Elementary Particle Physics: theory and experiments

Discovery of the Higgs boson

Measurements: mass, spin, couplings

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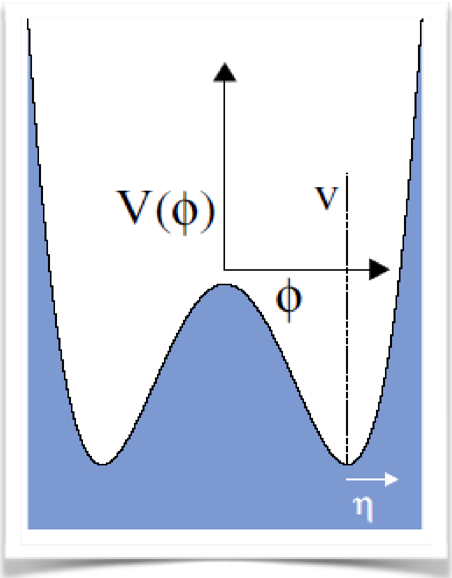
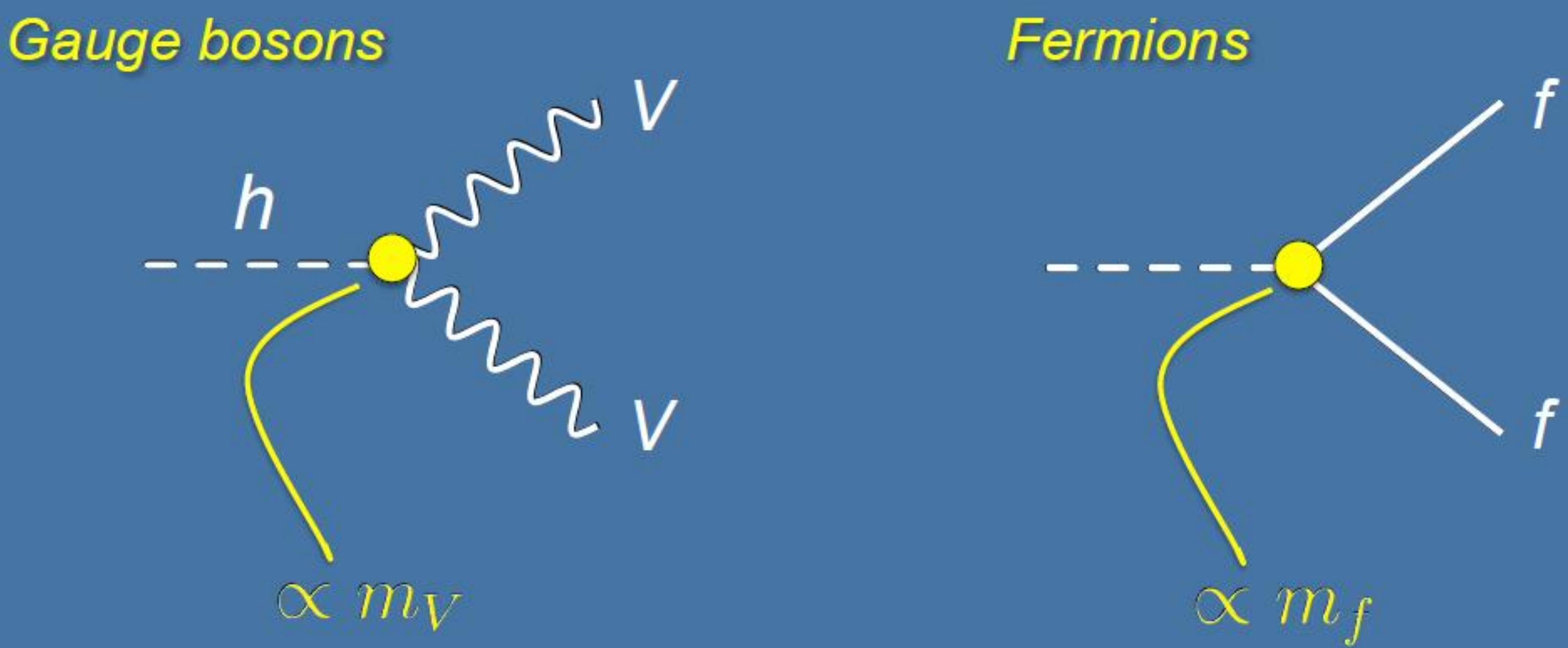
The Higgs boson in the Standard Model

- 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 $\mathbf{m_H}$) and vacuum expectation value, **v**
  - Discovered at CERN by the ATLAS and CMS collaborations in 2012 after 40+ years of searching



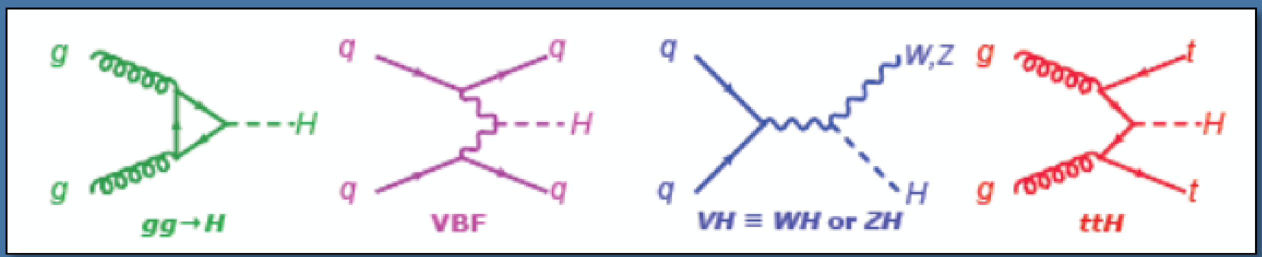
$$\mathcal{L} = |D^\mu \phi|^2 - y_i q_L^i q_R^i \phi - \mu^2 \phi^2 - \lambda \phi^4 + \ldots \qquad \mu^2 < 0$$

Higgs boson couplings



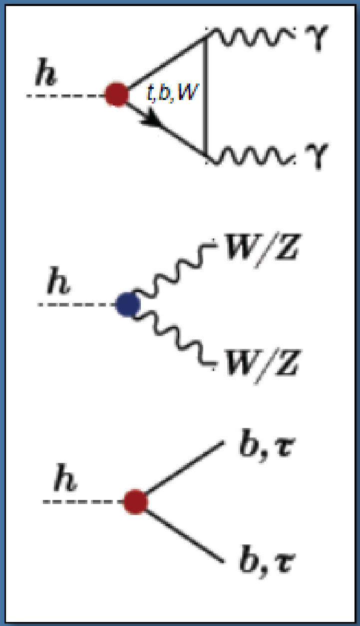
Higgs boson properties are fixed in the Standard Model (m_h)

Higgs boson phenomenology



‘production & decay matrix’

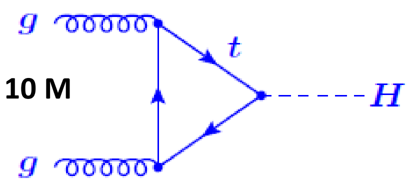
sensitivity to different Higgs properties



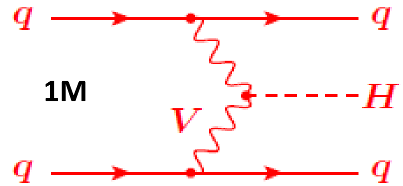
The Higgs Boson at the LHC

Production

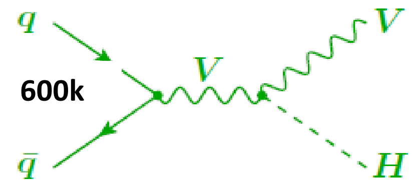
#Higgs produced at 13 TeV **(2015-2017)**



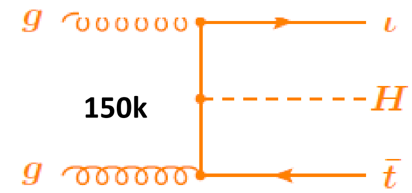
Main production channel



2 forward jets, little central hadronic activity

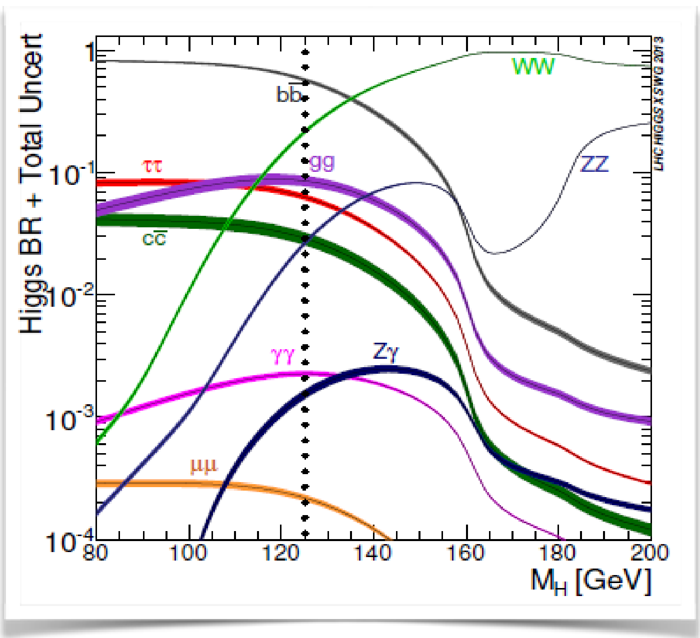


Tag W and Z decays



Tag 2 top quarks

Decays



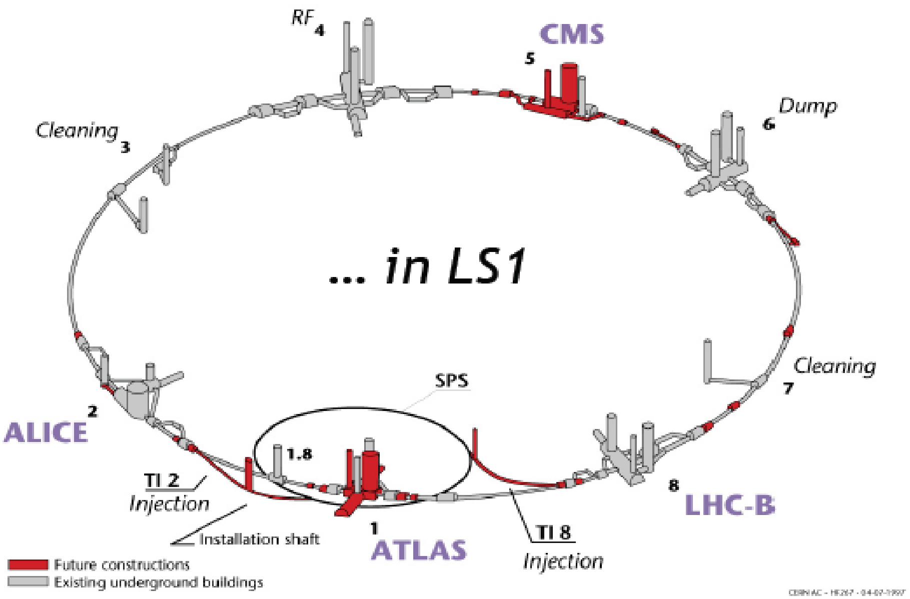
5 main channels at the LHC

Decay branching fractions for m_H = 125 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



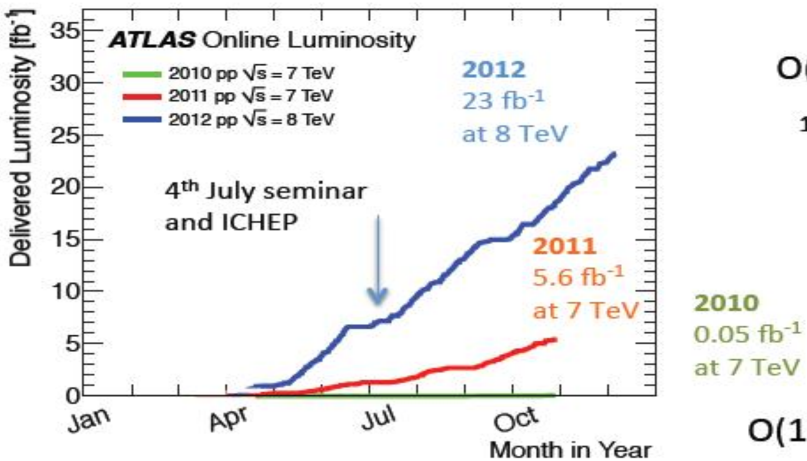
The LHC

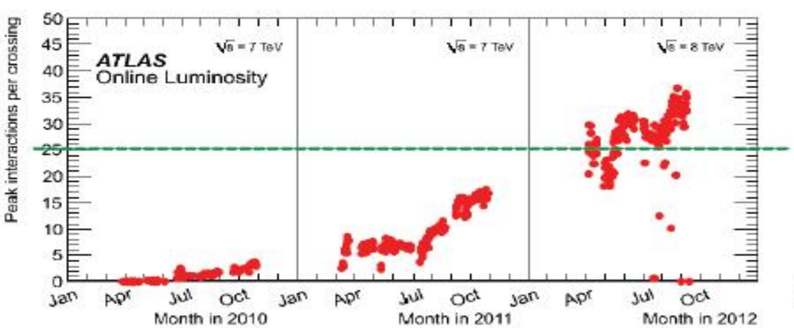
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

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

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 ($cm^{-2}s^{-1}$)	2×10^{32}	3.3×10^{33}	$\sim 7 \times 10^{33}$	10^{34}

The first LHC run





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

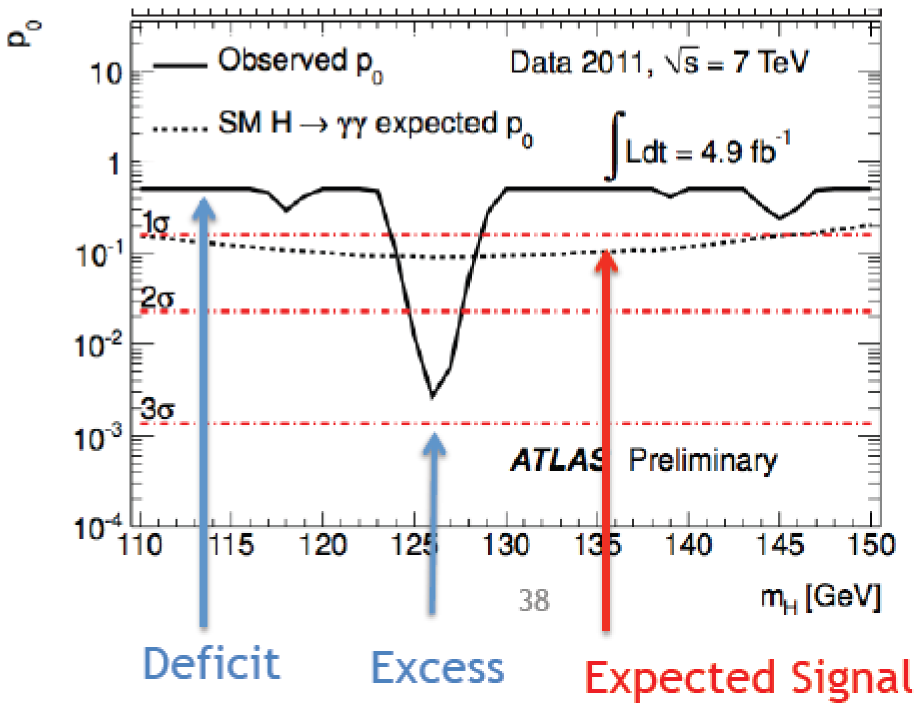
2010
O(2) Pile-up events
150 ns inter-bunch spacing

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

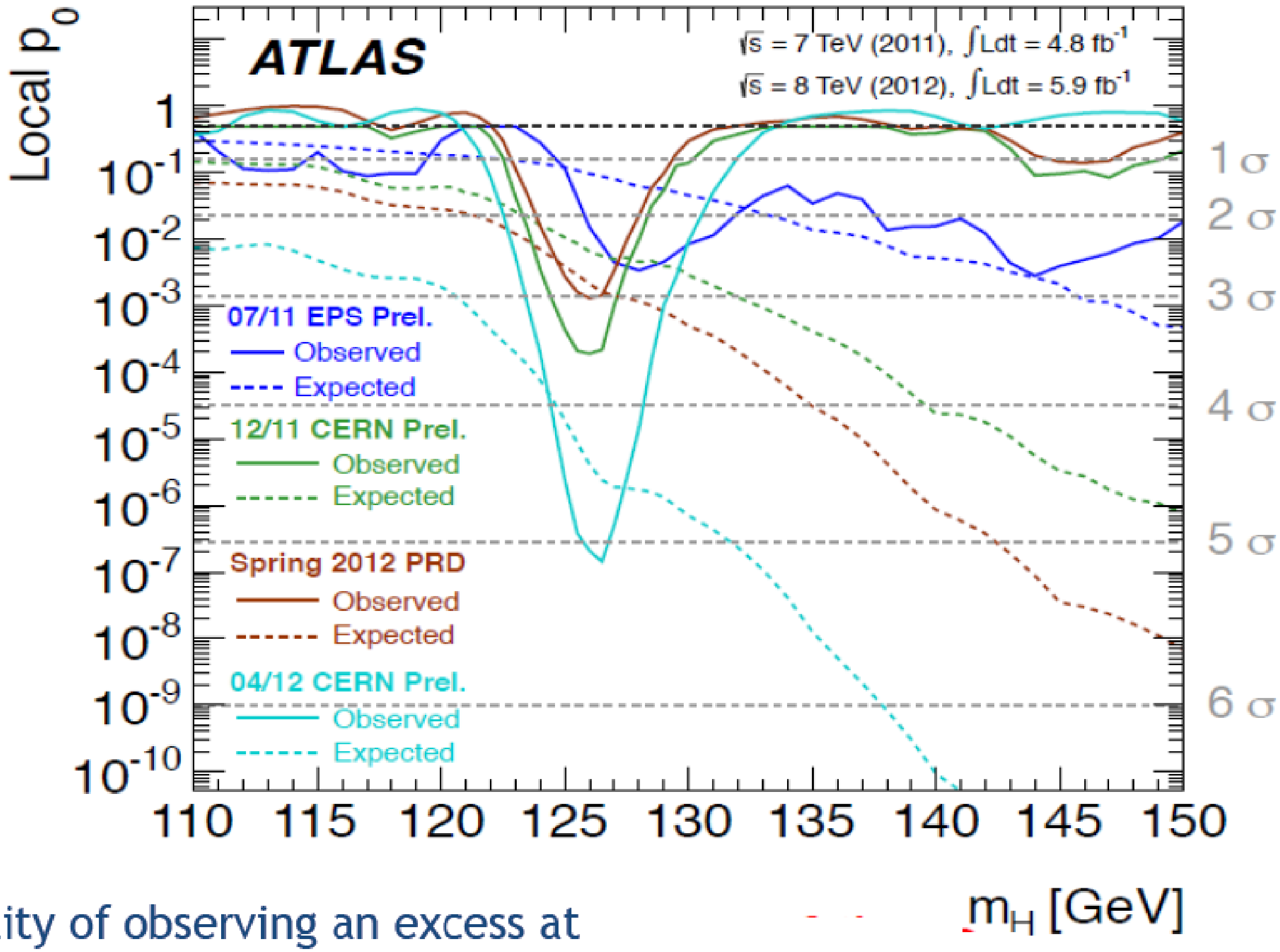
2012
O(20) Pile-up events
50 ns inter-bunch spacing

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.



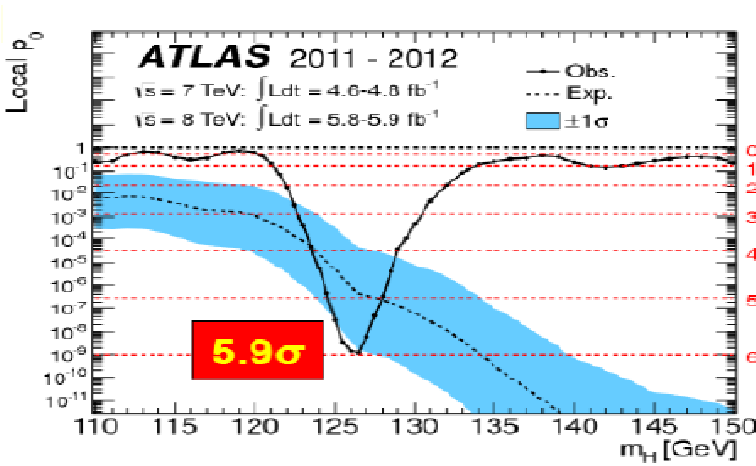
Birth of a particle

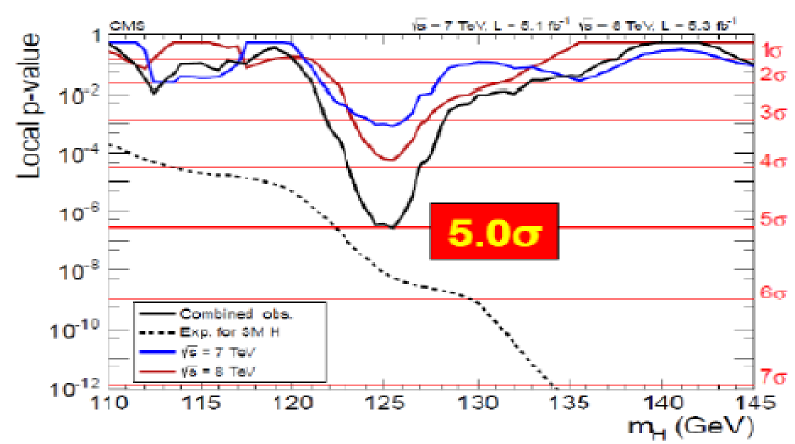


Probability of observing an excess at
one specific mass
(in absence of signal)…

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:
5.9σ at m_H= 126.5 GeV

H→γγ, bb, ττ, WW(lνlν, lνqq), ZZ(4l, llνν, llqq)

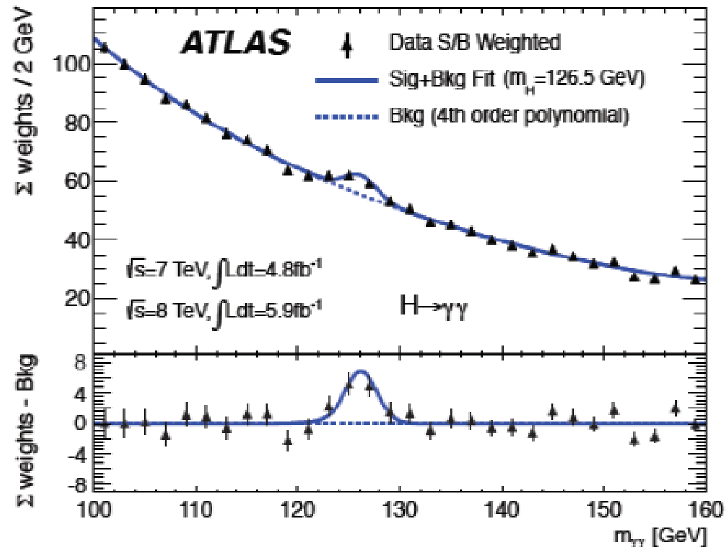
CMS [PLB 716 (2012) 30-61](), *Sept 17 (2012)*

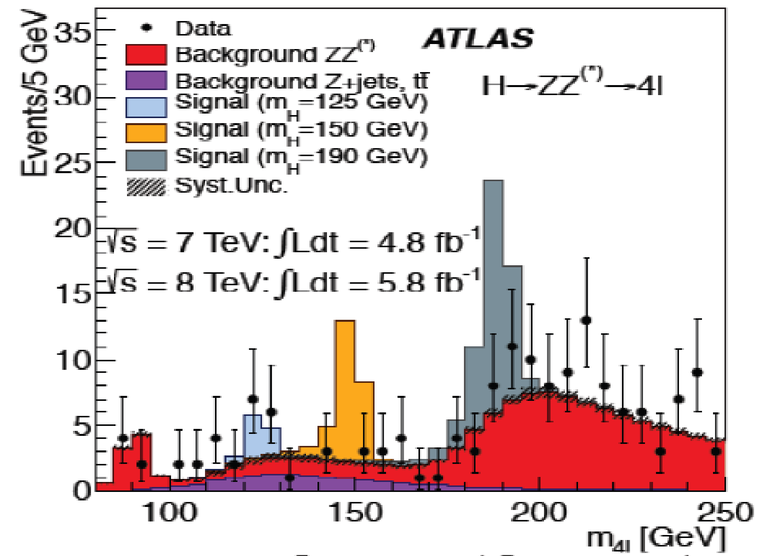
Largest local excess:
5.0σ at m_H= 125.5 GeV

H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)

