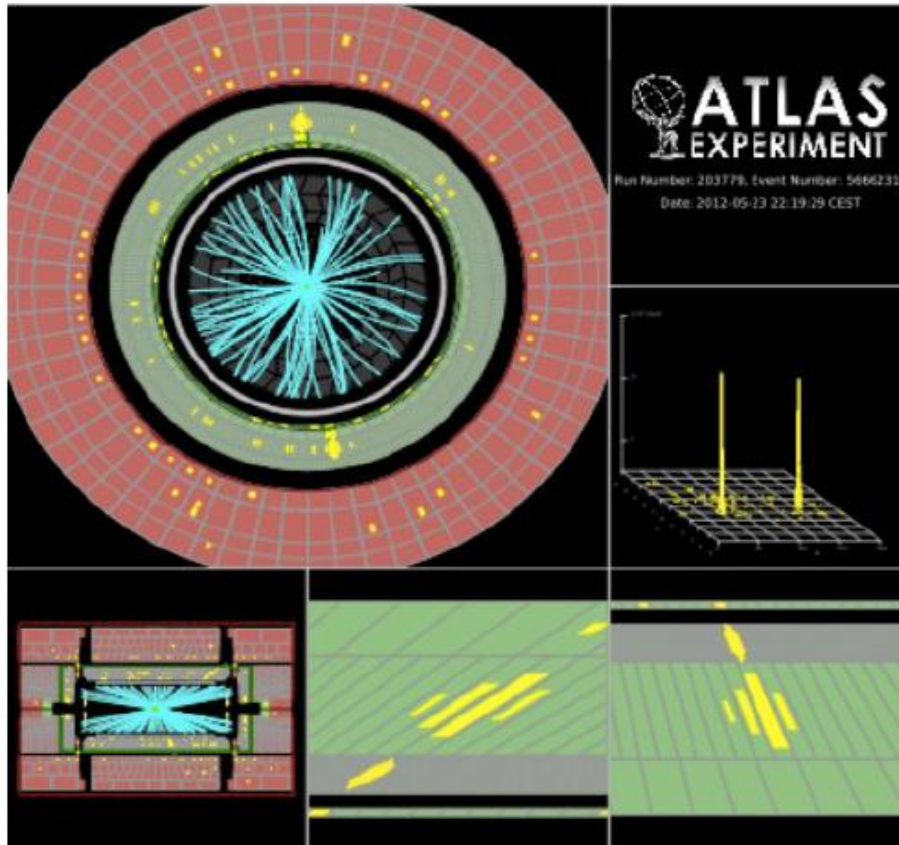
Phys.Lett. B716 (2012) 1-29



Phys.Lett. B716 (2012) 30-61



H- $\rightarrow\gamma\gamma$: events signature



Simple event signature

- Two high p_T photons
 $p_{T_1} > 40$ GeV and $p_{T_2} > 30$ GeV
- High trigger efficiency
 $\sim 99\%$
- High event selection efficiency
despite high jet-jet & γ -jet
production
 $\sim 40\%$
- High signal over background
 $\sim 3-10\%$ (depending on sub-category)

Invariant mass reconstruction $m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$

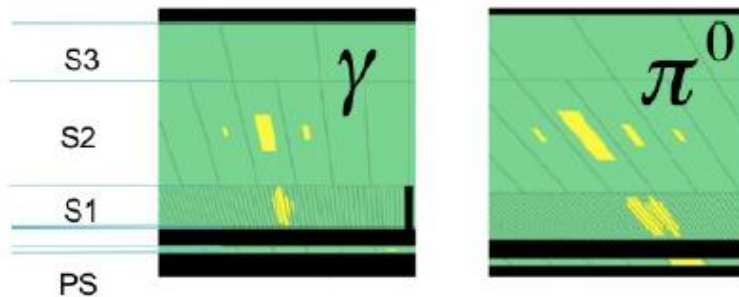
- Good energy calibration
- Robust primary vertex reconstruction

\rightarrow Excellent invariant mass resolution ~ 1.6 GeV with 90% of events within $\pm 2\sigma$

Shower shapes and vertex reconstr.

Photon ID 2 – Photon shower shapes and background rejection

π^0 - γ Rejection



- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

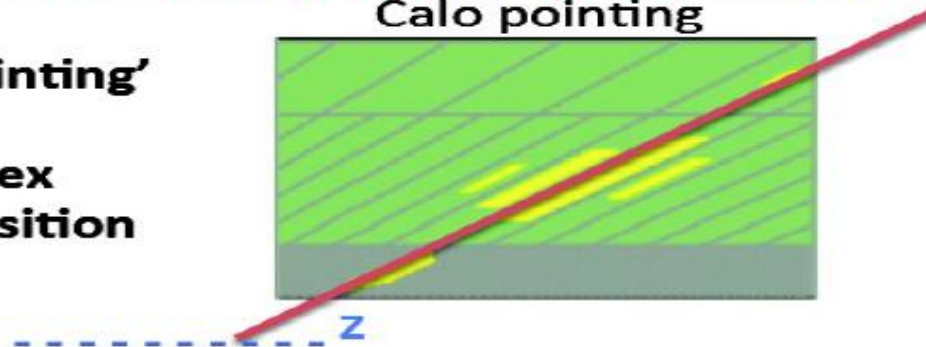
Vertex Reconstruction

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

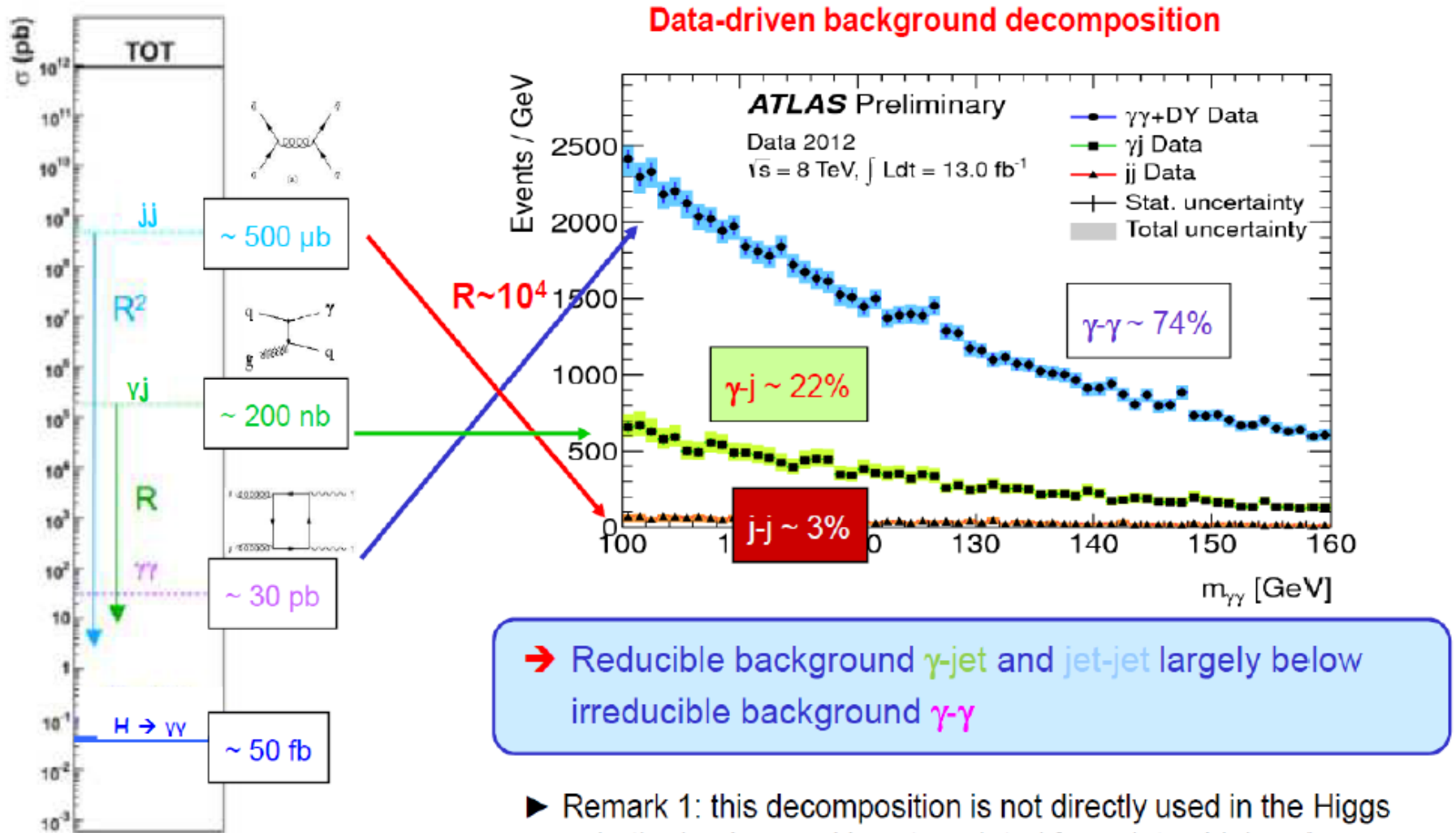
☐ Vertex reconstructed through likelihood combination

- Calorimeter 'pointing'
- Σ tracks p_T^2
- Conversion vertex
- Mean vertex position

Calo pointing



H- $\rightarrow\gamma\gamma$: background rejection



- ▶ Remark 1: this decomposition is not directly used in the Higgs search: the background is extrapolated from data sidebands
- ▶ Remark 2: Drell-Yan \sim negligible for $m_{\gamma\gamma} > 100 \text{ GeV}$ ($\sim 1\%$)

Event categorization

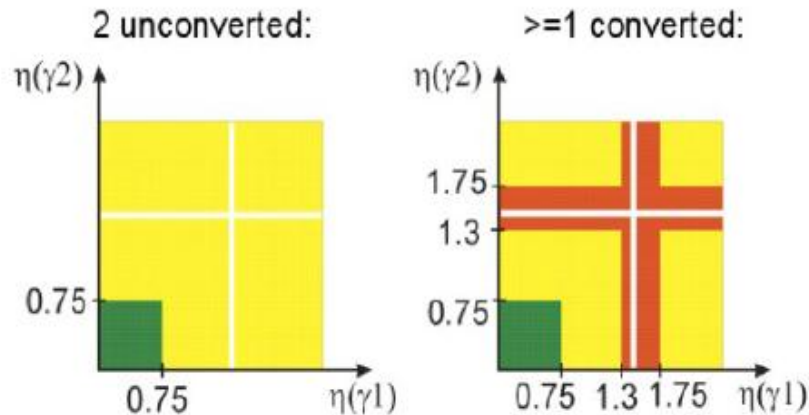
Event categories based on eta, pTt, and conversion

Both unconverted:

- Central
- Rest

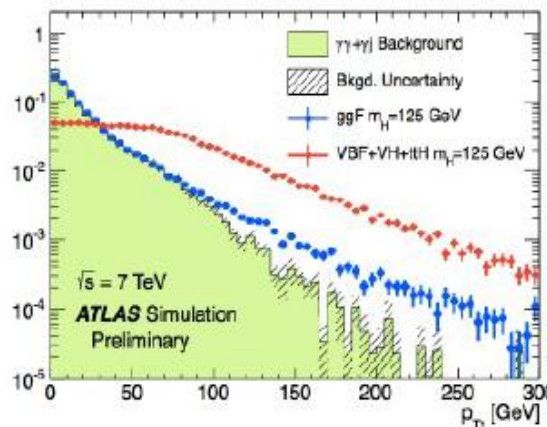
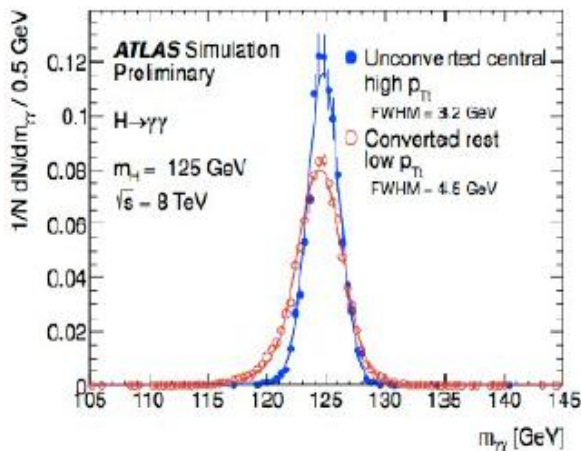
At least one converted:

- Central
- Transition
- Rest

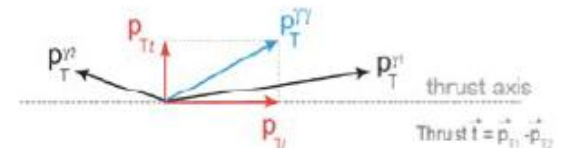


Resolution:

- Good
- Medium
- Poor



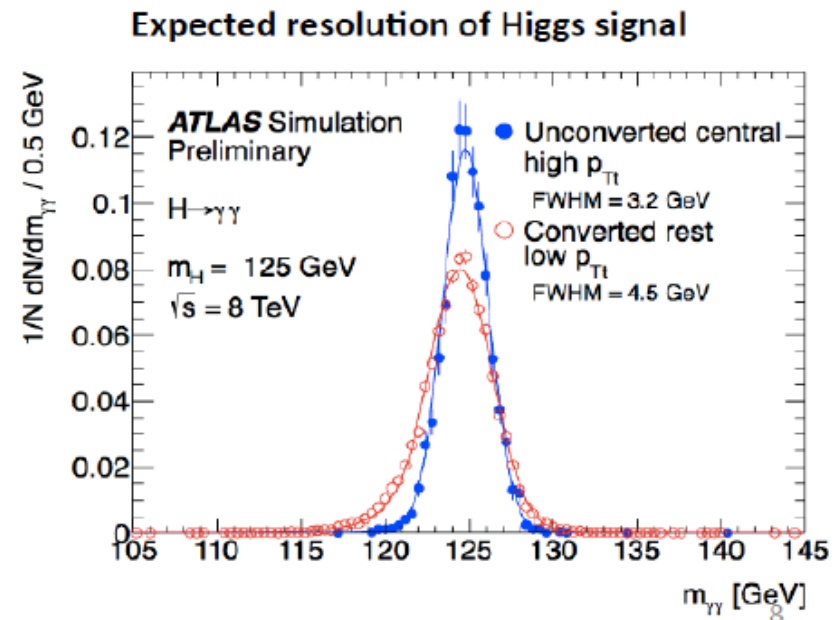
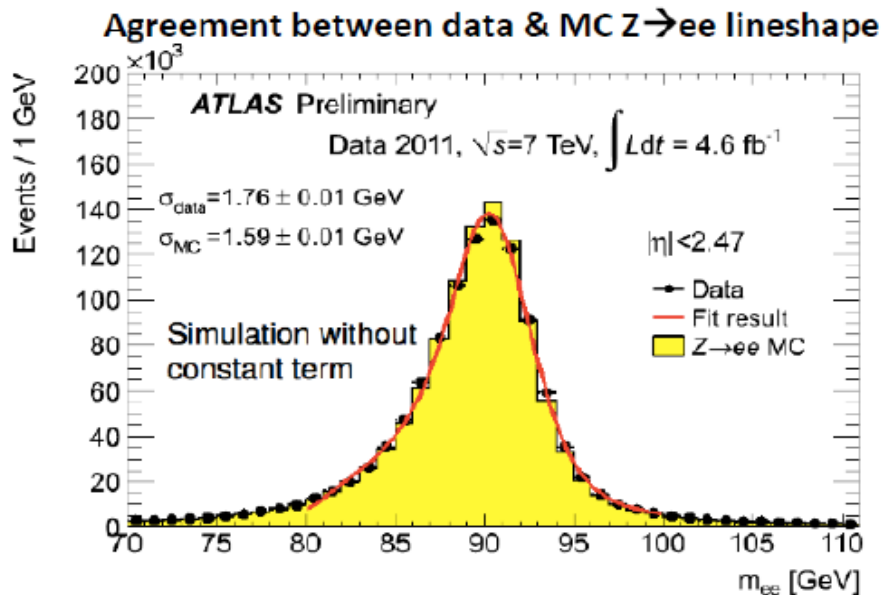
Central and Rest divided into $p_{Tt} < 60$ GeV and $p_{Tt} > 60$ GeV



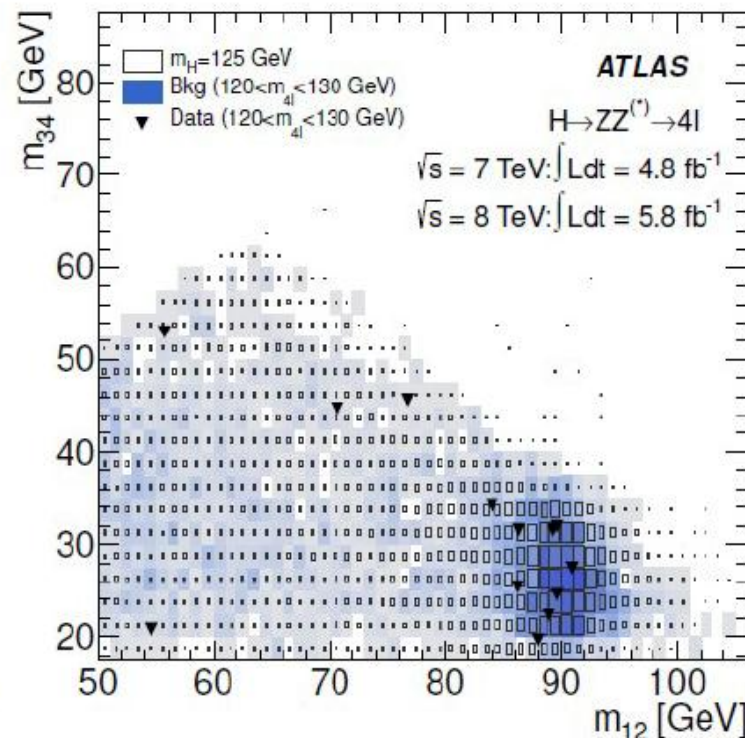
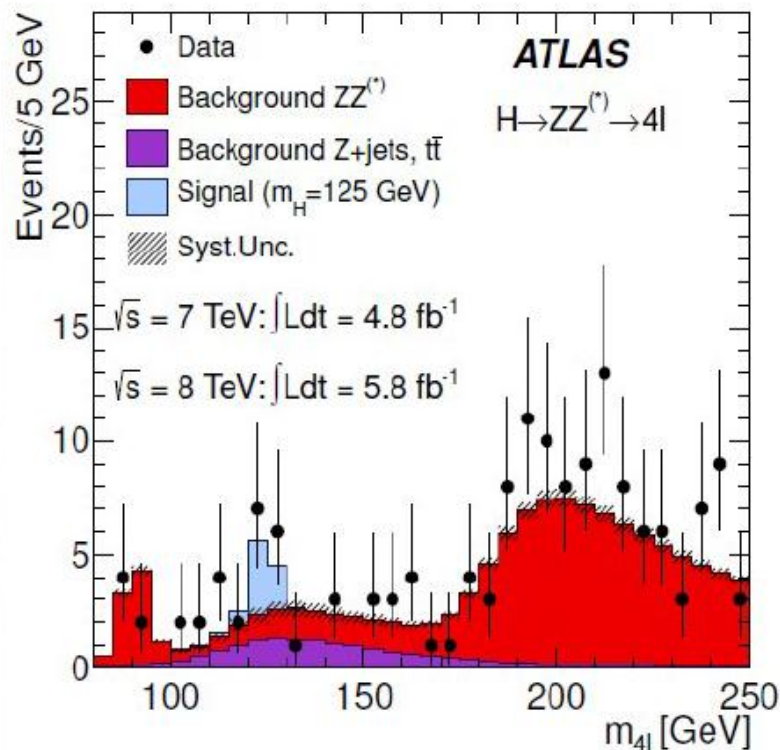
Energy calibration and resolution

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

- MC based calibration improved with energy scale and resolution corrections based on in-situ analysis of $Z \rightarrow ee$, $W \rightarrow ev$ and $J/\psi \rightarrow ee$
- Energy scale at m_Z known to 0.3%, uniformity (constant term) 1% in barrel, 1.2 – 2.1% in endcap



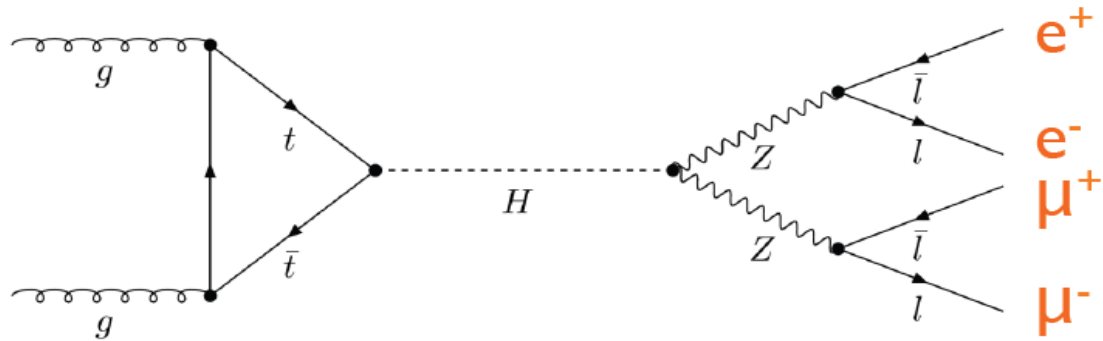
The golden channel: $H \rightarrow ZZ, Z \rightarrow ll$



In a m_{4l} window
around 120-130 GeV:

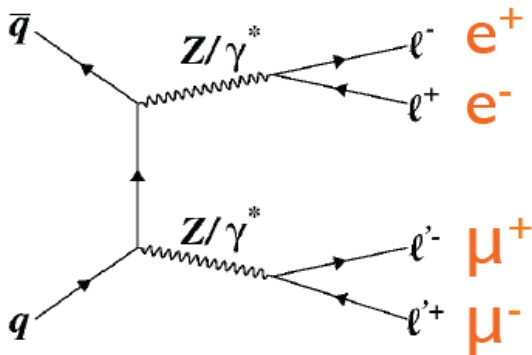
	Signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	Observed
4μ	2.09 ± 0.30	1.12 ± 0.05	0.13 ± 0.04	6
$2e2\mu/2\mu2e$	2.29 ± 0.33	0.80 ± 0.05	1.27 ± 0.19	5
$4e$	0.90 ± 0.14	0.44 ± 0.04	1.09 ± 0.20	2

Signal and background



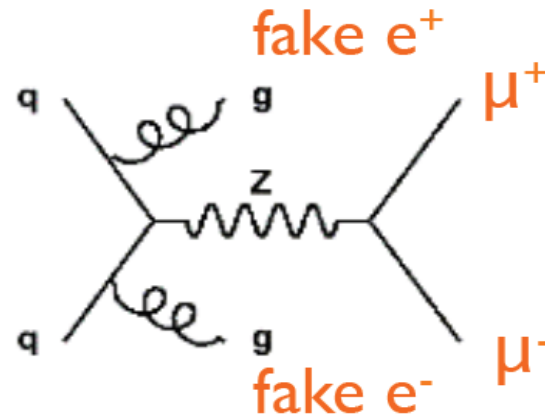
Irreducible background

The final state is exactly the same, but it does not come from the particle you are looking for



Reducible background

The final state looks like the same, but some of the particles fake what you are looking for



