Elementary Particle Physics: theory and experiments

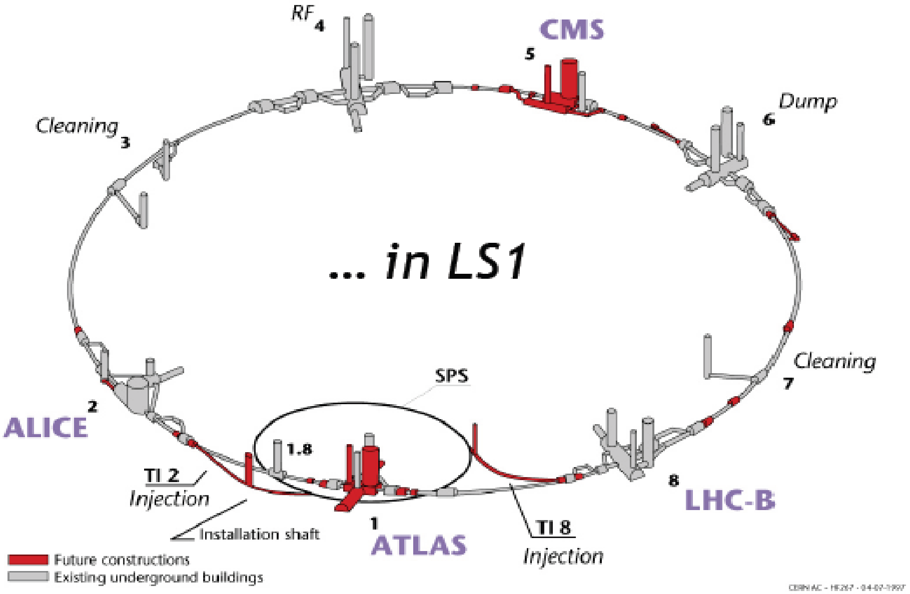
Discovery of the Higgs boson

Properties measurements

Prof. dr hab. Elżbieta Richter-Wąs

Three years of LHC operations

Energy frontier



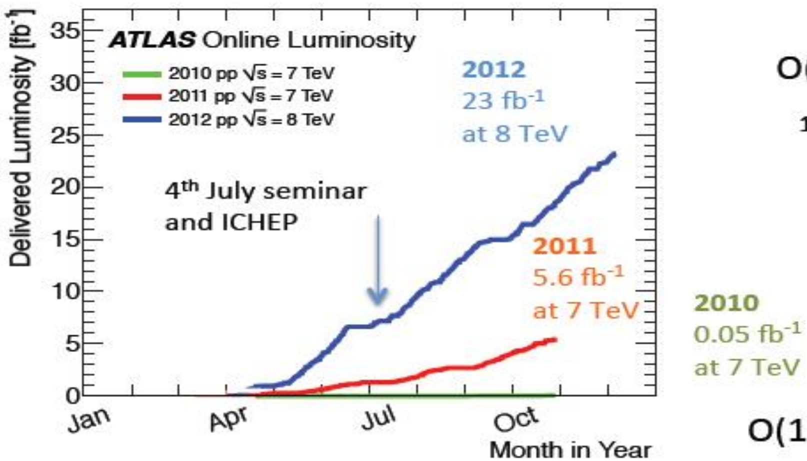
The LHC

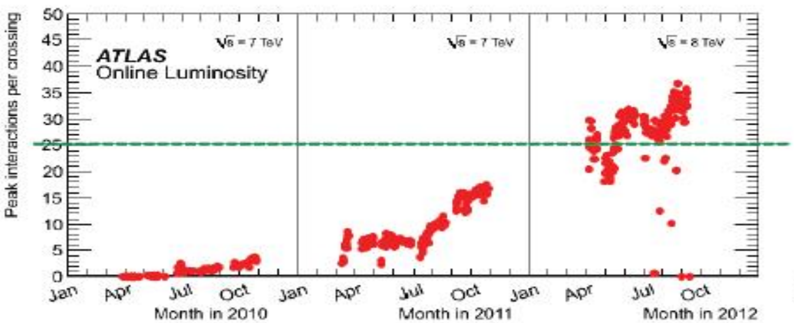
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

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

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 ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	$\sim 7x10^{33}$	10^{34}

The first LHC run



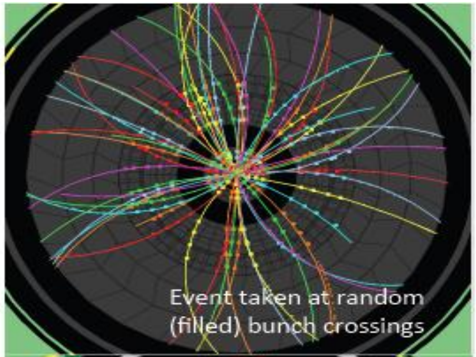


Design value
(expected to be
reached at L=10^{34} !)

2010

O(2) Pile-up events

150 ns inter-bunch spacing



2011

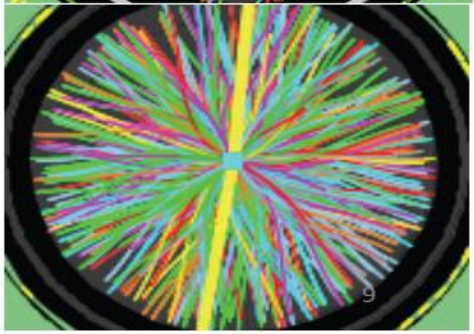
O(10) Pile-up events

50 ns inter-bunch spacing

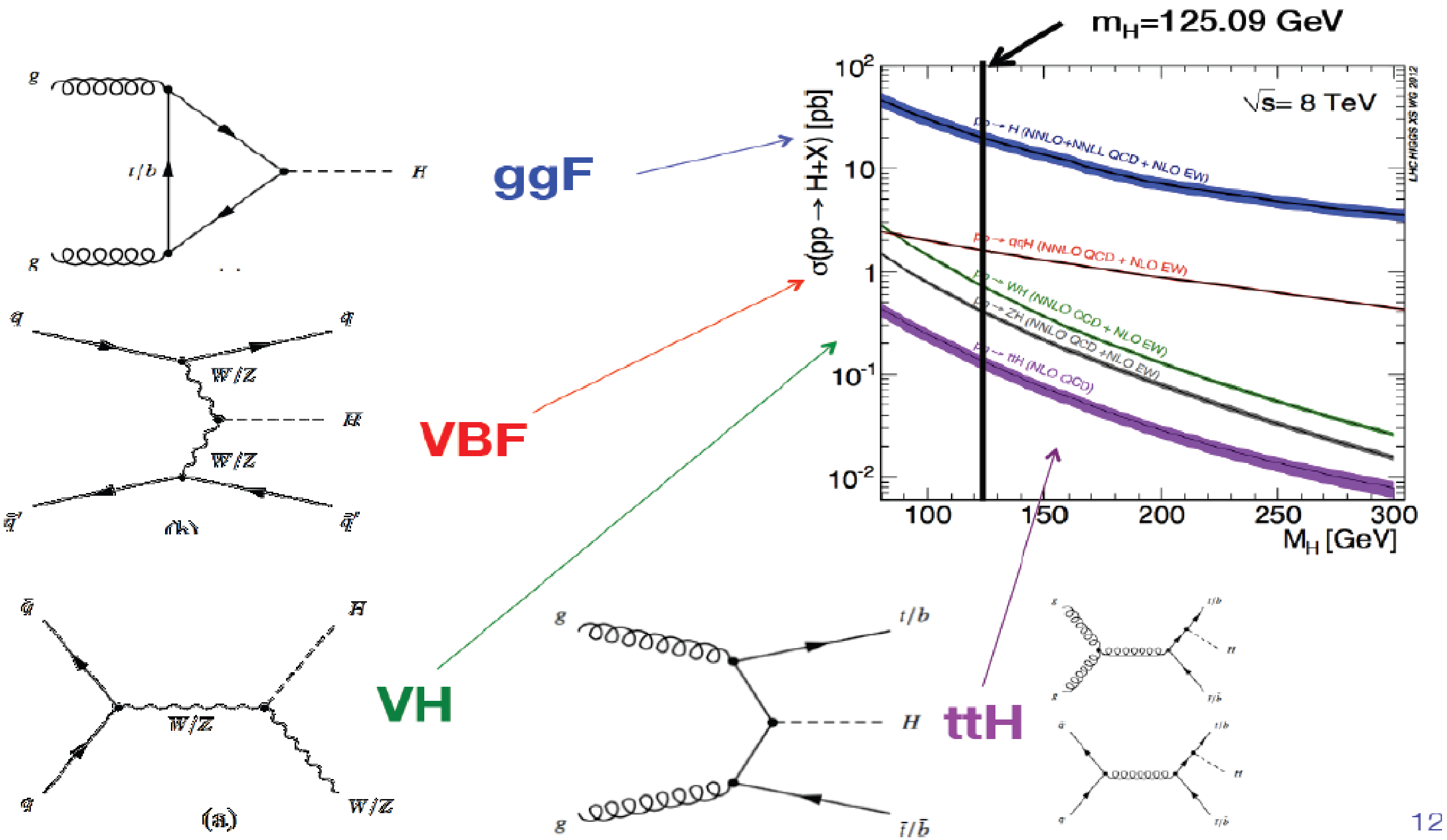
2012

O(20) Pile-up events

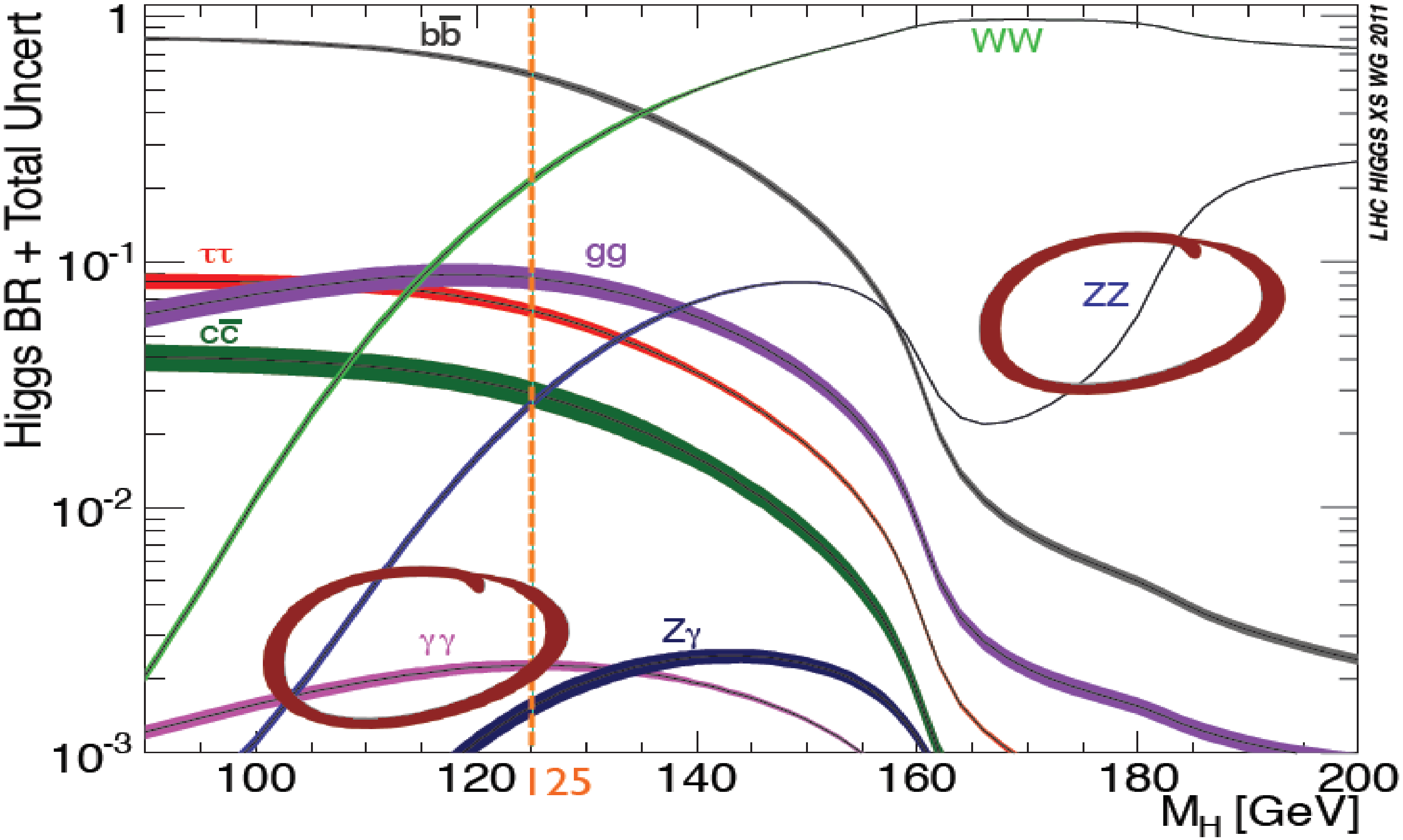
50 ns inter-bunch spacing



SM Higgs production at the LHC



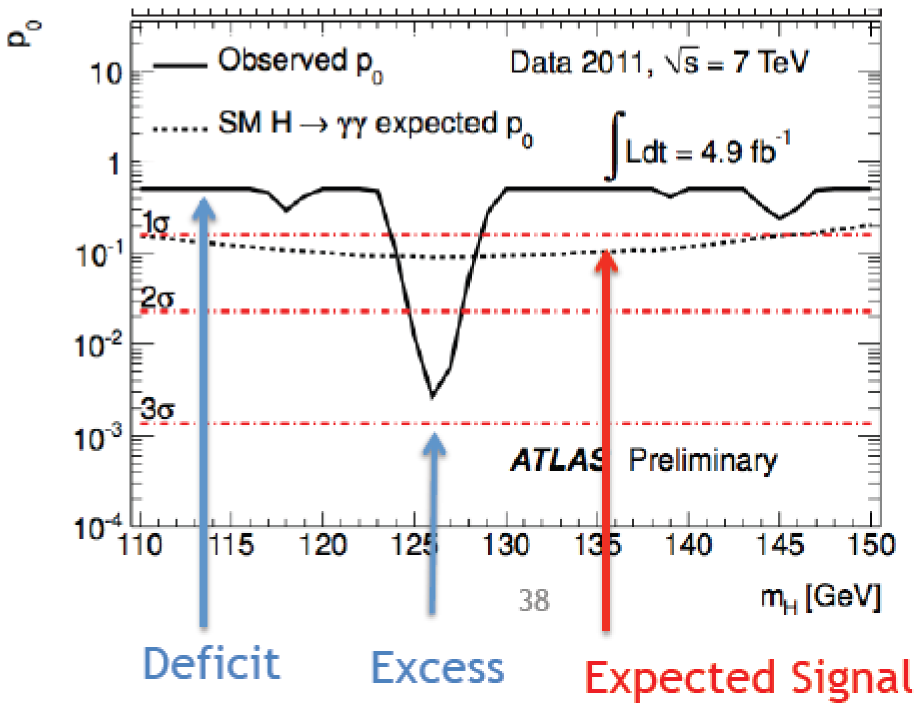
SM Higgs decays



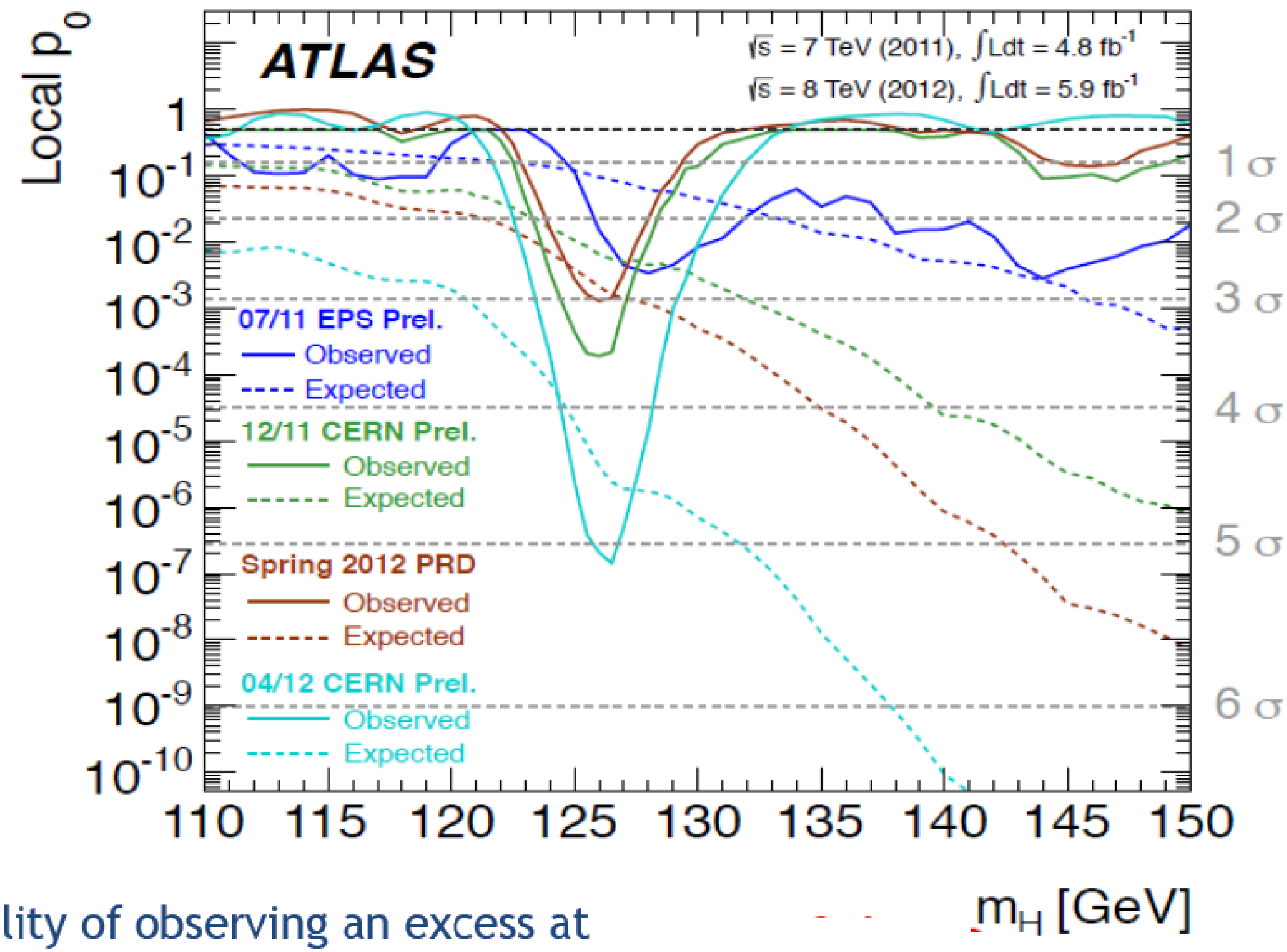
- 1 Higgs every 10 s
- 1 H→ γ γ every 1.5 h
- 1 H→ZZ→4ℓ(ℓ= e or μ) every 2 days

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.



