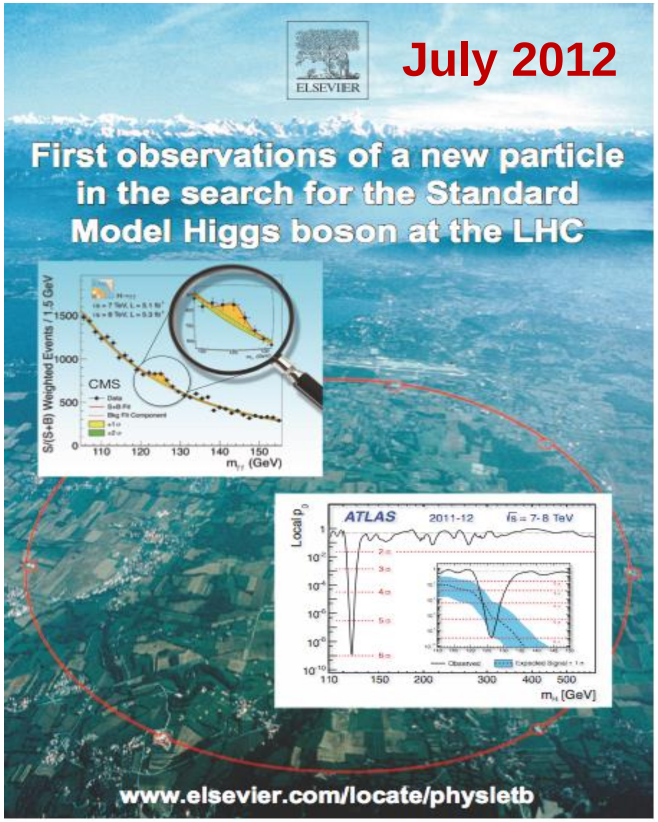
Dwa lata po odkryciu cząstki Higga



Jak dobrze już znamy:

- *masę,*
- *sprzężenia*
- *szerokość*
- *spin i parzystość*

E. Richter-Wąs
Instytut Fizyki, Uniwersytet Jagielloński

Large Hadron Collider: 25 years of preparation

1983 : $W^{\pm}/Z$ detected at SPS proton-antiproton collider
Tevatron becomes operational

1984 : First studies for a high-energy pp collider in the LEP tunnel

1989 : Start of SLC and LEP e^+e^- colliders

1993 : SSC is cancelled

1994 : LHC approved by the CERN Council

1995 : Top-quark discovery at the Tevatron

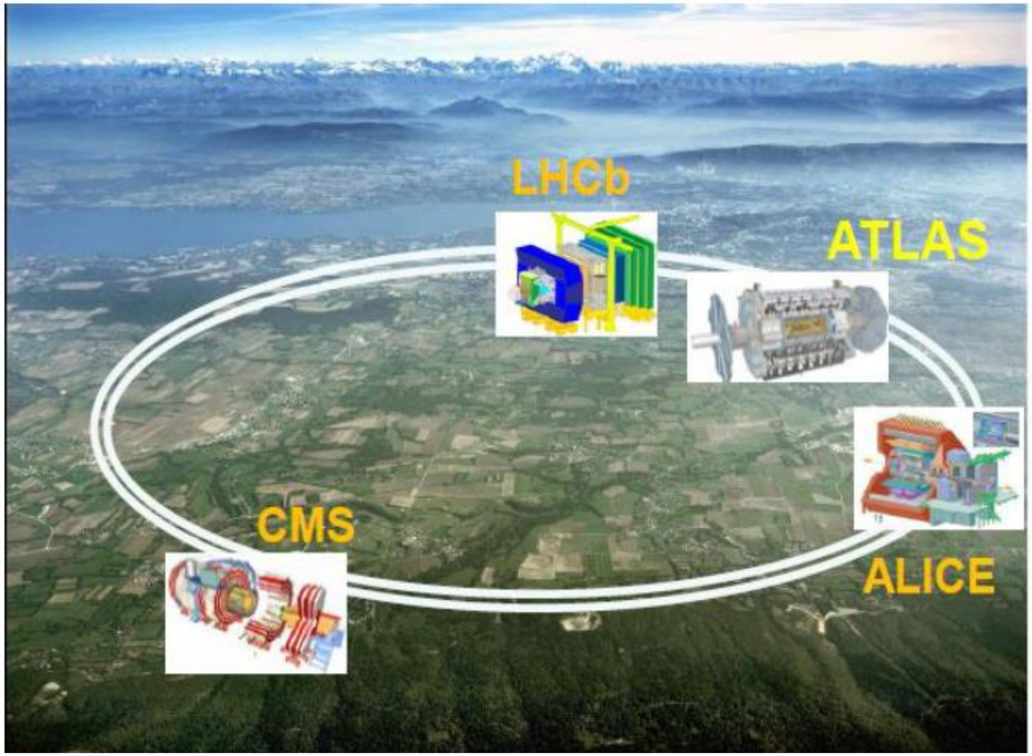
1996 : Construction of LHC machine and experiments start

2000 : End of LEP2

2003 : Start of the accelerator and experiments installation

Summer 2008 : Expect first collisions at $\sqrt{s}$ = 10TeV (14 TeV)

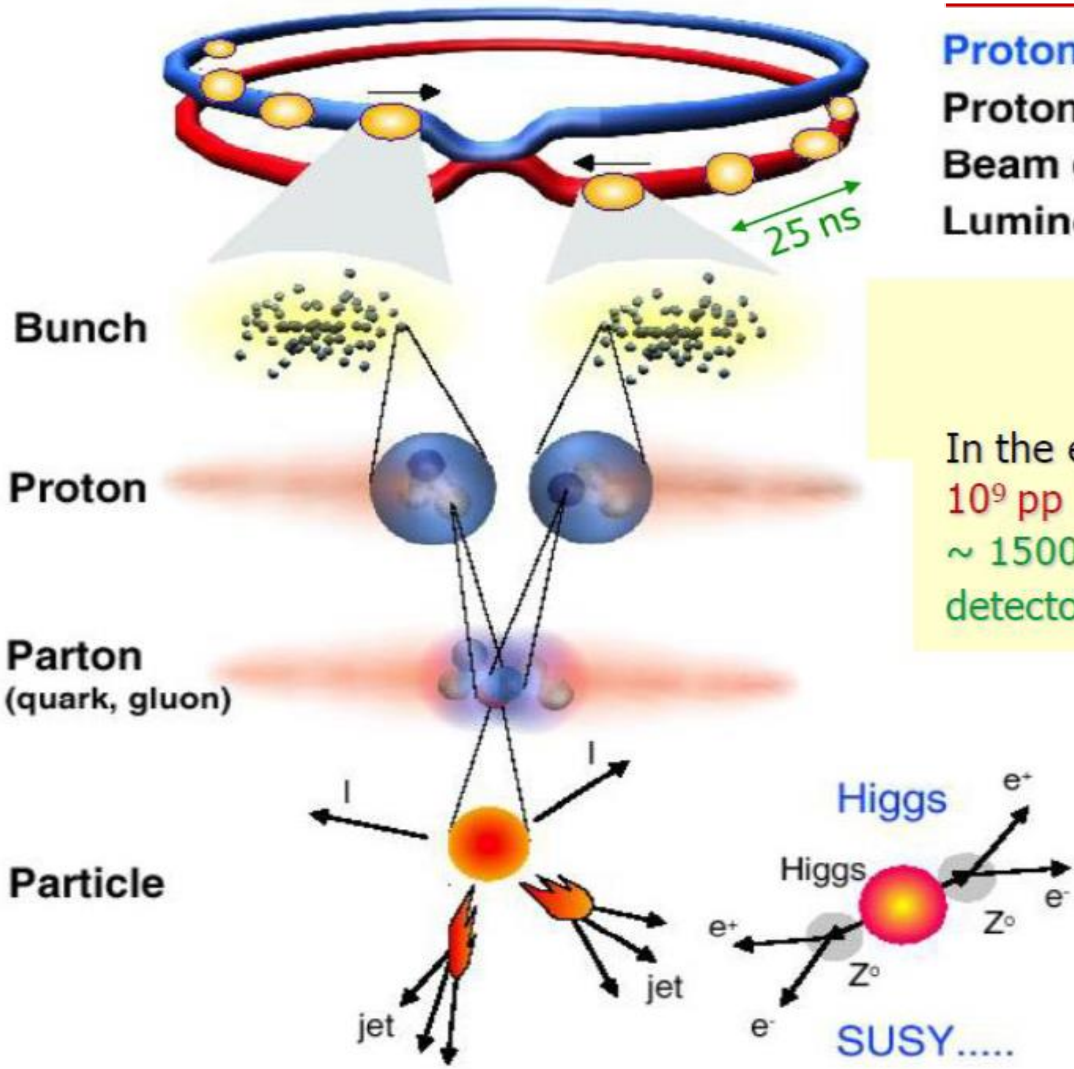
Large Hadron Collider



- 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)

Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
N_p	1.1 10^{11}	1.4 10^{11}	1.6 10^{11}	1.15 10^{11}
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}

Collisions at Large Hadron Collider



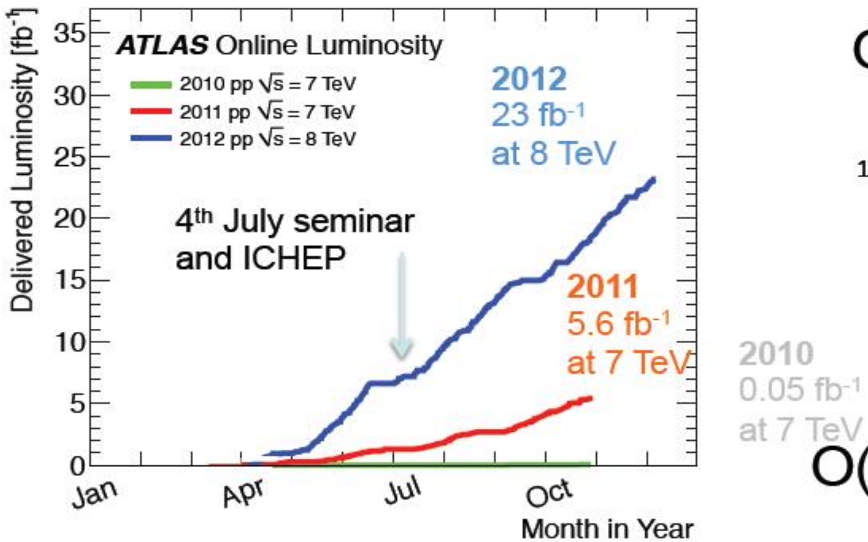
Nominal parameters

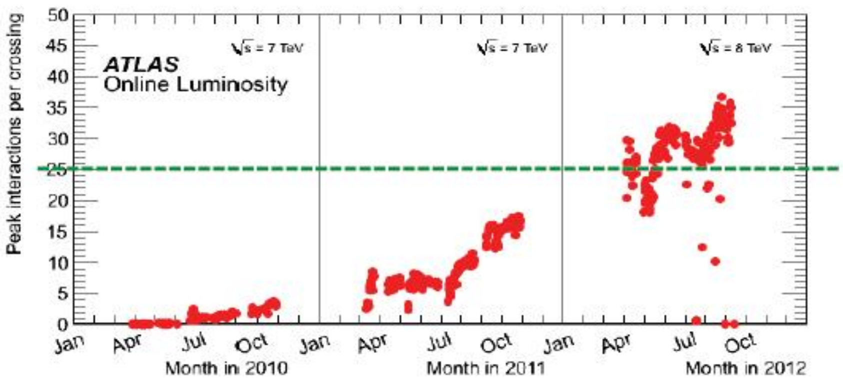
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}

In the experiments:
10^9 pp interactions per second
~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

Selection of 1 in 10,000,000,000,000

The first LHC run

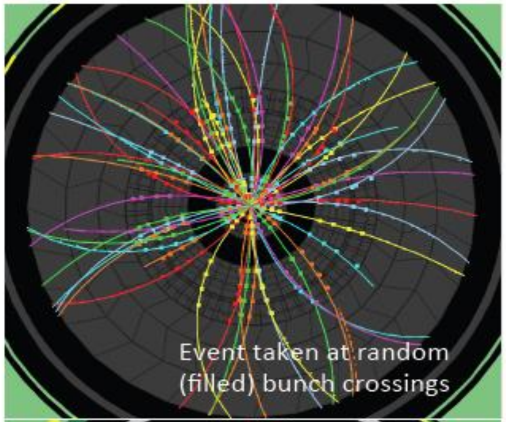




2010

O(2) Pile-up events

150 ns inter-bunch spacing



2011

O(10) Pile-up events

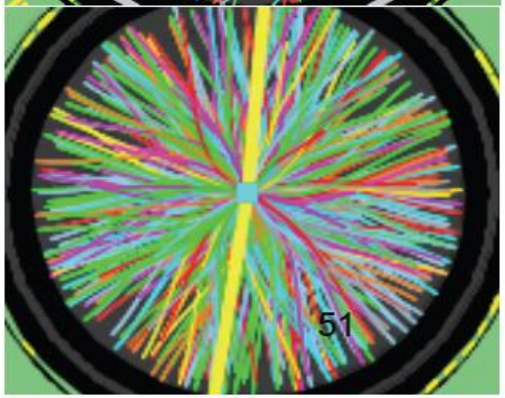
50 ns inter-bunch spacing

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

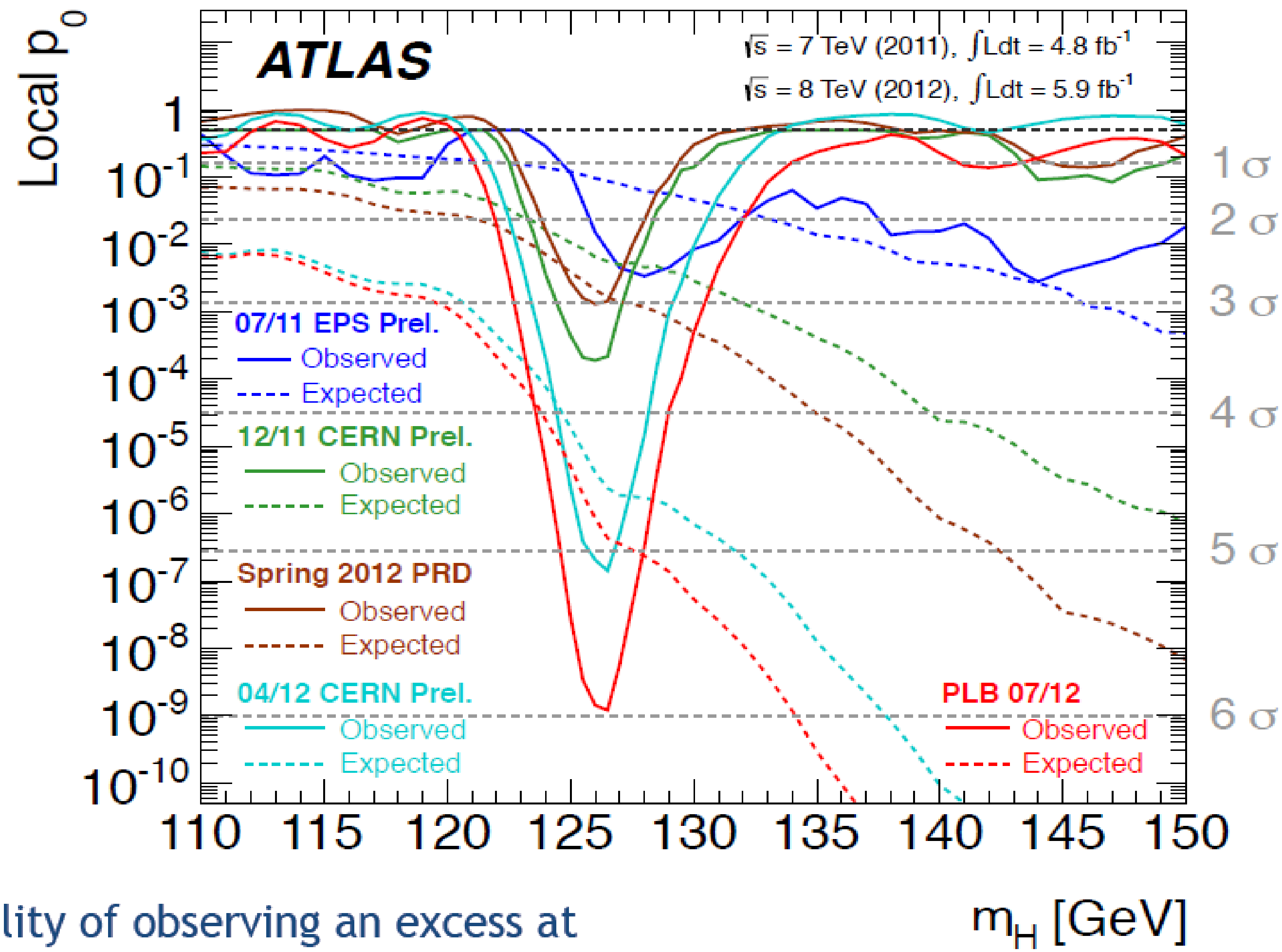
2012

O(20) Pile-up events

50 ns inter-bunch spacing



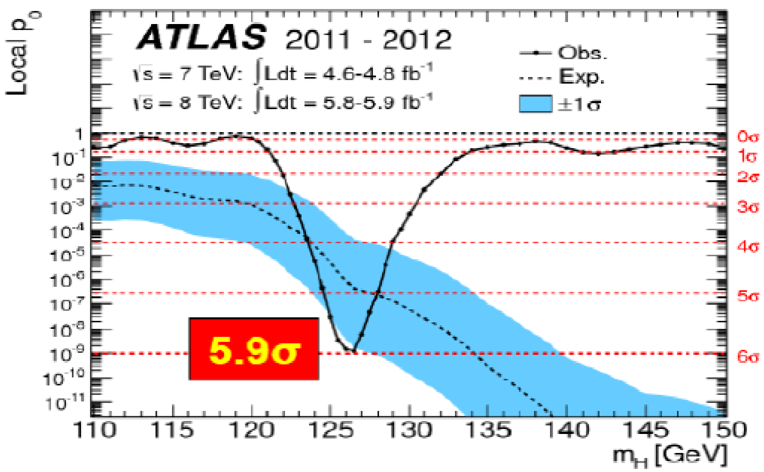
Birth of a particle ……

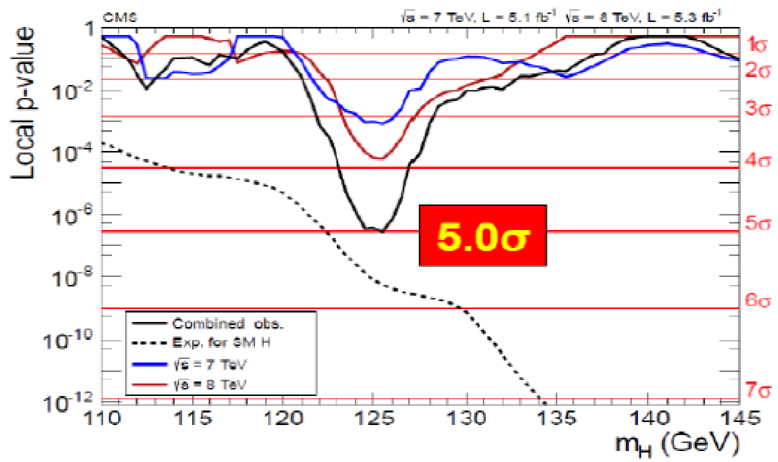


Probability of observing an excess at
one specific mass
(in absence of signal)…

Higgs-like particle: 4-July 2012

- We are living in a privileged moment in the history of High Energy Physics: **Our 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(lνlν, lνqq), ZZ(4l, llνν, llqq)

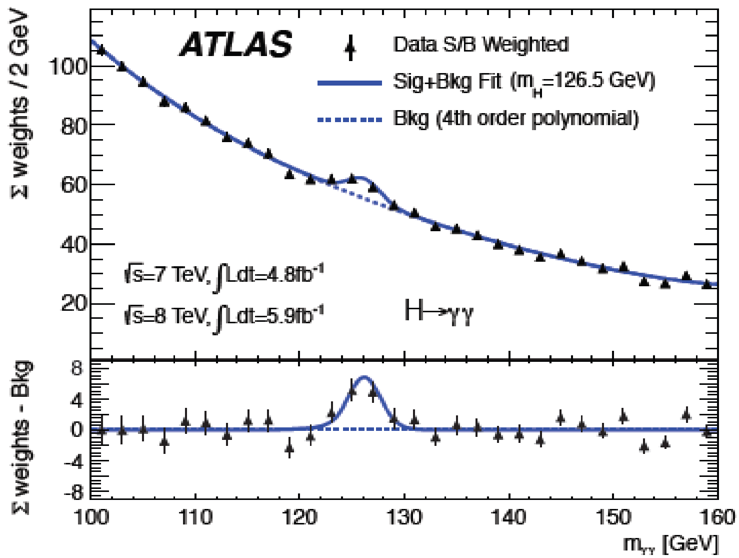
CMS *PLB 716 (2012) 30-61*, ***Sept 17 (2012)***

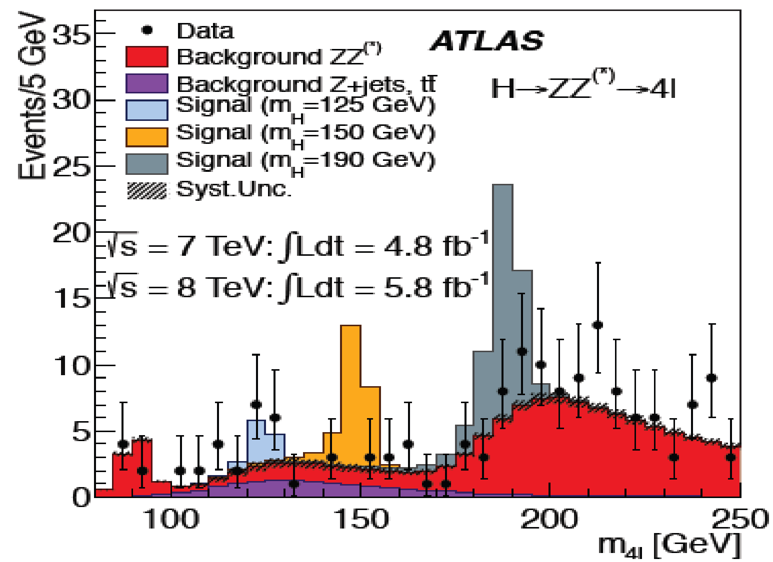
Largest local excess:
5.0σ at m_H= 125.5 GeV

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

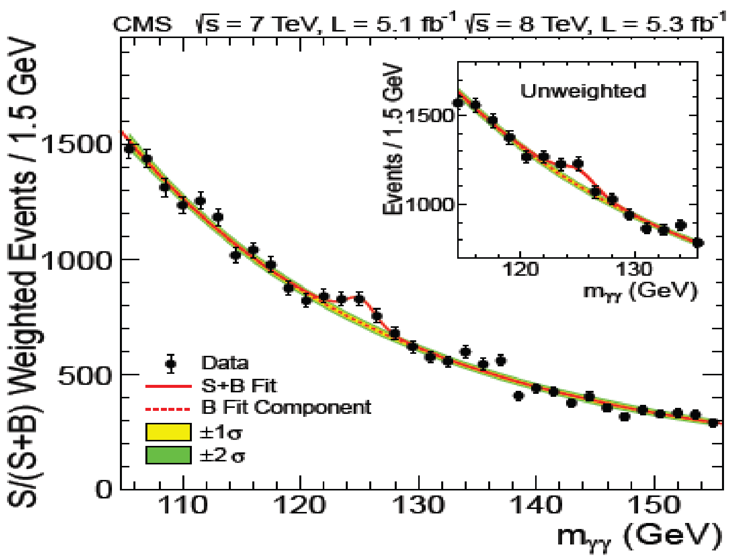
Higgs –like particle: 4 July 2012

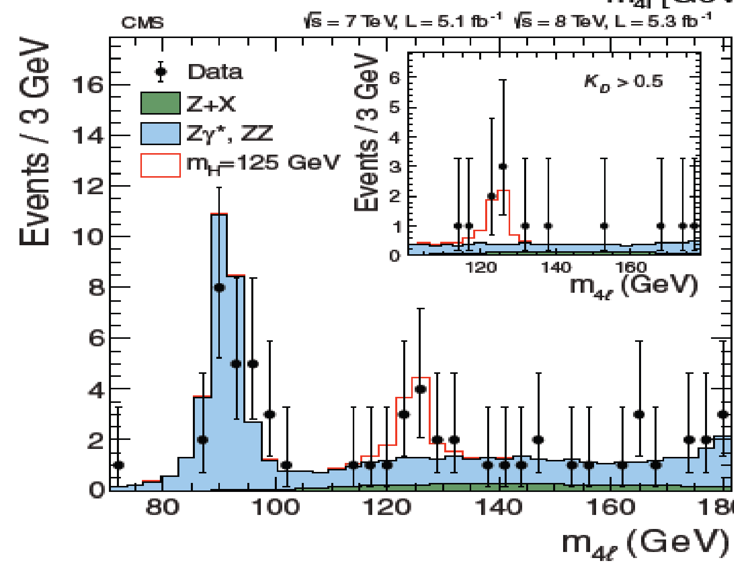
Phys.Lett. B716 (2012) 1-29





Phys.Lett. B716 (2012) 30-61





And since then ….

γγ channel basic facts :

7.4σ (4.3σ)

- Ns ~ O(500) per experiment
- Signal purity ~ 2% - 60%

4l channel basic facts :

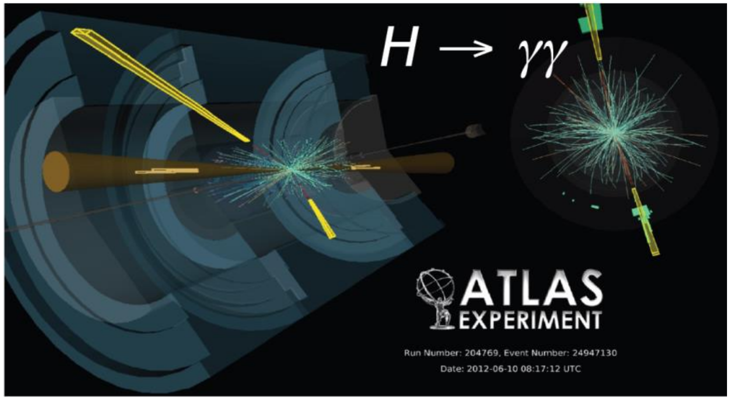
6.8σ (6.7σ)

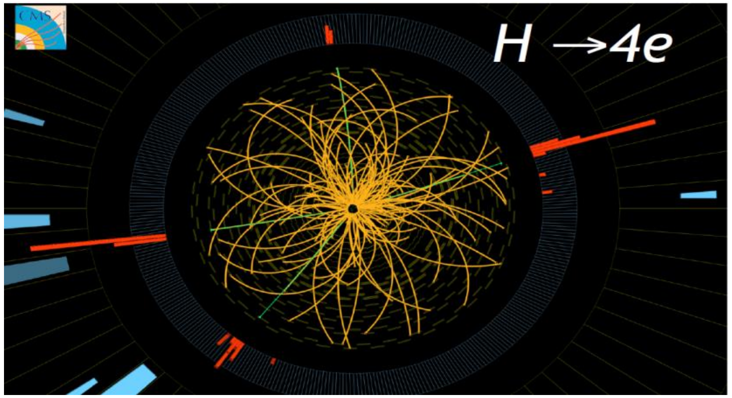
- Ns ~ O(15-20) per experiment
- Signal purity > 1.5

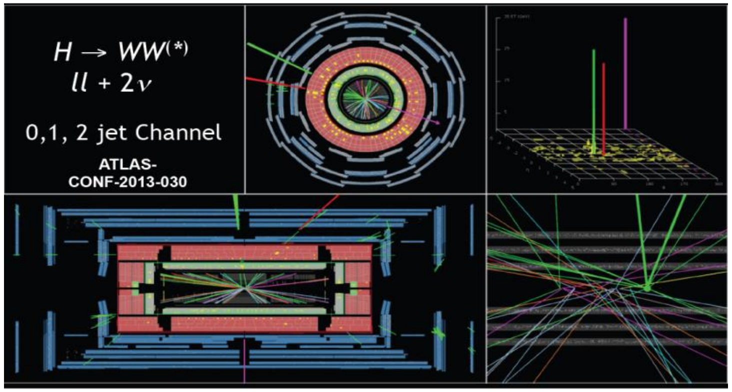
lνlν channel basic facts :

3.8σ (3.8σ)

- Ns ~ O(300) per experiment
- Signal purity ~ 5% and 40%





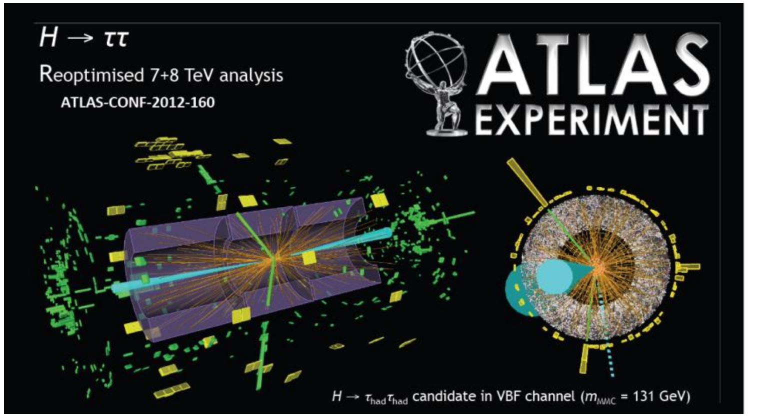


And since then ….

$\tau\tau$ channel basic facts :

- Ns ~ O(500) per experiment
- Signal purity ~ 0.3% - ~O(50%)

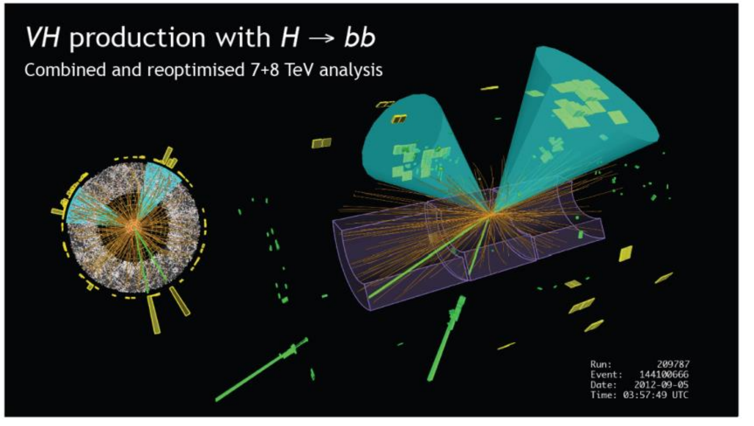
4.1σ (3.2σ)



VH(bb) channel basic facts :

- Ns ~ O(100) per experiment
- Signal purity ~ 1% - 15%

0.36σ (1.64σ)



Which Higgs boson we discovered?

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

- Higgs boson mass is ~125.6 GeV

  Measured in H->ZZ*->4l and H->$\gamma\gamma$

  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

All measured properties are compatible with SM hypothesis.

... in 2013 Entrance of the H^0 in the PDG!

Higgs Bosons — H^0 and $H^\pm$

NODE=S055
NODE=S055

A REVIEW GOES HERE – Check our WWW List of Reviews

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

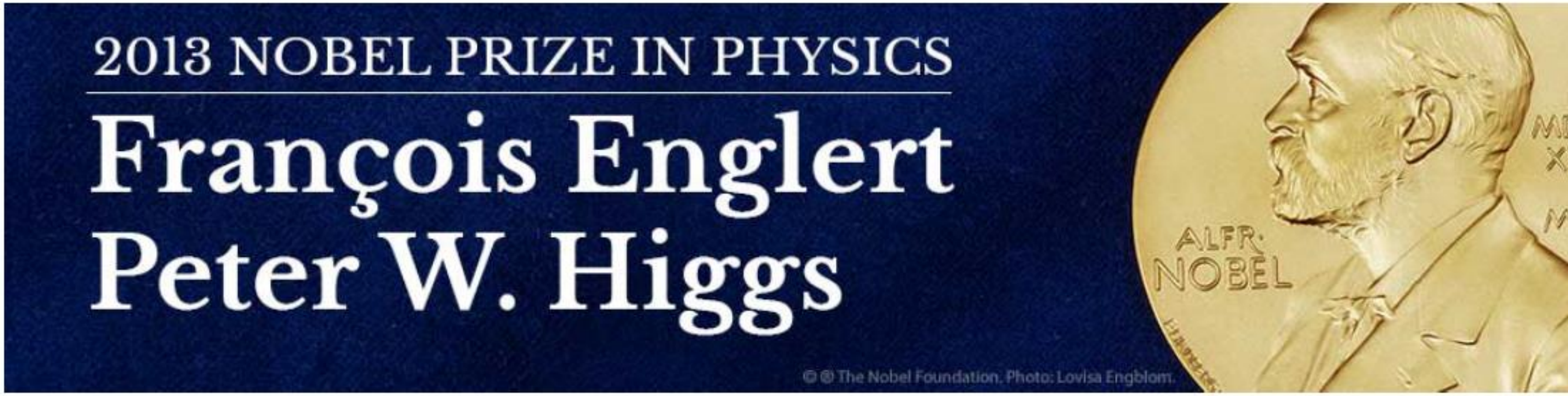
[3] Result based on $ZZ \to 4\ell$ final states in 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV. NODE=S055HBM;LINKAGE=CT

[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 !

