Discovery of a Higgs boson with the ATLAS detector at the LHC

Takashi Kubota

The University of Melbourne

Seminario @ Università degli Studi Roma Tre

08/10/2013

THE UNIVERSITY OF MELBOURNE

ATLAS EXPERIMENT

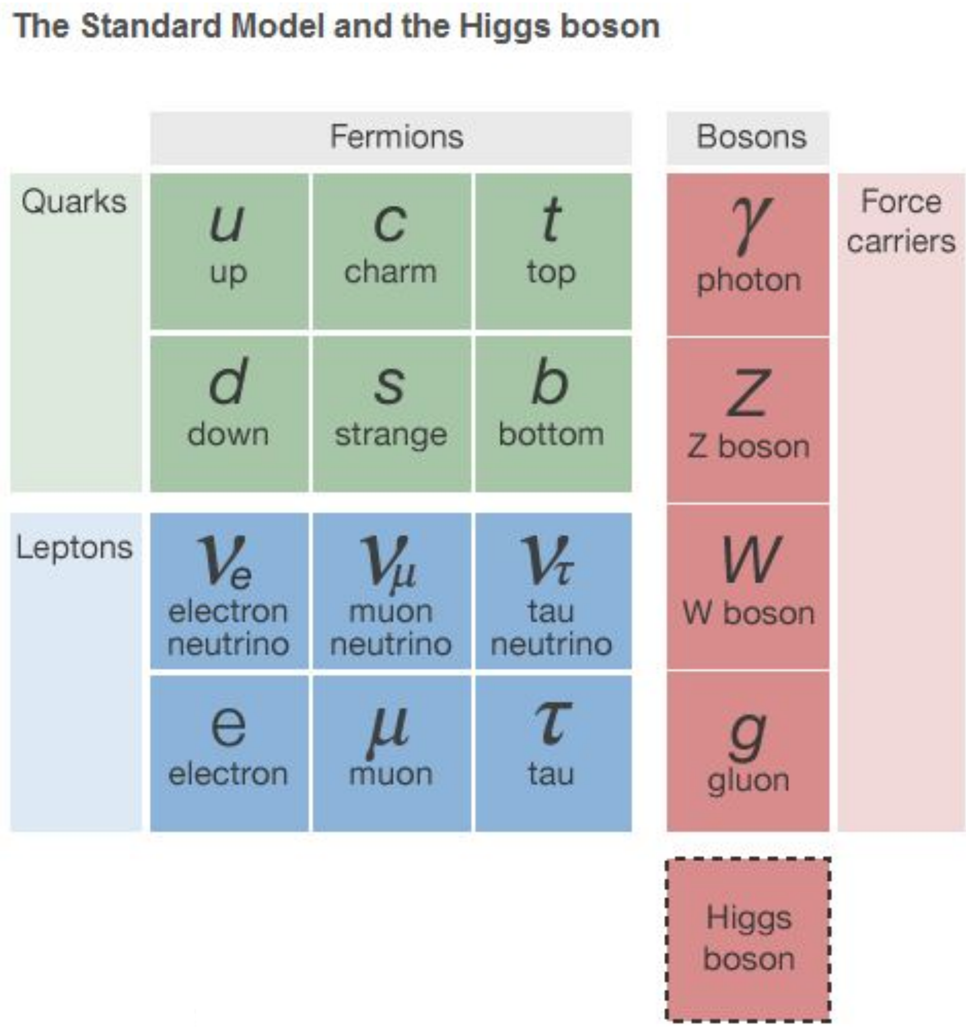
http://atlas.ch

Outline

- Introduction: Higgs boson
- Experimental overview
- Higgs boson couplings & mass measurement
  - Most of items are from *Phys. Lett. B* 726 (2013), pp. 88-119
- Higgs boson spin & parity measurement
  - Most of items are from *Phys. Lett. B* 726 (2013), pp. 120-144

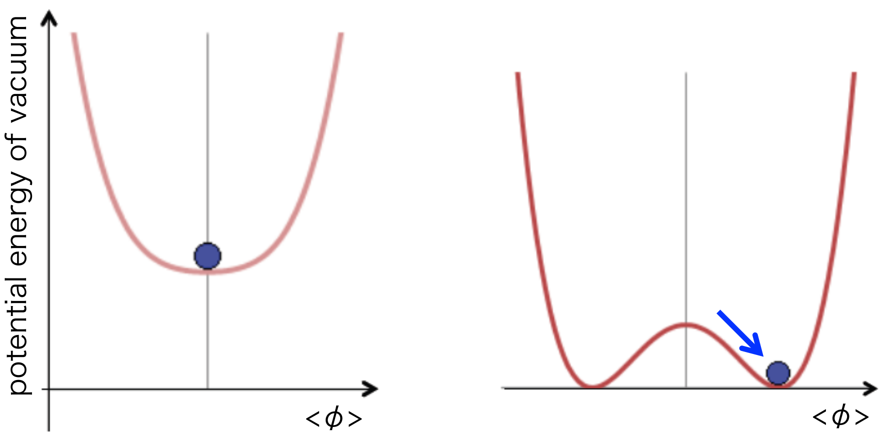
Higgs boson

- The quantum of the Higgs field, which has been introduced in 1960's
- Origin of elementary particles' mass
- Last missing piece of the standard model of elementary particle physics

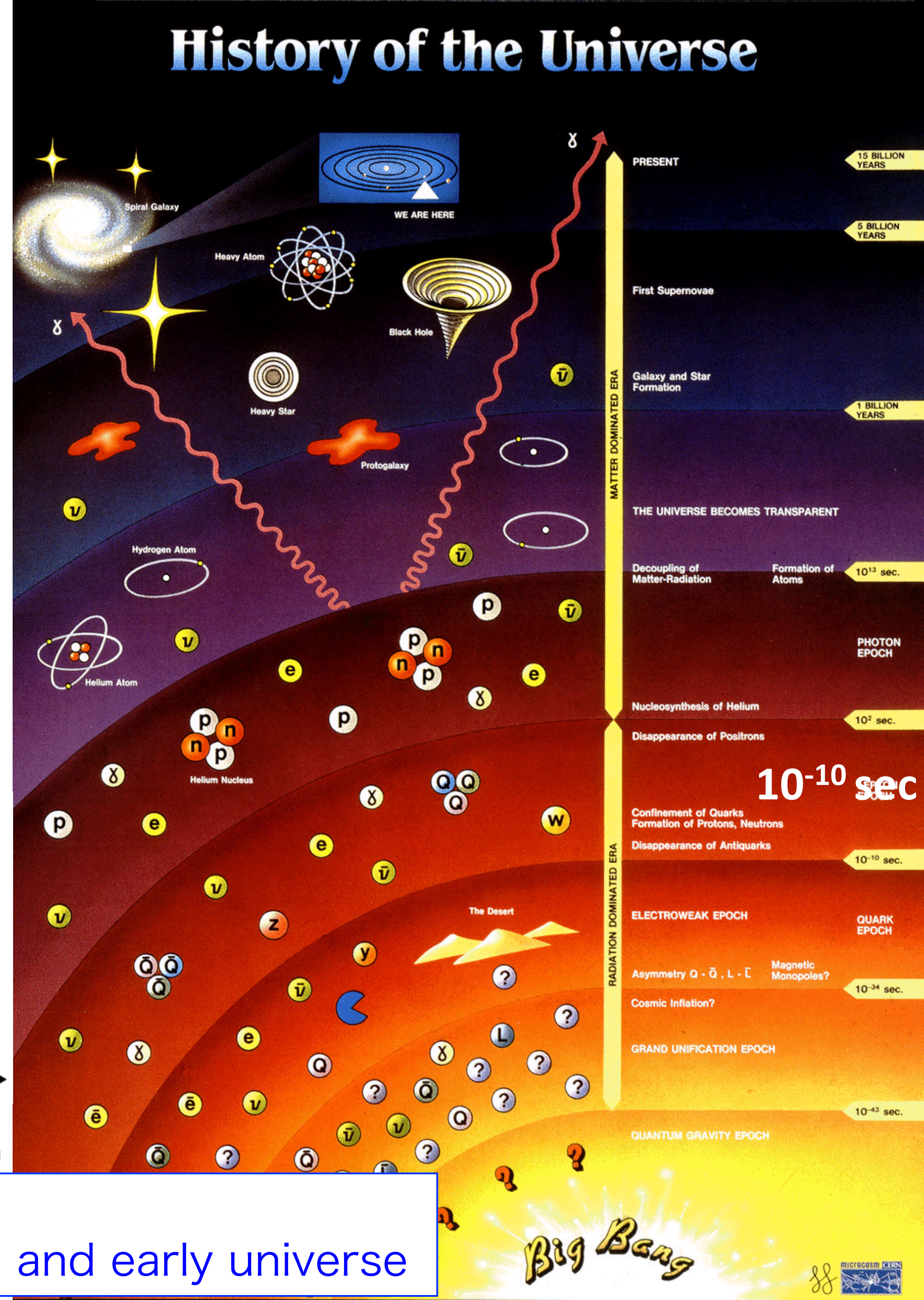


Significance

- Elementary particles are intrinsically massless
- Acquire ‘apparent mass’ through interaction with the vacuum (Higgs field)
- Phase transition of the vacuum 10^{-10} seconds after the birth of the universe



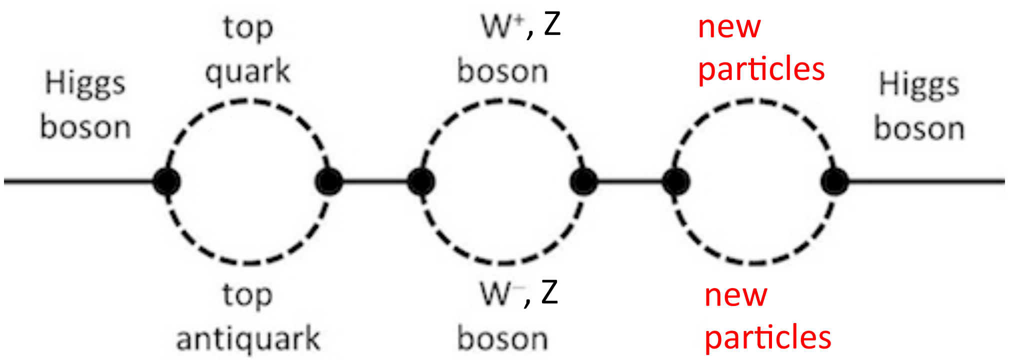
<ϕ> : Higgs expectation value in vacuum



discovery of the Higgs boson
= new paradigm of study of vacuum and early universe

Significance

Higgs properties are important probes to new physic in higher energy.
For example, mass.



$m_H(\text{obs.})^2 = m_H(\text{theory})^2 + [k\Lambda]^2 \times [m_Z^2 + 2\times m_W^2 + m_H(\text{theory})^2 - 4\times m_{top}^2 + (\text{new phys})]$

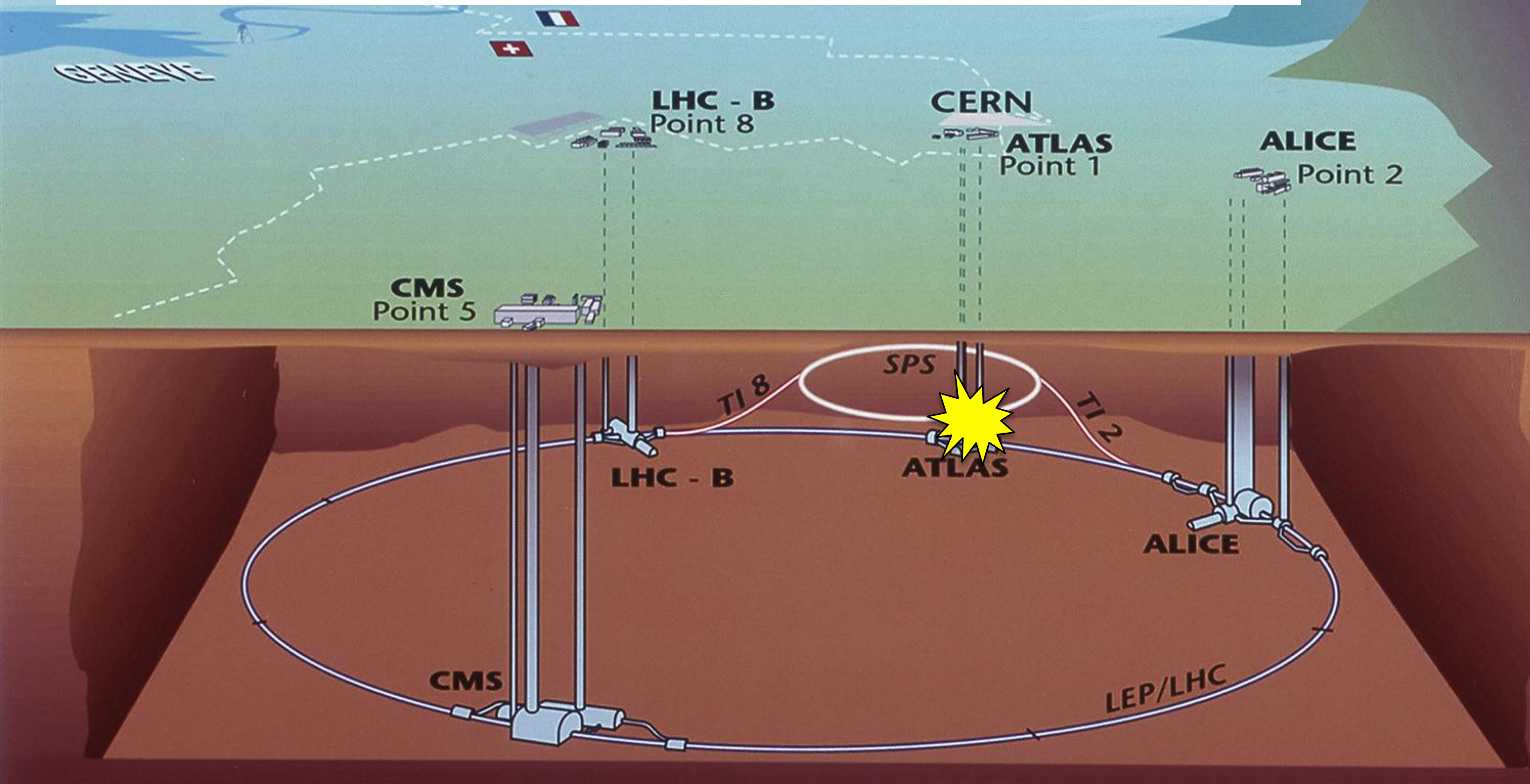
Experimental Overview

Overall view of the LHC experiments.

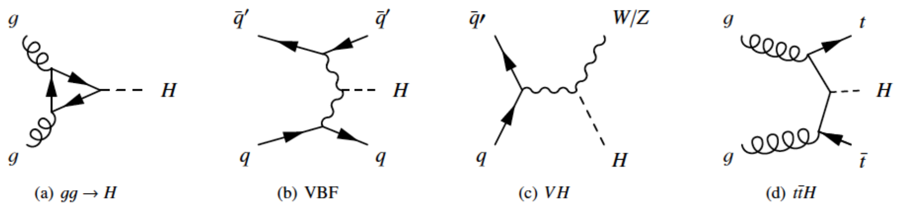
The LHC : proton-proton collider with the world highest energy:

- $\sqrt{s}$ = 7 TeV (2011)
- $\sqrt{s}$ = 8 TeV (2012)

Four experiments: ATLAS, CMS, LHCb, ALICE

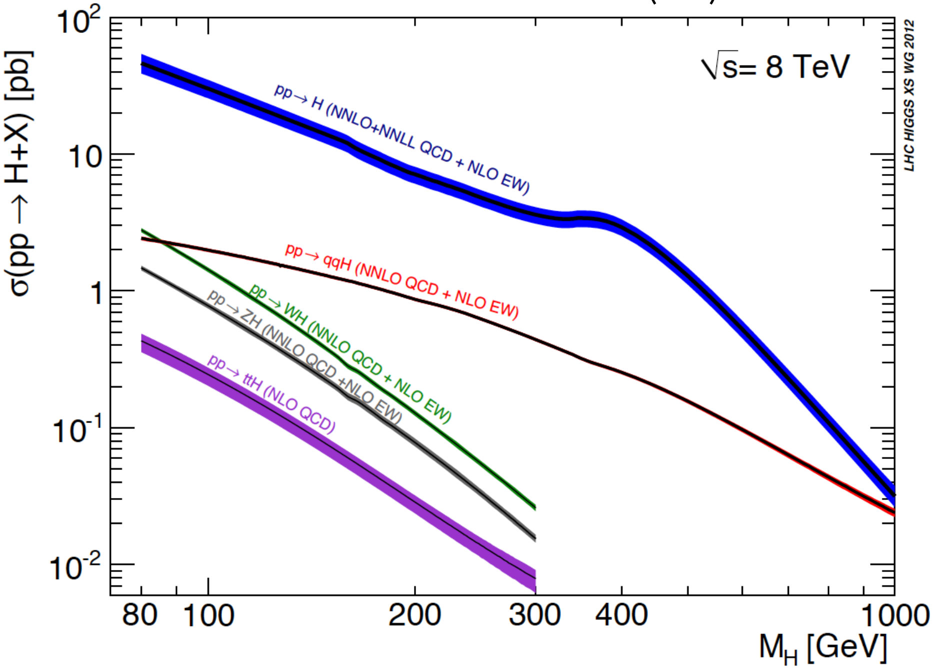


Higgs production and decay

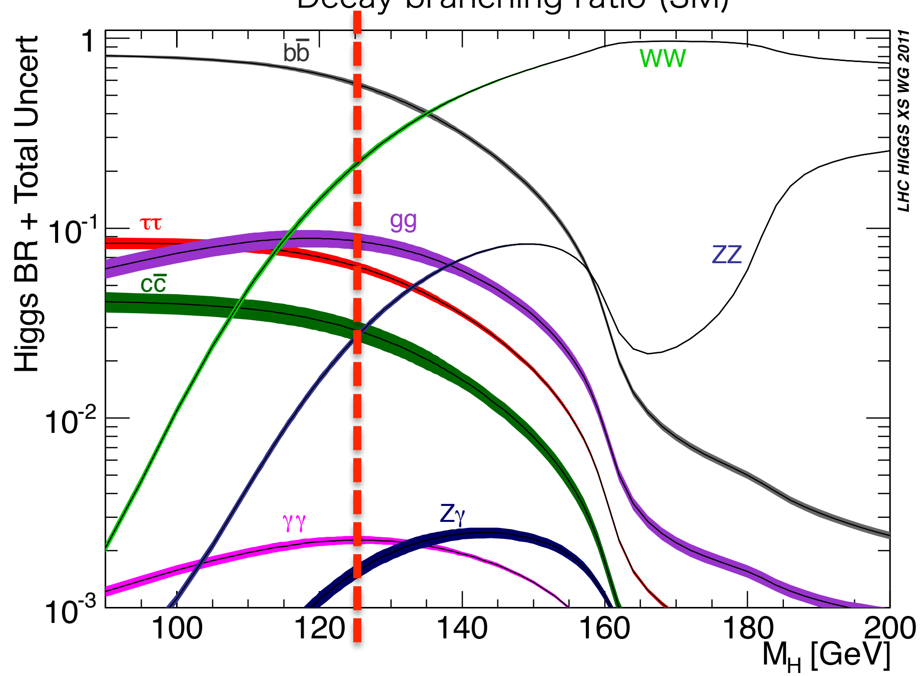


@ m_H=125 GeV:
bb: 58%, ττ: 6.3%
WW: 22%, ZZ: 2.6%, γγ: 0.2%

Production cross section (SM)



Decay branching ratio (SM)



