# New Boson Spin and Parity Measurements at ATLAS

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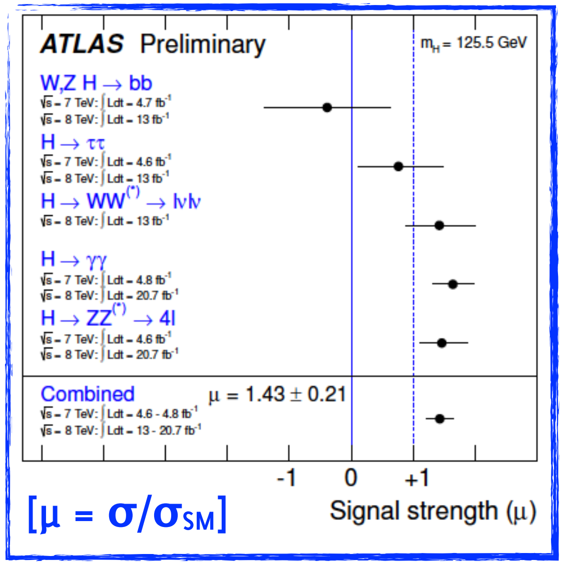
04.04.2013

Saclay

# Introduction and Outline




## why do we measure the spin-CP?

- is the newly discovered particle a SM Higgs boson?
  - ★ significance, mass and couplings seem to confirm this **up to now**
  - ★ **direct measurement of its spin-parity** allows to experimentally test the new particle nature

## talk outline

- how can we measure the Higgs boson spin-parity?
  - ★ observables definitions
  - ★ general method and assumptions
- measurements in the new particle bosonic decay channels @ATLAS using the full 2011+2012/2012 data samples
  - ★ $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ [L ~4.6 fb$^{-1}$@7TeV + 20.3 fb$^{-1}$@8TeV]
  - ★ $H \rightarrow \gamma\gamma$
  - ★ $H \rightarrow WW^{(*)} \rightarrow e\nu_e\mu\nu_\mu$

  [L ~20.3 fb$^{-1}$@8TeV]
- conclusions

Bolognesi et al.
http://arxiv.org/pdf/1208.4018v1.pdf

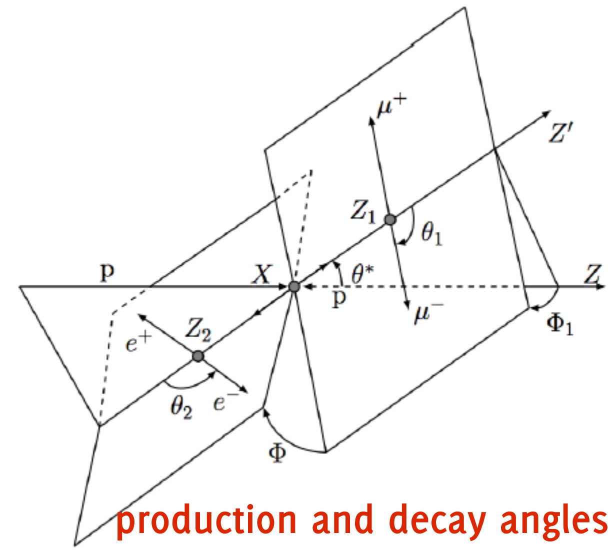
# Observables and Separation Power

Theoretical predictions: final state observables → $J^P$ boson

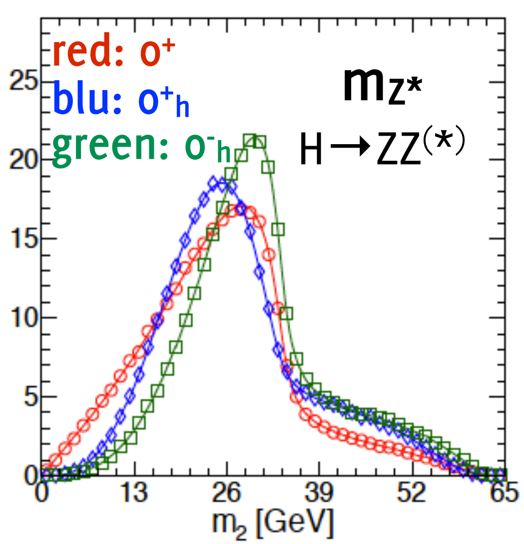
**Experimentally** this means we study

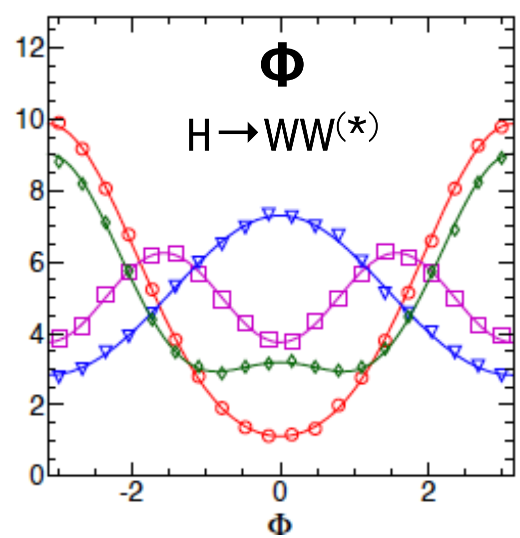
$m_1$, $m_2$, $\cos\theta^*$, $\phi_1$, $\cos\theta_1$, $\cos\theta_2$, $\phi$

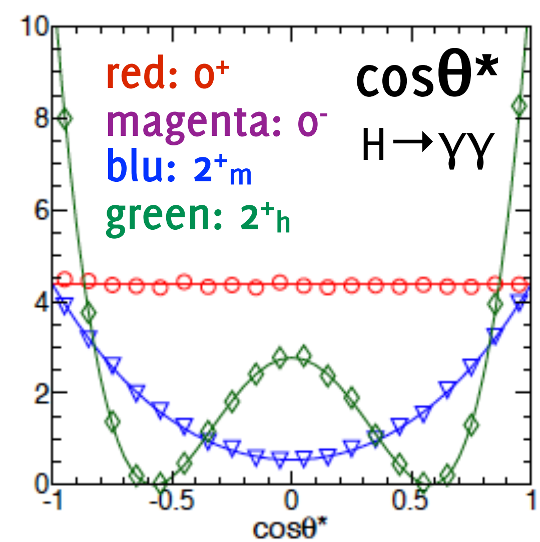
to say something on $J^{PC}$




production and decay angles definition in H→ZZ(*)→4ℓ



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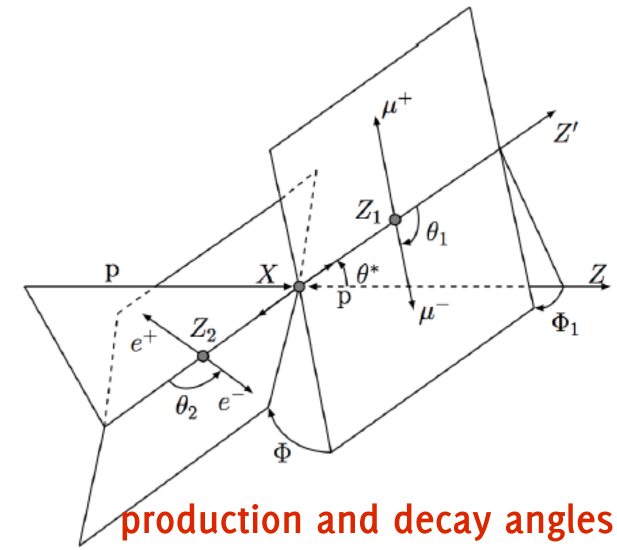
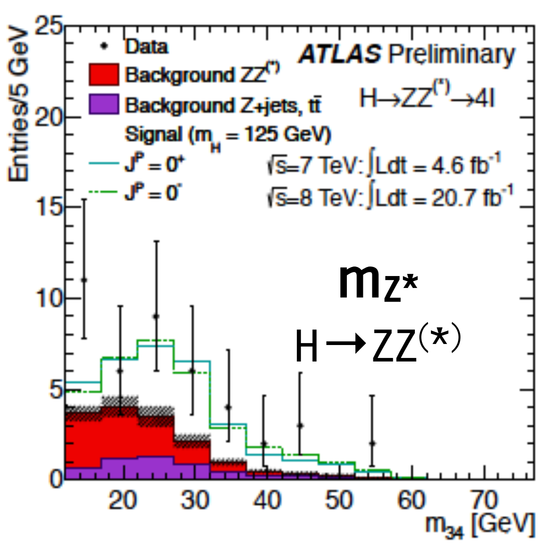
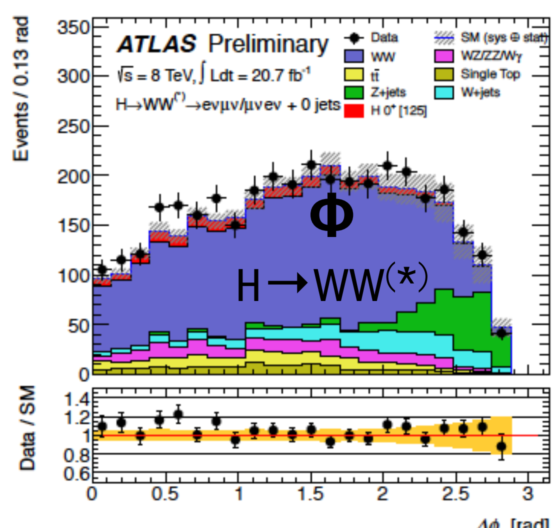
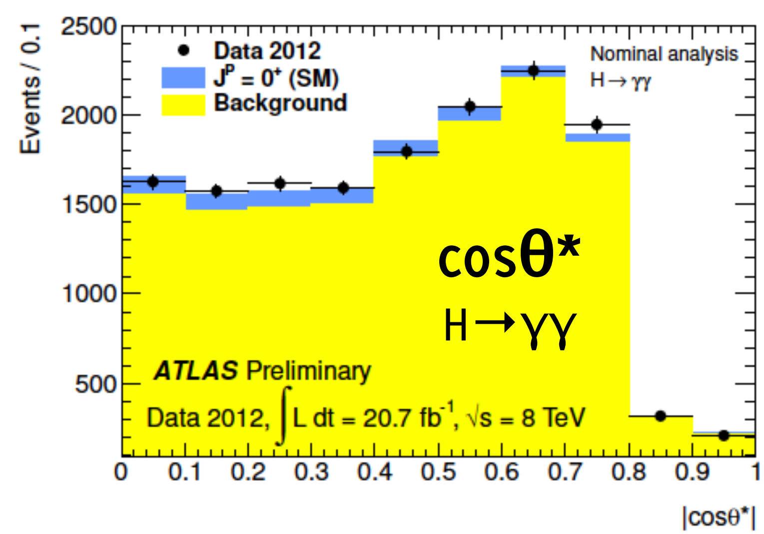
Separation power is altered by background presence and selection effects




production and decay angles definition in $H \to ZZ^{(*)} \to 4\ell$



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ATLAS EXPERIMENT http://atlas.ch