(not anymore as an hypothetical particle)

$$H^0$$



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

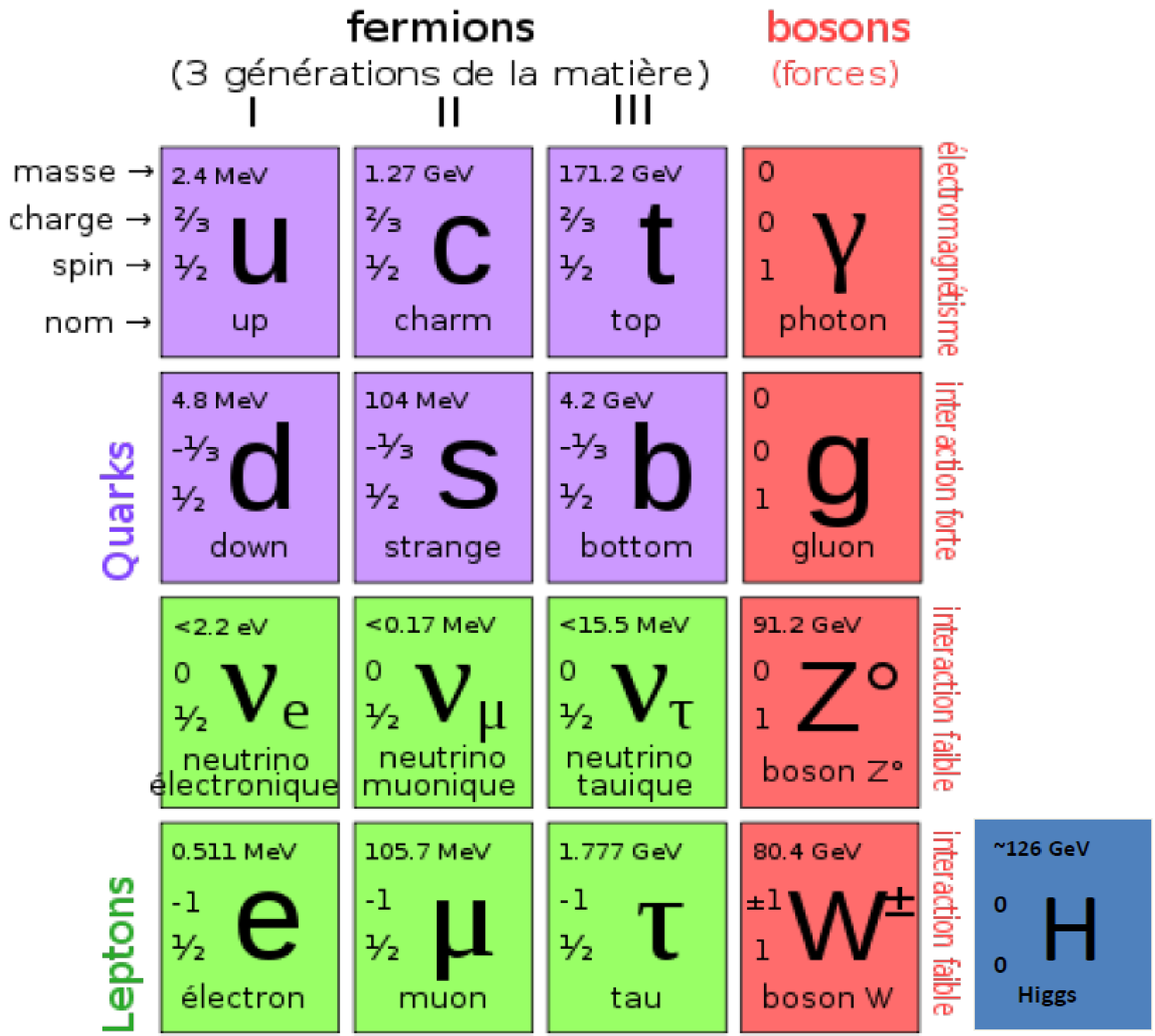
“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”

Standard Model particles

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

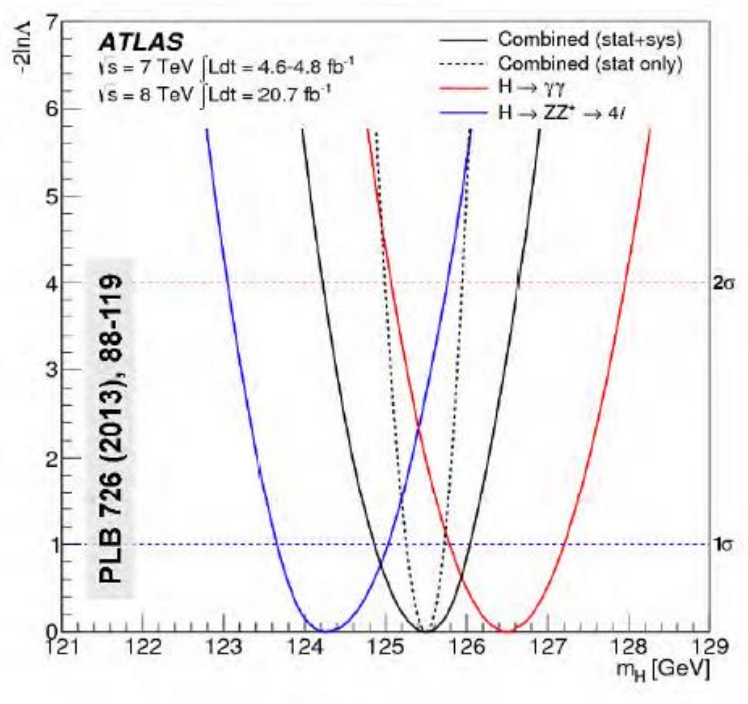
Through boson exchange
- EM : γ
- weak : W^+, W^- , Z
- strong : gluons

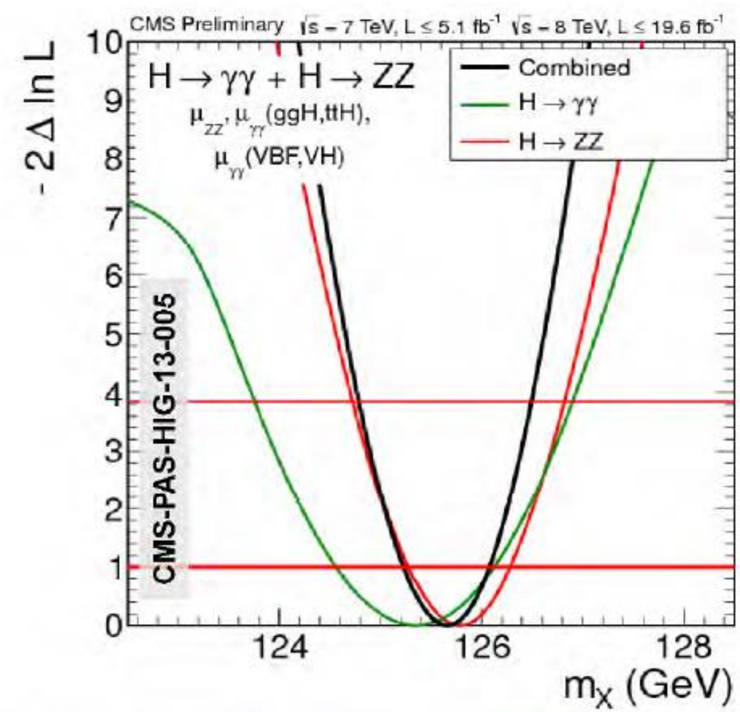
Higgs boson



Higgs boson: mass

- Both experiments should produce final results on a „summer" timescale.





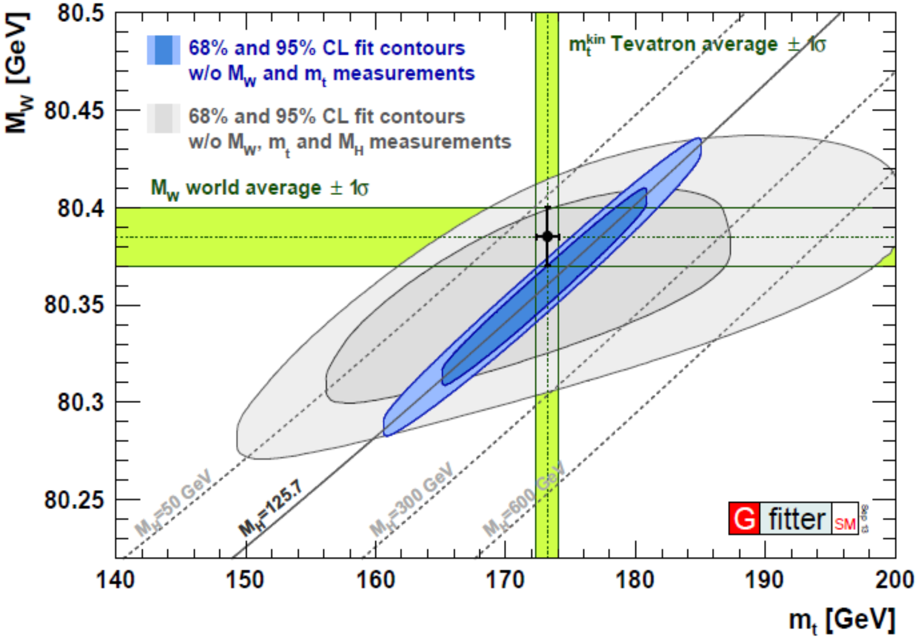
125.5 ± 0.2 (stat) ± 0.6 (syst)

125.7 ± 0.3 (stat) ± 0.3 (syst)

Standard Model after Higgs discovery

- Good agreement between measured mass and indirect prediction
- Very good agreement over large number of observables

GFitter '13



Direct measurements:

$M_W = 80385 \pm 15$ MeV

$m_t = 173.24 \pm 0.95$ GeV

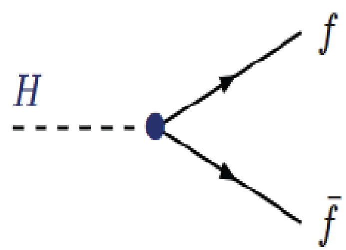
Indirect prediction:

$M_W = 80358 \pm 7$ MeV

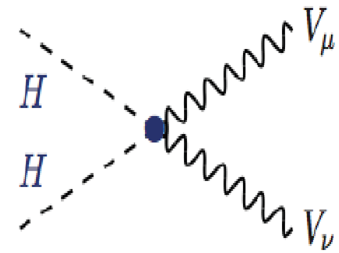
$m_t = 177.0 \pm 2.1$ GeV

More precise estimate of m_W than the direct measurement!

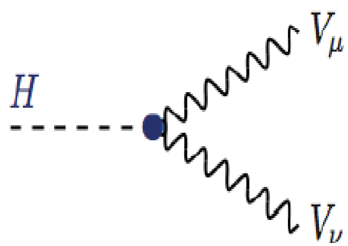
Higgs boson couplings



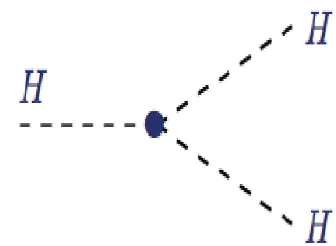
$$g_{Hff} = m_f/v$$



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

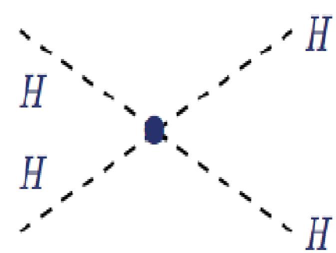


$$g_{HVV} = 2M_V^2/v$$



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

For the time being only test the bosonic and fermionic sector



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

Measuring Higgs couplings

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

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

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

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

Higgs boson couplings

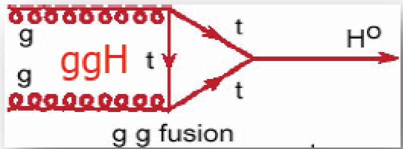
- **Pseudo-observables**, i.e. are not measured directly, certain „unfolding" procedure required to extract information
- **Simplified framework** (LO –like):
  - Signals originate from single resonance with mass ~125 GeV
  - The width of the assumed Higgs boson is neglected, i.e. zero-width approximation is used

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

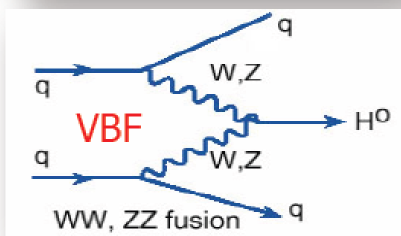
  - **Only modifications of coupling strenghts are considered**, the tensor structure is assumed as in the SM i.e. assume that it is „Higgs-like" resonance.

Higgs boson production

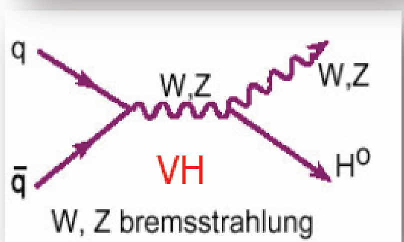
87%



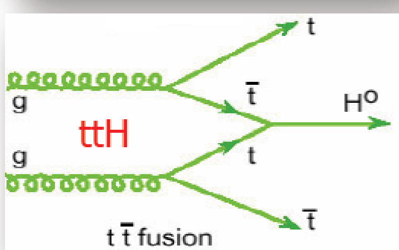
7.1%



4.9%

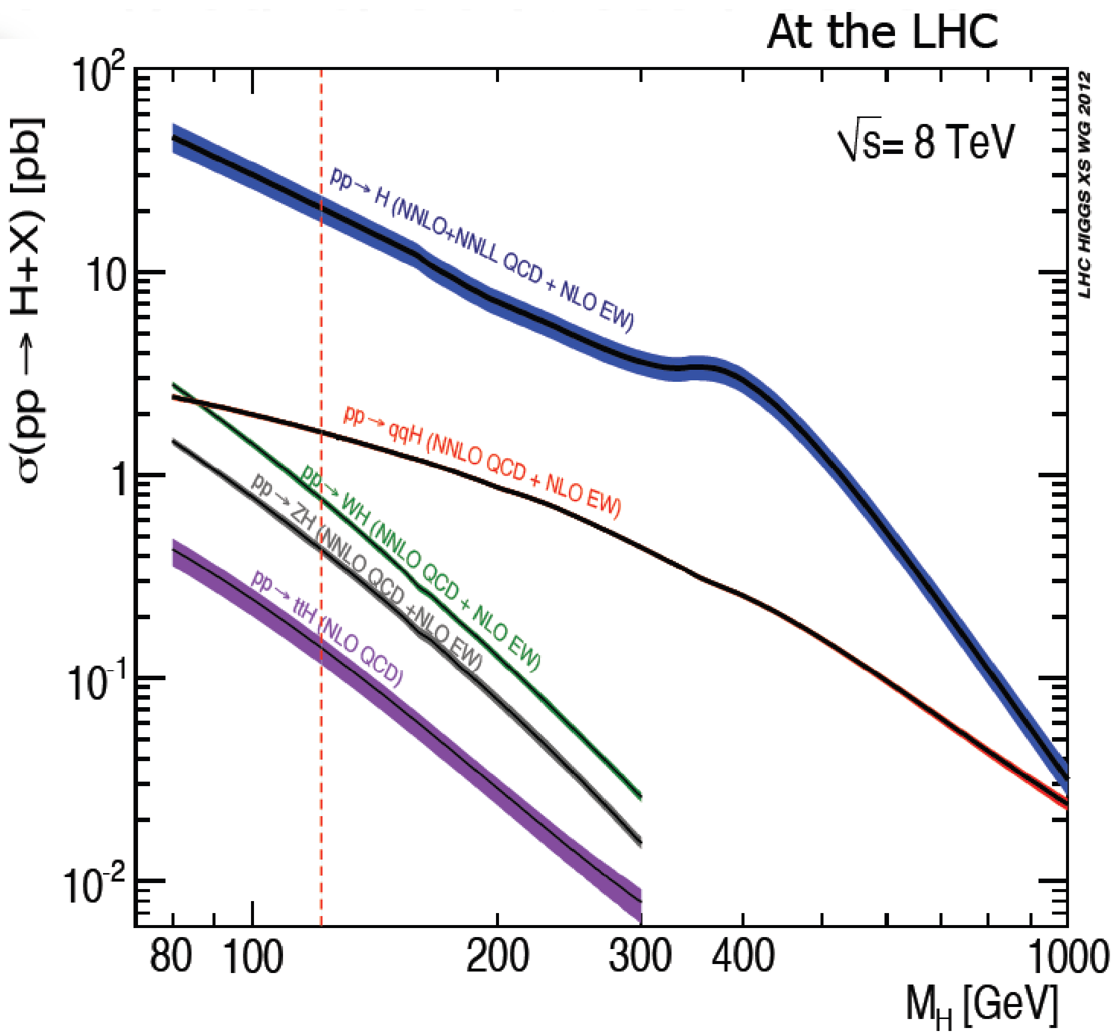


0.6%

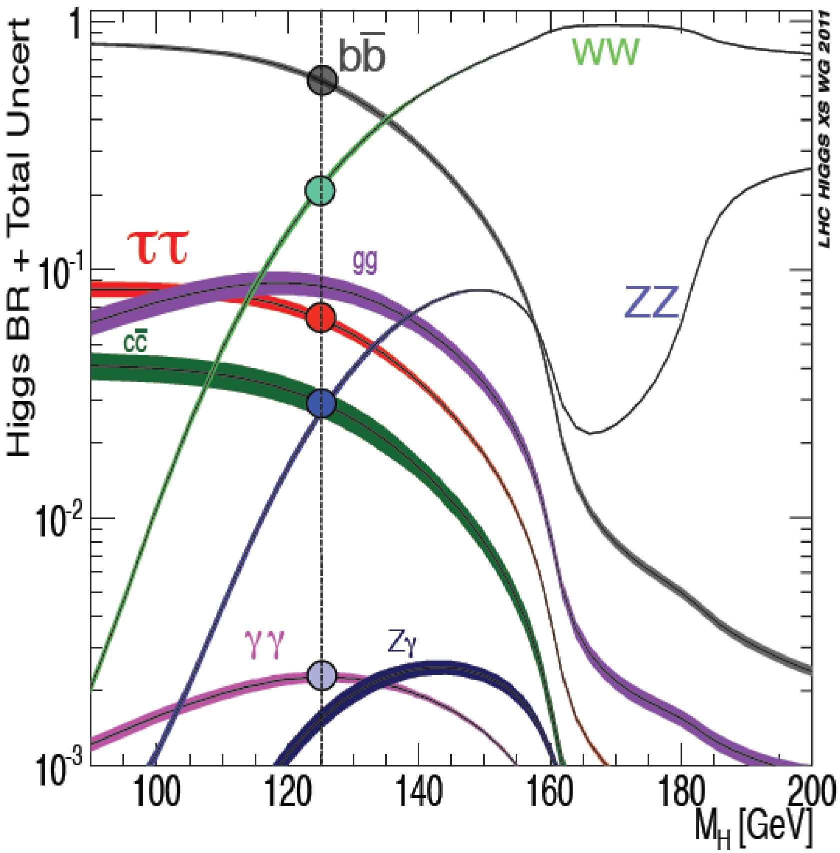


$\Updownarrow$

σ/σ_{tot} (M_H = 125 GeV)



Higgs boson decays



$\Delta M/M \sim$ 1-2% High resolution

$H \to \gamma\gamma$ Rare, S/B < 1

$H \to ZZ^* \to 4\ell$ Very rare, S/B >> 1

$\Delta M/M \sim$ 10-20% Medium resolution

$H \to bb$ Abundant, S/B << 1

$H \to \tau\tau$ Abundant, S/B < 1

$\Delta M/M$ > 30% Low resolution

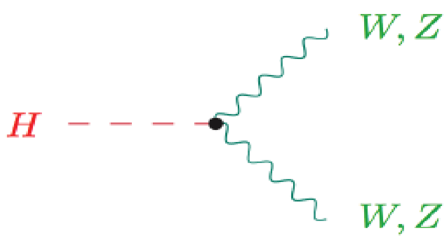
$H \to WW^* \to 2\ell 2\nu$ Very abundant, S/B < 1

4 production modes x 5 decay modes ($\gamma\gamma$,ZZ,WW,bb,$\tau\tau$)

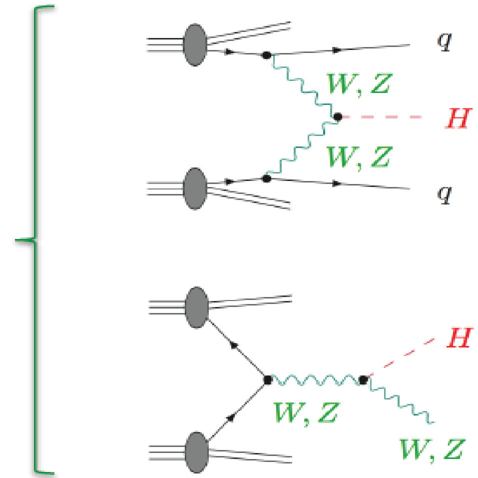
~ 100 exclusive final states (production, decay, event categories) are contributing to m_H ~125 GeV!

Relative couplings

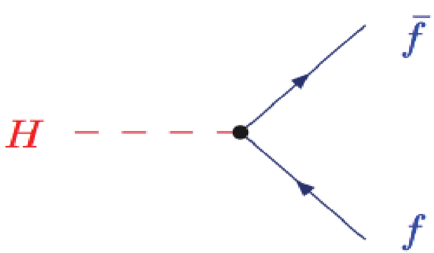
(I) Tree Level Couplings scale factors w.r.t. SM



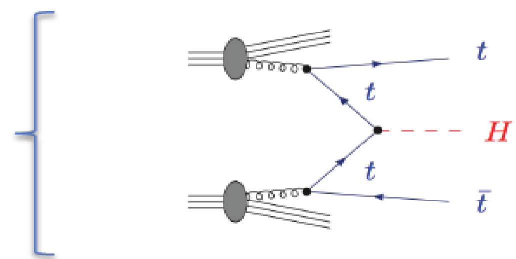
$\propto \kappa_V$



Affecting decay and production modes

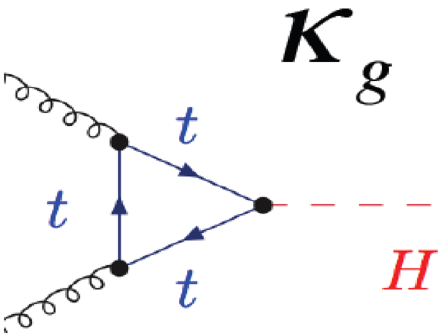


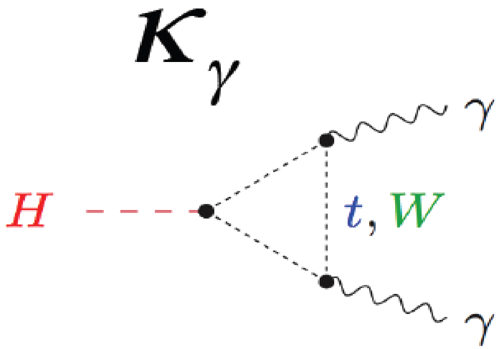
$\propto \kappa_F$



Relative couplings

(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)

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

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

Model (I): Couplings to fermions and vector bosons

Single scale factor for all fermion couplings κ_F and vector boson κ_V couplings

$Br_{\gamma\gamma,etc...}$

$\sigma_{ggH,VBF,etc...}$

Boson and fermion scaling without invisible or undetectable widths

Free parameters: $\kappa_V(=\kappa_W=\kappa_Z)$, $\kappa_f(=\kappa_t=\kappa_b=\kappa_\tau)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$	

Boson and fermion scaling without assumptions on the total width

Free parameters: $\kappa_{VV}(=\kappa_V\cdot\kappa_V/\kappa_H)$, $\lambda_{fV}(=\kappa_f/\kappa_V)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{VV}^2\cdot\lambda_{fV}^2\cdot\kappa_\gamma^2(\lambda_{fV},\lambda_{fV},\lambda_{fV},1)$	$\kappa_{VV}^2\cdot\lambda_{fV}^2$		$\kappa_{VV}^2\cdot\lambda_{fV}^2\cdot\lambda_{fV}^2$	
VBF WH ZH	$\kappa_{VV}^2\cdot\kappa_\gamma^2(\lambda_{fV},\lambda_{fV},\lambda_{fV},1)$	κ_{VV}^2		$\kappa_{VV}^2\cdot\lambda_{fV}^2$	

$\kappa_i^2=\Gamma_{ii}/\Gamma_{ii}^{SM}$

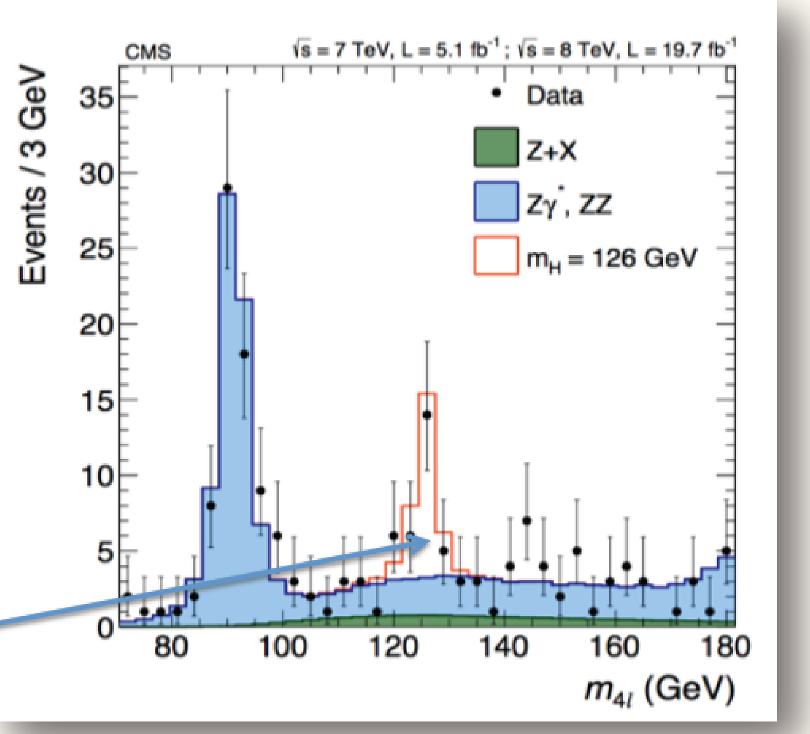
What do we measure?

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

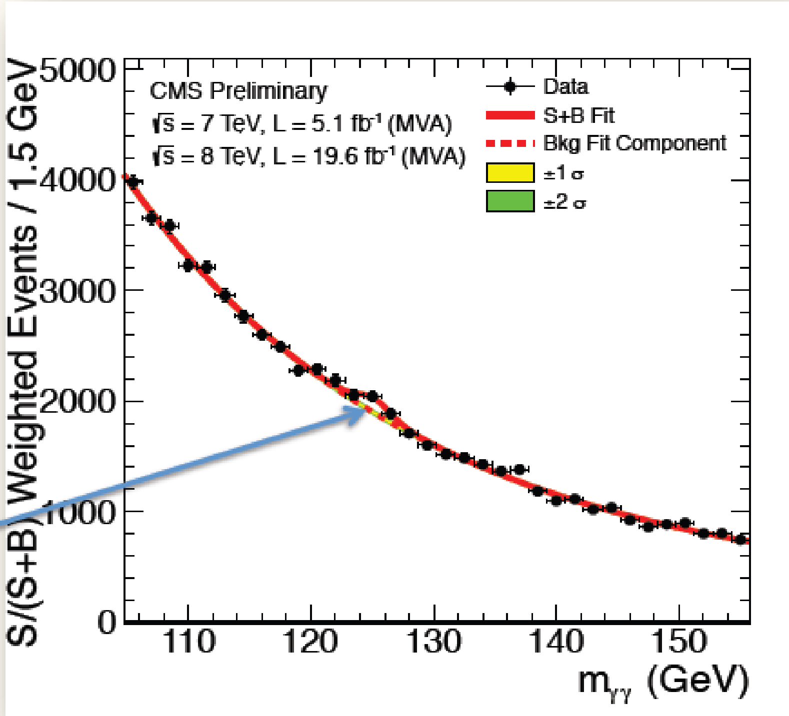
What do we measure?

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



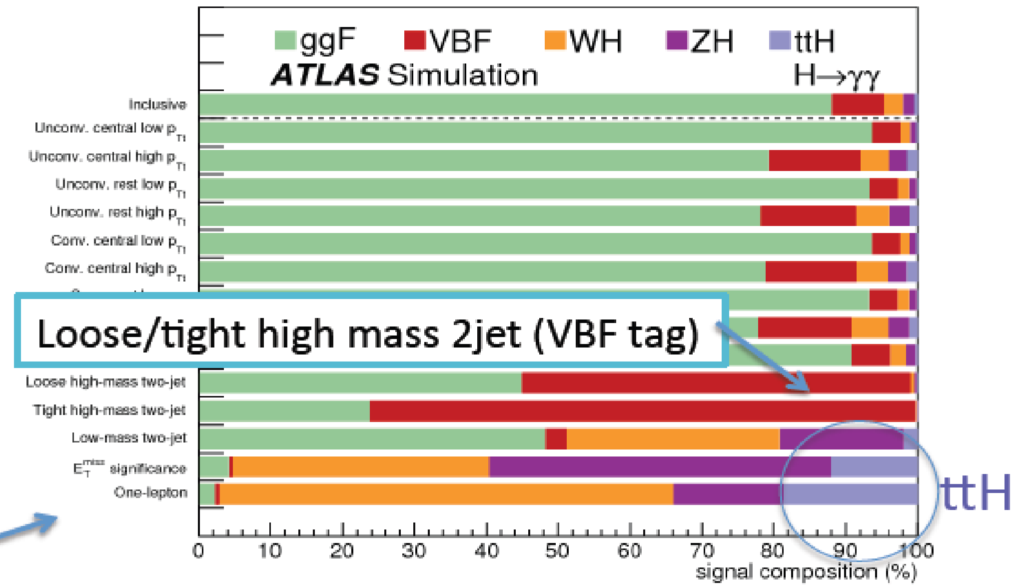
$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

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

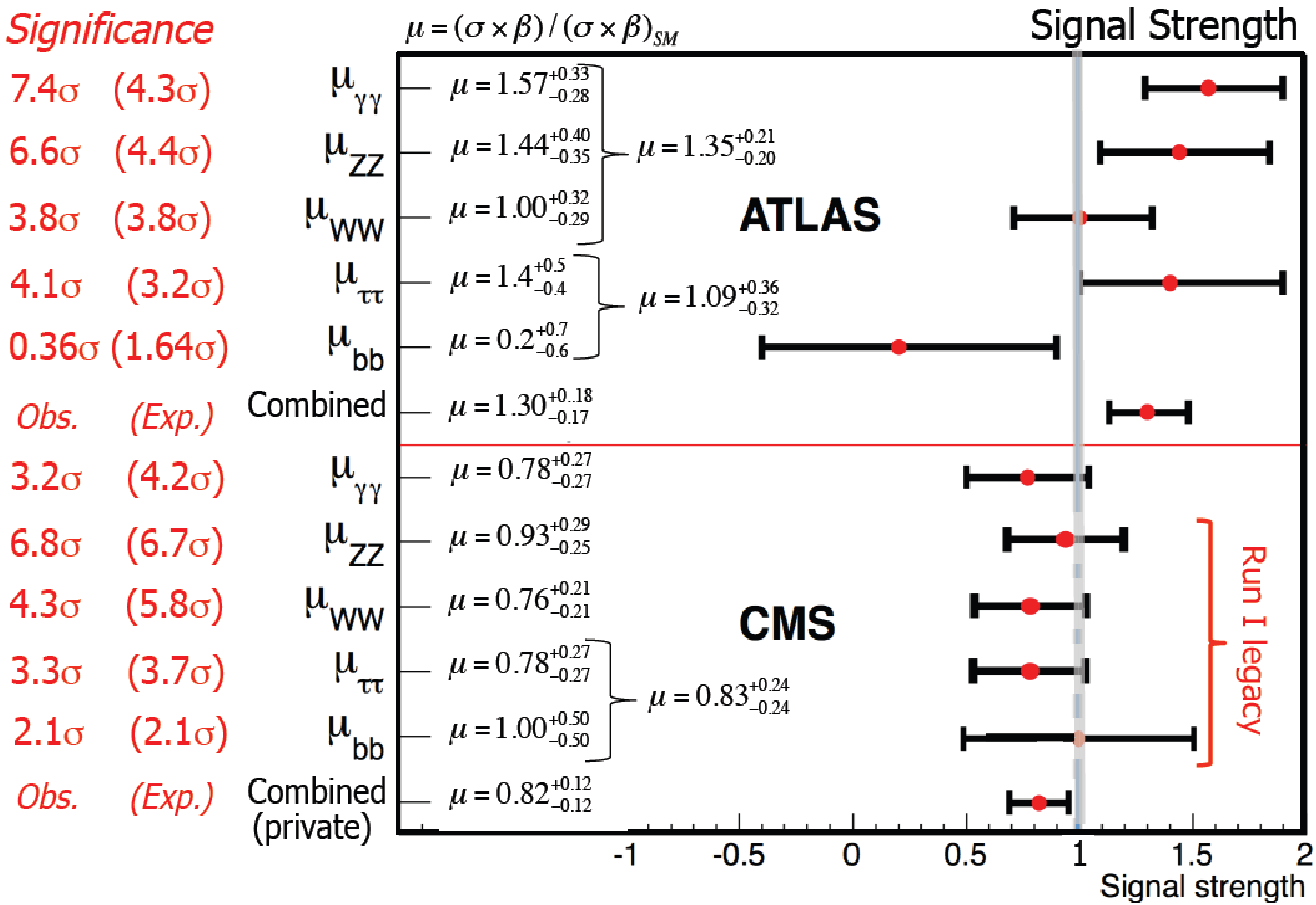
$$n_s^{c,i} = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

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

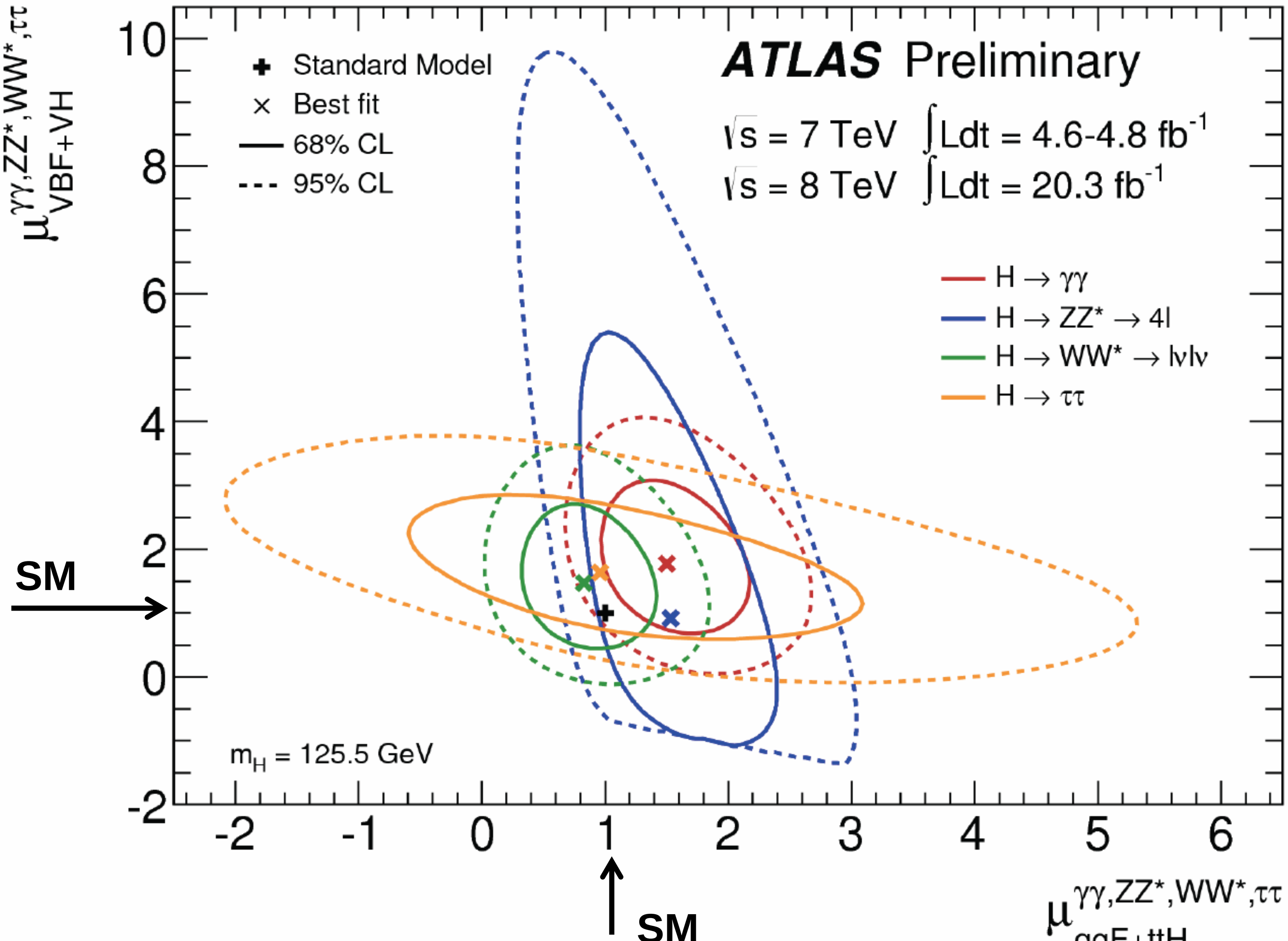
$\mu_{\gamma\gamma}$(@125.5 GeV) $= 1.57^{+0.33}_{-0.28}$ **7.4σ (4.3 exp) ATLAS**

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

Higgs boson decay channels



Probe the production mode



Probe the production mode

We fitted

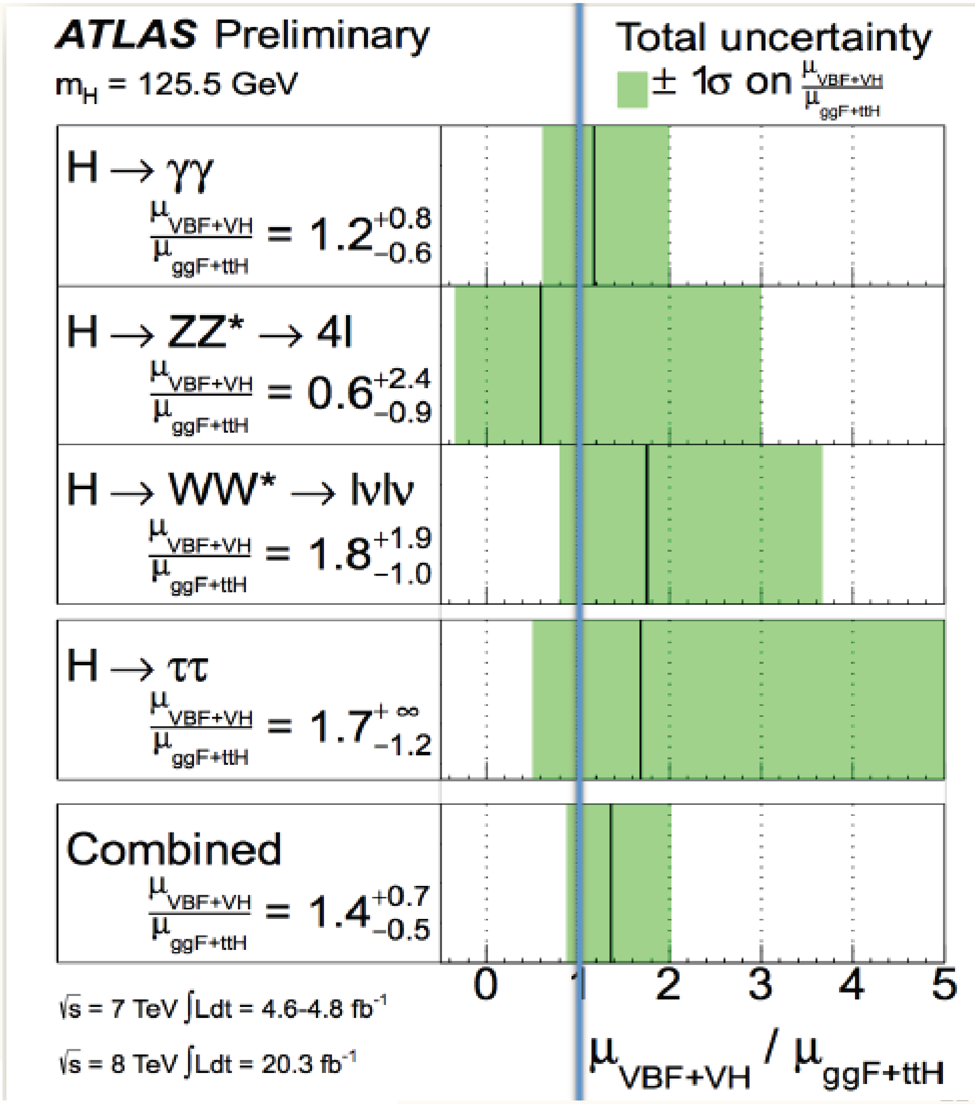
$$\mu^{i}_{VBF+VH} \equiv \left[\mu_{VBF+VH} \times \mu^{i}_{BR}\right]$$