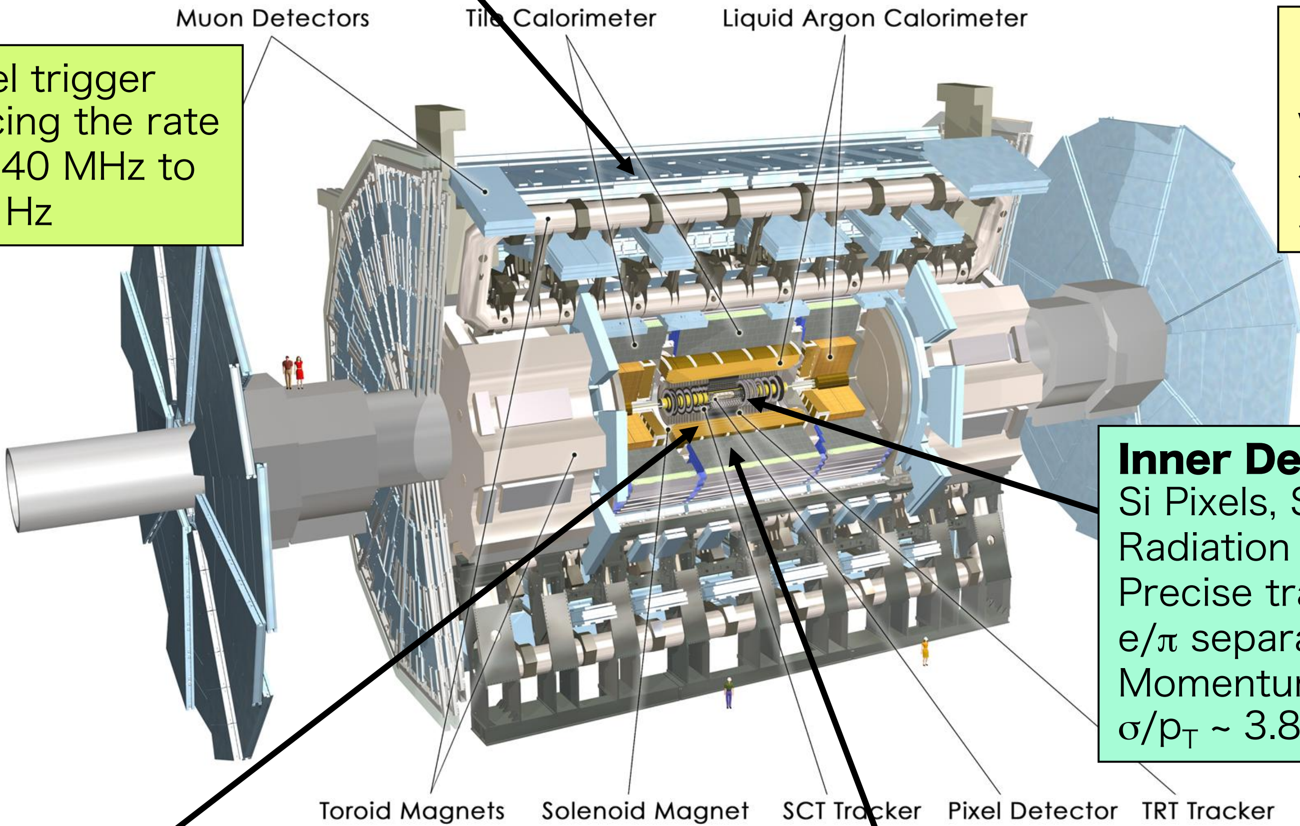
- Four main productions: ggF, VBF, VH, ttH
  - ggF dominates: ~ 20 pb @ m_H = 125 GeV
  - VBF, VH gives clean experimental signature
- Three sensitive decay modes: γγ, ZZ, WW

ATLAS experiment

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_{μ} ~ 1 TeV

3-level trigger reducing the rate from 40 MHz to ~200 Hz

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

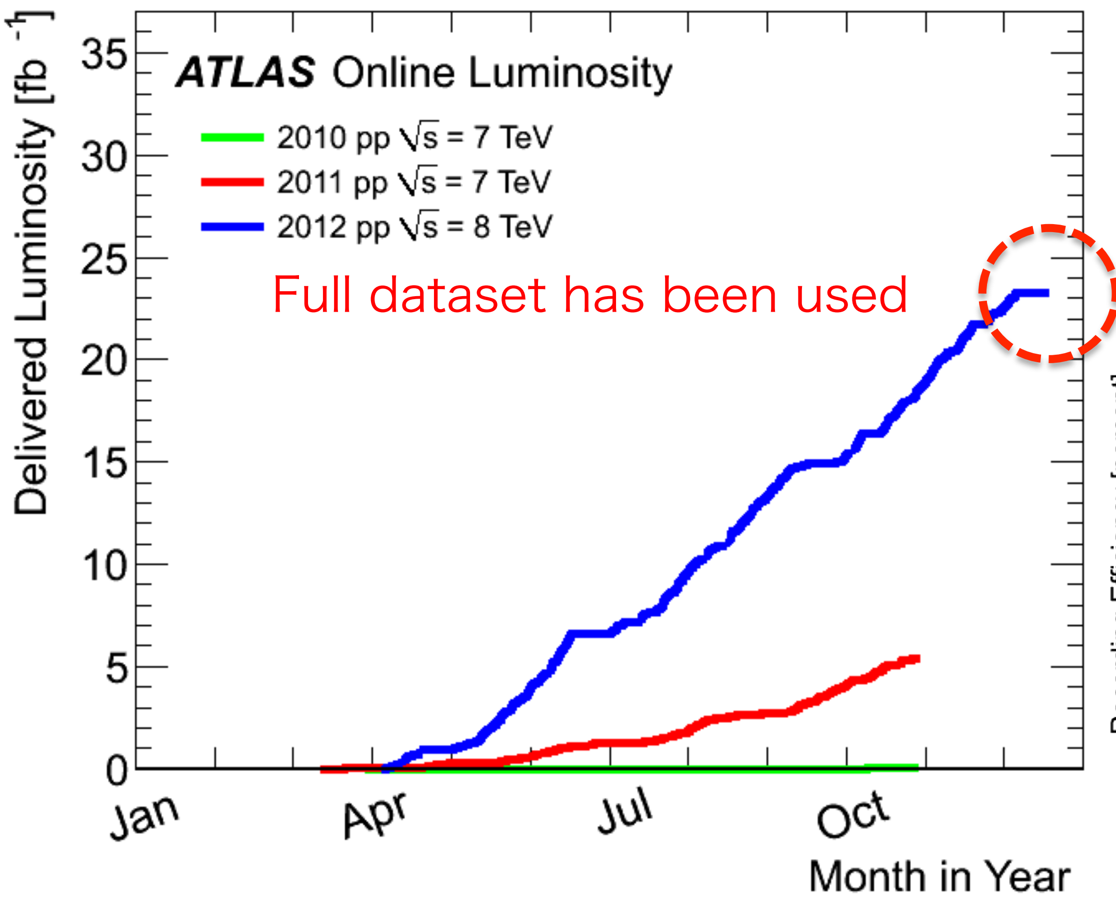


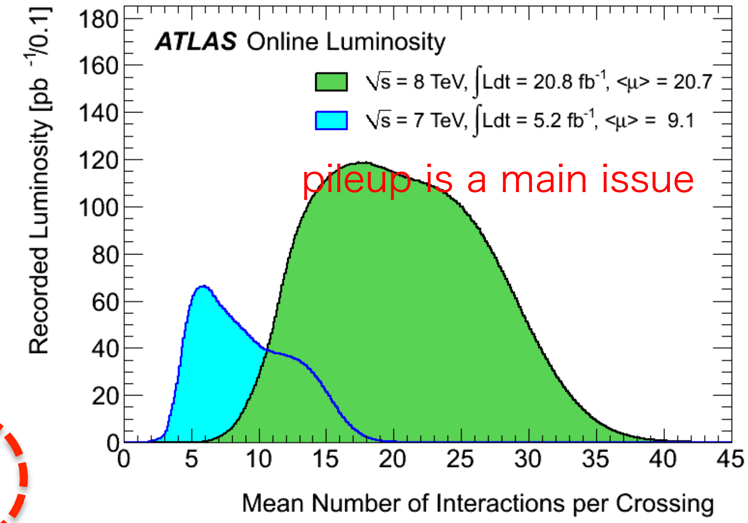
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\mathrm{GeV}) \oplus 0.015$

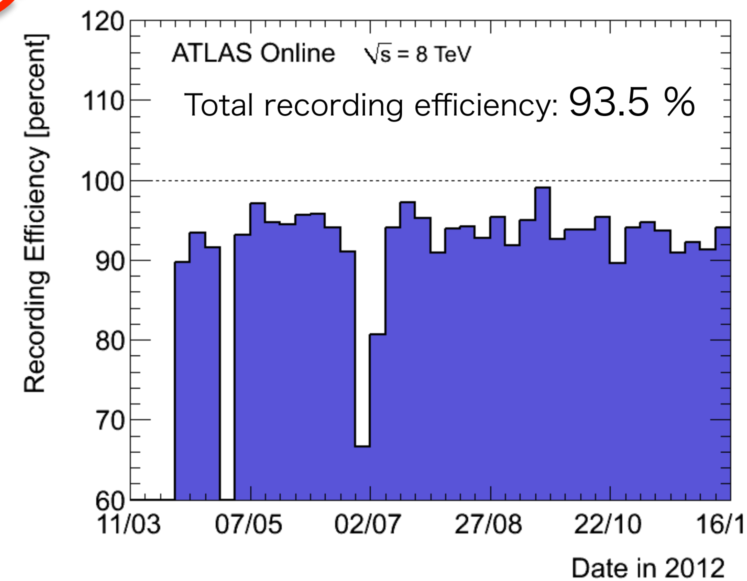
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Luminosity



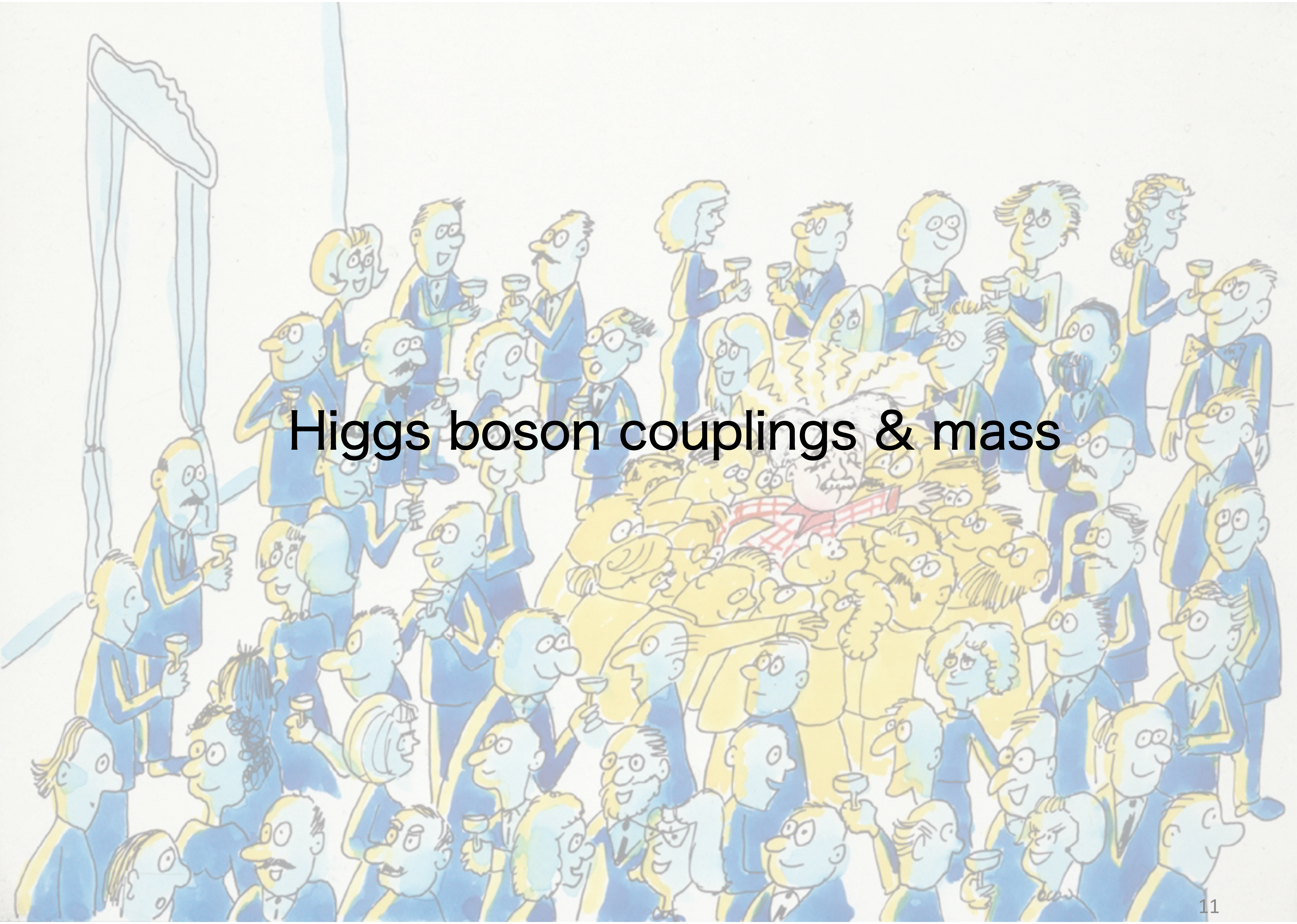




- Total luminosity for physics analysis: ~ 25 fb^{-1}
  - 20.7 fb^{-1} (2012)
  - 4.7 fb^{-1} (2011)

(order of) 10^5 Higgs bosons have been recorded

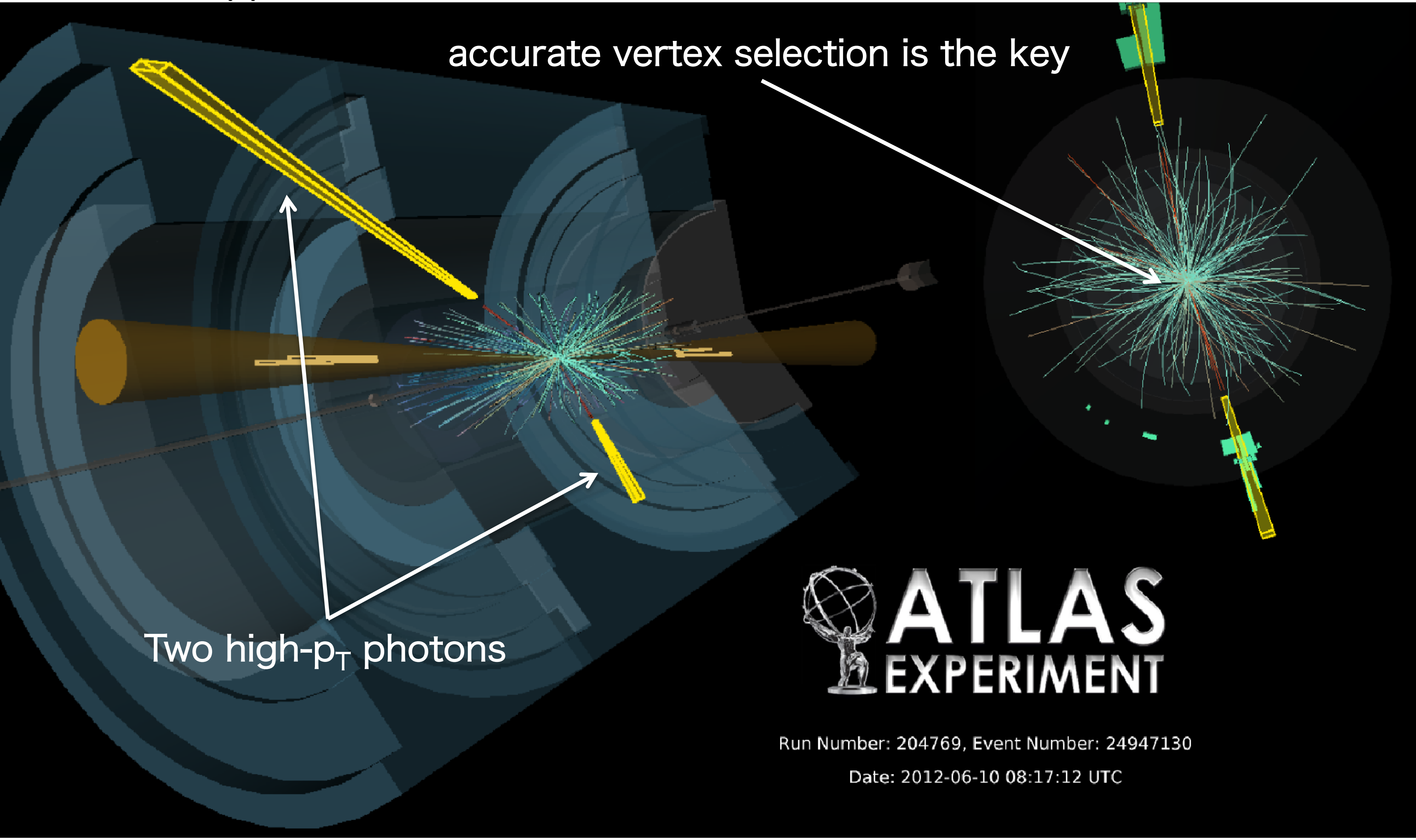
Higgs boson couplings & mass

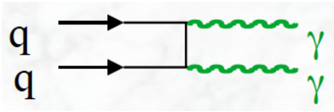


Overview of mass & coupling measurements

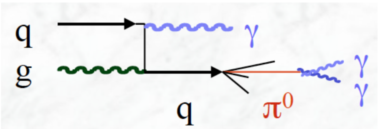
- Results of gauge boson decays: $\gamma\gamma$, WW, ZZ
  - Overview of the analyses
  - Higgs boson search
  - Mass measurement
  - Coupling measurement

$H \to \gamma\gamma$





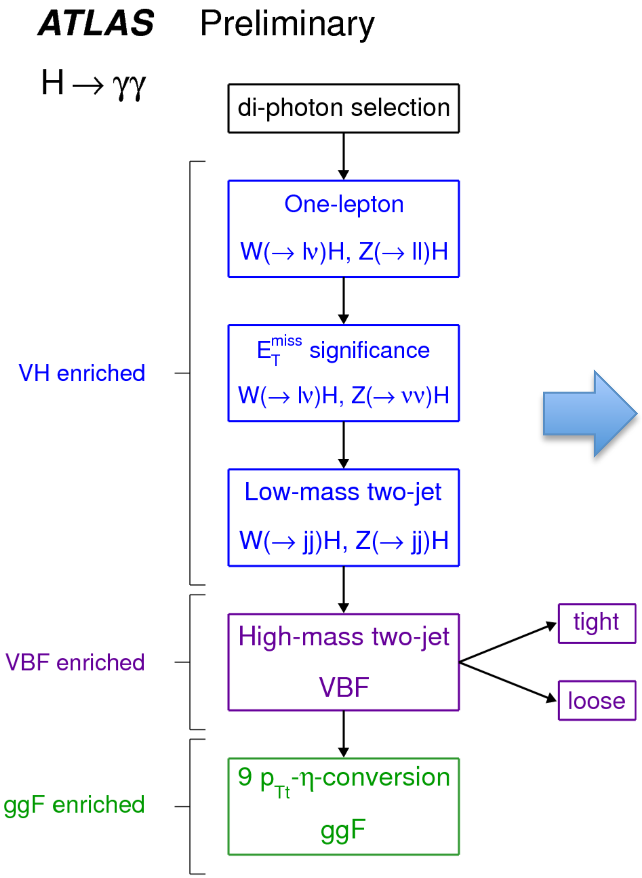
non-resonant $\gamma\gamma$
(irreducible bkg.)



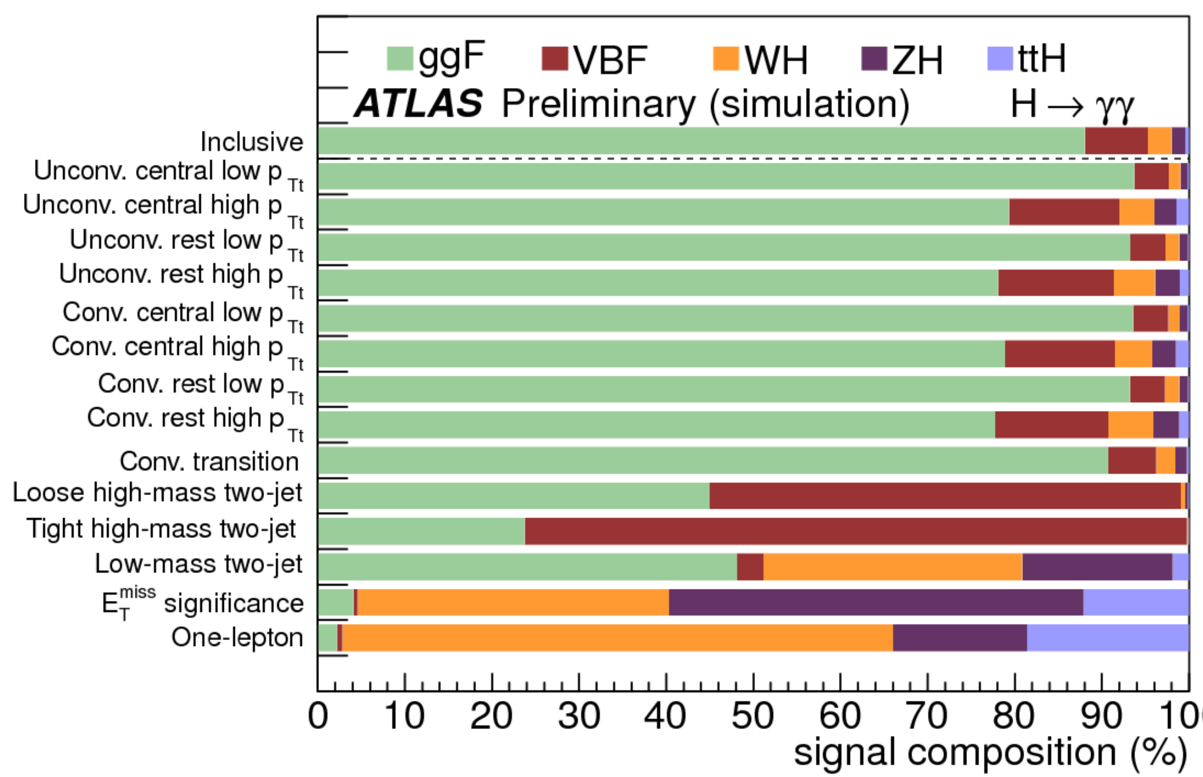
jet faking photons
(reducible bkg.)