# Analyses Method Outline

- define a **1D discriminant** which allows to separate between spin-parity hypotheses
  - using masses, angles
  - taking into account the **detector/selection effects**
- (always) test **one hypothesis ($H_0$) against another one ($H_1$)**
  - assuming that the spin-parity is **$0^+$**
  - testing against non-SM hypotheses: **$0^-$, $1^\pm$, $2_m^\pm$**
  - spin-2: variating ggF/$q\bar{q}$ production fraction

test for generic spin-2 impossible→graviton-like tensor with minimal couplings model

- using log-likelihood ratio to extract separations:

$$q = \log \frac{\mathcal{L}(H_0)}{\mathcal{L}(H_1)}$$

likelihood depending from μ and ε:

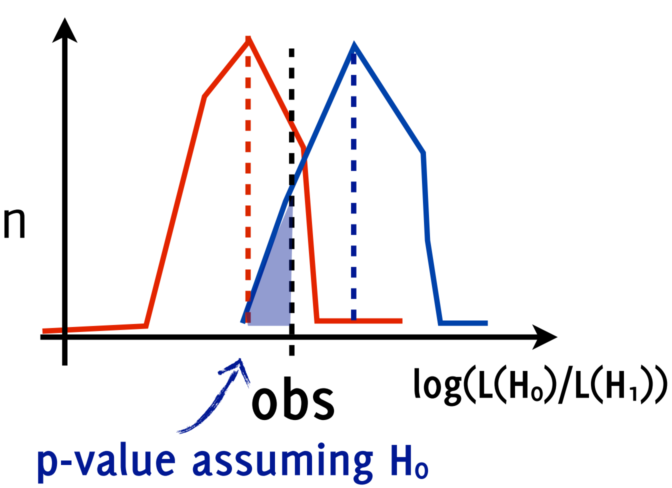
$\varepsilon=0 \rightarrow L(H_0)$

$\varepsilon=1 \rightarrow L(H_1)$

- generating pseudo-experiments → $q_{exp}$ distribution

→ extracting p-values

→ $1-CL_s(H_1) = 1- p(H_1)/(1-p(H_0))$



# Measurement Overview in $H \to ZZ^{(*)} \to 4\ell$ Decay

- very clean channel, full decay kinematic measured
- applying main $H \to ZZ^{(*)} \to 4\ell$ analysis selection
  - ★ dividing the mass interval in a signal and a background region to gain in sensitivity
    [121, 127] GeV [115,121] U [127, 130] GeV
- discriminant definition: two independent methods are used
  - ★ **BDT approach:** multivariate Boosted Decision Tree trained on pairs of different spin-parity MC signal samples
  - ★ **MELA approach:** Bayes Likelihood Ratio multivariate discriminant from **matrix element** description of the decay

    → using full theoretical description of signal final state

    → includes corrections for detector/selection effects: inefficiencies, ZZ mis-pairing [extracted from fully simulated JHU MC]
- main systematic uncertainties
  - ★ reconstruction: electron ES, mis-pairing fraction
  - ★ signal/background modelling: MC/control regions statistics, MC cross-sections
  - ★ mass regions migration

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http://atlas.ch

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H→ZZ

# $J^P$-MELA Discriminant Shape

- $J^P$-**MELA discriminant** defined as:

$$J^P\text{-MELA} = \frac{P(H_0)}{P(H_0) + P(H_1)}$$

$H_i = 0^\pm,\ 1^\pm,\ 2^\pm_m$

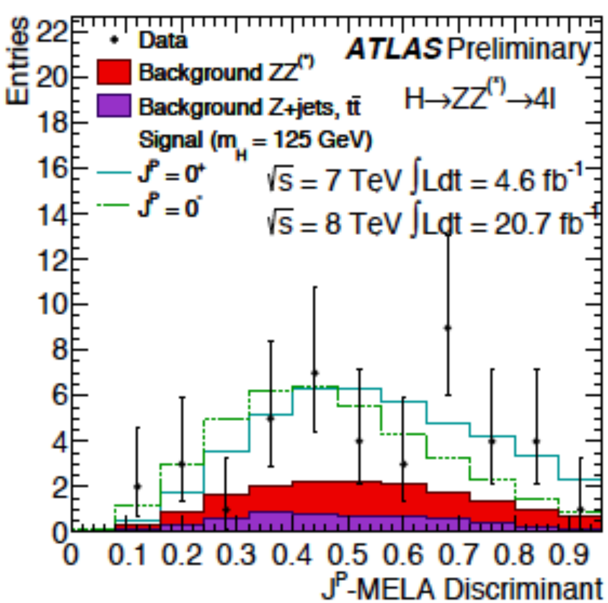
**p($H_i$)** → probability density function of $H_i$ hypothesis

**including detector/selection effects**

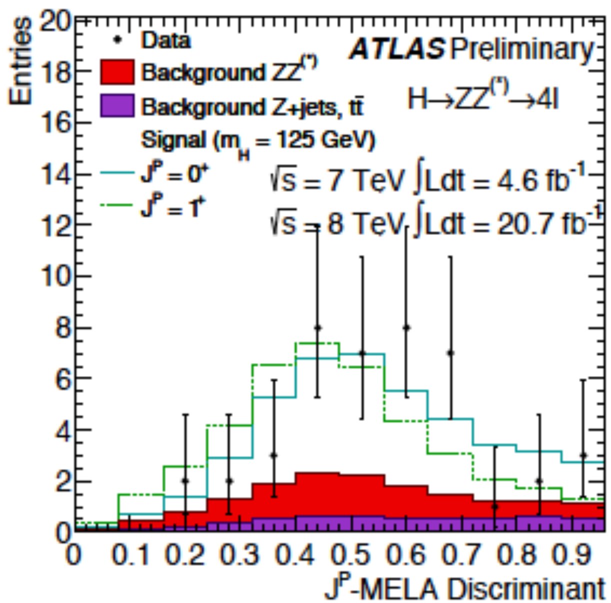
[$P = P(m_{4\ell}, m_1, m_2, \cos\theta^*, \phi_1, \cos\theta_1, \cos\theta_2, \phi)$]

- expected distributions computed using JHU MC (signal, ZZ background) and data (reducible background)

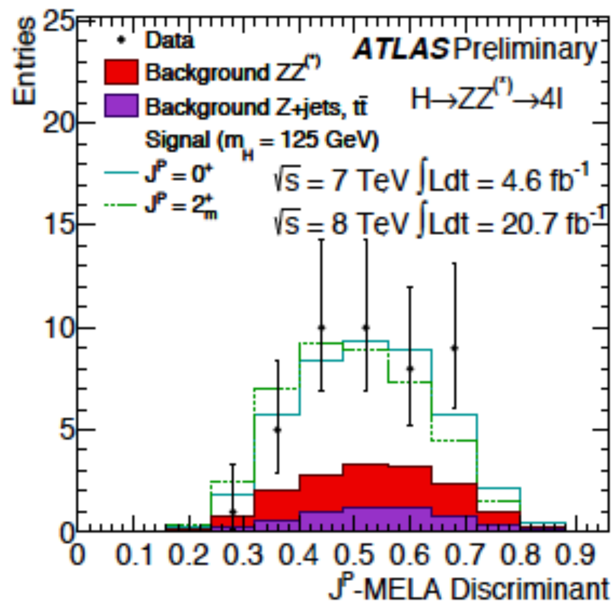
$0^+$ VS $0^-$




$0^+$ VS $1^+$

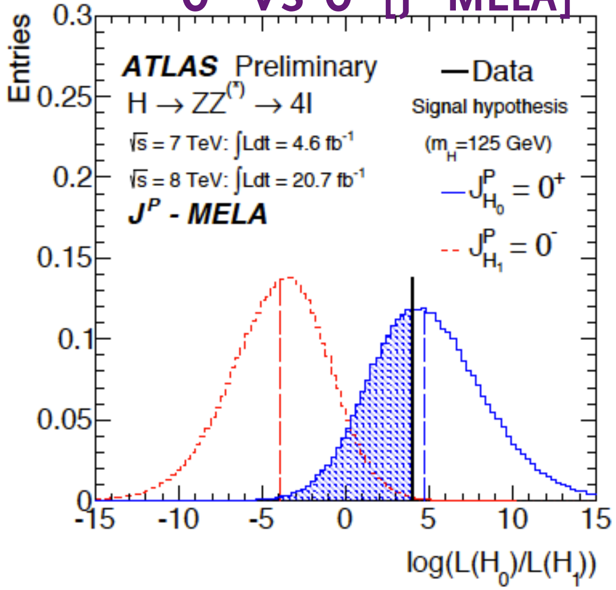



$0^+$ VS $2^+_m$

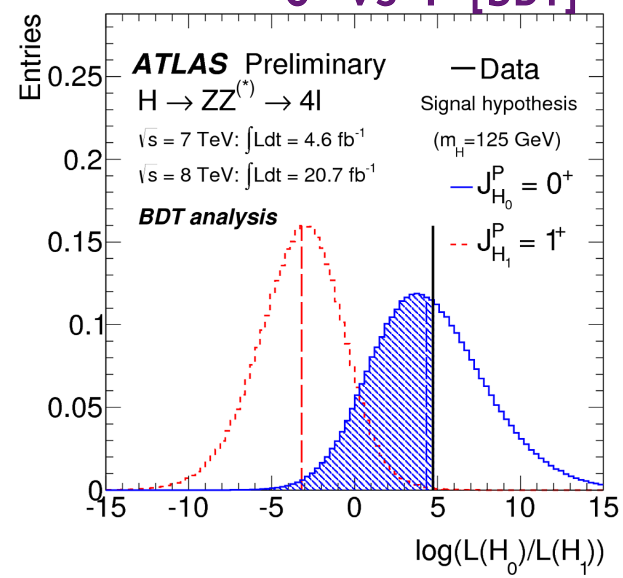


# SEPARATIONS IN $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

**$0^+$ VS $0^-$ [$J^P$-MELA]**




**$0^+$ VS $1^+$ [BDT]**




| $0^+$ VS $0^-$ | $0^+$ VS $1^+$ | $0^+$ VS $1^-$ | $0^+$ VS $2^+$ | $0^+$ VS $2^-$ |
|---|---|---|---|---|
| $p_0(0^-)$=0.0022 | $p_0(1^+)$=0.0028 | $p_0(1^-)$=0.027 | $p_0(2^+)$=0.113 | $p_0(2^-)$=0.11 |
| (exp 0.0011) | (exp 0.0031) | (exp 0.001) | (exp 0.064) | (exp 0.003) |
| $p_0(0^+)$=0.40 | $p_0(0^+)$=0.51 | $p_0(0^+)$=0.11 | $p_0(0^+)$=0.381 | $p_0(0^+)$=0.08 |
| **$CL_s$ =99.7%** | **$CL_s$ =99.5%** | **$CL_s$ =96.9%** | $CL_s$ =81.8% | $CL_s$ =88.5% |

