# Measurements of the Higgs boson properties with the ATLAS detector


戸本誠

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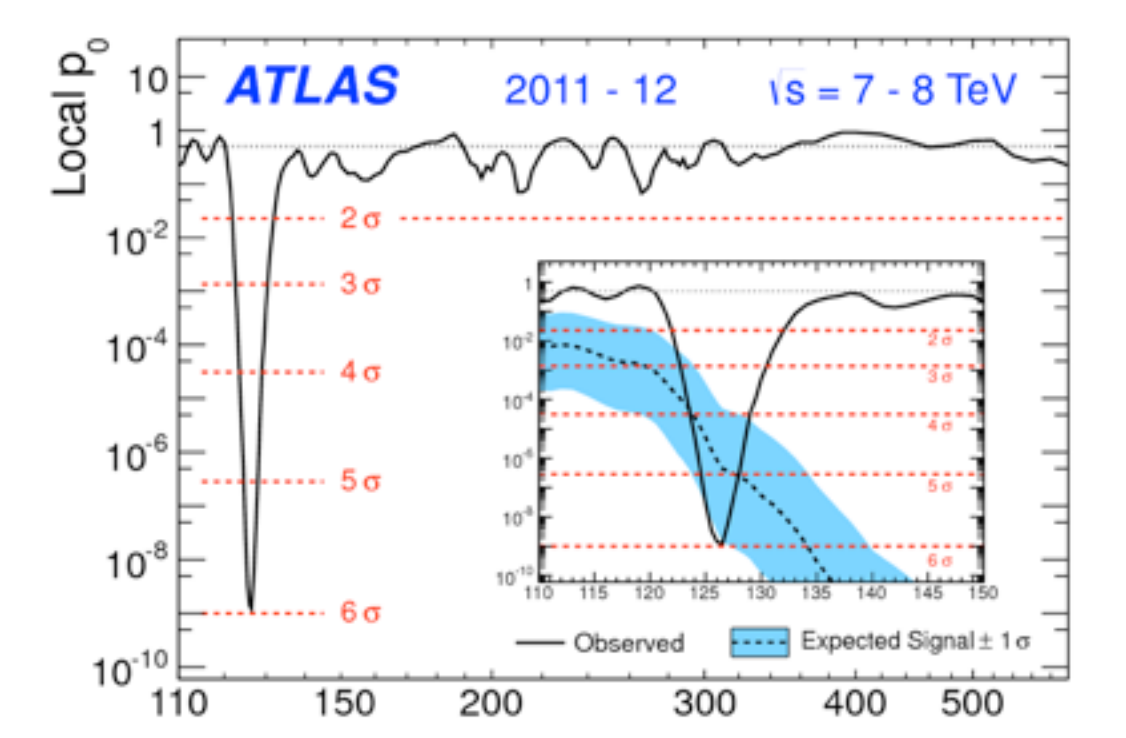
on behalf of the ATLAS collaboration

# Introduction

One year has passed since a new boson was discovered at LHC (ATLAS & CMS)




Phys. Lett. B716 (2012) 1-29

Since then, we focus our interests on

- Is this new boson really responsible for the EW symmetry breaking mechanism?

  i.e. – Does it provide masses to the fermions and bosons?

  – Is it the Higgs boson predicted by the SM i.e. a $J^P=0^+$ ?

- Are there any signs of physics beyond the SM found?

They are addressed experimentally by measurement of the properties

mass, couplings, spin-parity, ...

ATLAS and CMS are the only experiments in the world to measure them now.

# Higgs productions at the LHC

Dominant process is gluon-gluon fusion (ggF)

- Proceeds mainly through the top quark loop
  → Indirect probe of Higgs-fermion coupling

Vector Boson Fusion (VBF)

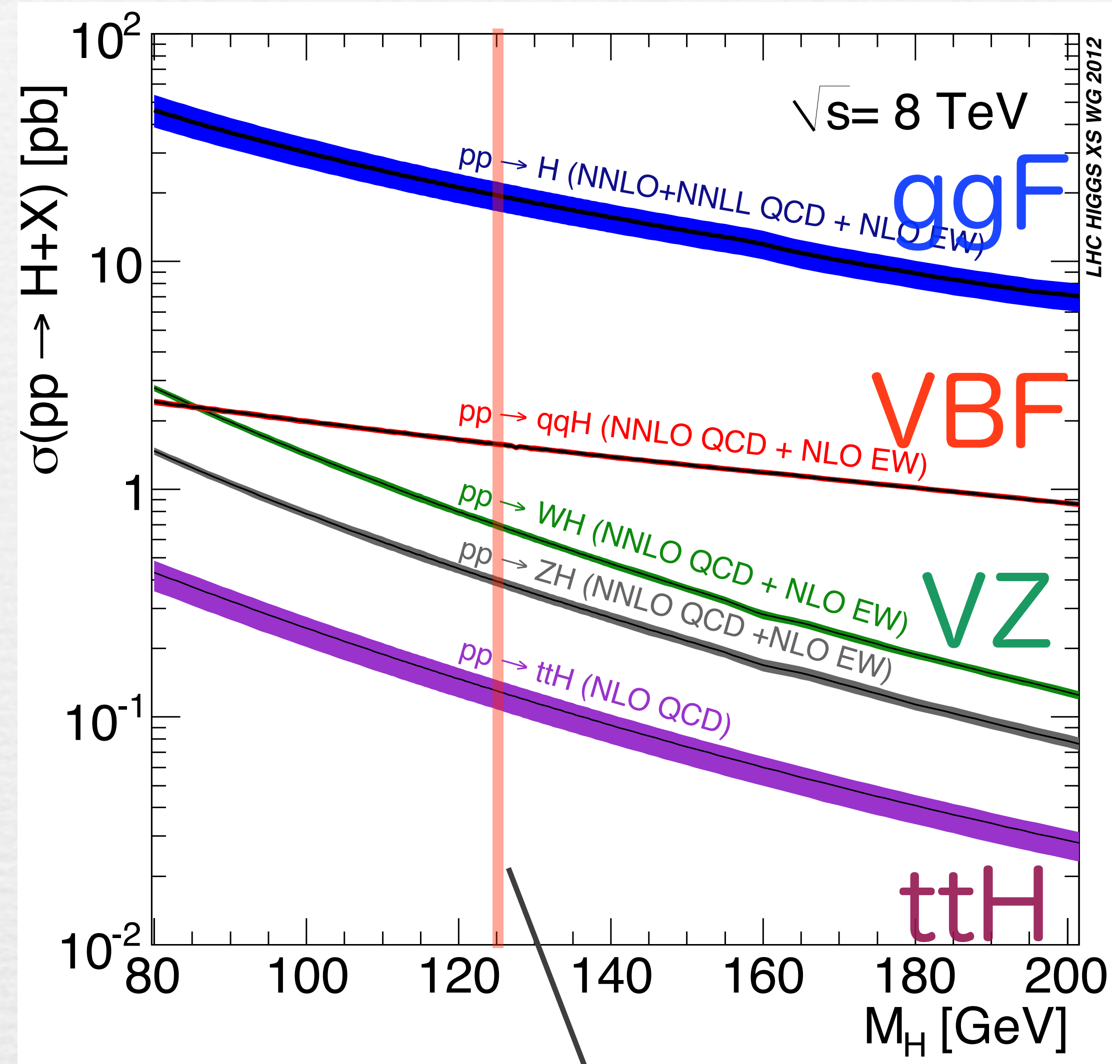
- Direct probe of vector boson coupling
- Signature includes two forward high-pT jets with a large rapidity-gap

Associated production with W/Z (VH)

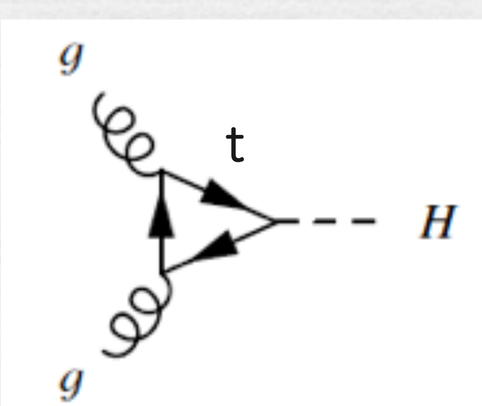
- Direct probe of vector boson coupling
- Signature includes high-pT leptons

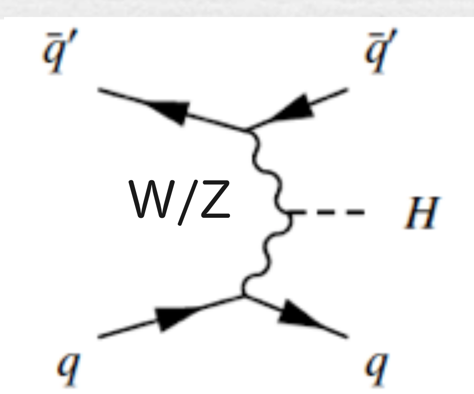
Associated production with a top quark pair (ttH)

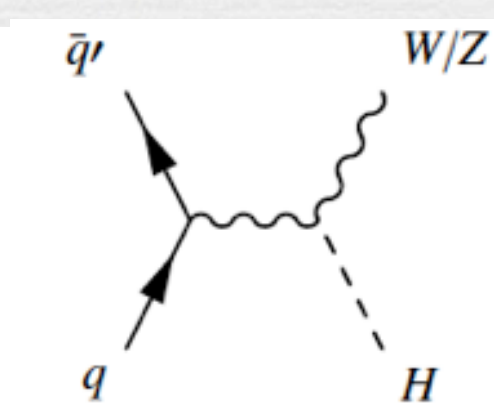
- Direct probe of Higgs-top quark coupling

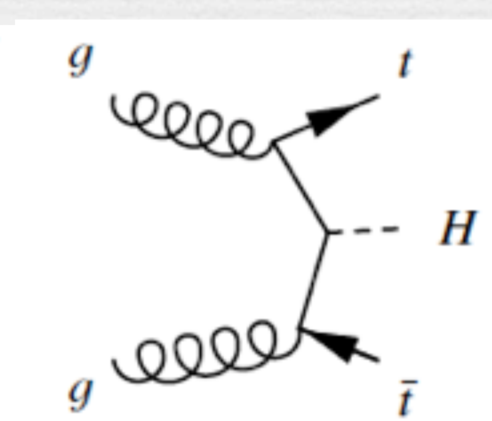



| σ (pb) | 7TeV | 8TeV |
|---|---|---|
| ggF | 15 | 19 |
| VBF | 1.2 | 1.6 |
| WH | 0.57 | 0.70 |
| ZH | 0.33 | 0.41 |
| ttH | 0.09 | 0.13 |



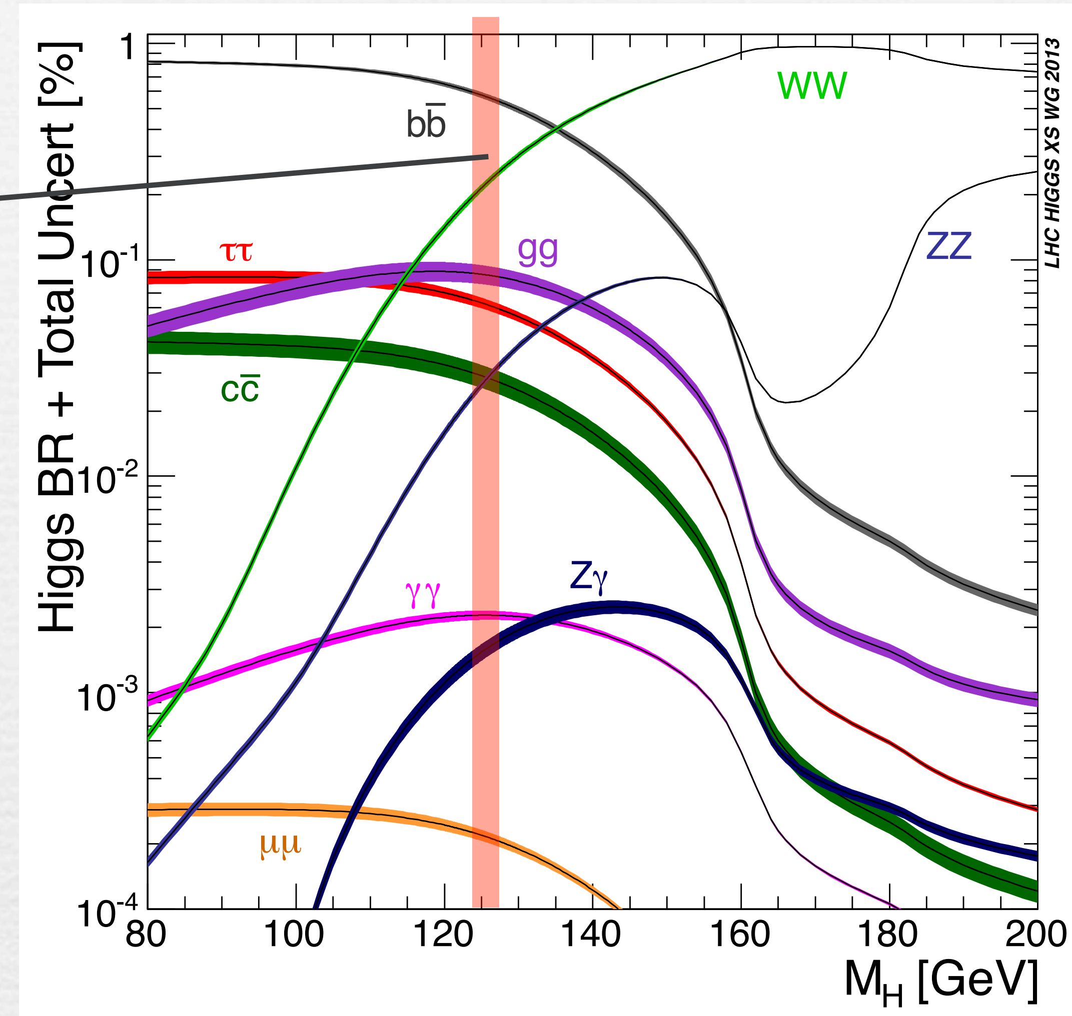



# Higgs decay modes at LHC

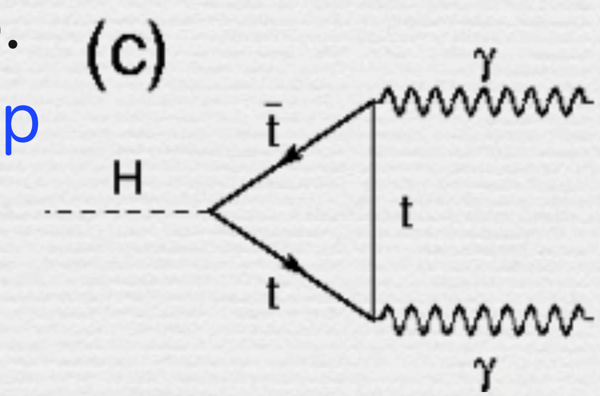
Higgs boson mass $m_H$~125.5GeV gives us maximally rich decay modes !!

| $m_H$=125.5GeV | BR(%) |
|---|---|
| $H\to\gamma\gamma$ | 0.23 |
| H→ZZ | 2.8 |
| H→WW | 22 |
| $H\to\tau\tau$ | 6.2 |
| H→bb | 57 |




Higgs boson can decay into a photon pair via W or t-quark loop.

- Negative interference between W-boson loop and t-quark loop helps the indirect measurement of the coupling to fermions



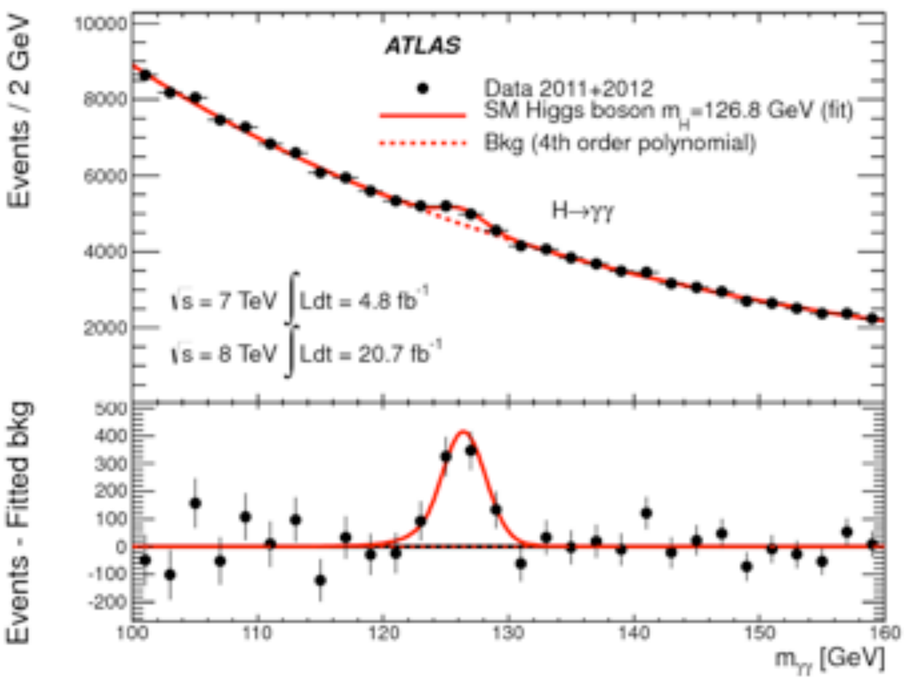

Final states with leptons or photons are easier to measure

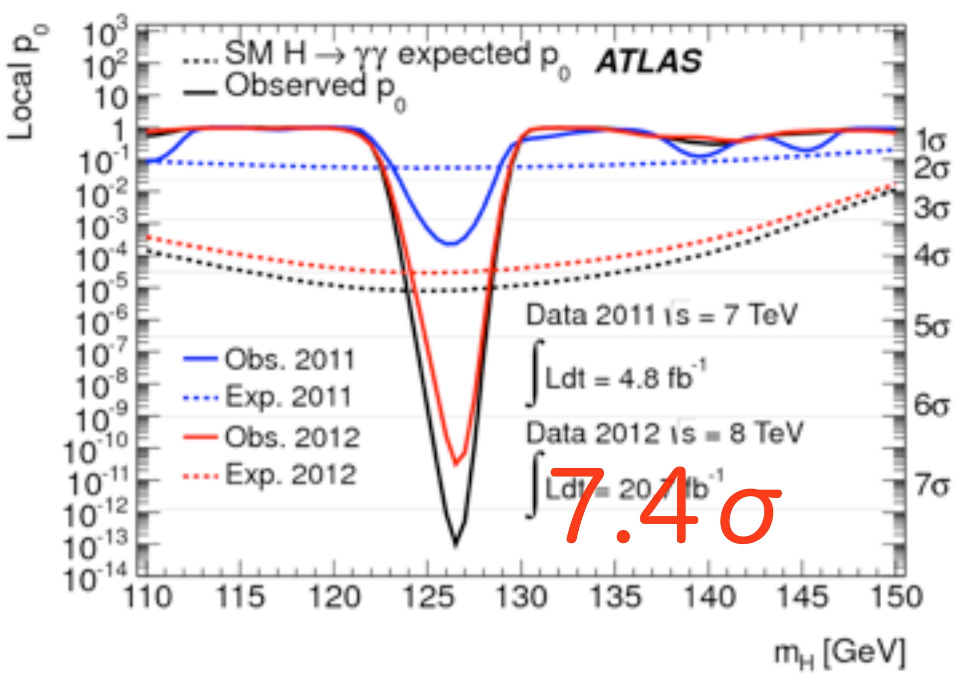
- Discovery channels : $H\to\gamma\gamma$、$ZZ(\to4\ell)$, $WW(\to\ell\nu\ell\nu)$

Decays to jets or $\tau$s are more difficult to separate from QCD background, but they are very important for the direct measurement of the coupling to fermions.