H → γγ

- p_T > 40 (30) GeV for (sub) leading photon
- Vertex selection combining tracks and photon pointing with NN
- Event categorization to enhance sensitivity (independent background estimation etc.)



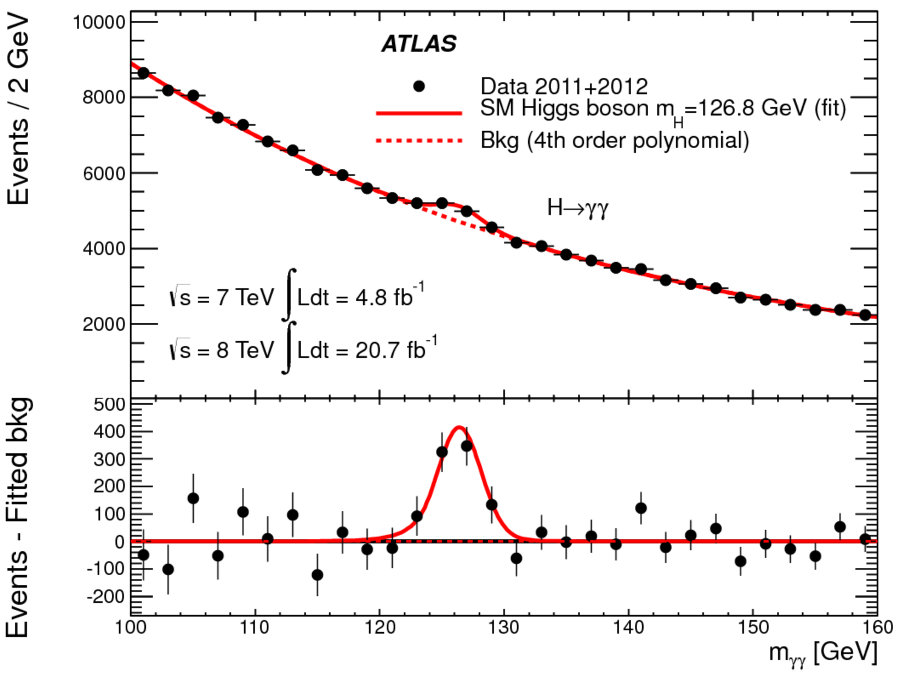
ATLAS-CONF-2013-012



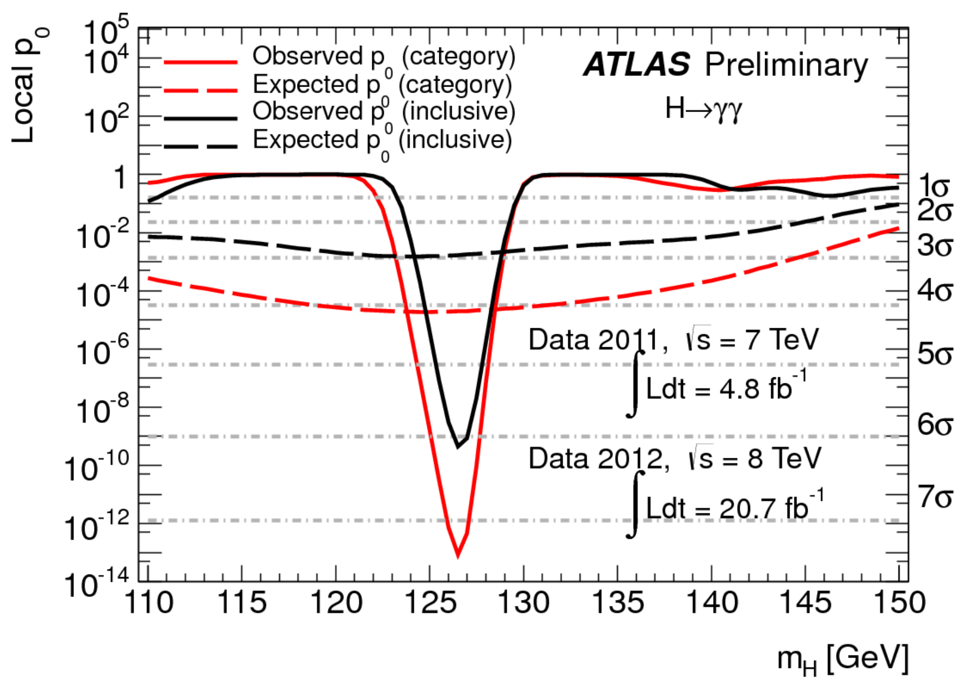
ATLAS-CONF-2013-012

$H \to \gamma\gamma$

- A significant excess at m_H = 126.8 ± 0.2(stat) ± 0.7(syst) GeV
  - 7.4 σ (observed)
  - 4.3 σ (expected)
- Establishes the discovery of a new particle in γγ channel alone

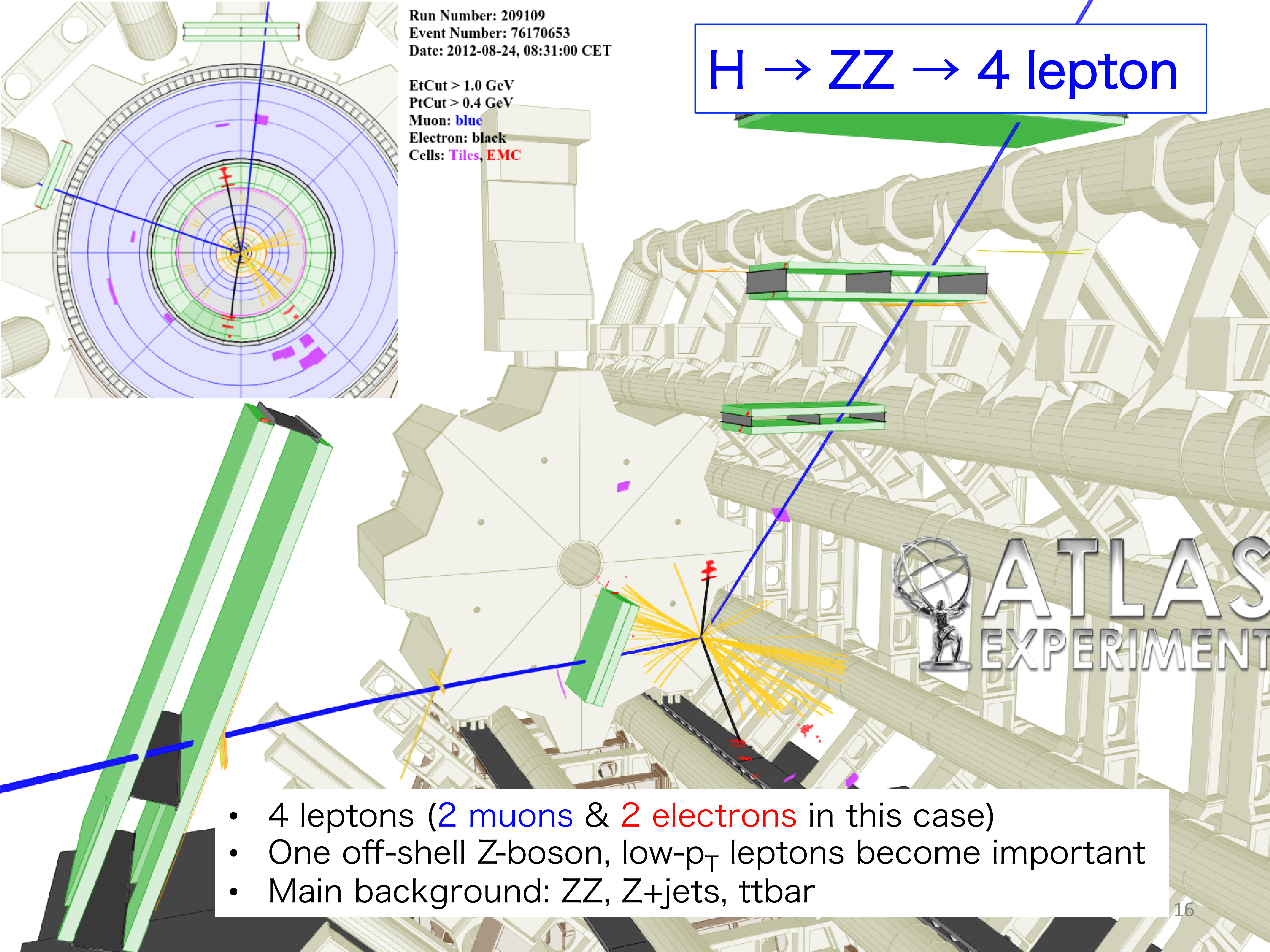


ATLAS-CONF-2013-012



$\sigma(m_{\gamma\gamma})$ ranges from 1.4 GeV to 2.5 GeV (depending on categories)

H → ZZ → 4 lepton



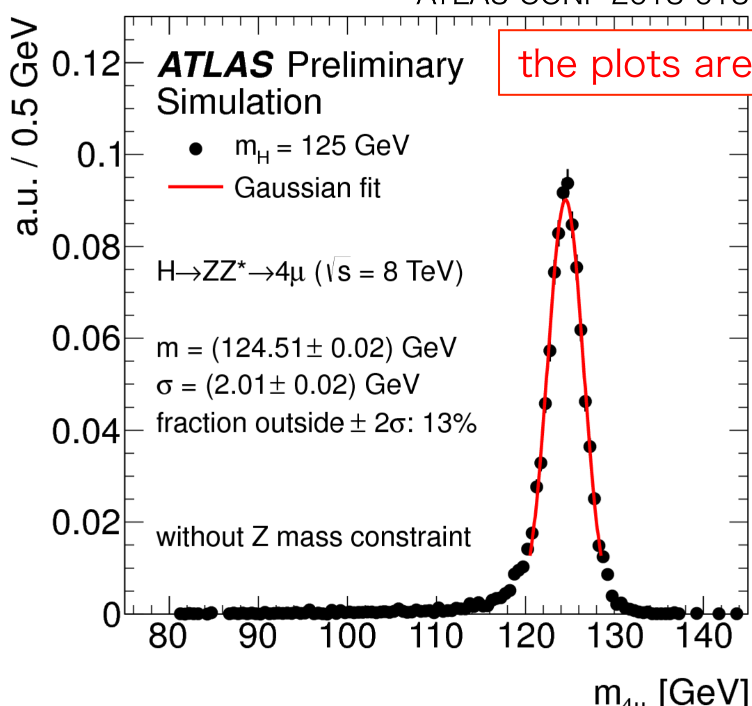
- 4 leptons (2 muons & 2 electrons in this case)
- One off-shell Z-boson, low-p_T leptons become important
- Main background: ZZ, Z+jets, ttbar

$H \to ZZ \to 4$ lepton

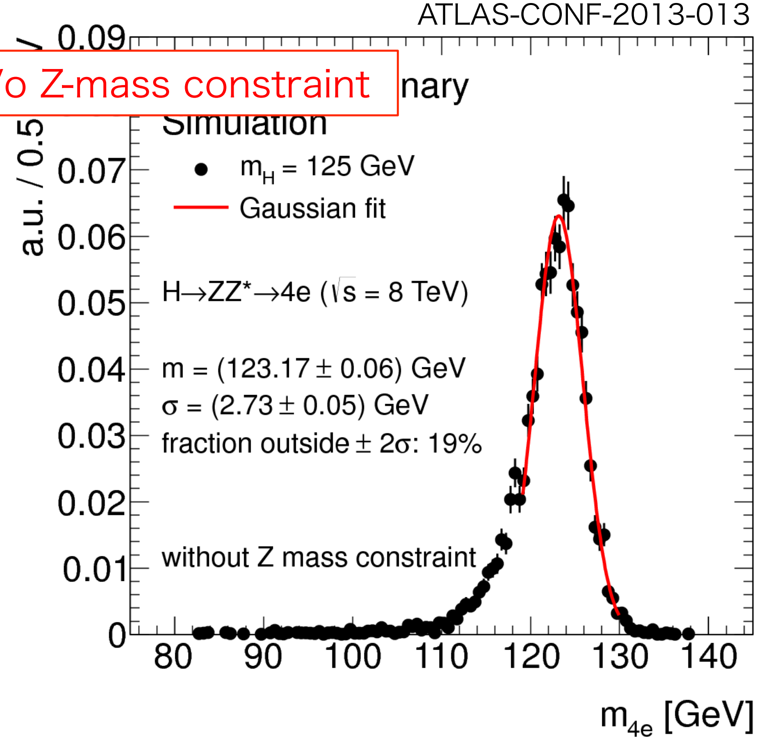
- Require four isolated leptons
  - μ: $p_T > 20, 15, 10, 6$ GeV in $|\eta| < 2.7$, $d_0 < 1$ mm
  - e: $p_T > 20, 15, 10, 7$ GeV in $|\eta| < 2.47$, $d_0 < 1$ mm
- One lepton pair with Z consistent mass: $50 < m_{12} < 115$ GeV
- One lepton pair with $m_{min} < m_{34} < 115$ GeV ($12 < m_{min} < 50$ GeV)
- Higgs mass reconstructed as m_{4l} (Z mas constraint on m_{12})

$\sigma(m_{4\mu})$ ~ 1.6 GeV $\sigma(m_{4e})$ ~ 2.4 GeV

ATLAS-CONF-2013-013



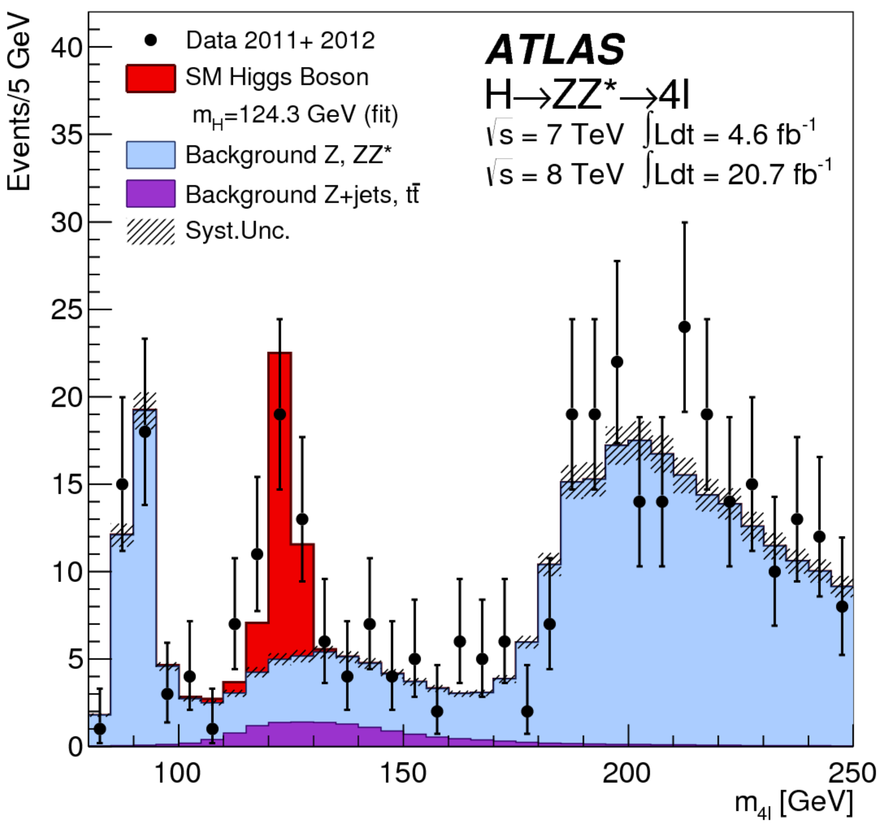
ATLAS-CONF-2013-013



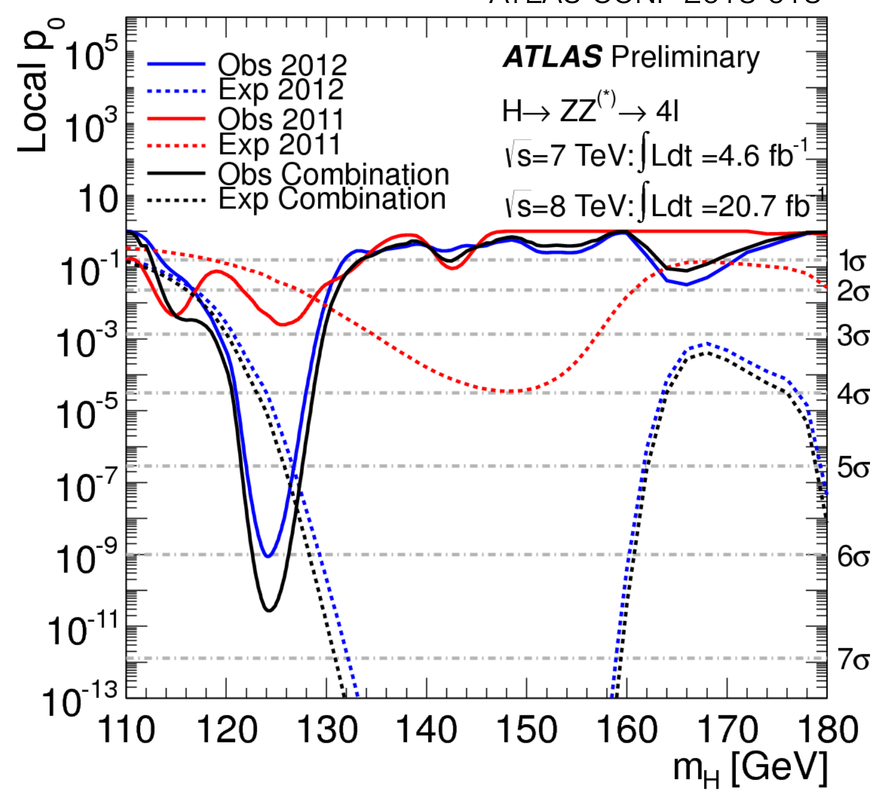
the plots are w/o Z-mass constraint

H → ZZ → 4 lepton

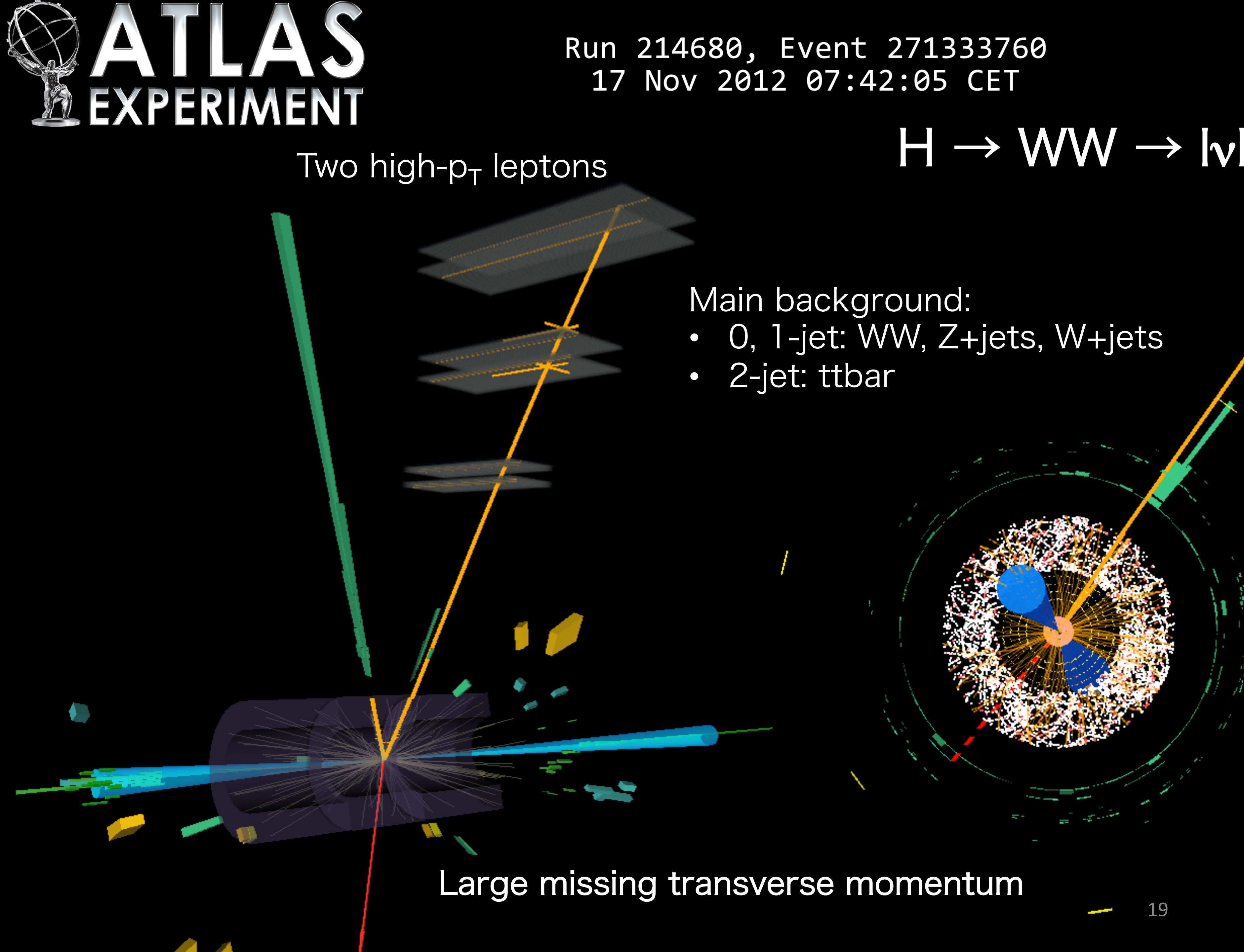
- a significant excess at $m_H = 124.3^{+0.6}_{-0.5}\,(\text{stat})^{+0.5}_{-0.3}\,(\text{syst})\,\text{GeV}$
  - 6.4 σ (observed)
  - 4.4 σ (expected)
- Establishes the discovery of a new particle in ZZ channel alone



