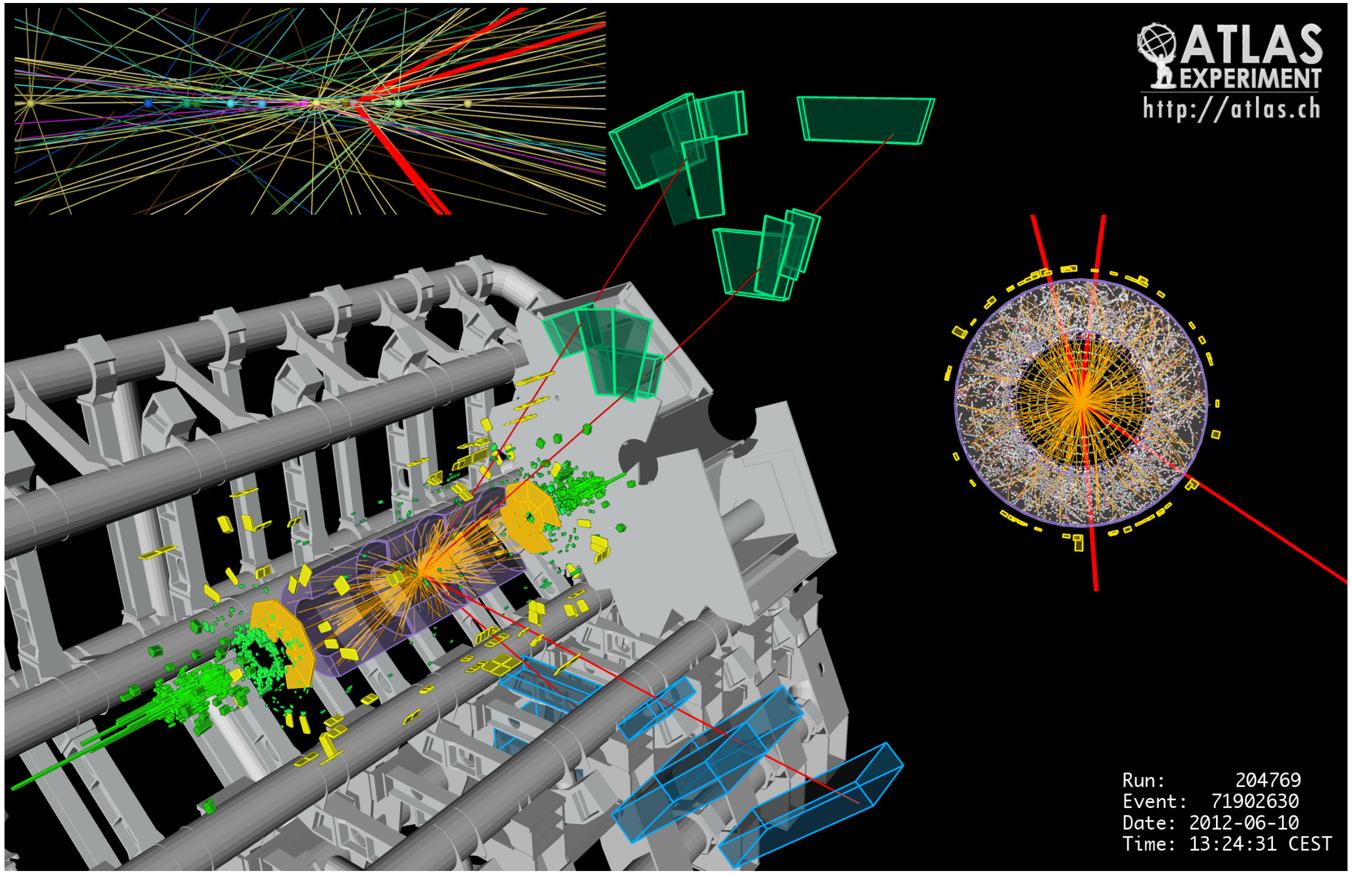
# Measurement of the spin and parity of the new boson discovered in ATLAS experiment at the LHC

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# Outline

- ATLAS detector at the LHC
- Discovery of the new boson
- Spin models and options
- Current spin measurements
- Beyond the Standard Model
- Summary and Outlook

# ATLAS detector overview

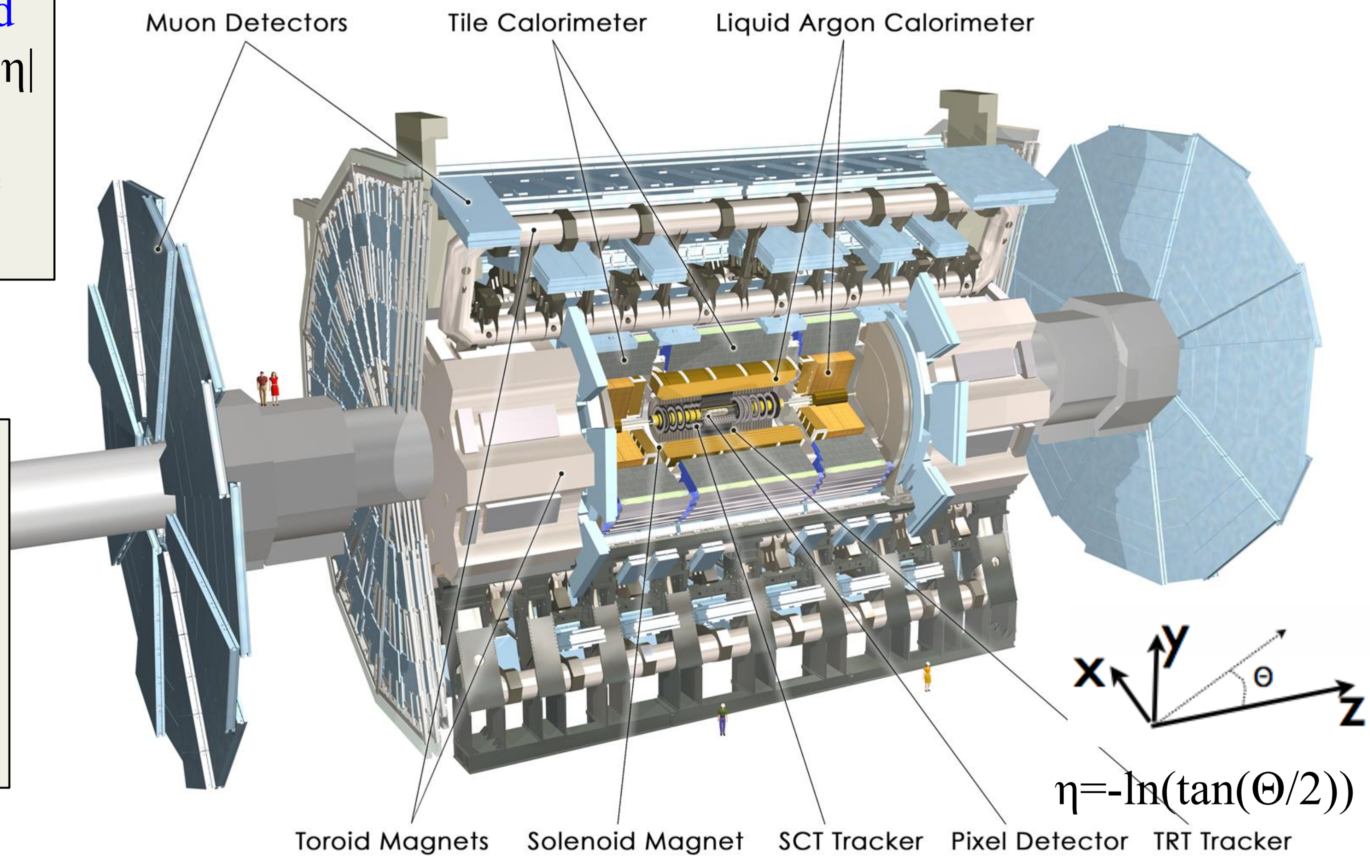
EM Calorimeter: (|η|<4.9) Pb-LAr accordion structure provides e/γ trigger, identification, measurement **σ/E ~10%√E**

Hadronic (Tile): provides trigger, jet measurement, $E_T^{miss}$ **σ/E ~50%√E ⊕ 0.03.** (|η|<1.7)

The Inner Detector provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at η = 0. Coverage: |η| < 2.5 (2.0 for TRT)

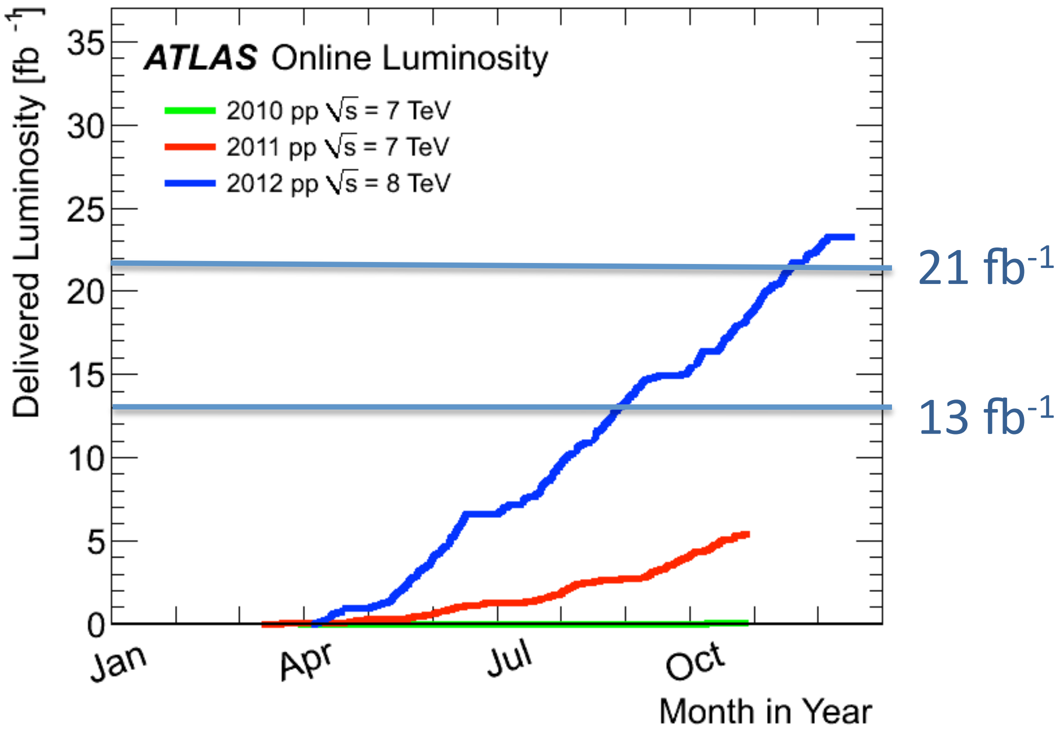
Resolution goal: $\sigma_{p_T} / p_T = 0.05\%\ p_T \oplus 1\%$

Muon spectrometer: high precision tracking and trigger chambers. |η| coverage up to 2.7. Magnetic field produced by 3x8 air-core toroids.



# Data taking in 2011 and 2012

| | √S | Delivered ($fb^{-1}$) | Recorded ($fb^{-1}$) |
|---|---|---|---|
| pp 2011 | 7 TeV | **5.61** | **5.25** |
| pp 2012 | 8 TeV | **23.3** | **21.7** |




In this presentation:

Data sets approved for the CERN Council Week 2012 (up to 13 $fb^{-1}$ collected at √s=8 TeV+ 4.6 $fb^{-1}$ collected at √s=7 TeV).

First results on full 2012 +2011 (Moriond) data set: up to 21 $fb^{-1}$ collected at √s=8 TeV + 4.6 $fb^{-1}$ collected at √s=7 TeV.

arXiv::11012185v1

ATLAS-CONF-2011-116

# Standard Model Higgs boson

- Higgs mechanism: most probable mechanism for the electroweak symmetry breaking. Used both in the Standard Model and theories beyond.

- In the Standard Model, the vector bosons and the fermions acquire mass via coupling to the Higgs field.

- Physical manifestation of the Higgs field in the Standard Model: scalar Higgs boson.

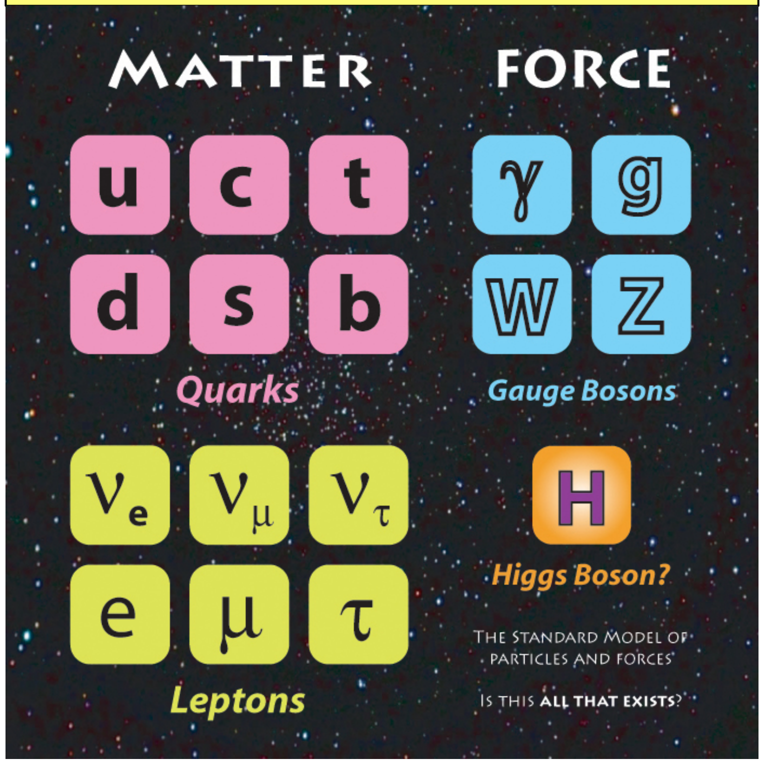
- Theories beyond the Standard Model often require presence of several Higgs bosons.

- Presently, the Higgs boson is the missing part of the Standard Model. Higgs-like resonance observed. No evidence for multiple Higgses is found so far.

LEP: $m_H$>114.4 GeV.

Tevatron: exclusion of the 147 GeV < $m_H$< 179 GeV region.

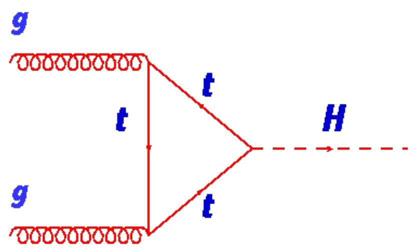
Indirect limits come from the precision measurements of electroweak observables.



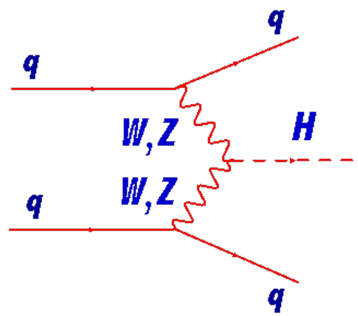

arXiv::1203.3774

# Standard Model Higgs searches at LHC

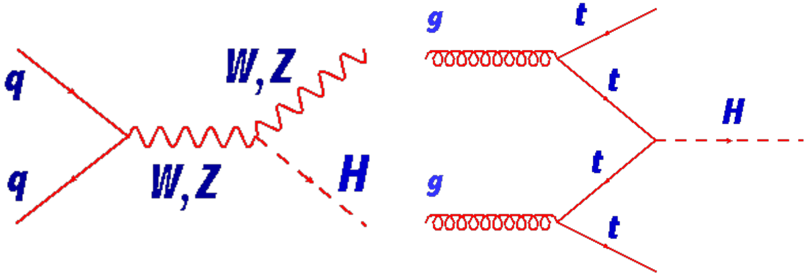
**Gluon-gluon fusion**

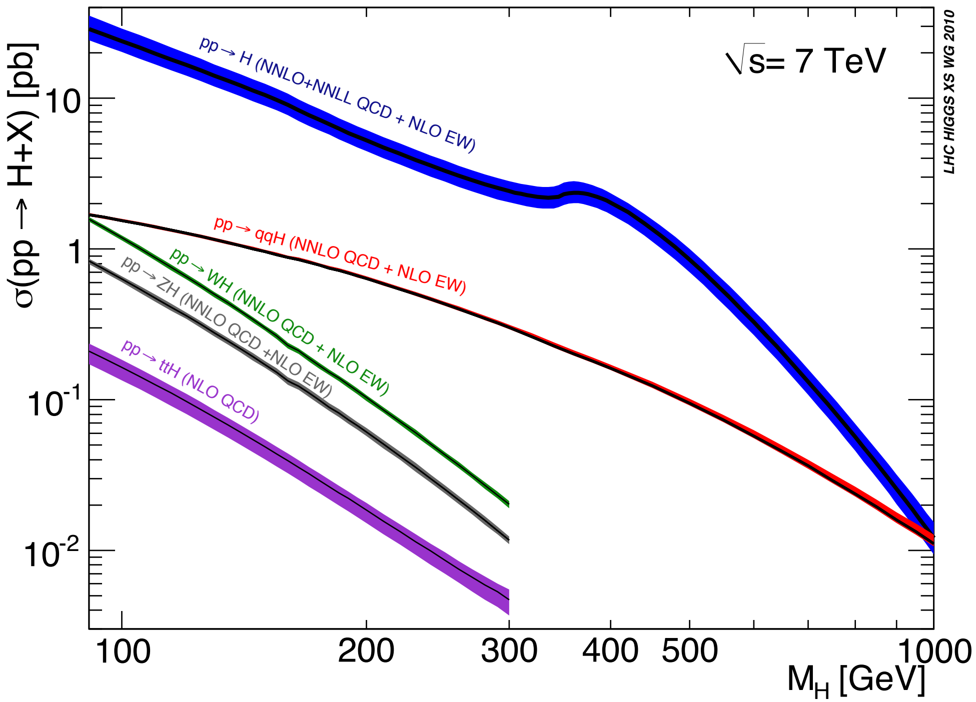


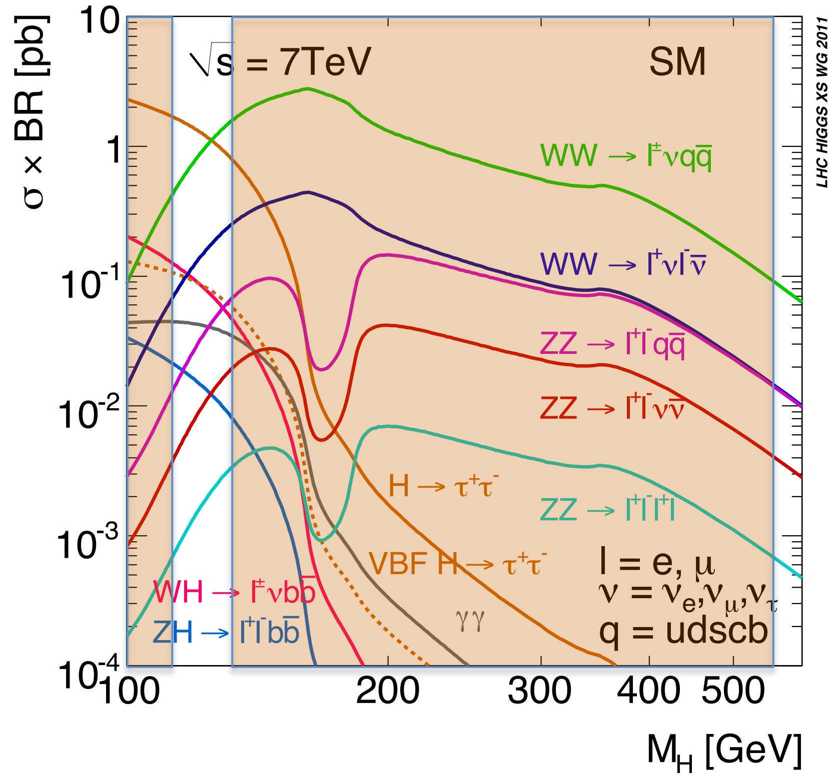

**Vector boson fusion**




**Associated production**




LHC Higgs Cross-Section Working group

# Discovery of the new resonance in ATLAS

# Considered search channels

| Higgs Boson Decay | Subsequent Decay | Sub-Channels | $\int L\,dt$ [fb$^{-1}$] | Ref. |
|---|---|---|---|---|
| | | 2011 $\sqrt{s}$ =7 TeV | | |
| $H \to ZZ^{(*)}$ | $4\ell$ | $\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$ | 4.6 | [10] |
| $H \to \gamma\gamma$ | – | 10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\}$ | 4.8 | [9] |
| $H \to \tau\tau$ | $\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ | $\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, p_{\mathrm{T},\tau\tau} > 100\text{ GeV}, VH\}$ | 4.6 | [11] |
| | $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ | $\{e, \mu\} \otimes \{\text{0-jet, 1-jet}, p_{\mathrm{T},\tau\tau} > 100\text{ GeV, 2-jet}\}$ | 4.6 | |
| | $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ | $\{\text{1-jet, 2-jet}\}$ | 4.6 | |
| $VH \to Vbb$ | $Z \to \nu\nu$ | $E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$ | 4.6 | [12] |
| | $W \to \ell\nu$ | $p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$ | 4.7 | |
| | $Z \to \ell\ell$ | $p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$ | 4.7 | |
| | | 2012 $\sqrt{s}$ =8 TeV | | |
| $H \to ZZ^{(*)}$ | $4\ell$ | $\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$ | 20.7 | [10] |
| $H \to \gamma\gamma$ | – | 14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\} \oplus \{\ell\text{-tag}, E_{\mathrm{T}}^{\mathrm{miss}}\text{-tag, 2-jet VH}\}$ | 20.7 | [9] |
| $H \to WW^{(*)}$ | $e\nu\mu\nu$ | $\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet}\}$ | 13 | [13] |
| $H \to \tau\tau$ | $\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ | $\{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, p_{\mathrm{T},\tau\tau} > 100\text{ GeV}, VH\}$ | 13 | [11] |
| | $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ | $\{e, \mu\} \otimes \{\text{0-jet, 1-jet}, p_{\mathrm{T},\tau\tau} > 100\text{ GeV, 2-jet}\}$ | 13 | |
| | $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ | $\{\text{1-jet, 2-jet}\}$ | 13 | |
| $VH \to Vbb$ | $Z \to \nu\nu$ | $E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$ | 13 | [12] |
| | $W \to \ell\nu$ | $p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$ | 13 | |
| | $Z \to \ell\ell$ | $p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$ | 13 | |

"Moriond EW" data set.