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

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

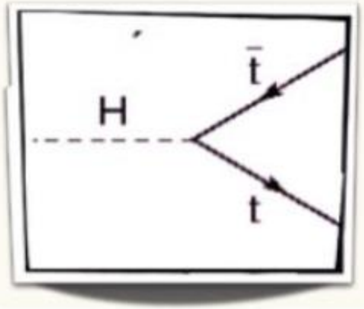
$$\frac{\mu^{i}_{VBF+VH}}{\mu^{i}_{ggF+ttH}} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

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



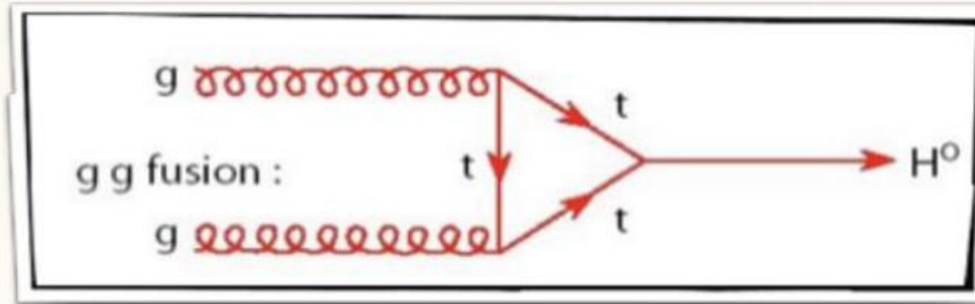
Indirect sensitivity to fermion couplings

Indirect Sensitivity to Fermion Couplings



$$k_t^2 = \frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}}$$

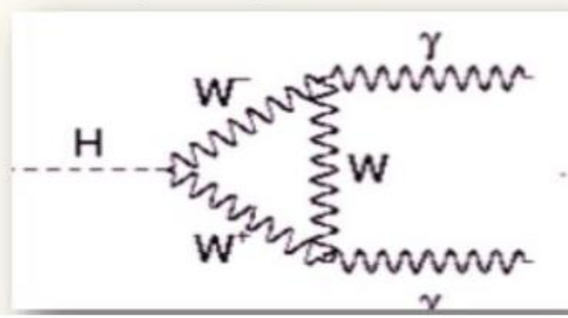
$$k_t^2 = \frac{g_t^2}{g_{t.SM}^2}$$



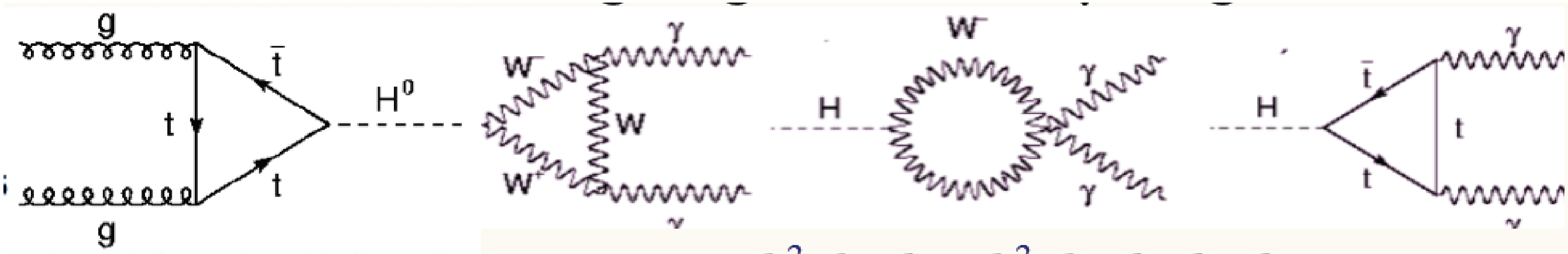
$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

Note that if all fermion couplings are set to be equal, $k_g^2 = k_F^2$

$$k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$



Disentangling the couplings



$$(\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) \sim \frac{k_g^2(k_b, k_t) \cdot k_\gamma^2(k_b, k_t, k_\tau, k_W)}{k_H^2(k_Z, k_W, k_\tau, k_t, k_b)}$$

Note, couplings are dependent on the Higgs mass

$$\sigma(ggF) \times BR(H \rightarrow \gamma\gamma) \sim \frac{k_F^2 \cdot \mathrm{k}_\gamma^2(k_F, k_F, k_F, k_V)}{0.75 k_F^2 + 0.25 k_V^2}$$

$$\sigma(VBF) \times BR(H \rightarrow \gamma\gamma) \sim \frac{k_V^2 \cdot \mathrm{k}_\gamma^2(k_F, k_F, k_F, k_V)}{0.75 k_F^2 + 0.25 k_V^2}$$

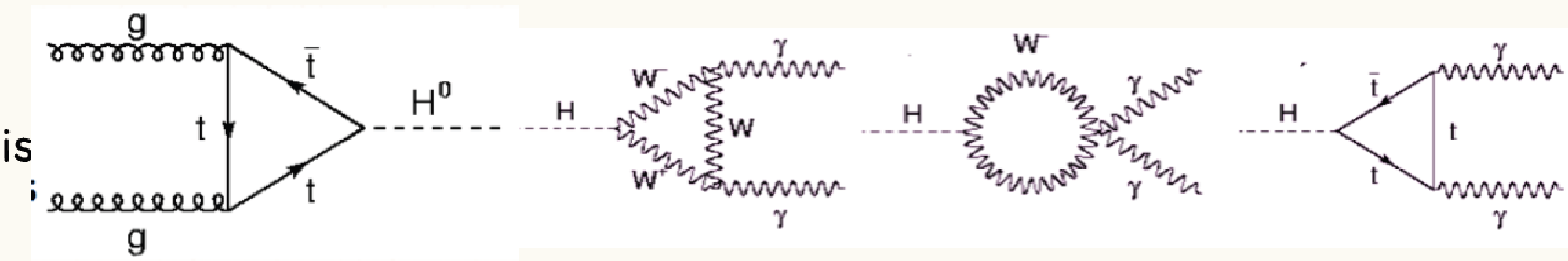
In the (k_F, k_V) benchmark:

$$\sigma(ggF) \times BR(H \rightarrow WW, ZZ) \sim \frac{k_F^2 \cdot \mathrm{k}_V^2}{0.75 k_F^2 + 0.25 k_V^2}$$

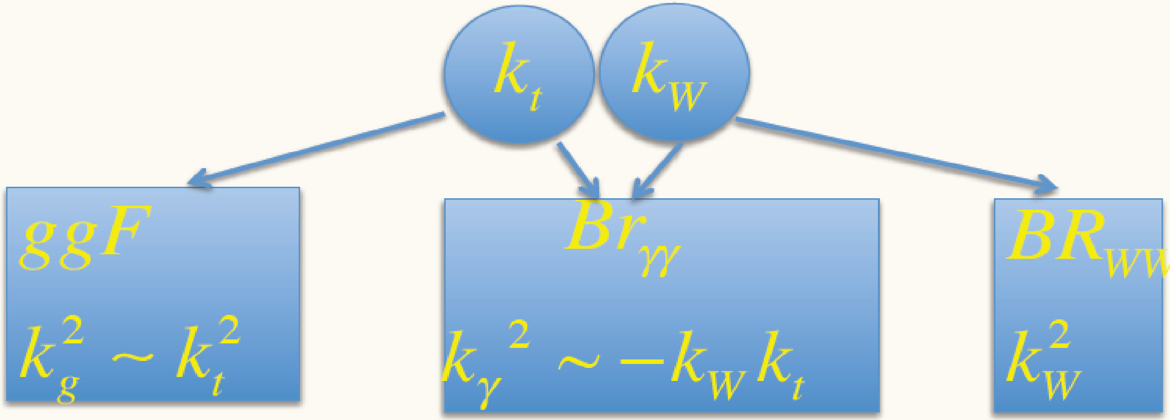
$$\sigma(VBF) \times BR(H \rightarrow WW, ZZ) \sim \frac{k_V^2 \cdot \mathrm{k}_V^2}{0.75 k_F^2 + 0.25 k_V^2}$$

$$\sigma(VBF, VH) \times BR(H \rightarrow \tau\tau, bb) \sim \frac{k_V^2 \cdot \mathrm{k}_F^2}{0.75 k_F^2 + 0.25 k_V^2}$$

A comment on interference



$$n_s^{\gamma\gamma} \sim k_g^2(k_t, k_b) \times k_\gamma^2(k_t, k_W) \quad k_\gamma^2 = |1.28 k_W - 0.28 k_t|^2$$



If k_t=-1 ggF slightly affected
WW unaffected
$\gamma\gamma$ increases

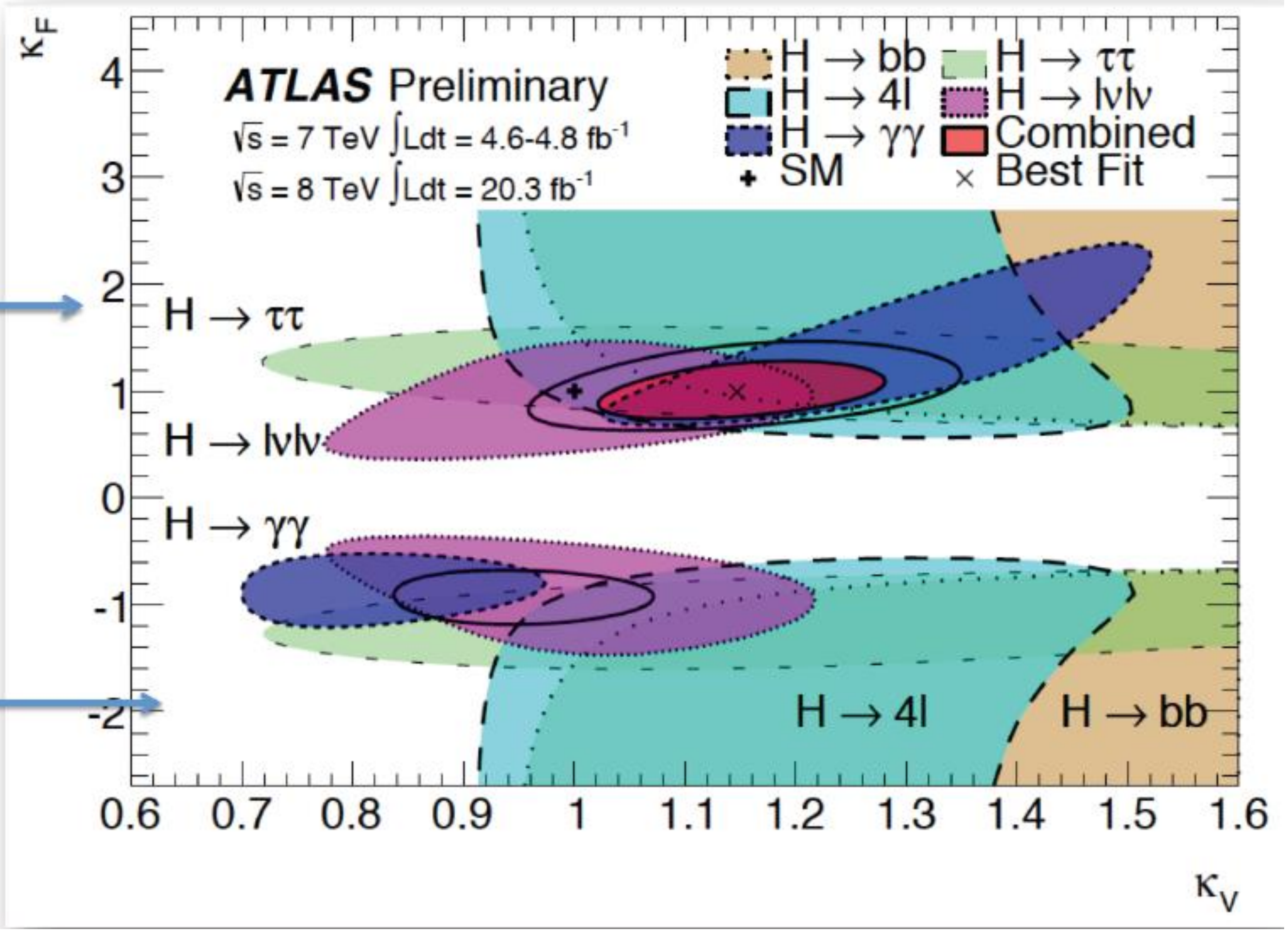
Allowing negative k_t is extremely important
Can be probed with tH

Model (I)

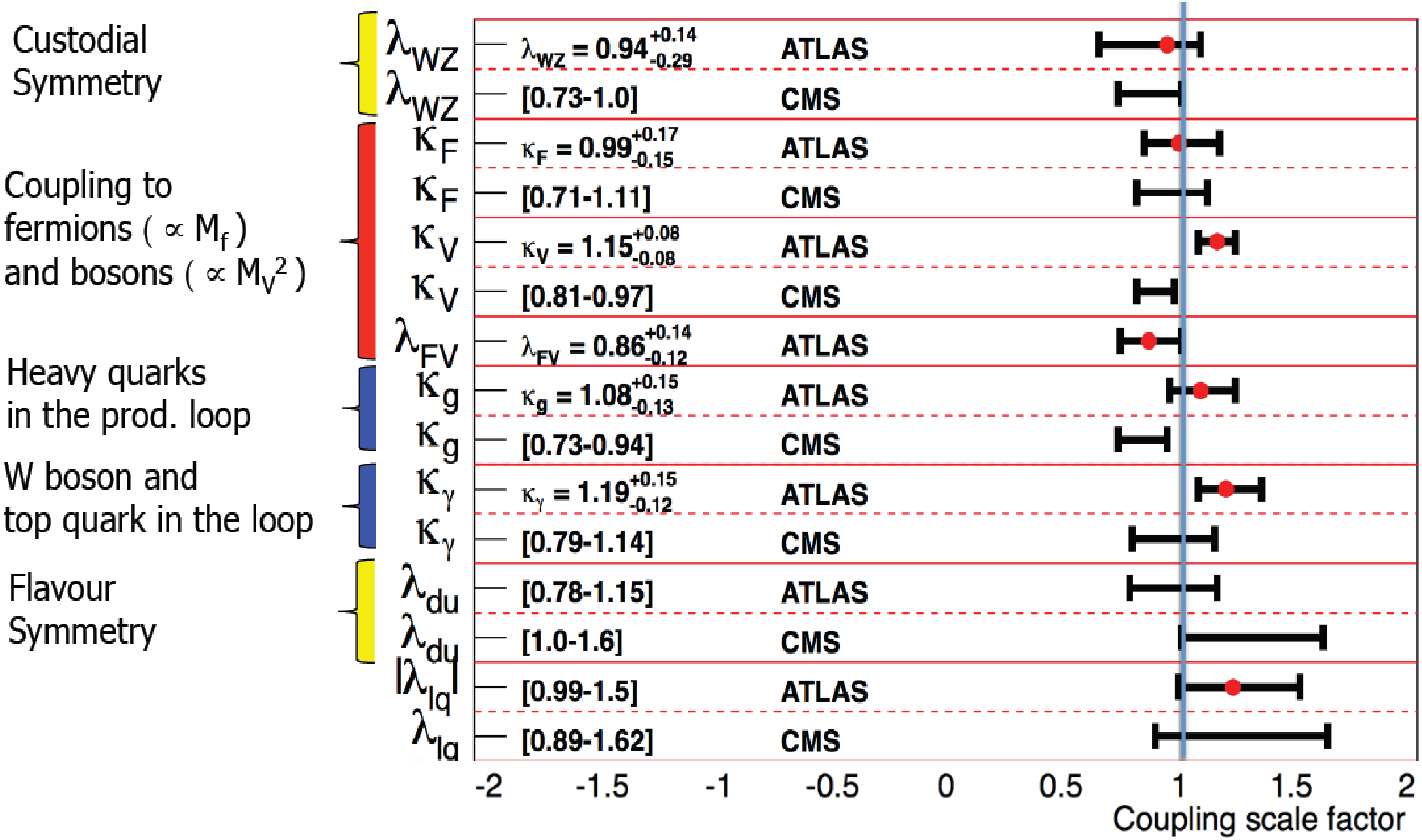
Precision today of 10-20% level:
$\kappa_V = 1.15 \pm 0.08$
$\kappa_F = 0.99 + 0.17 - 0.15$

SM – No Tension

Tension Drifting apart



Overall comparison of all coupling results



Higgs boson spin-parity

- Standard Model hypothesis predicts $J^P=0^+$
- Test several alternative J^P against the SM and observe which is favored by data.
  - Alternative models: $J^P = 0^-, 2^+, 1^+, 1^-$
- Use: $H\rightarrow\gamma\gamma$, H->ZZ* $\rightarrow$ 4l, H $\rightarrow$ W* $\rightarrow$ $l\nu l\nu$
  - Observation in the di-photon channel implies C=1 and J≠1
  - Observation in WW channel favors J=0
  - Observation in ZZ and WW channels disfavors P=-1
- Large number of options to probe spin directy:
  - From the associate poduction mode (VH, VBF, ggF)
  - From the decay angles and the spin correlations when applicable
  - From the production angle $\cos\theta^*$ distribution

What we are trying to exclude? J^{PC}

Spin 0

$$A(X \to V_1 V_2) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

Spin 1

$$A(X \to V_1 V_2) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X)\right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

Spin 2

$$A(X \to V_1 V_2) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}\left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)}\right)$$

$$+ g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} + m_V^2\left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}\left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}\right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^*\right)$$

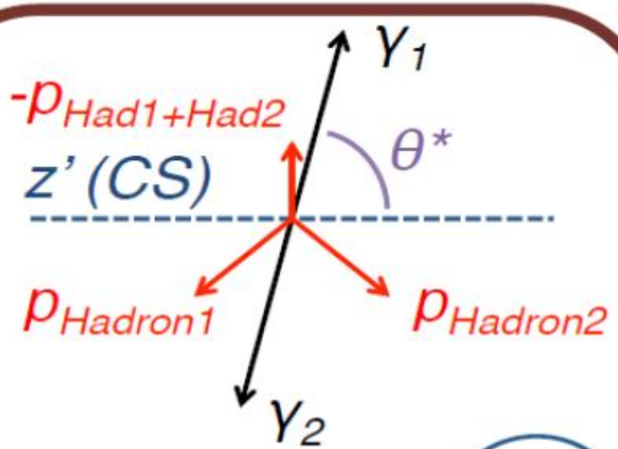
$$+ g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + m_V^2\left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\right)\Big]$$

What we are trying to exclude? J^{PC}

scenario	X production	$X \to VV$ decay	
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs scalar boson
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$	scalar higher-dim. op.
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar
1^+	$q\bar{q} \to X$	$b_2 \neq 0$	exotic pseudo-vector
1^-	$q\bar{q} \to X$	$b_1 \neq 0$	exotic vector
2_m^+	$g_1^{(2)} \neq 0$	$g_1^{(2)} = g_5^{(2)} \neq 0$	RS graviton min. coupl.
2_h^+	$g_4^{(2)} \neq 0$	$g_4^{(2)} \neq 0$	tensor higher-dim. op.
2_h^-	$g_8^{(2)} \neq 0$	$g_8^{(2)} \neq 0$	"pseudo-tensor"

Spin observables for H->$\gamma\gamma$

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



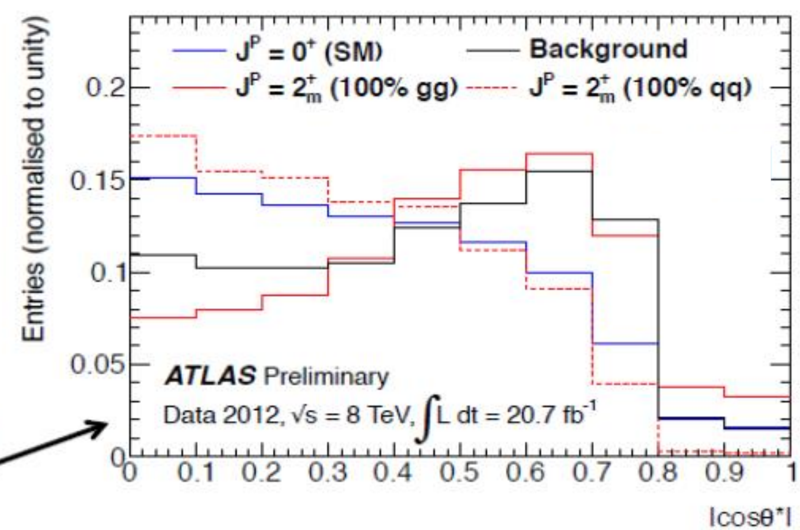
$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma1}p_T^{\gamma2}}{m^2_{\gamma\gamma}}$$

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 method for H->$\gamma\gamma$

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

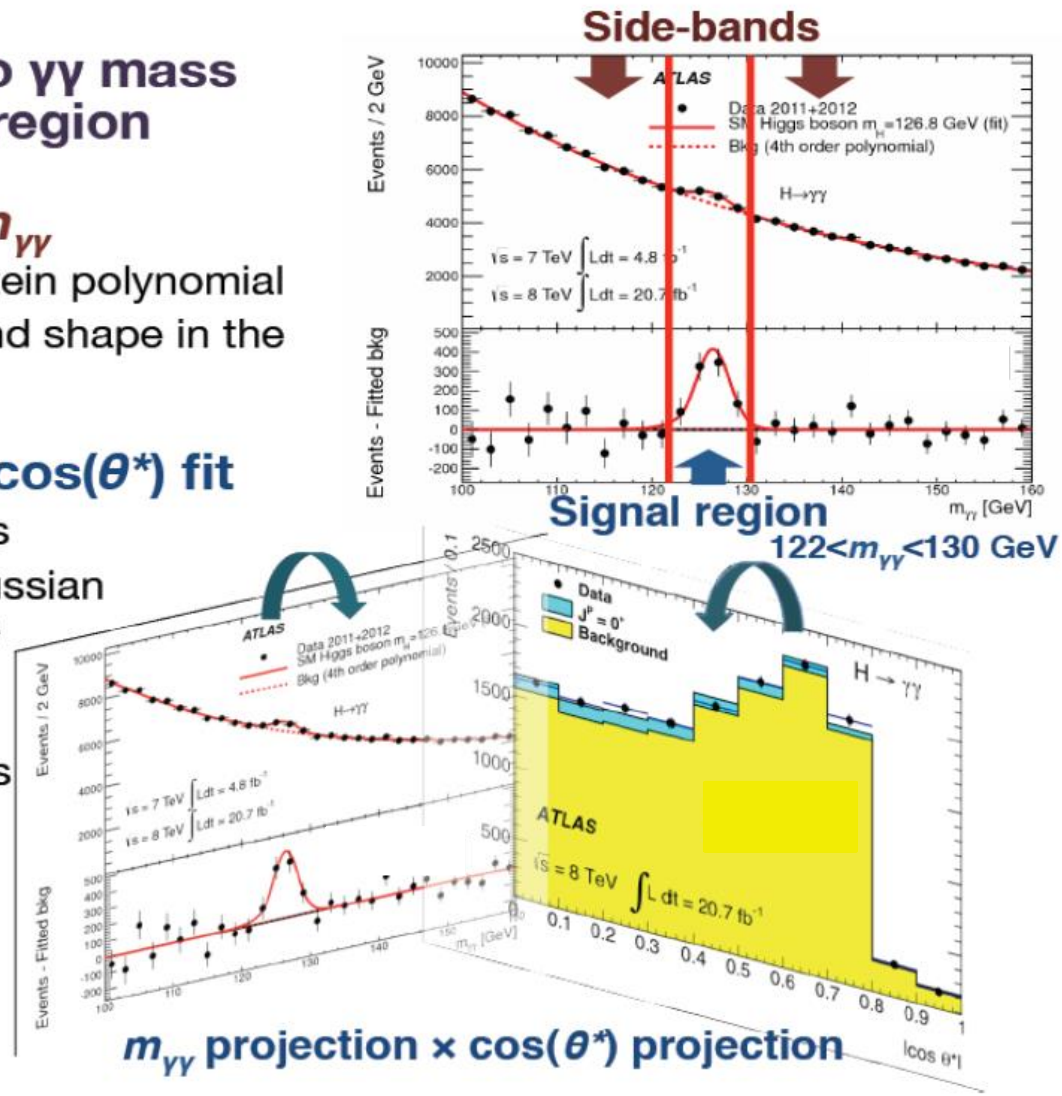
Side-bands: 1D fit in $m_{\gamma\gamma}$

- **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



Higgs boson spin-parity

Data are consistent with 0^+ on every test.

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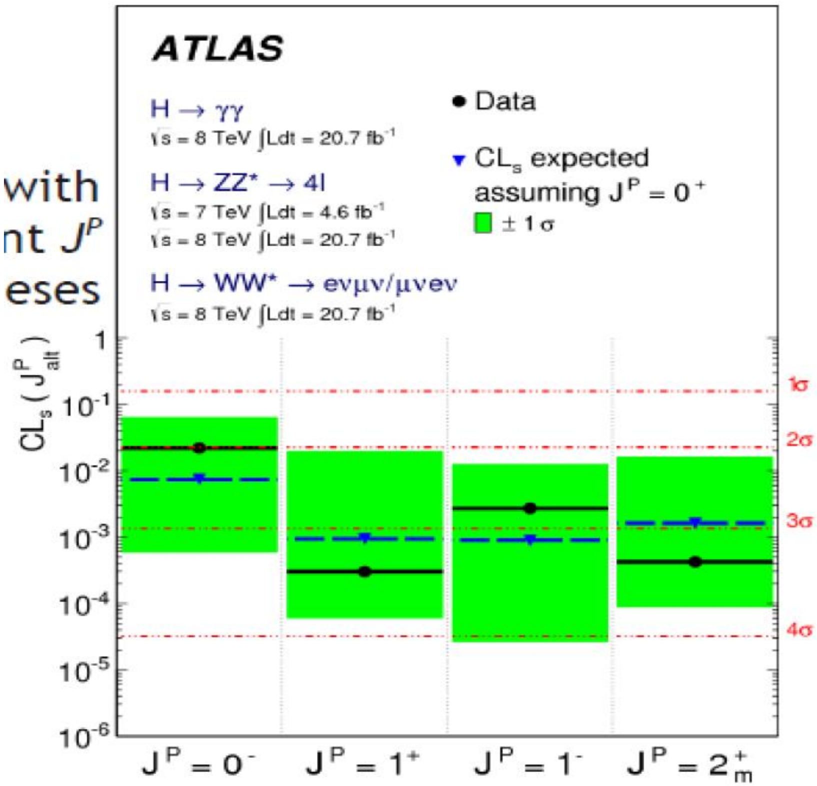


All alternative hypotheses disfavoured at >97.8% CL

Higgs boson width

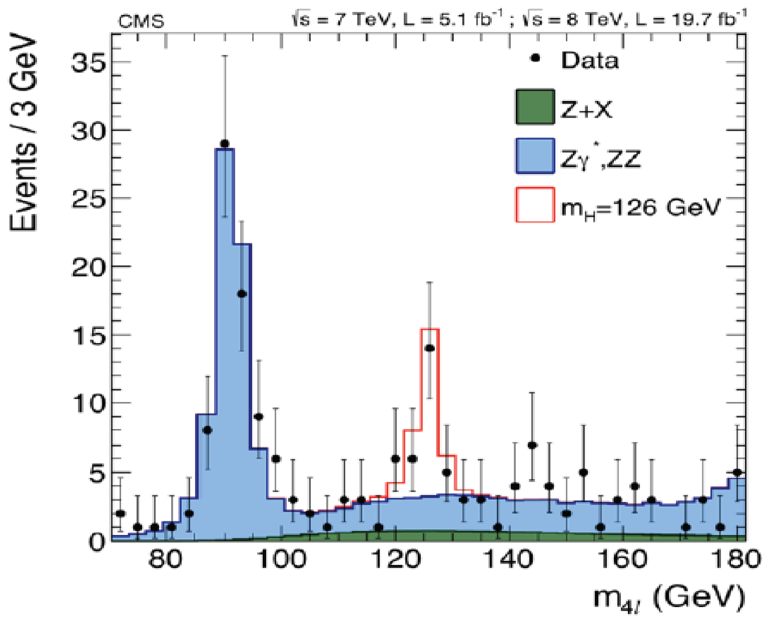
Particle	Width[MeV]	Lifetime[s]
t	$\sim 1,300$	$\sim 5 \times 10^{-25}$
W	$\sim 2,000$	$\sim 3 \times 10^{-25}$
Z	$\sim 2,500$	$\sim 2.6 \times 10^{-25}$
h	4.21 ± 0.16	$\sim 1.65 \times 10^{-22}$
b	4.4×10^{-10}	$\sim 1.5 \times 10^{-12}$

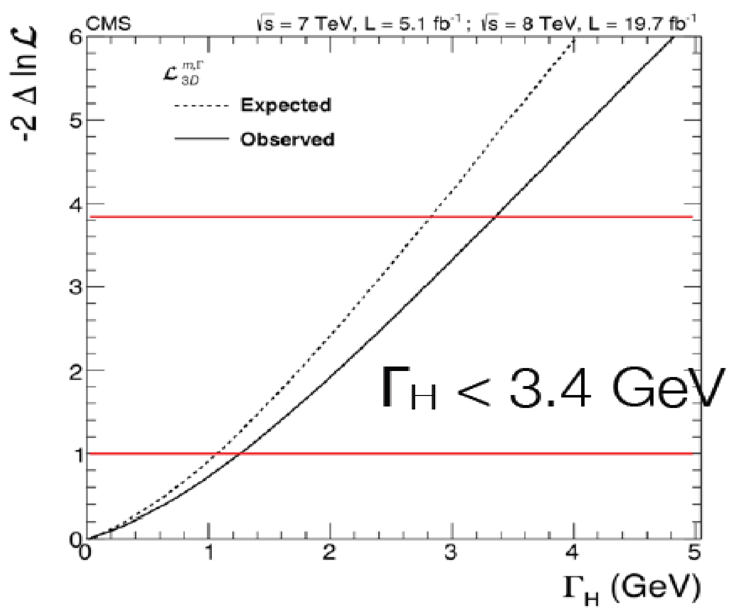
Direct measurements are limited by experimental resolution

CMS:

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

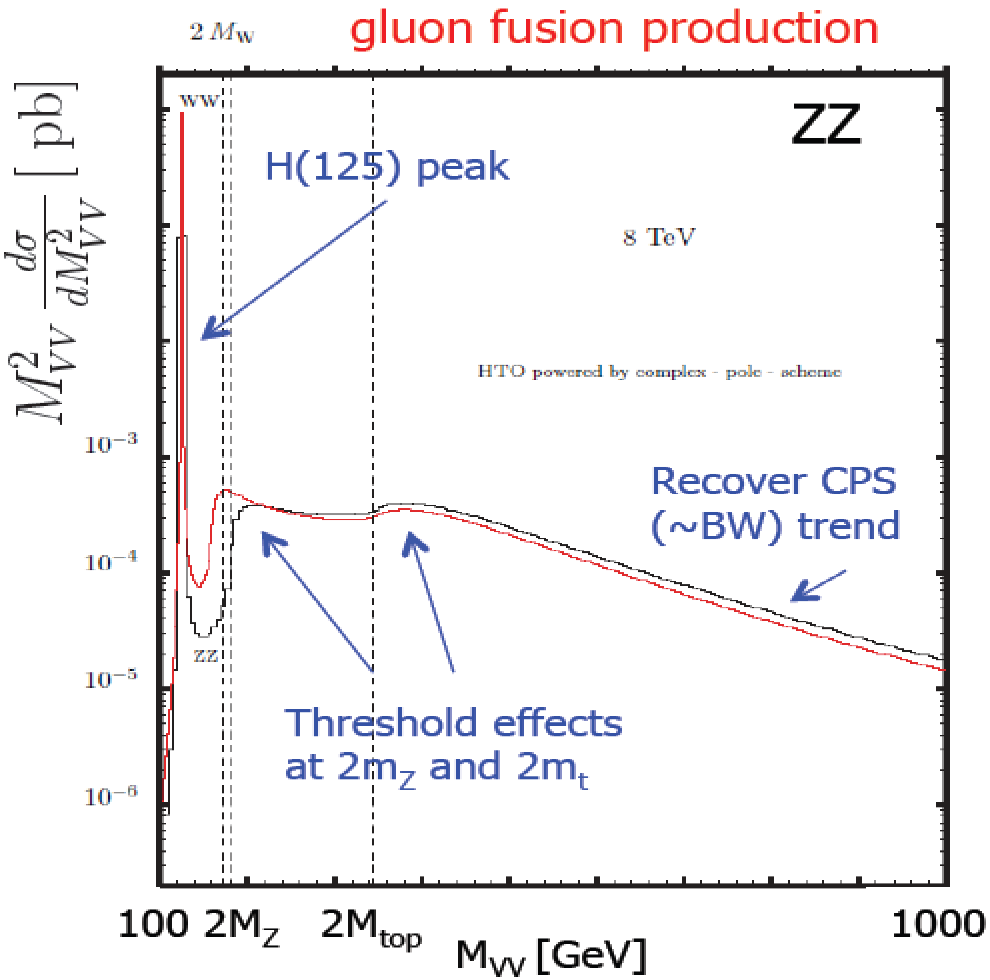
$H \to ZZ$ results $\Gamma_H < 3.4$ GeV





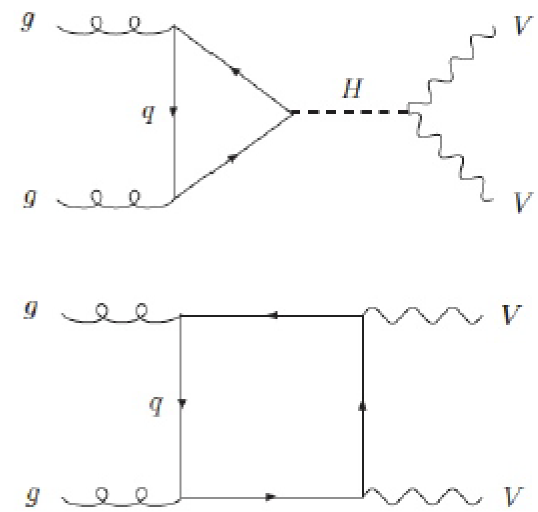
SM Higgs total width ~4 MeV @125GeV

Higgs interferometry



N. Kauer, G. Passarino, JHEP 08 (2012) 116

F. Caola, K. Melnikov (PRD 88 (2013) 054024)
J. Campbell et al., JHEP 1404 (2014) 060



Consider off- (H*) and on-shell (H) prod.

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot \text{BR})_{\text{SM}} \equiv \mu(\sigma\cdot\text{BR})_{\text{SM}}$$

$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2\cdot\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r\frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

$$\kappa_g = g_{ggH}/g^{\text{SM}}_{ggH}$$
$$\kappa_Z = g_{HZZ}/g^{\text{SM}}_{HZZ},$$
$$r = \Gamma_H/\Gamma_H^{\text{SM}}$$

μ measured on the resonance access ⇒ r !

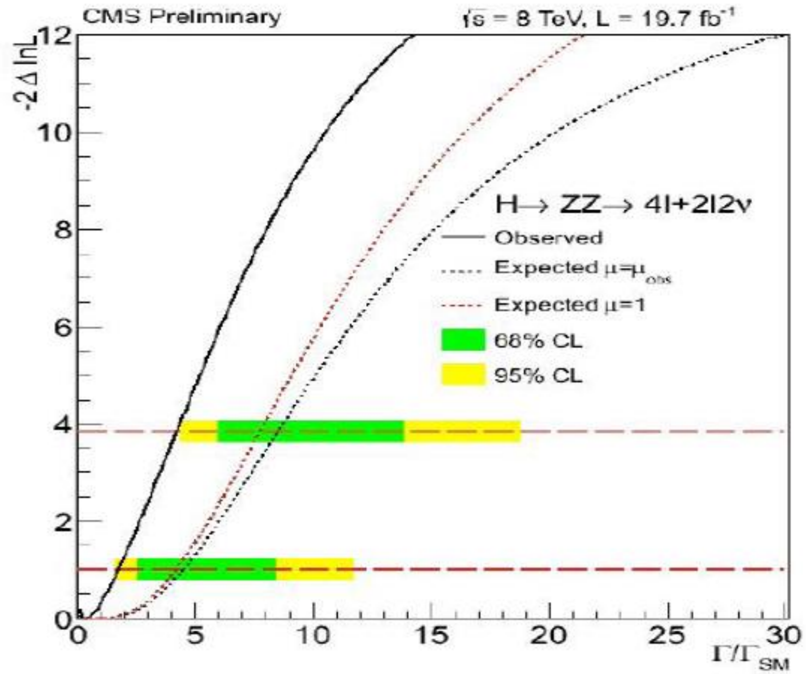
Higgs interferometry

Combined results

Observed (expected)
95% CL limit:
r < 4.2 (8.5)
p-value = 0.02

Best fit value:
$r = 0.3^{+1.5}_{-0.3}$

Equivalent to
$\Gamma < 17.4\ (35.3)$ MeV
$\Gamma = 1.4^{+6.1}_{-1.4}$ MeV



	4ℓ	$2\ell2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H (MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H (MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

Very important result! Observed limit is half of the expected – data deficits in both channel/ Theory systs (LO +Kf) under control?