ATLAS-CONF-2013-013



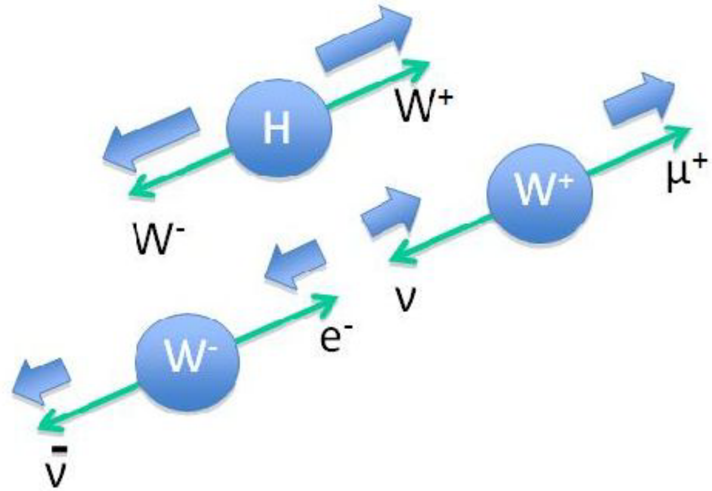
H → WW → lνl



Main background:

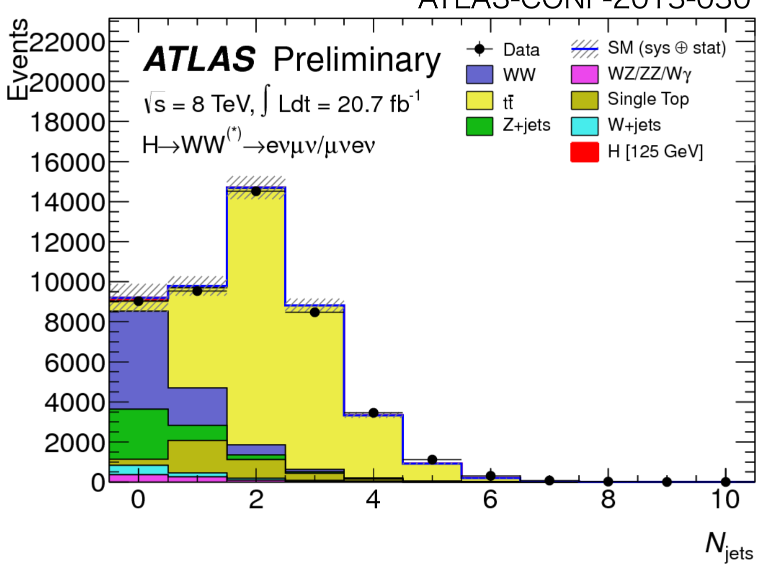
- 0, 1-jet: WW, Z+jets, W+jets
- 2-jet: ttbar

$H \rightarrow WW \rightarrow l\nu l\nu$

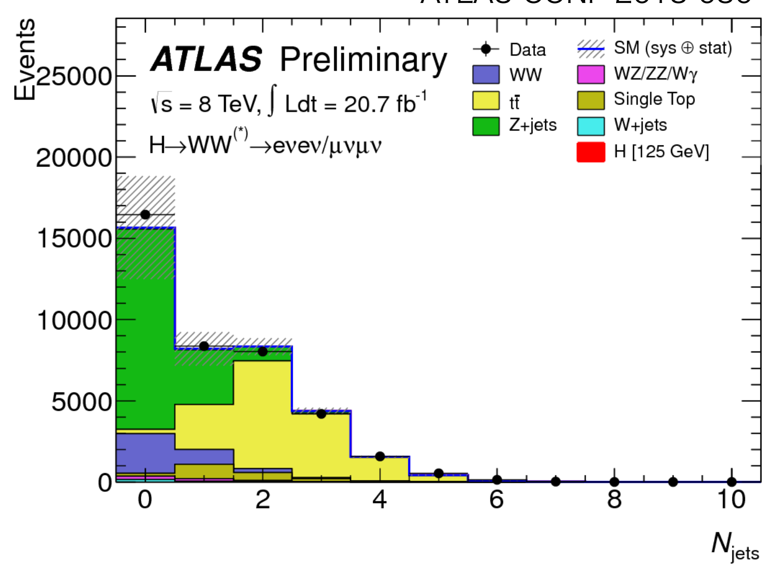


- Require two isolated leptons
  - p_T > 25 (15) GeV for (sub) leading leptons
- Large missing transvers momentum (neutrino)
- Jet multiplicity dependent analysis
  - 0, 1-jet: ggF dominant
  - 2-jet: VBF dominant
- Utilize lepton kinematics
  - Lepton collimation (spin-0 Higgs + V-A nature of weak interaction)
  - Large angular separation from leptons to neutrinos
  - Transverse mass for final fit

ATLAS-CONF-2013-030



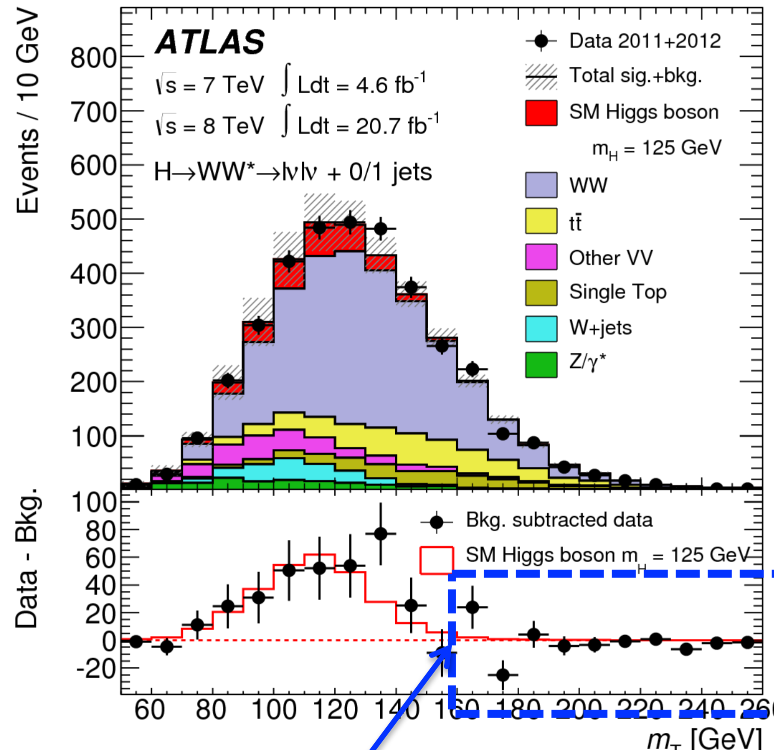
ATLAS-CONF-2013-030



$H \rightarrow WW \rightarrow l\nu l\nu$

- Dedicated background estimation for each lepton flavor/jet multiplicity

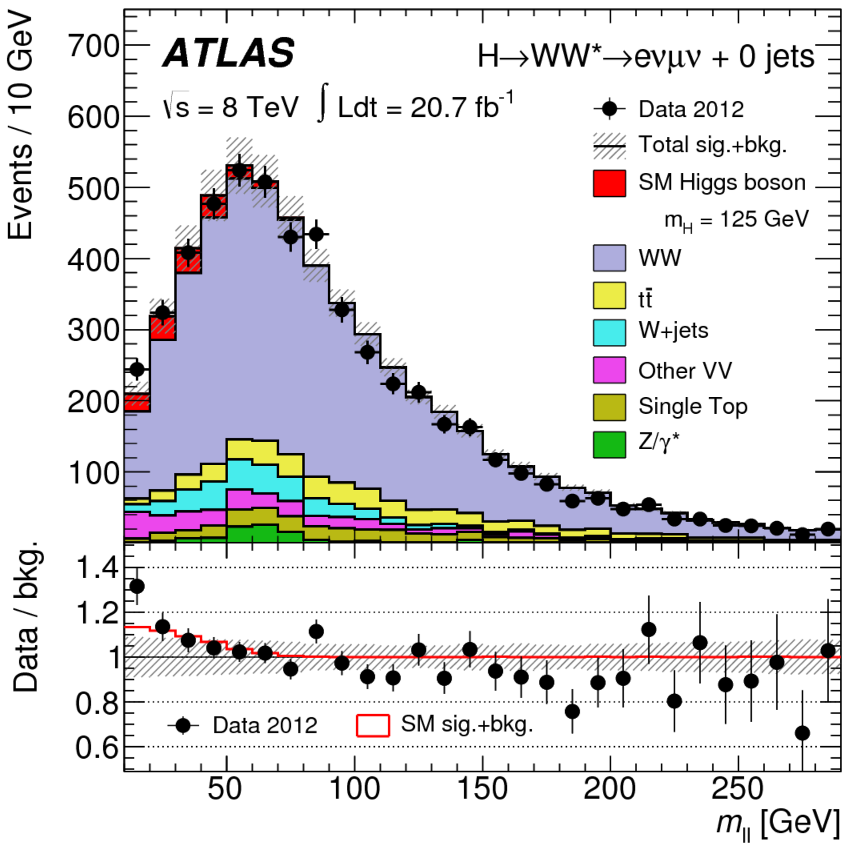
Channel	WW	Top	$Z/\gamma^* \rightarrow \tau\tau$	$Z/\gamma^* \rightarrow \ell\ell$	W+jets	VV
$N_{jet} = 0$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	Data	Data	MC + VR
$N_{jet} = 1$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	Data	Data	MC + VR
$N_{jet} \geq 2$						
$e\mu + \mu e$	MC	CR (merged)	CR	MC	Data	MC
$ee + \mu\mu$	MC	CR (merged)	CR ($e\mu + \mu e$)	Data	Data	MC



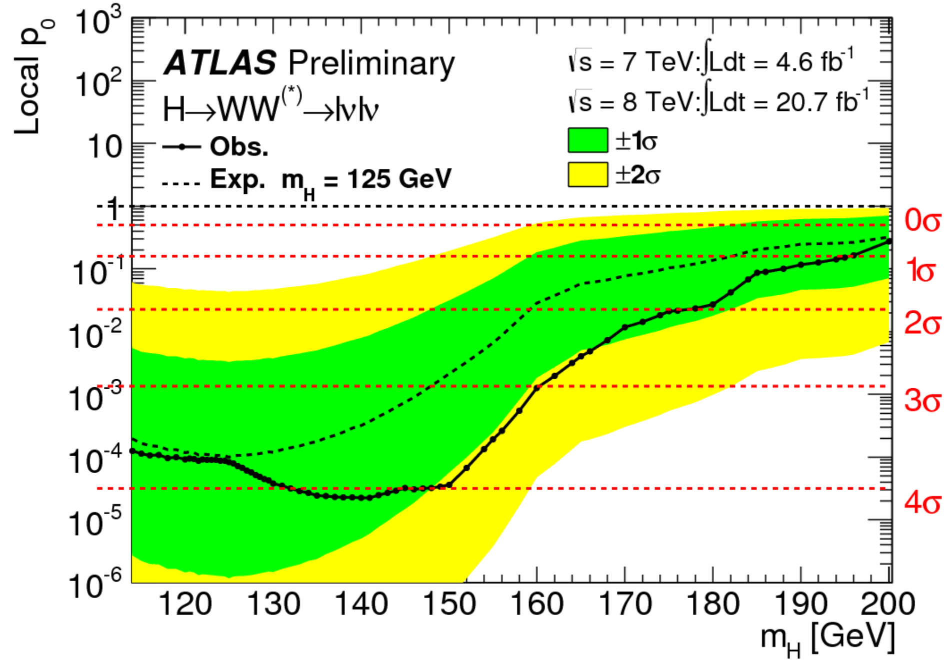
Signal depleted region (m_T > 150 GeV).
Background estimations work quite well

H → WW → lνlν

- Excess seen over wide m_{ll} range
- 3 to 4 σ level rejection of SM background only hypothesis



ATLAS-CONF-2013-030



Combined mass measurement

- Combined mass measurement with γγ and ZZ:

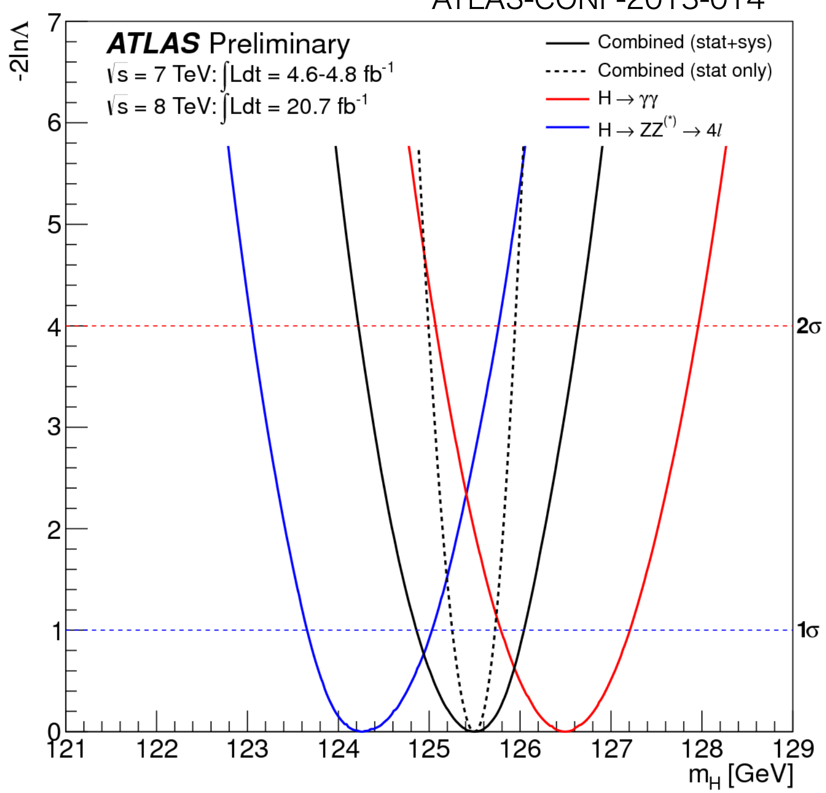
$$m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\;\text{GeV}$$

- Compatibility between γγ and ZZ:

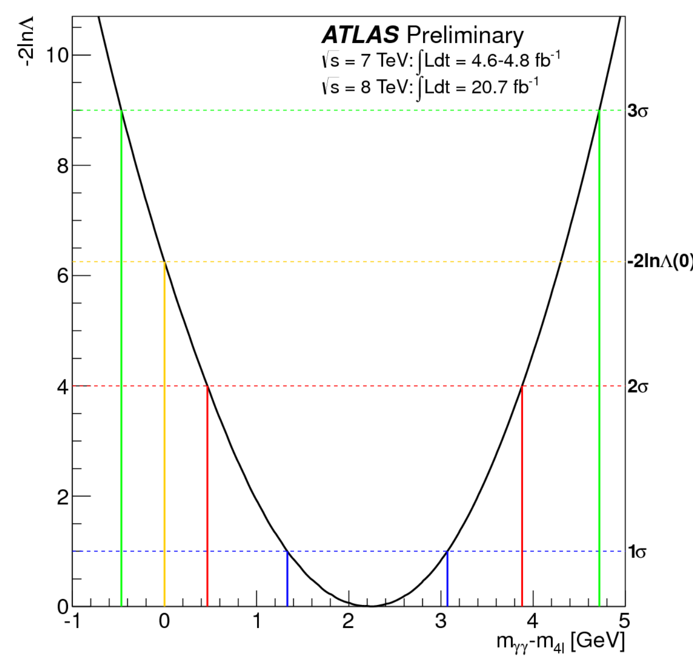
$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\;\text{GeV}$$

2.5 σ rejection of $\Delta m_H = 0$ hypothesis.
1.8 σ when if non-gaussian effect in e/γ energy calibration into account

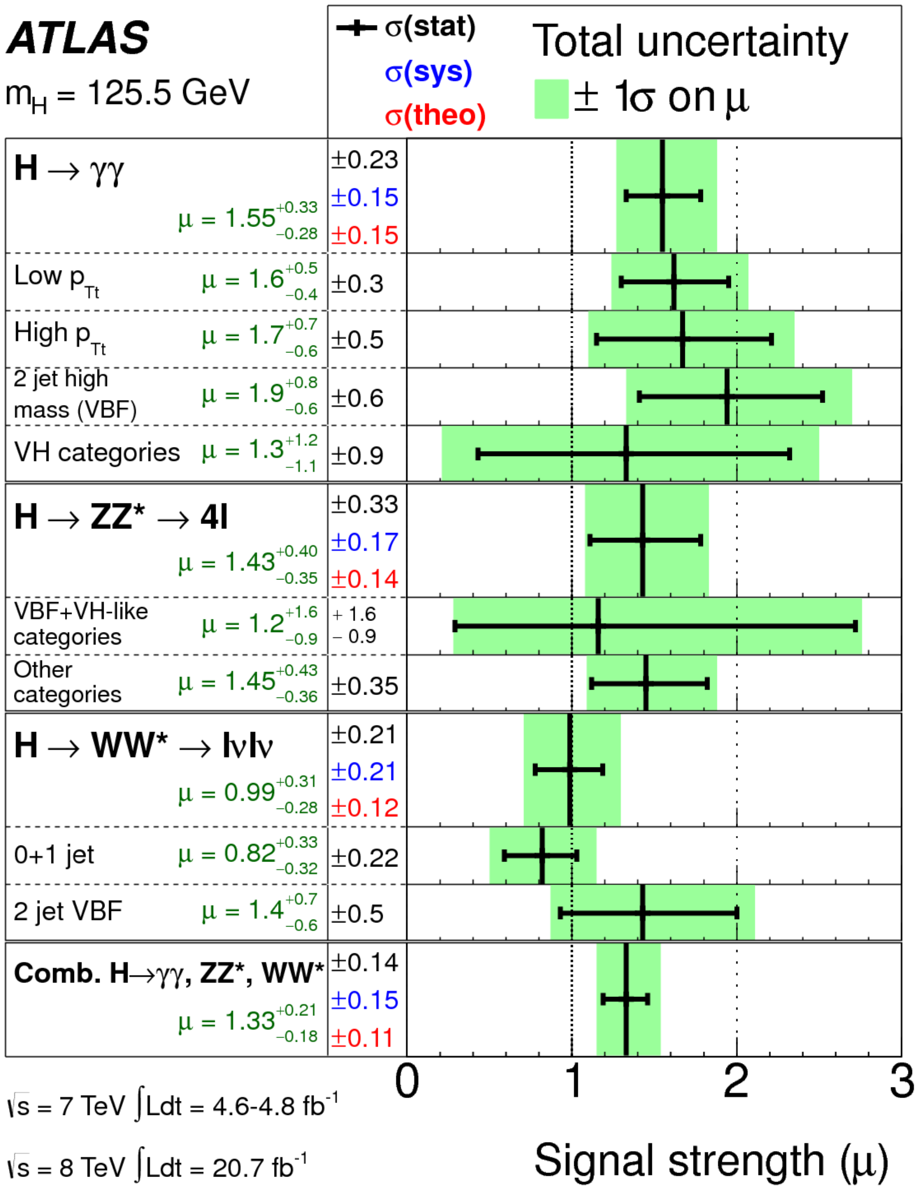
ATLAS-CONF-2013-014



ATLAS-CONF-2013-014



Signal strength measurements



- Global signal strength:

