Introduction to particle physics: experimental part

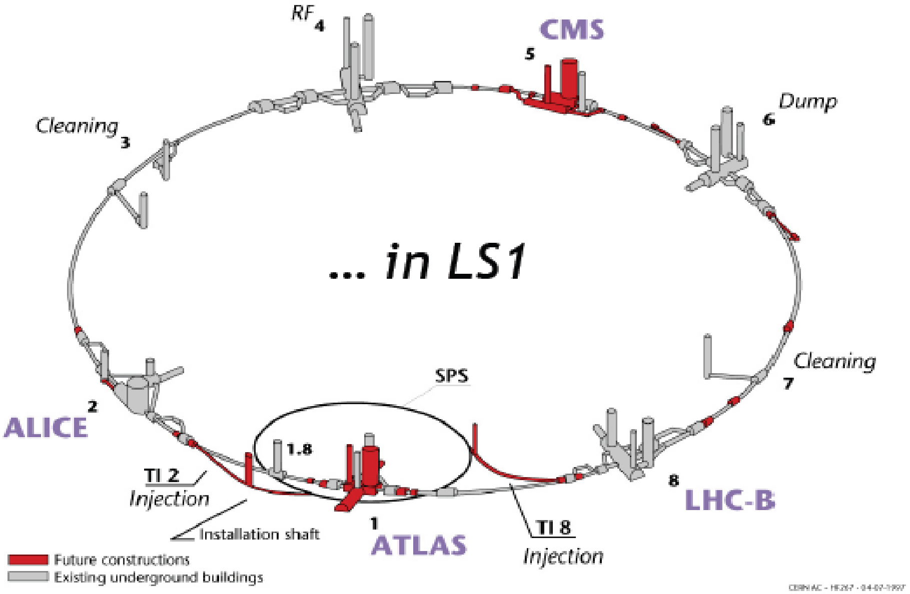
Discovery of the Higgs boson

Measurements: mass, spin, couplings

Prof. dr hab. Elżbieta Richter-Wąs

Three years of LHC operations

Energy frontier



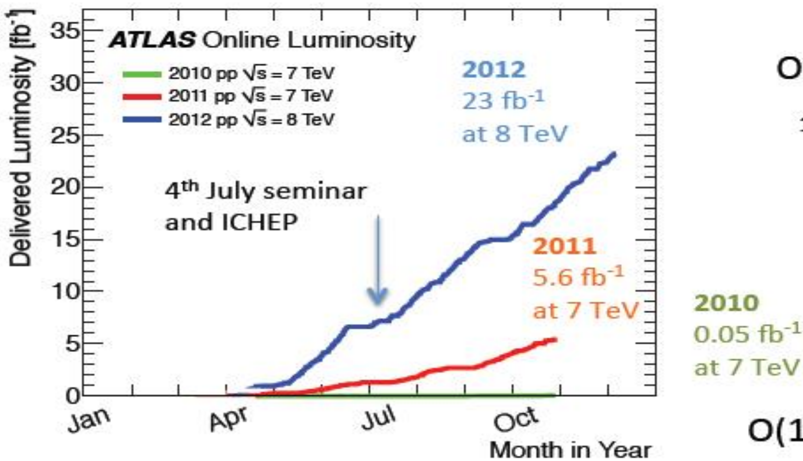
The LHC

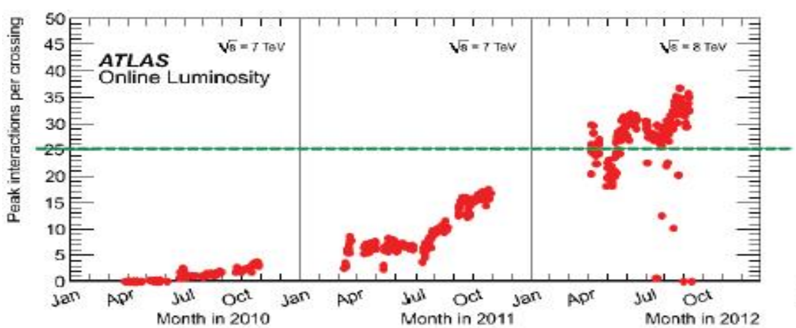
- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

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

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





2010

O(2) Pile-up events

150 ns inter-bunch spacing

2011

O(10) Pile-up events

50 ns inter-bunch spacing

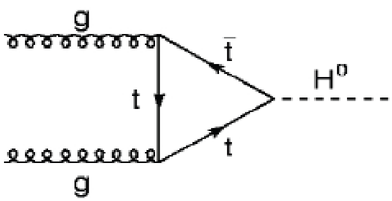
Design value
(expected to be
reached at L=10^{34} !)

2012

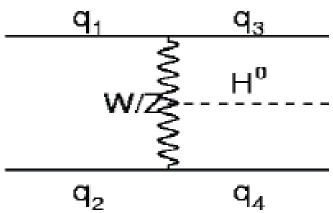
O(20) Pile-up events

50 ns inter-bunch spacing

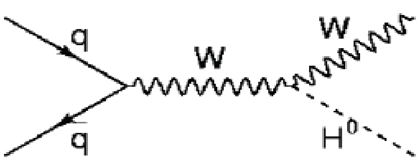
SM Higgs production at the LHC



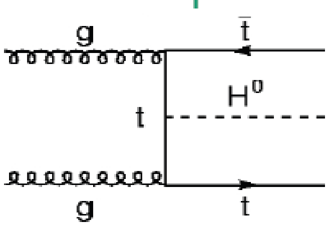
gluon fusion (ggF)



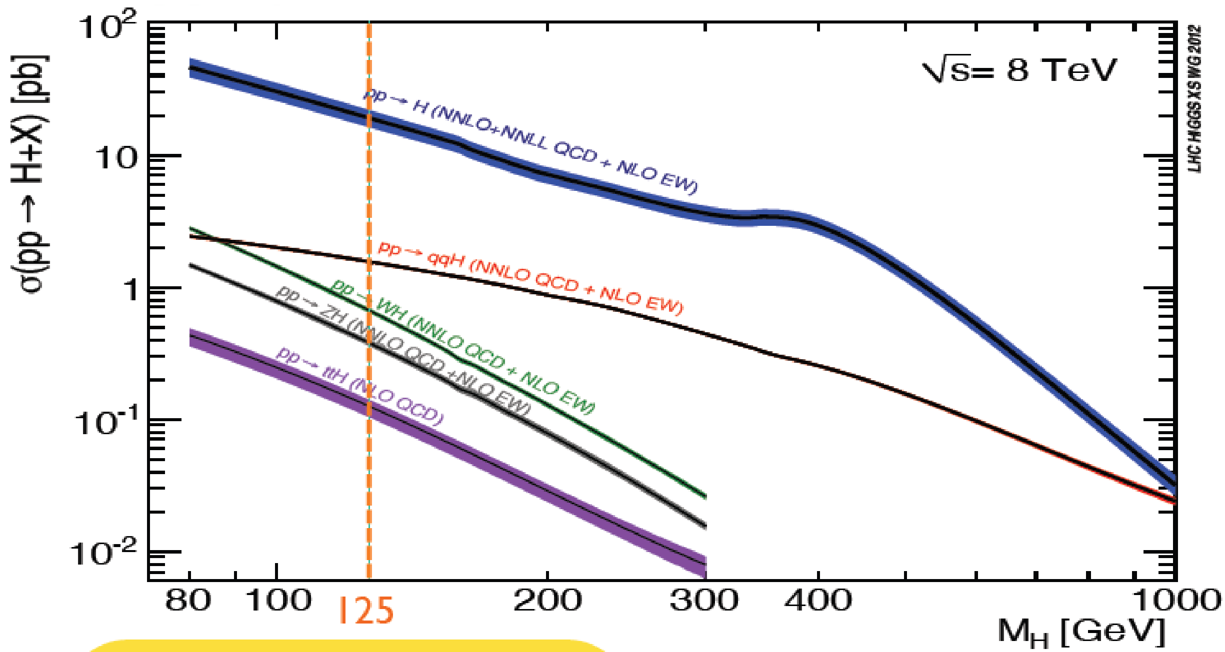
Vector-Boson-Fusion (VBF)



associated production (W, Z)

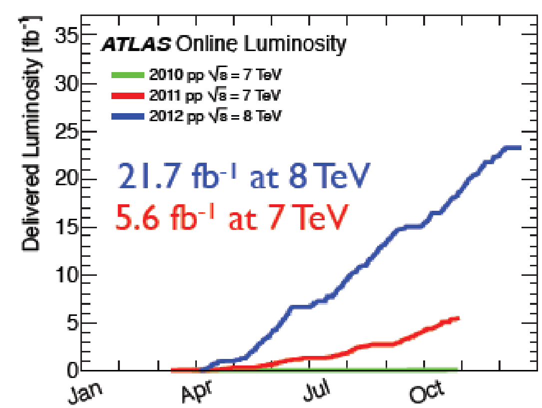


associated production (ttbar)

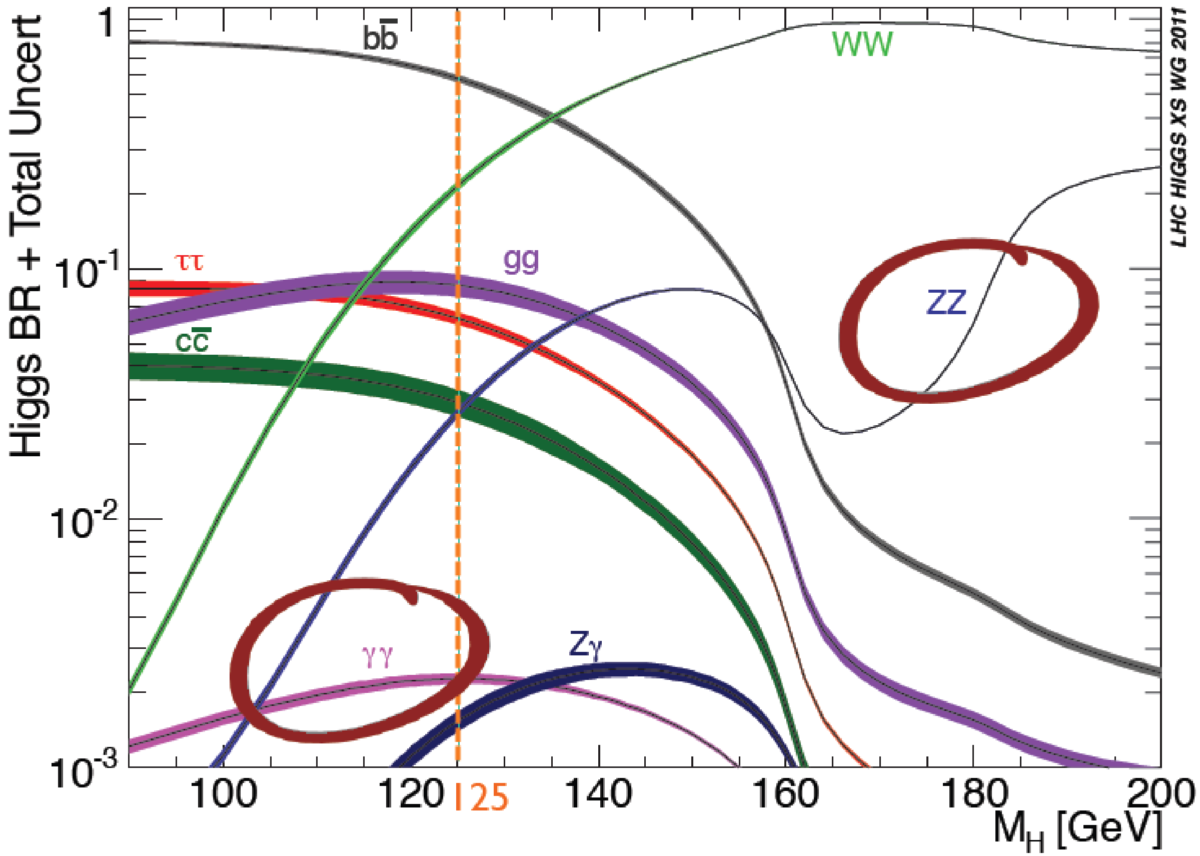


σ(125 GeV) = 22.3 pb

2 Higgs bosons @ m_H 125 GeV produced at LHC in 2012 every 10^{10} pp collisions



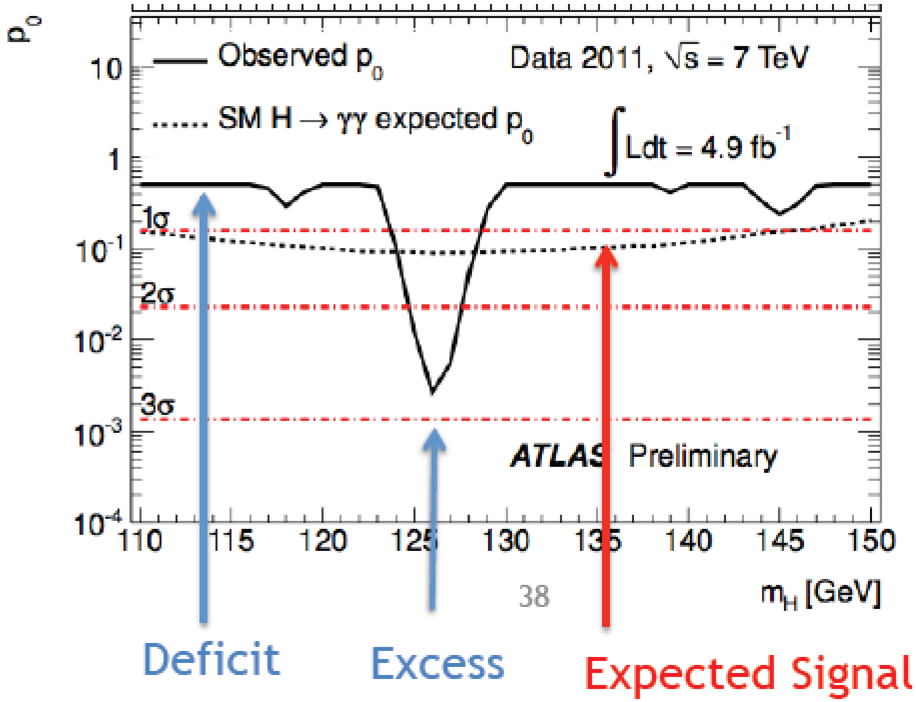
SM Higgs decays



- 1 Higgs every 10 s
- 1 $H \to \gamma\gamma$ every 1.5 h
- 1 $H \to ZZ \to 4\ell$ (ℓ = e or μ) every 2 days

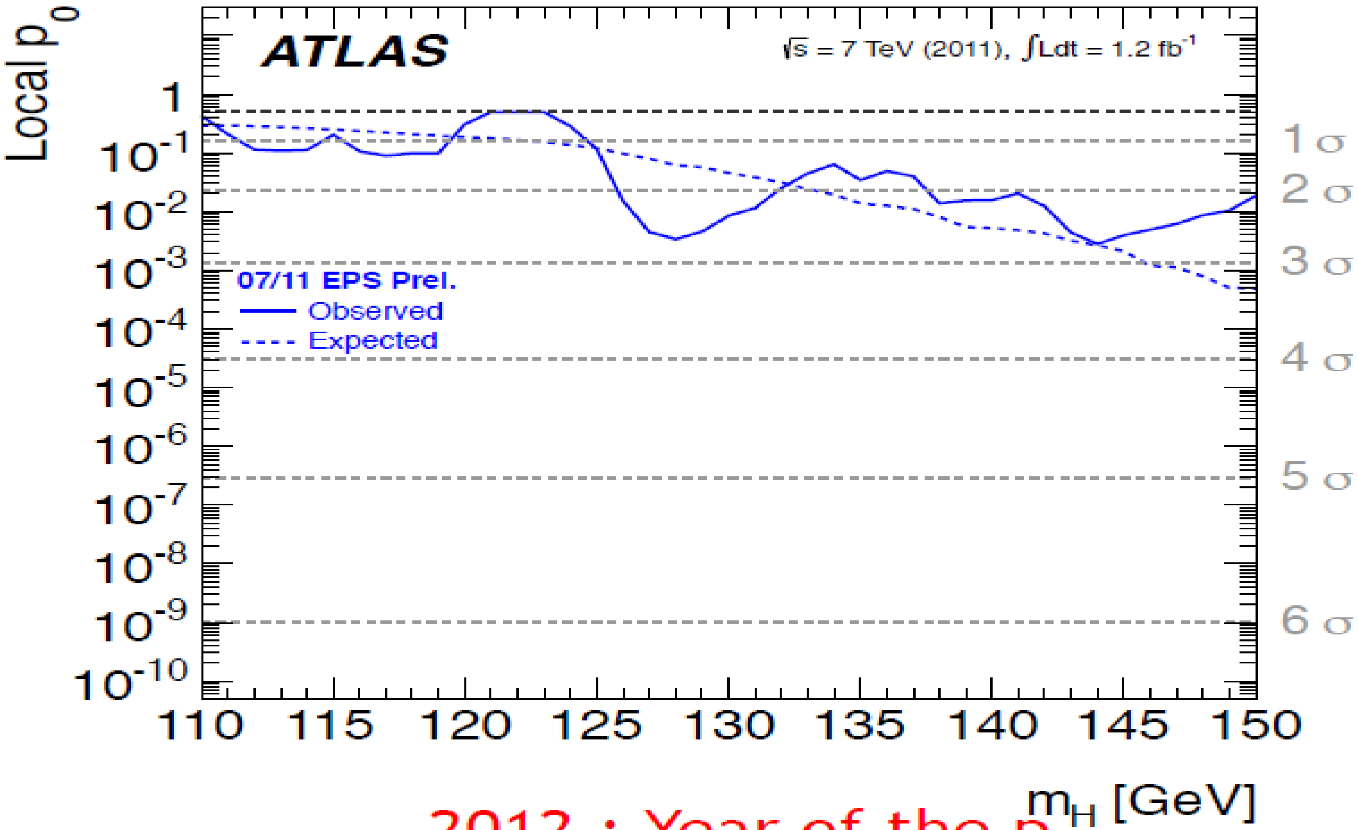
Local p_0

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.



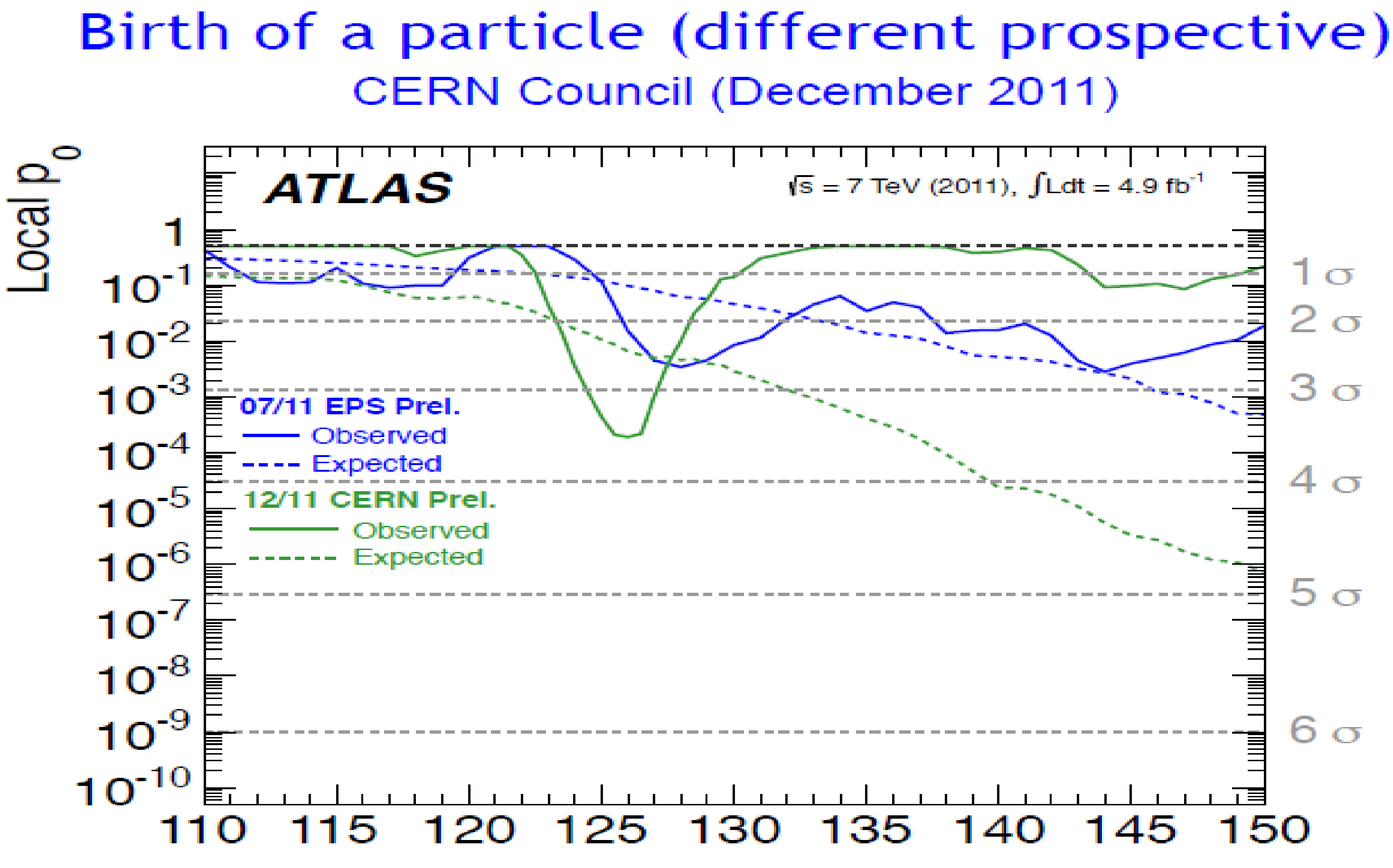
Since conference EPS 2011

Birth of a particle (different prospective)