The Higgs boson so far…..

- Higgs boson discovery is now firmly established at m_H ~125 GeV
  - Couplings to fermions and weak bosons (verified to ~10-30% precision)
  - Custodial symmetry verified (~15% precision)
  - Existence of a boson with non-universal familly couplings established ($\tau\tau$ evidence and no $\mu\mu$ signal)
  - The spin and parity is consistent with predicted in the Standard Model

A few words looking ahead to 2015

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 Prepare LHC for design *E* & lumi **LS1**

Collect ~30 fb^{-1} per year at 13/14 TeV

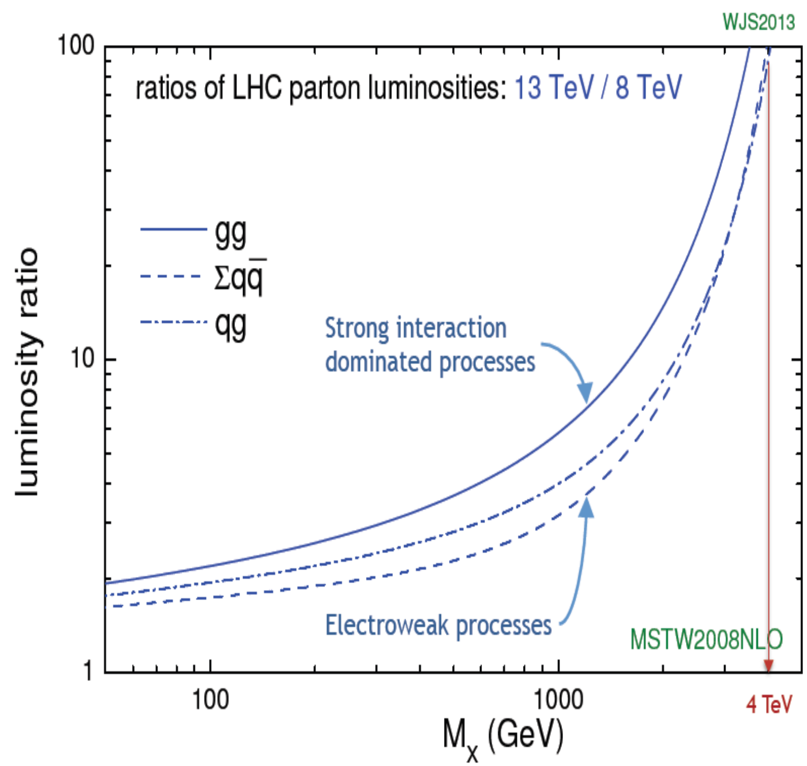
2018 Phase-1 upgrade ultimate lumi **LS2**

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

~2022 Phase-2 upgrade to HL-LHC **LS3**

~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

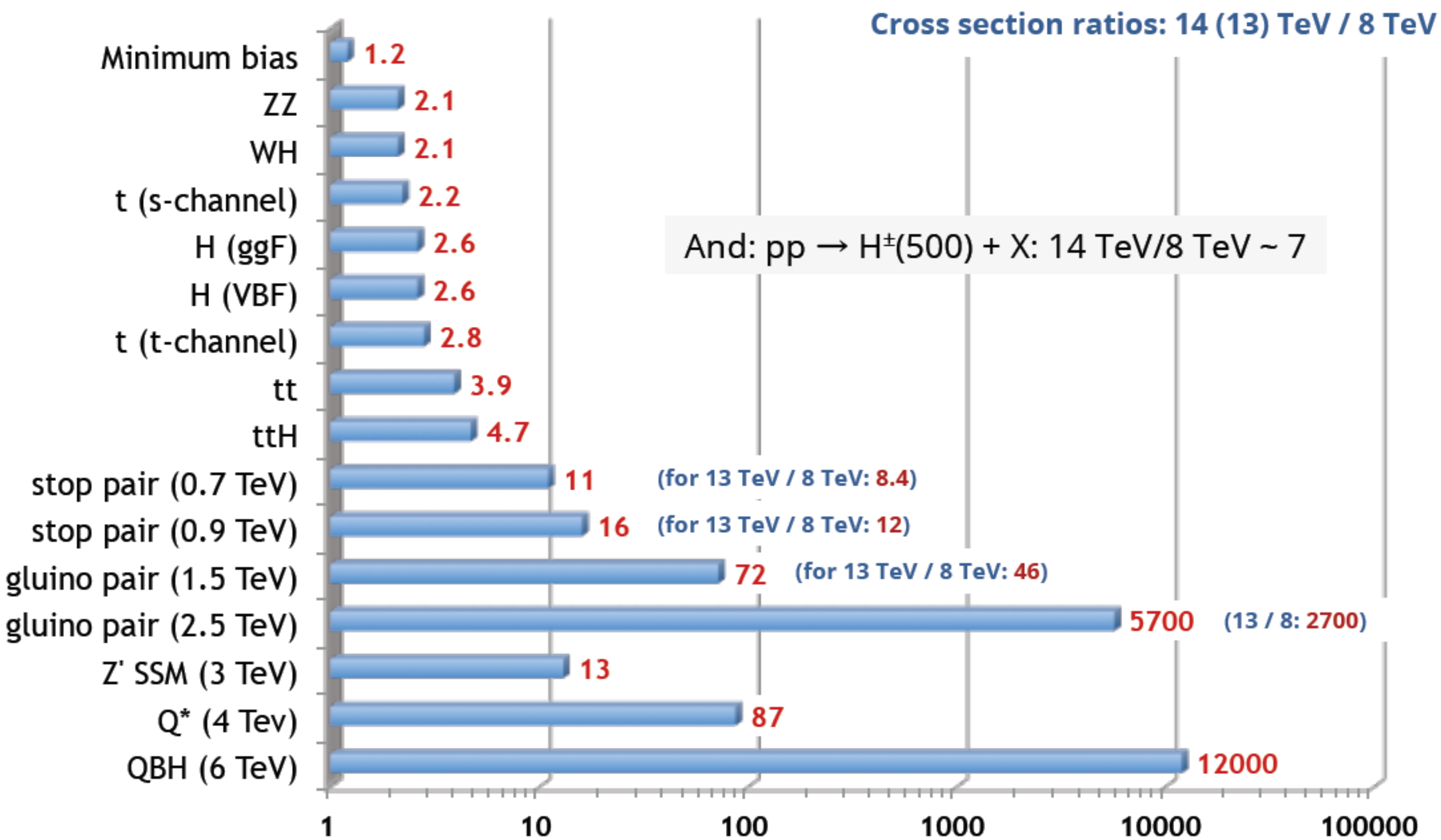
~2030



Cross section ratios

Hugely increased potential for discovery of heavy particles at ~13-14 TeV.

But life can become harder for states lighter than ttbar



Outlook

- The boson discovered at the LHC by ATLAS and CMS experiments has properties so far consistent with the „Higgs" scalar boson expected from the BEH mechanism (minimal sector of the Standard Model)
- New horisons and measurements possible involving Higgs boson.
- The capacity to establish additional New Physics heavily depends on the progress in experimental and theory modeling of the SM processes.

Additional slides

CP mixing

Measuring possible CP violating components of the amplitude

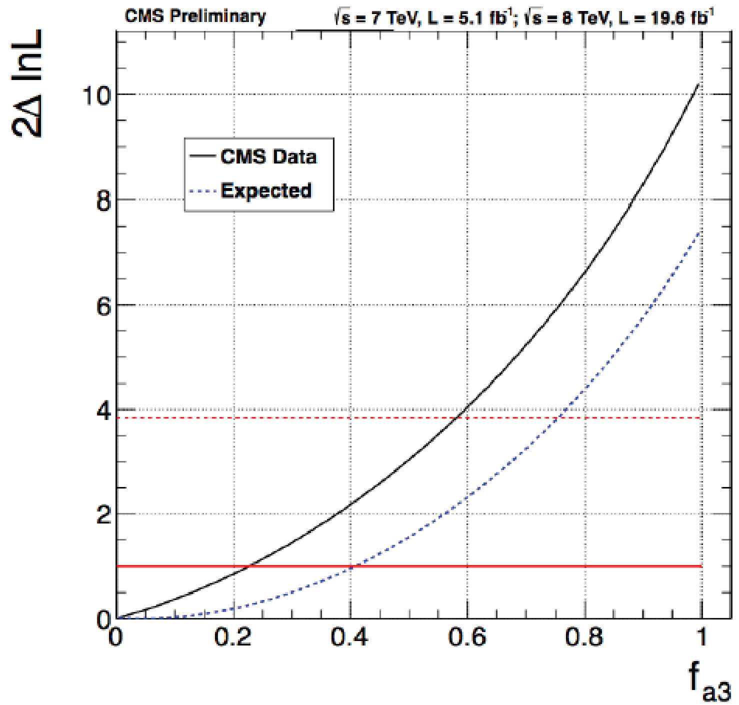
$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

- SM case $a_1 = 1$ and $a_2 = a_3 = 0$
- a_3 is a CP-odd amplitude
- Measure $f_{a3} = a_3/a_1$ (assuming $a_2 = 0$)

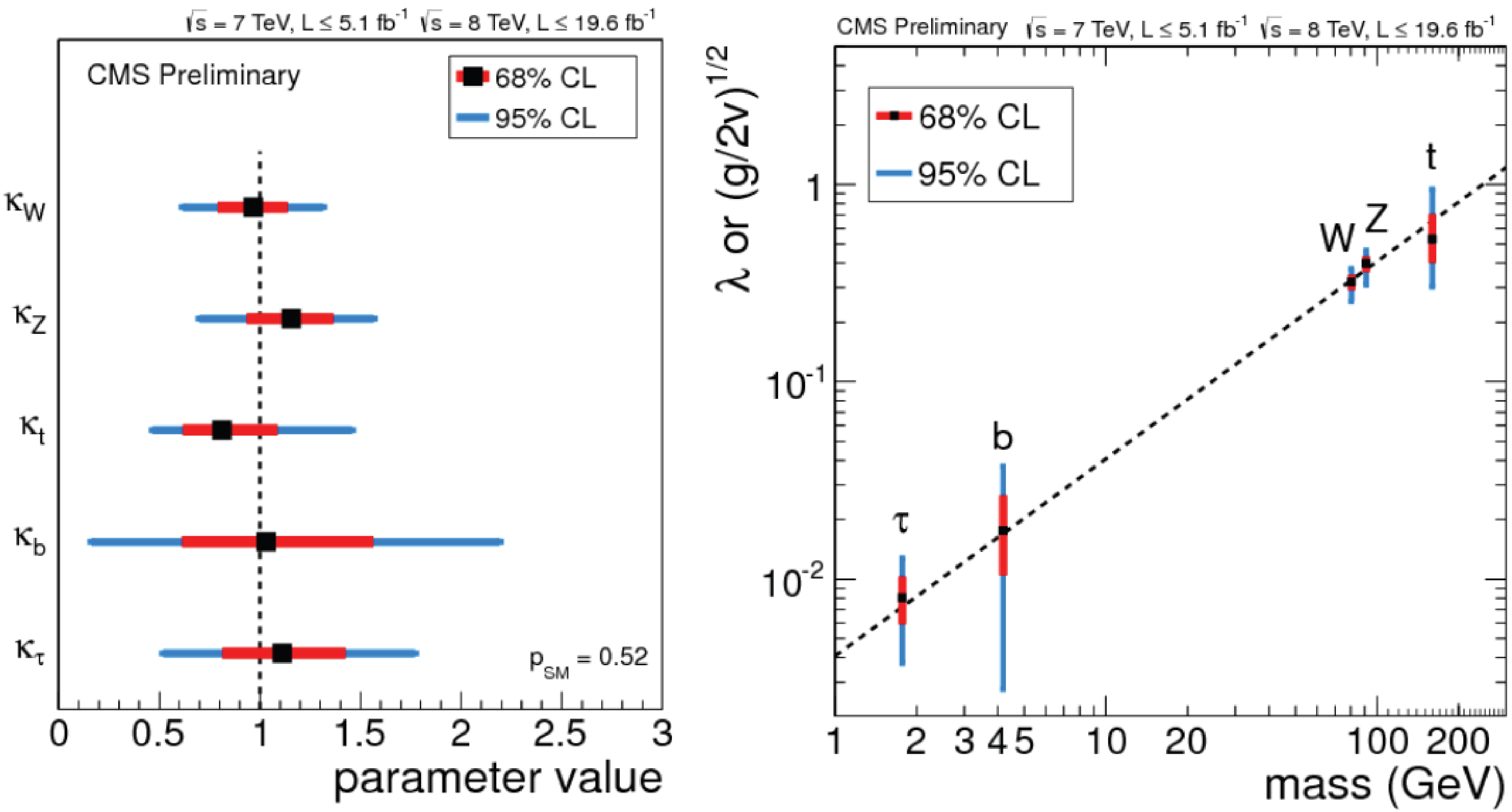
Check of a mixing with CP-odd component

CMS: $f_{a3} = 0.00^{+0.23}_{-0.00}$

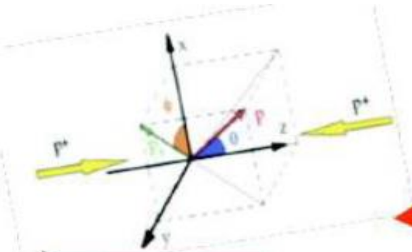
$f_{a3} < 0.56$ @ 95% CL (exp 0.76)



Test of predicted Yukawa structure of the couplings

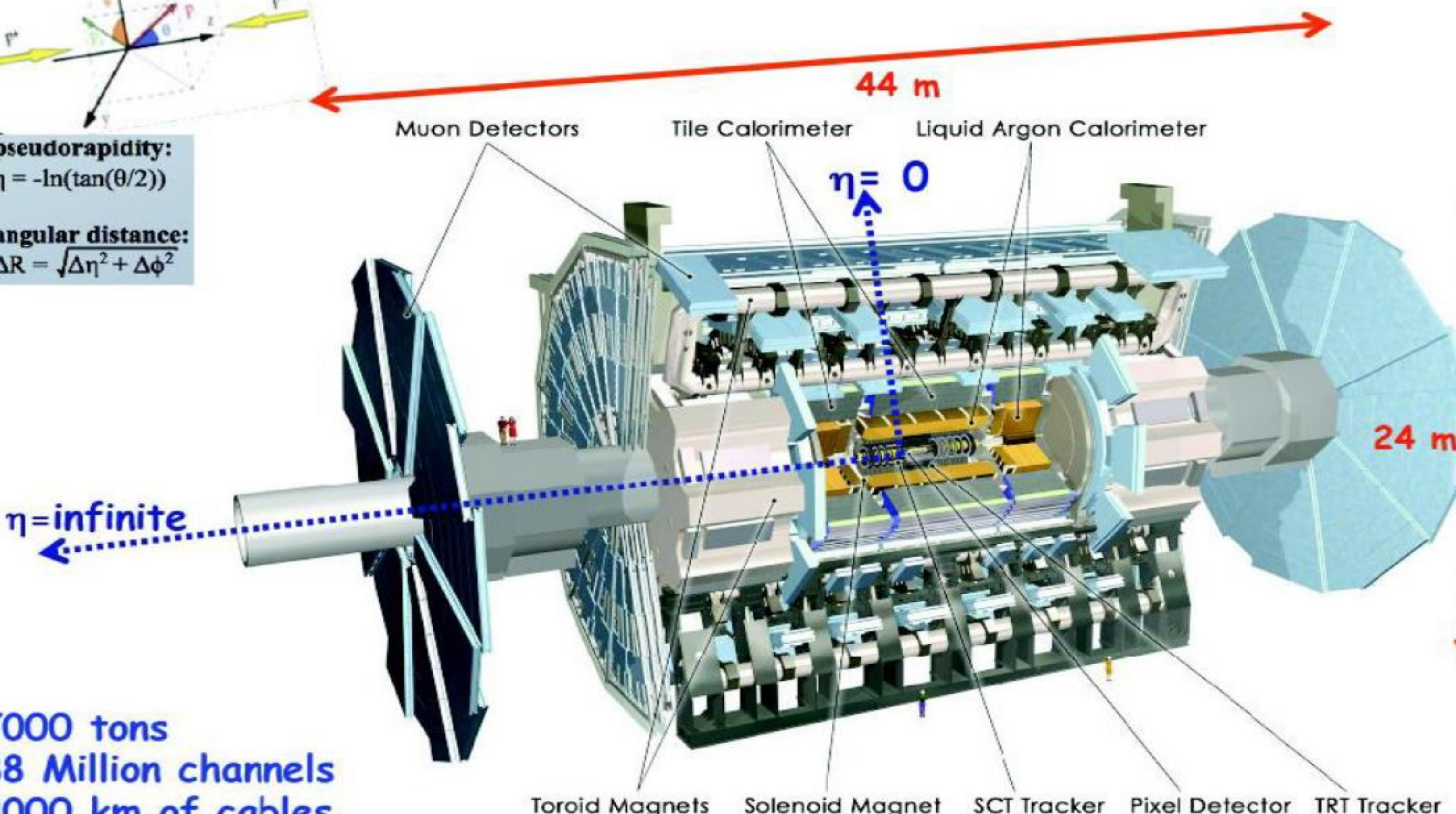


ATLAS detector



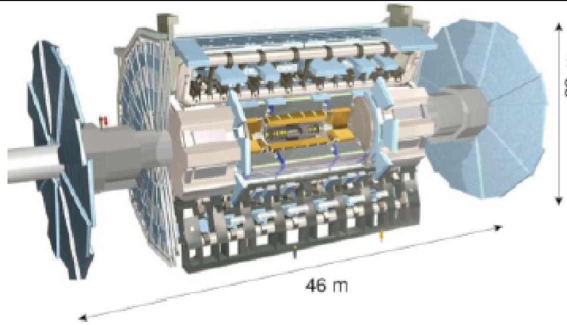
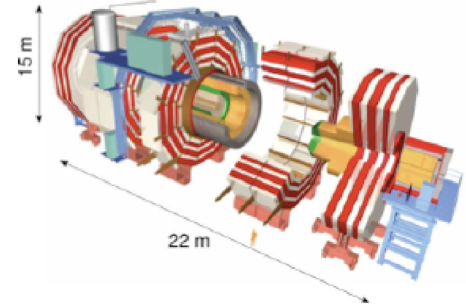
pseudorapidity:
$\eta = -\ln(\tan(\theta/2))$

angular distance:
$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



7000 tons
88 Million channels
3000 km of cables
2T solenoid
Toroid (B ~ 0.5T in barrel;~1T end-cap)

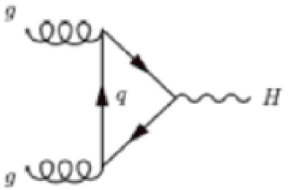
The ATLAS and CMS Detectors In a Nutshell

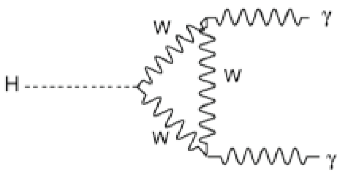
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

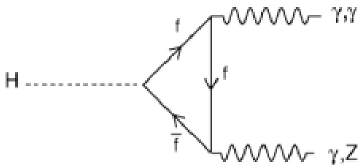
Interesting Facts about the γγ Channel

- Main production and decay processes occur through loops : Excellent probe for new physics !

known at NNnLO, still rather large uncertainty O(10%)







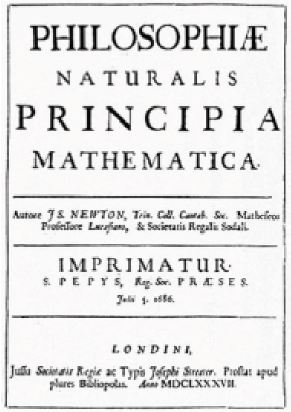
A priori potentially large possible enhancement…

$$1.6 \times A_W^2 - 0.7 \times A_t A_W + 0.1 \times A_t^2$$

… Not so obviously enhanced (e.g. SM4)

Seldom larger yields : e.g. NMSSM (U. Ellwanger et al.) up to x6, large stau mixing (M. Carena et al.), Fermiophobia…

- High mass resolution channel
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem
- If observed implies that its Charge Conjugation is +1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Not the origin of Mass

- Gallilean and Newtonian concept of mass :

Inertial mass (F=ma) Gravitational mass (P=mg)

Single concept: conserved intrinsic property of matter where the total mass of a system is the sum of its constituents

- Einstein : Does the mass of a system depend of its energy content?

Mass = rest energy of a system or $m_0=E/c^2$

- Atomic level : binding energy ~O(10eV) which is $\sim10^{-8}$ of the mass
- Nuclear level (nucleons) : binding energy ~2% of the mass
- Nucleon level (partons) : binding energy ~98% of the mass

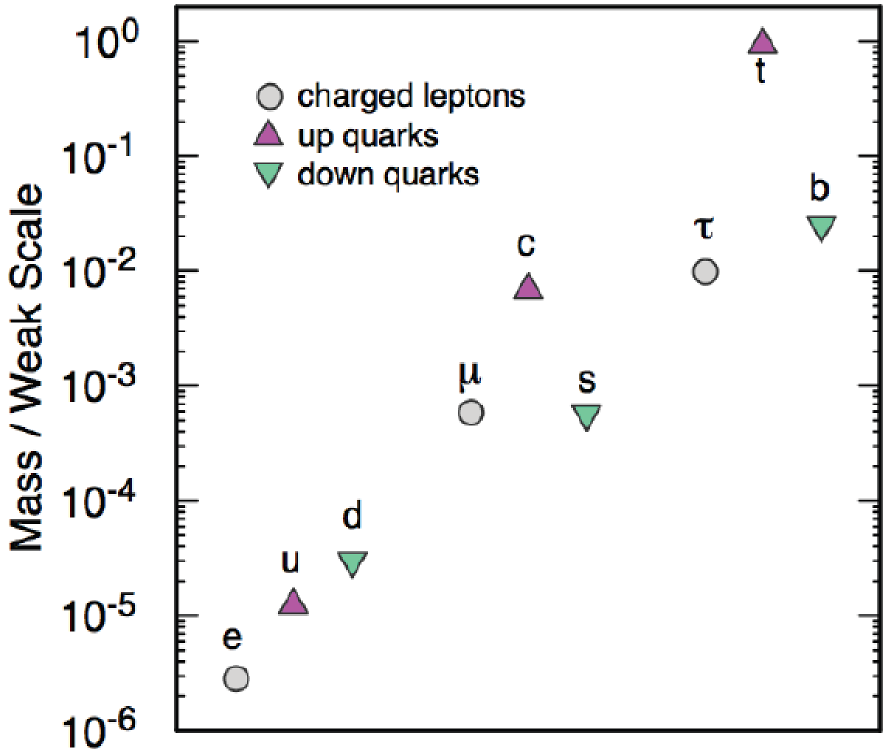
Most of the (luminous) mass in the universe comes from <u>QCD confinement energy</u>

The insight(s) of the BEH mechanism :

Making the weak force weak (short range, or W and Z bosons massive) and allowing fermion masses in the theory

Not explaining the flavor Hierarchy

Replacing mass terms by Yukawa couplings



~6 orders of magnitude

Neutrinos are not even on the scale!

The BEH sector includes most of the free parameters of the Standard Model

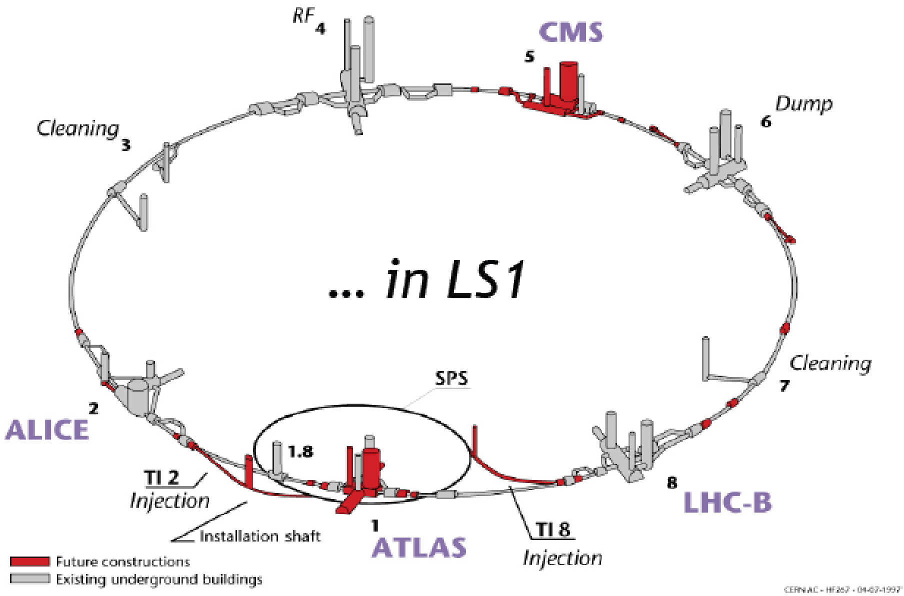
The Superconductor Analogy

SC (BCS) Theory	BEH Mechanism
Cooper pair condensate	Higgs field
Electrically charged (2e)	Weak charge
Mass of the photon	Mass of the W and Z bosons

- The Higgs field is inserted by hand...
- The vacuum has a weak charge

Further reading : L. Dixon, "From superconductors to supercolliders" (http://www.slac.stanford.edu/pubs/beamline/26/1/26-1-dixon.pdf)

Three Years of LHC operations at the 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
N_p	$1.1\ 10^{11}$	$1.4\ 10^{11}$	$1.6\ 10^{11}$	$1.15\ 10^{11}$
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 Higgs boson so far…..

- Higgs boson is not a gauge boson, mass not protected by symmetries of the theory

$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(A_a, \psi_i) + \mathscr{L}_{Higgs\ (Symm.\ Break.)}(\phi, A_a, \psi_i)$$

Natural
verified with high precision; stable with respect to quantum corrections; highly symmetric (gauge and flavour symmetries)

Ad hoc
but necessary (other mass terms forbidden by EWK gauge symmetries); unstable with respect to quantum corrections; at the origin of flavour structure and all other problems of the SM

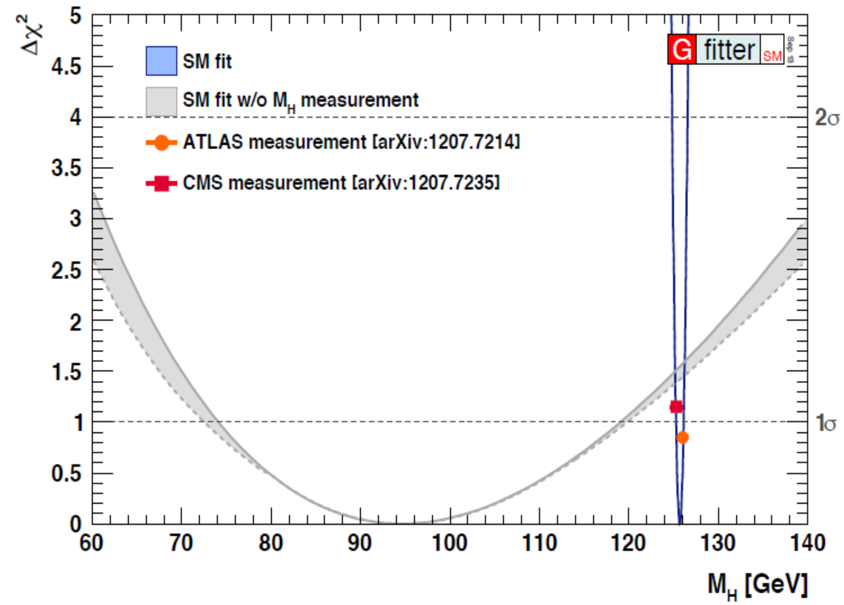
After the Higgs: the EW fit of the Standard Model

Unique situation:

- For the first time SM is fully over-constrained
- For the first time elekroweak observables can be unambiguously predicted at loop level.
- Powerfull predictions of kety observables now possible, much better than w/o m_H

Paradigm shift for EW fit.

- Self-consistency of the SM
- Possible contributions from BSM model
- Improved accuracies set benchmarks for the new measurements!



m_H consistent at 1.3σ with indirect predictions from SM fit. Prediction:

$$m_H = 94^{+24}_{-22}\ \text{GeV}$$

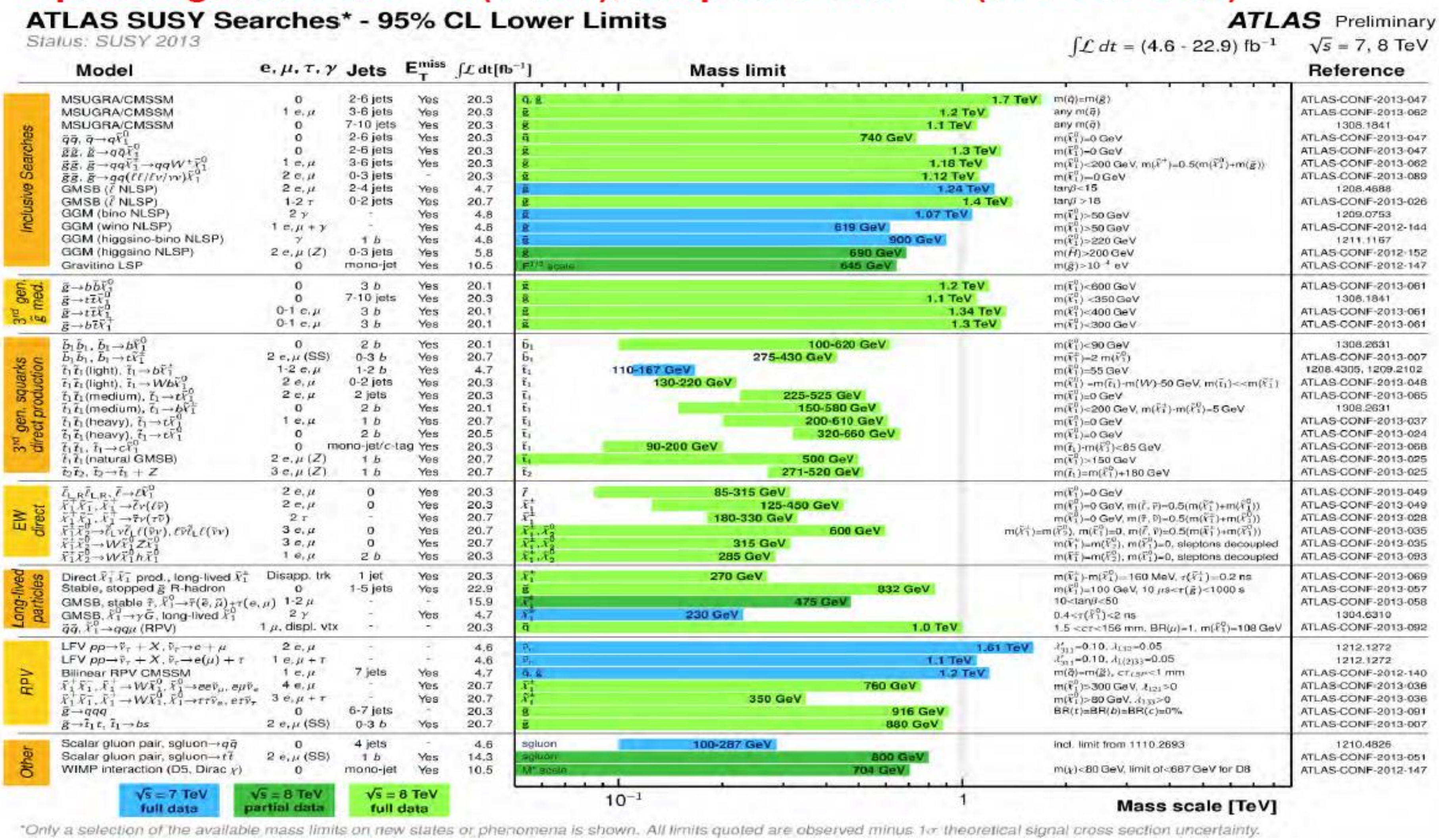
After the Higgs: the EW fit of the Standard Model

- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: not incl. M_H
- Right: fit incl M_H, not the row

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]$^\circ$	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.367^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021	91.1978 ± 0.0114
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014	2.4950 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	$0.23149^{+0.00010}_{-0.00008}$	$0.23149^{+0.00010}_{-0.00008}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6679^{+0.00034}_{-0.00028}$	$0.6679^{+0.00034}_{-0.00028}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93464^{+0.00005}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005	0.21547 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11	2718^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1190 ± 0.0027
$\delta_{\mathrm{th}} M_W$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	yes	4	4	–
$\delta_{\mathrm{th}} \sin^2\theta^\ell_{\mathrm{eff}}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\mathrm{theo}}$	yes	-0.6	-0.5	–

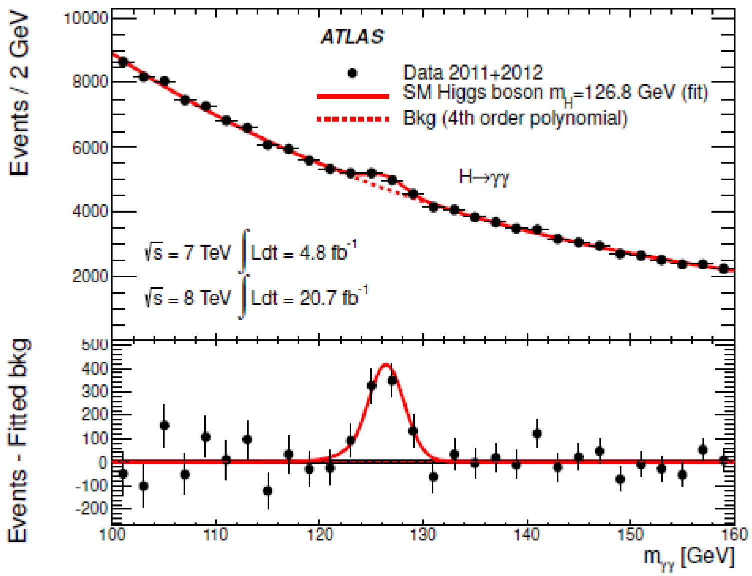
SUSY limits: ATLAS

Squarks/gluinos are > O(1 TeV), Stop/sbottom > O(300-600 GeV)



H->γγ analysis

- Rare Higgs boson decay, but very clear signature!
- Dominant background: continuum $\gamma\gamma$ and γ+jet
- Higgs mass reconstruction from diphoton invariant mass $m_{\gamma\gamma} \rightarrow$ Very good mass resolution!
- Inclusive selection: two energetic, isolated, high-quality photons.
- Analysis categorization to separate:
  - production mechanisms: ggF, VBF, *VH* and *ttH* measurements.
  - channels with high/low significance (S/B)
  - channels with good/bad mass resolution



Fit strategy

- Simultaneous Signal + background fit
  - Signal: Chrystal ball(core) + Gaussian(tails)
  - Bkg: E.g. forth-order Bernstein polynomial
  - Range: 100 GeV $< m_{\gamma\gamma} <$ 160 GeV
- Excess significant at 7.4σ level
- signal strength $\mu = \frac{\sigma \times B}{\sigma_{SM} \times B_{SM}}$ and Higgs boson mass m_H are parameters of the fit.