4e candidate. $m_{4\ell} = 124.6$ GeV, $m_{12} = 70.6$ GeV, $m_{34} = 44.7$ GeV.

e_1 : $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$

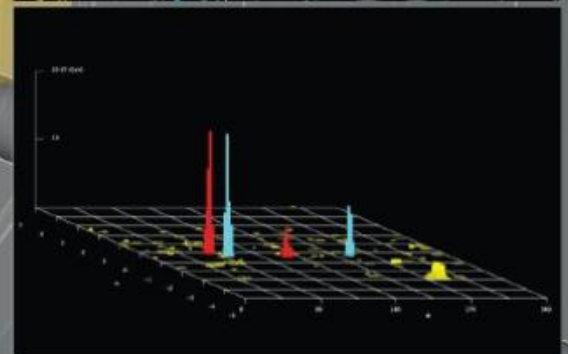
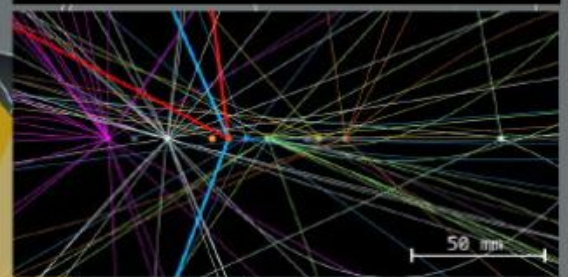
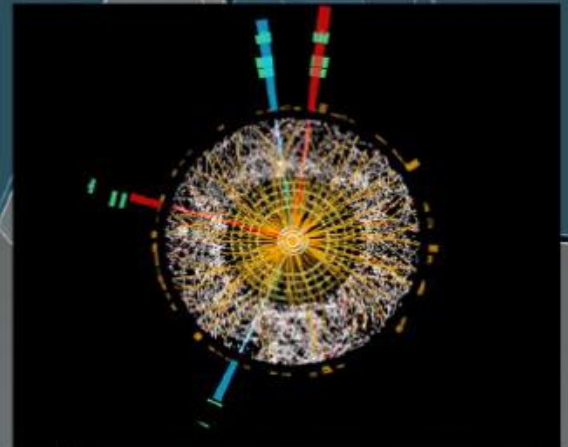
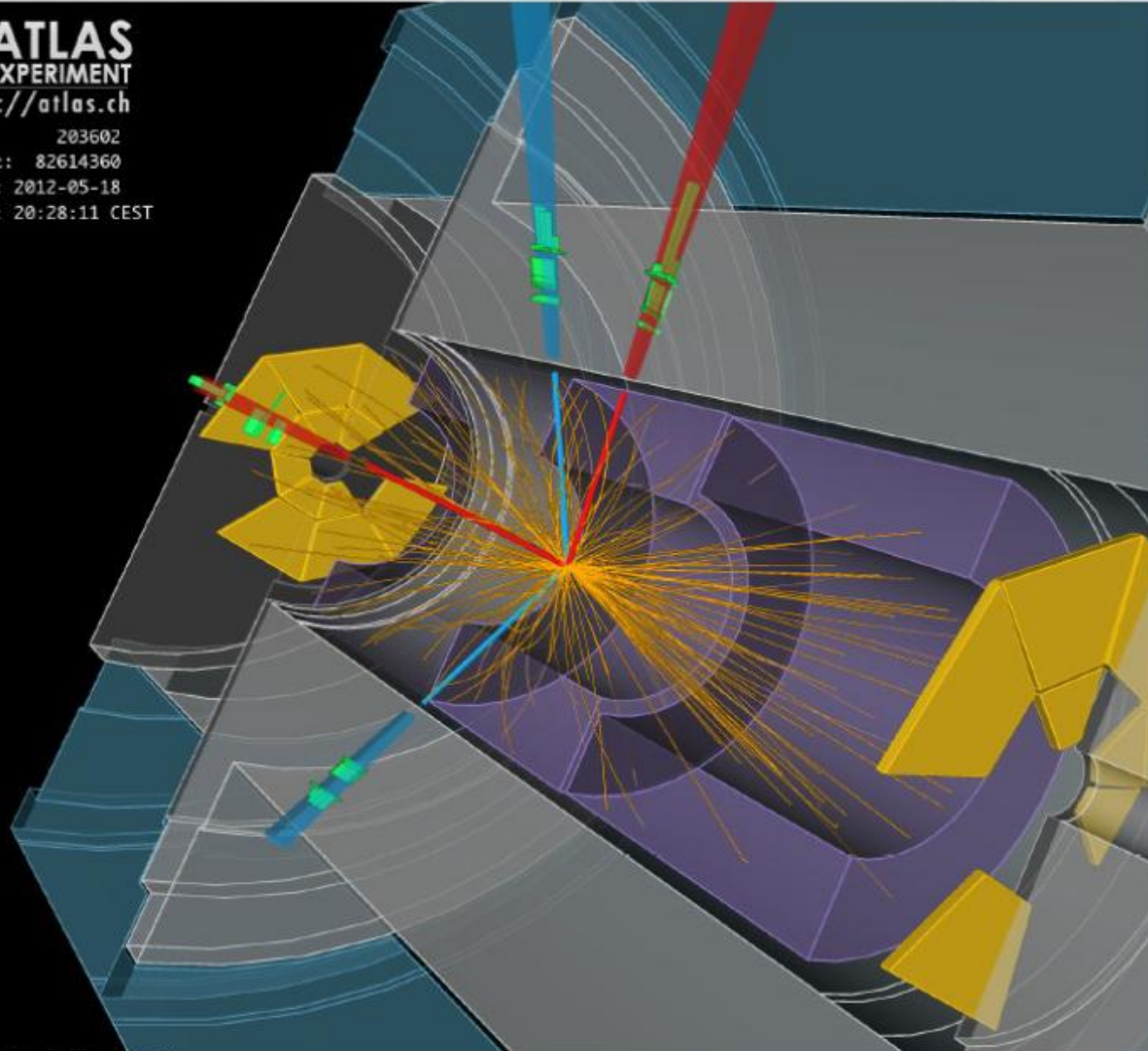
e_2 : $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

e_3 : $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$

e_4 : $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$

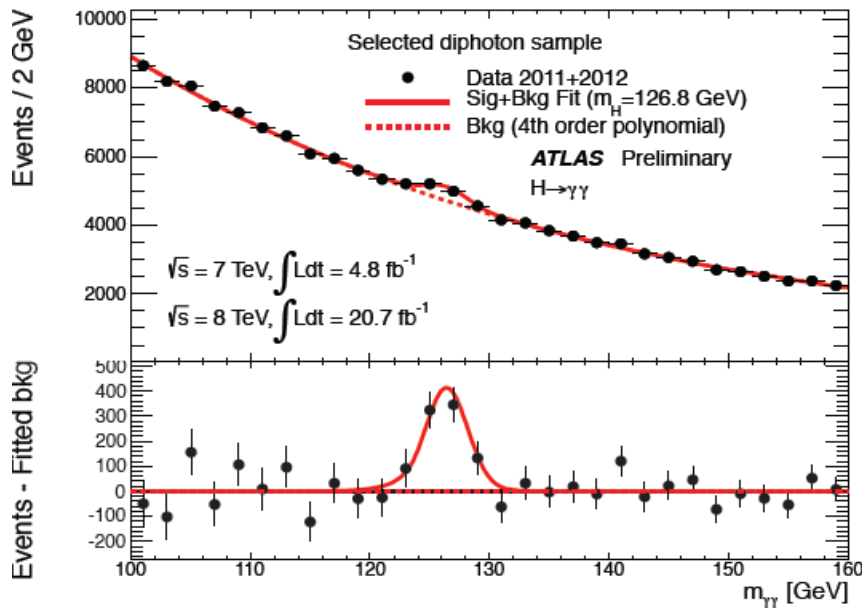
ATLAS
EXPERIMENT
<http://atlas.ch>

Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST



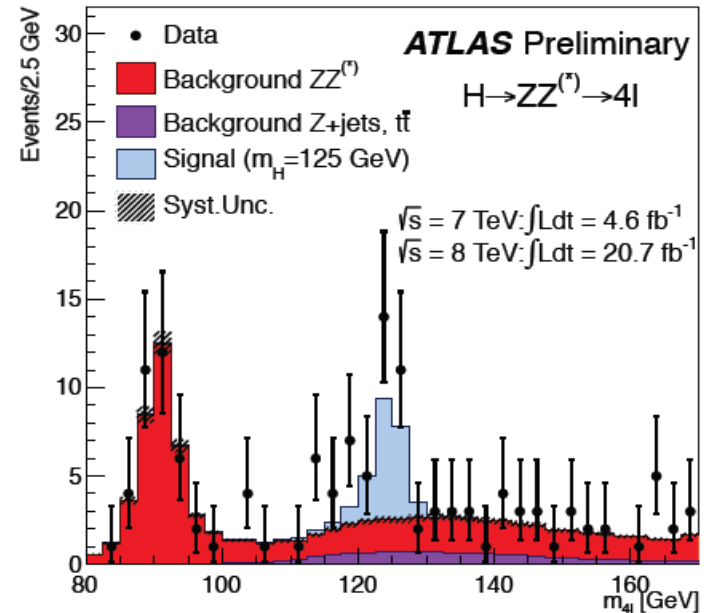
Higgs like signal with 7 TeV and 8 TeV data

$H \rightarrow \gamma\gamma$



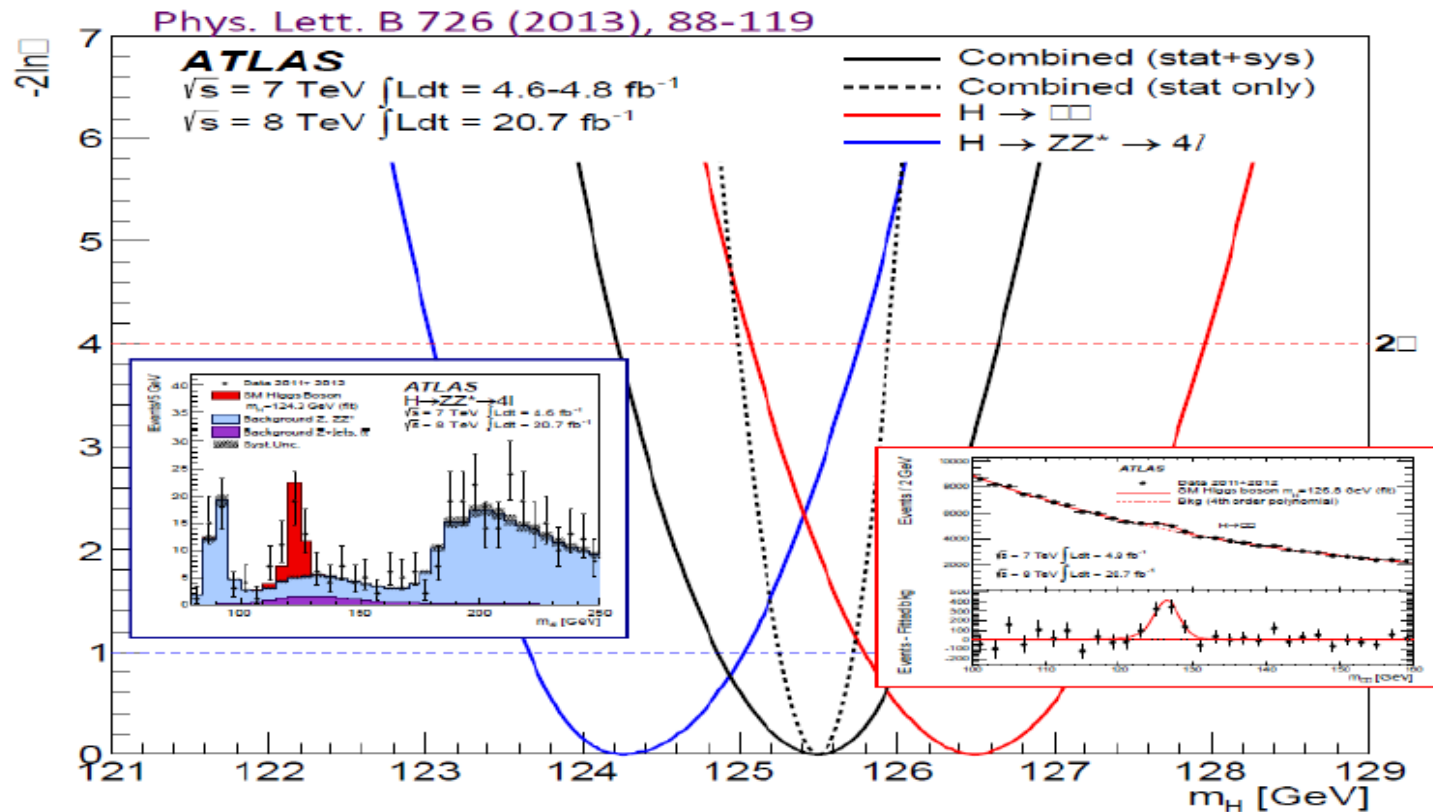
- Signal significance = 7.4σ
- $m_H = 126.8 \pm 0.2$ (stat) ± 0.7 (syst) GeV
- $\mu = 1.65 \pm 0.34$ (deviation w.r.t. SM at 2.3σ)

$H \rightarrow 4l$



- Signal significance = 6.6σ
- $m_H = 124.3^{+0.6}_{-0.5}$ (stat) $^{+0.6}_{-0.3}$ (syst) GeV
- $\mu = 1.7 \pm 0.34$

Mass measurement



$$4\ell: M_H = 124.3 \pm 0.6_{\text{stat}} \pm 0.4_{\text{sys}} \text{ GeV}$$

$$\gamma\gamma: M_H = 126.8 \pm 0.2_{\text{stat}} \pm 0.7_{\text{sys}} \text{ GeV}$$

$$\text{Combined: } M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}} \text{ GeV}$$

And since then

Panorama of ATLAS Higgs (125) Analyses

channel	ggF	VBF	VH	ttH	Yield	S/B (%)	Res. (GeV/c ²)
$\gamma\gamma$	✓	✓	✓	✓	~ 450	1 - 20%	~ 1.6
$ZZ \rightarrow 4l$	✓				~ 16	1	~ 2.2
$WW \rightarrow l\nu l\nu$	✓	✓	✓		~ 250	10%	Poor
$\tau\tau$	✓	✓	✓		~ 330	0.3 – 30%	~ 20
VH(bb)			✓		~ 50	1 - 10%	~ 15
ttH(bb)				✓	~20	Up to ~5%	Poor (combinatorial)
$\mu\mu$	Inclusive				~ 40	~ 0.2 %	~ 2.5
Invisible	(✓)		✓		~ 30	~ 0.2	Poor
$Z\gamma$	Inclusive				~ 15	~ 0.5%	~ 1.8

$H \rightarrow \gamma\gamma$ Update

Since “Discovery Paper” PLB 716
ATLAS-CONF-2013-012

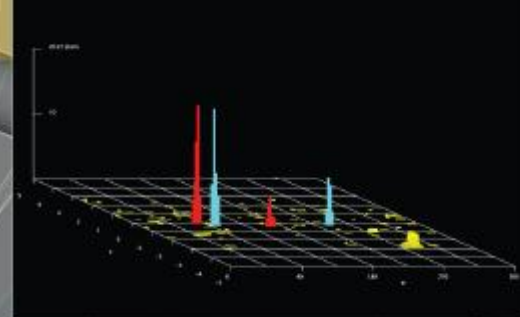
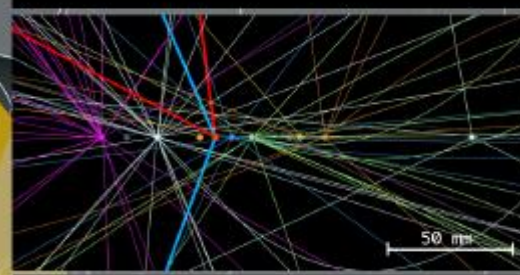
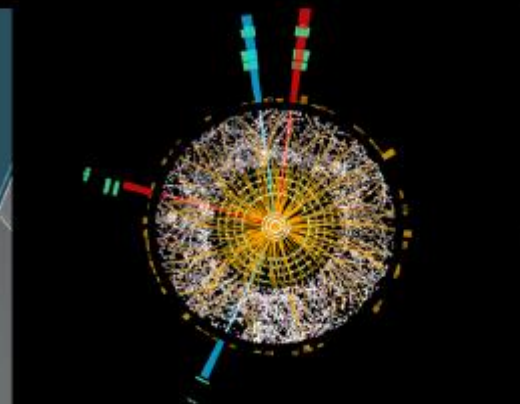
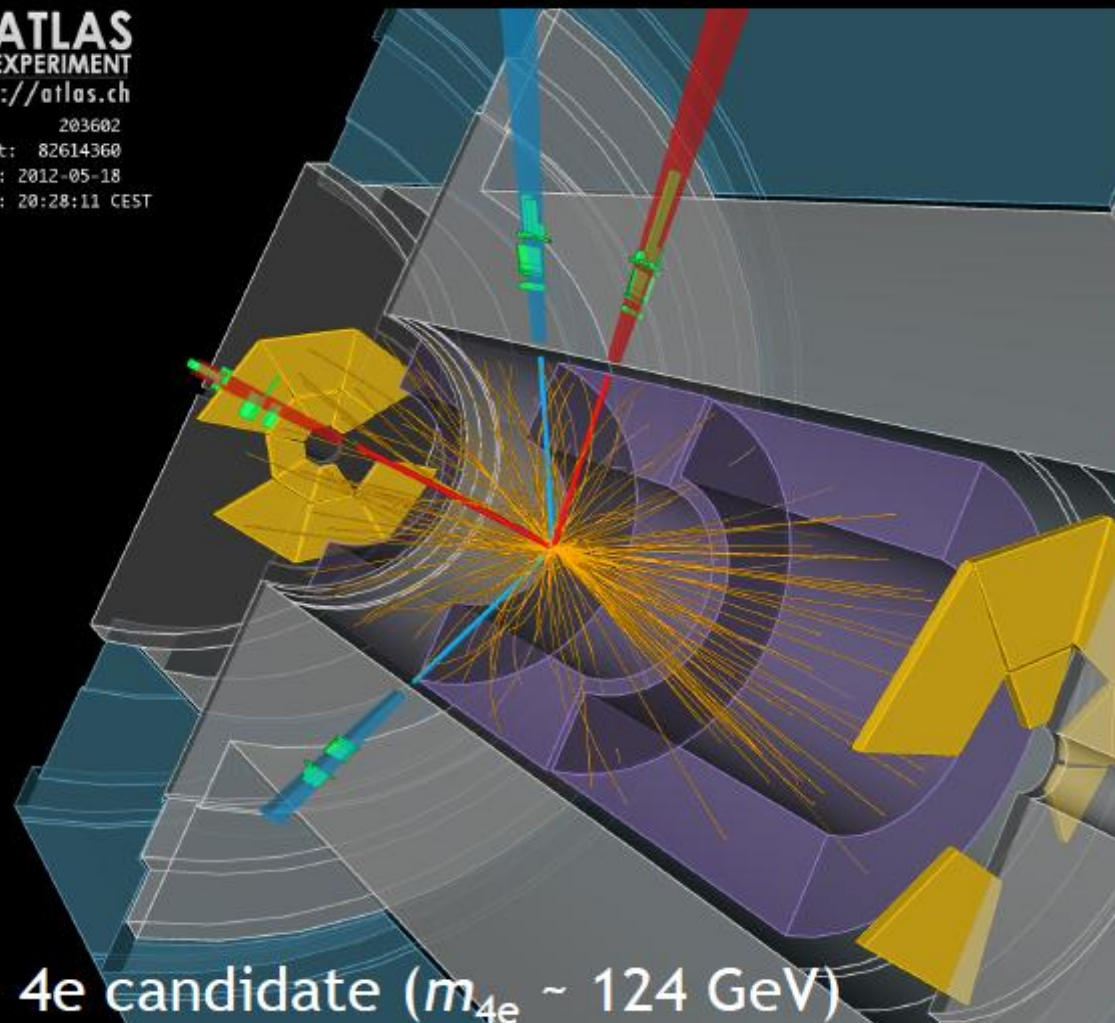


Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

$\gamma\gamma$ channel basic facts sheet :

Signal ($SM_{126 \text{ GeV}}$)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~450	2% - 60%	$\gamma\gamma, \gamma j$ and jj	Hgg, VBF, VH	4.9 & 20.7 fb^{-1}



$H \rightarrow 4e$ candidate ($m_{4e} \sim 124$ GeV)

4l channel basic facts sheet :

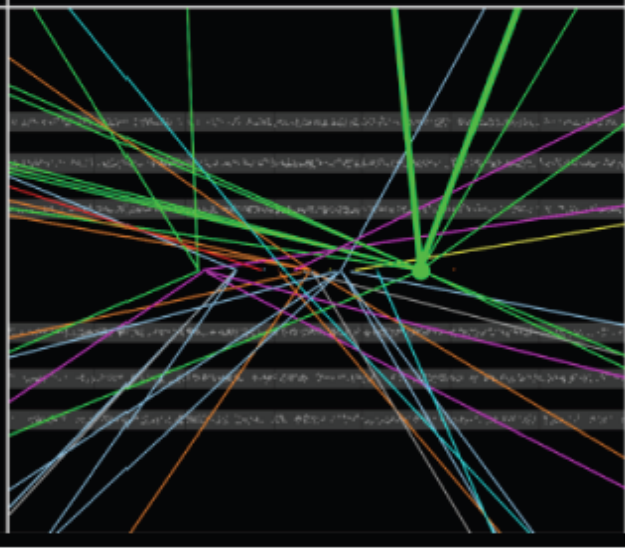
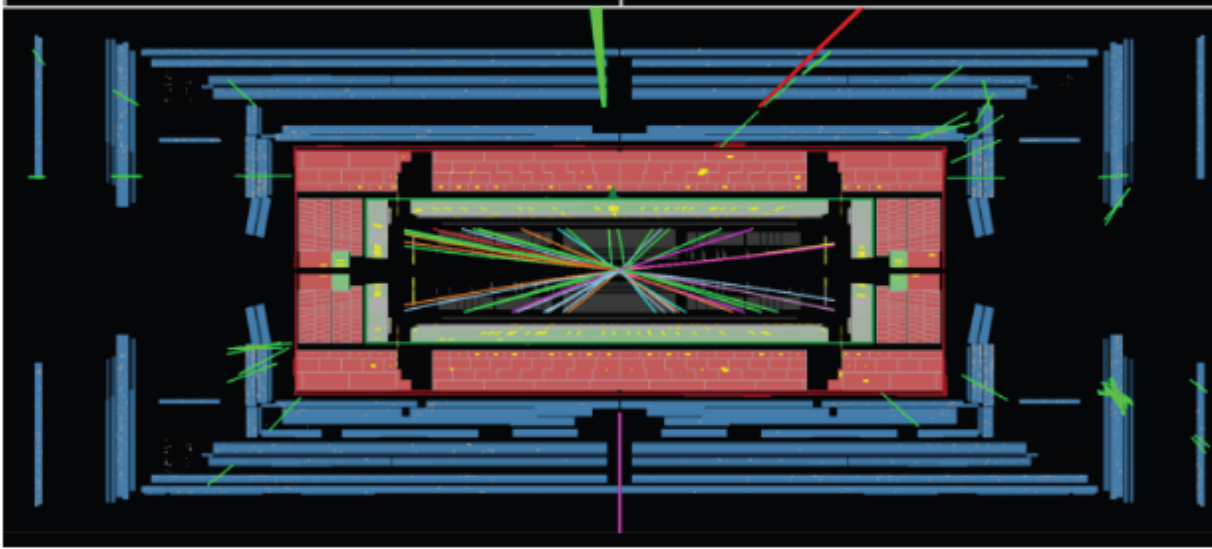
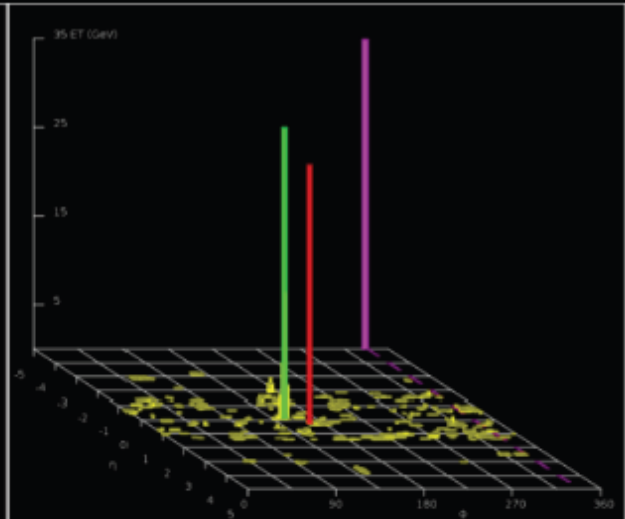
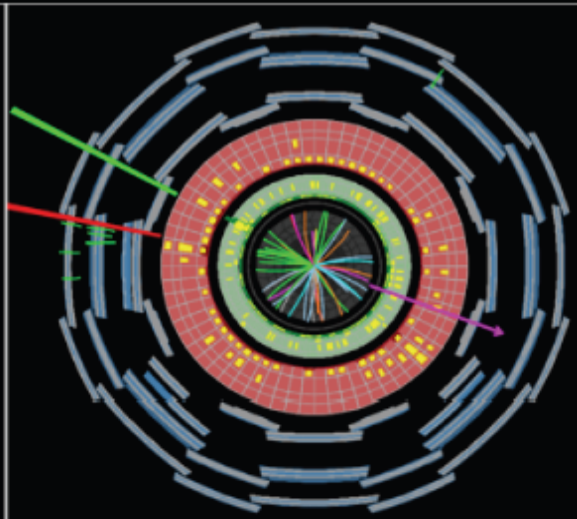
Signal	Signal Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~ 16	~ 1.5	ZZ, Z+jets, top	ggH, VBF & VH	4.9 & 20.7 fb ⁻¹

$$H \rightarrow WW^{(*)}$$

$$ll + 2\nu$$

0,1, 2 jet Channel

ATLAS-CONF-2013-030



WW channel basic facts sheet :