# Yields in the discovery channels

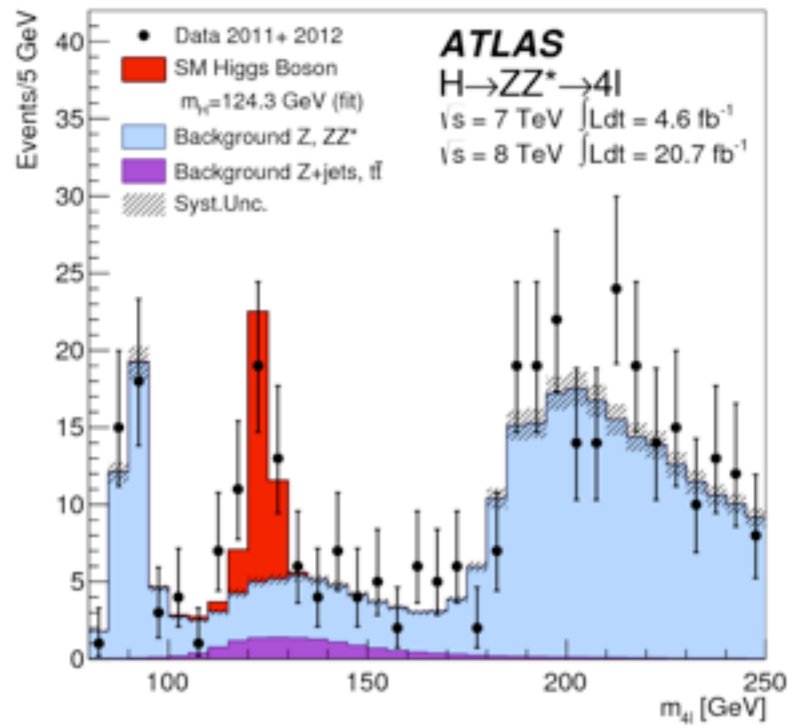
## $H \to \gamma\gamma$

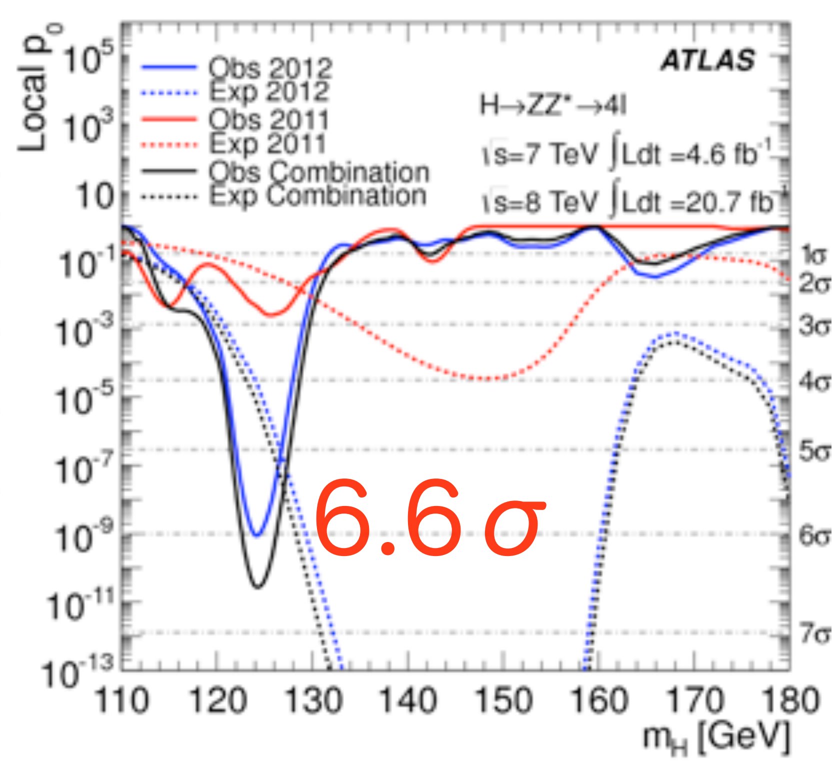



~370 signal events expected

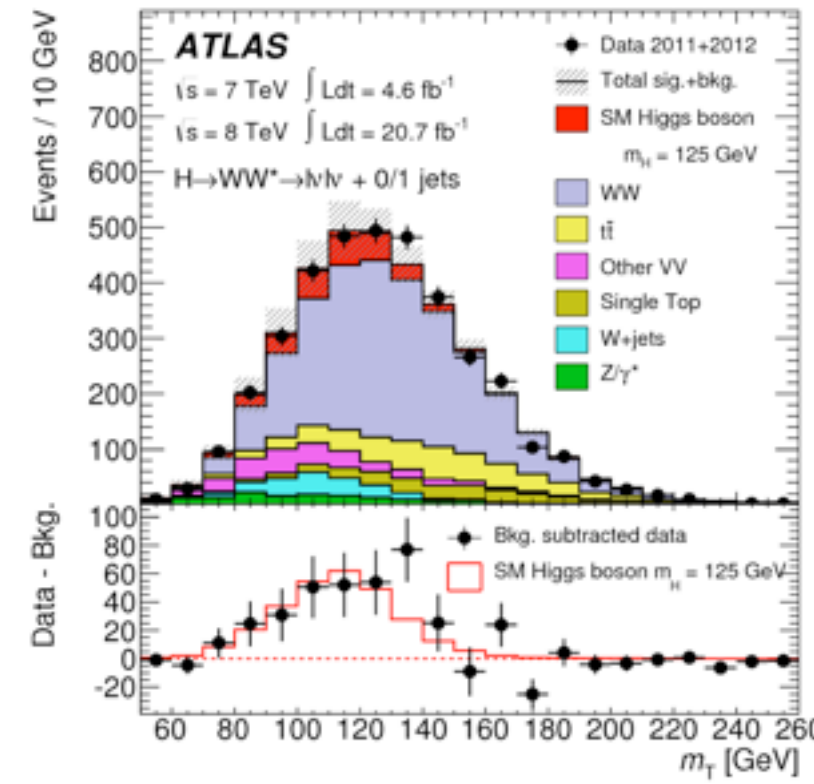
## $H \to ZZ$

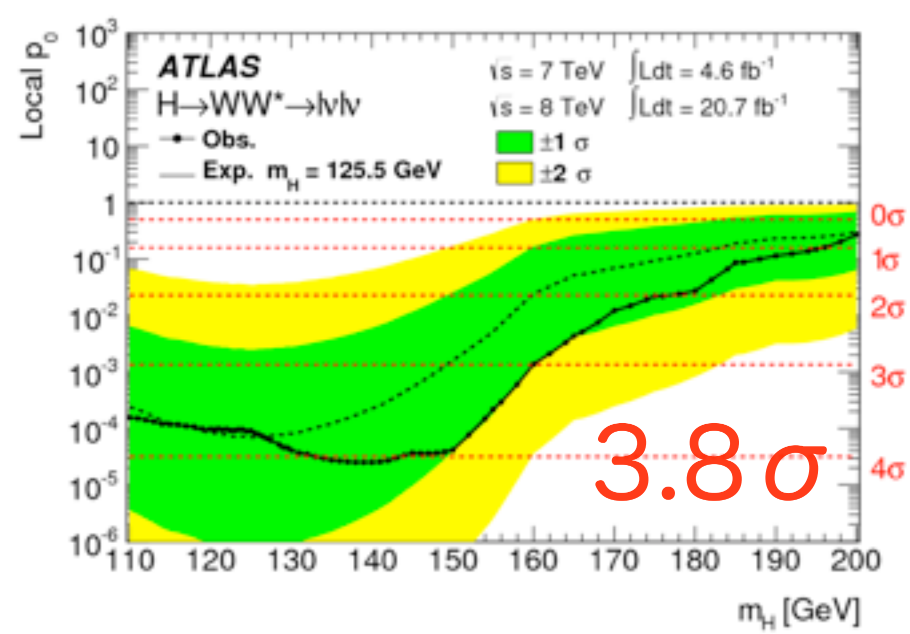



~15 signal events expected

## $H \to WW$

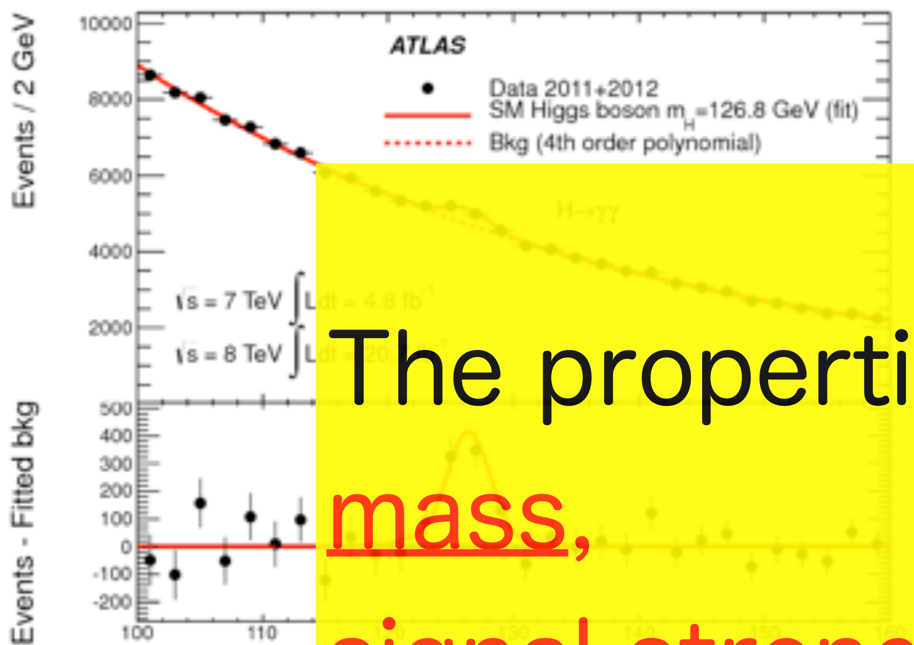


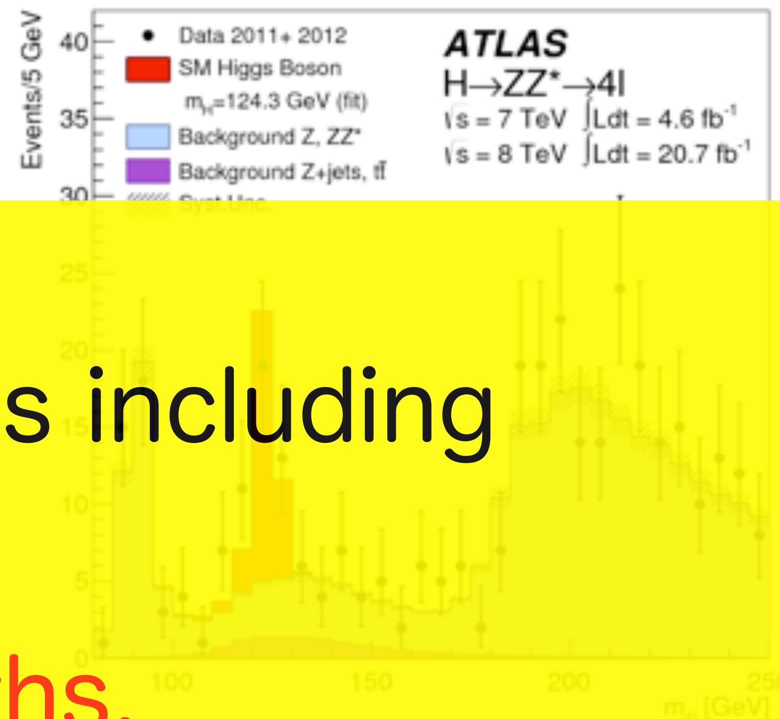



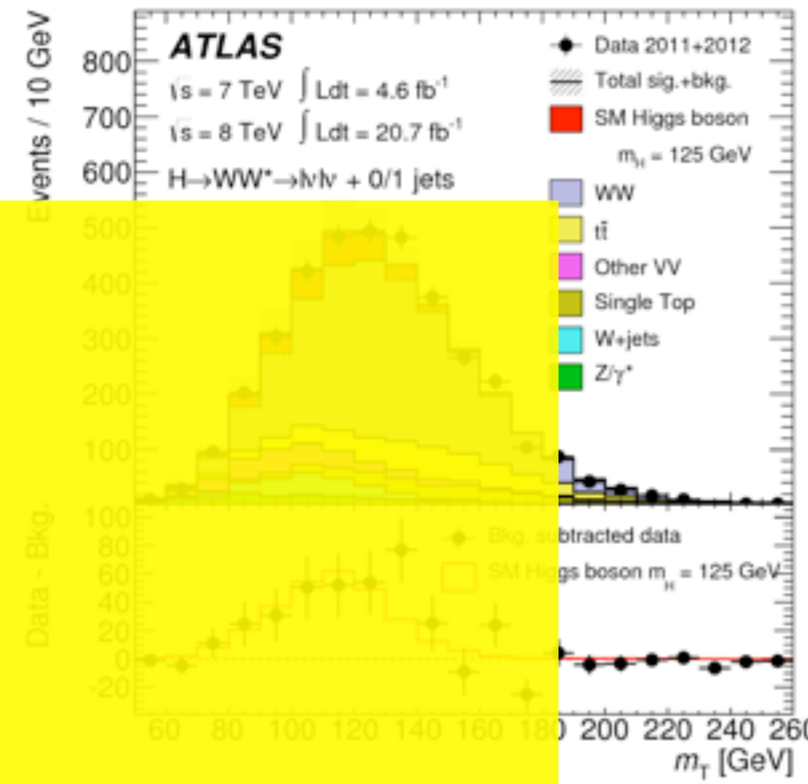

~150 signal events expected

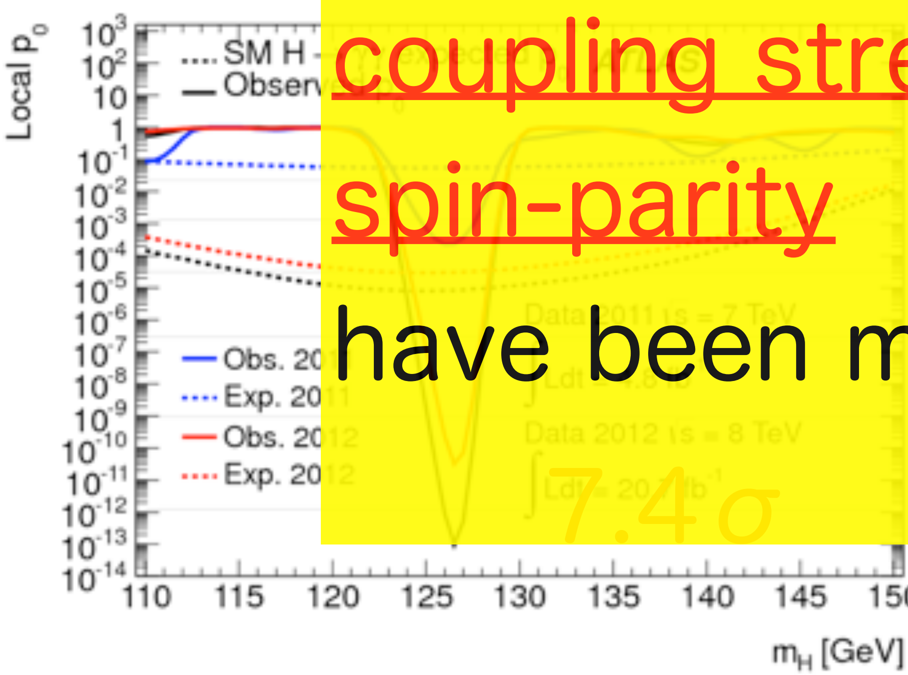
# Yields in the discovery channels

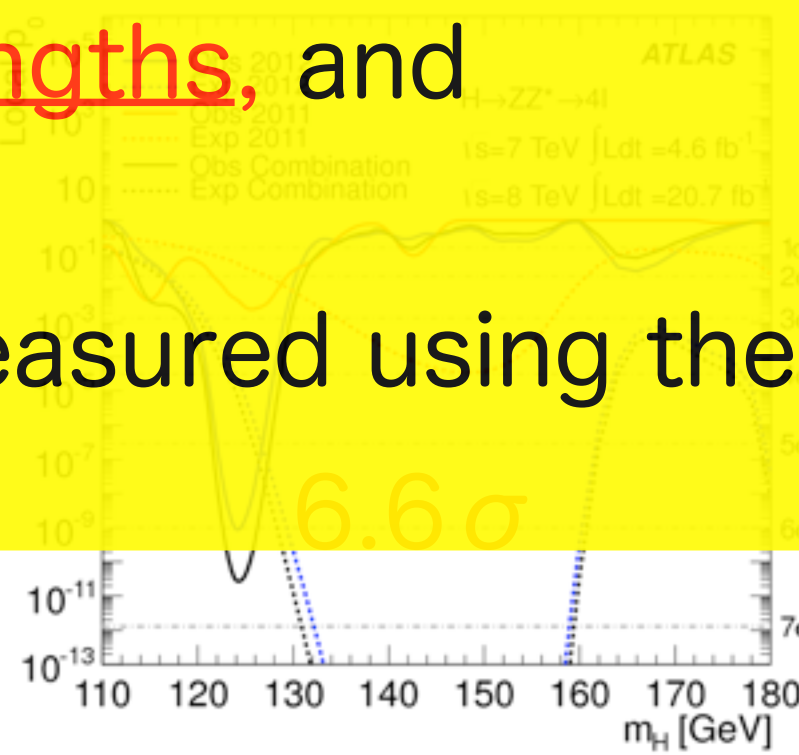
$H \to \gamma\gamma$ | $H \to ZZ$ | $H \to WW$

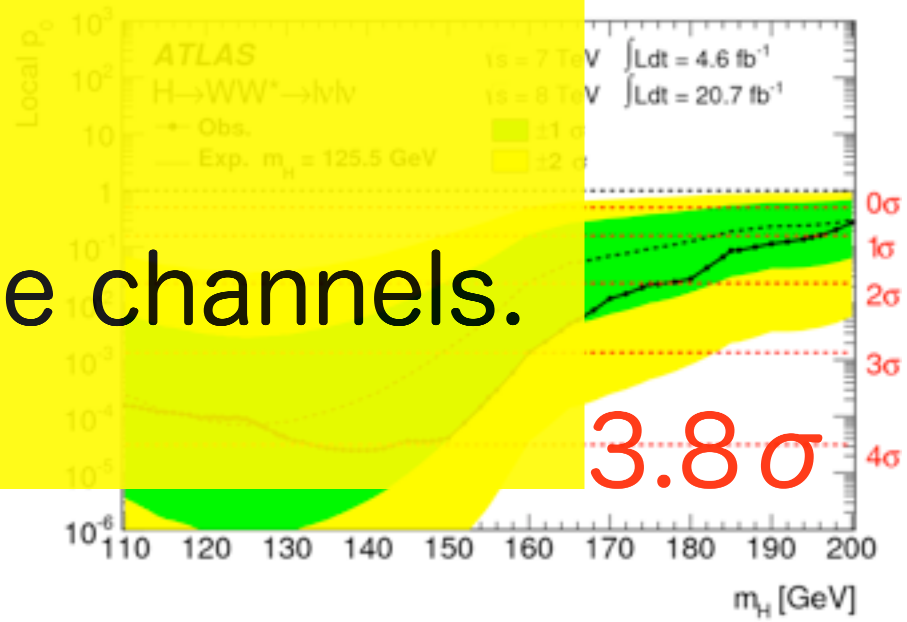



The properties including

<u>mass</u>,

<u>signal strengths</u>,

<u>coupling strengths</u>, and

<u>spin-parity</u>

have been measured using these channels.

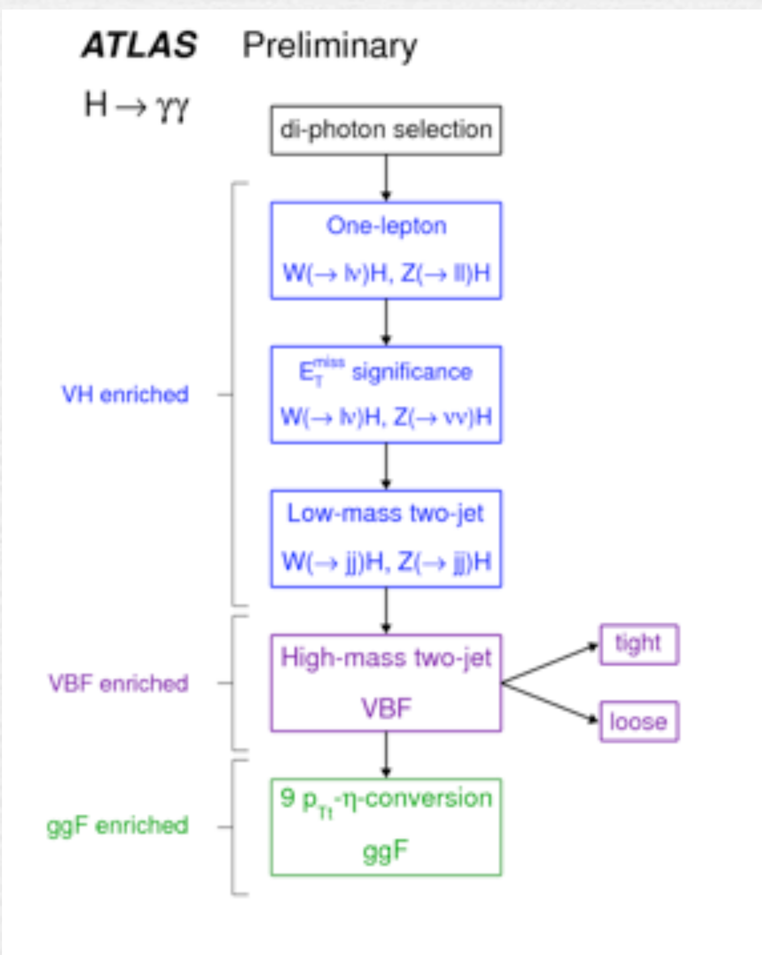
~370 signal events expected | ~15 signal events expected | ~150 signal events expected

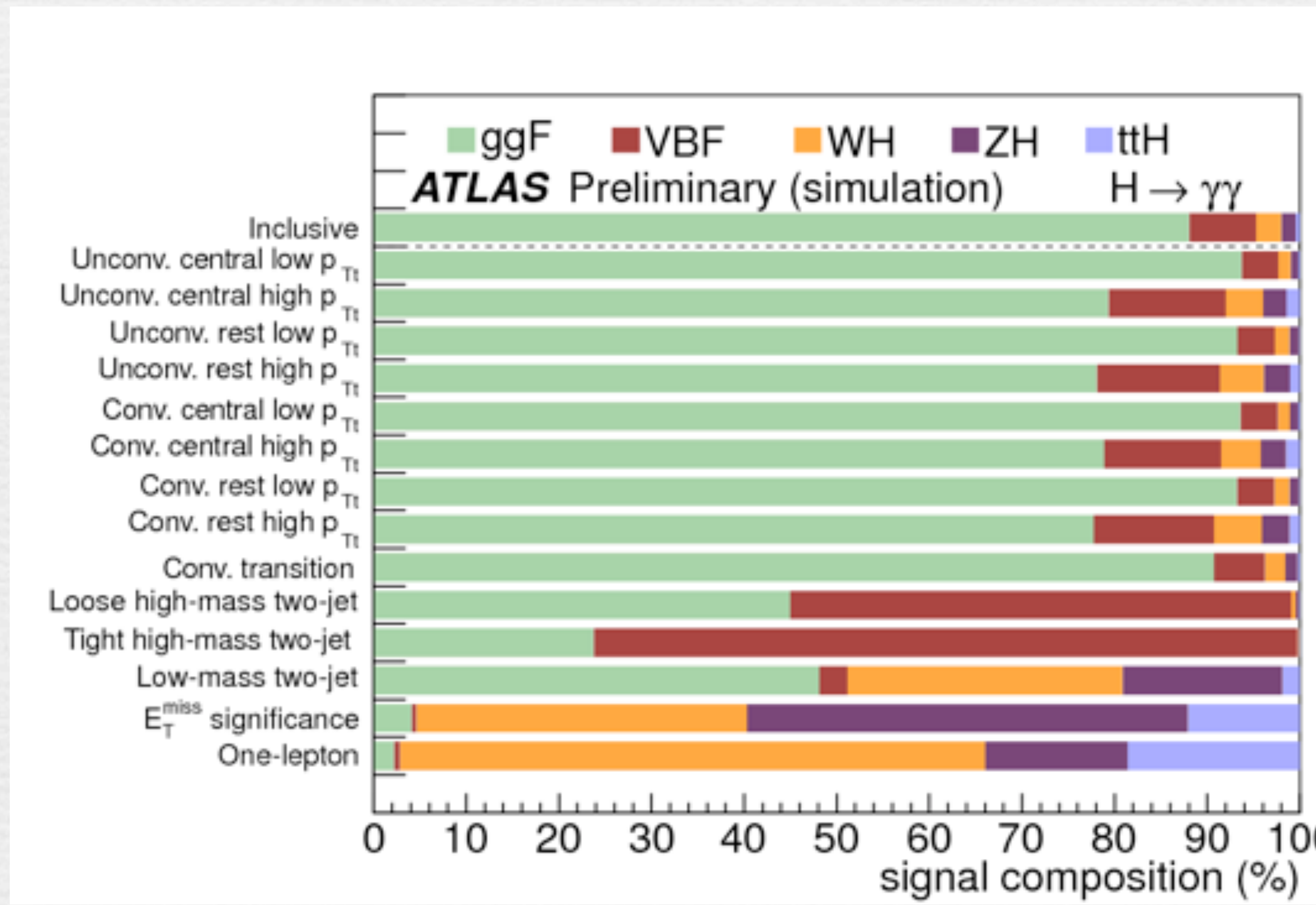
# Event categorization

Selected events are separated exclusive categories based on the existence of the extra jets, leptons, and $E_T^{miss}$

- To increase the sensitivity to the overall signals
- To specify the production processes (it is crucial to measure the couplings)