2012 : Year of the p_0

Since conference EPS 2011

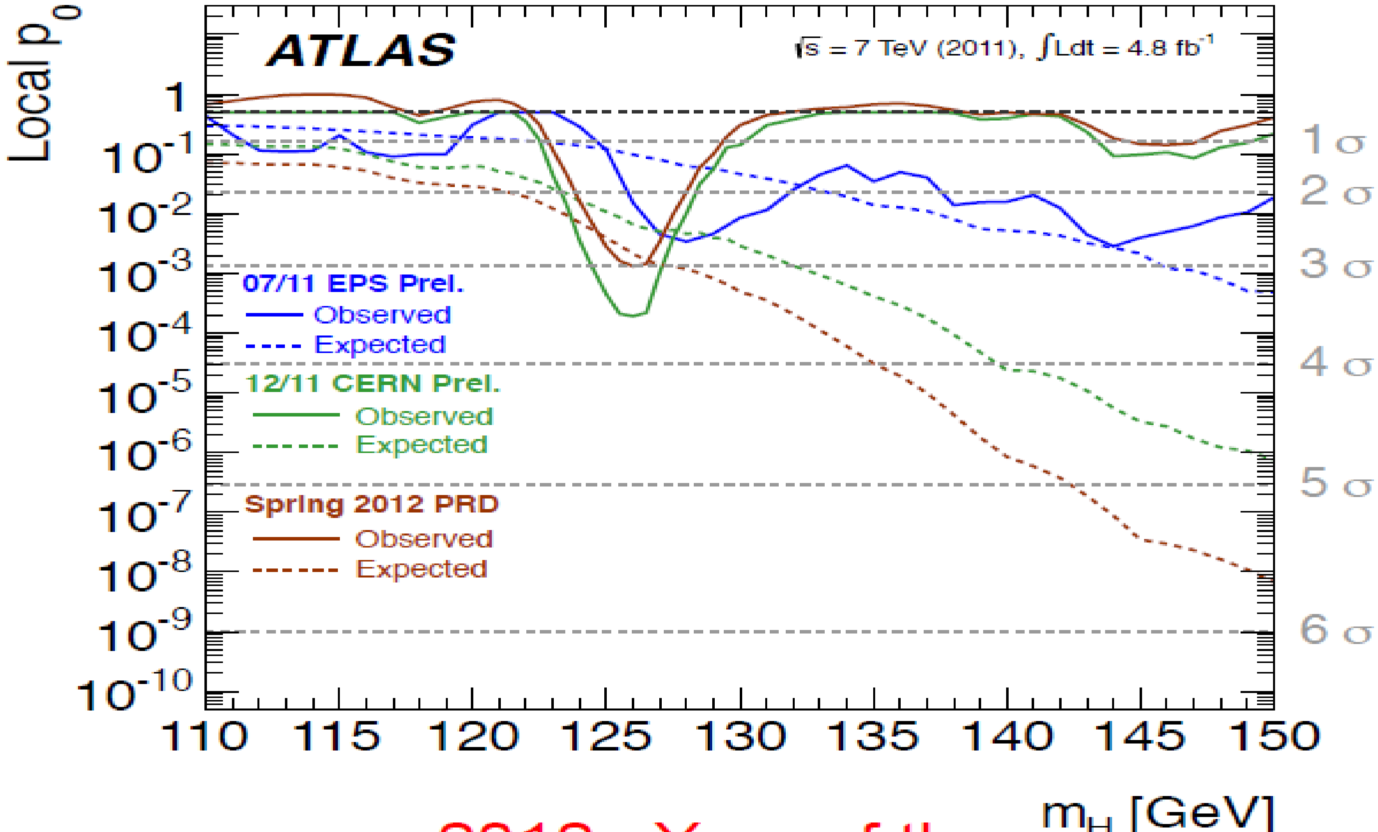


2012 : Year of the p_0

Since conference EPS 2011

Birth of a particle (different prospective)

Moriond (March 2012)

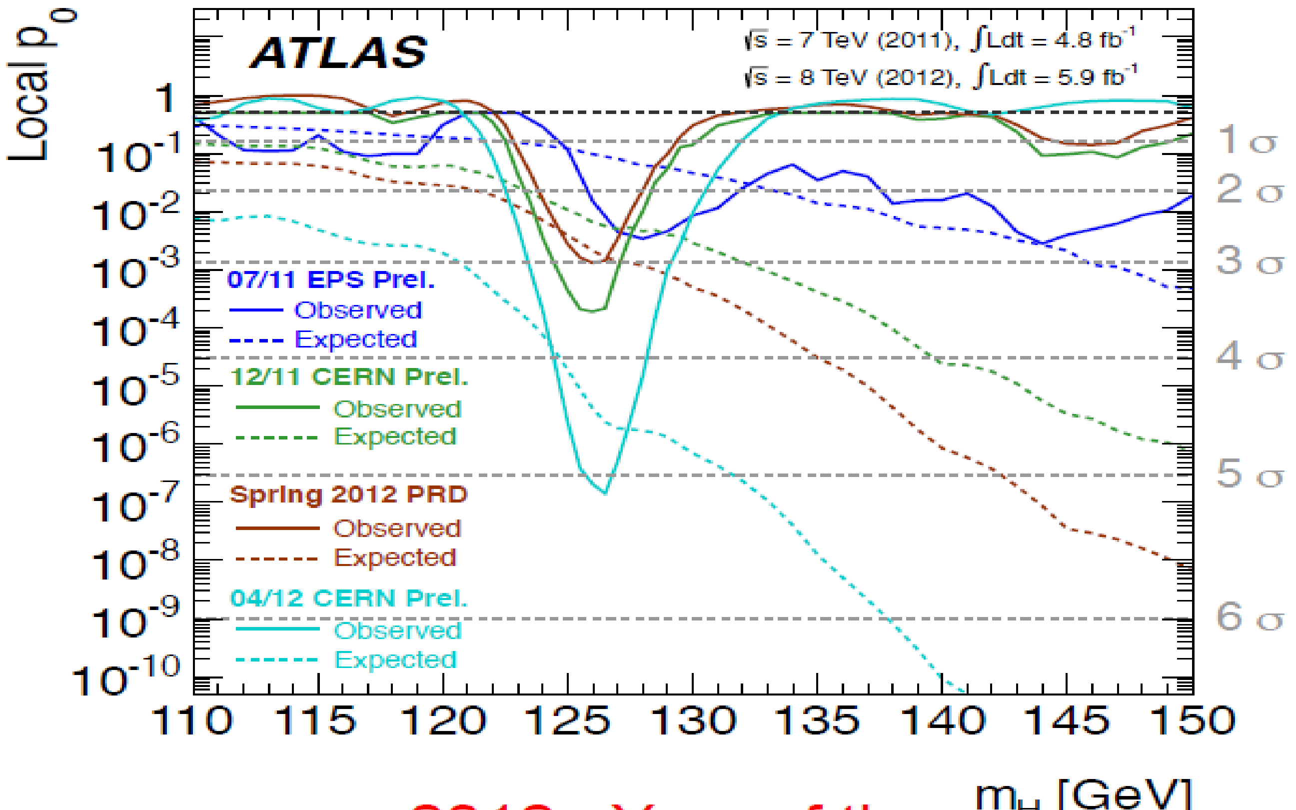


2012 : Year of the p_0

Since conference EPS 2011

Birth of a particle (different prospective)

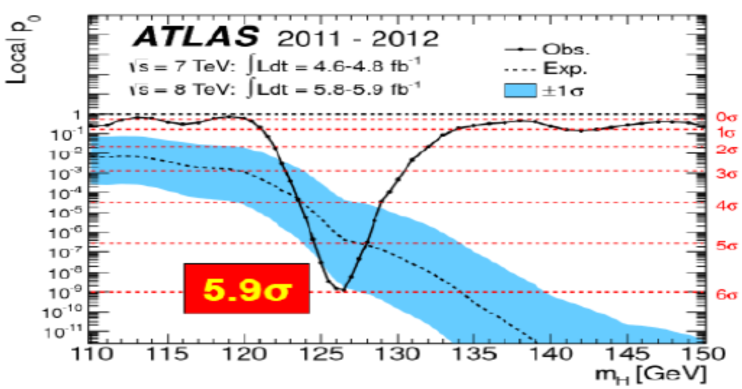
ICHEP (July 2012)

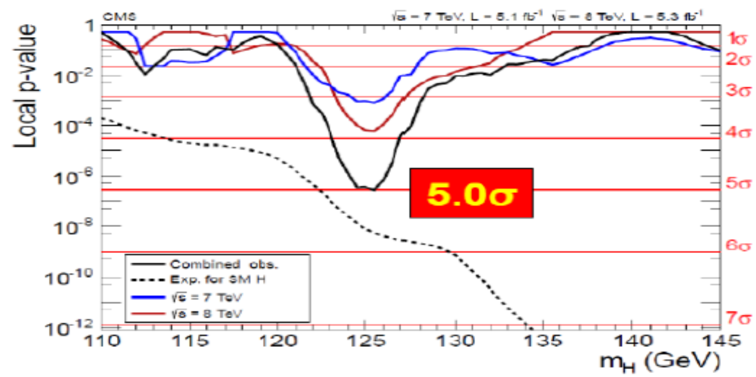


2012 : Year of the p_0

Higgs-like particle

- 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 necessary.





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(lvlv, lvqq), ZZ(4l, llvv, llqq)

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

Largest local excess:

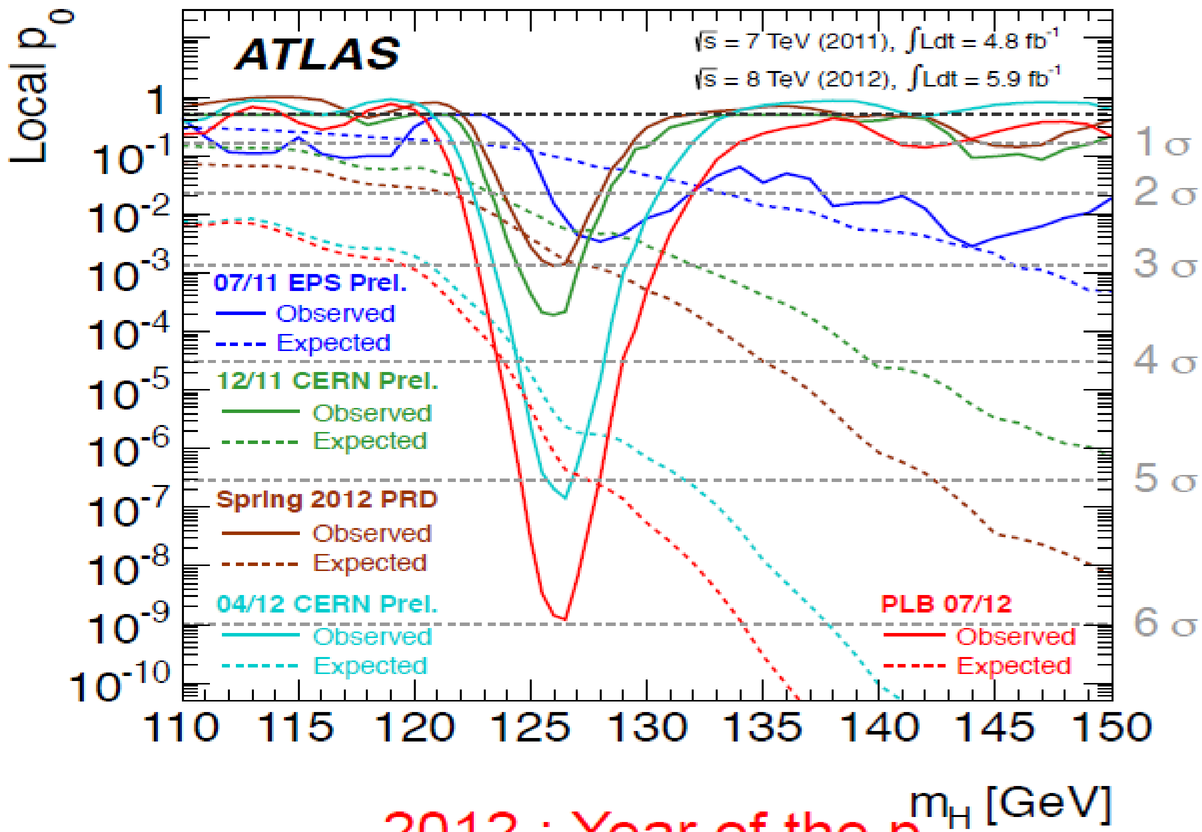
5.0σ at m_H= 125.5 GeV

H→γγ, bb, ττ, WW(lvlv), ZZ(4l, llττ, llvv, llqq)

Since conference EPS 2011

Birth of a particle (different prospective)

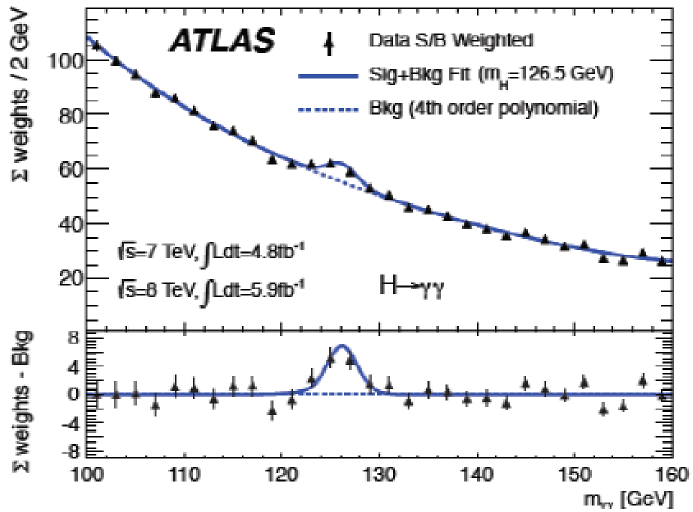
PLB (August 2012)

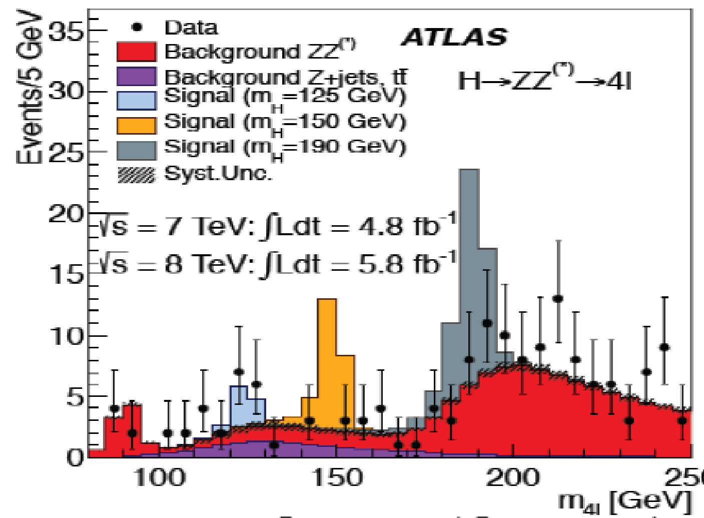


2012 : Year of the p_0

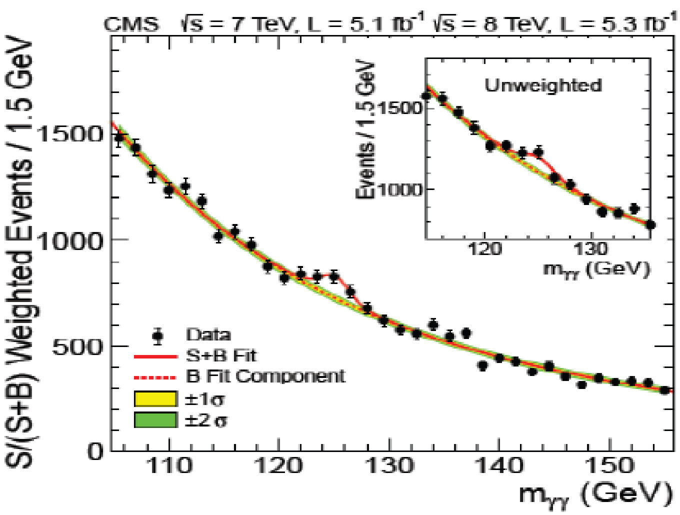
Higgs-like particle

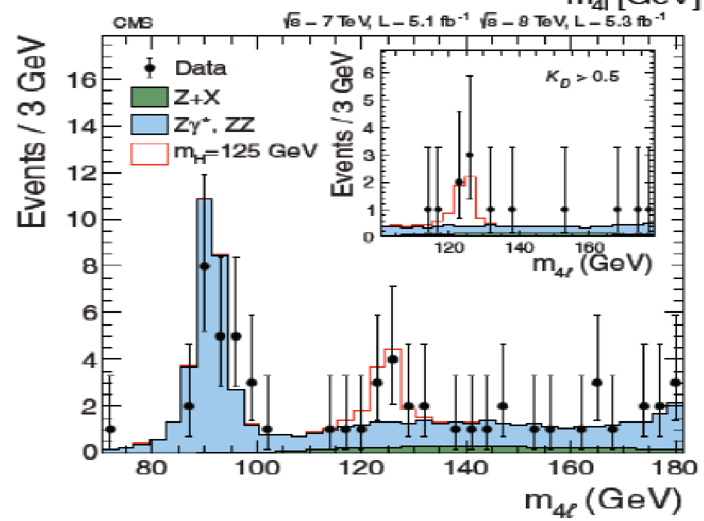
Phys.Lett. B716 (2012) 1-29



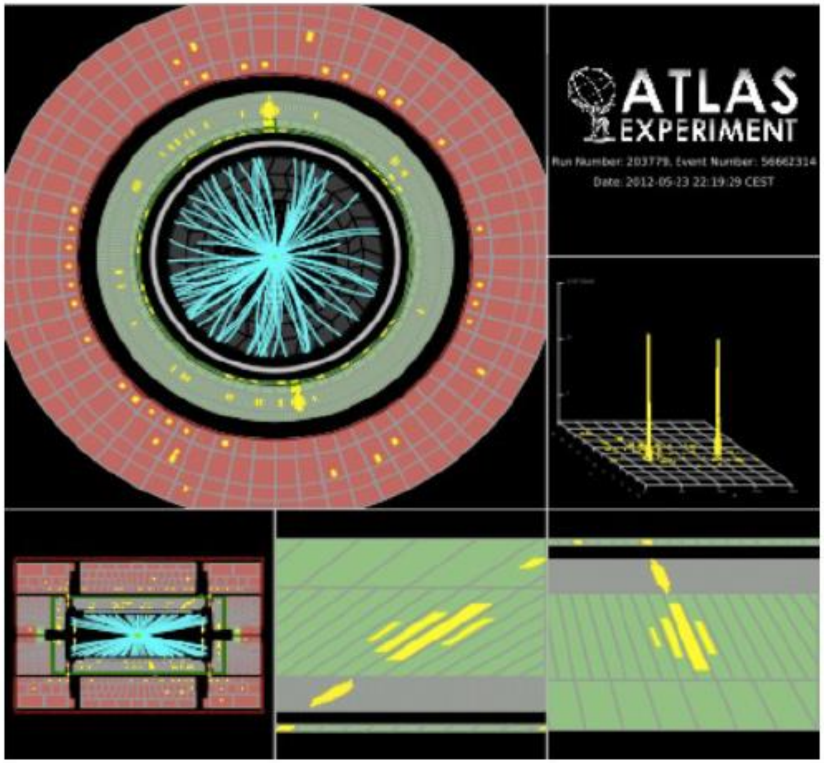


Phys.Lett. B716 (2012) 30-61





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

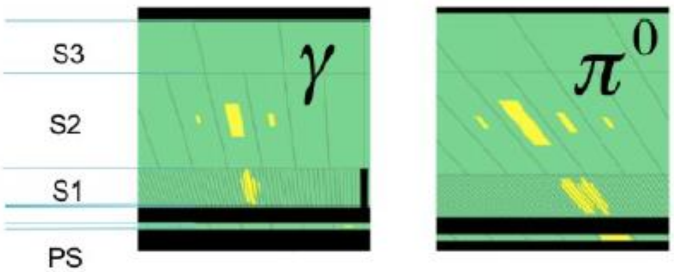
- ❑ **Good energy calibration**
- ❑ **Robust primary vertex reconstruction**

→ 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

π^0-γ Rejection



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

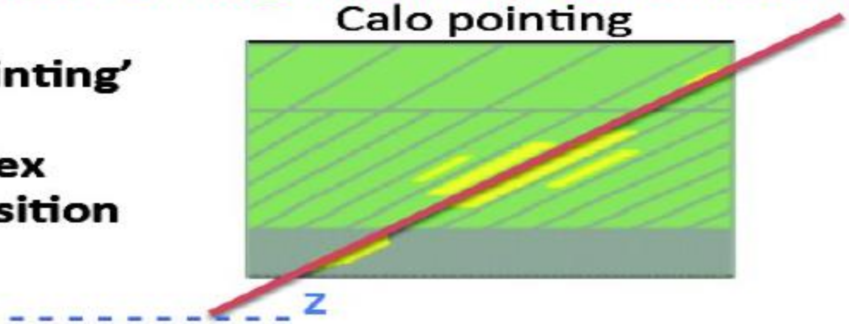
Vertex Reconstruction

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

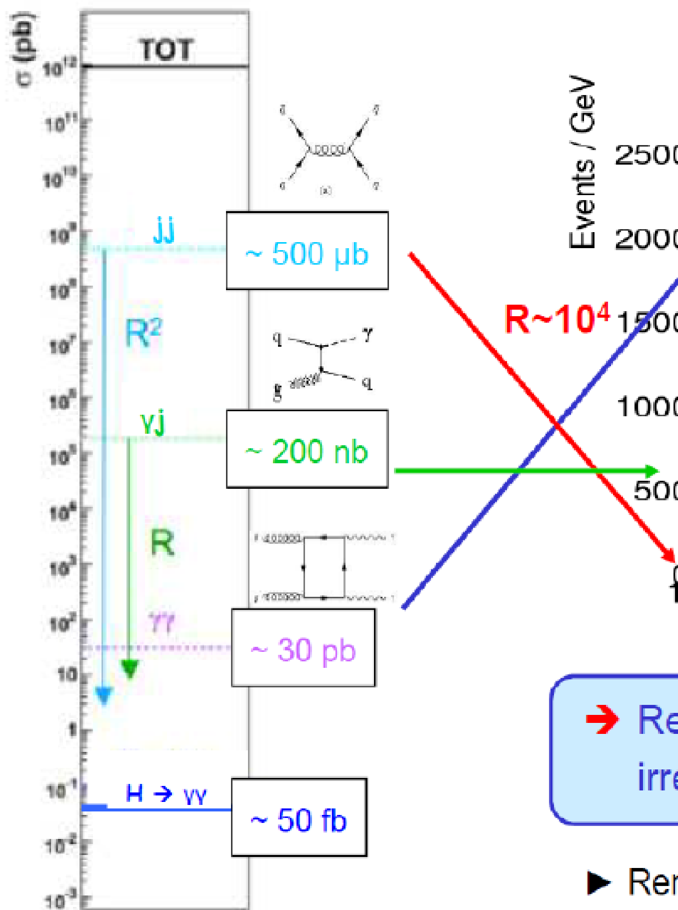
- ❑ **Vertex reconstructed through likelihood combination**

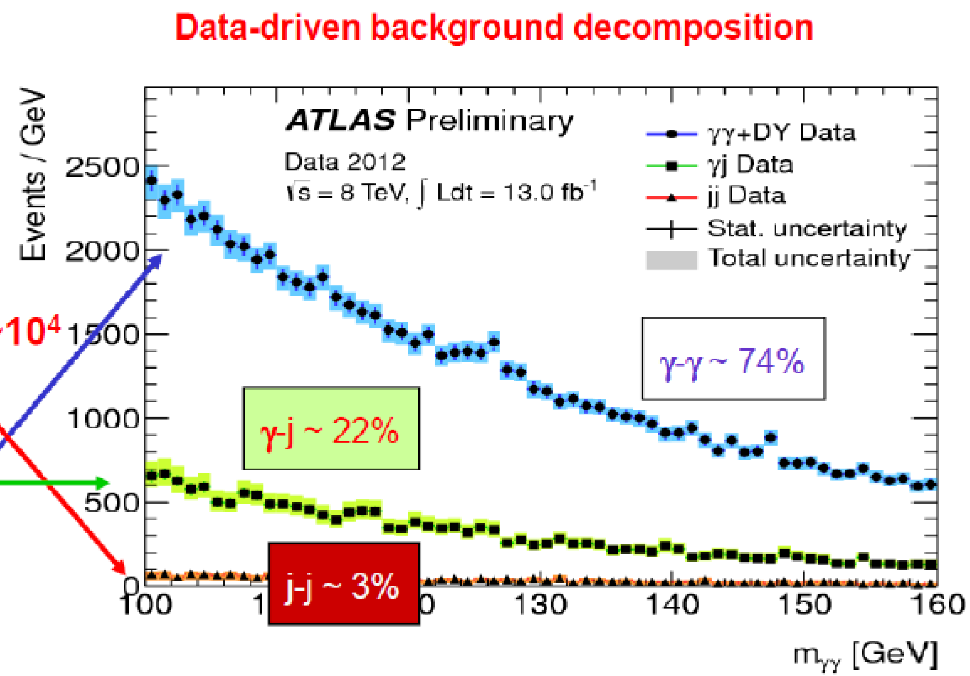
- **Calorimeter 'pointing'**
- **Σ tracks pT^2**
- **Conversion vertex**
- **Mean vertex position**