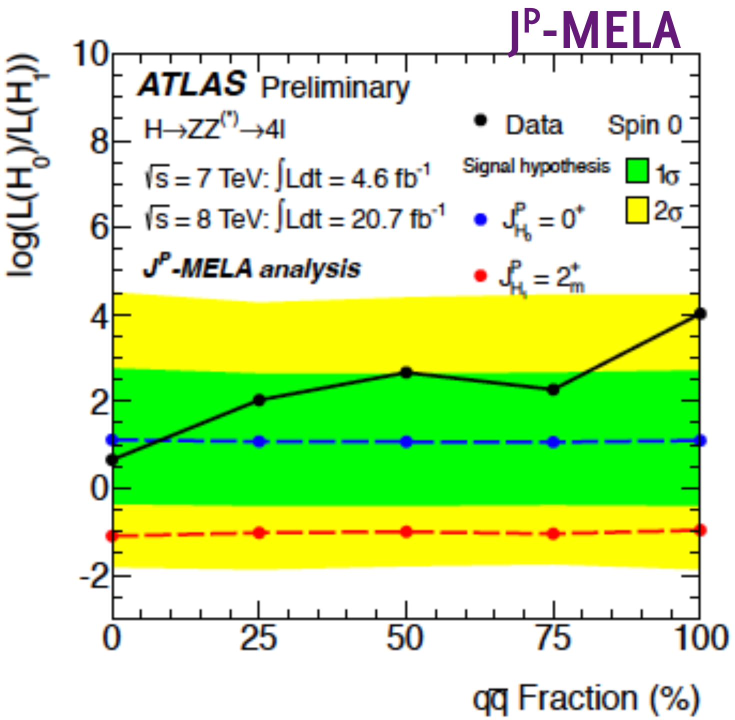
→results from both methods in good agreement

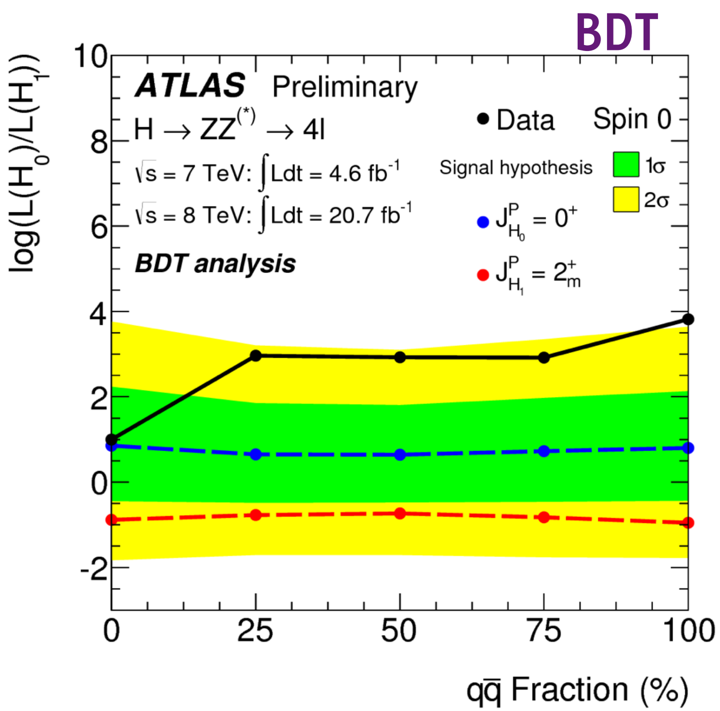
→ **excluding** $0^-$, $1^+$, $1^-$ at > 95% CL

→ data prefers the **$0^+$ hypothesis**

# Study of Spin-2 Admixtures

- for spin-2: gluon-gluon fusion, $q\bar{q}$ production mechanisms or an admixture of the two are allowed
- testing different spin-2 production mechanisms, **$f_{q\bar{q}}$ = 0, 25, 50, 75, 100%**




**expected distribution is FLAT → no dependency from production mechanism**
**variation observed on data: statistical effect, within 2σ**

# Measurement Overview in H→γγ Decay

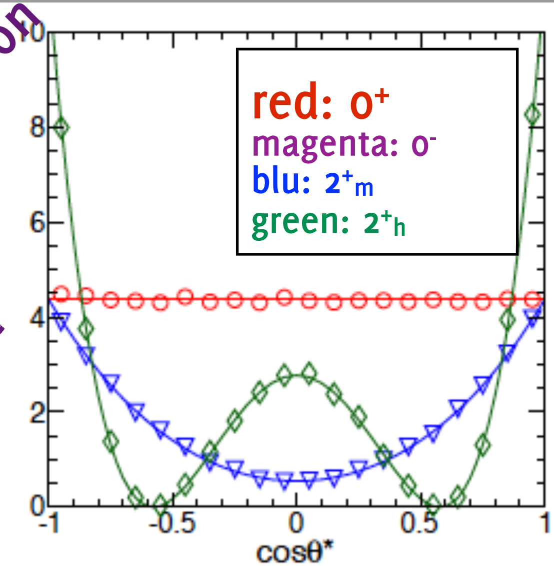
- separating spin-0⁺ vs spin-2⁺ using $m_{\gamma\gamma}$ and $\cos\theta^*$
  - ★ in the spin-0 case the Higgs decays isotropically in its frame
- applying main analysis selection
  - ★ additional selection on $p_T^{\gamma}/m_{\gamma\gamma}$

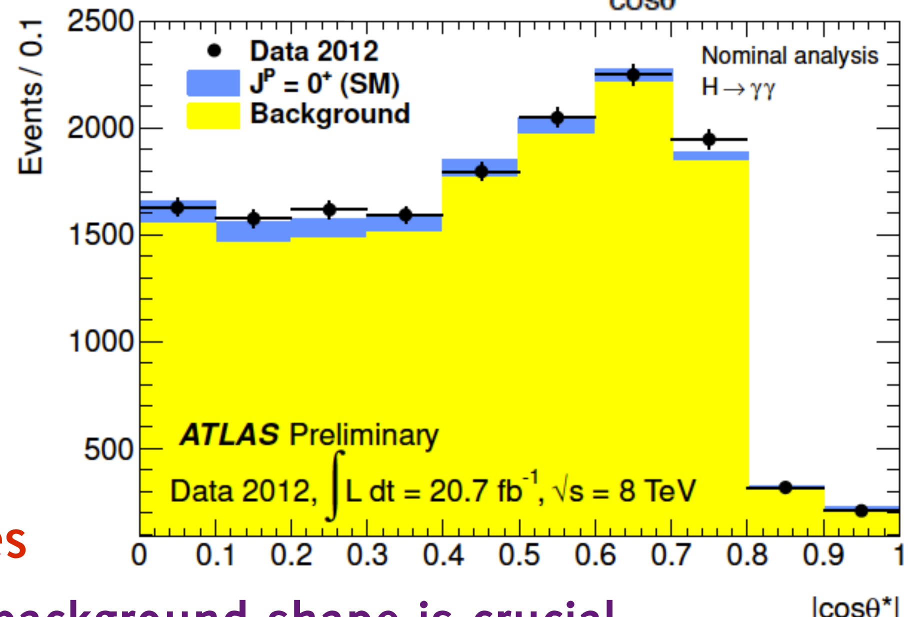
    → reduce $m_{\gamma\gamma}/\cos\theta^*$ correlations
- two independent analyses are used
  - ★ **nominal:** fit of $m_{\gamma\gamma}$ and $\cos\theta^*$ in the signal region, assuming them uncorrelated [factorized pdfs]

    → better separation
  - ★ **alternative:** performing fit of the full $m_{\gamma\gamma}$ spectrum in bins of $|\cos\theta^*|$

    → smaller systematic uncertainties

true distribution



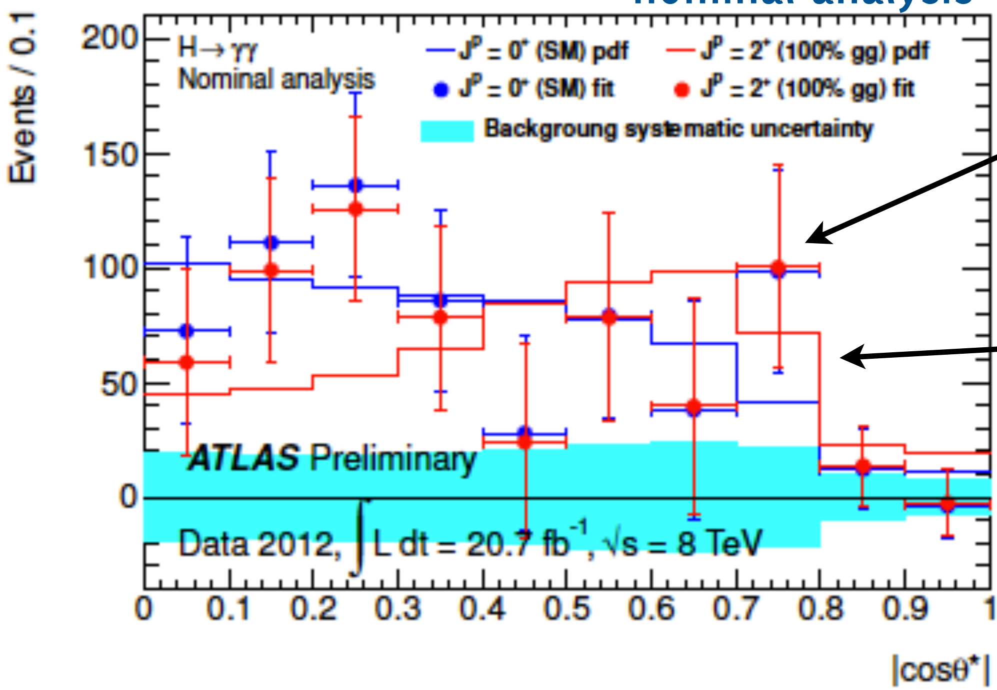




small S/B ratio, determination of background shape is crucial

# Modelling of the Signal and Backgrounds

- signal pdfs: from **JHU MC**
- background mass pdf: from **direct data fit** (alternative: in ten bins of |cosθ*|)
- background |cosθ*| pdf: from **mass sidebands**