H->γγ analysis

- Rare Higgs boson decay, but very clear signature!
- Dominant background: continuum $\gamma\gamma$ and γ+jet
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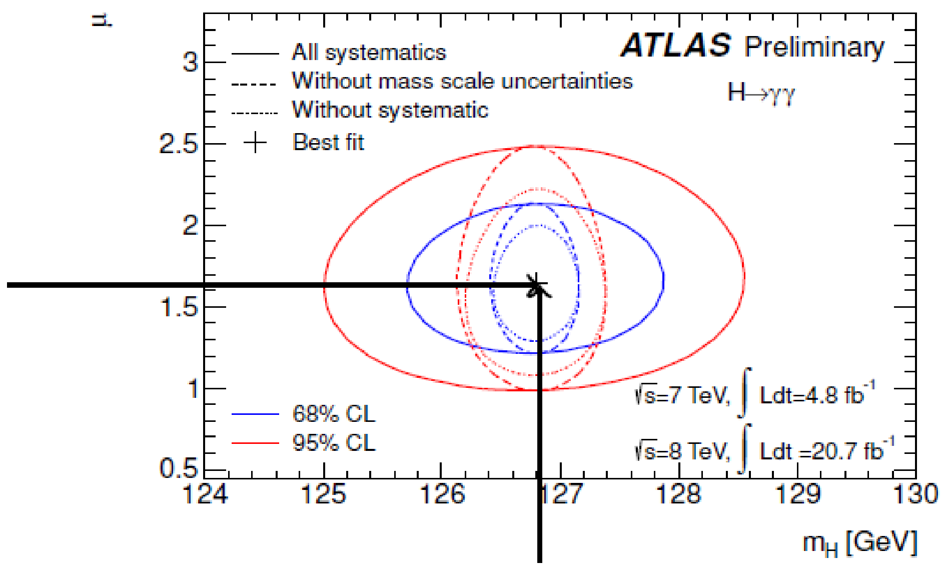
- Analysis categorization to separate:
  - production mechanisms: ggF, VBF, VH and ttH measurements.
  - channels with high/low significance (S/B)
  - channels with good/bad mass resolution

$\mu = 1.65 \pm 0.24(\mathrm{stat})^{+0.25}_{-0.18}(\mathrm{syst})$



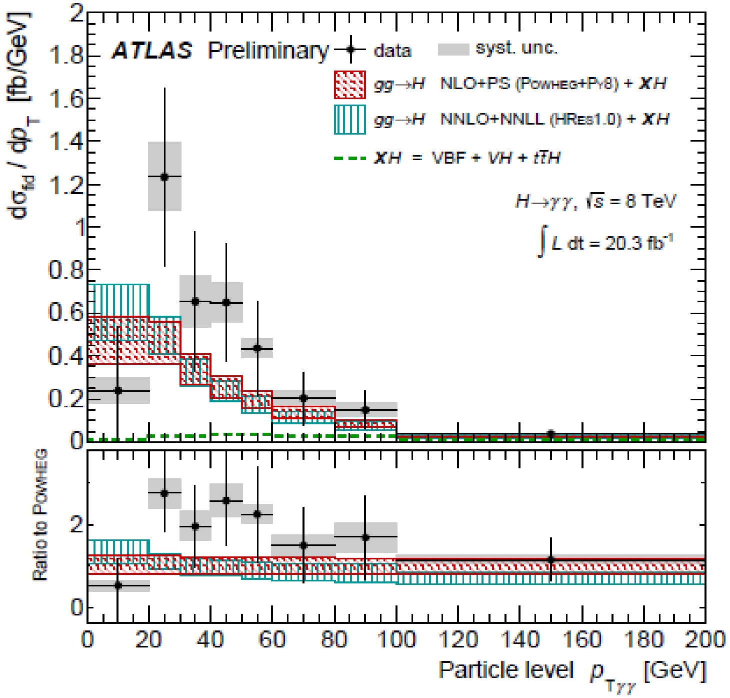
$m_H = 126.8 \pm 0.2(\mathrm{stat.}) \pm 0.7(\mathrm{syst}))$ GeV

Dominant mass scale uncertainty: photon energy scale

Differential cross-section measurements in H->$\gamma\gamma$

- The clear signature in the $H \to \gamma\gamma$ decay can be used to measure differential cross section
- Combined signal-plus-background fit for individual bins of variables of interest, such as:
  - Higgs kinematics, e.g.: **transverse momentum ($p_T^{\gamma\gamma}$)**, sensitive to higher order corrections.
  - or the jet multiplicity sensitive to different production mechanisms
    $\to$ jet veto fraction $\sigma_{n_{\text{jet}}=i}/\sigma_{n_{\text{jet}}\geq i}$ sensitive to quark/gluon radiation and α_s.

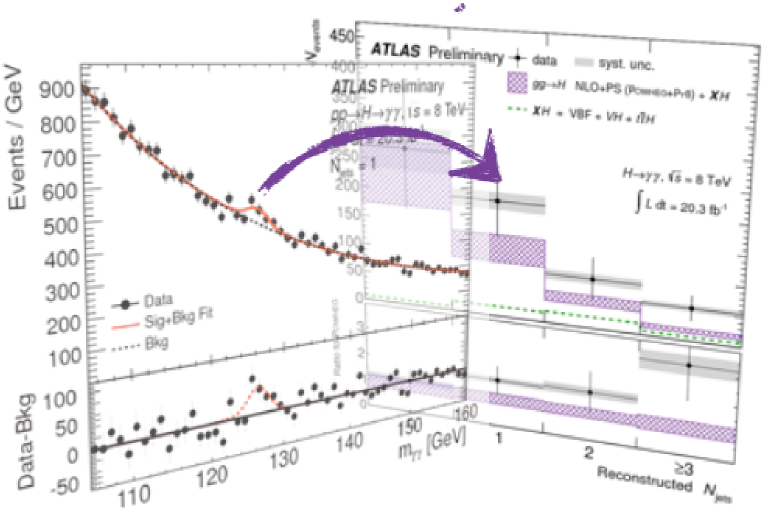
transverse momentum of diphoton system $p_T^{\gamma\gamma}$

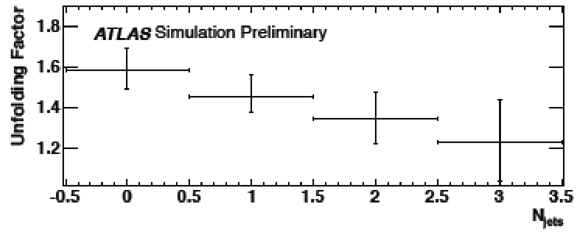


- Measurement compared to different ggF predictions:
  - NLO Powheg
  - NNLO+NNLL HRes
- small non-ggF contribution
- Uncertainties from missing higher order terms, UE, PDF, α_s

Analysis method

1. Signal extracted through signal+background fits in each bins of variable.

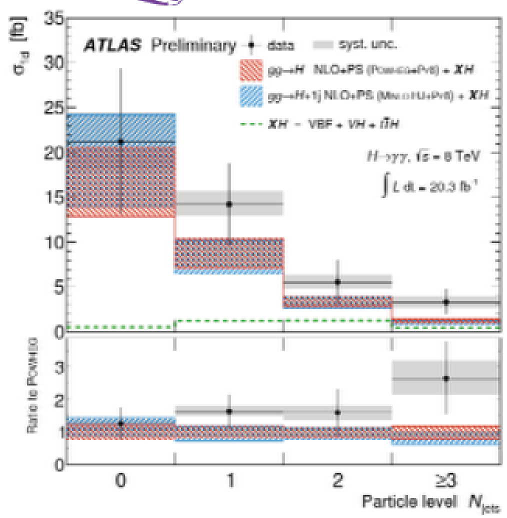




$\times \frac{1}{\mathscr{L}}$

2. Bin-by-bin factors correct for effects of imperfect detector. Convert to cross sections.

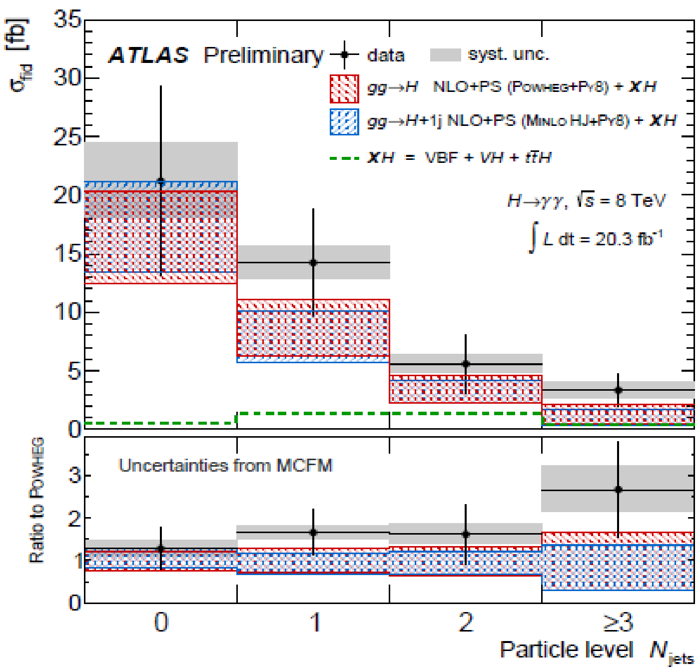
3. Differential cross sections at the particle level.



Differential cross-section measurements in H->γγ

- The clear signature in the $H \to \gamma\gamma$ decay can be used to measure differential cross section
- Combined signal-plus-background fit for individual bins of variables of interest, such as:
  - Higgs kinematics, e.g.: transverse momentum ($p_T^{\gamma\gamma}$), sensitive to higher order corrections.
  - or the **jet multiplicity** sensitive to different production mechanisms
    $\to$ jet veto fraction $\sigma_{n_{\text{jet}}=i}/\sigma_{n_{\text{jet}}\geq i}$ sensitive to quark/gluon radiation and α_s.

jet multiplicity



- Measurement compared to different ggF predictions:
  - NLO Powheg
  - MINLO NLO for ggF +1 jet
- non-ggF contribution for $n_{\text{jet}} \geq 2$
- Uncertainties from missing higher order terms, UE, PDF, α_s

Differential cross-section measurements in H->$\gamma\gamma$

- The clear signature in the $H \to \gamma\gamma$ decay can be used to measure differential cross section
- Combined signal-plus-background fit for individual bins of variables of interest, such as:
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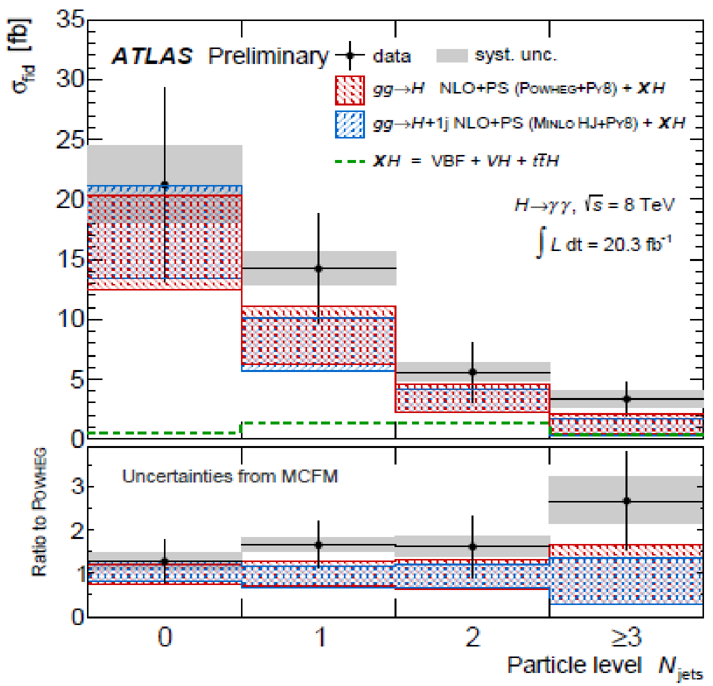
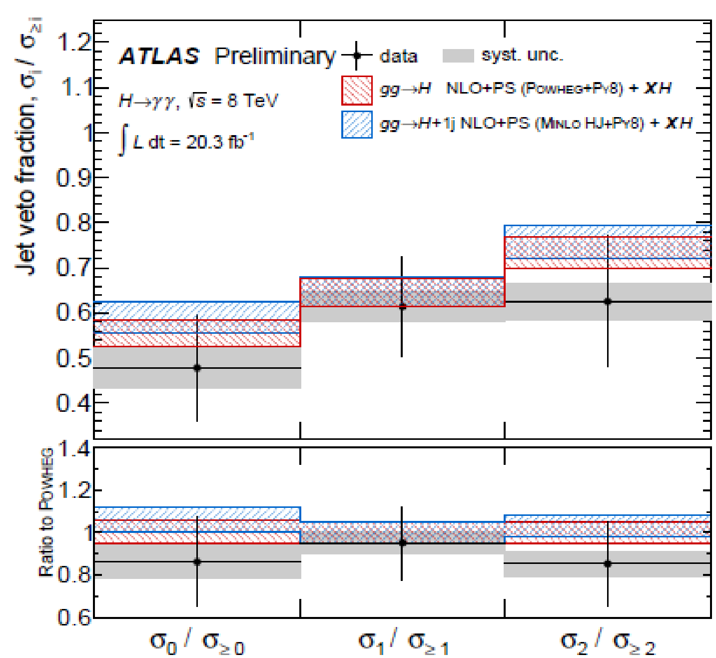
jet multiplicity



⇒

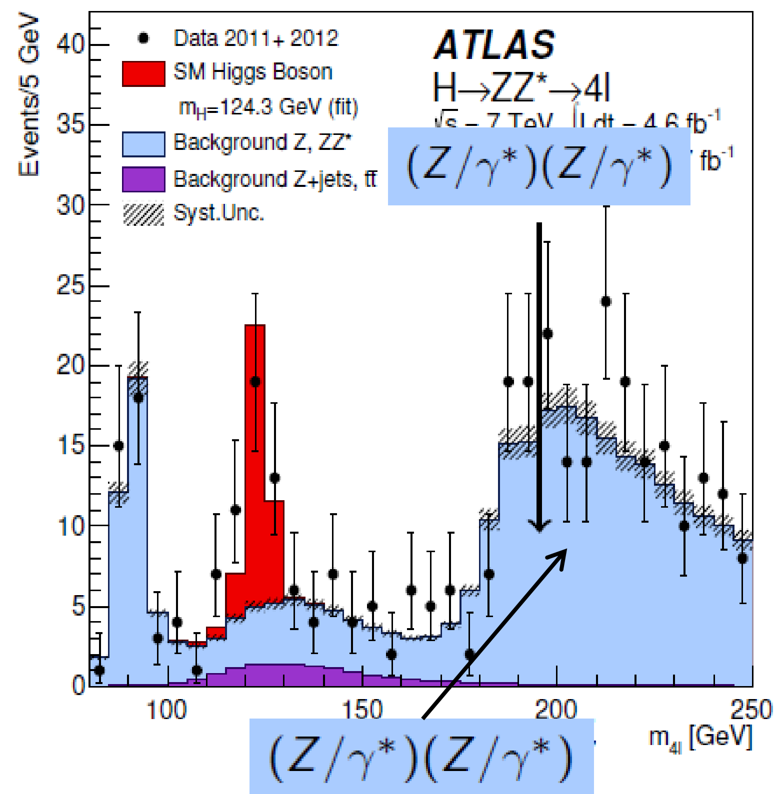
jet veto fraction



H->ZZ*->4l analysis

- Limited statistics due to low branching fraction BUT also very small background.
- Higgs boson mass reconstructable from lepton four-momenta ($m_{4\ell}$) $\rightarrow$ Good mass resolution.
- Baseline Selection: four high-energy, prompt, isolated leptons.
- Categorization for ggF, VBF and VH measurements.

- Different uncertainties on e/mu
  $\rightarrow$ categorization in 4μ, $2\mu 2e$, and $4e$
- Dominant Bkg.: $(Z/\gamma^*)(Z/\gamma^*)+Z \rightarrow 4\ell$
  - estimated from MC
- Bkg from fake leptons: Z+jets and $t\bar{t}$
  - Normalization estimated from control region
- Excess significant at 6.6σ level for $m_H = 124.3$ GeV!



H->ZZ*->4l analysis

- Estimate of mass distribution: smooth, non-parametric, unbinned.
- Parametrization of signal shape and signal strength as a function of m_H.
- Improved mass resolution using Z-mass constraint on leading dilepton-pair.
- Dominant systematic uncertainty on mass measurement from lepton energy scale.

$\hat{m}_H(4\mu) = 123.8^{+0.8}_{-0.8}(\text{stat})^{+0.2}_{-0.3}(\text{sys})$ GeV

$\hat{m}_H(4e) = 126.2^{+1.2}_{-1.3}(\text{stat})^{+0.8}_{-0.8}(\text{sys})$ GeV

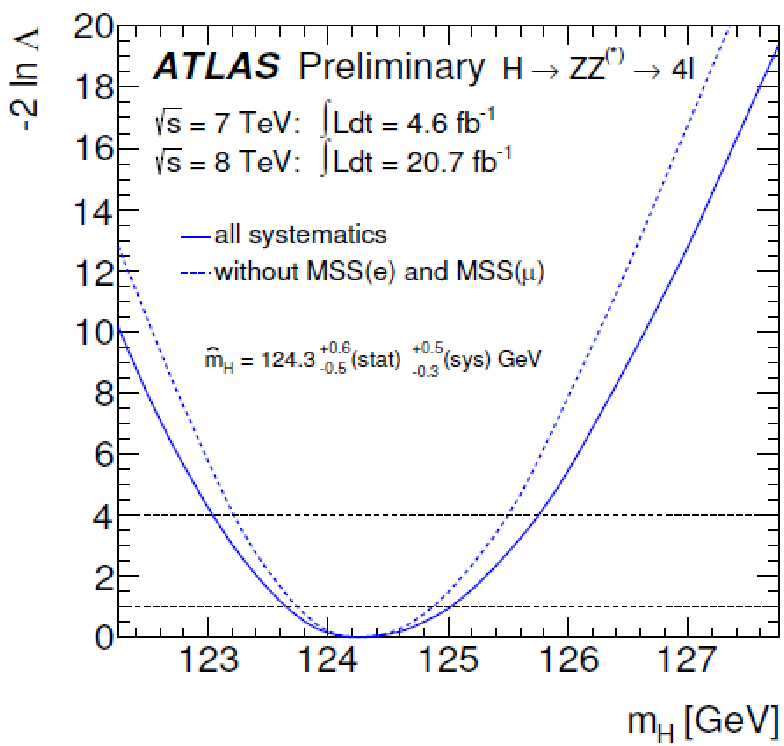
$\hat{m}_H(2e2\mu) = 125.0^{+1.0}_{-0.9}(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV

$\hat{m}_H(2\mu 2e) = 122.6^{+1.9}_{-4.1}(\text{stat})^{+0.5}_{-0.2}(\text{sys})$ GeV

Measurements compatible within at 2σ

$\hat{m}_H(\text{combined}) = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})$ GeV

Profile likelihood as a function of m_H:



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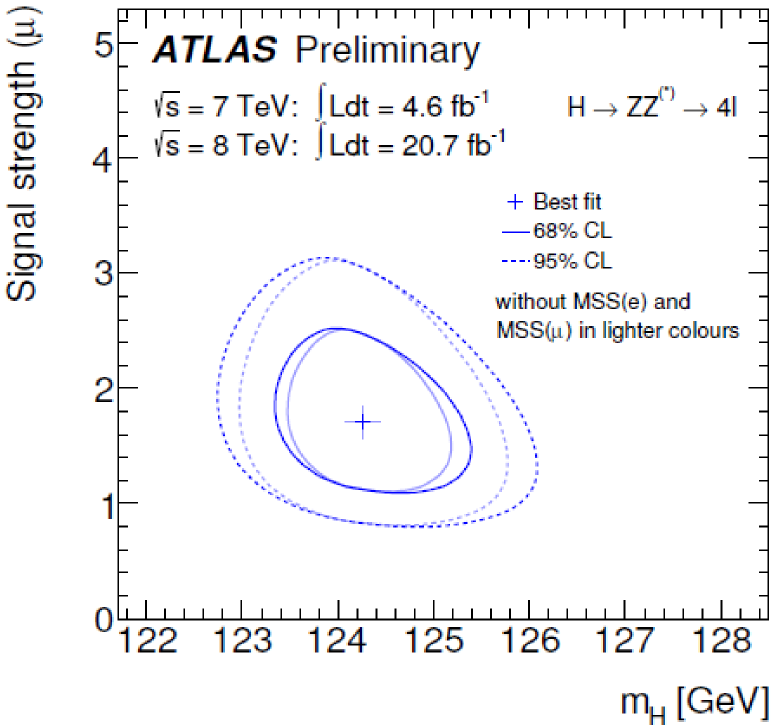
Signal strength μ vs. Higgs boson mass m_H:



- Mass: $124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})$ GeV
- Signal strength: $\hat{\mu} = 1.7^{+0.5}_{-0.4}$

Combined mass measurement

$-2\ln\Lambda(m_H)$

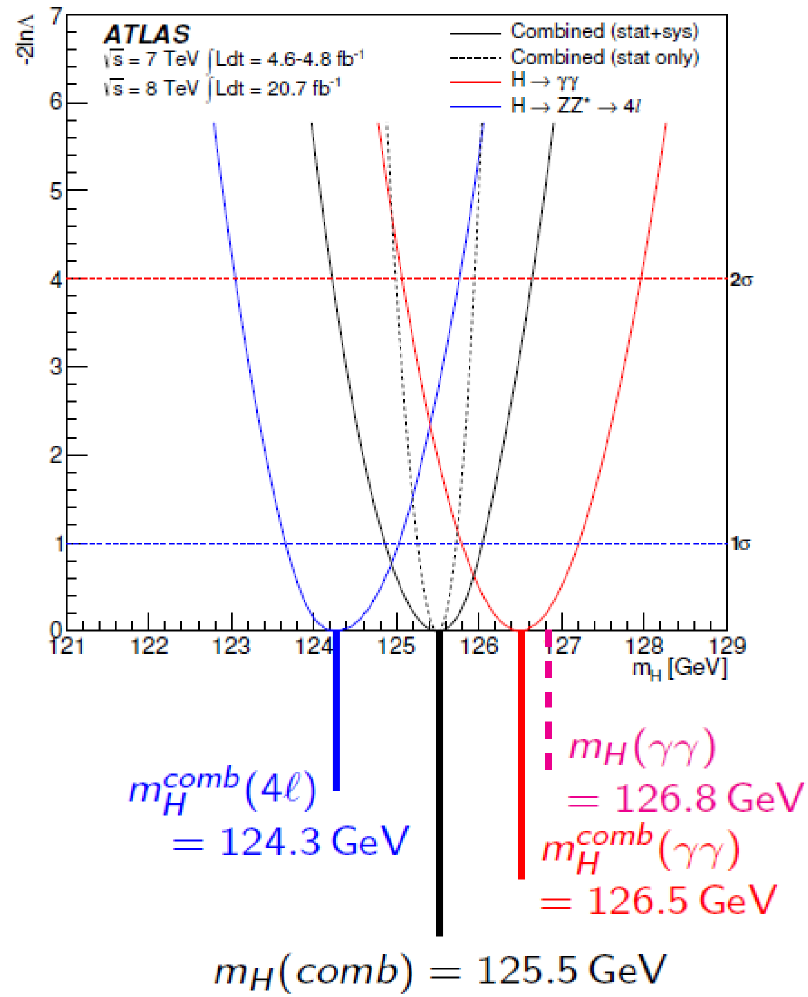
- Individual mass measurements:
  - $H\to\gamma\gamma$: $m_H = 126.8 \pm 0.2(\mathrm{stat}) \pm 0.7(\mathrm{stat})$
  - $H\to 4\ell$: $m_H = 124.3^{+0.6}_{-0.5}(\mathrm{stat})^{+0.5}_{-0.3}(\mathrm{stat})$
- Measurements correlated through systematic uncertainties (mainly e/γ energy scale)

  $\to$ Combined fit to treat correlations correctly,

  $\to$ 0.3 GeV shift of measurement in $H\to\gamma\gamma$.
- Cross sections for production modes are fixed to SM values (no bias on result!)

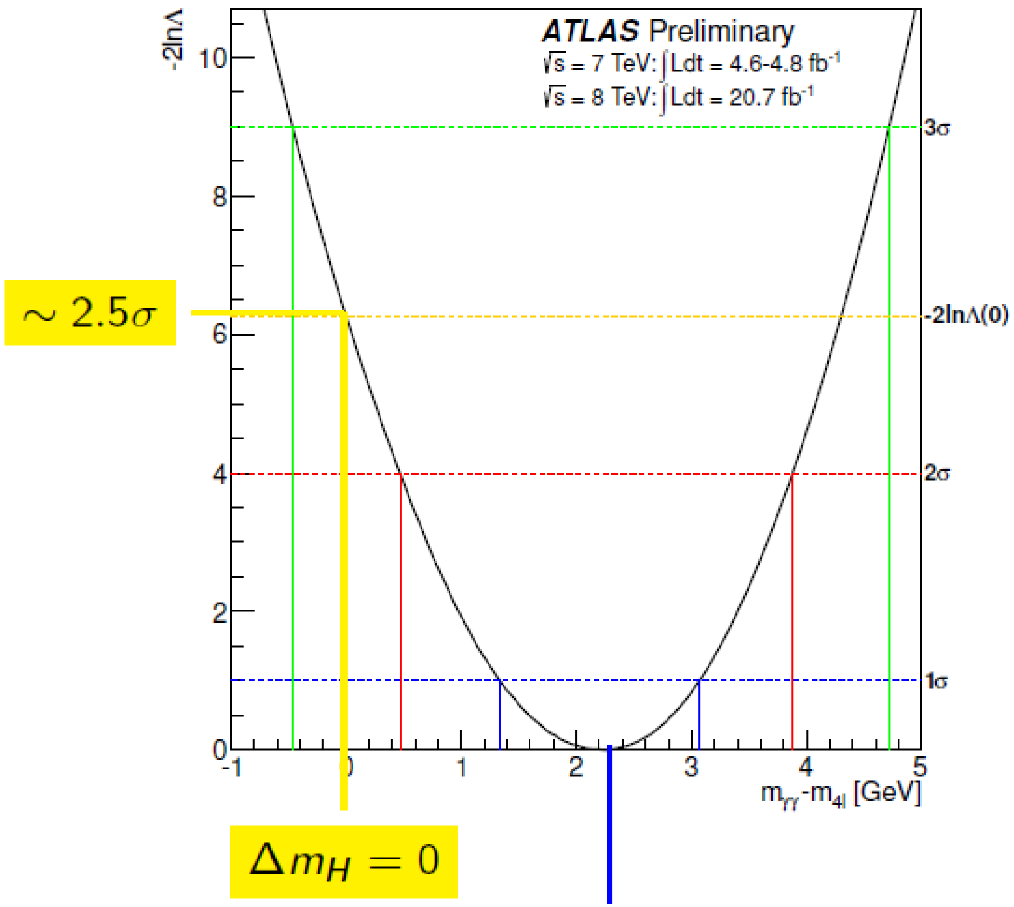
combined mass:

$$m_H = 125.5 \pm 0.2(\mathrm{stat})^{+0.5}_{-0.6}(\mathrm{sys})\ \mathrm{GeV}$$



Compatibility of the mass measurement

$-2\ln\Lambda(m_{\gamma\gamma} - m_{4\ell})$



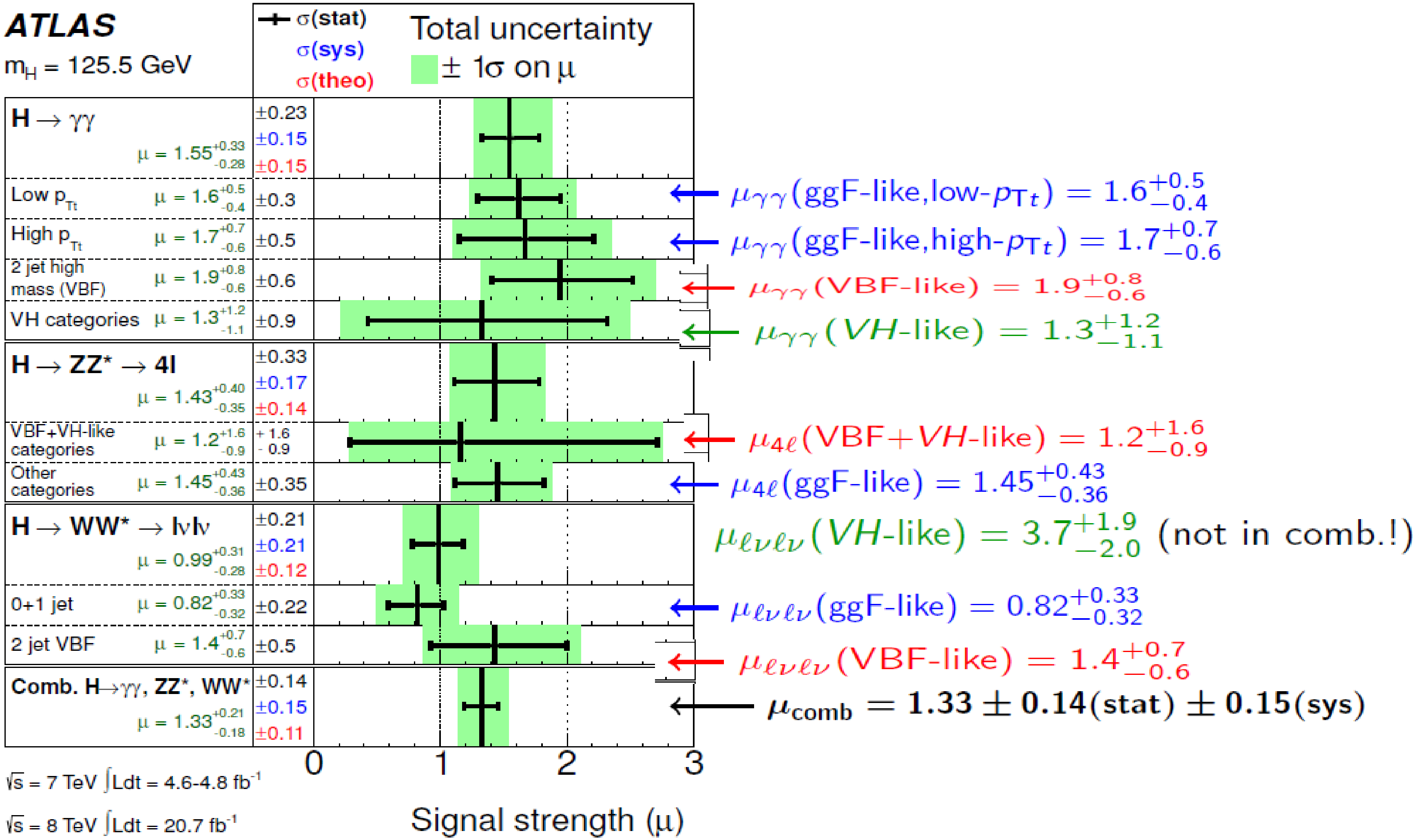
$\Delta m_H = 2.3^{+0.6}_{-0.7}(\text{stat}) \pm 0.6(\text{syst})$ GeV

- Combined fit with parameter of interest: $\Delta m_H = m_H^{\gamma\gamma} - m_H^{4\ell}$

  $\Rightarrow \Delta m_H = 2.3^{+0.6}_{-0.7}(\text{stat}) \pm 0.6(\text{syst})$

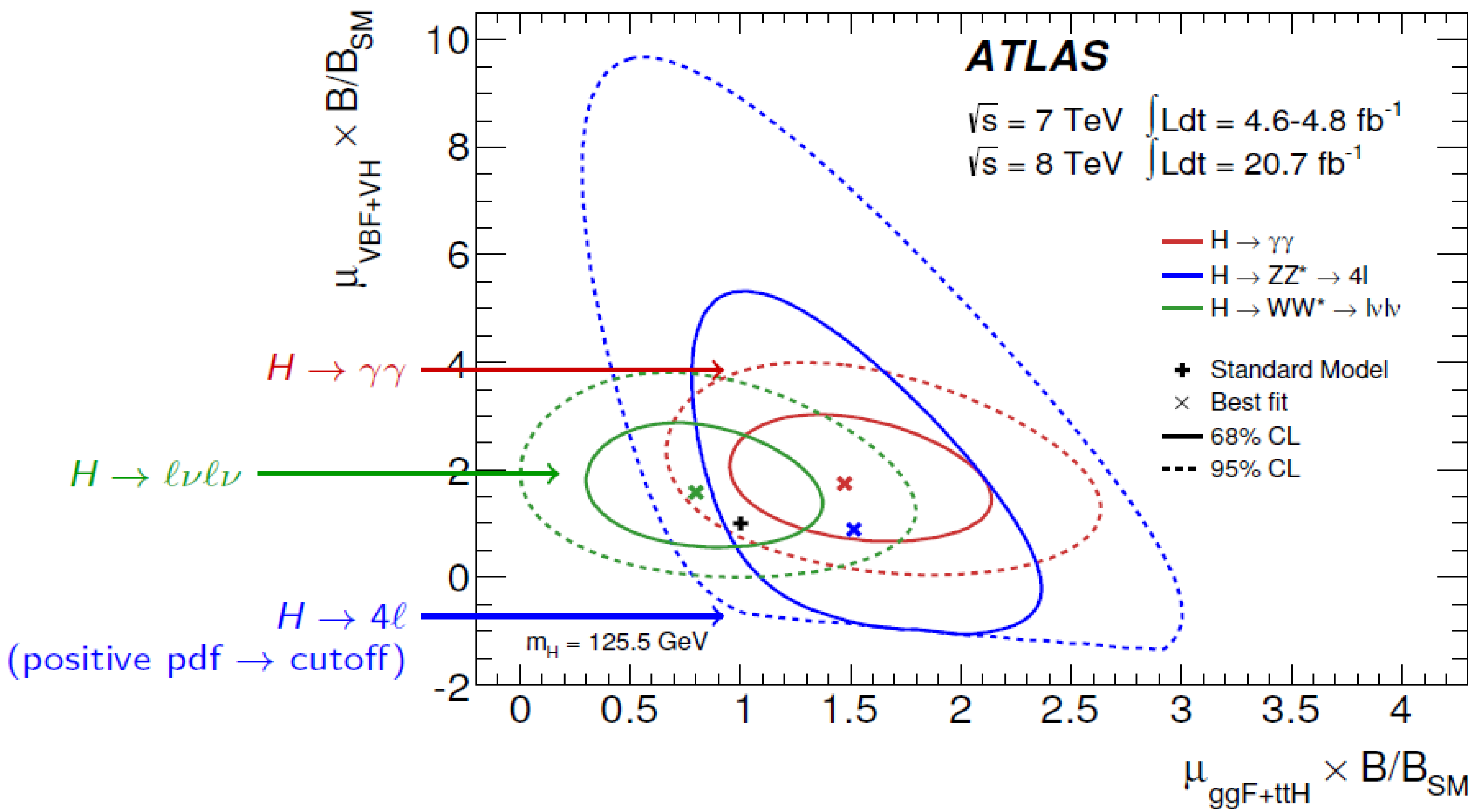
  $\Rightarrow$ Difference significant at $2.5\,\sigma$
- Significance $< 2\sigma$ when rectangular (not Gaussian) pdfs are used to constrain systematics.

Combined signal strength for m_H = 125 GeV



Measurement of differential production rate

- Separate production mechanisms in vector-boson (μ_{VBF+VH}) and fermion coupled ($\mu_{ggF+ttH}$) processes:



- Model independent combination only possible for measurement of ratio $\mu_{VH}/\mu_{ggF+ttH}$
  $\Rightarrow$ Evidence for VBF production at $3.3\,\sigma$ level found!