Calo pointing



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 categorisation

Event categories based on eta, pTt, and conversion

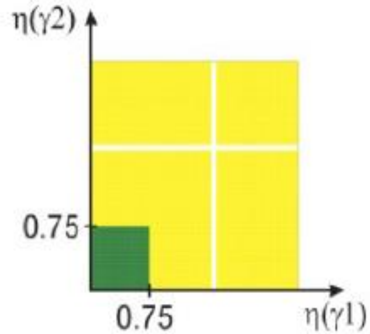
Both unconverted:

- Central
- Rest

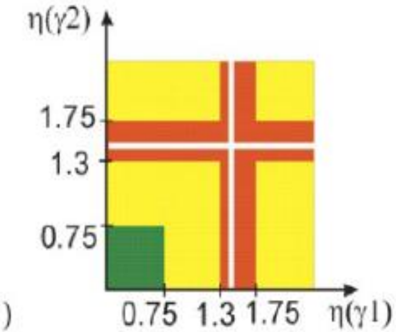
At least one converted:

- Central
- Transition
- Rest

2 unconverted:

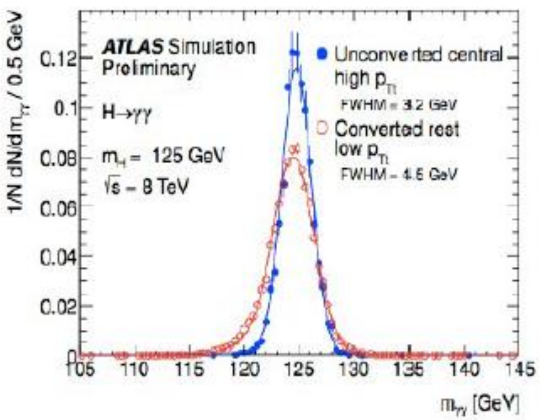


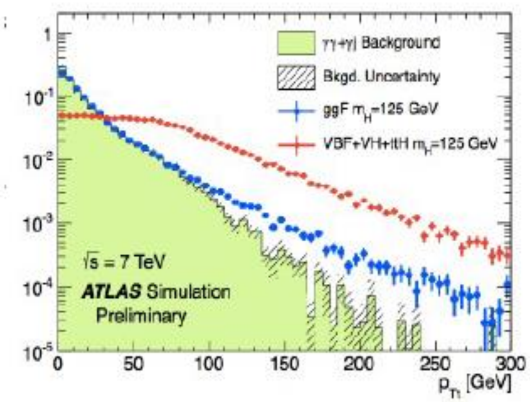
>=1 converted:



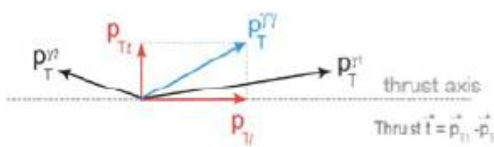
Resolution:

Good
Medium
Poor





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



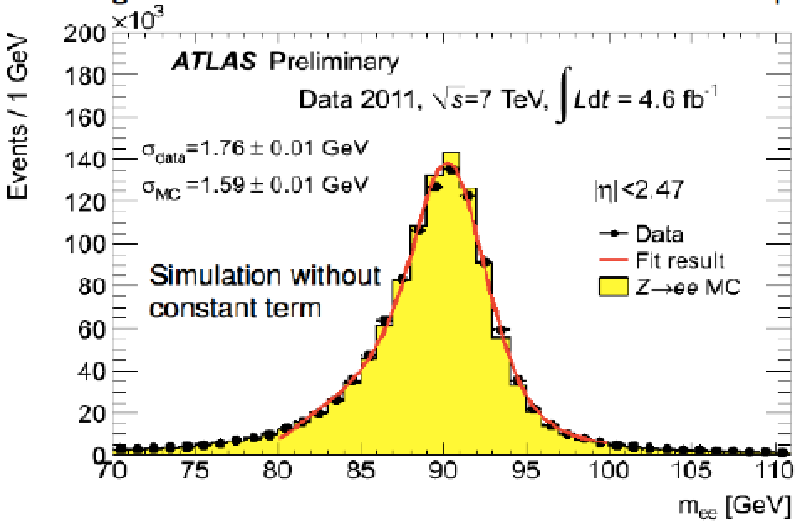
Energy calibration and resolution

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

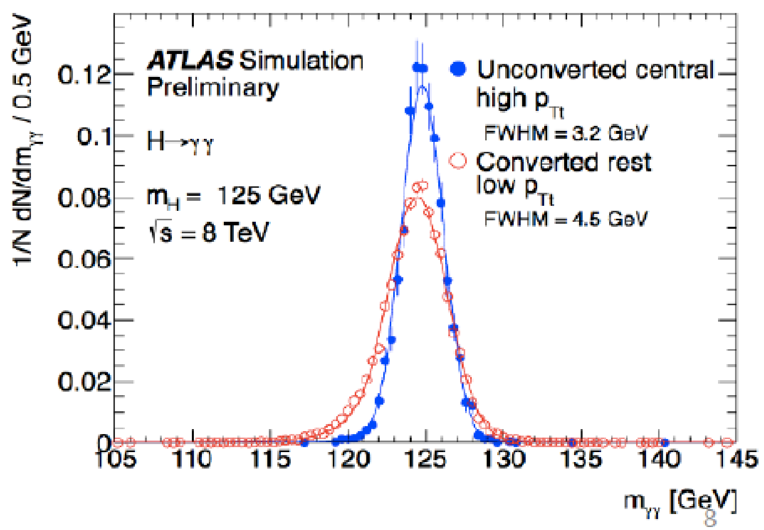
- MC based calibration improved with energy scale and resolution corrections based on in-situ analysis of Z→ee, W→eν and J/ψ → ee

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

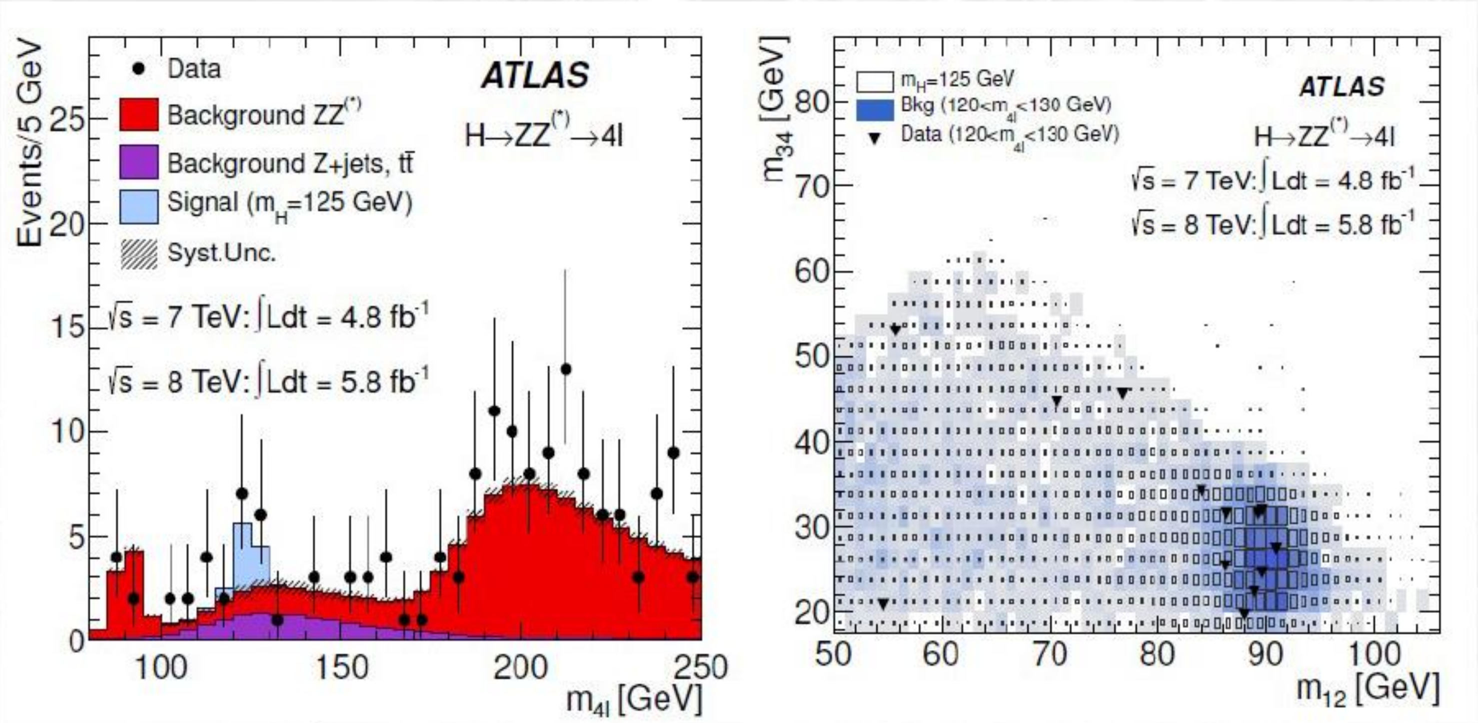
Agreement between data & MC Z→ee lineshape



Expected resolution of Higgs signal



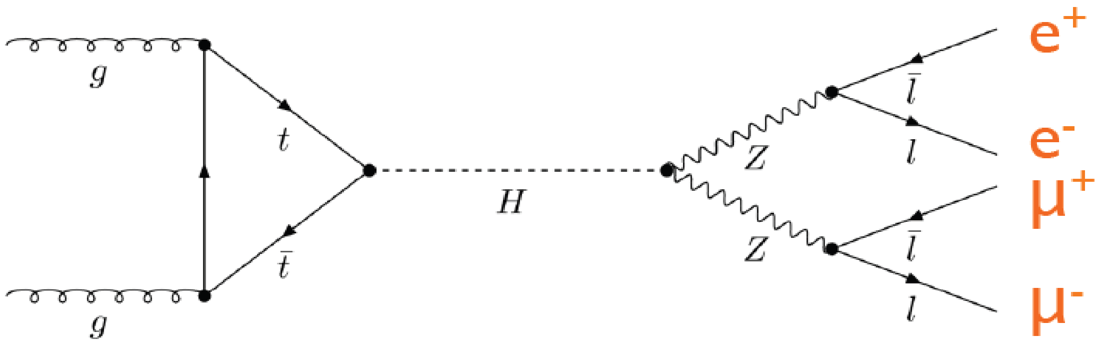
The golden channel Z->ll



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

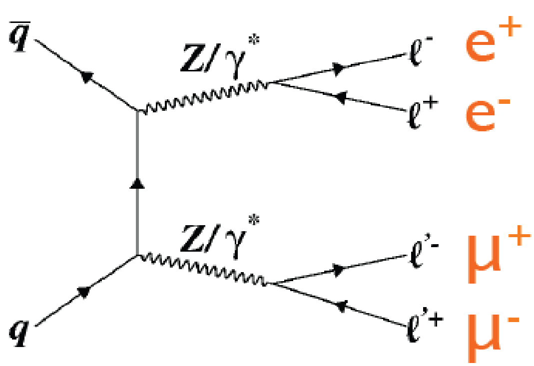
	Signal	$ZZ^{(*)}$	$Z+$ jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

Signal and background



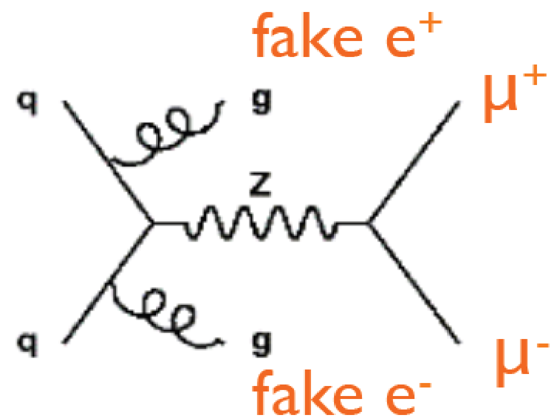
Irreducible background

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



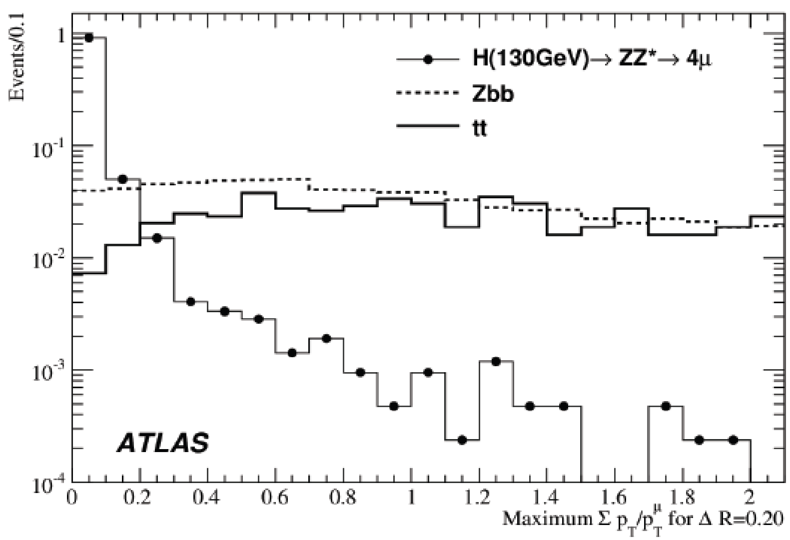
Reducible background

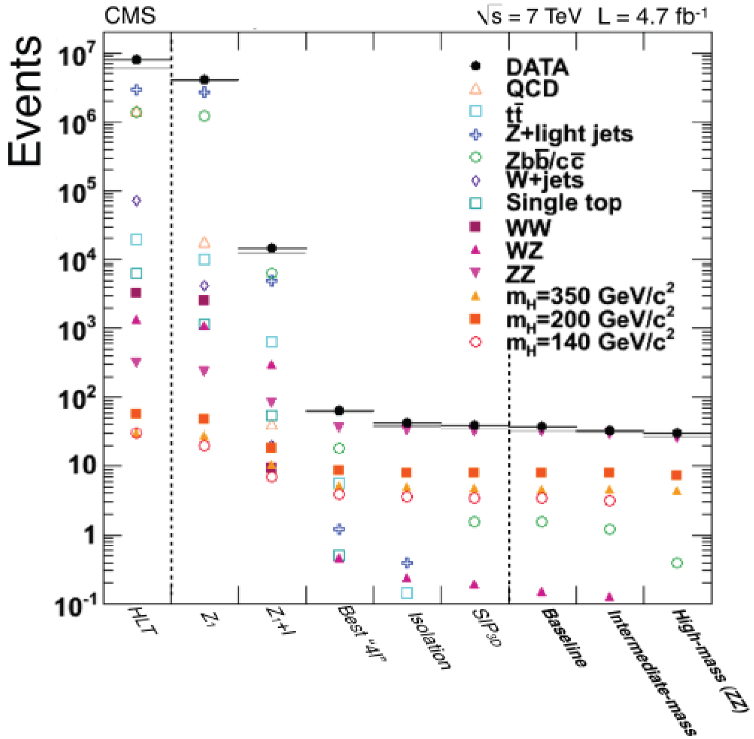
The final state looks like the same, but some f the particle fakes what you are looking for



Selection

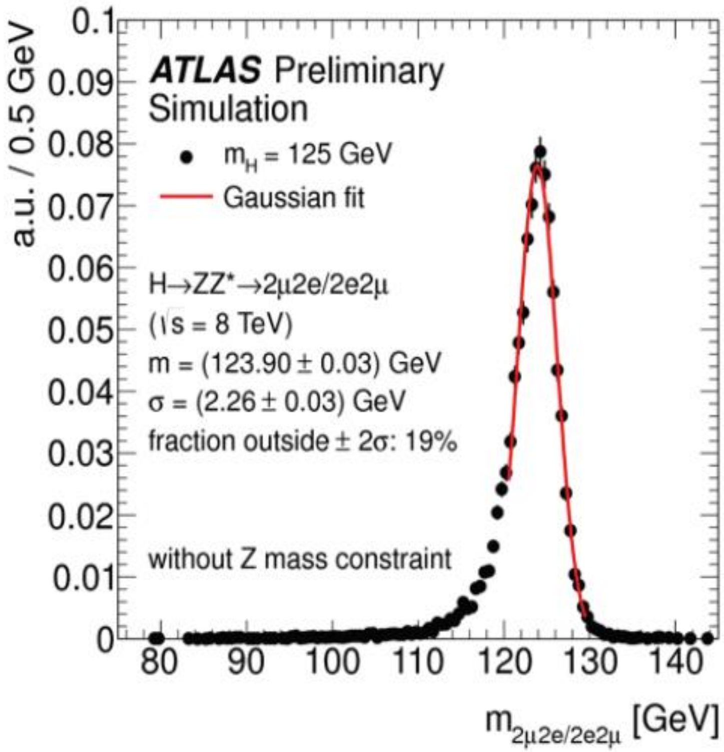
- Cut on particle properties to reduce reducible background
  - ✓ Shower shapes, track properties, …
- Cut on event properties to distinguish signal from background
  - ✓ Particle kinematics, decay kinematics event shape, …
- Try to keep signal while reducing background!
  - ✓ Increase S/B





Reconstruct properties of initial particles

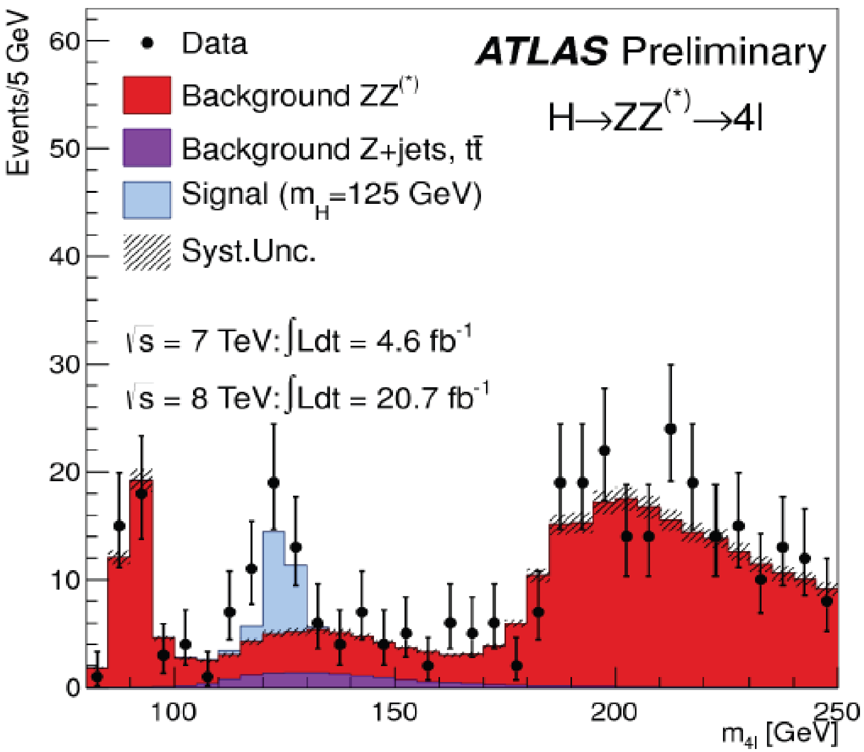
- We have 4 particles…
  - ✓ … with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^+\mu^-$
- Reconstruct invariant mass from the 4 particles $M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$



Signal and background

Background gets estimated…

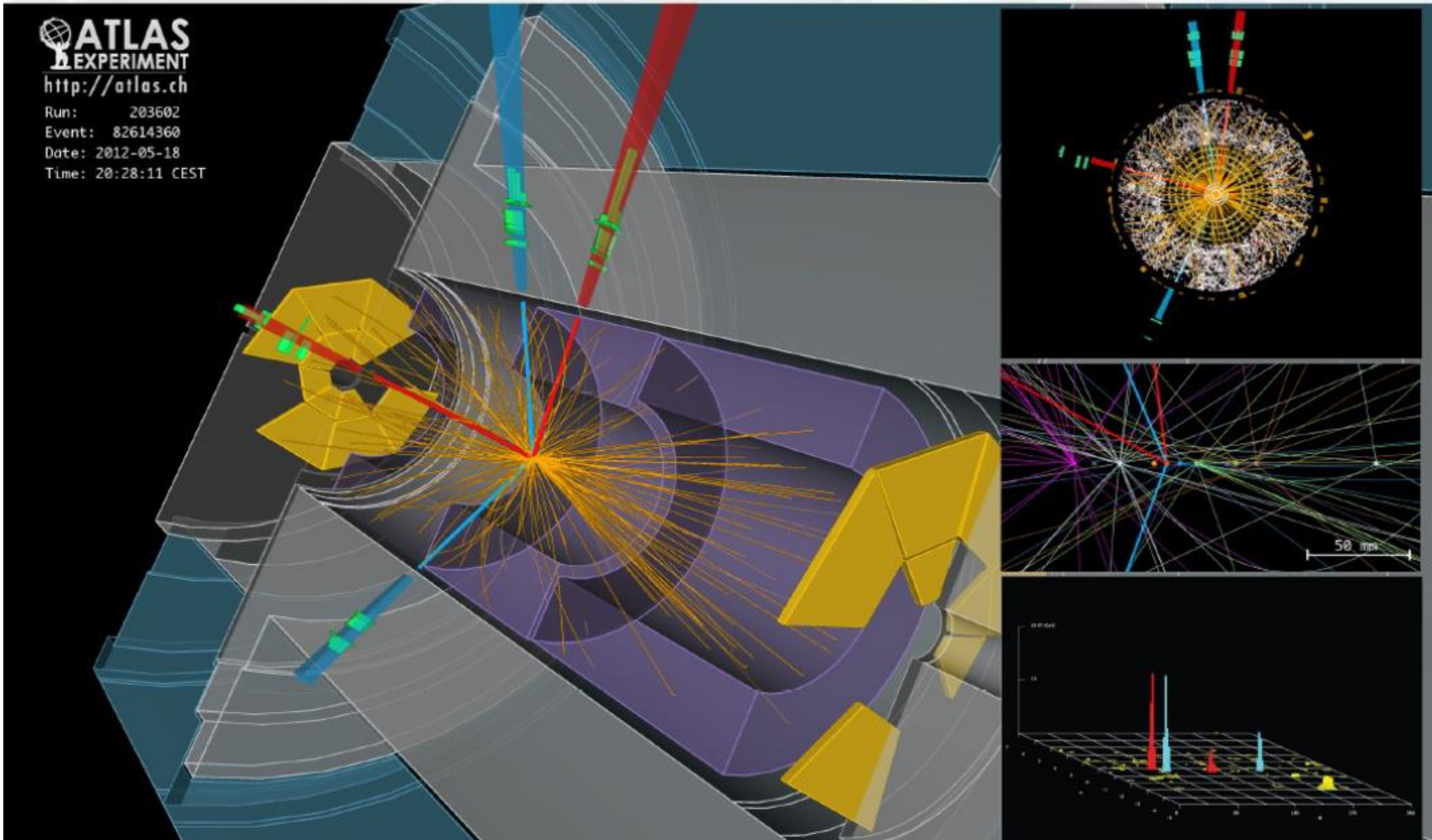
- ✓ … from simulation (normalized to data)
- ✓ … directly from data ("control regions", enriched in background events)



