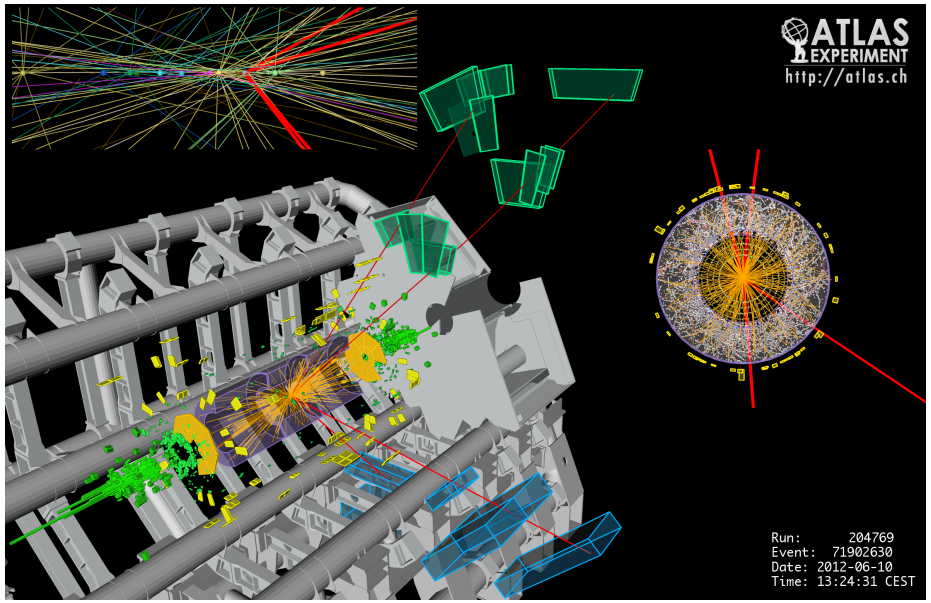
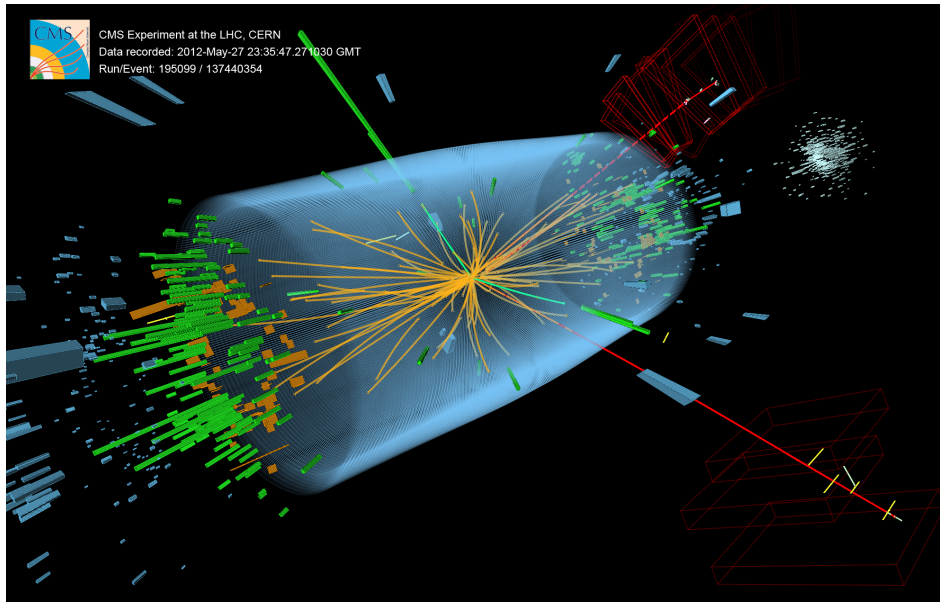
Measurement of the spin and parity of the new boson discovered in ATLAS and CMS experiments at the LHC





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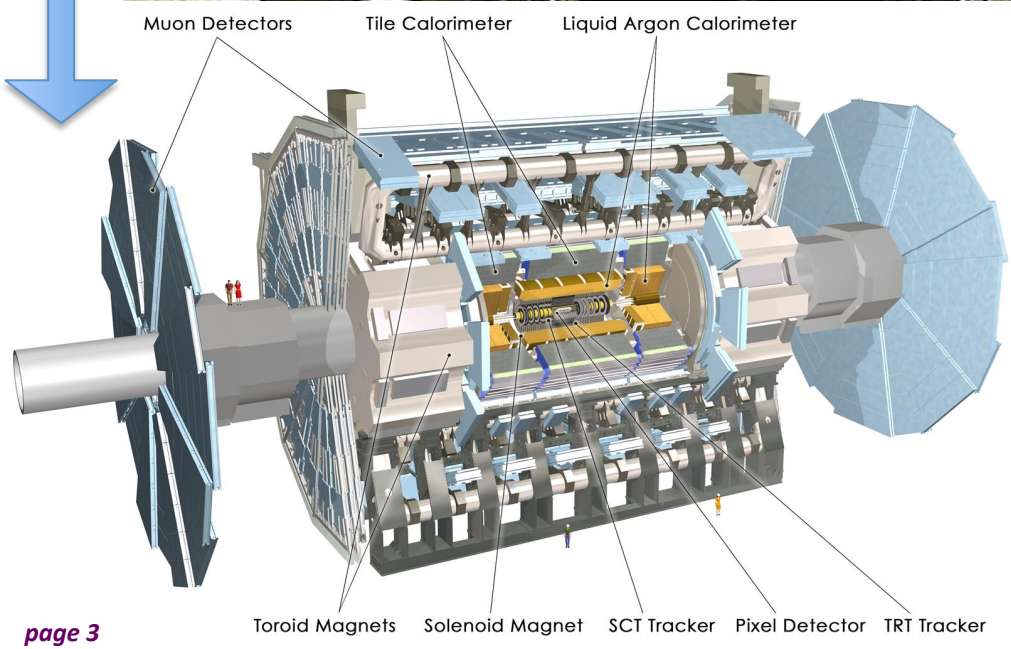
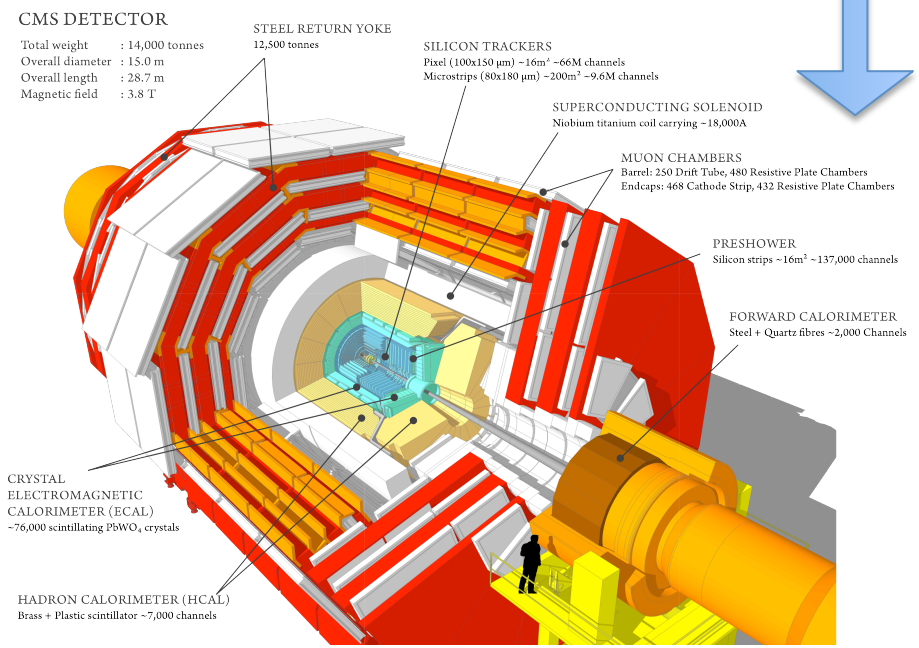
Outline

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

ATLAS and CMS detectors

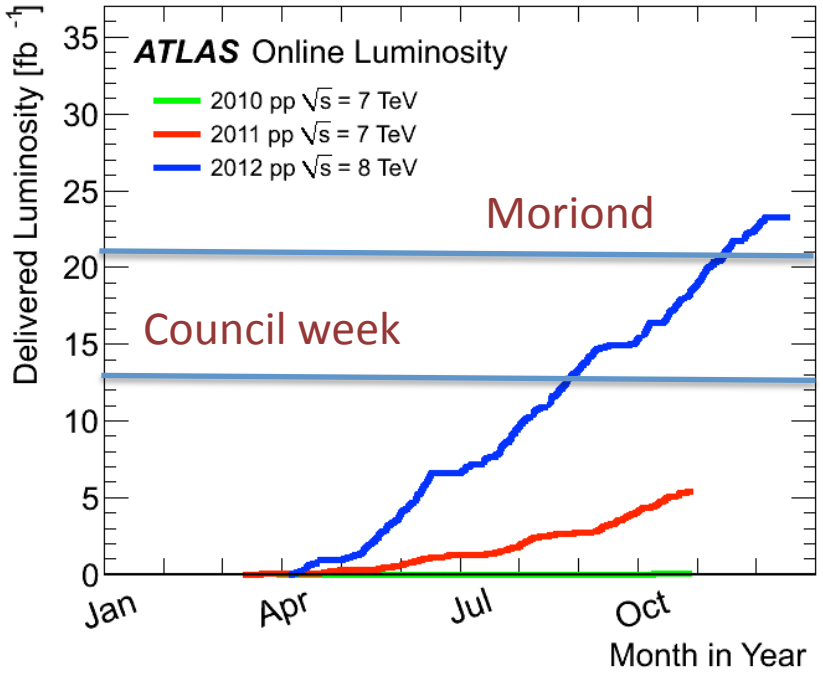




Data taking in 2011 and 2012

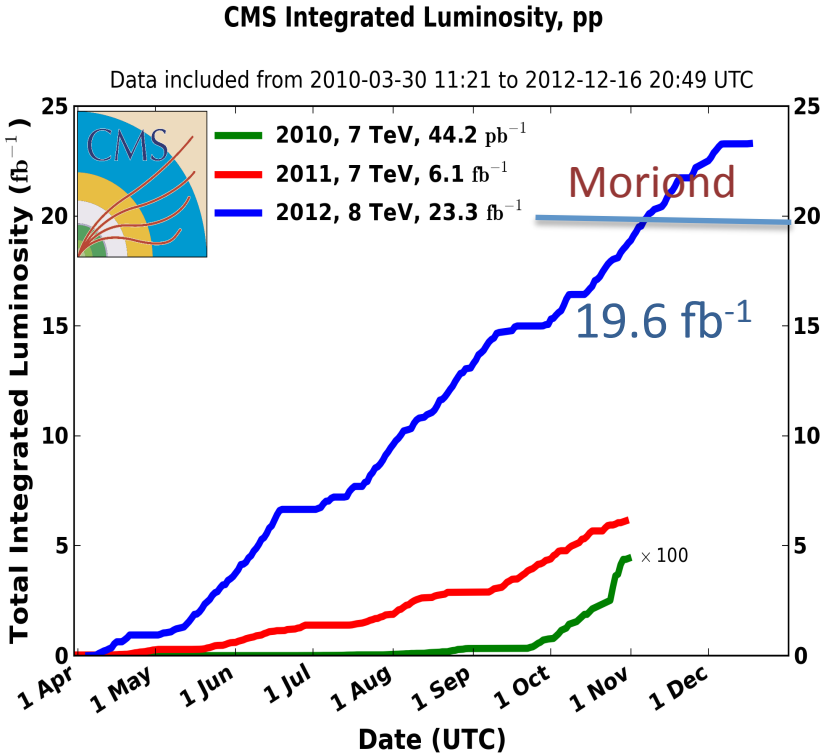
	√S	Delivered (fb^{-1})	Recorded (fb^{-1})
pp 2011	7 TeV	**5.61**	**5.25**
pp 2012	8 TeV	**23.3**	**21.7**

	√S	Delivered (fb^{-1})	Recorded (fb^{-1})
pp 2011	7 TeV	**6.1**	**5.55**
pp 2012	8 TeV	**23.3**	**21.79**



21 fb^{-1}

13 fb^{-1}



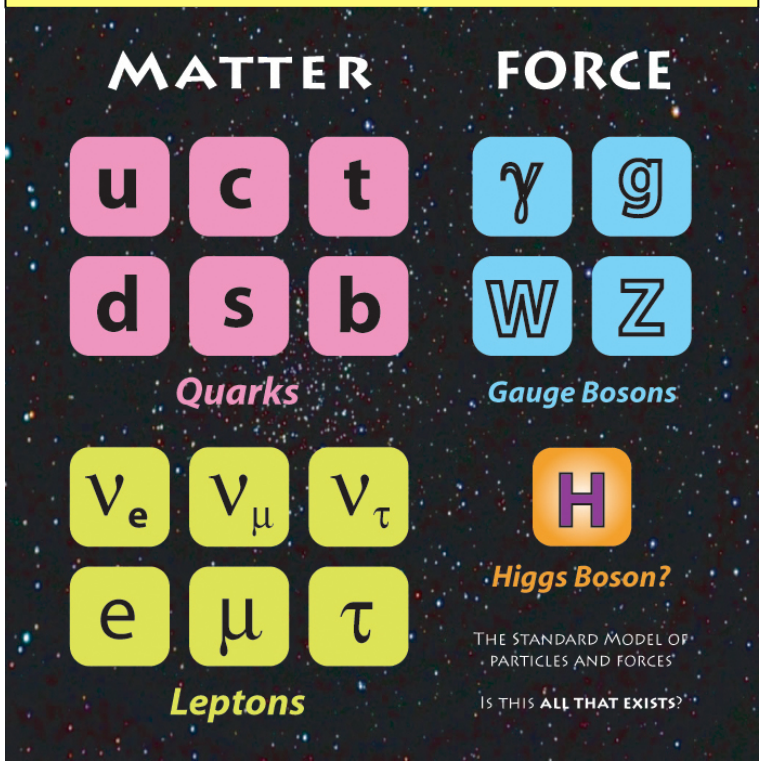
Standard Model Higgs boson

- 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.

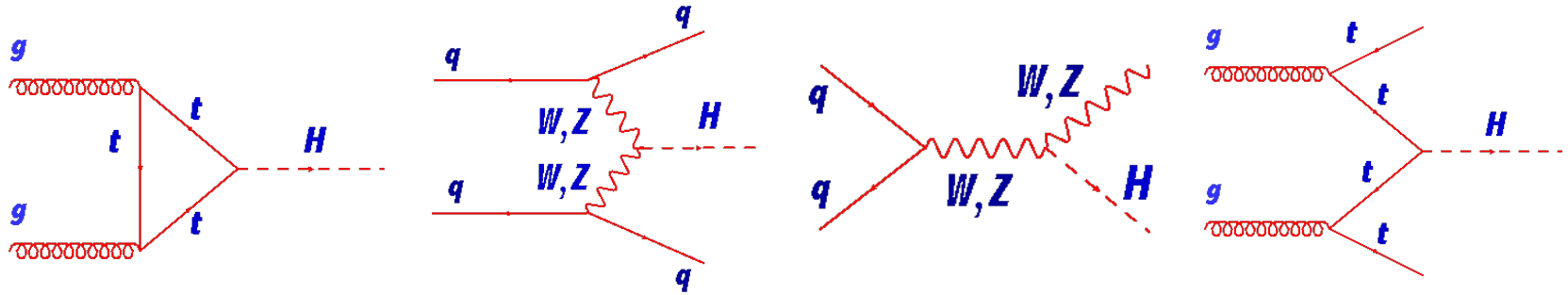
Indirect limits come from the precision measurements of electroweak observables.