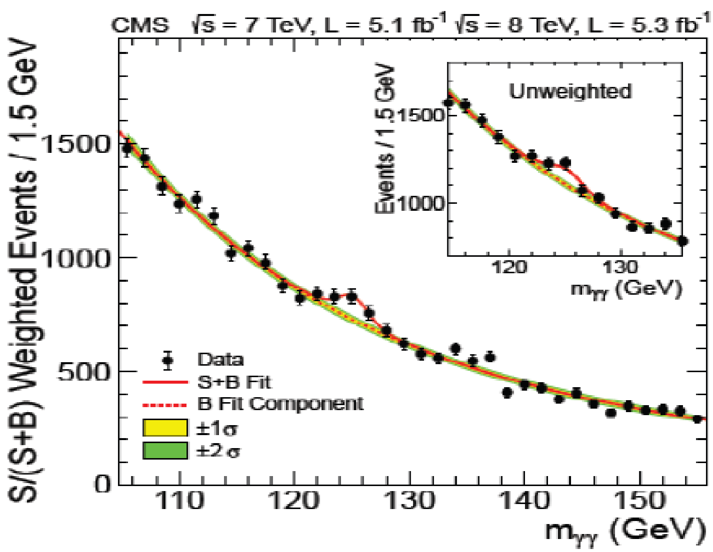
Higgs-like particle – 4 July 2012

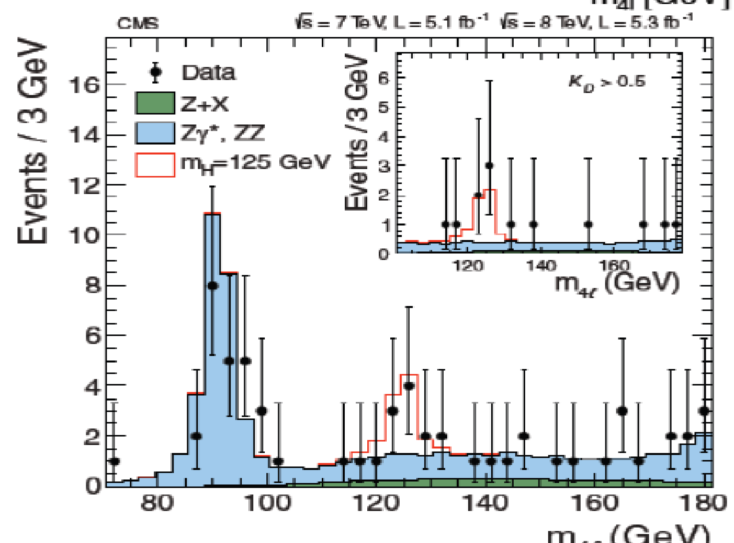
Phys.Lett. B716 (2012) 1-29



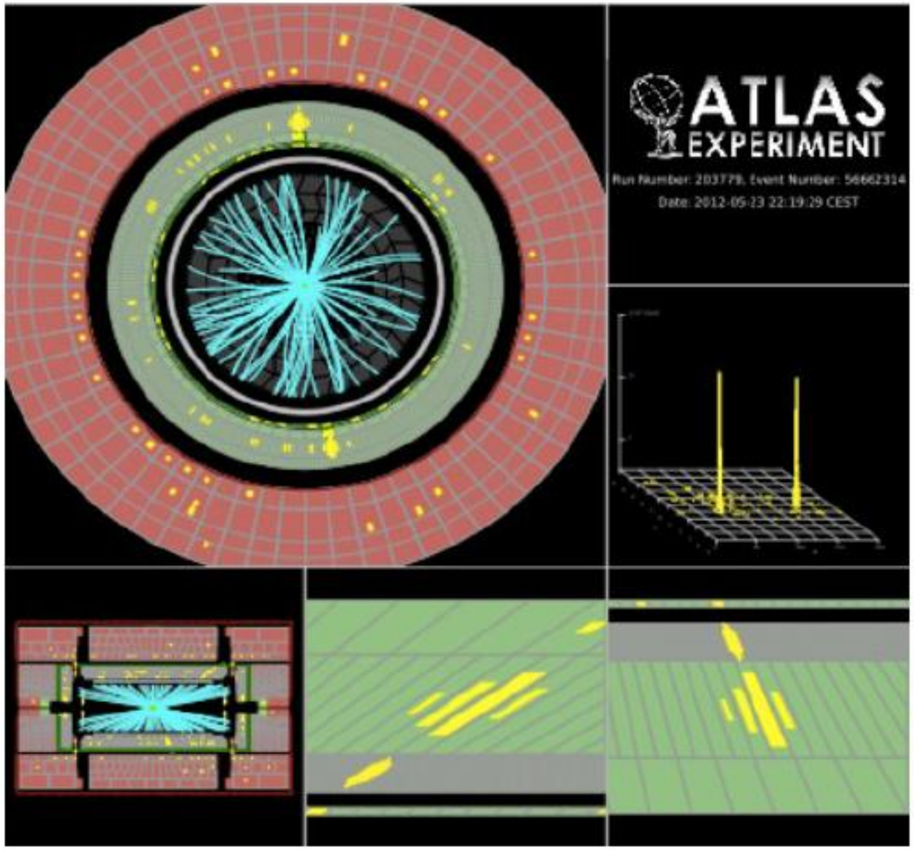


Phys.Lett. B716 (2012) 30-61





H->γγ: events signature



Simple event signature

- Two high pT photons
$pT_1 > 40$ GeV and $pT_2 > 30$ GeV

- High trigger efficiency
~99%

- High event selection efficiency despite high jet-jet & γ-jet production
~40%

- High signal over background
~3-10 % (depending on sub-category)

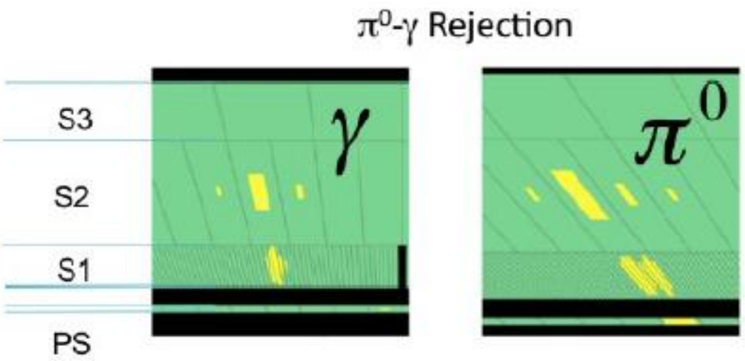
Invariant mass reconstruction $m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos\alpha)$

- Good energy calibration
- Robust primary vertex reconstruction

→ Excellent invariant mass resolution ~1.6 GeV with 90% of events within ±2σ

Shower shapes and vertex reconstr.

Photon ID 2 – Photon shower shapes and background rejection

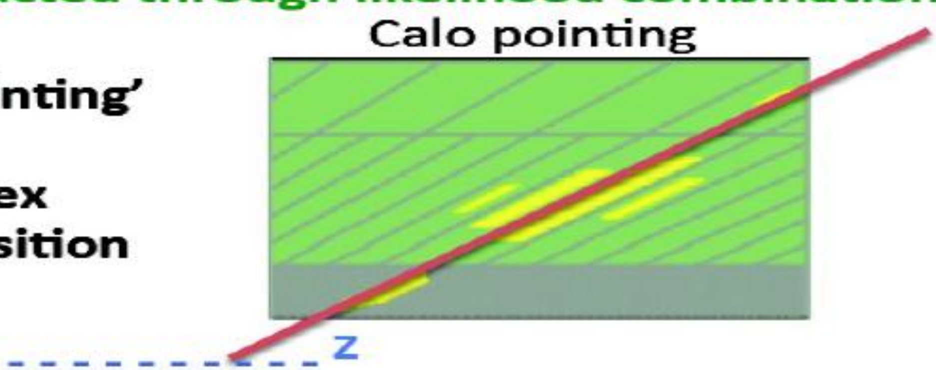


- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

Vertex Reconstruction

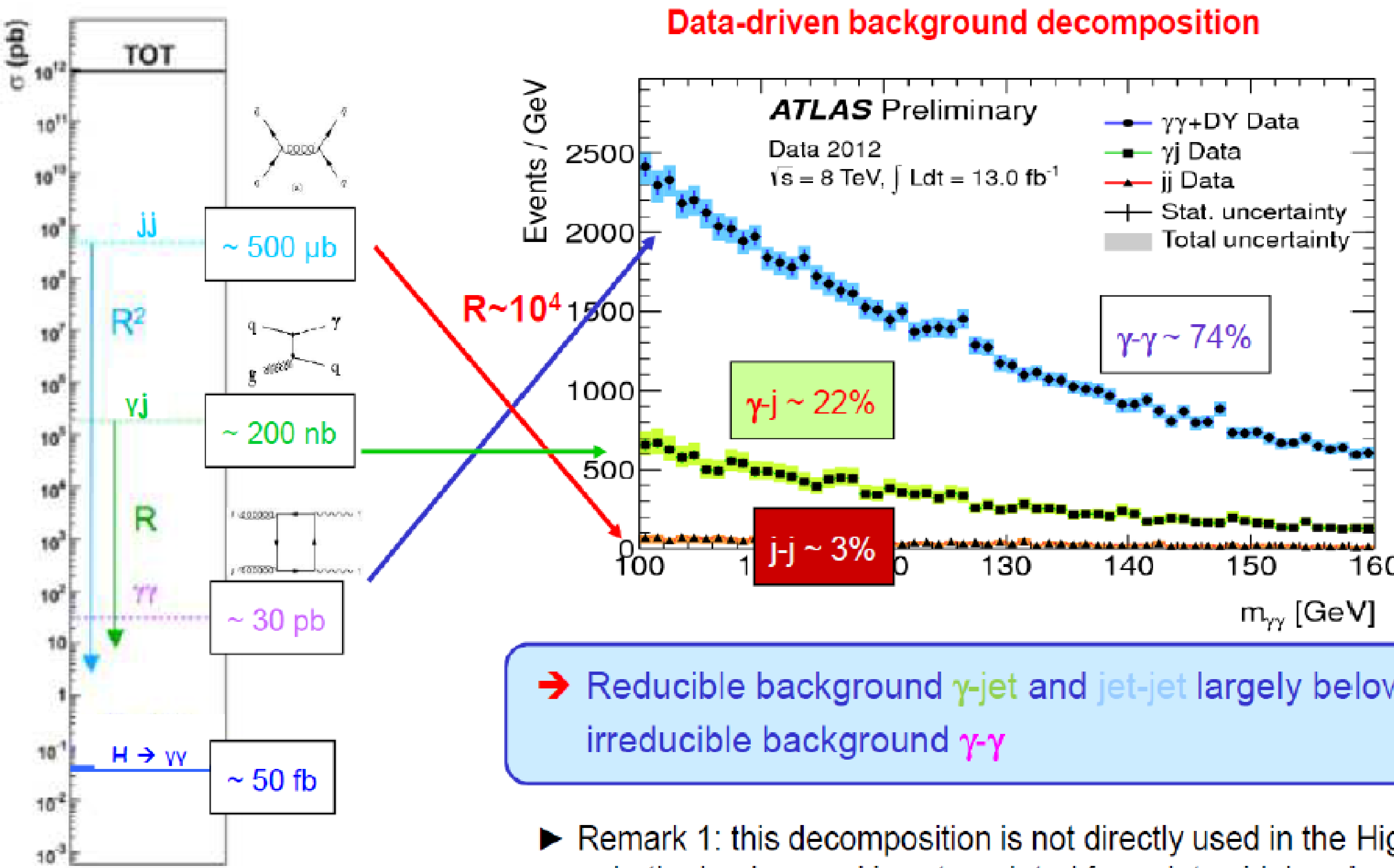
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos\alpha)$$

- ❑ Vertex reconstructed through likelihood combination



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

H->γγ: background rejection



➔ Reducible background γ-jet and jet-jet largely below irreducible background γ-γ

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

Event categorization

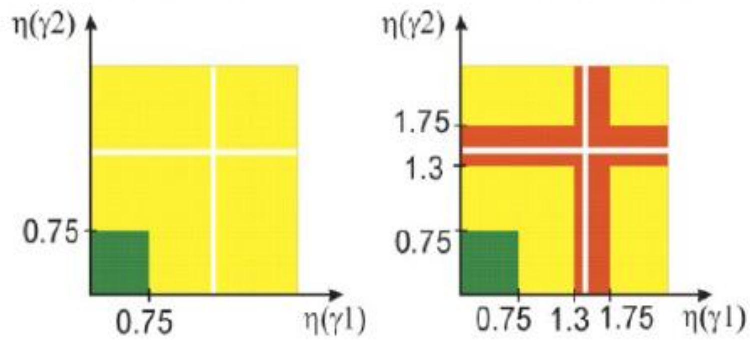
Event categories based on eta, pTt, and conversion

Both unconverted:

- Central
- Rest

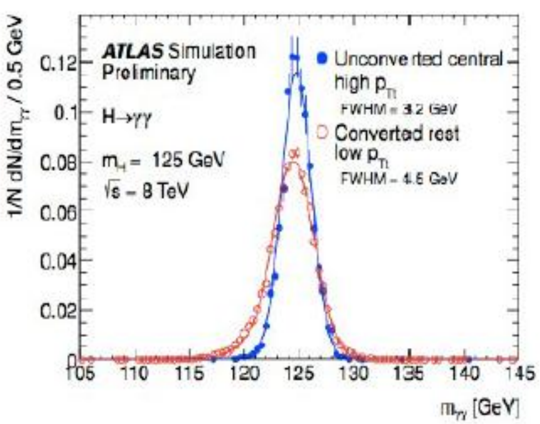
At least one converted:

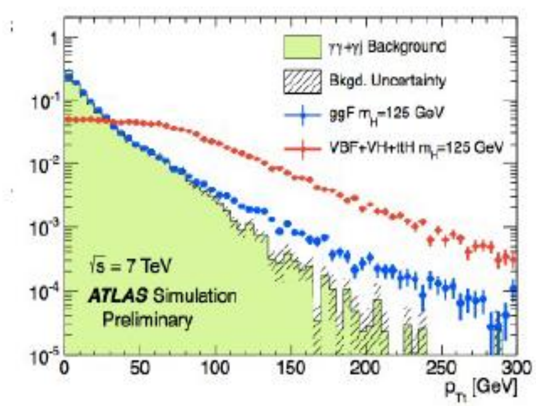
- Central
- Transition
- Rest



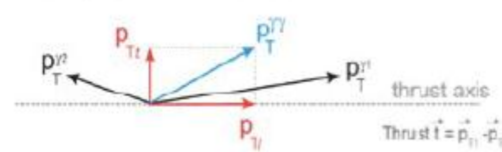
Resolution:

Good
Medium
Poor





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

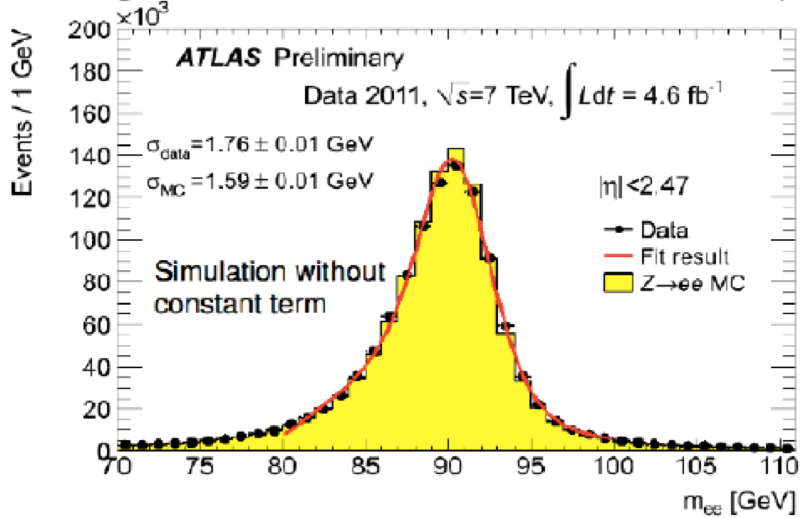


Energy calibration and resolution

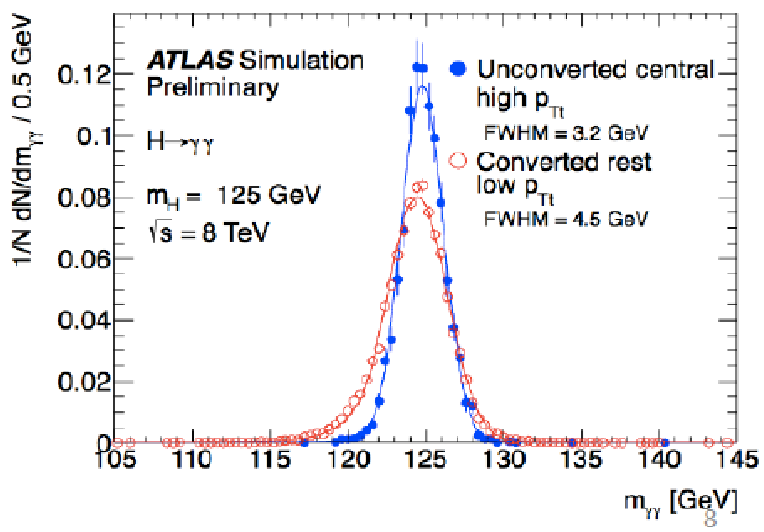
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos\alpha)$$

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

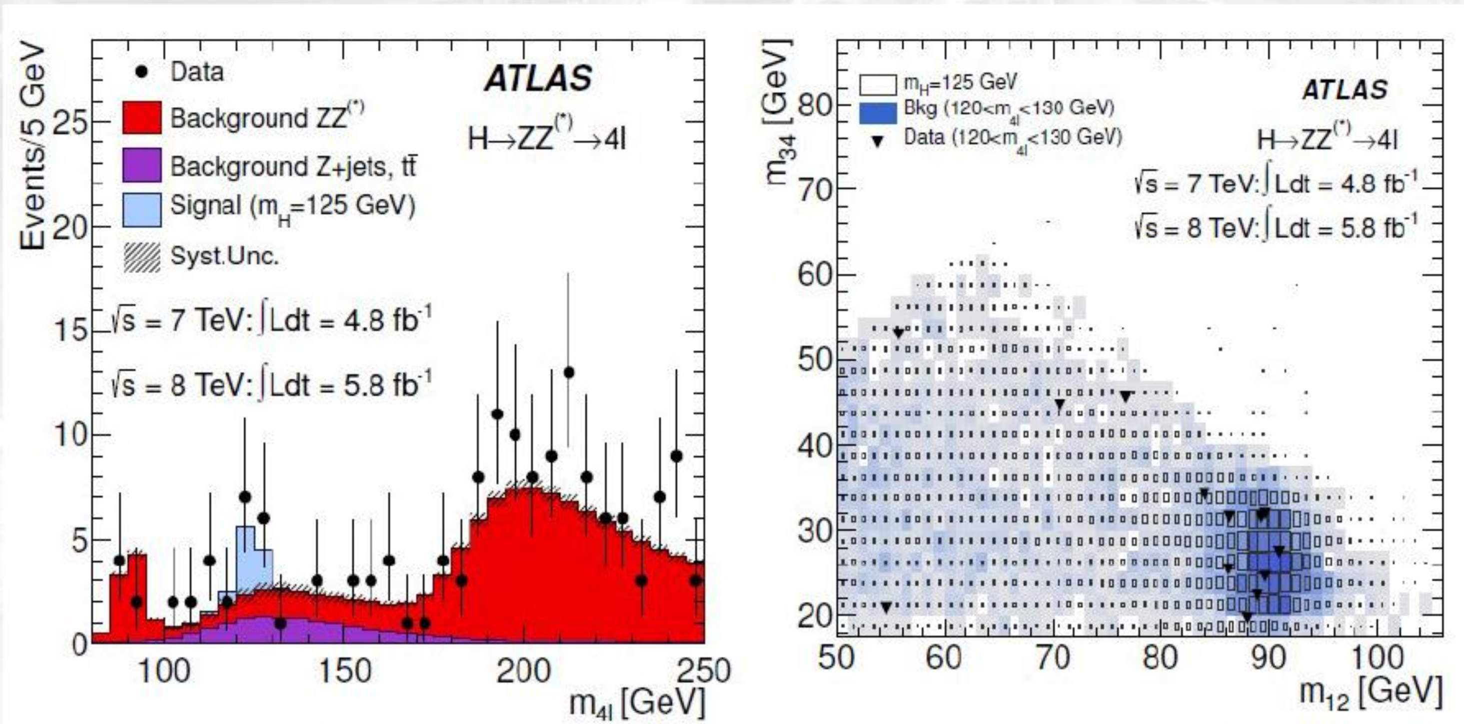
Agreement between data & MC Z→ee lineshape



Expected resolution of Higgs signal



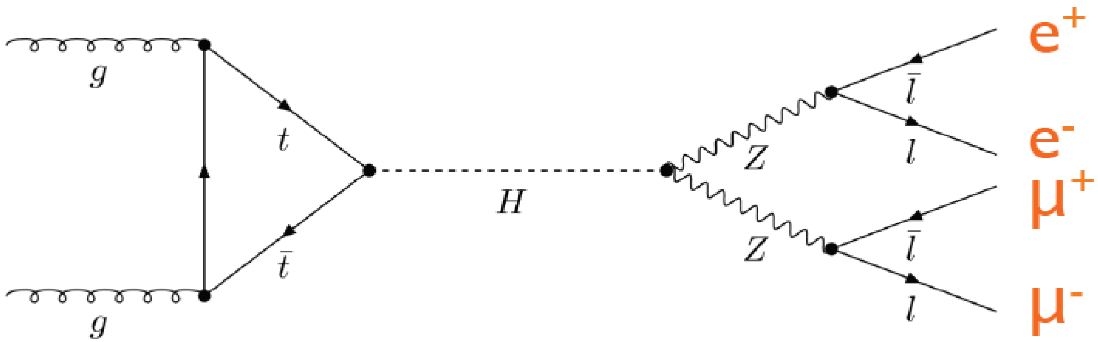
The golden channel Z->ll



In a $m_{4\ell}$ window around 120-130 GeV:

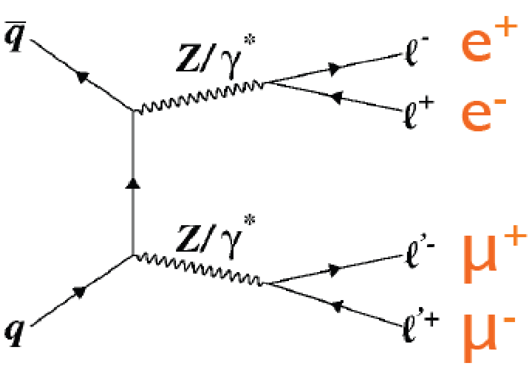
	Signal	$ZZ^{(*)}$	$Z+$ jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

Signal and background



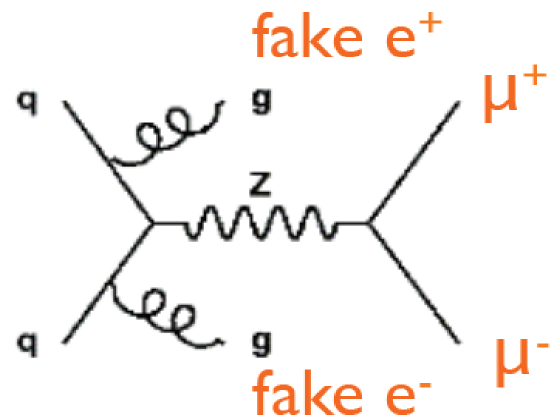
Irreducible background

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



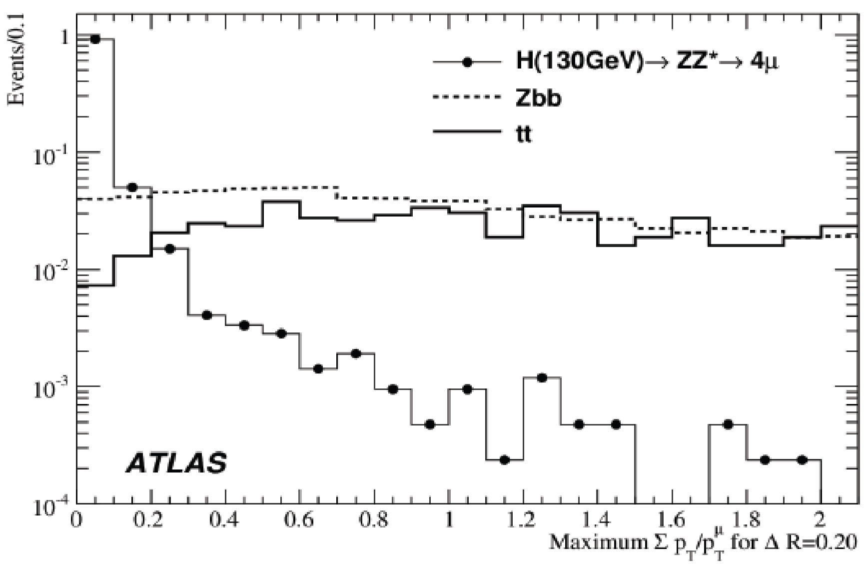
Reducible background

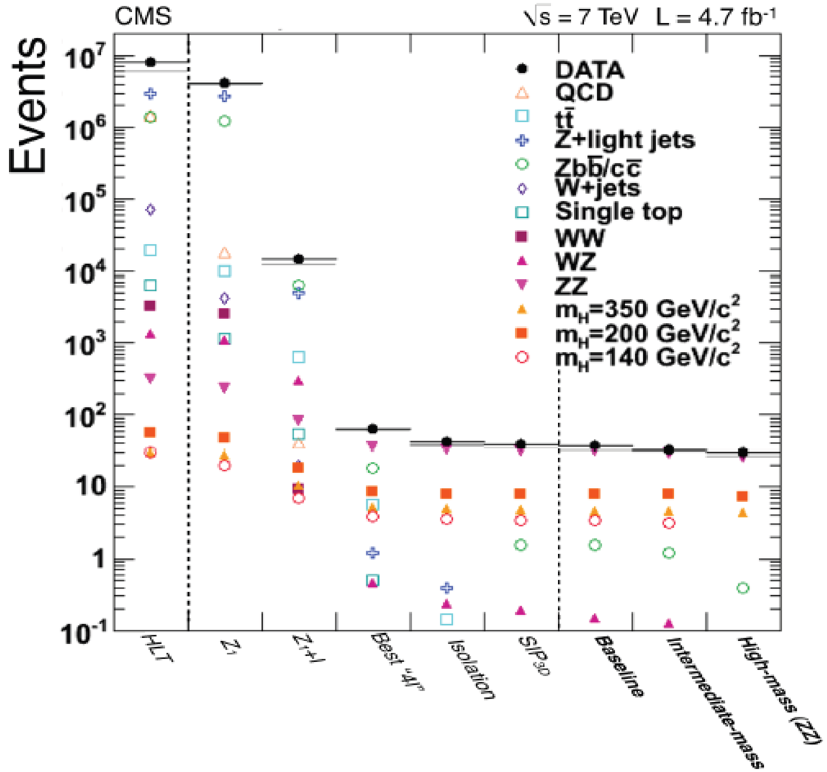
The final state looks like the same, but some f the particle fakes what you are looking for



Selection

- Cut on particle properties to reduce reducible background
  - ✓ Shower shapes, track properties, …
- Cut on event properties to distinguish signal from background
  - ✓ Particle kinematics, decay kinematics event shape, …
- Try to keep signal while reducing background!
  - ✓ Increase S/B