Signal	Sig. Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~250	~5%-40%	WW, W+jets, top, etc...	ggH & VBF	25fb ⁻¹

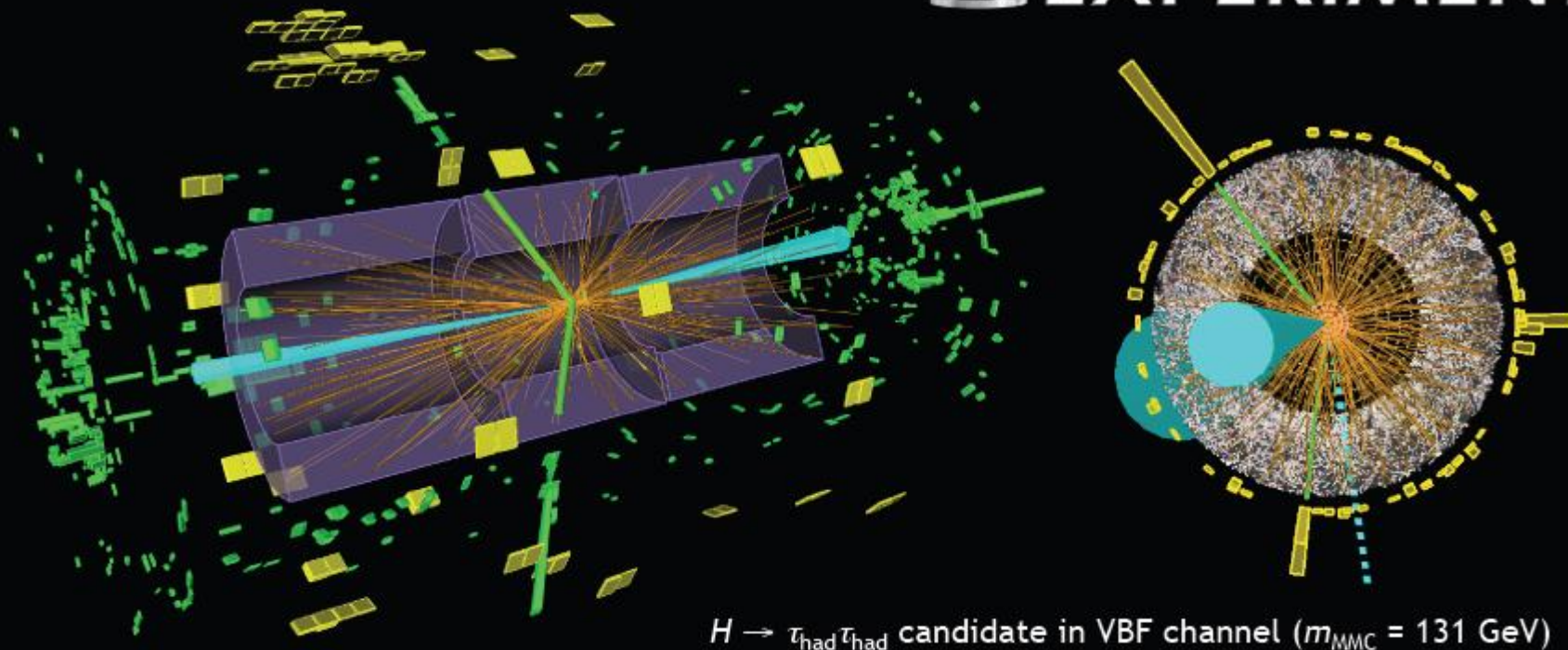
$H \rightarrow \tau\tau$

Reoptimised 7+8 TeV analysis

ATLAS-CONF-2012-160



ATLAS
EXPERIMENT

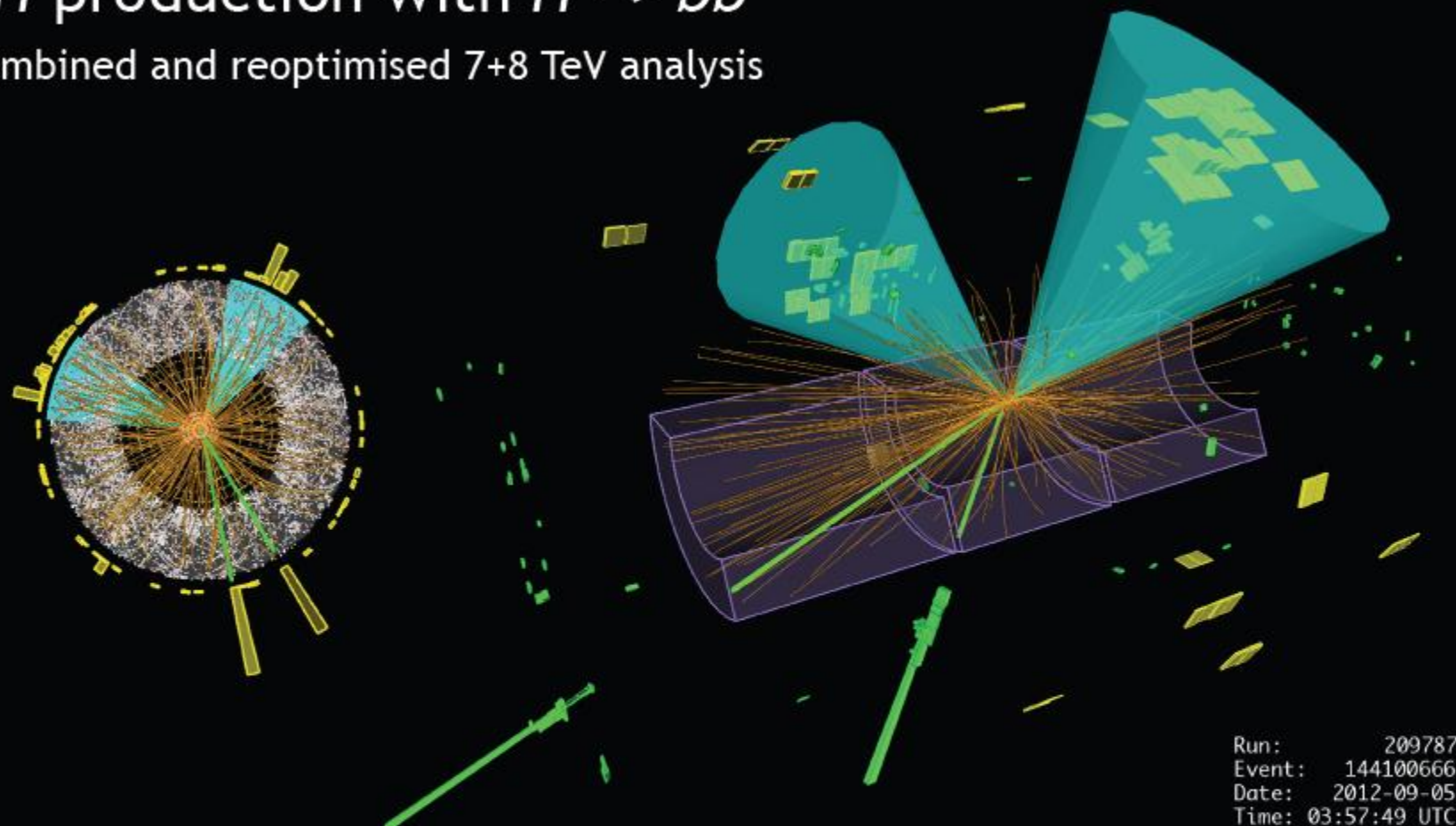


$\tau\tau$ channel basic facts sheet :

Signal (SM)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~330	0.3% - 30%	ZZ, Z+jets, top	VBF, Hgg, VH	4.9 & 13 fb ⁻¹

VH production with $H \rightarrow bb$

Combined and reoptimised 7+8 TeV analysis



VH(bb) channel basic facts sheet :

Signal (SM)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~50	~1% - 10%	Wbb,Zbb, top, etc...	VH	4.9 & 13 fb ⁻¹

Which Higgs boson we have discovered?

Higgs boson was discovered in ZZ^* , $\gamma\gamma$ and WW^* decays

- Higgs boson mass is ~ 125.6 GeV

Measured in $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$

ATLAS: $m_H = 125.5 \pm 0.2$ (stat) ± 0.6 (syst) GeV

CMS: $m_H = 125.7 \pm 0.3$ (stat) ± 0.3 (syst) GeV

- ATLAS and CMS data strongly favour $J^P = 0^+$ SM quantum numbers; alternative models excluded at 95% CL.
- Signal strength $\mu = \sigma/\sigma_{SM}$ consistent with 1

Summer 2013:

All measured properties are compatible with SM hypothesis.

Nobel price for predicting Higgs particle

2013 NOBEL PRIZE IN PHYSICS

François Englert
Peter W. Higgs



© The Nobel Foundation. Photo: Lovisa Engblom.

THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES
AND SCALAR PARTICLES



8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter Higgs

“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”

Entrance of the Higgs into PDG

2013

Higgs Bosons — H^0 and H^\pm

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
NODE=S055

CONTENTS:

NODE=S055CNT
NODE=S055CNT

- H^0 (Higgs Boson)
 - H^0 Mass
 - H^0 Spin
 - H^0 Decay Width
 - H^0 Decay Modes
 - H^0 Signal Strengths in Different Channels
 - Combined Final States
 - W^+W^- Final State
 - ZZ^* Final State
 - $\gamma\gamma$ Final State
 - $b\bar{b}$ Final State
 - $\tau^+\tau^-$ Final State
- Standard Model H^0 (Higgs Boson) Mass Limits
 - H^0 Direct Search Limits
 - H^0 Indirect Mass Limits from Electroweak Analysis
- Searches for Other Higgs Bosons
 - Mass Limits for Neutral Higgs Bosons in Supersymmetric Models
 - H^0 (Higgs Boson) Mass Limits in Supersymmetric Models
 - A^0 (Pseudoscalar Higgs Boson) Mass Limits in Supersymmetric Models
 - H^0 (Higgs Boson) Mass Limits in Extended Higgs Models
 - Limits in General two-Higgs-doublet Models
 - Limits for H^0 with Vanishing Yukawa Couplings
 - Limits for H^0 Decaying to Invisible Final States
 - Limits for Light A^0
 - Other Limits
 - H^\pm (Charged Higgs) Mass Limits
 - Mass Limits for $H^{\pm\pm}$ (doubly-charged Higgs boson)
 - Limits for $H^{\pm\pm}$ with $T_3 = \pm 1$
 - Limits for $H^{\pm\pm}$ with $T_3 = 0$

H^0 (Higgs Boson)

NODE=S055CNT

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055210

NODE=S055210

H^0 MASS

UNDE (GeV)

126.0 ± 0.4 OUR AVERAGE

UNDE (GeV)	DOCUMENT ID	TECN	COMMENT
125.0 ± 0.4 ± 0.4	¹ CHATRCHYAN13J	CMS	pp , 7 and 8 TeV
126.0 ± 0.4 ± 0.4	² AAD	12N ATLAS	pp , 7 and 8 TeV
●●● We do not use the following data for averages, fits, limits, etc. ●●●			
126.2 ± 0.0 ± 0.2	³ CHATRCHYAN13J	CMS	pp , 7 and 8 TeV
125.3 ± 0.4 ± 0.5	⁴ CHATRCHYAN12N	CMS	pp , 7 and 8 TeV

NODE=S055HBM
NODE=S055HBM

OCCUR=2

¹ Combined value from ZZ and $\gamma\gamma$ final states.

² AAD 12N obtain results based on $4.6\text{--}4.8\text{ fb}^{-1}$ of pp collisions at $E_{\text{CM}} = 7\text{ TeV}$ and $5.9\text{--}5.9\text{ fb}^{-1}$ at $E_{\text{CM}} = 8\text{ TeV}$. An excess of events over background with a local significance of 3.9σ is observed at $m_{H^0} = 126\text{ GeV}$. See also AAD 120A.

³ Result based on $ZZ \rightarrow 4\ell$ final states in 5.1 fb^{-1} of pp collisions at $E_{\text{CM}} = 7\text{ TeV}$ and 12.2 fb^{-1} at $E_{\text{CM}} = 8\text{ TeV}$.

⁴ CHATRCHYAN 12N obtain results based on $4.9\text{--}5.1\text{ fb}^{-1}$ of pp collisions at $E_{\text{CM}} = 7\text{ TeV}$ and $5.1\text{--}5.1\text{ fb}^{-1}$ at $E_{\text{CM}} = 8\text{ TeV}$. An excess of events over background with a local significance of 5.0σ is observed at about $m_{H^0} = 125\text{ GeV}$. See also CHATRCHYAN 120Y.

NODE=S055HBM;LINKAGE=CA
NODE=S055HBM;LINKAGE=AA

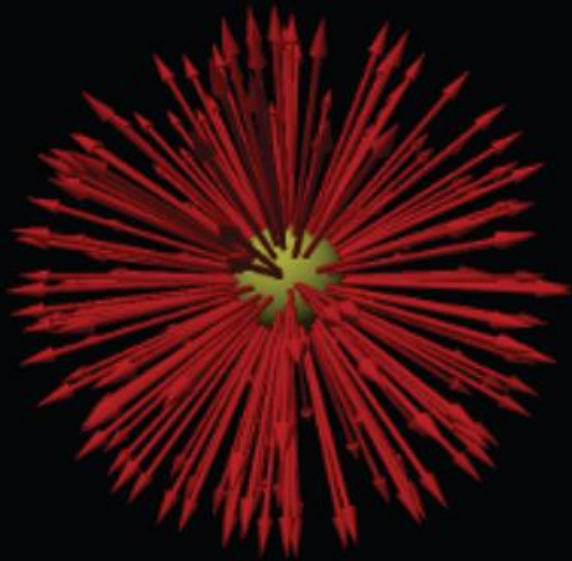
NODE=S055HBM;LINKAGE=CT

NODE=S055HBM;LINKAGE=CH

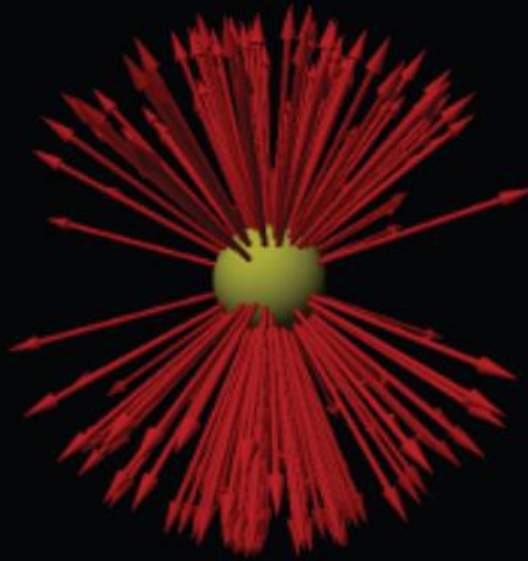
Inaugural entrance of the Higgs boson in the PDG particle listing !

H^0

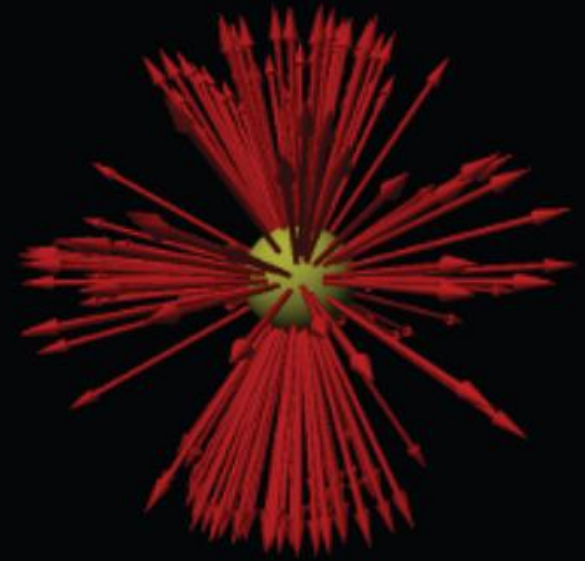
How we can recognize spin?



spin 0



spin 1

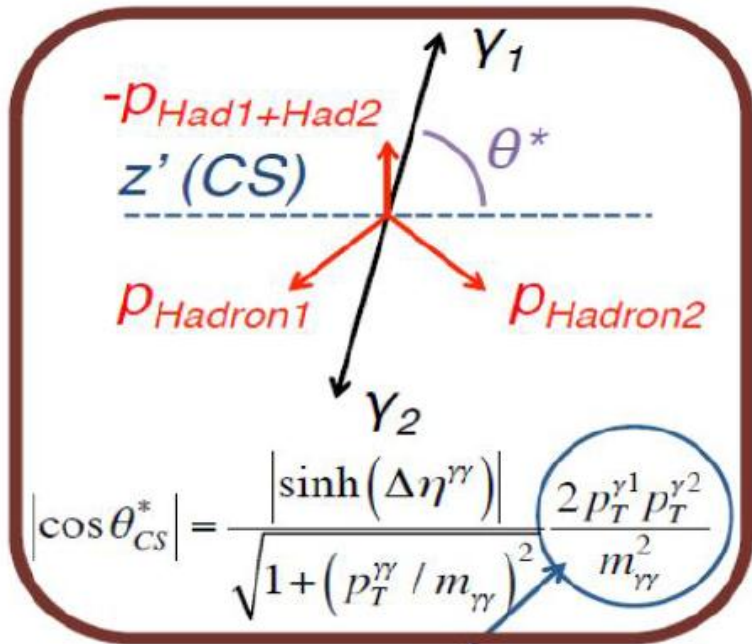


spin 2

Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

Spin observables for $H \rightarrow \gamma\gamma$

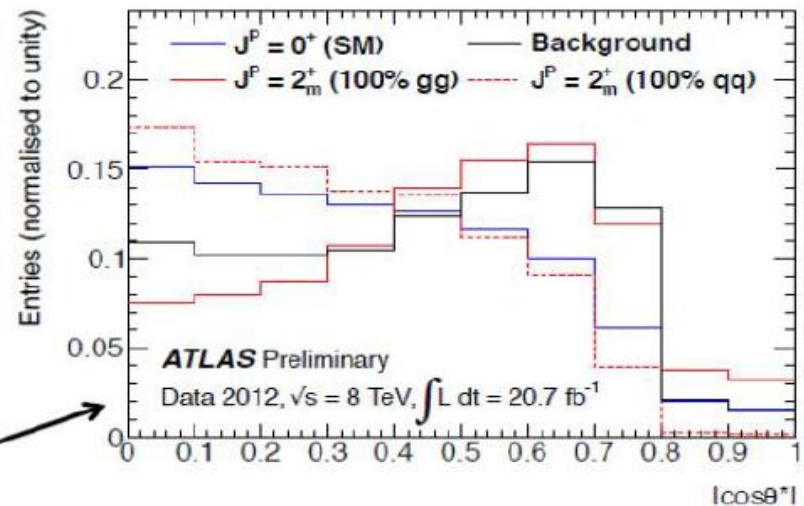
Separate 0^+ and 2^+ spin hypotheses using the angular correlation of the two photons



Collins-Soper frame used to get reference axis z' for $\cos(\theta^*)$

- z -axis bisects angle between the momenta of colliding hadrons
- Minimizes impact of ISR
- Better 0^+ / 2^+ discrimination

Relative p_T cuts on the photons remove most correlation with $m_{\gamma\gamma}$
 $qq \rightarrow 2^+$ very similar to SM $gg \rightarrow 0^+$