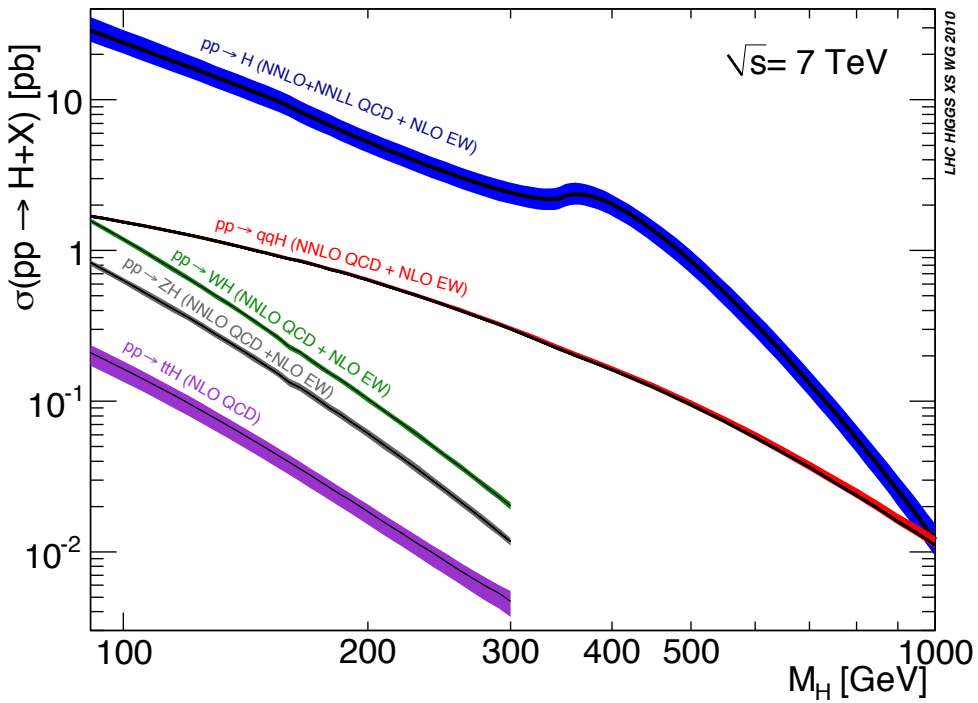


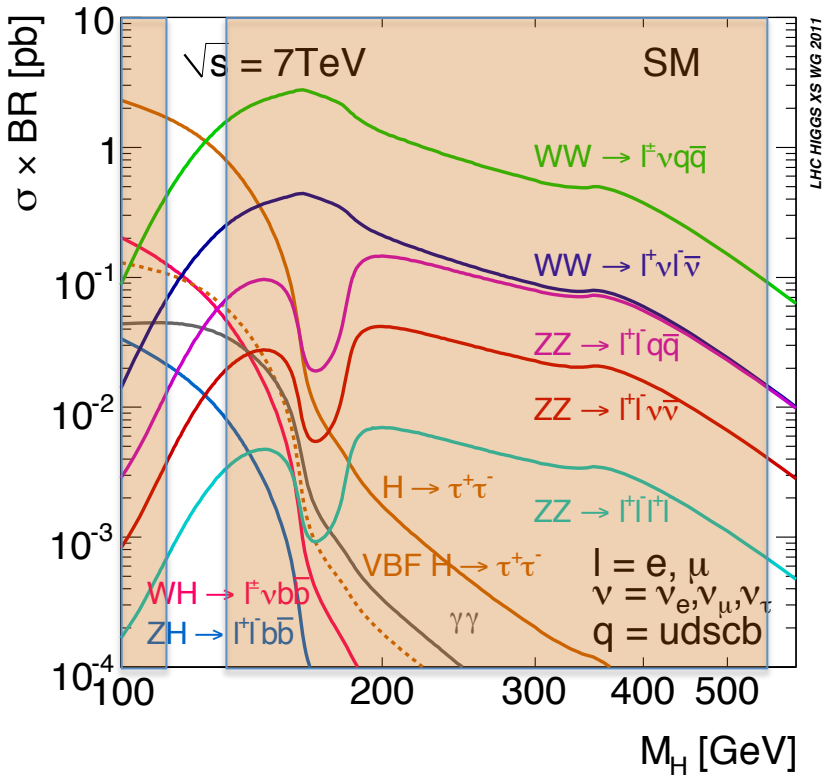
arXiv::1203.3774

Standard Model Higgs searches at LHC

Gluon-gluon fusion | Vector boson fusion | Associated production







LHC Higgs Cross-Section Working group

Discovery and status of the new resonance in ATLAS and CMS

Considered search channels (ATLAS)

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.6	[10]
$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\}$	4.8	[9]
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, p_{T,\tau\tau} > 100\text{ GeV}, VH\}$	4.6	[11]
	$\tau_{lep}\tau_{had}$	$\{e,\mu\} \otimes \{\text{0-jet, 1-jet}, p_{T,\tau\tau} > 100\text{ GeV, 2-jet}\}$	4.6	
	$\tau_{had}\tau_{had}$	$\{\text{1-jet, 2-jet}\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200\text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6	[12]
	$W \to \ell\nu$	$p_T^W \in \{<50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_T^Z \in \{<50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	20.7	[10]
$H \to \gamma\gamma$	–	14 categories $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\} \oplus \{\ell\text{-tag}, E_T^{miss}\text{-tag, 2-jet VH}\}$	20.7	[9]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet}\}$	13	[13]
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{\ell\ell\} \otimes \{\text{1-jet, 2-jet}, p_{T,\tau\tau} > 100\text{ GeV}, VH\}$	13	[11]
	$\tau_{lep}\tau_{had}$	$\{e,\mu\} \otimes \{\text{0-jet, 1-jet}, p_{T,\tau\tau} > 100\text{ GeV, 2-jet}\}$	13	
	$\tau_{had}\tau_{had}$	$\{\text{1-jet, 2-jet}\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200\text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	13	[12]
	$W \to \ell\nu$	$p_T^W \in \{<50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	13	
	$Z \to \ell\ell$	$p_T^Z \in \{<50, 50-100, 100-150, 150-200, \geq 200\text{ GeV}\}$	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.

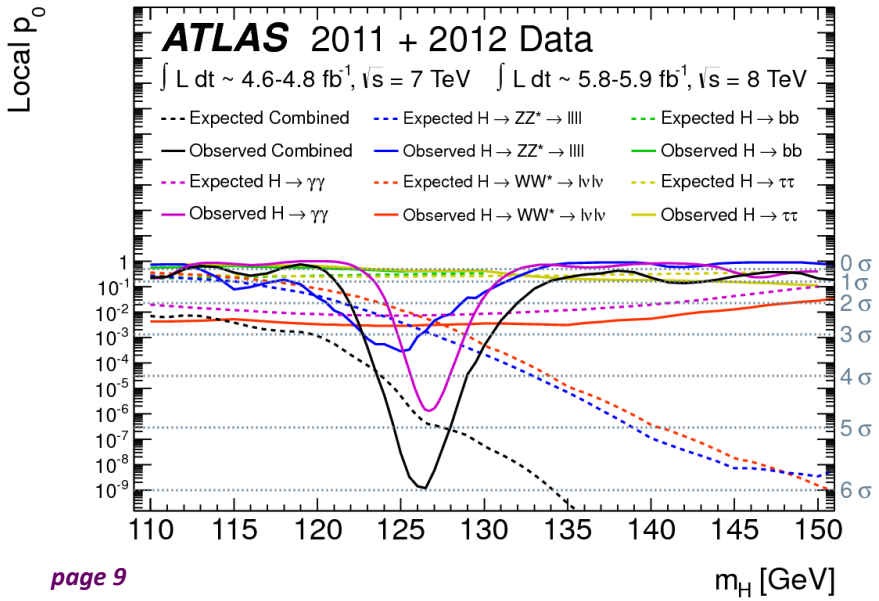
ATLAS-CONF-2013-014

Phys. Lett. B 716 (2012) 1-29 ATLAS-CONF-2012-170

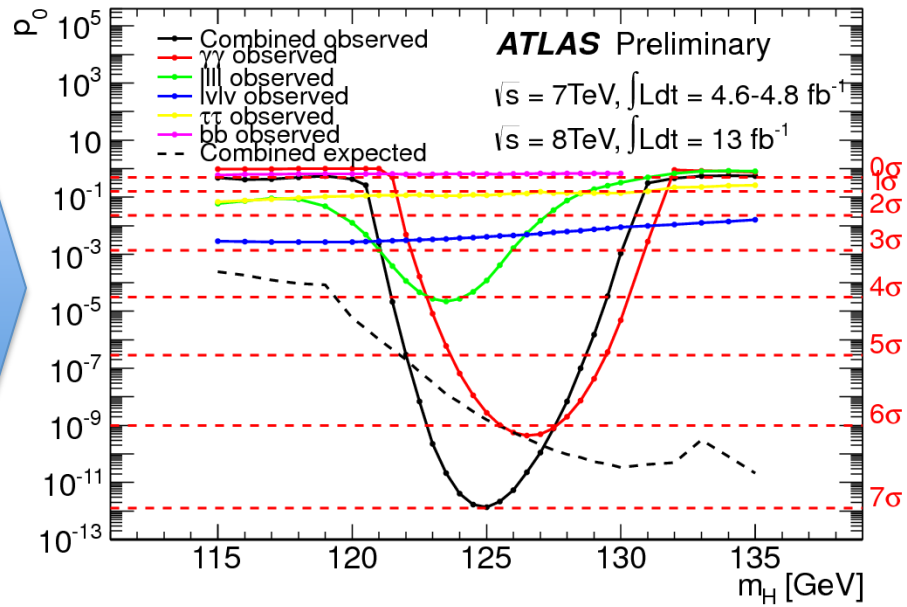
Discovery of the new resonance (ATLAS)

- The initial observation of the new resonance by ATLAS was done in the combination of channels with 4.8 fb^{-1} at $\sqrt{s}$ = 7 TeV and 5.8 fb^{-1} at $\sqrt{s}$ = 8 TeV.
  - $H \to ZZ^{(*)} \to 4l$, $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$, $H \to b\bar{b}$ and $H \to \tau^+\tau^-$.
- 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

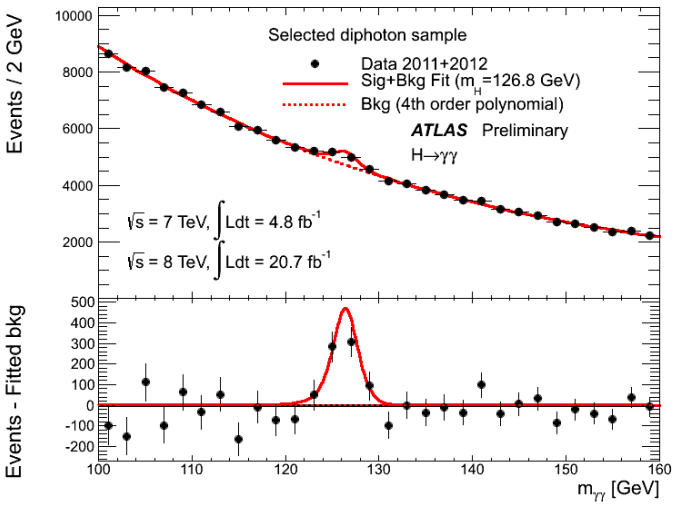


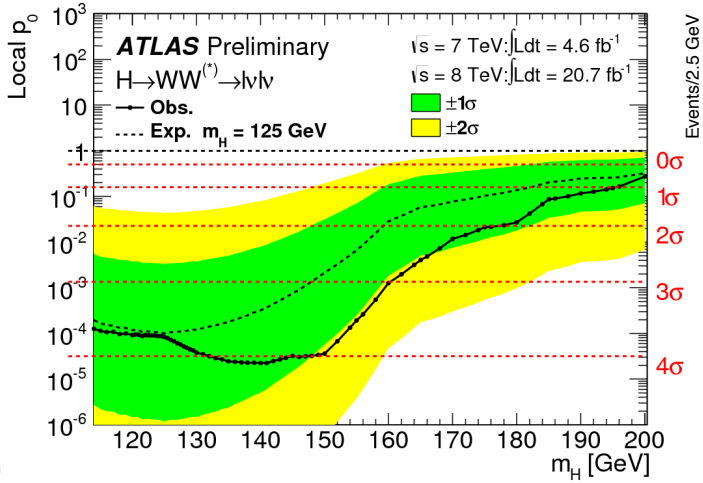
4.8 fb^{-1} at 7 TeV and 13 fb^{-1} at 8 TeV

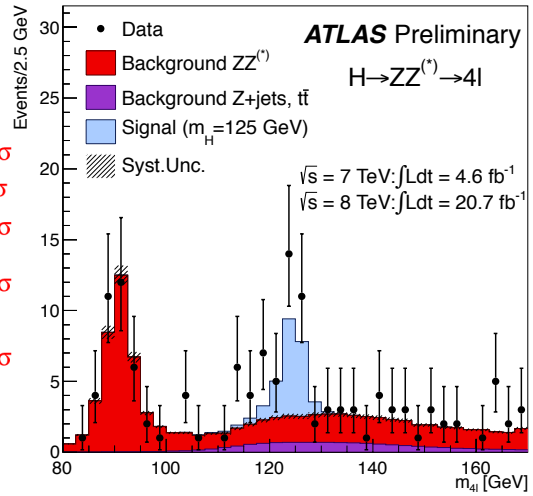


Status of the new resonance (ATLAS)

- In February-March 2013, the ZZ, γγ and WW 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), 6.8 (ZZ) and 3.8 (WW) standard deviations.







ATLAS-CONF-2013-012

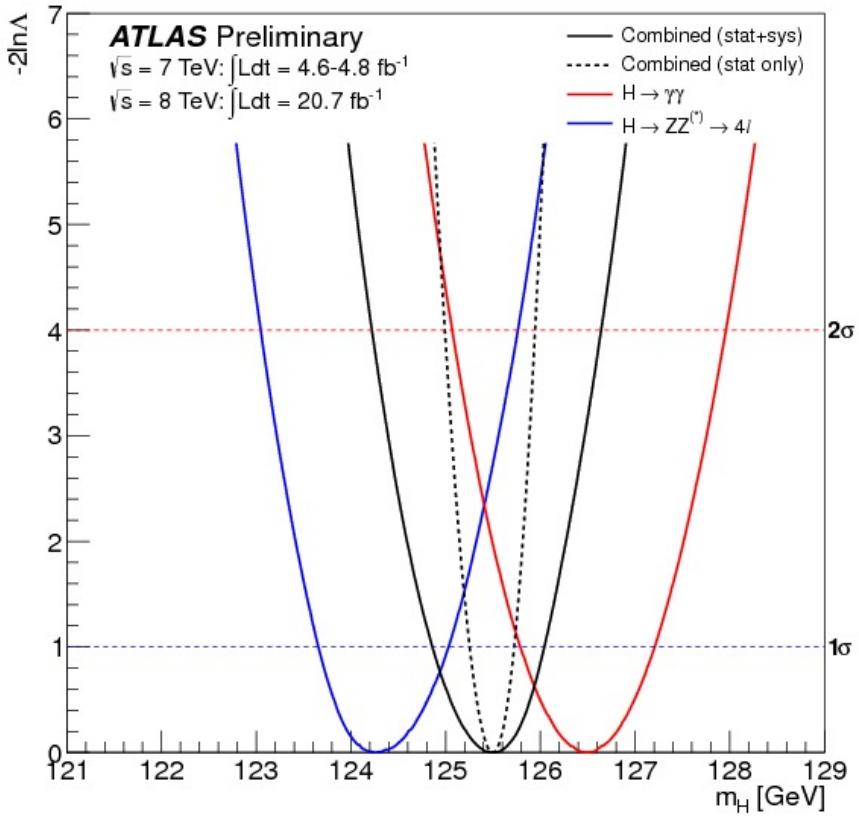
ATLAS-CONF-2013-013

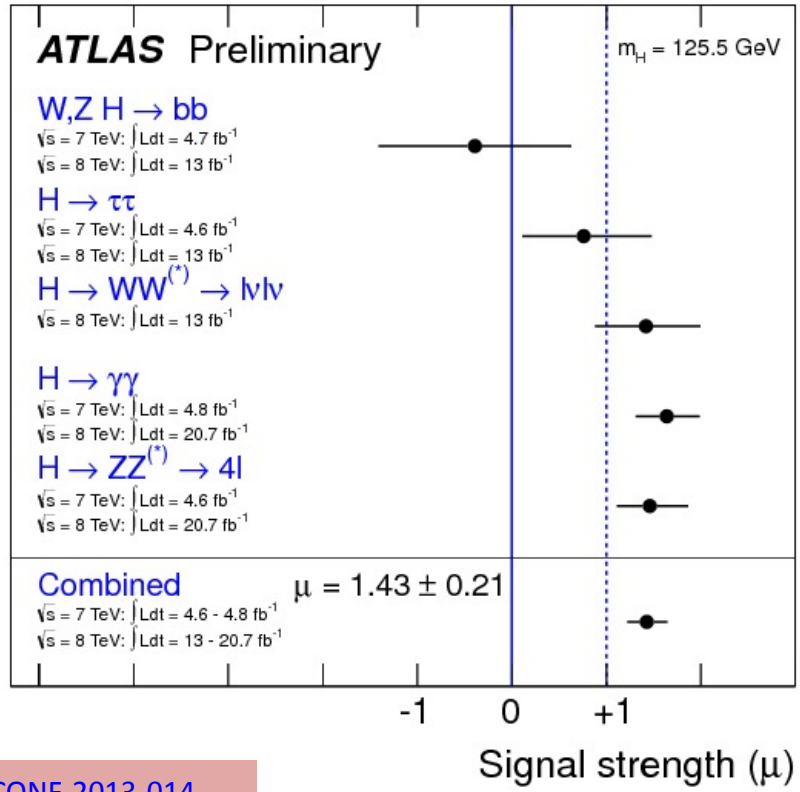
ATLAS-CONF-2013-030

Status of the new resonance (ATLAS)

- Combined mass measurement from $H \to ZZ^{(*)} \to 4l$, $H \to \gamma\gamma$ 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).