**H→γγ** 9 categories for ggF, 2 categories for VBF, 3 for VH




ggH

VBF

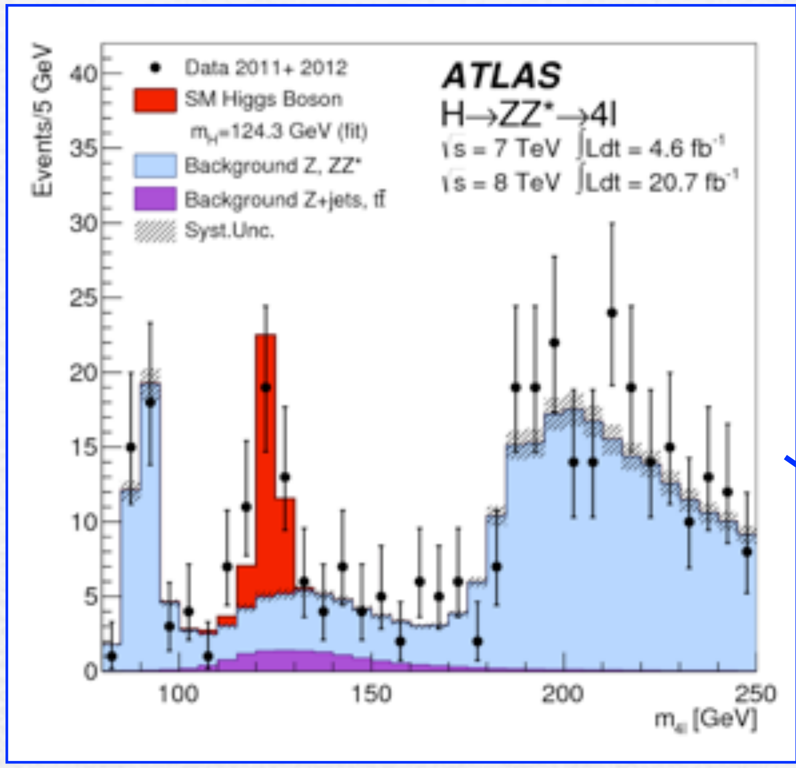
VH

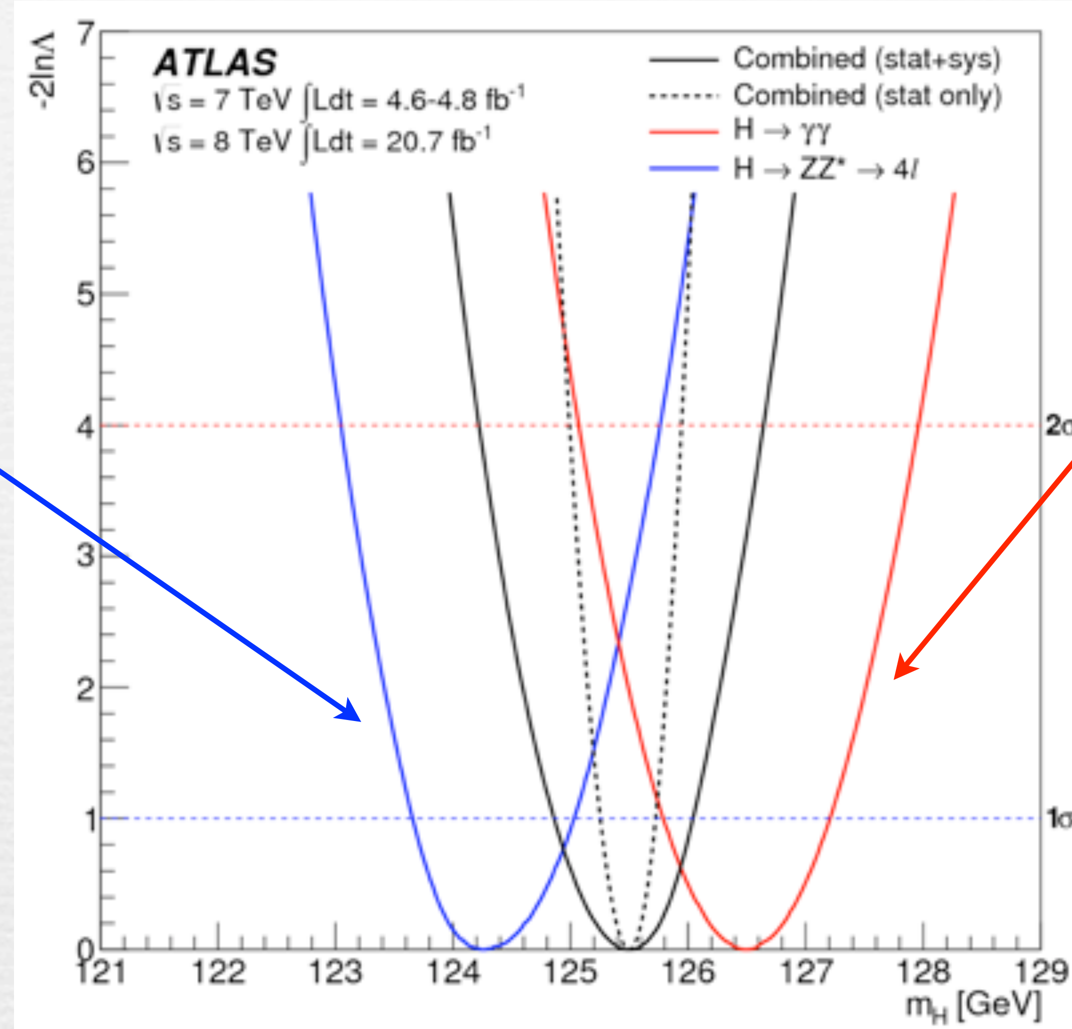
**H→ZZ** no other objects for ggF, di-jet for VBF, lepton for VH

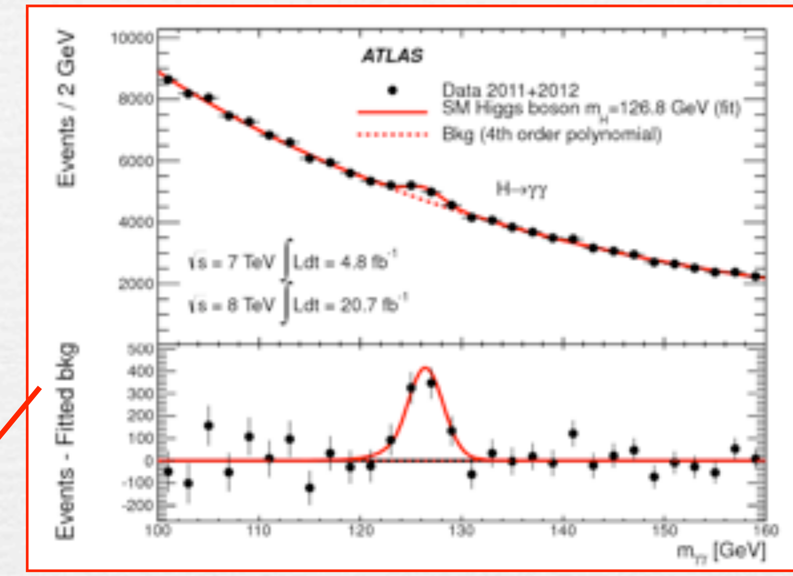
**H→WW** 0-jet and 1-jet for ggF, or 2- jets for VBF

# Mass of the new boson

arXiv:1307.1427




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

$$\Delta m_H = m_H^{\gamma\gamma} - m_H^{ZZ} = 2.3\ ^{+0.3}_{-0.7}\ (\mathrm{stat}) \pm 0.6\ (\mathrm{sys})\ \mathrm{GeV}$$

Mass difference ~2.4 $\sigma$ (1.5% probability to occur)

It increases to 8%, if we assume a flat prior for the energy scale uncertainties

# Signal strength

arXiv:1307.1427

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

$\mu$=1 (if SM Higgs), $\mu$=0 (if no SM Higgs)

combined

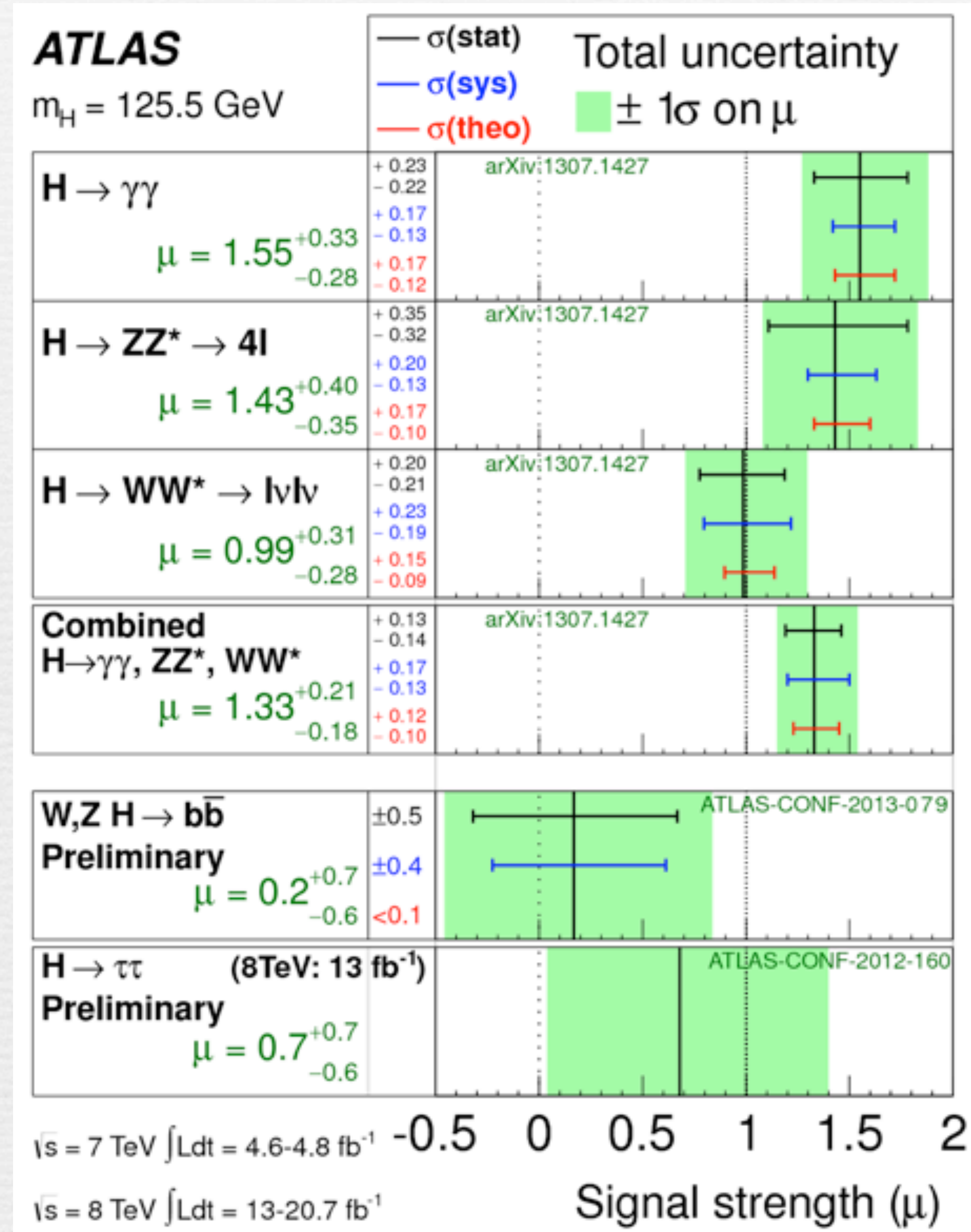
$$\mu = 1.33 \pm 0.14(\mathrm{stat}) \pm 0.15(\mathrm{sys})$$

($m_H$=125.5GeV)

Result is consistent with the SM prediction with 15% precision.

H→bb and H→$\tau\tau$ not in the combination

Statistical, systematic and theory (QCD scale, PDF) uncertainties are already comparable.



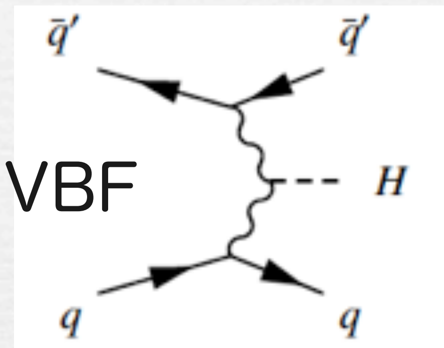
# Evidence for production via VBF

arXiv:1307.1427

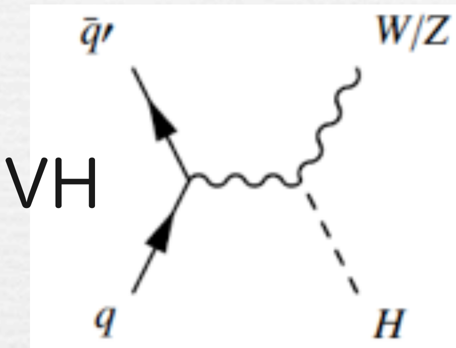
Signal strength categorized by

vector-boson-mediated processes and gluon-mediated processes

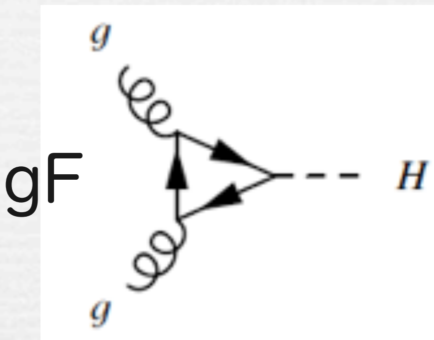
VBF



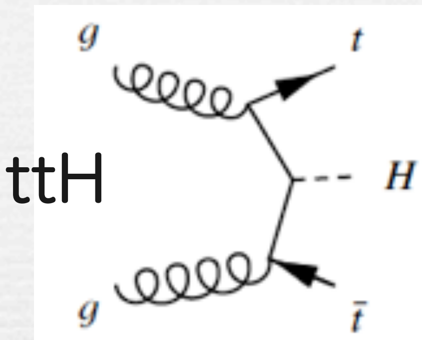
VH

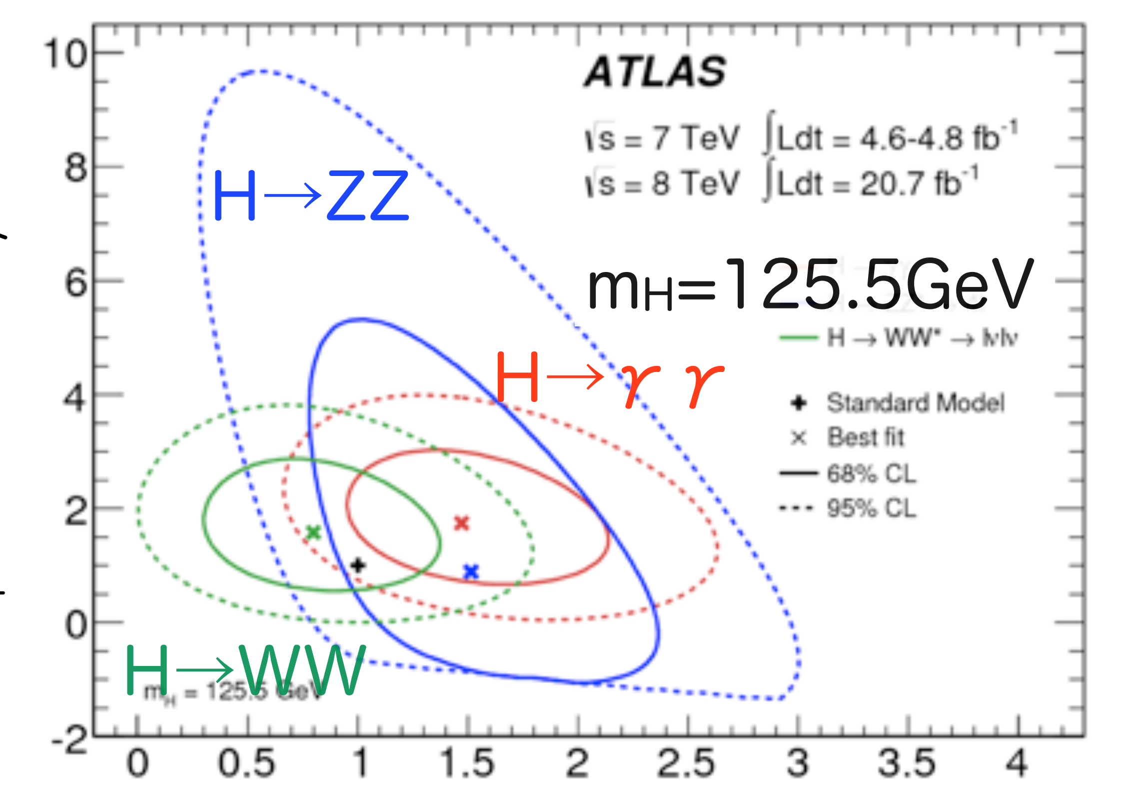


ggF



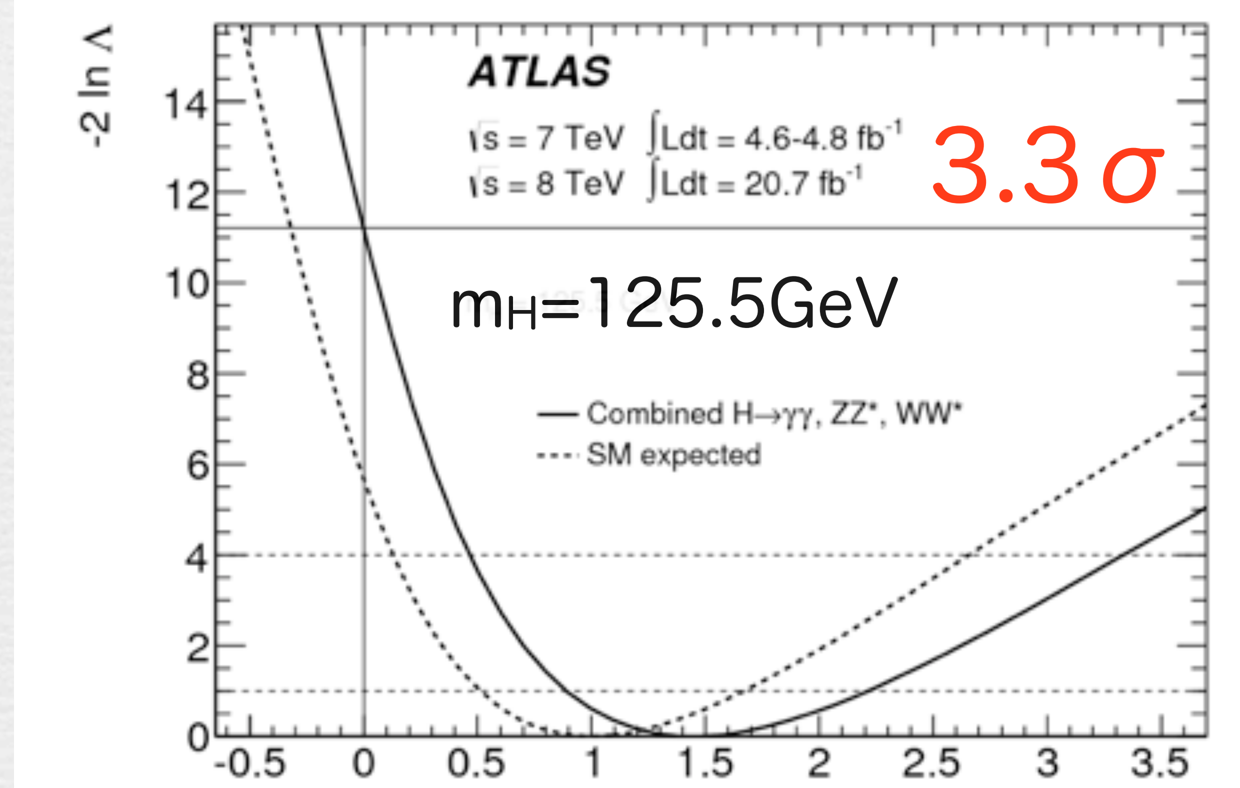
ttH






$\mu_{VBF+VH} \times B/B_{SM}$

$\mu_{ggF+ttH} \times B/B_{SM}$




$\mu_{VBF}/\mu_{ggF+ttH}$

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

3.3σ evidence that a fraction of Higgs boson production occurs through VBF

# Coupling measurements

Crucial test of the SM Higgs mechanism

coupling to fermion $g_F = \sqrt{2}\frac{m_F}{v}$ coupling to gauge boson $g_V = 2\frac{m_V^2}{v}$

SM couplings are tested introducing coupling scale factors $\kappa$ : $g_i = g_i^{\mathrm{SM}} \times \kappa_i$

The total Higgs boson width is also tested introducing $\kappa_H{}^2$ : $\Gamma_H = \Gamma_H^{\mathrm{SM}} \times \kappa_H^2$

Assumption for the coupling measurements:

1 resonance, zero-width approximation, SM Lagrangian tensor structure ($J^P=0^+$)

$$\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

For example, gg→H→$\gamma\gamma$ process can be written as

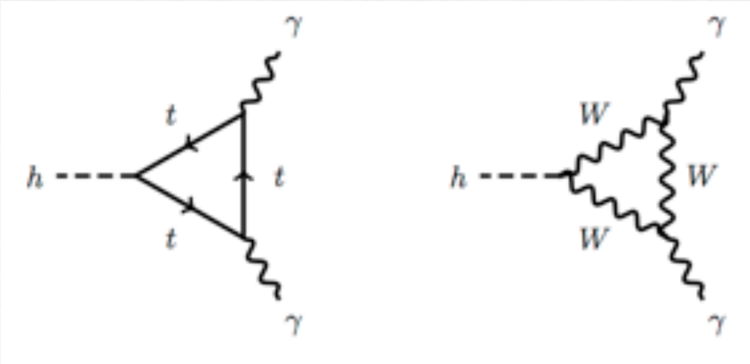
$$\frac{\sigma \cdot \mathrm{B}(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$\kappa_H$ and effective scale factors $\kappa_\gamma$, $\kappa_g$ (loop induced processes)

- Expressed as a function of the SM coupling scale factors

$\kappa_\gamma(\kappa_W, \kappa_t)$ $\kappa_g(\kappa_b, \kappa_t)$ $\kappa_H(\kappa_b, \kappa_W, \kappa_Z, \ldots)$

- Treated as free parameters to test BSM contributions

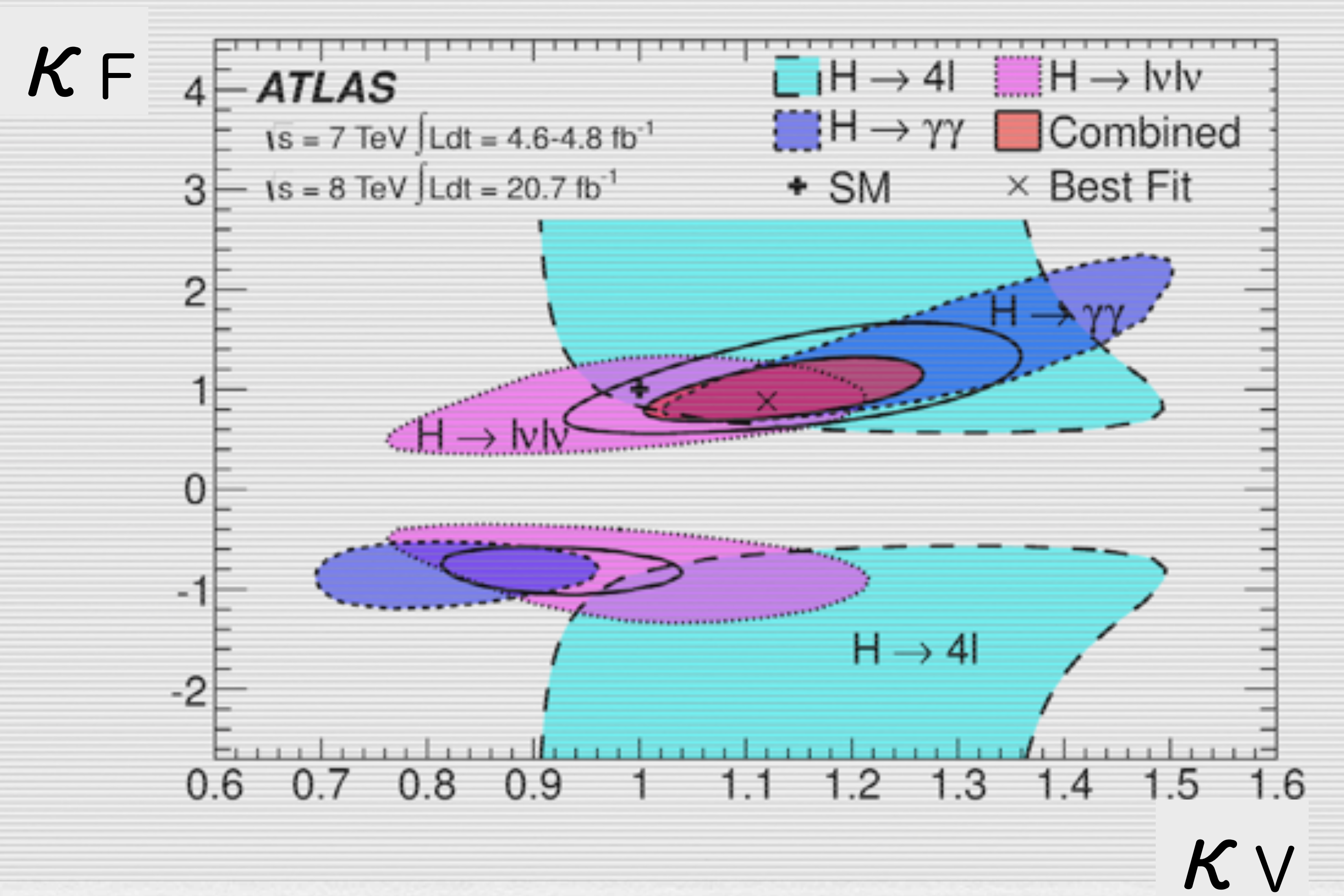


# Couplings to fermions and bosons

arXiv:1307.1427

We assume

- One coupling scale factor for fermions ....... $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \ldots.$
- One coupling scale factor for bosons ........ $\kappa_V = \kappa_W = \kappa_Z$
- $\kappa_g$, $\kappa_\gamma$, and $\kappa_H$ depends only on $\kappa_F$ and $\kappa_V$ → No contributions from BSM