Fit method for $H \rightarrow \gamma\gamma$

Events are divided into $\gamma\gamma$ mass sidebands and signal region

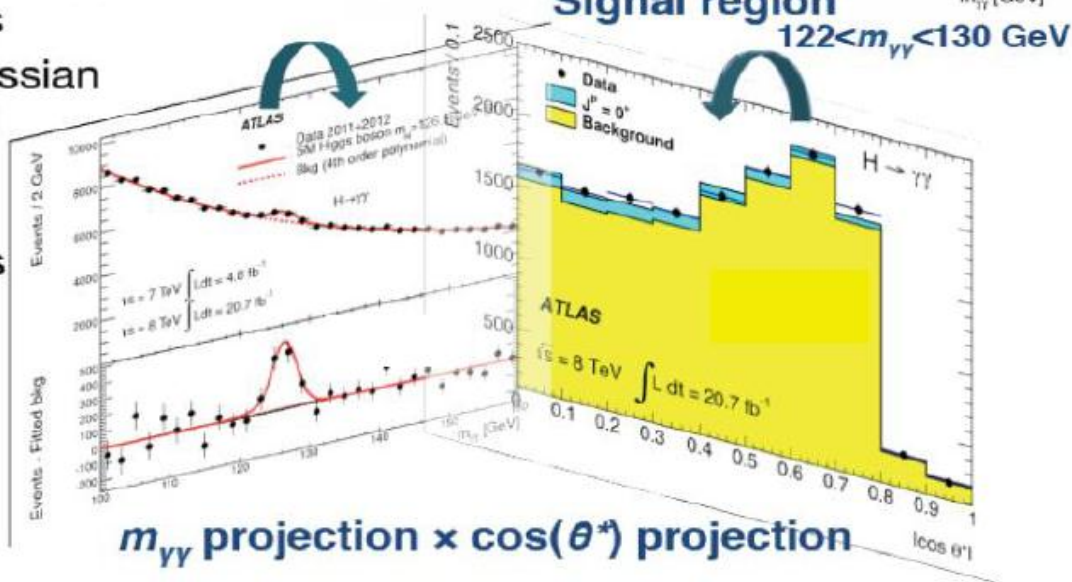
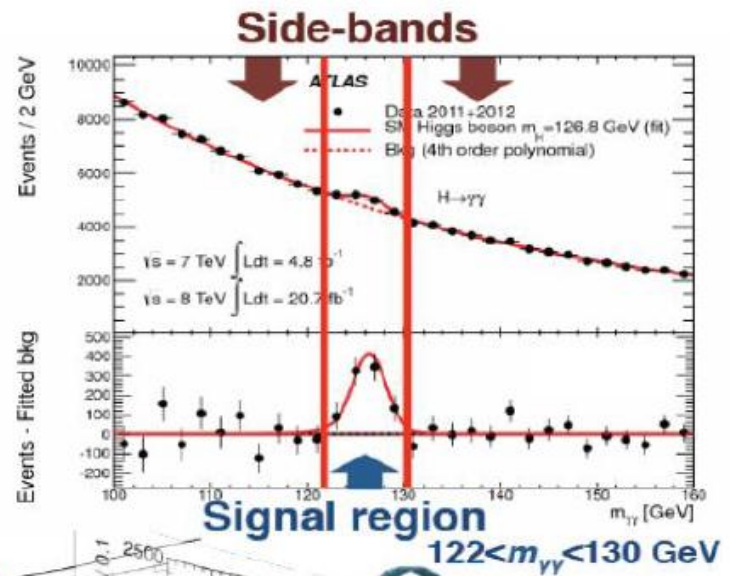
Side-bands: 1D fit in $m_{\gamma\gamma}$

- **Background:** O(5) Bernstein polynomial
- Constrains the background shape in the signal region of mass

Signal region: 2D $m_{\gamma\gamma}$ - $\cos(\theta^*)$ fit

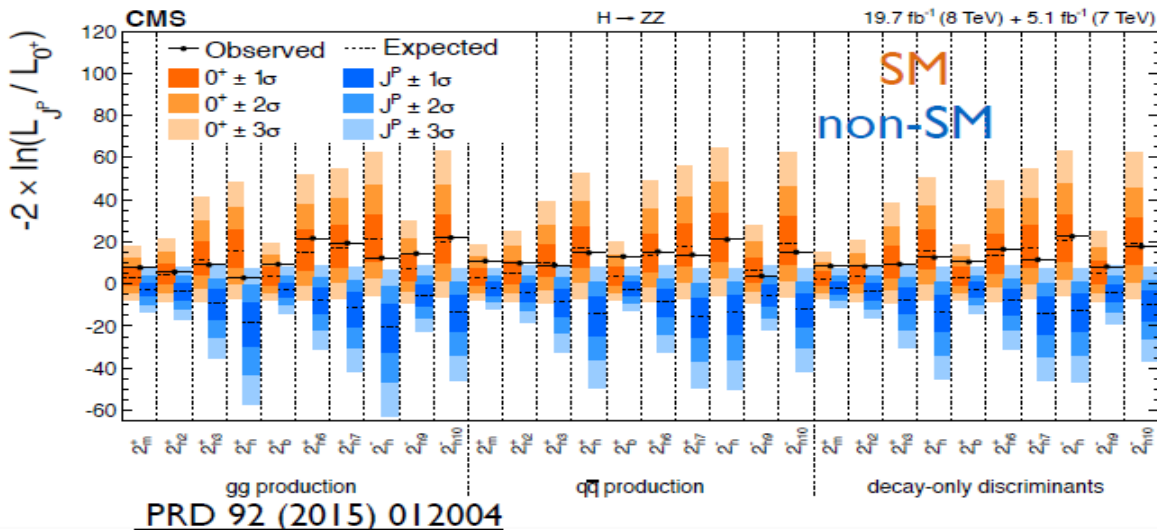
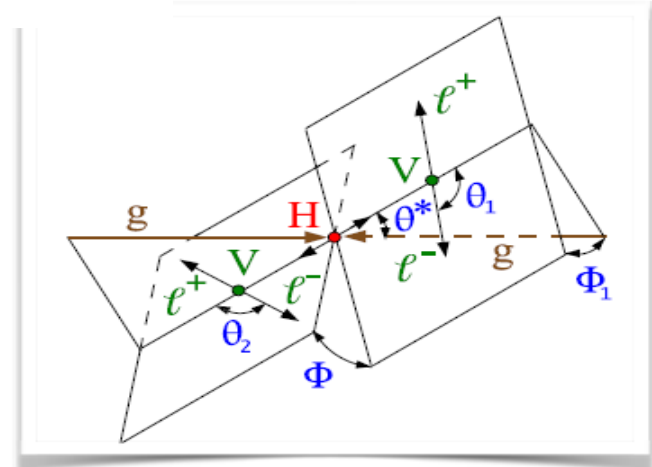
- Product of two 1D shapes
- **Signal:** Crystal ball + Gaussian mass peak, $\cos(\theta^*)$ shape from MC
- **Background:** $\cos(\theta^*)$ shape from $m_{\gamma\gamma}$ sidebands

Method assumes minimal correlation between mass and $\cos(\theta^*)$ in background



Spin study with H->4l

- SM predicts $J^{PC} = 0^{++}$
- Angular distributions sensitive to JP
- Wide range of alternative quantum numbers excluded at >99% CL
- All observations consistent with expectations for the SM Higgs boson



Tests of
alternative J^P
hypotheses in ZZ

Higgs boson decay width

$$m_h = 125 \text{ GeV} \rightarrow \Gamma_h = 4.07 \text{ MeV}$$

$$\tau_h = 1.62 \cdot 10^{-22} \text{ [s]}$$

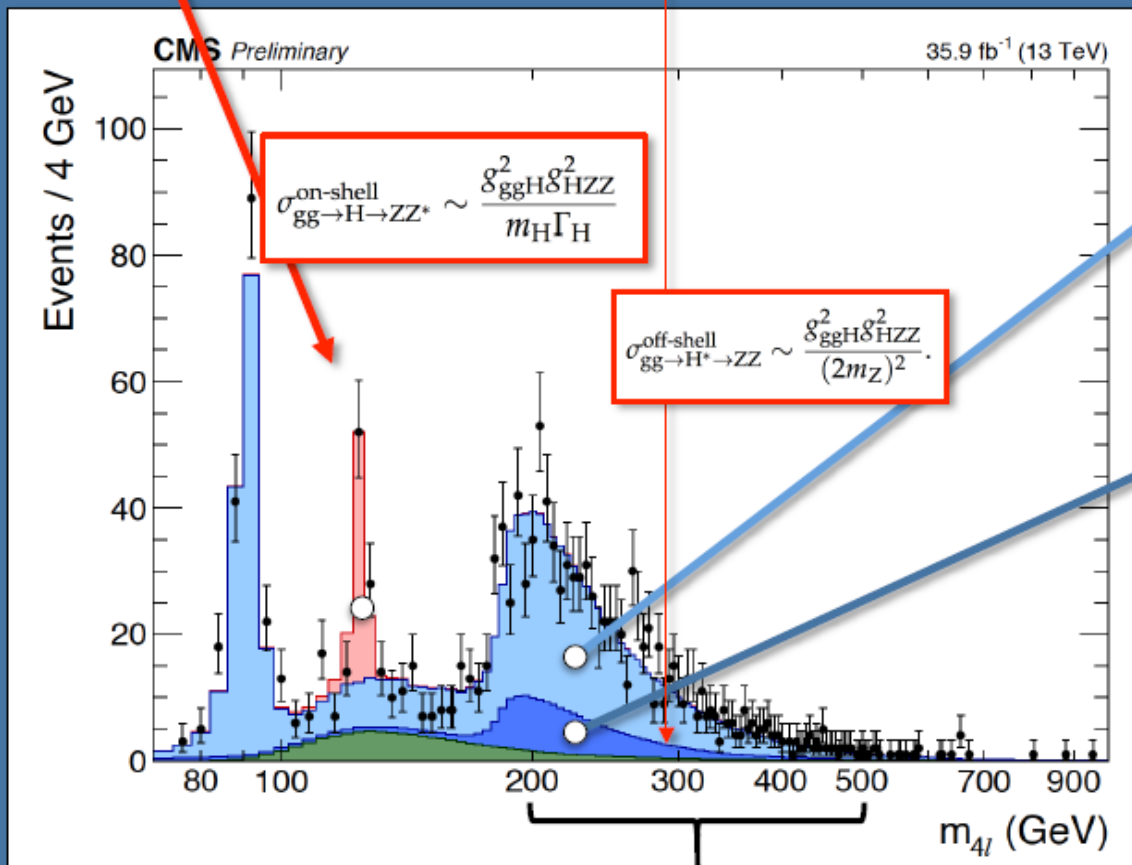
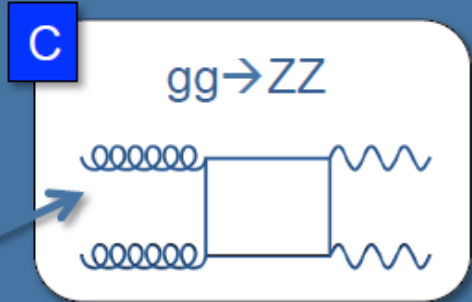
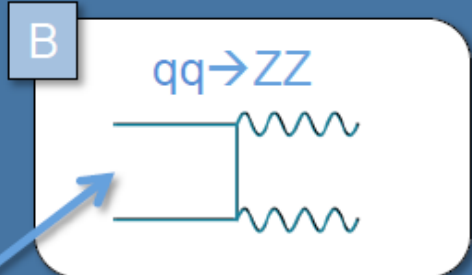
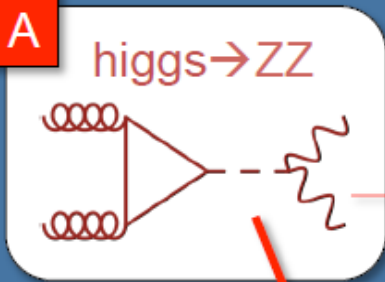
A deviation would imply a decay to non-SM particles

Differential Higgs production cross-section

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

Γ_h cannot be accessed directly (experimental resolution $\sim 1\text{-}2 \text{ GeV}$)

Indirect measurement



Interference between **A** and **C** : $(A+C)^2 = A^2 + C^2 + 2AC$

tiny \leftarrow \rightarrow *accessible*

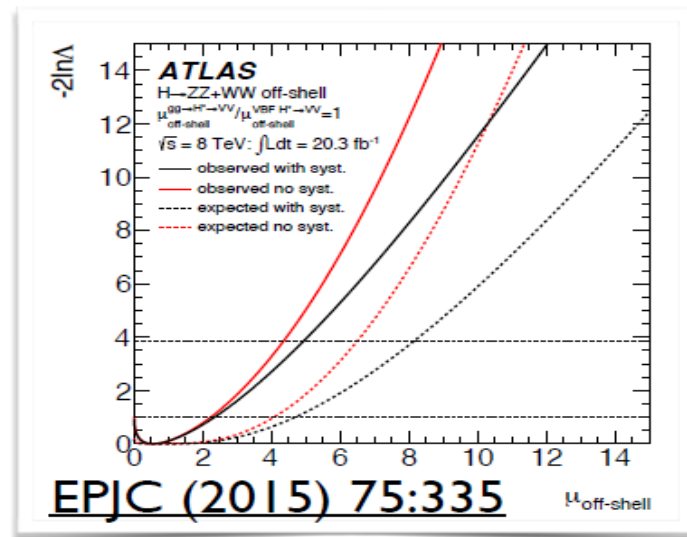
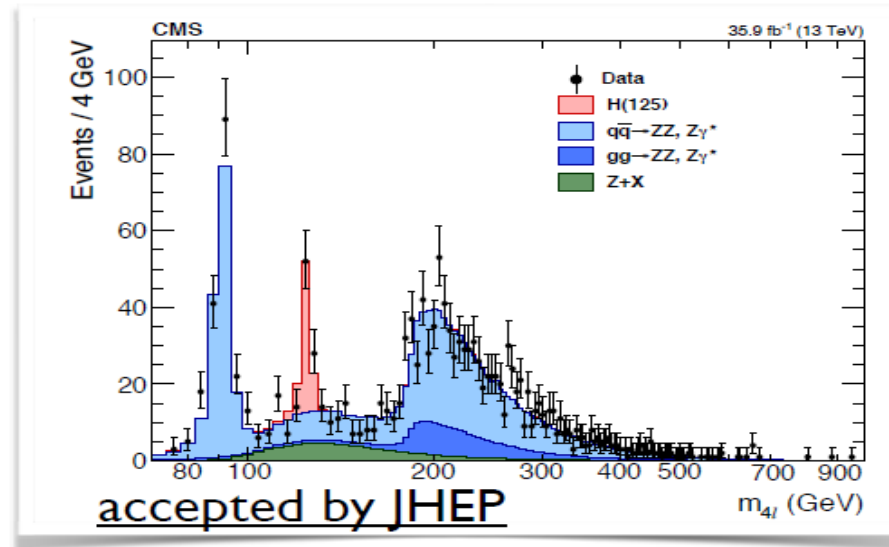
Higgs boson decay width

Total width

- Lower bound on total width from decay measurements
- Direct experimental measurements probe 3 orders of magnitude larger than SM width ($\Gamma=4$ MeV)
- Indirect constraint* on the width via measurement of ratio of off-peak to on-peak cross-section
 - CMS: $\Gamma < 13$ MeV
 - ATLAS: $\Gamma < 22$ MeV

*N. Kauer and G. Passarino, JHEP (2012) 2012: 116

*F. Caola and K. Melnikov, PRD88 (2013) 054024

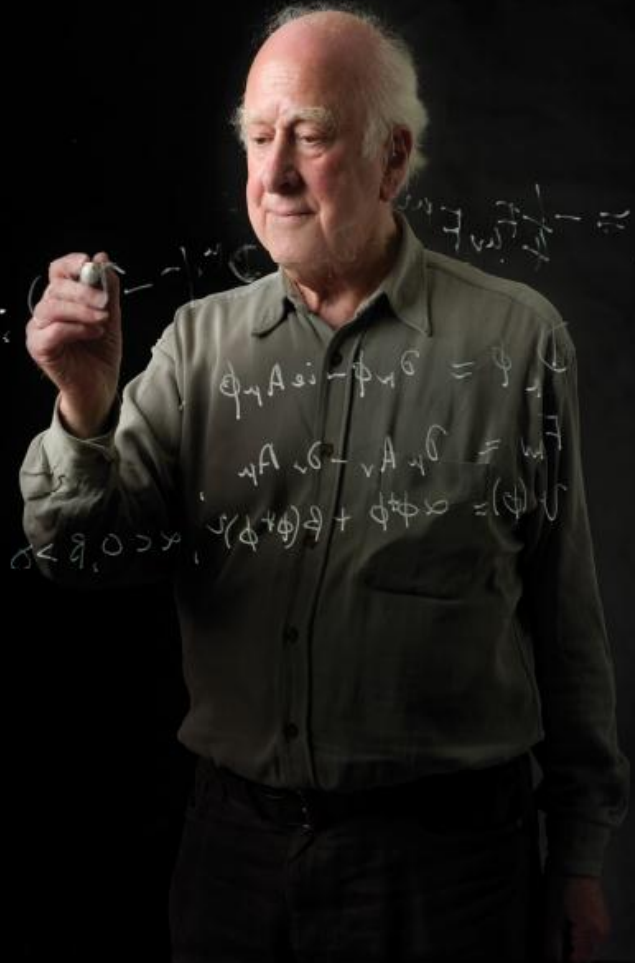


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i\bar{\psi} \not{D} \psi + h.c$$

$$+ \bar{\psi}_i \gamma_{ij} \psi_j \phi + h.c$$

$$+ |D_\mu \phi|^2 - V(\phi)$$



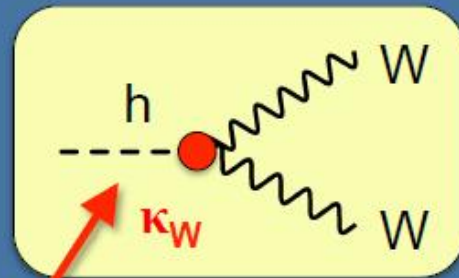
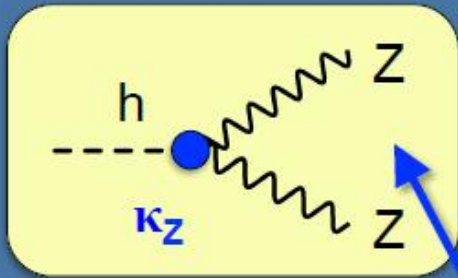
Couplings: kappa-framework

Scale factor for each (fundamental) coupling:

$$\sigma(i \rightarrow h \rightarrow f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_h^2 \Gamma_h^{SM}}$$

$$\begin{aligned} \mathcal{L} = & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H \end{aligned}$$

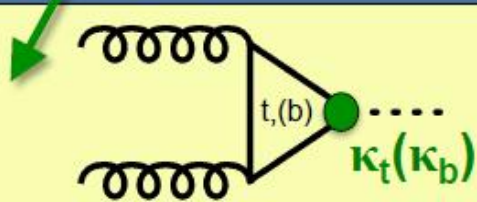
Scale Higgs boson couplings (wrt SM): production & decay



$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$

$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$

$$+ \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$



$$\kappa_g^2 \propto 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$



$$\kappa_\gamma^2 \propto 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$

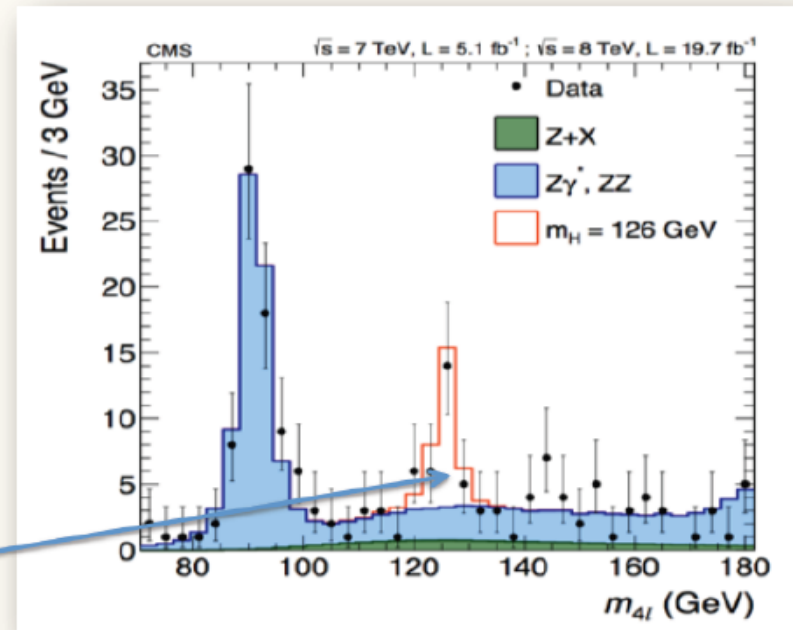
What do we measure?

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \epsilon_p^i \times Lumi$$

$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

$$\mu^{ZZ}(@125.5 \text{ GeV}) = 1.44^{+0.40}_{-0.35}$$

6.6 σ (4.4 exp) ATLAS

$$\mu^{ZZ}(@125.6 \text{ GeV}) = 0.93^{+0.26+0.13}_{-0.23-0.09}$$

6.8 σ (6.7 exp) CMS

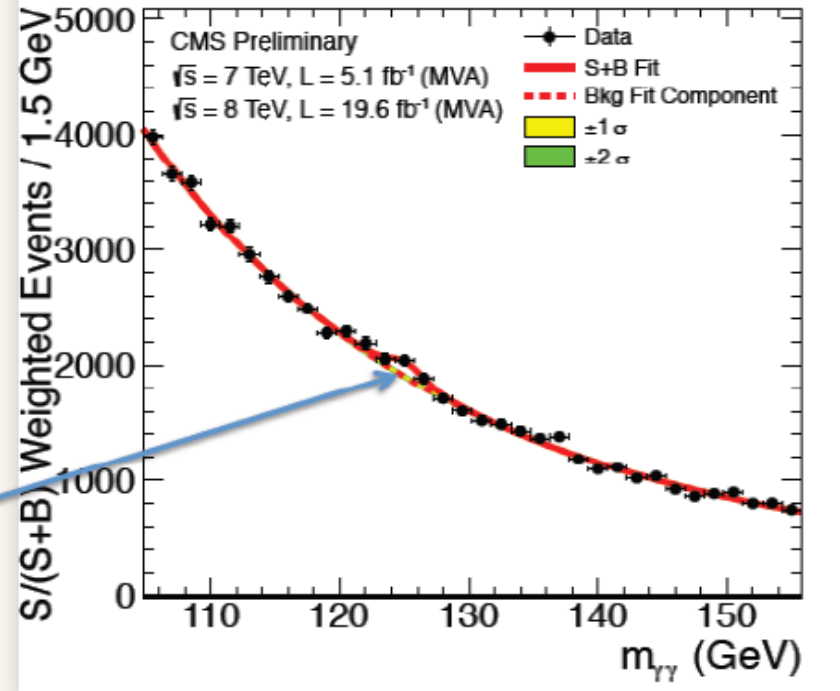
What do we measure?

We measure event yields

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The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B

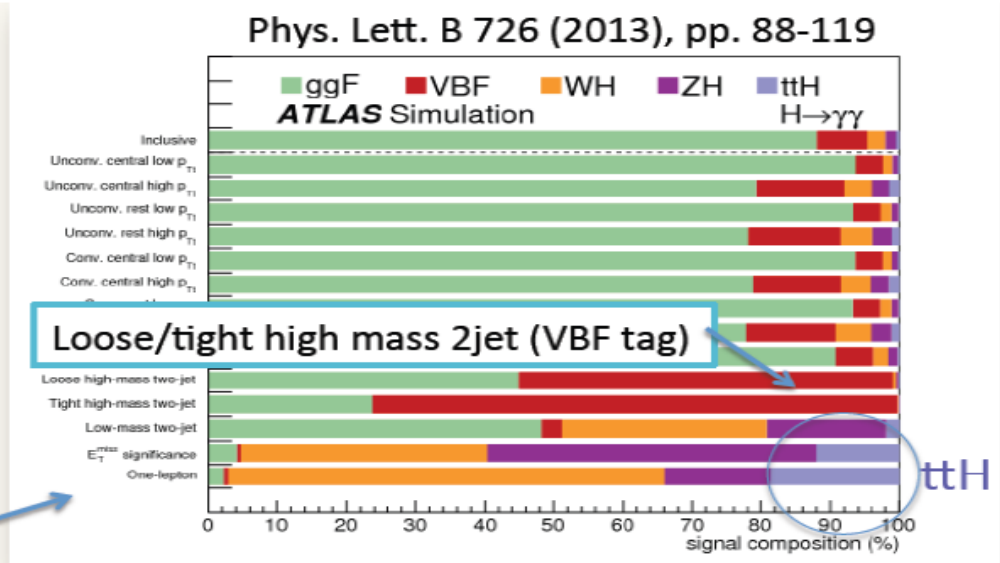


$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \epsilon_p^i \times Lumi$$

$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

What do we measure?