ATLAS-CONF-2013-014

Status of the new resonance (CMS)

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: 3D analysis using matrix element-based kinematic discriminant for each m_{4l}.

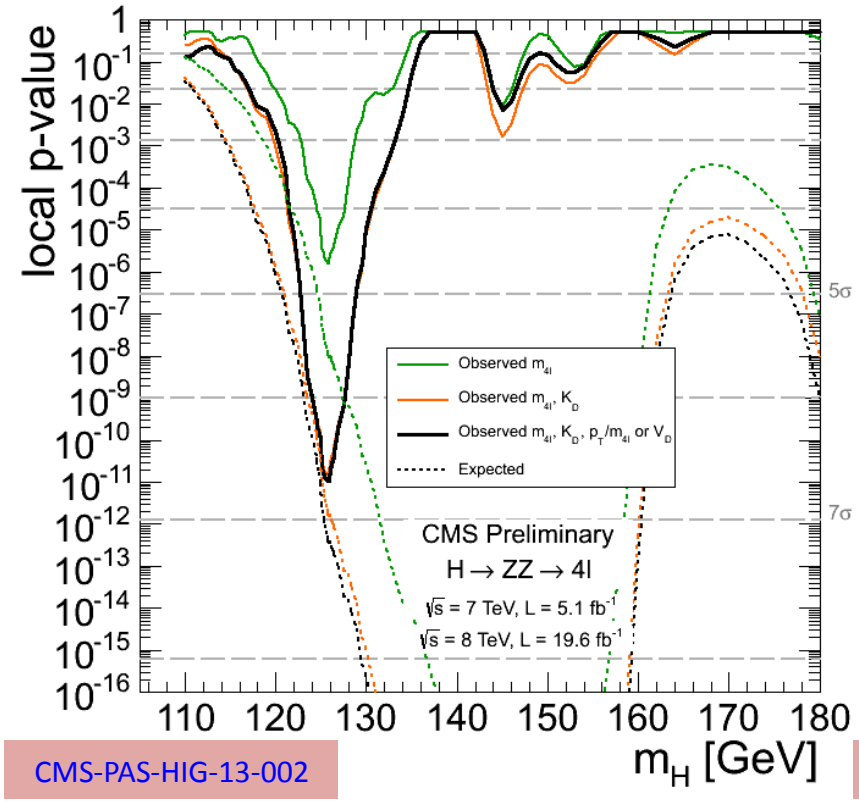
$m_H = 125.8 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.})$ GeV

$\mu = 0.91^{+0.30}_{-0.24}$

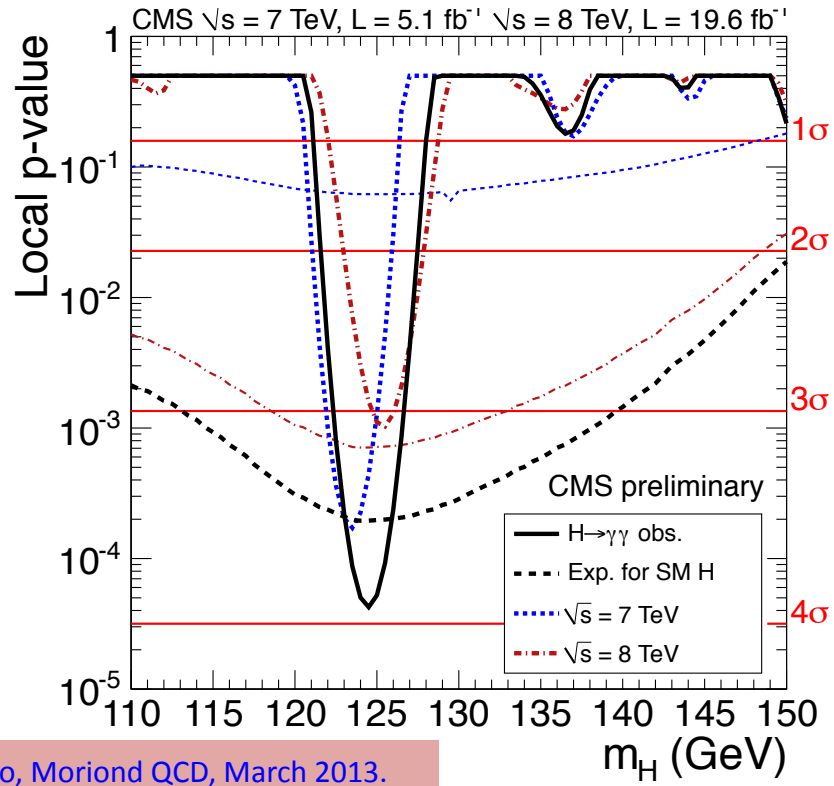
$H \rightarrow \gamma\gamma$: cut-based and MVA analyses. Statistically compatible (<2σ).
Significance (Moriond): 3.2 σ (4.2 exp)

$m_H = 125.4 \pm 0.5\ (\text{stat.}) \pm 0.6\ (\text{syst.})$

$H \rightarrow WW$: 4σ significance



CMS-PAS-HIG-13-002



C.Ochando, Moriond QCD, March 2013.

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

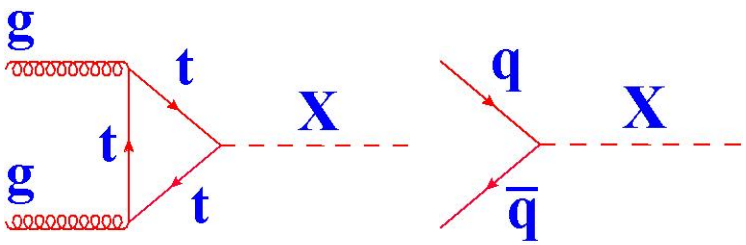
- Summary of spin possibilities given the observed decays.
- In principle, the observation of γγ disfavors the spin-1 hypothesis.
- The observation of the two-fermion decays will disfavor the spin-2 hypothesis.
- In both cases the loopholes exist.

	Spin-0	Spin-1	Spin-2	Observed
γγ	YES	NO	YES	YES
WW/ZZ	YES	YES	YES	YES
Fermions (bb,ττ)	YES	YES	NO	YES?

Present spin measurements in ATLAS and CMS (Moriond 2013)

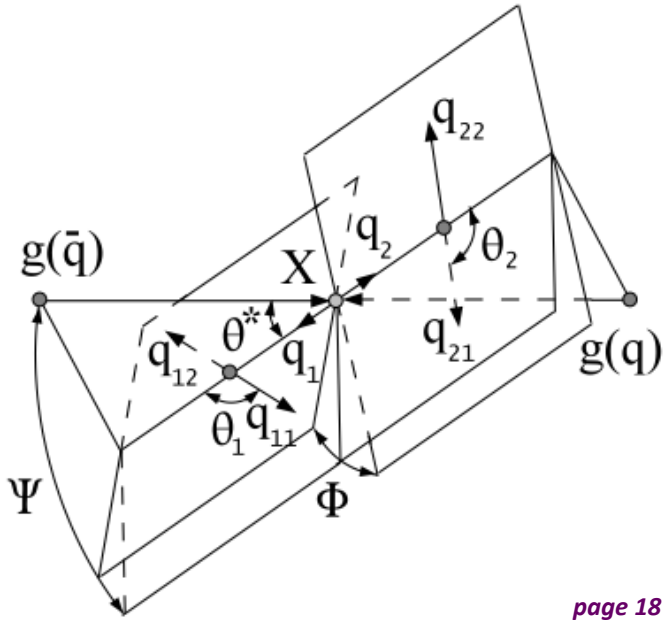
Measurements of Spin and Parity

- 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 an CMS

- In 2012-2013 ATLAS has presented three major studies of the spin and parity of the Higgs-like resonance.
  - Council week: H->ZZ->4l and H->γγ.
  - Moriond: H->ZZ->4l (update), H->γγ (update) and H->WW->lν lν

ATL-CONF-2013-013 ATL-CONF-2013-029 ATL-CONF-2013-031

- CMS has shown two major results:
  - Council week: H->ZZ->4l.
  - Moriond: H->ZZ->4l (update) and H->WW->lν lν.

CMS-CMS-PAS-HIG-13-002 CMS-PAS-HIG-13-003

- CMS has also produced a journal publication following the Council Week result in the 4l decay channel.
  - Phys. Rev. Lett. 110 (2013) 081803

Common spin and parity models

- ATLAS and CMS are working on the common set of benchmarks for spin studies.
  - Theoretically sound.
  - Easy to compare (combine).

- Spin and parity hypotheses considered in ATLAS : 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: ρ_{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.

Spin measurements in H->γγ decay (ATLAS)

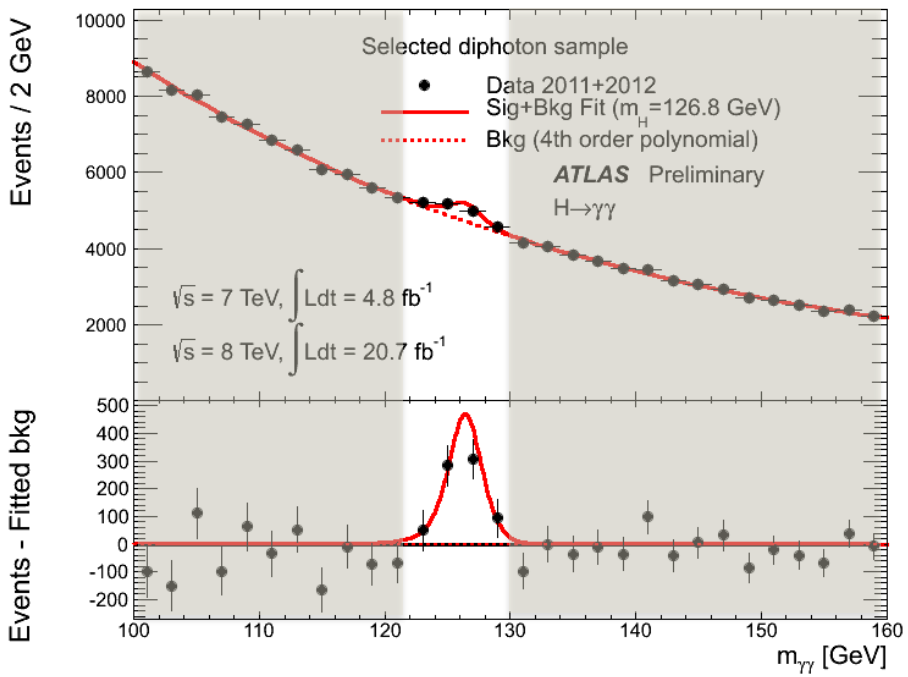
20.7 fb^{-1} at 8 TeV

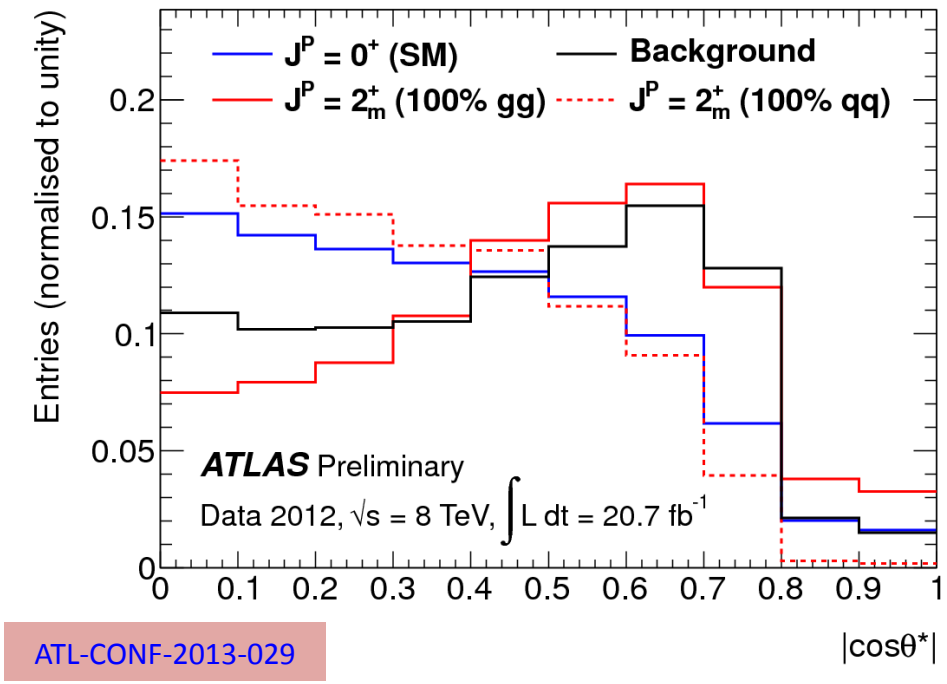
Study based on the single production angle: $|\cos\theta^*|$.

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

Signal region: 122 GeV $< m_{\gamma\gamma} <$ 130 GeV.

$|\cos\theta^*|$ and $m_{\gamma\gamma}$ are treated as uncorrelated. Fit to the product of their PDFs in the signal region.