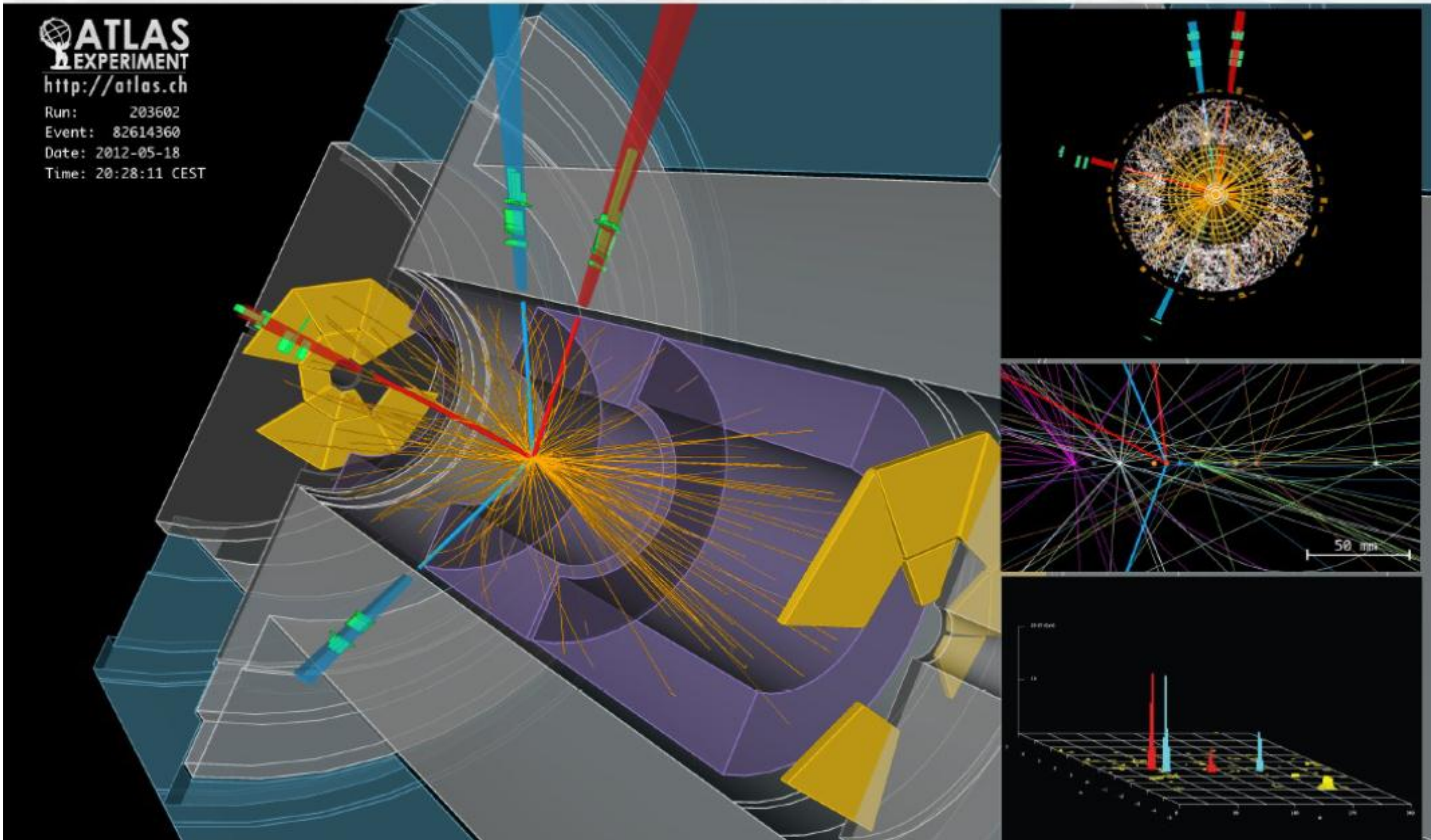




$4e$ candidate. $m_{4\ell} = 124.6$ GeV, $m_{12} = 70.6$ GeV, $m_{34} = 44.7$ GeV.

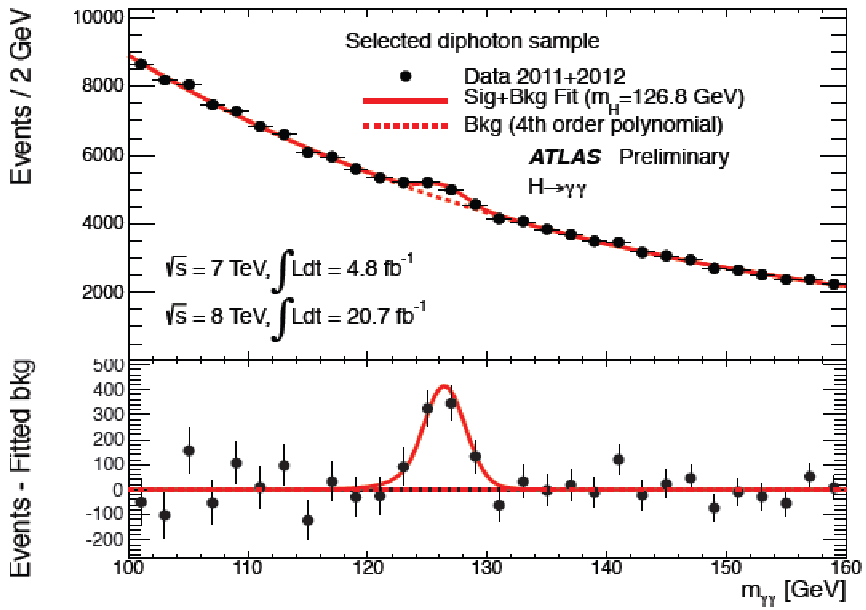
e_1: $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$ e_2: $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

e_3: $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$ e_4: $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$

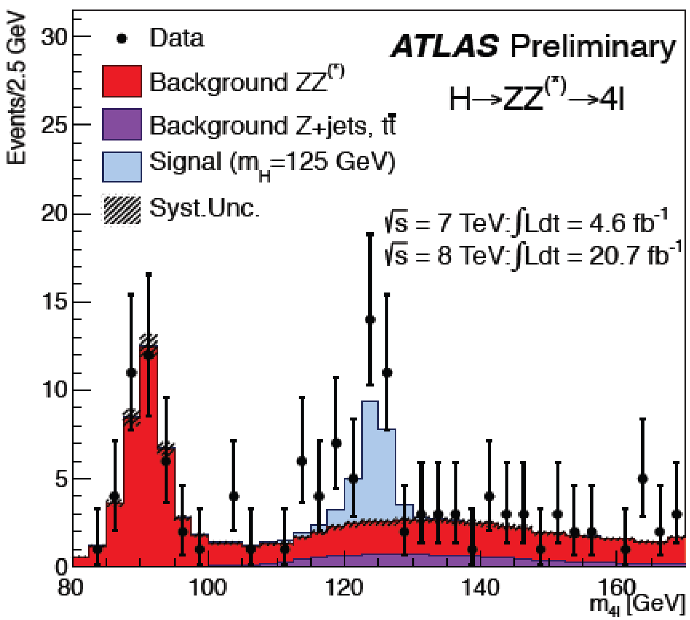


Higgs like signal with 7 TeV and 8 TeV data

H→γγ



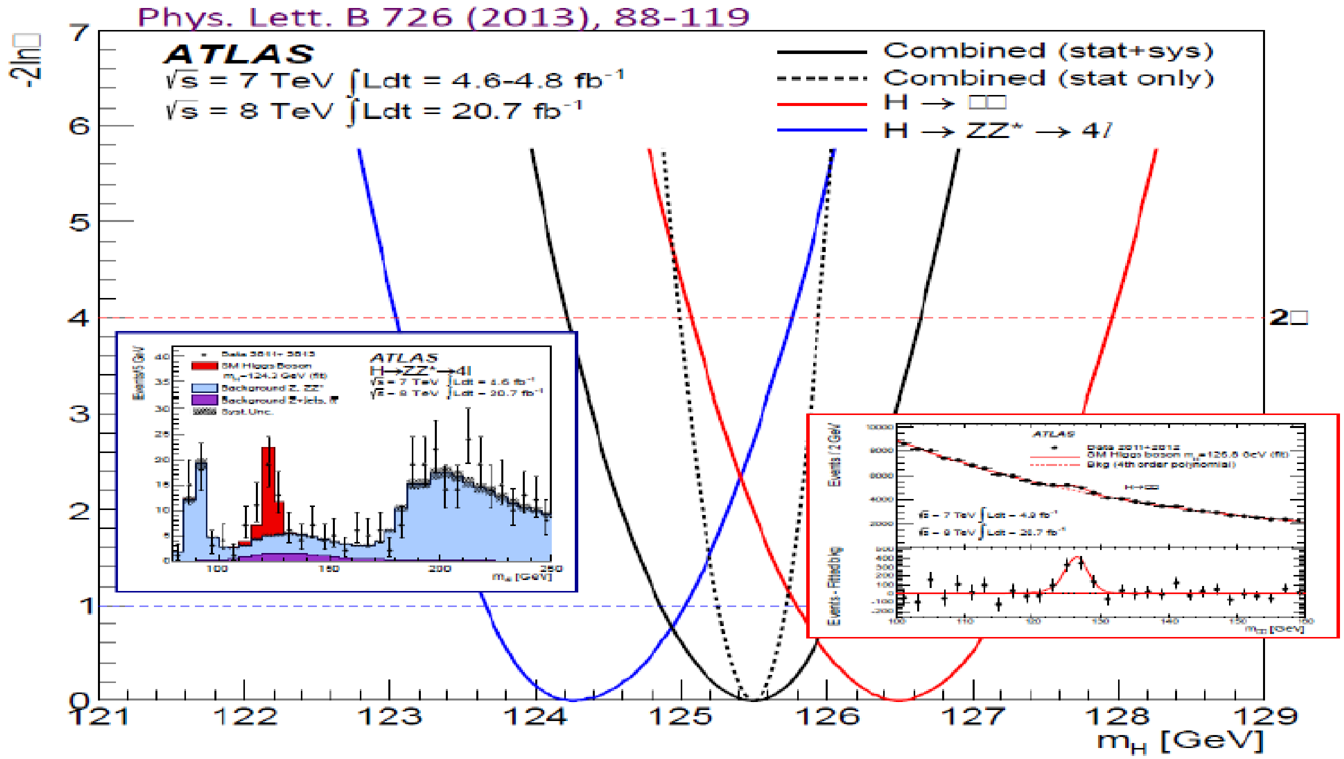
H→4l



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

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

Mass measurement



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

γγ: $M_H = 126.8 \pm 0.2_{stat} \pm \mathbf{0.7}_{sys}$ GeV

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

And since then ….

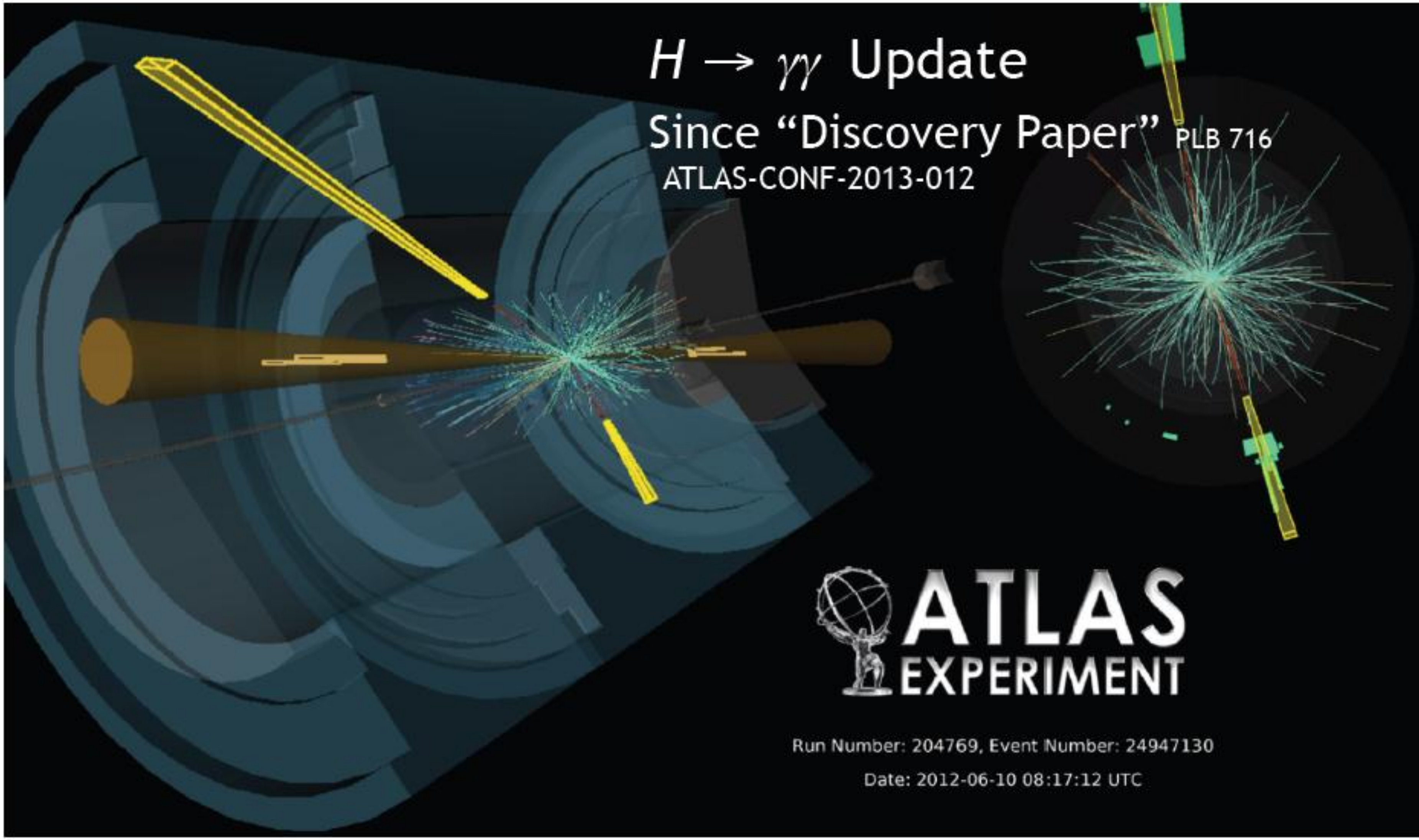
Panorama of ATLAS Higgs (125) Analyses

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

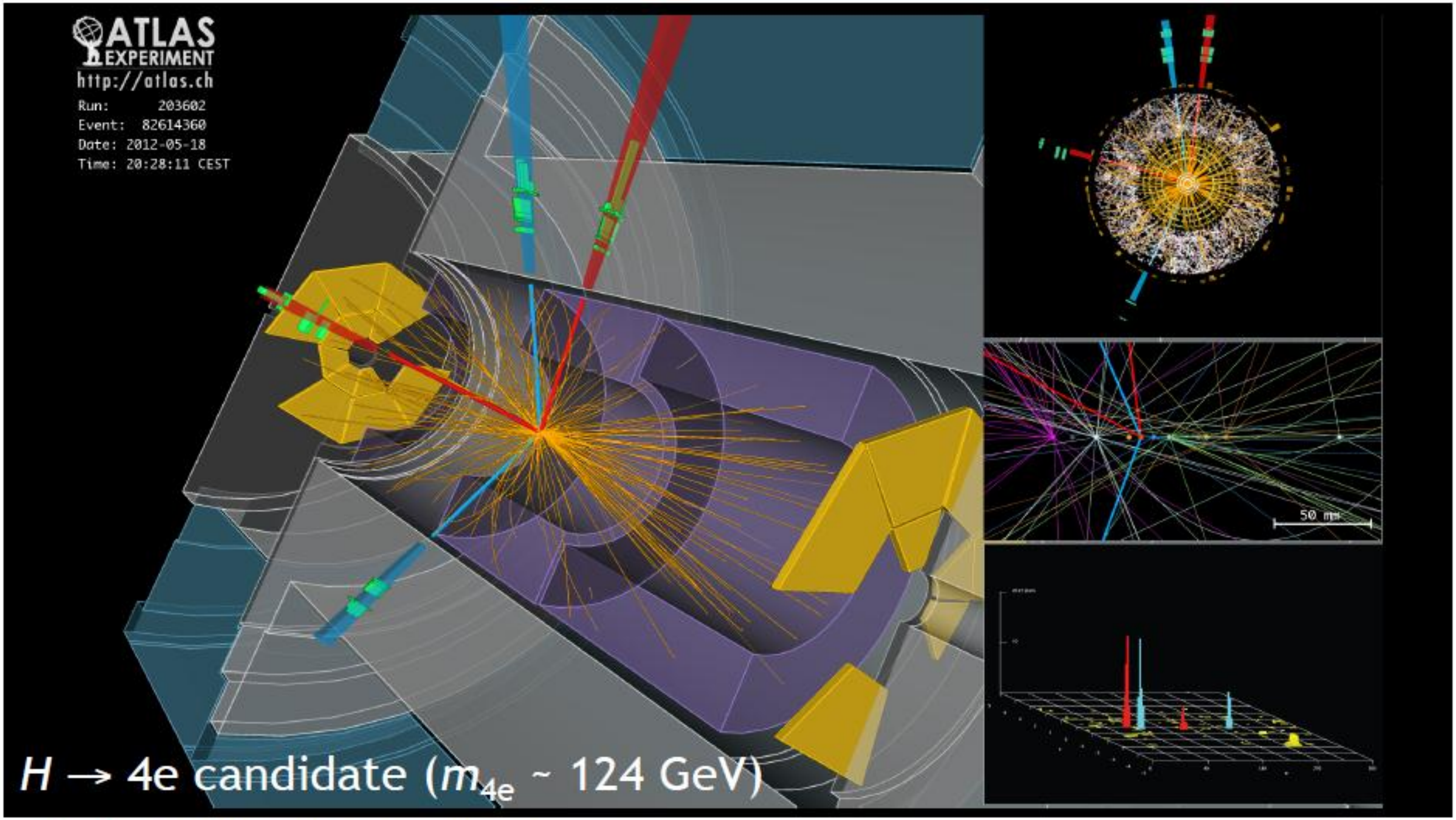
Since "Discovery Paper" PLB 716

ATLAS-CONF-2013-012



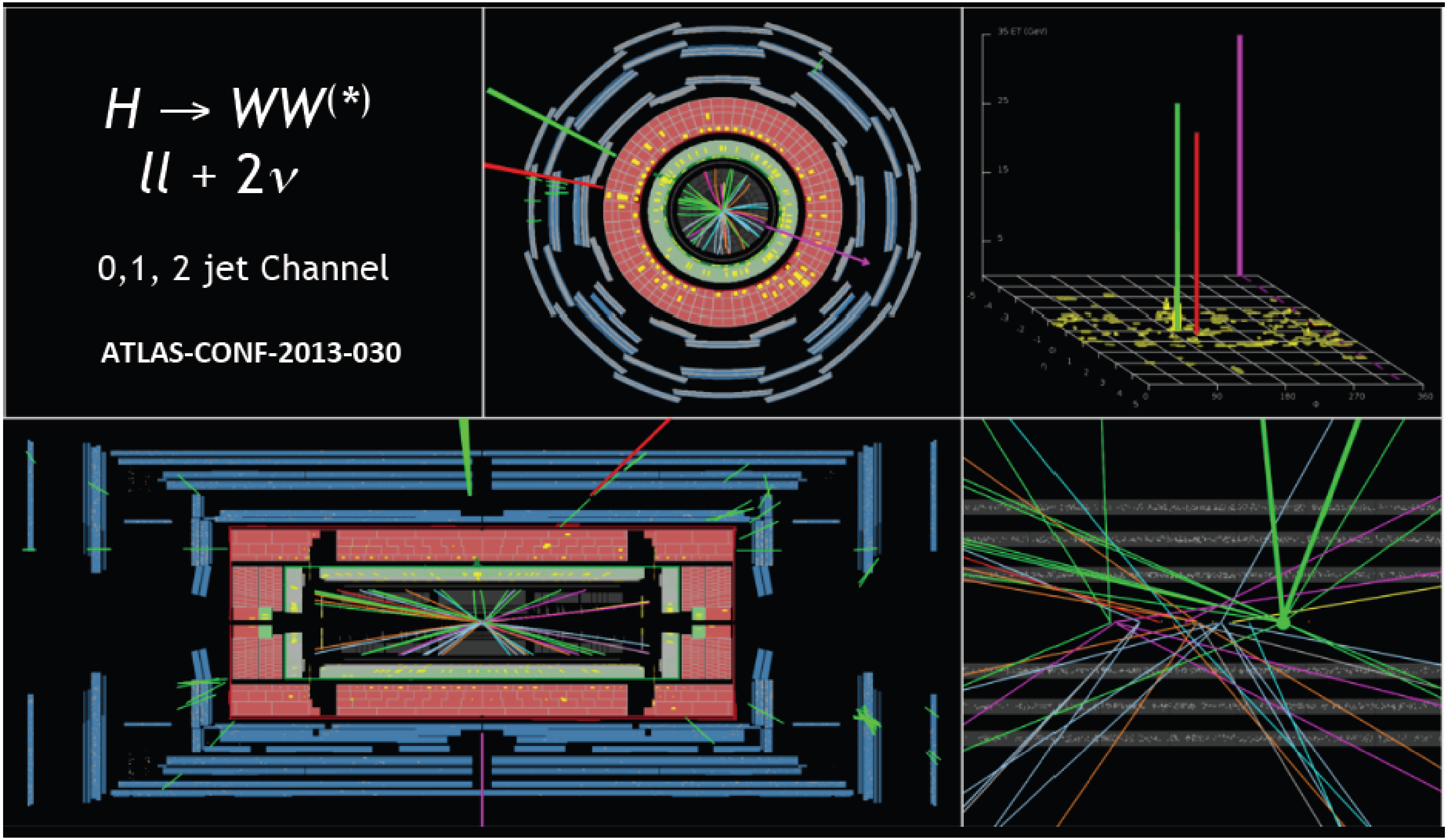
γγ channel basic facts sheet :

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



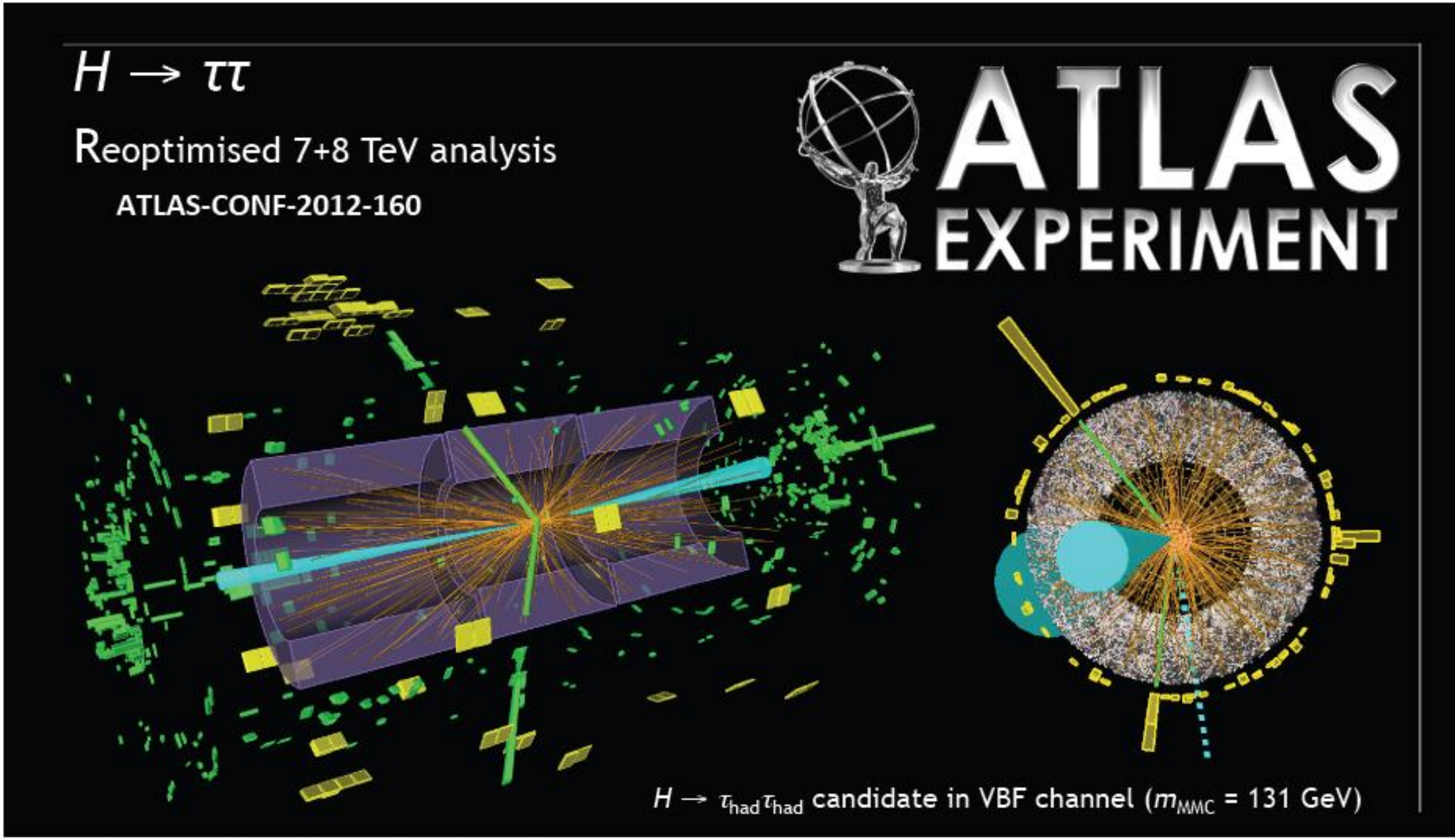
4l channel basic facts sheet :