$4e$ 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, $\eta = -0.40$, $\phi = 1.69$

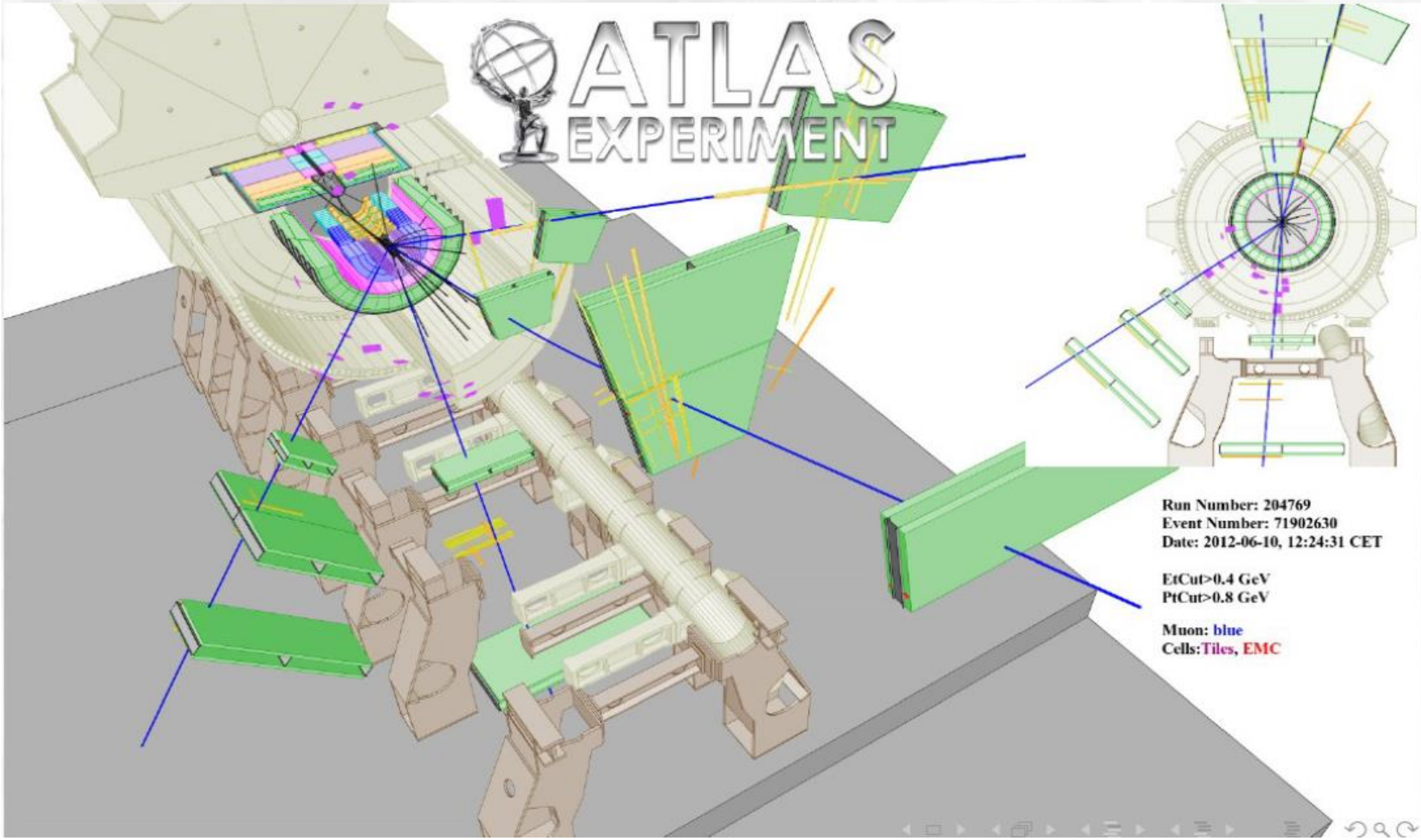
e_3: $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$ e_4: $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$



4μ candidate. $m_{4\ell} = 125.1$ GeV, $m_{12} = 86.3$ GeV, $m_{34} = 31.6$ GeV.

μ_1: $P_T = 36.1$ GeV, $\eta = 1.29$, $\phi = 1.33$ μ_2: $P_T = 47.5$ GeV, $\eta = 0.69$, $\phi = -1.65$

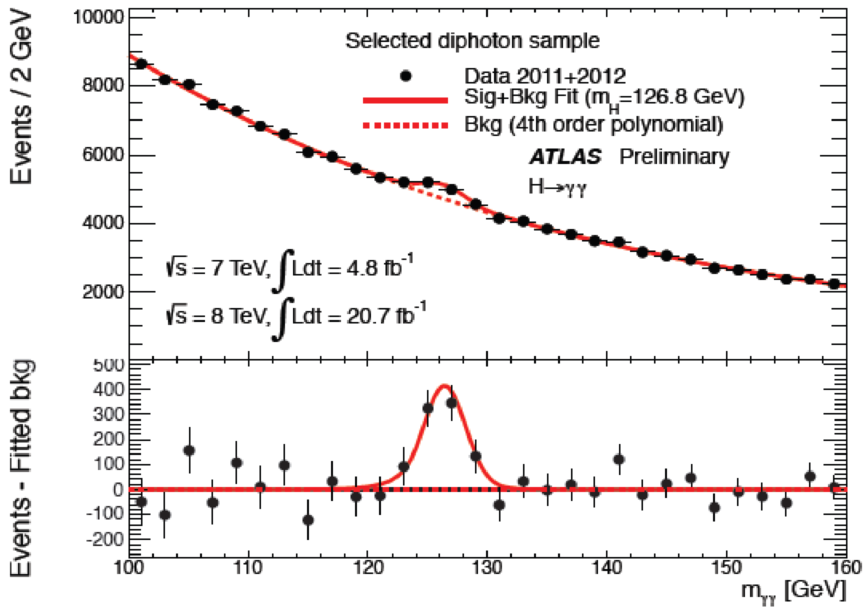
μ_3: $P_T = 26.4$ GeV, $\eta = 0.47$, $\phi = -2.51$ μ_4: $P_T = 71.7$ GeV, $\eta = 1.85$, $\phi = 1.65$



Higgs like signal with 7 TeV and 8 TeV data

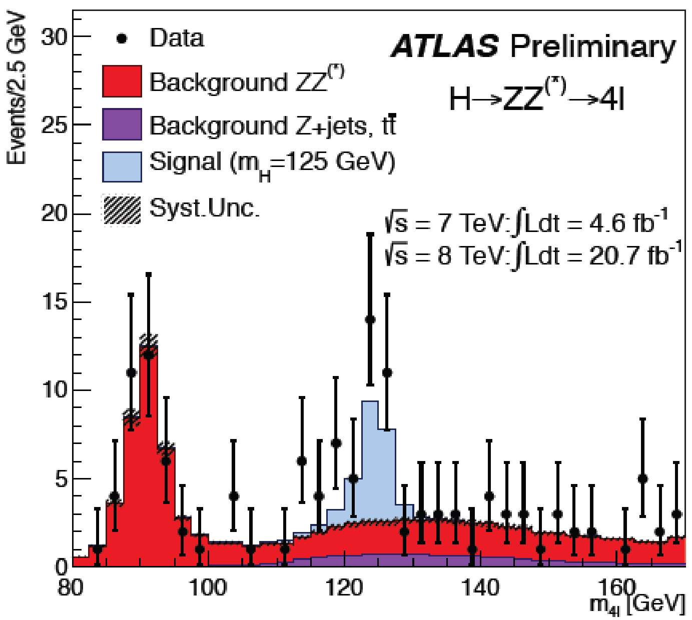
2013

H→γγ



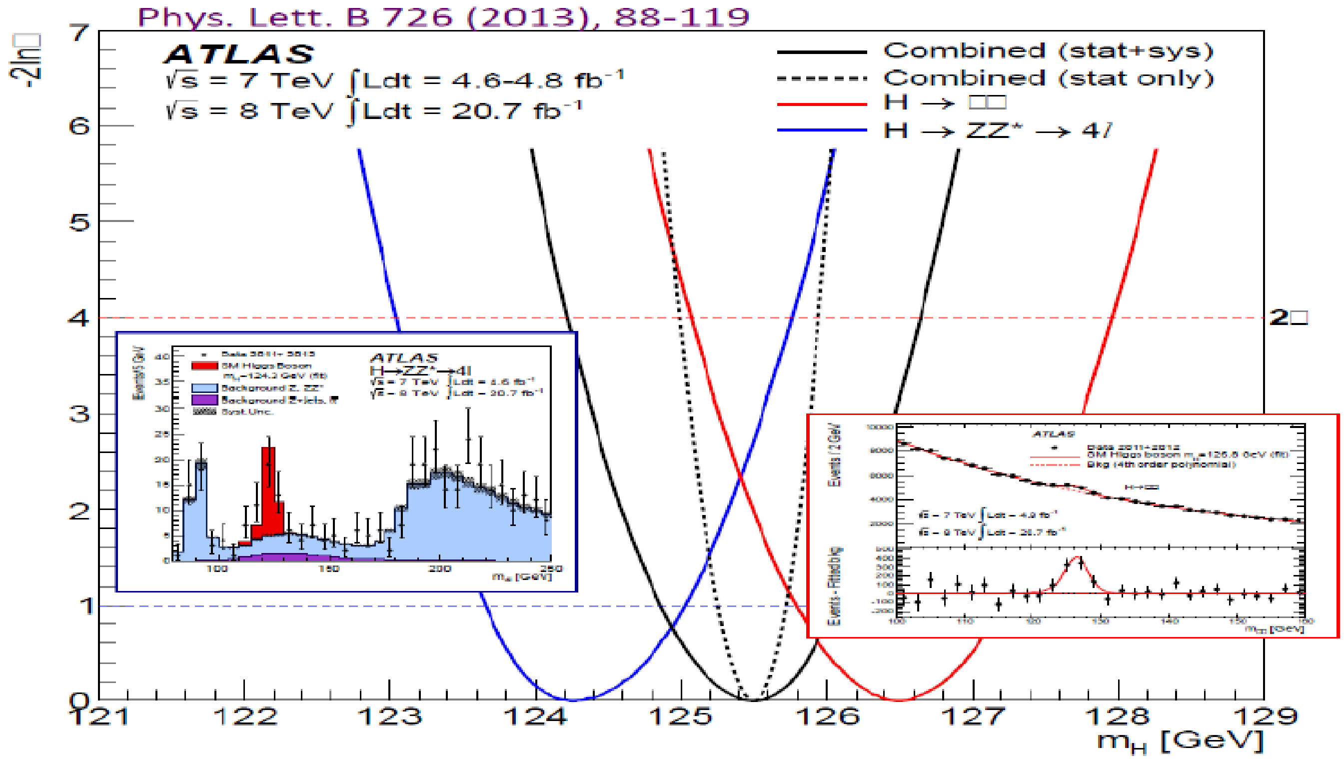
- Signal significance = 7.4 σ
- m_H = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
- μ = 1.65 ± 0.34 (deviation w.r.t. SM at 2.3σ)

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

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 …. (2013)

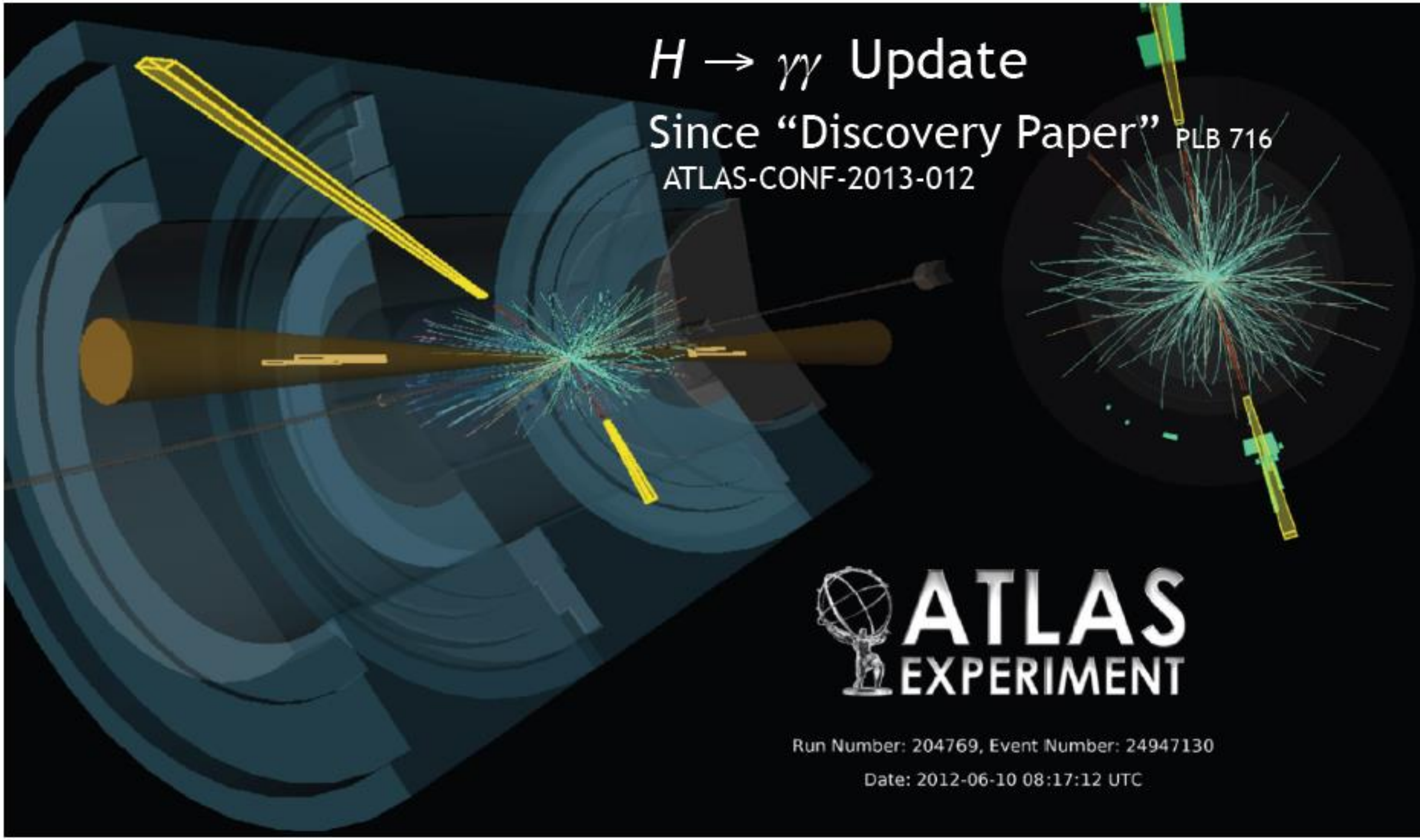
Panorama of ATLAS Higgs (125) Analyses

channel	ggF	VBF	VH	ttH	Yield	S/B (%)	Res. (GeV/c²)
$\gamma\gamma$	✓	✓	✓	✓	~ 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

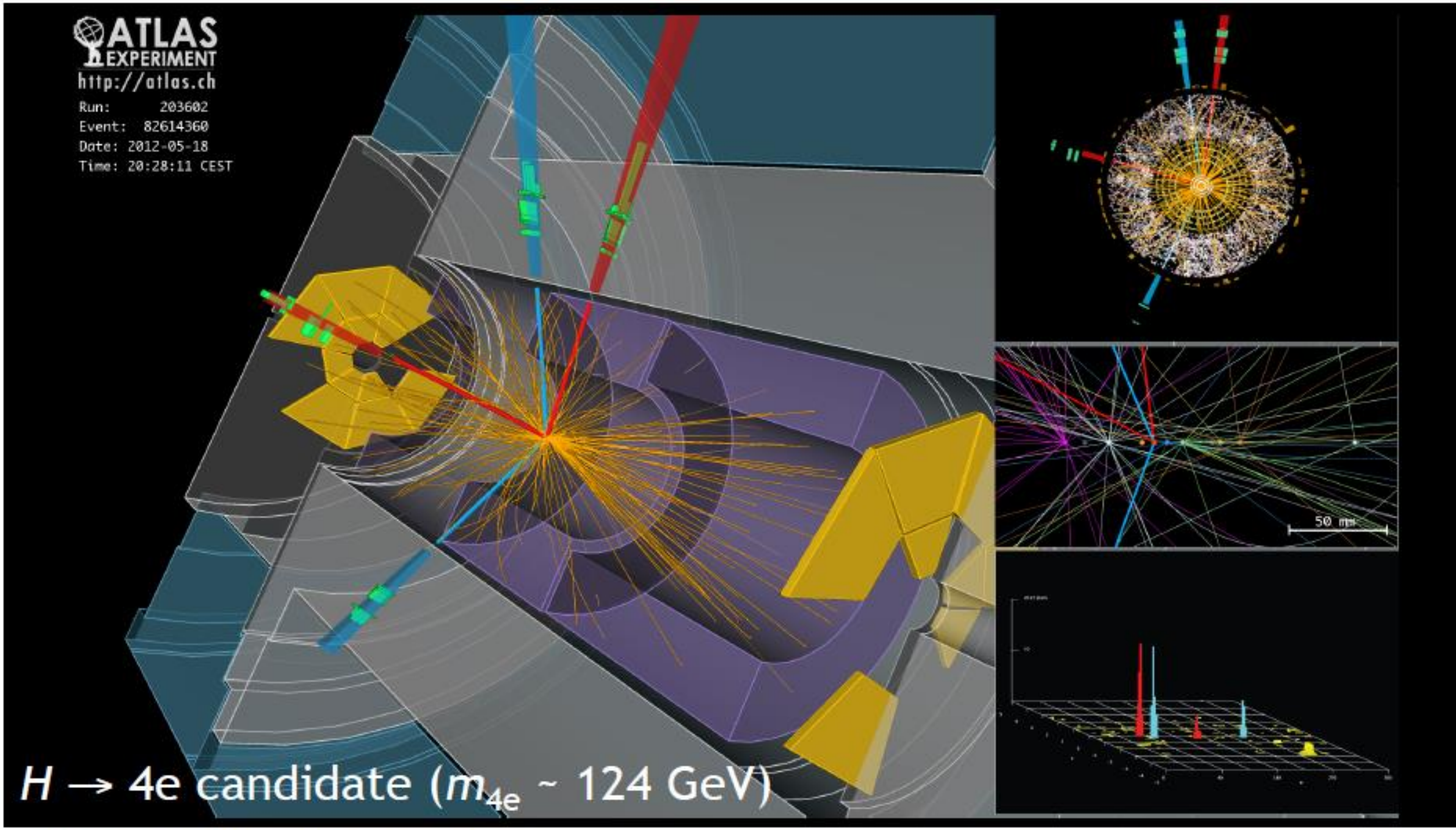
Since "Discovery Paper" PLB 716

ATLAS-CONF-2013-012



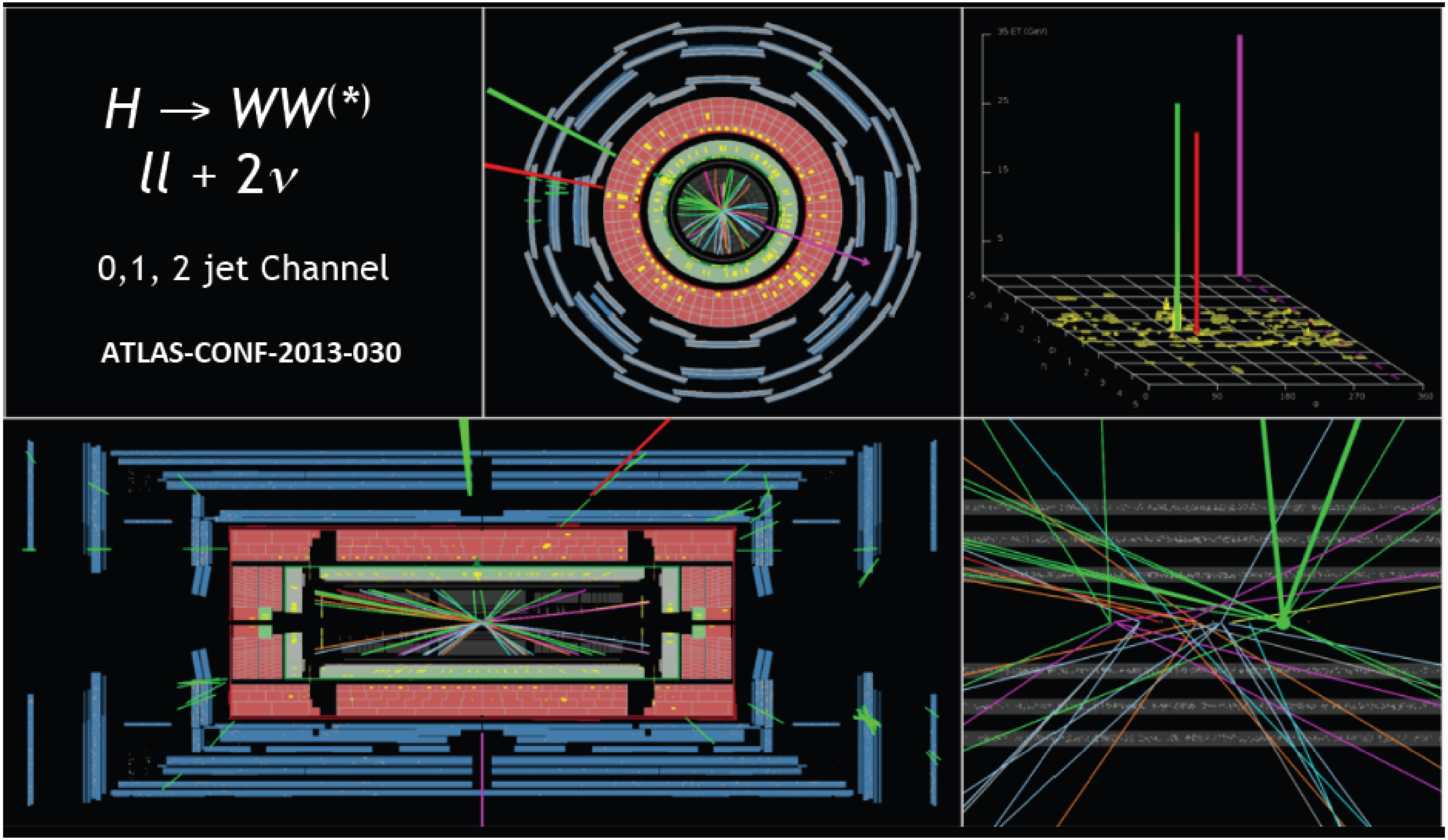
γγ channel basic facts sheet :