Spin-parity

Following the discovery of a new boson, important to establish spin and parity (J^P) quantum numbers

- Standard Model hypothesis predicts $J^P=0^+$

Test several alternative J^P against the SM and observe which is favored by data

- Find observables in bosonic channels sensitive to spin and parity, also preserve background discrimination

Several alternative models:

- Landau-Yang theorem strongly disfavors spin 1 since the boson appears in the di-photon channel. Can test in $WW^{(*)}$ and $ZZ^{(*)}$ anyway

γγ: $J^P=0^+$ tested against $J^P= 2^+$ (no sensitivity to parity)

$WW^{(*)}$: $J^P=0^+$ tested against $J^P= 1^+, 1^-, 2^+$

$ZZ^{(*)}$: $J^P=0^+$ tested against $J^P= 0^-, 1^+, 1^-, 2^+$

$J^P=2^+$

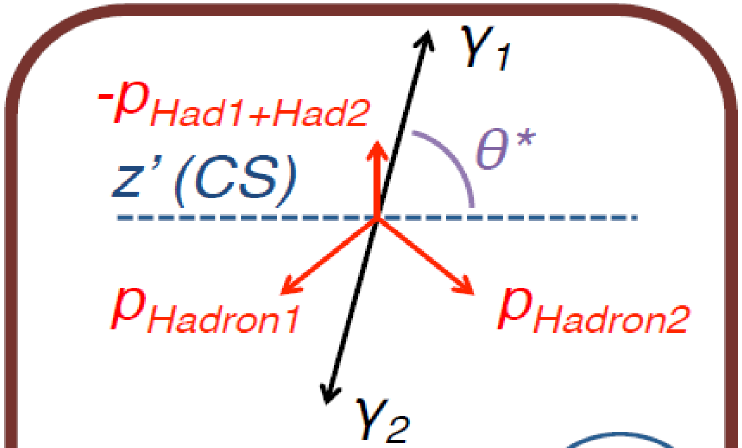
- Graviton-like tensor, minimal couplings to SM particles
- Test production via combinations of *gg* fusion and *qq* annihilation, which are beyond the minimal coupling model, which would give 96% gg, 4% qq at LO

$J=1$ models have signal produced via *qq* annihilation (*gg*→($J=1$) forbidden)

$J^P=0^-$ models from *gg* production (negligible *qq* production expected)

Spin observables for H->γγ

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



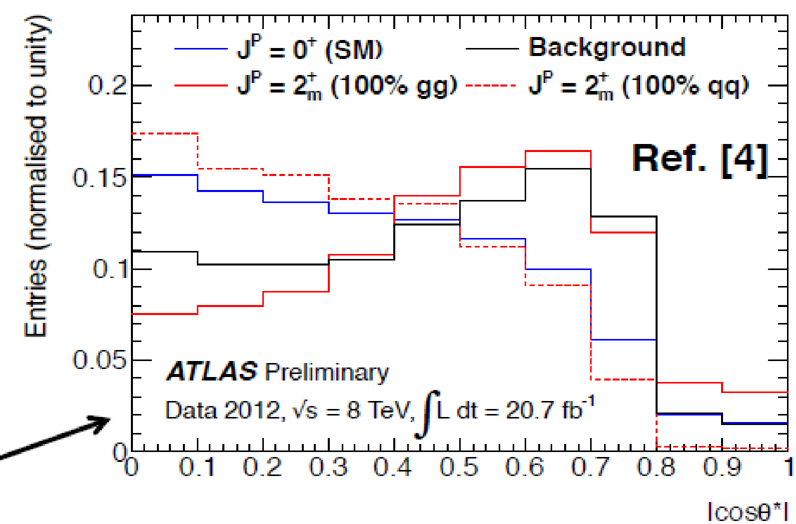
$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

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 $m_{\gamma\gamma}$

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



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

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

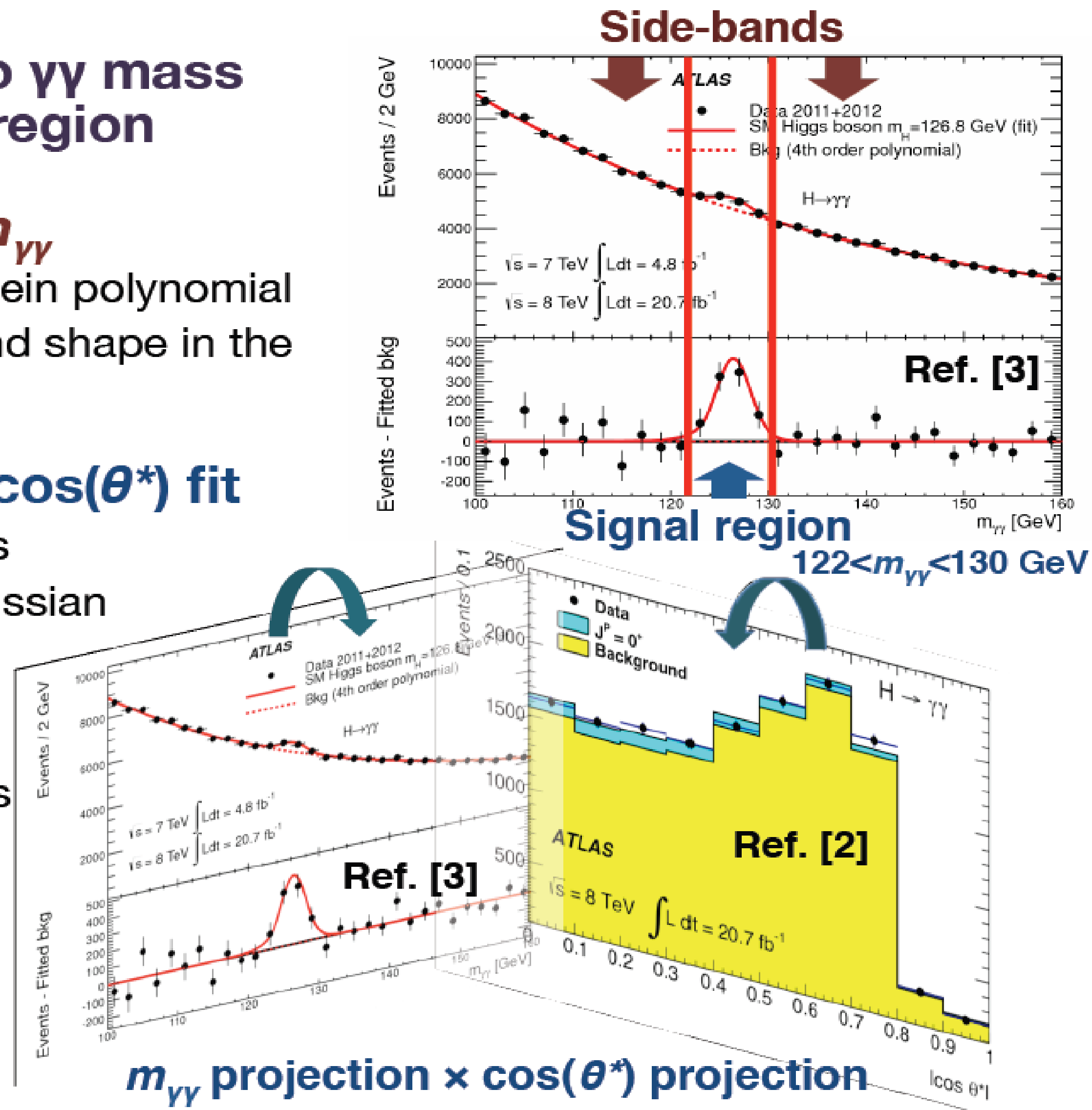
Side-bands: 1D fit in $m_{\gamma\gamma}$

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

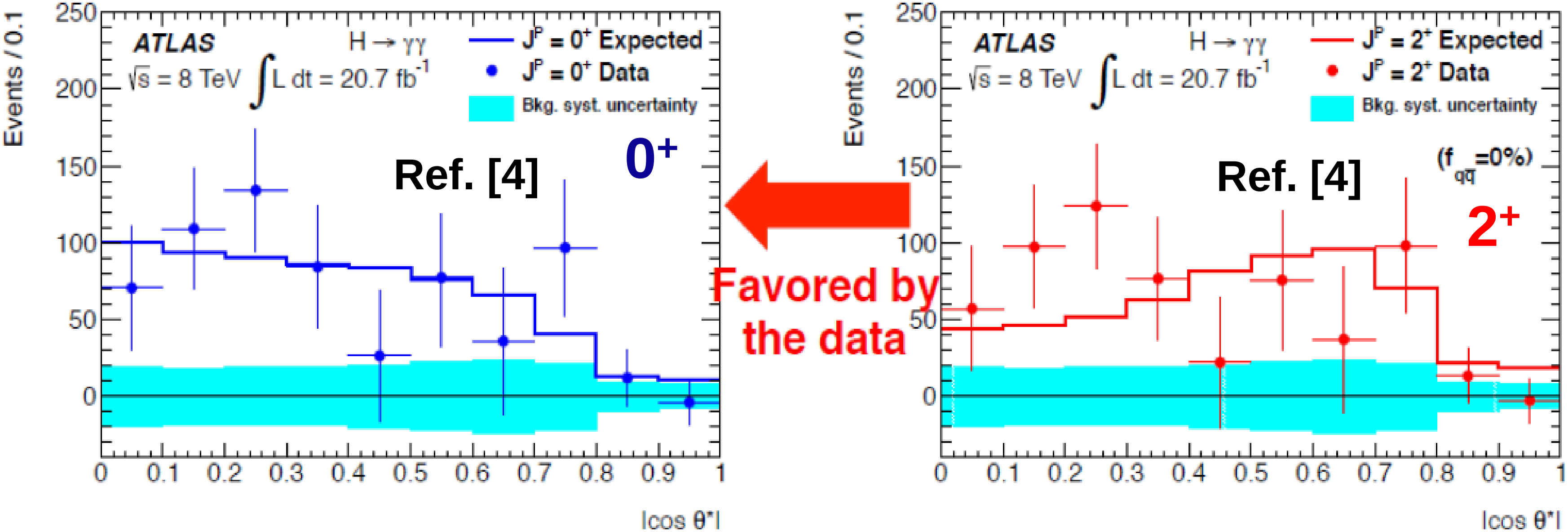
Signal region: 2D $m_{\gamma\gamma}$-cos(θ*) fit

- 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



Bgd subtracted cosθ* distribution



Fit (points) and 0^+ expectation (line)

Fit (points) and *gg*→2^+ expectation (line)

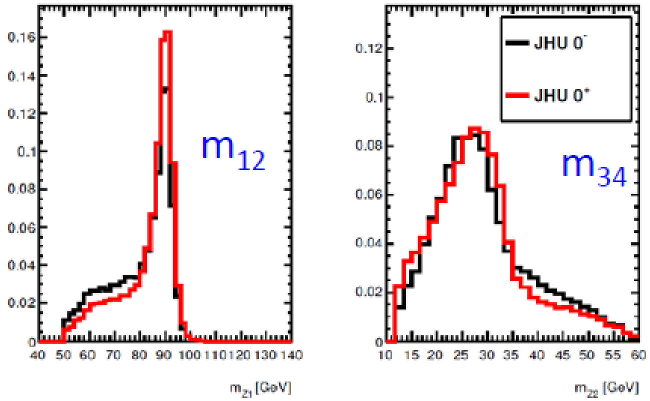
2. Evidence for the spin-0 nature of the Higgs boson using ATLAS data
http://arxiv.org/abs/1307.1432

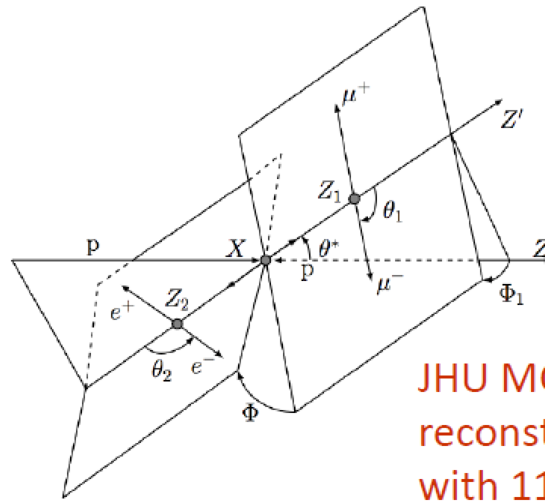
3. Measurement of the Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC
http://arxiv.org/abs/1307.1427

4. Study of the spin of the Higgs-like boson in the two photon decay channel using 20.7 fb^{-1} of pp collisions collected at $\sqrt{s}$=8 TeV with the ATLAS detector
https://cds.cern.ch/record/1527124

Spin-parity observables for H->ZZ*->4l

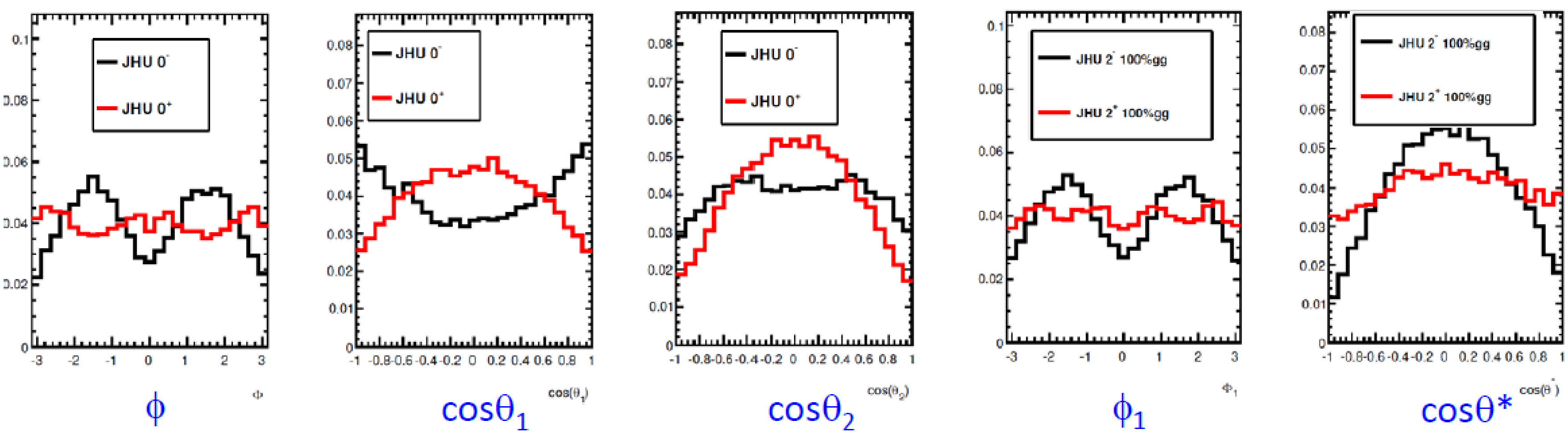
- Kinematic variables: m_{12}, m_{34}





JHU MC after the reconstruction and all cuts with 115 GeV < m4l < 130 GeV

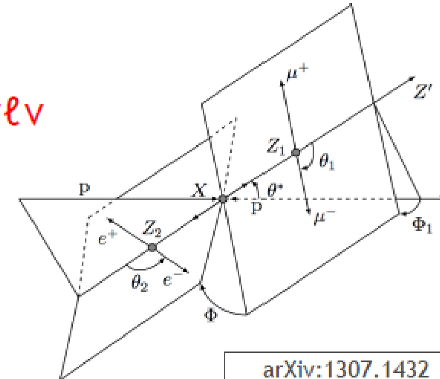
- Angular variables: ϕ, ϕ_1, $\cos\theta_1$, $\cos\theta_2$, $\cos\theta^*$



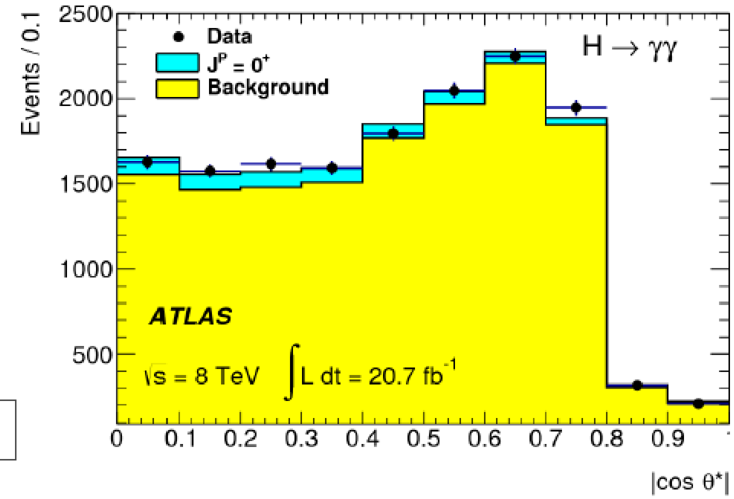
Spin-parity

Use H→γγ, H→4ℓ, H→WW→ℓνℓν
Variables sensitive to decay angles

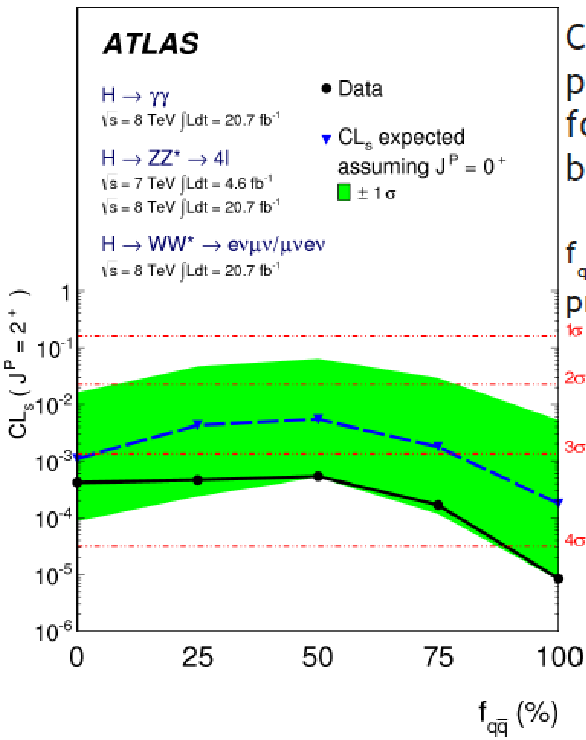
Make pairwise hypothesis tests J^P vs 0^+



arXiv:1307.1432
accepted by PLB



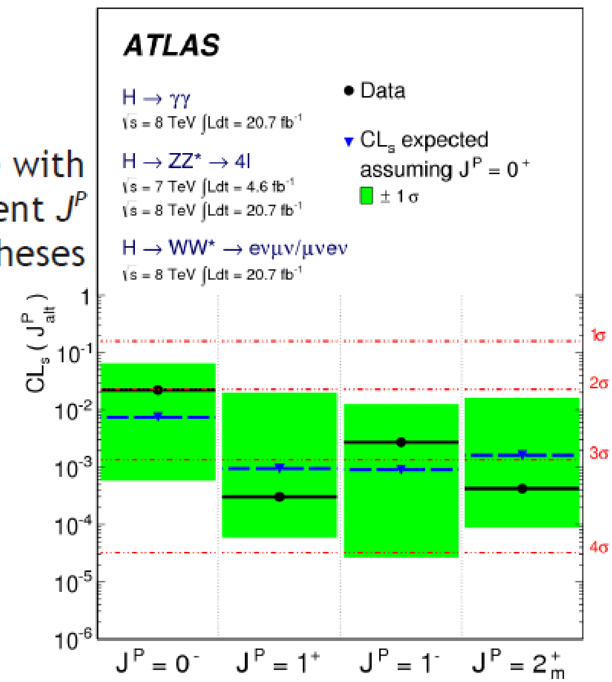
Data are consistent with 0^+ on every test



Compare with a range of production hypotheses for a spin-2 graviton-like boson

f_{qq} = fraction of qq production (rather than gg)

Compare with different J^P hypotheses



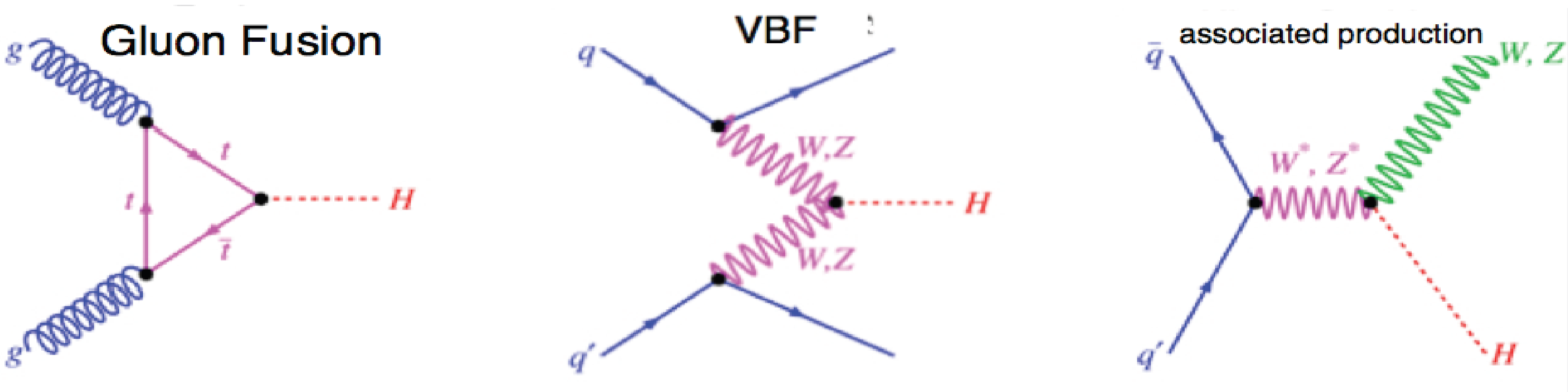
All alternative hypotheses disfavoured at >97.8% CL

Higgs boson: what is next?

- **Evidence of coupling to fermions so far**
  - **Tevatron VH(→bb) combination:** 2.8σ excess @ M_H=125 GeV
  - **CMS VH(→bb):** 2.1σ excess @ M_H=125 GeV
  - **CMS H→ττ:** 2.85σ excess @ M_H=125 GeV
    - CMS H→ττ and H→bb combination: 3.4σ excess @ M_H=125 GeV
- **Search for H→fermions decays is one of the most important goals for the Higgs program**
  - In particular, does Higgs couple to leptons?
    - We already indirectly know that it couples to quarks
  - Are $\Gamma_{H \to ff}$ consistent with SM predictions?
  - Is it the same Higgs decaying to H→VV & H→ff?
    - Is mass the same? CP properties?

$$\Gamma_{H \to ff} = \frac{N_C M_H}{8\pi v^2} m_f^2 \beta_f^3, \quad \beta_f = \sqrt{1 - \frac{4m_f^2}{M_H^2}}$$

SM Higgs boson production (m_H = 125 GeV)



Largest production mode: ~88%
Utilized by H→ττ & H→μμ analyses

Unique signature of two jets with large M_{jj} & $|\Delta\eta_{jj}|$
Utilized by H→ττ

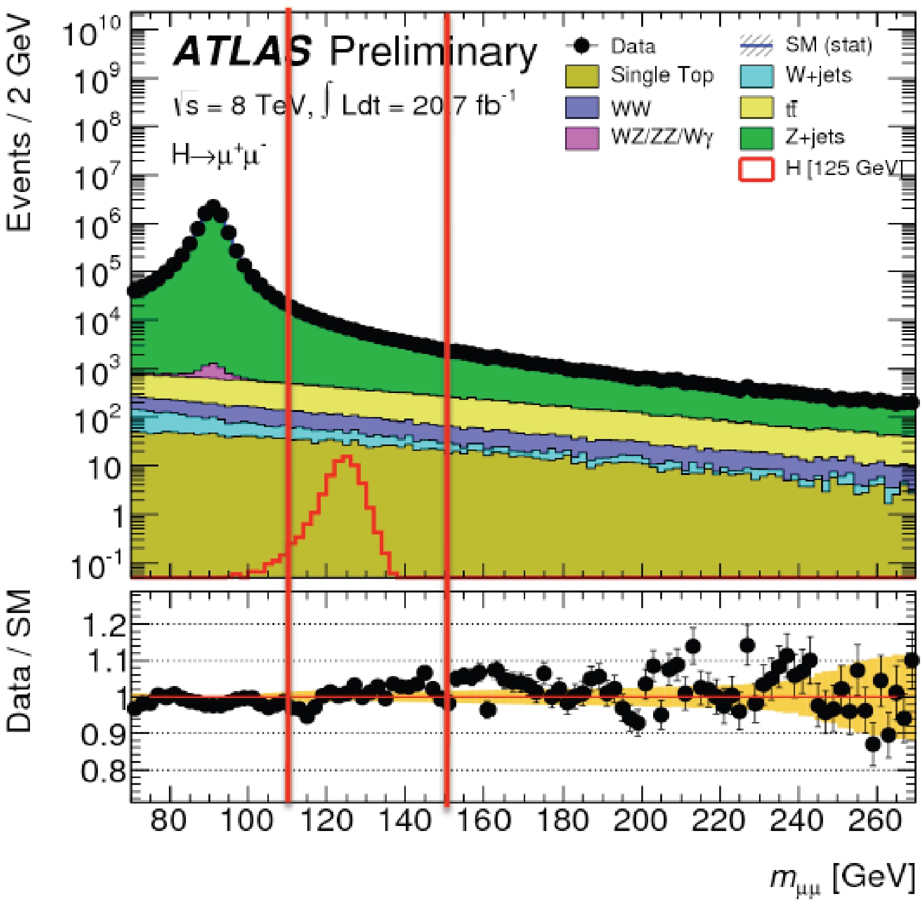
Unique signature with leptons & neutrinos
Utilized by VH(→bb)

	gg→H	VBF	VH
LHC: 8 TeV	19.5 pb	1.57 pb	1.08 pb

	H→bb	H→ττ	H→μμ
Br	57.8%	6.32%	0.0219%

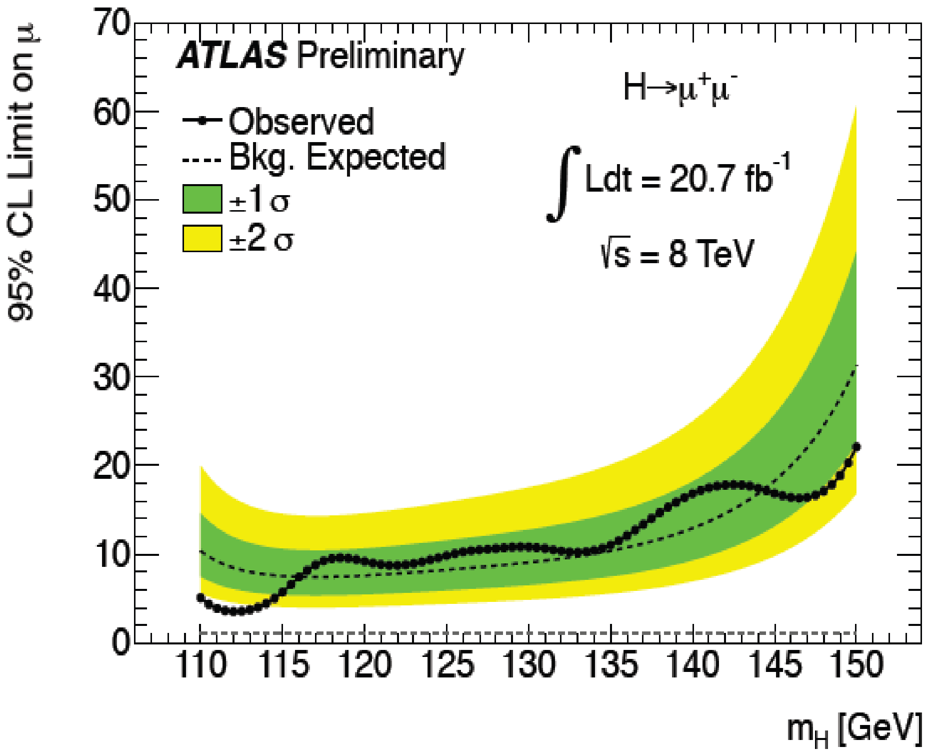
H -> μμ search

- Analysis strategy
  - Inclusive search
  - **Fit M(μμ) with analytic Signal +Bckg shape**
  - Two analysis categories based on muon resolution:
    - Central: $|\eta(\mu 1,2)|<1.0$
    - Non-central: rest
- Event selection for signal region
  - Single muon trigger
  - Two isolated opposite-sign muons
  - $P_T(\mu 1)>25$ GeV, $P_T(\mu 2)>15$ GeV
  - $P_T(\mu\mu)>15$ GeV



Search window: 110-150 GeV
MC background predictions are not used in the search (for optimization only)

H -> μμ search: results

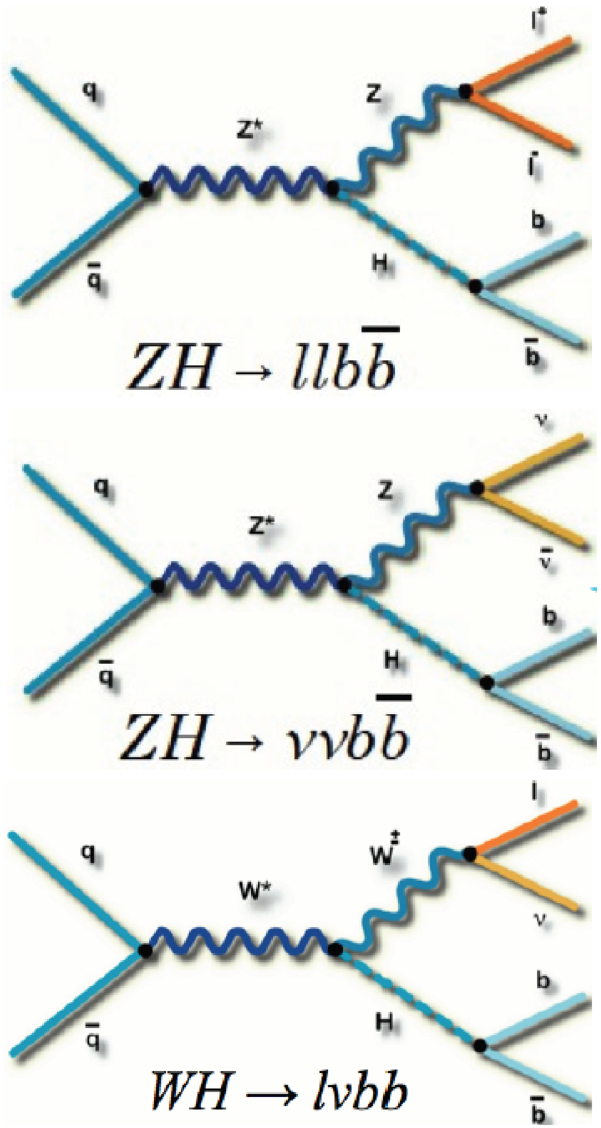


- Systematic uncertainties on signal normalization @125 GeV
  - Cross-section: 15%
  - Br($H \to \mu\mu$): ~6%
  - Acceptance uncertainty
    - Theory: ~2.6%
    - Experimental: ~4.2%

$$Signal\ strength\ \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

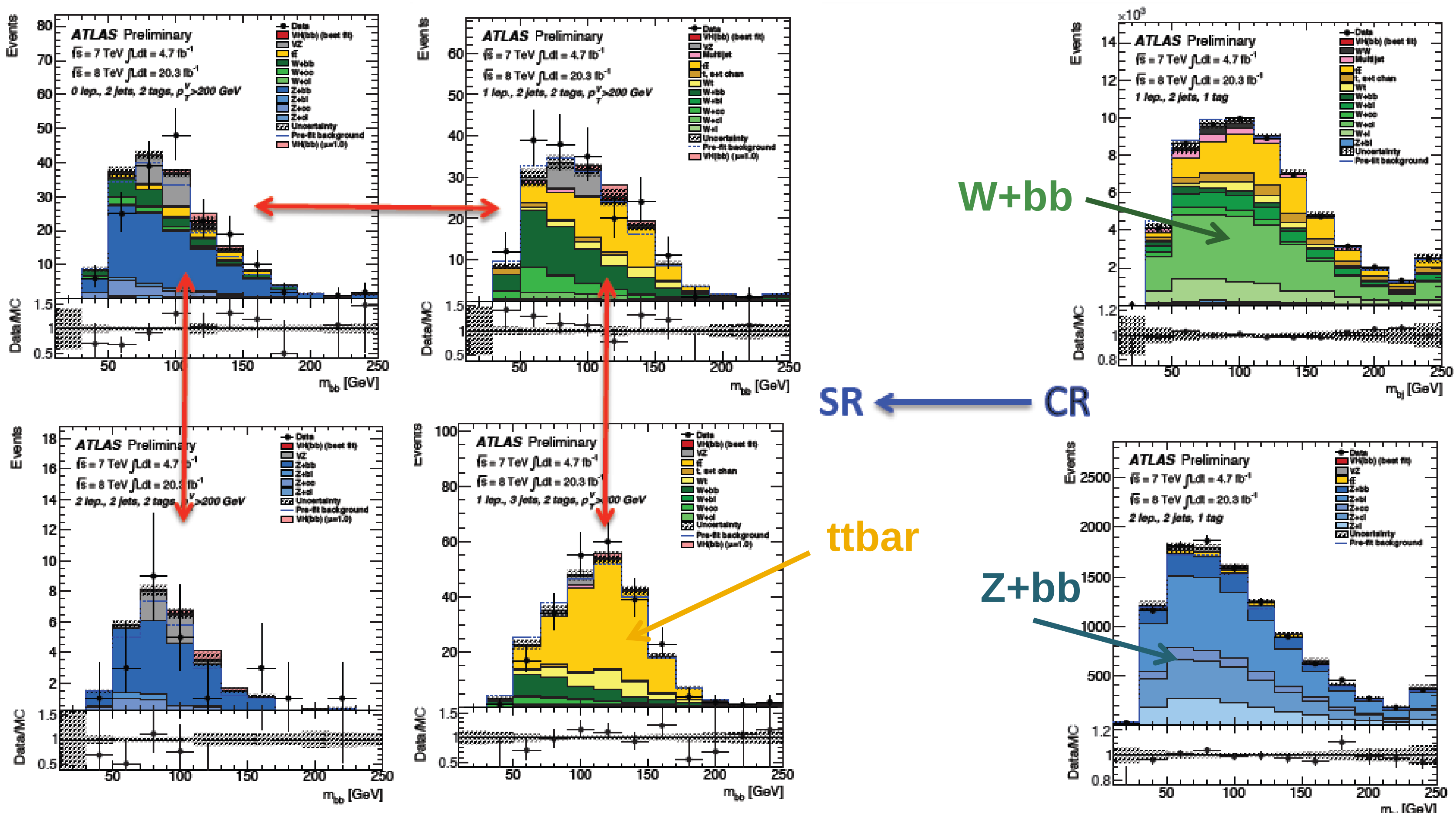
- ATLAS results with 20.7 fb^{-1} of data at 8 TeV
  - No significant deviations outside uncertainty bands are observed
  - 95% CL limit on μ @ 125 GeV: expected (μ=0) 8.2×SM, observed 9.8×SM

H->bb search: exploit unique topology



- Cut-based analysis in 3 final states
- ZH→ll+bb
  - **Signature:** two opposite sign leptons and 2 b-tagged jets
  - **Major backgrounds**: Z+ heavy flavor jets
- ZH→νν+bb
  - **Signature:** large MET and 2 b-tagged jets
  - **Major backgrounds**: top, Z/W+ heavy flavor jets
- WH→l+ν+bb
  - **Signature:** one lepton, MET and 2 b-tagged jets
  - **Major backgrounds**: top, W+ heavy flavor jets

H->bb search: the fits

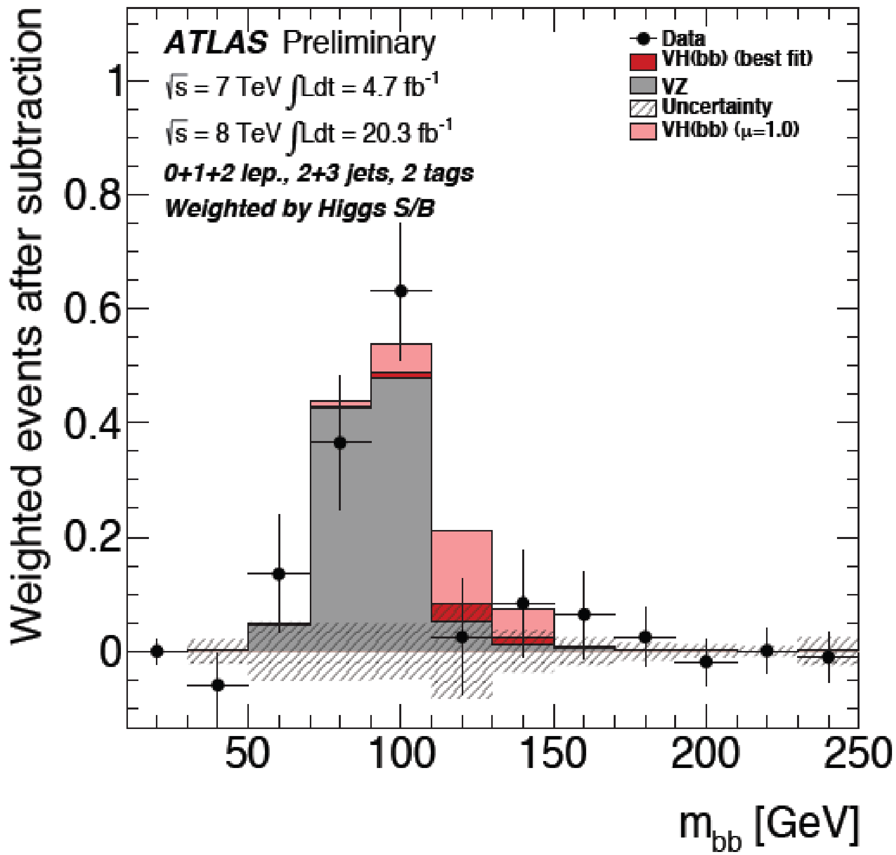


- Signal and control regions have different background compositions & shape
- **Simultaneous fit allows to reduce effect of systematic uncertainties and constrain flavor composition of backgrounds**

H->bb search: cross-check with VZ(->bb)