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}



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	$25 fb^{-1}$

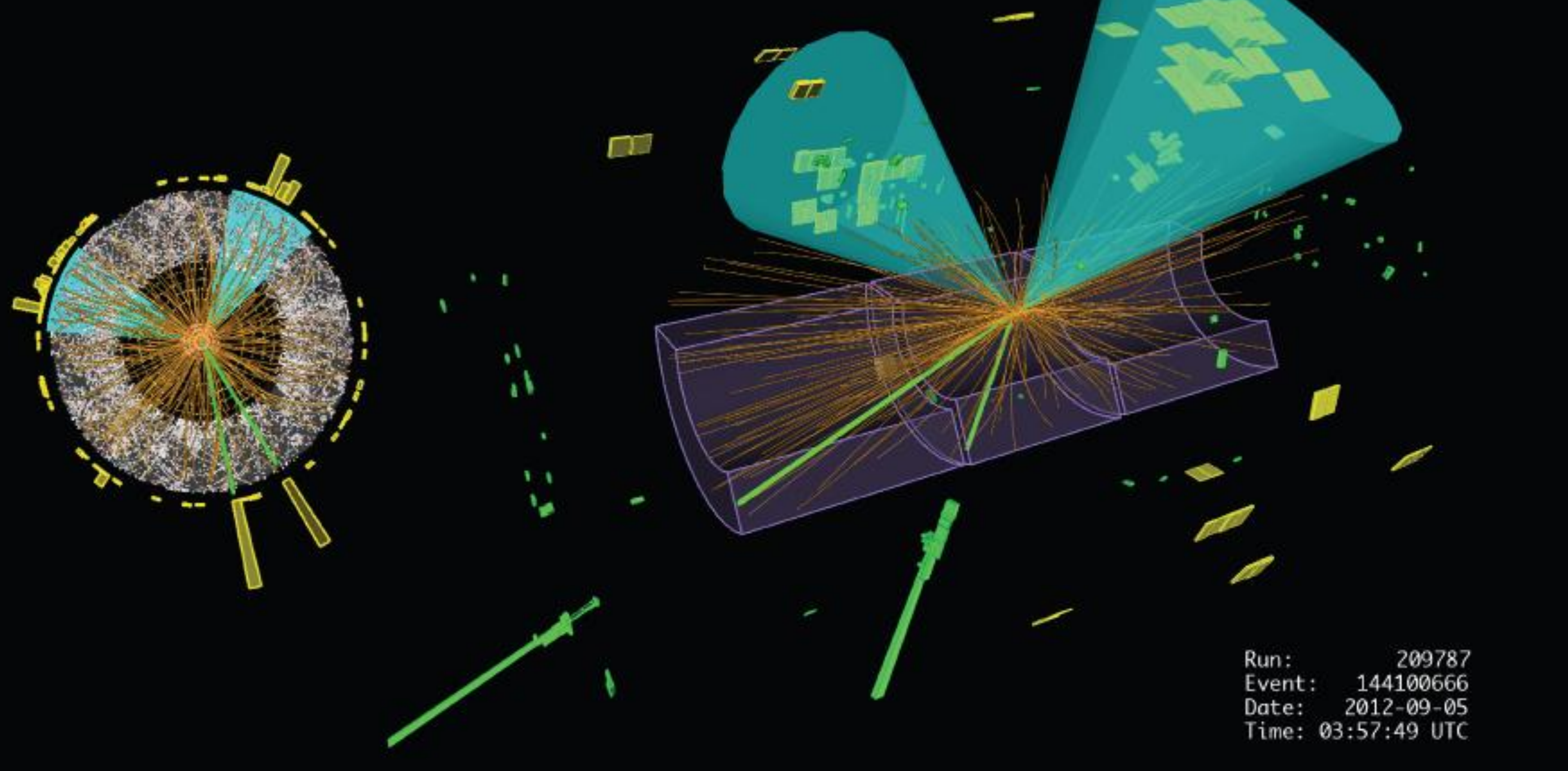


ττ channel basic facts sheet :

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* → *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) $\pm$ 0.6 (syst) GeV

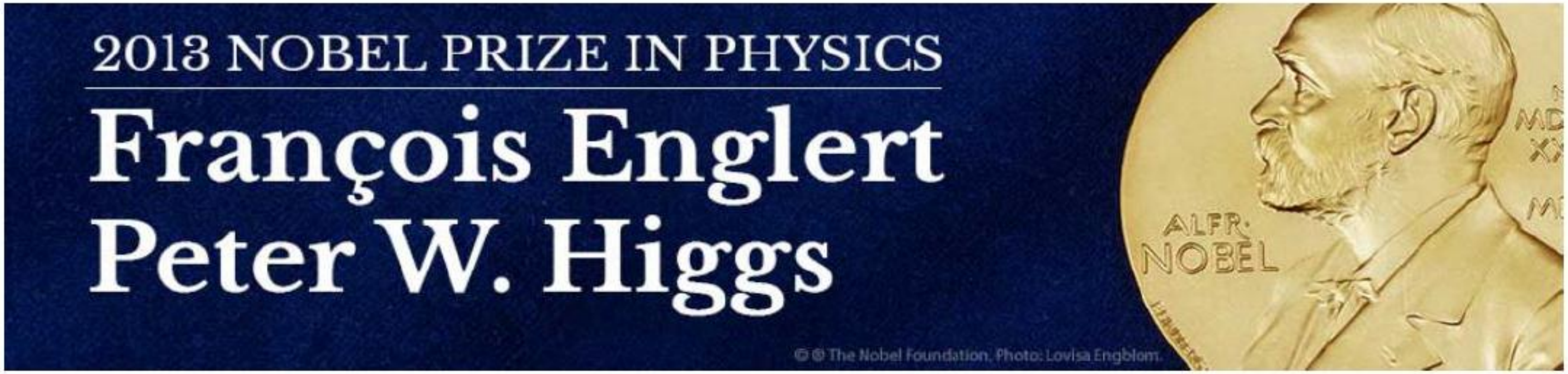
  CMS: $m_H = 125.7 \pm 0.3$(stat) $\pm$ 0.3 (syst) GeV

- 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



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

8 October 2013

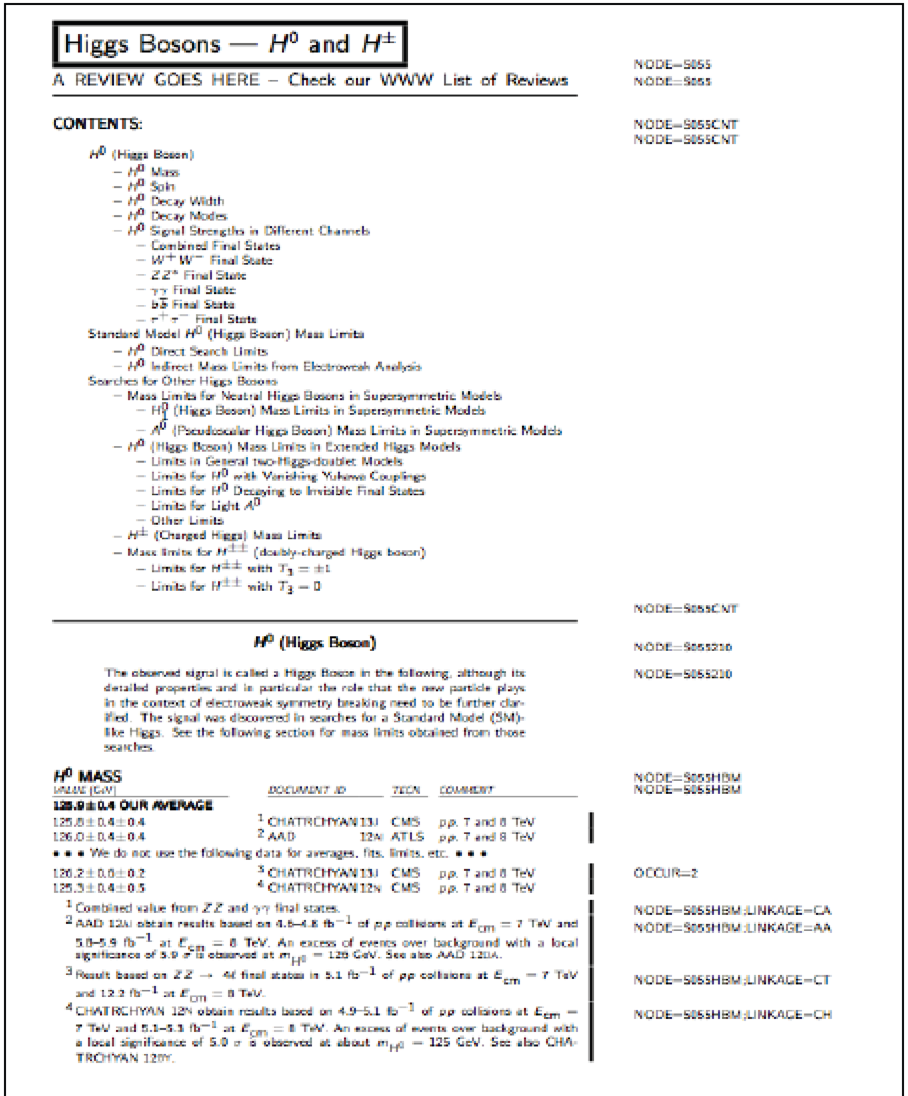
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

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

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

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

H^0 MASS

NODE=S055HBM
NODE=S055HBM

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
125.9±0.4 OUR AVERAGE			
125.8±0.4±0.4	[1] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD 12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
126.2±0.6±0.2	[3] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN 12N	CMS	pp, 7 and 8 TeV

OCCUR=2

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

NODE=S055HBM;LINKAGE=CA

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.8–5.9 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 12DA.

NODE=S055HBM;LINKAGE=AA

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

NODE=S055HBM;LINKAGE=CT

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 5.1–5.3 fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 12BY.

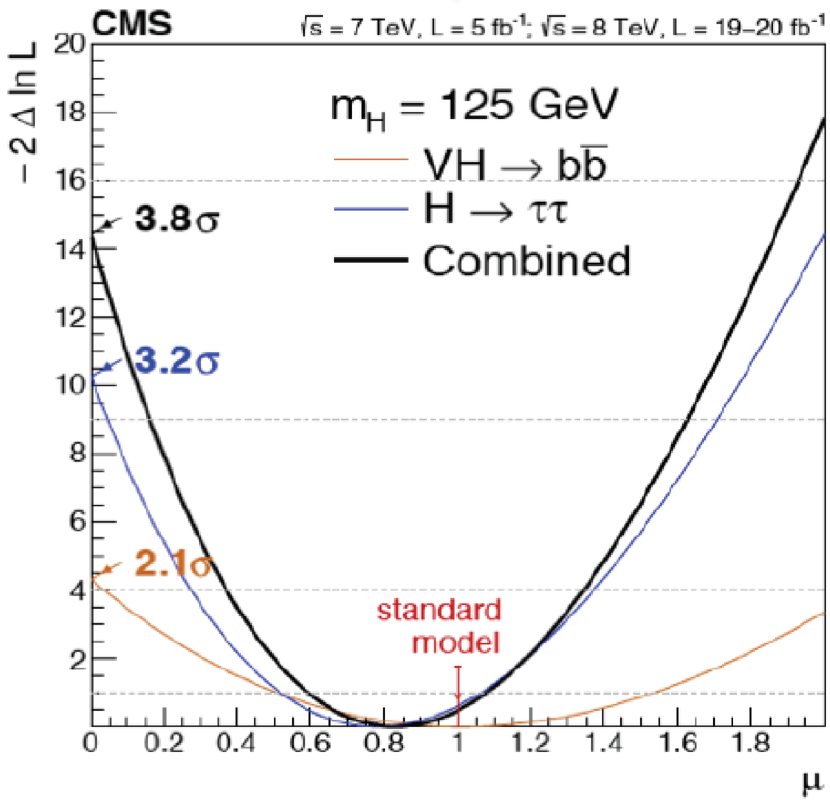
NODE=S055HBM;LINKAGE=CH

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

$$H^0$$

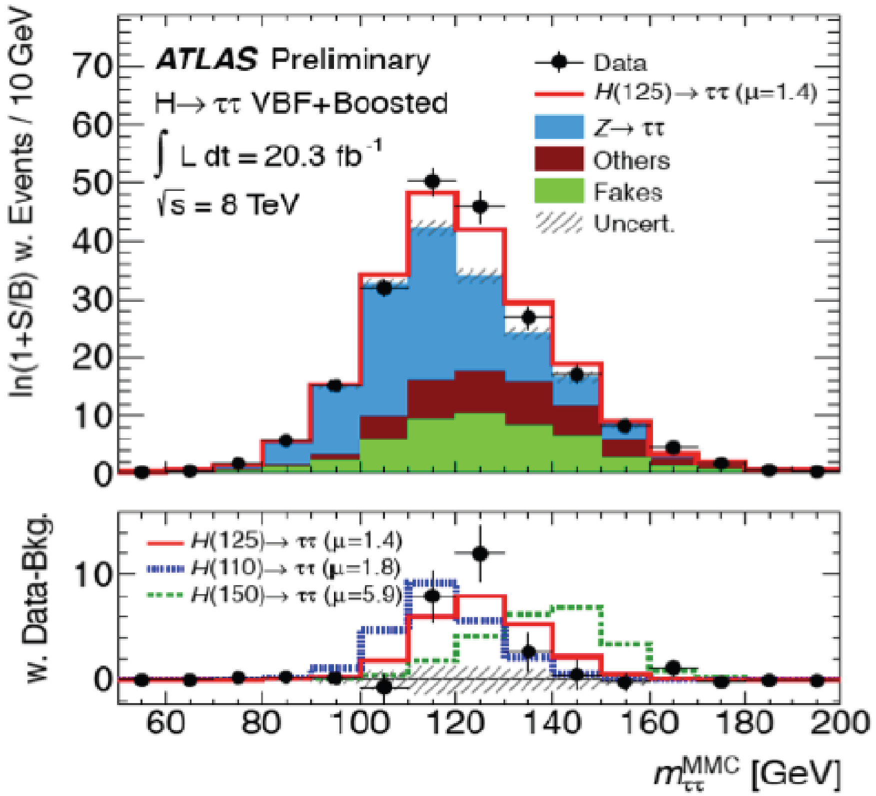
Higgs decays to fermions (2014)

CMS: H→ ττ, bb Channels



Significance	Exp	Obs
CMS (ττ)	3.4 σ	3.2 σ
CMS (bb)	2.1 σ	2.1 σ

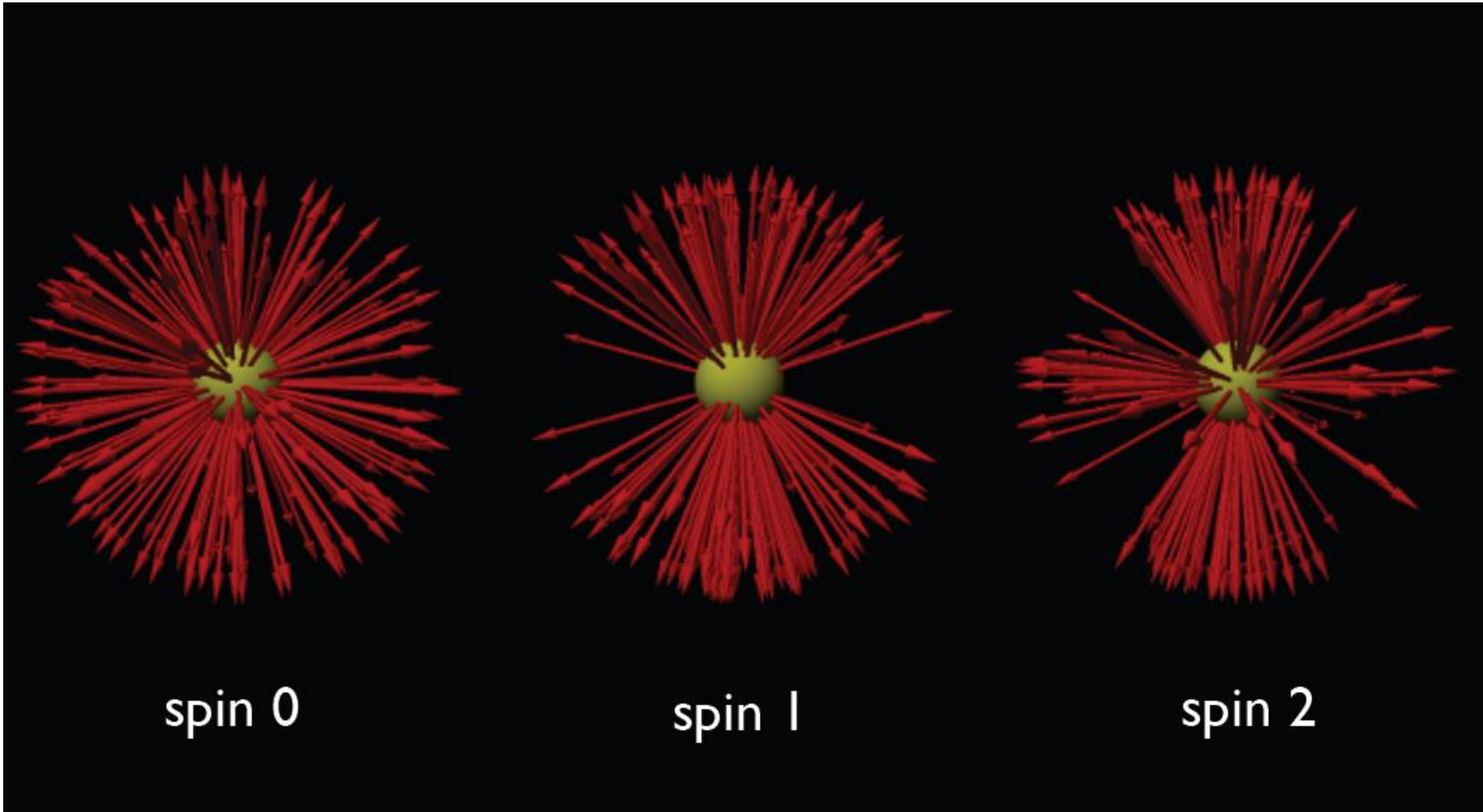
ATLAS: H→ ττ Channel



Significance	Exp	Obs
ATLAS (ττ)	3.2 σ	4.1 σ

Tevatron: exp (2.1σ), obs (3.0σ)

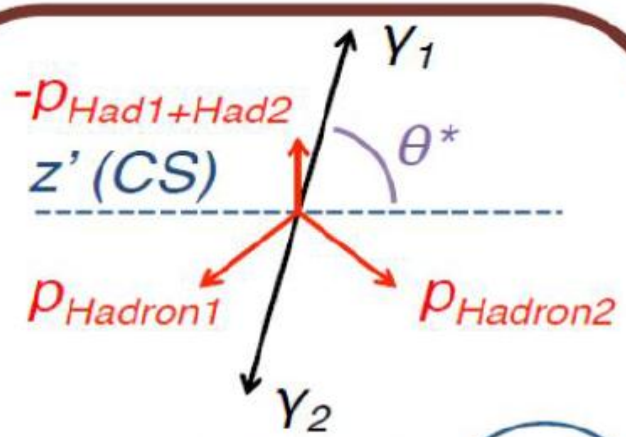
How we can recognize spin?



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->$\gamma\gamma$

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



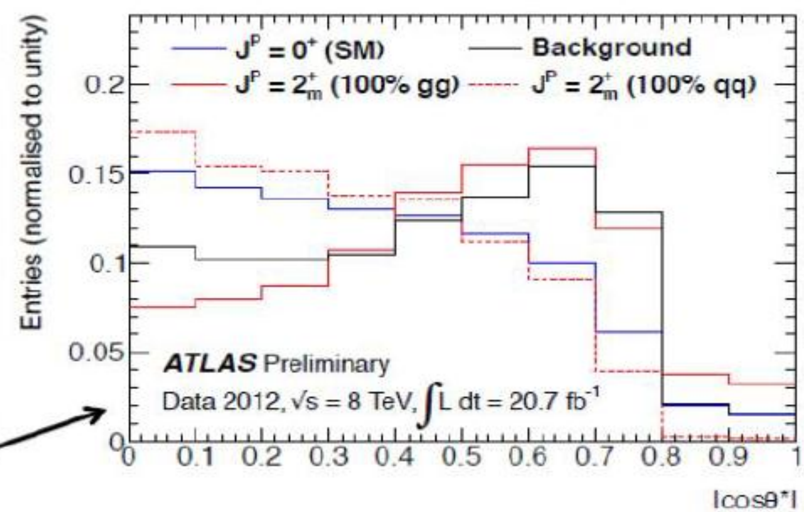
$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

Collins-Soper frame used to get reference axis z' for cos(θ*)

- 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→2⁺ very similar to SM *gg*→0⁺



Fit metod for H->$\gamma\gamma$

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

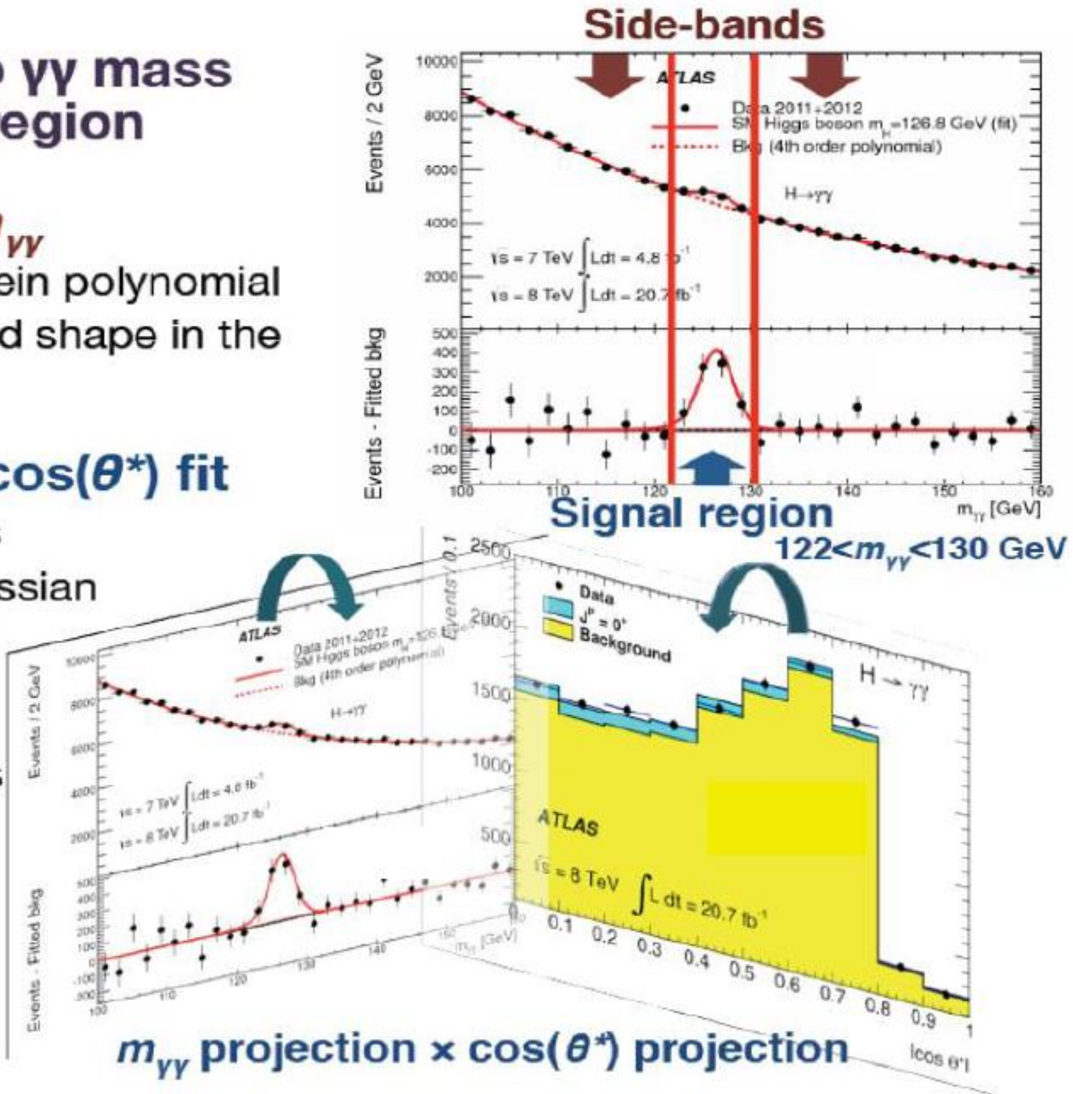
Side-bands: 1D fit in $m_{\gamma\gamma}$

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

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

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

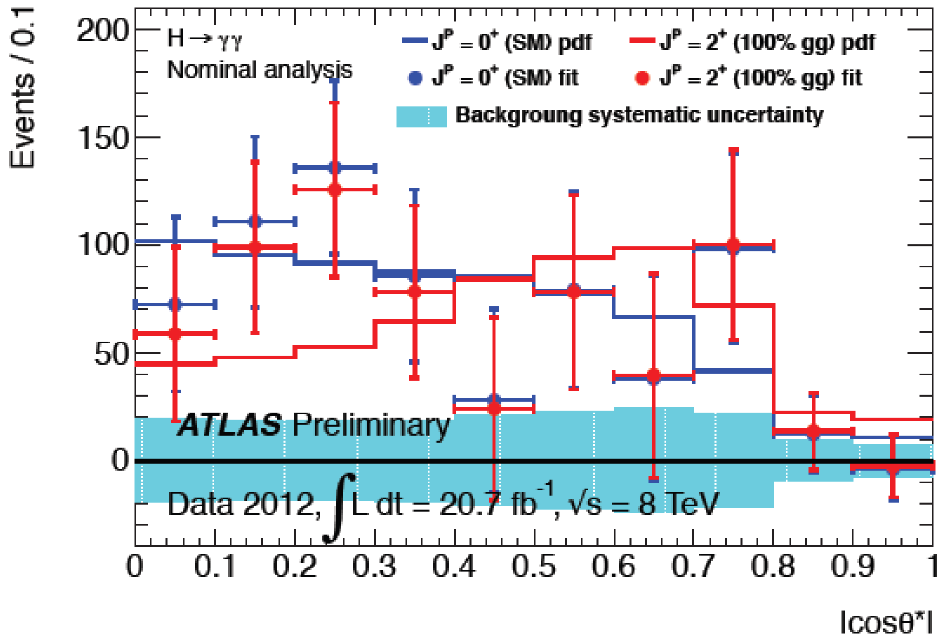
Method assumes minimal correlation between mass and cos(θ*) in background