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}



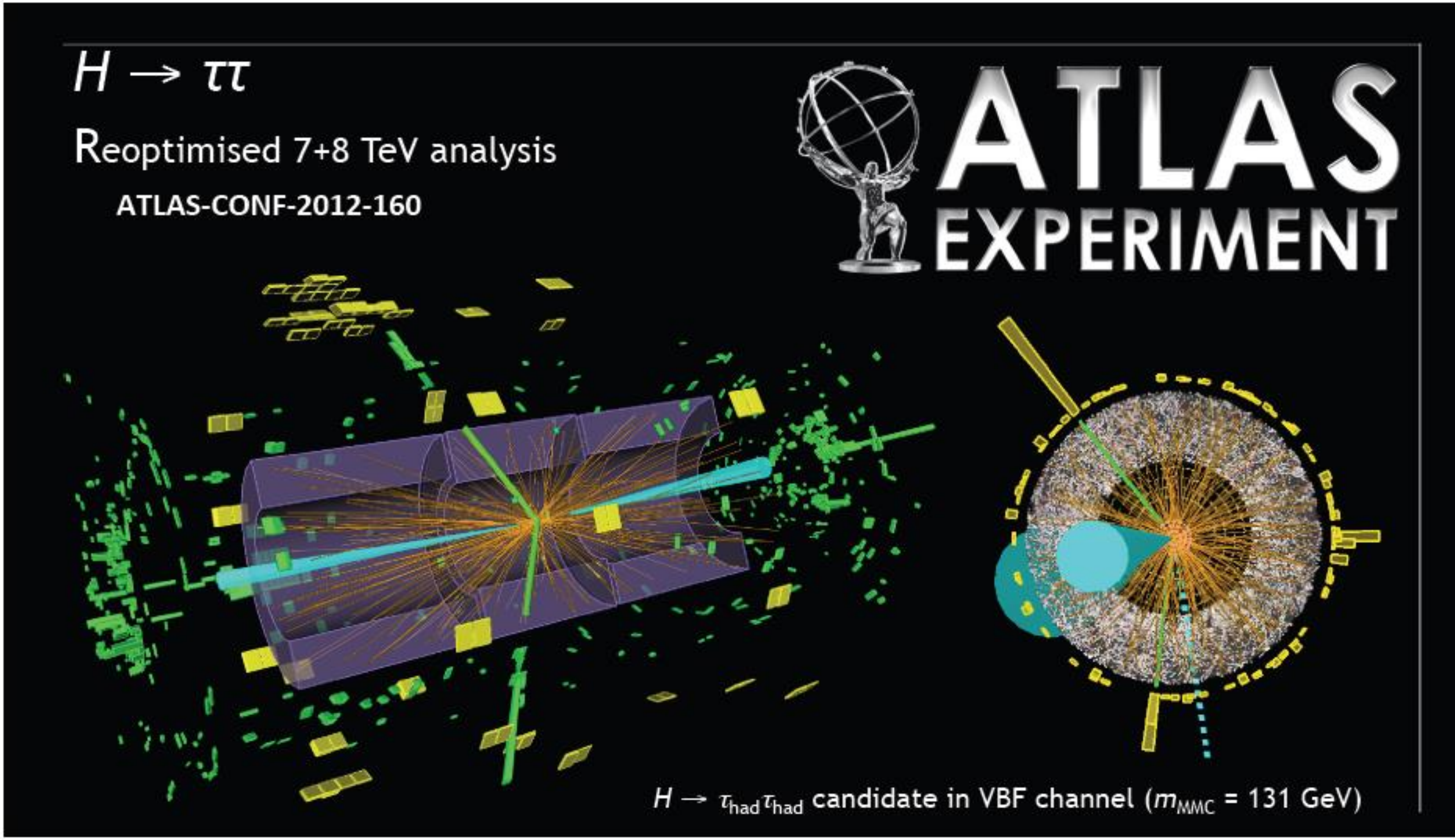
4l channel basic facts sheet :

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	25fb^{-1}

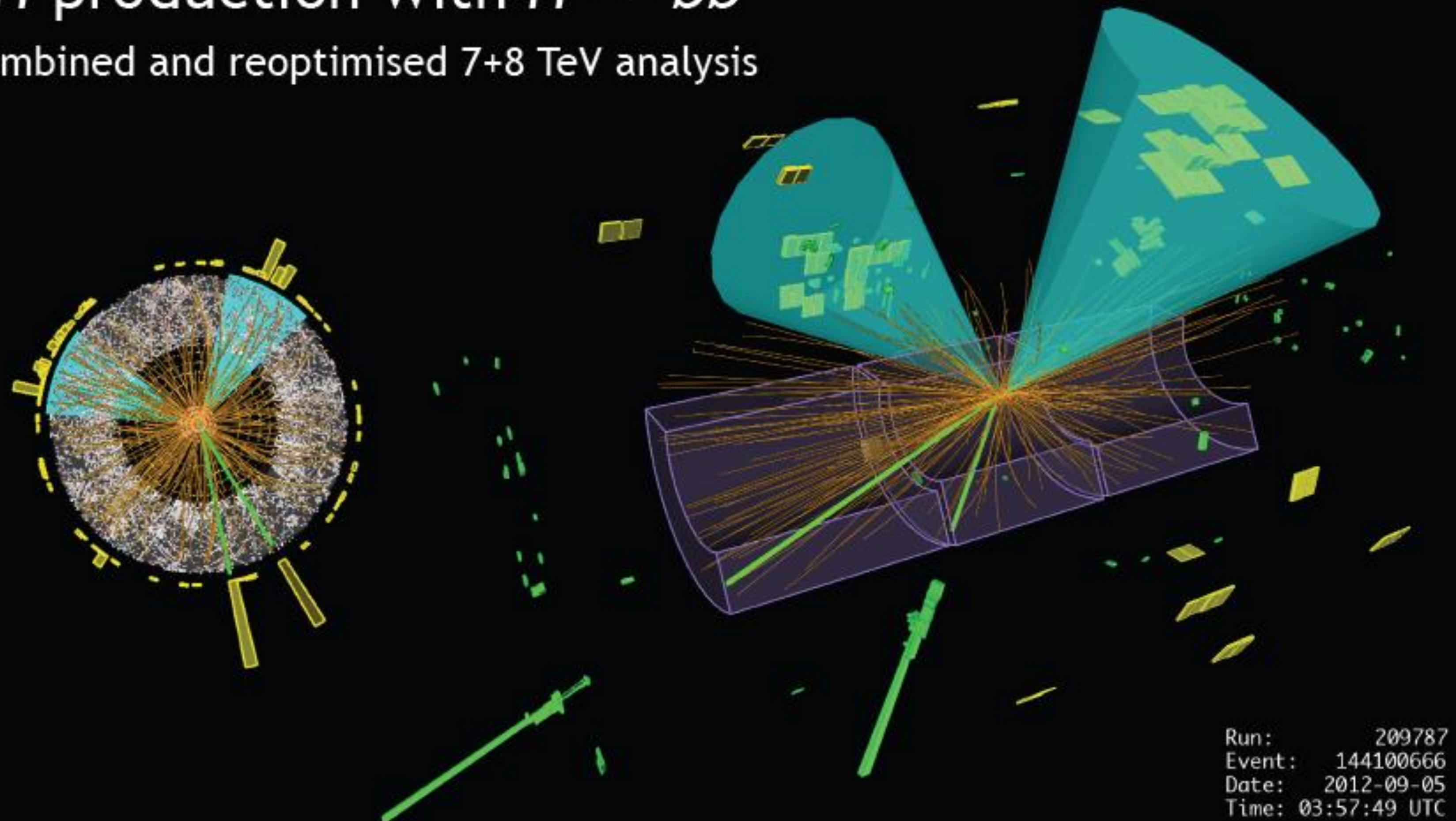


ττ channel basic facts sheet :

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 $H \to bb$

Combined and reoptimised 7+8 TeV analysis



VH(bb) channel basic facts sheet :

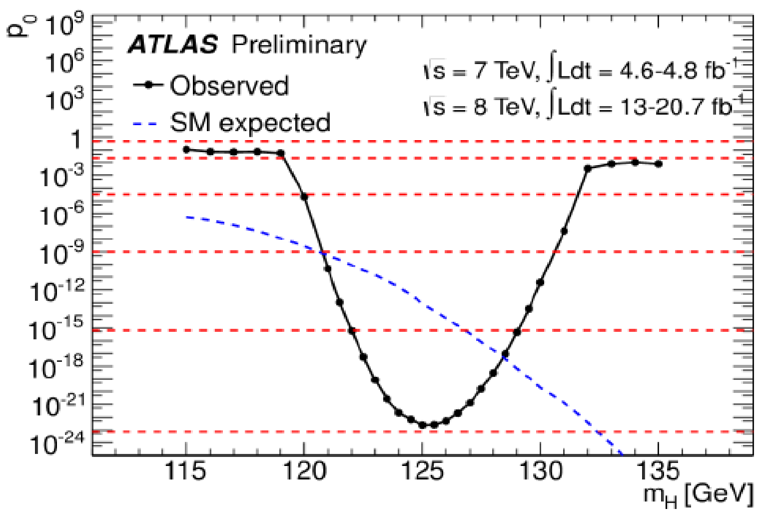
Signal (SM)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L\,dt$
~50	~1% - 10%	Wbb,Zbb, top, etc...	VH	4.9 & 13 fb^{-1}

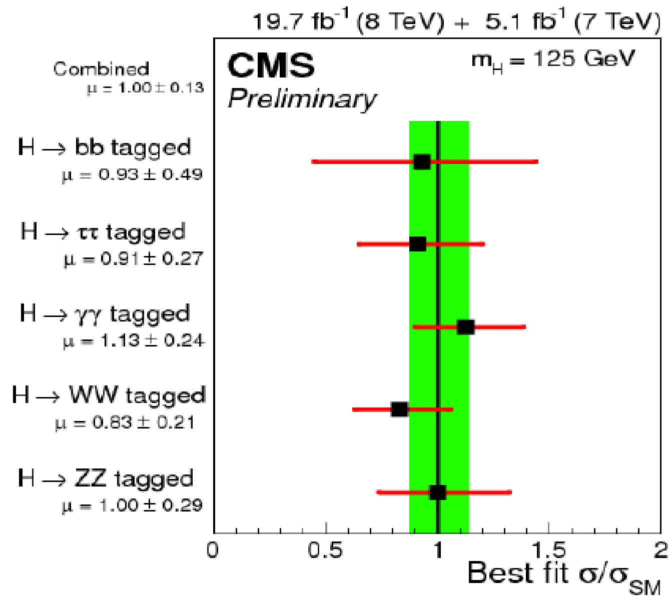
How significant is the signal for the new particle?

Mass = 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV [ATLAS]
125.03 ± 0.26 (stat) ± 0.14 (syst) GeV [CMS]

Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

Signal strength
$\mu = 0$ background only hypothesis
$\mu = 1$ SM Higgs hypothesis





ATLAS-CONF-2013-034, 2014-009

CMS-PAS-HIG-14-009

Phys. Rev. D 90 (2014) 052004

$\mu = 1.30 \pm 0.18$ [ATLAS]
$\mu = 1.00 \pm 0.13$ [CMS]

112

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

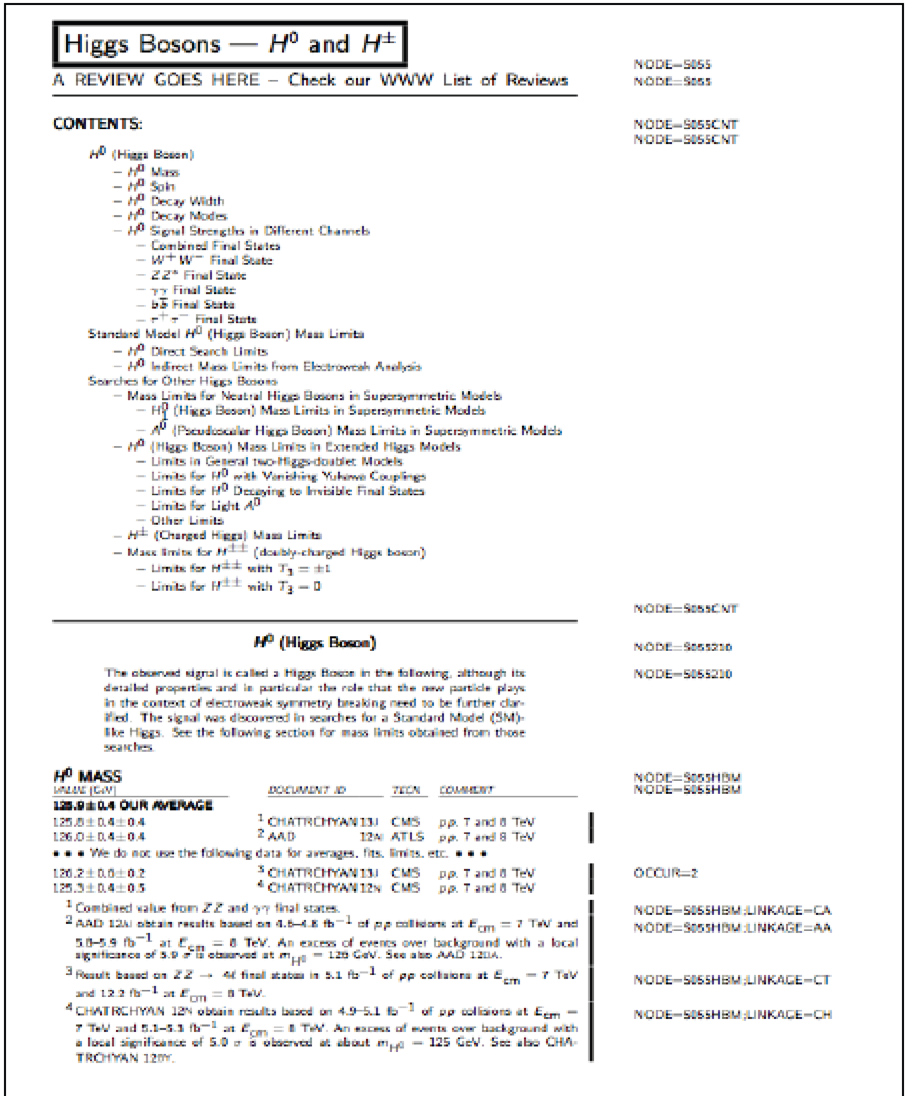
- ATLAS and CMS data strongly favour $J^P = 0^+$ SM quantum numbers; alternative models excluded at 95% CL.
- Signal strength $\mu = \sigma/\sigma_{SM}$ consistent with 1

Summer 2013:

All measured properties are compatible with SM hypothesis.

Entrance of the Higgs into PDG

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				
$125.8 \pm 0.4 \pm 0.4$	[1] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV	
$126.0 \pm 0.4 \pm 0.4$	[2] AAD 12AI	ATLS	pp, 7 and 8 TeV	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$126.2 \pm 0.6 \pm 0.2$	[3] CHATRCHYAN 13J	CMS	pp, 7 and 8 TeV	OCCUR=2
$125.3 \pm 0.4 \pm 0.5$	[4] CHATRCHYAN 12N	CMS	pp, 7 and 8 TeV	

[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 $ZZ \to 4\ell$ 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 !

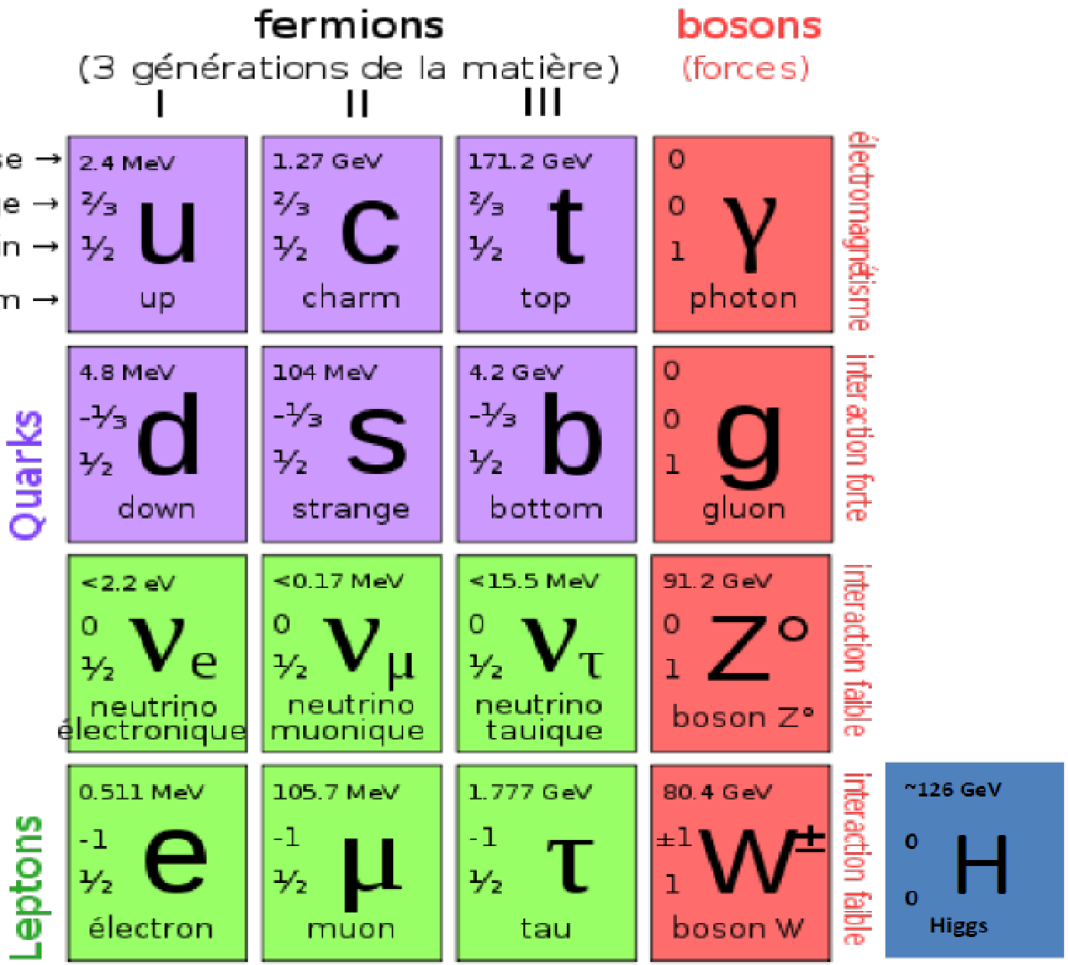
H^0

Standard Model particles

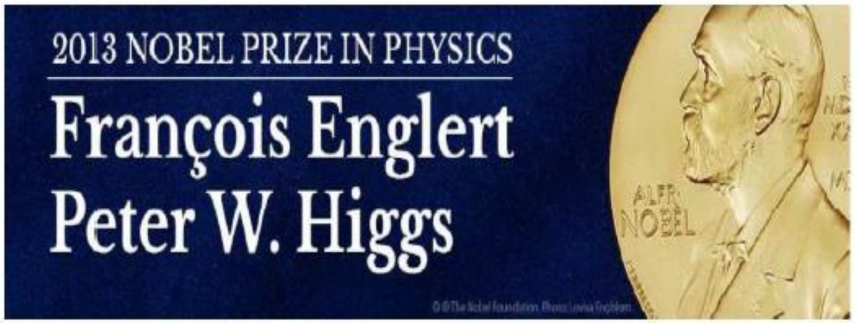
Model interaction between fermions
- **quarks**
- **leptons**

Through boson exchange
- **EM : γ**
- **weak : W^+, W^- , Z**
- **strong : gluons**

Higgs boson

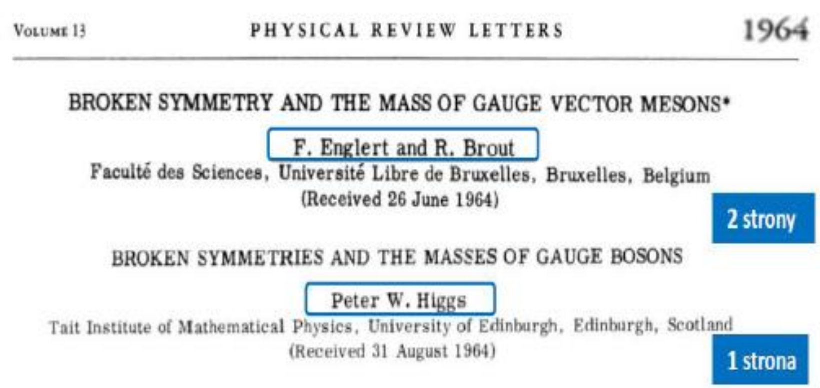


W dniu 4 lipca 2012, eksperymenty ATLAS i CMS na akceleratorze LHC w laboratorium CERN ogłosiły odkrycie nowej cząstki zgodnej z przewidywaniami tzw. mechanizmu Higgsa.



8 październik 2013
Królewska Szwedzka Akademia Nauk przyznaje Nagrodę Nobla w dziedzinie fizyki

„ za sformułowanie mechanizmu który wyjaśnia źródło masy cząstek elementarnych i który został potwierdzony poprzez odkrycie przewidywanej przez ten mechanizm cząstki elementarnej (eksperymenty ATLAS i CMS na LHC)".