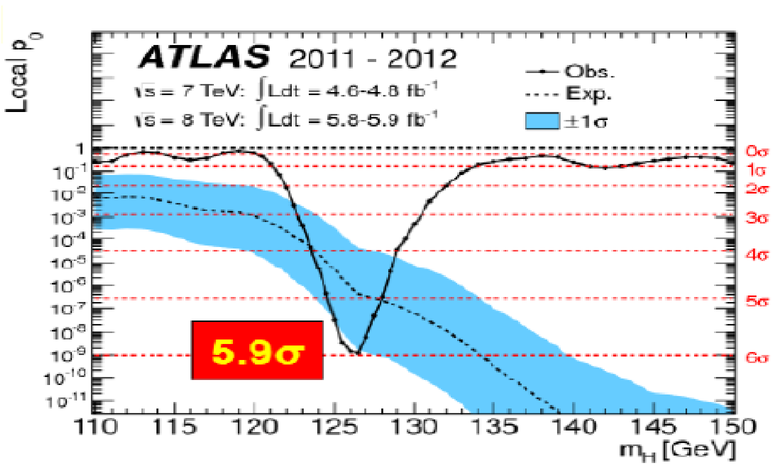
Birth of a particle

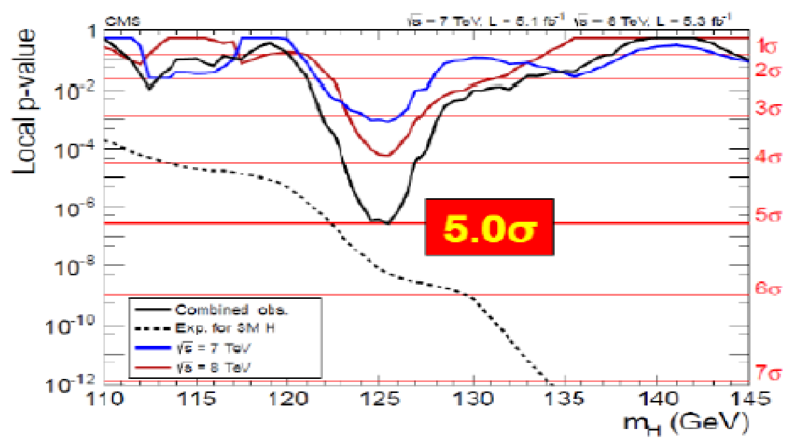


Probability of observing an excess at
one specific mass
(in absence of signal)…

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

$H \to \gamma\gamma$, 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

$H \to \gamma\gamma$, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)

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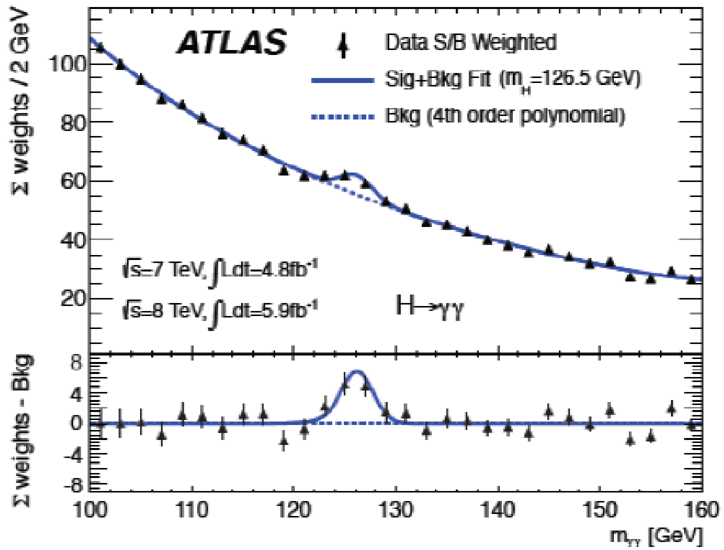
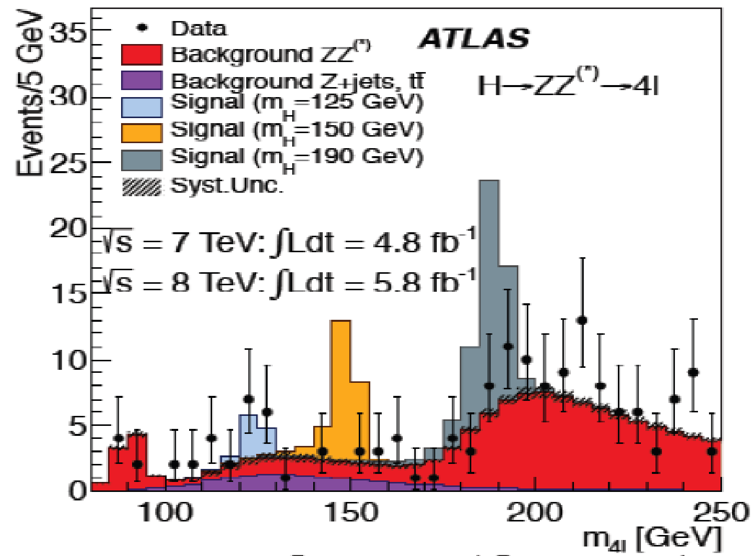
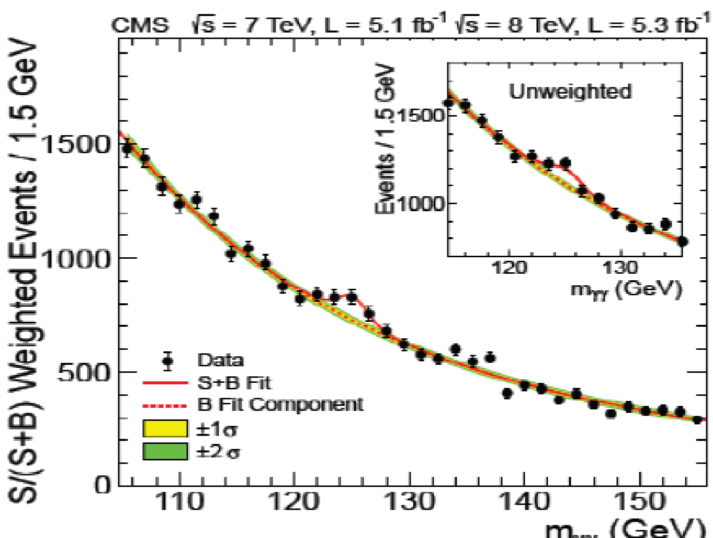
Higgs-like particle – 4 July 2012

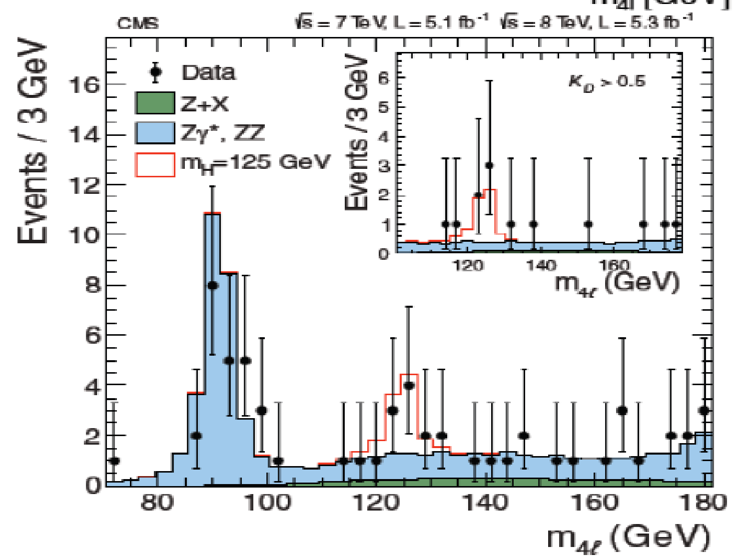
Phys.Lett. B716 (2012) 1-29



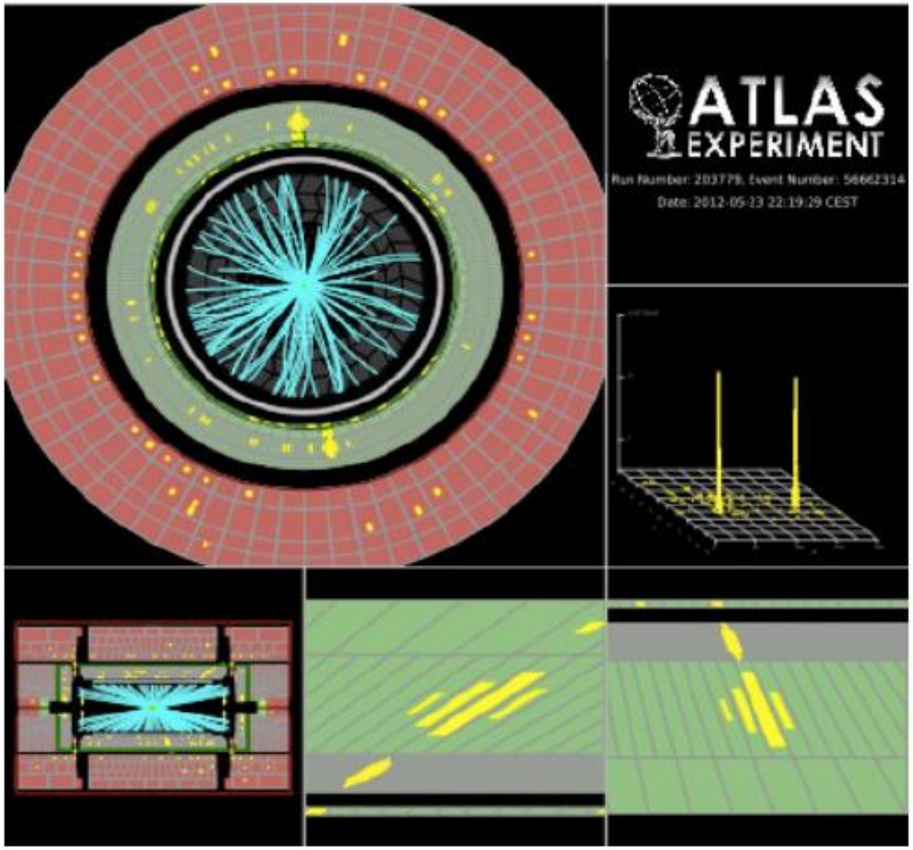


Phys.Lett. B716 (2012) 30-61





H->γγ: events signature



Simple event signature

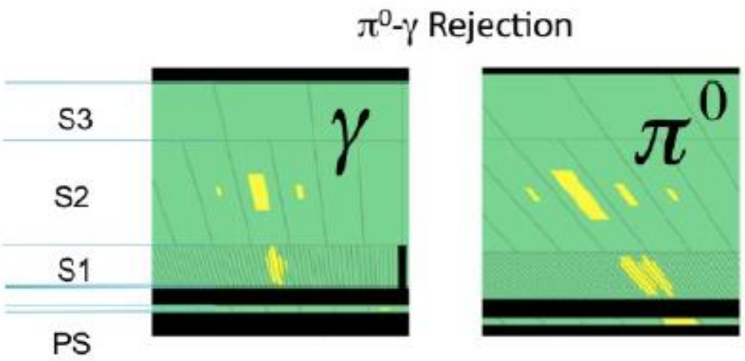
- Two high pT photons
$pT_1 > 40$ GeV and $pT_2 > 30$ GeV
- High trigger efficiency
~99%
- High event selection efficiency despite high jet-jet & γ-jet production
~40%
- High signal over background
~3-10 % (depending on sub-category)

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

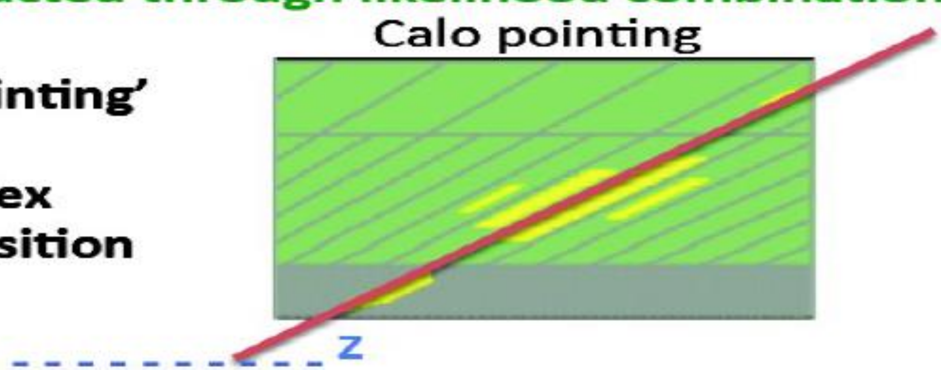


- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

Vertex Reconstruction

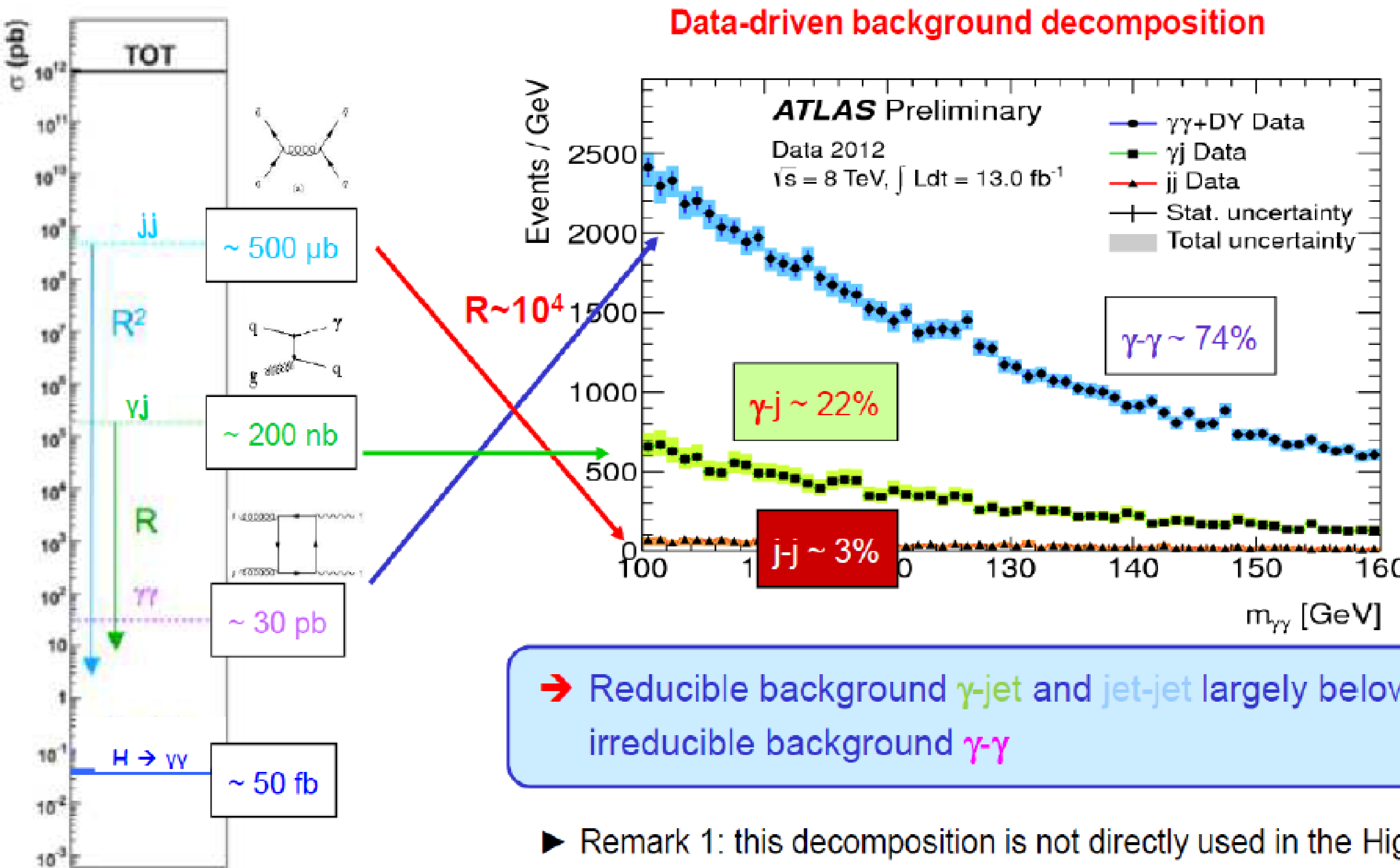
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

- ❑ 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

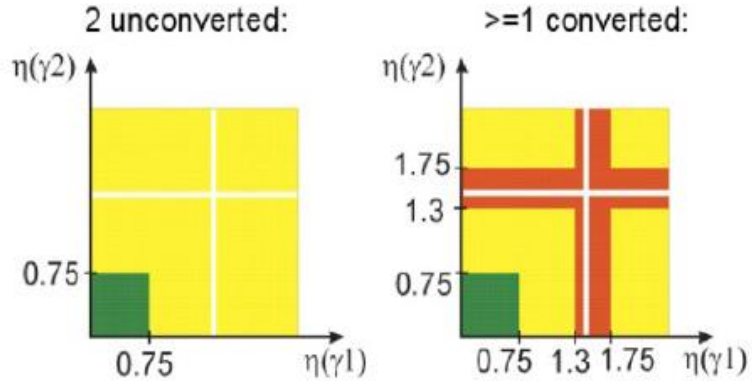
Event categories based on eta, pTt, and conversion

Both unconverted:

- Central
- Rest

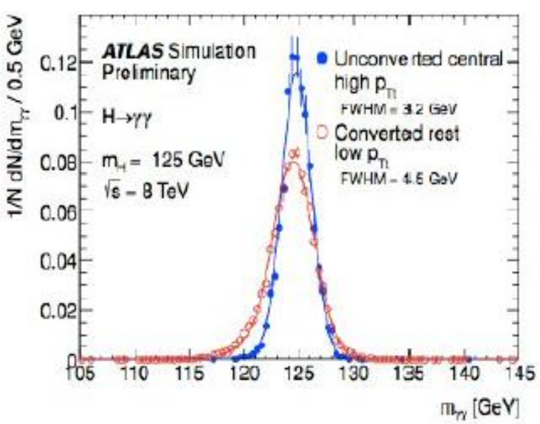
At least one converted:

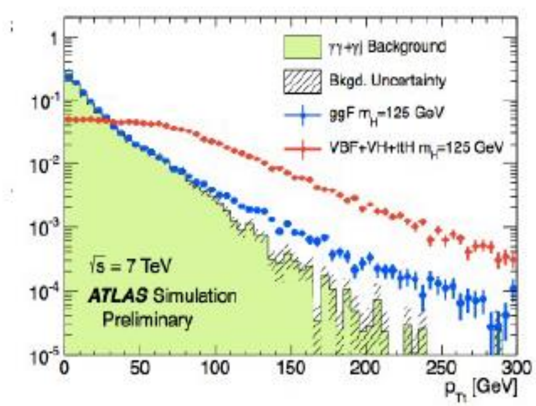
- Central
- Transition
- Rest



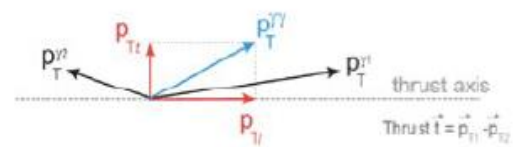
Resolution:

Good
Medium
Poor





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



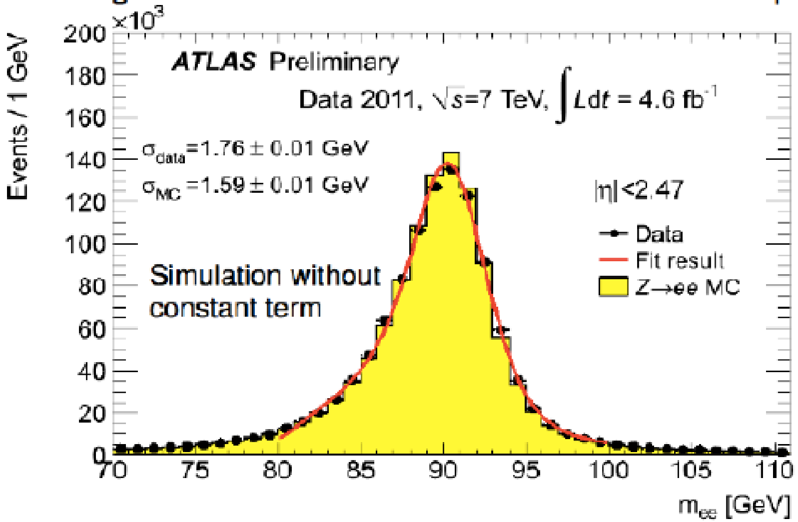
Energy calibration and resolution

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

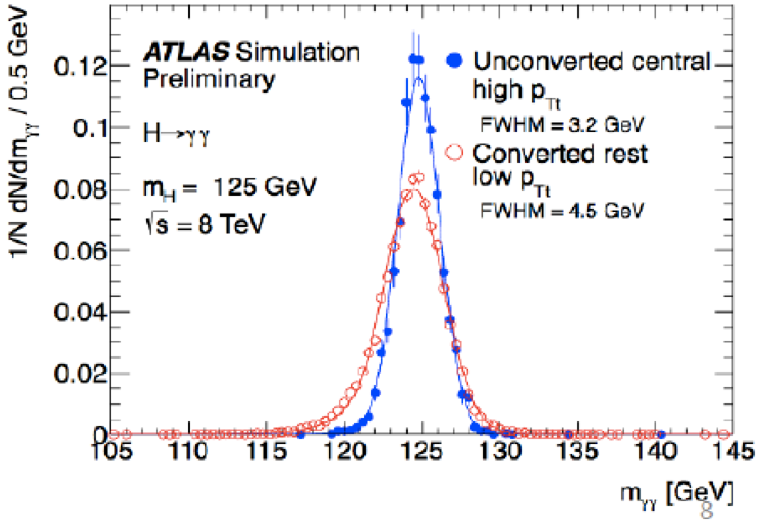
- MC based calibration improved with energy scale and resolution corrections based on in-situ analysis of Z→ee, W→eν and J/ψ → ee

- Energy scale at m_Z known to 0.3%, uniformity (constant term) 1% in barrel, 1.2 – 2.1% in endcap

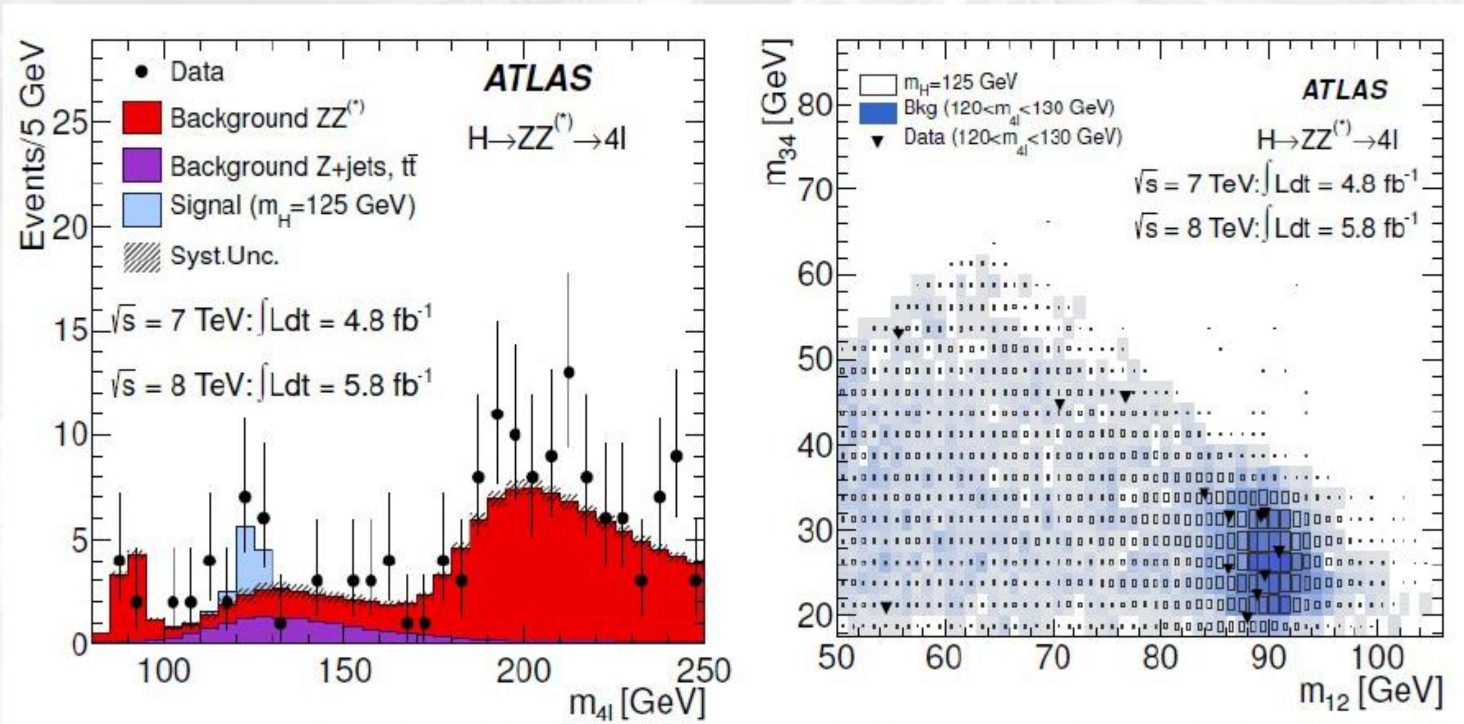
Agreement between data & MC Z→ee lineshape



Expected resolution of Higgs signal



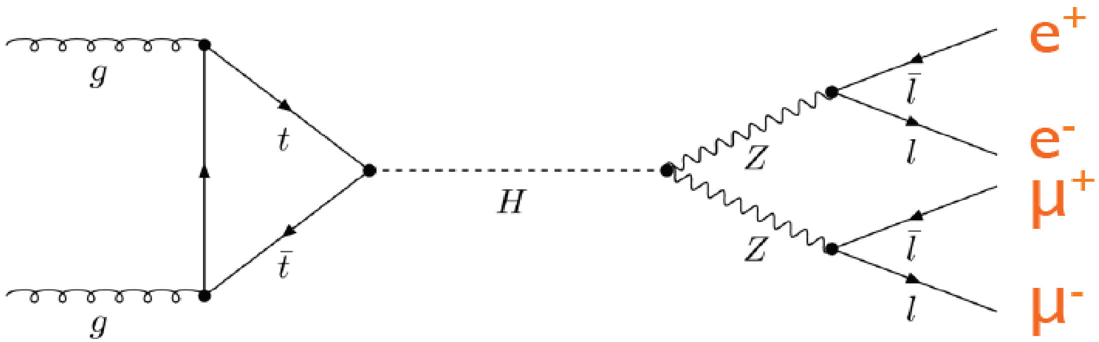
The golden channel Z->ll



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

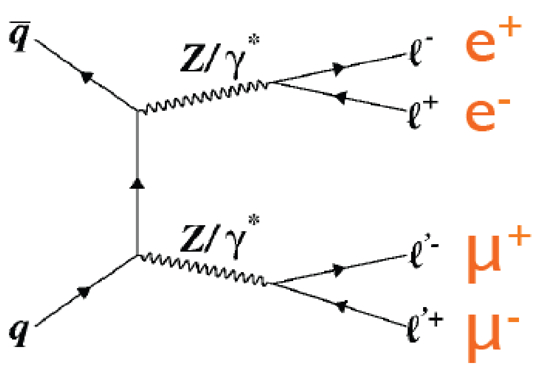
	Signal	$ZZ^{(*)}$	$Z+$ jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

Signal and background



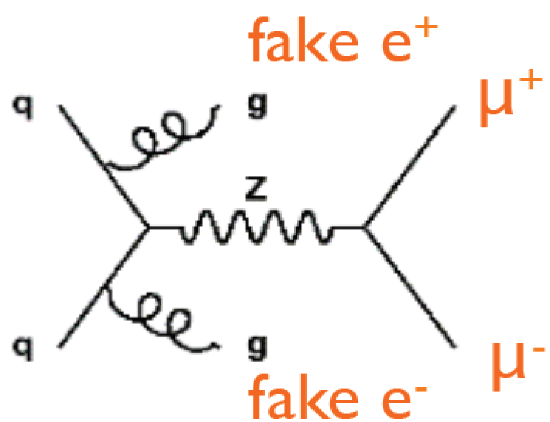
Irreducible background

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



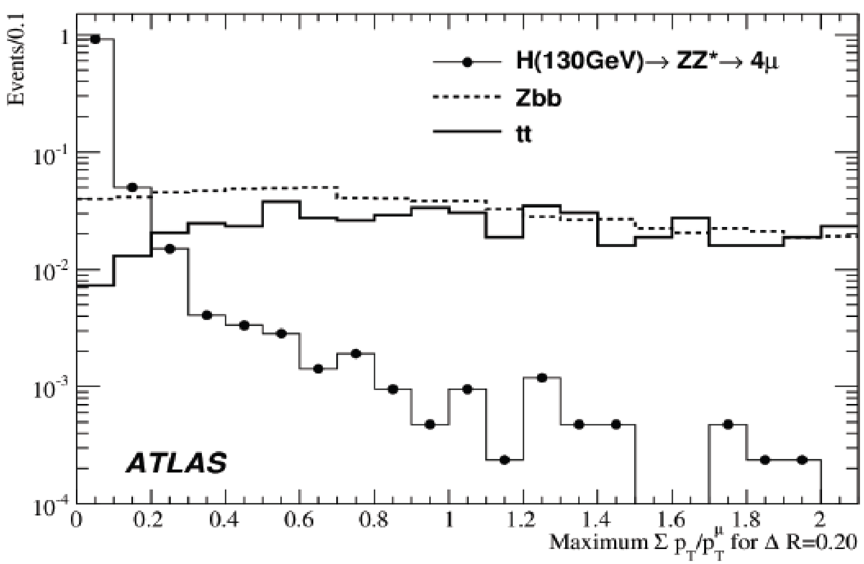
Reducible background

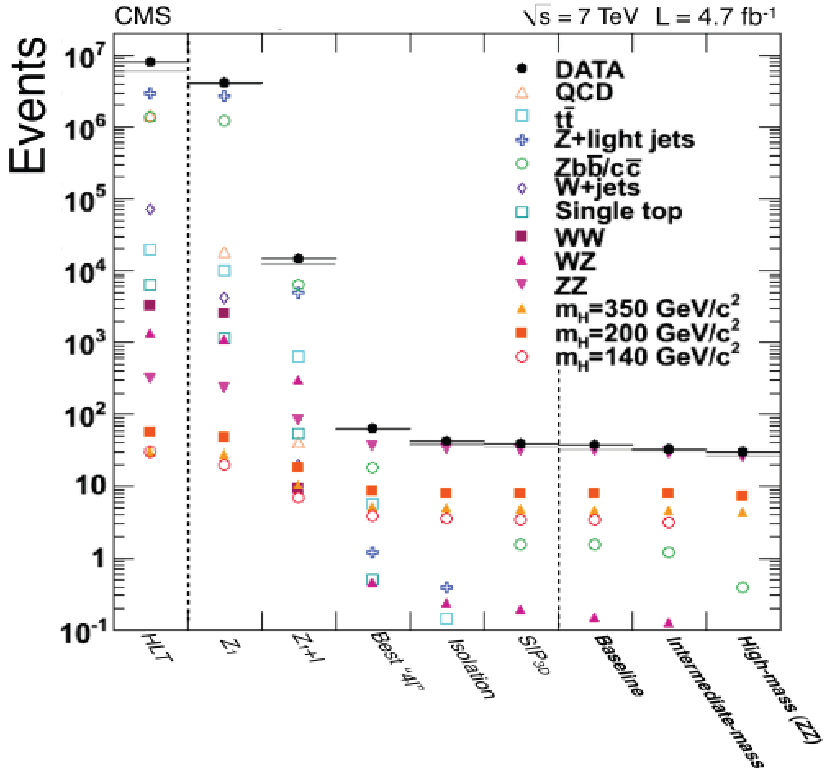
The final state looks like the same, but some f the particle fakes what you are looking for



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

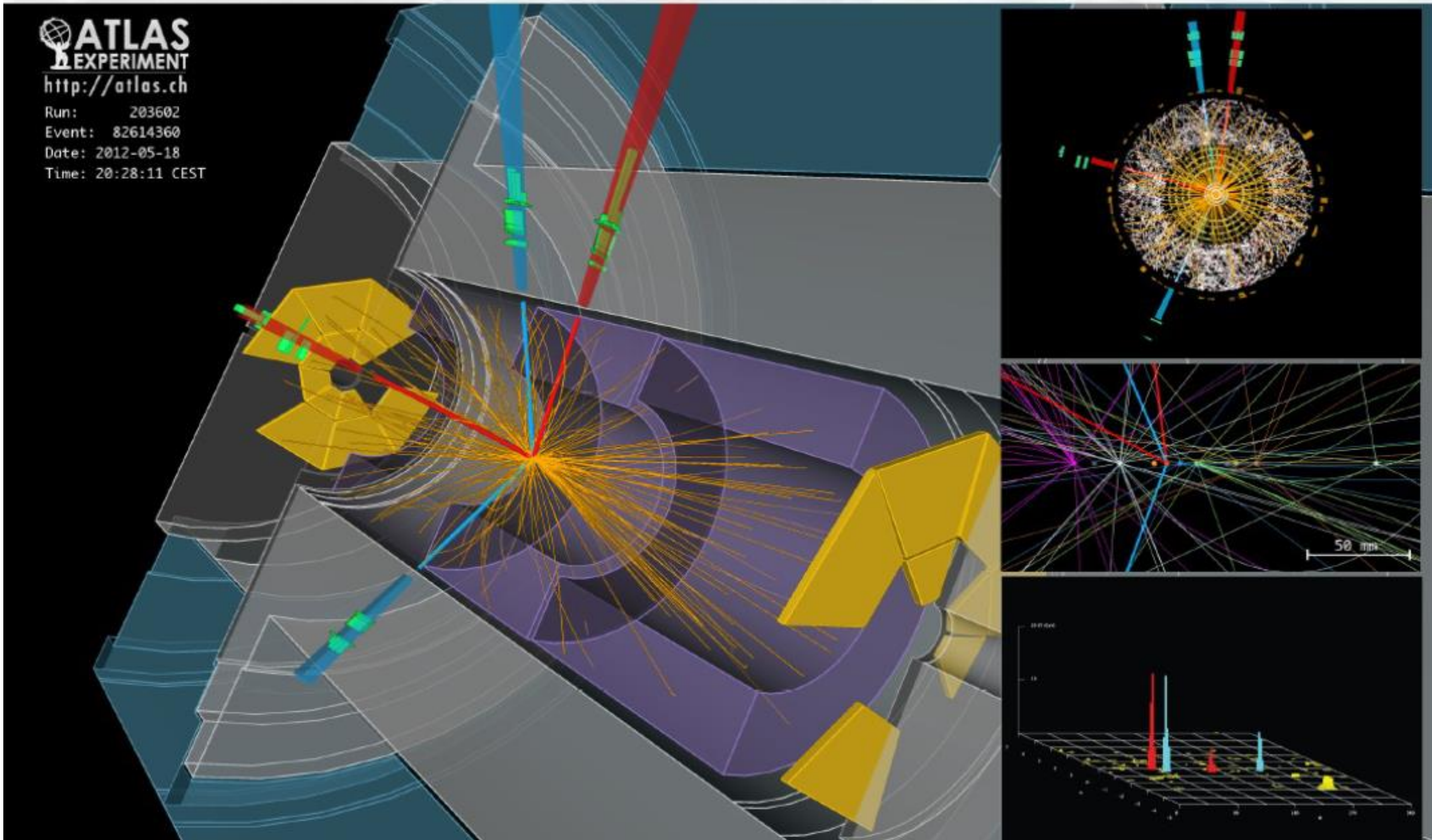




4e candidate. $m_{4\ell} = 124.6$ GeV, $m_{12} = 70.6$ GeV, $m_{34} = 44.7$ GeV.

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

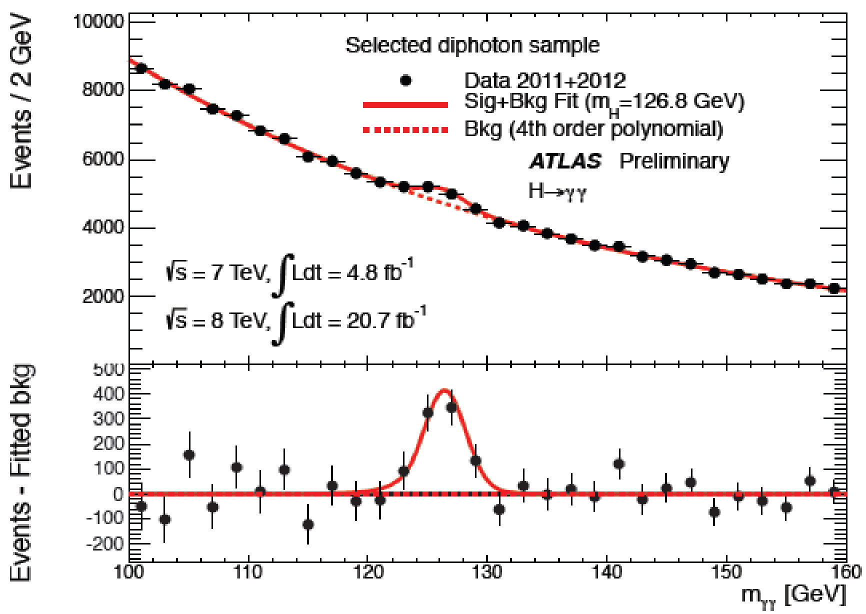
e_3: $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$ e_4: $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$