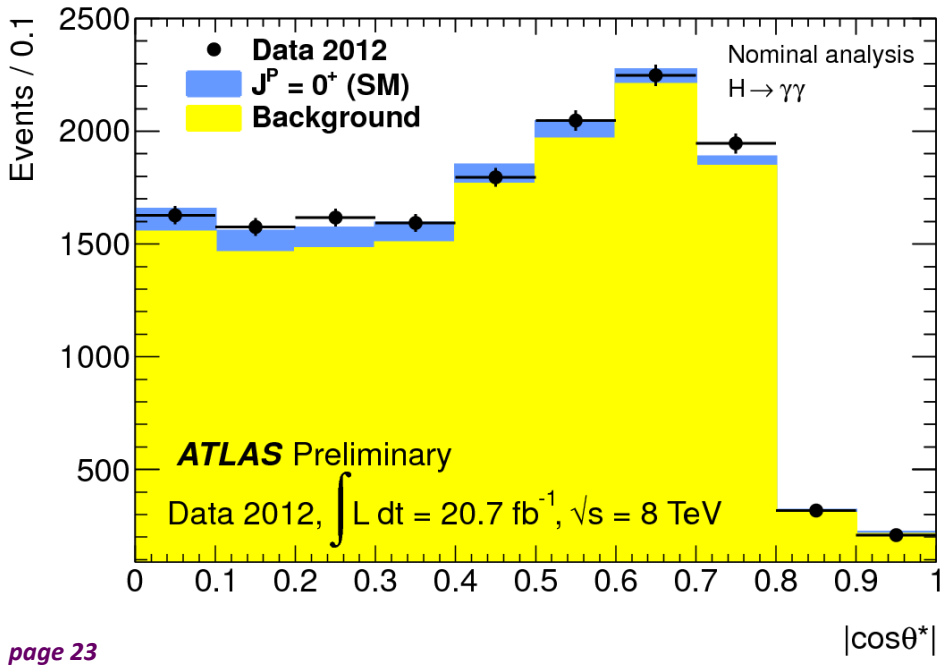


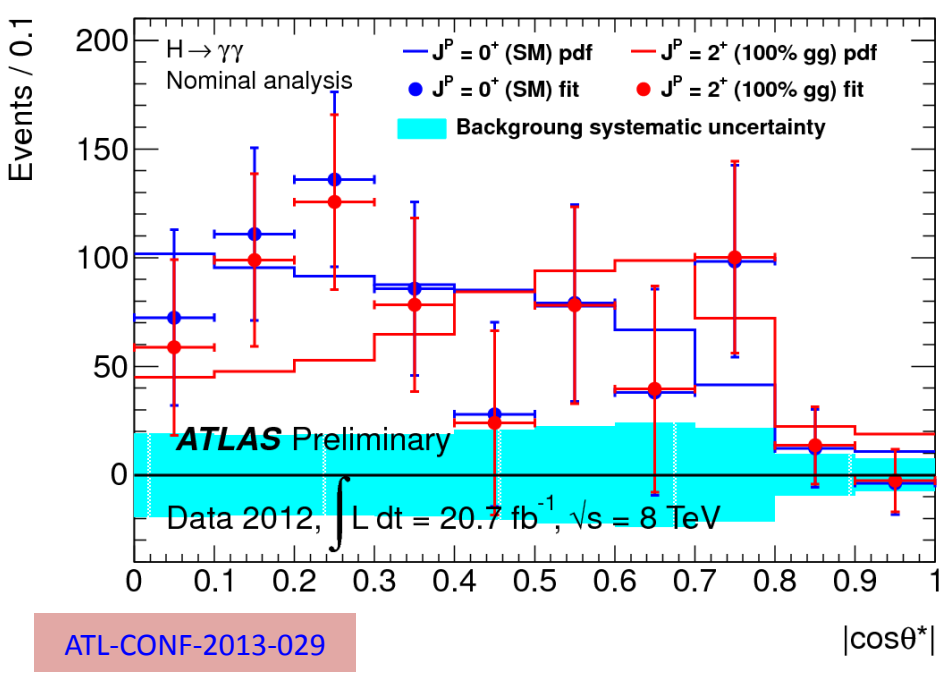


ATL-CONF-2013-029

Spin measurements in H->γγ decay (ATLAS)

- Left: obseved distribution of |cos θ*| in the signal region overlaid with the signal and background components of the pdf obtained from the inclusive fit of the data.
- Right: background-subtracted data distributions, profiled with a fit where the $0^+/2^+_m$ ratio is free.





ATL-CONF-2013-029

Spin measurements in H->γγ decay (ATLAS)

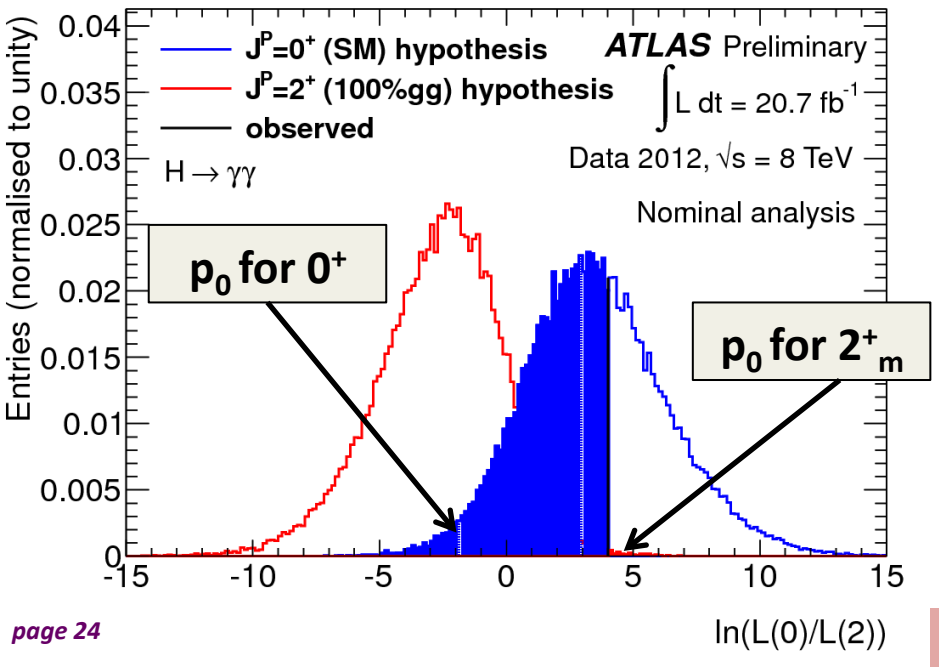
Expected p-value for 2^+_m (100% ggF): 0.5%.

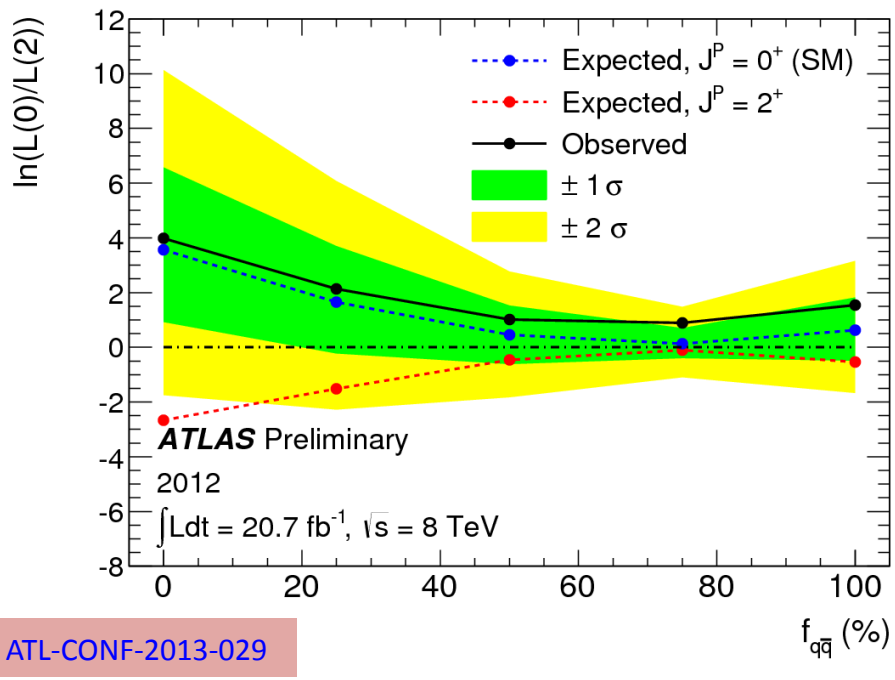
Observed p-value for 2^+_m (100% ggF): 0.3%.

Observed p-value for 0^+: 58.8%.

Data exclude $J^P=2^+_m$ in favor of $J^P=0^+$ at 99.3% CL.

$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%) expected	p-values (%) observed	$1-CL_S(2^+)$ (%)
0	0^+	1.2	58.8	99.3
	2^+	0.5	0.3	
25	0^+	5.2	60.9	94.6
	2^+	3.9	2.1	
50	0^+	19.8	70.8	74
	2^+	18.7	7.6	
75	0^+	31.9	90.2	66
	2^+	30.5	3.3	
100	0^+	14.8	79.8	88
	2^+	13.5	2.5	

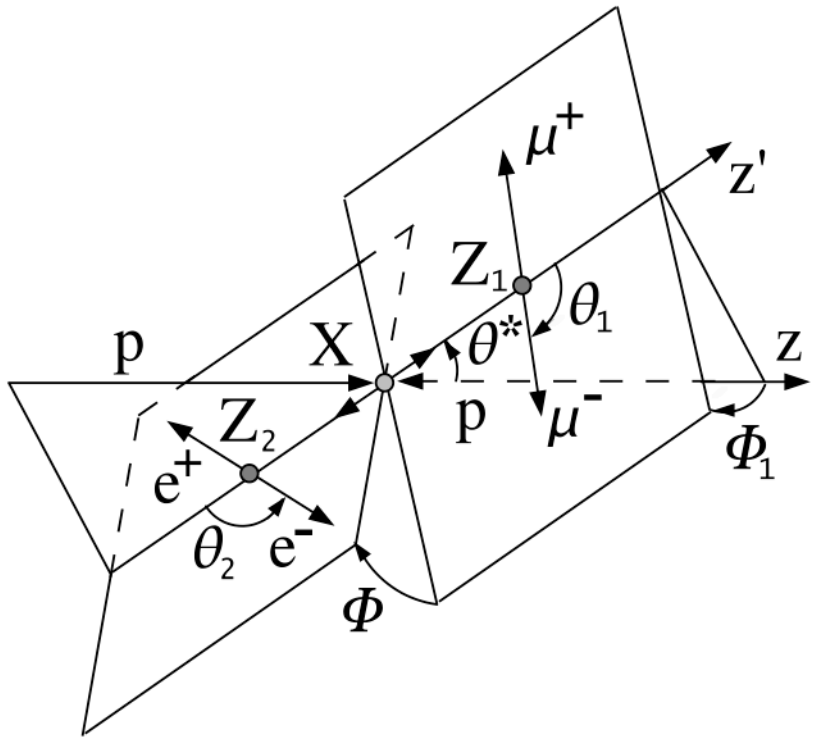




ATL-CONF-2013-029

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 Φ_1 between the decay planes defined in the Higgs rest frame.

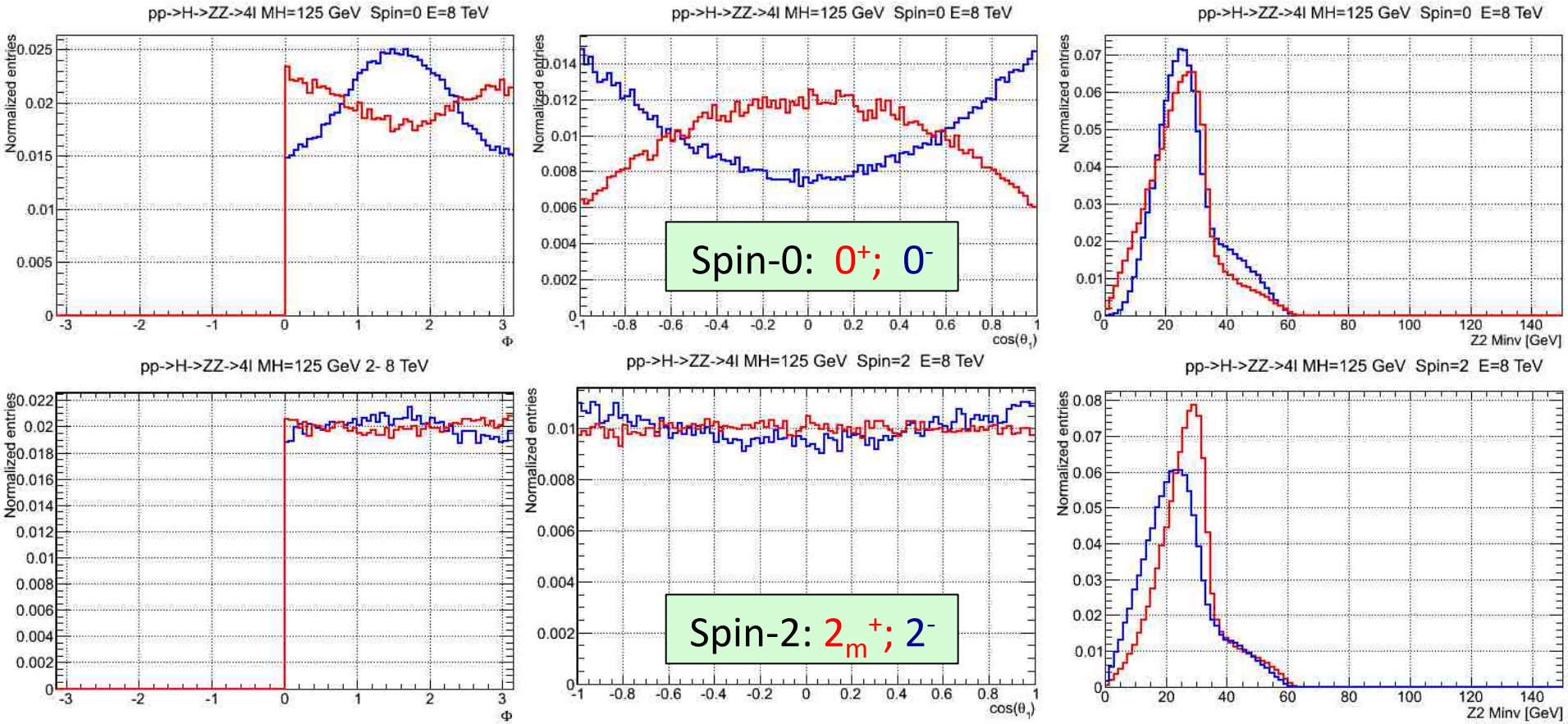
Θ_1 and Θ_2 of the negative leptons defined in the corresponding Z rest frame.