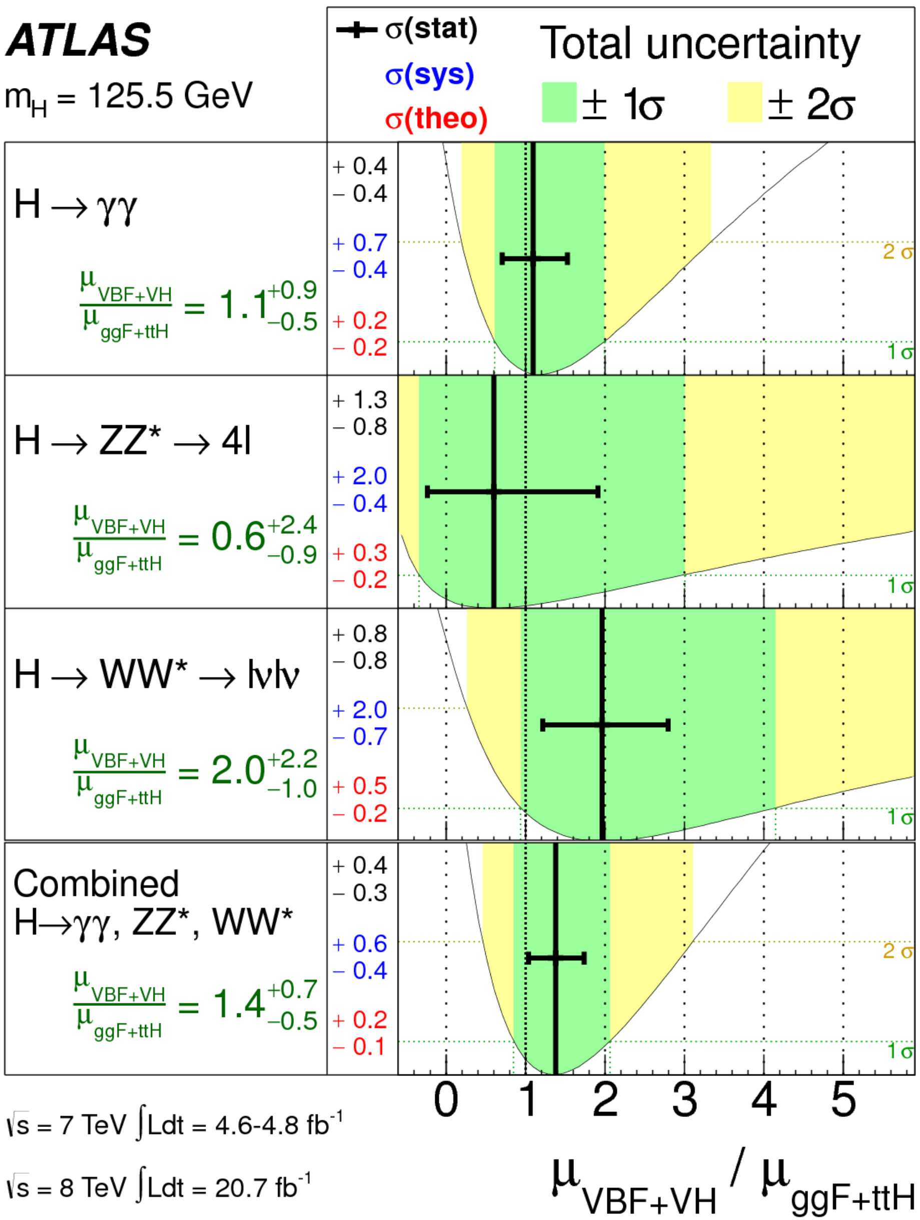
$$\mu = 1.33 \pm 0.14\,(\text{stat}) \pm 0.15\,(\text{sys})$$

- If preliminary results of $H\rightarrow bb$ and $H\rightarrow\tau\tau$ (13 fb^{-1}) are included:

$$\mu = 1.23 \pm 0.18$$

- Still, compatible with SM

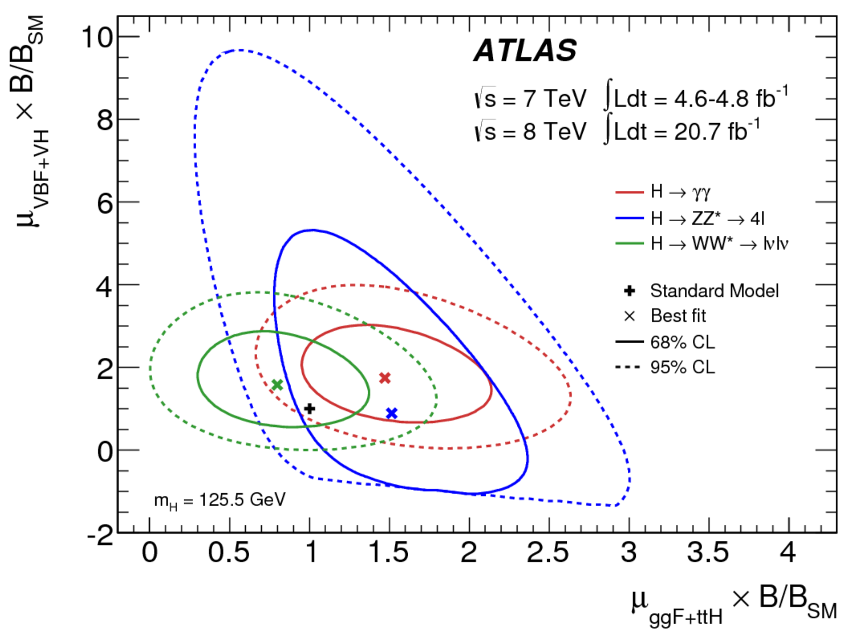
VBF production evidence



- The μ ratio between bosonic (VBF+VH) and fermionic (ggF+ttH) productions: 3 σ evidence of VBF production

$$\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.4}_{-0.3}\,(\text{stat})\,^{+0.6}_{-0.4}\,(\text{sys})$$

- Individual 2D measurements has compatible with the SM

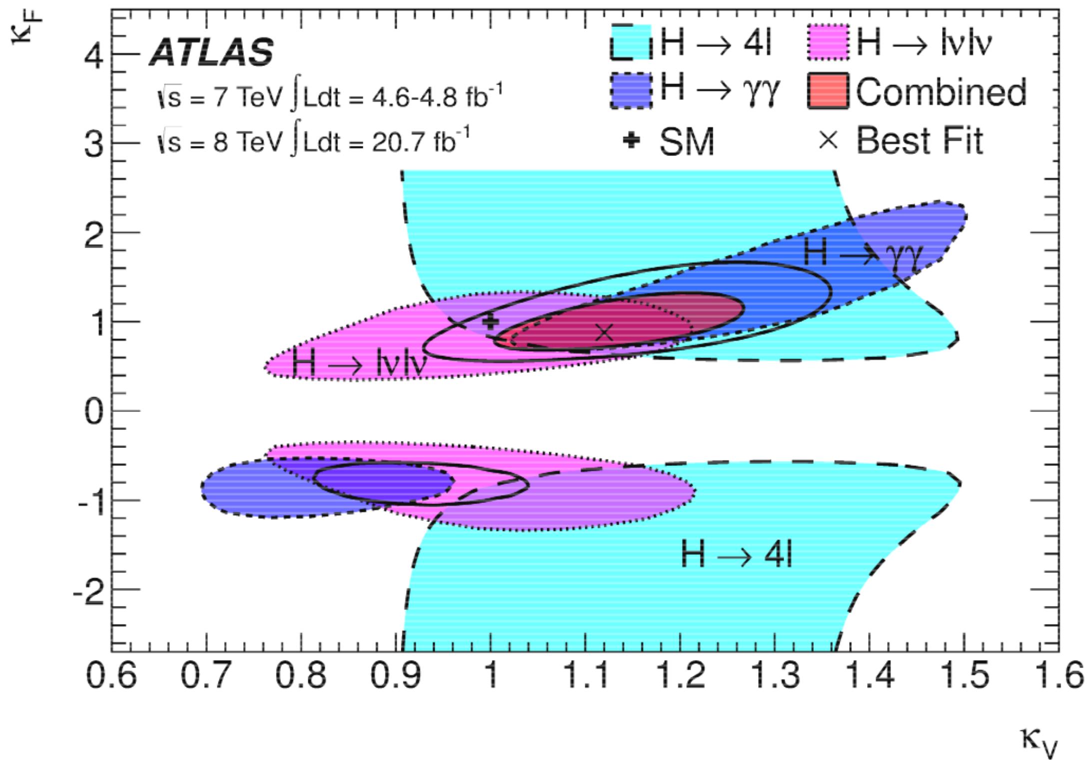


Fermion coupling scale factors

κ_V: Gauge boson coupling scale factor to the SM
κ_F: fermion coupling scale factor to the SM

- With several assumptions
  - Signal comes from single resonance
  - Zero width: $\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$

    i, f: initial, final states
    Γ_f, Γ_H: partial & total width
  - Tensor structure as in the SM ($J^P = 0^+$ assumed)
  - No New Physics contribution to the Higgs width

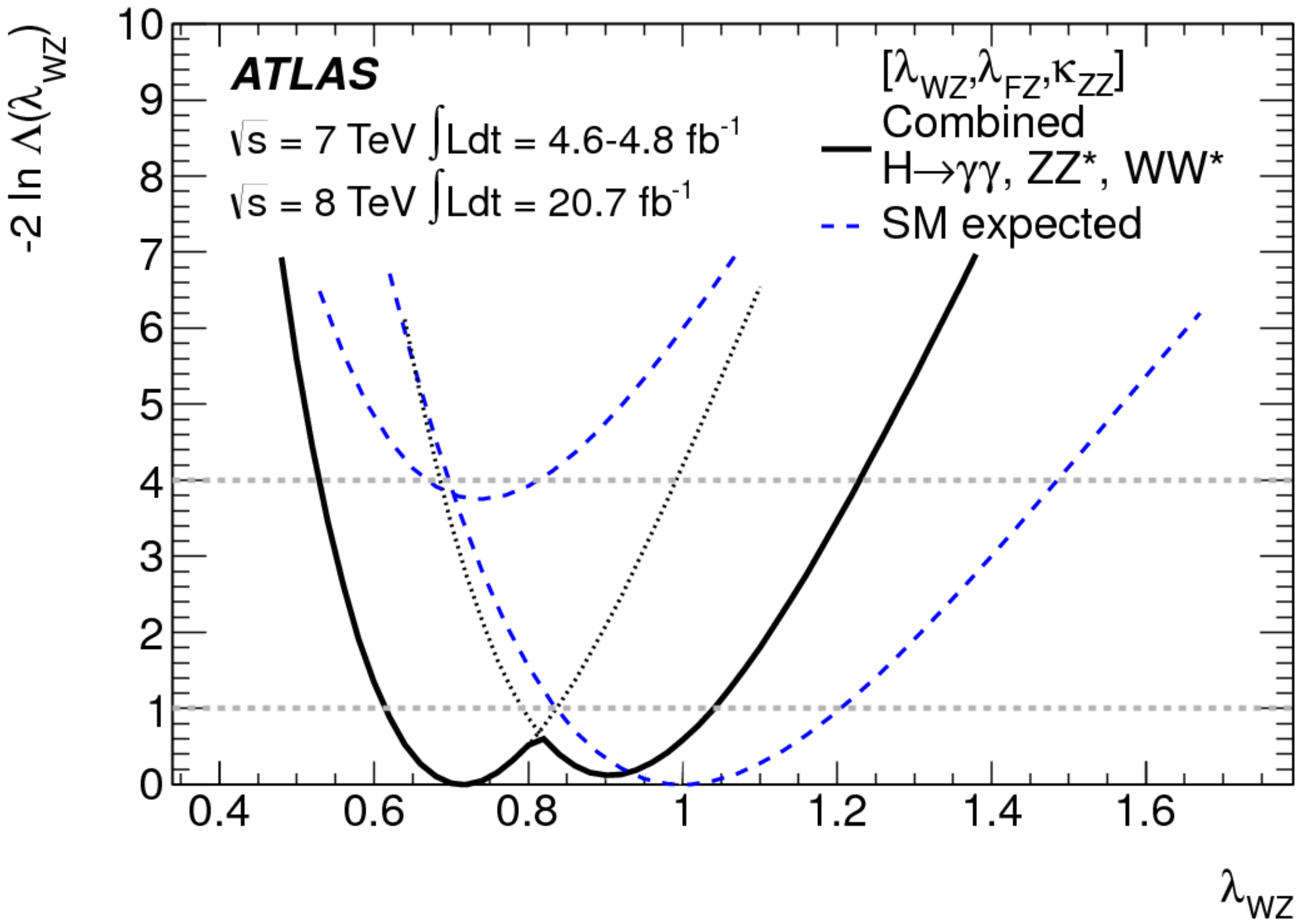


$$\kappa_F \in [0.76, 1.18]$$
$$\kappa_V \in [1.05, 1.22]$$

Vanishing Higgs to fermion Coupling has been excluded by more than 5 σ

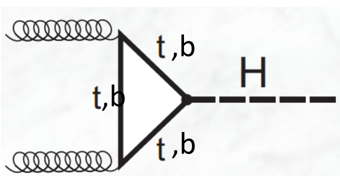
Custodial symmetry

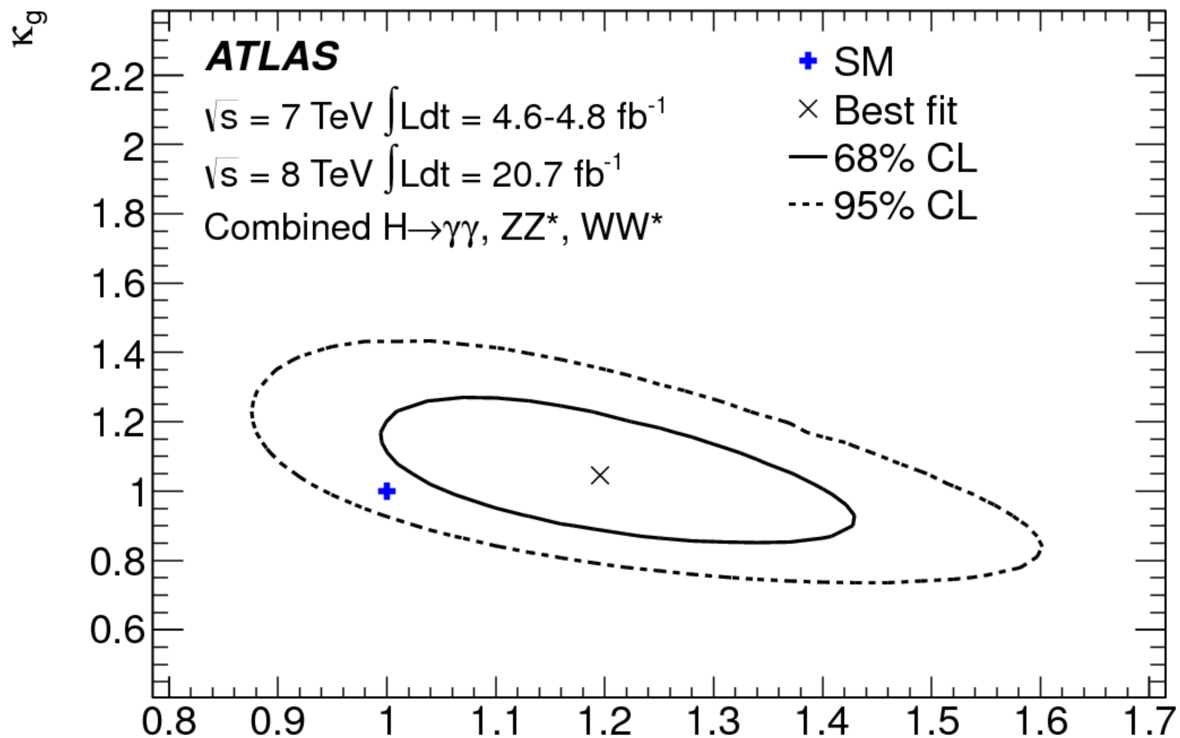
- $\lambda_{WZ} = \kappa_W / \kappa_Z$ (1 in the SM)
- $\lambda_{WZ} \in [0.61, 1.04]$

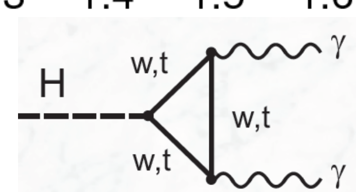


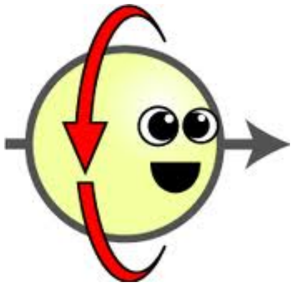
Anomaly check in gg→H and H→γγ loop

- Anomaly check in the loops
  - Scale factor for the couplings to the SM particles are set to 1
  - Assuming the SM total width

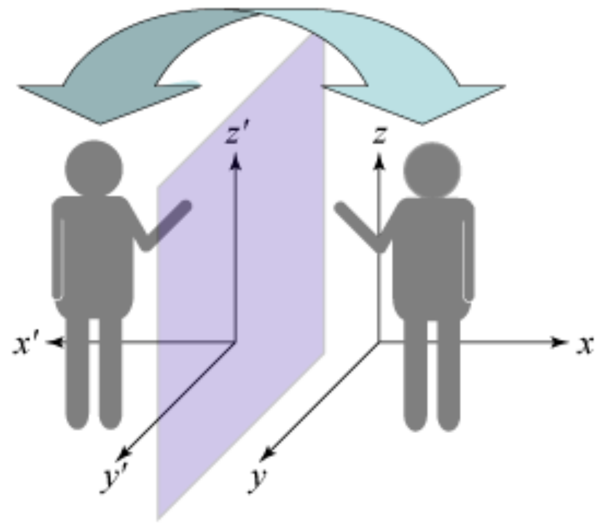








Higgs boson spin & parity



Overview of J^P measurements

- The SM Higgs boson: $J^P = 0^+$
- The strategy is to falsify the other hypothesis (0^-, 1^+, 1^-, 2^+), and demonstrate the consistency of the SM hypothesis
  - Spin 0: only gluon fusion (gg) production is considered
  - Spin 1: only quark-antiquark (qq) annihilation is considered (Landau-Yan Theorem)
  - Spin 2: a model corresponds to a graviton-inspired tensor with minimal couplings to SM particles is chosen (arXiv:1001.3396). gg-qq fraction has been scanned over entire range
- See distributions of spin & parity sensitive variables which preserve the discrimination against various background

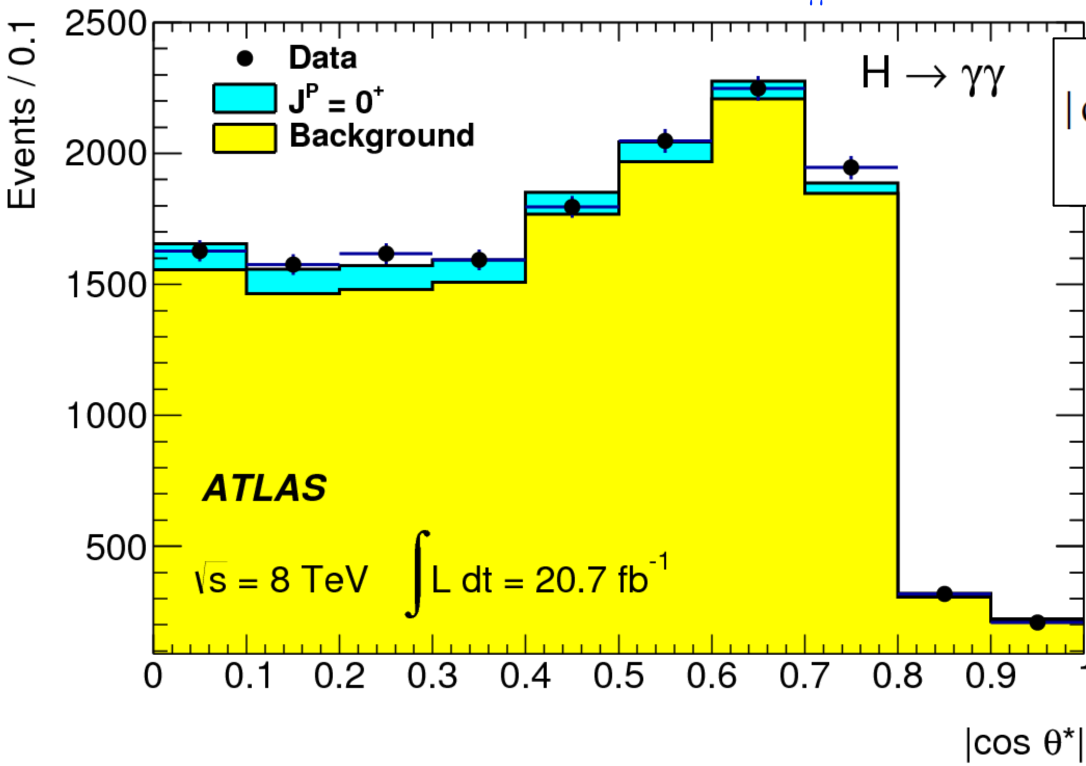
	H→γγ	H→ZZ	H→WW
vs 0^-		○	○
vs 1^+, 1^-		○	○
vs 2^+	○	○	○