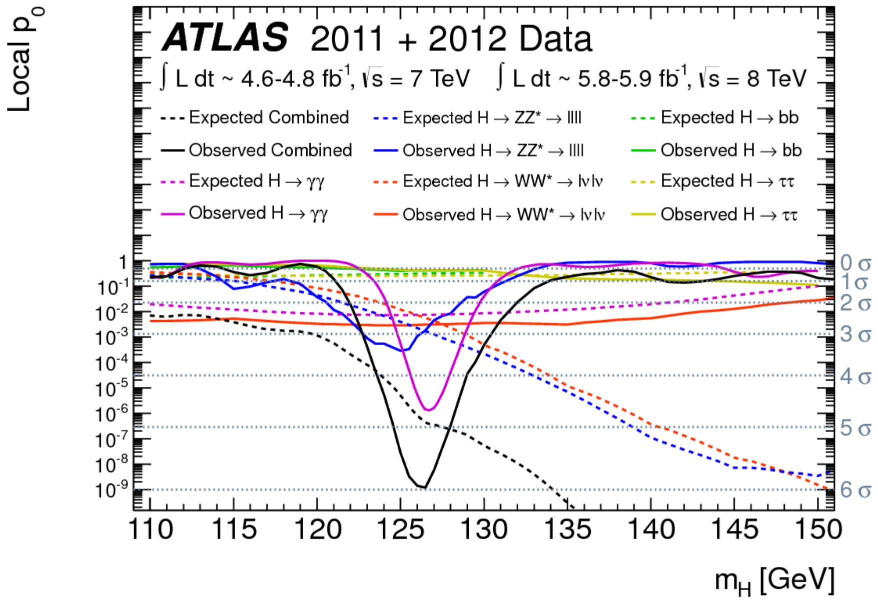
"Council week" data set.

- Current status of analysis in the individual channels where the searches were performed.
- Final result is the combination of all considered modes.
- Search performed in the range $m_H$ = 110 – 600 GeV.

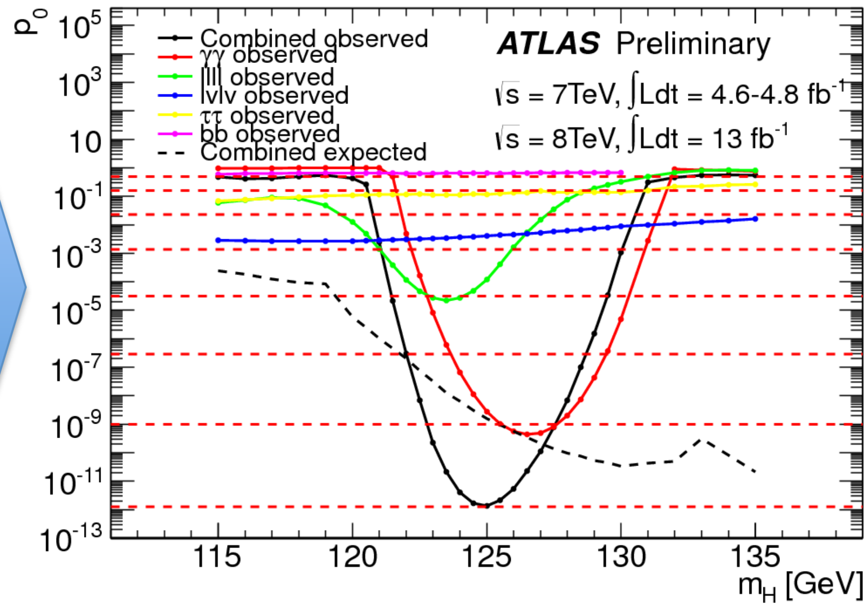
# Discovery of the new resonance

- The initial observation of the new resonance by ATLAS was done in the combination of channels with 4.8 $fb^{-1}$ at √s = 7 TeV and 5.8 $fb^{-1}$ at √s = 8 TeV.
  - $H \rightarrow ZZ^{(*)} \rightarrow 4l$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$.
- Excess with local (global) significance of 5.9σ (5.1σ) driven by the $ZZ^{(*)}$, γγ and WW decays. $M_H$ = 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV.
  - Confirmed with subsequent study of 4.8 $fb^{-1}$ at 7 TeV + 13 $fb^{-1}$ at 8 TeV

4.8 $fb^{-1}$ at 7 TeV and 5.8 $fb^{-1}$ at 8 TeV

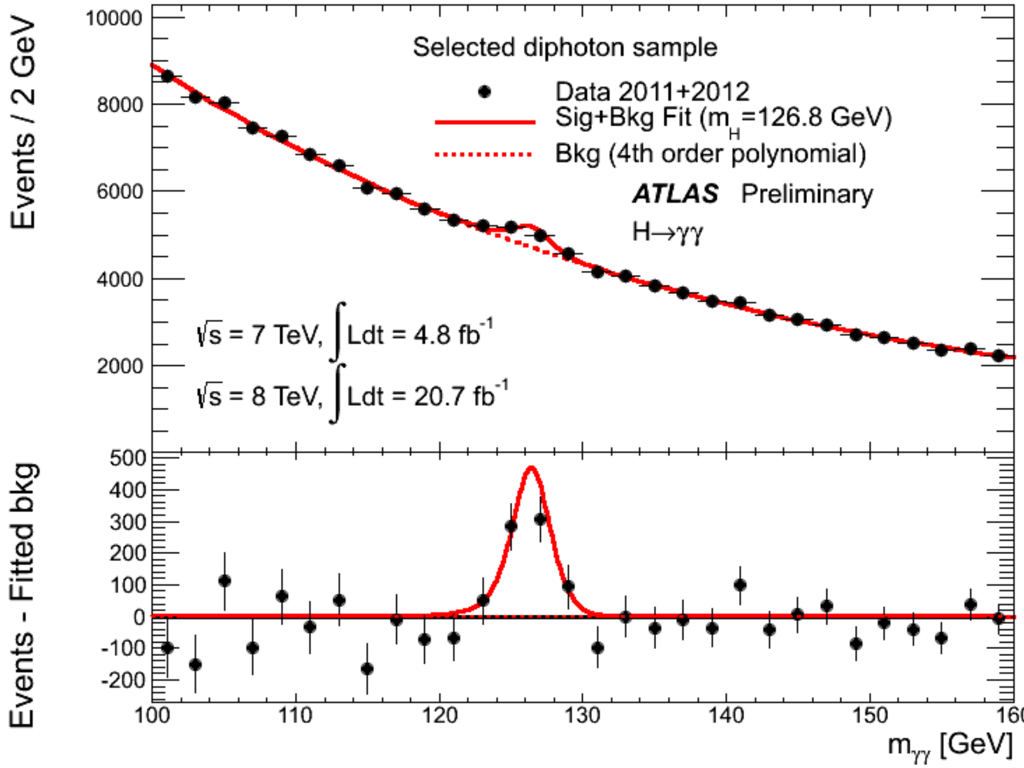


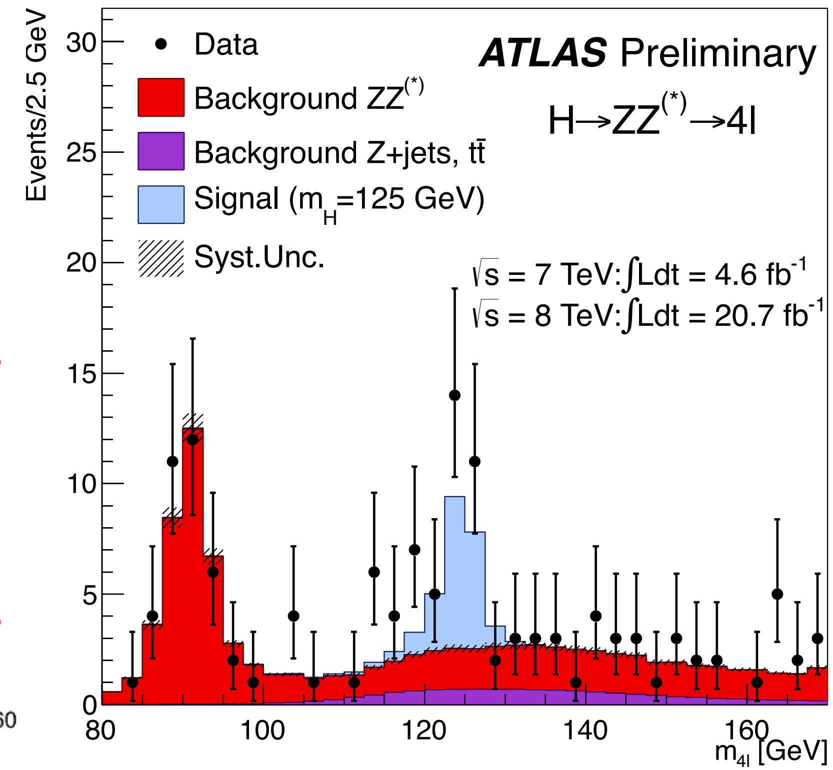

4.8 $fb^{-1}$ at 7 TeV and 13 $fb^{-1}$ at 8 TeV



# Current status of the new resonance

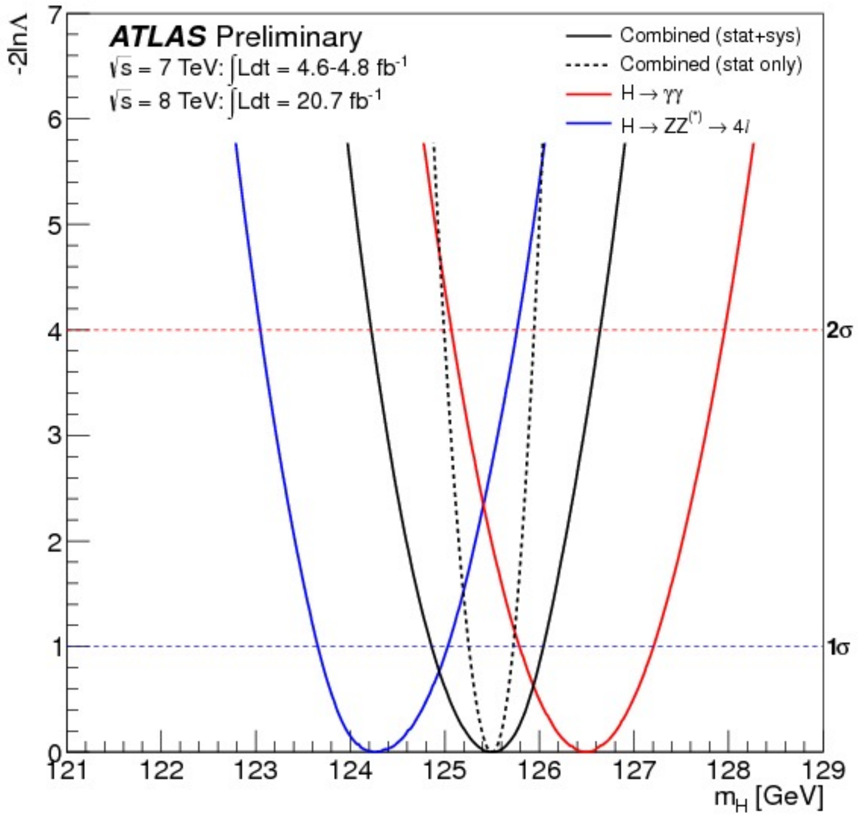
- In February-March 2013, the in ZZ and γγ results were updated with larger data sets
  - Up to 20.7 $fb^{-1}$ at 8 TeV + 4.6 $fb^{-1}$ at 7 TeV.
- Individual local significance of excess reached 7.4 (γγ) and 6.8 (ZZ) standard deviations.

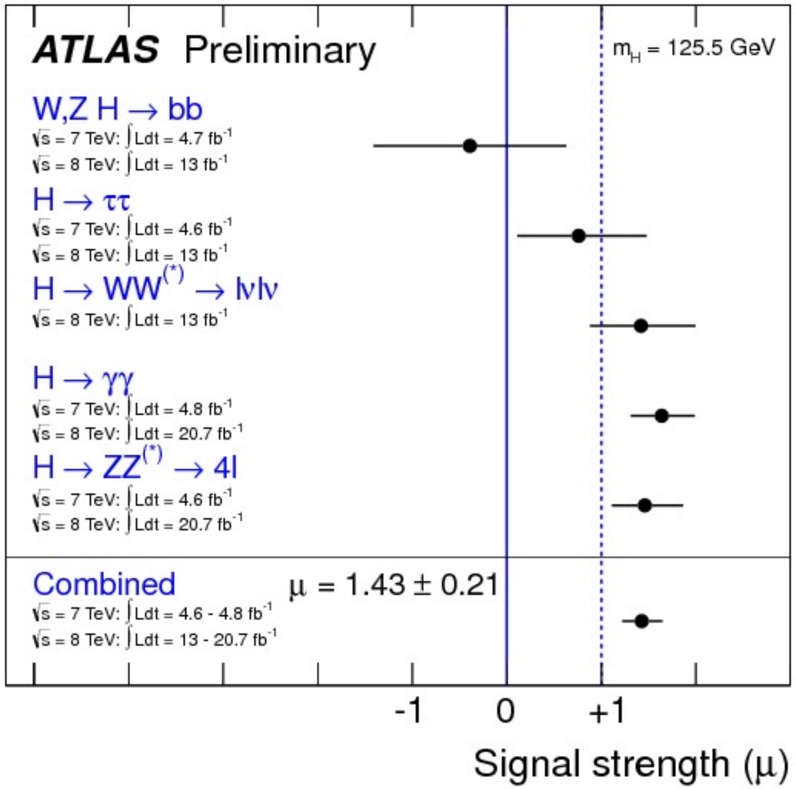


# Current status of the new resonance

- Combined mass measurement from $H \rightarrow ZZ^{(*)} \rightarrow 4l$, $H \rightarrow \gamma\gamma$ channels: $m_H = 125.5 \pm 0.2\ (stat)\ ^{+0.5}_{-0.6}\ (sys)$ GeV.
- The mass difference between two channels: $\Delta m_H = 2.3\ ^{+0.6}_{-0.7}\ (stat) \pm 0.6\ (sys)$ GeV.
  - Corresponds to probability of 1.5% (2.4 standard deviations).



# Spin and parity models of the new resonance

# Properties of the new resonance

- The production of a new resonance with the mass around 126 GeV is observed in proton-proton collisions.

- Can we attribute this resonance to the Standard Model Higgs boson? The Standard Model Higgs:
  - Neutral scalar.
  - CP-even: $J^{CP}=0^{++}$.
  - Predicted couplings to the fermions and gauge bosons.
  - Self-couplings.

- The new resonance is a neutral boson: it decays to pairs of gauge bosons (and fermions?) with total charge 0.
  - Integer spin.
  - Parity is to be defined.

# Spin and parity of the new resonance

- What do we know about the spin and parity ($J^P$) of the new resonance so far:
  - Integer spin. Currently considering 0, 1 or 2.

- Spin-1 is disfavored due to the observation of the $\gamma\gamma$ decay (Landau-Yang theorem). However there are loopholes.

- To associate this particle to a particular model, one needs to measure the spin and parity in the experiment without theoretical prejudice.

- Need to study J=0,1,2 cases to exclude all hypotheses alternative to the $J^P=0^+$.

# Spin and parity of the new resonance

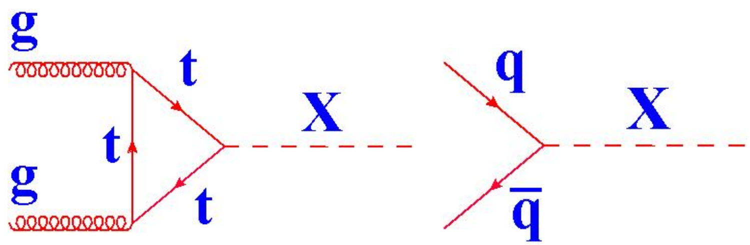
- Summary of spin possibilities given the observed decays.
- In principle, the observation of $\gamma\gamma$ disfavors the spin-1 hypothesis.
- The observation of the two-fermion decays will disfavor the spin-2 hypothesis.
- In both cases the loopholes exist.

| | Spin-0 | Spin-1 | Spin-2 | Observed |
|---|---|---|---|---|
| $\gamma\gamma$ | YES | NO | YES | YES |
| WW/ZZ | YES | YES | YES | YES |
| Fermions ($bb,\tau\tau$) | YES | YES | NO | YES? |

# Present spin measurements in ATLAS (Council week 2012 and Moriond 2013)

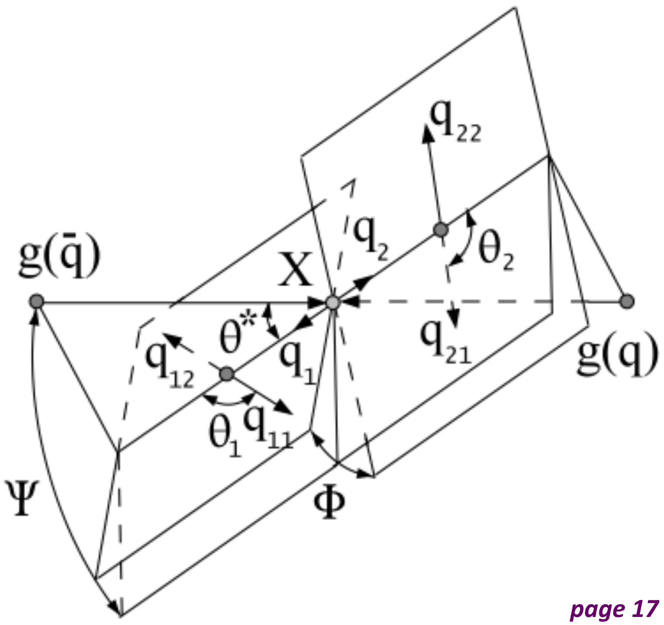
# Measurements of Spin and Parity

- Assume possible production mechanisms which can be responsible for the observation in WW, ZZ and γγ:
  - Spin-0: gluon-gluon Fusion.
  - Spin-1: qqbar production.
  - Spin-2: gluon-gluon Fusion and qqbar production.