nominal analysis

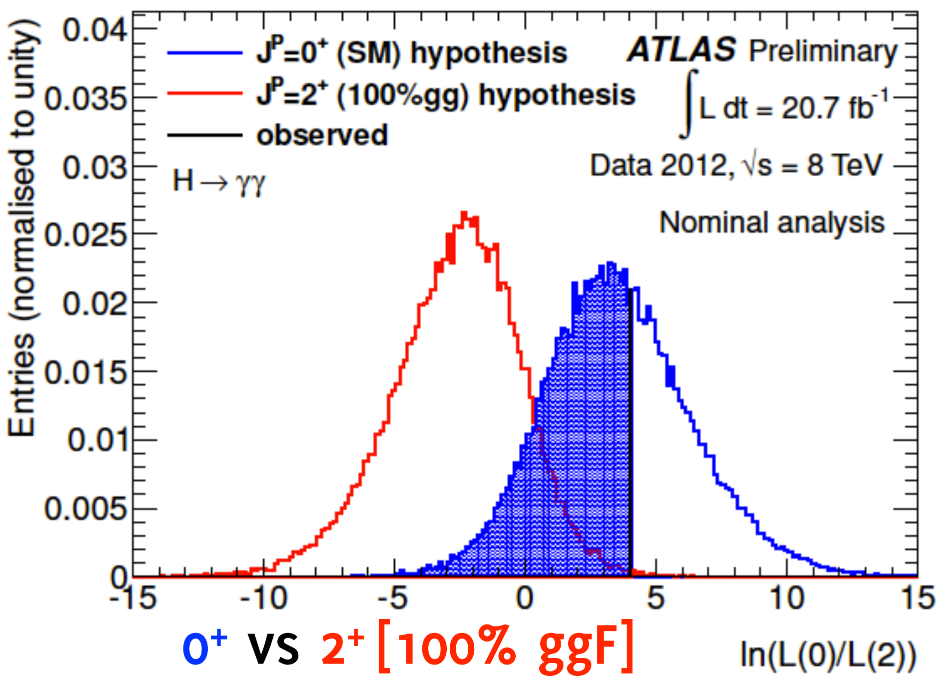



data - background (from fit): $0^+$, $2^+$

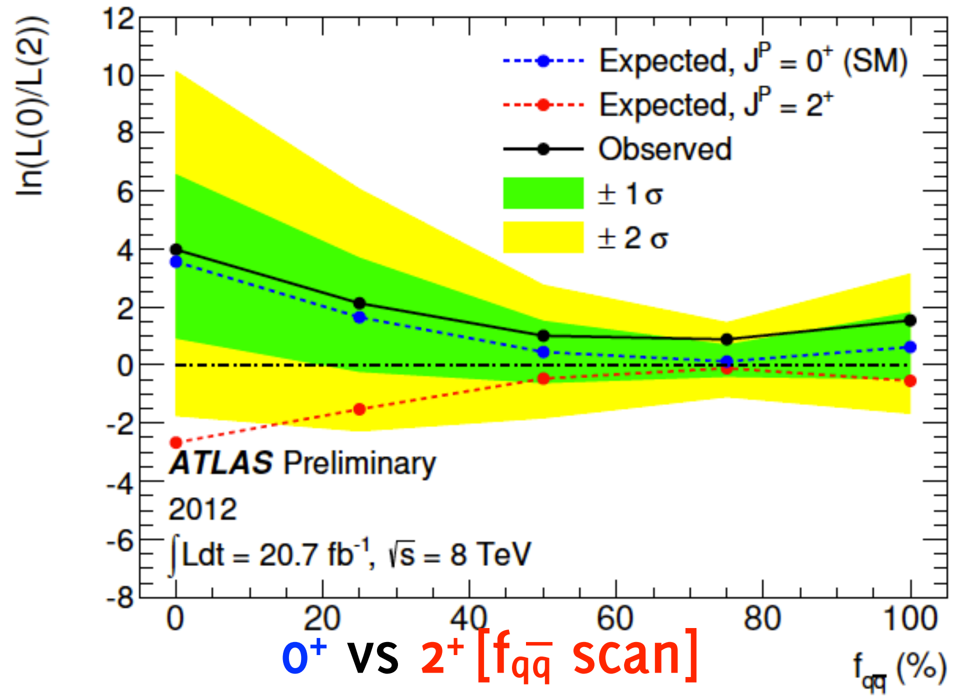
signal pdfs $0^+$, $2^+$

- main systematic uncertainties
  - **photon ES** ~20%
  - material effects
  - background modelling
  - theoretical uncertainties

# Results in the H→γγ Decay




$0^+$ vs $2^+$ [100% ggF]




$0^+$ vs $2^+$ [$f_{q\bar{q}}$ scan]

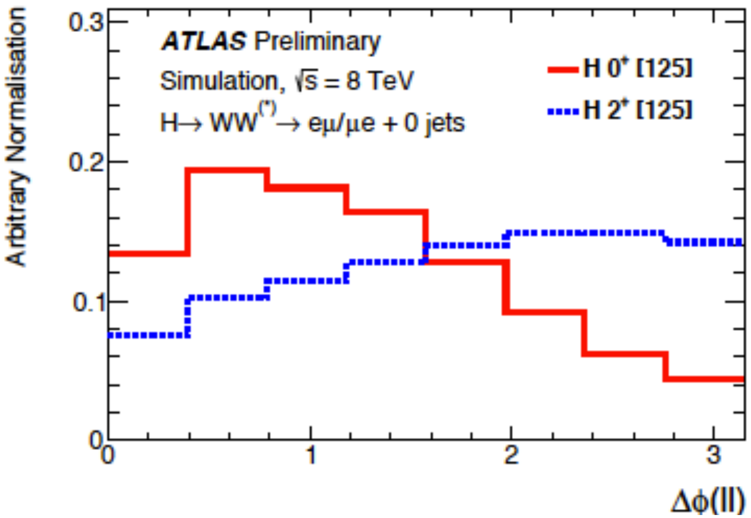
| $0^+$ vs $2^+$ [ggF] | $0^+$ vs $2^+$ [$q\bar{q}$] |
|---|---|
| $p_0(0^-)$=0.003 | $p_0(0^-)$=0.025 |
| (exp 0.005) | (exp 0.135) |
| $p_0(0^+)$=0.59 | $p_0(0^+)$=0.80 |
| **$CL_s$ =99.3%** | **$CL_s$ =88.0%** |

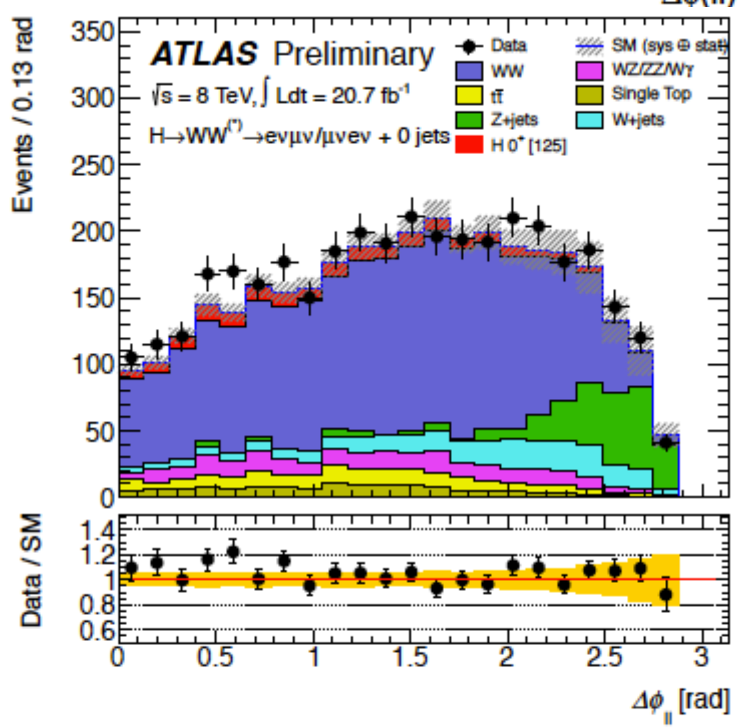
→ **excluding $2^+$ ggF at > 99% CL**

→ **$0^+$ hypothesis is favoured**

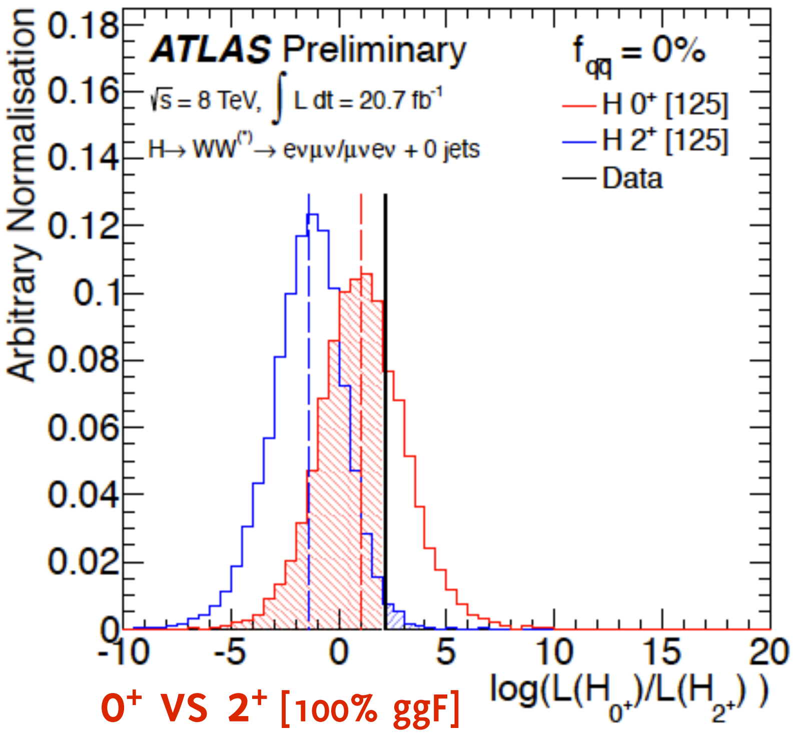
# MEASUREMENT OVERVIEW IN $H \to WW \to e\nu_e\mu\nu_\mu$ DECAY