We increase sensitivity by classifying the events via categories and measure the signal strength per category and then combining them taking all the systematic and statistical errors uncertainties into account



The categories are also sensitive to different production modes, allowing the measurement of the couplings

$$n_s^{c,i} = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \epsilon_p^{c,i} \times Lumi$$

$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

$$\mu^{\gamma\gamma}(@125.5 \text{ GeV}) = 1.57^{+0.33}_{-0.28}$$

7.4σ (4.3 exp) ATLAS

$$\mu^{\gamma\gamma}(@125.7 \text{ GeV}) = 0.77^{+0.29}_{-0.26}$$

3.2σ (3.9 exp) CMS

Higgs boson decay channels

Significance

7.4 σ (4.3 σ)

6.6 σ (4.4 σ)

3.8 σ (3.8 σ)

4.1 σ (3.2 σ)

0.36 σ (1.64 σ)

Obs. (Exp.)

3.2 σ (4.2 σ)

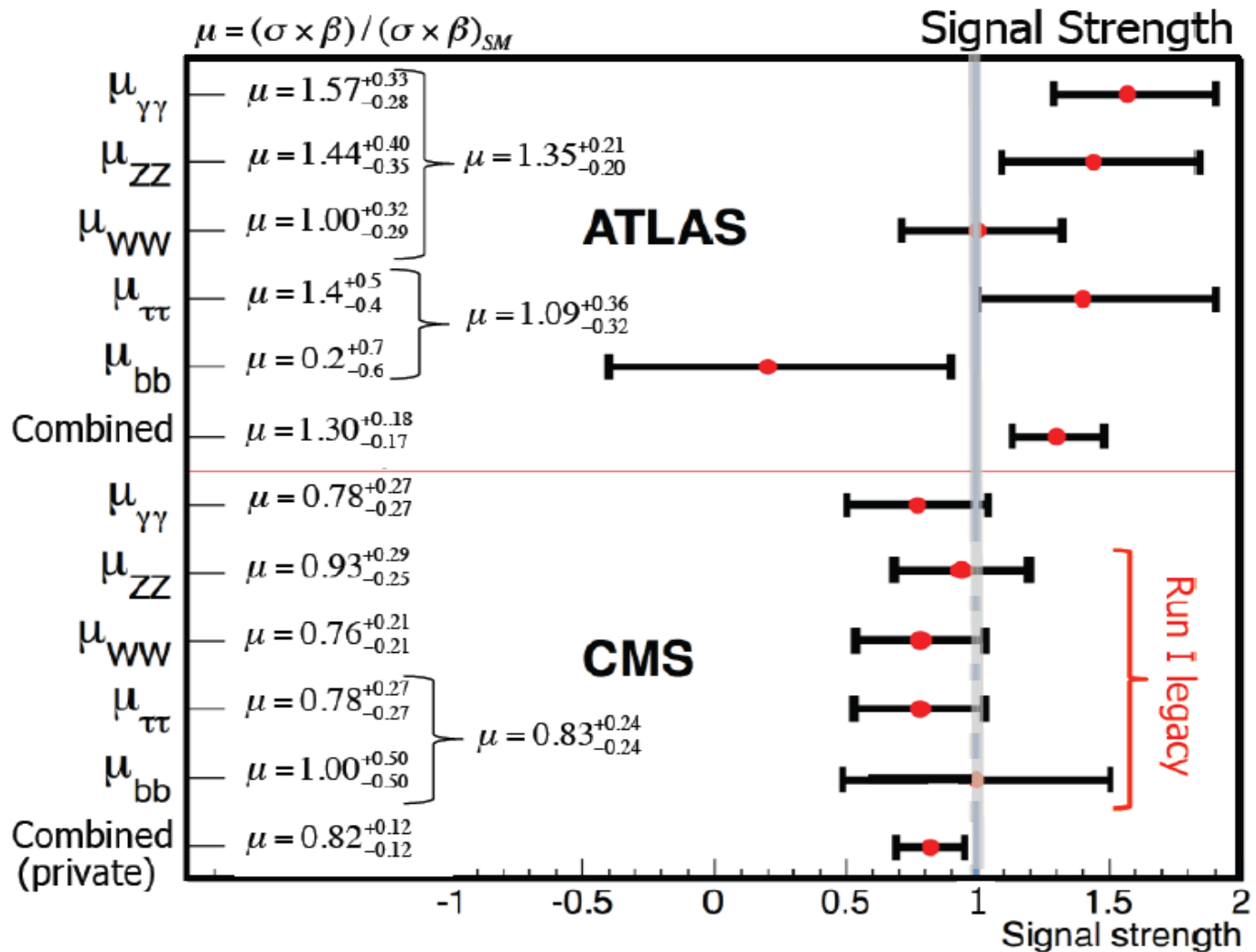
6.8 σ (6.7 σ)

4.3 σ (5.8 σ)

3.3 σ (3.7 σ)

2.1 σ (2.1 σ)

Obs. (Exp.)



Probe the production mode

We fitted

$$\mu_{VBF+VH}^i \equiv \left[\mu_{VBF+VH} \times \mu_{BR}^i \right]$$

$$\mu_{ggF+ttH}^i \equiv \left[\mu_{ggF+ttH} \times \mu_{BR}^i \right]$$

Taking one decay mode at a time we can go one step further and fit the ratio per channel

$$\frac{\mu_{VBF+VH}^i}{\mu_{ggF+ttH}^i} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

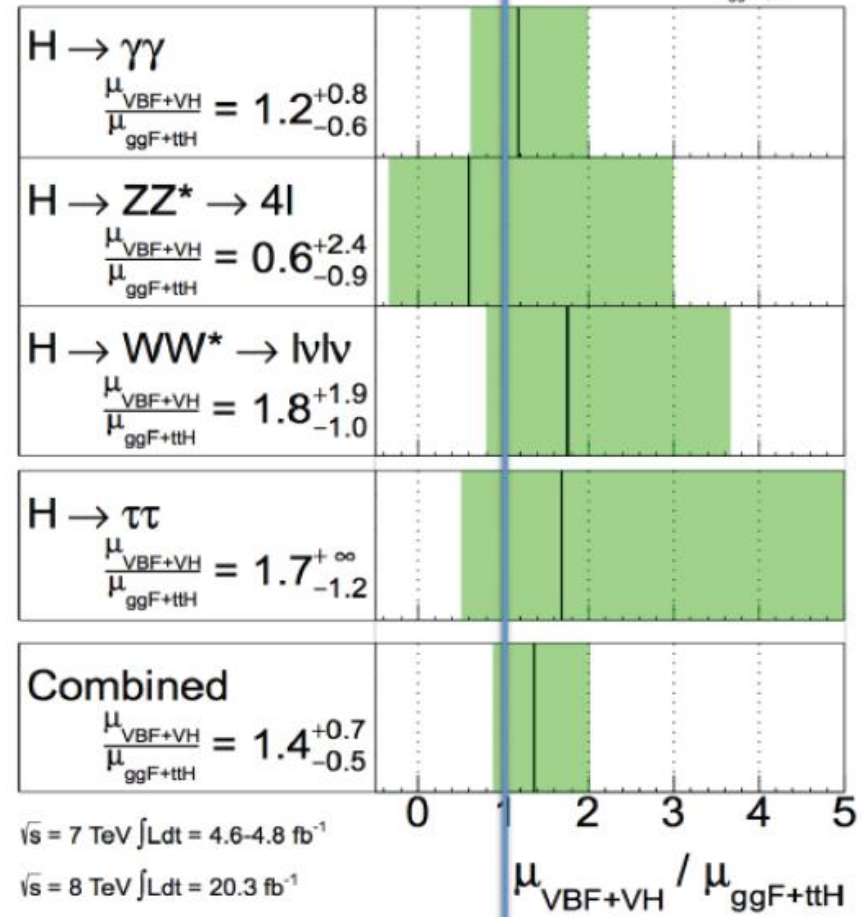
This ratio is INDEPENDENT of the decay channel so we can combine

ATLAS Preliminary

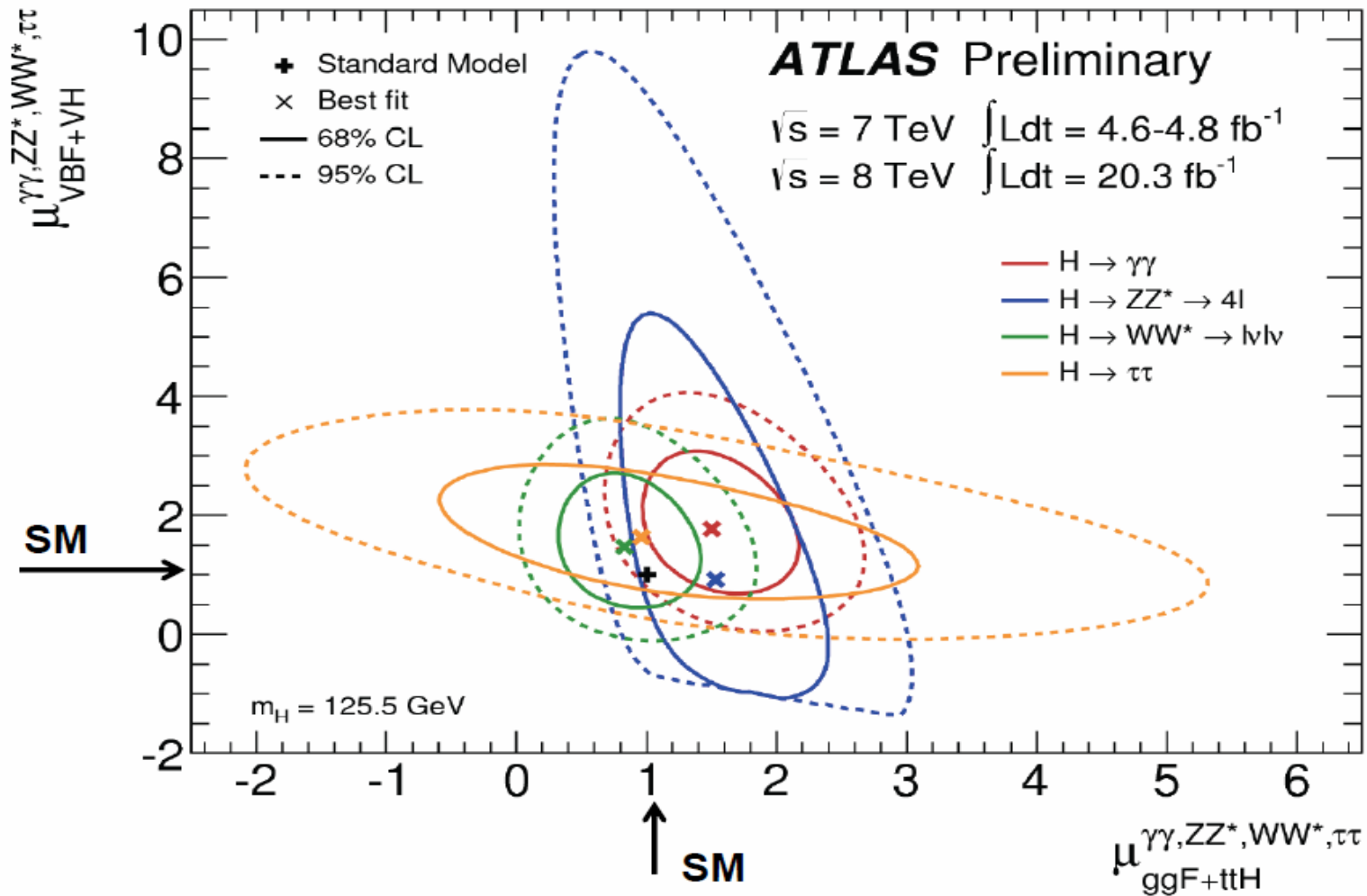
$m_H = 125.5 \text{ GeV}$

Total uncertainty

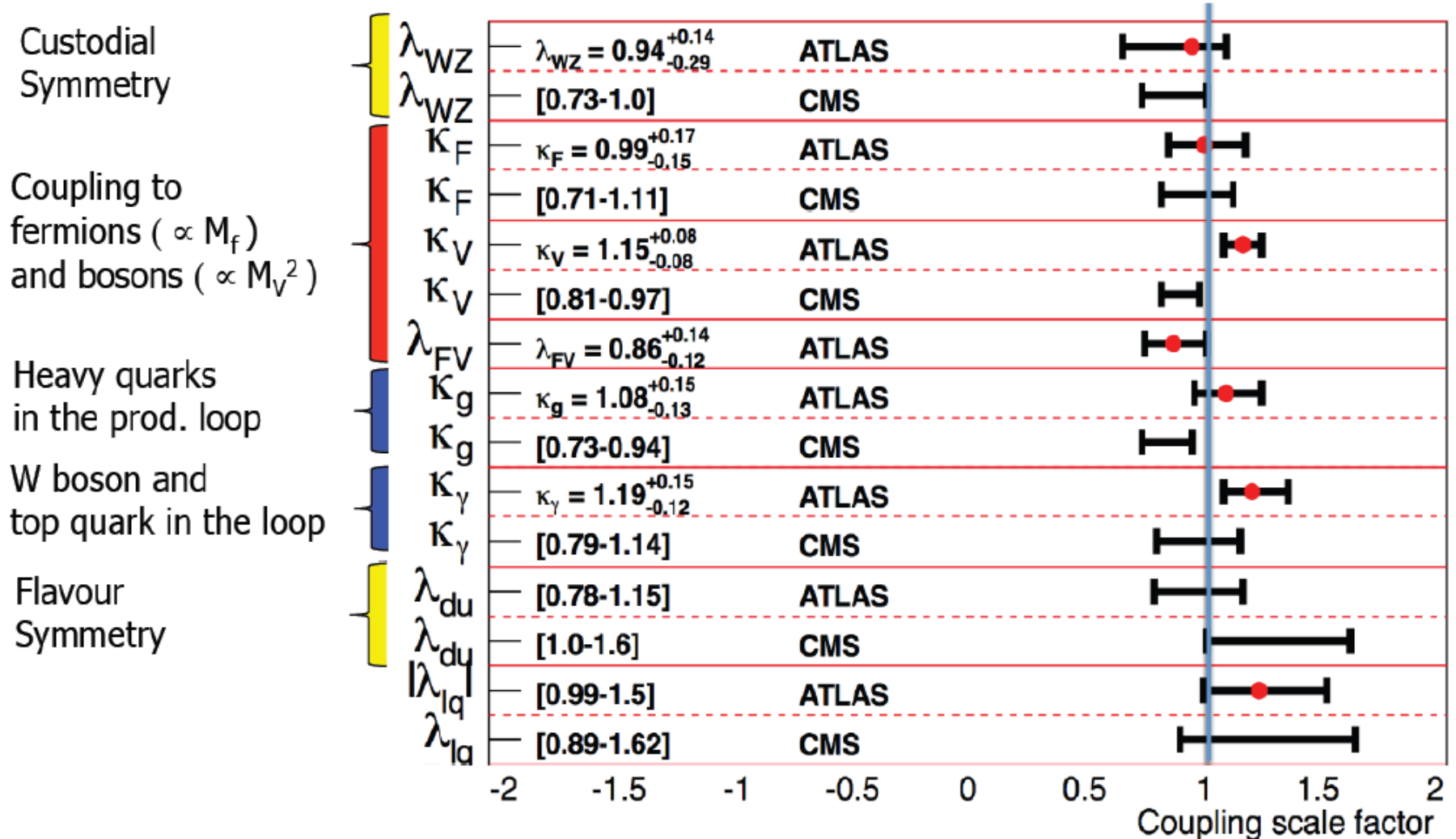
■ $\pm 1\sigma$ on $\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$



Probe the production mode



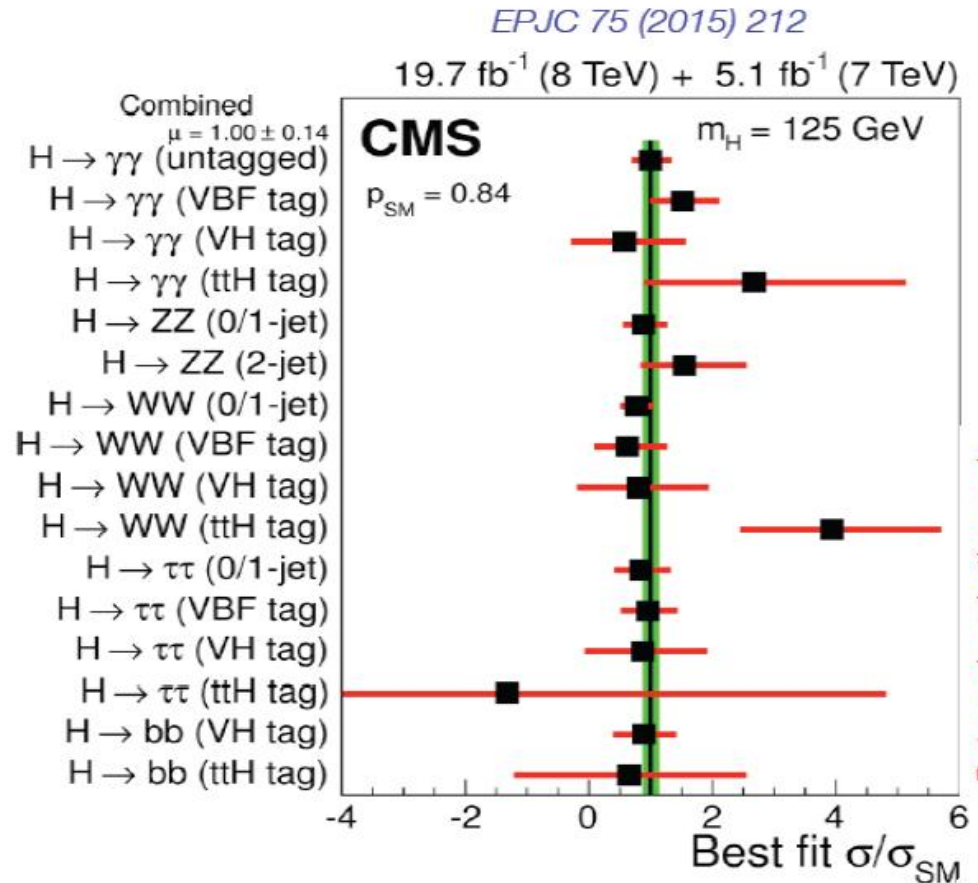
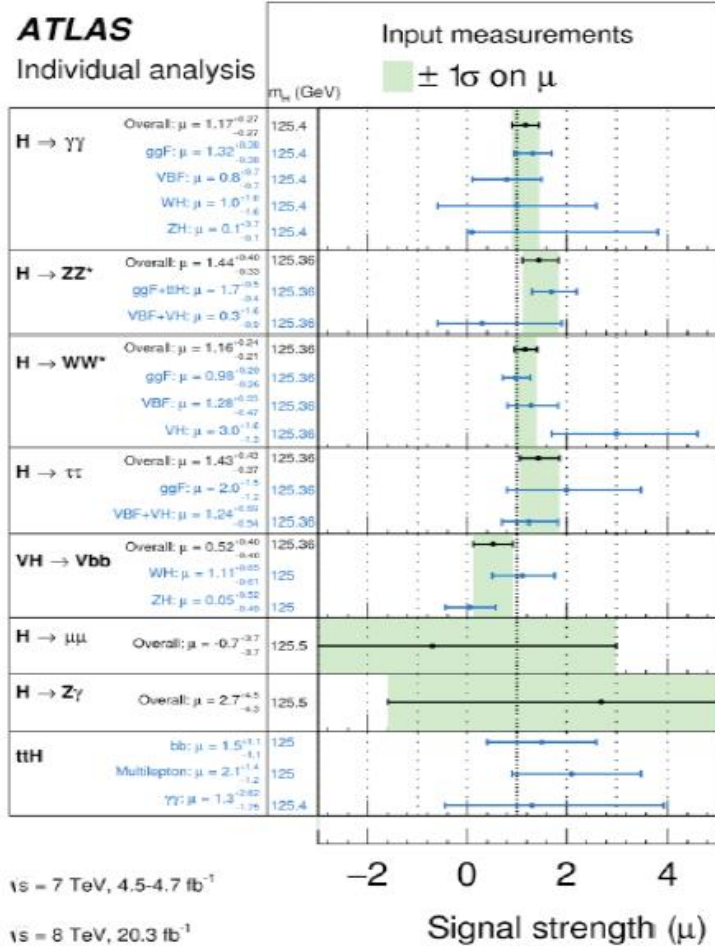
Overall comparison of all couplings results



Combination of two experiments

(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

By fitted production mode arXiv:1507.04548 [hep-ex]



The global signal strength

- Assuming SM ratios of production cross-sections and decay rates

$$\mu = 1.09^{+0.11}_{-0.10}$$

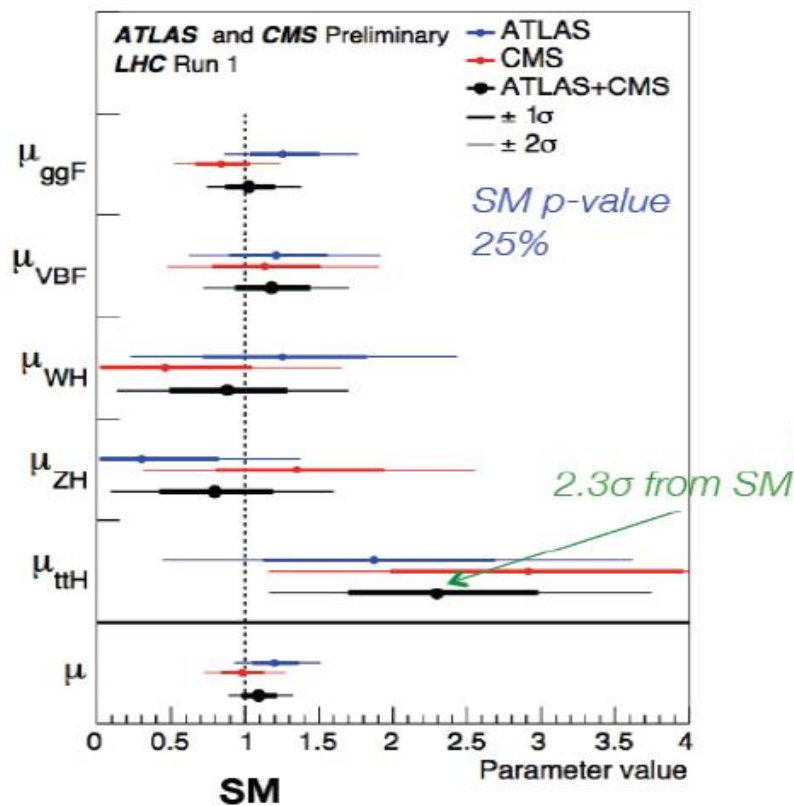
Most precise result at the expense of the largest assumptions

$$= 1.09^{+0.07}_{-0.07} \text{ (stat)} \quad ^{+0.04}_{-0.04} \text{ (expt)} \quad ^{+0.03}_{-0.03} \text{ (thbgd)} \quad ^{+0.07}_{-0.06} \text{ (thsig)}$$