Table. Channels used in each J^P hypothesis

H → γγ

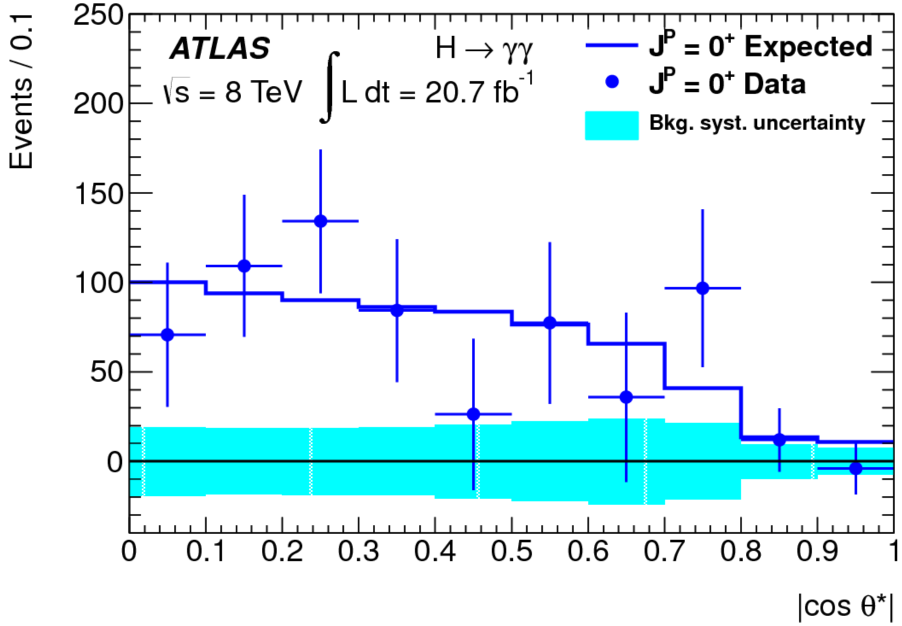
- |cos θ*| and $m_{\gamma\gamma}$ of photons has been used, where θ* is the polar angle of the Collins-Soper frame (*Phys. Rev. D* 16 (1977), pp 2219-2225)
- Asymmetric photon p_T cut depending on $m_{\gamma\gamma}$ to reduce correlation between |cos θ*| and $m_{\gamma\gamma}$

|cos θ*| distribution in the signal region
(background shape taken from $m_{\gamma\gamma}$ sideband)

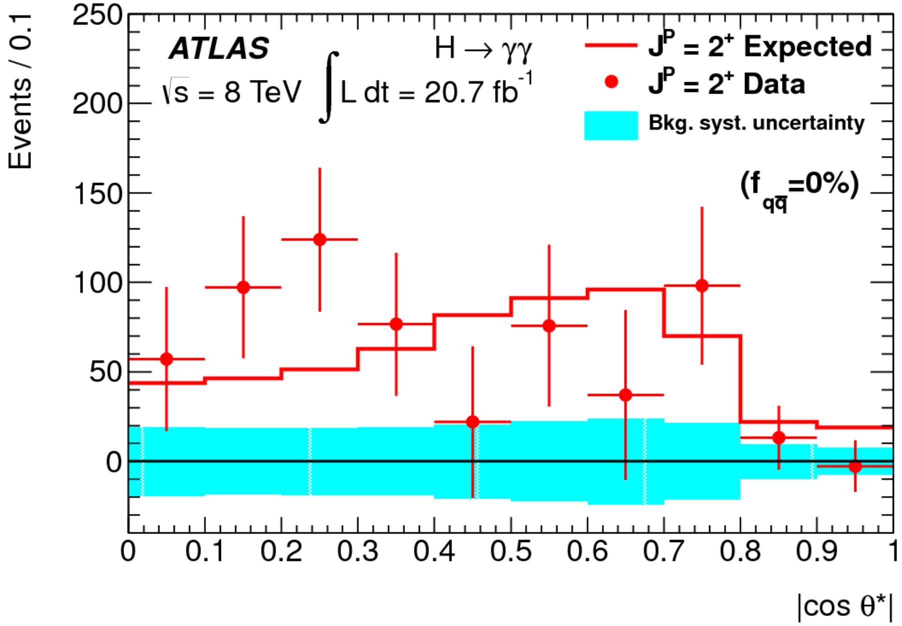


$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

with 0^+

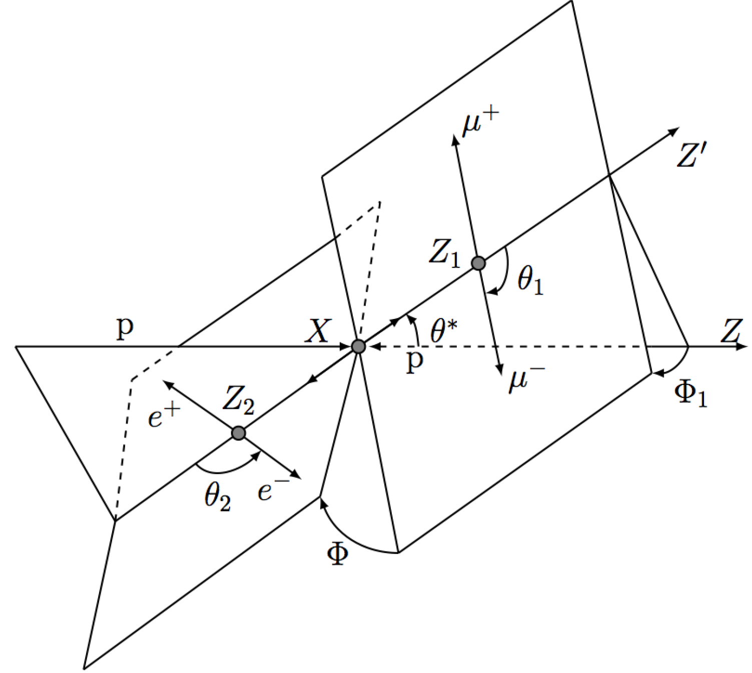

ATLAS
√s = 8 TeV
∫L dt = 20.7 fb⁻¹
H → γγ
J^P = 0+ Expected
J^P = 0+ Data
Bkg. syst. uncertainty
Events / 0.1
|cos θ*|

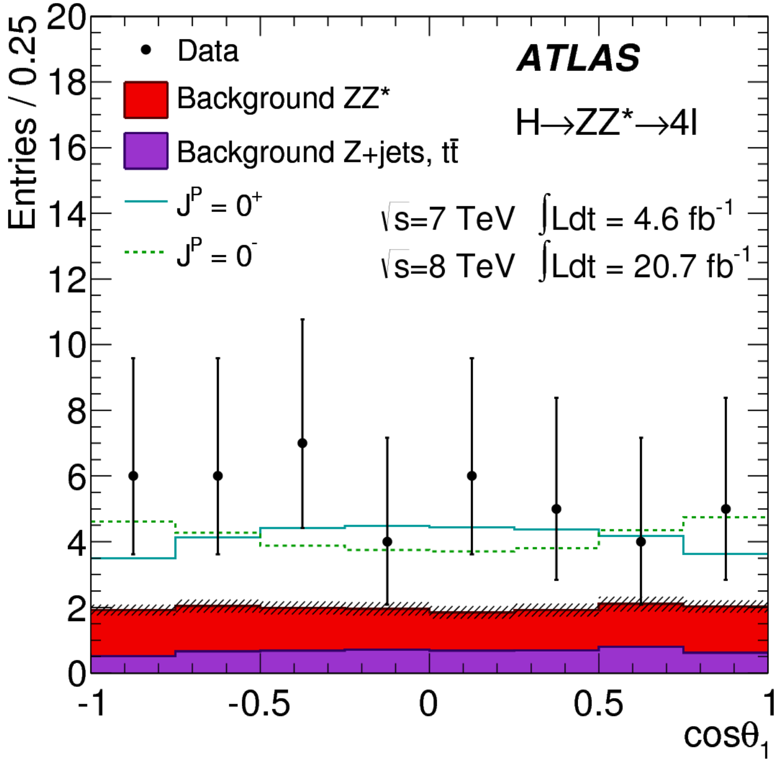
with 2^+

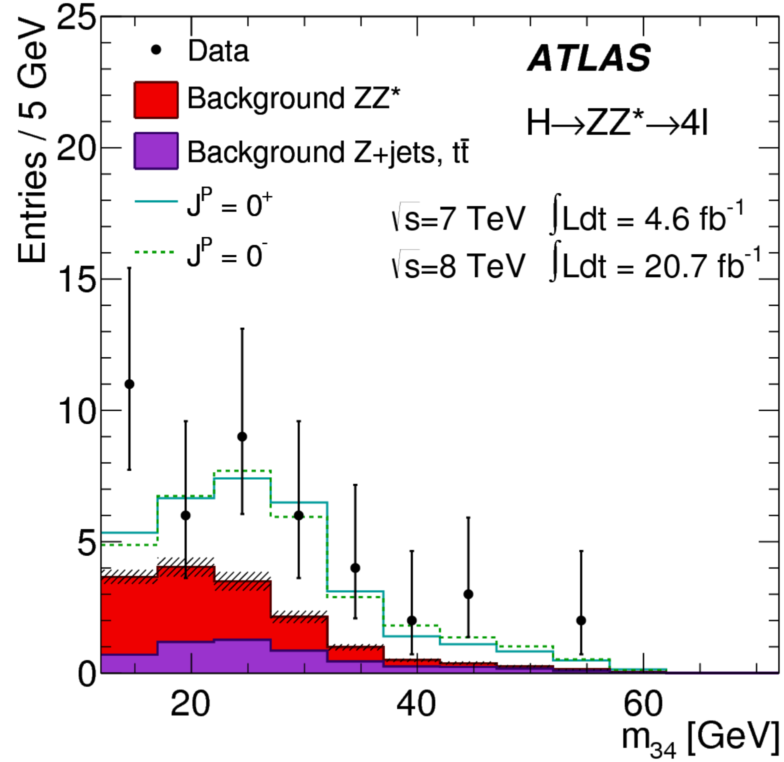

ATLAS
√s = 8 TeV
∫L dt = 20.7 fb⁻¹
H → γγ
J^P = 2+ Expected
J^P = 2+ Data
Bkg. syst. uncertainty
(f_qq̄=0%)
Events / 0.1
|cos θ*|

$H \to ZZ \to 4$ lepton

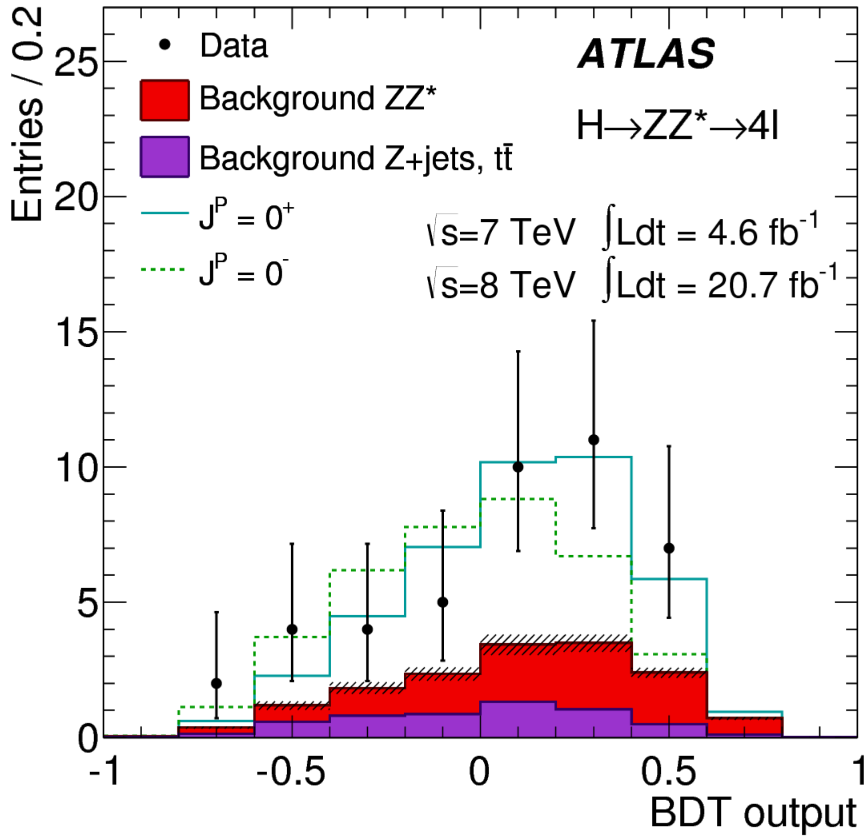
- m_{12}, m_{34}, θ, θ_1, θ^*, Φ, Φ_1
- Boosted Decision Tree (BDT)





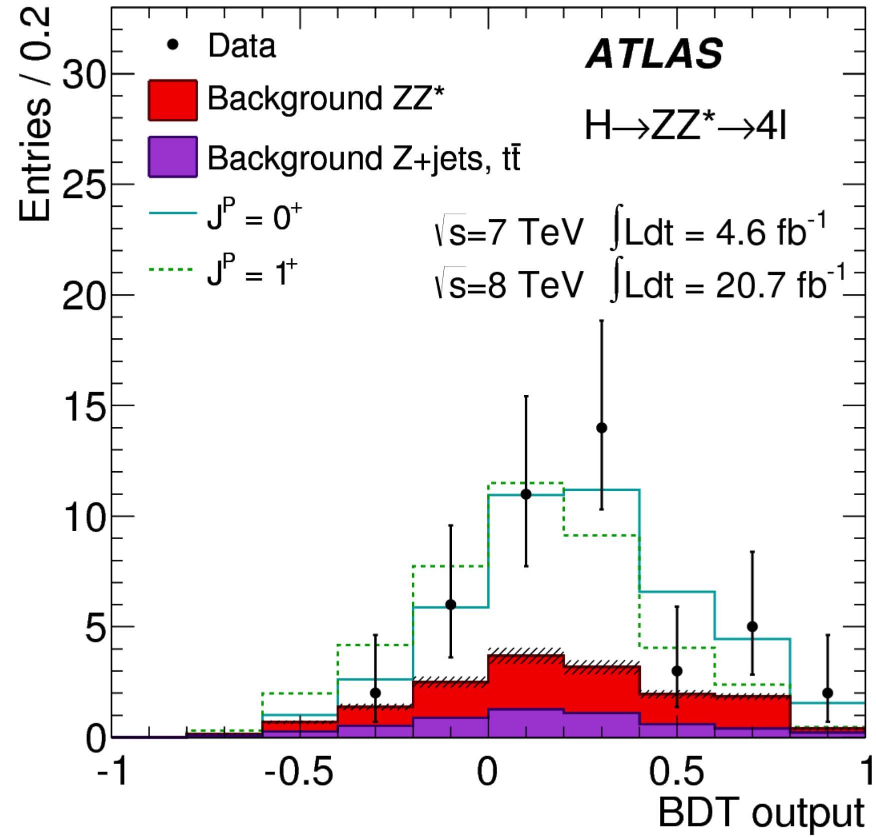


vs 0^-



Entries / 0.2
Data
Background ZZ*
Background Z+jets, tt̄
$J^P = 0^+$
$J^P = 0^-$
ATLAS
H→ZZ*→4l
$\sqrt{s}$=7 TeV ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$=8 TeV ∫Ldt = 20.7 fb^{-1}
BDT output

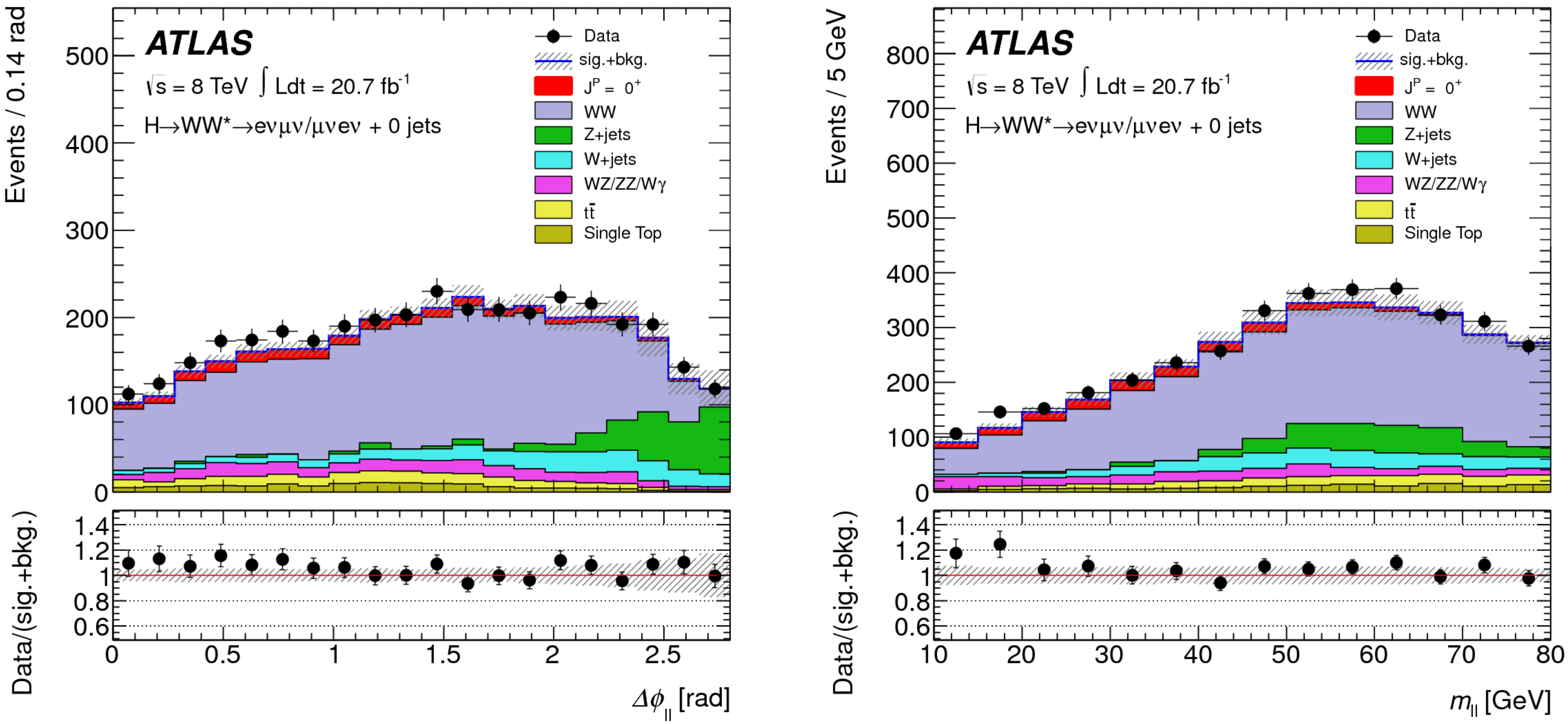
vs 1^+



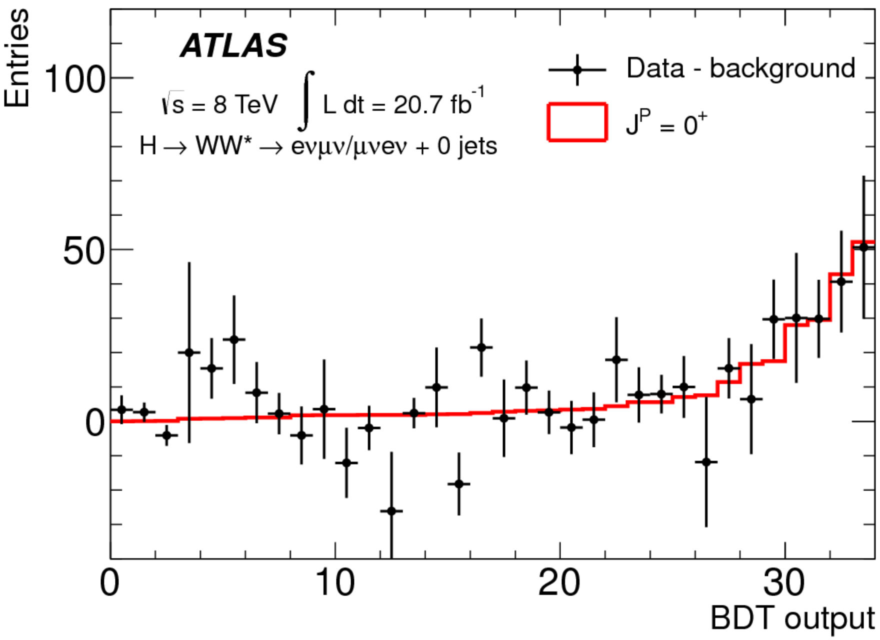
Entries / 0.2
Data
Background ZZ*
Background Z+jets, tt̄
$J^P = 0^+$
$J^P = 1^+$
ATLAS
H→ZZ*→4l
$\sqrt{s}$=7 TeV ∫Ldt = 4.6 fb^{-1}
$\sqrt{s}$=8 TeV ∫Ldt = 20.7 fb^{-1}
BDT output