Higgs like signal with 7 TeV and 8 TeV data

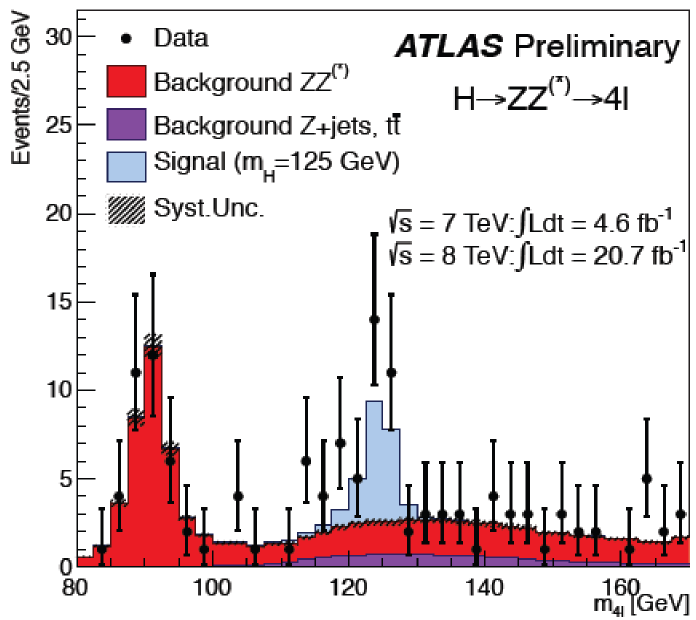
2013

H→γγ



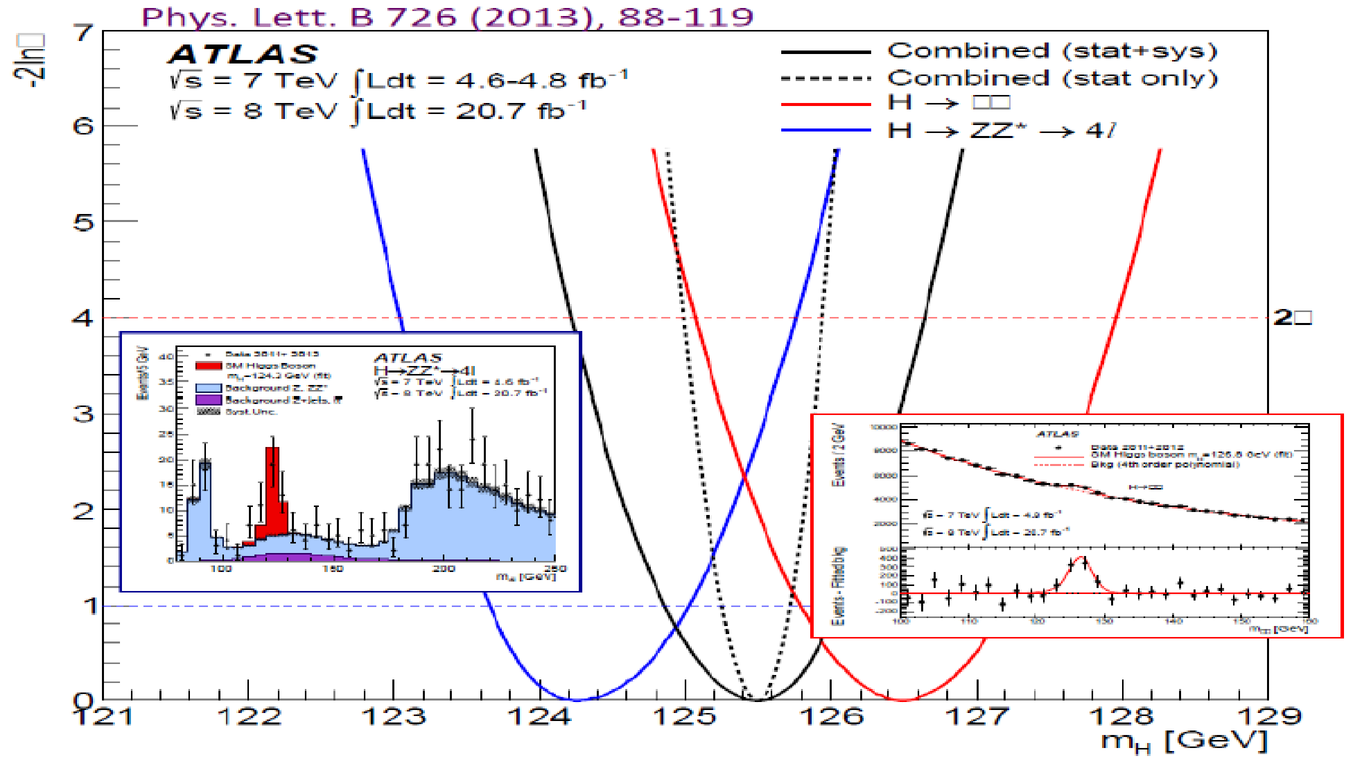
- Signal significance = 7.4 σ
- m_H = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
- μ = 1.65 ± 0.34 (deviation w.r.t. SM at 2.3σ)

H→4l



- 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

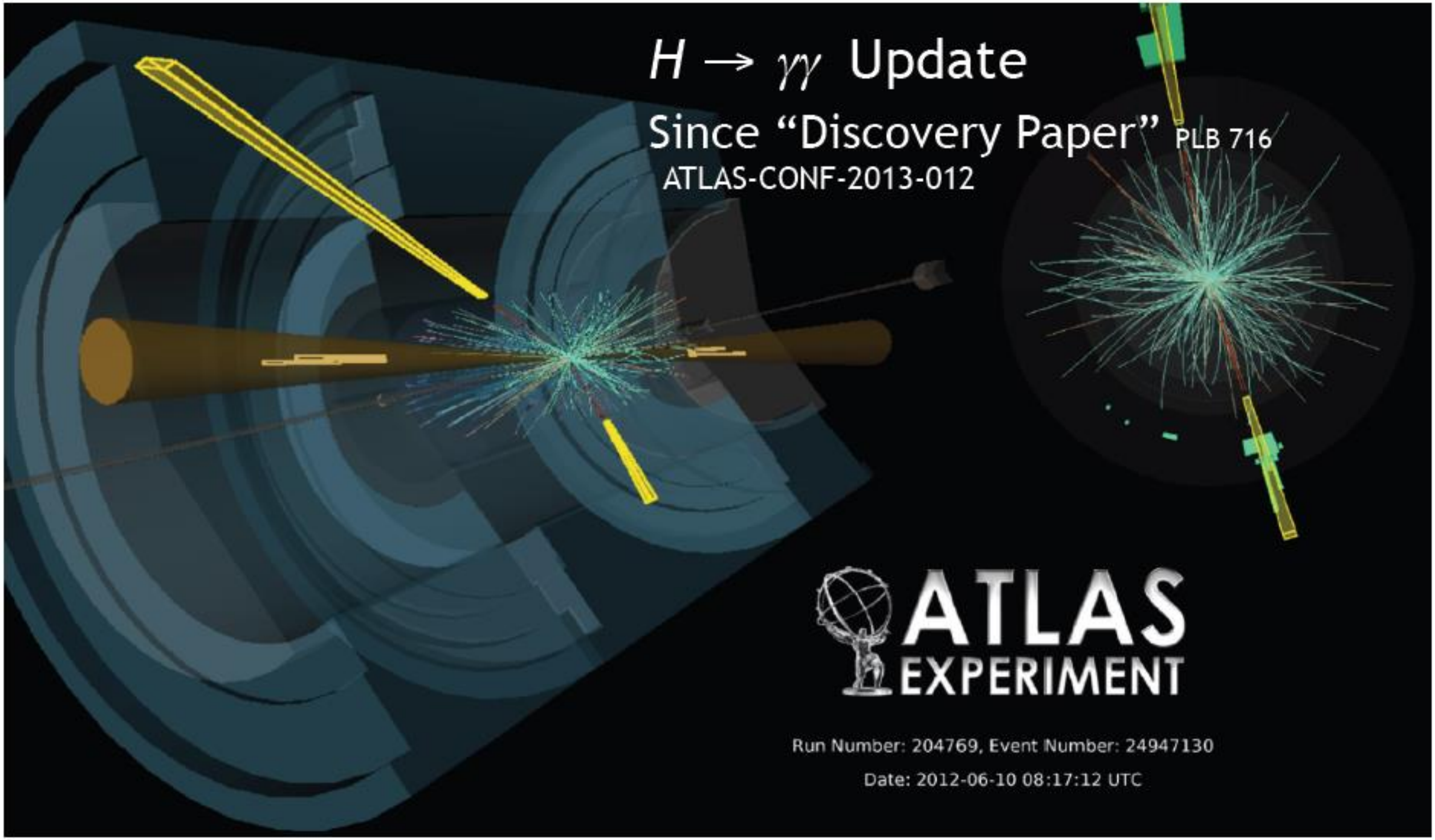
$\gamma\gamma$: $M_H = 126.8 \pm 0.2_{stat} \pm \mathbf{0.7}_{sys}$ GeV

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

And since then …. (2013)

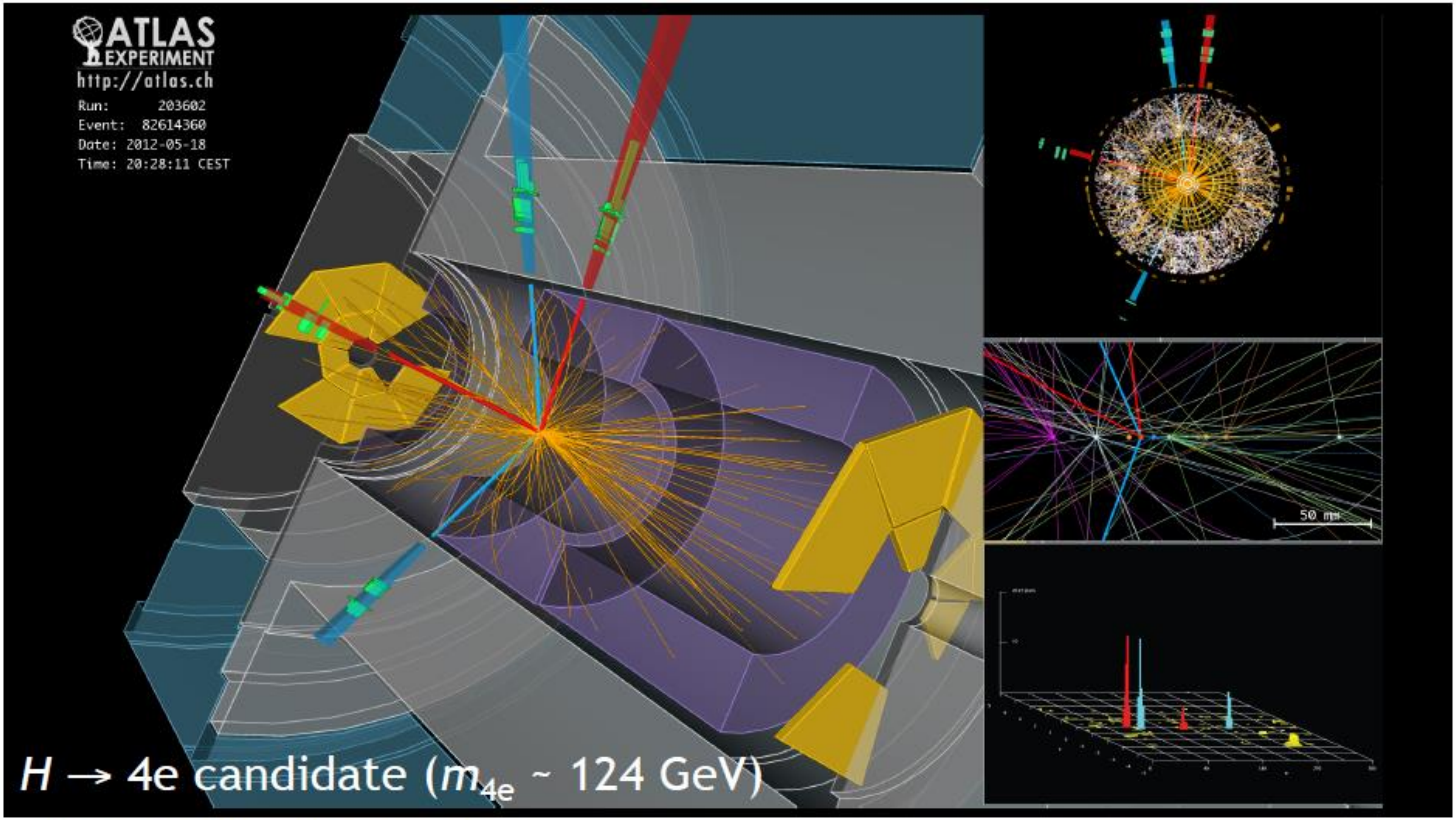
Panorama of ATLAS Higgs (125) Analyses

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



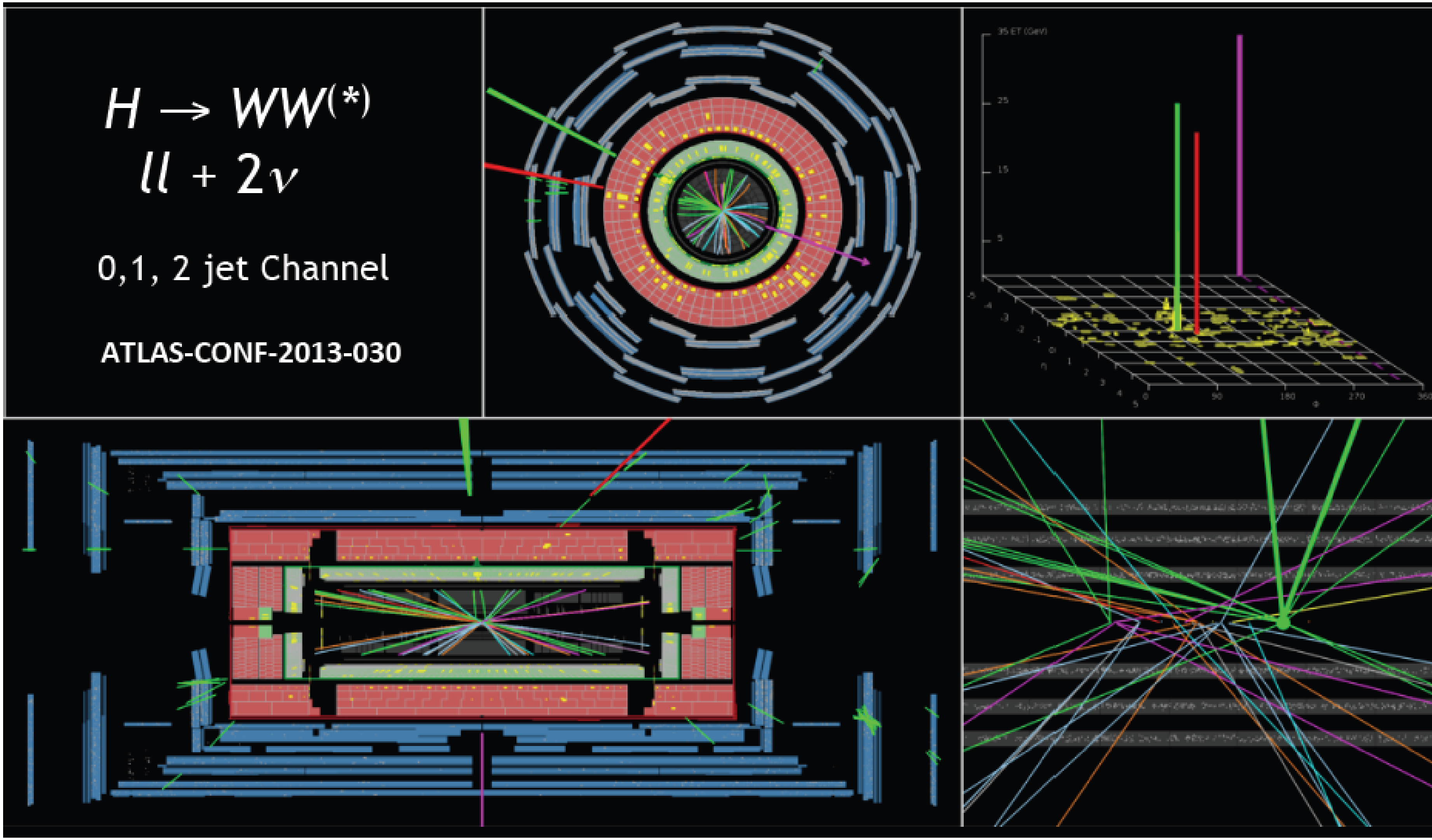
γγ channel basic facts sheet :

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}



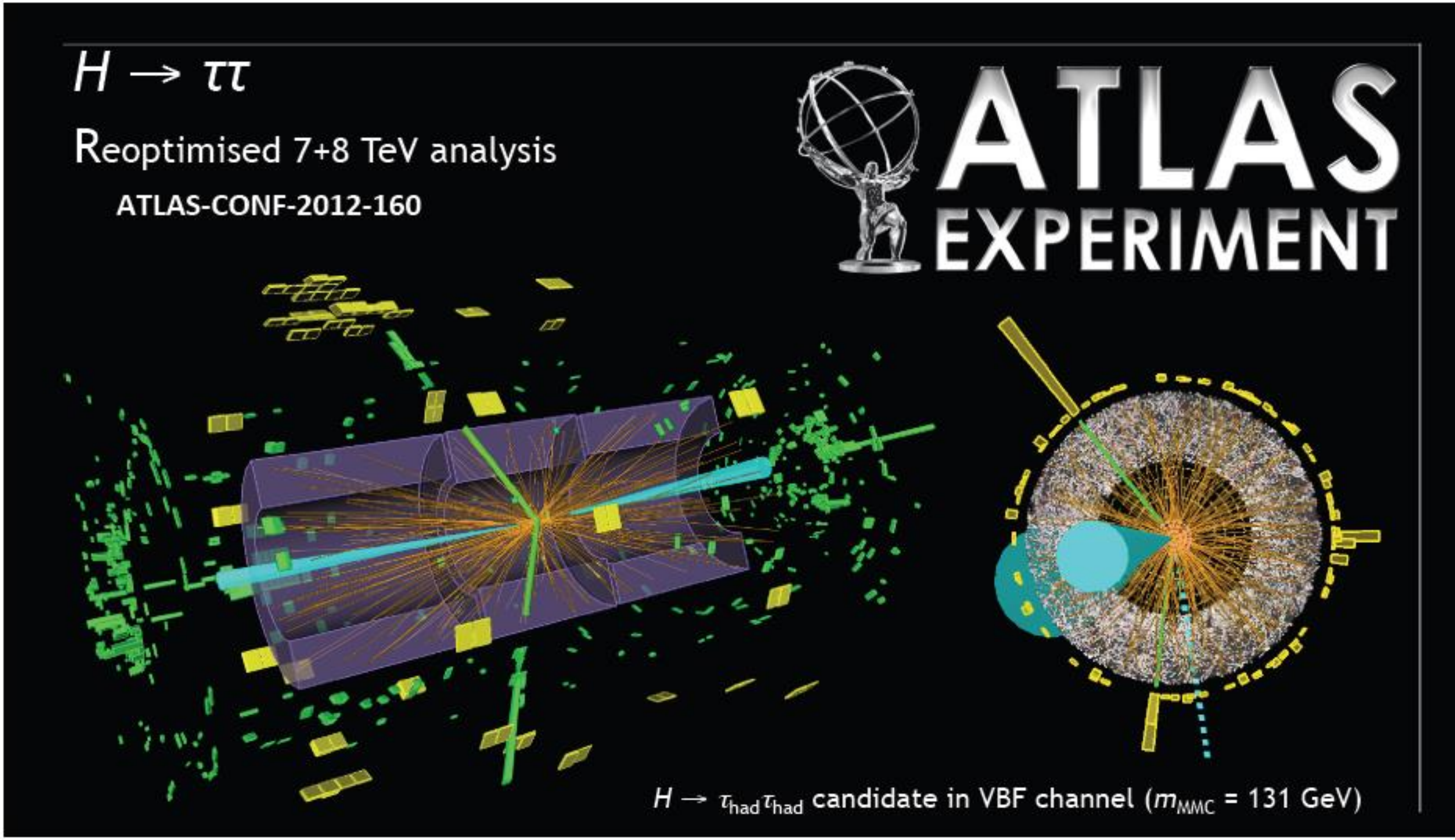
4l channel basic facts sheet :