- Measurement of properties: deduce spin and parity from measured distributions of kinematic observables.

- Observables:
  - Angular distributions of decay products in the rest frame of the resonance.
  - For some channels: invariant masses of the gauge bosons.




arXiv:1001.3396 arXiv:1208.4018

# Spin-2 models

- Which Spin-2 models makes sense?
  - The interaction of a spin-two particle with electroweak gauge bosons is described by at least 10 independent tensor couplings.
  - Production mechanism can also vary: gg, qq.

- General idea:
  - Given the number of possibilities, we cannot exclude 'generic' spin-2.
  - We should start with the model with minimal couplings and exclude it in favor of the SM hypothesis, which is relatively well defined.
  - If during this study we observe something 'funny' – have a deeper look in spin-2 models.
  - It is possible that both ggF and qq production mechanisms contribute to the spin-2 state. The possible mixtures should thus be studied.

arXiv:1001.3396 arXiv:1208.4018

# Present spin studies in ATLAS

- In 2012 and 2013 ATLAS has presented two major studies of the spin and parity of the Higgs-like resonance around 126 GeV.

- Decays: H->ZZ->4l and H->γγ.

- Spin and parity hypotheses considered: $0^+$, $0^-$,$1^+$,$1^-$, graviton-like tensor with minimal couplings $2_m^+$, pseudo-tensor $2^-$.
  - $2_m^+$ and $2^-$ production. gg->X: $g_1$=1; qq->X: $\rho_{12}$=1.
  - $2_m^+$ decay $g_1$=$g_5$=1.
  - $2^-$ decay: $g_8$=$g_9$=1.

- The choice of coupling constants follows the formalism described in the JHU papers:
  - Y. Gao, *et al., "Spin determination of single-produced resonances at hadron colliders"*, Phys. Rev. D81 (2010) 075022, arXiv:1001.3396 [hep-ph]
  - S. Bolognesi, *et al., "On the spin and parity of a single-produced resonance at the LHC"*, Phys. Rev. D86 (2012) 21.

ATL-CONF-2012-168 ATL-CONF-2013-013

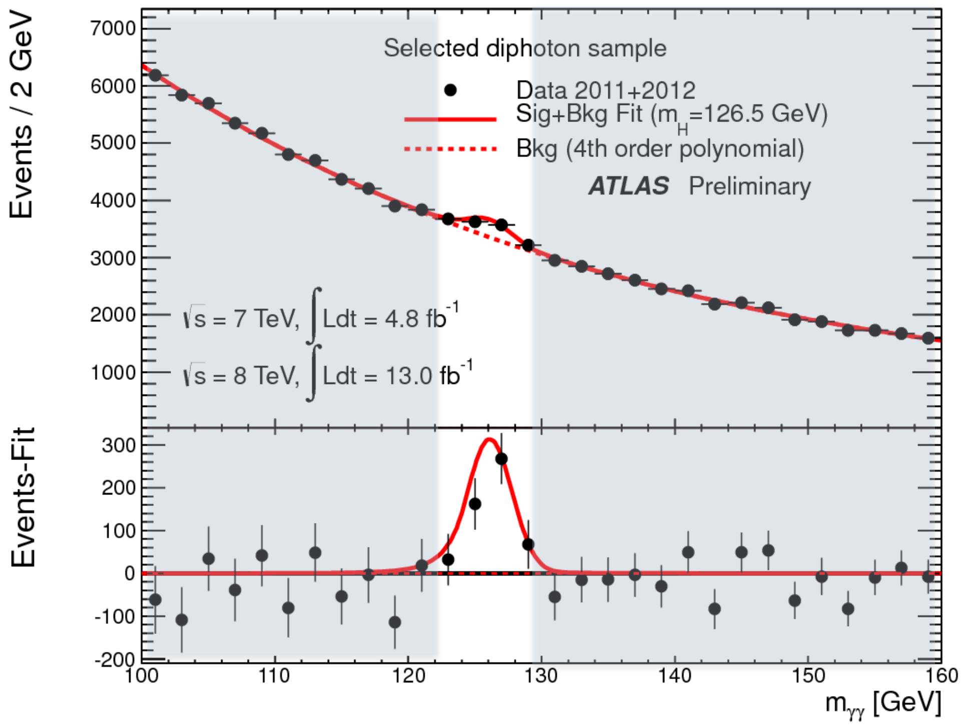
# Two photon decay channel

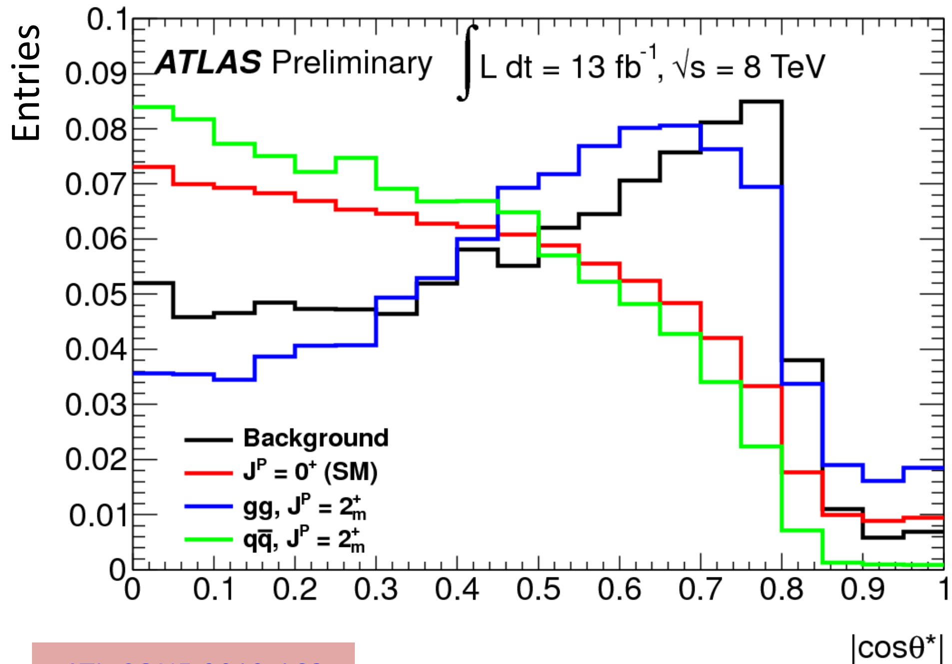
13 fb$^{-1}$ at 8 TeV

Two-photon decay channel: Study based on the single production angle: |cos θ*|.

Considered models: $0^+$ and $2^+_m$ (both qqbar and ggF production mechanisms).

No categorization: 123.8 GeV < $m_{\gamma\gamma}$ < 128.6 GeV



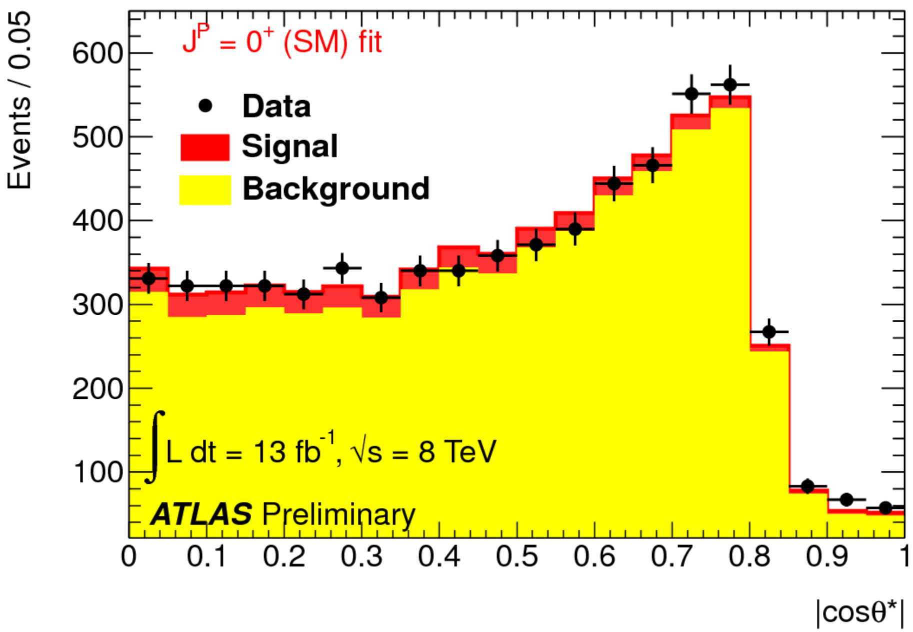



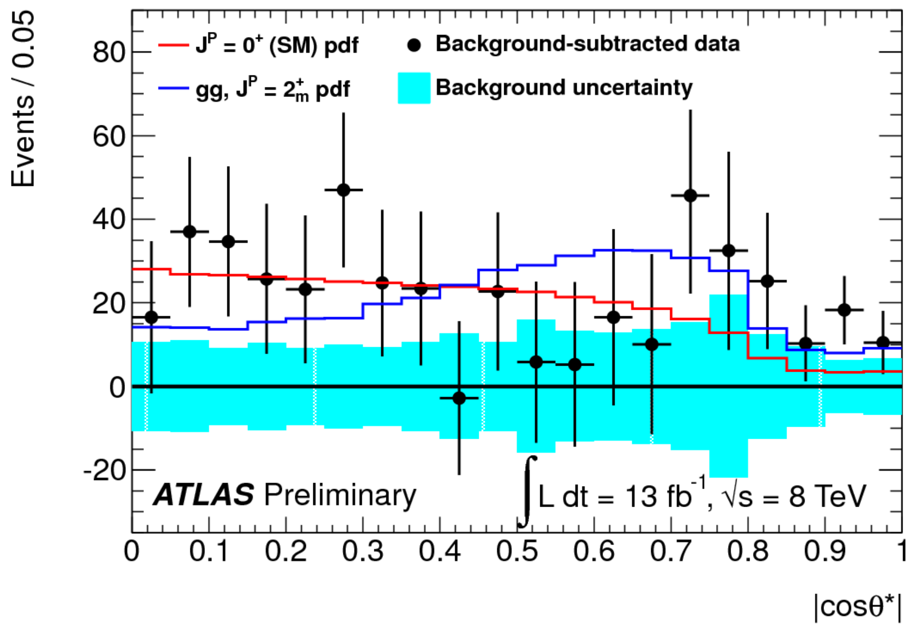

ATL-CONF-2012-168

# Two photon decay channel

- Left: fitted distribution of |cos θ*| for the SM Higgs boson signal plus background hypothesis, for the data, the background and the signal.

- Right: background-subtracted data distributions, profiled with a fit where the $0^+/2^+_m$ ratio is free.



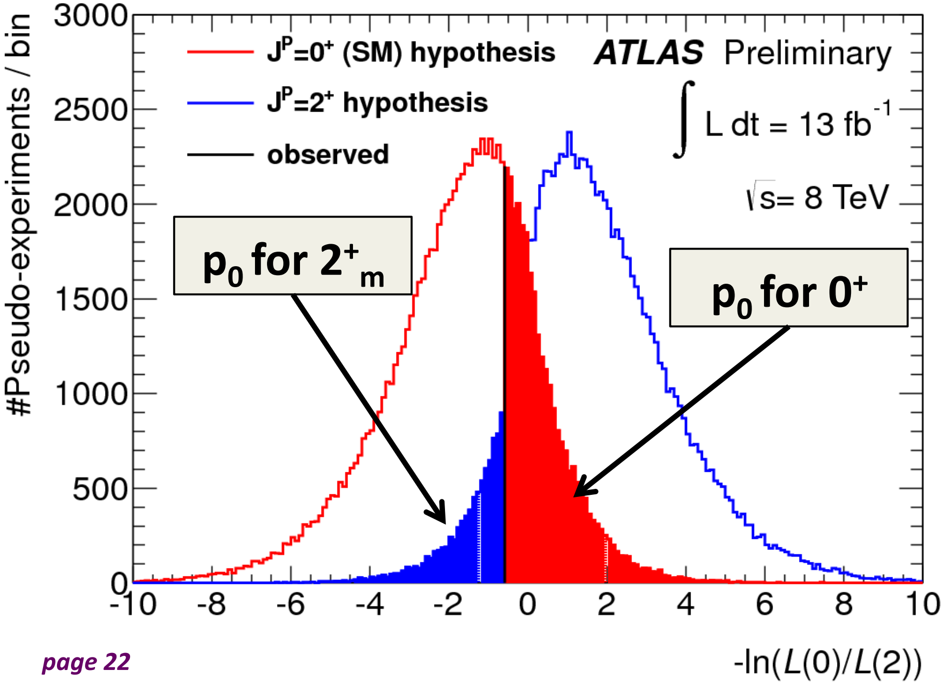
# H->γγ 13 $fb^{-1}$ at 8 TeV

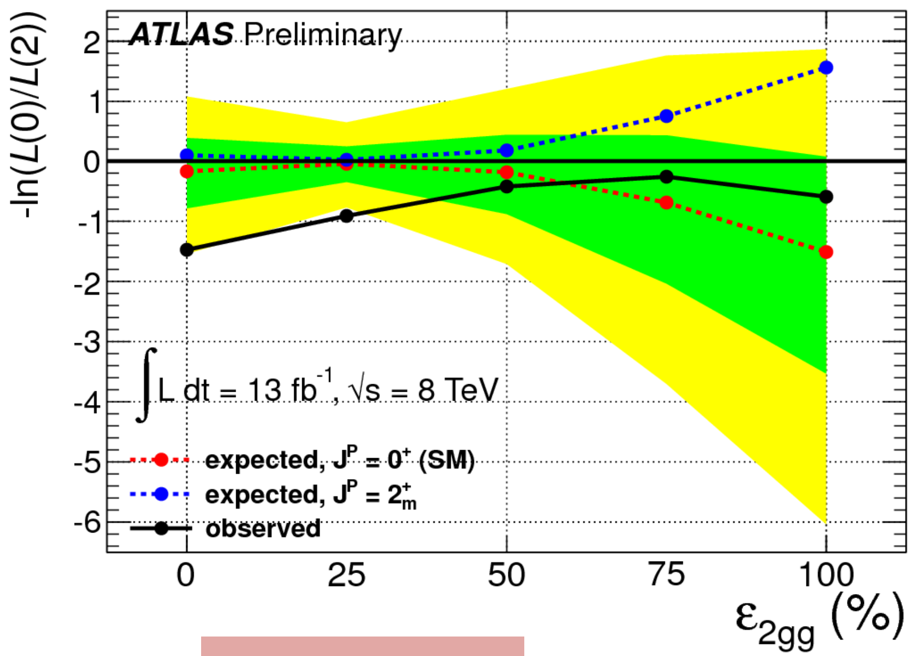
Expected $p_0$-value for $2^+_m$ (100% ggF) : 3.4% (1.8σ)

Observed $p_0$-value for $0^+$ hypothesis: 29% (0.55 σ).

For $2^+_m$ (100% ggF): 8.4% (1.4 σ).

Data show slight preference for $J^P=0^+$.



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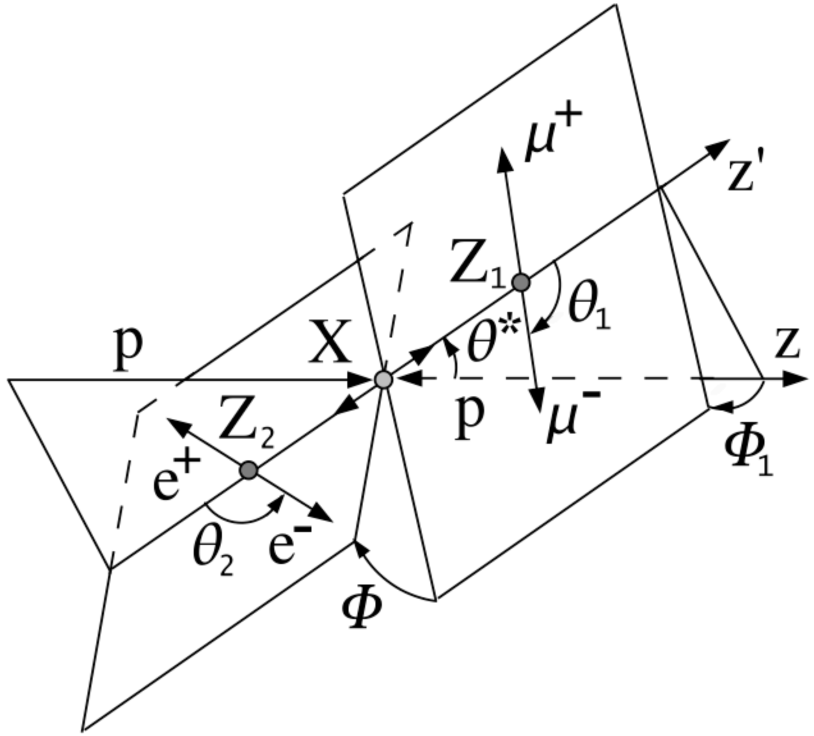
# Spin/Parity measurement in H->ZZ->4l

The H->ZZ->4l decay is sensitive to Spin and CP nature of the underlying resonance. In the case of low mass (<190 GeV) the observables are 5 production and decay angles and reconstructed masses of the intermediate Z's: $m_{12}$ and $m_{34}$.




Sensitivity to all Spin-parity combinations.

Production and decay angles fully characterizing orientation of the decay chain:

Θ* of the first Z-boson.

Φ and $\Phi_1$ between the decay planes defined in the Higgs rest frame.