$H \rightarrow WW \rightarrow l\nu l\nu$

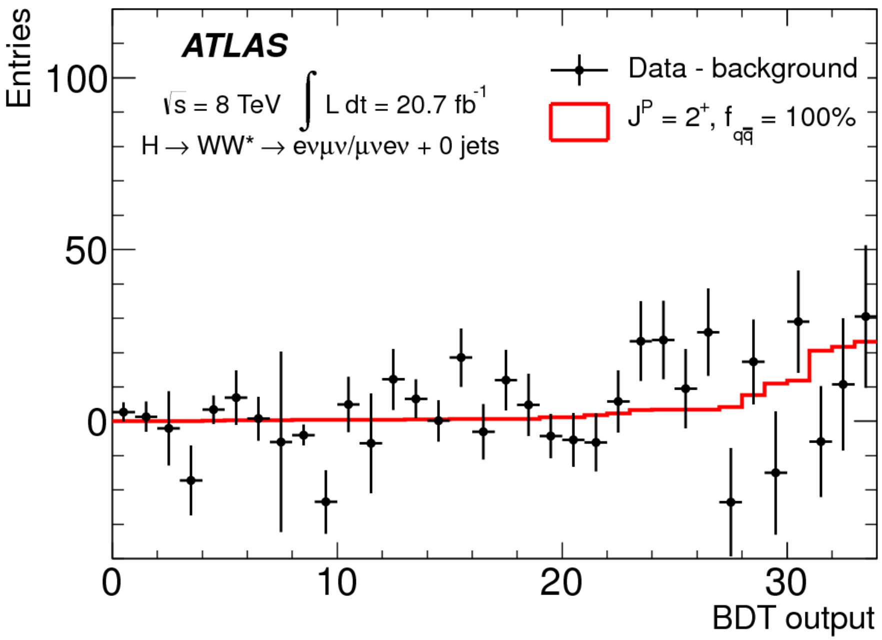
- Only e/μ, 0 jet events are used
- m_{ll}, $\Delta\varphi_{ll}$, p_T^{ll}, and m_T
- 2D BDT (0^+ vs bkg – alt vs bkg)



with 0^+

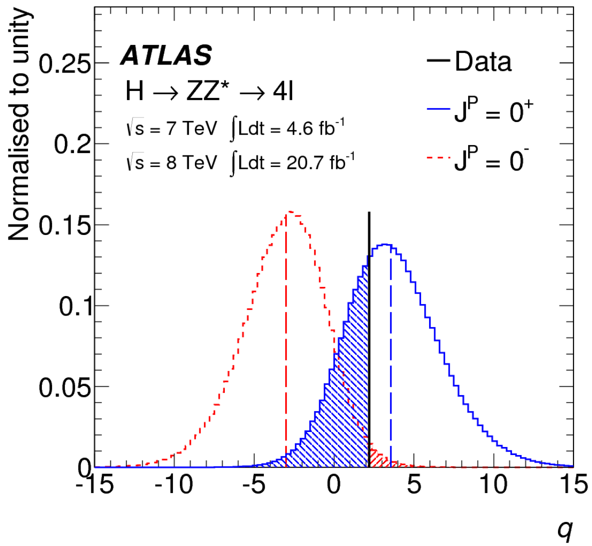

ATLAS
$\sqrt{s}$ = 8 TeV $\int L\,dt = 20.7\ fb^{-1}$
$H \rightarrow WW^* \rightarrow e\nu\mu\nu/\mu\nu e\nu$ + 0 jets
Data - background
$J^P = 0^+$
Entries
100
50
0
0
10
20
30
BDT output

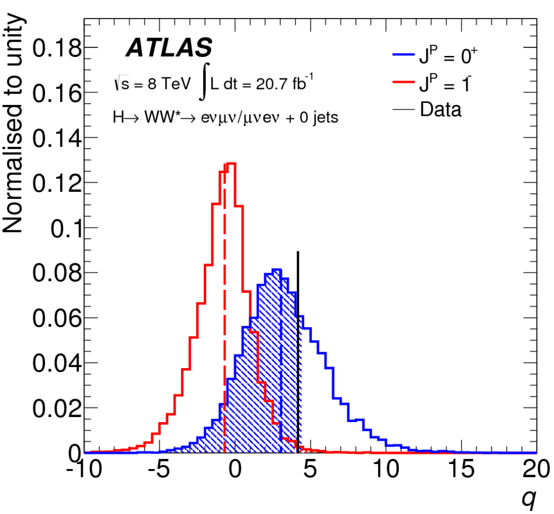
with 2^+

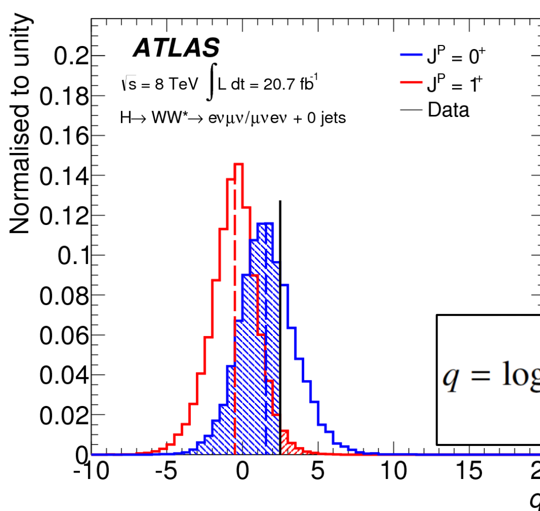

ATLAS
$\sqrt{s}$ = 8 TeV $\int L\,dt = 20.7\ fb^{-1}$
$H \rightarrow WW^* \rightarrow e\nu\mu\nu/\mu\nu e\nu$ + 0 jets
Data - background
$J^P = 2^+$, $f_{q\bar{q}}$ = 100%
Entries
100
50
0
0
10
20
30
BDT output

Spin & Parity Results

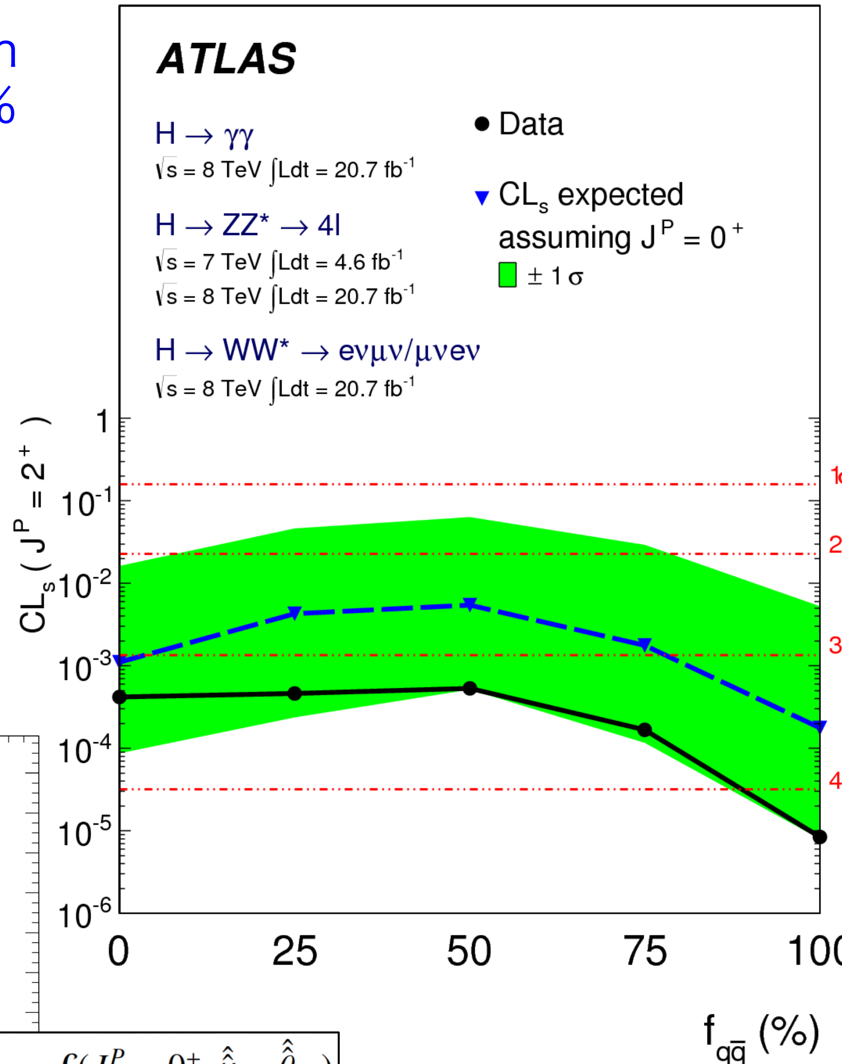
All the alternatives (0^-, 1^+, 1^-, 2^+) have been excluded at confidence levels above 97.8%







$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$



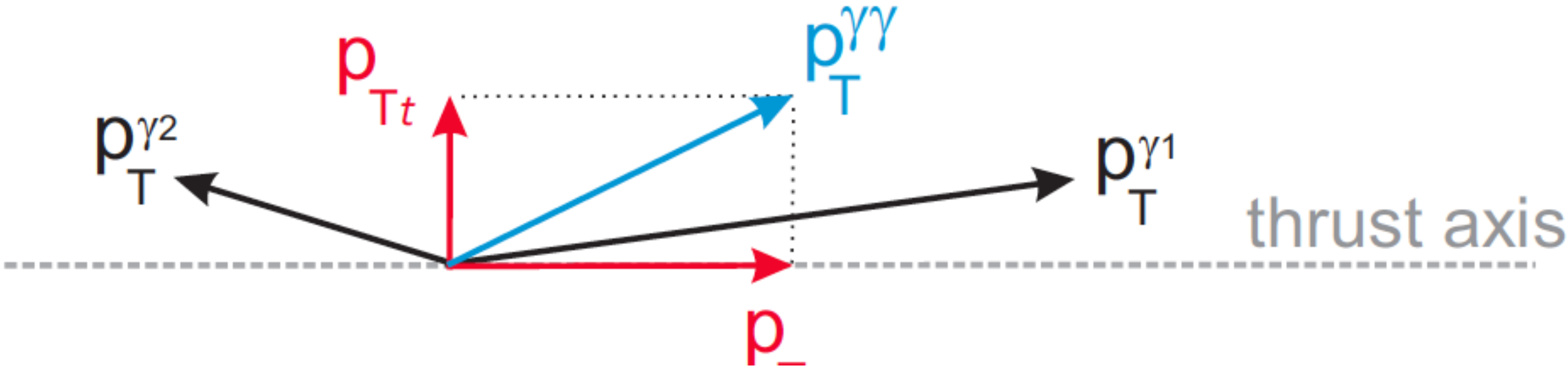
Conclusion

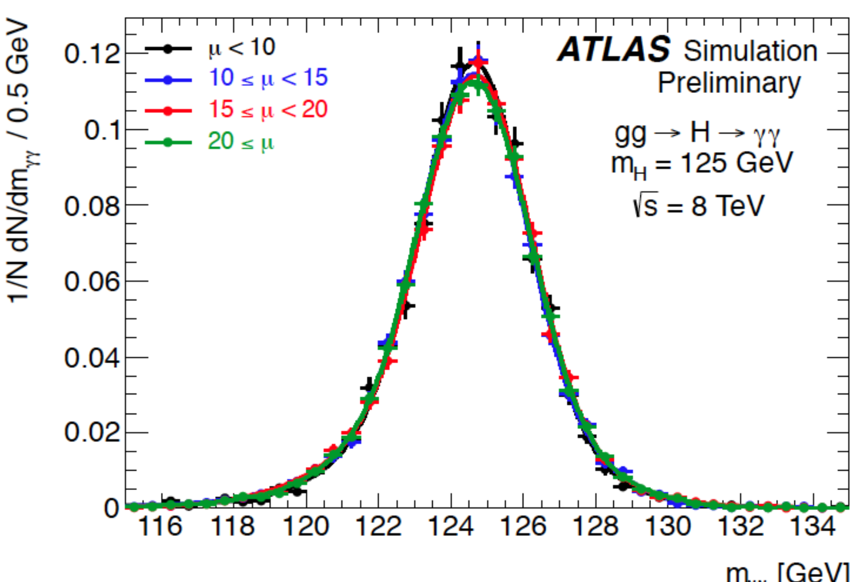
- A new particle has been found
  - 7.4 σ in gg decay
  - 6.4 σ in ZZ decay
  - 3.8 σ in WW decay
- The mass has been measured as $m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\;\text{GeV}$
  - Compatible with the only one resonance assumption
- The coupling properties has been measured
  - The evidence of the VBF production
  - 5 σ exclusion of vanishing fermion coupling
  - Custodial symmetry has been observed
  - No anomalies found in production/decay loops
- The spin/parity strongly favors $J^P = 0^+$

All the properties indicates the discovery of a (SM consistent) Higgs boson!!
Deviations, more Higgs bosons…? Stay tuned for 2015!!
Grazie mille!!!!!!