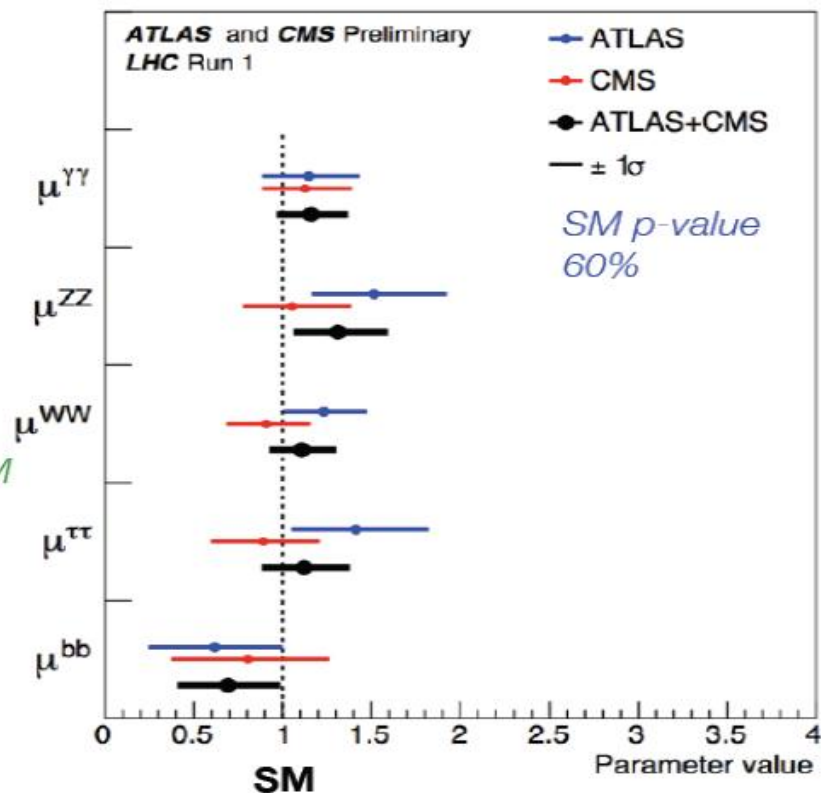
*Stat and Th.Sig of comparable size
(Th.Sig dominated by ggF cross-section uncertainty)*

Signal strength by production and decay mode

Production signal strengths
(SM values of BRs assumed)

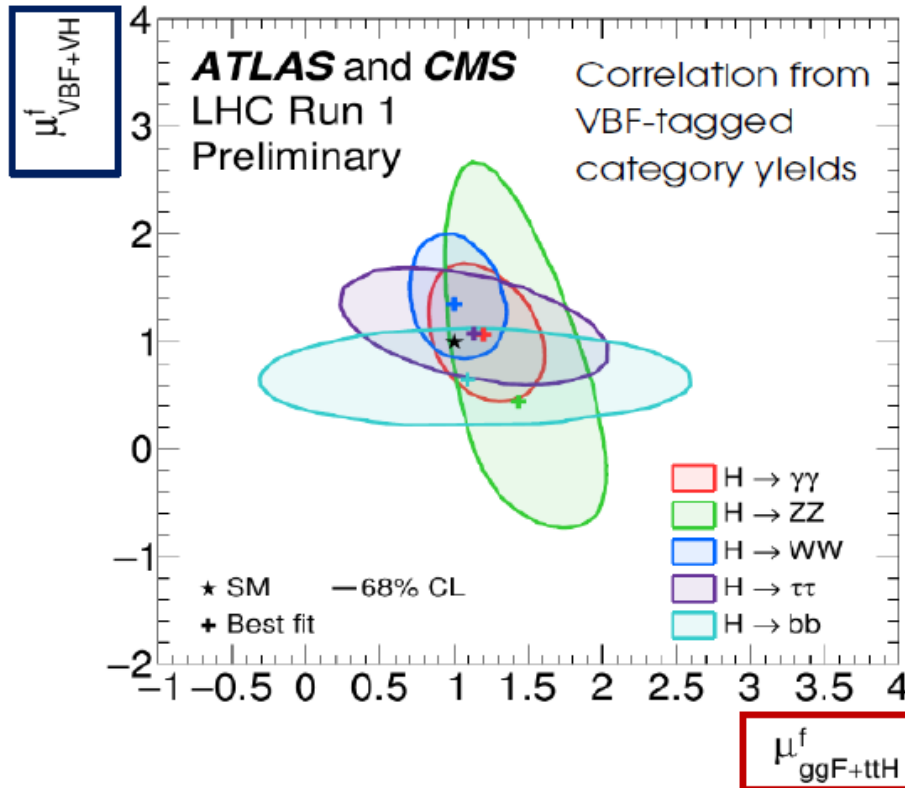


Decay signal strengths
(SM value of production σ 's assumed)



Signal strength in V, F mediated

- Measure **ggF+ttH production „fermion mediated”** and **VBF+VH production „boson mediated”** for each decay mode



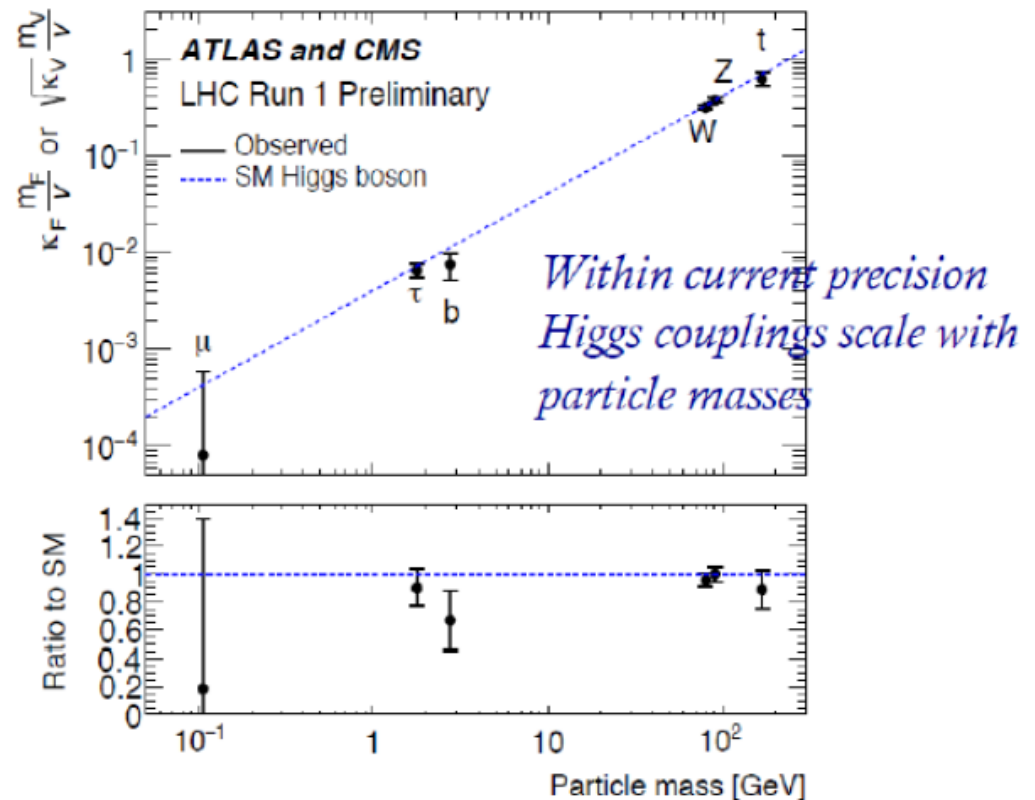
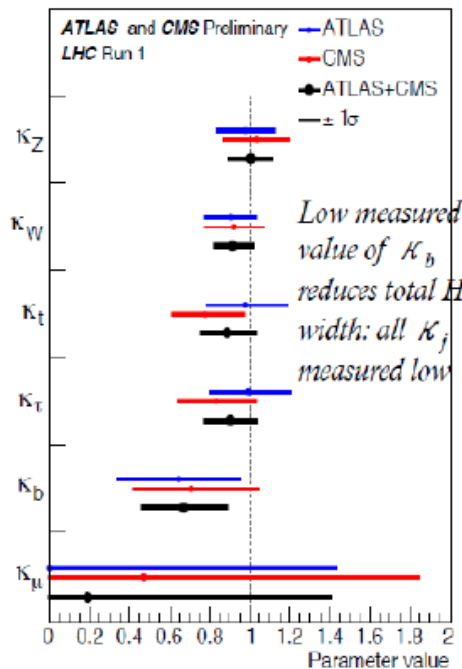
$$\mu_V / \mu_F = 1.06^{+0.35}_{-0.27}$$

Production process	Measured significance (σ)
VBF	5.4
WH	2.4
ZH	2.3
VH	3.5
ttH	4.4
<hr/>	
Decay channel	
H → $\tau\tau$	5.5
H → $b\bar{b}$	2.6

New!

Constraints on three-level Higgs couplings

- Assume only SM physics in loops, no invisible or unseen BSM Higgs decays
- Fit for scaling parameters for Higgs couplings to W, Z, b, t, τ , μ



Concluding Higgs couplings measurements

ATLAS and CMS Higgs boson coupling results have been combined, **sensitivity on signal strength improved by almost $\sqrt{2}$**

- **Higgs to $\tau\tau$ and VBF production established at more than 5σ level**
- The most precise results on Higgs production and decay and constraints on its couplings have been obtained at $O(10\%)$ precision.
- Different parametrisations have been studied, all consistent with the SM predictions within uncertainties
- **SM p-value of all combined fits in range of 10%-88%**

What do we know from Run I

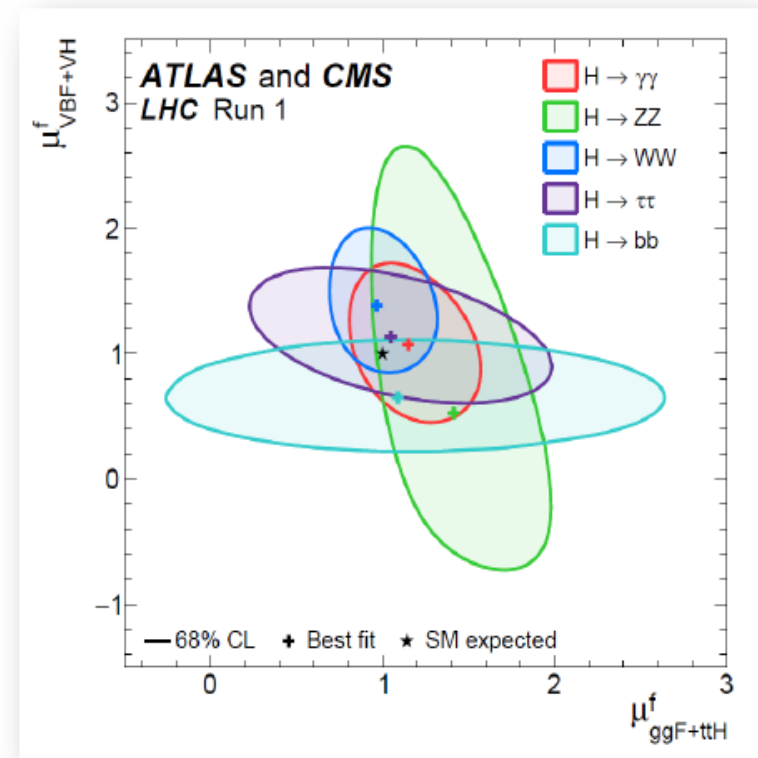
- Discovery of a new neutral scalar boson, first in diboson, then in di-fermion decays

- Observations:

- $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow WW \rightarrow 2l2\nu$
- $H \rightarrow \tau\tau$
- gg-fusion and VBF production
- Evidence for VH and ttH processes

- Individual and combined ATLAS and CMS measurements include

- Mass and width
- Production rate (@10% accuracy)
- Decays
- Spin, parity $J^{PC} = 0^{++}$



- Initial compatibility with the Standard Model Higgs

JHEP08 (2016) 045

PRL114 (2015)191803

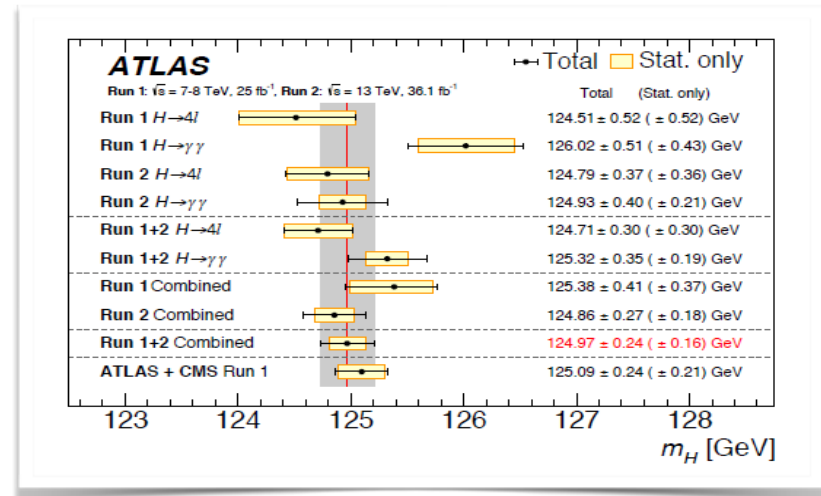
EPJC75(2015) 212

PLB726 (2013) 120

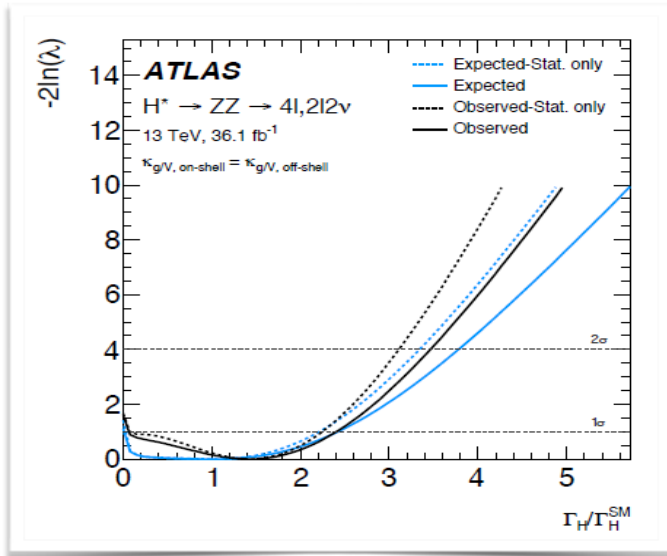
Run II : Higgs boson mass

Higgs Properties

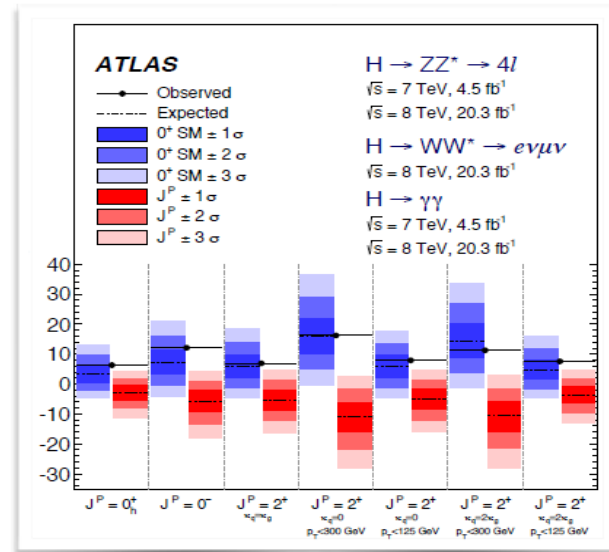
- Mass: 124.97 ± 0.24 GeV
- (Indirect) width: < 14.4 MeV
 - (15.2 MeV)
- Spin and parity $J^{PC} = 0^{++}$
- Couplings



PLB784 (2018) 345



PLB786 (2018) 223



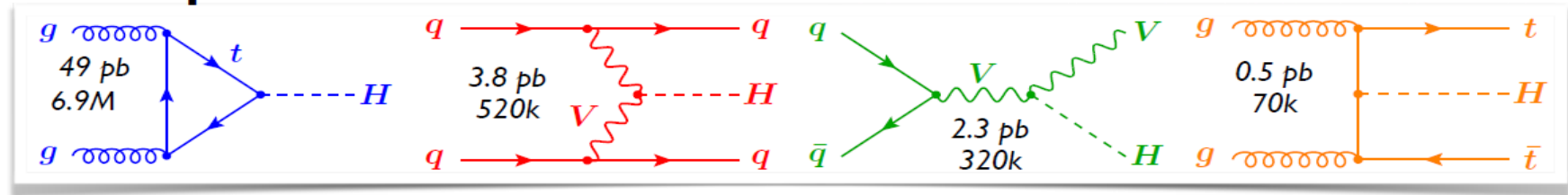
EPIC75 (2015) 476

Run II : Higgs boson couplings

Probing Higgs Couplings at the LHC

4 main production modes

σ [pb]
#Higgs produced during
Run-2

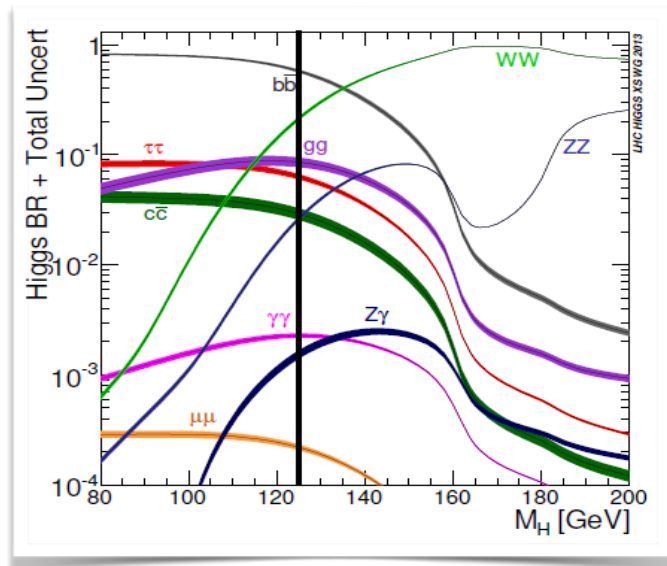


Main production channel: gluon-gluon fusion

2 forward jets, little central hadronic activity

Tag W and Z decays

Tag 2 top quarks



5 key decay channels

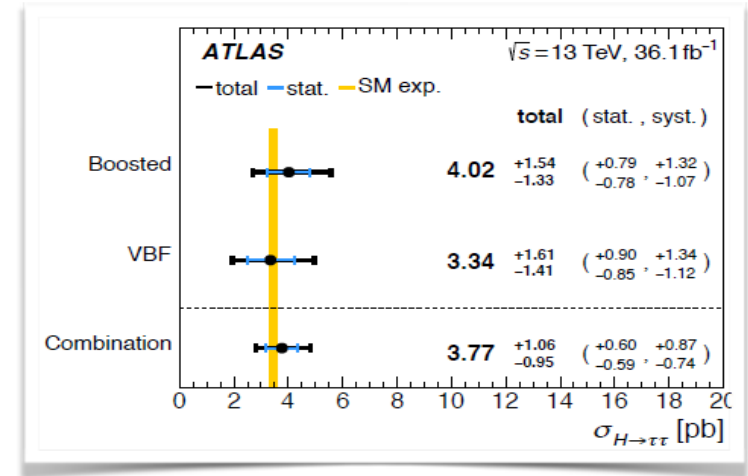
- $H \rightarrow b\bar{b}$: 58 %
- $H \rightarrow W W^*$: 21%
- $H \rightarrow \tau^+ \tau^-$: 6.3%
- $H \rightarrow Z Z^*$: 2.6%
- $H \rightarrow \gamma \gamma$: 0.23%

Decay branching fractions for $m_H = 125$ GeV

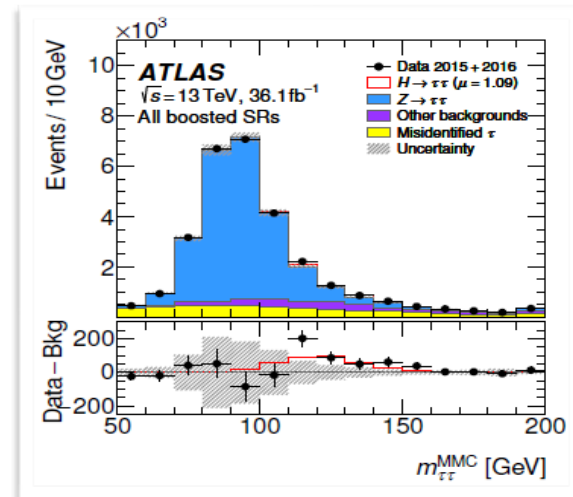
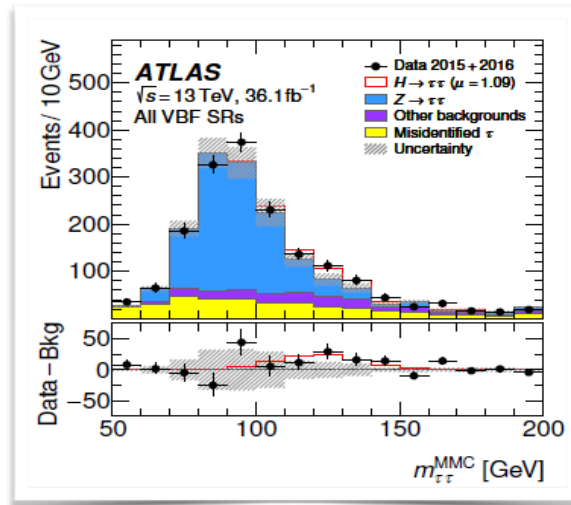
Run II : Higgs boson couplings to fermions

Observation of coupling to τ -leptons

- 5.5 (5.0) σ for $H \rightarrow \tau\tau$ (ATLAS/CMS Run-I)
- 6.4 (5.4) σ from ATLAS (7-13 TeV results)
- Sensitive decay channel for VBF production
 - $ggF: 3.1 \pm 0.1$ (stat) $^{+0.1.6}_{-1.3}$ (syst.) pb
 - (SM: 3.05 ± 0.13 pb)
 - VBF: 0.28 ± 0.09 (stat) $^{+0.11}_{-0.9}$ (syst.) pb
 - (SM: 0.237 ± 0.006 pb)



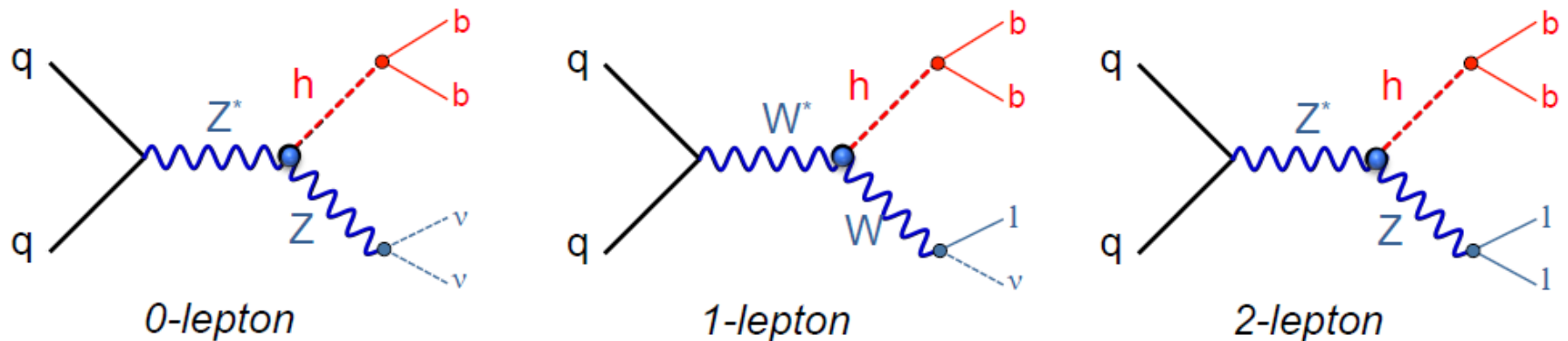
JHEP08(2016)045, arXiv:1811.08856



Higgs decay to b-quarks

$$\text{Br}(h \rightarrow bb) = 0.577$$

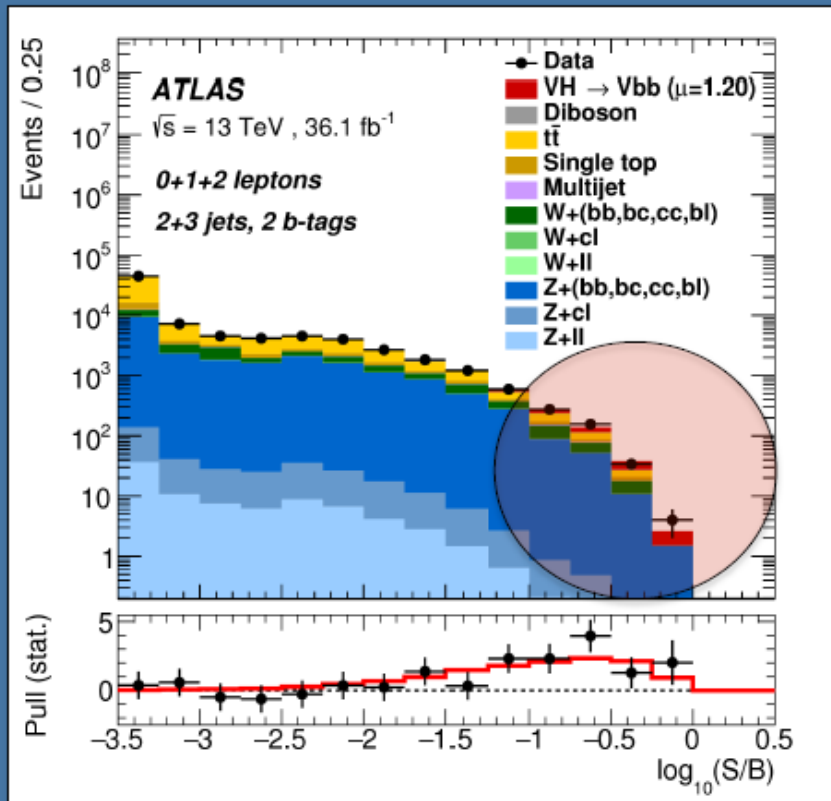
Enormous QCD bb background. Highest sensitivity in the VBF channel.