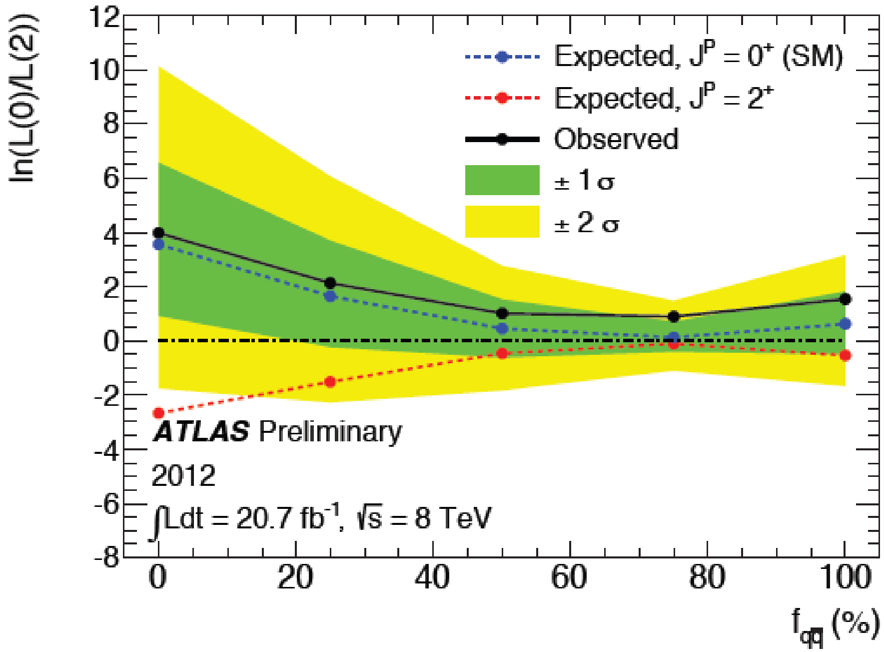


Spin study with H->γγ

γγ polar angle θ with respect to Z-axis in Colin-Sopper frame*

$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

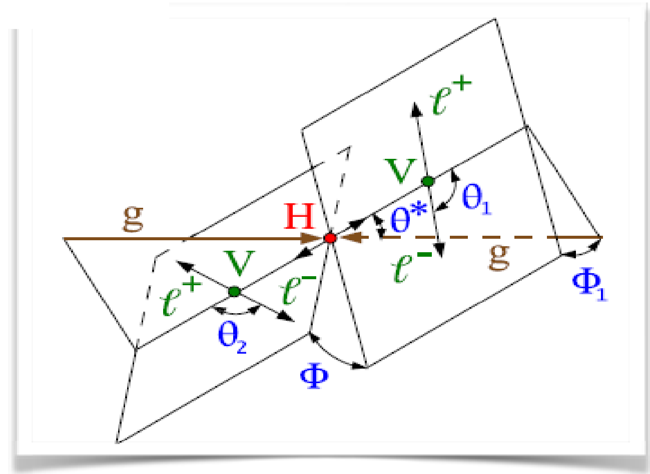


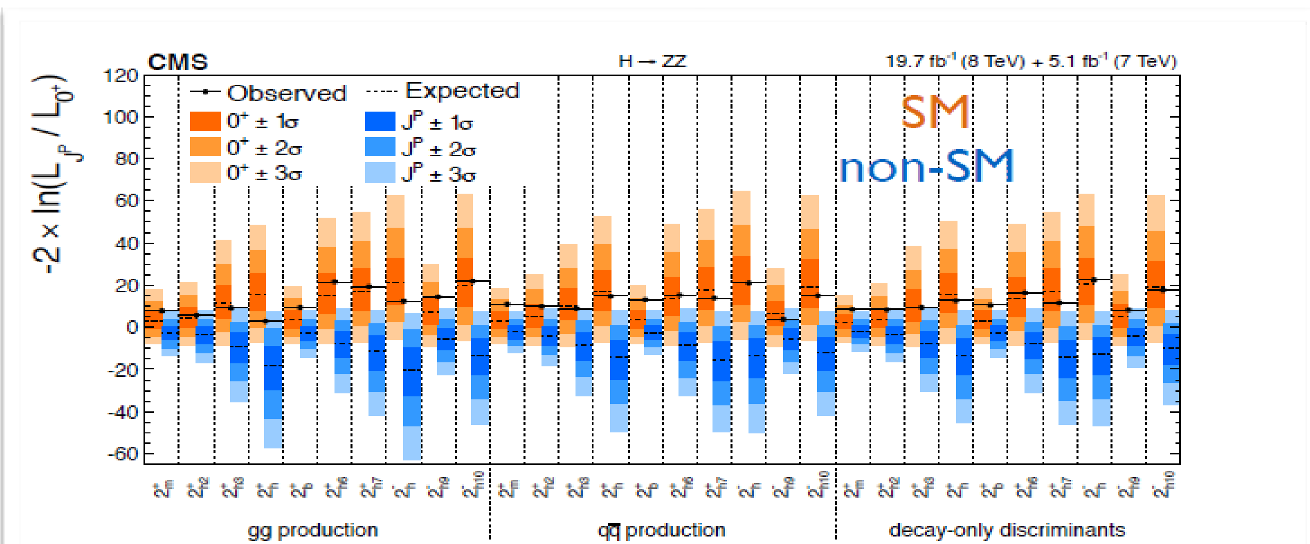


- If spin-2 resonance is produced 100% by gluon fusion, observed *rejection* p-values are:
  - ✓ spin-0 → 58.8% (1.2% expected) → good agreement with spin-0 hypothesis
  - ✓ spin-2 → 0.3% (0.5% expected) → spin-2 excluded at 99.3% CL

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





PRD 92 (2015) 012004

Tests of alternative J^P hypotheses in ZZ

Higgs boson decay width

m_h= 125 GeV → Γ_h= 4.07 MeV

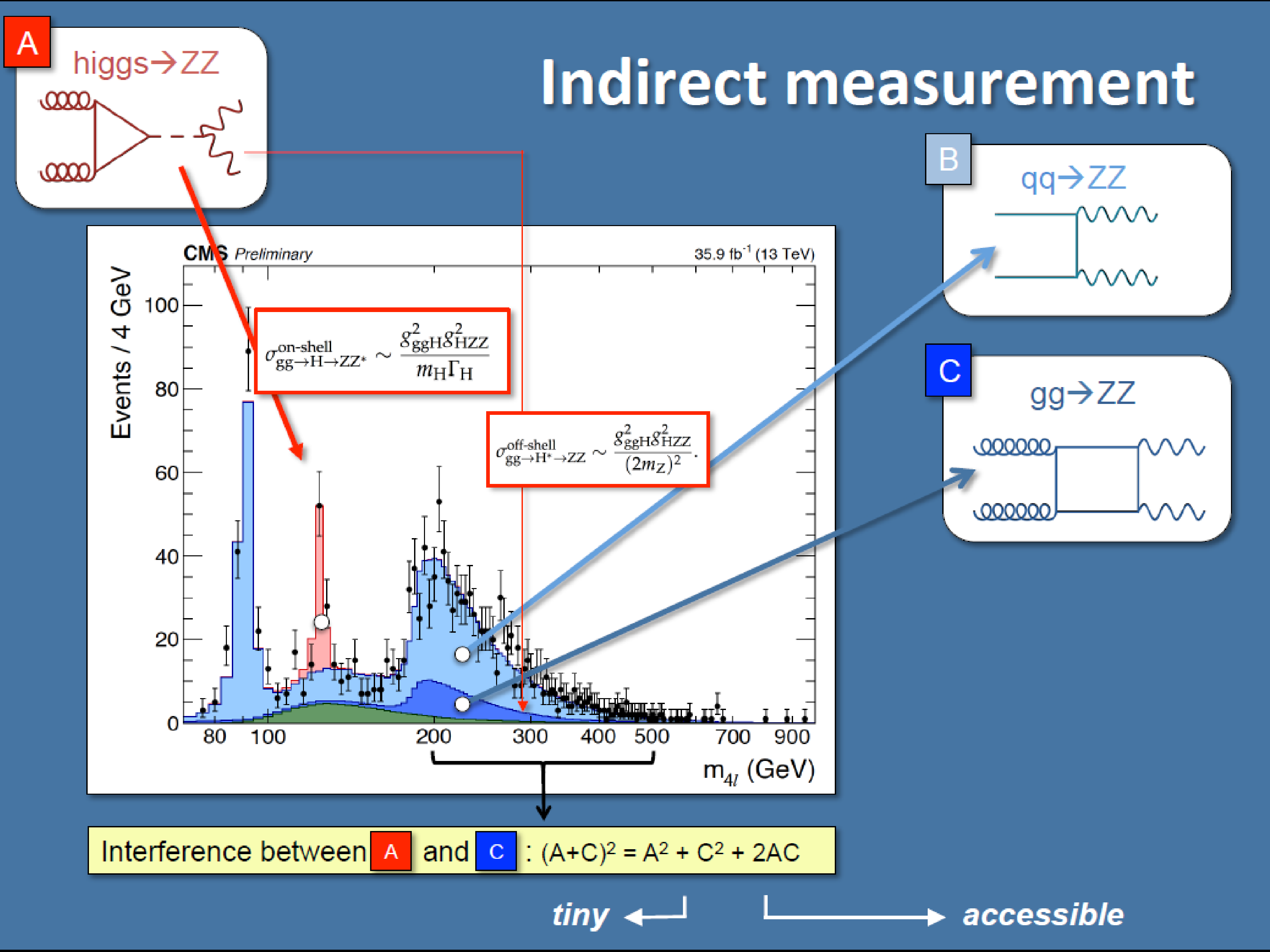
τ_h = 1.62 10^{-22} [s]

A deviation would imply a decay to non-SM particles

Differential Higgs production cross-section

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H},$$

Γ_h cannot be accessed directly (experimental resolution ~ 1-2 GeV)

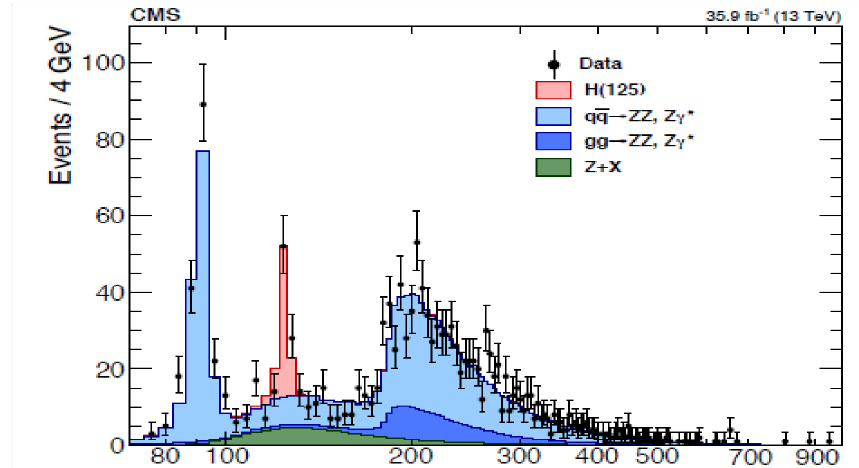


Indirect measurement
A
higgs→ZZ
B
qq→ZZ
C
gg→ZZ
CMS Preliminary
35.9 fb^{-1} (13 TeV)
Events / 4 GeV
0
20
40
60
80
100
80
100
200
300
400
500
700
900
m_{4l} (GeV)
$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$
$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$.
Interference between A and C : $(A+C)^2 = A^2 + C^2 + 2AC$
tiny
accessible

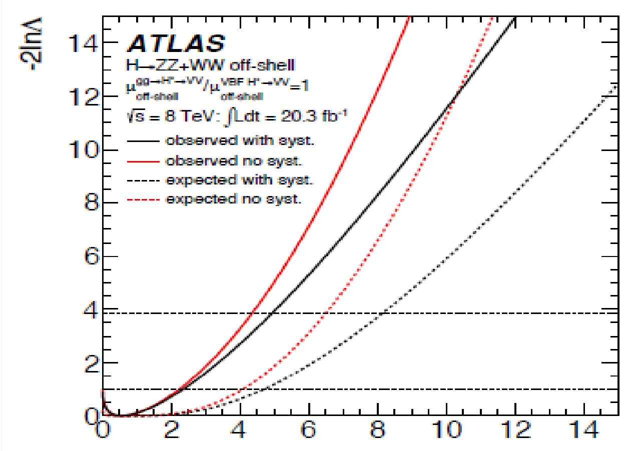
Higgs boson decay width

Total width

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

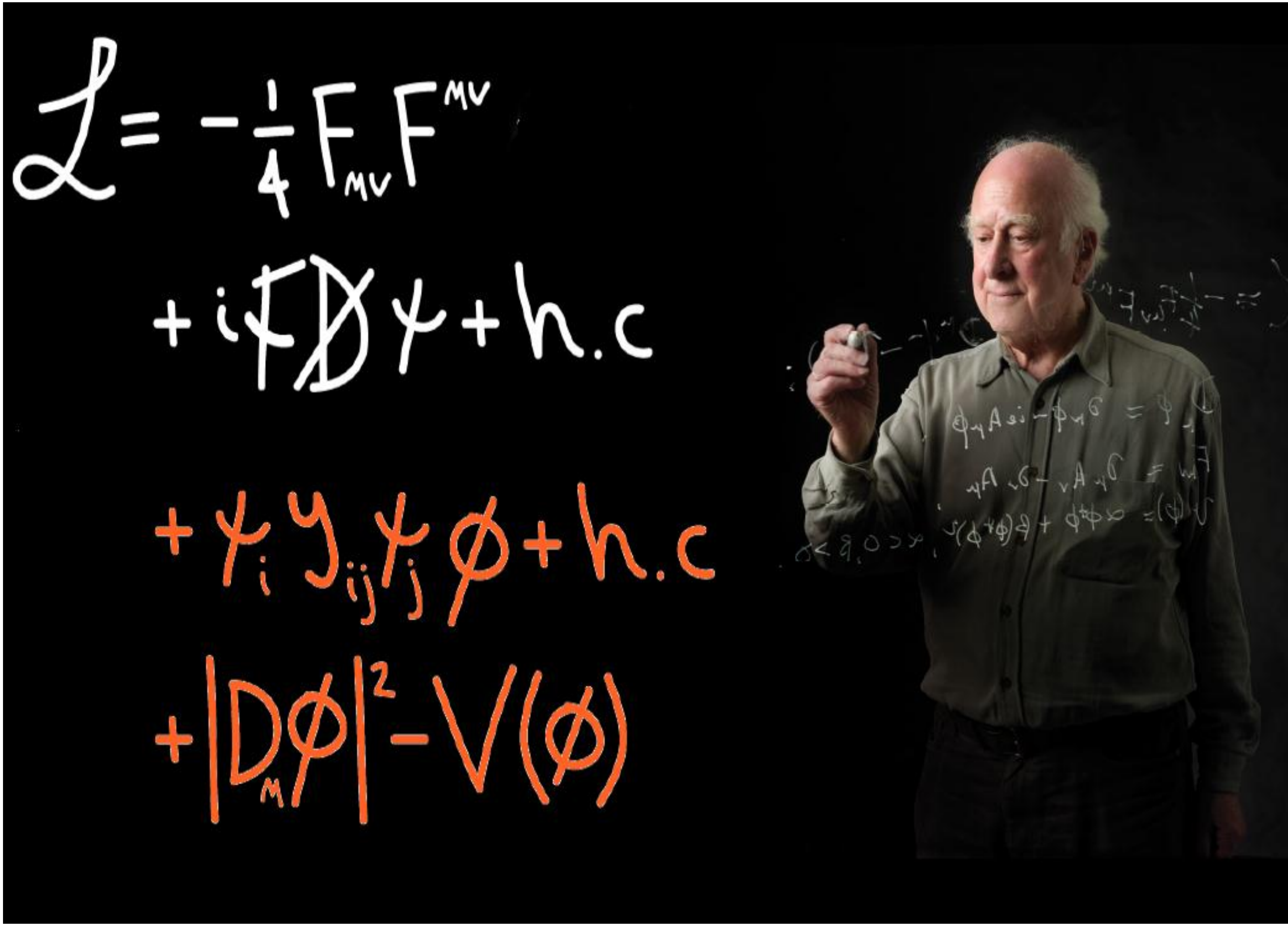


accepted by JHEP



EPJC (2015) 75:335

*N. Kauer and G. Passarino, JHEP (2012) 2012: 116
*F. Caola and K. Melnikov,PRD88 (2013) 054024


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c$
$+ \psi_i y_{ij} \psi_j \phi + h.c$
$+ |D_\mu \phi|^2 - V(\phi)$

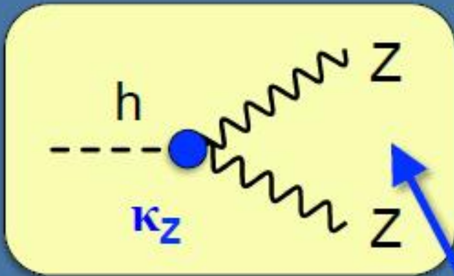
Couplings: kappa-framework

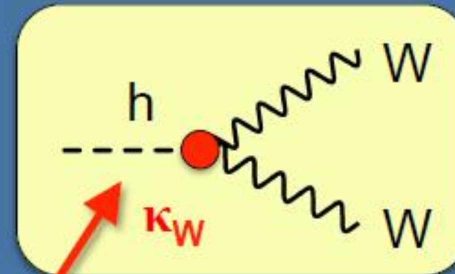
Scale factor for each (fundamental) coupling:

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

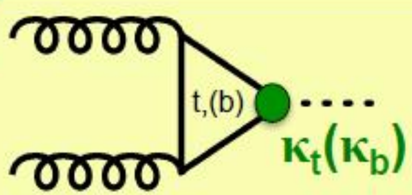
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v}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

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

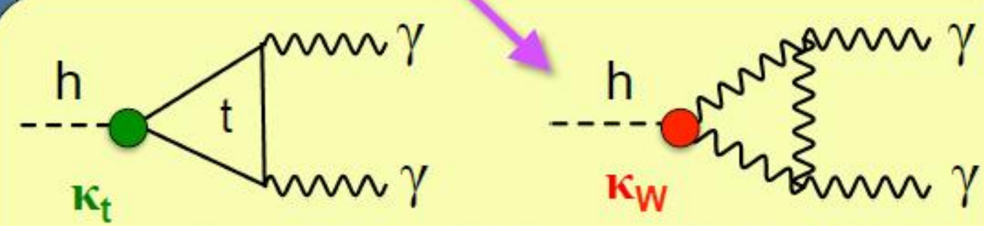




$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v}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



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



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

Higgs boson couplings

- **Simplified framework** (LO –like):
  - Signals originate from single resonance with mass ~125 GeV
  - The width of the assumed Higgs boson is neglected, i.e. zero-width approximation is used

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

  - **Only modifications of coupling strenghts are considered**, the tensor structure is assumed as in the SM i.e. assume that it is „Higgs-like" resonance.
- **Couplings represent pseudo-observables**, i.e. are not measured directly, certain ‚unfolding" procedure required to extract information

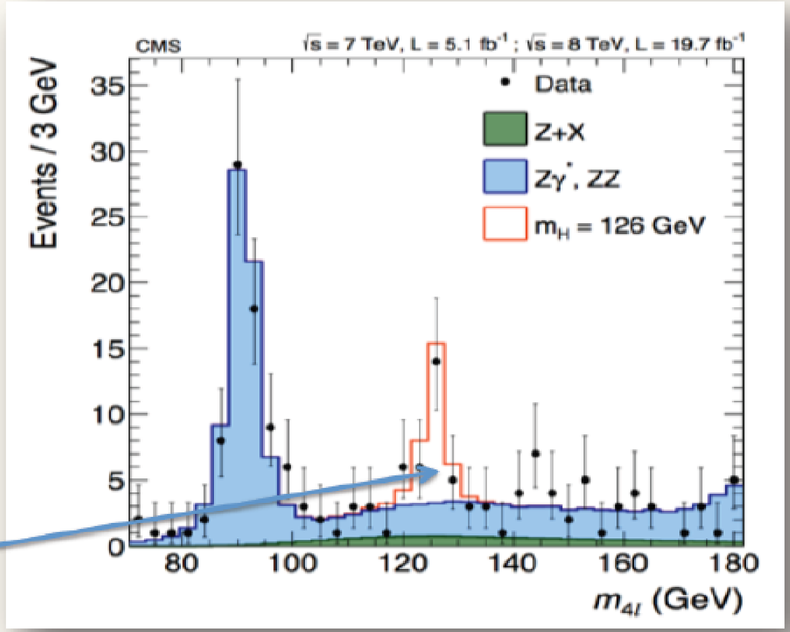
What do we measure?

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



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

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

μ^{ZZ}(@125.5 GeV) = 1.44 $^{+0.40}_{-0.35}$ 6.6σ (4.4 exp) ATLAS

μ^{ZZ}(@125.6 GeV) = 0.93 $^{+0.26+0.13}_{-0.23-0.09}$ 6.8σ (6.7 exp) CMS

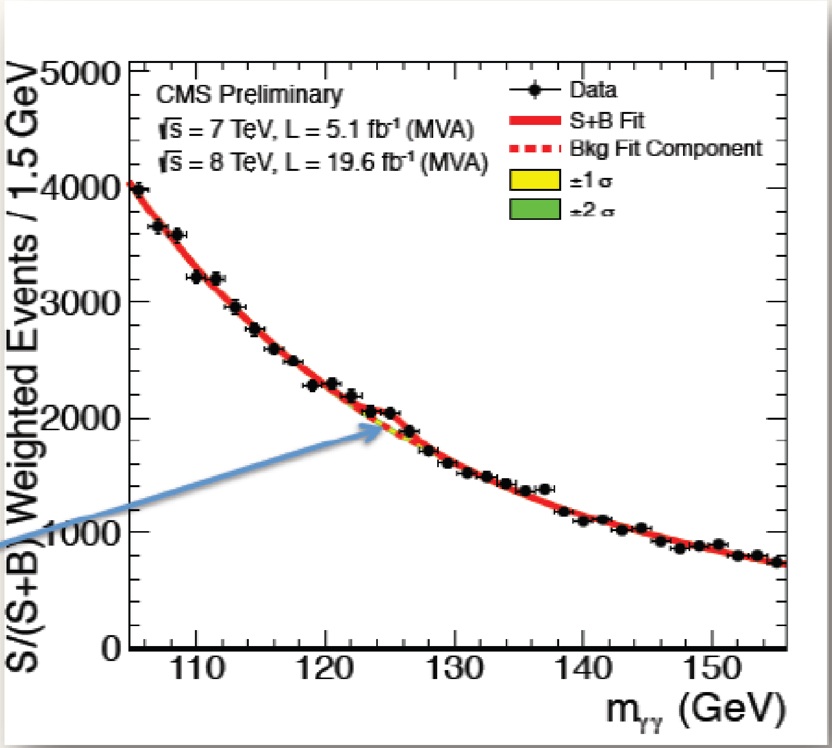
What do we measure?