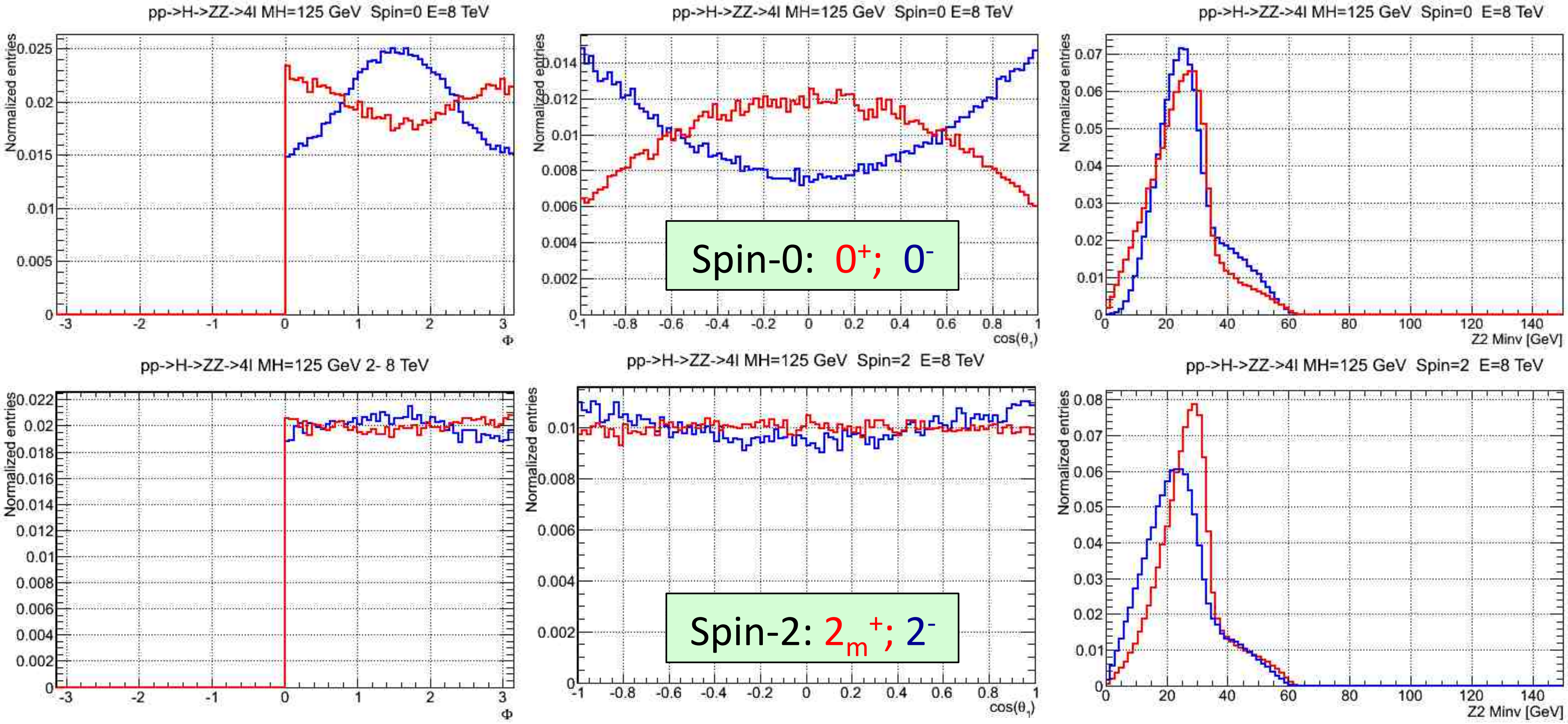
$\Theta_1$ and $\Theta_2$ of the negative leptons defined in the corresponding Z rest frame.

Test: $0^+$, $0^-$,$1^+$,$1^-$, $2_m^+$ (graviton –like tensor with min. couplings), $2^-$.

# Spin/Parity measurement in H->ZZ->4l

Examples of signal distributions for various spin and parity hypotheses at the generator level. (JHU 2.0.2 Leading Order MC generator)

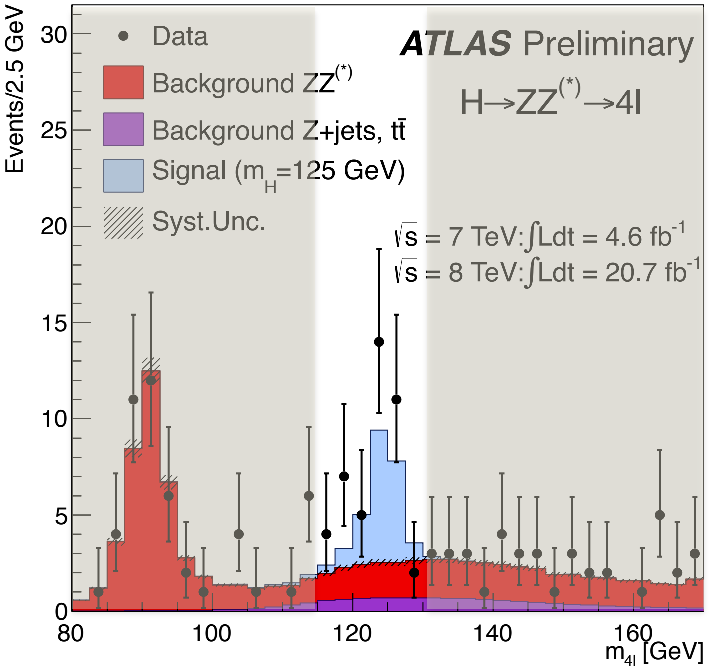
| $\Phi$ | $\cos\theta_1$ | $m_{Z2}$ |
|---|---|---|

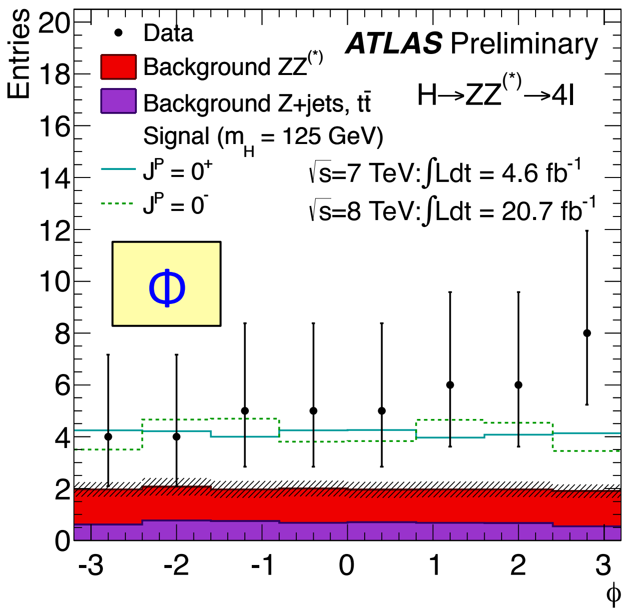


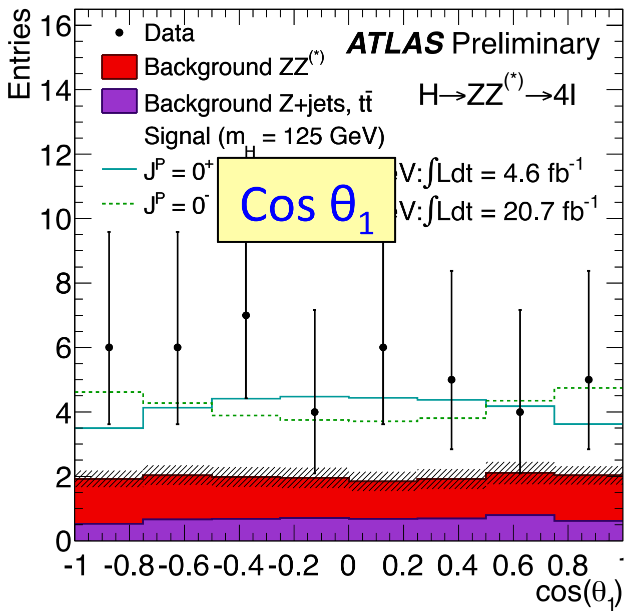
# Four lepton decay channel

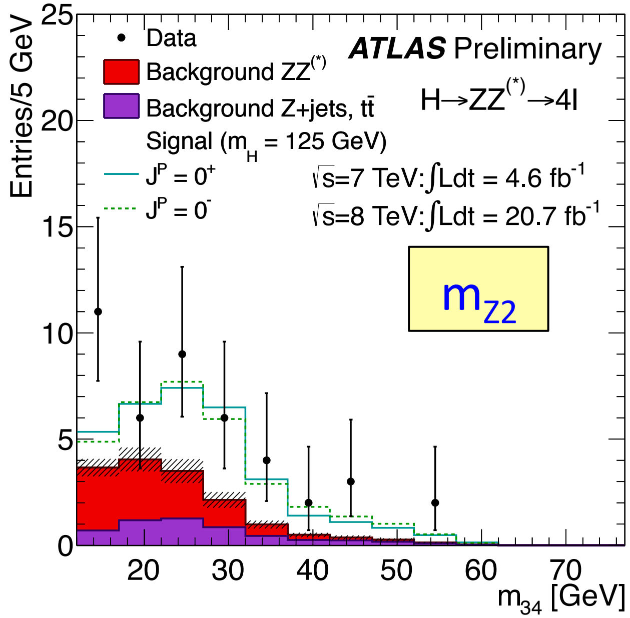
- Selection of 4l candidate events in the signal region: 115 GeV – 130 GeV.
- Reconstruction of the spin and parity sensitive variables after all selection cuts.
- Comparison to the signal and background expectations (MC and control regions).

4.6 $fb^{-1}$ at 7 TeV and 21 $fb^{-1}$ at 8 TeV



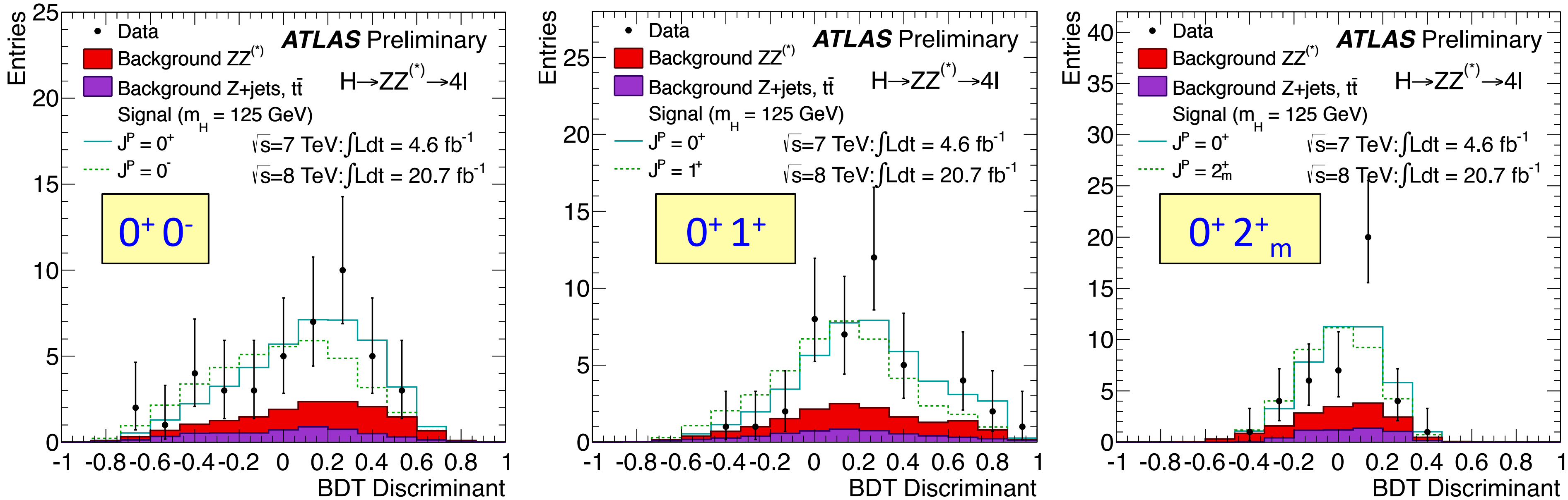



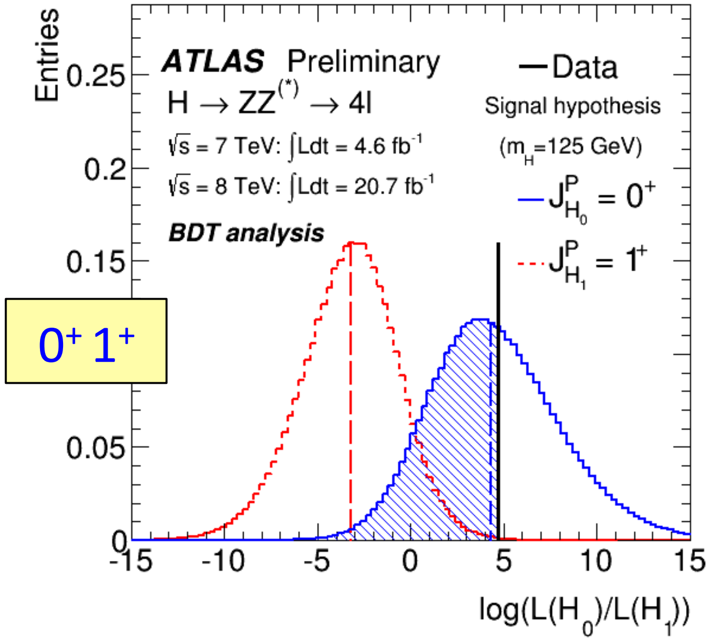
ATL-CONF-2013-013

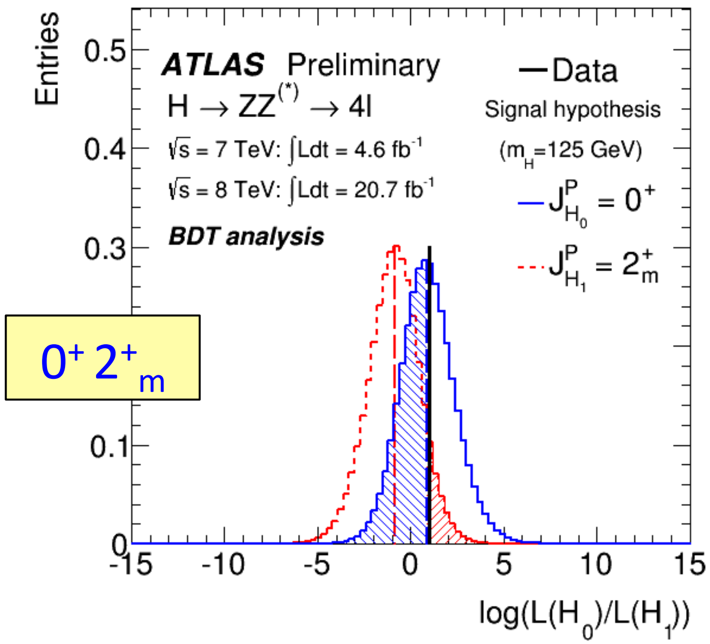
# Four lepton decay channel

- Two complimentary multivariate approaches.
  - BDT analysis: discriminants trained to separate pairs of different Spin/CP states. Training on signal Monte Carlo after full reconstruction and selection.
  - $J^P$-MELA: discriminants based on the full Matrix Element analytical calculation for each Spin/CP hypothesis.
- Background: from full simulation (ZZ) and from control regions (others).

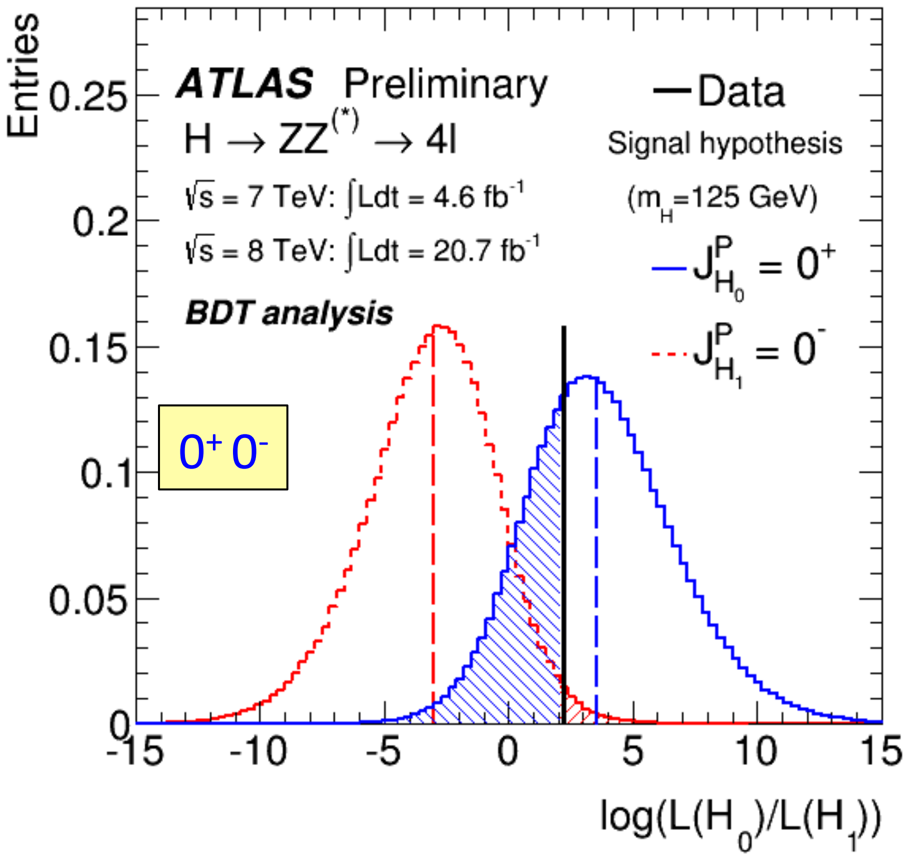


# Four lepton decay channel




- Test statistic: ratio of profiled likelihoods.



# Four lepton decay channel

4.6 $fb^{-1}$ at 7 TeV and 21 $fb^{-1}$ at 8 TeV

Expected and observed $p_0$ values to exclude various spin and parity hypotheses. The shaded column shows the $p_0$ to exclude an alternative spin and parity hypotheses in favor of the $J^P=0^+$ state.

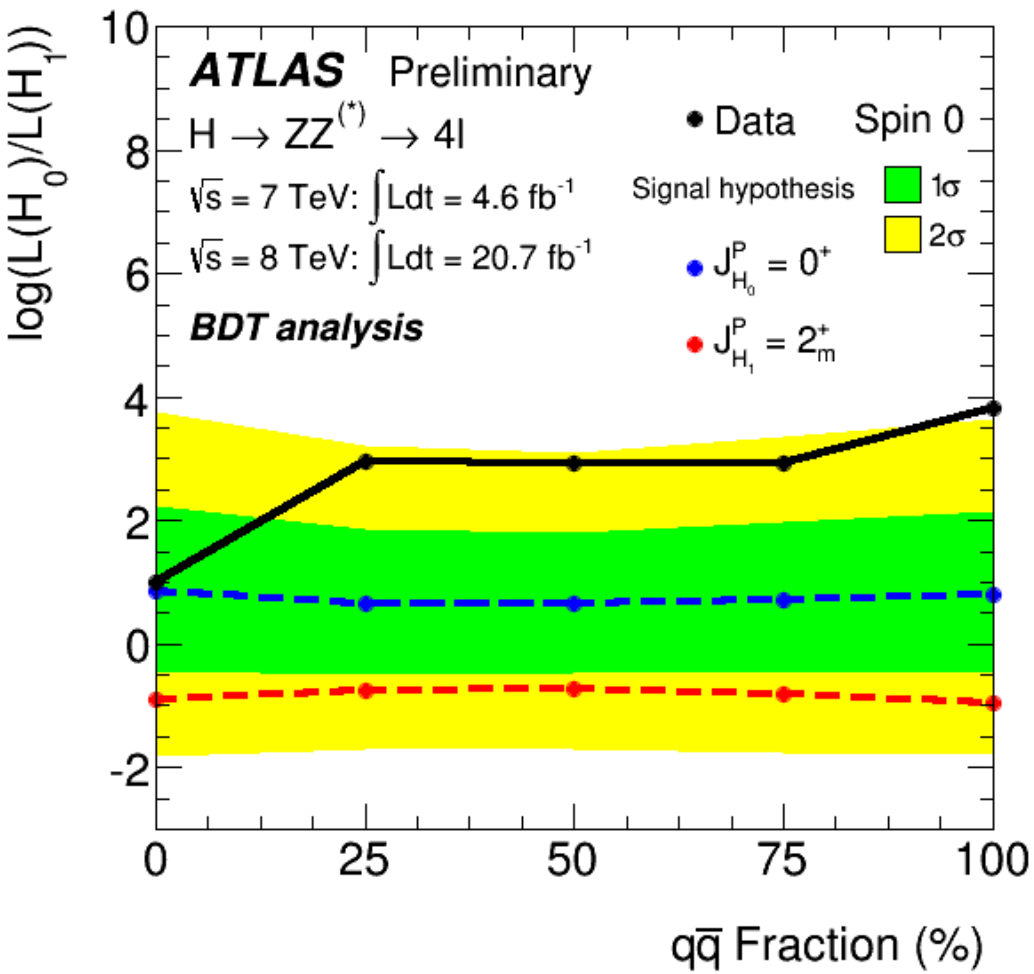
| $P_0$ (BDT analysis) | $0^-$ | $1^+$ | $1^-$ | $2^+_m$ | $2^-$ |
|---|---|---|---|---|---|
| **Observed exclusion of hypotheses in favor of $J^P=0^+$** | 0.0015 | 0.001 | 0.051 | 0.079 | 0.258 |
| **Observed exclusion of $J^P=0^+$ in favor of alternative hypotheses** | 0.31 | 0.55 | 0.15 | 0.53 | 0.037 |

| | | | | | |
|---|---|---|---|---|---|
| **Exclusion of hypothesis in favor of $J^P=0^+$. $CL_S$. BDT ($J^P$-MELA)** | **0.022 (0.003)** | **0.002 (0.005)** | **0.061 (0.030)** | **0.169 (0.182)** | **0.258 (0.115)** |

The results are consistent between BDT and $J^P$-MELA approaches. Data prefer $J^P=0^+$ over other hypotheses.