VOLUME 13 PHYSICAL REVIEW LETTERS 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

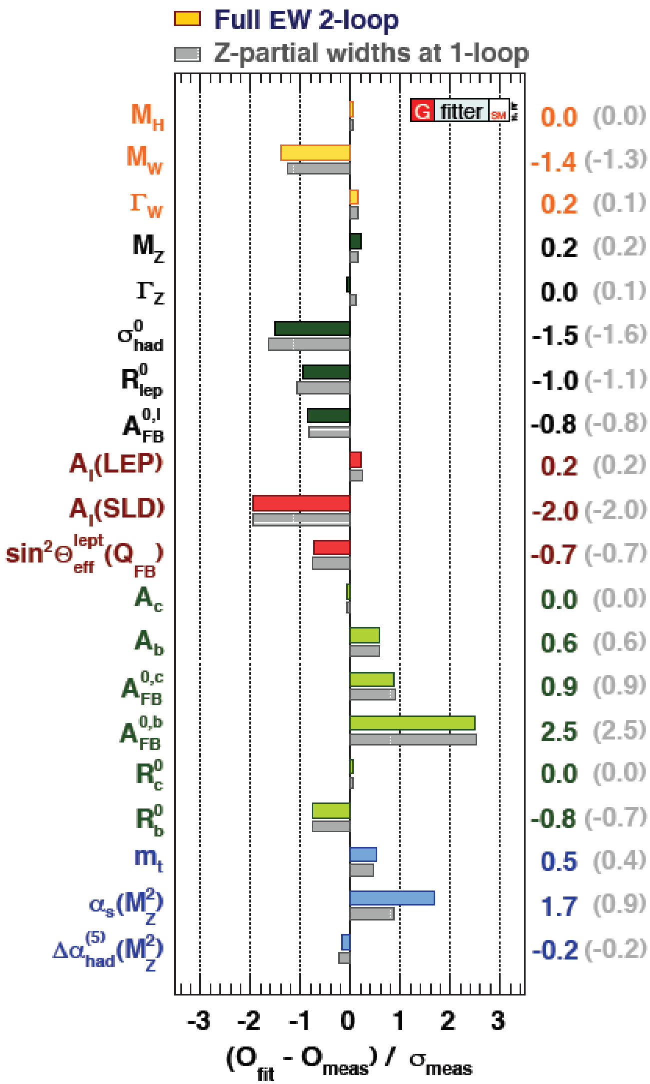
2 strony

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

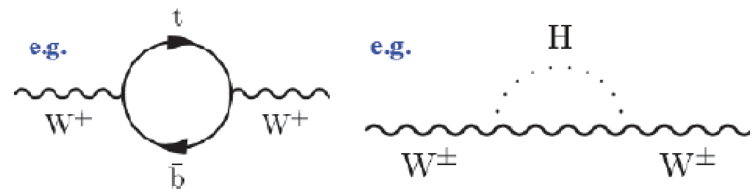
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

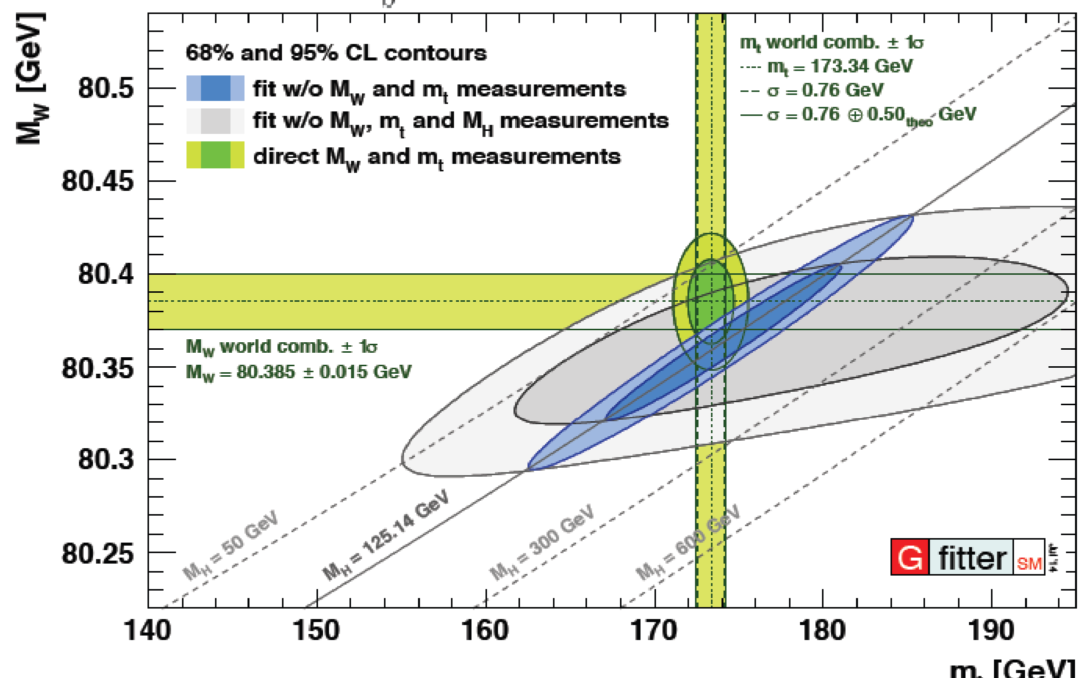
1 strona

Standard Model measurements



- Excellent agreement between measurements and SM prediction!
  - ✓ Very few tensions…
- More precise measurements of W and t mass needed: indirect constrain are now better!





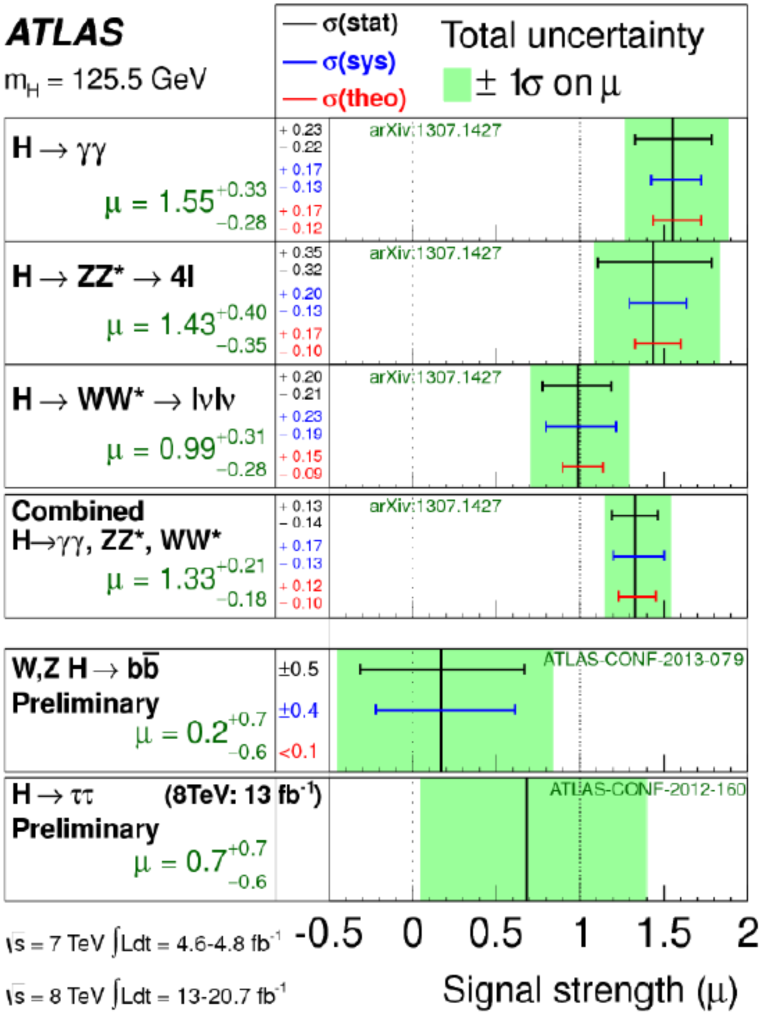
Higgs boson signal strength

$$\mu = \sigma/\sigma_{SM}$$

Individual channels are consistent

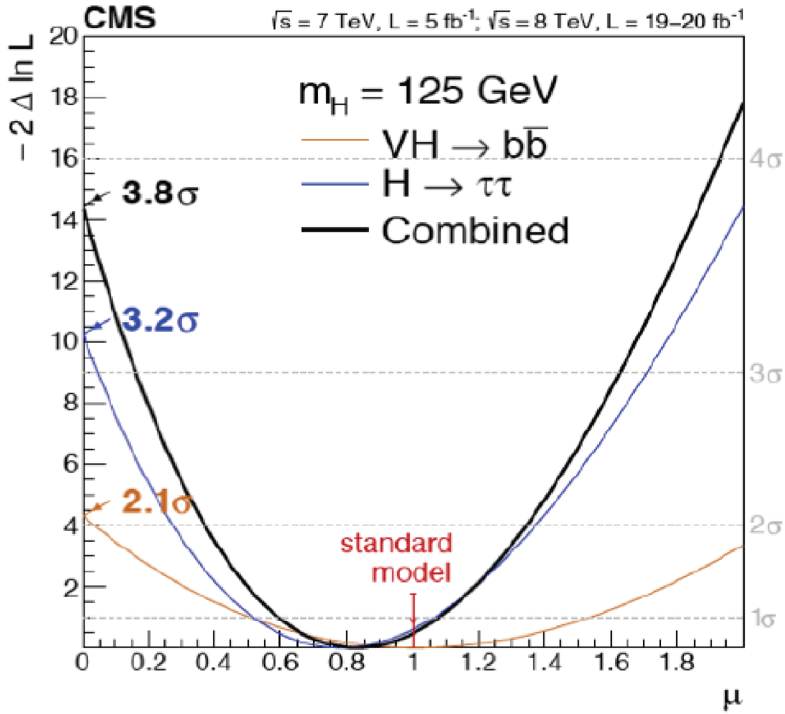
SM describes the rates well, so far

More detailed studies have been done of coupling constraints which can be derived, including on new processes in the loops



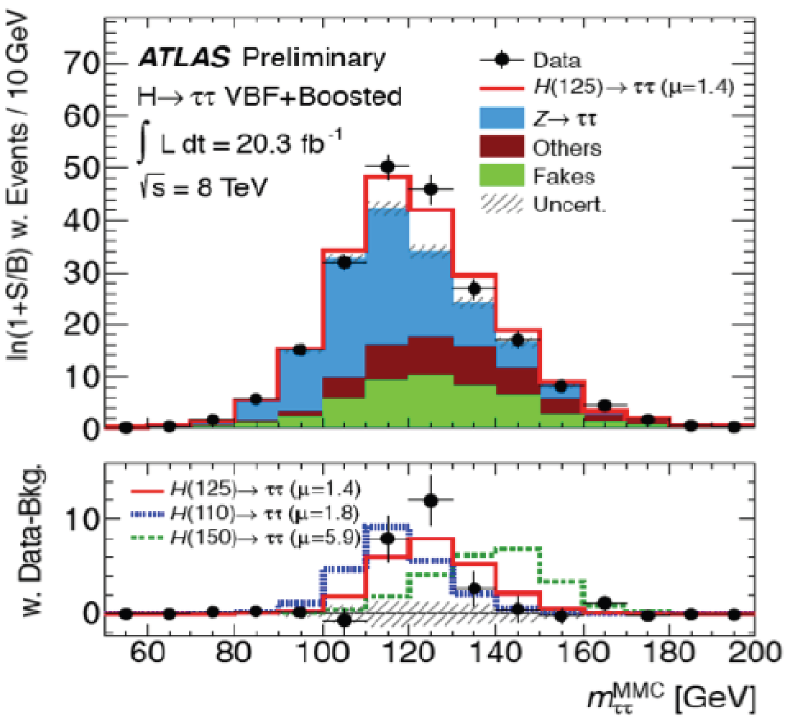
Higgs decays to fermions (2014)

CMS: H→ ττ, bb Channels



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

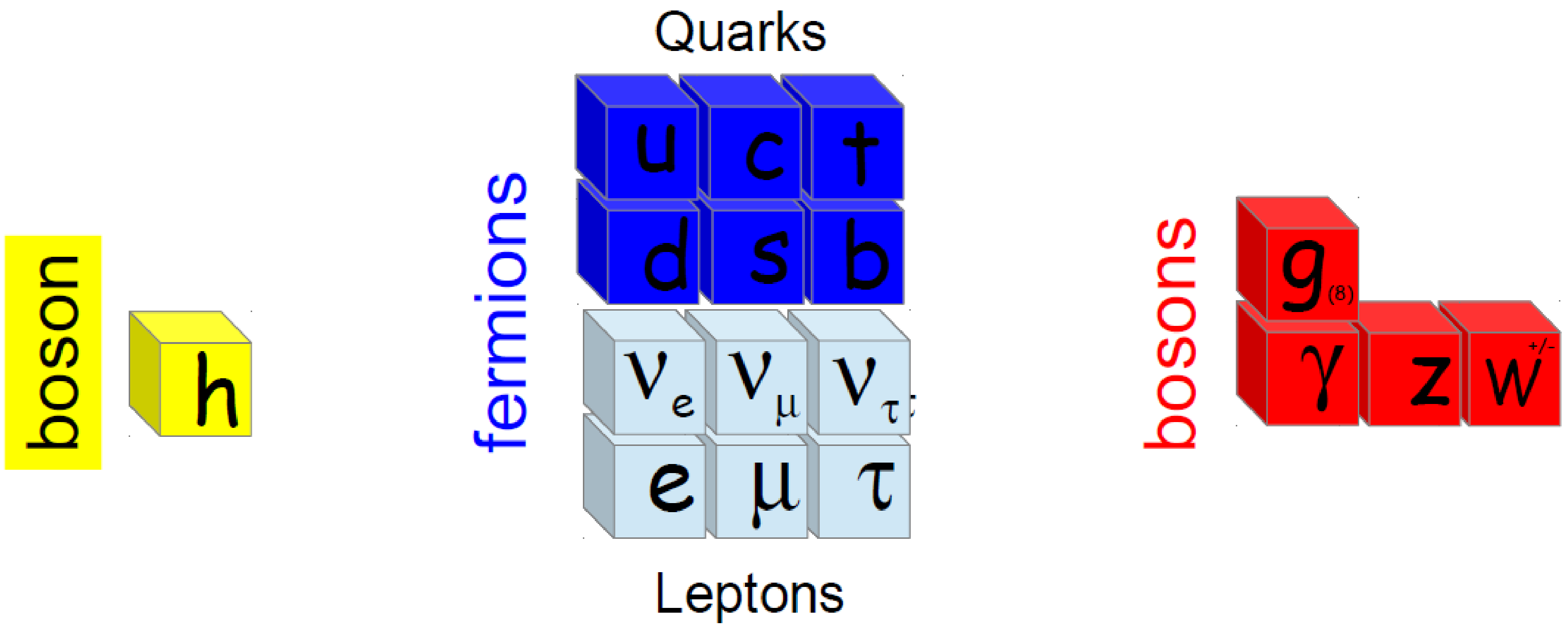
ATLAS: H→ ττ Channel



Significance	Exp	Obs
ATLAS (ττ)	3.2 σ	4.1 σ

Tevatron: exp (2.1σ), obs (3.0σ)

What spin do particles have?

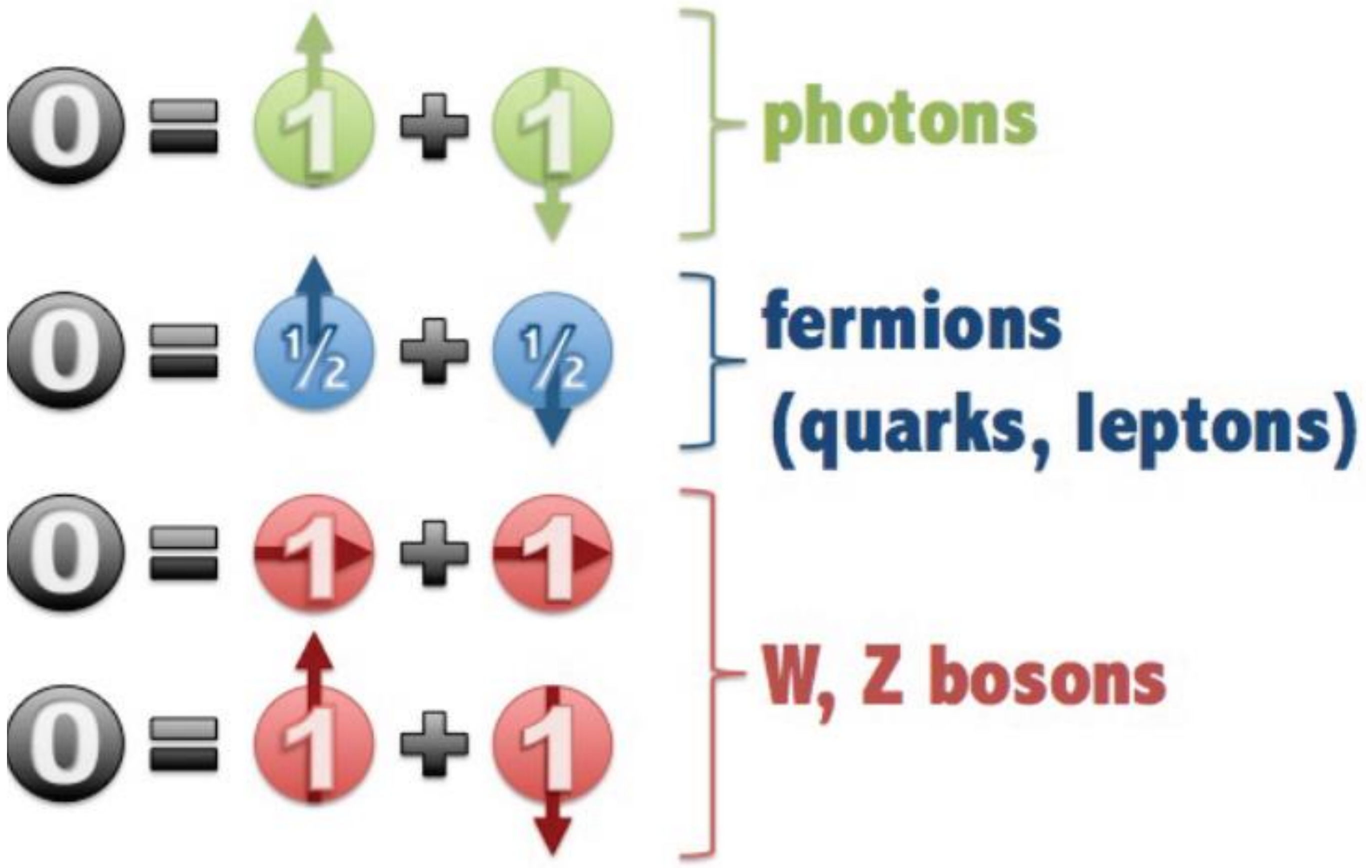


Spin 0

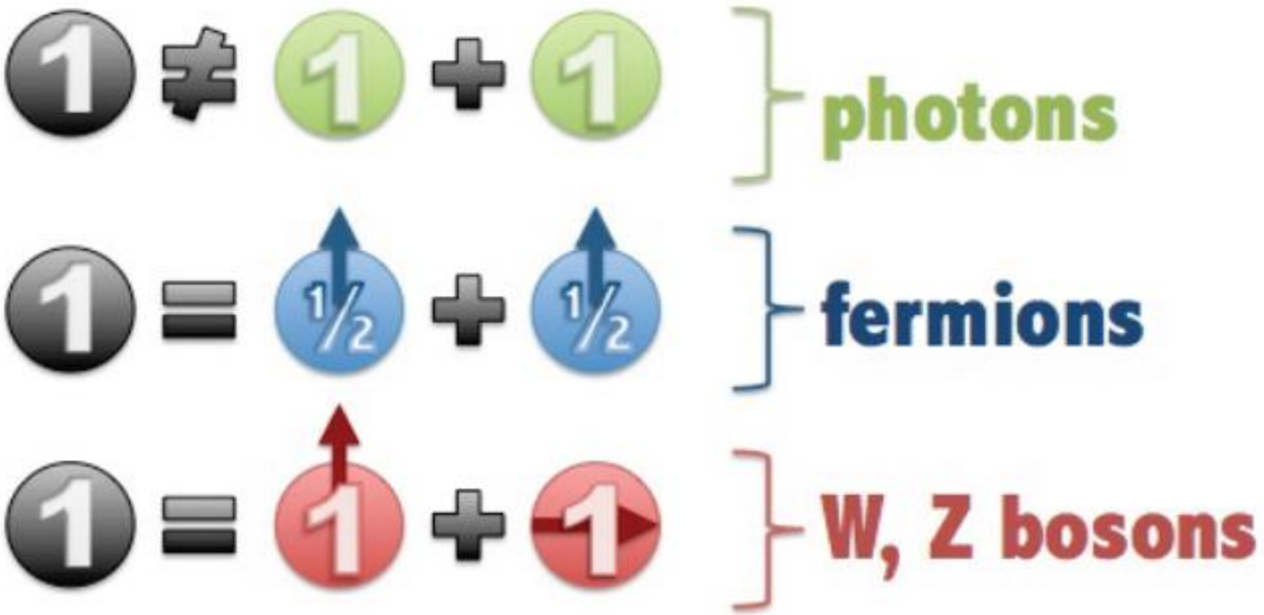
Spin 1/2

Spin 1

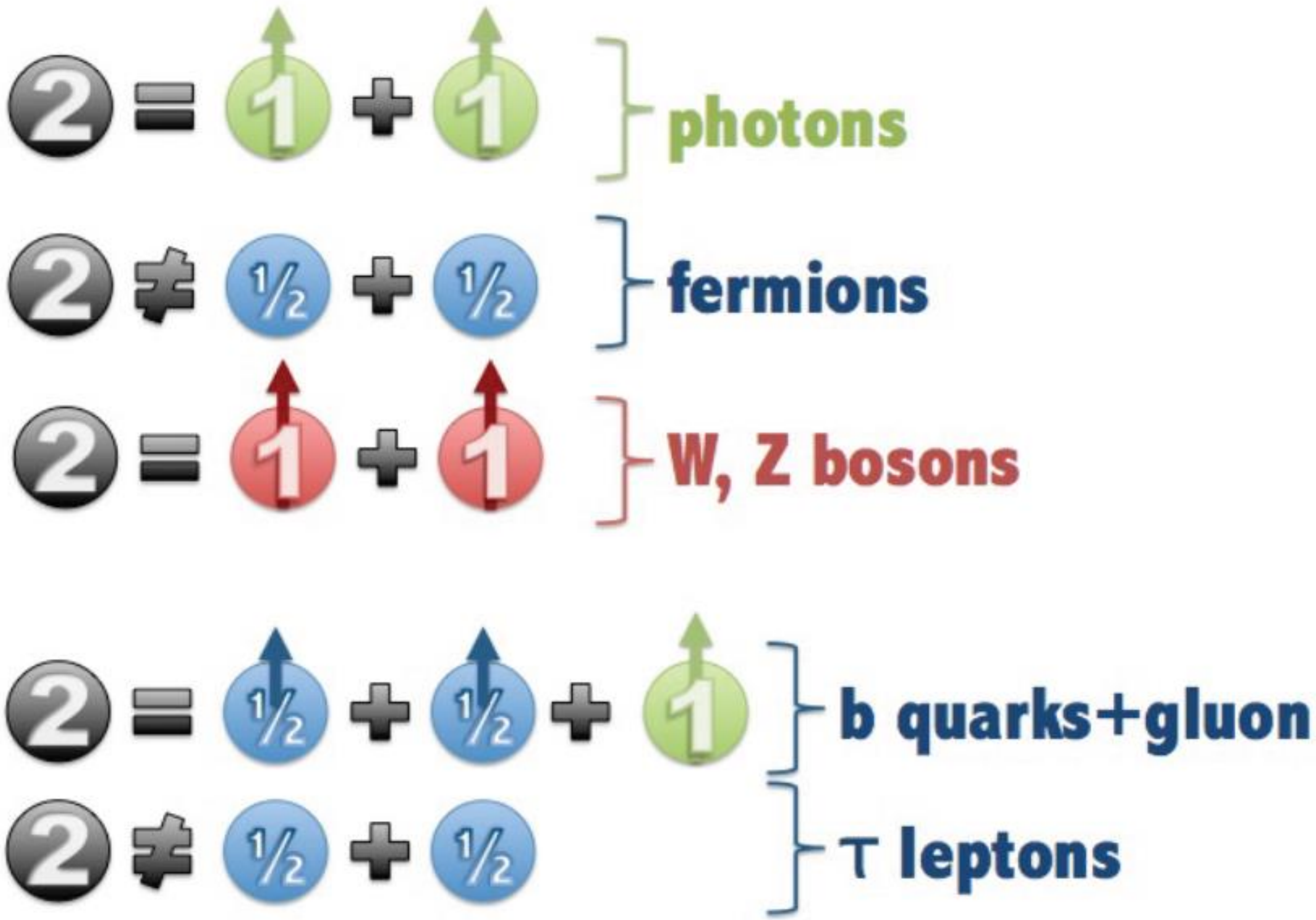
What can a spin 0 particle decay to?