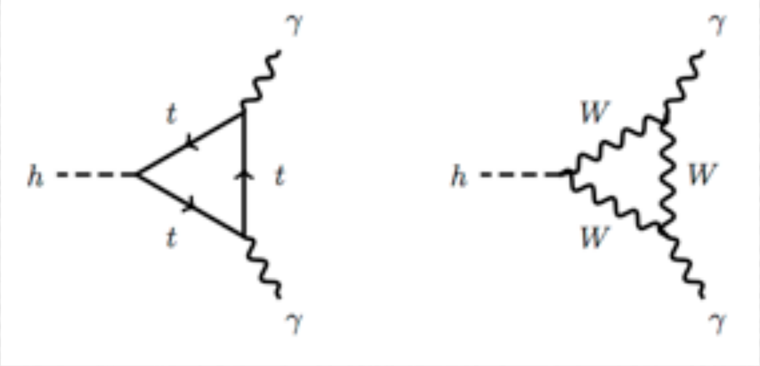

$$\kappa_F \in [0.76, 1.18]$$

$$\kappa_V \in [1.05, 1.22]$$

at 68% C.L.

compatibility of the SM is 12%

$$\kappa_\gamma^2 \simeq |1.26\kappa_V - 0.26\kappa_F|^2$$




H→$\gamma\gamma$ prefers the minimum with positive relative sign

- Provided by the negative interference between W-boson loop and t-quark loop

$\kappa_F$=0 is excluded at >5$\sigma$ (mainly through gg→H production loop)

# Loop induced couplings ( $\kappa_g$ v.s. $\kappa_\gamma$ )

arXiv:1307.1427

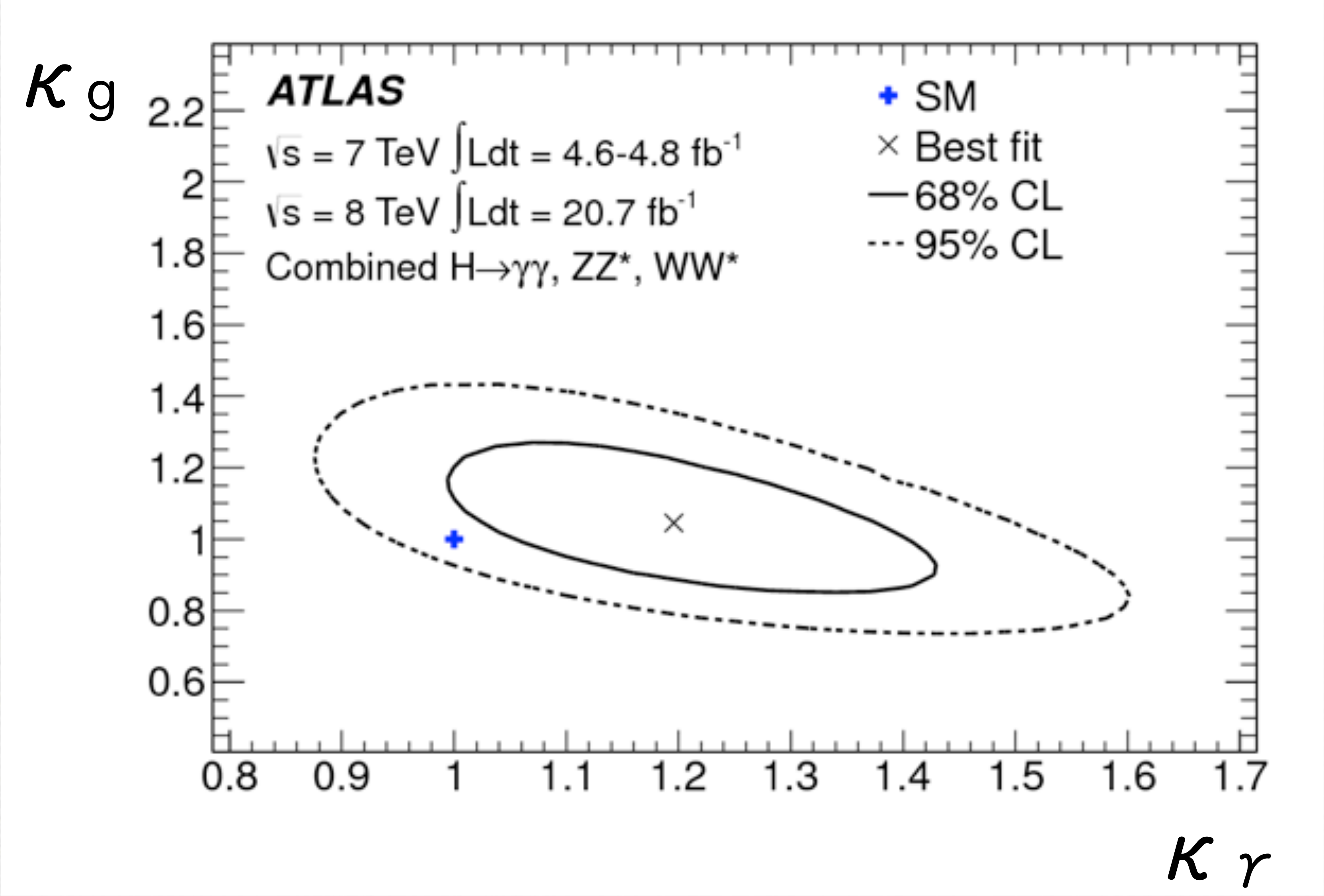
Prove the BSM contributions in the loop of gg→H and H→$\gamma\gamma$

We assume

Couplings of the known particles to the Higgs boson have SM strength

$$\kappa_W = \kappa_Z = \kappa_t = \kappa_b = \kappa_\tau = \ldots = 1$$

New particles do not contribute to the Higgs boson width $\Gamma_H$




$$\kappa_g = 1.04 \pm 0.14$$

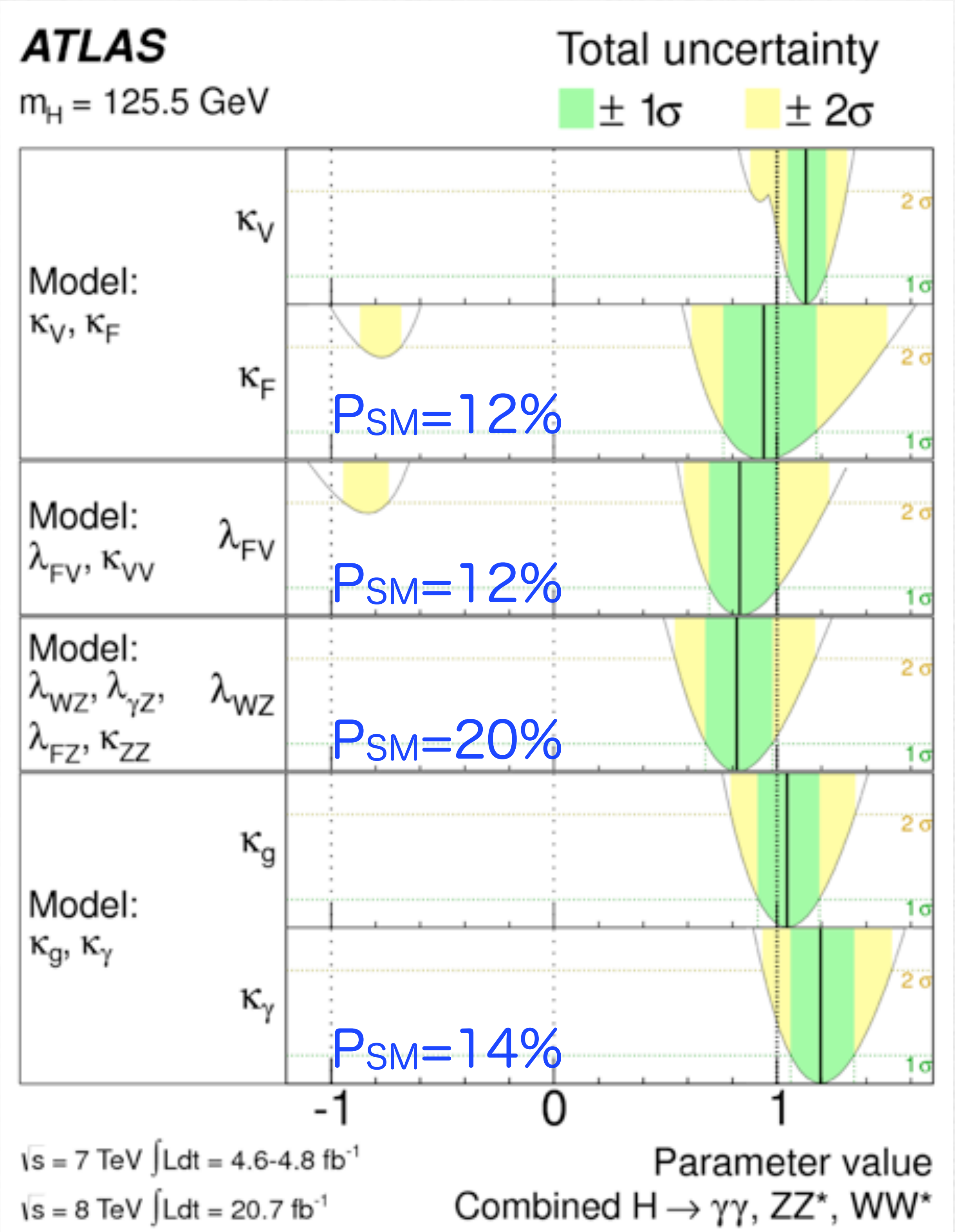
$$\kappa_\gamma = 1.20 \pm 0.15$$

at 68% C.L.

Compatibility of the SM is 14%

# Summary of the Higgs couplings

arXiv:1307.1427




Measurements compatible with SM Higgs expectations

Their compatibilities are 12%~20%

# Spin-Parity Determination

SM Higgs boson is scalar particle, i.e. $J^P=0^+$

Several alternative specific models, $J^P= 0^-, 1^+, 1^-, 2^+$, are tested against the SM Higgs $J^P=0^+$ hypothesis, using angular and kinematic distributions in $H\to\gamma\gamma$, $H\to ZZ\to 4$ lepton, and $H\to WW\to e\nu\mu\nu$

- For $J^P=2^+$, Graviton-inspire model with minimal coupling to SM particles is chosen

arXiv:1001.3396

$H\to\gamma\gamma$

Only sensitive for $J^P=0^+$ v.s. $J^P=2^+$

Landau-Yang theorem forbids the direct decay of an on-shell spin-1 particle into a pair of massless particles

$H\to WW$

Used to test $J^P=0^+$ v.s. $J^P=1^-, 1^+$, and $2^+$

Only $WW\to e\nu\mu\nu$ is used

$H\to ZZ\to 4$ lepton

Used to test $J^P=0^+$ v.s. $J^P=0^-, 1^-, 1^+$, and $2^+$

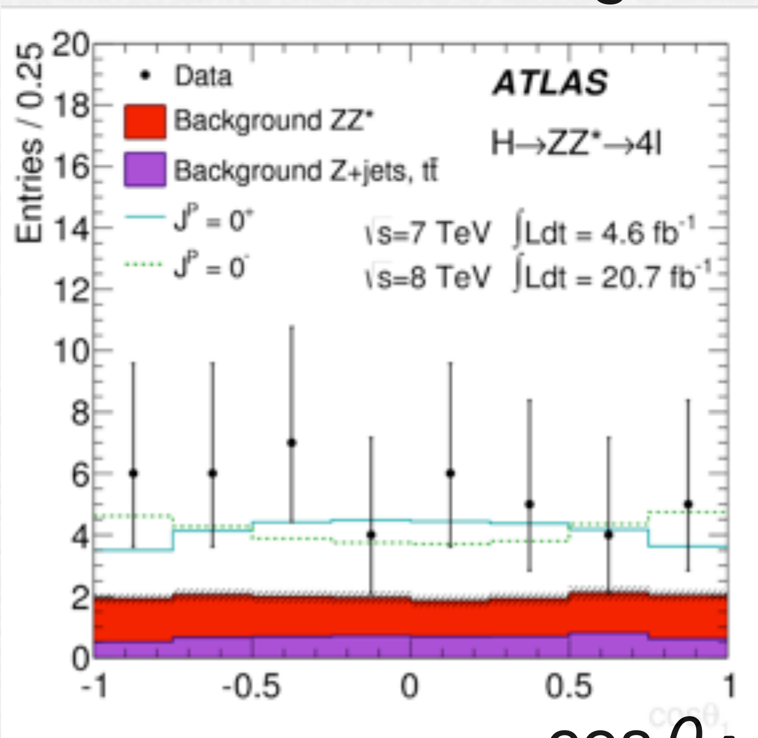
arXiv:1307.1432

# $J^P=0^+$ v.s. $0^-$

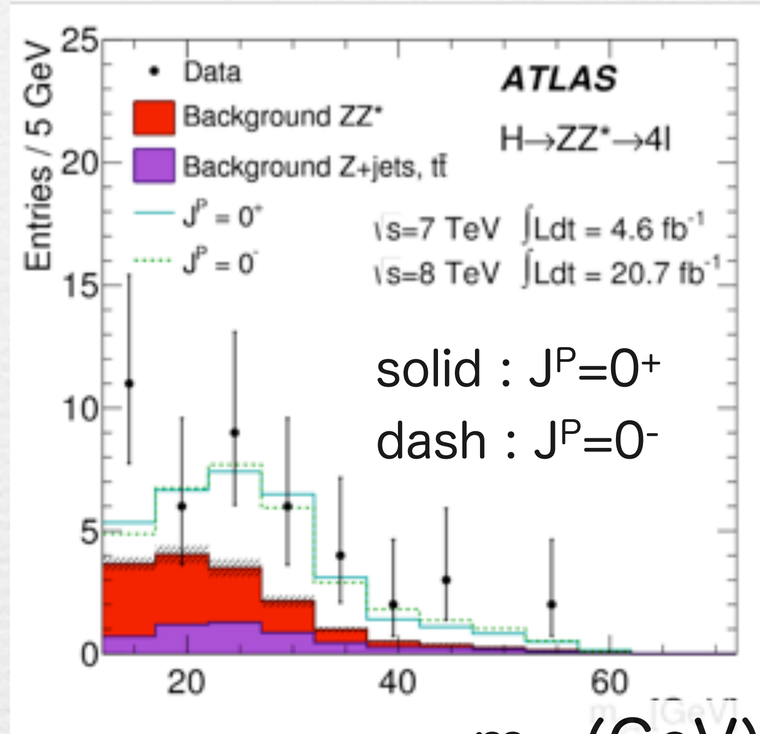
J=0 boson is produced mainly from gluon-gluon fusion

Only $ZZ^* \rightarrow 4$ lepton is used for this study

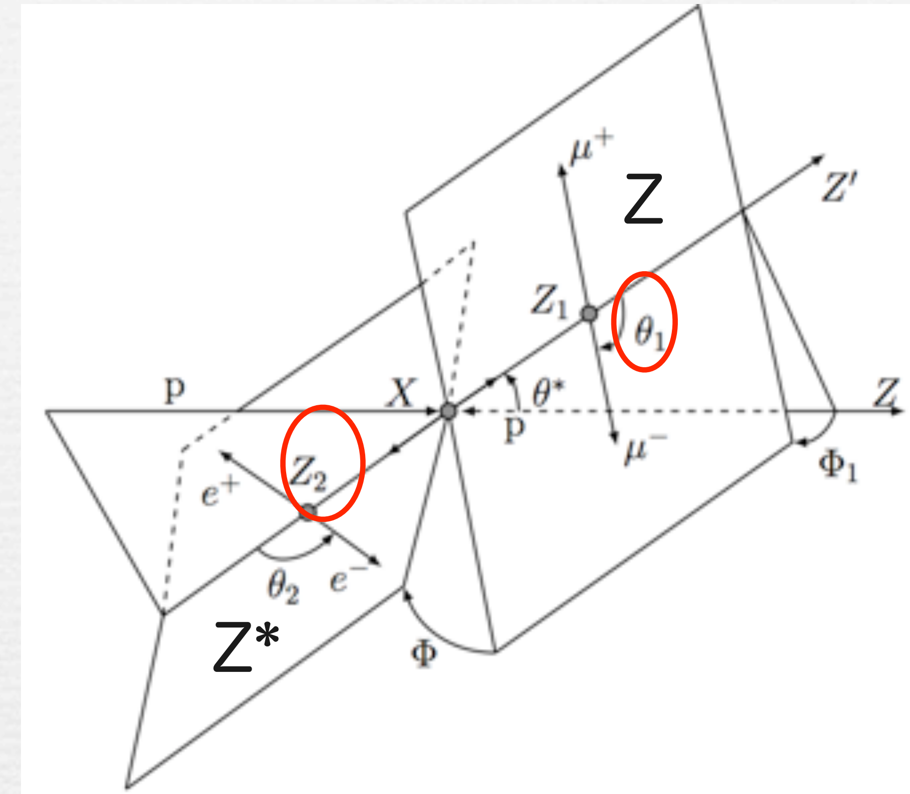
$m_{12}$, $m_{34}$, and 5 angles are the input of the BDT

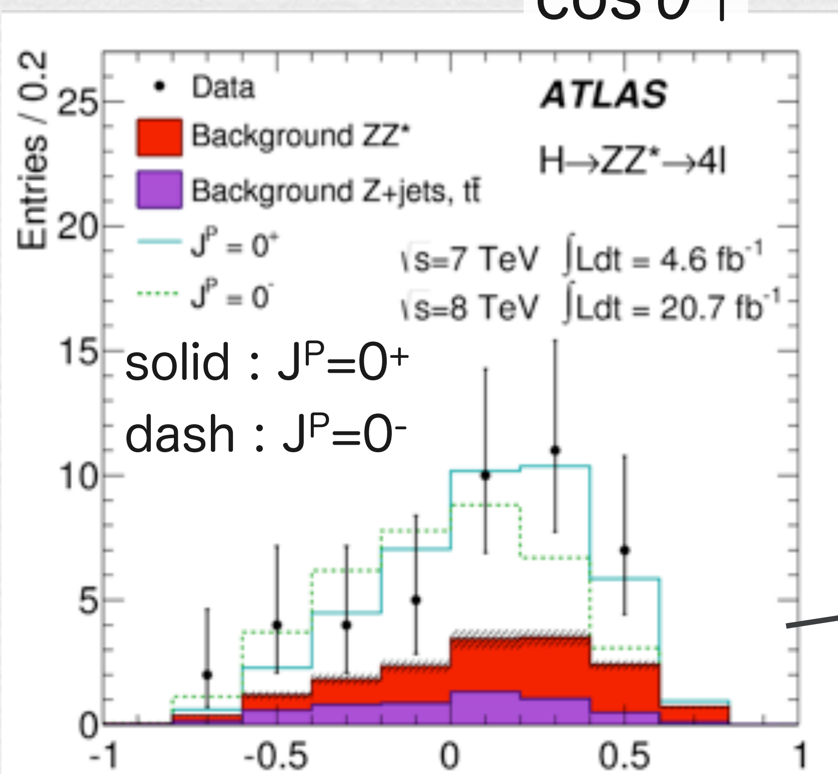



cos $\theta_1$




$m_{34}$(GeV)

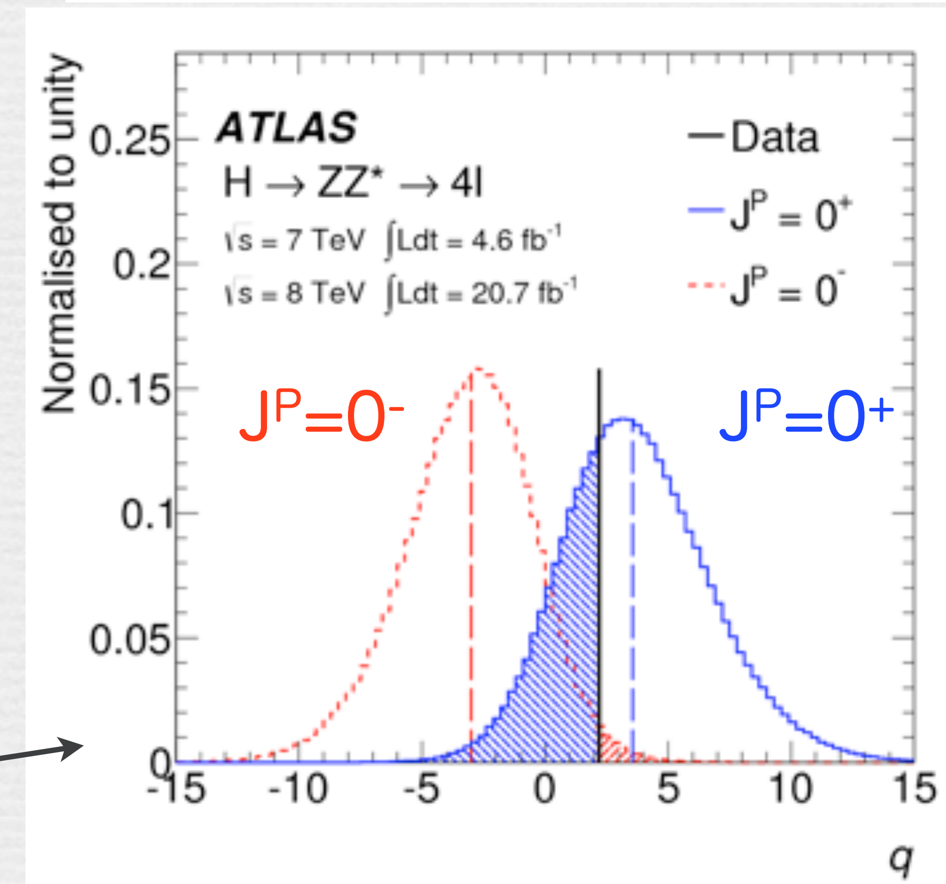



BDT output

Log likelihood ratio q

$$q = \log \frac{L(J^P = 0^+)}{L(J^P = 0^-)}$$




Data agree with 0+ hypothesis,
0- hypothesis is excluded at 97.8% C.L.