# Four lepton decay channel

Separation between the Standard Model $J^P=0^+$ and $J^P=2^+_m$ hypotheses as the function of the production mechanism for spin-2 hypothesis.




Moderate, but stable expected separation for all fractions of production mechanisms.

Observed data fluctuations due to low statistics.

To provide a stable separation between $J^P=0^+$ and $J^P=2^+_m$ for all fractions of production mechanisms, the H->γγ, H->WW->lν lν and $H\text{->}ZZ^{(*)}\text{->}4l$ decay channels can be combined.

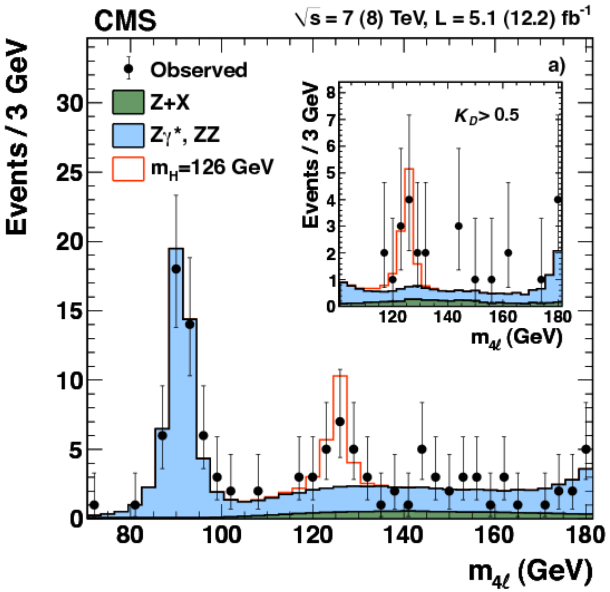
# CMS results

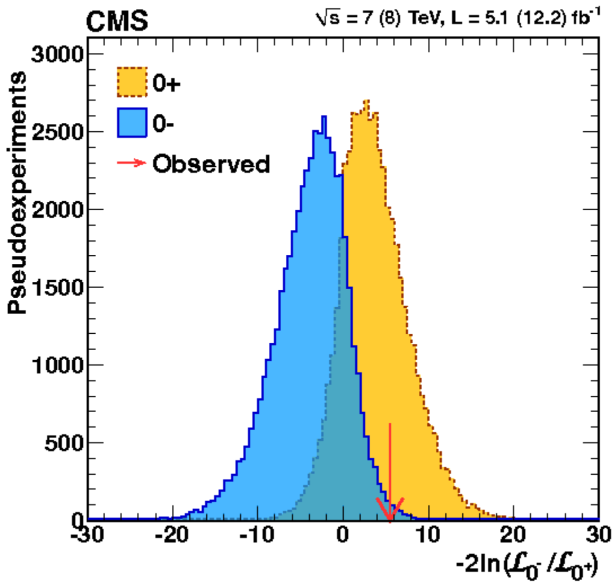
5.1 $fb^{-1}$ at 7 TeV + 12.2 $fb^{-1}$ at 8 TeV.

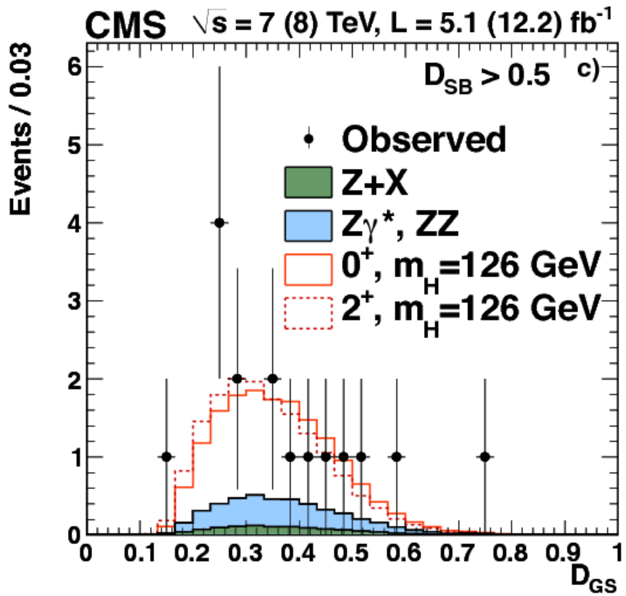
Discriminant based on the analytical calculation of the matrix element.

$p_0(0^-)=0.072$; $p_0(0^+)=0.7$. Exclusion of $J^P=0^-$ in favor of $J^P=0^+$: $CL_S = 2.4\%$

No conclusion on the $J^P=2^+_m$ exclusion: more data required.




Phys. Rev. Lett. 110, 081803 (2013)

CMS-PAS-13-002

# CMS results

## Spin-parity: results

| | Expected [σ] | | Observed (μ from data) | | |
|---|---|---|---|---|---|
| | μ=1 | μ from data | P(q > Obs \| alternative) [σ] | P(q > Obs \| SM Higgs) [σ] | CLs [%] |
| $gg \to 0^-$ | 2.8 | 2.6 | 3.3 | -0.5 | 0.16 |
| $gg \to 0_h^+$ | 1.8 | 1.7 | 1.7 | +0.0 | 8.1 |
| $q\bar{q} \to 1^+$ | 2.6 | 2.3 | > 4.0 | -1.7 | < 0.1 |
| $q\bar{q} \to 1^-$ | 3.1 | 2.8 | > 4.0 | -1.4 | < 0.1 |
| $gg \to 2_m^+$ | 1.9 | 1.8 | 2.7 | -0.8 | 1.5 |
| $q\bar{q} \to 2_m^+$ | 1.9 | 1.7 | 4.0 | -1.8 | < 0.1 |

**Assuming spin-0, fitting for CP-odd contribution gives**
$f_{a3} = 0.00^{+0.23}_{-0.00}$ (more in backup)

**The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher**

# Next steps

- The LHC has delivered 23.3 $fb^{-1}$ at $\sqrt{s}$=8 TeV and 5.6 $fb^{-1}$ at $\sqrt{s}$=7 TeV before the technical stop.

- So far we made preliminary analysis on the full dataset for H->γγ and H->ZZ->4l decay channels.
  - The data seem to prefer $J^P=0^+$ over other hypotheses.
  - Adding the spin measurement in the WW decay.
  - Making the statistical combination of all channels.

  } In progress

- The most popular alternative hypotheses are likely to be excluded in favor of the $0^+$ in the following months. Further studies (up to 300 $fb^{-1}$ and beyond):
  - If it is a Higgs boson – is it the Standard Model Higgs boson?
  - Study of the structure of HVV interaction.
  - Searches for the CP-violation in the Higgs sector.

  } In preparation, estimates exist.

# Beyond the Standard Model

# CP-violation in ZZ coupling

- The separation between pre-defined spin and parity hypotheses is possible with the present dataset.
  - Given current indications, one can expect the dominant $J^P=0^+$.
  - Several Beyond the Standard Model theories with extended Higgs sector predict possible anomalous contribution and/or CP-violation in the Higgs sector.

- Required to explain the matter-antimatter asymmetry of the Universe.
  - In addition to the known CP-violation in B, K, D meson systems.

- The magnitude of the CP-mixing in the Higgs sector may vary significantly from model to model.
  - Observing the dominant $J^P=0^+$ state, can we tell if it has a CP-odd admixture?

arXiv:0708.0458v2

# CP-violation in ZZ coupling

- The $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel well suited for this measurement.
  - Same observables as for the spin and parity measurement: decay angles and masses of the Z's.

- Methods for CP-violation measurements (consider $0^+$ $0^-$ mixing).
  - Likelihood fit to matrix element where the unknown parameters (non-SM couplings) left free.
  - Study of asymmetries directly sensitive to different amplitude parts.
  - Modeling scenarios with different admixtures and excluding them.

- In general, this investigation makes sense: at very least, it gives insights on HZZ vertex.
  - May provide hints of non-Standard Model contributions to the HZZ vertex.

# CP-violation in ZZ coupling

Most general vertex for Spin-0 boson coupling to 2 vector bosons:

$$A(X \to VV) \sim (\underline{a_1} M_X^2 g_{\mu\nu} + \underline{a_2}(q_1 + q_2)_\mu (q_1 + q_2)_\nu + \underline{a_3}\varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta)\varepsilon_1^{*\mu}\varepsilon_2^{*\nu}$$

**CP-even** ($a_1$, $a_2$) **CP-odd** ($a_3$)

CP-conserving tree-level SM: $a_1 = 1$, $a_2 = a_3 = 0$.

CP-violation: $a_3 \neq 0$, given $a_1 \neq 0$ and/or $a_2 \neq 0$.

In general $a_i$ can be momentum-dependent form factors that may be generated in loops with new heavy particles.

It is always possible to select $a_1$ to be real. $a_2$ and $a_3$ are in general complex.

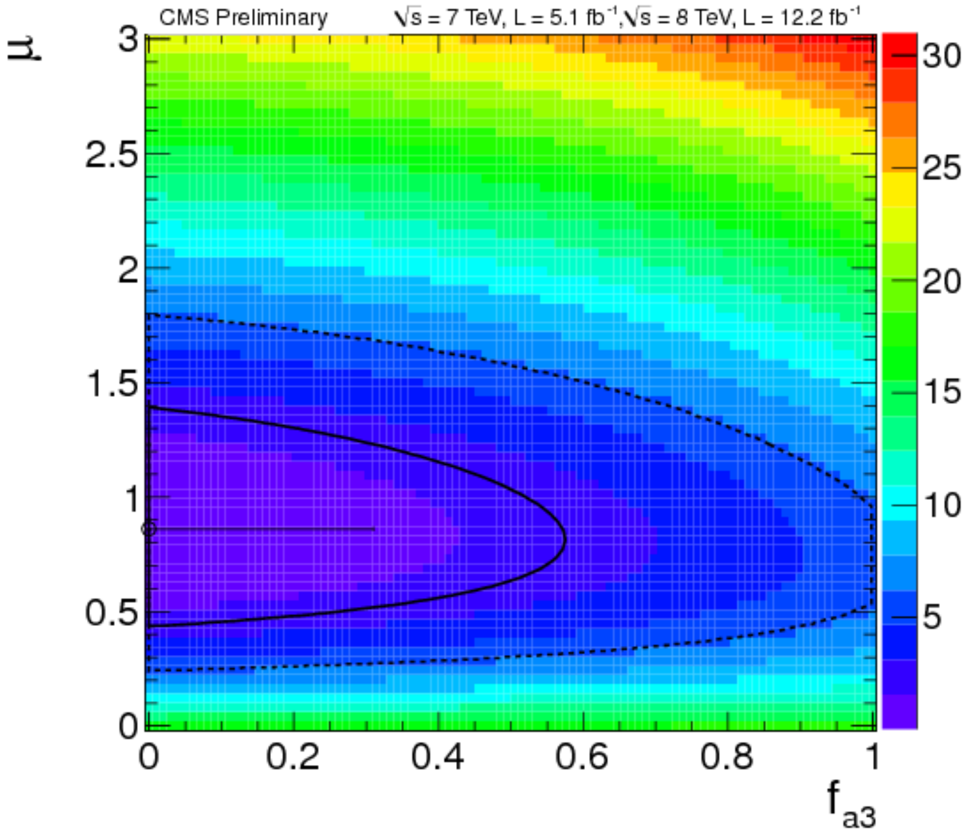
This vertex is in principle valid at all orders of perturbation theory. Contributions from loop corrections will only alter the $a_i$.

ATLAS-PHYS-PUB-2012-004

# CP-violation in ZZ coupling

The first limit is currently available from CMS. Scan of 2 times the log-likelihood ratio between the two signal models as a function the signal strength and $f_{a3}$, the fraction of observed $0^-$ events in the dataset.

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




$$f_{a3} = |A_3|^2/(|A_1|^2 + |A_3|^2).$$

5.1 $fb^{-1}$ at 7 TeV + 12.2 $fb^{-1}$ at 8 TeV

Best fit result:

$$f_{a3} = 0.00^{+0.31}_{-0.00}$$

95% CL exclusion of $f_{a3}$> 0.8

CMS-PAS-HIG-12-041

# CP-violation in ZZ coupling

European Strategy for Particle Physics. Study of the ATLAS sensitivity to the CP-violating effects in HZZ vertex.

Choose the form factor $a_1$ = 1, $a_2$ =0 (Standard Model) and vary $a_3$ (The CP-odd coupling constant).

- Generator level Monte Carlo study. Pythia showering (AU2 CTEQ6L1).
- Smearing functions to simulate detector resolution effects.
- Trigger and lepton reconstruction efficiencies are accounted for by assigning event weights.
- Calculating the expected exclusion of the CP-mixed hypothesis in favor of the Standard Model $J^P=0^+$.
- BDT analysis.

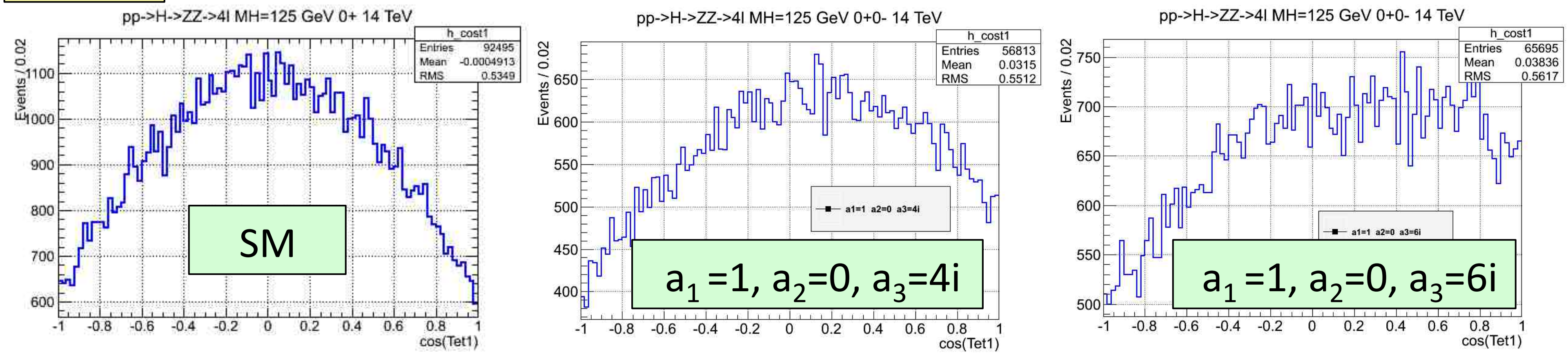
ATLAS-PHYS-PUB-2012-004

# CP-violation in Higgs sector

- Considering a CP-even 0+ sample with a strong CP-odd admixture: $a_1 = 1$, $a_2 = 0$, $a_3 = 6+6i$.
  - $a_3=6+6i$ maximizes the interference between CP-even and CP-odd components.

- The mixture of CP-even and CP-odd states is subject to an interference.
  - The interference is responsible for the asymmetries of observed distributions.

Cos $\theta_1$




ATLAS-PHYS-PUB-2012-004

# CP-violation in Higgs sector

Exclusion (N standard deviations) of CP-violating contribution in favor of the Standard Model $J^P=0^+$ for $H \to ZZ^{(*)} \to 4l$ channel.

Signal region: 100 GeV to 150 GeV.

The ZZ background is scaled to the total background expectation.

ATLAS-PHYS-PUB-2012-004

| | $a_3 = 6+6i$ | $a_3 = 6i$ | $a_3 = 4+4i$ |
|---|---|---|---|
| **100 $fb^{-1}$** | 3.0 | 2.4 | 2.2 |
| **200 $fb^{-1}$** | 4.2 | 3.3 | 3.1 |
| **300 $fb^{-1}$** | 5.2 | 4.1 | 3.8 |

Presently approved LHC program

Very large CP-violating amplitudes can be excluded with more than $3\sigma$ at 100 $fb^{-1}$.
If the observed signal yield is higher than expected, we can put the limit further.

# Further studies

One of the ways to find a beyond the Standard Model contribution in the HZZ vertex is to study the asymmetries of the final state angular distributions.