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)

Φ | $\cos\theta_1$ | m_{Z2}

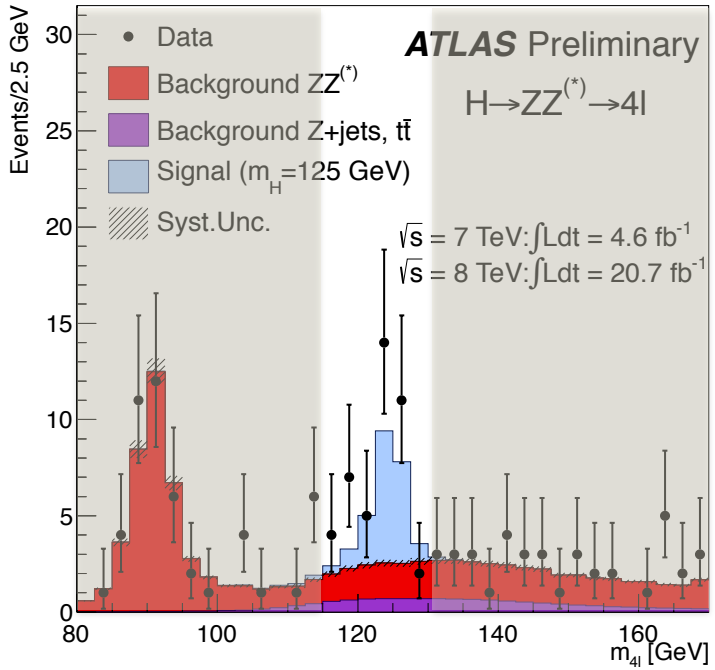


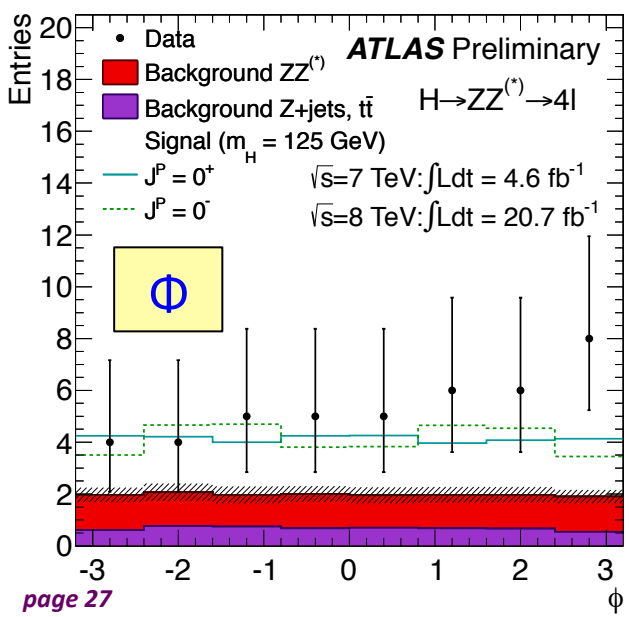
ATL-CONF-2013-013

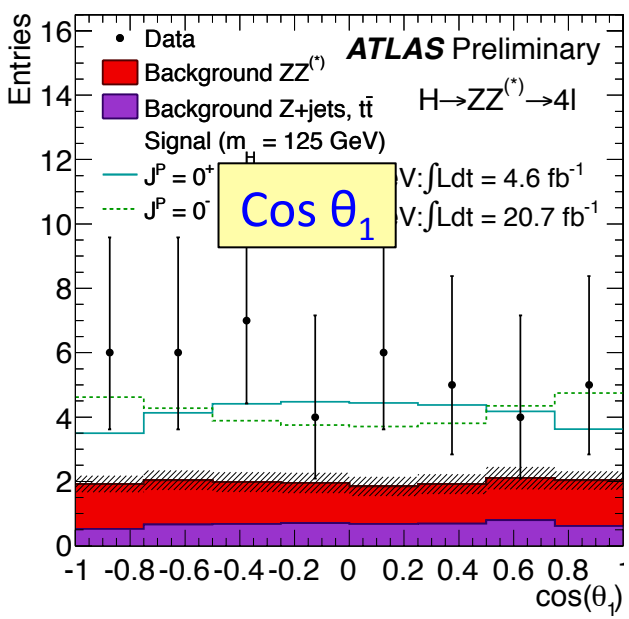
Four lepton decay channel

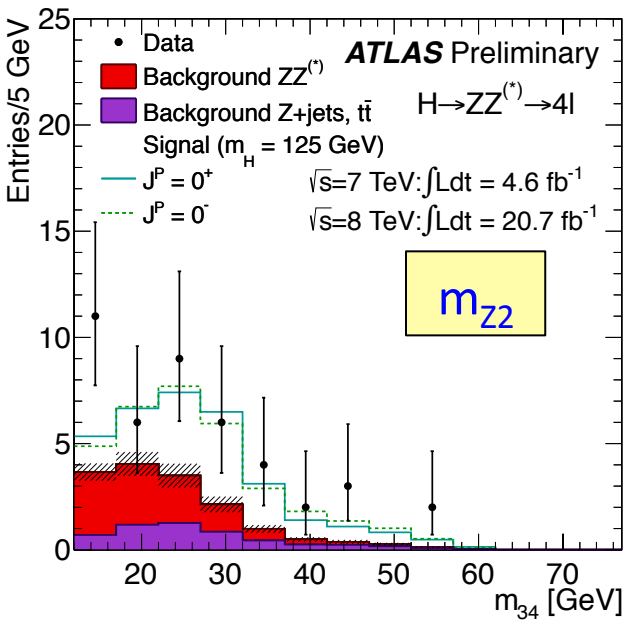
- Selection of 4l candidate events in the signal region: 115 GeV – 130 GeV.
- Reconstruction of the spin and parity sensitive variables after all selection cuts.
- Comparison to the signal and background expectations (MC and control regions).

4.6 fb^{-1} at 7 TeV and 20.7 fb^{-1} at 8 TeV



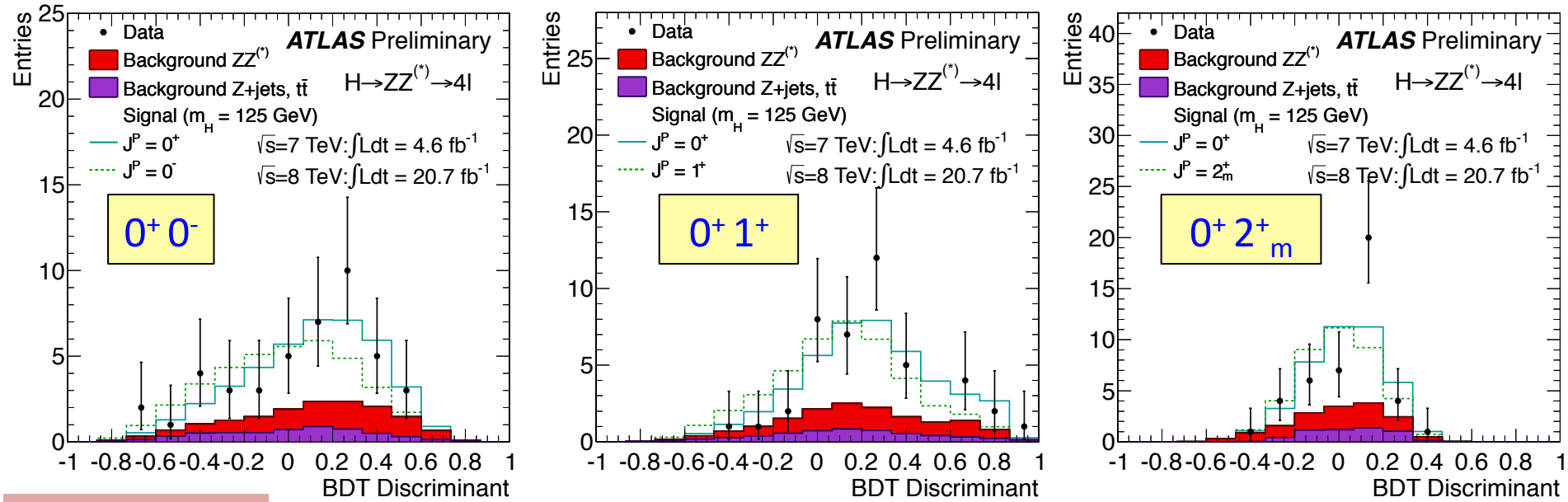






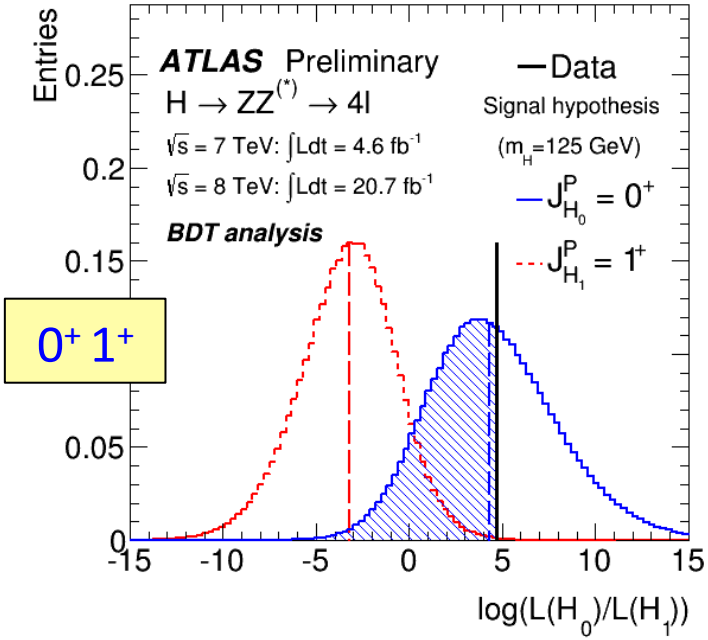
Four lepton decay channel (ATLAS)

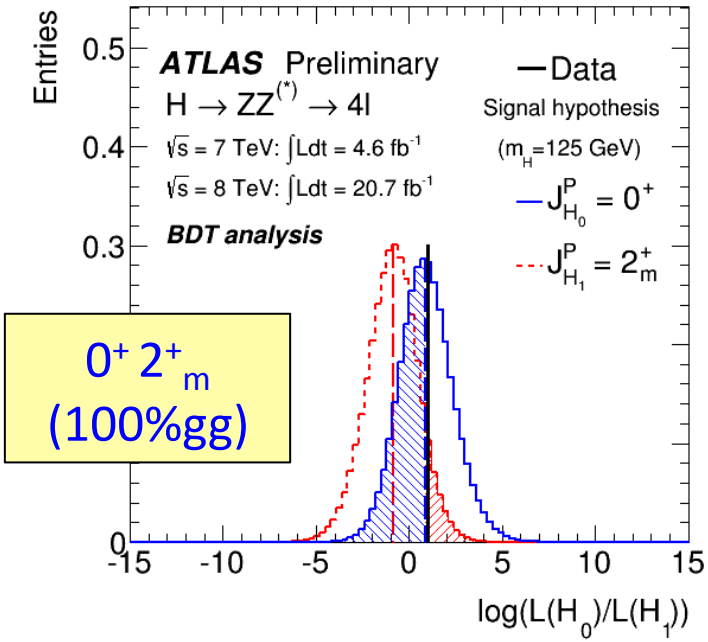
- Two complimentary multivariate approaches.
  - BDT analysis: discriminants trained to separate pairs of different Spin/CP states. Training on signal Monte Carlo after full reconstruction and selection.
  - J^P-MELA: discriminants based on the full Matrix Element analytical calculation for each Spin/CP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



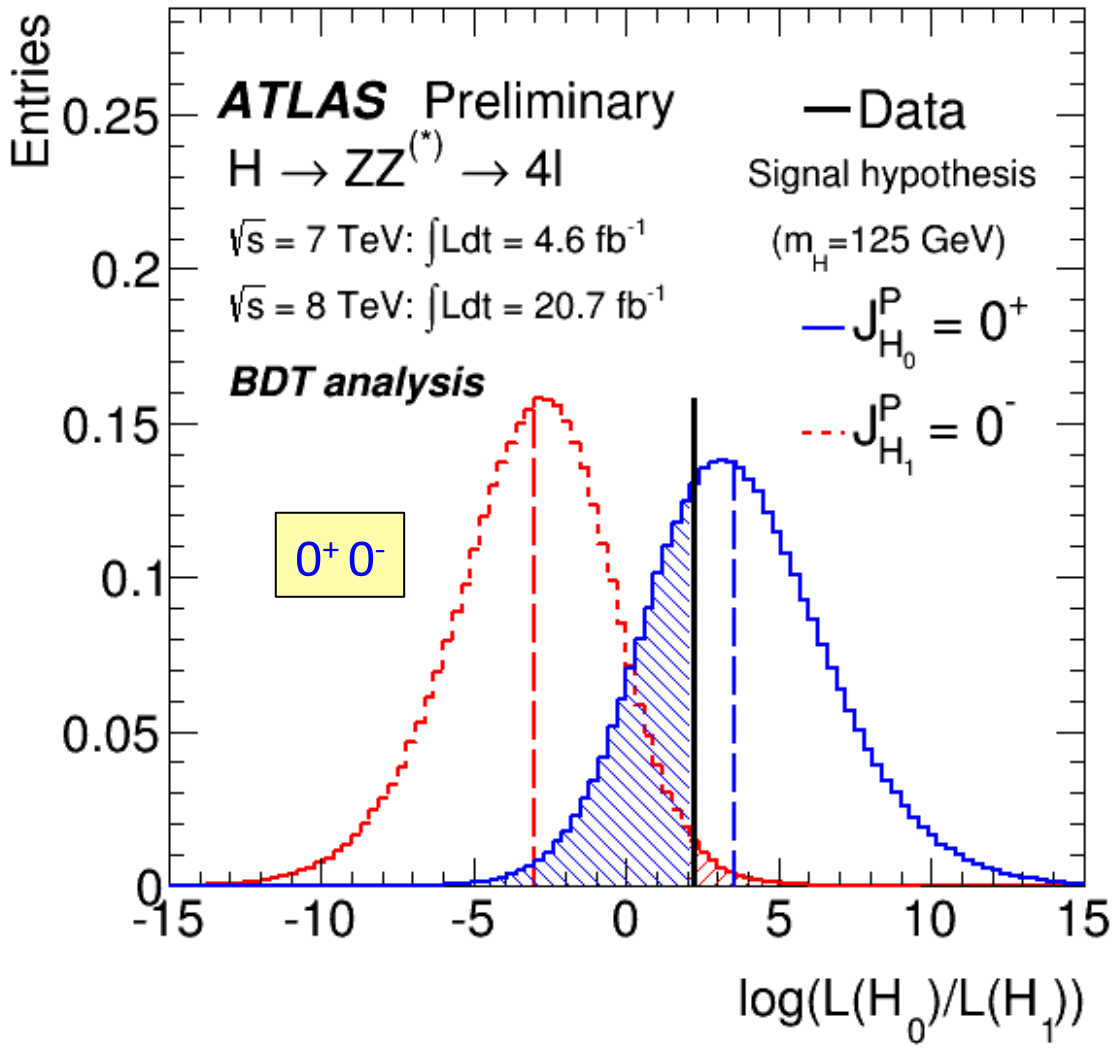
ATL-CONF-2013-013

Four lepton decay channel (ATLAS)





- Test statistic: ratio of profiled likelihoods.



ATL-CONF-2013-013

Four lepton decay channel (ATLAS)

4.6 fb^{-1} at 7 TeV and 20.7 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

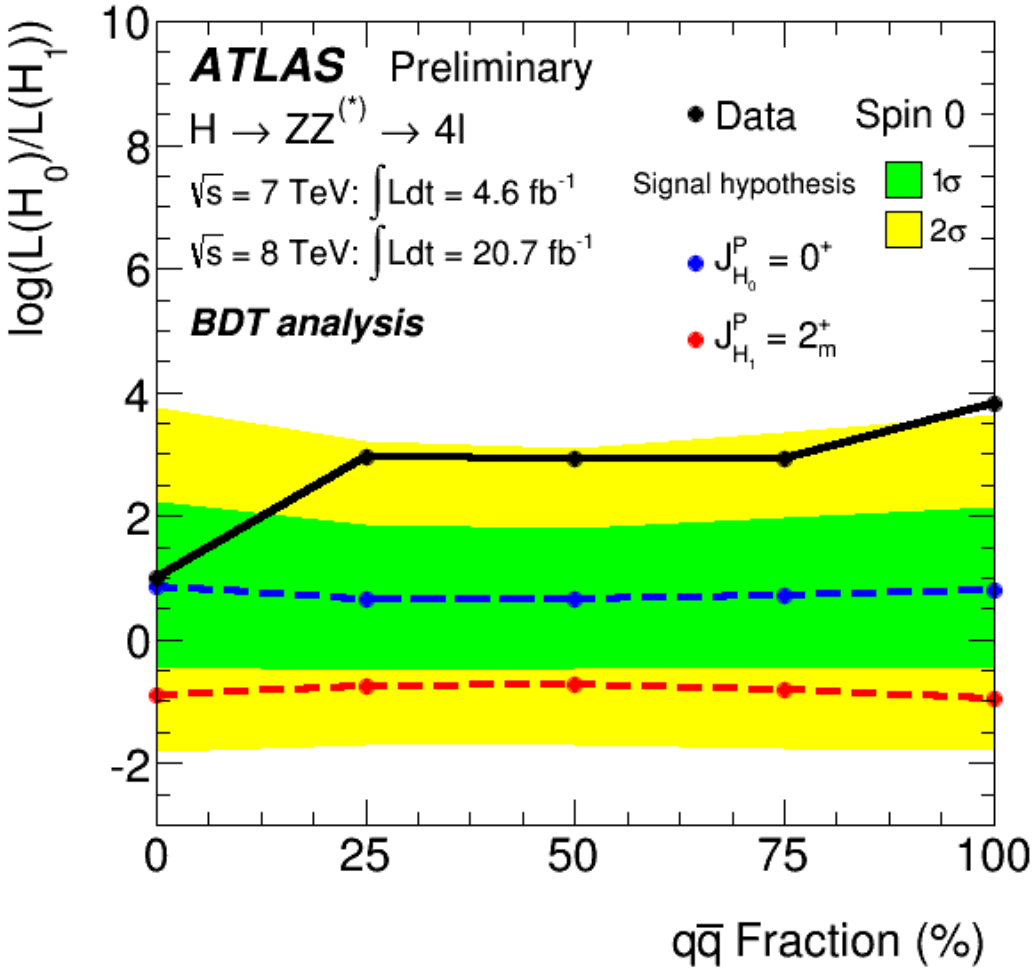
Exclusion of hypothesis in favor of $J^P=0^+$. CL_S. BDT (J^P-MELA)	**0.022 (0.003)**	**0.002 (0.005)**	**0.061 (0.030)**	**0.169 (0.182)**	**0.258 (0.115)**

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

ATL-CONF-2013-013

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->ZZ$^{(*)}$->4l decay channels can be combined.