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	25fb^{-1}

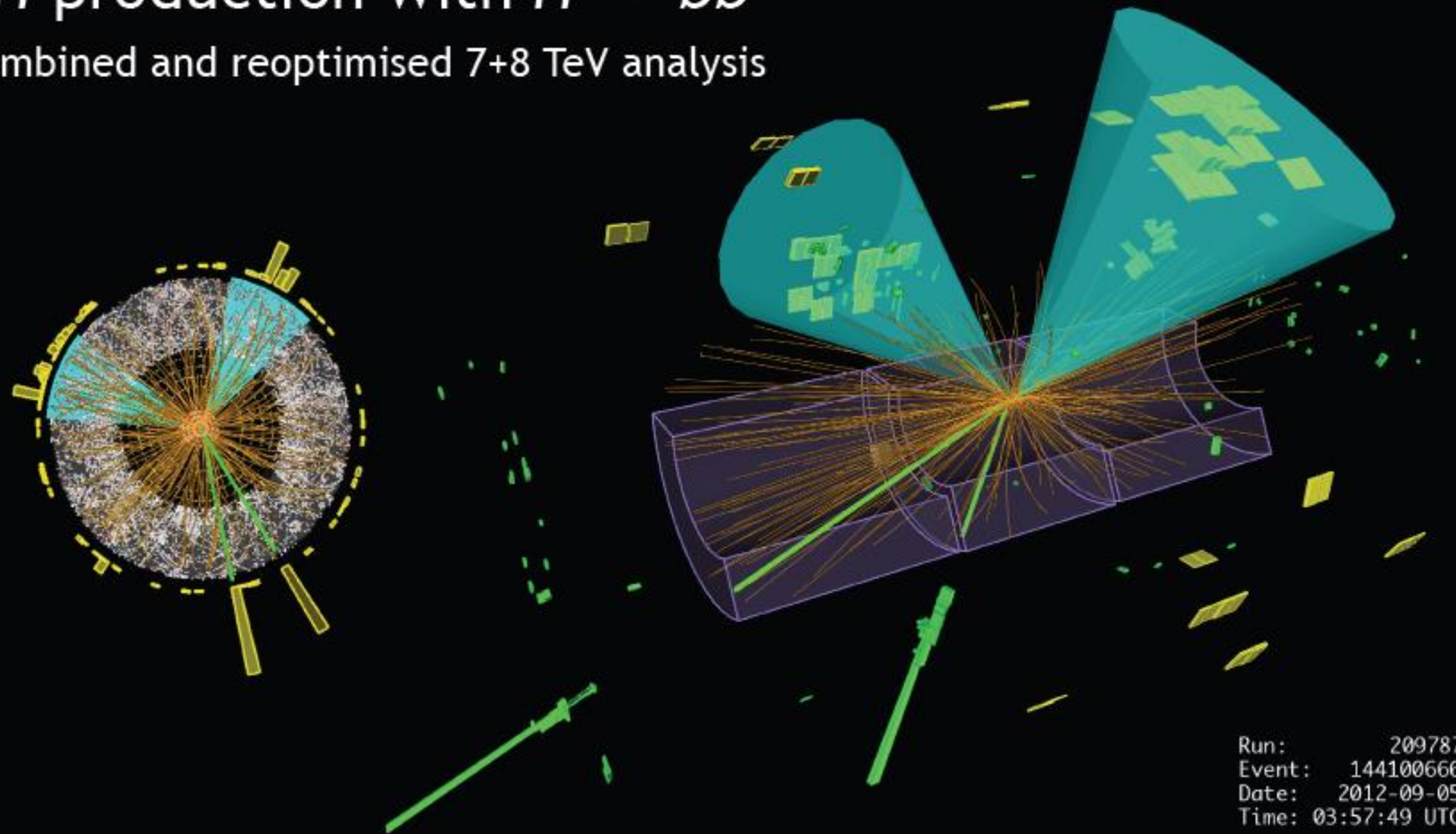


ττ channel basic facts sheet :

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 $H \rightarrow bb$

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

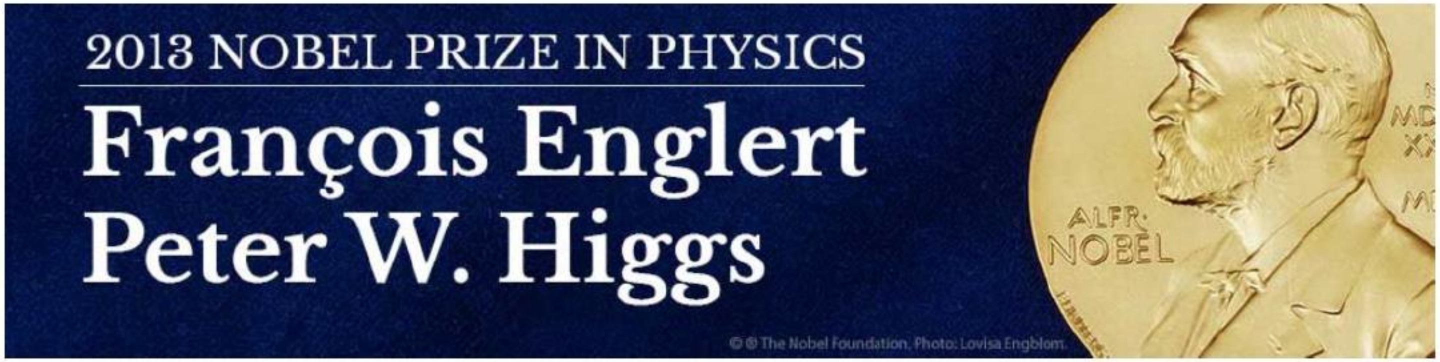
  CMS: $m_H = 125.7 \pm 0.3$(stat) ± 0.3 (syst) GeV

- 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.

Entrance of the Higgs into PDG



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"

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.

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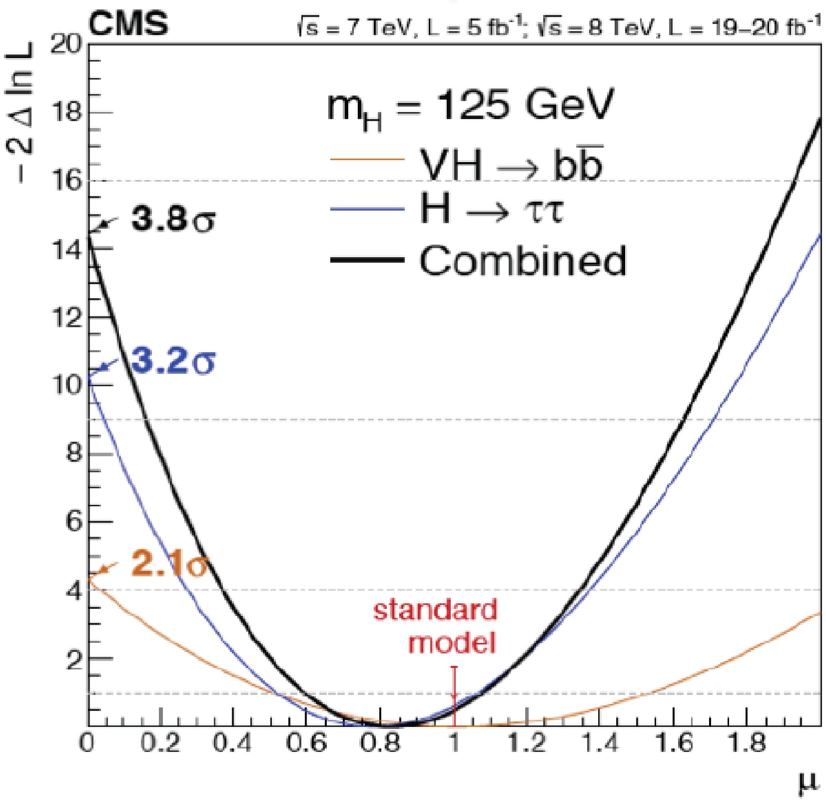
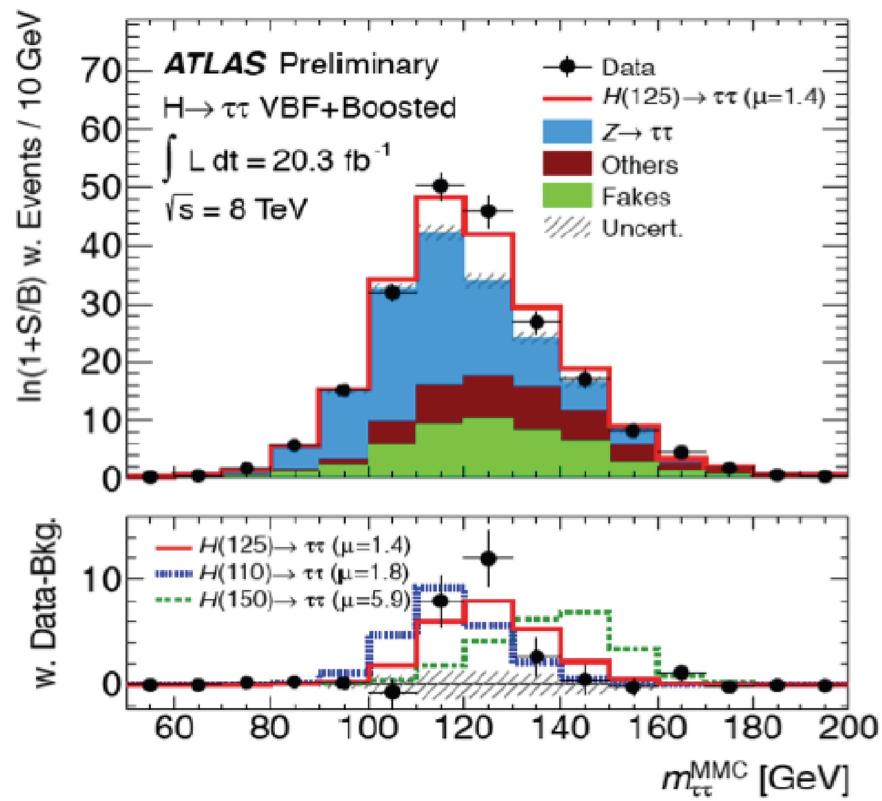
Higgs decays to fermions (2014)

CMS: H→ ττ, bb Channels



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

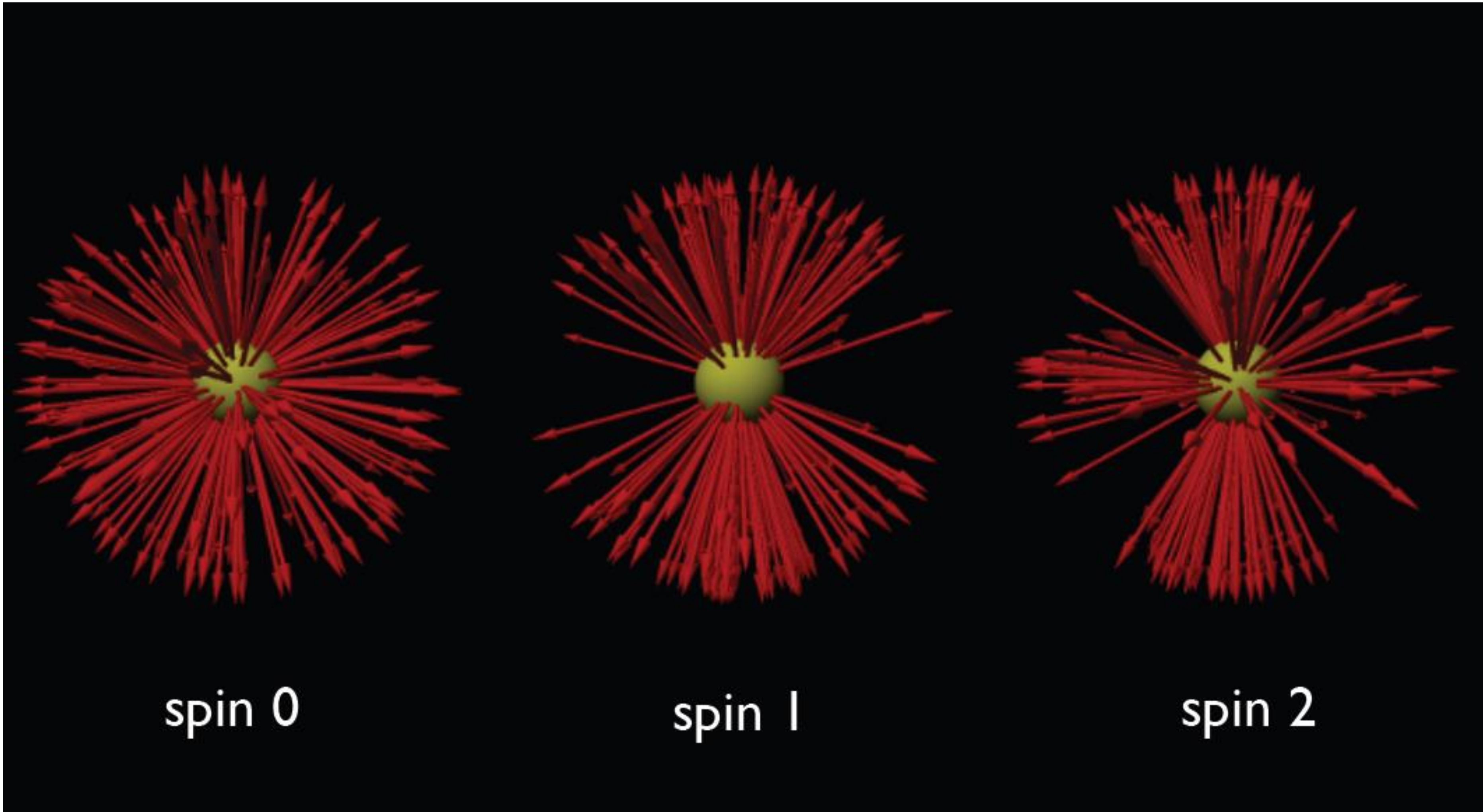
ATLAS: H→ ττ Channel



Significance	Exp	Obs
ATLAS (ττ)	3.2 σ	4.1 σ

Tevatron: exp (2.1σ), obs (3.0σ)

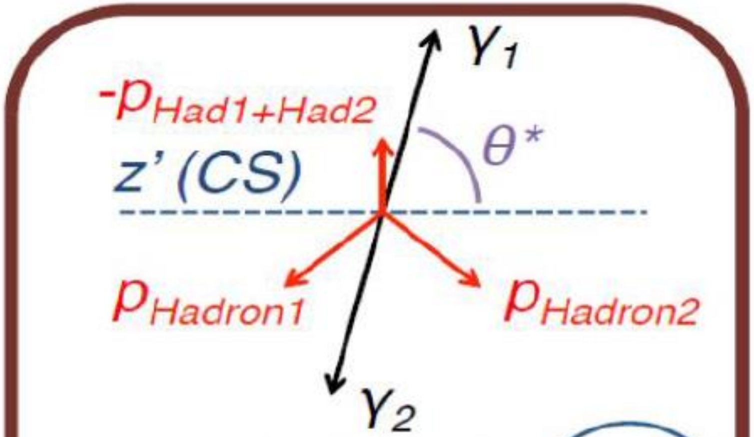
How we can recognize spin?



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->γγ

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



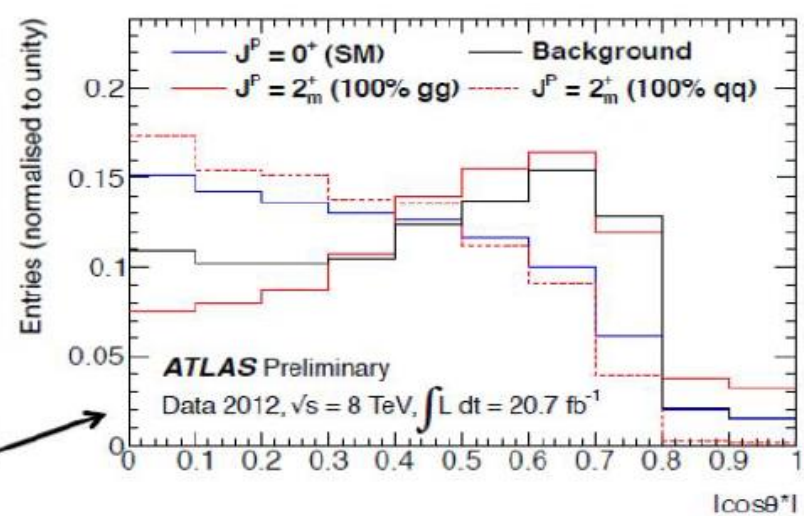
$$\left|\cos\theta^{*}_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma1}p_T^{\gamma2}}{m_{\gamma\gamma}^2}$$

Relative p_T cuts on the photons remove most correlation with $m_{\gamma\gamma}$

$qq\rightarrow 2^+$ very similar to SM $gg\rightarrow 0^+$

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



Fit metod for H->γγ

Events are divided into γγ mass sidebands and signal region

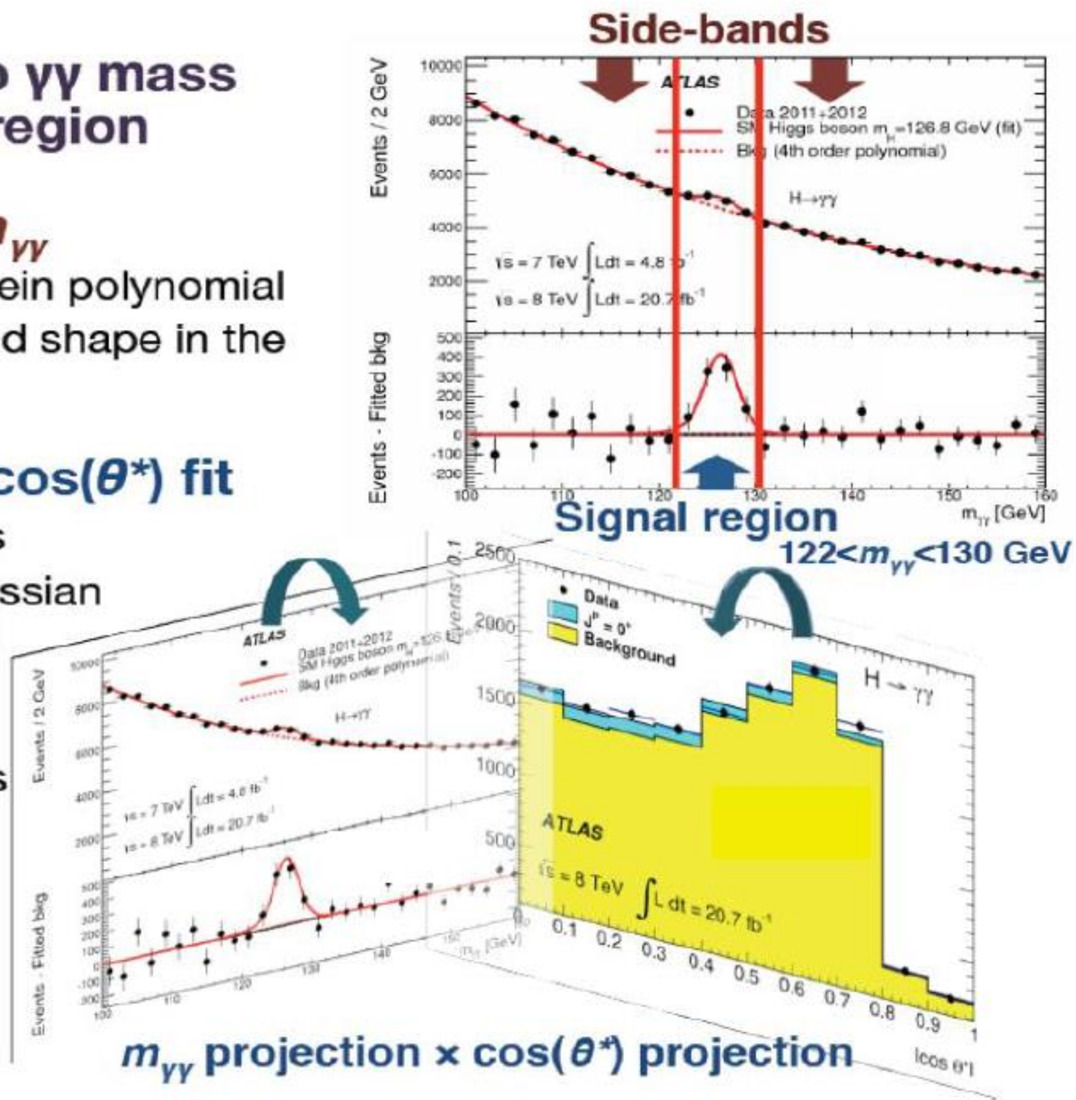
Side-bands: 1D fit in $m_{\gamma\gamma}$