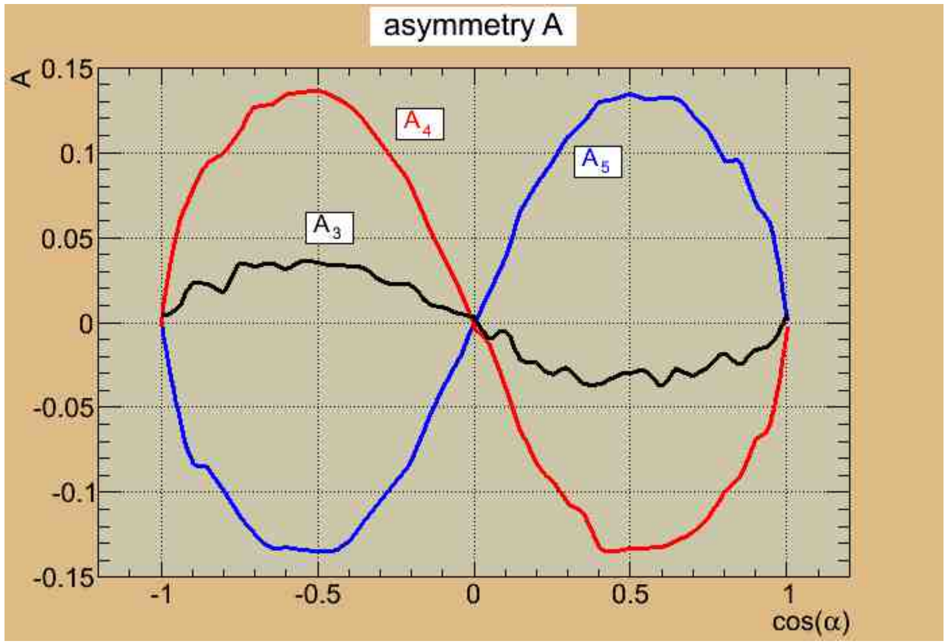
$$A_i = \frac{N(F_i > 0) - N(F_i < 0)}{N(F_i > 0) + N(F_i < 0)}$$

$$F_3 = \cos\theta_1 \sin\theta_2 \cos\theta_2 \sin\phi$$

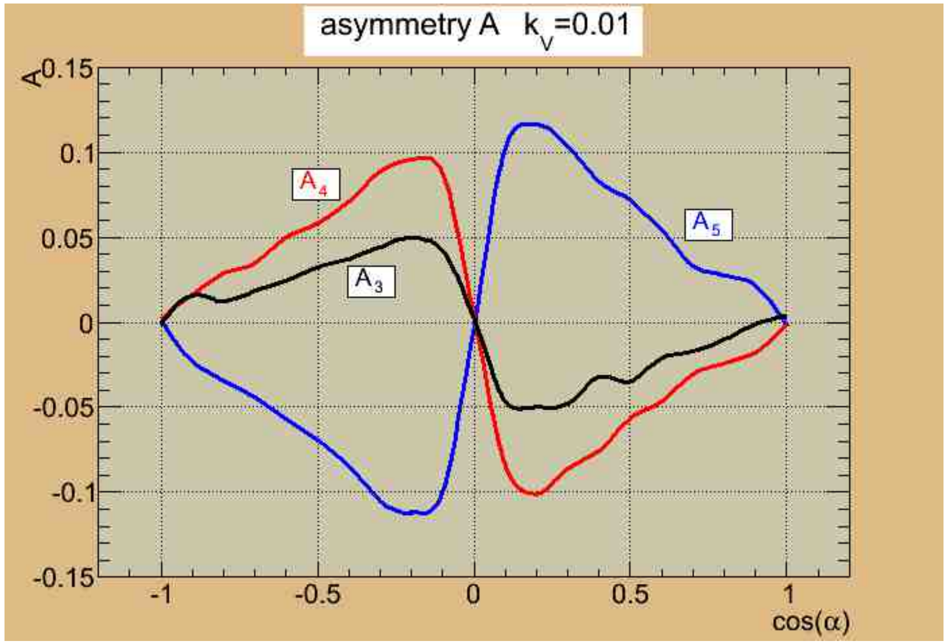
$$F_4 = \sin^2\theta_1 \sin^2\theta_2 \sin\phi \cos\phi$$

$$F_5 = \sin\theta_1 \sin\theta_2 \sin\phi[\sin\theta_1 \sin\theta_2 \cos\phi - \cos\theta_1 \cos\theta_2]$$

$a_1=0$, $a_2=\cos(\alpha)$; $a_3=\sin(\alpha)$




$a_1=\cos(\alpha)$; $a_2=k_V*\cos(\alpha)$; $a_3=k_V*\sin(\alpha)$



# Summary

- First spin and parity results start appearing in LHC experiments.
  - No decisive conclusion yet, but data start looking more like $J^P=0^+$.

- Further studies of the 23.3 $fb^{-1}$ at 8 TeV + 5.6 $fb^{-1}$ at 7 TeV dataset should help us to:
  - Exclude all popular alternative hypotheses in combinations of decay channels.
  - Understand the gg/qq production mechanism for spin-2.
  - Start working with VBF, VH.

- By the end of 2013 we will most probably find ourselves in the situation when the $J^P=0^+$ is the dominant spin and parity hypothesis.
  - Is this the Standard Model Higgs then?

# Summary

- CP-violation and tensor structure of the HZZ vertex: present status.
  - First limits on the observed CP-even-CP-odd mixing published by CMS.
  - With 23.3 $fb^{-1}$ + 5.6 $fb^{-1}$ it will be possible to set an upper limit on the CP-violation in the Higgs sector.
  - ATLAS study shows that the exclusion of large CP-violating form factors will require a lot of data (hundreds of $fb^{-1}$).

- Further studies (after the re-start of the LHC)
  - Establish the dominant spin and parity in the individual channels (ZZ).
  - Searches for the CP-violation and study of the tensor structure of the HZZ vertex.
  - Likelihood fit to matrix element.
  - Study of asymmetries directly sensitive to different amplitude parts.
  - Modeling scenarios with different admixtures and excluding them.

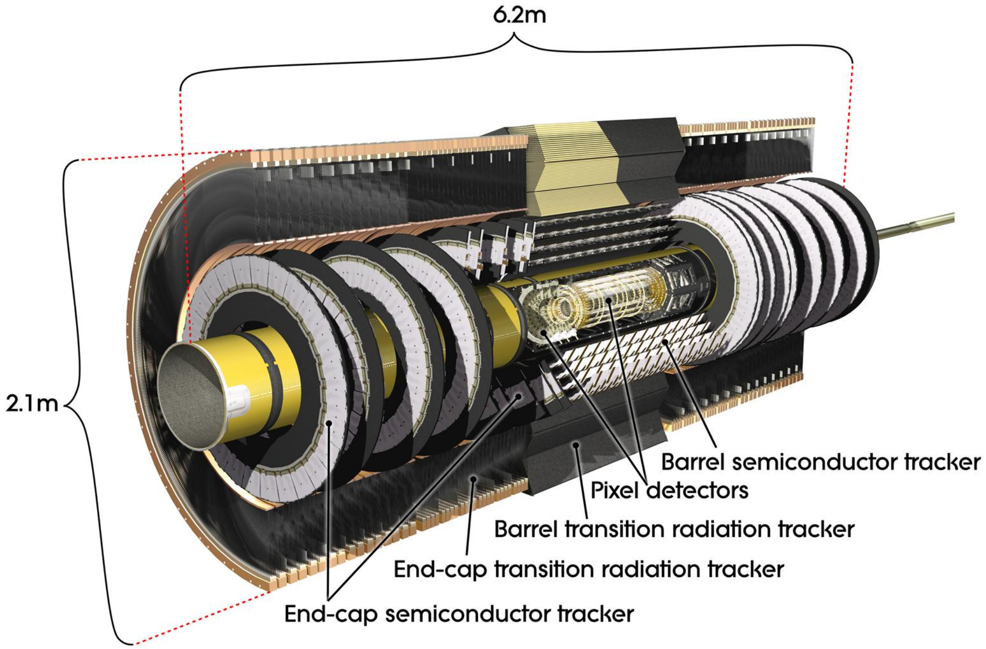
# Further Higgs studies (LHC and beyond)

- Important studies which were not discussed in this talk.
- Study of the spin and parity in channels with VBF, VH, ttH production mechanisms.
- Searches for the CP-violation in ttH H->μμ decay.
- Measurements of the Higgs self-couplings.
- Direct searches for additional (heavy) Higgs bosons.

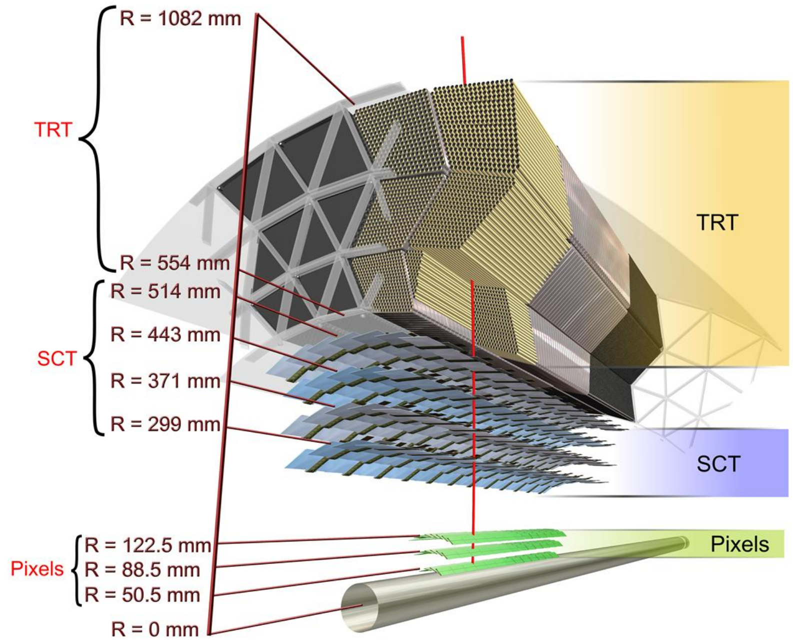
# Backup

# ATLAS detector overview

# ATLAS Inner Detector




Tracking detector with
2 Tesla solenoid field.
3 sub-detectors: (resolution)
Pixel: 10/115 μm in Rϕ/z
Silicon strip (SCT): 17/580 μm
Transition radiation tracker (TRT):
130μm in Rϕ



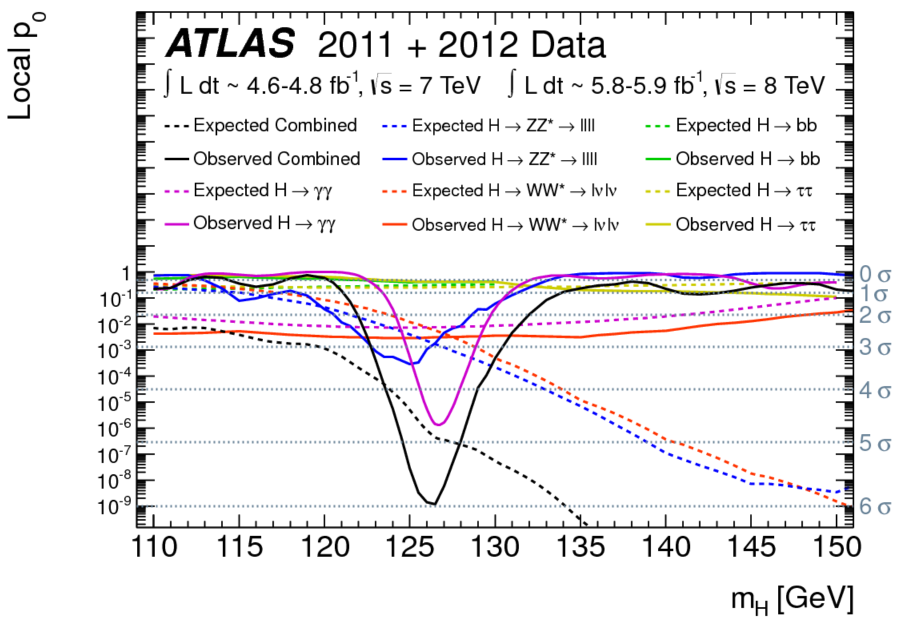

The ID provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at $\eta = 0$.
Coverage: $|\eta| < 2.5$ (2.0 for TRT)
Allows for accurate track and vertex reconstruction.
Resolution goal: $\sigma_{p_T}/p_T = 0.05\%\, p_T \oplus 1\%$

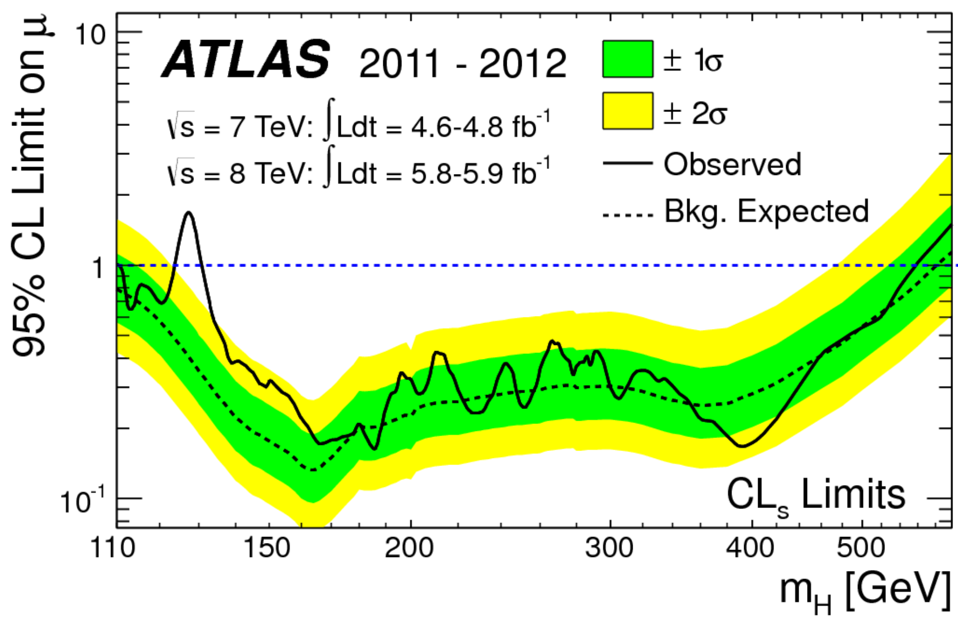
# Discovery of the new resonance

- The initial observation of the new resonance by ATLAS was done in the combination of channels with 4.8 $fb^{-1}$ collected at $\sqrt{s}$ = 7 TeV and 5.8 $fb^{-1}$ at $\sqrt{s}$ = 8 TeV.

- $H \rightarrow ZZ^{(*)} \rightarrow 4l$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$ .

- Excess with local (global) significance of 5.9σ (5.1σ) driven by the $ZZ^{(*)}$, $\gamma\gamma$ and $WW^{(*)}$ decays. $M_H$ = 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV.



# Spin-2 models

$$A(X \to V_1V_2) = \Lambda^{-1}\Big[2g_1 X_{\mu\nu} f^{*(1)\mu\alpha} f_{\alpha}^{*(2)\nu}$$
$$+2g_2 X_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} X_{\beta\nu}\left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)}\right)$$
$$+g_4 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} X_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} + m_V^2 X_{\mu\nu}\left(2g_5 \varepsilon_1^{*\mu}\varepsilon_2^{*\nu} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2}(\varepsilon_1^{*\nu}\varepsilon_2^{*\alpha} - \varepsilon_1^{*\alpha}\varepsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2}(\varepsilon_1^*\varepsilon_2^*)\right)$$
$$+g_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} X_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + m_V^2 X_{\mu\alpha}\tilde{q}^\alpha \varepsilon_{\mu\nu\rho\sigma}\left(g_9 \frac{q^\sigma}{\Lambda^2}\varepsilon_1^{*\nu}\varepsilon_2^{*\rho} + g_{10}\frac{q^\rho \tilde{q}^\sigma}{\Lambda^4}(\varepsilon_1^{*\nu}(q\varepsilon_2^*) + \varepsilon_2^{*\nu}(q\varepsilon_1^*))\right)\Big] \quad (3)$$

- The interaction of a spin-two particle with a pair of electroweak gauge bosons is described by at least 10 independent tensor couplings.

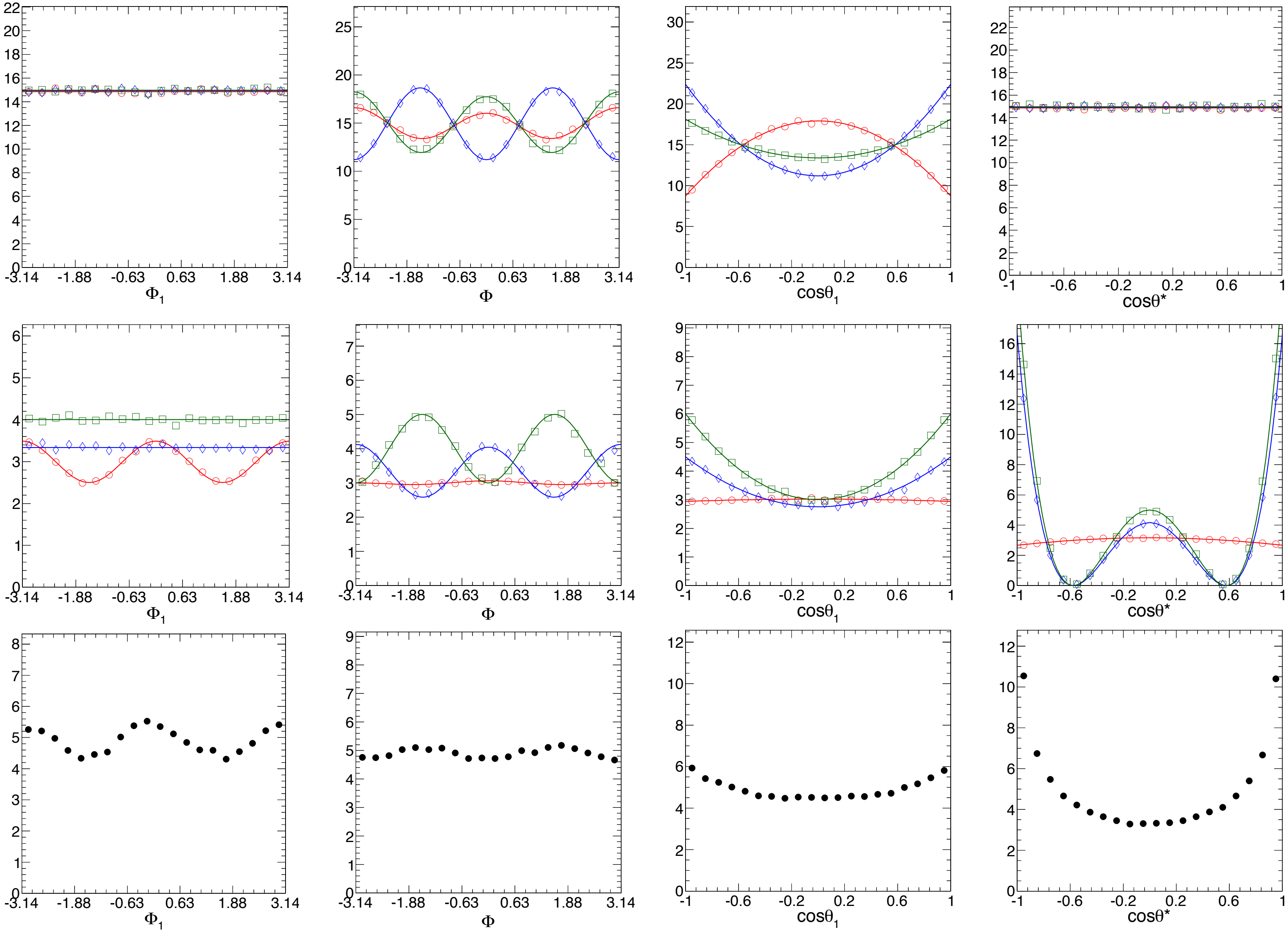
- General idea:
  - Given the number of possibilities, we cannot exclude ‘generic’ spin-2.
  - We should start with the model with minimal couplings and exclude it in favor of the SM hypothesis, which is relatively well defined.
  - If during this study we observe something ‘funny’ – have a deeper look in spin-2 models.
  - It is possible that both ggF and qq production mechanisms contribute to the spin-2 state. The possible mixtures should thus be studied.

arXiv:1001.3396 arXiv:1208.4018

# Distributions of the Spin/CP sensitive variables

Examples of signal and background distributions as shown in arXiv:1208.4018v1.

| | $\Phi_1$ | $\Phi$ | Cos $\theta_1$ | Cos $\theta^*$ |
|---|---|---|---|---|
| Spin-0 $0_m^+$; $0_h^+$; $0_h^-$ | | | | |
| Spin-2 $2_m^+$; $2_h^+$; $2_h^-$ | | | | |
| ZZ background | | | | |

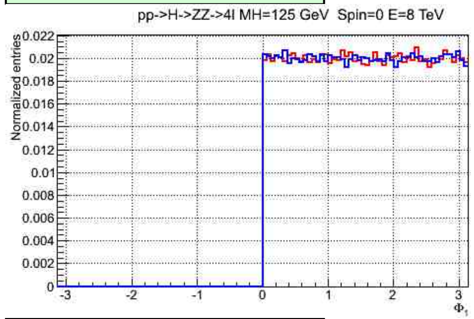


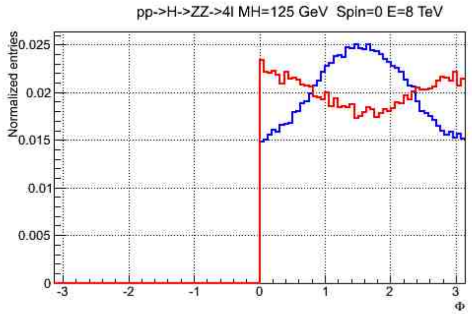
# Distributions of the Spin/CP sensitive variables

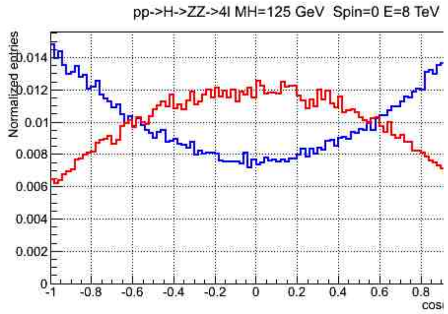
Examples of signal and background distributions at the generator level.