- different analysis selection than H→WW analysis
  - → **optimized for a 0⁺ signal**
- only using opposite flavour channel $H \to WW \to e\nu_e\mu\nu_\mu$
  - ★ better S/B ratio
  - ★ most sensitive channel
- testing $0^+$ vs $2^+_m$
  - ★ separation power mainly from: **ΔΦ between the leptons**, dilepton invariant mass, $E_T^{miss}\sin(\Delta\Phi)$, dilepton $p_T$
  - ★ using a kinematic fit on **two different BDT** trained over $0^+$ and $2^+$ JHU MC samples

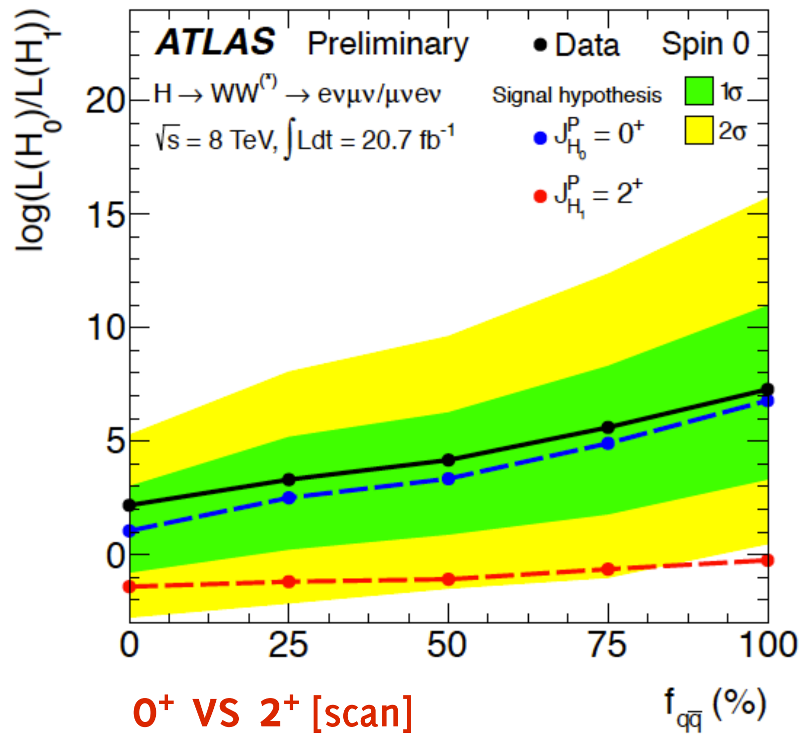


# Measurement Results




0+ VS 2+ [100% ggF]




0+ VS 2+ [scan]

- data show a better agreement with a spin-0+ hypothesis
- the **hypothesis 2+ is excluded** in favor of 0+ with a CLs which varies between 99% for $f_{qq}$ = 100% and 95% for $f_{qq}$ = 0%
- main systematic uncertainties
  - objects reconstruction: JES, lepton ES, $E_T^{miss}$, ..
  - signal/background (WW) theoretical uncertainties

# Conclusions

- showed latest results on spin-parity of the new-found particle measured at ATLAS with the full 2011+2012/2012 data samples
- performed hypothesis testing in different decay channels using different analysis techniques
- we exclude with CL > 95% the following models:
  - ★ $0^-$, $1^+$, $1^-$ **[H→ZZ]**
  - ★ $2_m^+$ **[H→γγ, H→WW]**
- in all decay channels we observe that data favours a $0^+$ spin-parity configuration

→ **supporting SM Higgs hypothesis!**

# Backup Slides

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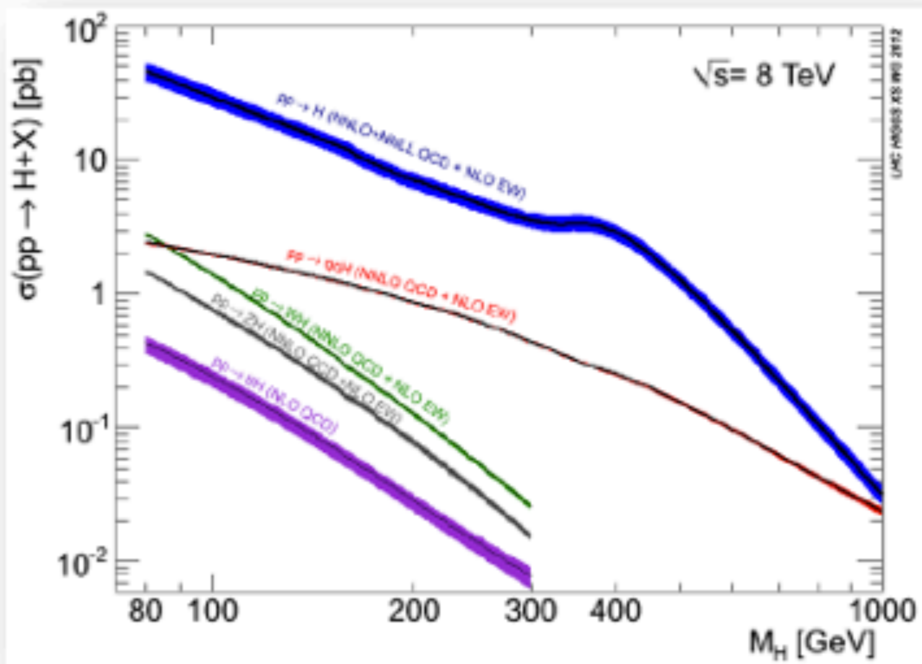
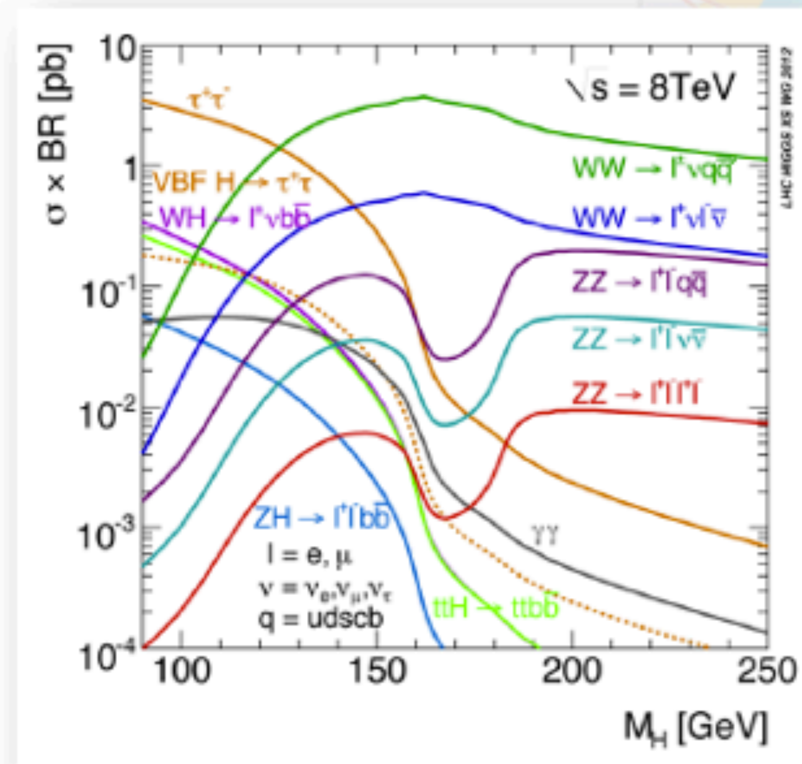
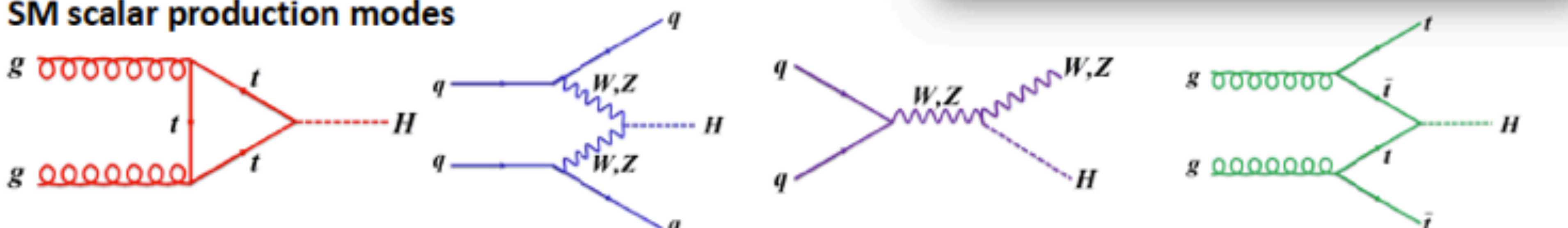
# Higgs Boson Production and Decays




**SM scalar production modes**



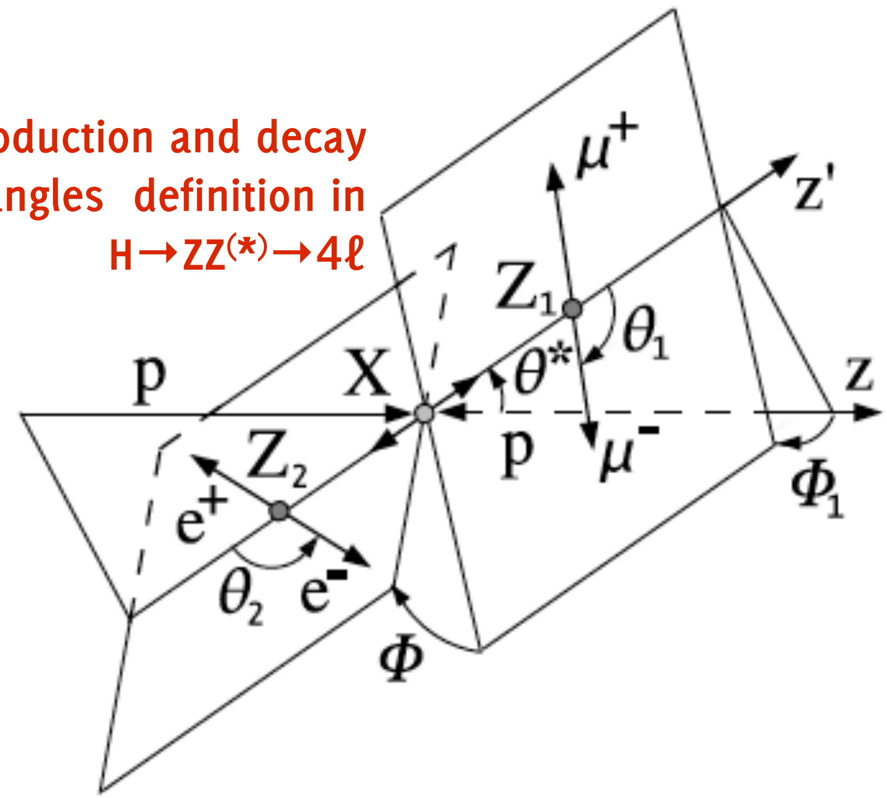
gluon fusion | vector boson fusion | W/Z-associated production | tt-associated production