- **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

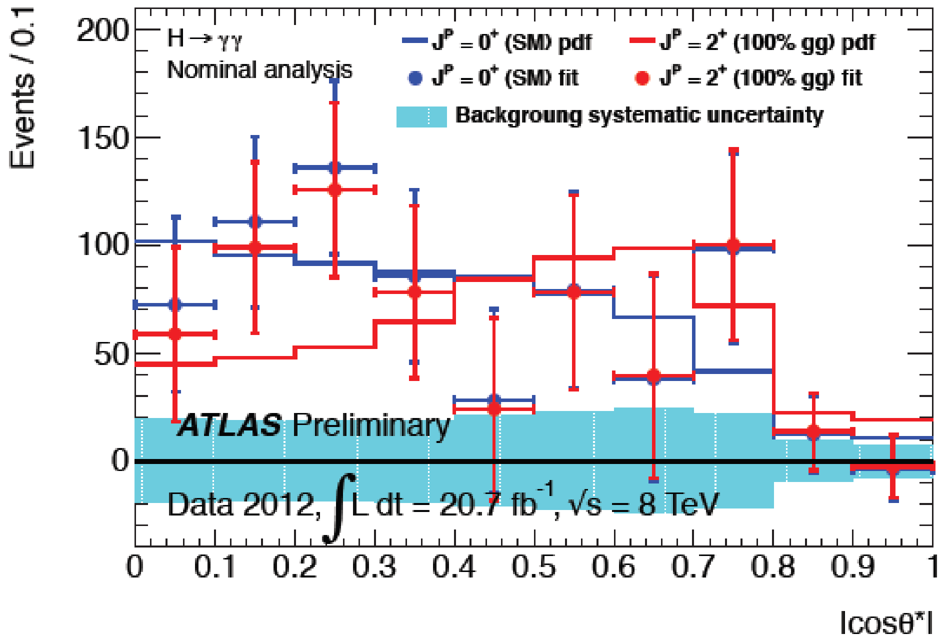
Method assumes minimal correlation between mass and cos(θ*) in background

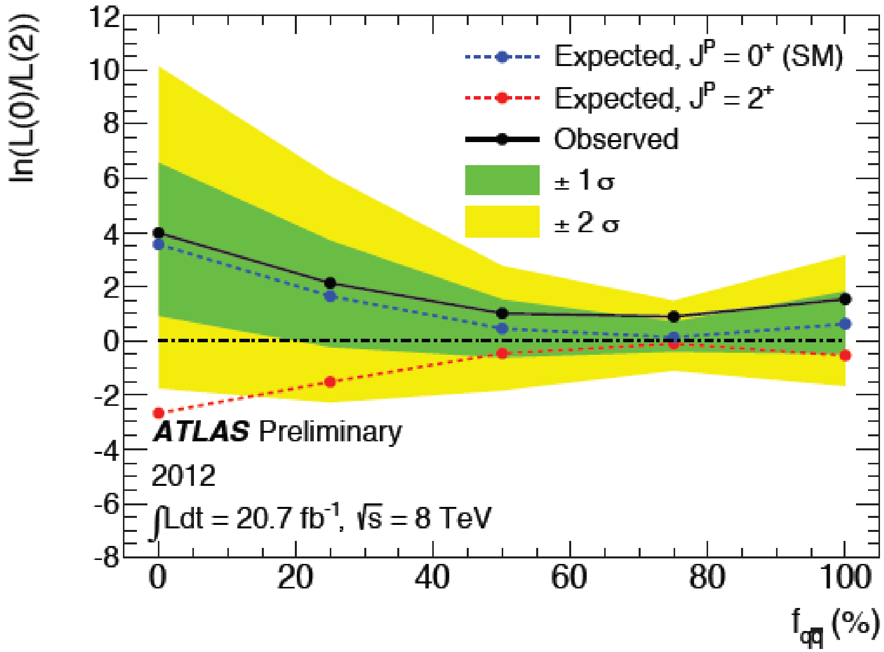


Spin study with H->γγ

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

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

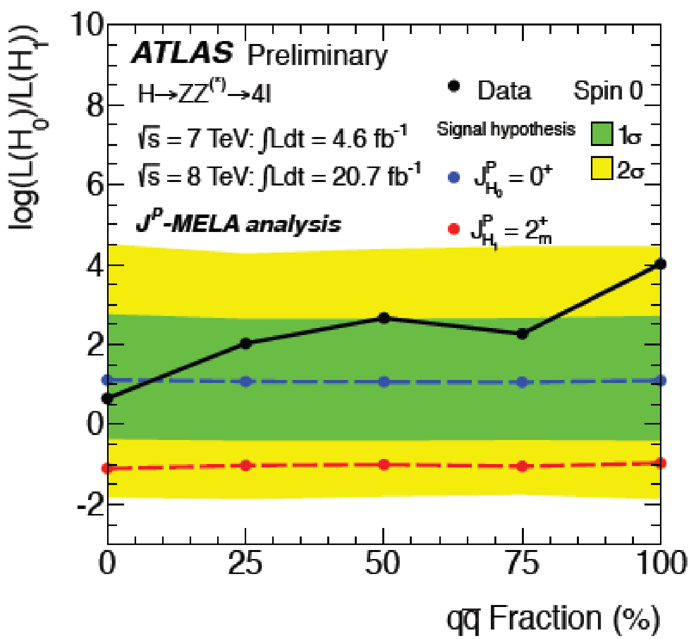


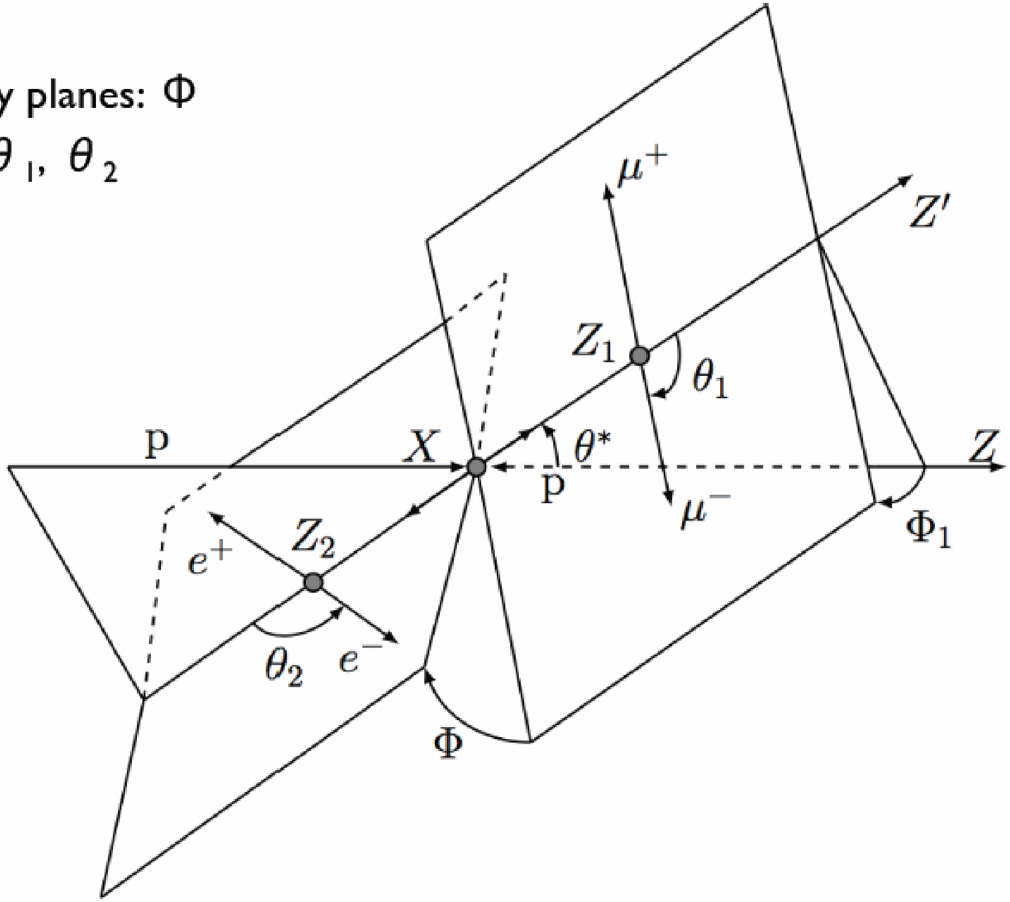


- If spin-2 resonance is produced 100% by gluon fusion, observed *rejection* p-values are:
  - ✓ spin-0 → 58.8% (1.2% expected) → good agreement with spin-0 hypothesis
  - ✓ spin-2 → 0.3% (0.5% expected) → spin-2 excluded at 99.3% CL

Spin study with H->4l

- Sensitive variables
  - ✓ Intermediate boson masses: m_{Z1}, m_{Z2}
  - ✓ Z_1 production angle: θ^*
  - ✓ Z_1 decay plane angle: Φ_1
  - ✓ Angle between the Z_1 and Z_2 decay planes: Φ
  - ✓ Decay angles of negative leptons: θ_1, θ_2
- Expected separation >2.5 σ, except for 2+m (~1.5 σ)
  - ✓ New boson compatible with SM 0+ Higgs hypothesis when compared pair-wise with 0-, 1-, 1+, 2+m





Higgs boson width

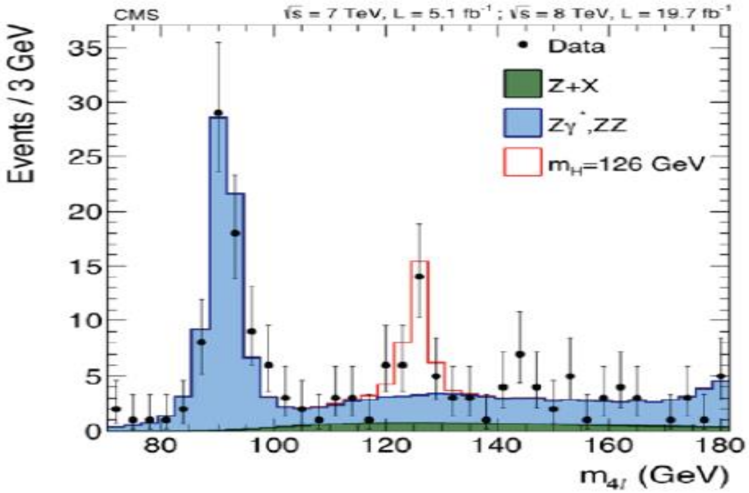
Direct measurements are limited by experimental resolution

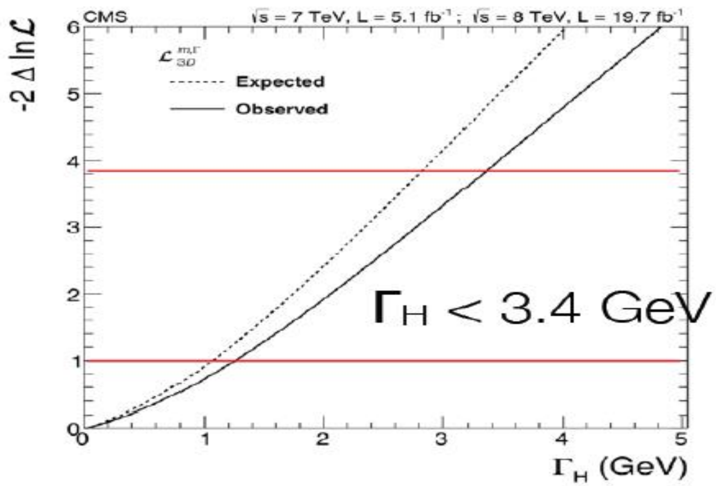
CMS:

$H \to \gamma\gamma$ results $\Gamma_H < 6.9$ GeV

$H \to ZZ$ results $\Gamma_H < 3.4$ GeV

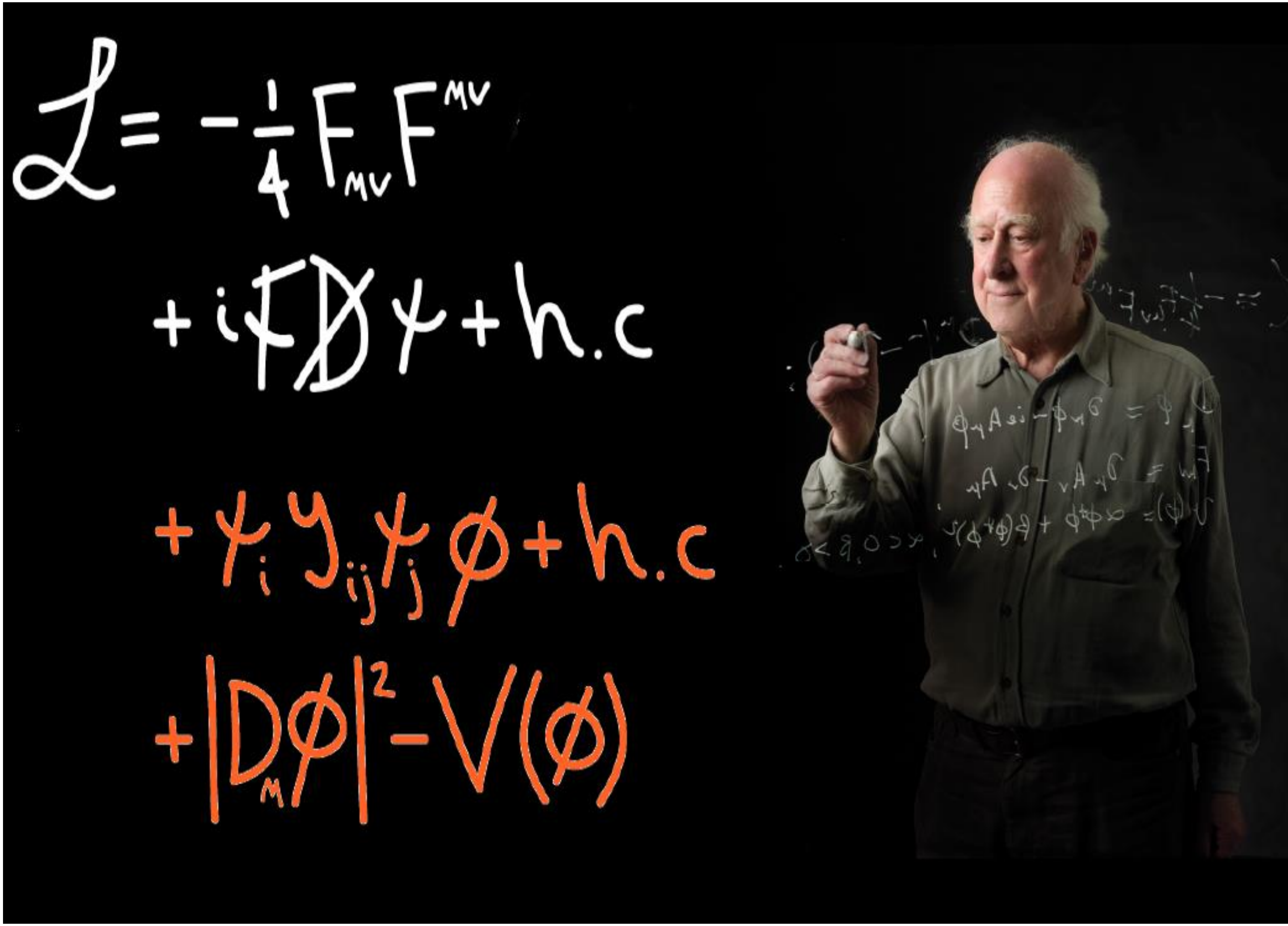
Particle	Width[MeV]	Lifetime[s]
t	$\sim 1,300$	$\sim 5 \times 10^{-25}$
W	$\sim 2,000$	$\sim 3 \times 10^{-25}$
Z	$\sim 2,500$	$\sim 2.6 \times 10^{-25}$
h	4.21 ± 0.16	$\sim 1.65 \times 10^{-22}$
b	4.4×10^{-10}	$\sim 1.5 \times 10^{-12}$



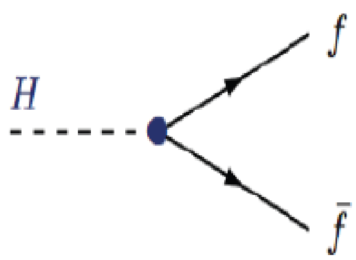


SM Higgs total width ~4 MeV @125GeV

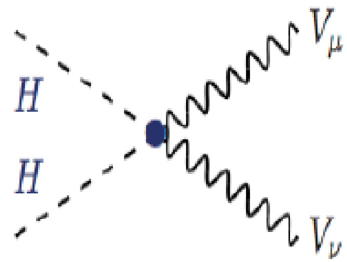
42


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

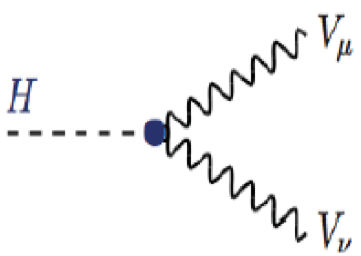
Higgs boson couplings



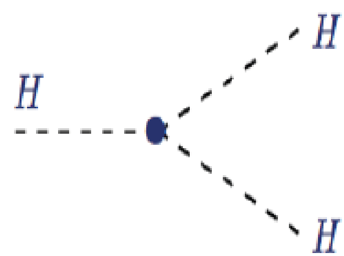
$$g_{Hff} = m_f/v$$



$$g_{HHVV} = 2M_V^2/v^2$$

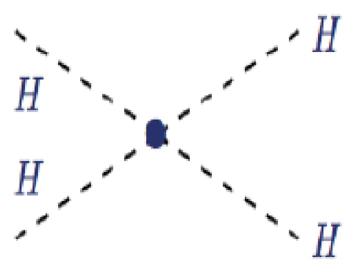


$$g_{HVV} = 2M_V^2/v$$



$$g_{HHH} = 3M_H^2/v$$

For the time being only test the bosonic and fermionic sector



$$g_{HHHH} = 3M_H^2/v^2$$

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

Measuring Higgs boson couplings

Rather than discussing couplings, introduce concept of „scale factors" κ_i : cross-section or partial width scale with κ_i^2

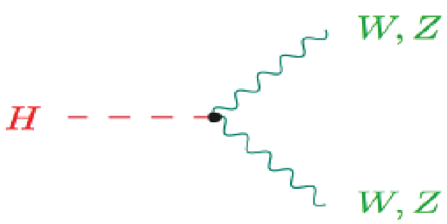
$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v}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

Define the normalized coupling constants (w.r.t. the SM couplings)