Signal strength

$$\mu_{VZ} = \frac{\sigma^{VZ}_{measured}}{\sigma^{VZ}_{SM}}$$

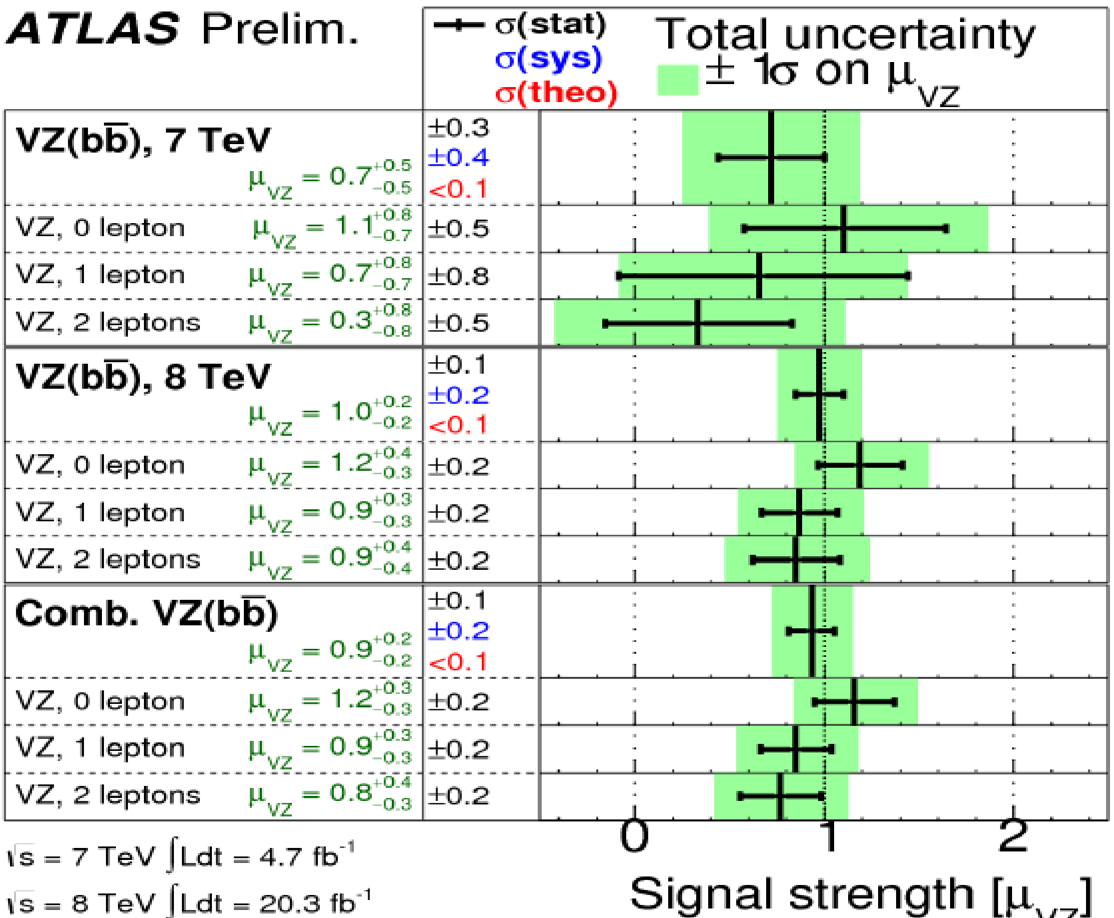


- Measured VZ(→bb) production cross-section is consistent with SM
  - 4.8σ significance; μ_{VZ}=0.9±0.2
  - Same signature as VH(→bb) allows for direct test of analysis procedure

H->bb search: cross-check with VZ(->bb)

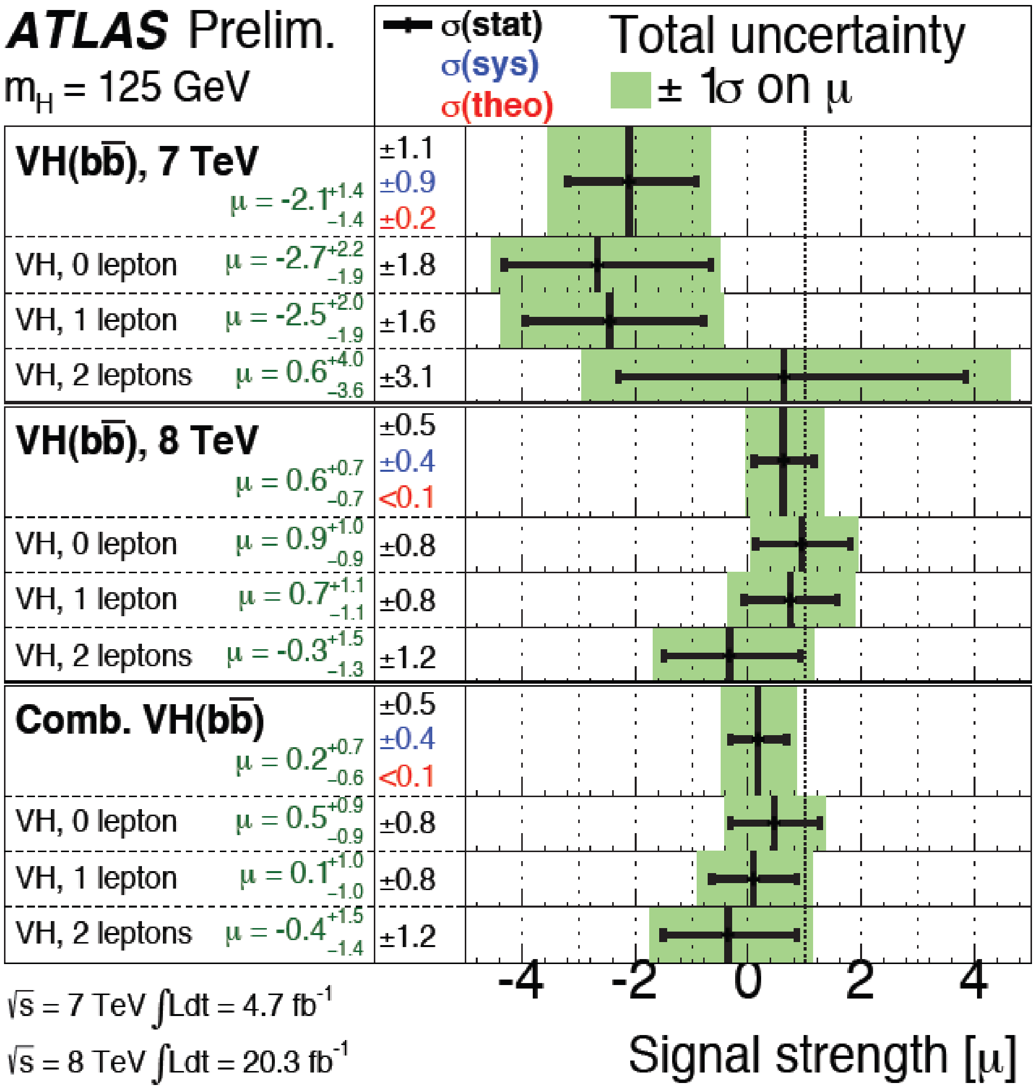
Signal strength

$$\mu_{VZ} = \frac{\sigma^{VZ}_{measured}}{\sigma^{VZ}_{SM}}$$



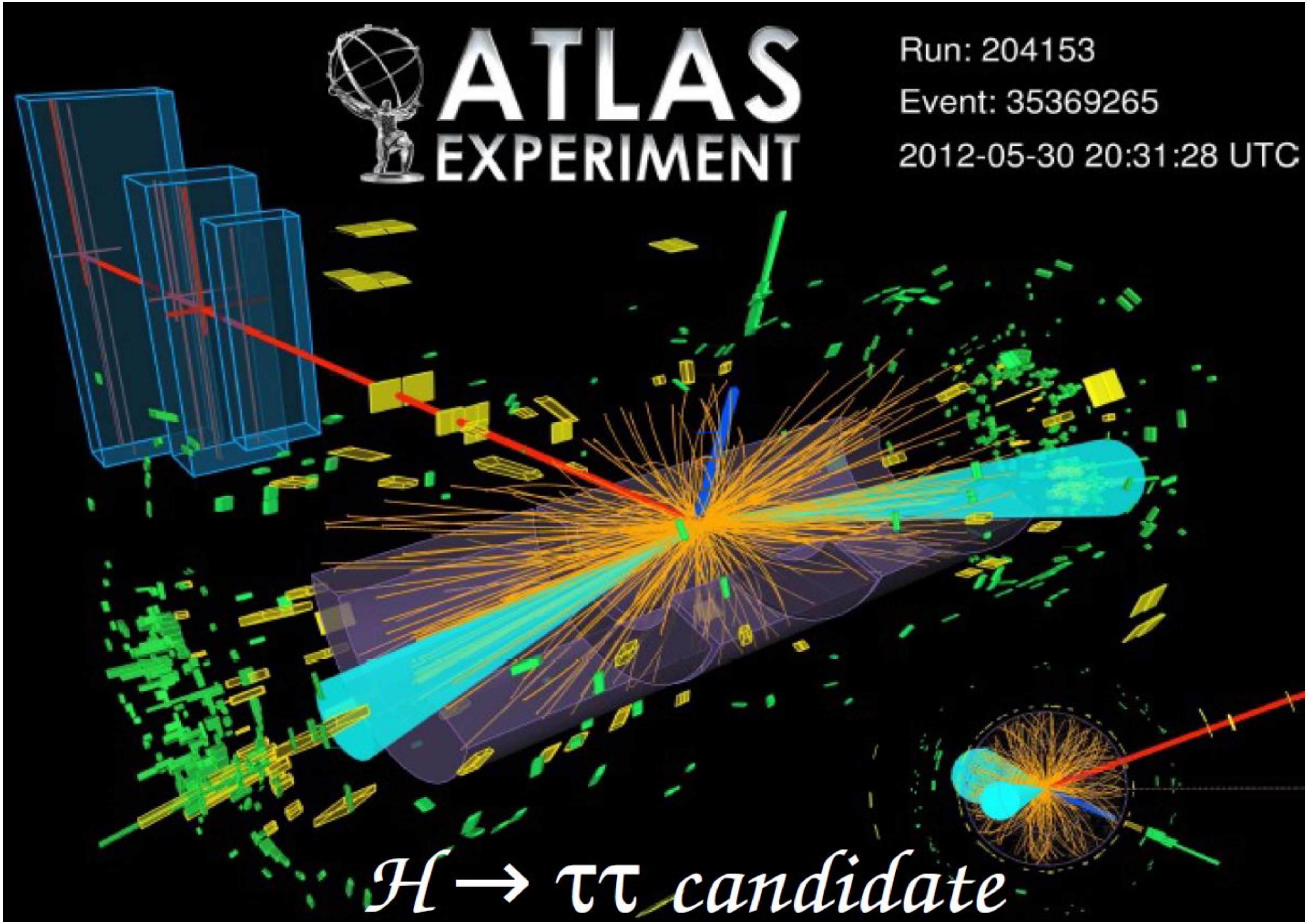
- Measured VZ(→bb) production cross-section is consistent with SM
  - 4.8σ significance; μ_{VZ}=0.9±0.2
  - Same signature as VH(→bb) allows for direct test of analysis procedure

H->bb search: results



- Fitted signal strength
  - 7+8 TeV: $\mu=0.2^{+0.7}_{-0.6}$
- 95% CLs @125 GeV
  - Expected: 1.3×SM
  - Observed: 1.4×SM
- Results consistent with SM H→bb and background-only hypotheses
- Dominant uncertainties:
  - Modeling of ttbar: M_{bb}, $P_T(V)$, 2-jet/3-jet ratio
  - c-jet tagging efficiency
  - Multijet normalization in 1-lepton channel
  - Signal acceptance

$$\textit{Signal strength } \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$


ATLAS
EXPERIMENT
Run: 204153
Event: 35369265
2012-05-30 20:31:28 UTC
$\mathcal{H} \to \tau\tau$ candidate

H->ττ analysis (1)

- SM $H \to \tau\tau$ analysis with full 2012 dataset, following recent results on Higgs coupling to bosons and $H \to bb$
- **Features:**
  - ATLAS exploits the $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ final states
  - Events are separated in 2-jets (VBF) and $p_T^{\tau\tau}$ boosted categories.
  - MVA Analysis: signal is extracted from a binned fit of the BDT score.

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \to \ell\ell$ normalization ($\tau_{lep}\tau_{had}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{lep}\tau_{had}$ VBF)	0.12
Top normalization ($\tau_{lep}\tau_{had}$ boosted)	0.12
$Z \to \ell\ell$ normalization ($\tau_{lep}\tau_{had}$ VBF)	0.12
QCD scale	0.07
di-τ_{had} trigger efficiency	0.07
Fake backgrounds ($\tau_{lep}\tau_{lep}$)	0.07
τ_{had} identification efficiency	0.06
$Z \to \tau^+\tau^-$ normalization ($\tau_{lep}\tau_{had}$)	0.06
τ_{had} energy scale	0.06

Control Region Checks:

Agreement between data and MC is checked in Control Regions. Examples of BDT distributions in data CR's for major backgrounds.

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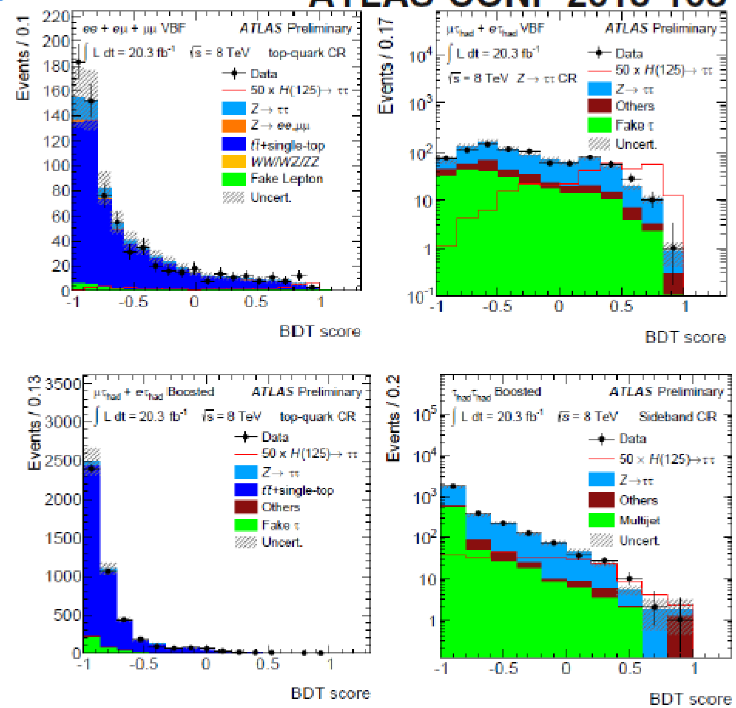
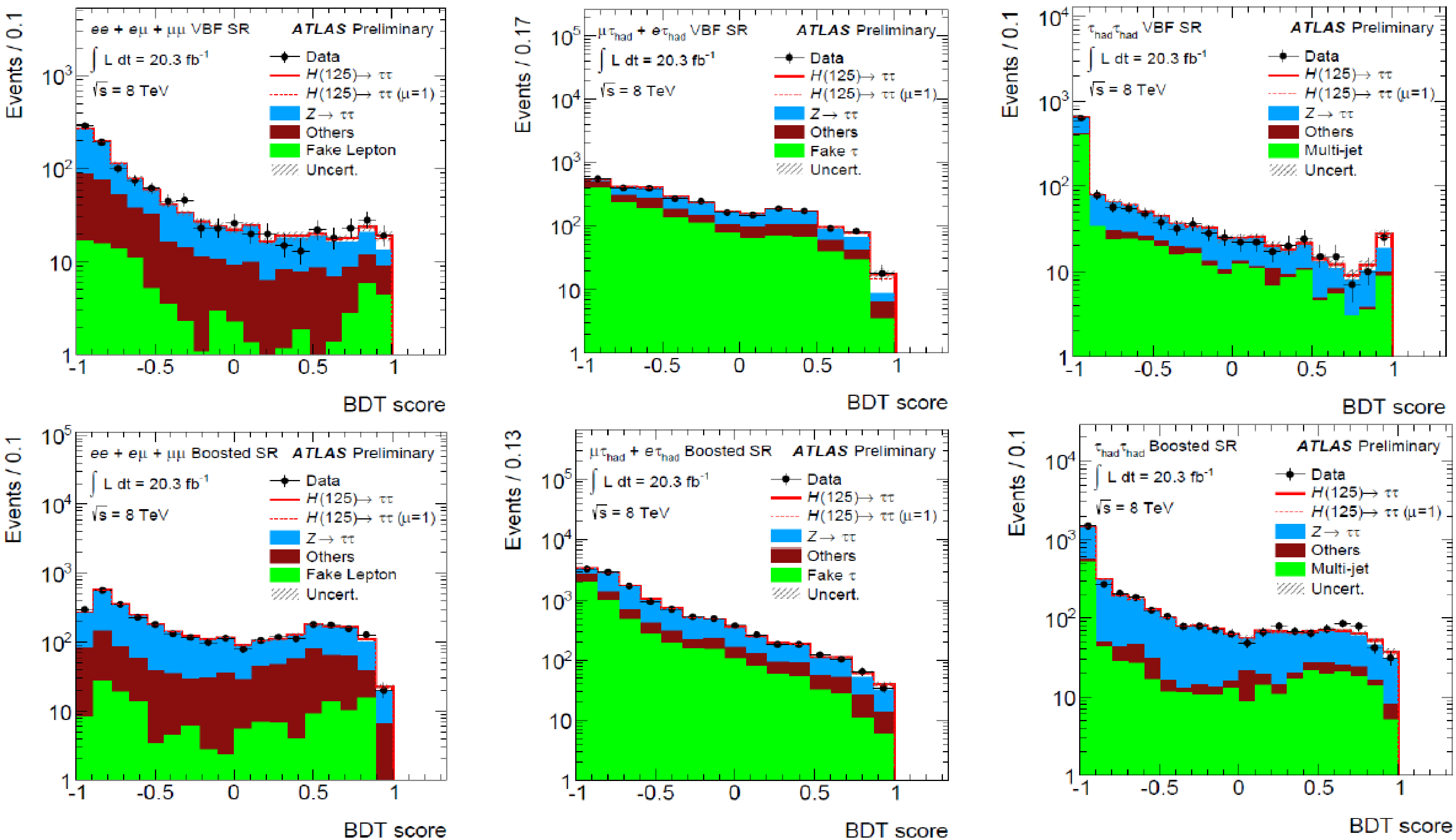


H->ττ analysis (2)

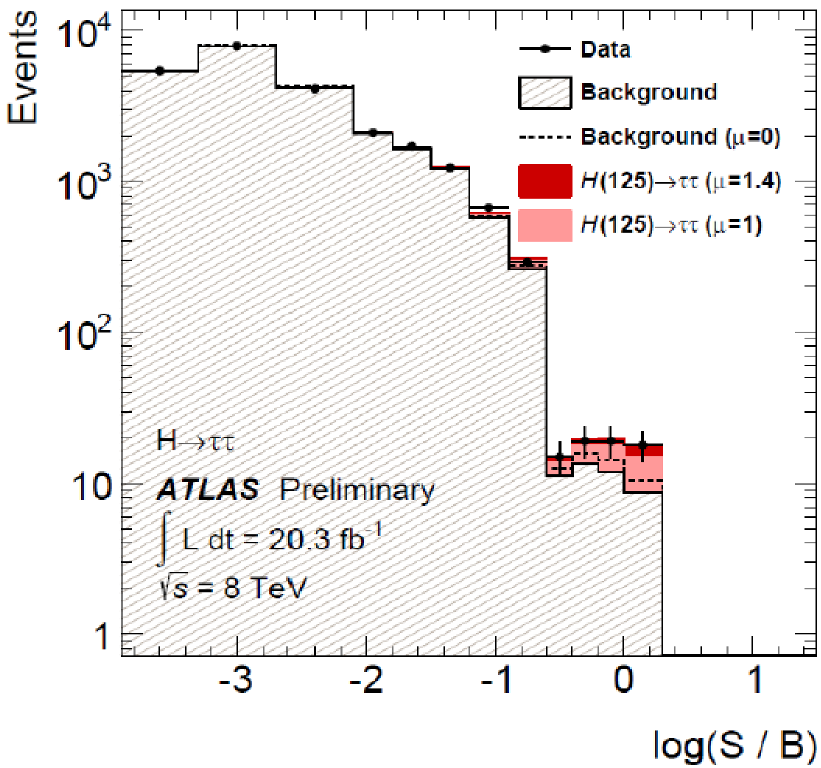


- Data is divided in 6 signal regions and 9 control region to simultaneously fit signal and backgs.

H->ττ analysis (3)

- ATLAS observes significant excess of data events in high S/B region:
  - Excess is observed in all three channels
  - *First strong evidence of $H \rightarrow \tau\tau$ decay*: **4.1 σ observed @125 GeV (3.2 σ expected).**

For each BDT score calculate S/B, fill into this plot.



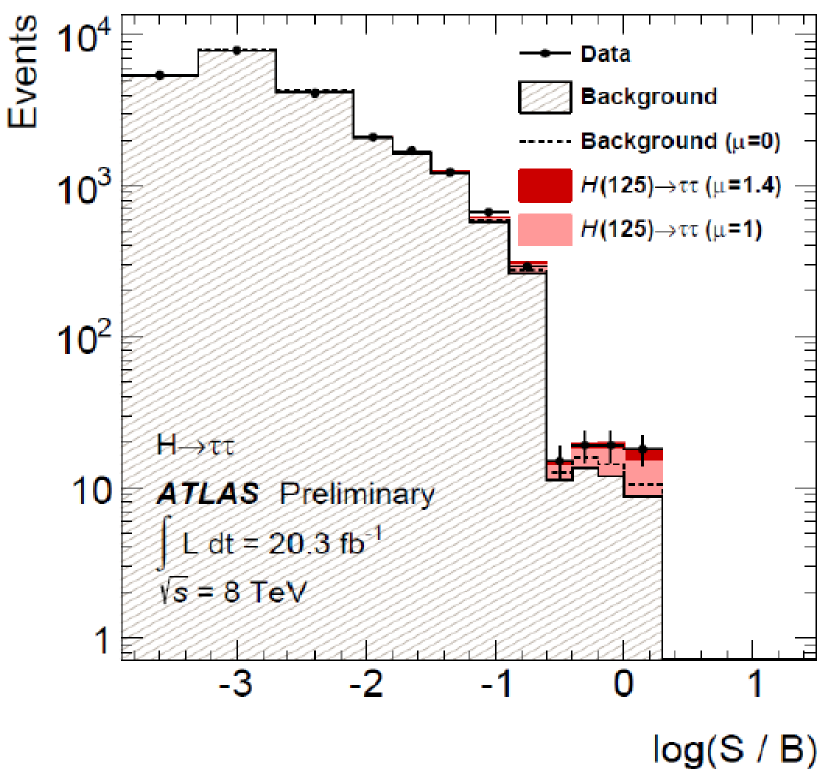
ATLAS-CONF-2013-108

Numbers of events in highest BDT-score bin

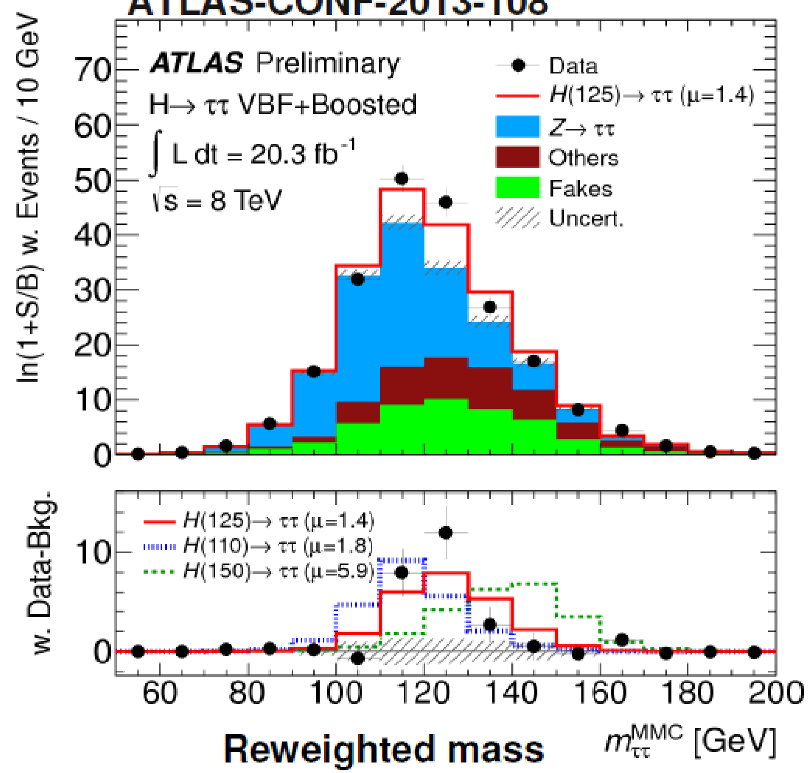
		Lep-lep	Lep-had	Had-had
VBF	Signal	5.7±1.7	8.7±2.5	8.8±2.2
	Bckg	13.5±2.4	8.7±2.4	11.8±2.6
	Data	**19**	**18**	**19**
Boosted	Signal	2.6±0.8	8.0±2.5	3.6±1.1
	Bckg	20.2±1.8	32±4	11.2±1.9
	Data	20	34	15

H->ττ analysis (4)

- ATLAS observes significant excess of data events in high S/B region:
  - Excess is observed in all three channels
  - *First strong evidence of $H \to \tau\tau$ decay*: **4.1 σ observed @125 GeV (3.2 σ expected).**
  - Excess of data events is compatible with presence of Higgs at 125 GeV (events are weighted by ln[1+S/B] value of the corresponding BDT-score bin)

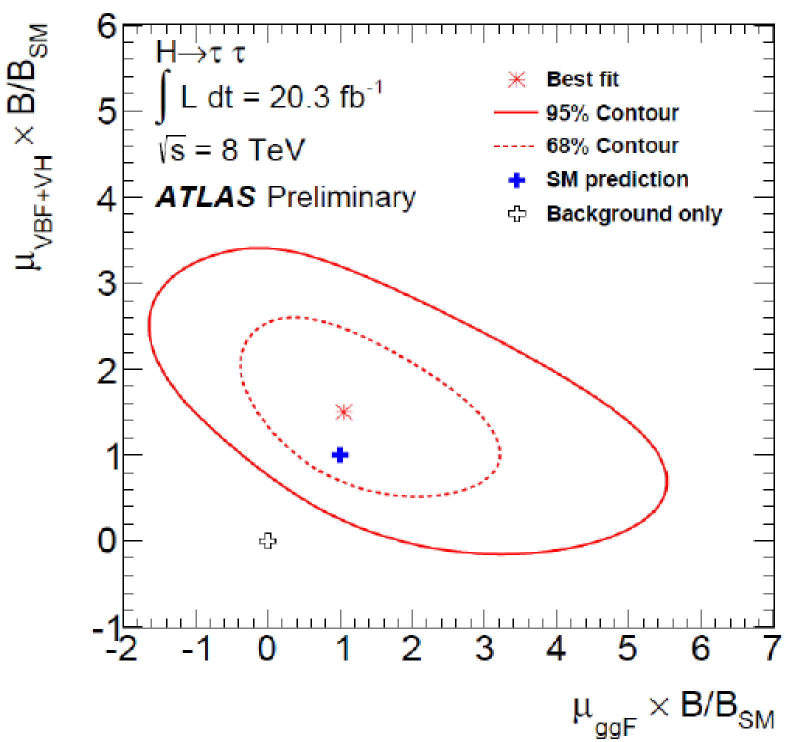


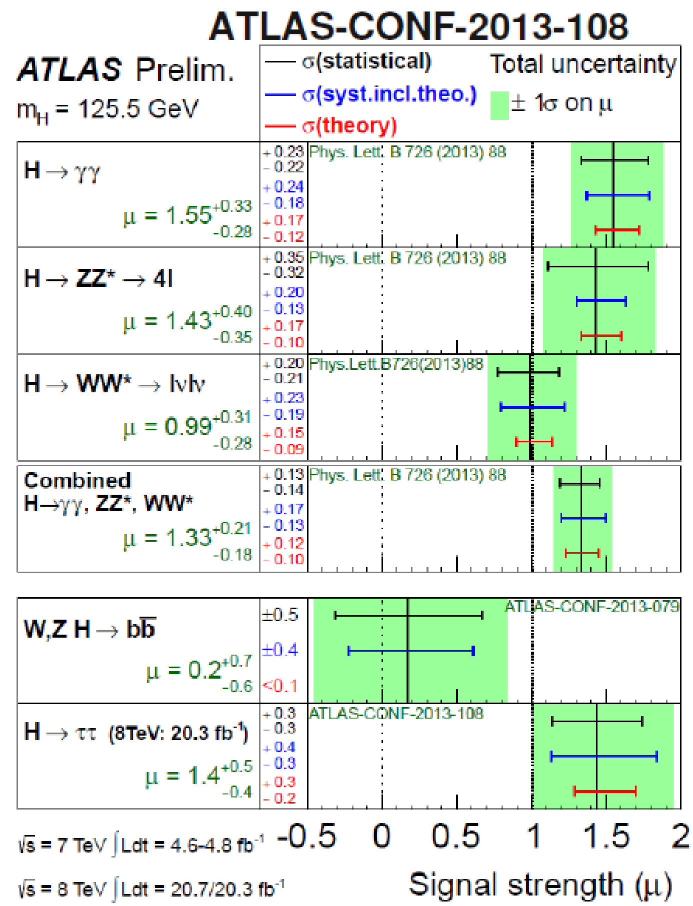
ATLAS-CONF-2013-108



H->ττ results

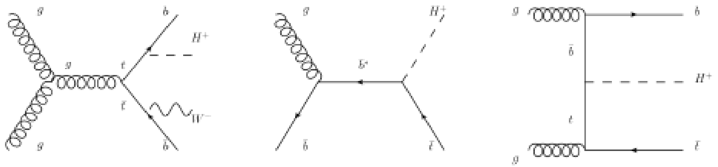
- Good sensitivity to VBF production mode
- Together with ATLAS $H \rightarrow \mu\mu$ results, it proves that the Higgs couplings is not the same for all lepton flavours, in agreement with SM.
- **Best fit $\sigma/\sigma_{SM} = 1.4^{+0.5}_{-0.4}$**

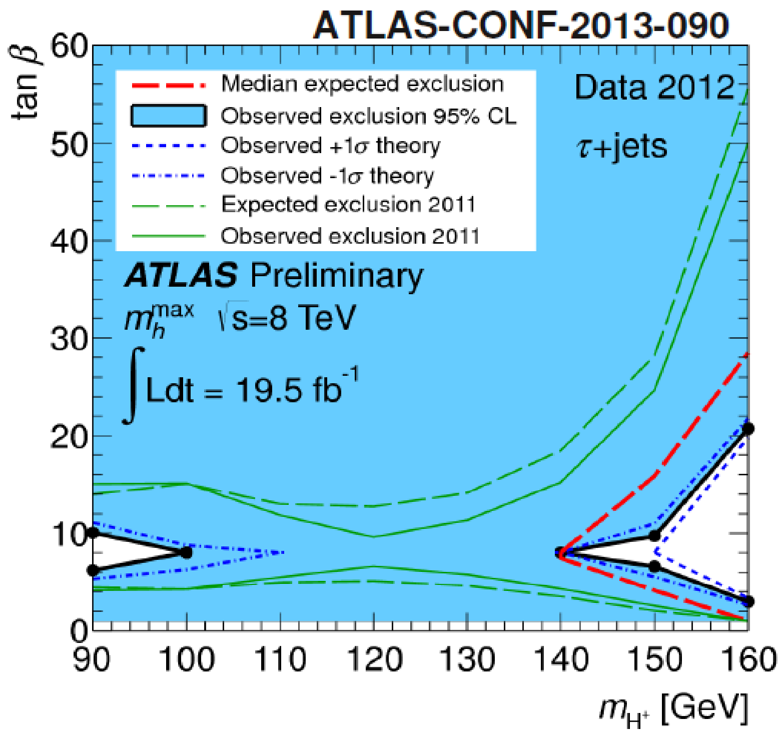


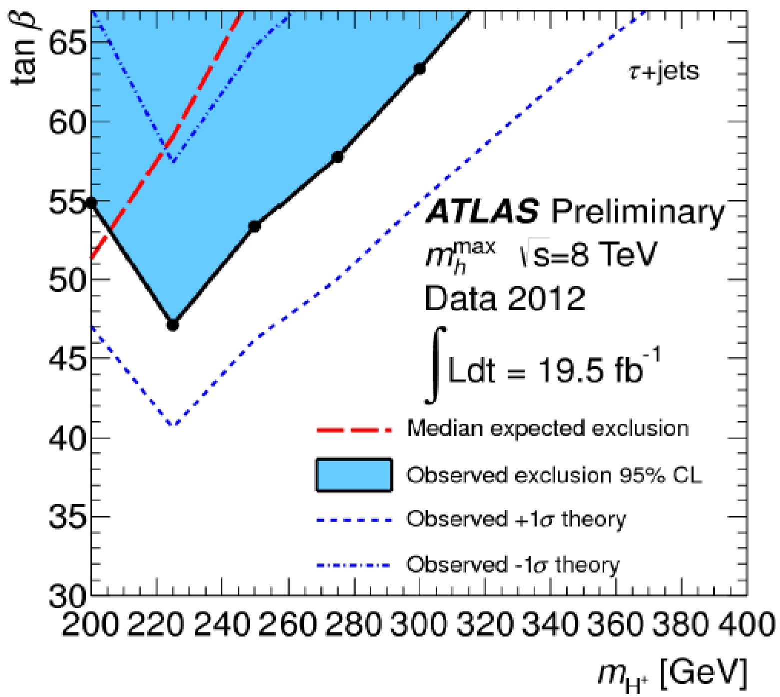


More Higgs highlights

- Recent update on charged $H^+ \rightarrow \tau^+\nu$ searches:
  - Final states with hadronically decaying taus
  - Exploit m_T distribution to extract the signal
  - Results for both below and above top-quark threshold: ($t \rightarrow Hb$ and $pp \rightarrow tH$)







Prospects for Higgs measurement precision

Within a short year, we have gone from the discovery of a *Higgs-like* boson to a *SM-like* Higgs boson.