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



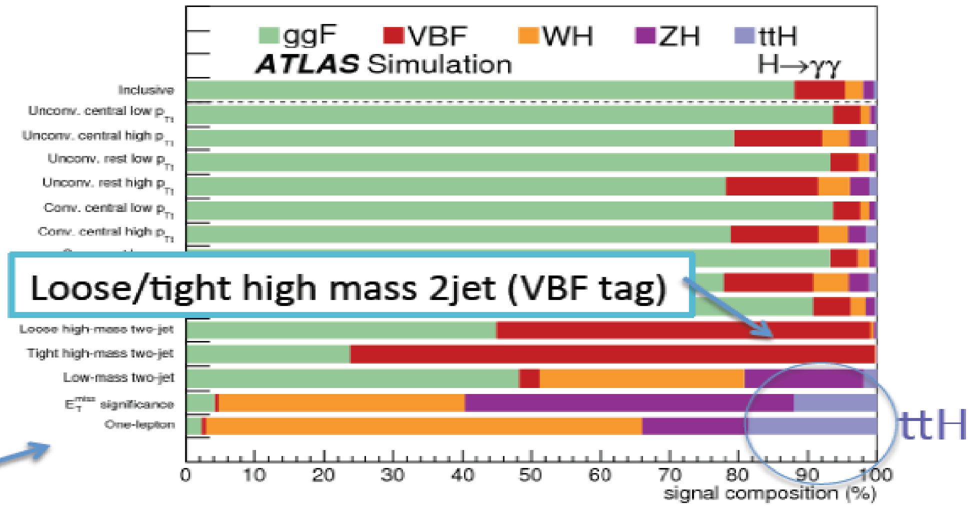
$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

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 sytematic and statistical errors uncertainties into account

Phys. Lett. B 726 (2013), pp. 88-119



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

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

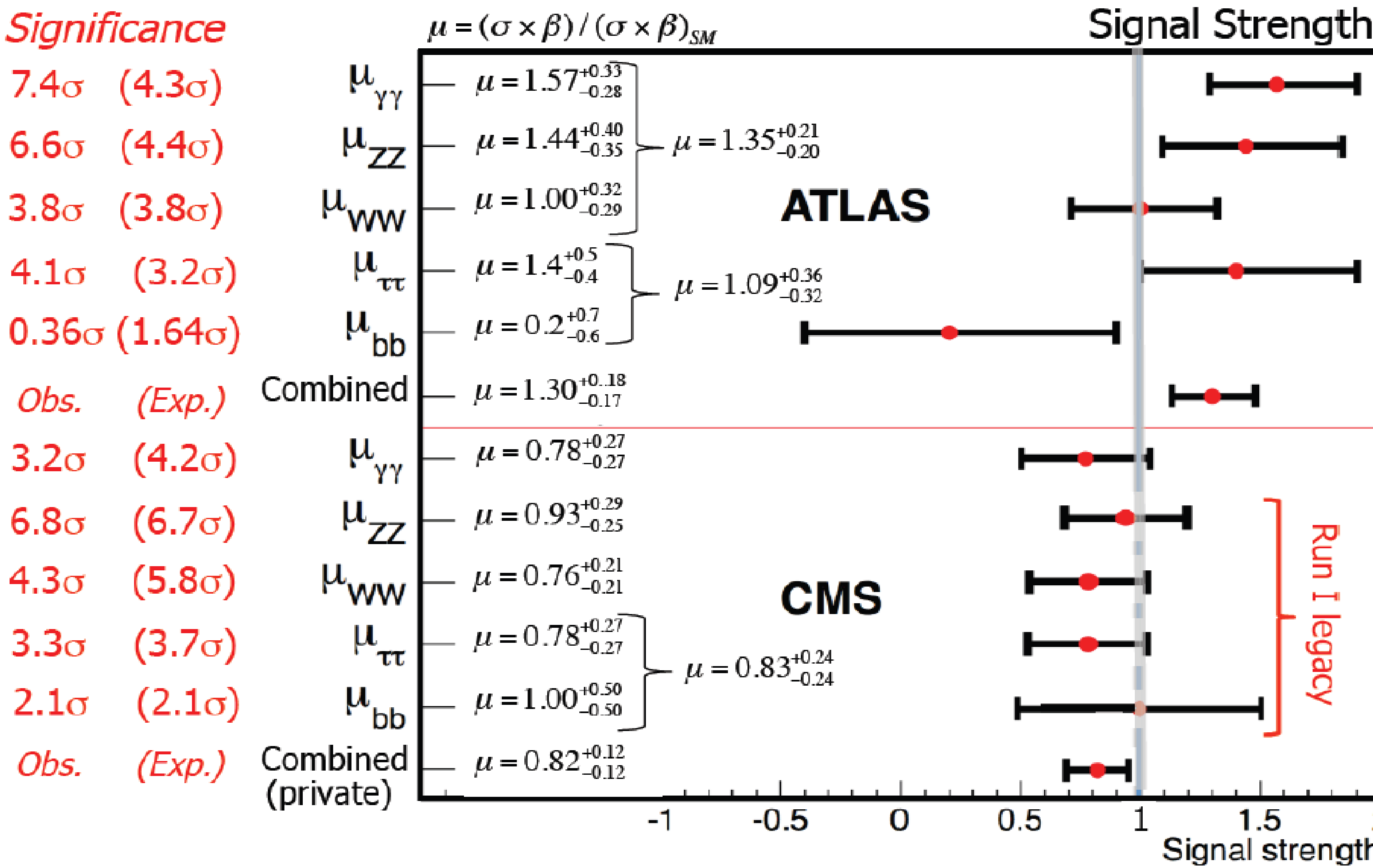
$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

$\mu^{\gamma\gamma}$(@125.5 GeV) = $1.57^{+0.33}_{-0.28}$ **7.4σ (4.3 exp) ATLAS**

$\mu^{\gamma\gamma}$(@125.7 GeV) = $0.77^{+0.29}_{-0.26}$ **3.2σ (3.9 exp) CMS**

27

Higgs boson decay channels



Probe the production mode

We fitted

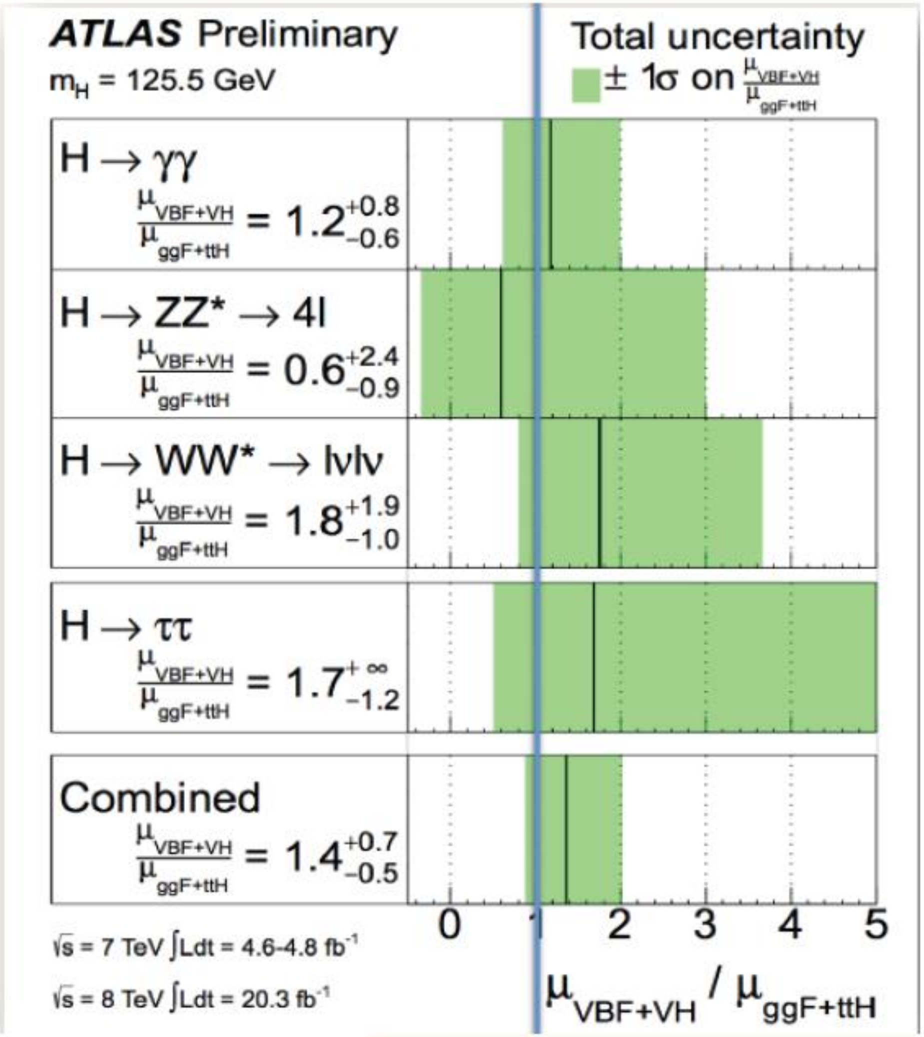
$$\mu^{i}_{VBF+VH} \equiv \left[\mu_{VBF+VH} \times \mu^{i}_{BR}\right]$$

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

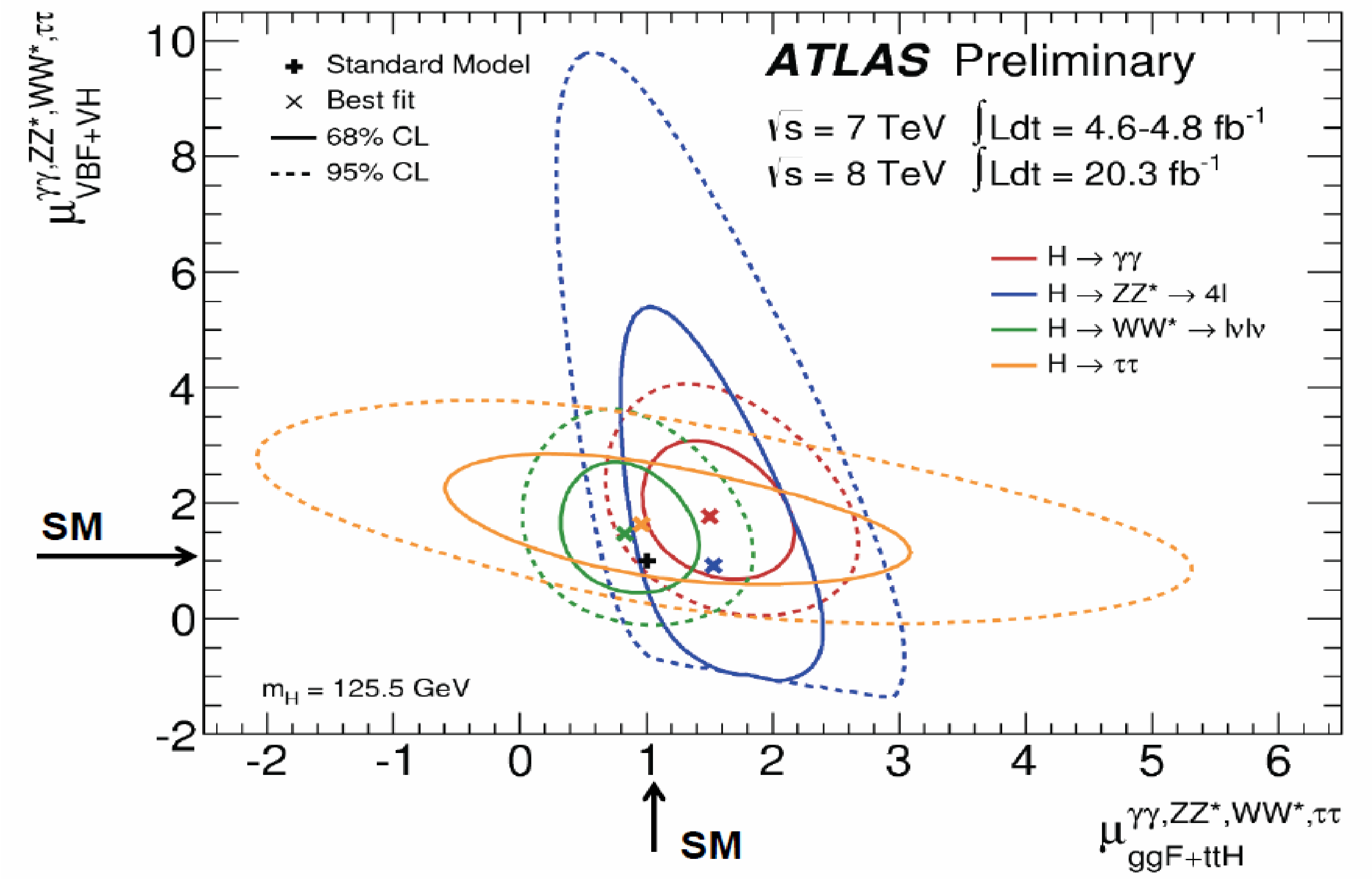
Taking one decay mode at a time we can go one step further and fit the ratio per channel

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

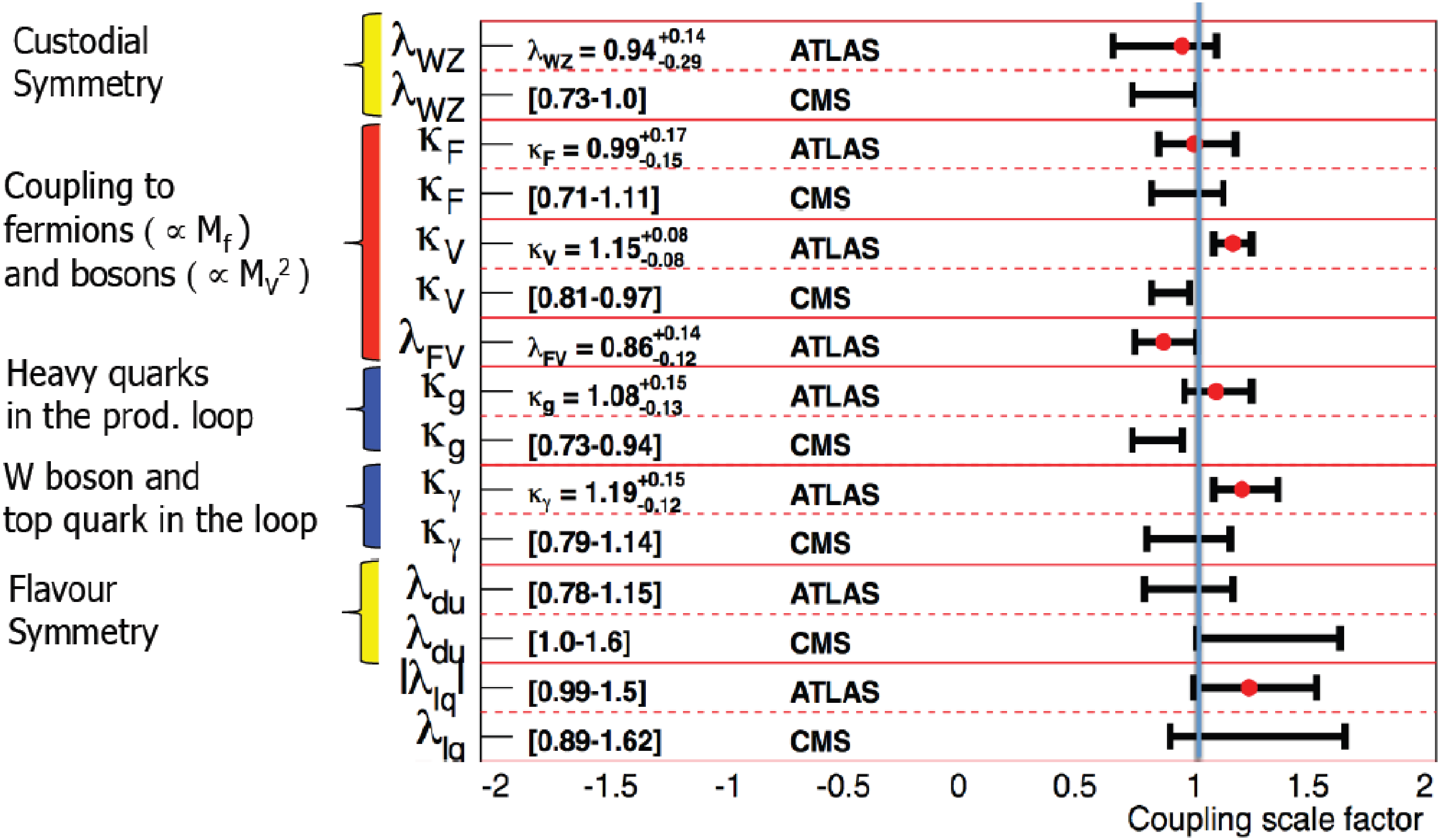
This ratio is INDEPENDENT of the decay channel so we can combine



Probe the production mode

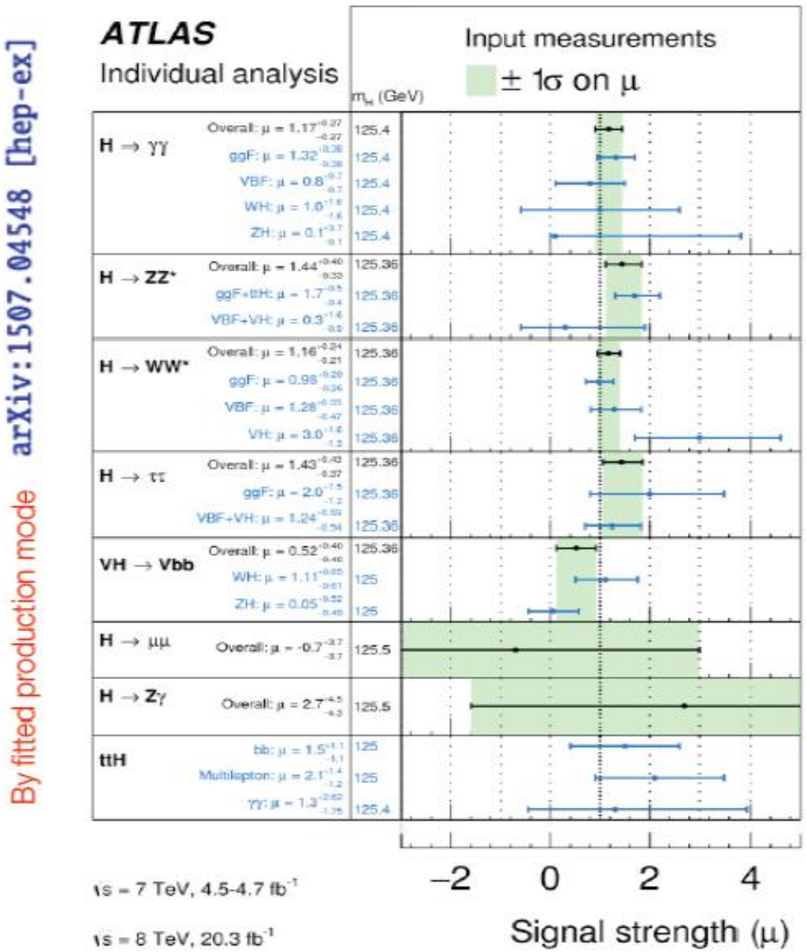


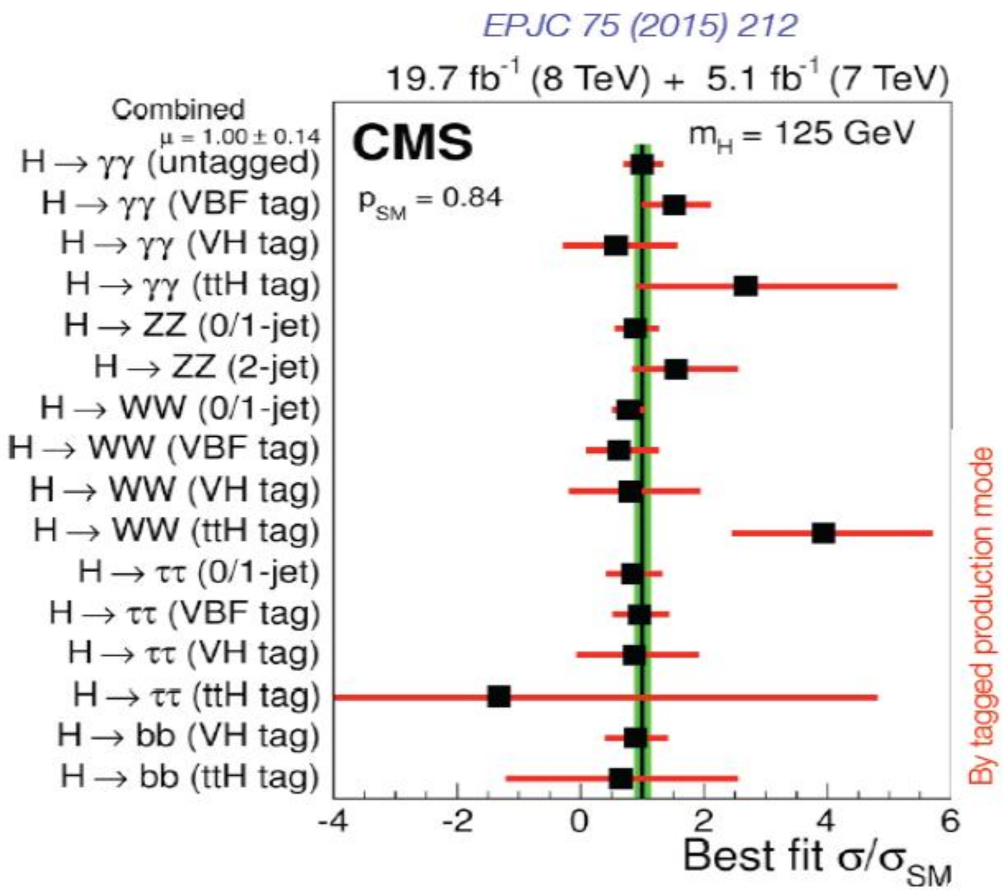
Overall comparison of all couplings results



Combination of two experiments

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





The global signal strength

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

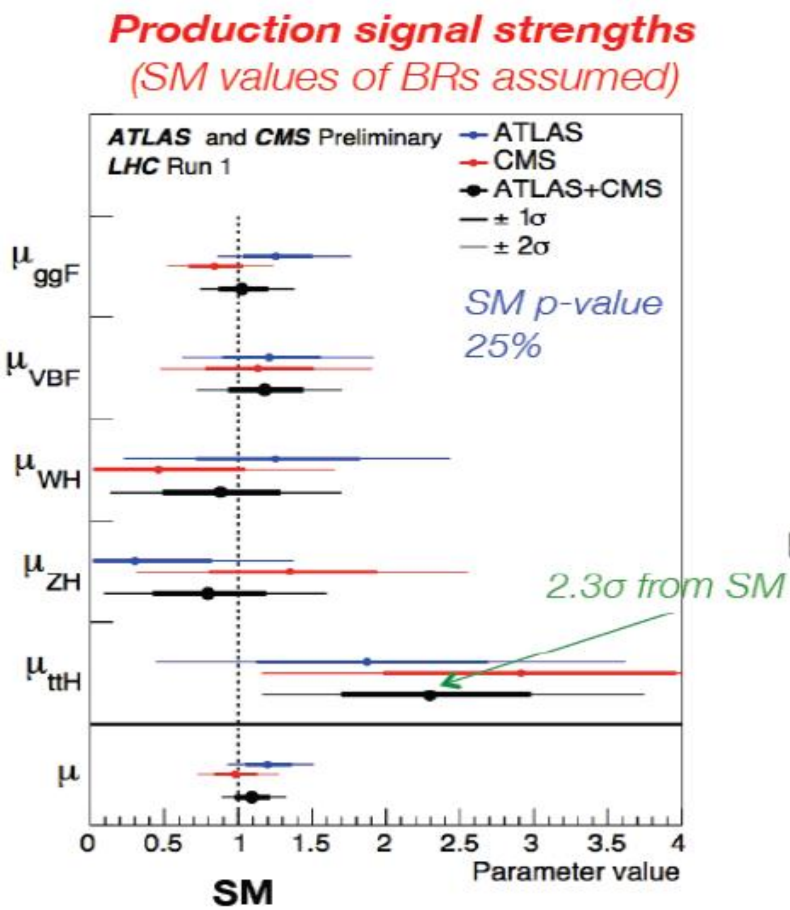
$$\mu = 1.09^{+0.11}_{-0.10}$$

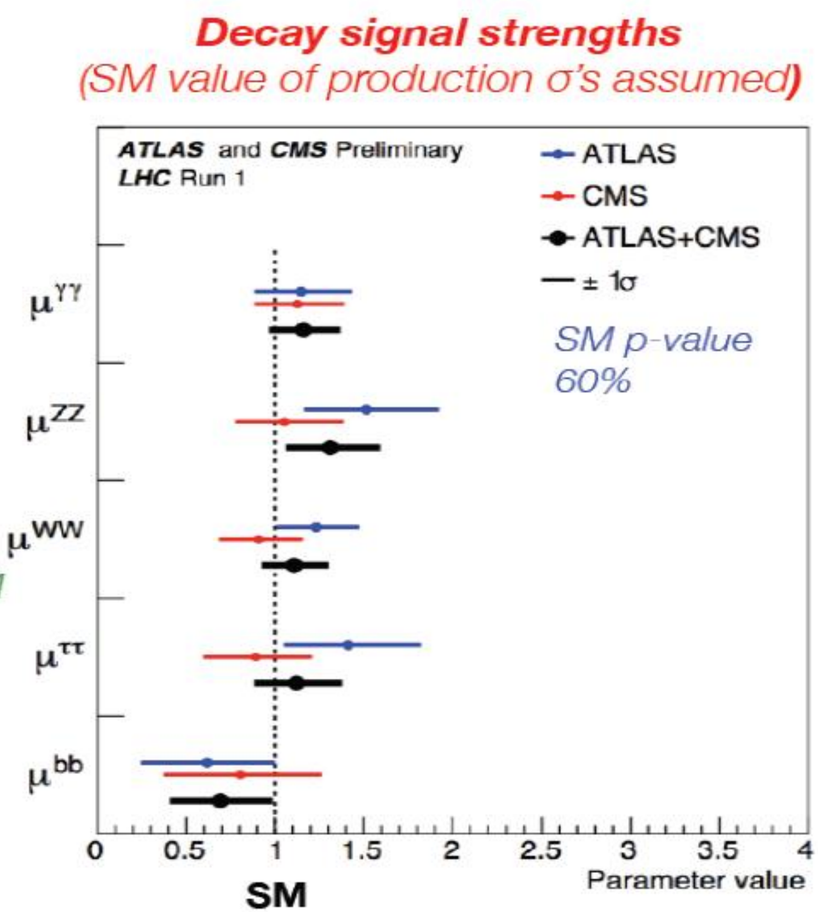
Most precise result at the expense of the largest assumptions

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

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

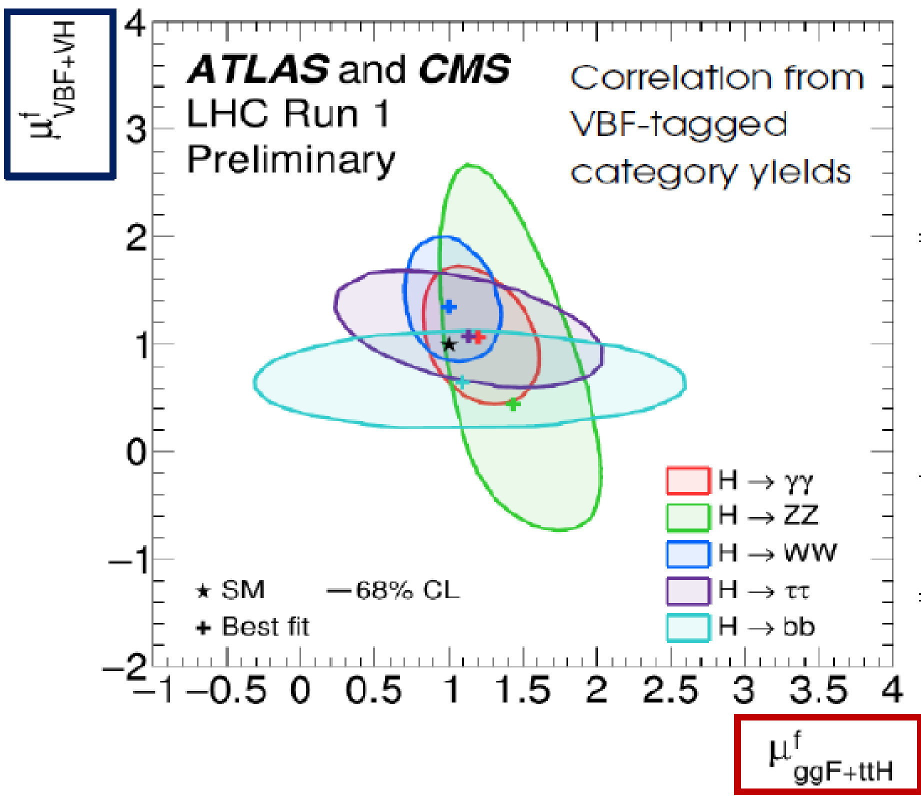
Signal strength by production and decay mode