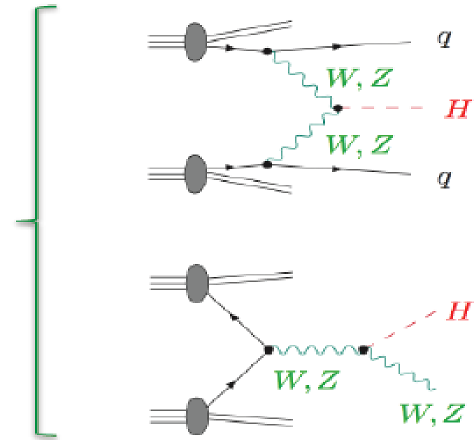
$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \quad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

Cpuplings scale factors

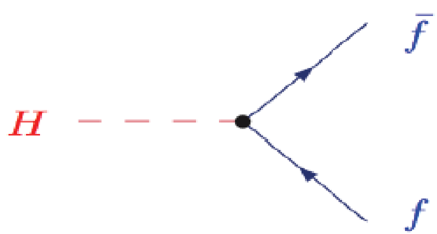
(I) Tree Level Couplings scale factors w.r.t. SM



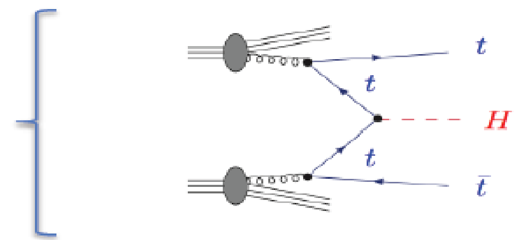
$\propto \kappa_V$



Affecting decay and production modes

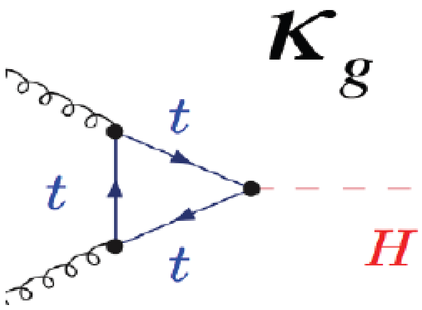


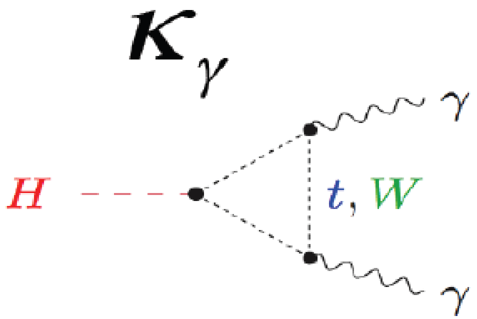
$\propto \kappa_F$



Couplings scale factors

(II) Scale factors of loop induced couplings w.r.t. SM





- Loop expression ambiguity :
  - Can be expressed in terms of k_F and k_V (Assuming the SM field content)
  - Or treated effectively (Allowing for possible additional particles)

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t\kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

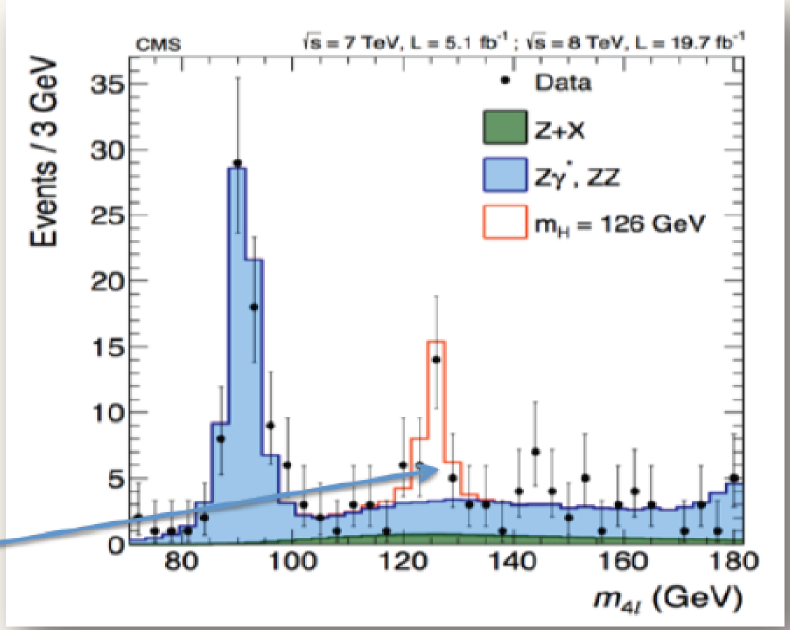
What do we measure?

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

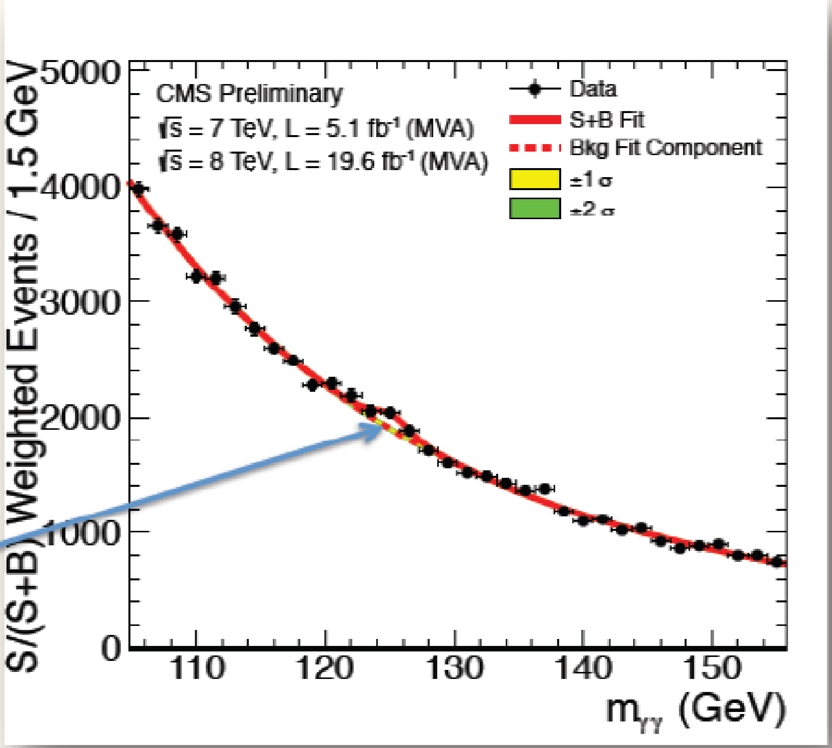
What do we measure?

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



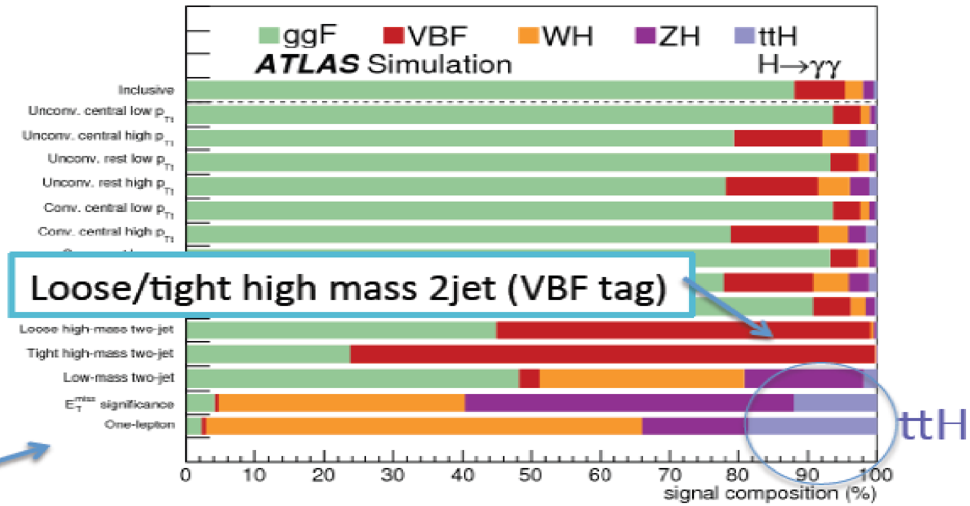
$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

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

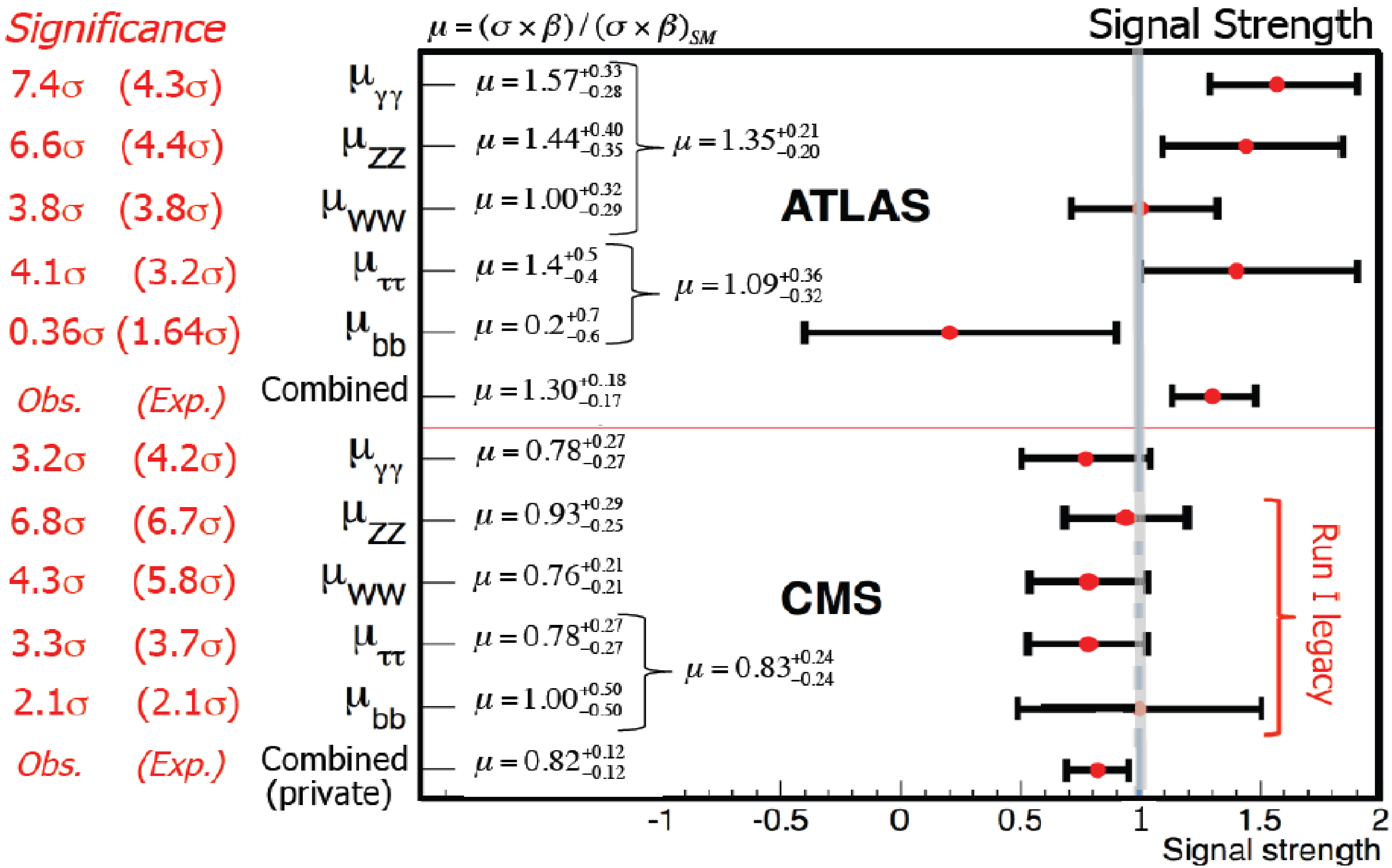
$$n_s^{c,i} = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

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

$\mu^{\gamma\gamma}$(@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

Higgs boson decay channels



Probe the production mode

We fitted

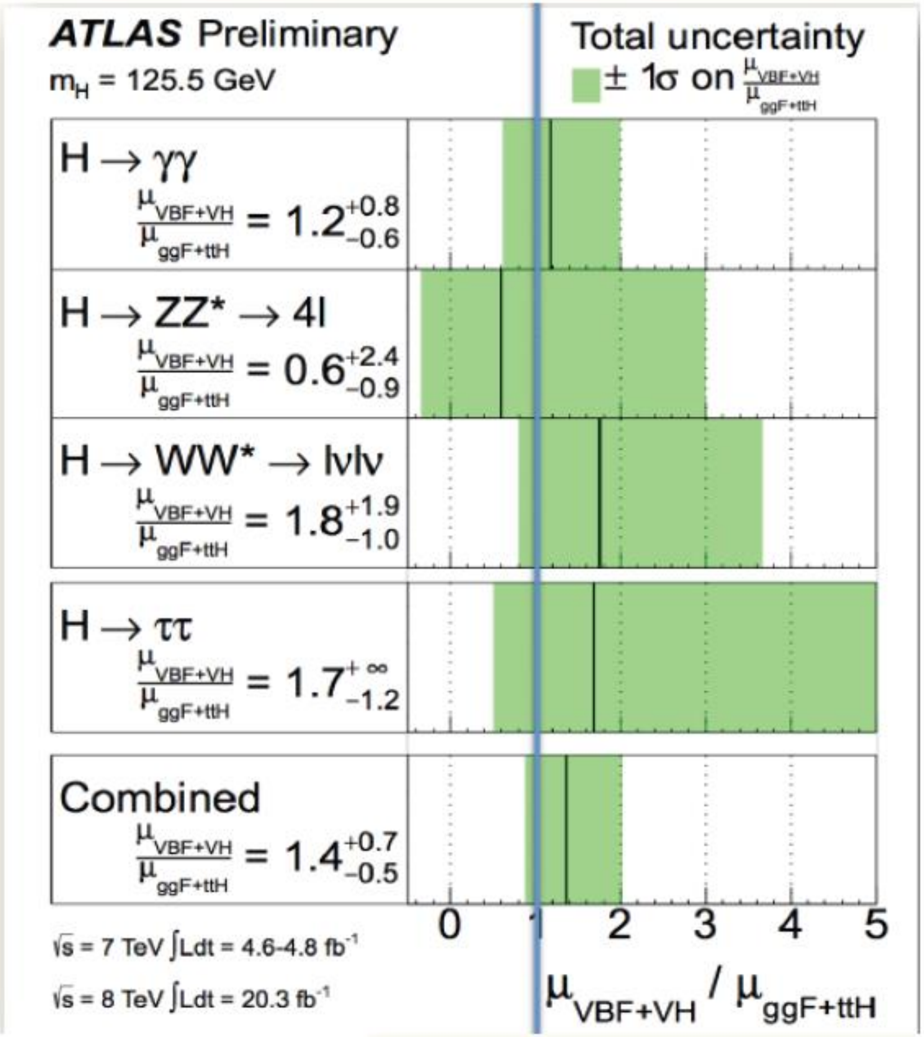
$$\mu^{i}_{VBF+VH} \equiv \left[\mu_{VBF+VH} \times \mu^{i}_{BR}\right]$$

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

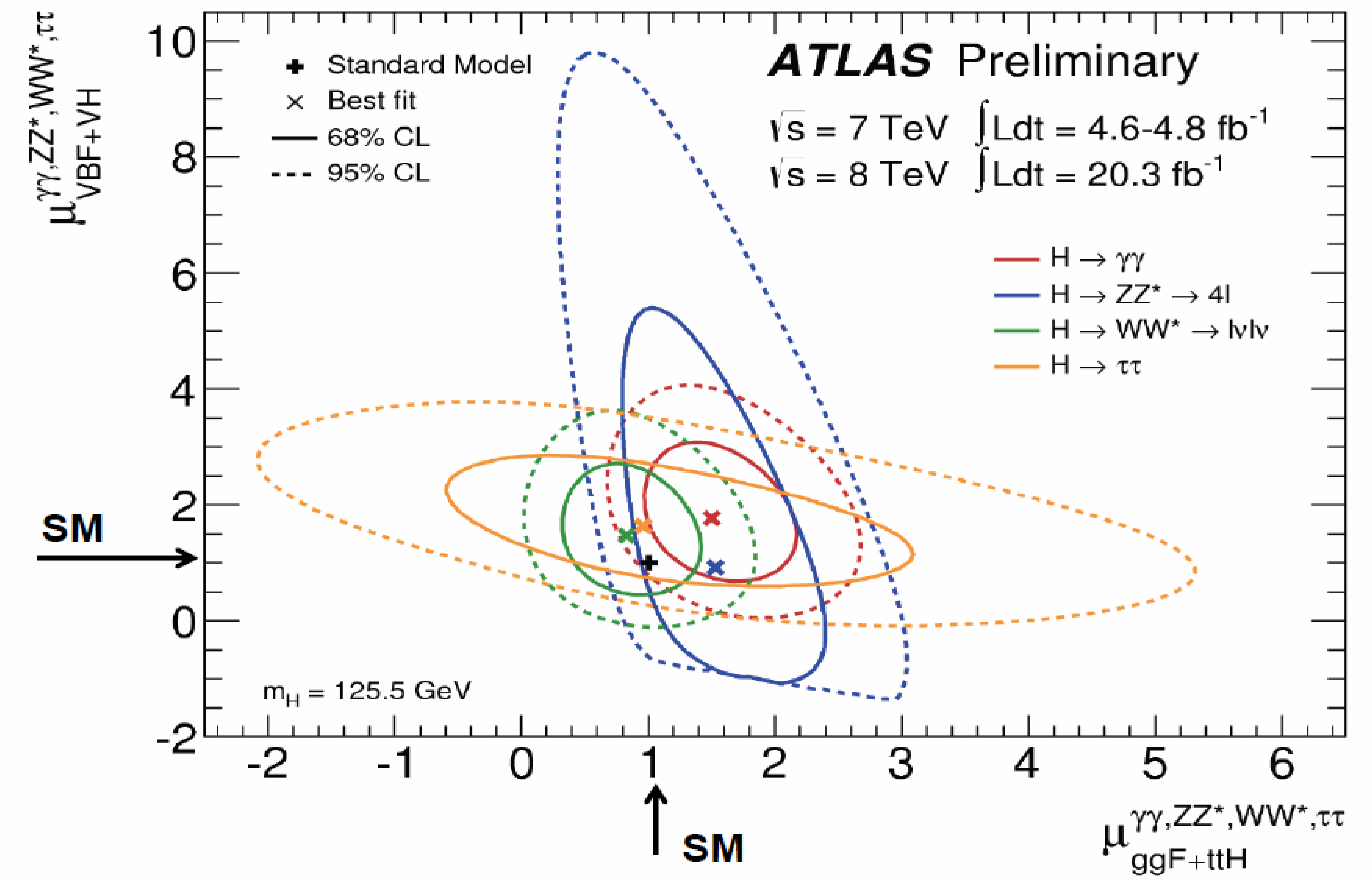
Taking one decay mode at a time we can go one step further and fit the ratio per channel