# $J^P=0^+$ v.s. $1^+$ / $1^-$

arXiv:1307.1432

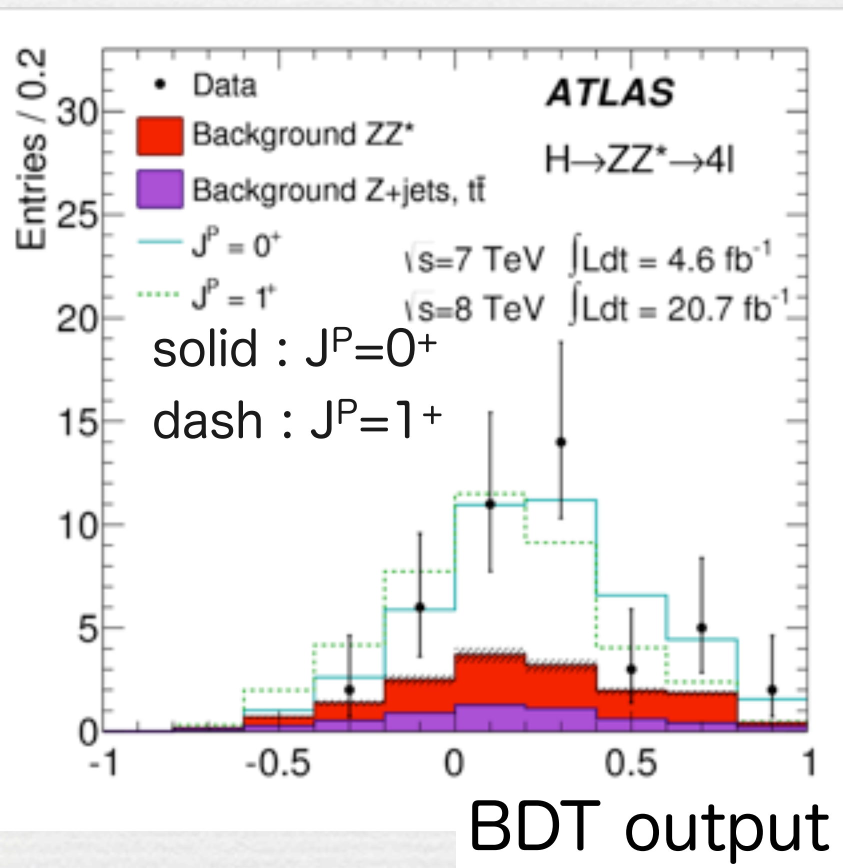
J=1 boson is produced only from qqbar annihilation

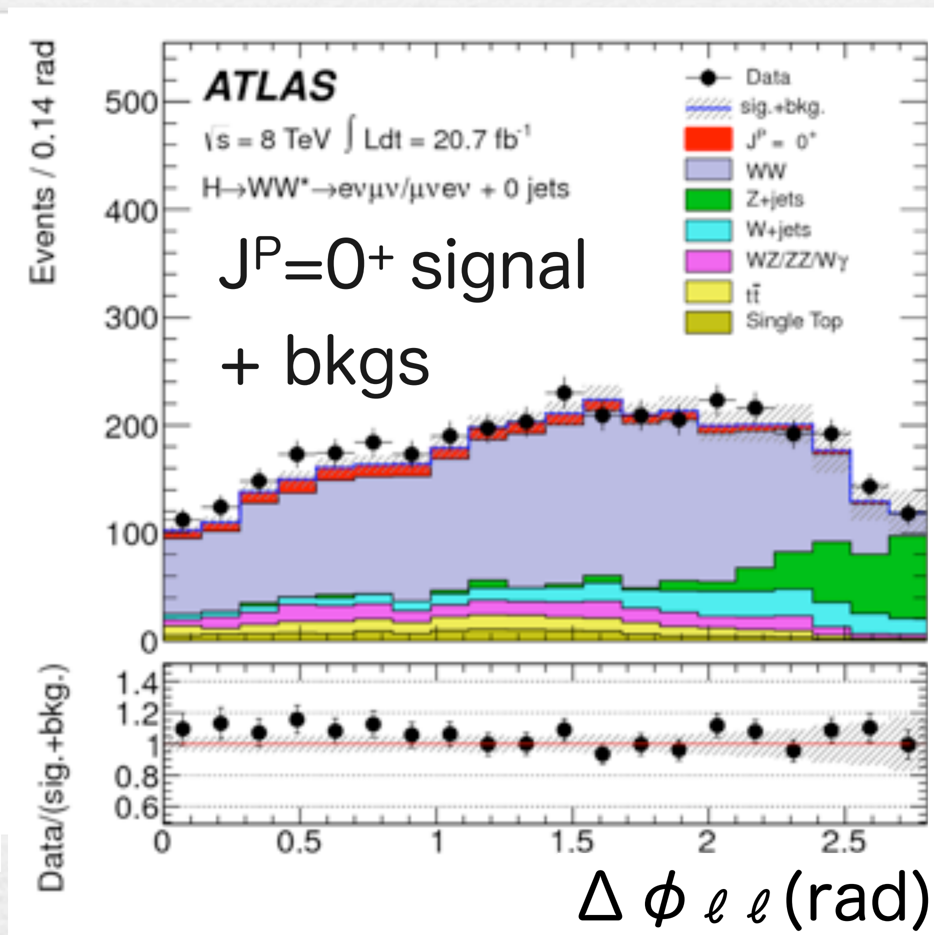
ZZ*→4 lepton and WW→$\ell\nu\ell\nu$ are sensitive for this study

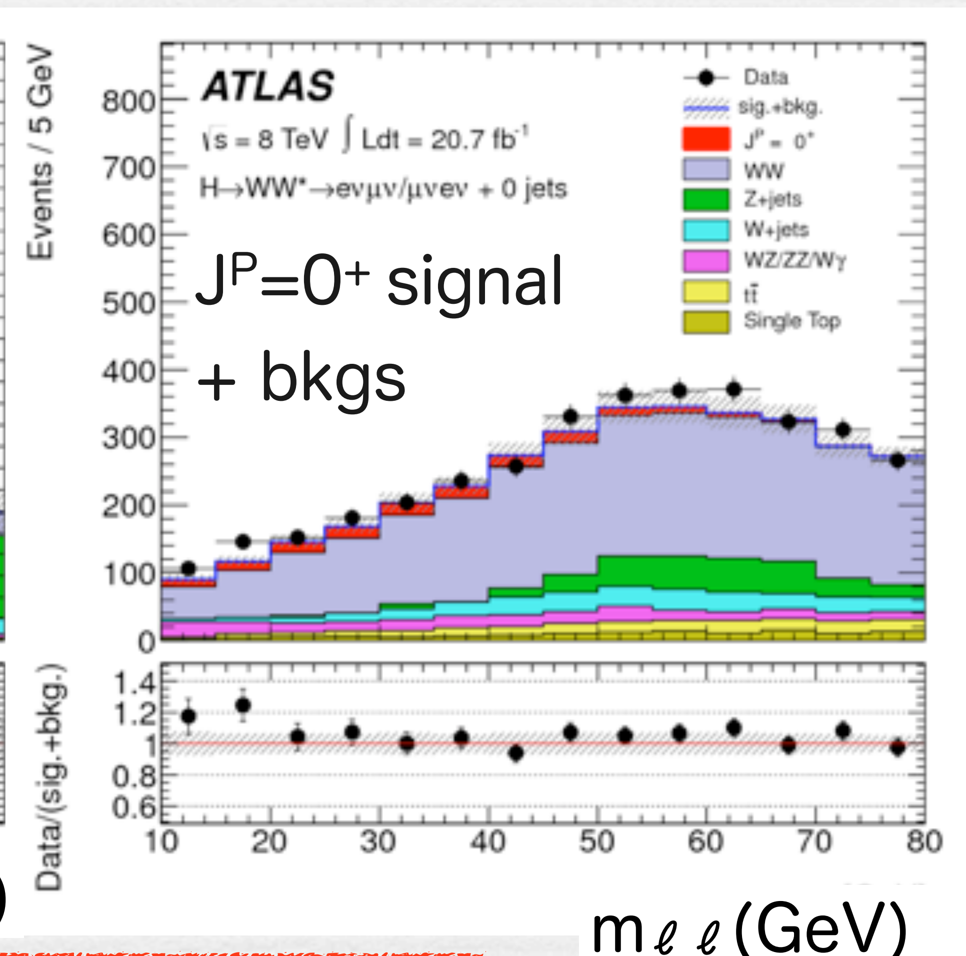
ZZ*→4 lepton : uses BDT from the inputs of $m_{12}$, $m_{34}$, and 5 angles

WW→$e\nu\mu\nu$ : uses 2 BDTs from the inputs of $m_T$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, and $p_T^{\ell\ell}$

- Classifier 1 : Distinguishes the $J^P=0^+$ from sum of the all backgrounds
- Classifier 2 : Distinguishes the $J^P=1^+$, $1^-$ from sum of the all backgrounds




Combined ZZ/WW data agree with 0+ hypothesis,
$J^P=1^+$ ($=1^-$) hypothesis is excluded at 99.97% (99.7%) C.L.

# $J^P=0^+$ v.s. $2^+$

arXiv:1307.1432

Graviton-inspire model with minimal coupling to SM particles is chosen

- $2^+$ boson can be produced via gluon-gluon or qqbar annihilation

$\gamma\gamma$, ZZ*→4 lepton and WW→$\ell\nu\ell\nu$ are sensitive for this study

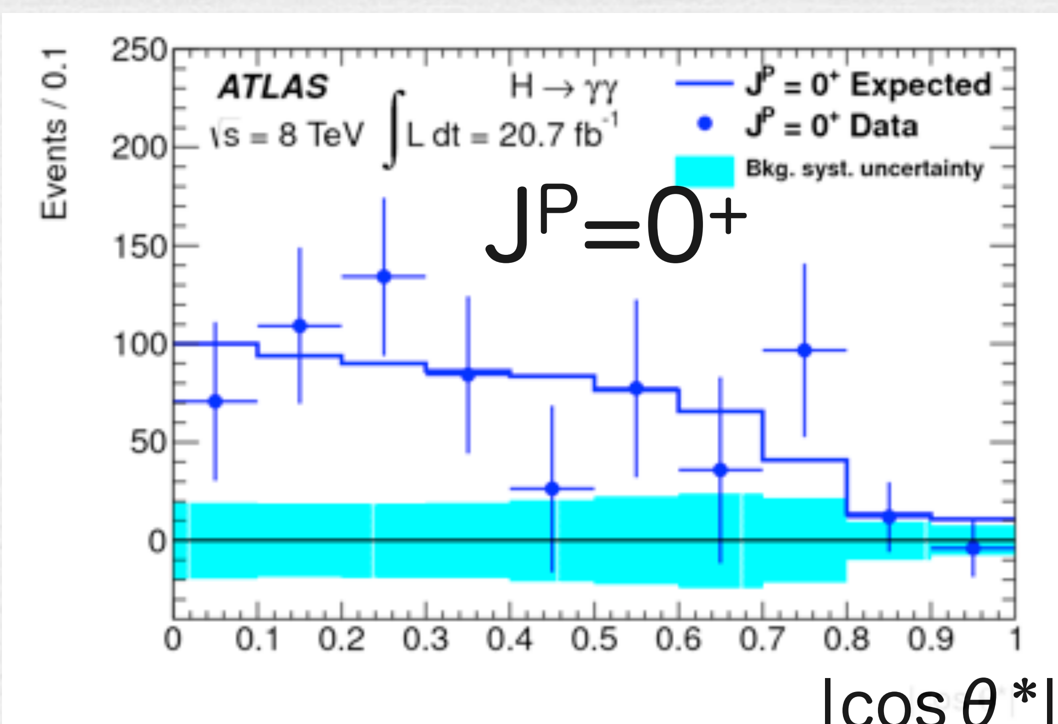
ZZ*→4 lepton : uses BDT from the inputs of $m_{12}$, $m_{34}$, and 5 angles

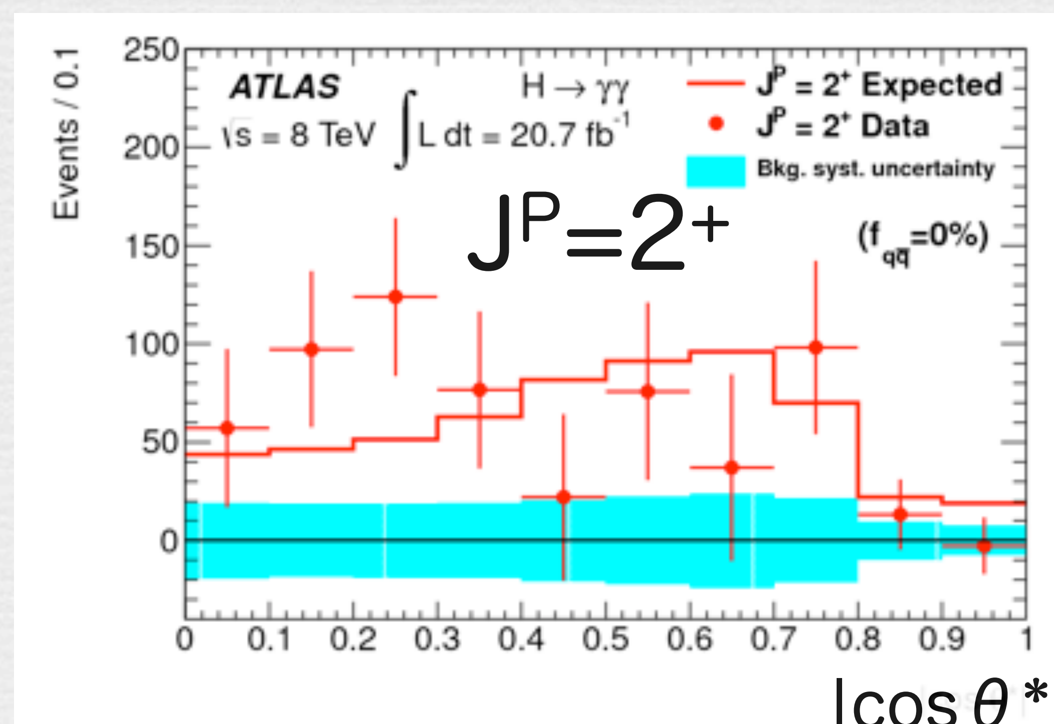
WW→$e\nu\mu\nu$ : uses 2 BDTs from the inputs of $m_T$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, and $p_T^{\ell\ell}$

$\gamma\gamma$ : uses $m_{\gamma\gamma}$ and decay angle $|\cos\theta^*|$ in di-photon rest frame,

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma}^2)}}\frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

$|\cos\theta^*|$ distribution for the backgrounds is extracted from sideband of $m_{\gamma\gamma}$



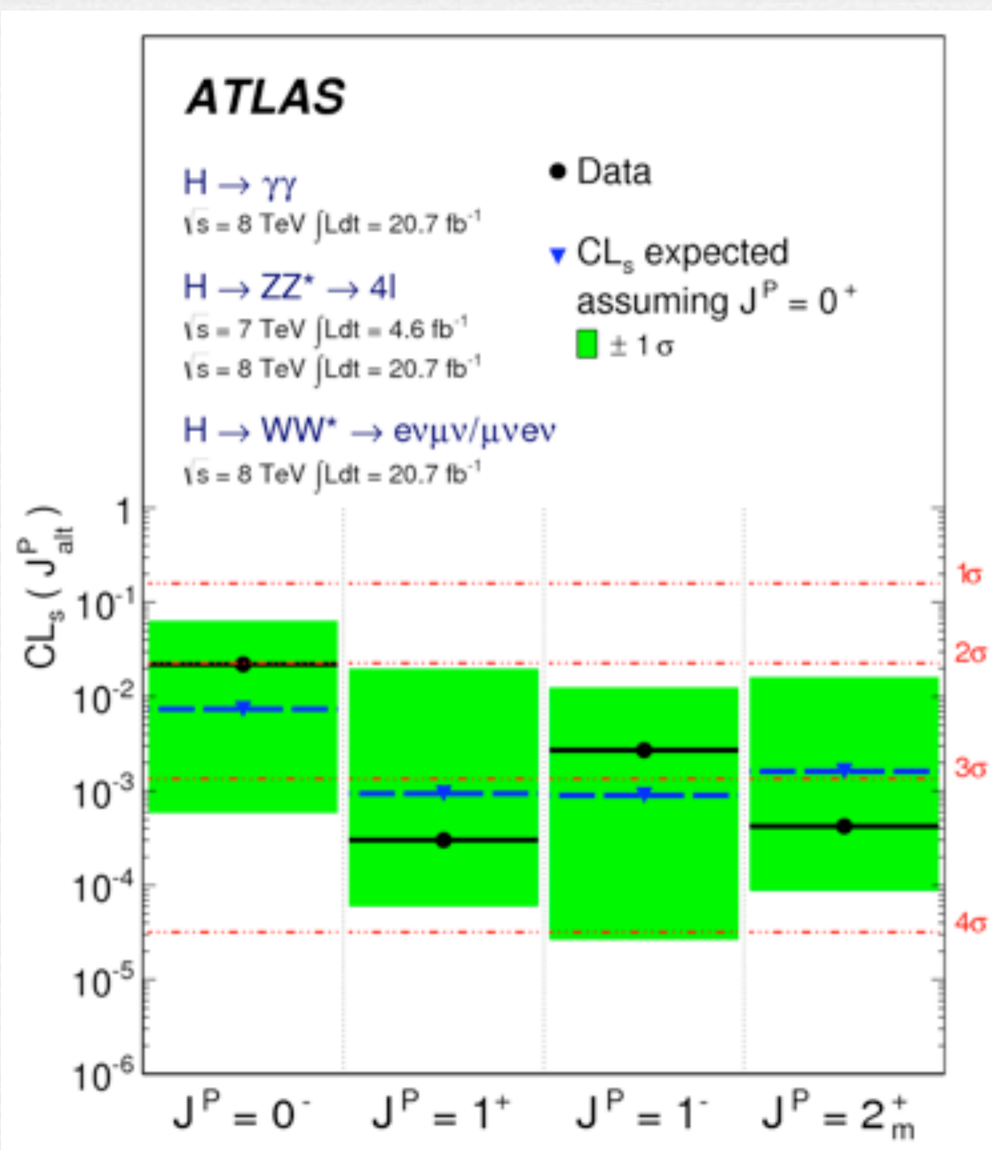

Data agree with 0+ hypothesis: $J^P=2^+$ hypothesis is excluded at 99.9% C.L.

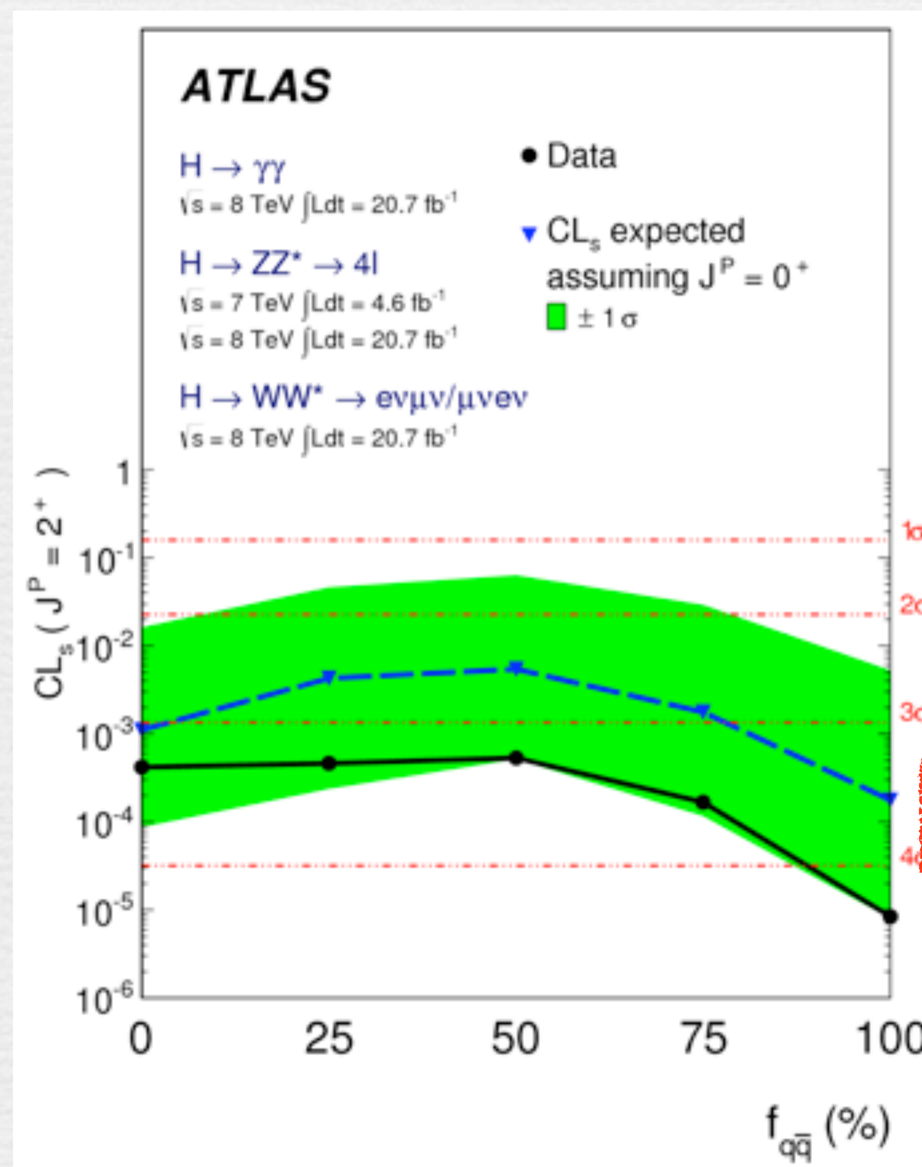
# Spin-Parity summary

arXiv:1307.1432

$J^P=0^-$, $1^+$, $1^-$ and $2^+$ are excluded at > 97.8% CL

- $2^+$ boson can be produced via gluon-gluon or qqbar annihilation
- It is tested as a function of $f_{qq}$ = fraction of qq/gg produced signals
  - $f_{qq}$=4% at LO for $2^+_m$ minimal model