Back Up

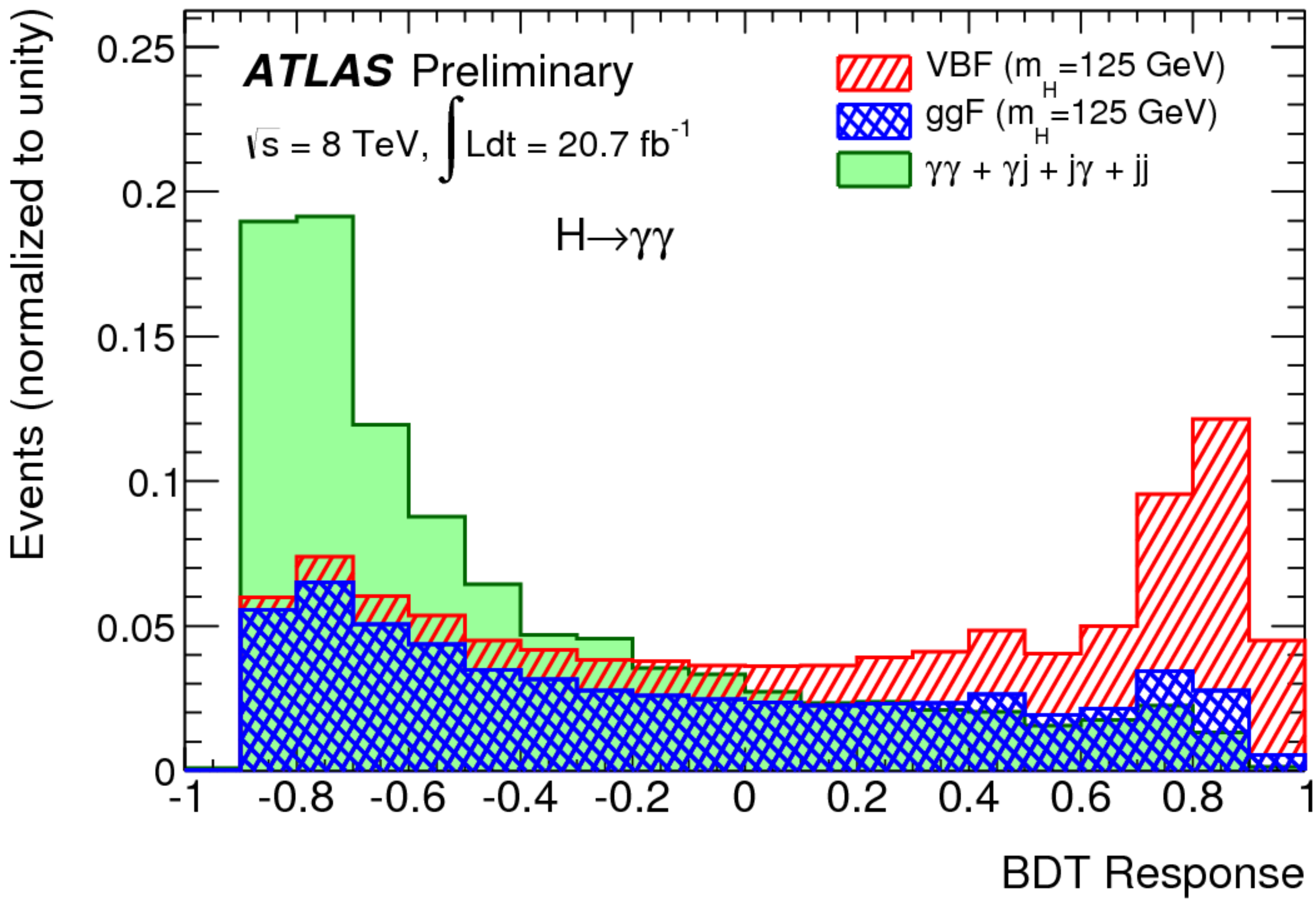
p_{Tt}, $m_{\gamma\gamma}$





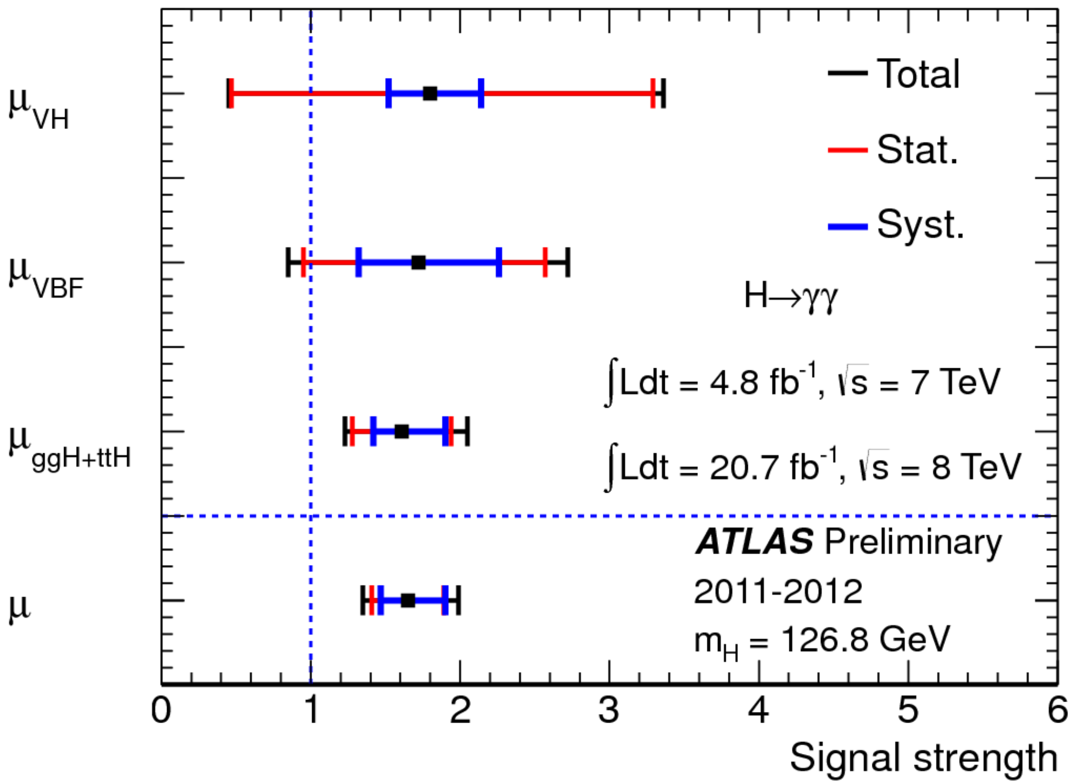
pile-up-robust mass reconstruction

$H \rightarrow \gamma\gamma$



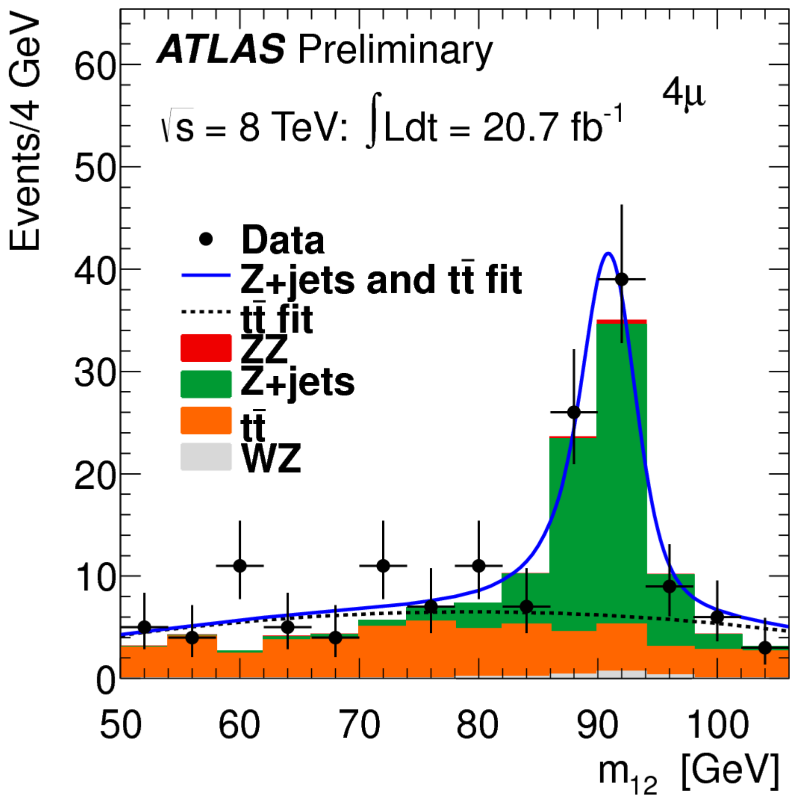
$H \to \gamma\gamma$

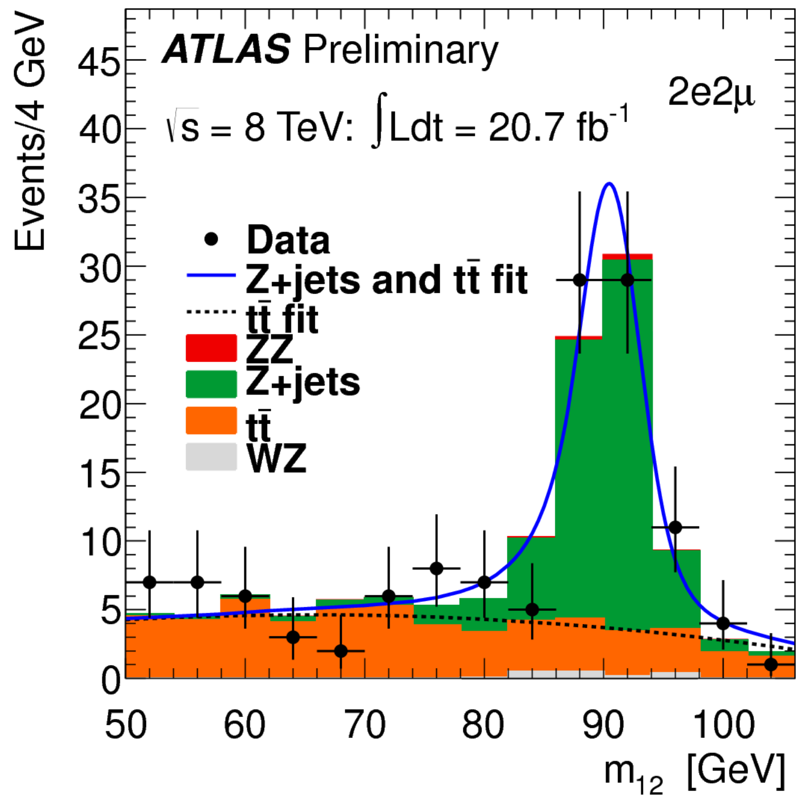
- Signal strength for each production mode
  - $\mu_{VH} = 1.8^{+1.5}_{-1.3}(\text{stat})^{+0.3}_{-0.3}(\text{syst})$
  - $\mu_{VBF} = 1.7^{+0.8}_{-0.8}(\text{stat})^{+0.5}_{-0.4}(\text{syst})$
  - $\mu_{ggH+ttH} = 1.6^{+0.3}_{-0.3}(\text{stat})^{+0.3}_{-0.2}(\text{syst})$
  - $\mu = 1.65^{+0.24}_{-0.24}(\text{stat})^{+0.25}_{-0.18}(\text{syst})$



$H \to ZZ \to 4$ lepton backgrounds

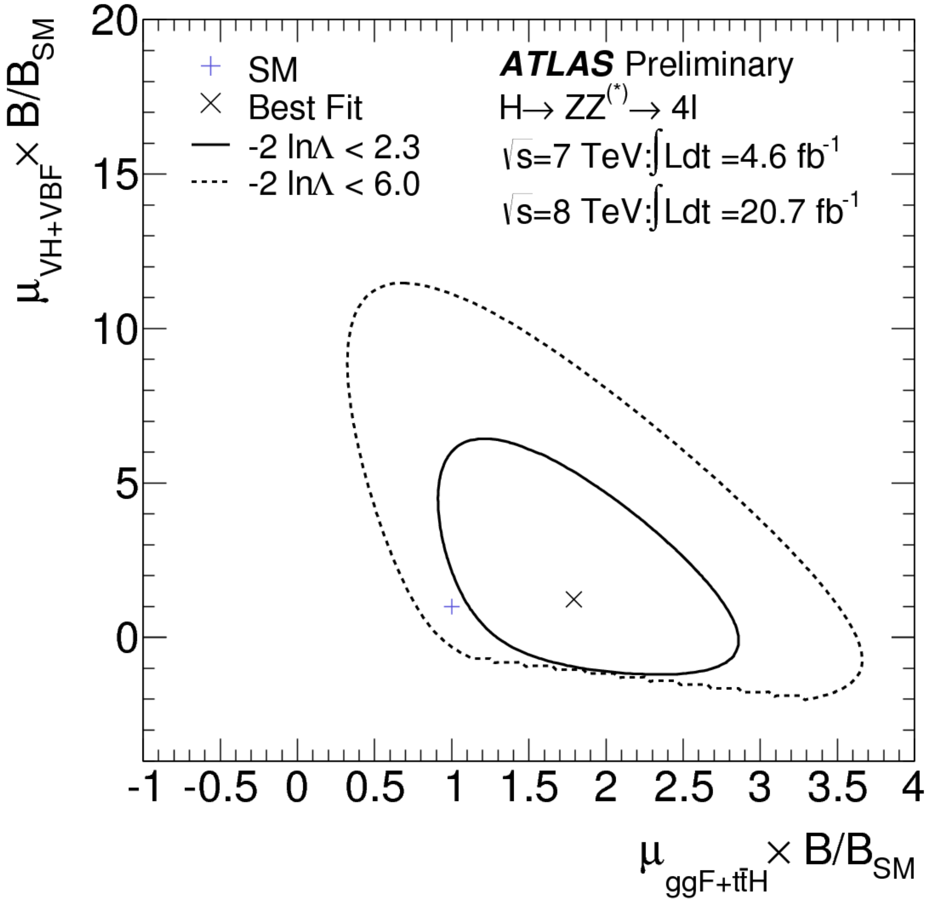
- ZZ*: MC simulation
- Z+jets, ttbar: control regions
  - CR: Loosen the selection of sub-leading lepton pair
  - Extrapolate the event yield in CR to SR by using a transfer function derived from MC



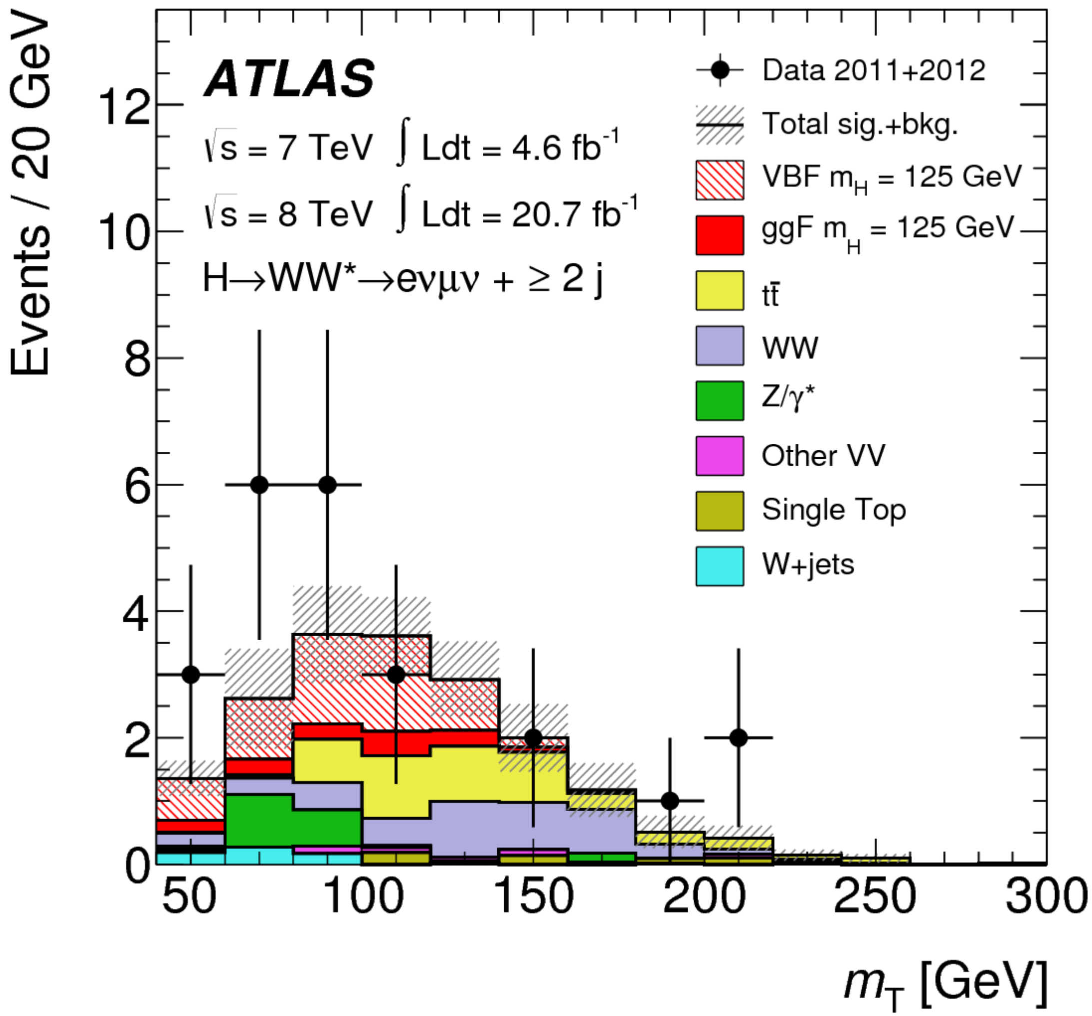


H → ZZ → 4 lepton

- Signal strength for each production mode
  - $\mu_{ggF+ttH} = 1.8^{+0.8}_{-0.5}$
  - $\mu_{VH + VBF} = 1.2^{+3.8}_{-1.4}$
  - $\mu = 1.7^{+0.5}_{-0.4}$



$H \rightarrow WW \rightarrow l\nu l\nu$



$H \rightarrow WW \rightarrow l\nu l\nu$

- Signal strength for each production mode:
  - $\mu_{ggF} = 0.82 \pm 0.36$
  - $\mu_{VBF} = 1.66 \pm 0.79$
  - $\mu = 1.26 \pm 0.35$

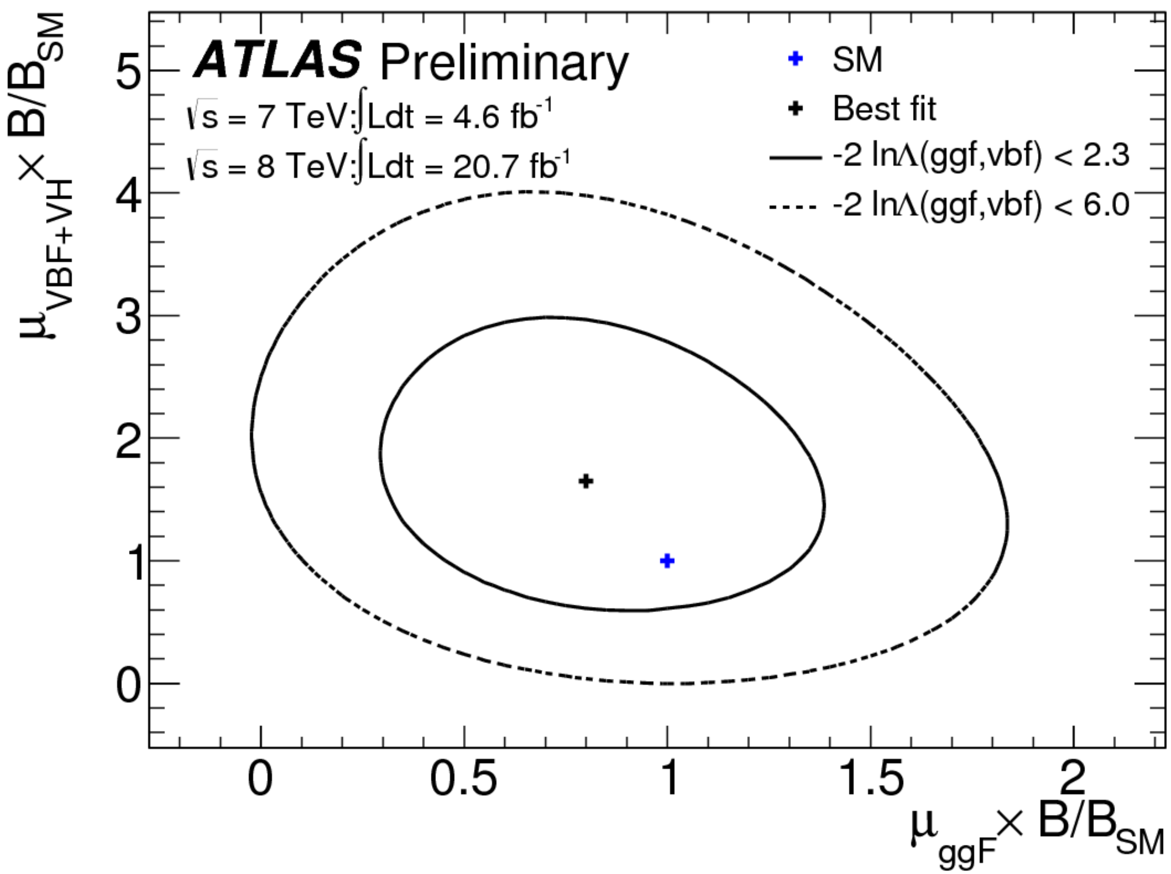


Table 10: Summary of the coupling benchmark models discussed in this paper, where $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ii} = \kappa_i\kappa_i/\kappa_H$, and the functional dependence assumptions are: $\kappa_V = \kappa_W = \kappa_Z$, $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ (and similarly for the other fermions), $\kappa_g = \kappa_g(\kappa_b, \kappa_t)$, $\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)$, and $\kappa_H = \kappa_H(\kappa_i)$. The tick marks indicate which assumptions are made in each case. The last column shows, as an example, the relative couplings involved in the $gg \to H \to \gamma\gamma$ process, see Eq. (7), and their functional dependence in the various benchmark models.

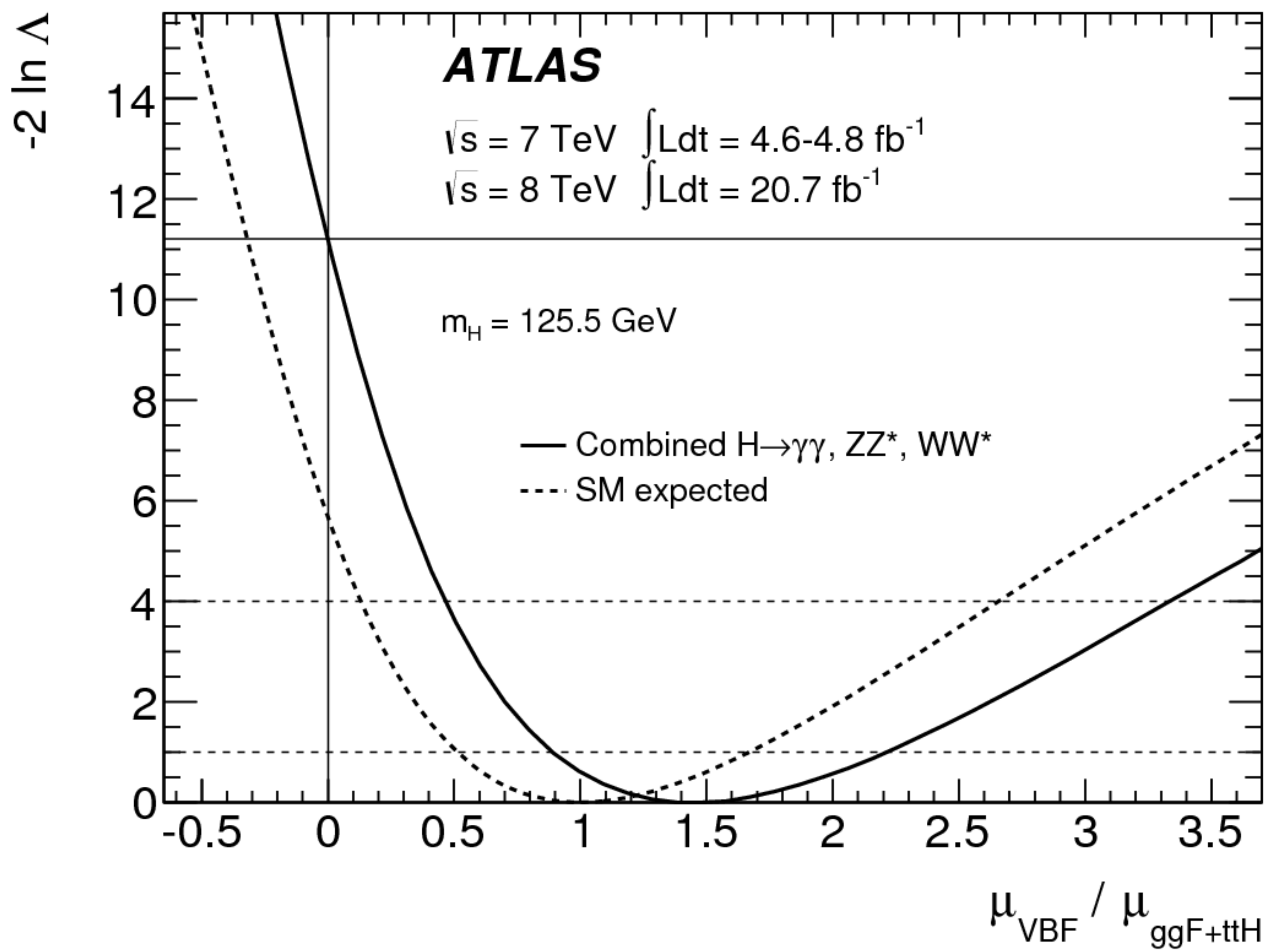
Model	Probed couplings	Parameters of interest	Functional assumptions					Example: $gg \to H \to \gamma\gamma$
			κ_V	κ_F	κ_g	κ_γ	κ_H	
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$

$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \qquad (7)$$

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

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W) = \frac{\sum_{i,j} \kappa_i\kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}} \qquad (8)$$

$$\kappa_H^2 = \sum_{\substack{jj = WW^*,\, ZZ^*,\, b\bar{b},\, \tau^-\tau^+,\\ \gamma\gamma,\, Z\gamma,\, gg,\, t\bar{t},\, c\bar{c},\, s\bar{s},\, \mu^-\mu^+}} \frac{\kappa_j^2 \Gamma_{jj}^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$


ATLAS
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
mH = 125.5 GeV
Combined H→γγ, ZZ*, WW*
SM expected
-2 ln Λ
μVBF / μggF+ttH
0
2
4
6
8
10
12
14
-0.5
0
0.5
1
1.5
2
2.5
3
3.5