ATL-CONF-2013-013

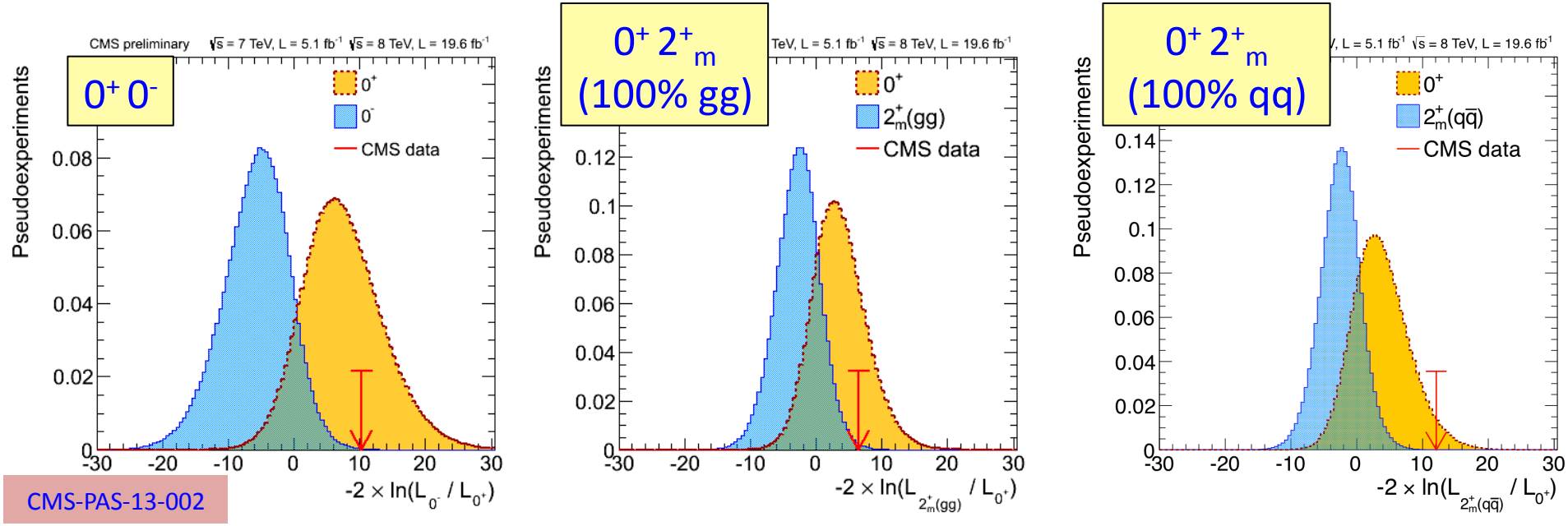
Four lepton decay channel (CMS)

Discriminant based on the analytical calculation of the matrix element.

2D analysis featuring two discriminants: one to separate pairs of spin-parity states and one to reject the ZZ background.

5.1 fb^{-1} at $\sqrt{s}$ = 7 TeV and 19.6 fb^{-1} at $\sqrt{s}$ = 8 TeV

Considered spin-parity hypotheses: 0^+, 0^+_h, 0^-, 1^+, 1^-, 2_m^+ for different production mechanisms.



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

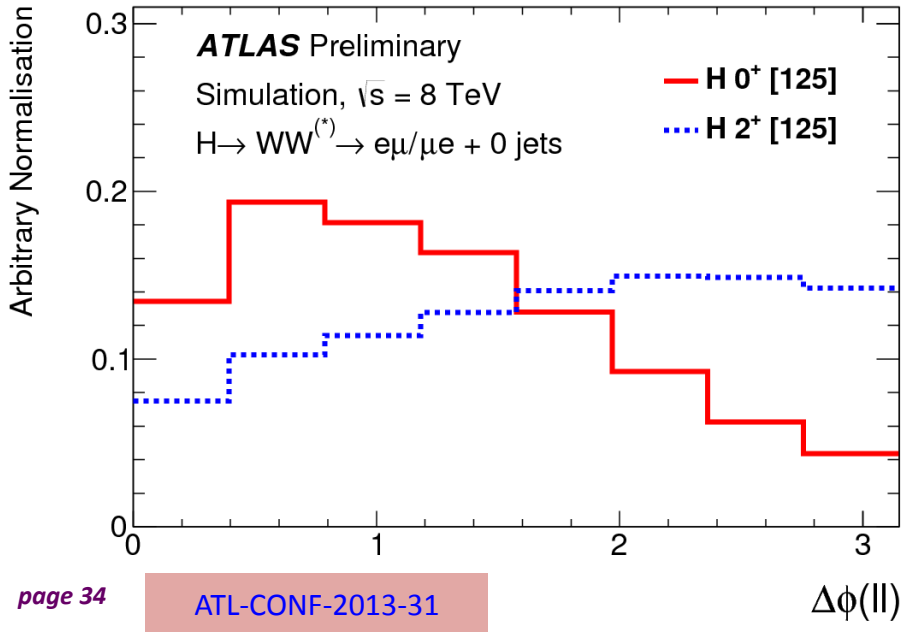
CMS-PAS-13-002

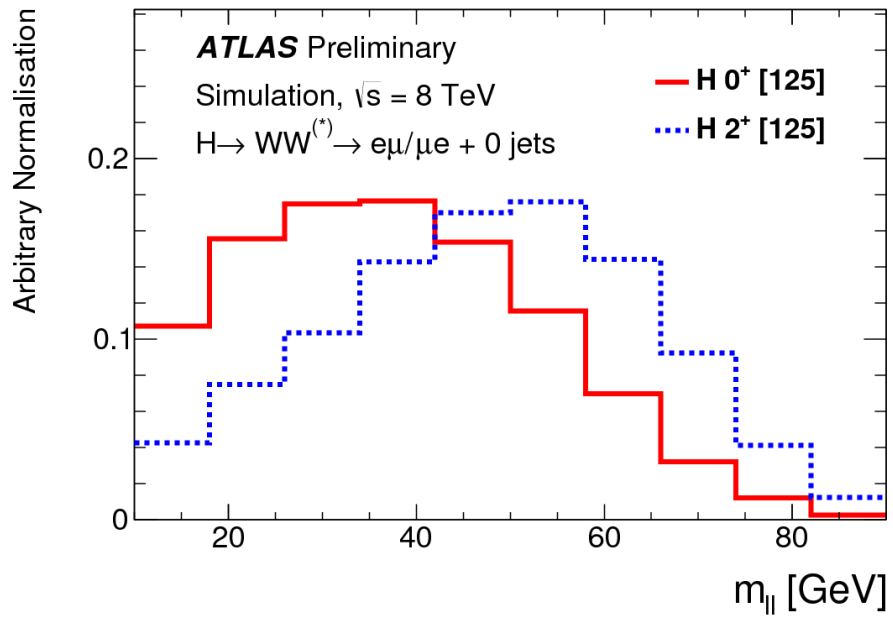
H->WW->$e\nu_e\mu\nu_\mu$ (ATLAS)

- Analysis uses the 0-jet *e/μ* channel only. Most sensitive to the spin due to the relatively low backgrounds.
  - Hypotheses: 0^+ and 2^+_m
- Spin-sensitive variables: m^{ll}, p^{ll}_T, $\Delta\phi^{ll}$ and m_T.
- Analysis method: two dimensional fit. Two BDT scores are calculated for each event.
  - 0^+ or 2^+_m against background.

20.7 fb^{-1} at 8 TeV.
Different cuts from 'discovery' analysis.

Main analysis: 3.8σ;
μ= 1.01 ± 0.31



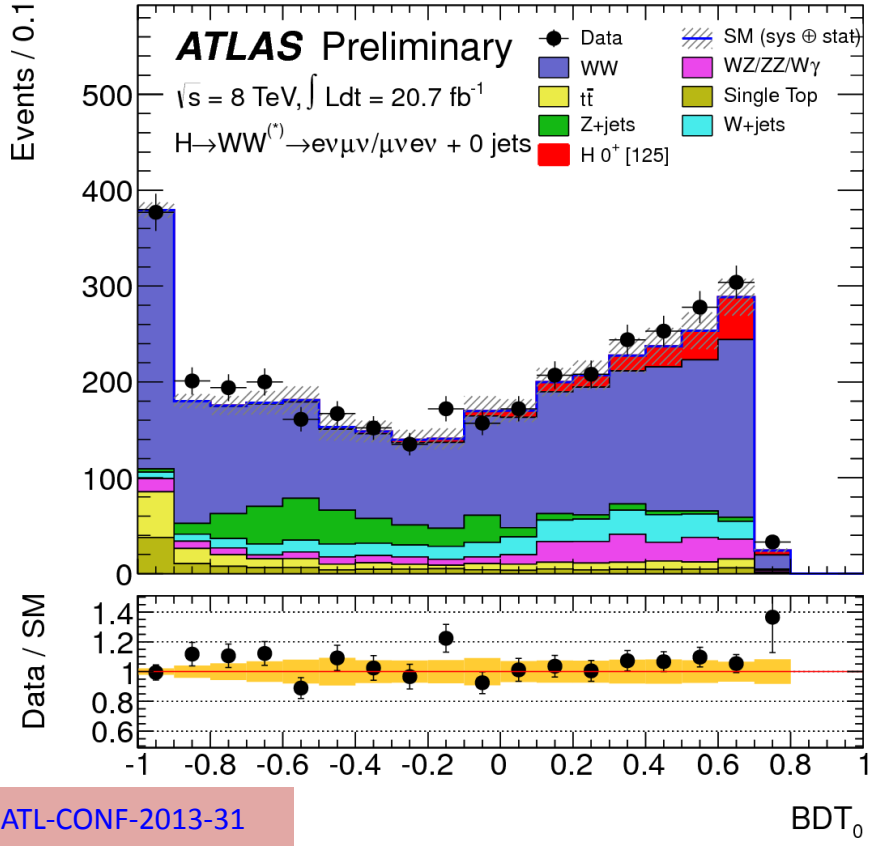


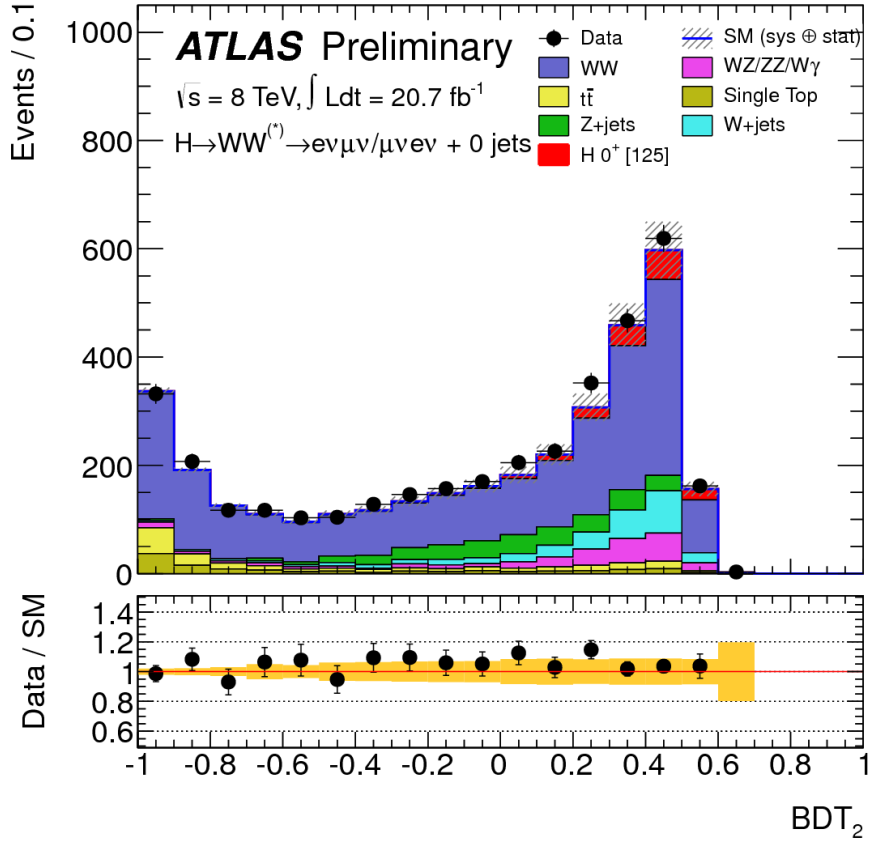
ATL-CONF-2013-31

H->WW->$e\nu_e\mu\nu_\mu$ (ATLAS)

Distributions of BDT_0 and BDT_2 for the signal region superimposed with the Standard Model $J^P=0^+$ expectation.

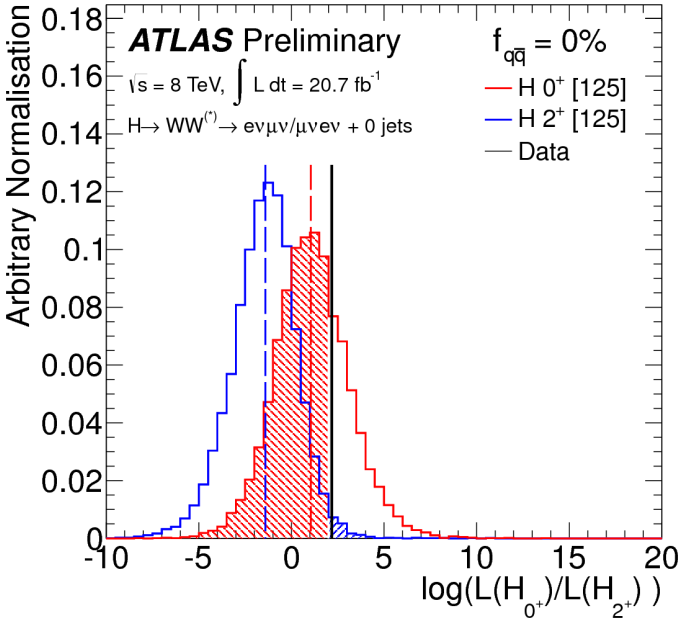
Backgrounds: W+jets, Z/γ->ττ, WW, top.