- Data
- CLs expected assuming $J^P=0^+$

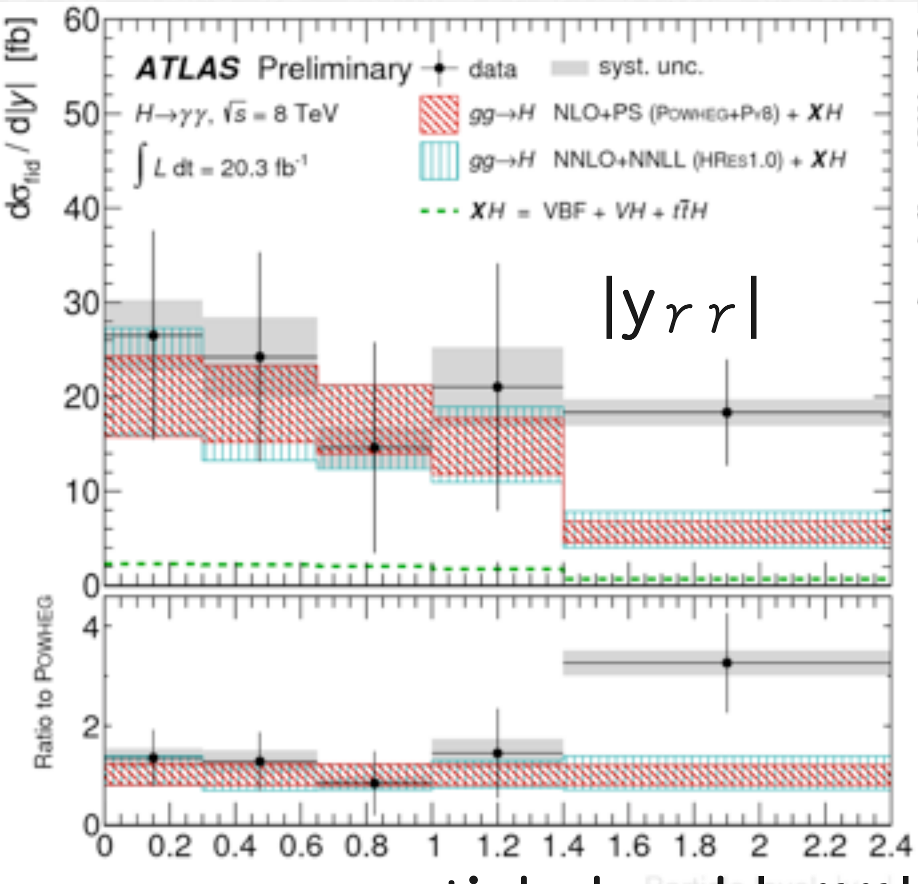
Compatible with SM $0^+$

# Differential cross-section in H→γγ

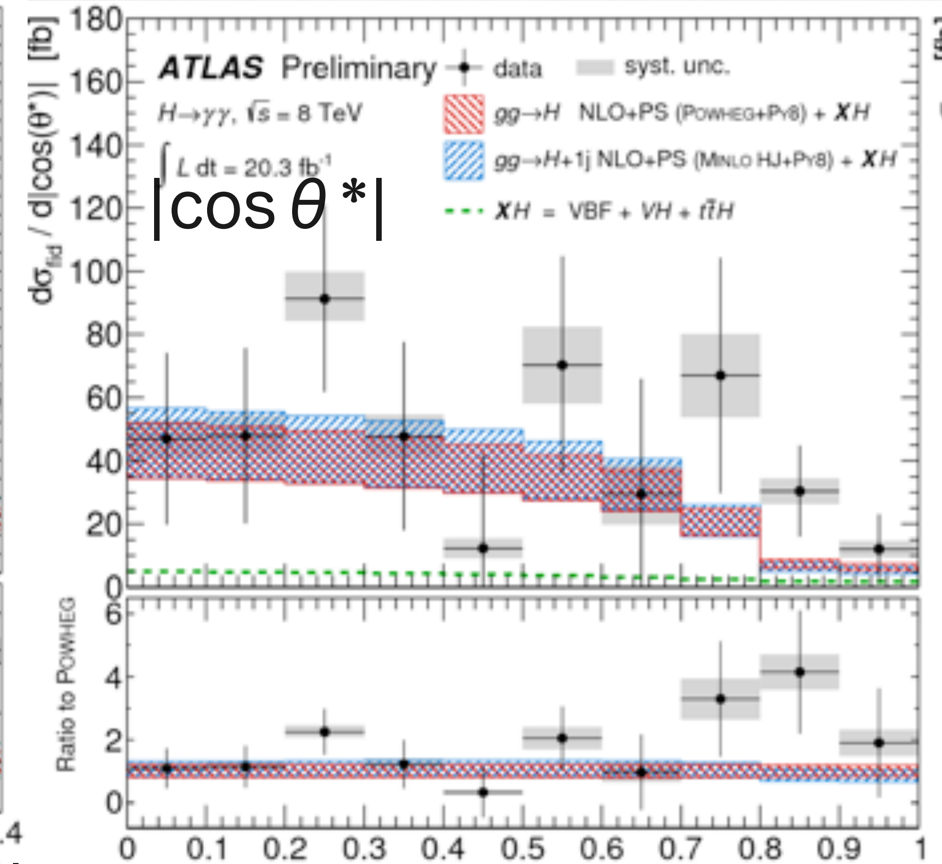
ATLAS-CONF-2013-072

We measured the fiducial differential cross-section as a function of

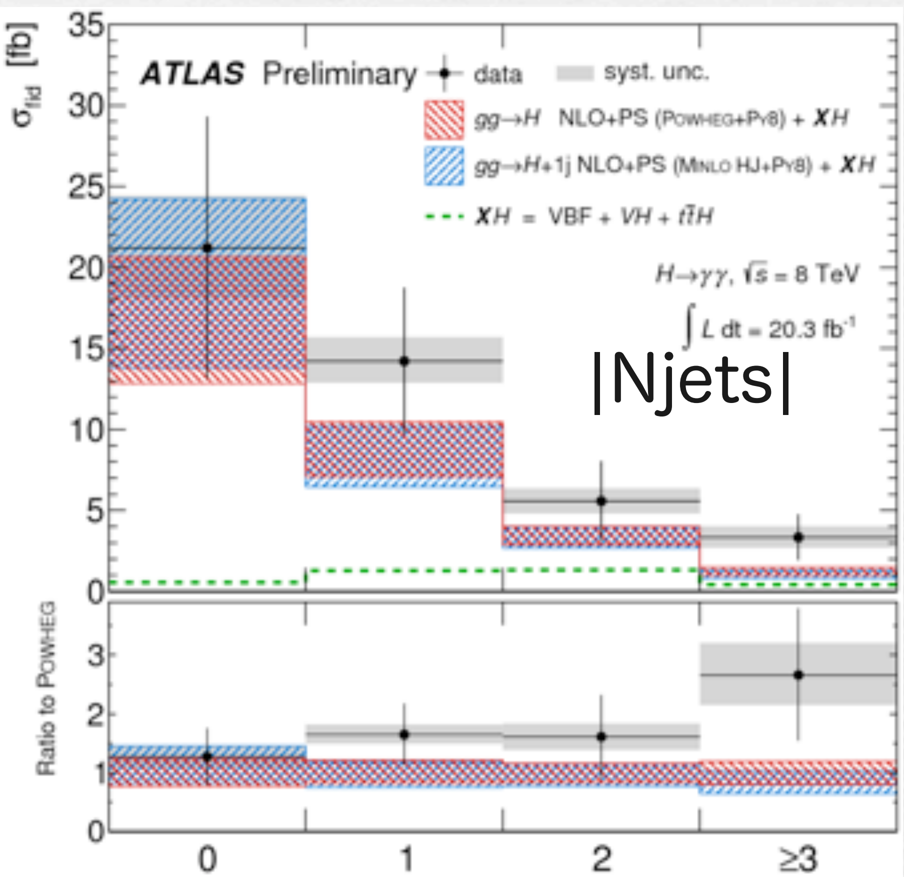
- 8 observables : $p_{T\gamma\gamma}$, $|y_{\gamma\gamma}|$, $|\cos\theta^*|$, $N_{jets}$, $\Phi_{jj}$, ....,
- The distributions are unfolded to particle level and compared with MC generators
- Sensitive to PDF, radiative correction, relative rate of Higgs production, spin,...




particle level $|y_{\gamma\gamma}|$




particle level $|\cos\theta^*|$




particle level Njets

Probability of $\chi^2$ test

| | $N_{\text{jets}}$ | $p_T^{\gamma\gamma}$ | $\lvert y^{\gamma\gamma}\rvert$ | $\lvert\cos\theta^*\rvert$ | $p_T^{j_1}$ | $\Delta\phi_{jj}$ | $p_T^{\gamma\gamma jj}$ |
|---|---|---|---|---|---|---|---|
| POWHEG | 0.54 | 0.55 | 0.38 | 0.69 | 0.79 | 0.42 | 0.50 |
| MINLO | 0.44 | – | – | 0.67 | 0.73 | 0.45 | 0.49 |
| HRES 1.0 | – | 0.39 | 0.44 | – | – | – | – |

No significant deviation from SM (POWHEG, MINLO, HRES1.0) is observed.

# Conclusions

LHC-ATLAS Run1 ends with a great success

Since the discovery of a new boson,
we have measured its property with increasing precision

- Mass is measured as $m_H = 125.5 \pm 0.2\ (\text{stat})\ ^{+0.5}_{-0.6}\ (\text{stat})\ \text{GeV}$
- Signal strength is measured as $\mu = 1.33 \pm 0.14(\text{stat}) \pm 0.15(\text{sys})$
- Evidence for the vector boson mediated process with $3.3\sigma$ significance
- Evidence for the coupling to the fermion with $>5\sigma$ significance
- Evidence for the $J^P=0^+$ scalar nature of the Higgs boson

All measured properties are compatible with the SM Higgs boson

LHC will increase $\sqrt{s}$ (=13~14TeV) and Luminosity (~$10^{34}cm^{-2}s^{-1}$)

- More precise measurements will be achieved to challenge the SM predictions.
- It will give us hints of the BSM

This is just the beginning of the exciting "Higgs physics"..... Stay tuned!!

# backup

# LHC-ATLAS Run I performance

LHC has performed very well

- Peak luminosity : 7.7 x $10^{33}$ $cm^{-2}$ $s^{-1}$
- Delivered luminosity to ATLAS ~29 $fb^{-1}$

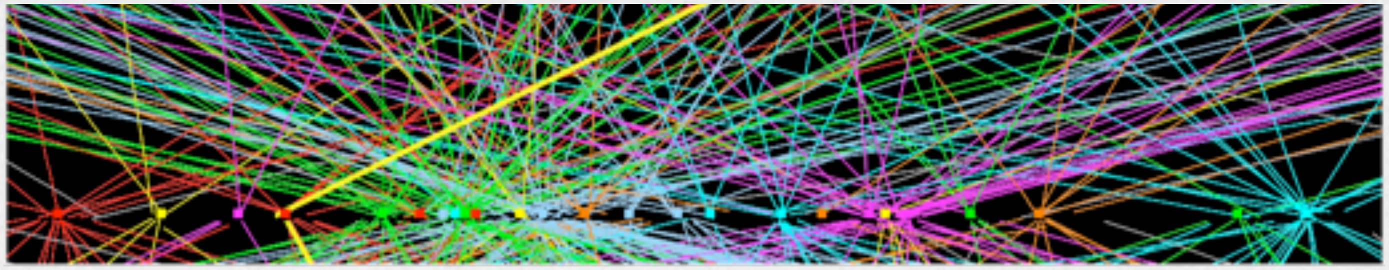
ATLAS collects good quality of data 95% of the time

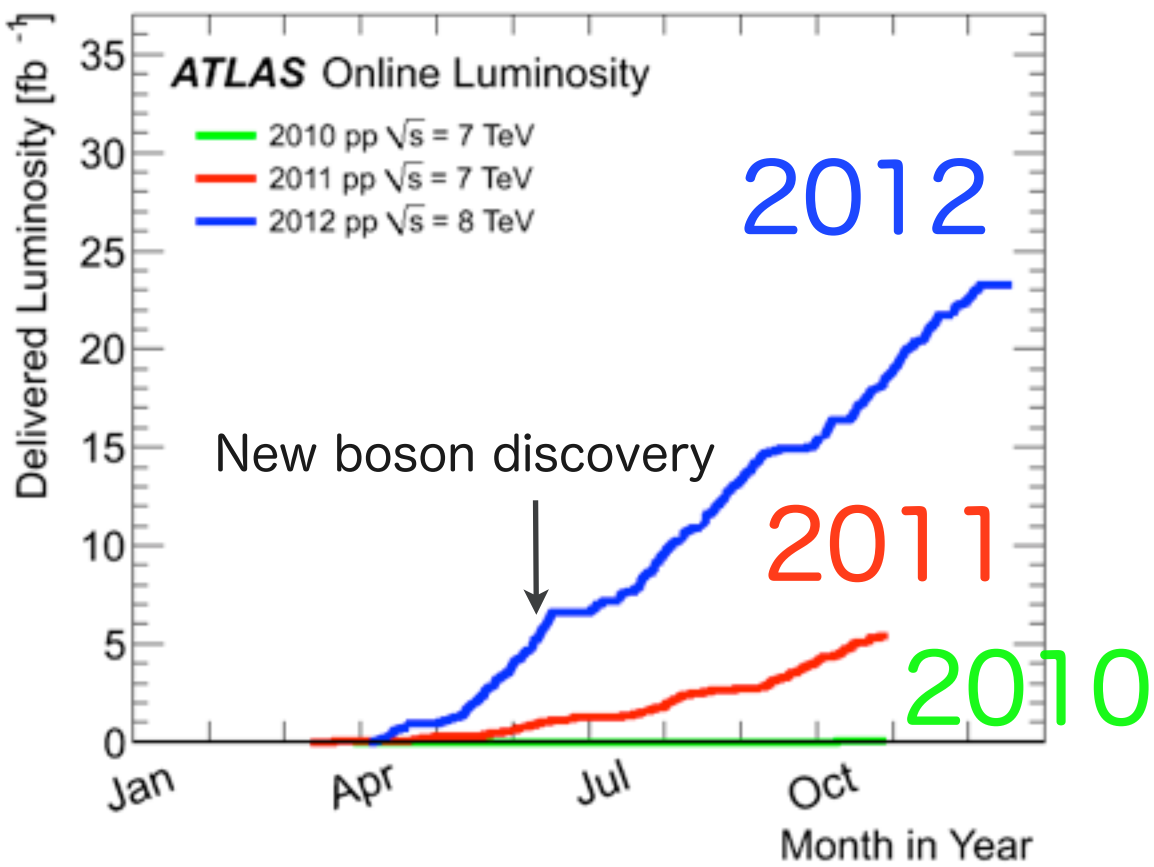
For physics analysis presented here, we use

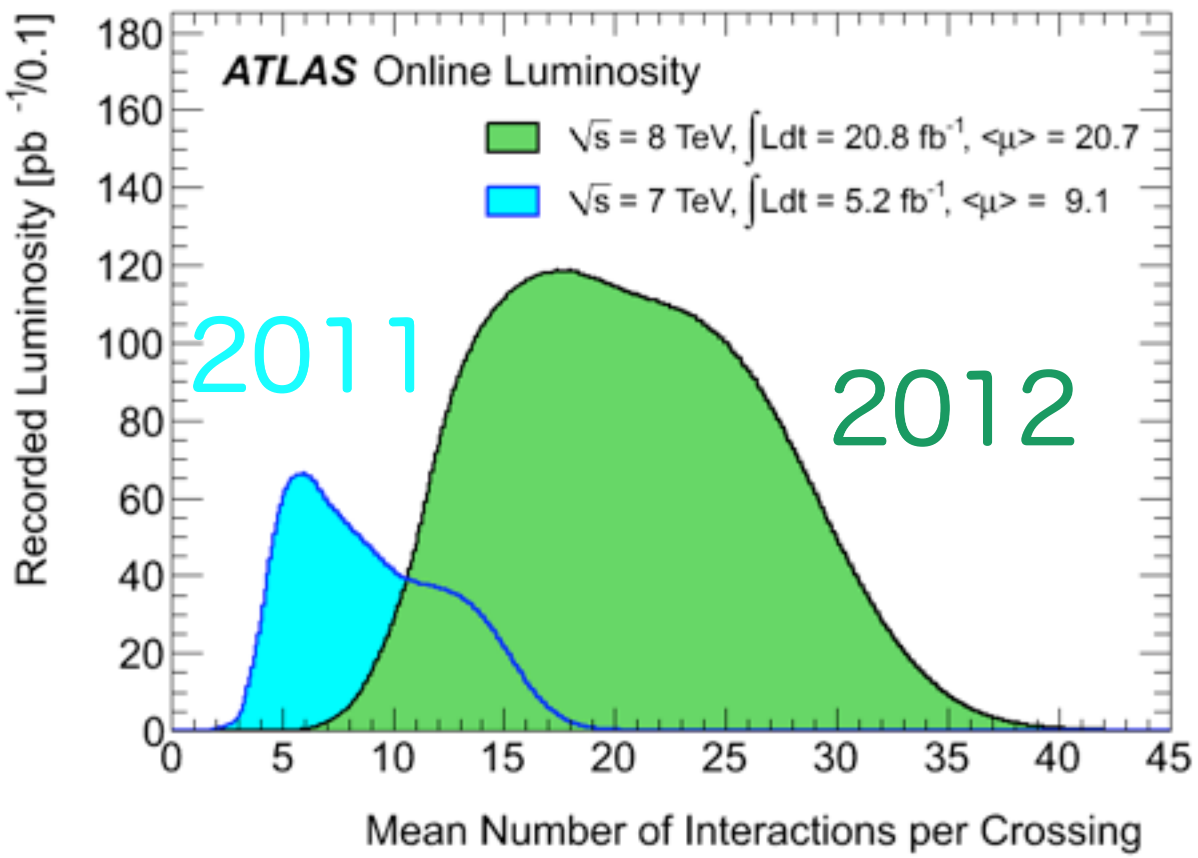
- ~5$fb^{-1}$ collected in 2011 $\sqrt{s} = 7$ TeV
- ~21$fb^{-1}$ collected in 2012 $\sqrt{s} = 8$ TeV

With increase of the luminosity, pile-up becomes higher.

Typically, we must reconstruct ~20 vertices within the space of ~5 cm (=p-beam length)



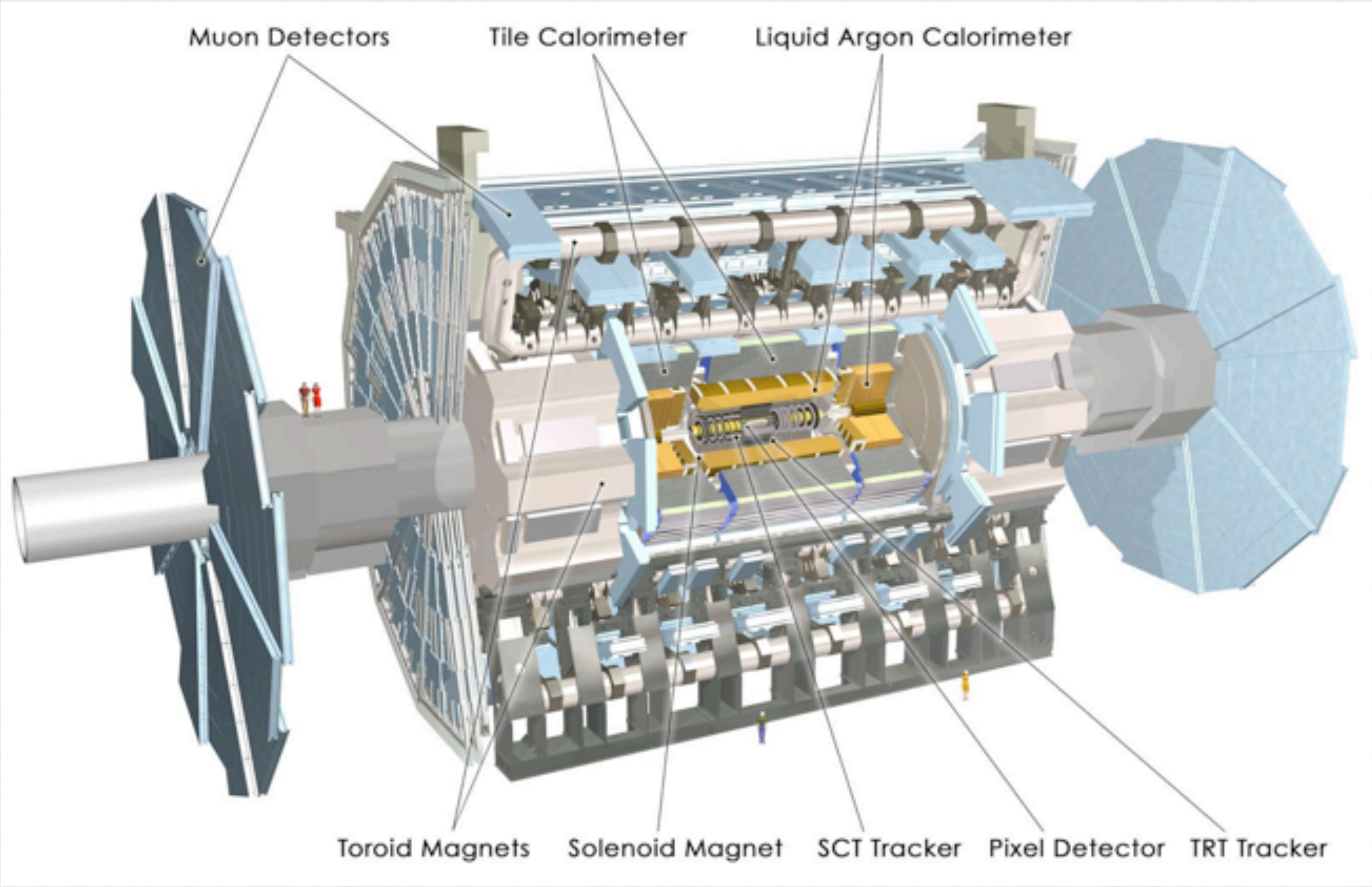


# ATLAS detector

The ATLAS detector was designed with discovery of the Higgs boson in mind.