# ANGLES DEFINITIONS

The $H \to V_1 V_2$ process is fully characterized by the three masses involved and 5 of the 6 production/decay angles:

* "Production" angles:
  - $\theta^*$ of the first boson
* "Decay" angles:
  - $\Phi$ is the angle between the two bosons decay planes in the Higgs rest frame
  - $\Phi_1$ is the angle between the first boson decay plane and the Higgs direction in the Higgs rest frame
  - $\theta_1$ and $\theta_2$ of the negative leptons in the corresponding boson rest frame

production and decay angles definition in $H \to ZZ^{(*)} \to 4\ell$




$m_1$, $m_2$, $\cos\theta^*$, $\phi_1$, $\cos\theta_1$, $\cos\theta_2$, $\phi$

# Likelihood Definition

likelihood is in the form $$L = \prod_{ij} \mathrm{Poiss}(N^{ij}_{\mathrm{data}} | \mathscr{P}^{ij})$$

- i,j run over mass bin and discriminant bin
- $P^{ij}$ is $$\mathscr{P}^{ij} = \mu^{\mathrm{signal}} \mathscr{L} f_i^{\mathrm{signal}} N_{\mathrm{signal}} \left[ \varepsilon \cdot \mathrm{PDF}^{ij}_{\mathrm{signal\ 1}} + (1-\varepsilon) \cdot \mathrm{PDF}^{ij}_{\mathrm{signal\ 2}} ) \right] + \sum_{\mathrm{backgrounds}\ (k)} f_i^{\mathrm{background}\ k} N_{\mathrm{background}\ k} \mathrm{PDF}^{\mathrm{ij}}_{\mathrm{background\ k}},$$

  * ε is the parameter of interest
  * signal strength μ is profiled

ε = 0 for assumed hypothesis $H_0$

ε = 1 for tested hypothesis $H_1$

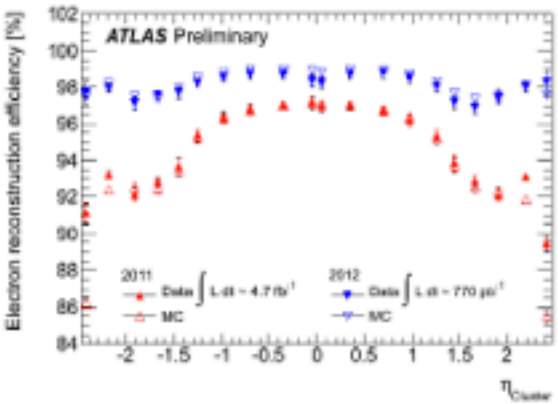
# H→ZZ(*)→4l (l=e,μ) : Overview

ATLAS-CONF-2013-013

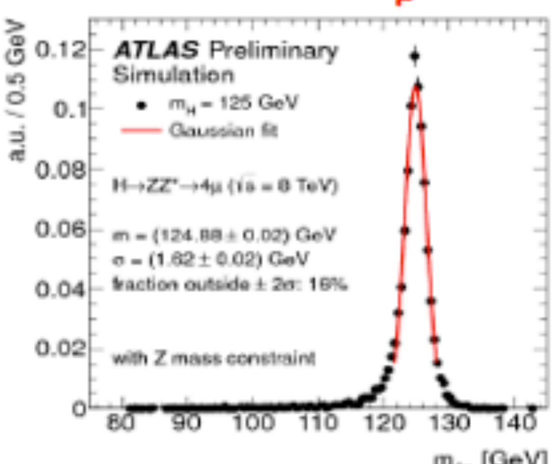
**The golden channel, with small cross-section but very good S/B ratio and fully-reconstructed mass**

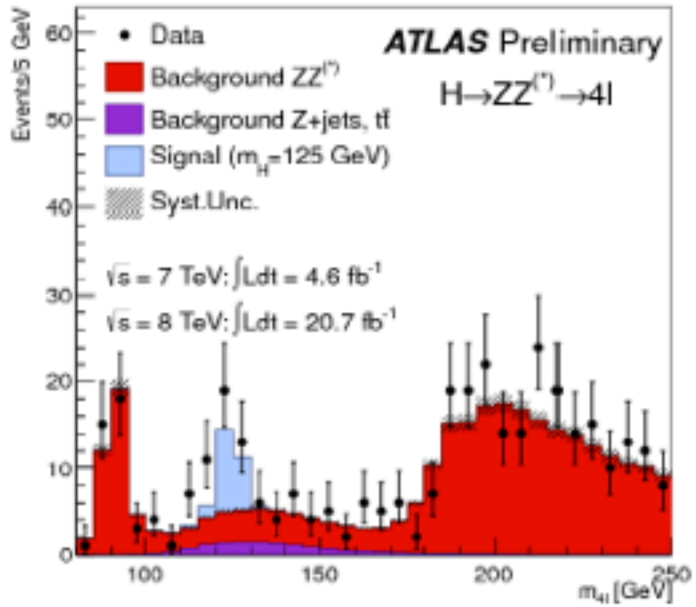
## Signal reconstruction

Electron reco ε measured with Z→ee




Mass resolution in 4-μ channel

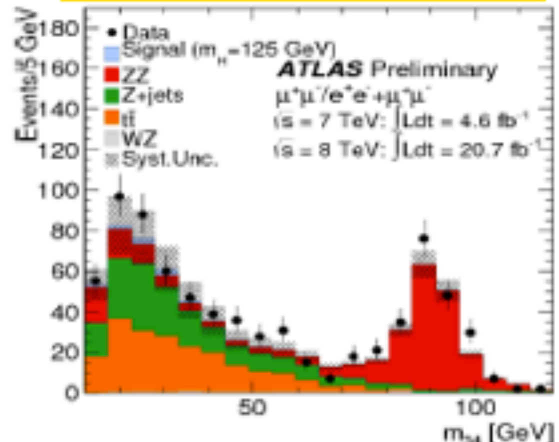


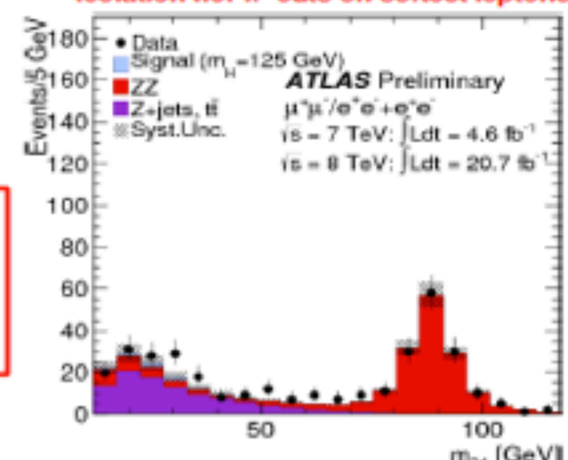

Two pairs of opposite-sign same-flavor isolated leptons

➔ In region 125±5 GeV: 32 events observed [11.1±1.3 expected from bknd & 15.9±2.1 from SM Higgs]

## Background control




Example of control regions: no isolation nor IP cuts on softest leptons



# Spin-2 model

Spin 2 model for X→VV:

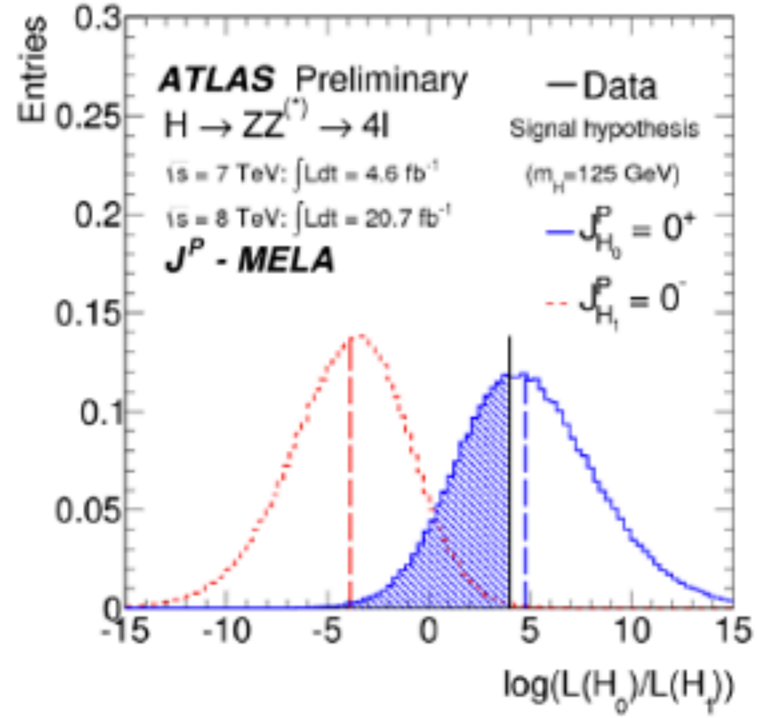
$$
\begin{aligned}
A(X \to VV) = \Lambda^{-1} \Big[ & 2g_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\alpha} \\
& + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\
& + m_V^2 \left( 2g_5 t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
& + g_8 \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9 t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\
& + \frac{g_{10} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)) \Big].
\end{aligned}
$$

General interaction of spin-2 particle with gauge bosons pair has 10 independent tensor couplings