Signal strength in V, F mediated

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



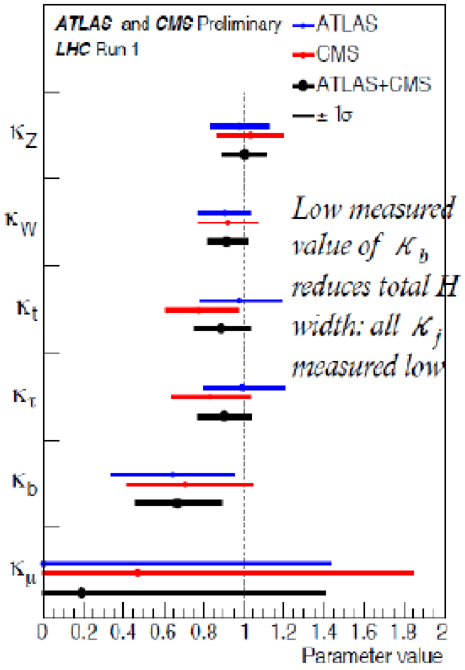
$$\mu_V / \mu_F = 1.06^{+0.35}_{-0.27}$$

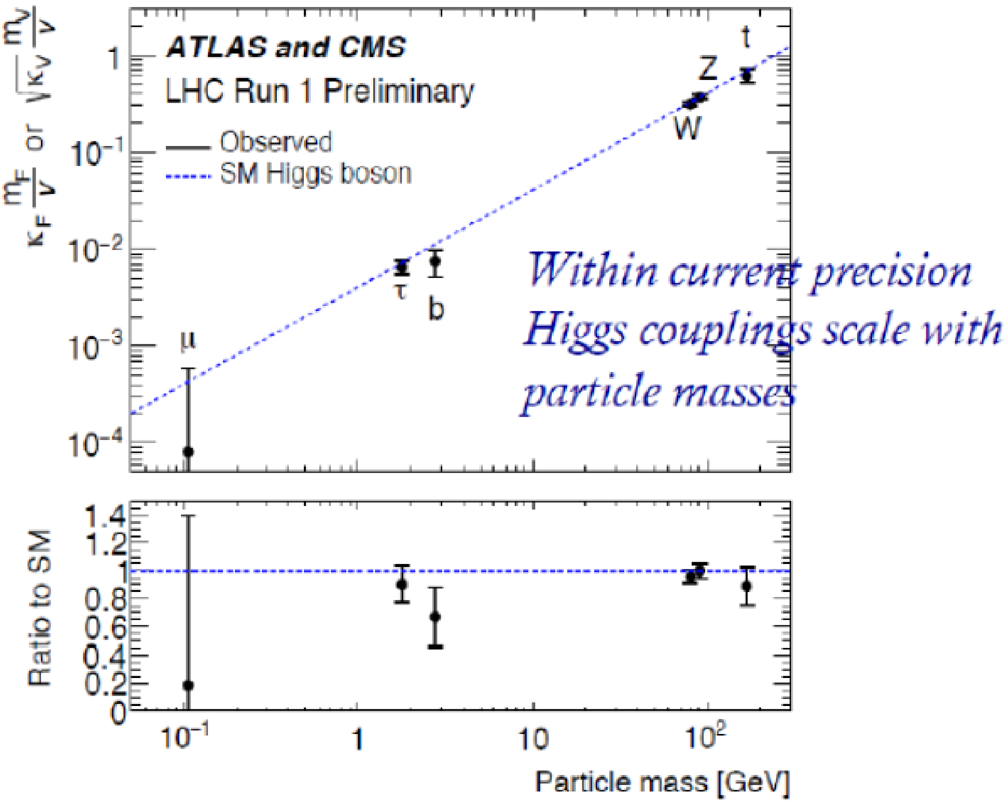
Production process	Measured significance (σ)
VBF	5.4
WH	2.4
ZH	2.3
VH	3.5
ttH	4.4
Decay channel	
$H \rightarrow \tau\tau$	5.5
$H \rightarrow b\bar{b}$	2.6

New!

Constrains 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





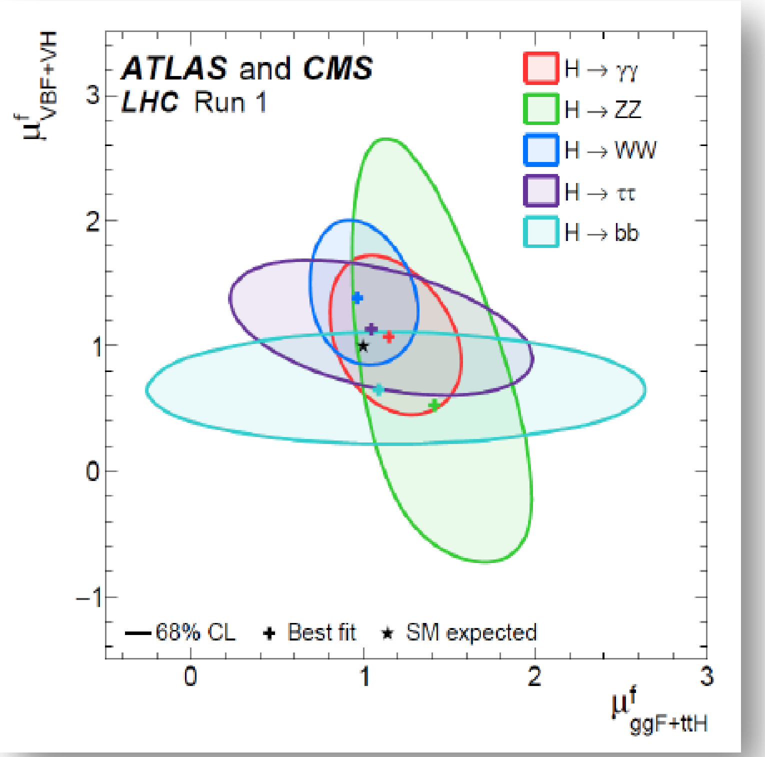
Concluding Higgs couplings measurements

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**

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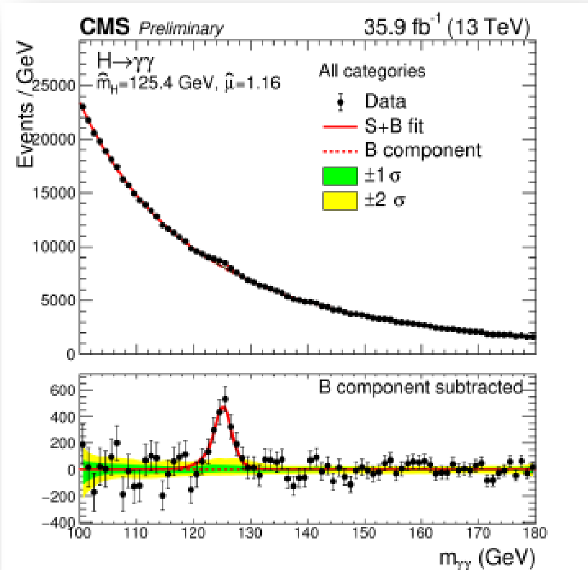
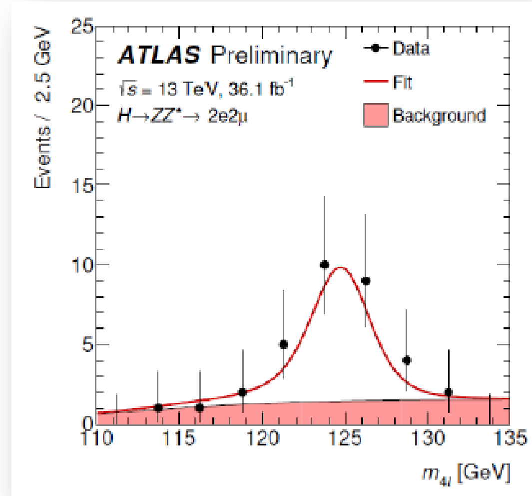
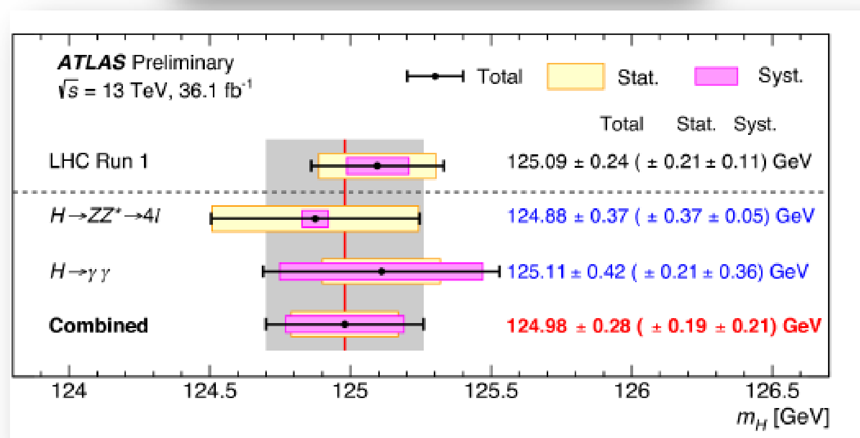
Run II : Higgs boson mass



CMS-PAS-HIG-16-040





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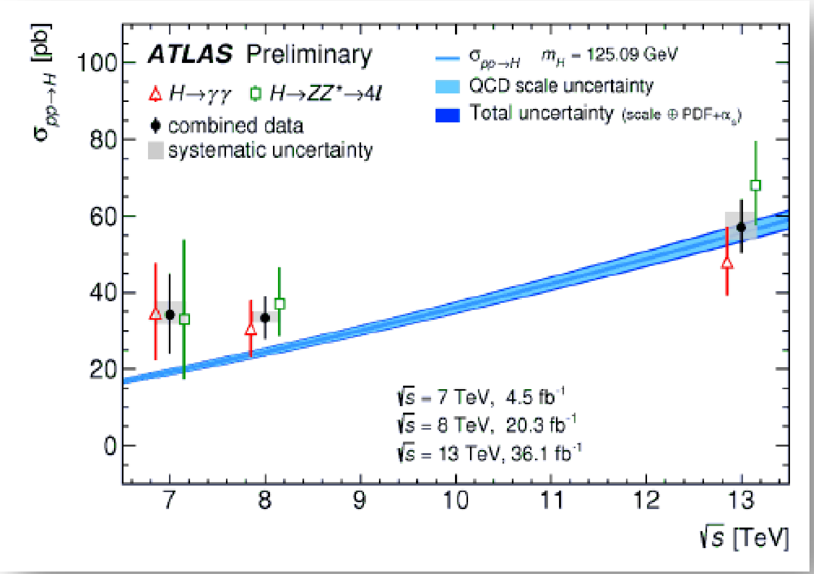
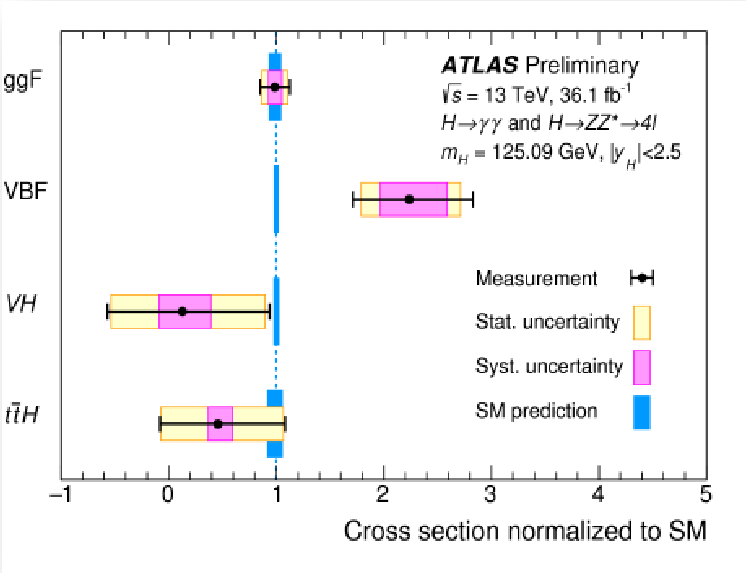
- **LHC Run1: 125.09±0.24 GeV**
- **CMS Run2: 125.26±0.21 GeV**
- **ATLAS Run2: 124.98±0.28 GeV**

Run II : Higgs cross-section

ATLAS-CONF-2017-047



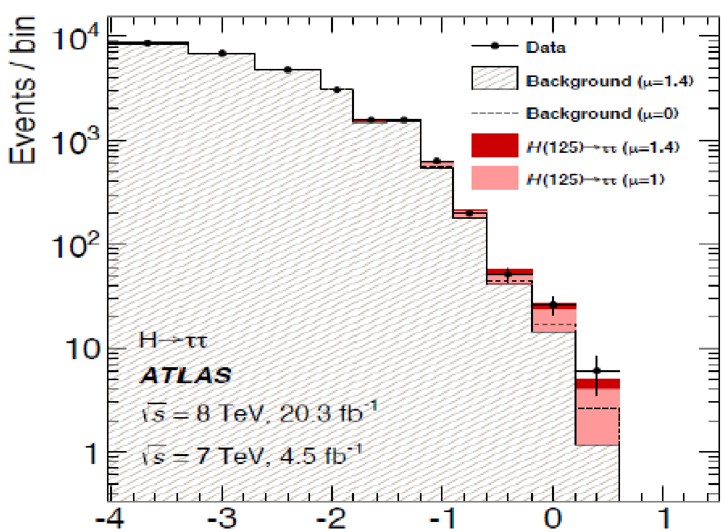


- **Combined total and by production mechanism cross section**
- **Total pp→H+X cross sections compared to SM predictions up to N3LO QCD**
- **Overall good agreement except for VBF**

Run II : Higgs boson couplings to fermions

Observation of coupling to τ-leptons

- 5.5σ observation of H→ττ from combination of ATLAS and CMS Run-I results
- 5.9σ observation from CMS from combination of 7, 8 and 13 TeV results
- Most sensitive decay channel for VBF production



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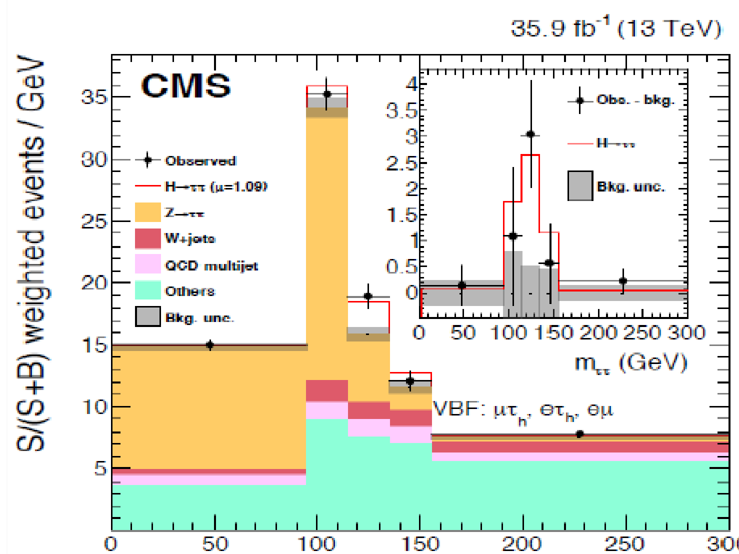
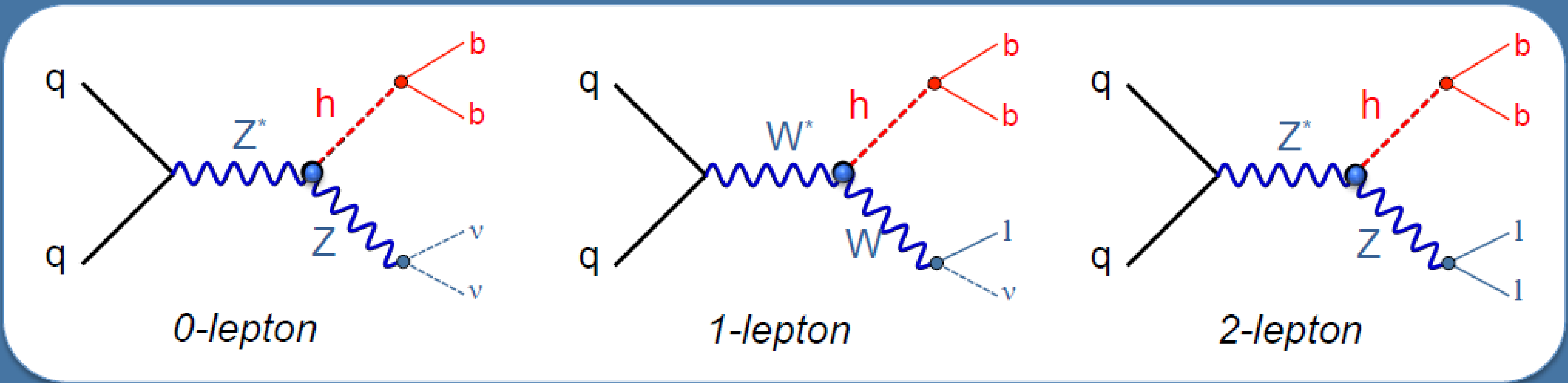


Submitted to PLB

Higgs decay to b-quarks

Br(h→bb) = 0.577

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

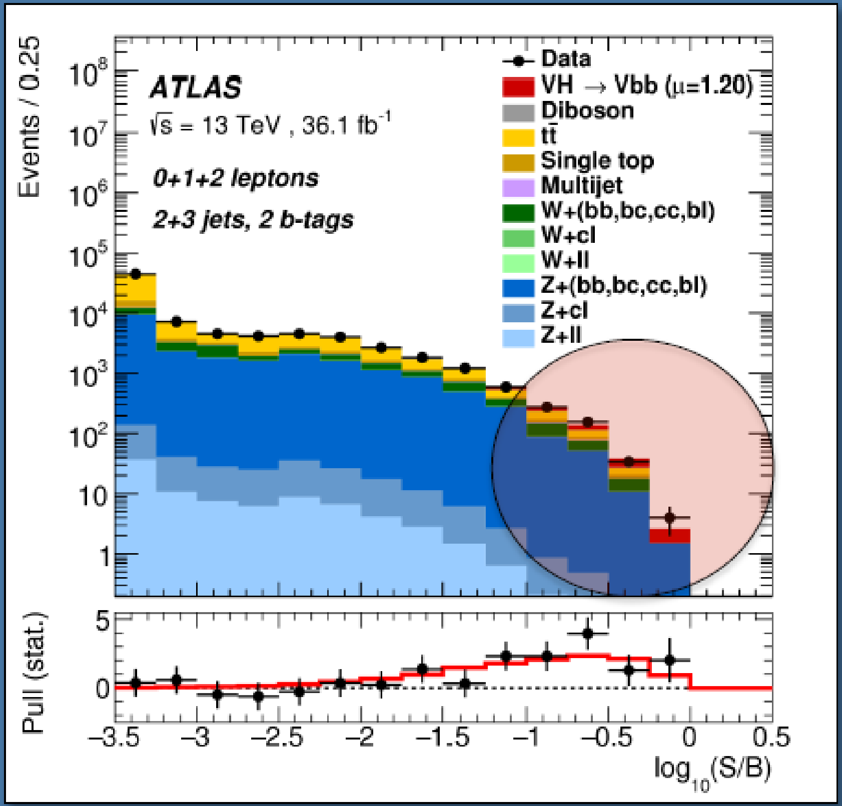


- Categories: jet multiplicity & transverse momentum vector boson (dedicated boosted decision tree for each category)

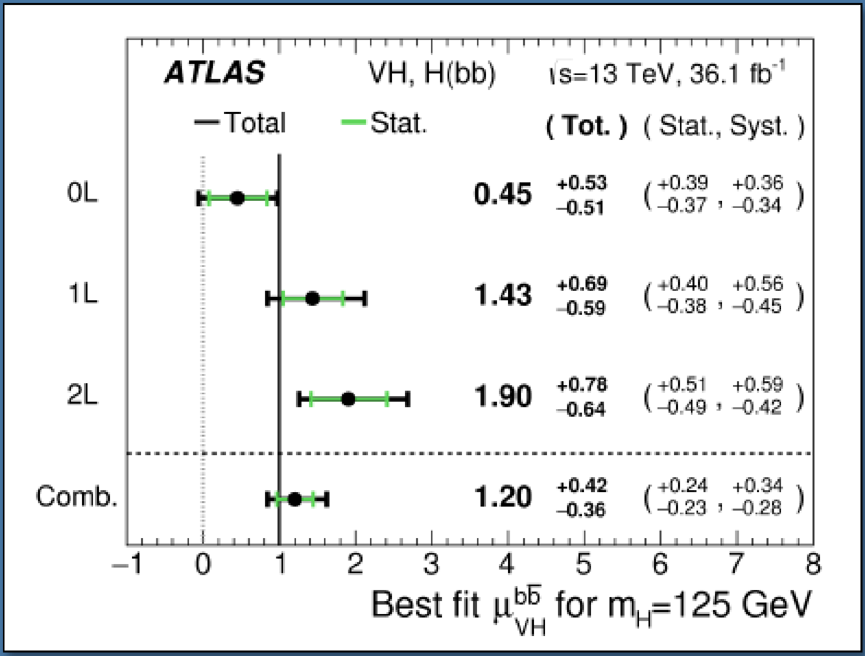
- Validation using VV channels ($\sigma_{VV(bb)} \sim 9x\sigma_{VH(bb)}$)

h→bb: analysis for √s=13 TeV

Combined BDT(S/B) ranking



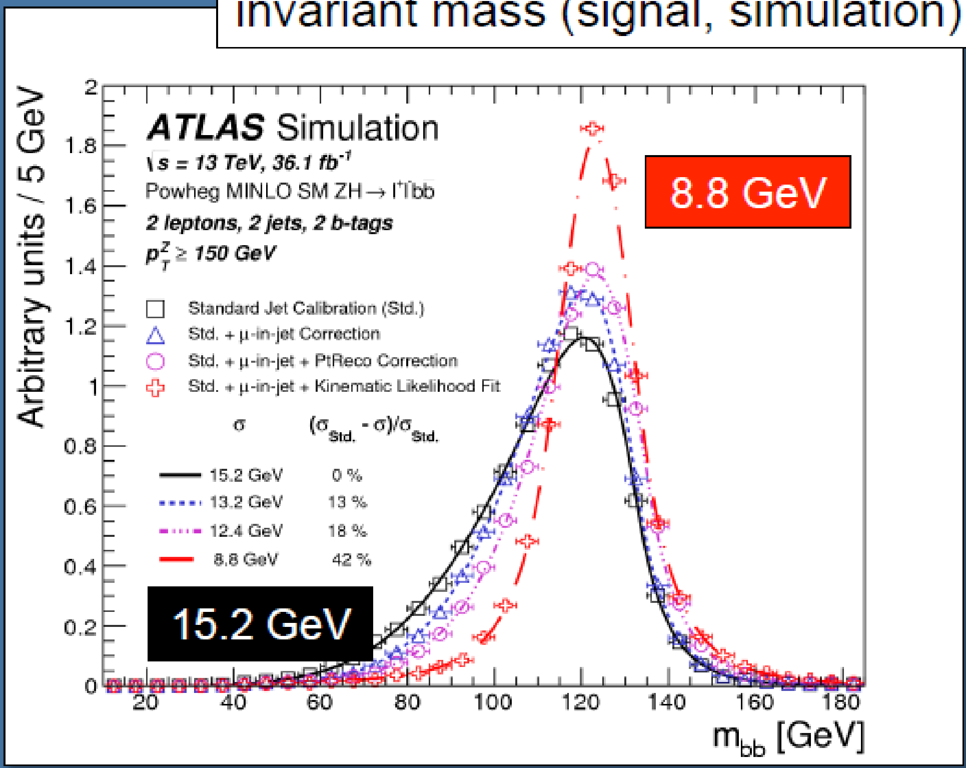
Production rates topology: 0l, 1l, 2l



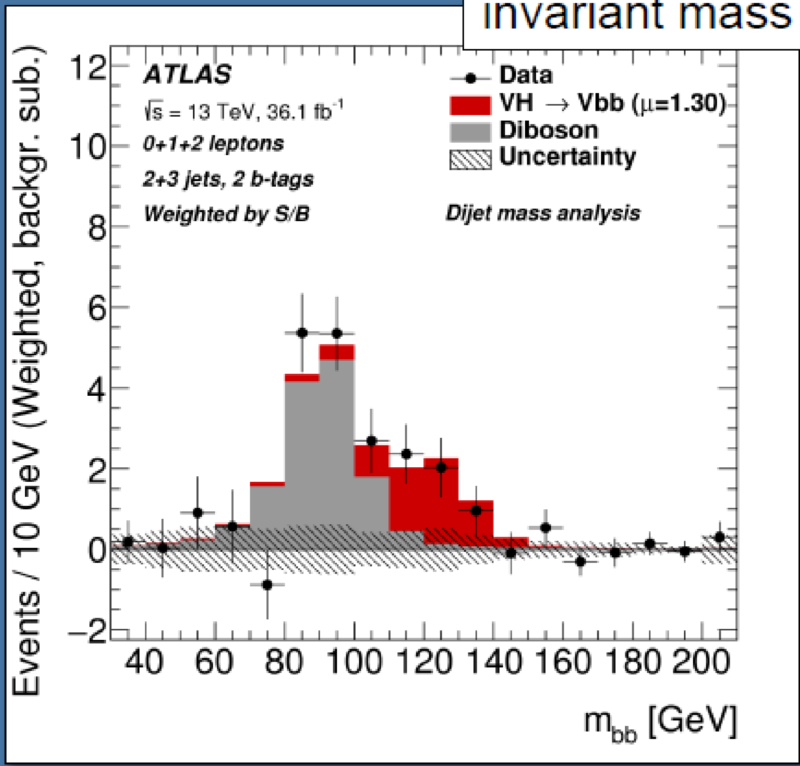
$$\mu = 1.20^{+0.24}_{-0.23}(stat.)^{+0.34}_{-0.28}(syst.)$$