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

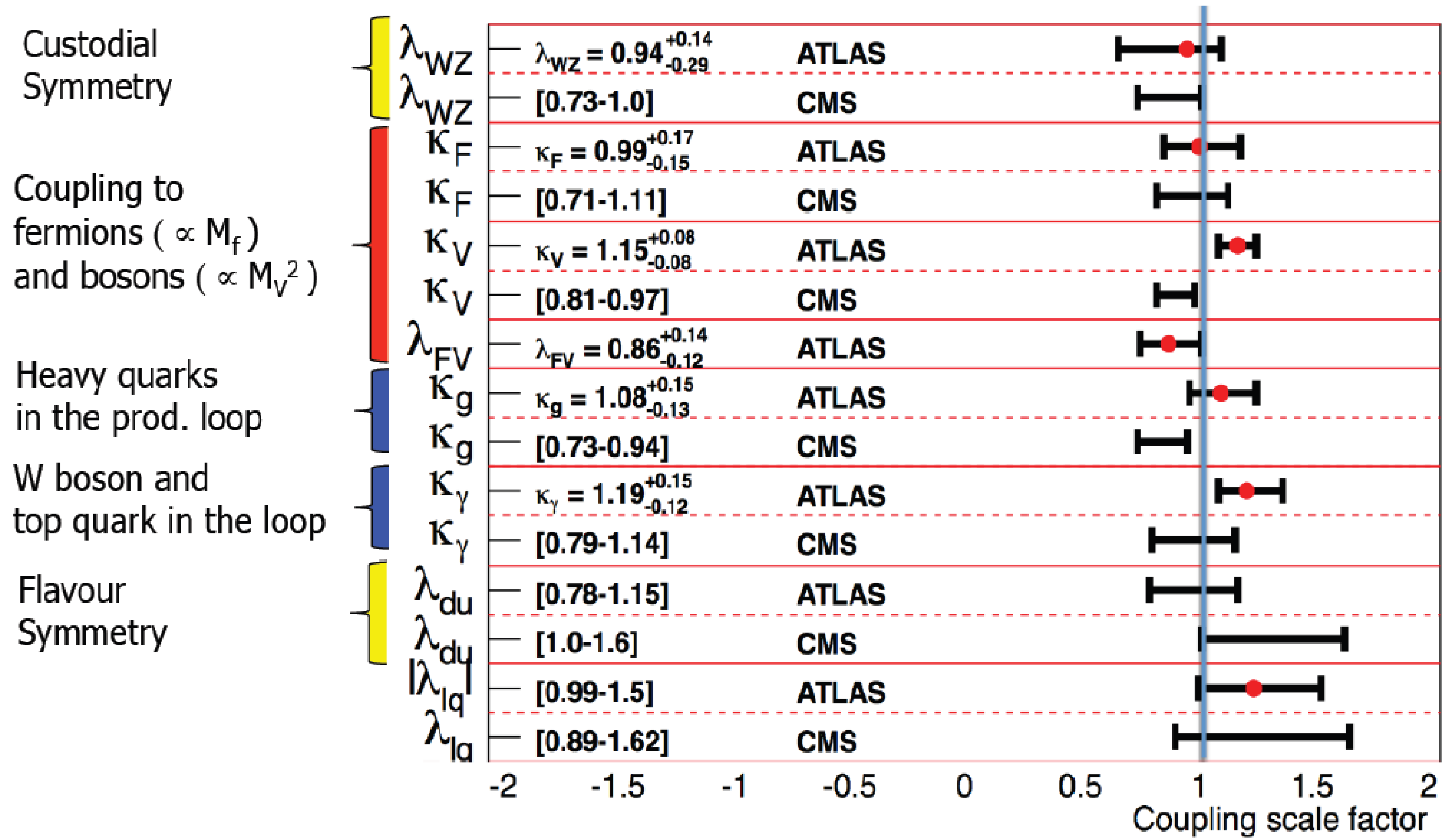
This ratio is INDEPENDENT of the decay channel so we can combine



Probe the production mode

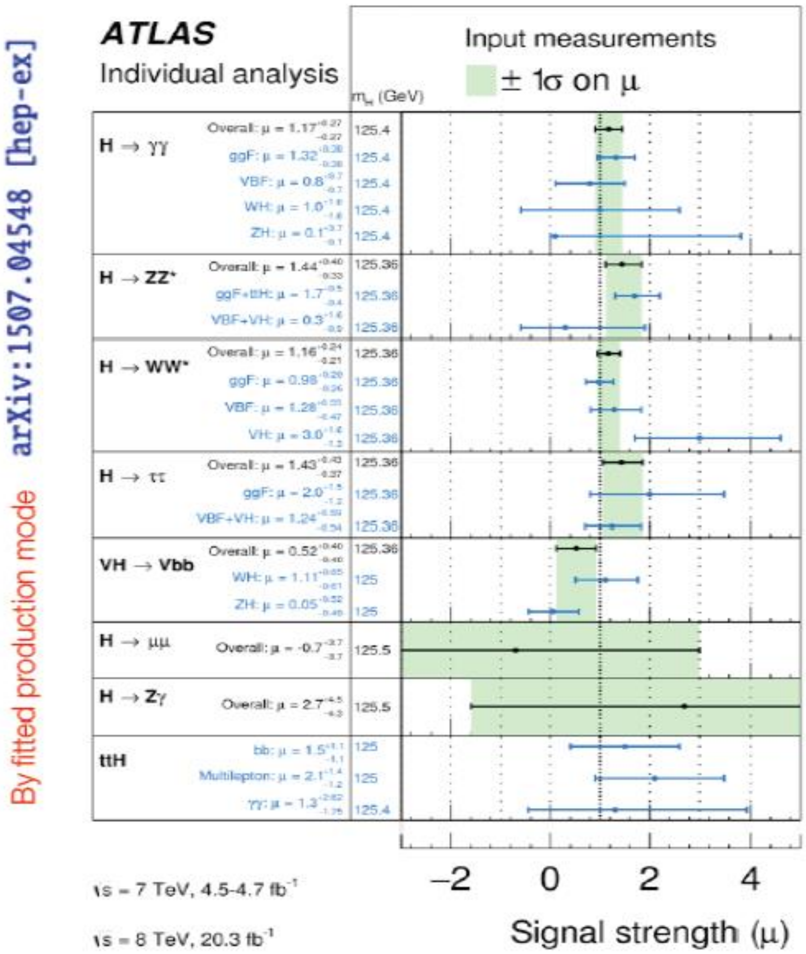


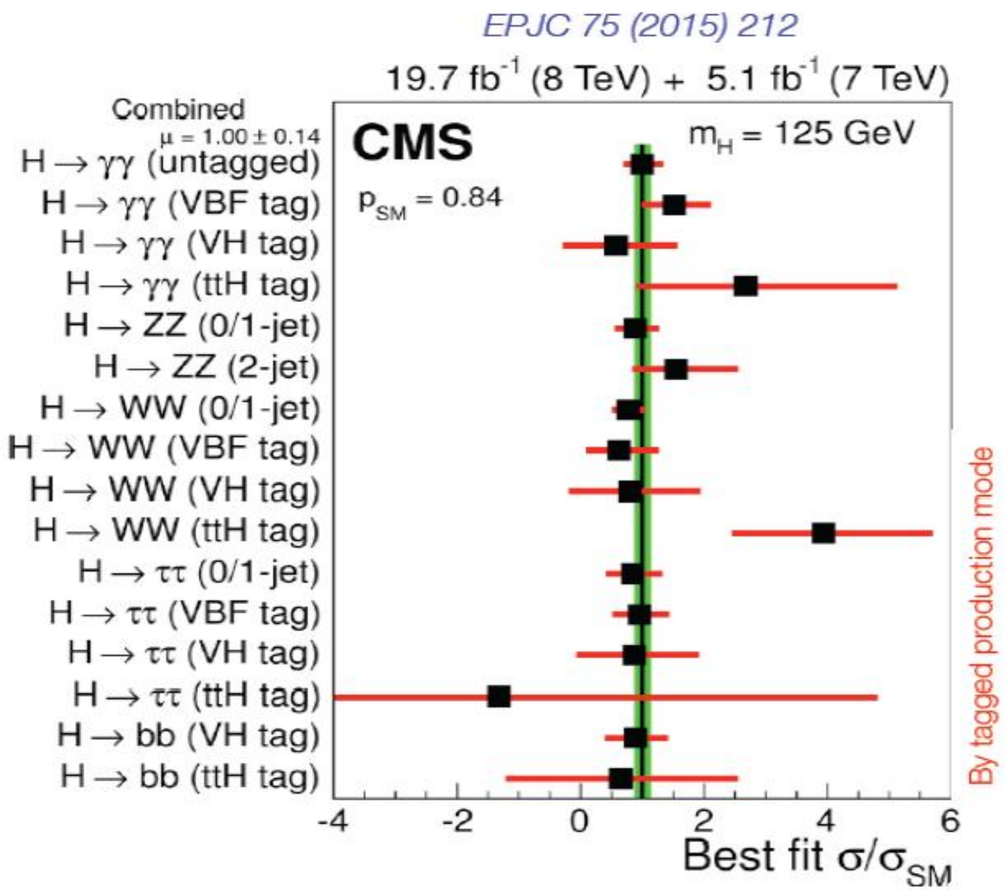
Overall comparison of all couplings results



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

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

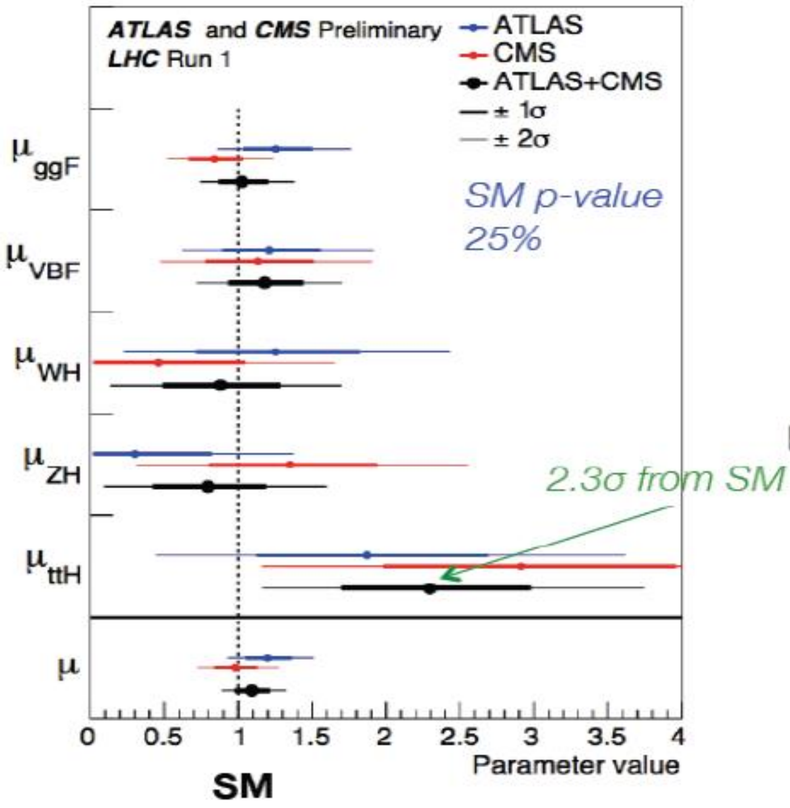
Most precise result at the expense of the largest assumptions

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

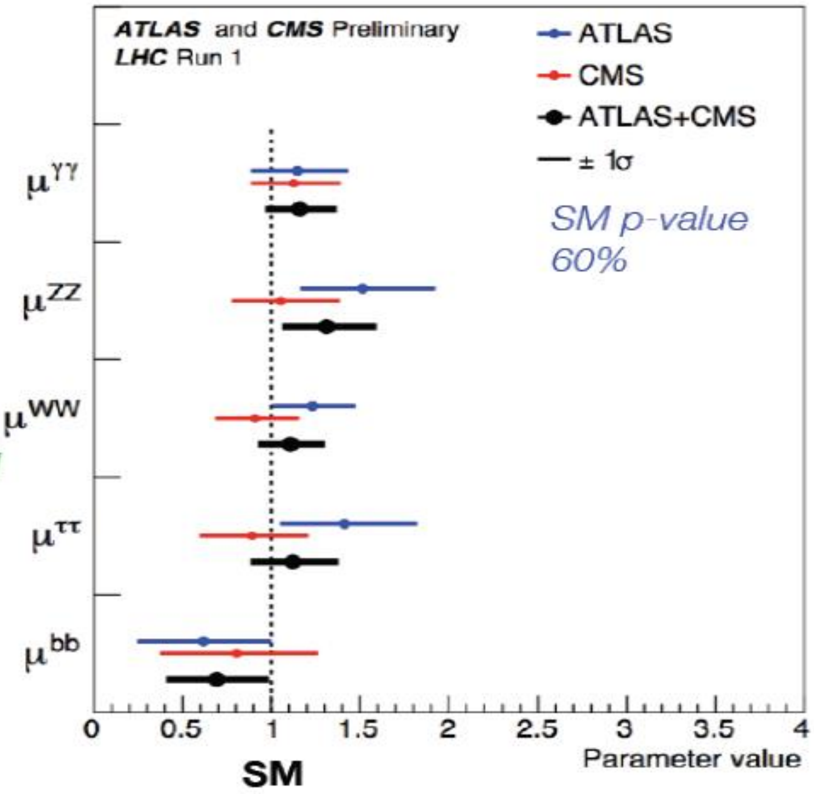
Stat and Th.Sig of comparable size
(Th.Sig dominated by ggF cross-section uncertainty)

Signal strength by production and decay mode

Production signal strengths
(SM values of BRs assumed)

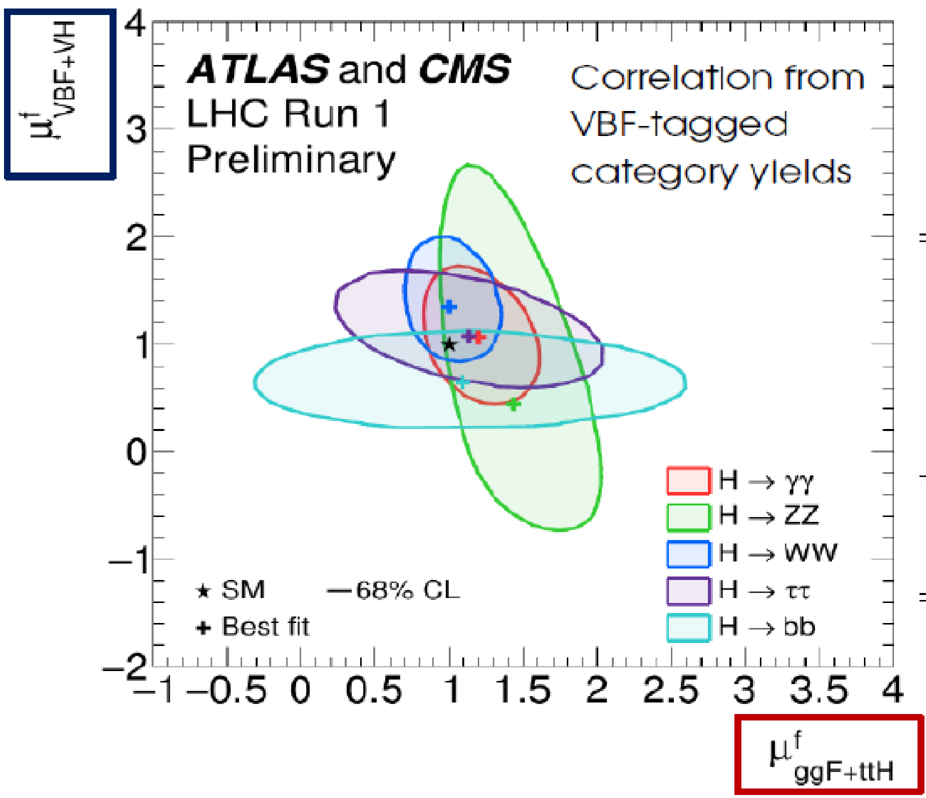


Decay signal strengths
(SM value of production σ's assumed)



Signal strength in V, F mediated

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



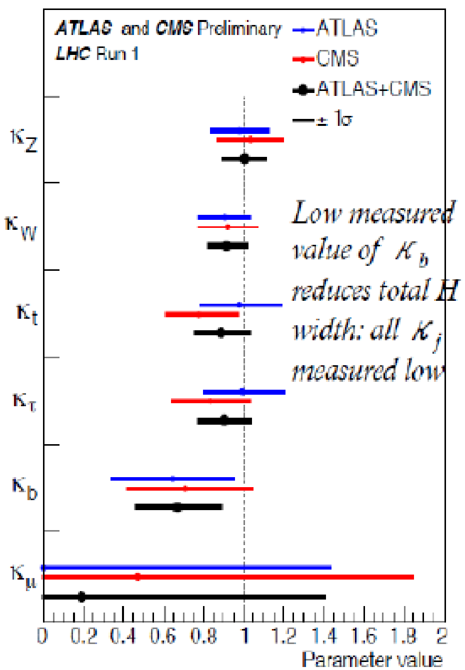
$$\mu_V / \mu_F = 1.06^{+0.35}_{-0.27}$$

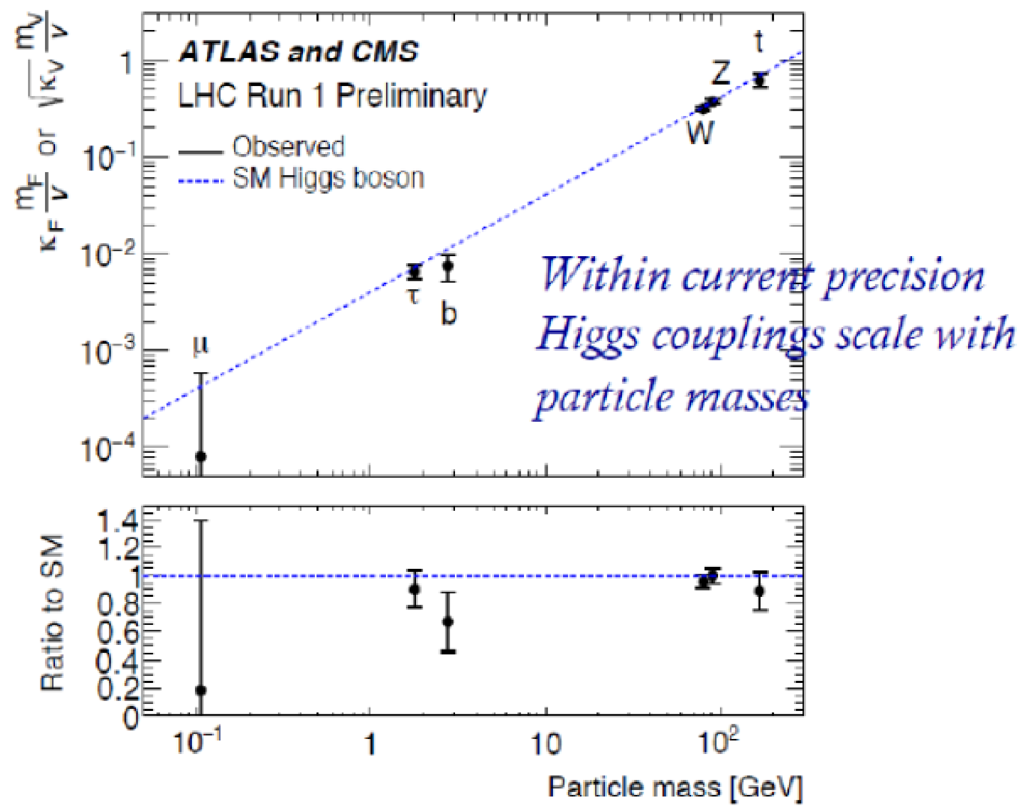
Production process	Measured significance (σ)
VBF	5.4
WH	2.4
ZH	2.3
VH	3.5
ttH	4.4
Decay channel	
$H \to \tau\tau$	5.5
$H \to b\bar{b}$	2.6

New!

Constrain 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%**