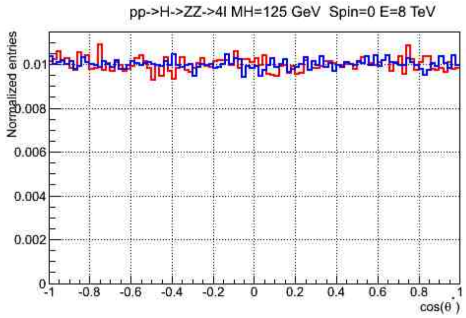
Spin-0: $0^+$; $0^-$

$\Phi_1$ | $\Phi$ | $\cos\theta_1$ | $\cos\theta^*$

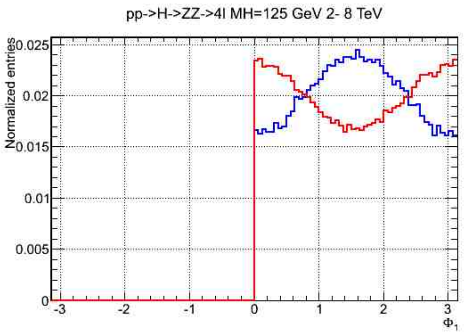


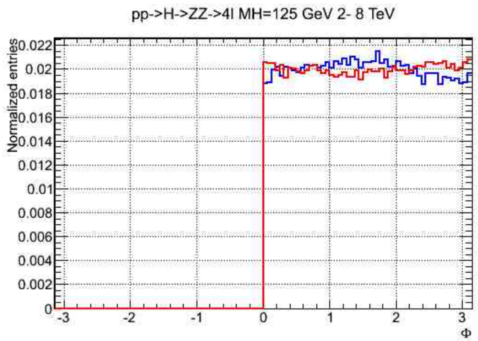


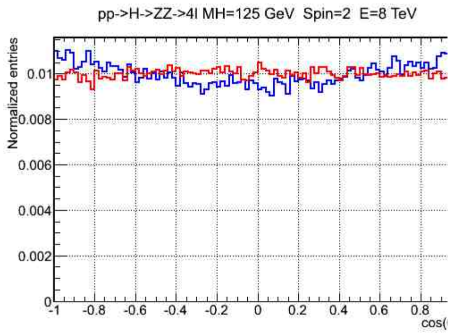


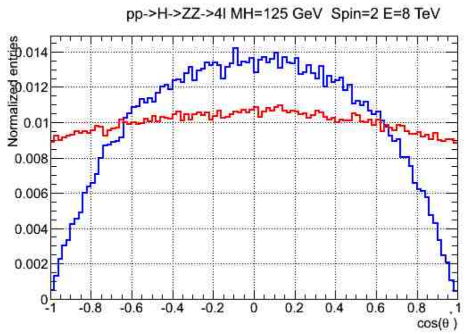



Spin-2: $2_m^+$; $2^-$

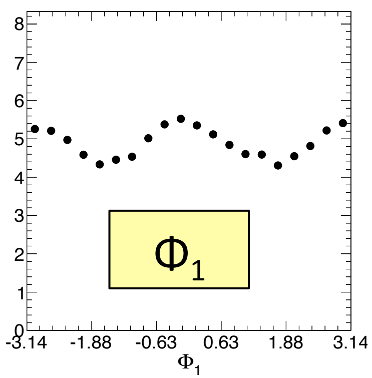


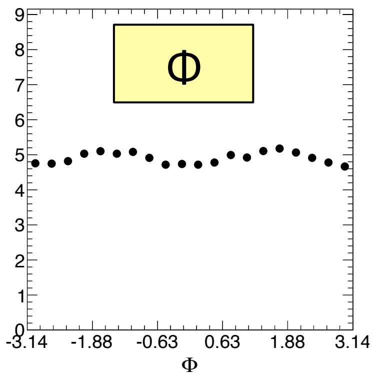


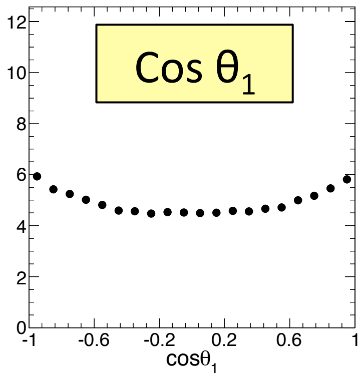


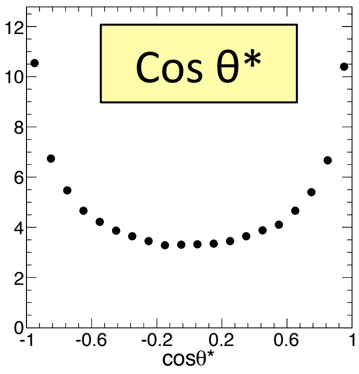



ZZ background










arXiv: 1208.4018v1

# Distributions of the Spin/CP sensitive variables

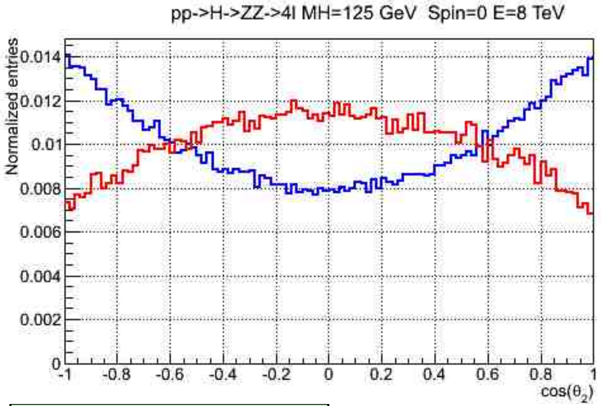
Examples of signal and background distributions at the generator level.

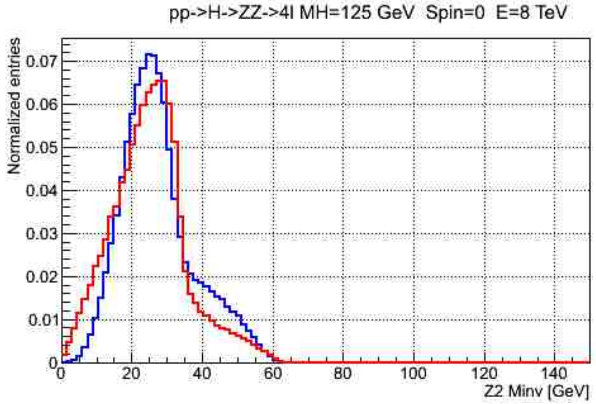
Spin-0: $0^+$; $0^-$

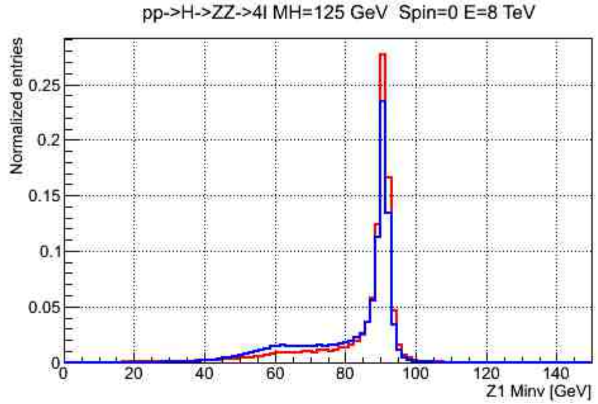
Cos $\theta_2$

$m_{Z2}$

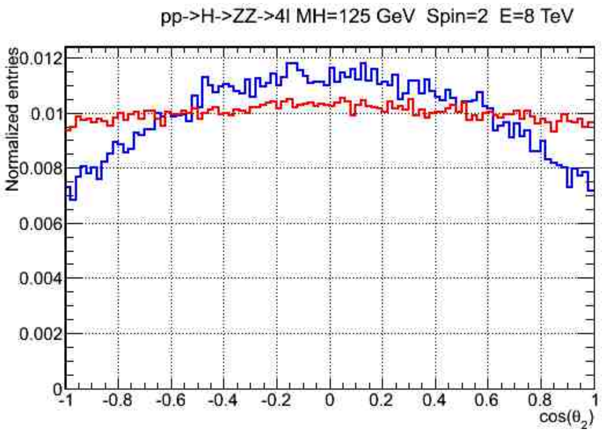
$m_{Z1}$

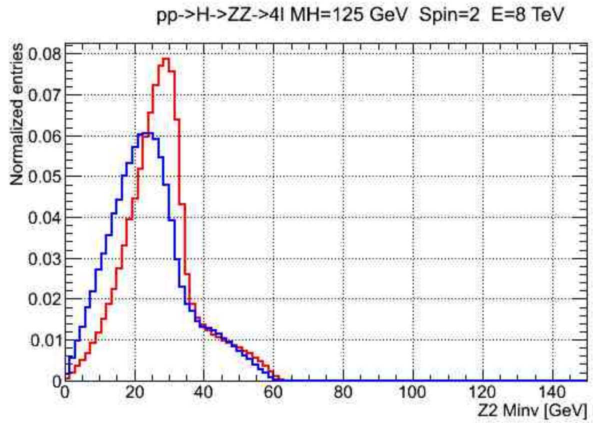


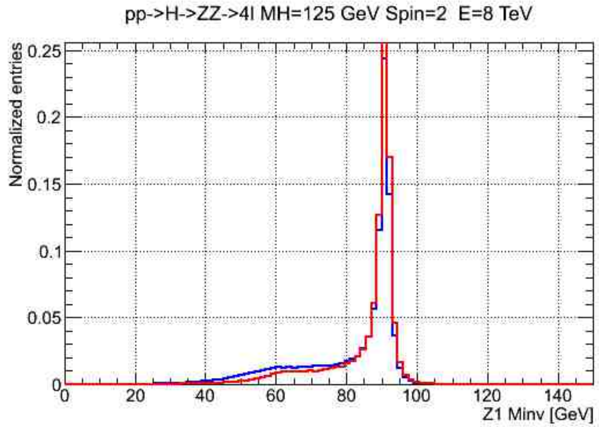




Spin-2: $2_m^+$; $2^-$

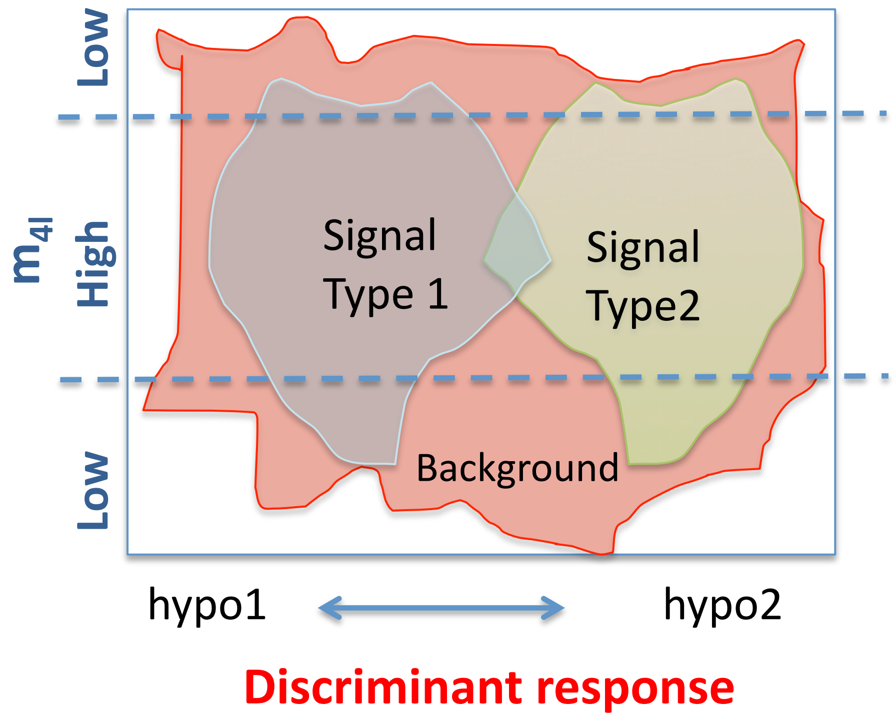


# Analysis structure

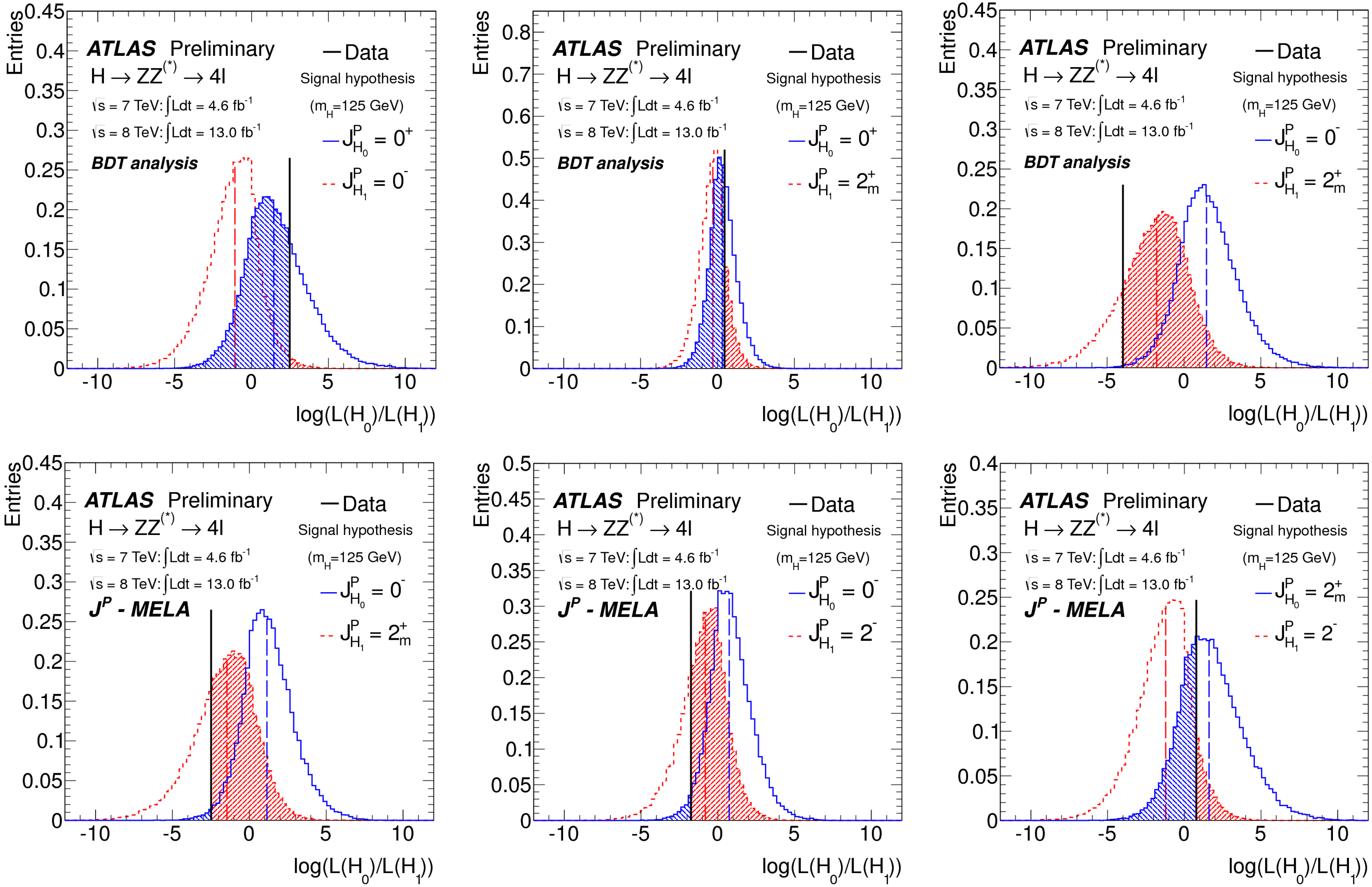
- All samples split in four the different final states (4μ , 4e, 2e2μ, 2μ2e);
  - Different S/B
- Cuts in $m_{4l}$ define regions with different S/B:
  - Signal enhanced with higher S/B and bkg enhanced with lower S/B




- In total, the analysis has 8 channels:
  (4μ; 4e; 2e2μ; 2μ2e) × (high S/B bin; low S/B bin)
- Reducible BKG
  - Same control region as in the main analysis -> normalization + discriminant responses shape.
  - From here we calculate normalizations for high and low S/B bins.

# Four lepton decay channel

- Test statistic: ratio of profiled likelihoods.



ATL-CONF-2012-169

# Four lepton decay channel (Council)

Expected $p_0$ (Nσ) (BDT)

| | $0^+$ | $0^-$ | $2^+_m$ | $2^-$ |
|---|---|---|---|---|
| $0^+$ | | 0.044 (1.7) | 0.20 (0.83) | 0.051 (1.6) |
| $0^-$ | 0.041 (1.7) | | 0.048 (1.7) | 0.089 (1.3) |
| $2^+_m$ | 0.20 (0.84) | 0.055 (1.6) | | 0.032 (1.9) |
| $2^-$ | 0.046 (1.7) | 0.095 (1.3) | 0.028 (1.9) | |

Expected and observed $p_0$ values to exclude various spin and parity hypotheses. The shaded column shows the $p_0$ to exclude spin and parity hypotheses in favor of the $0^+$ state.

Both methods show comparable results.
0+ is the favorite hypothesis preferred by data.
0- is disfavored by all other hypotheses.
Data slightly prefer $2^+$ over $2^-$.
100% ggF production assumed for the spin-2.