- Precise measurement of the charged tracks by inner detectors
- Identification of electrons and photons against QCD jets
- Excellent calorimeter hermeticity and energy resolution
- Kinematics of photon path by fine segmentation of the calorimeter layer
- Precise muon reconstruction and triggering by muon detectors



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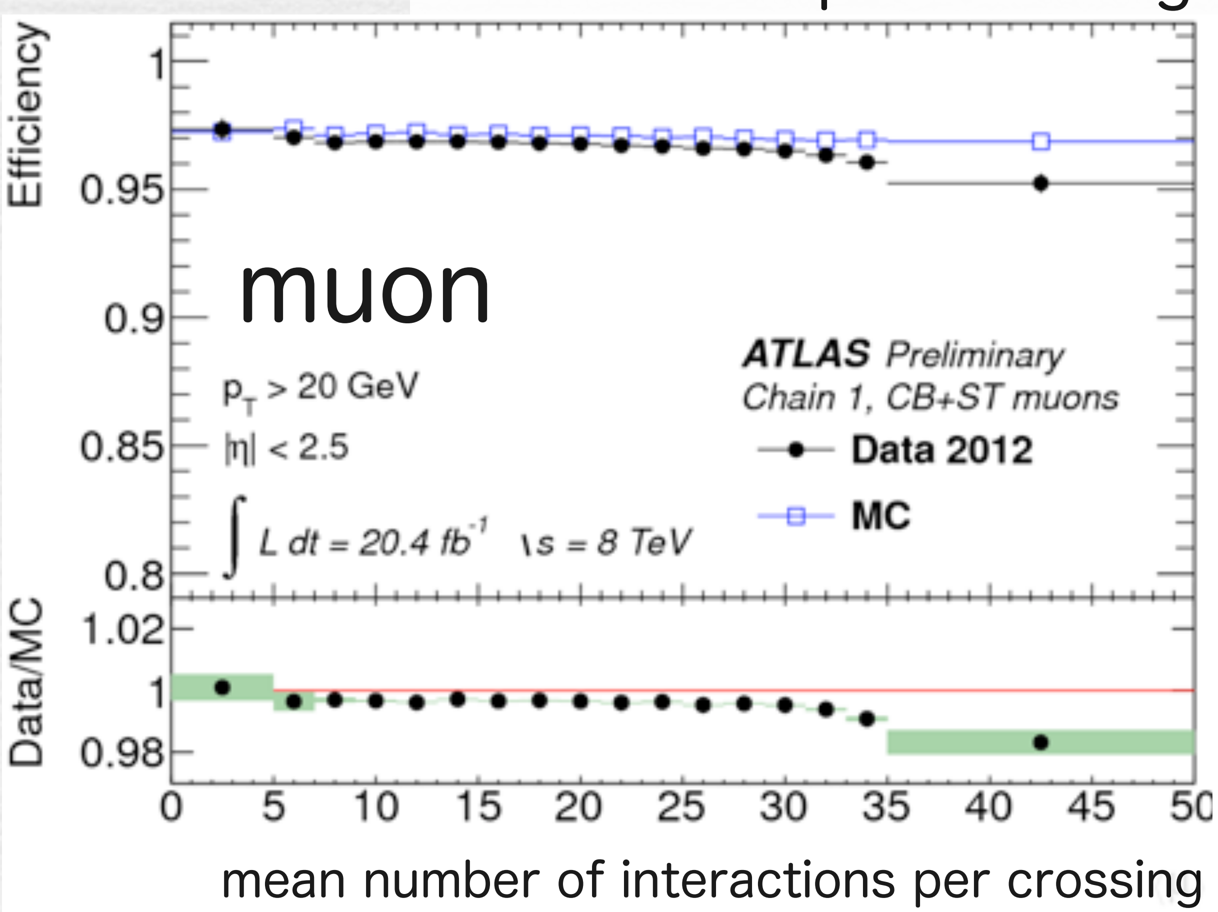
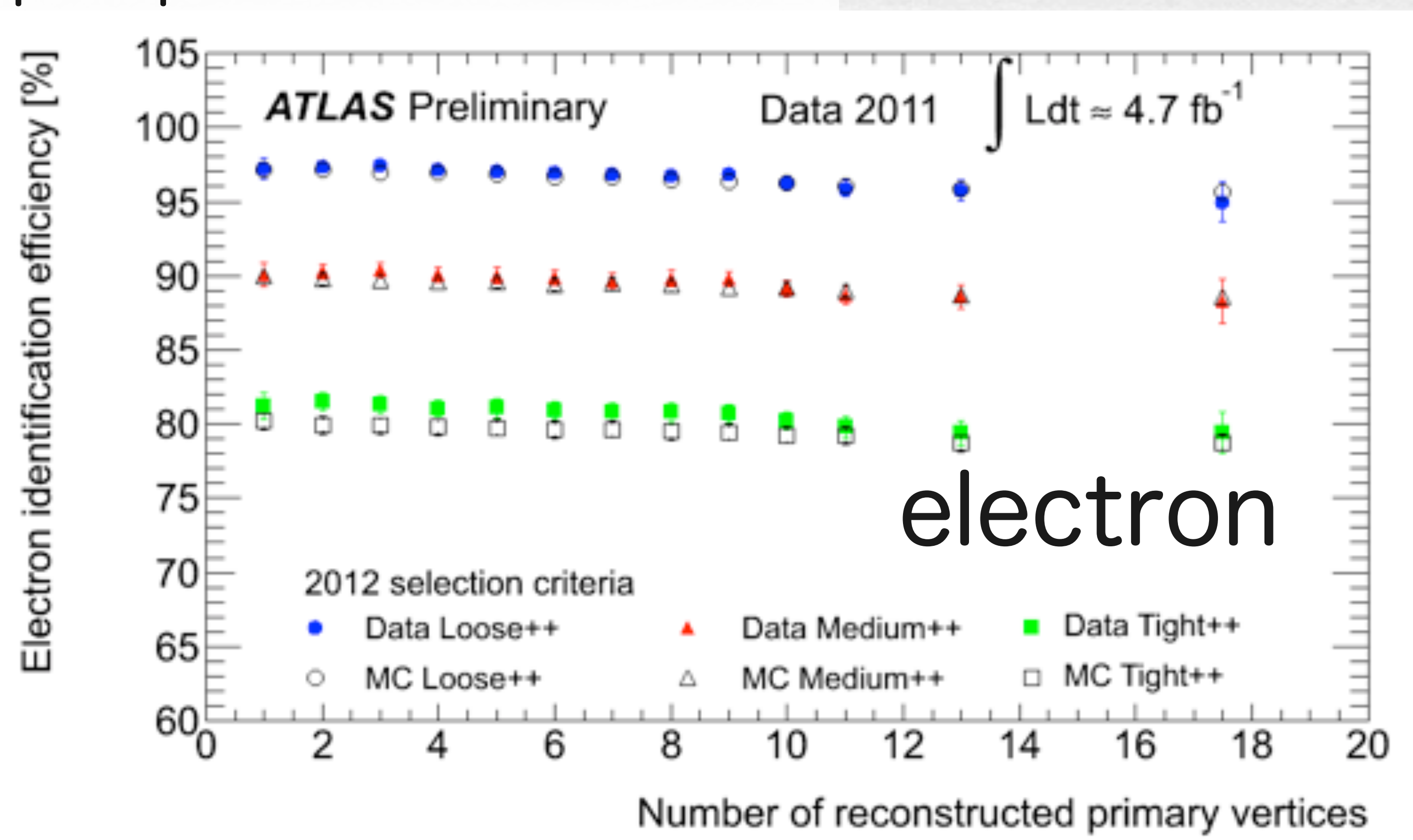
- Precise muon reconstruction and triggering by muon detectors

Detector response in high pileup is under-controlled



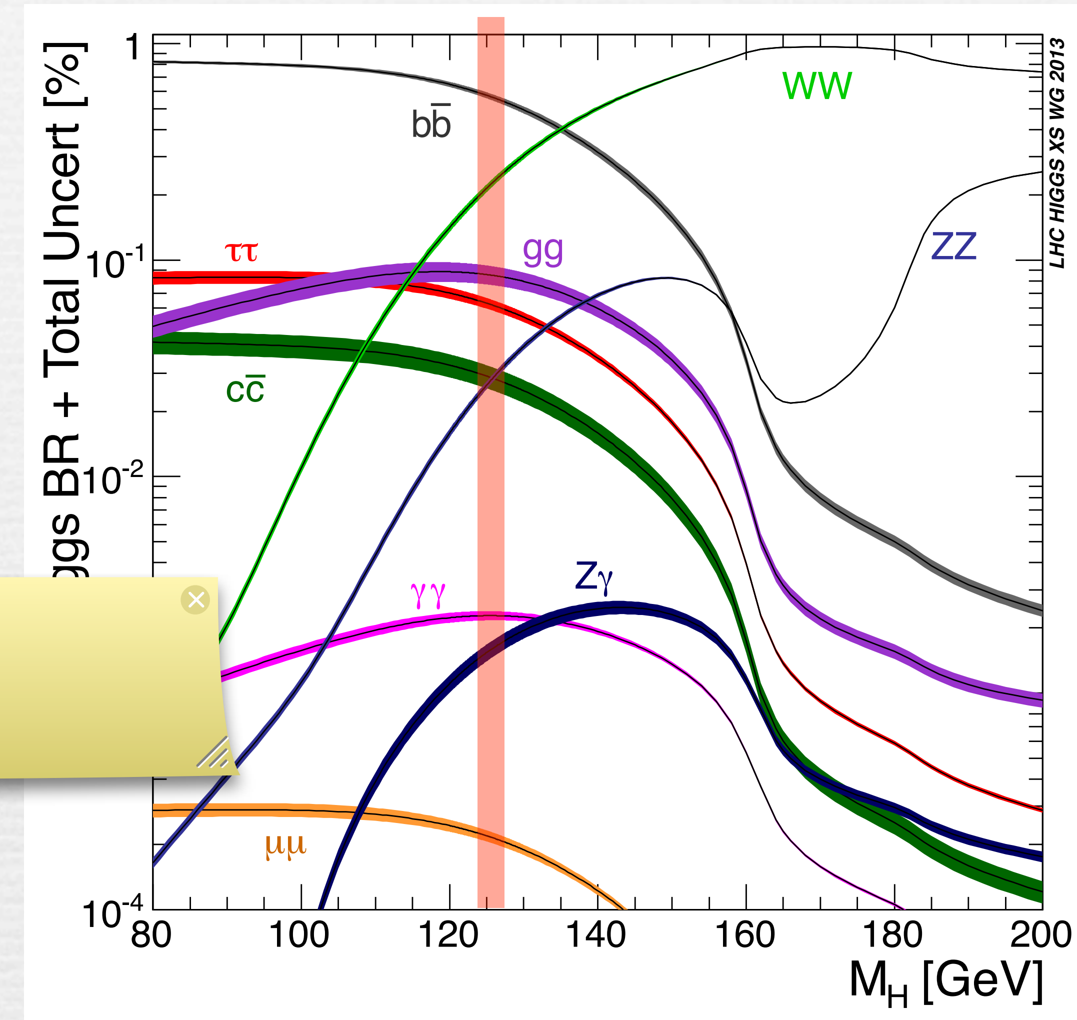
# Higgs decay modes at LHC

Higgs boson mass $m_H$~125.5GeV gives us maximally rich decay modes !!

| $m_H$=125.5GeV | BR(%) |
|---|---|
| H→γγ | 0.23 |
| H→ZZ | 2.8 |
| H→WW | 22 |
| H→ττ | 6.2 |
| H→bb | 57 |

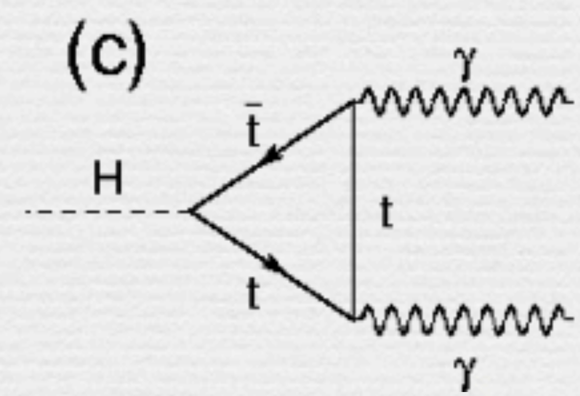
| | BR(%) |
|---|---|
| H→Zγ | 0.16 |
| H→μμ | 0.02 |

if rare decay is presented,
page 6 need to be swapped this one.




Higgs boson can decay into a photon pair via W or t-quark loop.

- Helps the indirect measurement of the coupling to fermions



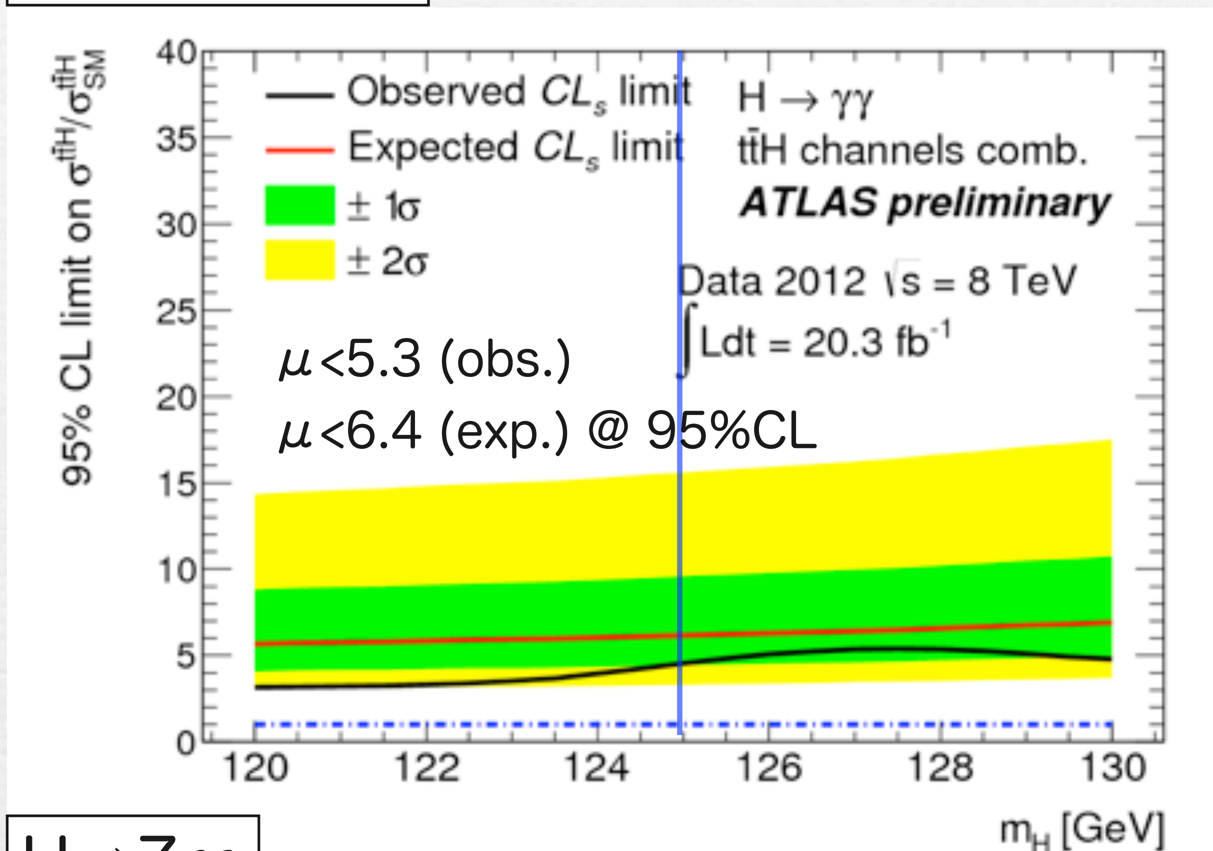

Final states with leptons or photons are easier to measure

- Discovery channels : H→γγ、ZZ(→4ℓ), WW(→ℓνℓν)

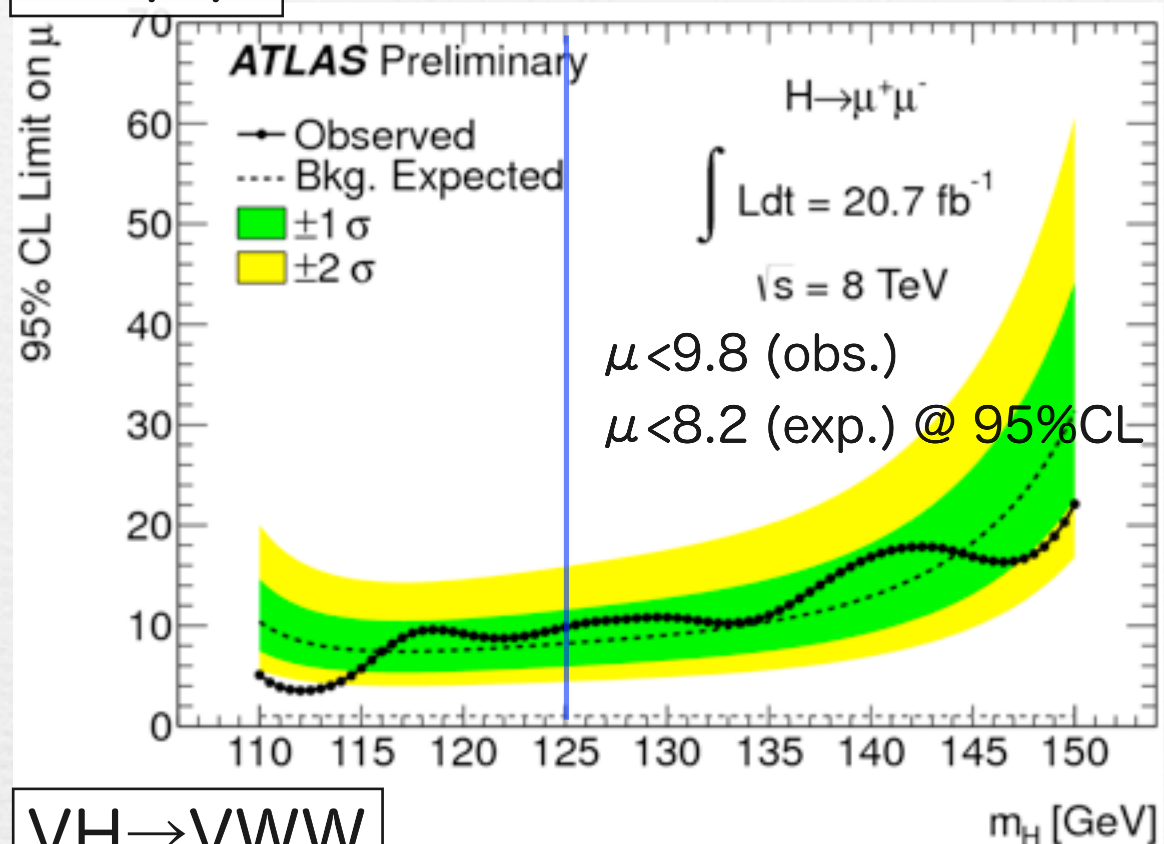
Decays to jets or τs are more difficult to separate from QCD background, but they are very important for the direct measurement of the coupling to fermions.

# Rare decays

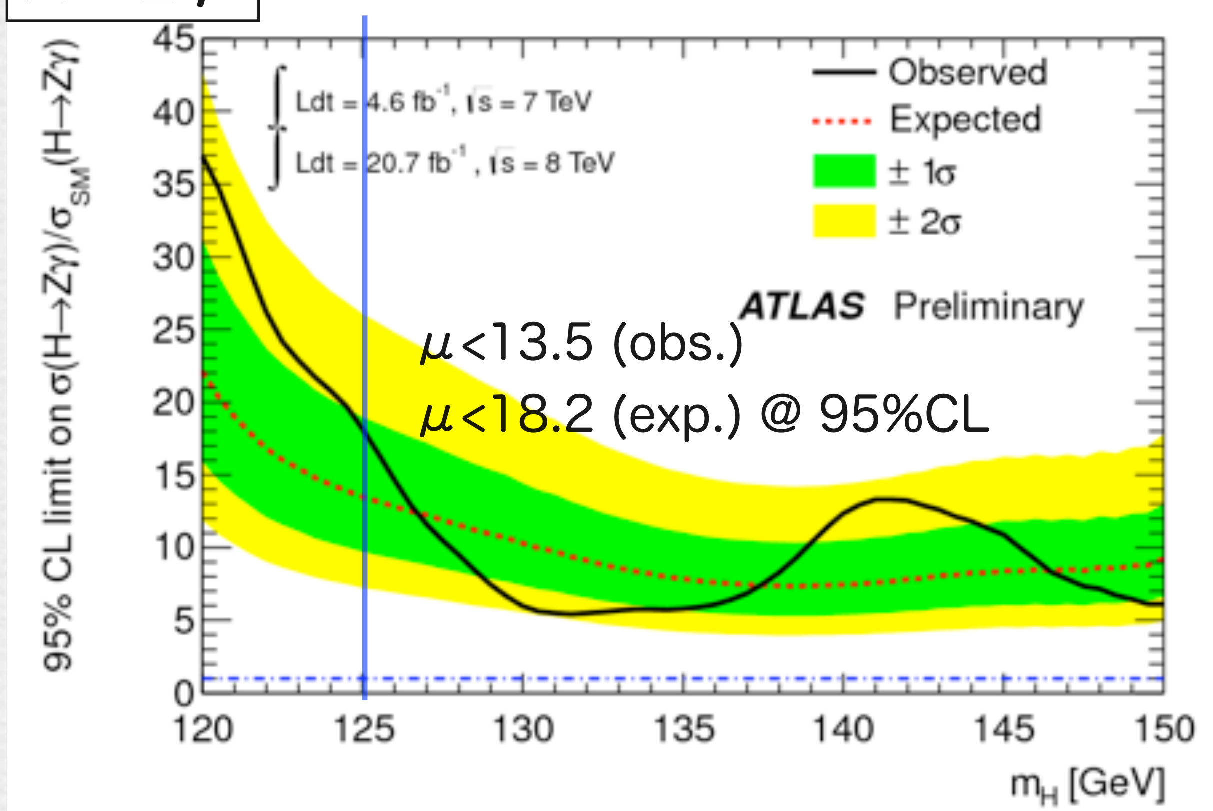
ttH(H→γγ)



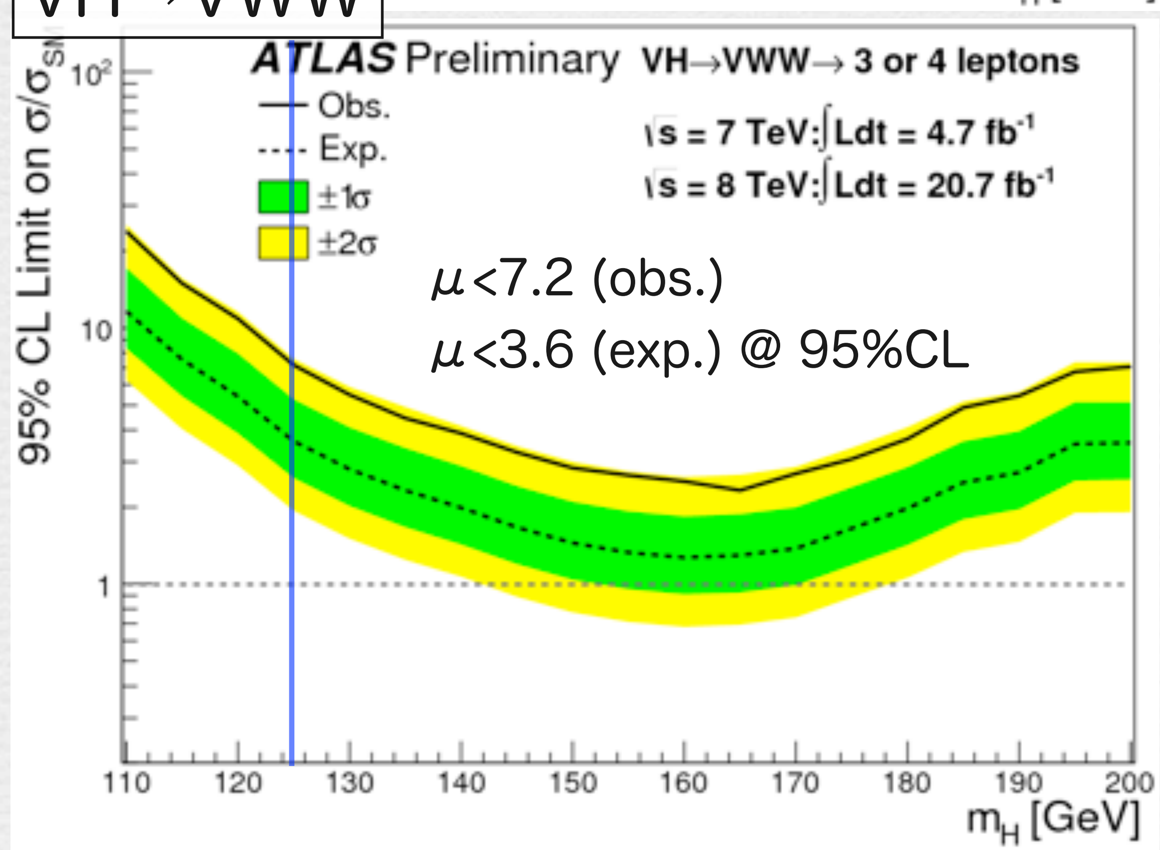

H→μμ




H→Zγ




VH→VWW



# Higgs property measurement

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

$\alpha$ parameters interests :

mass($m_H$),

signal strengths($\mu$),

coupling strengths($\kappa$),

ratios of coupling strengths($\lambda$)