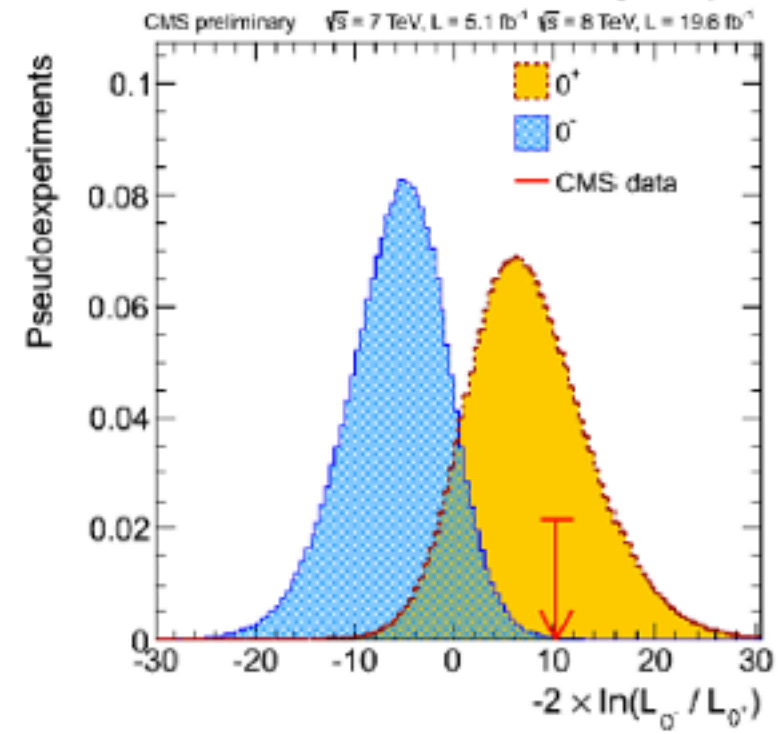
- Excluding generic spin-2 model is impossible at this stage
- Start with model with minimal couplings (g1=g5=1)
- Two production modes allowed: gg and qqbar
- Study 5 different gg fractions from 0% to 100%

# $0^+$ vs $0^-$

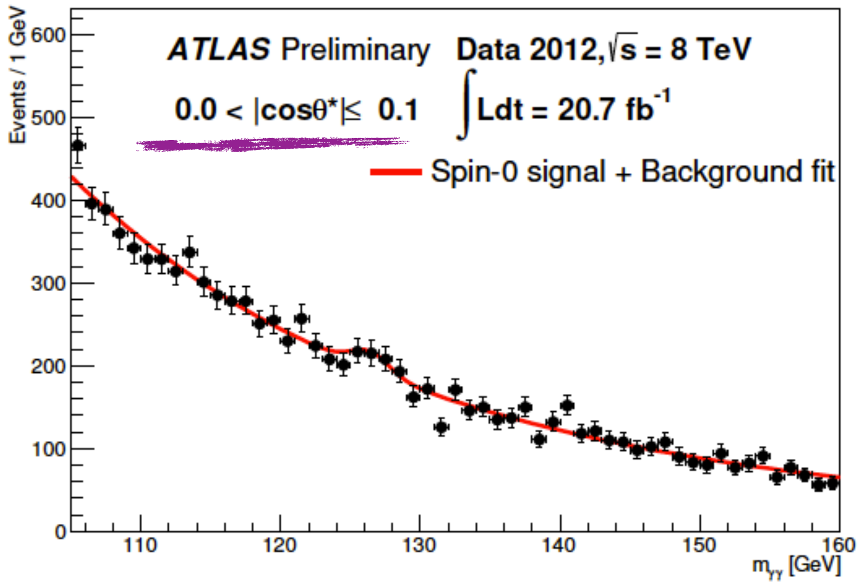
- ATLAS ($j^P$-MELA)
  - Expected $p_0$ for $0^-$ = 3.1 σ .
  - Observed $p_0$ for $0^-$ = 2.8 σ .
  - Observed $p_0$ for $0^+$= 0.25 σ .
  - CLs = 0.004 (1-CLs = 99.6 %) .

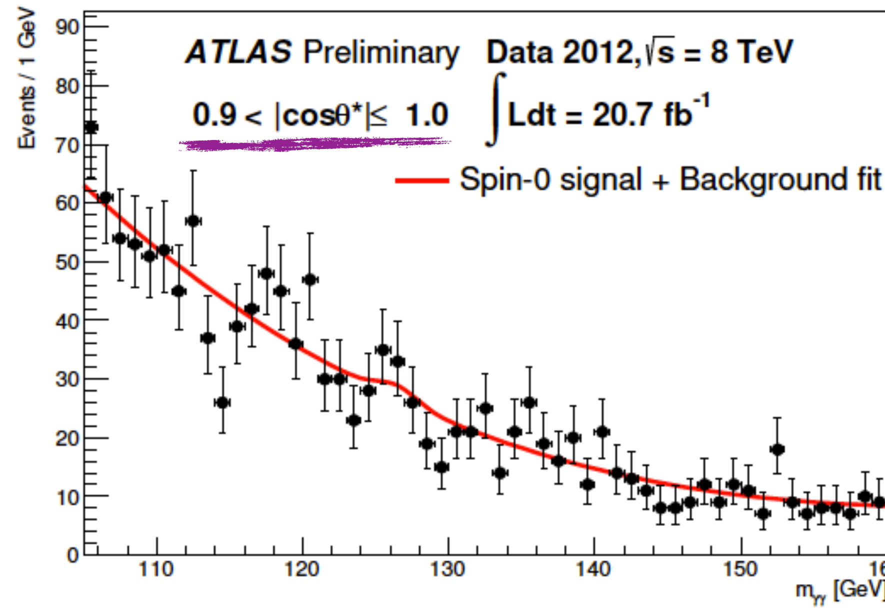


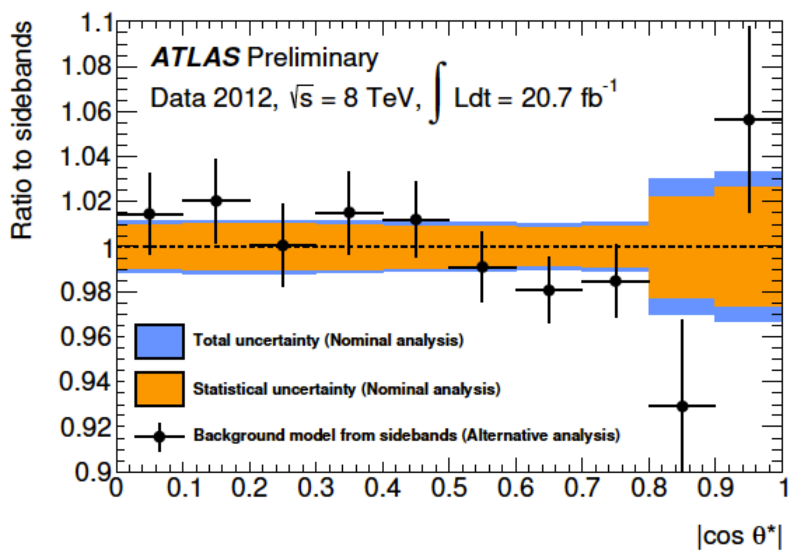

- CMS ($D_{JP}$)
  - Expected $p_0$ for $0^-$ = 2.6 σ .
  - Observed $p_0$ for $0^-$ = 3.3 σ .
  - Observed $p_0$ for $0^+$= 0.5 σ .
  - CLs = 0.0016 (1-CLs = 99.84 %) .



# $M_{\gamma\gamma}$ and cos$\theta^*$ Correlation




→ good agreement between bands (from nominal method) and points (from alternative)

→ no large correlations observed

# H→γγ : Overview

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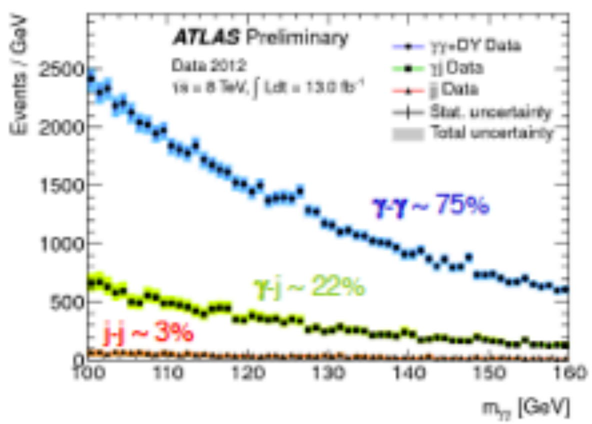
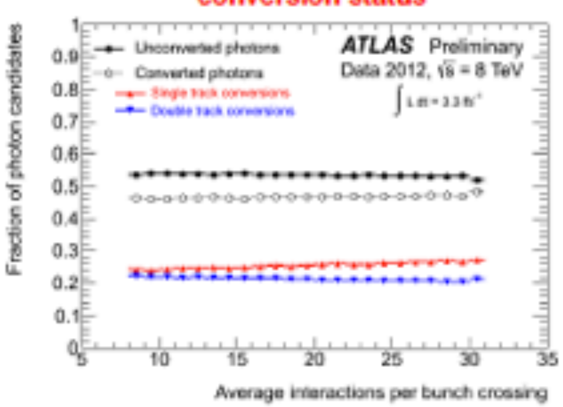
**Main production mode and decay through loops → sensitive to t / W couplings and to New Physics**

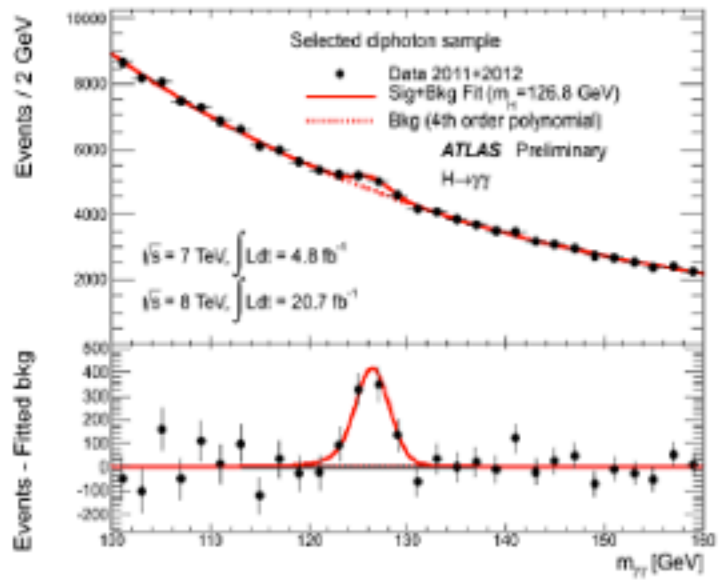
## Background reduction

**Data-driven background decomposition**




**Fraction of photon candidates per conversion status**



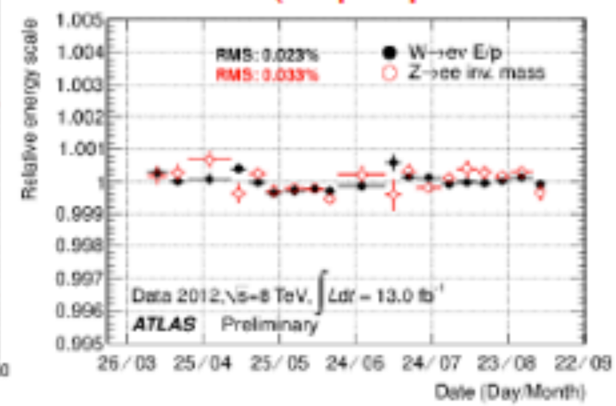

Simple topology: two high-$E_T$ (>40,30 GeV) isolated photons

142681 events in 100<$m_{\gamma\gamma}$ [GeV]<160

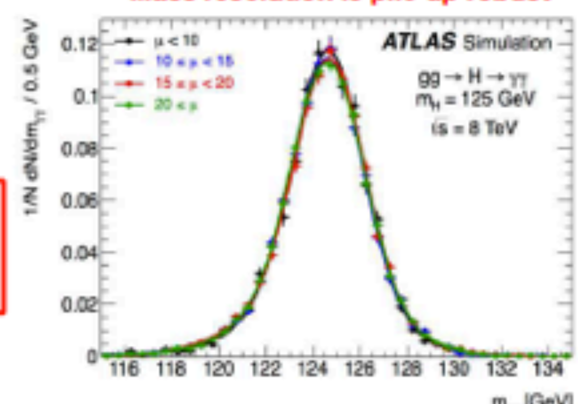
→ S/B~3% in mass window ~125 GeV with 90% signal