What can a spin 1 particle decay to?



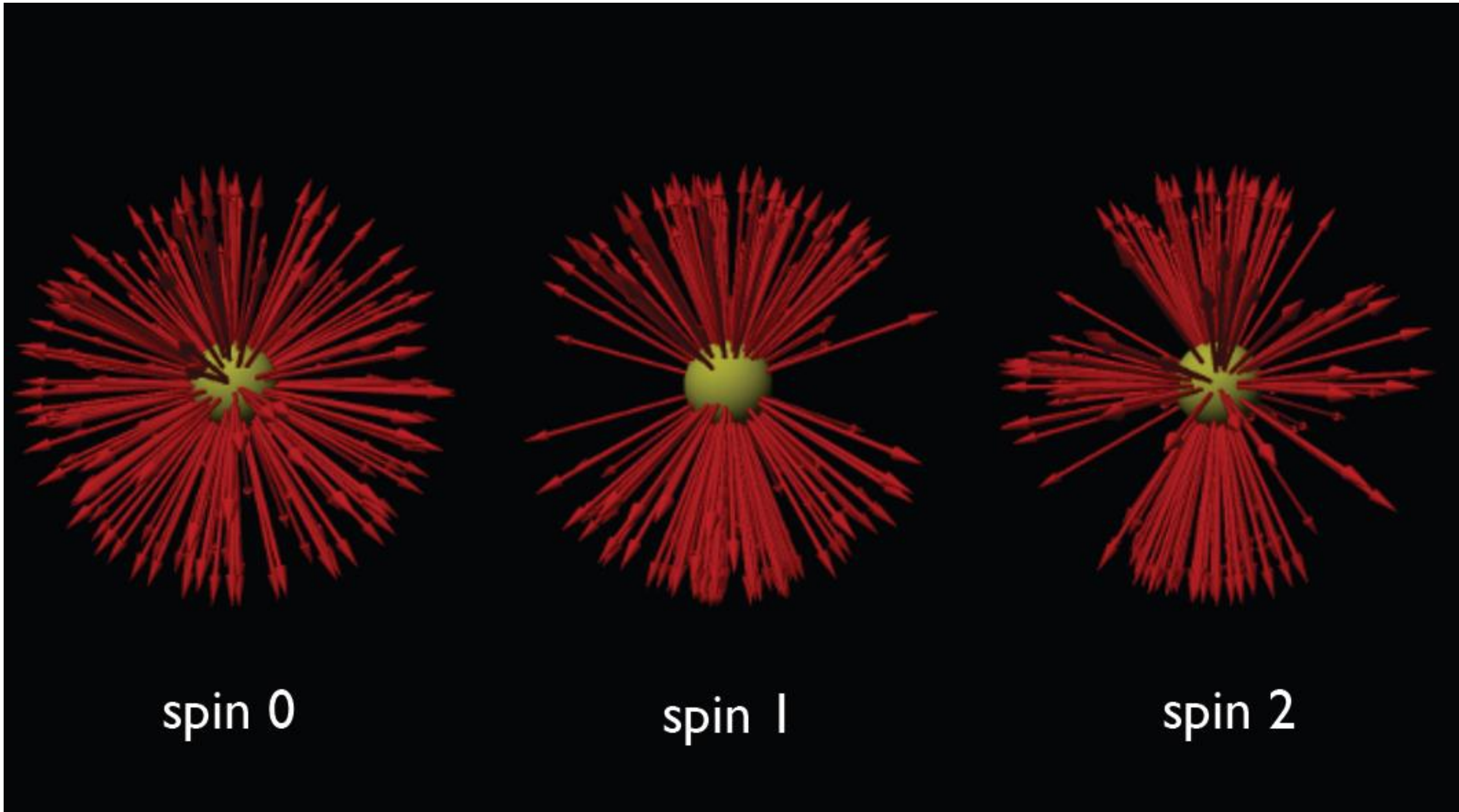
What can a spin 2 particle decay to?



So what spin has Higgs-like particle?

Spin of particle	γγ	ZZ*
Spin 0	☺	☺
Spin 1	☹	☺
Spin 2	☺	☺

How we can recongnize spin?

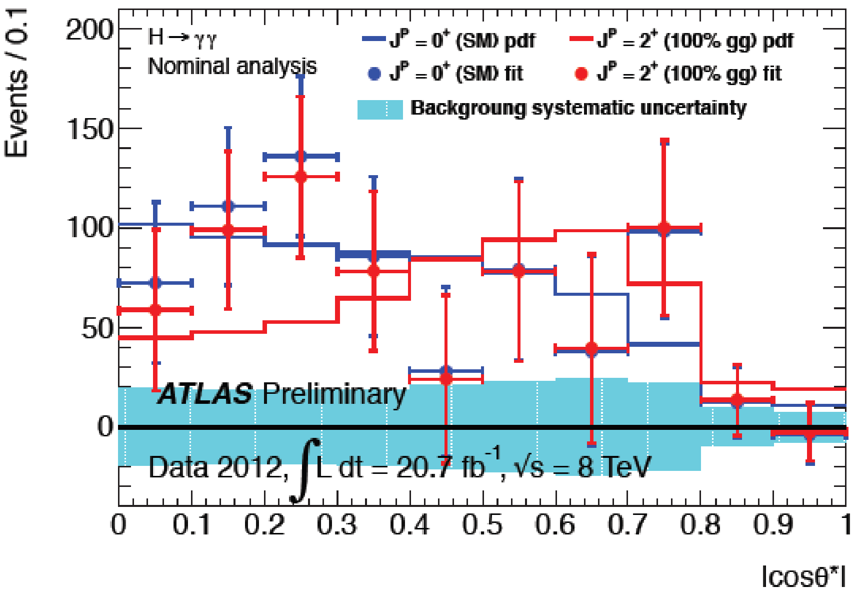


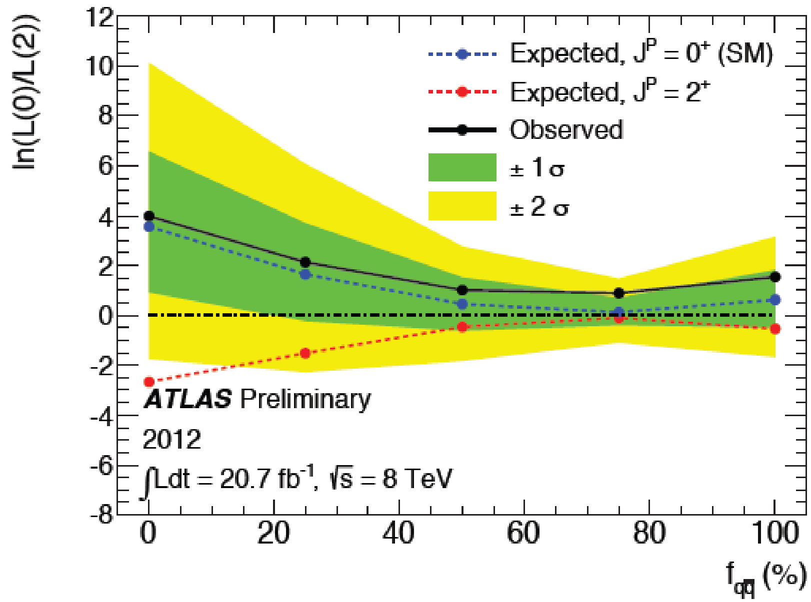
Spin-0 decays in all directions with equal probability; spin-1 prefers decaying toward or away from the direction of spin; spin-2 prefers the poles and the equator to the region in between. These pictures exaggerate the real distributions for clarity.

Spin study with H->γγ

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

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

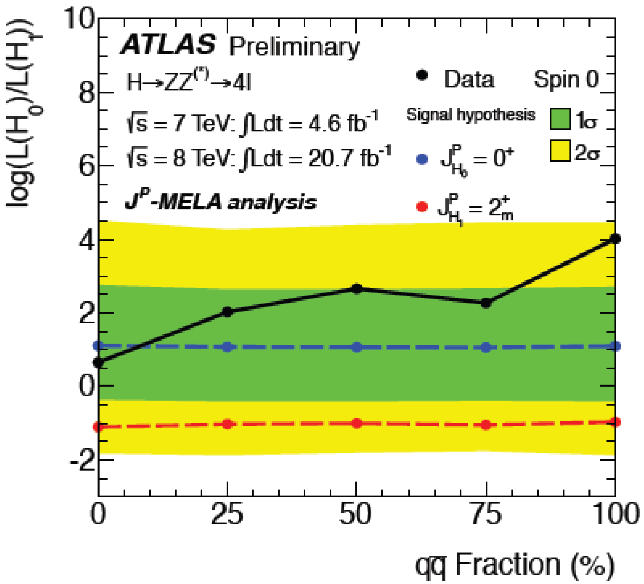




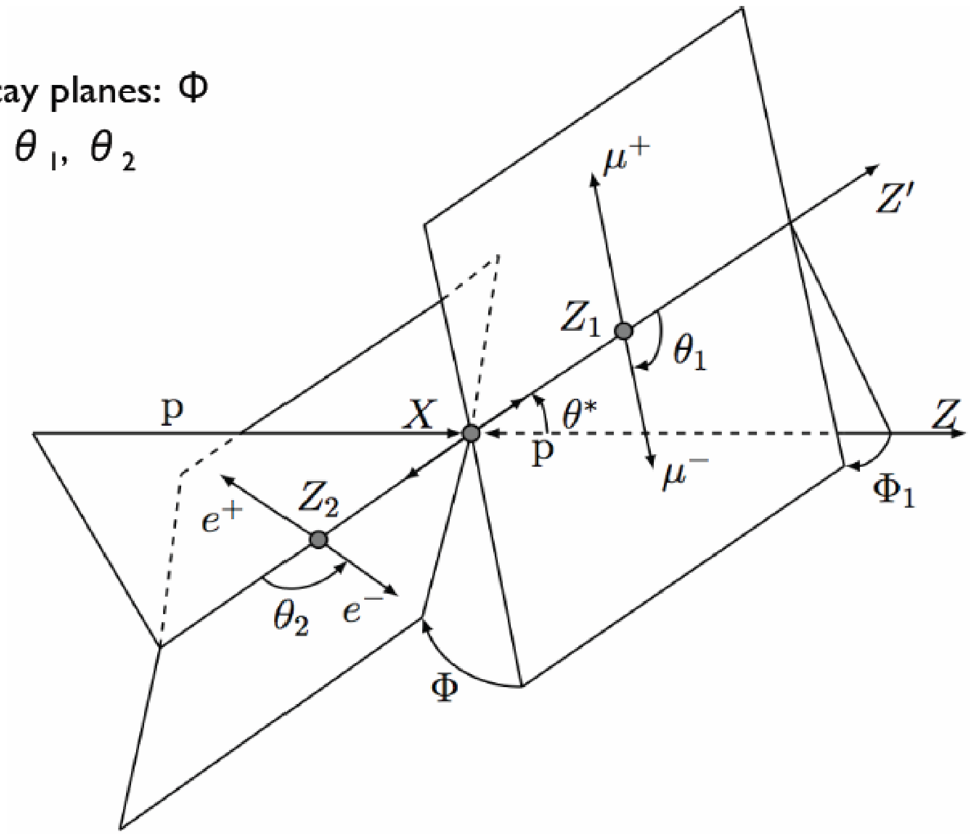
- If spin-2 resonance is produced 100% by gluon fusion, observed *rejection* p-values are:
  - ✓ spin-0 → 58.8% (1.2% expected) → good agreement with spin-0 hypothesis
  - ✓ spin-2 → 0.3% (0.5% expected) → spin-2 excluded at 99.3% CL

Spin study with H->4l

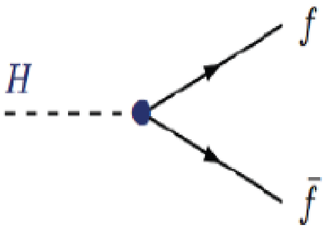
- Sensitive variables
  - ✓ Intermediate boson masses: m_{Z1}, m_{Z2}
  - ✓ Z_1 production angle: θ^*
  - ✓ Z_1 decay plane angle: Φ_1
  - ✓ Angle between the Z_1 and Z_2 decay planes: Φ
  - ✓ Decay angles of negative leptons: θ_1, θ_2



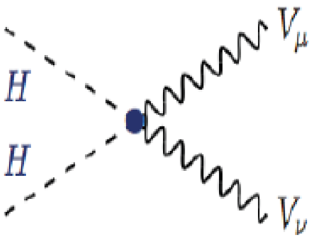
- Expected separation >2.5 σ, except for 2+m (~1.5 σ)
  - ✓ New boson compatible with SM 0+ Higgs hypothesis when compared pair-wise with 0-, 1-, 1+, 2+m



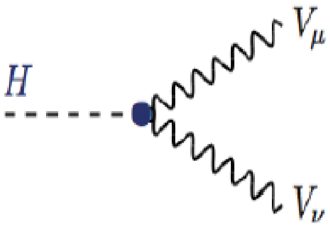
Higgs boson couplings



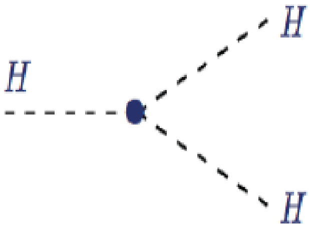
$$g_{Hff} = m_f/v$$



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

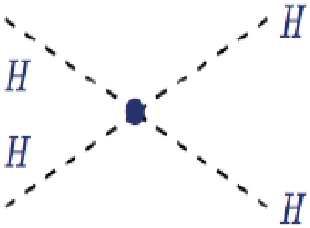


$$g_{HVV} = 2M_V^2/v$$



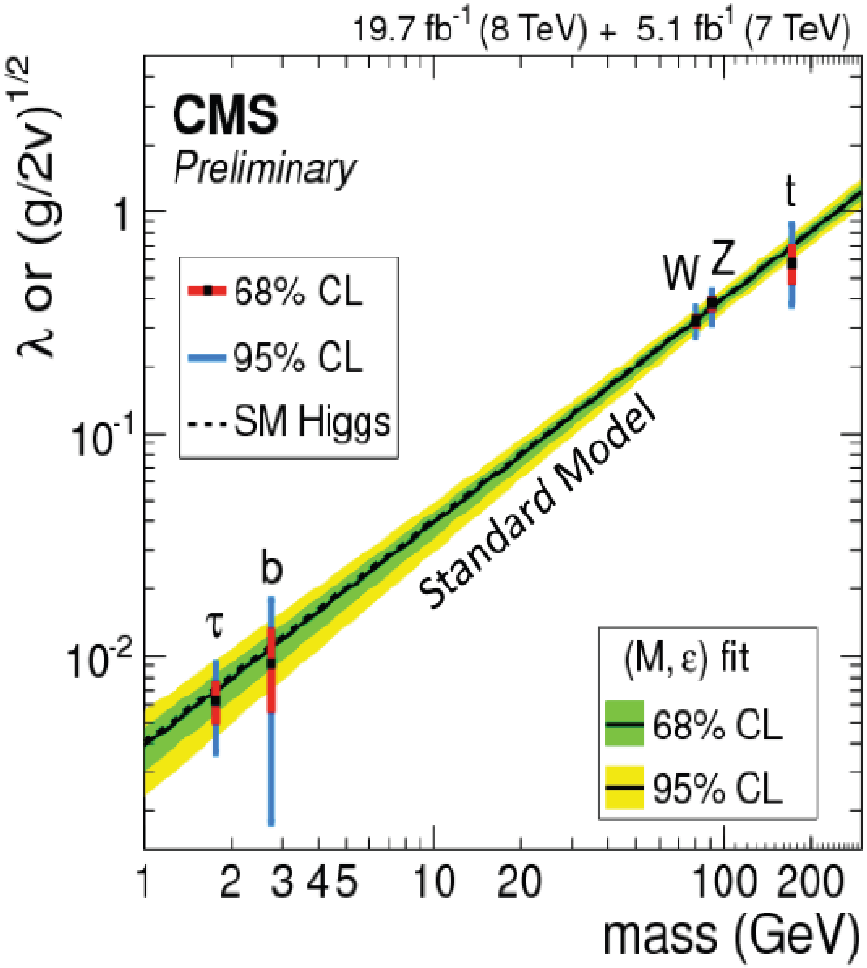
$$g_{HHH} = 3M_H^2/v$$

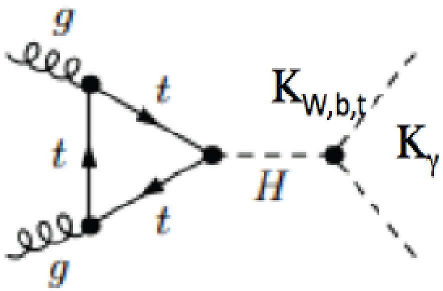
For the time being only test the bosonic and fermionic sector

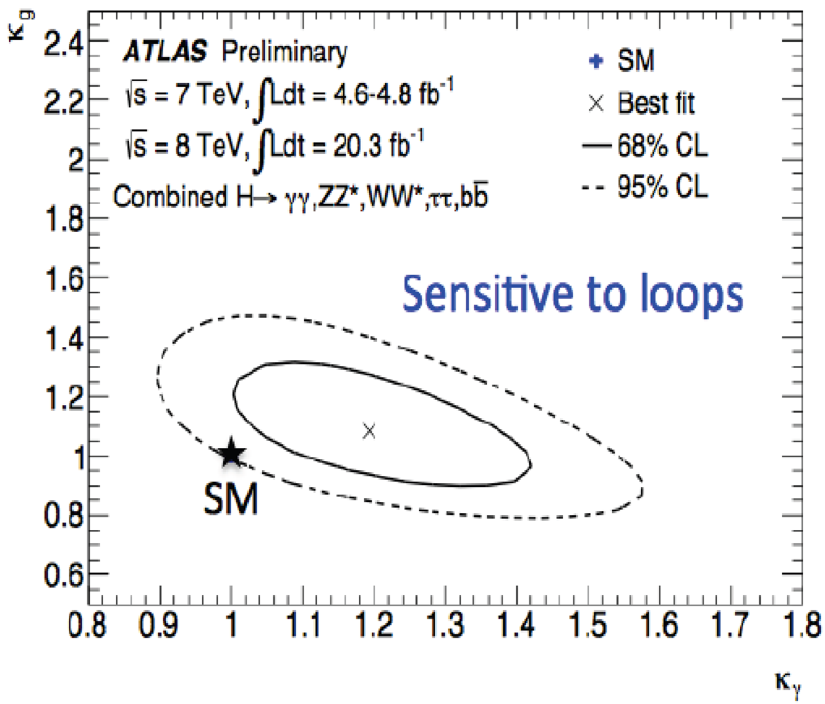


$$g_{HHHH} = 3M_H^2/v^2$$

Higgs boson couplings







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

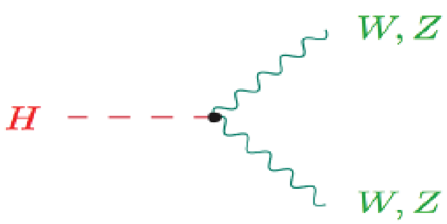
$$
\begin{aligned}
\mathcal{L} = & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma}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

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

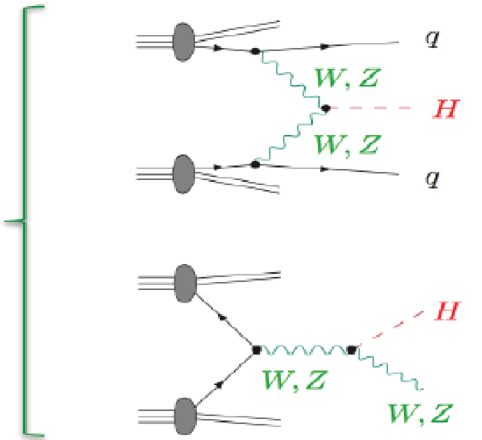
$$
k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \qquad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}
$$

Cpuplings scale factors

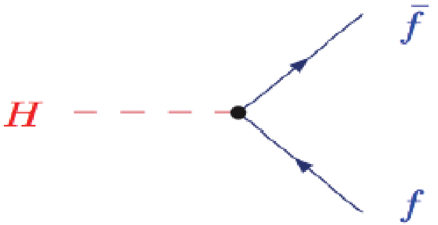
(I) Tree Level Couplings scale factors w.r.t. SM



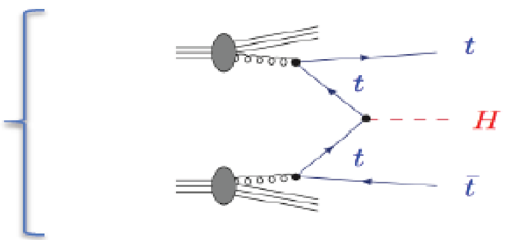
$\propto \kappa_V$



Affecting decay and production modes

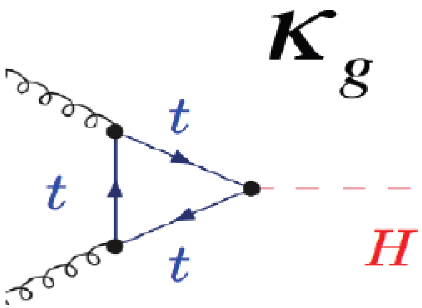


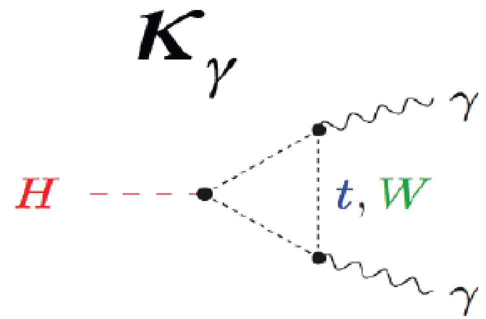
$\propto \kappa_F$



Couplings scale factors

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



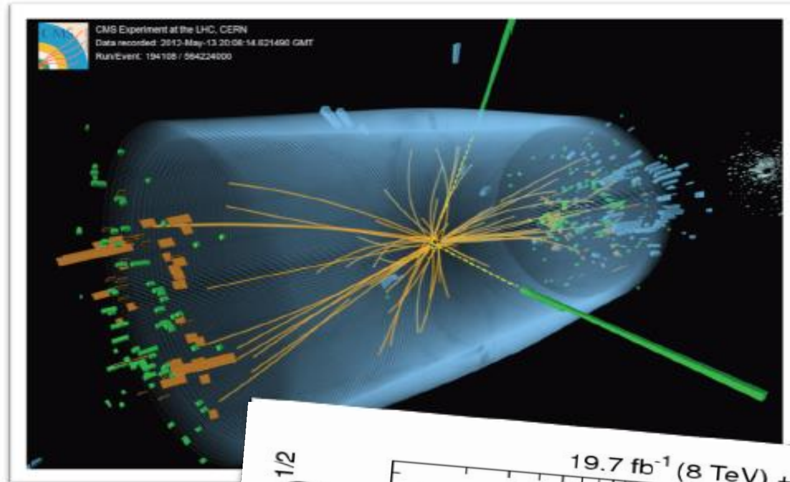


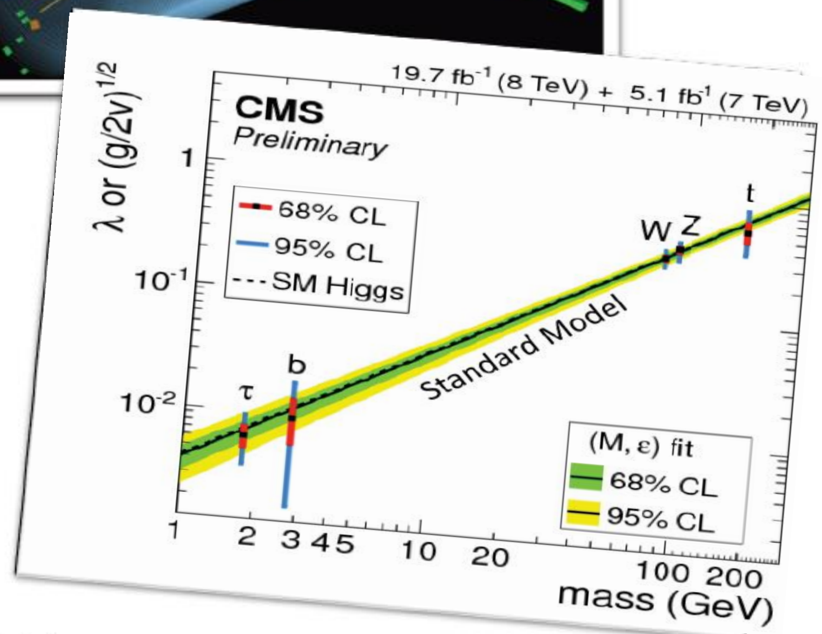
- Loop expression ambiguity :
  - Can be expressed in terms of k_F and k_V (Assuming the SM field content)
  - Or treated effectively (Allowing for possible additional particles)