Is the particle the SM Higgs boson?
⇒ will need more data as well as improved theory calculations…

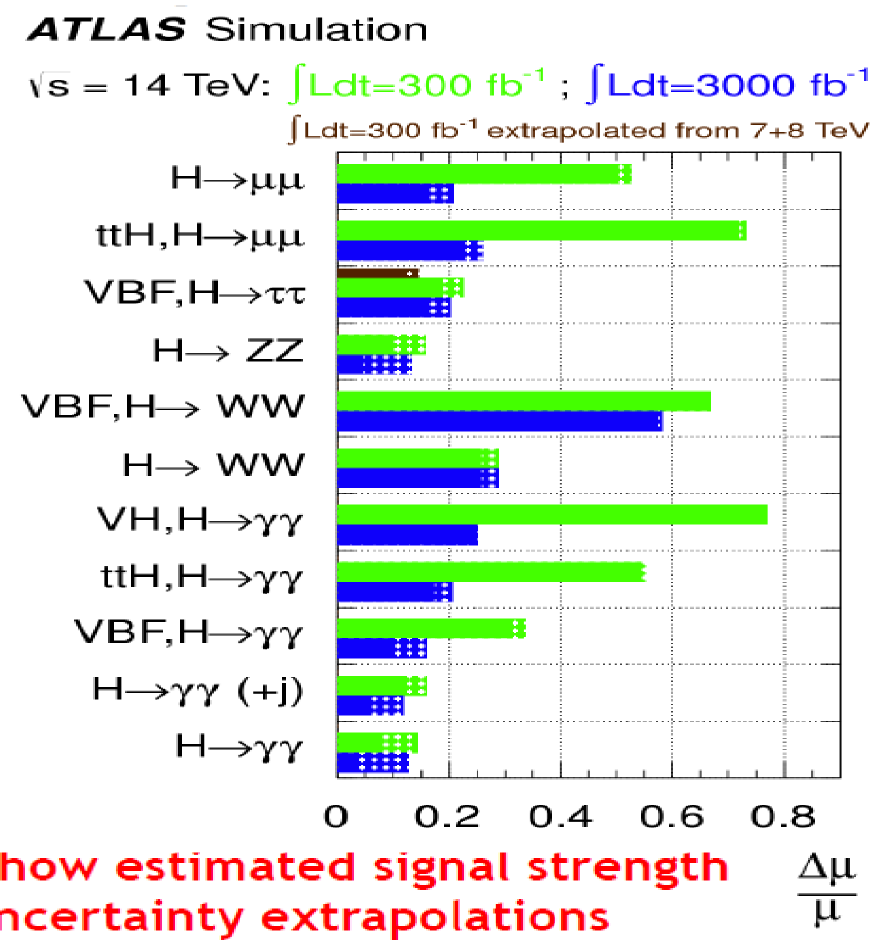
Extrapolating from 25 fb^{-1} to 300 fb^{-1} or 3000fb^{-1} is toug

Experimental systematic errors: will improve

- tighter/better selections
- constrain uncertainties increasingly using data

Theoretical uncertainties:

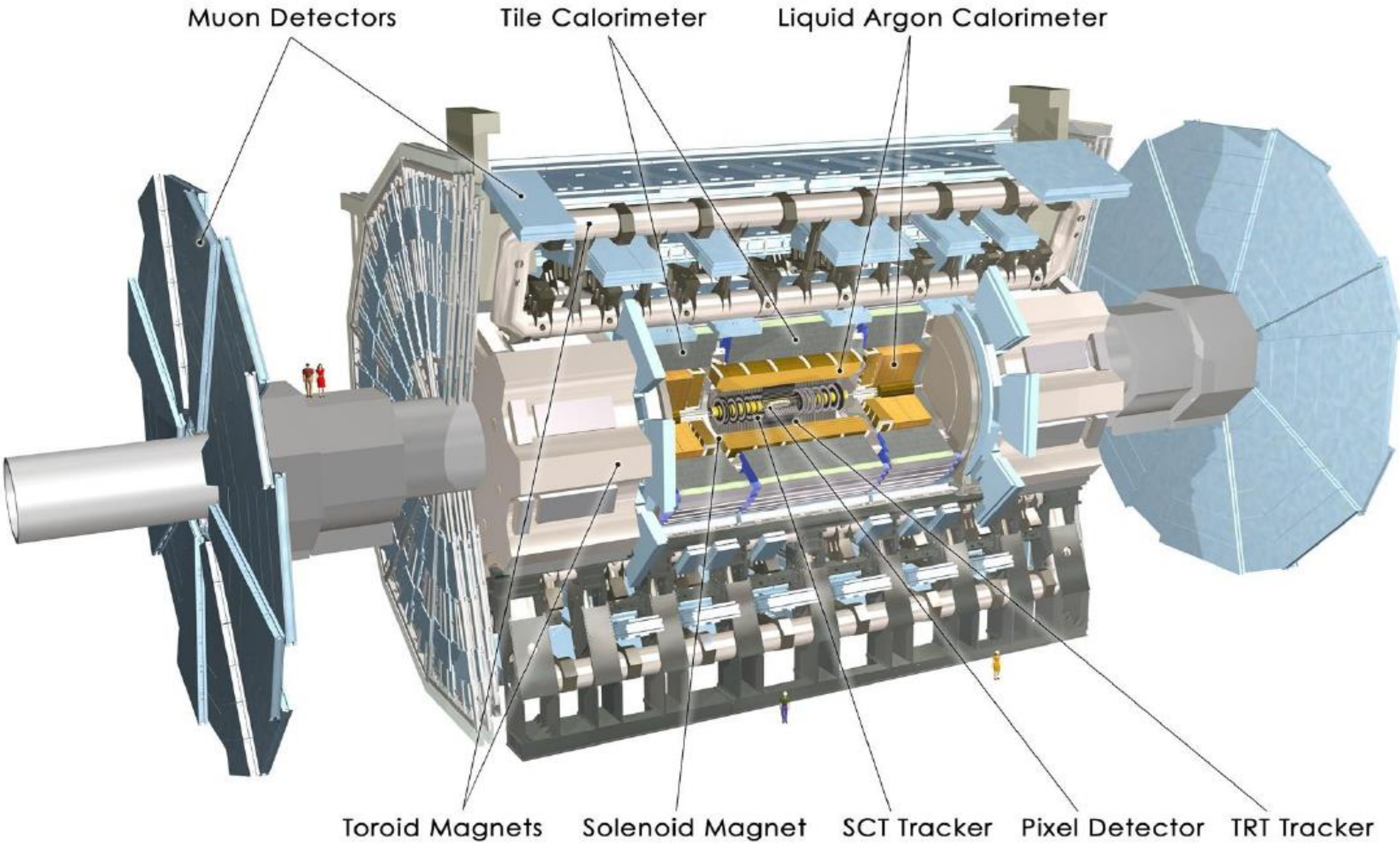
- Now 3-15% for production, 3-10% on decays
- Dominant errors: QCD scale (HOs) and PDFs



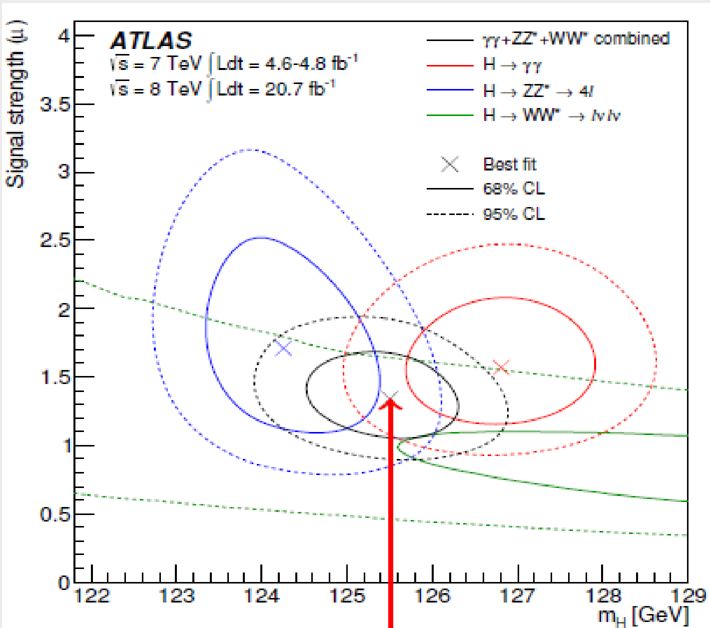
Plots show estimated signal strength uncertainty extrapolations

ATLAS Detector

Central tracking out to $|\eta|=2.5$, calorimetry to $|\eta|=4.9$
2T solenoid and toroids with $\int Bdl=1\text{-}7.5$ Tm
25m high, 45m long, 100M channels, 7000t, 10y construction

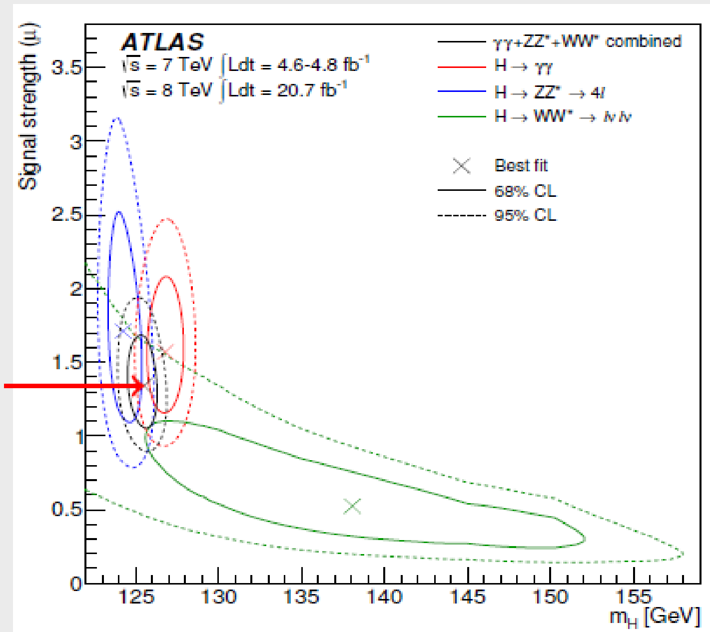


Summary on properties in bosonic channels



Combined mass: $m_H = 125.5 \pm 0.6$ GeV

Combined signal strength: $\mu = 1.33 \pm 0.21$



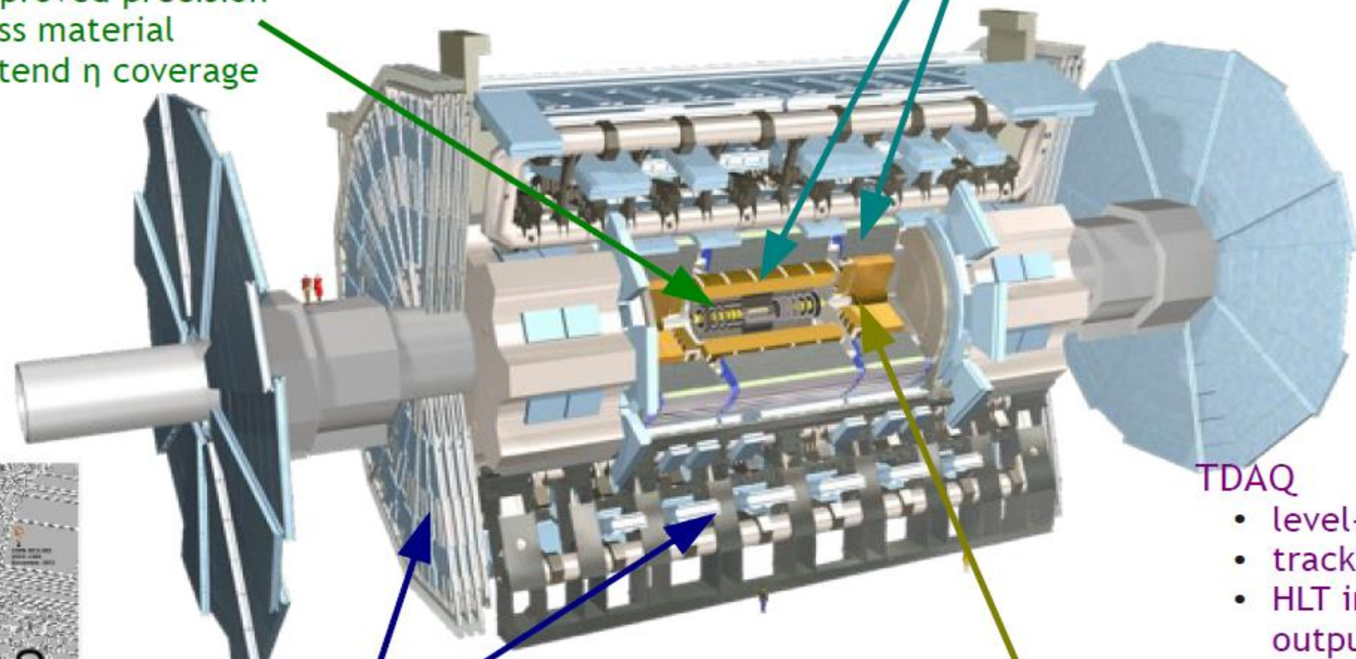
- Individual claim for Higgs boson discovery possible in $H \to \gamma\gamma$ and $H \to 4\ell$ final states.
- Mass difference between $H \to \gamma\gamma$ and $H \to 4\ell$ measurements significant at $2.5\,\sigma$.
  $\Rightarrow$ No significant deviation from prediction of single resonance.
- Evidence for VBF production (mainly from $H \to \gamma\gamma$ and $H \to \ell\nu\ell\nu$ channels)
- Differential cross sections measurement in $H \to \gamma\gamma$ show no sign of deviations from SM.
- First ttH analysis performed in $H \to \gamma\gamma$ final state $\to$ other final states underway!

Current Measurements No significant deviations from SM predictions!

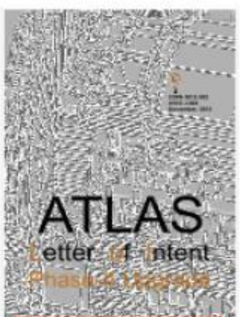
ATLAS upgrades for HL-LHC

New Inner Tracker
- Radiation hardness
- Better granularity and faster links
- Improved precision
- Less material
- Extend η coverage

LAr and Tile Calorimeters
- new FE and BE electronics



TDAQ
- level-0 at 0.5 MHz
- tracking at level-1
- HLT input 200 kHz, output 5 kHz?



Letter of Intent Dec 2012

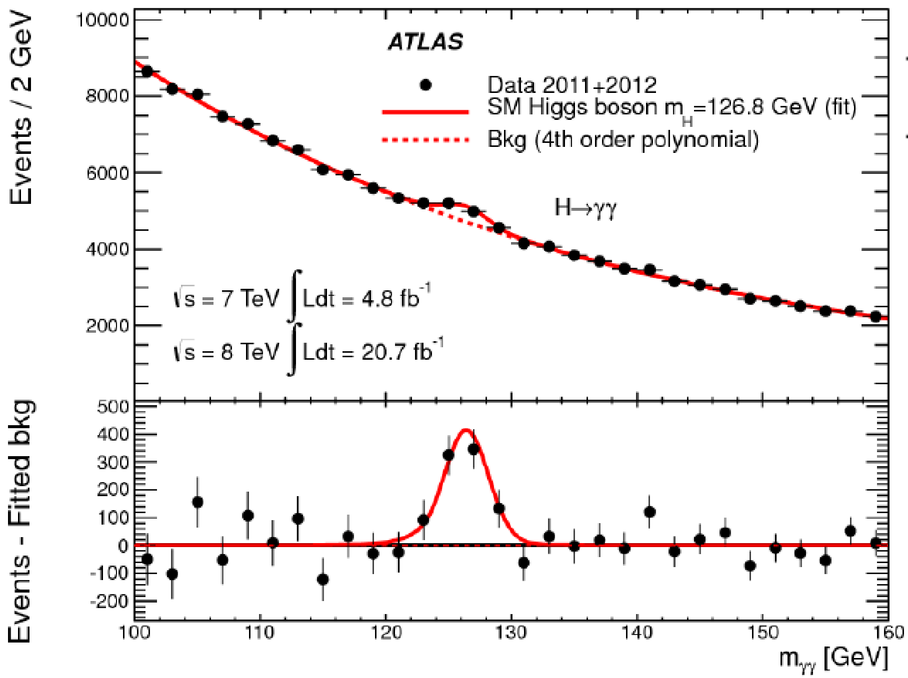
Muons
- new FE electronics
- improve resolution

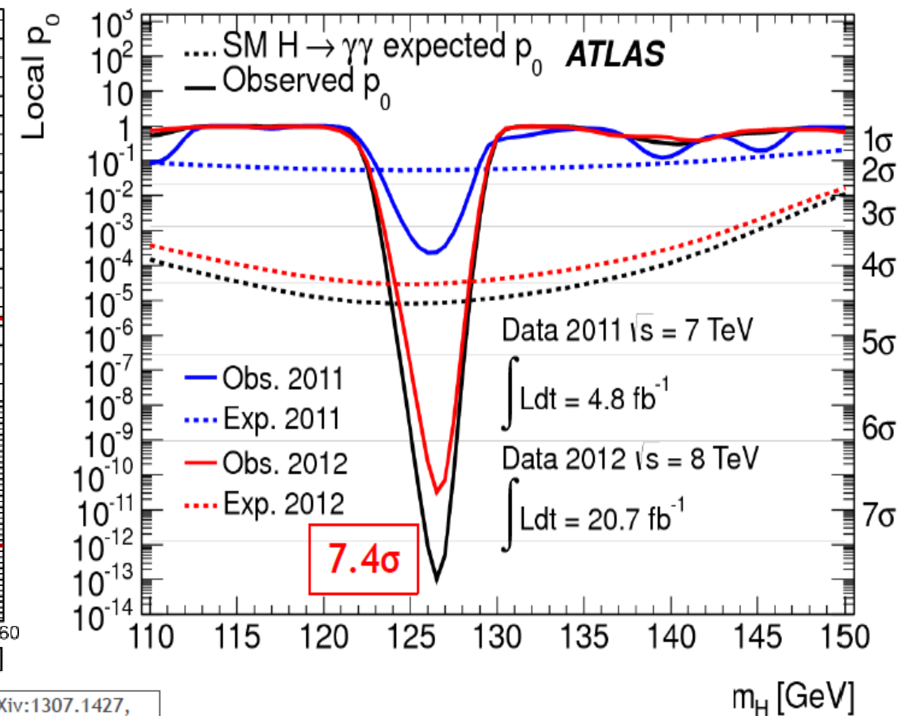
Forward Calorimeters
- Replace FCal?
- Replace endcap hadronic calorimeter cold electronics?

H->γγ

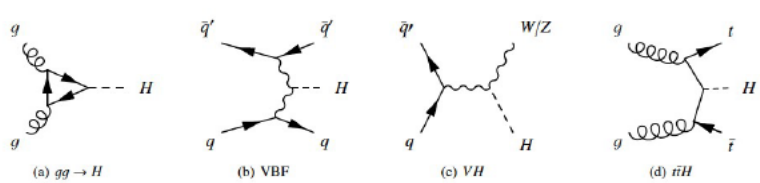
Excellent mass resolution (γ pointing in calorimeter), poor S/B

Signal significance 7.4σ, expected 4.3σ (SM)

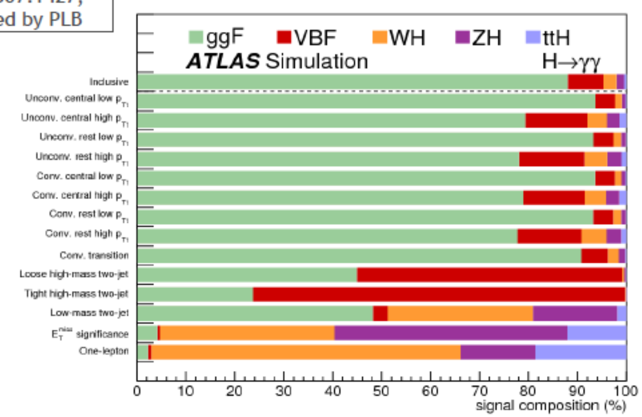




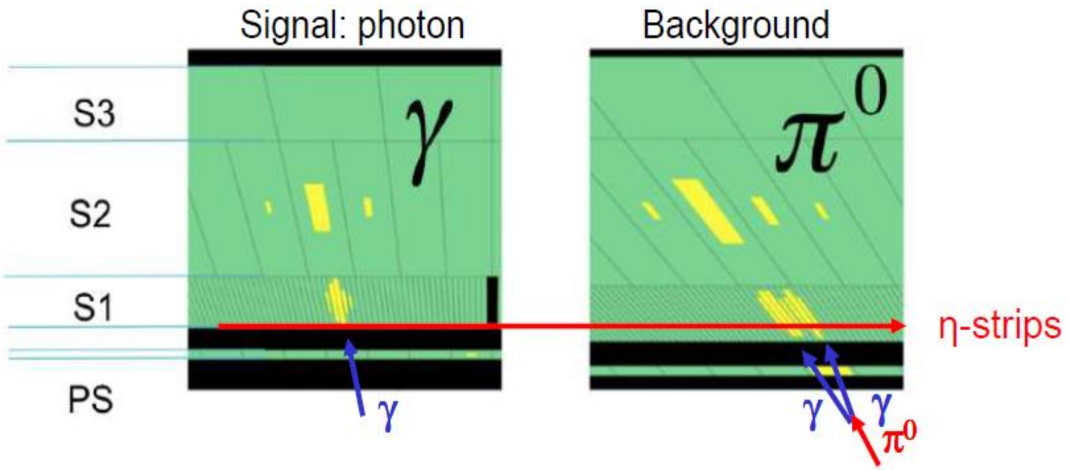
arXiv:1307.1427, accepted by PLB

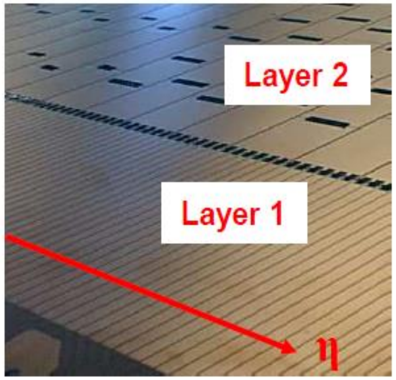


Subdivide into categories, including vector-boson fusion (VBF) and (W/Z)H (=VH) targeted selections



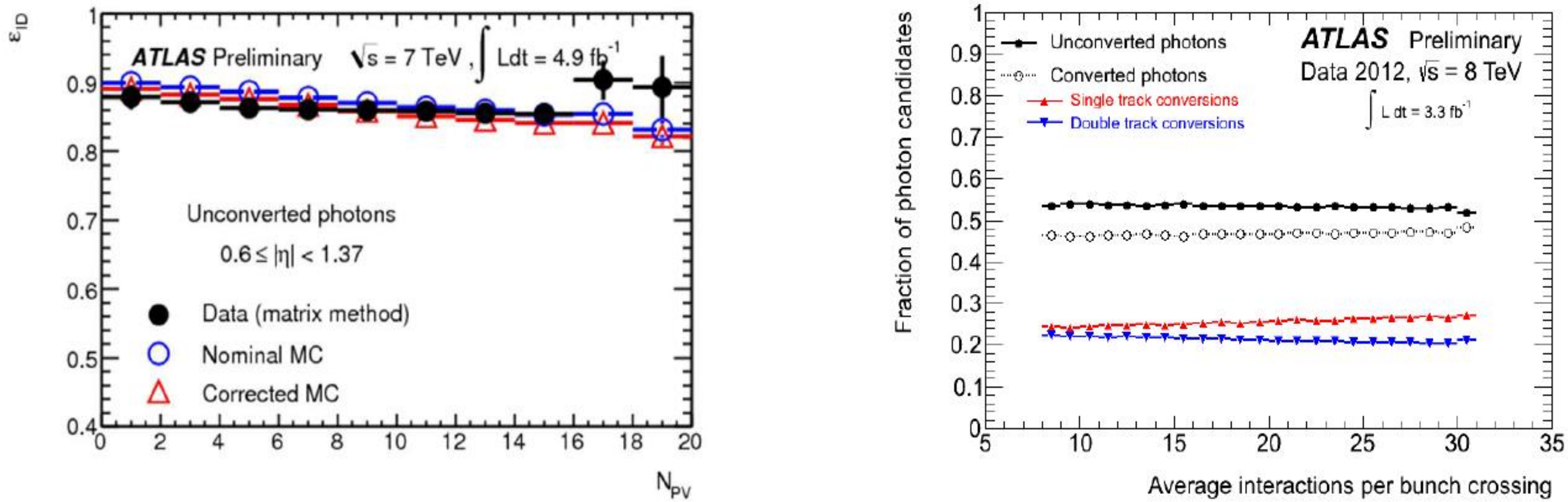
H->γγ: photon reco/identification



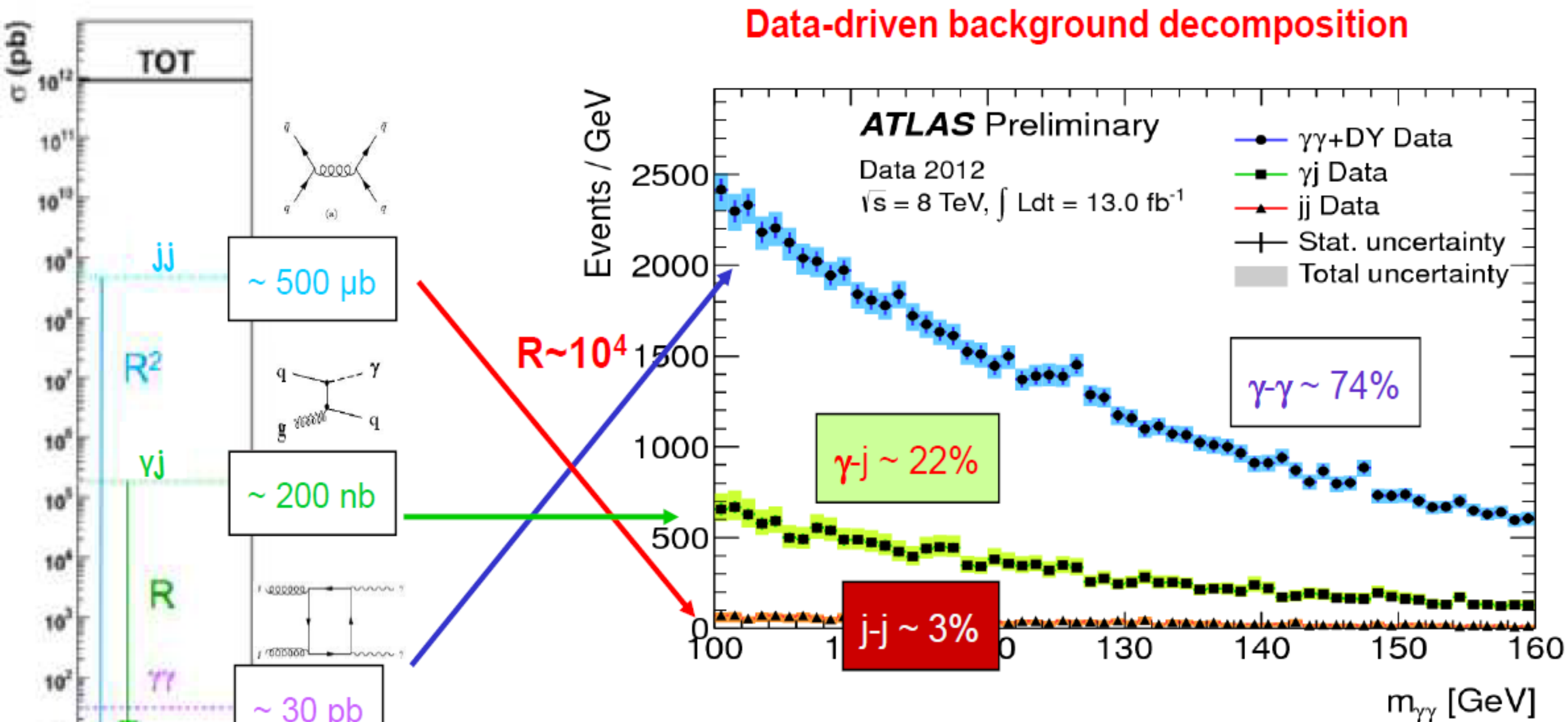


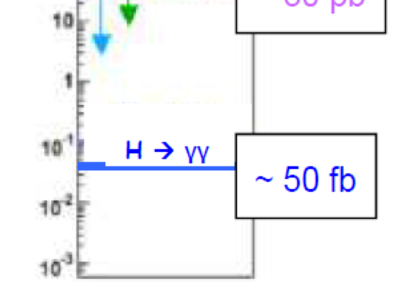
Identification efficiency (unconverted photons) vs pile-up

Fraction of converted photons vs pile-up



H->γγ: background rejection





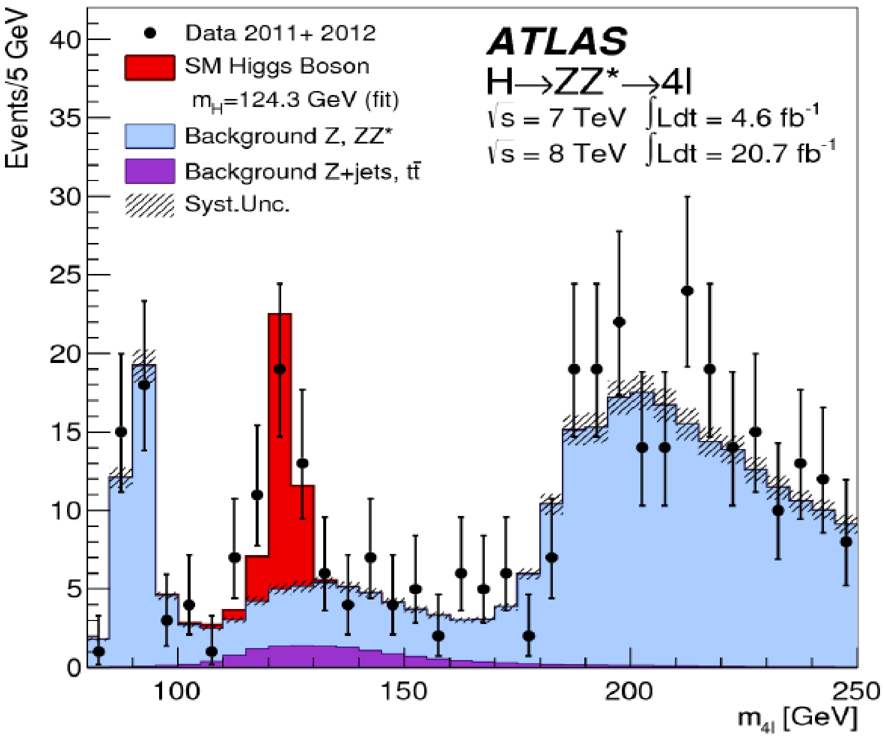
➔ Reducible background γ-jet and jet-jet largely below irreducible background γ-γ

▶ Remark 1: this decomposition is not directly used in the Higgs search: the background is extrapolated from data sidebands

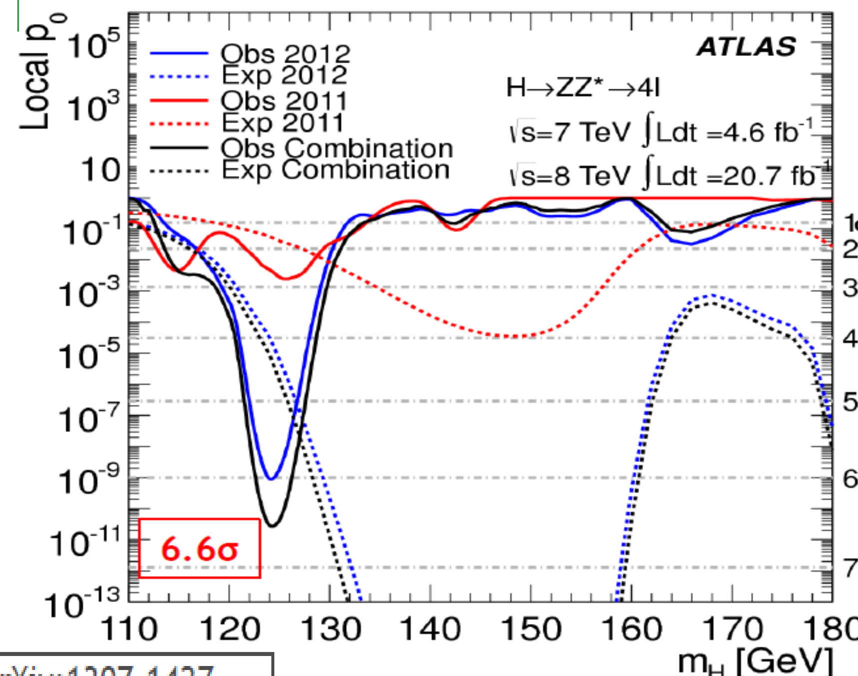
▶ Remark 2: Drell-Yan ~negligible for $m_{\gamma\gamma}$>100 GeV (~1%)

H->ZZ*->4l

“Golden” channel, high S/B, excellent mass resolution, but low statistics



Signal significance 6.6σ, expected 4.4σ (SM)



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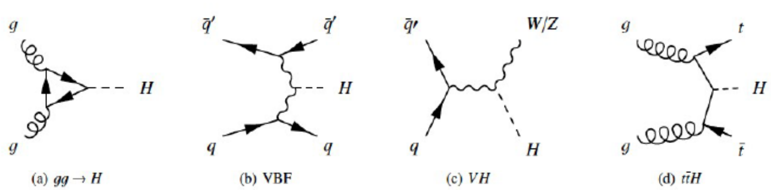
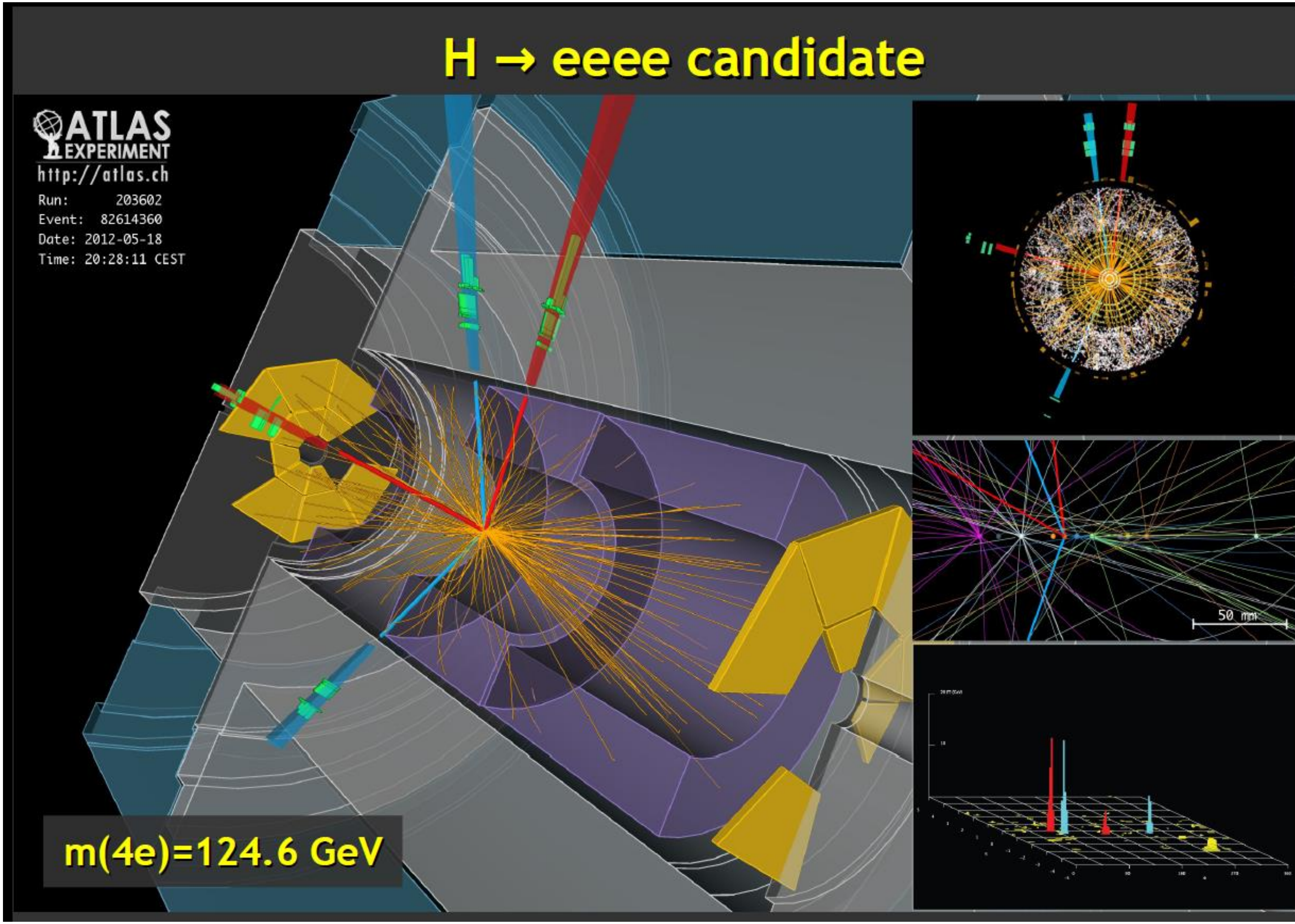
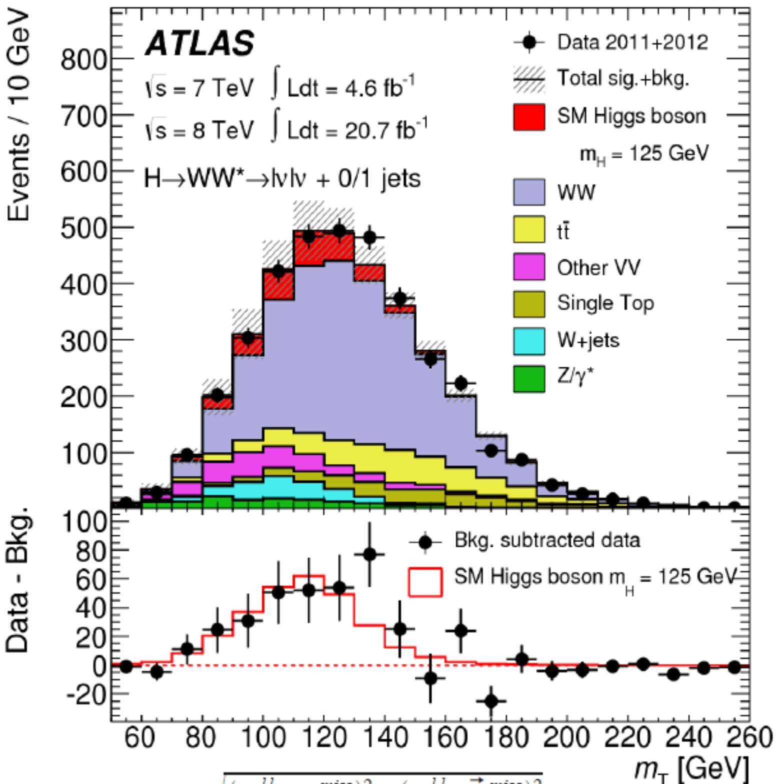


Again, categorisation of events to enhance VBF and VH sensitivity


H → eeee candidate
ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm
m(4e)=124.6 GeV

H->WW*->lνlν

Moderate statistics but poor mass resolution → poor S/B



$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (\vec{p}_T^{\,ll} + \vec{E}_T^{miss})^2}$$

Transverse mass distribution for e and μ, 0 or 1 jet

2 or more jets → strong VBF sensitivity

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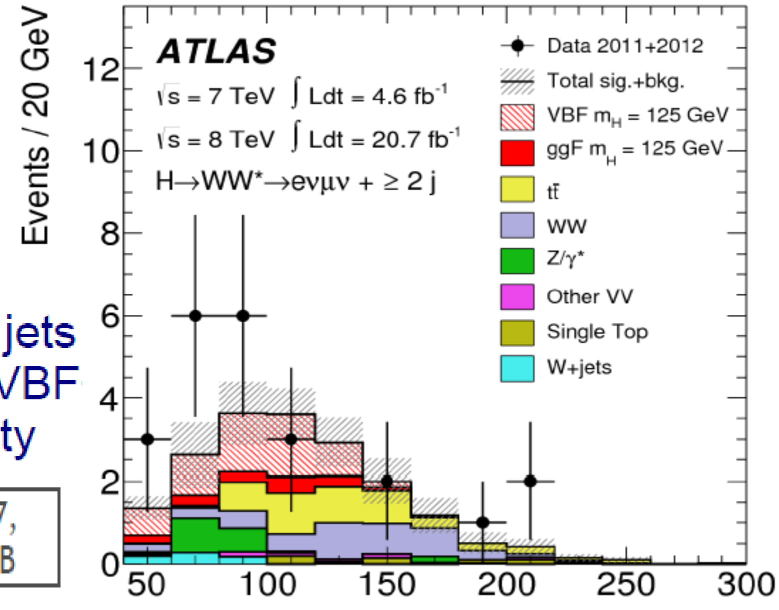

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (\vec{p}_T^{\,ll} + \vec{E}_T^{miss})^2}$$

Signal significance of 3.8σ at m_H=125.5 GeV, expect 3.8σ (SM)