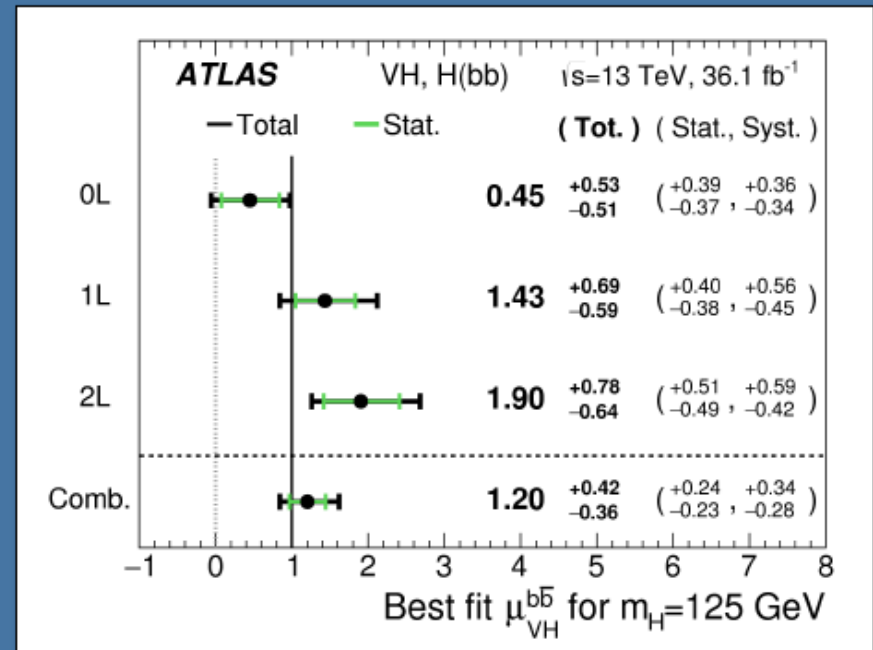
- Categories: jet multiplicity & transverse momentum vector boson (dedicated boosted decision tree for each category)
- Validation using VV channels ($\sigma_{VV(bb)} \sim 9 \times \sigma_{VH(bb)}$)

$h \rightarrow bb$: analysis for $\sqrt{s}=13$ TeV

Combined BDT(S/B) ranking



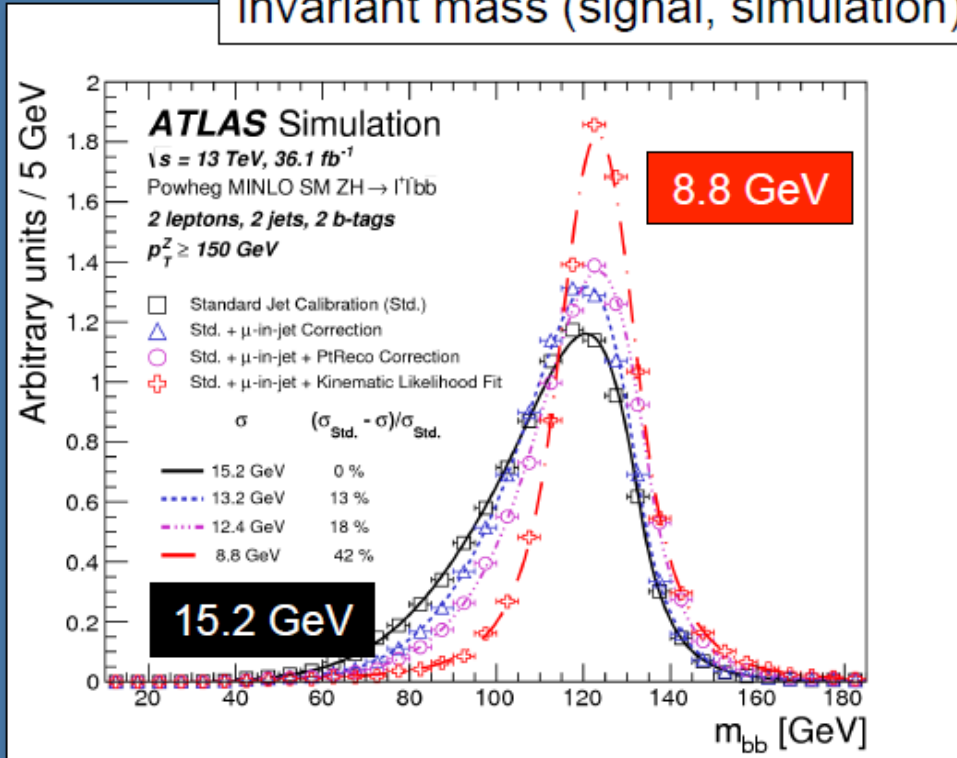
Production rates topology: 0l, 1l, 2l



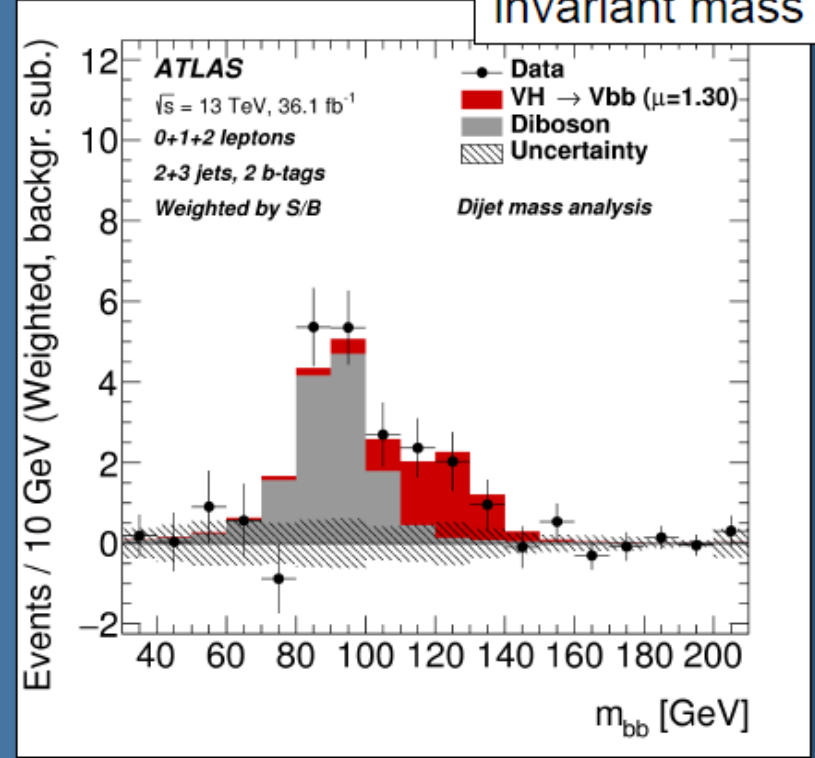
$$\mu = 1.20_{-0.23}^{+0.24} (stat.)_{-0.28}^{+0.34} (syst.)$$

H → bb: invariant mass distribution

invariant mass (signal, simulation)

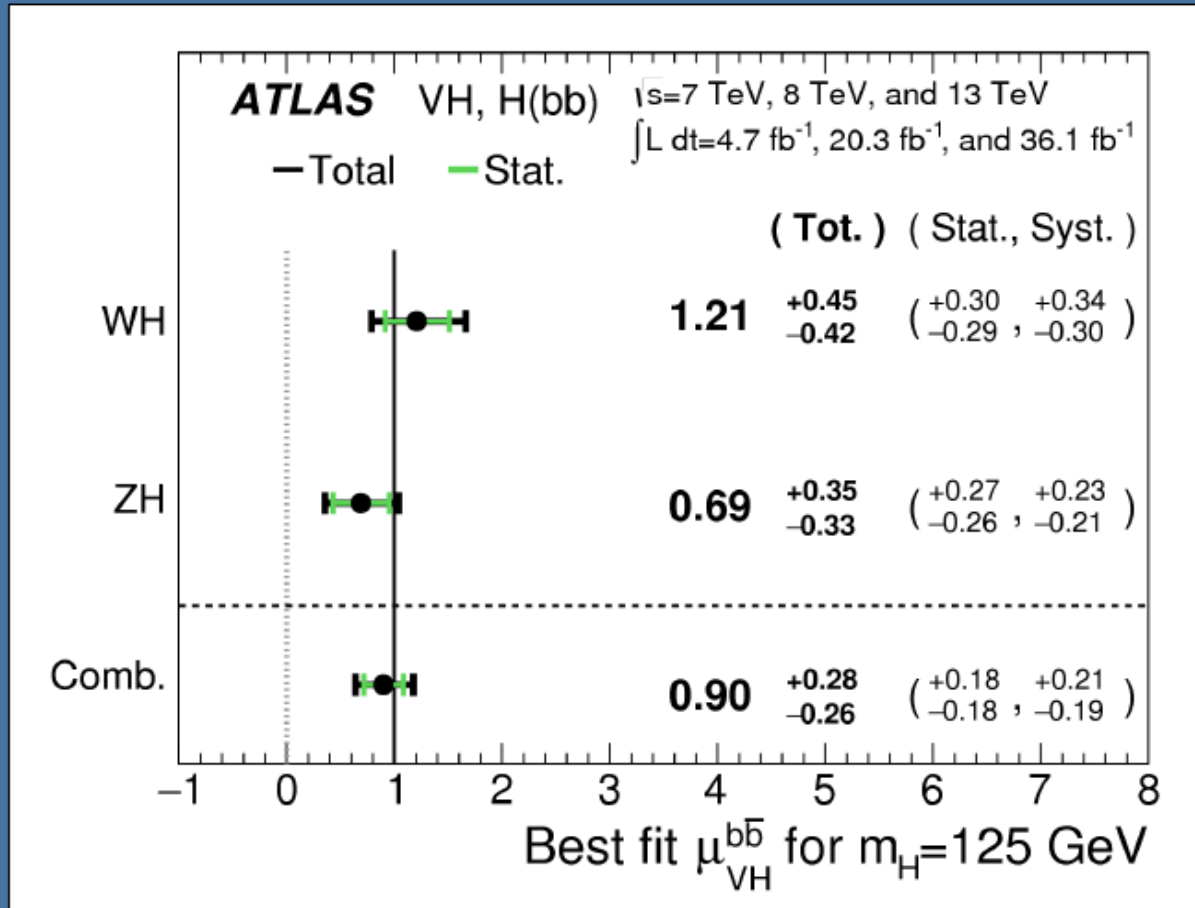


invariant mass



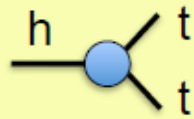
Resolution improvement in channel:
 2 leptons, 2 jets, 2 b-tags, $P_T^V \geq 150 \text{ GeV}$

H → bb: RUN1 & RUN2 combination



3.6 sigma excess ←

$$\mu = 0.90 \pm 0.18(stat.)_{-0.19}^{+0.21}(syst.)$$

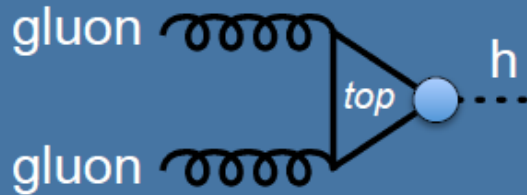


Top-Yukawa

$$\lambda_t = \frac{m_t \sqrt{2}}{V} = 0.996$$

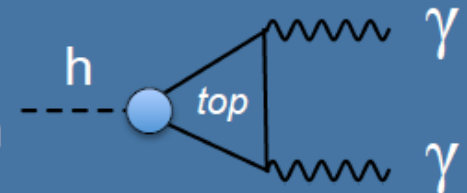
Top Yukawa coupling

INDIRECT



Production:
gluon fusion

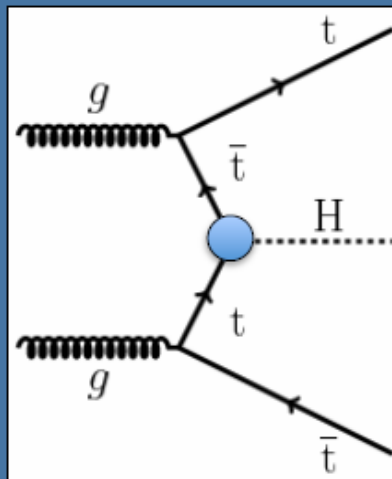
Decay:
gluon fusion



γ

γ

DIRECT



b-jet + qq/lv

bb
4l
 $\gamma\gamma$

b-jet + qq/lv

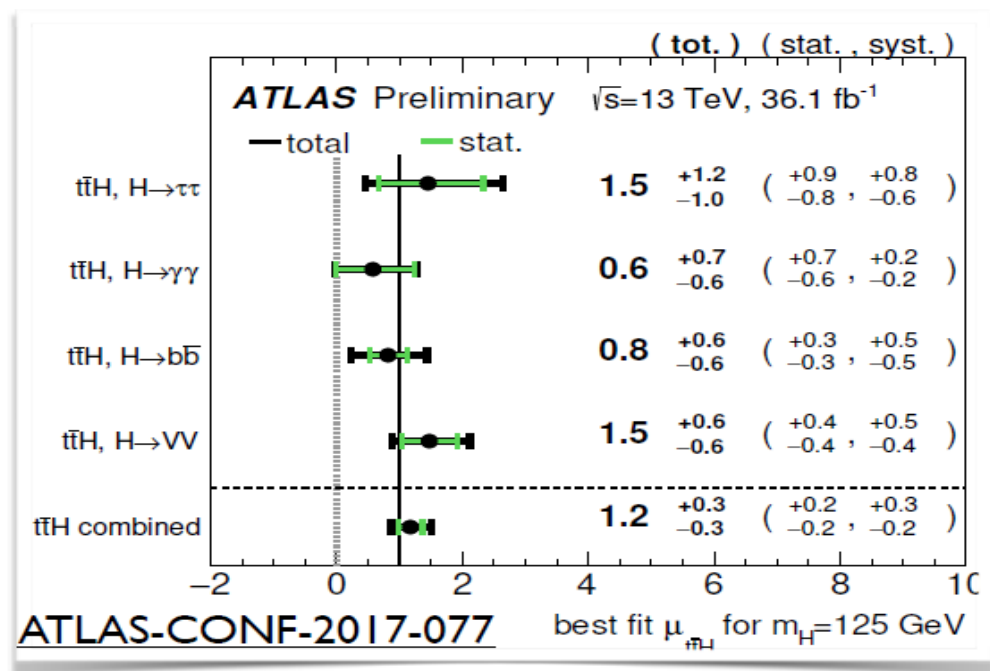
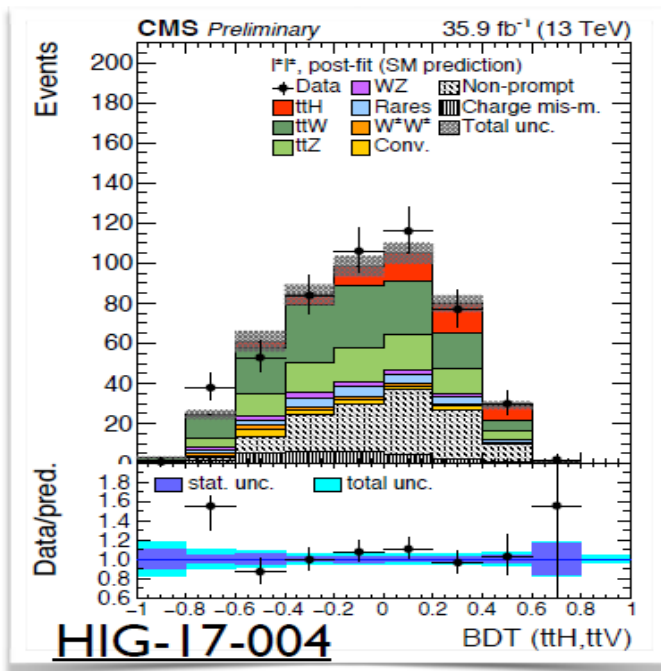
- 1% of gluon-fusion process
- (many) complex final states
- ... very very difficult

RUN1 ATLAS: $\mu = 1.9 \pm 0.8$

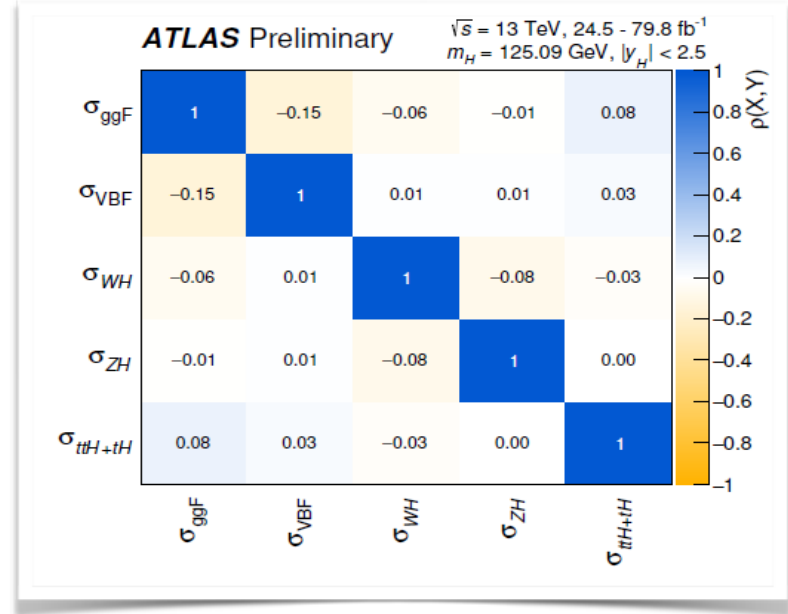
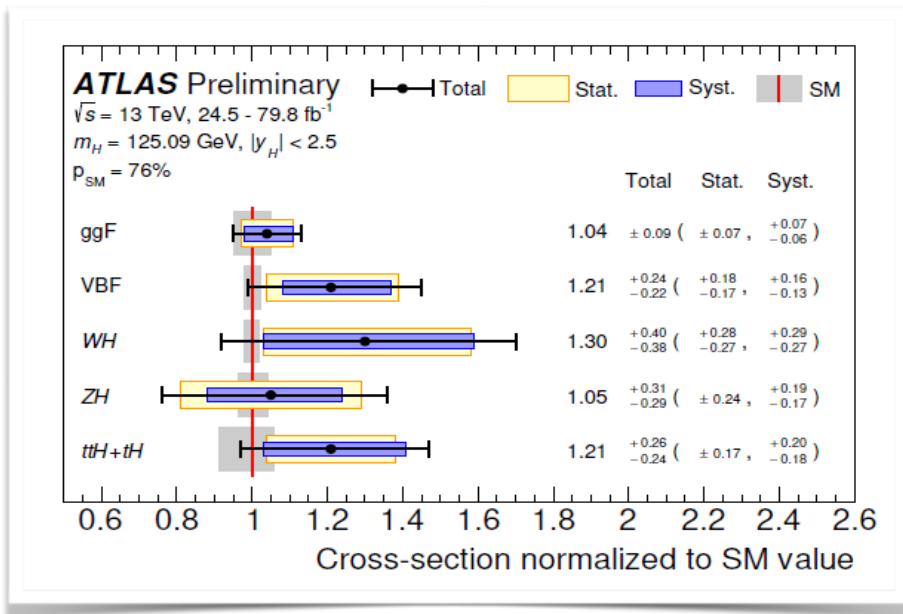
Higgs boson couplings to top quarks

Direct evidence for coupling to top quarks

- $t\bar{t}H$ production provides a probe of the direct coupling of the Higgs boson to top quarks
- 3.3σ evidence for $t\bar{t}H$ production from CMS using leptonic final states
- 4.2σ evidence from ATLAS from combination of five major decay modes