H→bb: invariant mass distribution

invariant mass (signal, simulation)

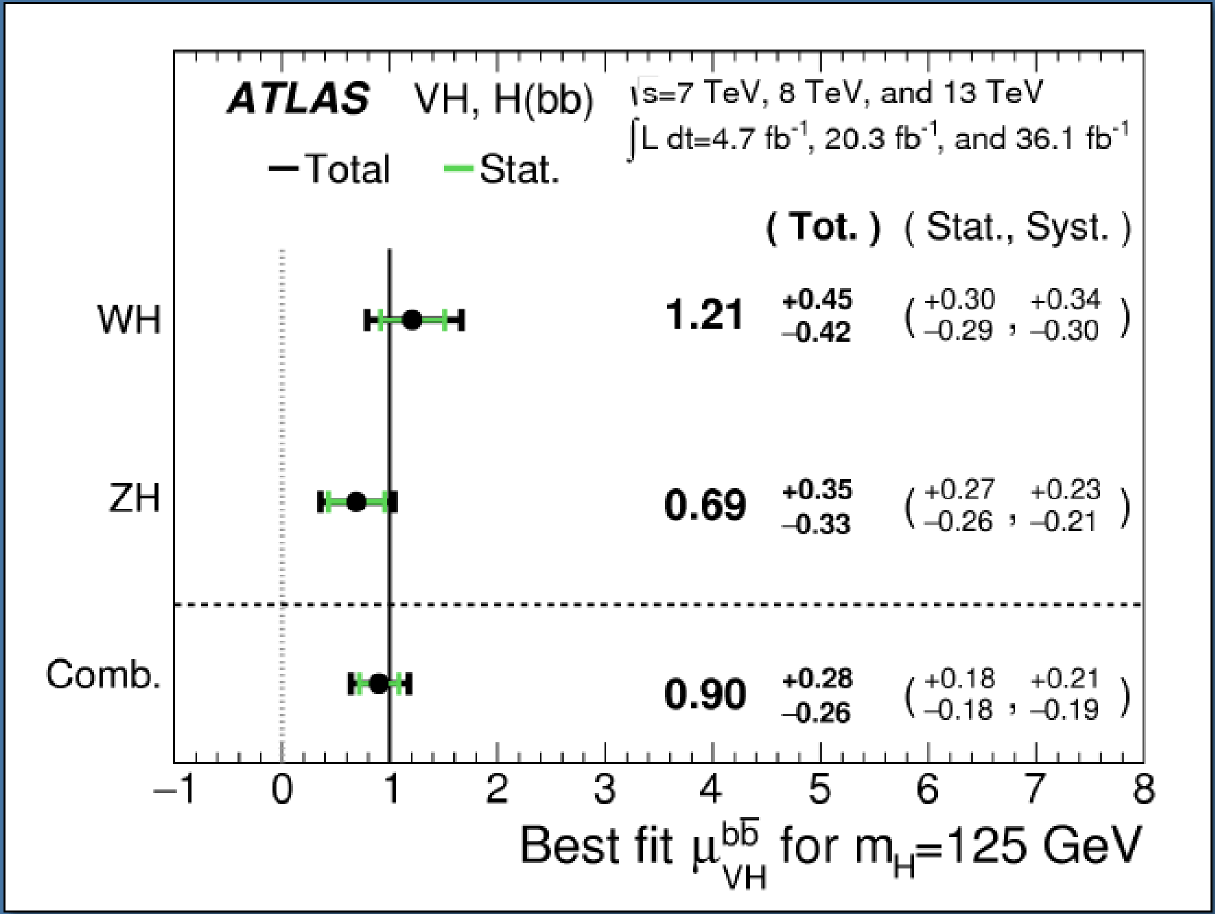


invariant mass



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

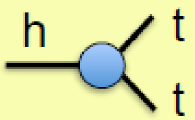
H→bb: RUN1 & RUN2 combination



3.6 sigma excess ←

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

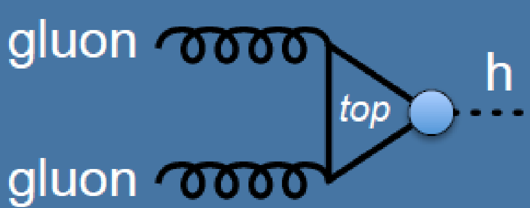
Top Yukawa coupling



Top-Yukawa

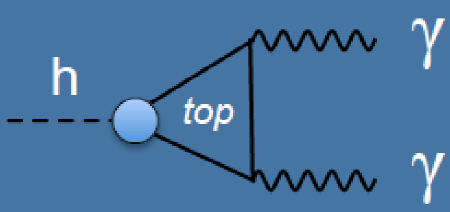
$$\lambda_t = \frac{m_t\sqrt{2}}{V} = 0.996$$

INDIRECT

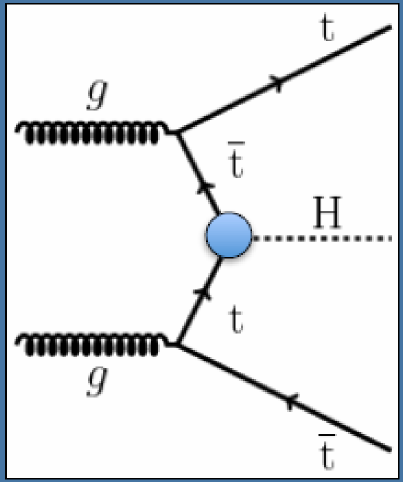


Production:
gluon fusion

Decay:
gluon fusion



DIRECT



b-jet + qq/lν

- bb
- 4l
- γγ

b-jet + qq/lν

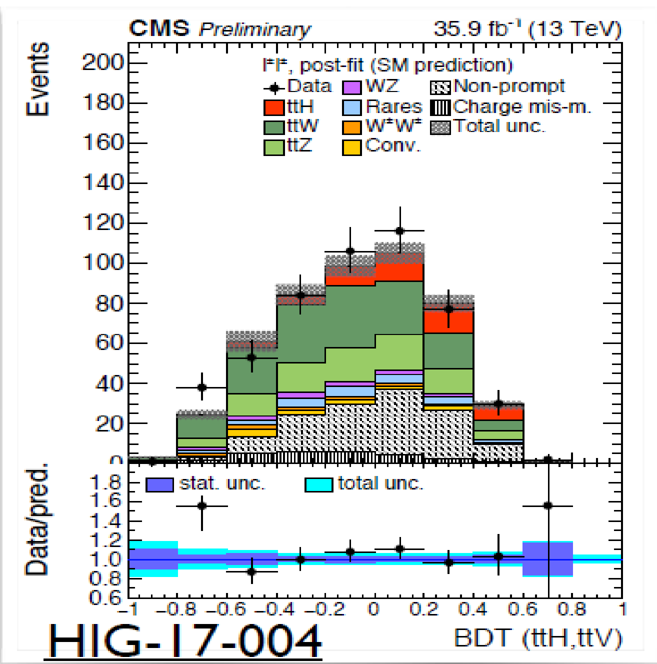
- 1% of gluon-fusion process
- (many) complex final states
  … very very difficult

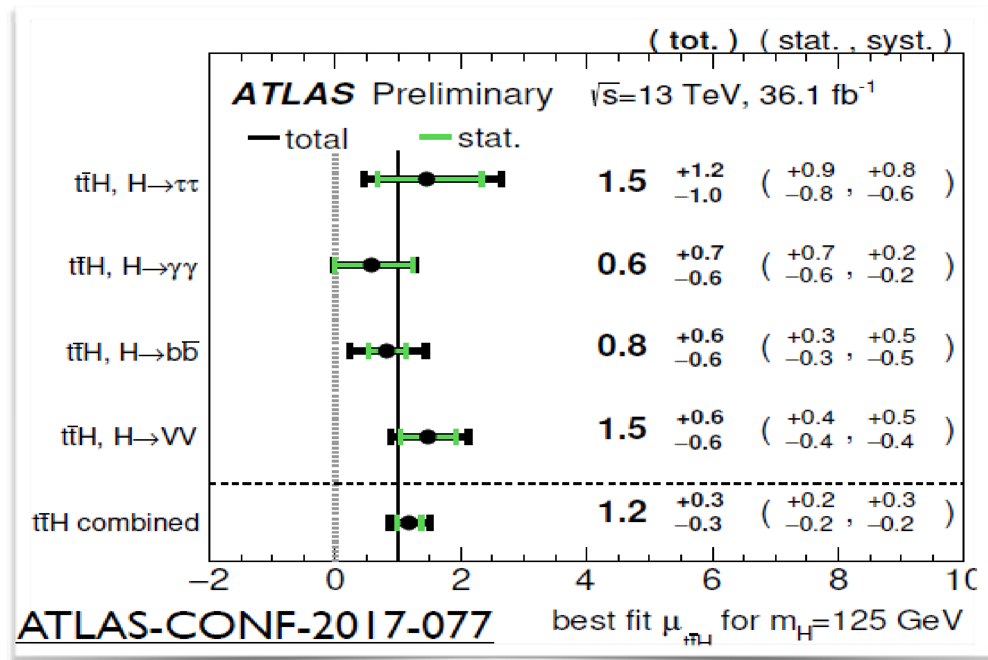
RUN1 ATLAS: $\mu = 1.9 \pm 0.8$

Higgs boson couplings to top quarks

Direct evidence for coupling to top quarks

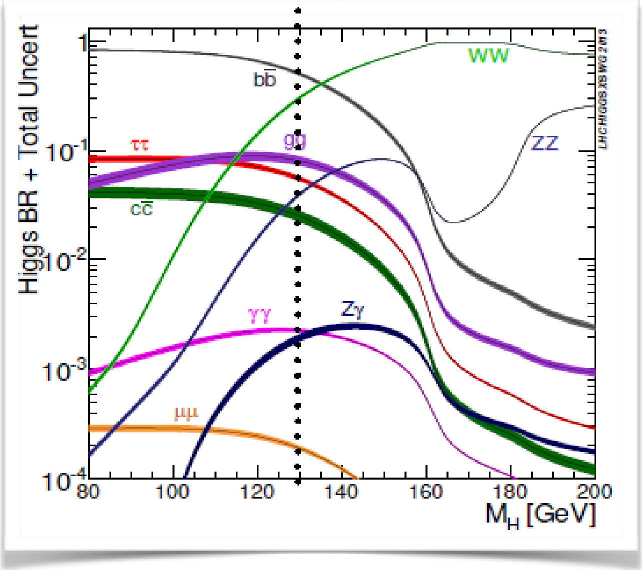
- ttH production provides a probe of the direct coupling of the Higgs boson to top quarks
- 3.3σ evidence for ttH production from CMS using leptonic final states
- 4.2σ evidence from ATLAS from combination of five major decay modes

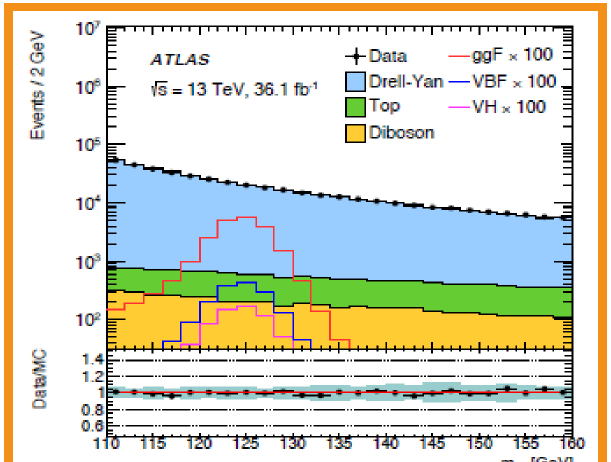




Probing rare Higgs decays

- Exploit growing LHC dataset to explore further decay channels
  - $H\to\mu\mu$: 2.8 x SM
  - $H\to Z\gamma$: 6.6 x SM
  - $H\to cc$:
    - 110 x SM (ZH(cc))
    - 200 x SM ($J/\psi\gamma$)
  - $H\to\varphi\gamma$: 200 x SM
  - $H\to\rho\gamma$: 50 x SM





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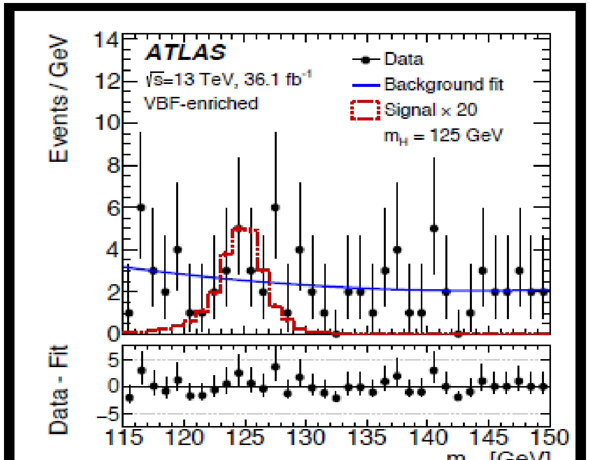

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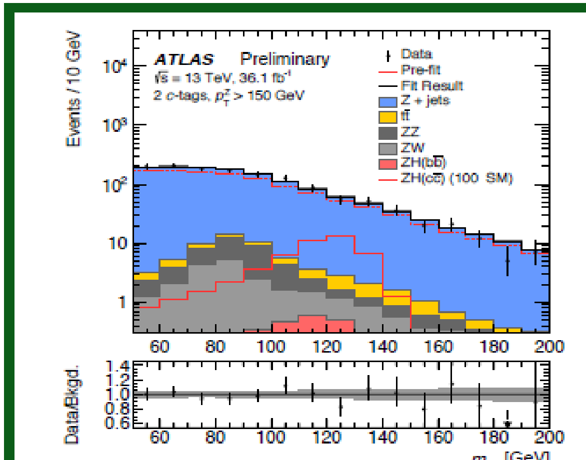

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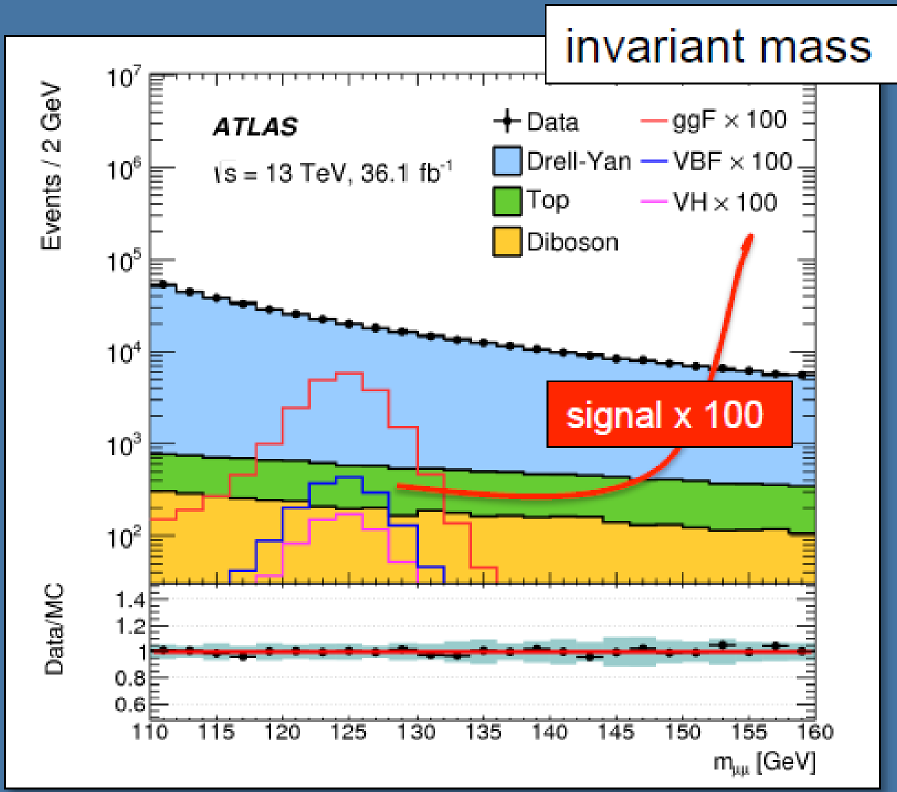
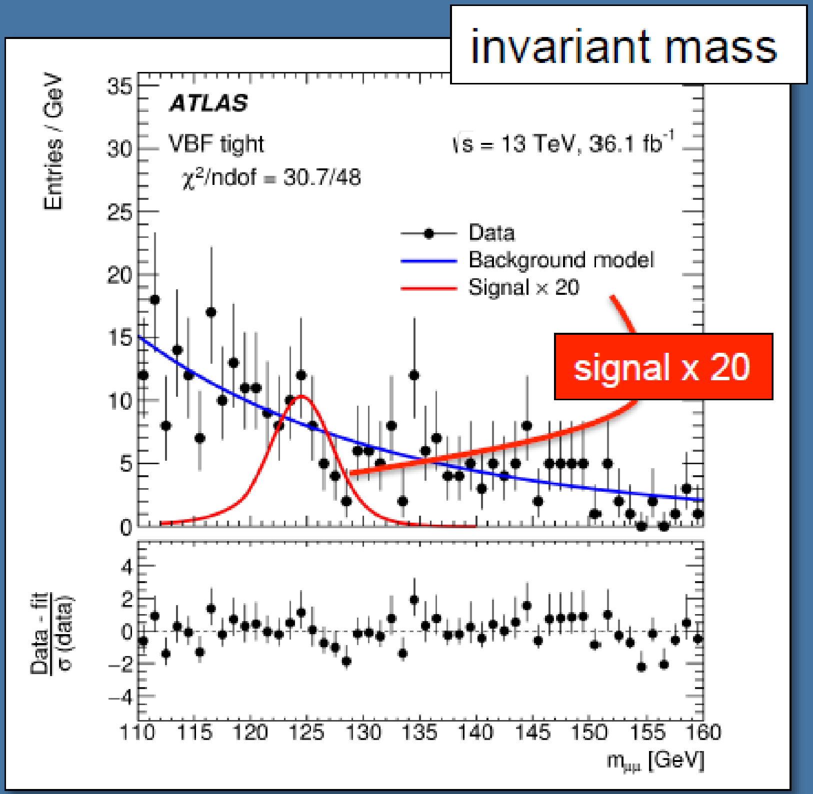
Higgs decay to a muon pair

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

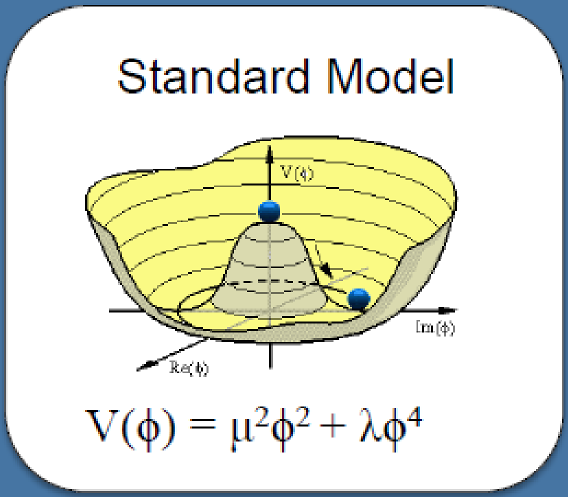


inclusive selection → 8 categories

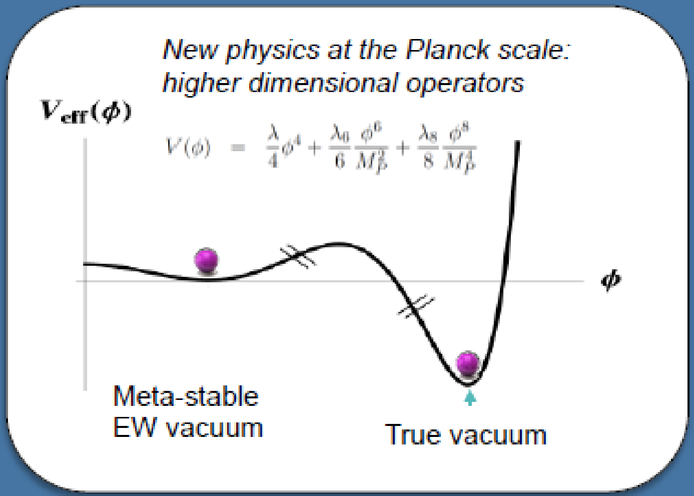


VBF-tight selection

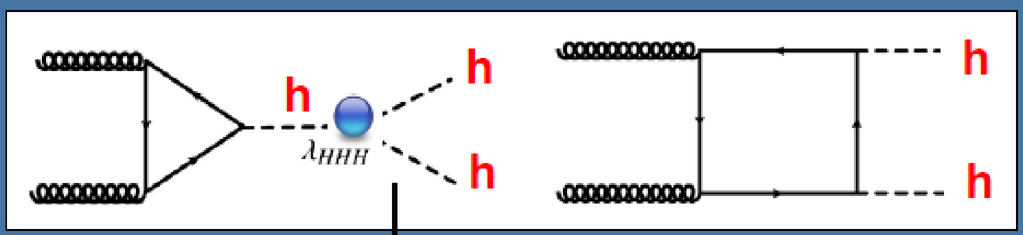
observed limit (RUN1 + RUN2): $\mu < 2.8$



Higgs potential

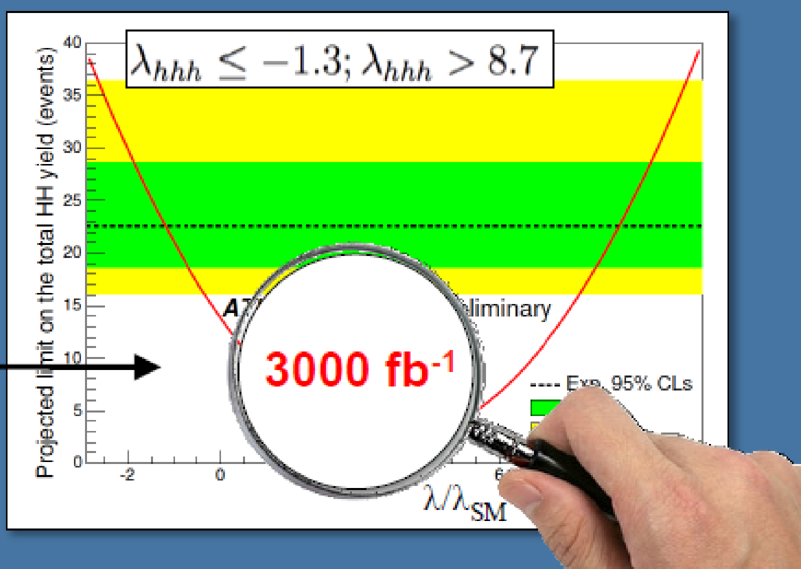


Higgs self-interaction *di-Higgs production*



Negative interference

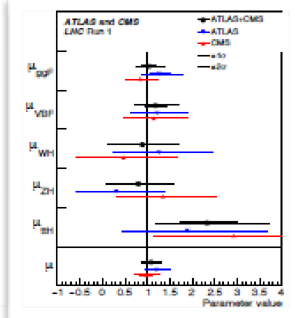
bbγγ cross-section



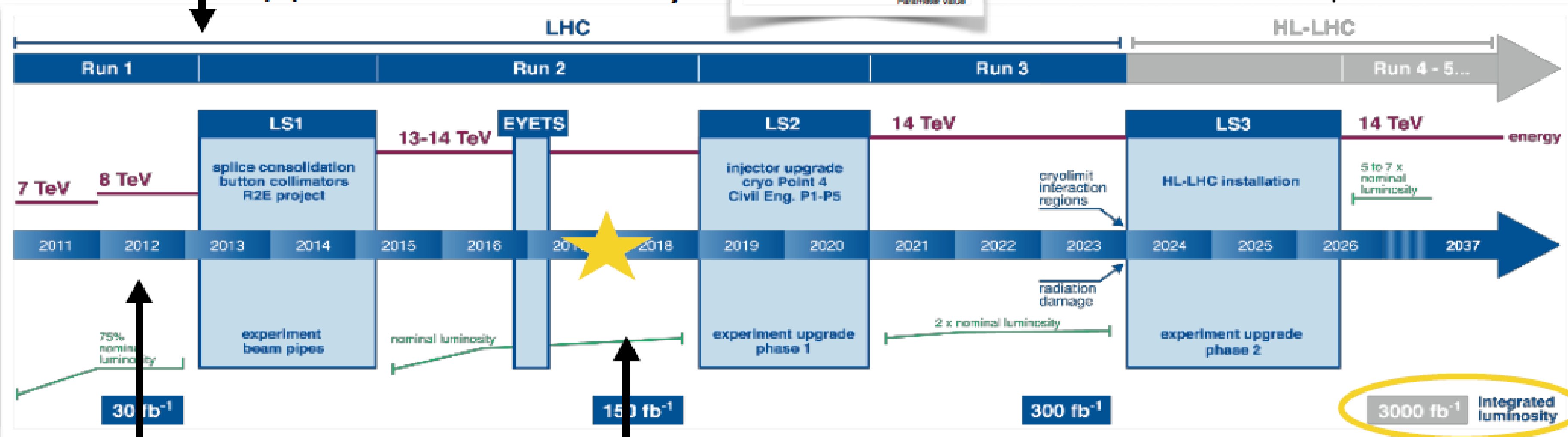
Evolution of Higgs potential in early universe has consequences for baryogenesis

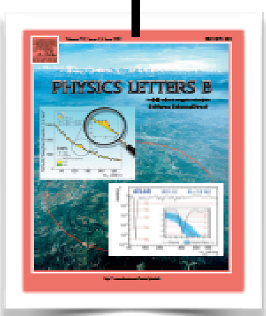
Overwiew of the LHC Higgs program

- ggF, VBF production
- mass
- spin/parity,
- γγ, ZZ, WW, ττ decays



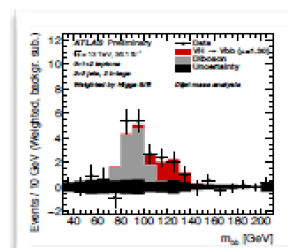
- HH & self-coupling
- ?





Higgs discovery

- VH, ttH production
- bb decay
- rare decays



BSM: additional Higgs bosons, non-SM decays

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