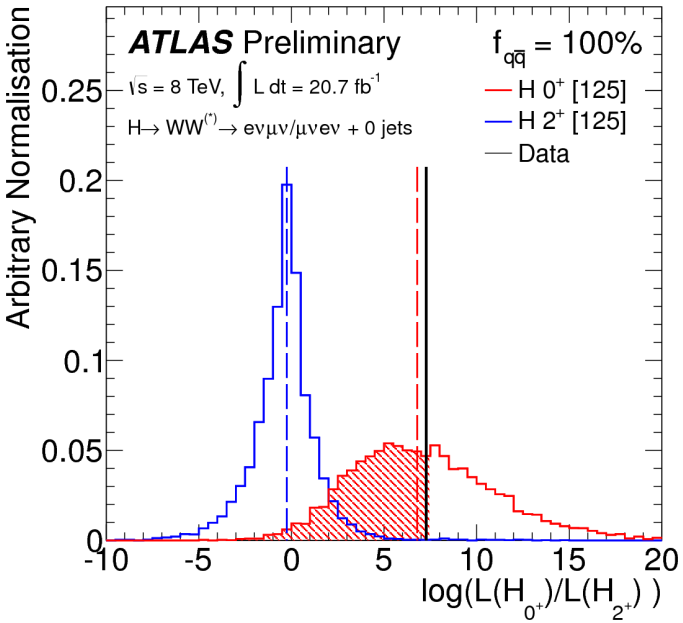




ATL-CONF-2013-31

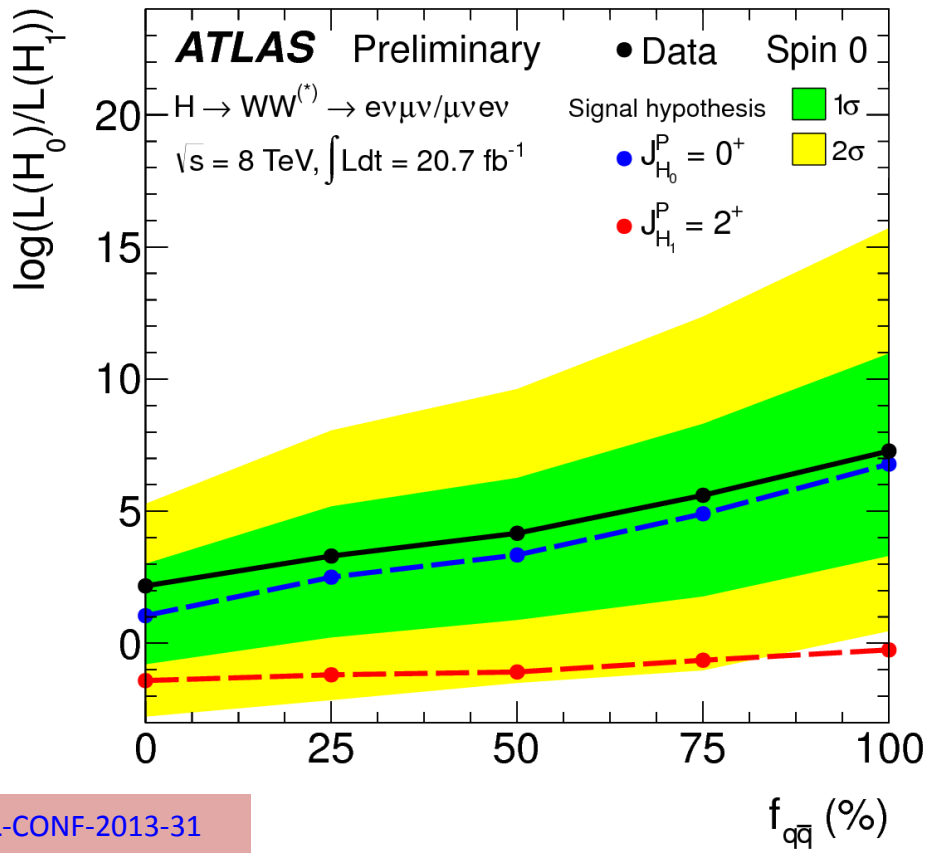
H->WW->$e\nu_e\mu\nu_\mu$ (ATLAS)





Separation between the Standard Model $J^P=0^+$ and $J^P=2^+_m$ hypotheses grows as the function of the qqbar fraction.

Observed exclusions: 95%CL to 99% CL in favor of the Standard Model $J^P=0^+$ hypothesis.



ATL-CONF-2013-31

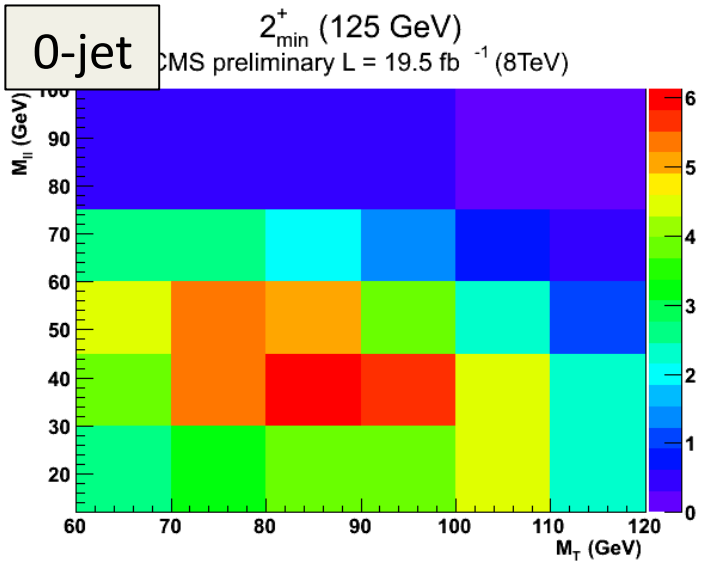
H->WW->lvlv (CMS)

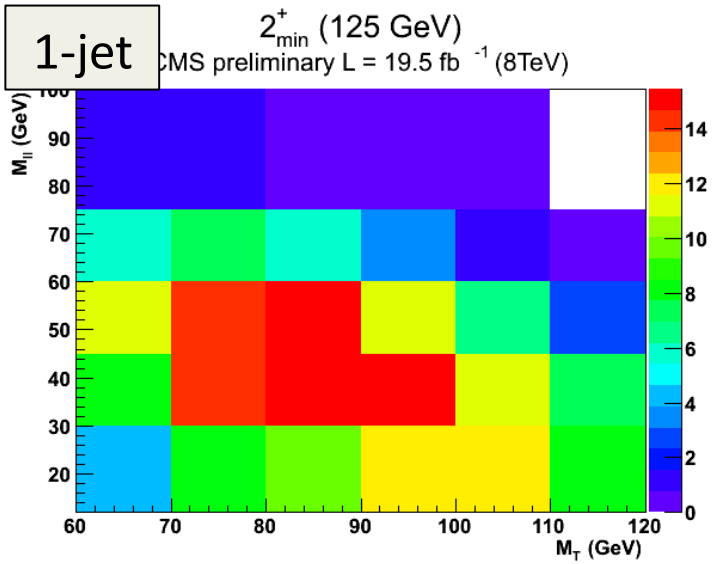
4.9 fb^{-1} at 7 TeV and 19.5 fb^{-1} at 8 TeV

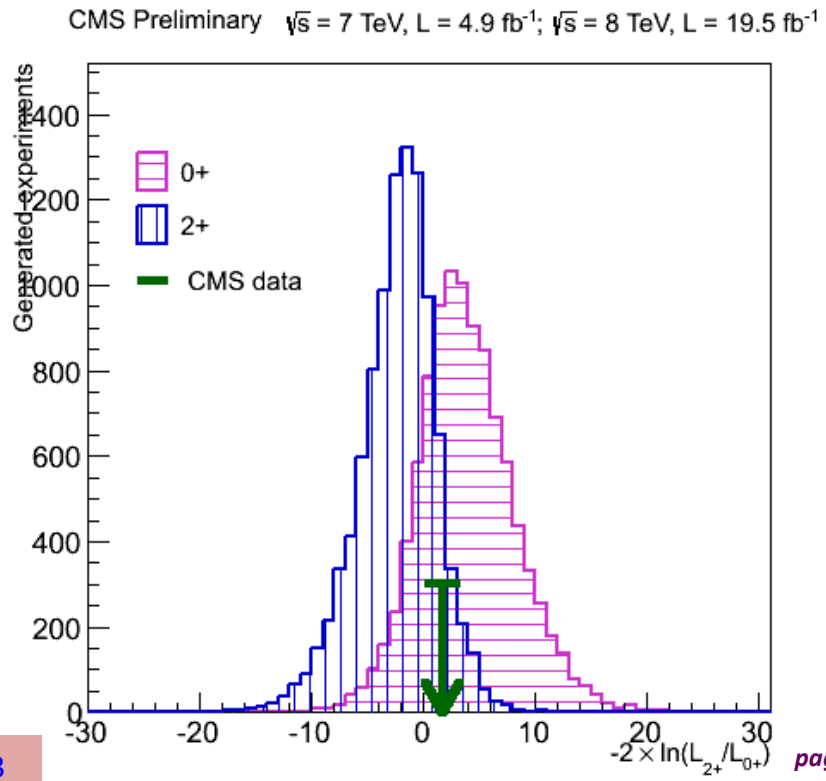
Likelihood fit to two-dimensional templates: m_{ll} vs m_T. 0- and 1- jet categories.

Test statistic on data is 0.5σ and 1.3σ away from the expected values for the 0^+ and 2^+_m (100% gg).

$CLs(2^+_m)$ = 14%. Slight preference towards $J^P=0^+$.





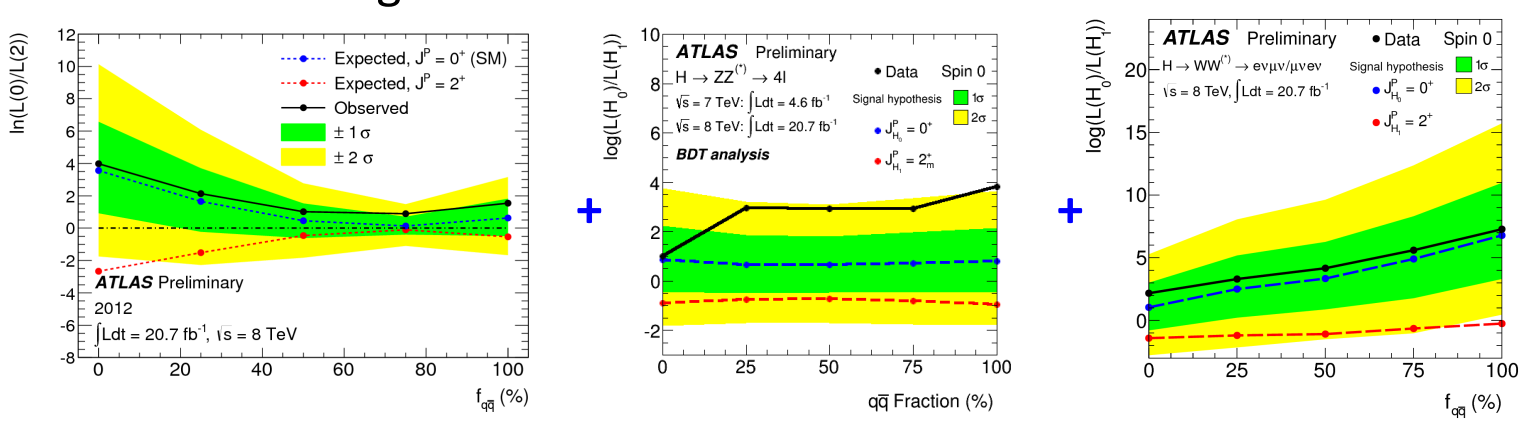


CMS-PAS-13-003

Next steps

- The LHC has delivered 23.3 fb^{-1} at √s=8 TeV and 5.6 fb^{-1} at √s=7 TeV before the technical stop.
  - The data seem to prefer $J^P=0^+$ over other hypotheses.

- So far we made preliminary analysis on the full dataset for H->γγ, H->ZZ->4l and H->WW decay channels.
  - 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 HVV 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->ZZ$^{(*)}$->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.
  - Modeling scenarios with different admixtures and excluding them.
  - Study of asymmetries directly sensitive to different amplitude parts.

- 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:

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

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.

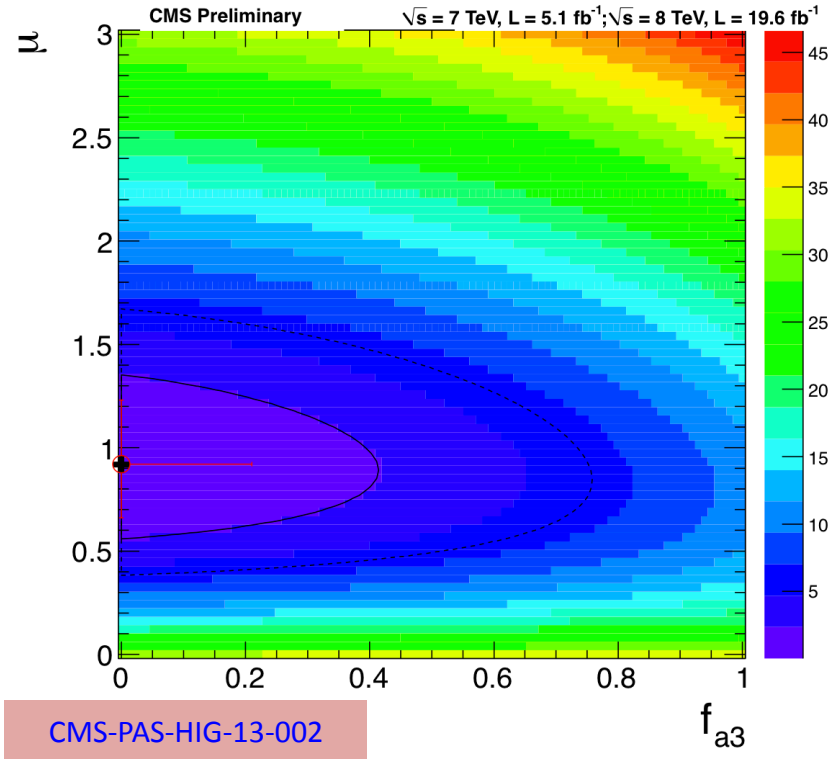
CP-violation in ZZ coupling

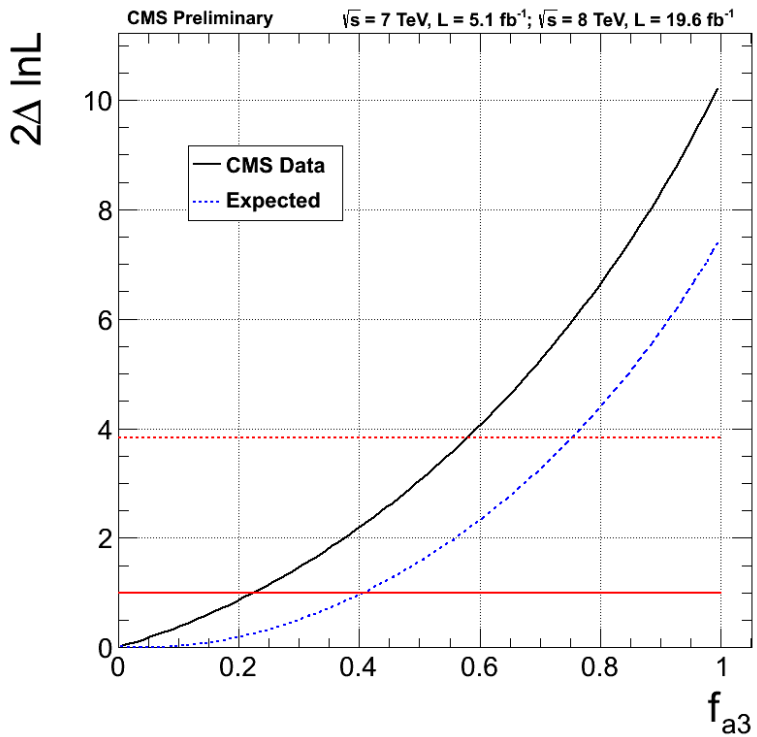
The first limit is currently available from CMS. Scan of 2 times the log-likelihood ratio between the two signal models as a function the signal strength and f_{a3}, the fraction of observed 0^- events in the dataset.

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

$f_{a3} < 0.58$ at 95% CL

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





5.1 fb^{-1} at 7 TeV + 19.6 fb^{-1} at 8 TeV

CMS-PAS-HIG-13-002

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.