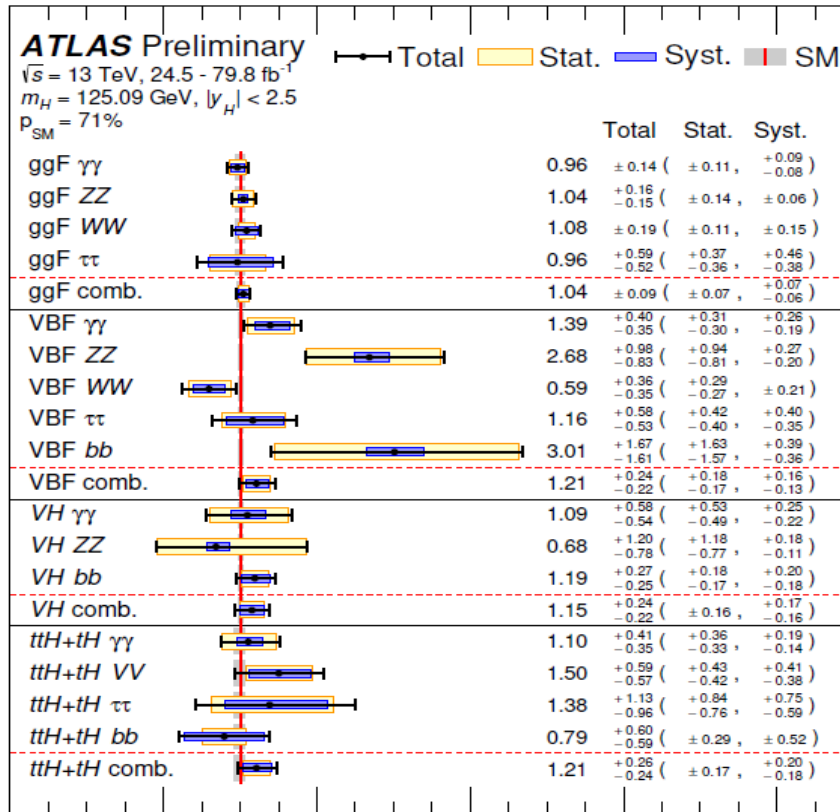
Higgs boson production modes



- Significances above 5σ are obtained for ggF, VBF (6.5σ), VH (5.3σ) and ttH (5.8σ) production modes when assuming SM branching ratios
- Low correlations between production modes
- Results are consistent with predictions from the Standard Model

[ATLAS-CONF-2019-005](#)

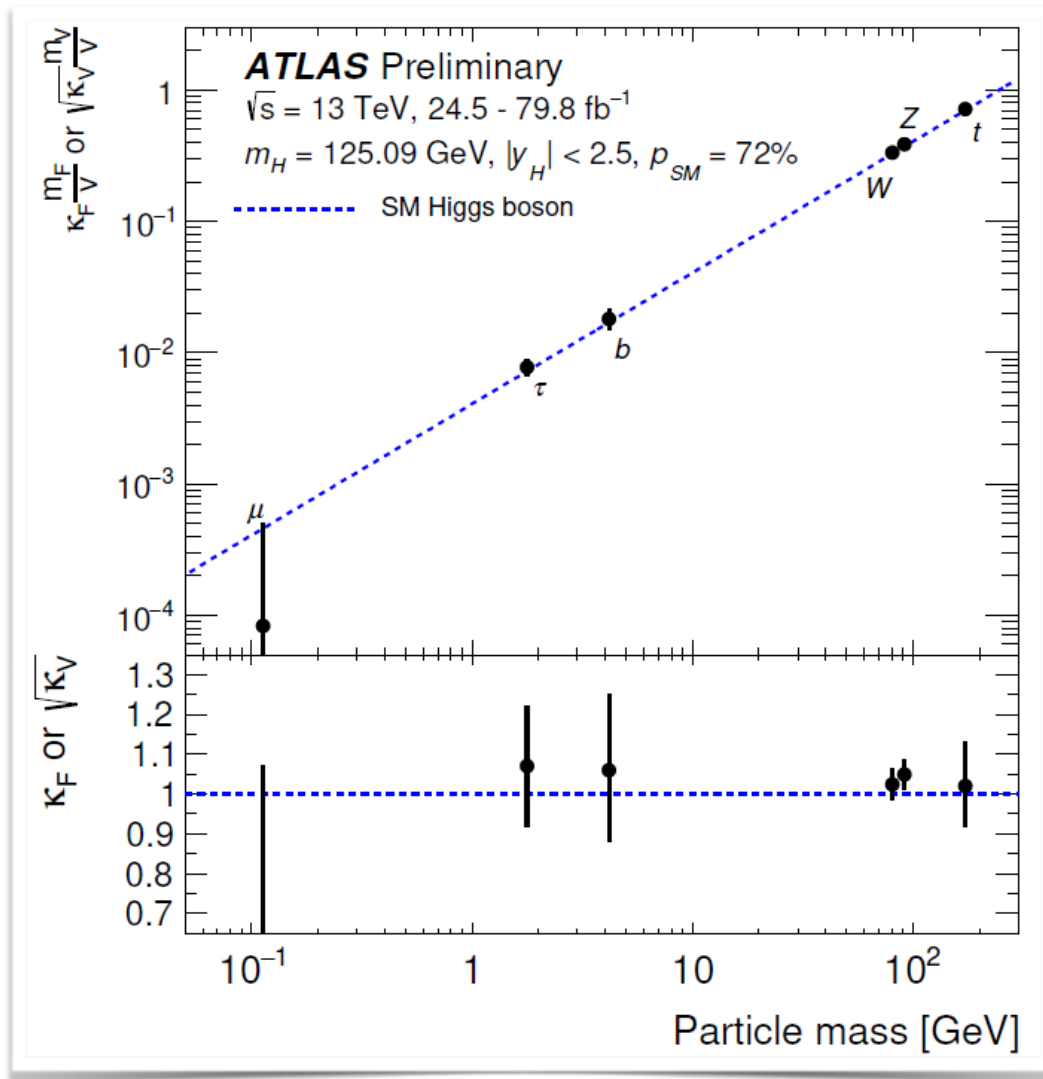
Production and decay modes



Fix production/decays with low sensitivity to SM values

ATLAS-CONF-2019-005

Couplings vs mass



Interpret the results in the K framework as a function of the particle mass assuming no BSM contributions to the total width

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma_{\text{SM}}^j}$$

[ATLAS-CONF-2019-005](#)

ATLAS combination

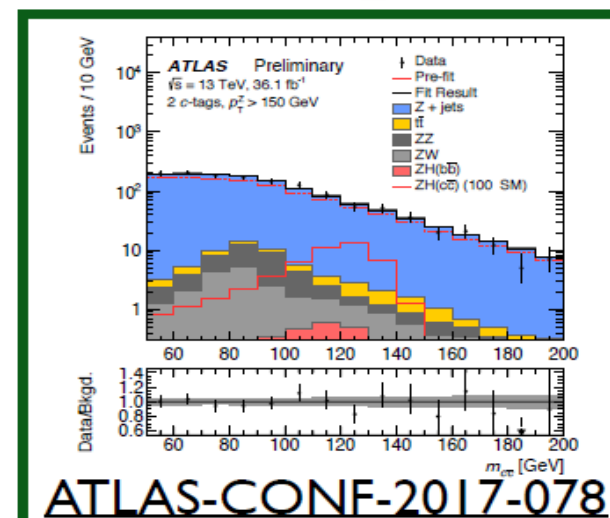
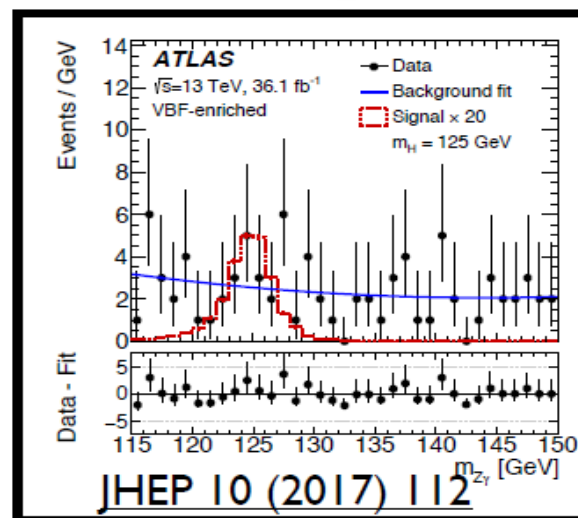
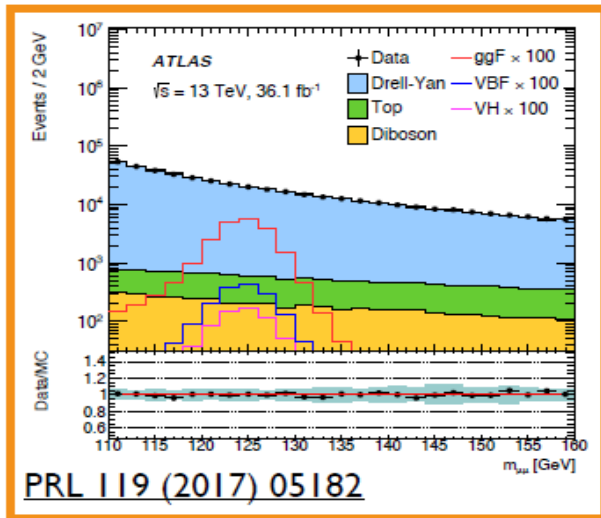
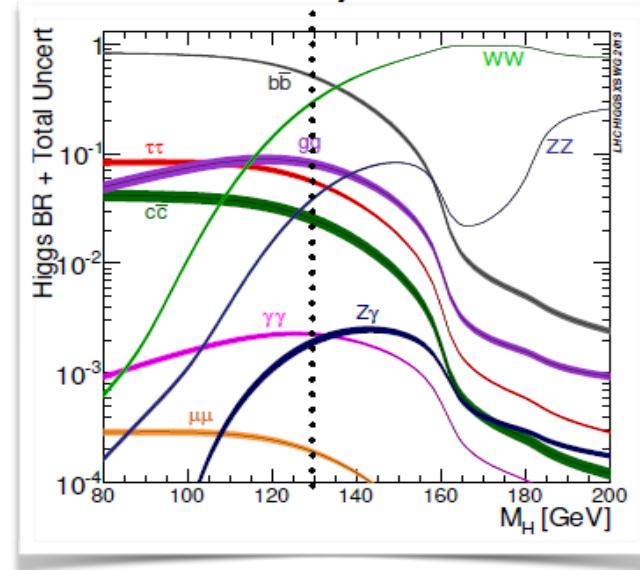
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^*$	$H \rightarrow WW^*$	$H \rightarrow \tau\tau$	$H \rightarrow b\bar{b}$
$t\bar{t}H$	$t\bar{t}H$ leptonic (3 categories) $t\bar{t}H$ hadronic (4 categories)	$t\bar{t}H$ multilepton 1 $\ell + 2 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 opposite-sign $\ell + 1 \tau_{\text{had}}$ $t\bar{t}H$ multilepton 2 same-sign ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 3 ℓ (categories for 0 or 1 τ_{had}) $t\bar{t}H$ multilepton 4 ℓ (except $H \rightarrow ZZ^* \rightarrow 4\ell$) $t\bar{t}H$ leptonic, $H \rightarrow ZZ^* \rightarrow 4\ell$ $t\bar{t}H$ hadronic, $H \rightarrow ZZ^* \rightarrow 4\ell$			$t\bar{t}H$ 1 ℓ , boosted $t\bar{t}H$ 1 ℓ , resolved (11 categories) $t\bar{t}H$ 2 ℓ (7 categories)
VH	VH 2 ℓ VH 1 ℓ , $p_T^{\ell+E_T^{\text{miss}}} \geq 150 \text{ GeV}$ VH 1 ℓ , $p_T^{\ell+E_T^{\text{miss}}} < 150 \text{ GeV}$ VH $E_T^{\text{miss}}, E_T^{\text{miss}} \geq 150 \text{ GeV}$ VH $E_T^{\text{miss}}, E_T^{\text{miss}} < 150 \text{ GeV}$ $VH+VBF$ $p_T^{j1} \geq 200 \text{ GeV}$ VH hadronic (2 categories)	VH leptonic 0-jet, $p_T^{4\ell} \geq 100 \text{ GeV}$ 2-jet, $m_{jj} < 120 \text{ GeV}$			2 ℓ , $75 \leq p_T^V < 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 2 ℓ , $75 \leq p_T^V < 150 \text{ GeV}$, $N_{\text{jets}} \geq 3$ 2 ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 2 ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} \geq 3$ 1 ℓ $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 1 ℓ $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 3$ 0 ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 2$ 0 ℓ , $p_T^V \geq 150 \text{ GeV}$, $N_{\text{jets}} = 3$
VBF	VBF, $p_T^{\gamma\gamma jj} \geq 25 \text{ GeV}$ (2 categories) VBF, $p_T^{\gamma\gamma jj} < 25 \text{ GeV}$ (2 categories)	2-jet VBF, $p_T^{j1} \geq 200 \text{ GeV}$ 2-jet VBF, $p_T^{j1} < 200 \text{ GeV}$	2-jet VBF	VBF $p_T^{\tau\tau} > 140 \text{ GeV}$ ($\tau_{\text{had}}\tau_{\text{had}}$ only) VBF high- m_{jj} VBF low- m_{jj}	VBF, two central jets VBF, four central jets VBF + γ
ggF	2-jet, $p_T^{\gamma\gamma} \geq 200 \text{ GeV}$ 2-jet, $120 \text{ GeV} \leq p_T^{\gamma\gamma} < 200 \text{ GeV}$ 2-jet, $60 \text{ GeV} \leq p_T^{\gamma\gamma} < 120 \text{ GeV}$ 2-jet, $p_T^{\gamma\gamma} < 60 \text{ GeV}$ 1-jet, $p_T^{\gamma\gamma} \geq 200 \text{ GeV}$ 1-jet, $120 \text{ GeV} \leq p_T^{\gamma\gamma} < 200 \text{ GeV}$ 1-jet, $60 \text{ GeV} \leq p_T^{\gamma\gamma} < 120 \text{ GeV}$ 1-jet, $p_T^{\gamma\gamma} < 60 \text{ GeV}$ 0-jet (2 categories)	1-jet, $p_T^{4\ell} \geq 120 \text{ GeV}$ 1-jet, $60 \text{ GeV} \leq p_T^{4\ell} < 120 \text{ GeV}$ 1-jet, $p_T^{4\ell} < 60 \text{ GeV}$ 0-jet, $p_T^{4\ell} < 100 \text{ GeV}$	1-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 1-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$ 1-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 1-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} < 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} < 20 \text{ GeV}$ 0-jet, $m_{\ell\ell} \geq 30 \text{ GeV}$, $p_T^{\ell_2} \geq 20 \text{ GeV}$	Boosted, $p_T^{\tau\tau} > 140 \text{ GeV}$ Boosted, $p_T^{\tau\tau} \leq 140 \text{ GeV}$	

$$\mu = 1.11_{-0.08}^{+0.09} = 1.11 \pm 0.05 \text{ (stat.) }_{-0.04}^{+0.05} \text{ (exp.) }_{-0.04}^{+0.05} \text{ (sig. th.) }_{-0.03}^{+0.03} \text{ (bkg. th.)}$$

Probing rare Higgs decays

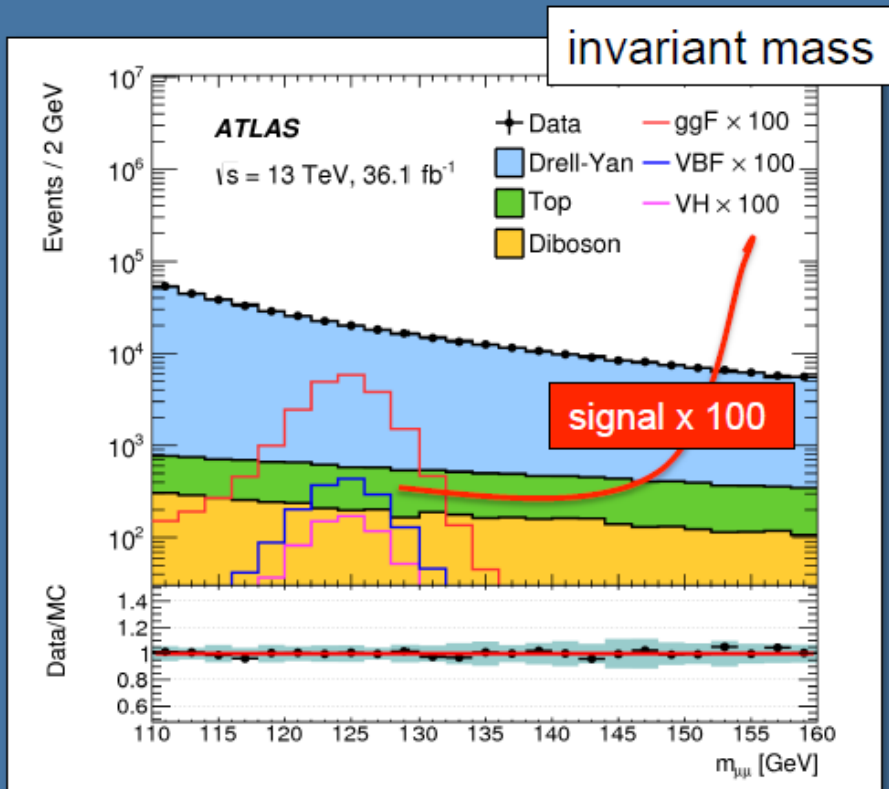
- Exploit growing LHC dataset to explore further decay channels

- $H \rightarrow \mu\mu$: $2.8 \times SM$
- $H \rightarrow Z\gamma$: $6.6 \times SM$
- $H \rightarrow c\bar{c}$:
 - $110 \times SM$ ($ZH(c\bar{c})$)
 - $200 \times SM$ ($J/\psi\gamma$)
- $H \rightarrow \varphi\gamma$: $200 \times SM$
- $H \rightarrow \rho\gamma$: $50 \times SM$

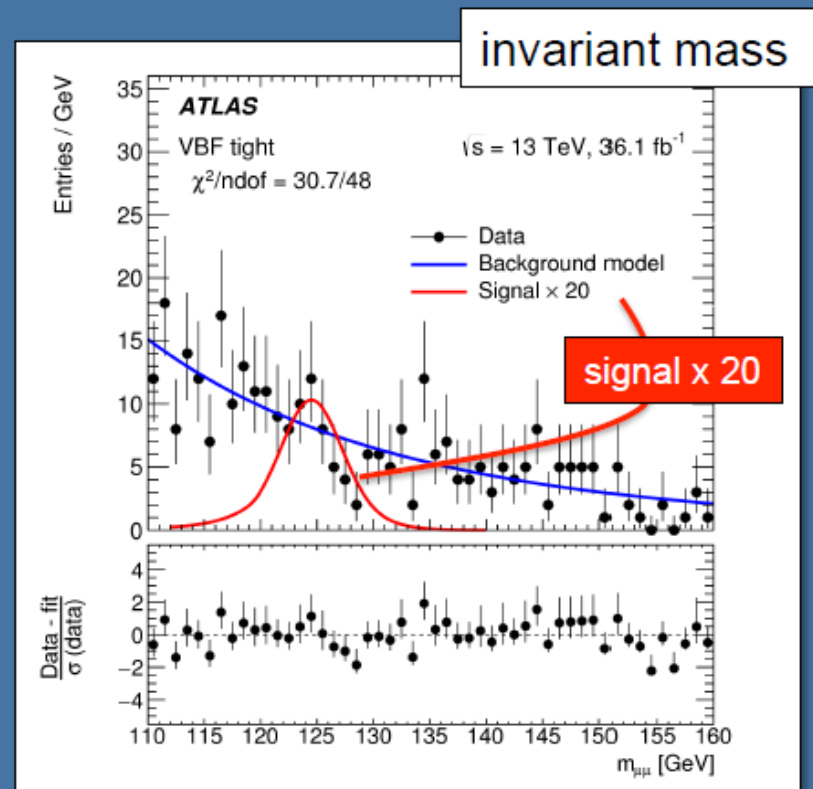


Higgs decay to a muon pair

$$\text{Br}(h \rightarrow \mu^+ \mu^-) = 2.19 \cdot 10^{-4}$$



inclusive selection → 8 categories

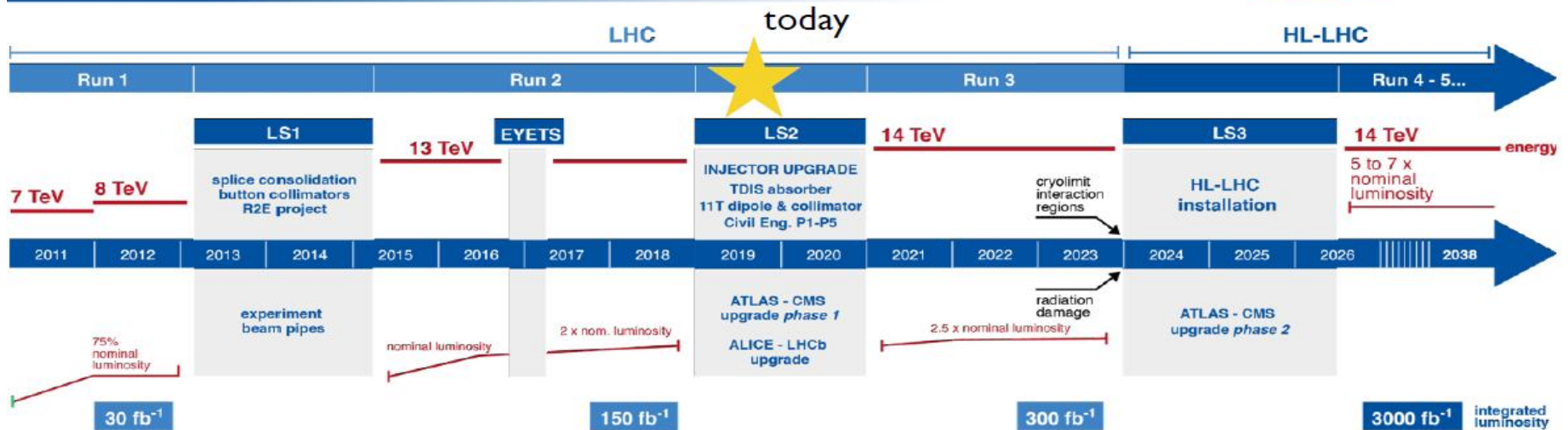


VBF-tight selection

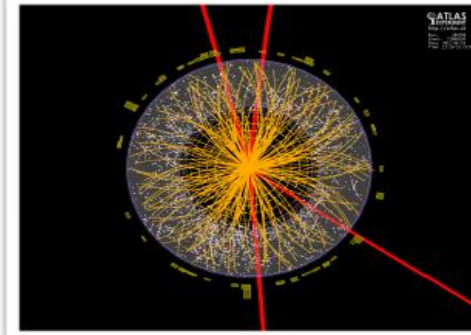
observed limit (RUN1 + RUN2): $\mu < 2.8$

The Higgs and the LHC

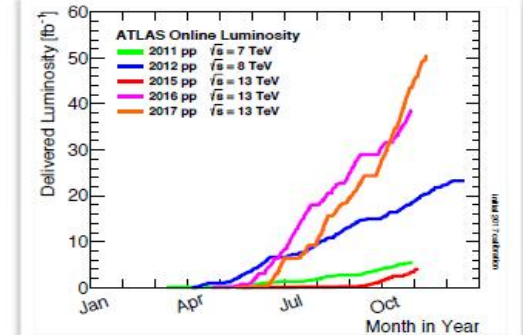
LHC / HL-LHC Plan



First beam in ATLAS (2009)



Higgs discovery (2012)



Only ~5% of total expected data

Conclusions (Higgs Boson)

- Rapid progress in the Higgs measurement program at the LHC
- Observation or evidence for all main production and decay modes
 - Recent exploration of the fermionic sector
 - Searches for additional decay modes are being developed
- Mass measured to 0.2% precision
- Constraints on width from off-shell measurements
- Charge and parity consistent with SM predictions
- Searches have begun for diHiggs production
- No evidence for non-SM Higgs decays
- No evidence for additional Higgs bosons

Overall, excellent consistency with SM predictions