Observed $p_0$ (Nσ) (BDT)

| | $0^+$ | $0^-$ | $2^+_m$ | $2^-$ |
|---|---|---|---|---|
| $0^+$ | | 0.69 (−0.50) | 0.57 (−0.18) | 0.56 (−0.15) |
| $0^-$ | 0.011 (2.3) | | 0.0015 (3.0) | 0.028 (1.9) |
| $2^+_m$ | 0.16 (0.99) | 0.83 (−0.95) | | 0.41 (0.22) |
| $2^-$ | 0.029 (1.9) | 0.69 (−0.50) | 0.055 (1.6) | |

Observed $p_0$ (Nσ) (pseudo-MELA)

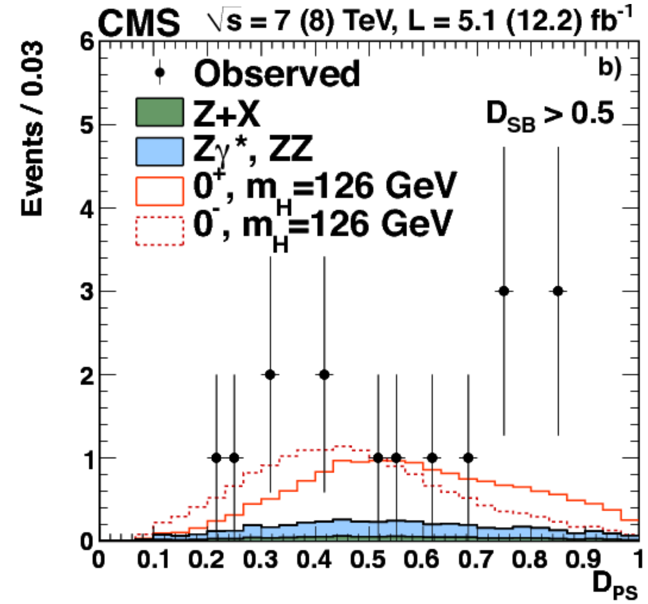
| | $0^+$ | $0^-$ | $2^+_m$ | $2^-$ |
|---|---|---|---|---|
| $0^+$ | | 0.76 (−0.72) | 0.53 (−0.082) | 0.56 (−0.15) |
| $0^-$ | 0.003 (2.7) | | 0.01 (2.3) | 0.025 (2.0) |
| $2^+_m$ | 0.17 (1.0) | 0.69 (−0.51) | | 0.33 (0.44) |
| $2^-$ | 0.025 (2.0) | 0.73 (−0.62) | 0.089 (1.3) | |

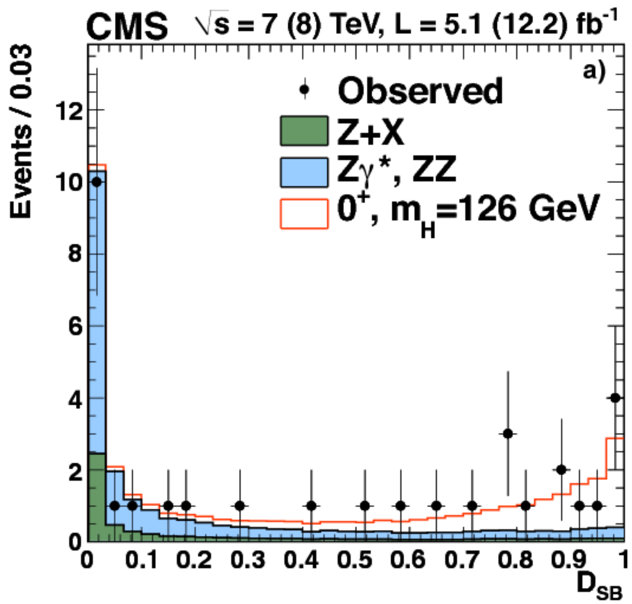
# Moriond results (ZZ)

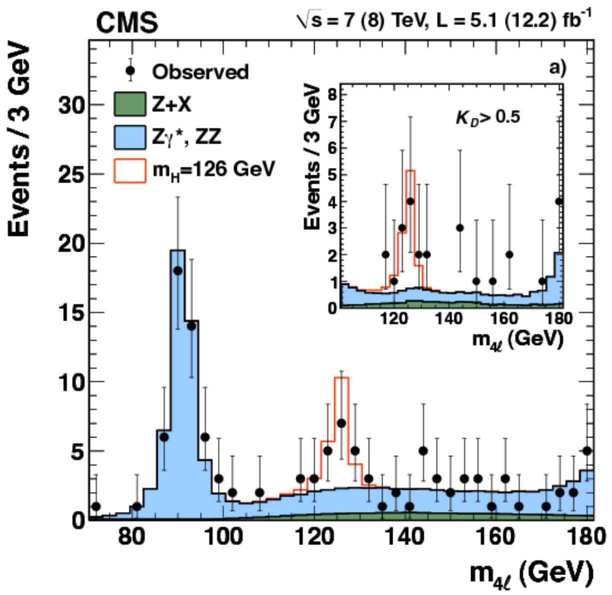
Table 9: For an assumed $0^+$ hypothesis $H_0$, the values for the expected and observed $p_0$-values of the different tested spin and parity hypotheses $H_1$ for the BDT and $J^P$-MELA analyses. The results are given combining the $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeVdata sets. Also given is the observed $p_0$-value where $0^+$ is the test hypothesis and the other spins states are the assumed hypothesis (observed*). These two observed $p_0$-values are combined to provide the $CL_S$ confidence level for each test hypothesis (i.e. observed $p_0$-value/(1 - observed* $p_0$-value)). The production mode is assumed to be 100% ggF.

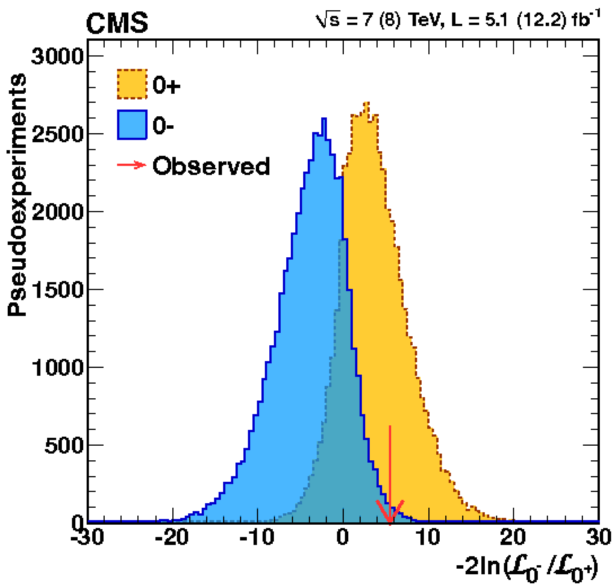
| | | BDT analysis | | | | $J^P$-MELA analysis | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | tested $J^P$ for an assumed $0^+$ | | tested $0^+$ for an assumed $J^P$ | $CL_S$ | tested $J^P$ for an assumed $0^+$ | | tested $0^+$ for an assumed $J^P$ | $CL_S$ |
| | | expected | observed | observed* | | expected | observed | observed* | |
| $0^-$ | $p_0$ | 0.0037 | 0.015 | 0.31 | 0.022 | 0.0011 | 0.0022 | 0.40 | 0.004 |
| $1^+$ | $p_0$ | 0.0016 | 0.001 | 0.55 | 0.002 | 0.0031 | 0.0028 | 0.51 | 0.006 |
| $1^-$ | $p_0$ | 0.0038 | 0.051 | 0.15 | 0.060 | 0.0010 | 0.027 | 0.11 | 0.031 |
| $2^+_m$ | $p_0$ | 0.092 | 0.079 | 0.53 | 0.168 | 0.064 | 0.11 | 0.38 | 0.182 |
| $2^-$ | $p_0$ | 0.0053 | 0.25 | 0.034 | 0.258 | 0.0032 | 0.11 | 0.08 | 0.116 |

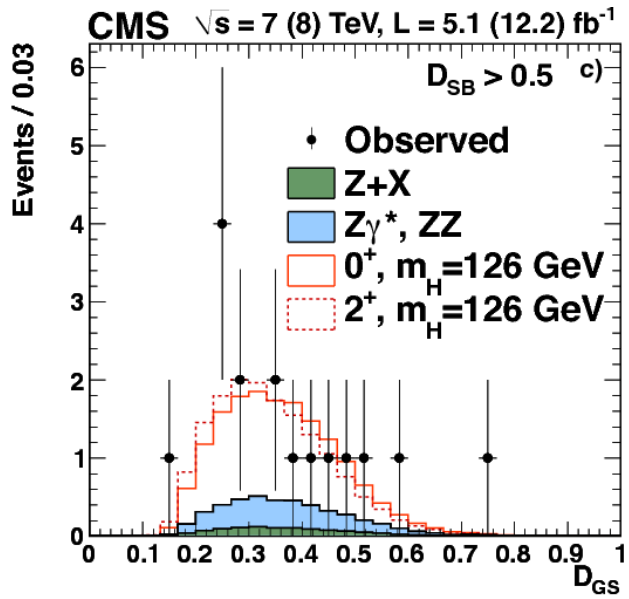
# CMS results (backup)




Phys. Rev. Lett. 110, 081803 (2013)

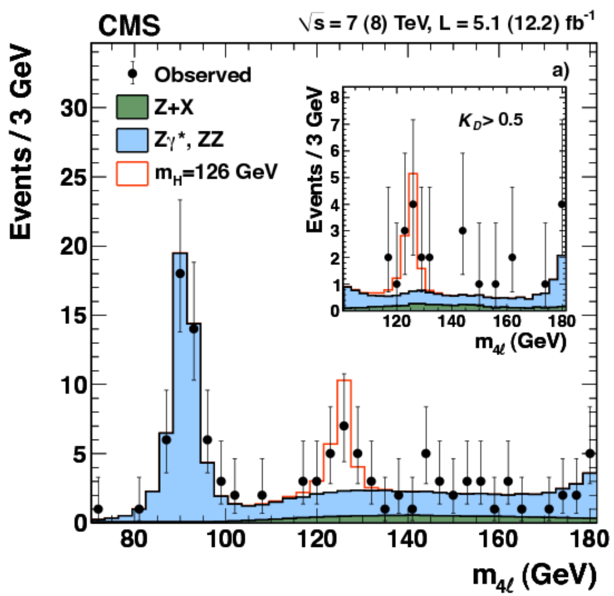
# CMS results

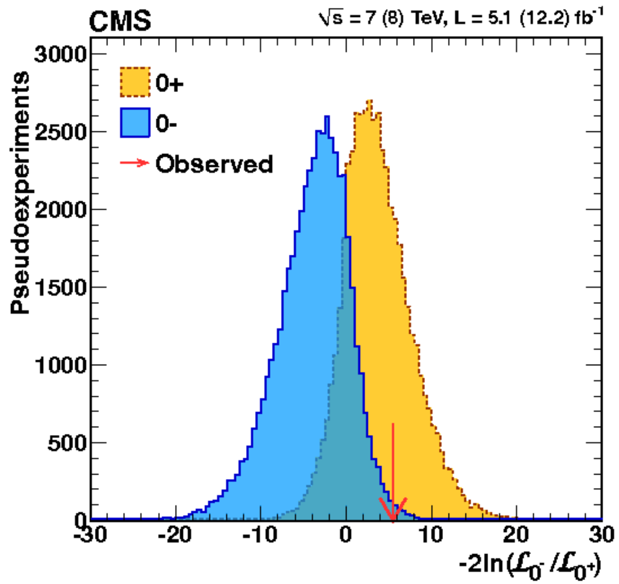
5.1 $fb^{-1}$ at 7 TeV + 12.2 $fb^{-1}$ at 8 TeV.

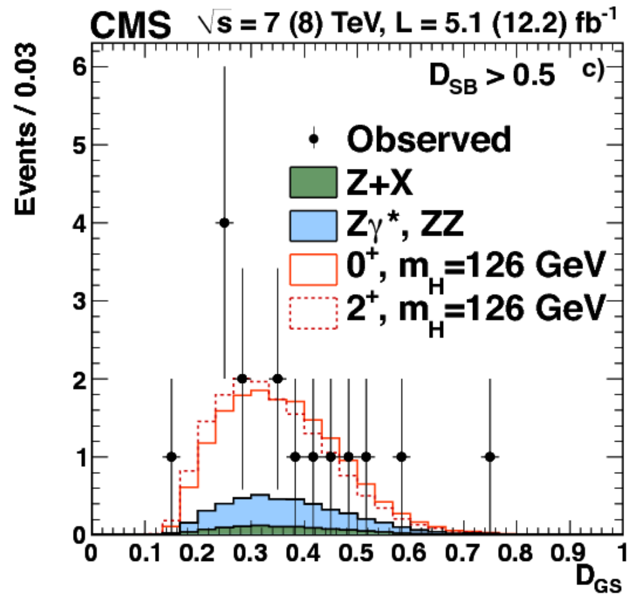
Discriminant based on the analytical calculation of the matrix element.

$p_0(0^-)=0.072$; $p_0(0^+)=0.7$. Exclusion of $J^P=0^-$ in favor of $J^P=0^+$: $(1-CL_S)$ = 97.6%

No conclusion on the $J^P=2^+_m$ exclusion: more data required.

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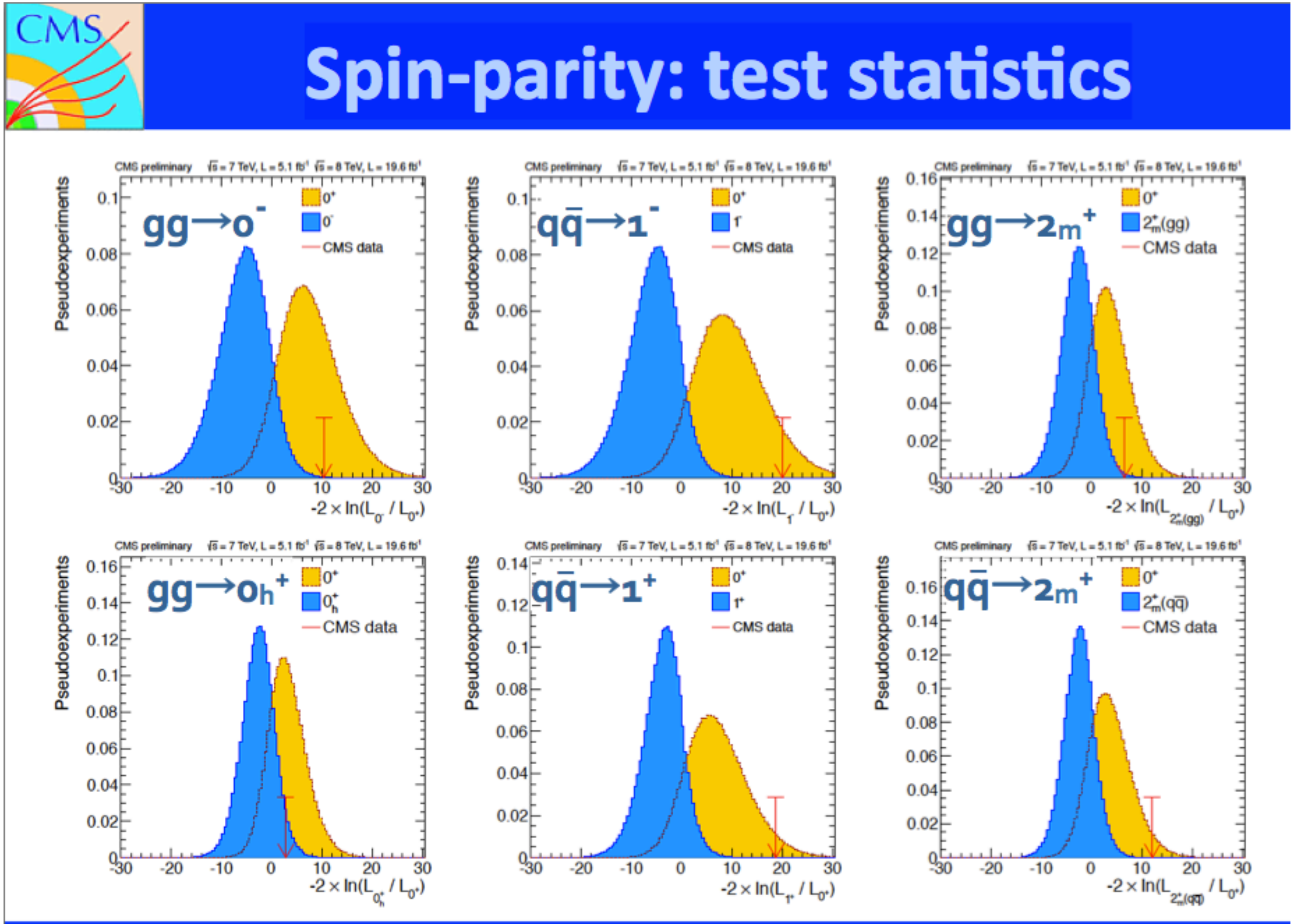
# CMS results



Spin-parity: test statistics
CMS preliminary
gg→0-
qq̄→1-
gg→2m+
gg→0h+
qq̄→1+
qq̄→2m+
CMS data
Pseudoexperiments

# Next steps in the Spin and parity studies

- The data so far seem to prefer the $0^+$ hypothesis.
- The LHC has delivered 23.3 $fb^{-1}$ at $\sqrt{s}$=8 TeV before the technical stop.
  - During at least next 2 years this will be the only data we will have.
- Program for further studies (current dataset and beyond)
  - Exclude $0^-$, $2^+_m$, $1^+$.
  - Exclude $1^-$, $2^-$.
  - Exclude large qq contributions in spin-2 production.
  - Start studying other production mechanisms: VBF, VH, ttH.
- The most popular alternative hypotheses are likely to be excluded in favor of the $0^+$ in the following months/years.
  - Next step: study of the tensor structure of HVV interaction.

# CP-violation in Higgs sector

- Event selection in general matches the discovery analysis (H->ZZ->4l section). Phys. Lett. B716 (2012) 1-29

- Analysis: Applying two independent BDT discriminants to separate spin and parity states and to reject the ZZ background.
  - First BDT is trained to separate spin-CP states using angular and mass variables: $\cos\vartheta_1$, $\cos\vartheta_2$, $\phi$, $\cos\vartheta^*$, $\phi_1$, $m_{Z1}$, $m_{Z2}$.
  - Second BDT is trained to separate Higgs signal from the ZZ background using kinematic variables.
  - Stat test: profiled likelihood on the combination of four final states.

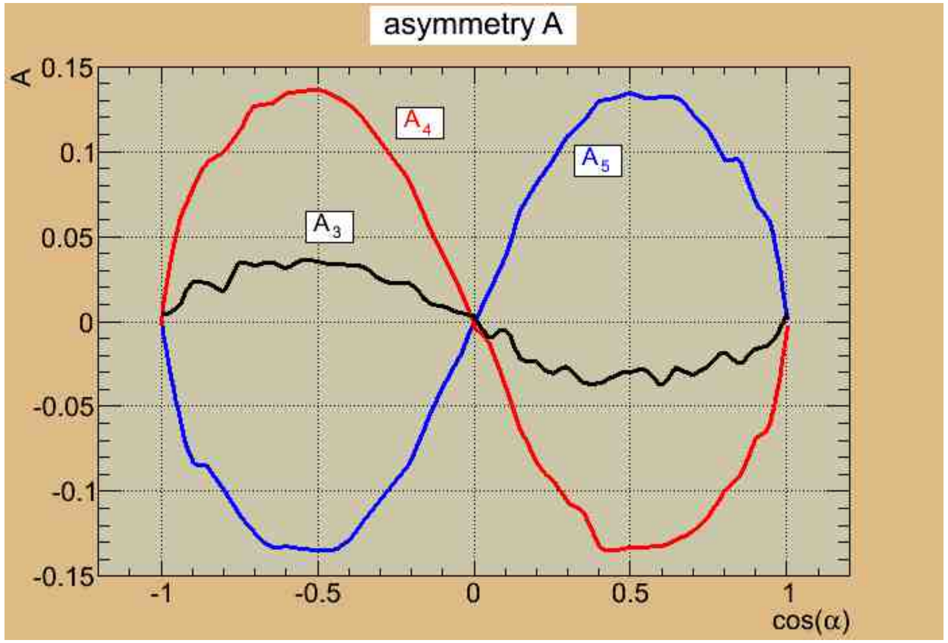
- Calculating the expected exclusion of the CP-mixed hypothesis in favor of the Standard Model $0^+$.

# H->μμ

- CP-odd amplitudes are naturally expected to be suppressed in the HVV coupling.
  - The channels containing the HVV coupling in the final state are hence not ideal for the CP-studies.
- Naturally remain the channels where there is no HVV couplings in the final state.
- Studies were done for ttH, H->μμ and ttA, A->μμ.
  - Too little statistics.
  - About 1σ separation between pure CP-even and CP-odd states at 3000 $fb^{-1}$.

# CP-violation in Higgs sector

$a_1$=0, $a_2$=cos(α); $a_3$=sin(α)




$a_1$=cos(α); $a_2$=$k_V$*cos(α); $a_3$=$k_V$*sin(α)