$\theta$ nuisance parameters

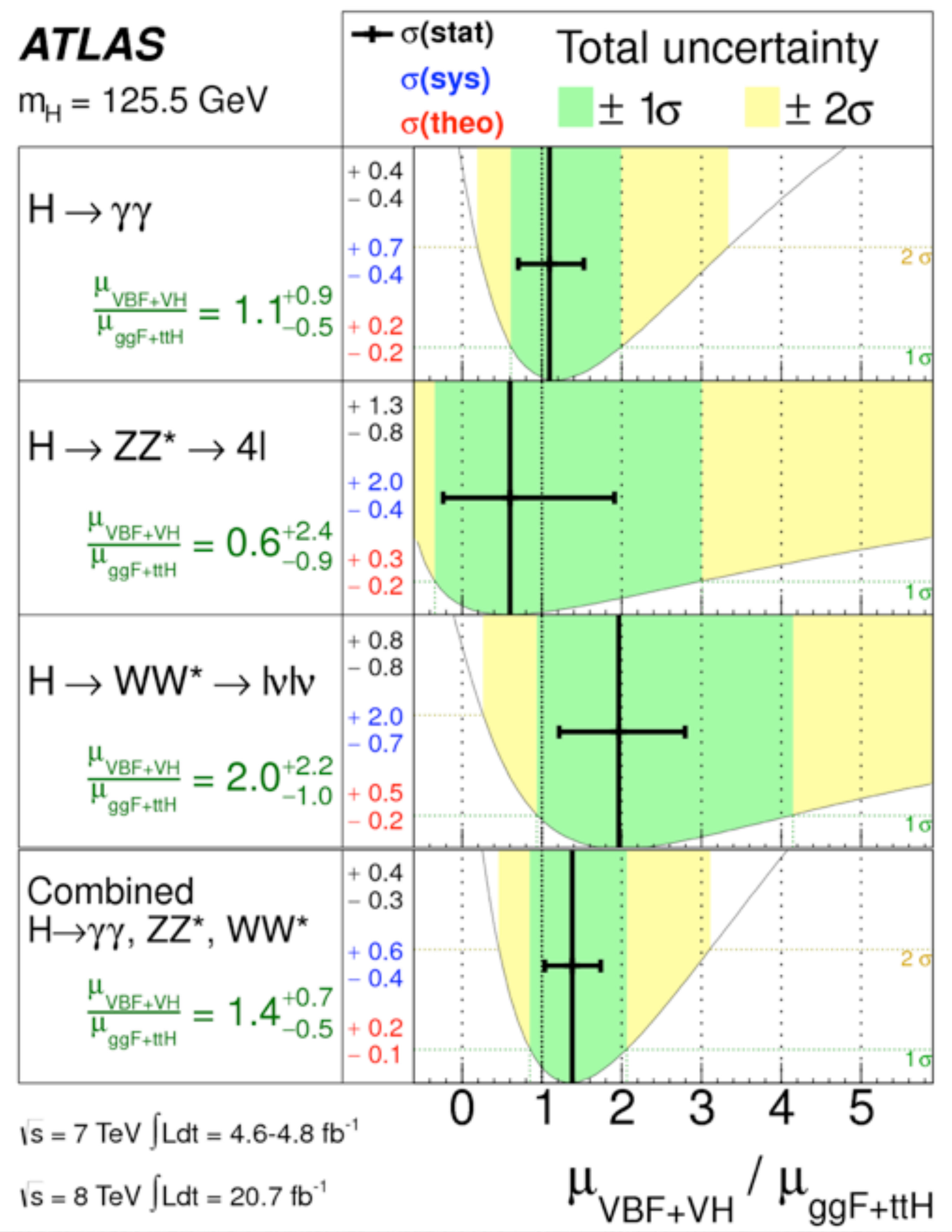
pdf :

$m_{\gamma\gamma}$(H→$\gamma\gamma$)

$m_{ZZ}$ (H→ZZ),

$m_T$ (H→WW)

# Summary of the VBF-strength



# $J^P=0^+$ v.s. $1^+$ / $1^-$

arXiv:1307.1432

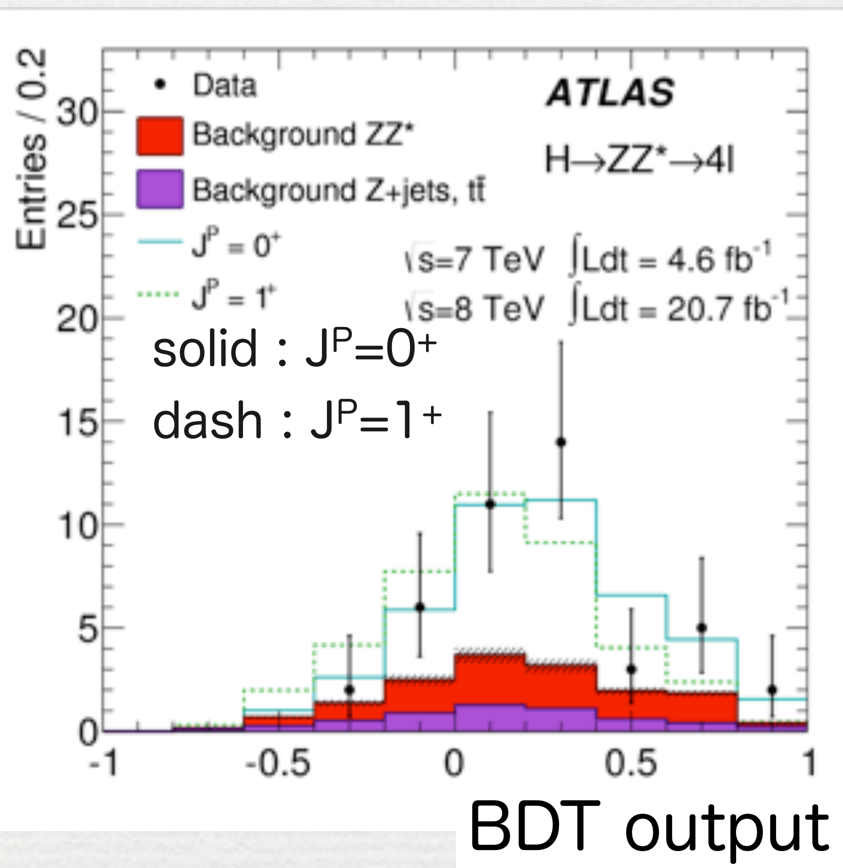
ZZ*→4 lepton and WW→$\ell\nu\ell\nu$ are sensitive for this study

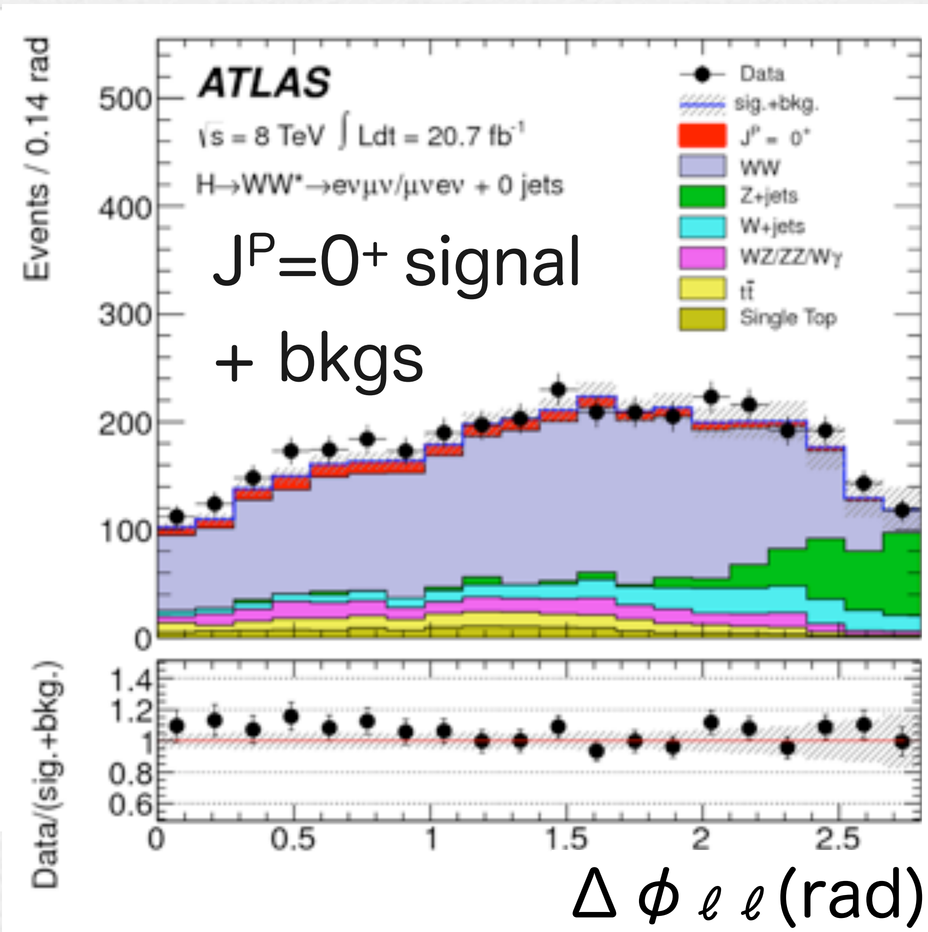
- $\gamma\gamma$ decay is forbidden (Landau-Yang theorem)
- For same reason, J=1 boson is produced only from qqbar annihilation

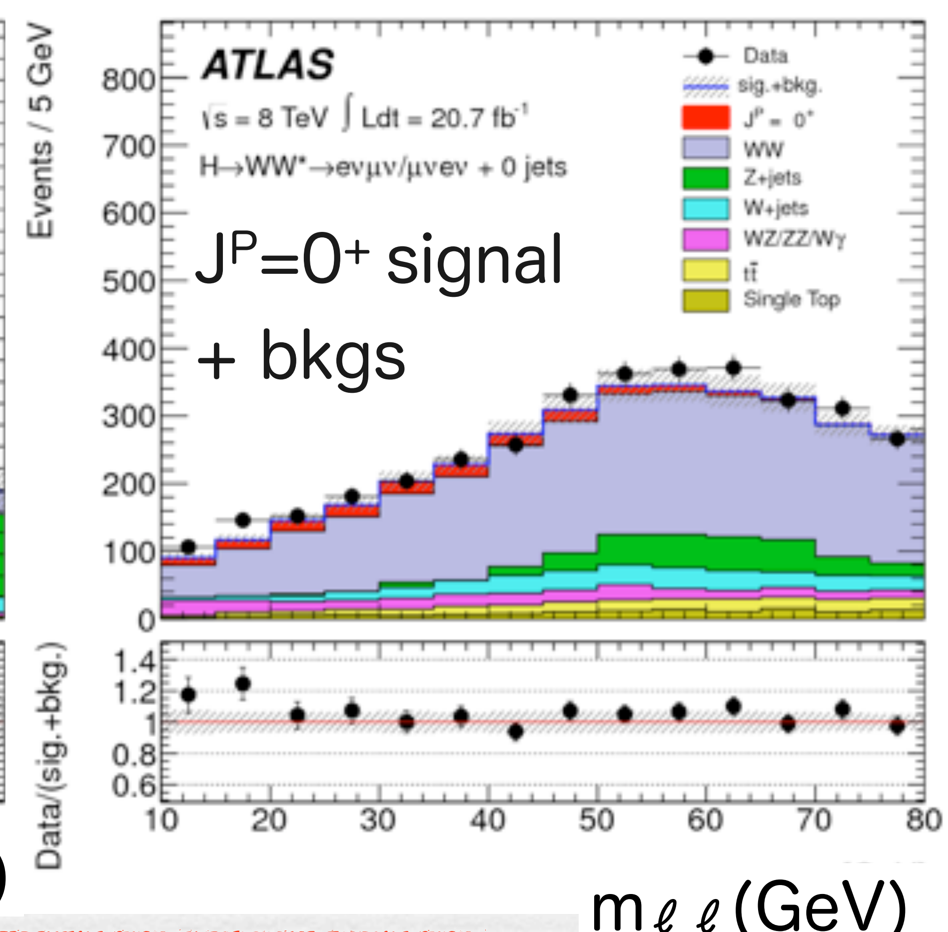
ZZ*→4 lepton : uses BDT from the inputs of $m_{12}$, $m_{34}$, and 5 angles

WW→$e\nu\mu\nu$ : uses 2 BDTs from the inputs of $m_T$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, and $p_T^{\ell\ell}$

- Classifier 1 : Distinguishes the $J^P=0^+$ from sum of the all backgrounds
- Classifier 2 : Distinguishes the $J^P=1^+$, $1^-$ from sum of the all backgrounds




Combined ZZ/WW data agree with 0+ hypothesis,
$J^P=1^+$ ($=1^-$) hypothesis is excluded at 99.97% (99.7%) C.L.

# Spin-Parity summary

arXiv:1307.1432

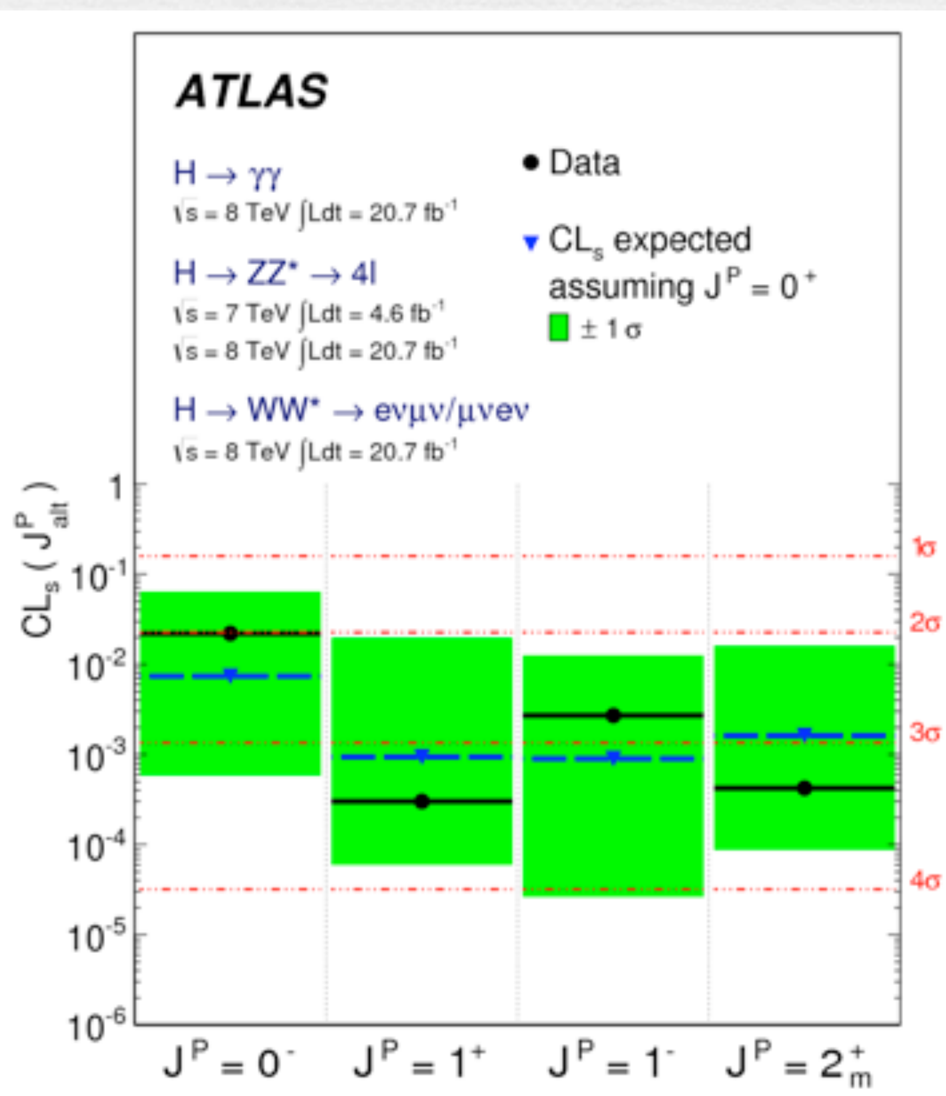
$J^P=0^-$ is excluded at 97.8% CL by ZZ→4 lepton channel

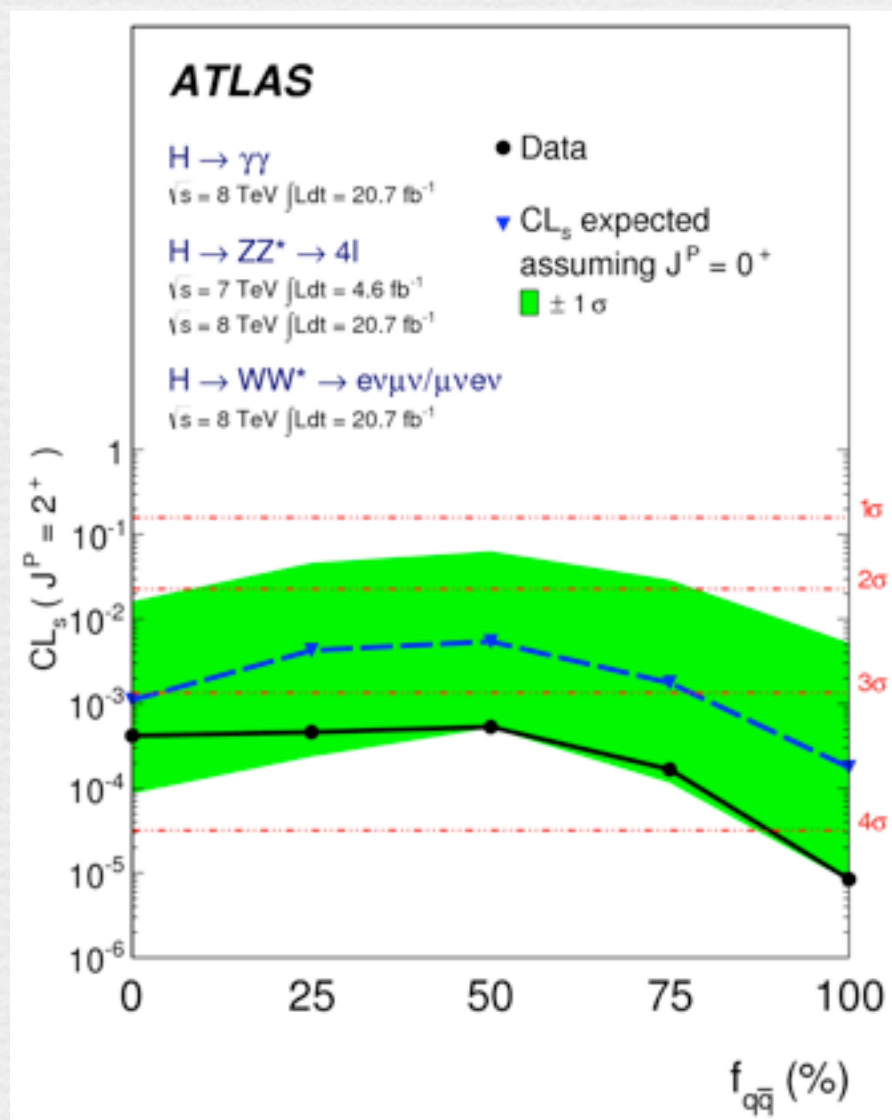
$J^P=1^-$ is excluded at 99.97% CL by ZZ→4 lepton and WW→$e\nu\mu\nu$ channels

$J^P=1^+$ is excluded at 99.7% CL by ZZ→4 lepton and WW→$e\nu\mu\nu$ channels

$J^P=2^+$ is excluded at 99.9% CL by ZZ→4 lepton, WW→$e\nu\mu\nu$, and $\gamma\gamma$ channels

- It can be produced via gluon-gluon or qqbar annihilation
- $2^+$ is tested as a function of $f_{qq}$ = fraction of qq/gg produced signals
  - $f_{qq}$=4% at LO for $2^+_m$ minimal model



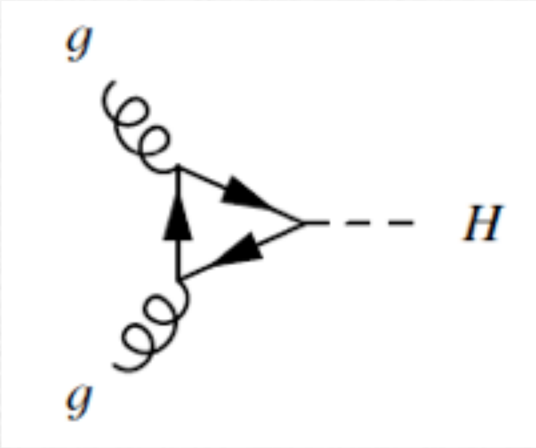



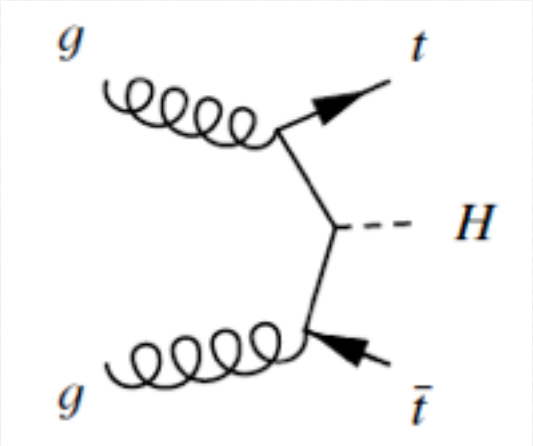

● Data

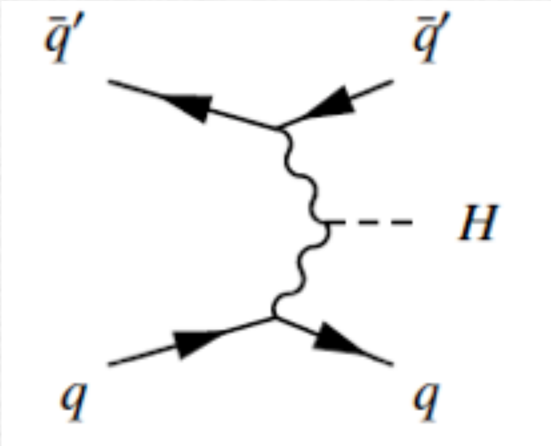
▼ CLs expected assuming $J^P=0^+$

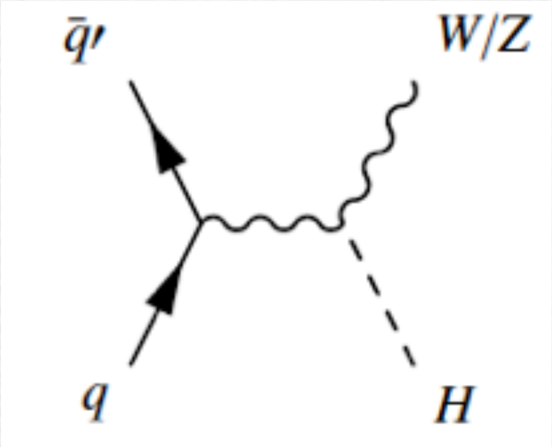
Compatible with SM $0^+$

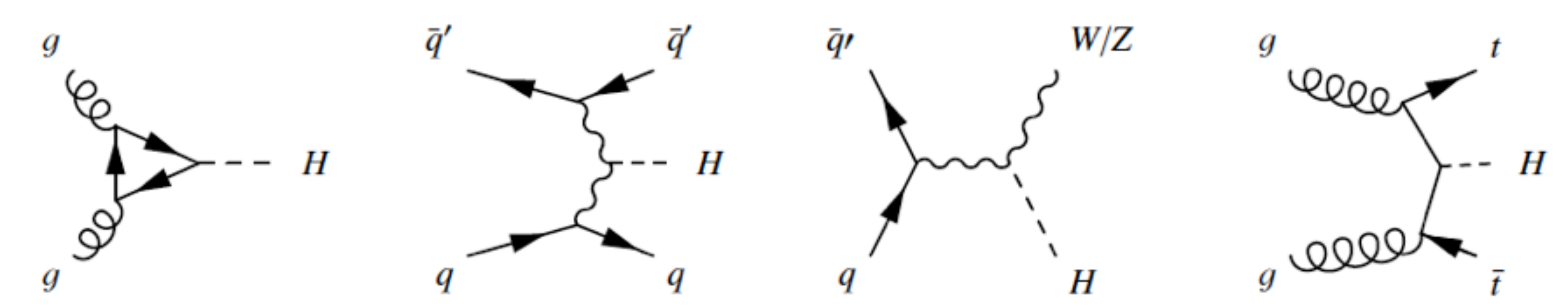
# Production diagrams




(a) $gg \rightarrow H$ (b) VBF (c) $VH$ (d) $t\bar{t}H$