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

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

Experiment = probing theories with data





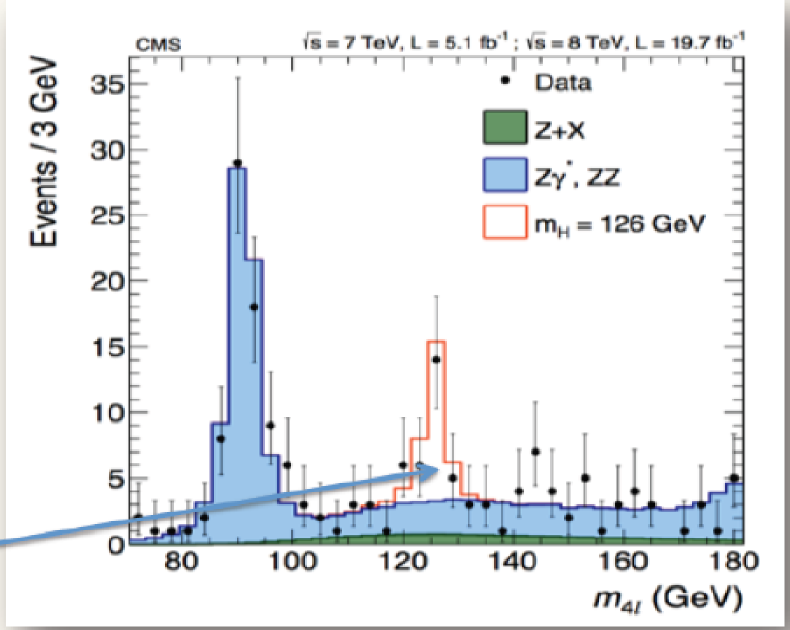
What do we measure?

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

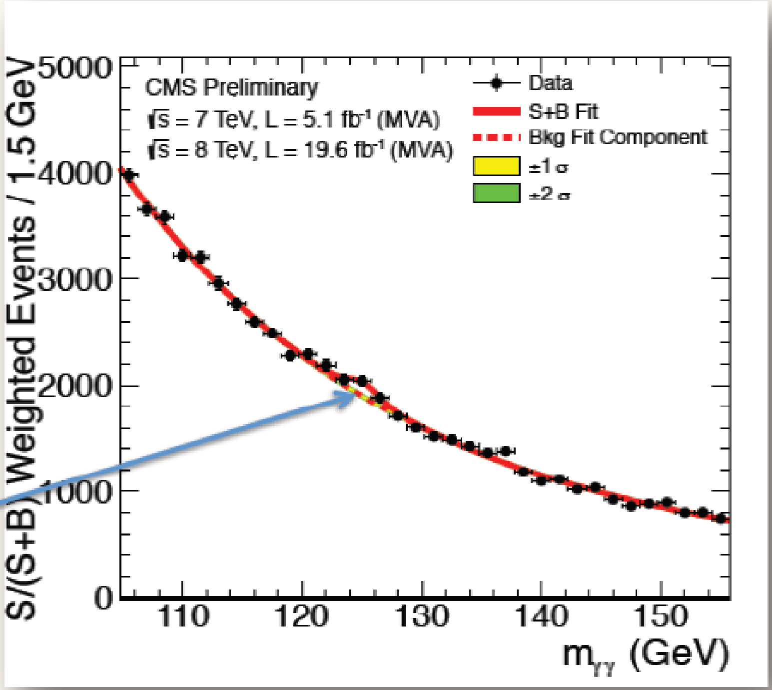
What do we measure?

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



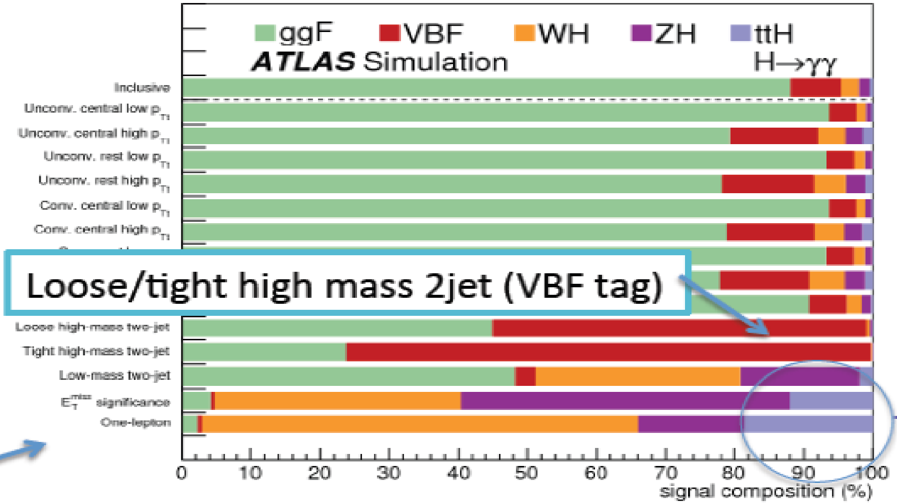
$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

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

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

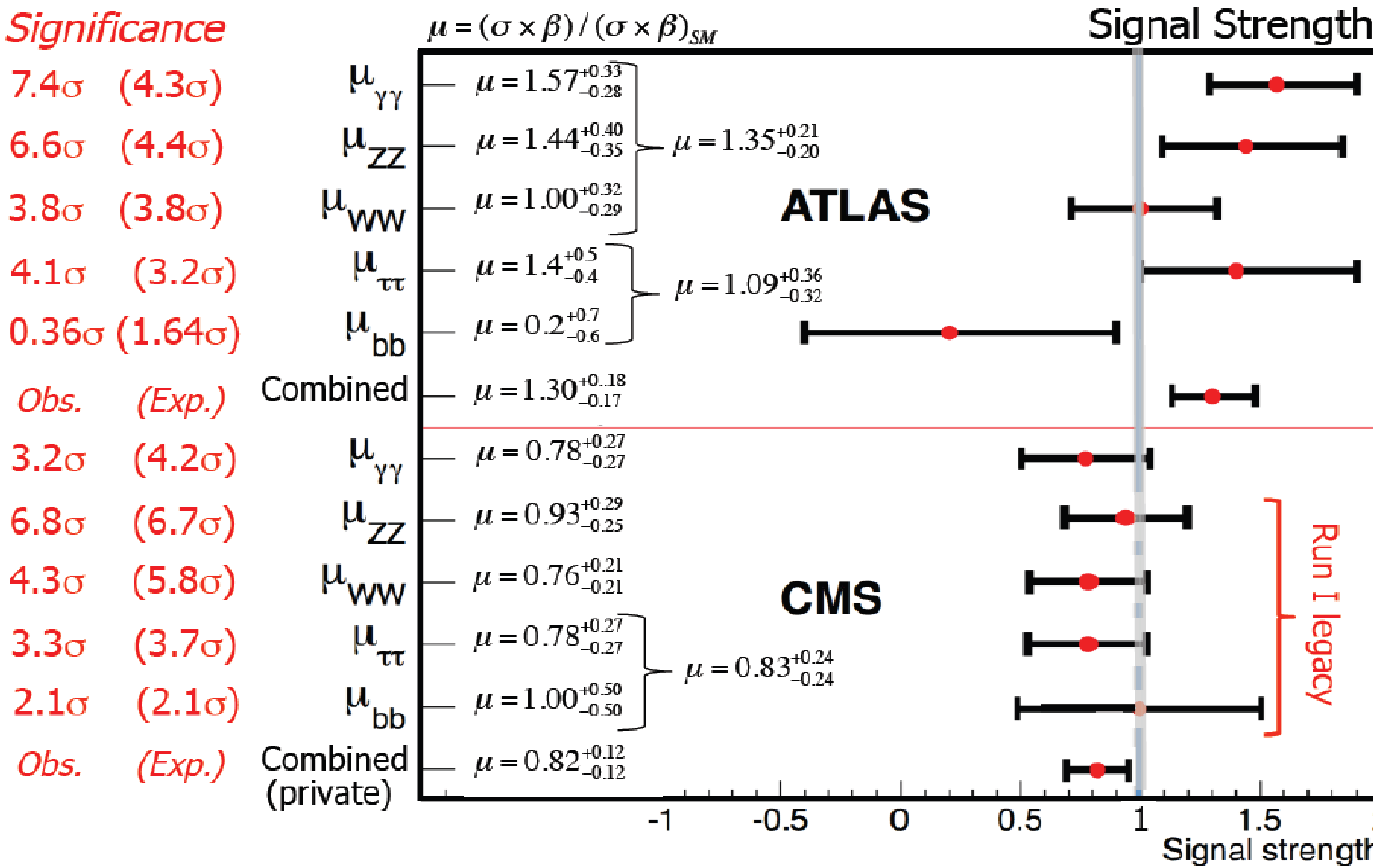
$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

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

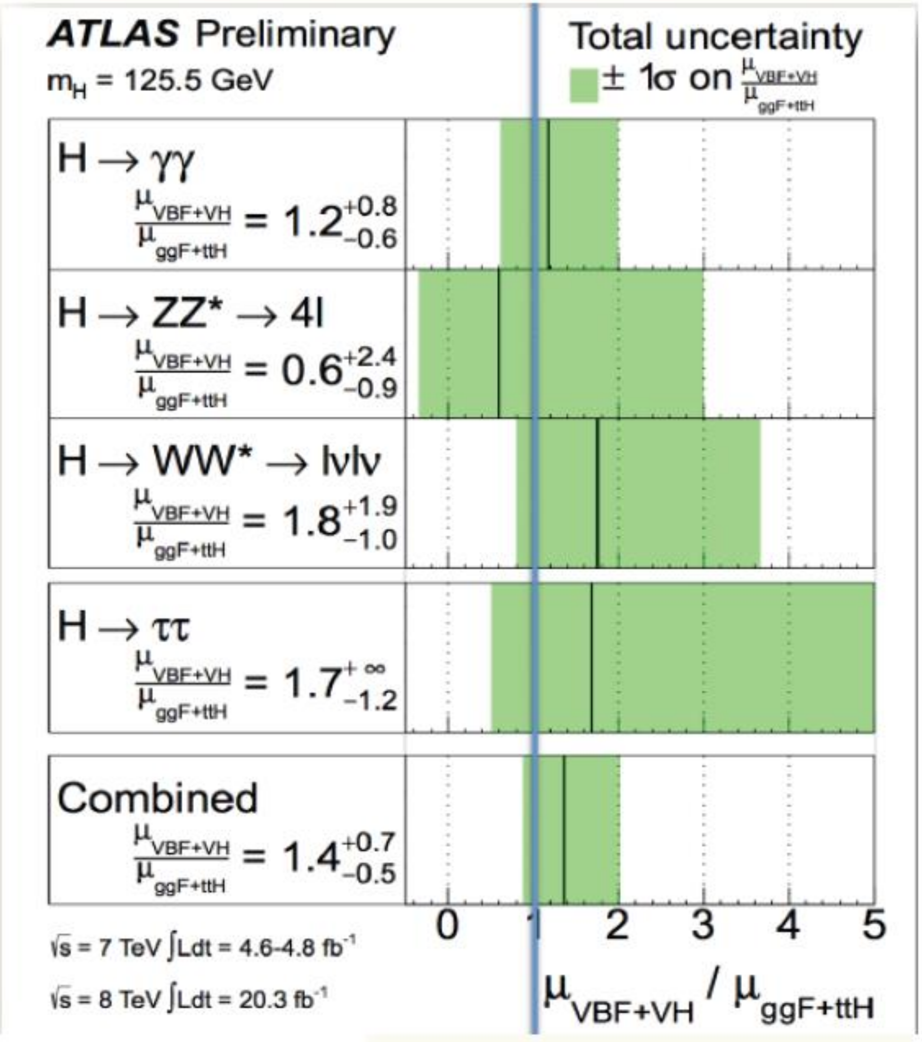
$$\mu^i_{VBF+VH} \equiv \left[\mu_{VBF+VH} \times \mu^i_{BR}\right]$$

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

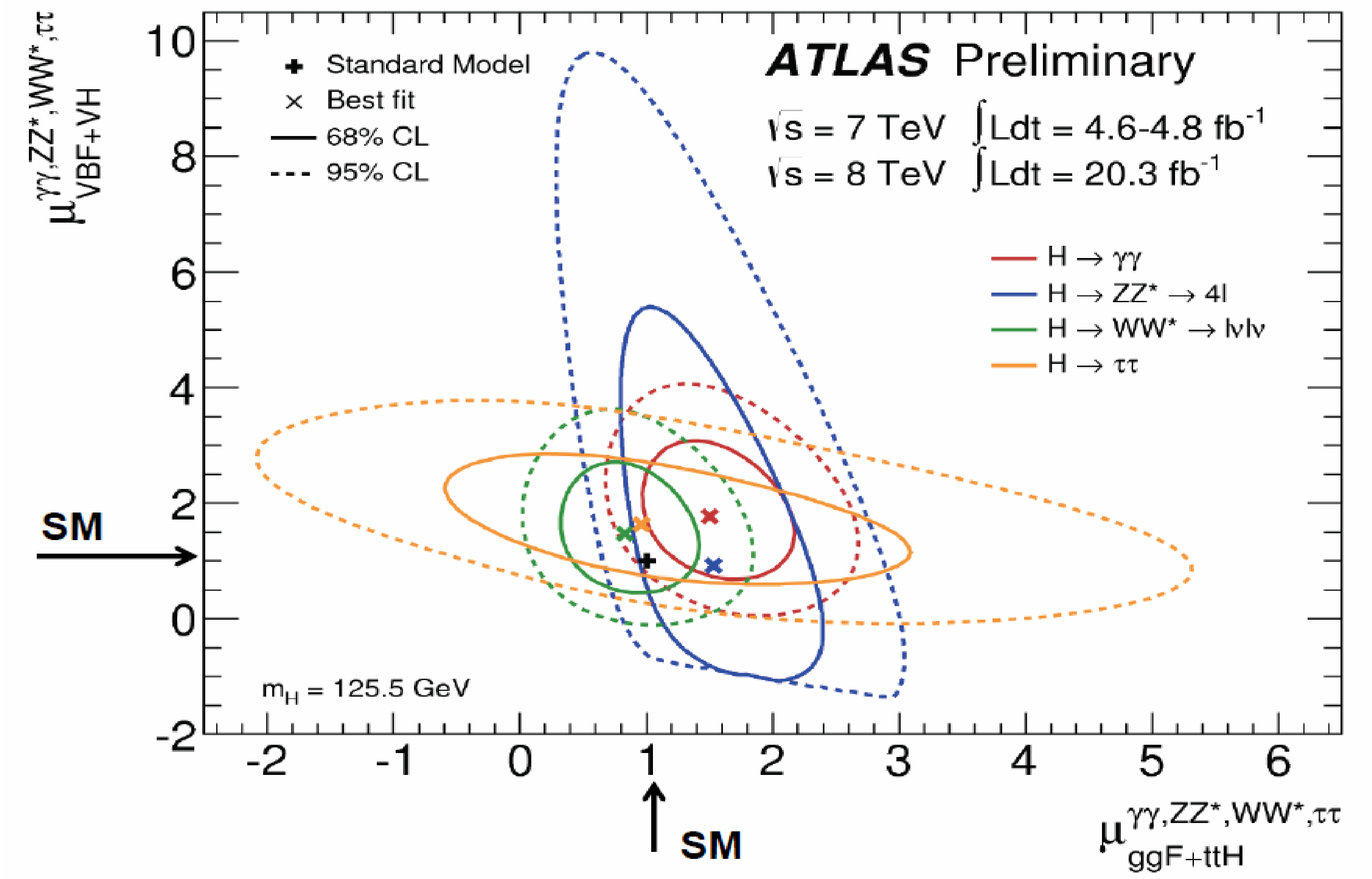
Taking one decay mode at a time we can go one step further and fit the ratio per channel

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

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

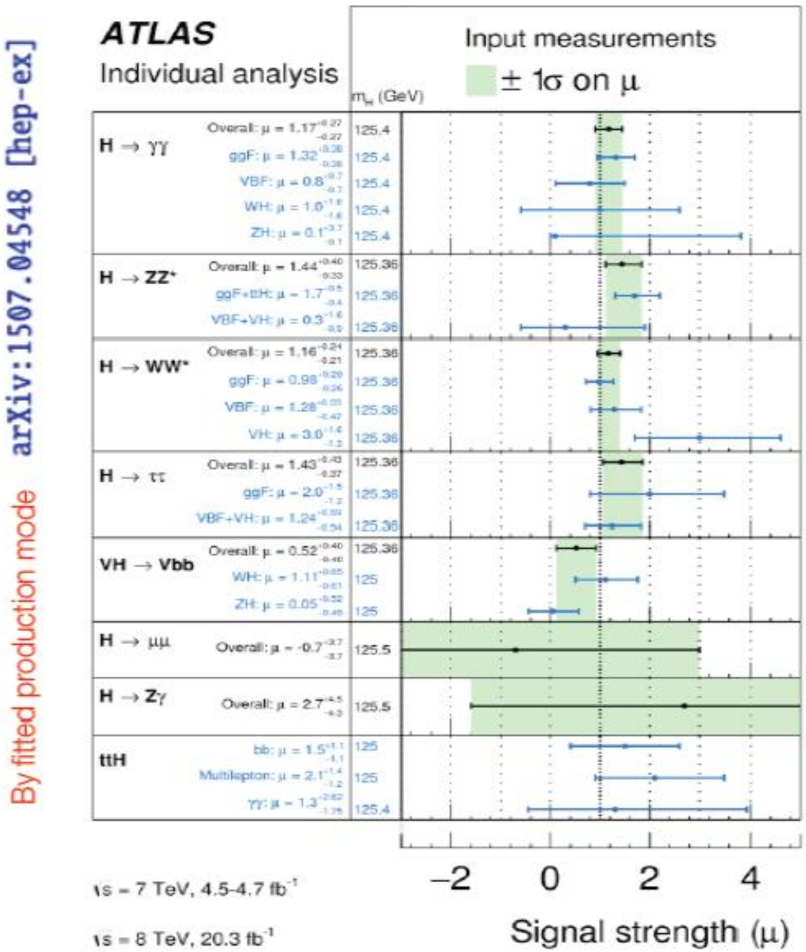


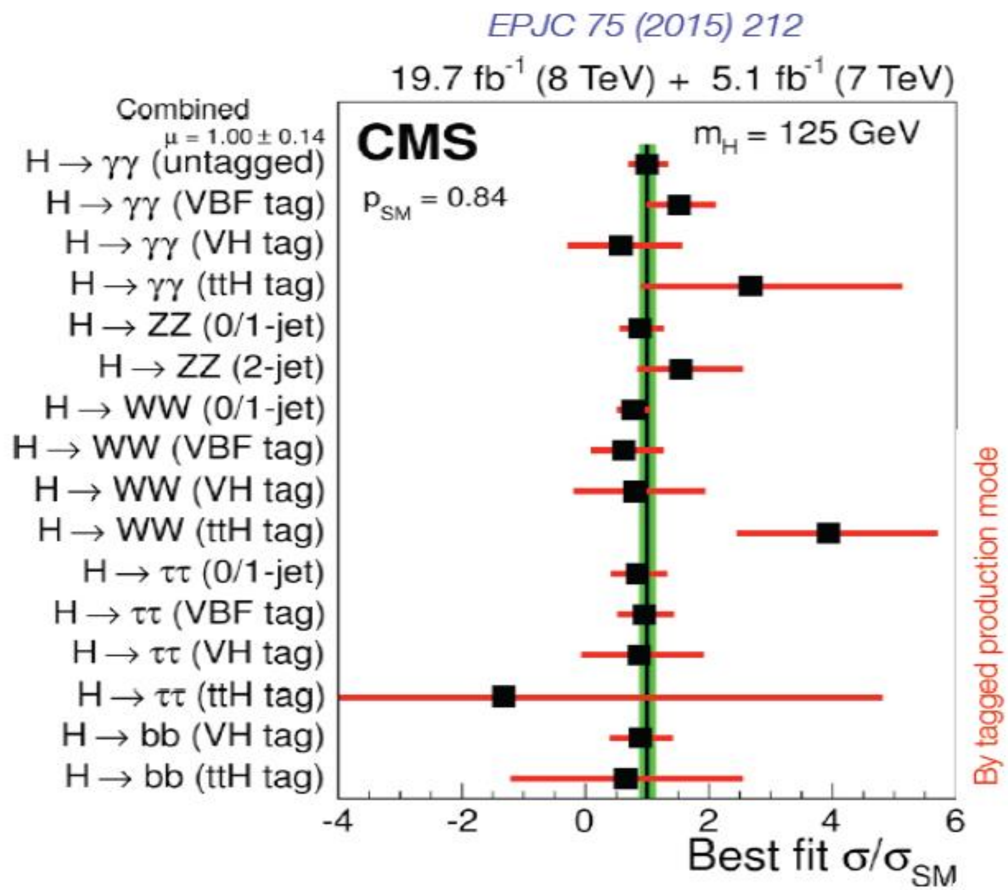
Probe the production mode



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)