## Invariant mass resolution

**Stability of EM calorimeter response vs time (and pile-up) <0.1%**




**Mass resolution is pile-up robust**



# H→WW(*)→lνl'ν (l=e,μ)

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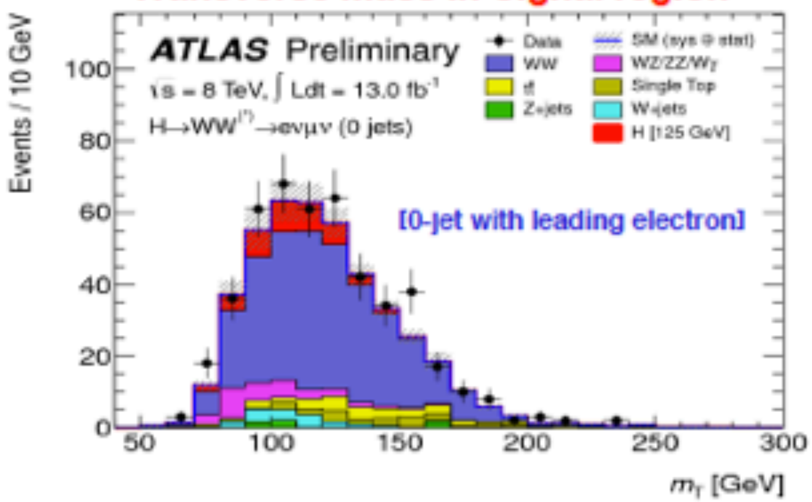
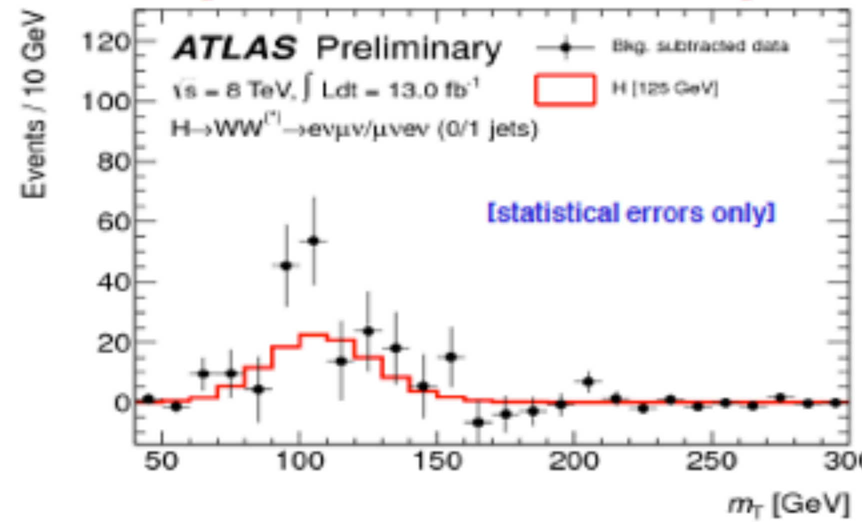
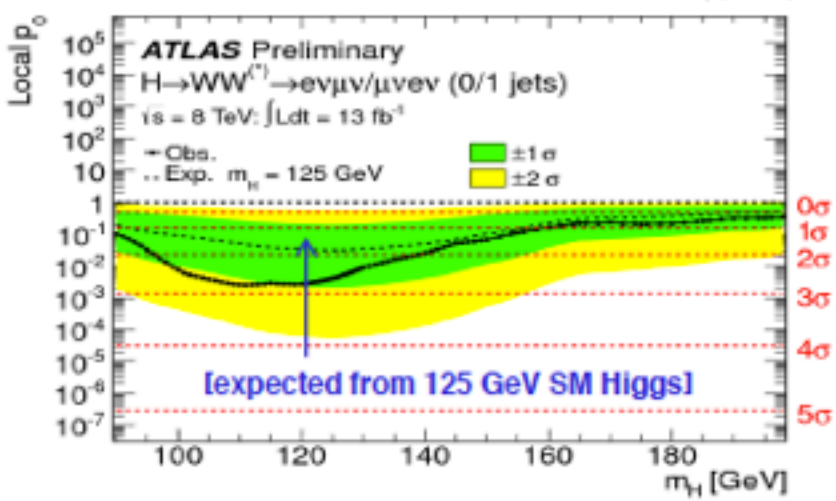
**Results using different lepton-flavor final states with 0/1-jet and 13 fb$^{-1}$ of 8 TeV data**

**Transverse mass in Signal region**




**Background-subtracted data and signal MC**



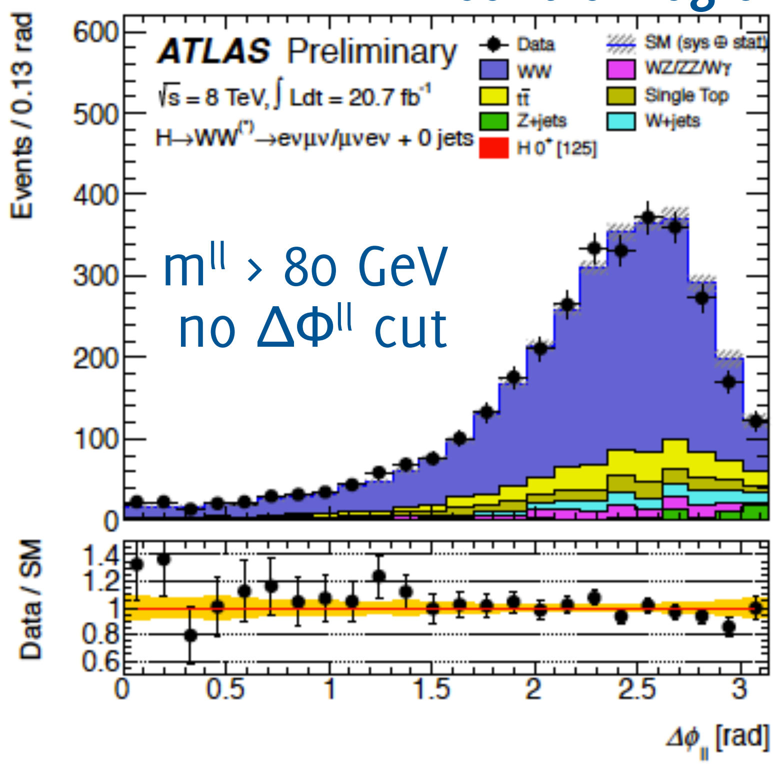

- Main backgrounds estimated from signal-free control regions in data
- Observed local significance of the broad excess @ 125 GeV: **2.6σ** (1.9σ expected for SM Higgs)
- Signal strength @ 125GeV **μ=1.5±0.6**

**[dominated by systematic uncertainties]**

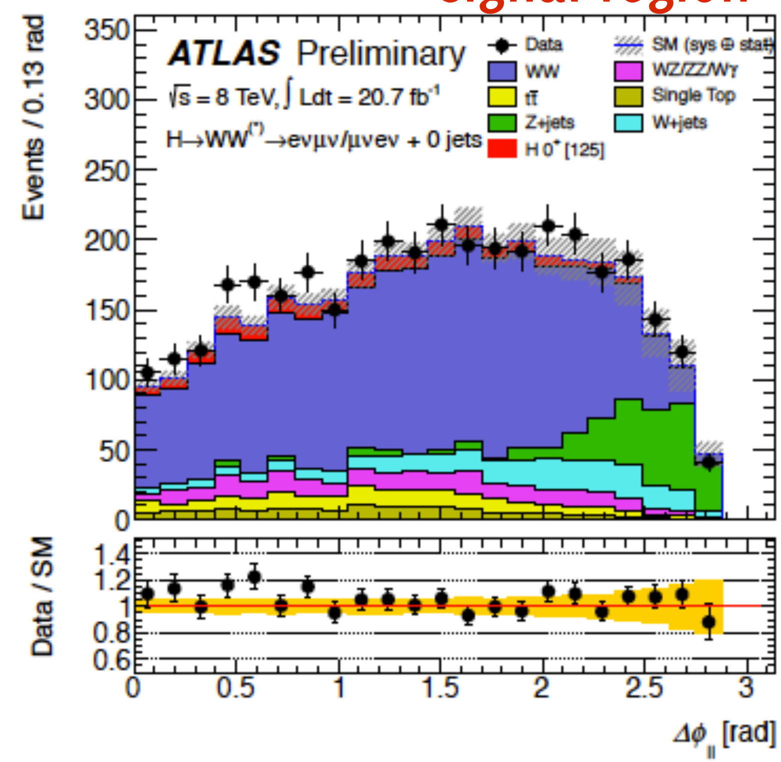
H→WW

# Signal Selection and Control Regions

**WW control region**




**signal region**




- W+jets fully data driven
- WW, top, Z+jets, normalization from control regions

**excess compatible with new particle @ 125 GeV**

| Variable | Spin analysis | Rate analysis [5] |
|---|---|---|
| | common $e\mu/\mu e$ lepton selection | |
| $E_{\mathrm{T,rel}}^{\mathrm{miss}}$ | $> 20$ GeV | $> 25$ GeV |
| $N_{jets}$ | 0 jets | $0, 1, \geq 2$ jet selections |
| $p_{\mathrm{T}}^{\ell\ell}$ | $> 20$ GeV | $> 30$ GeV |
| $m_{\ell\ell}$ | $< 80$ GeV | $< 50$ GeV |
| $\Delta\phi_{\ell\ell}$ | $< 2.8$ | $< 1.8$ |

# BDT Discriminants