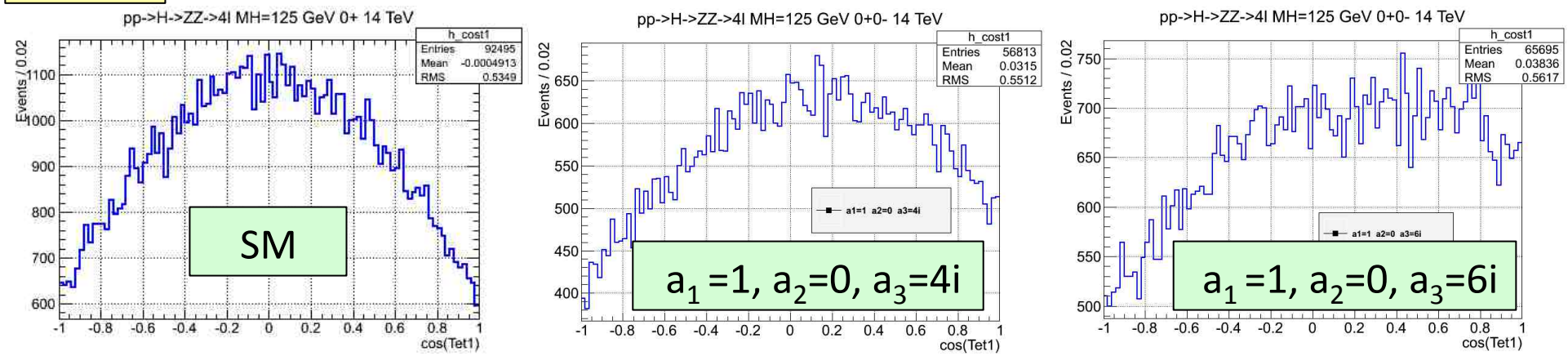
ATLAS-PHYS-PUB-2012-004

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 θ_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 3σ at 100 fb^{-1}.
If the observed signal yield is higher than expected, we can put the limit further.

arXiv:0708.0458v2

Further studies (asymmetries)

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.

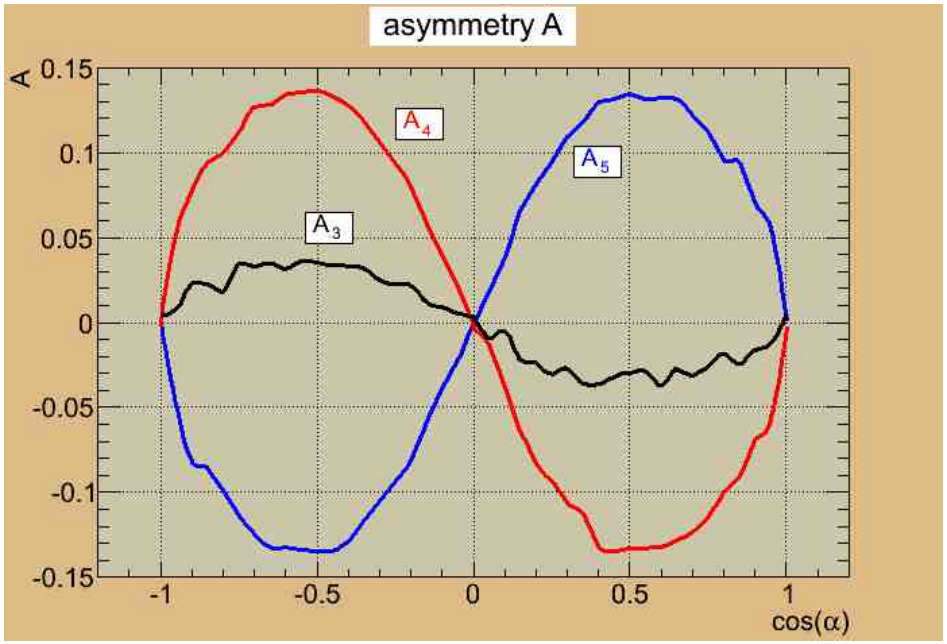
$$A_i = \frac{N(F_i > 0) - N(F_i < 0)}{N(F_i > 0) + N(F_i < 0)}$$

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

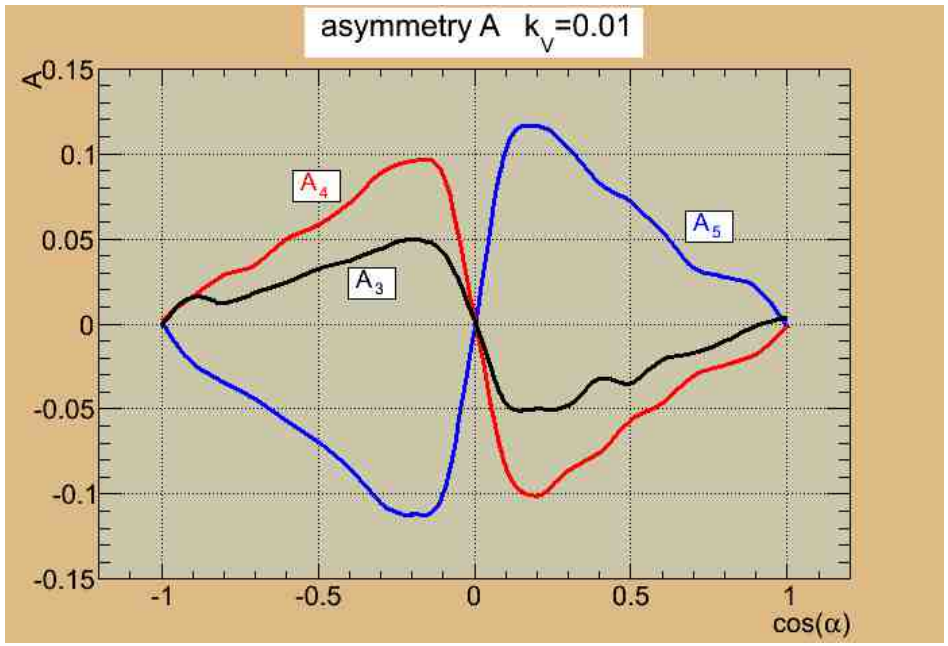
$$F_4 = \sin^2\theta_1 \sin^2\theta_2 \sin\phi \cos\phi$$

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

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



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



Summary

- First spin and parity results start appearing in LHC experiments.
  - The 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)

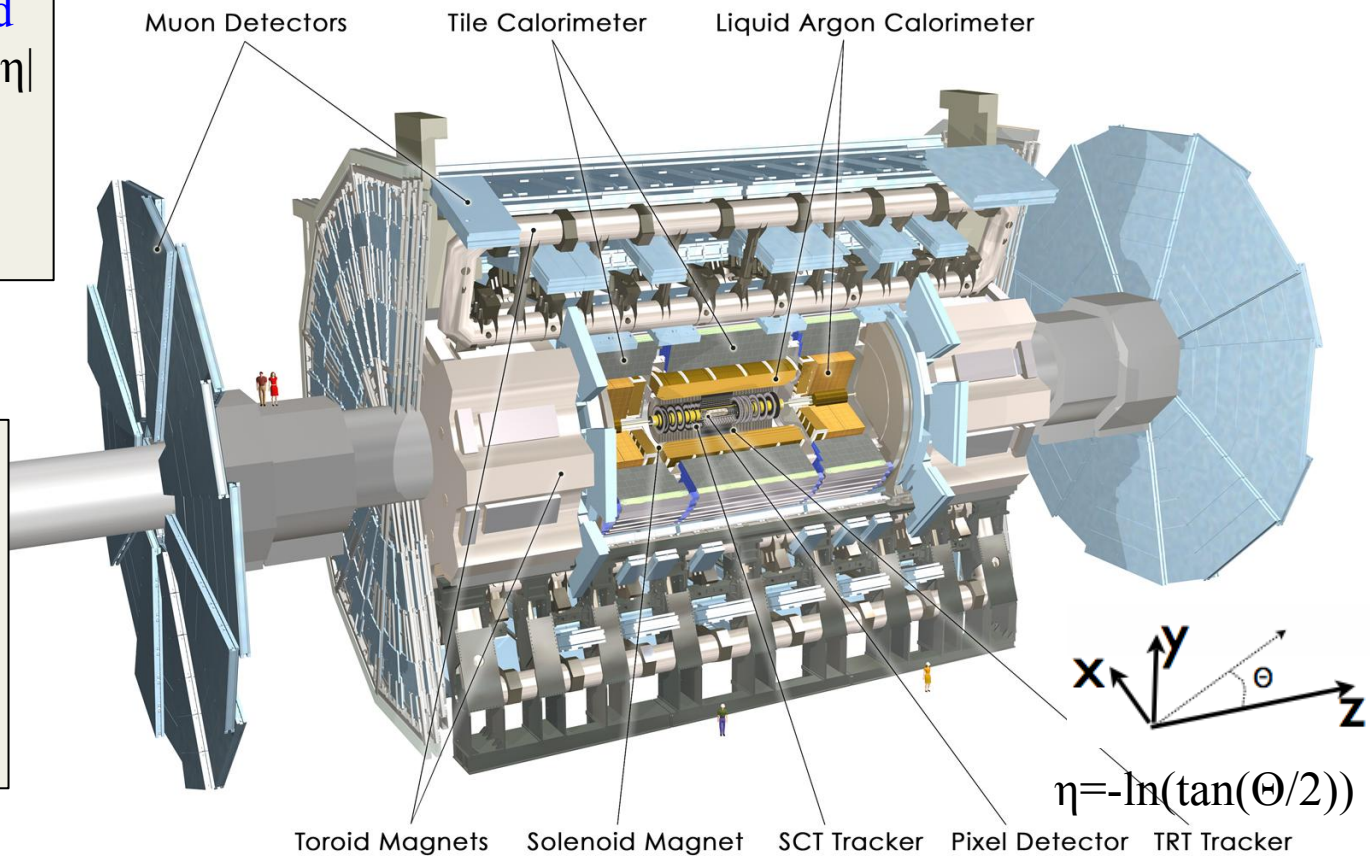
- Important studies which were not discussed in this talk.
- Study of the spin and parity in channels with VBF, VH, ttH production mechanisms.
- Searches for the CP-violation in ttH H->μμ decay.
- Measurements of the Higgs self-couplings.
- Direct searches for additional (heavy) Higgs bosons.

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)

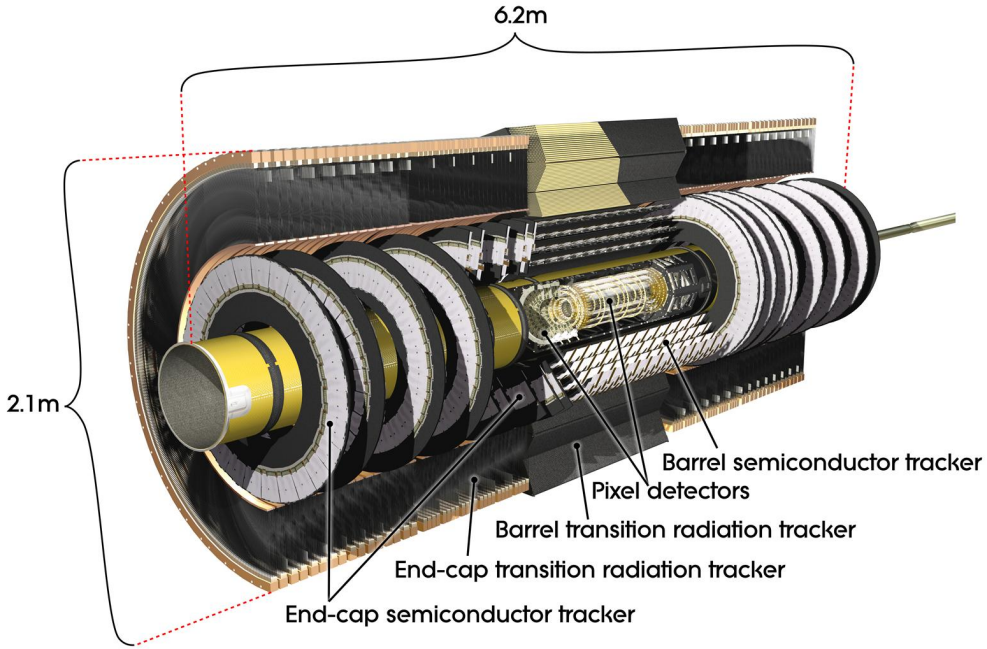
The Inner Detector provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at η = 0. Coverage: |η| < 2.5 (2.0 for TRT)
Resolution goal: $\sigma_{pT}/p_T = 0.05\%\ p_T \oplus 1\%$

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



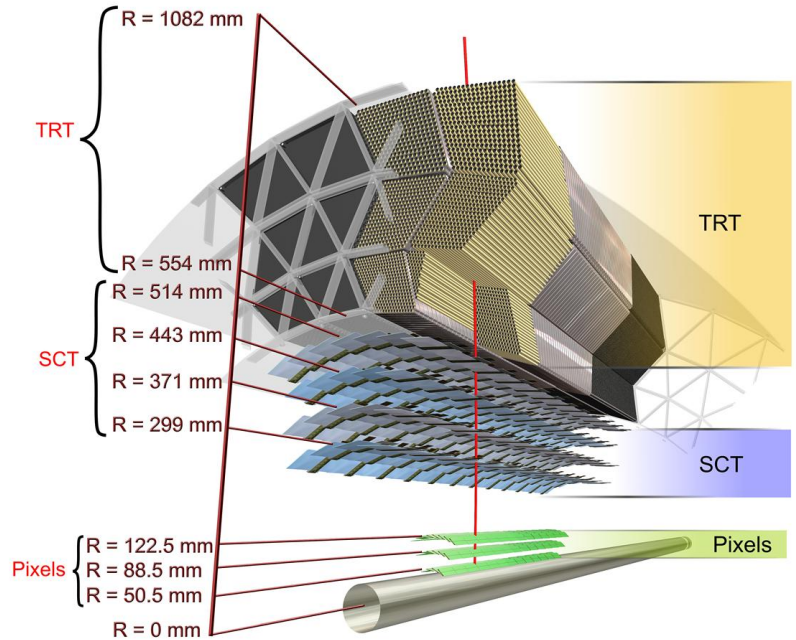
$\eta = -\ln(\tan(\Theta/2))$

ATLAS Inner Detector



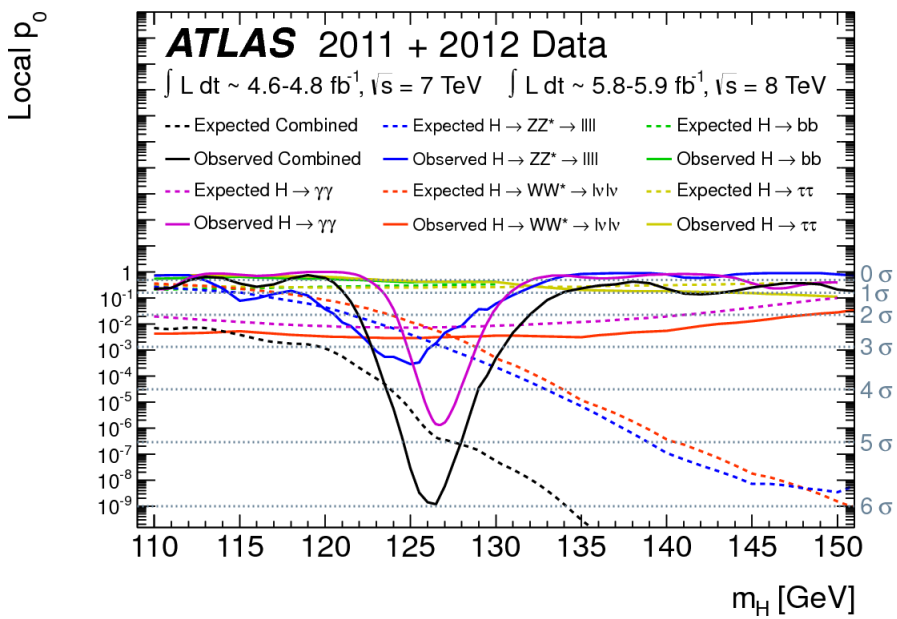
Tracking detector with
2 Tesla solenoid field.
3 sub-detectors: (resolution)
Pixel: 10/115 μm in Rϕ/z
Silicon strip (SCT): 17/580 μm
Transition radiation tracker (TRT):
130μm in Rϕ

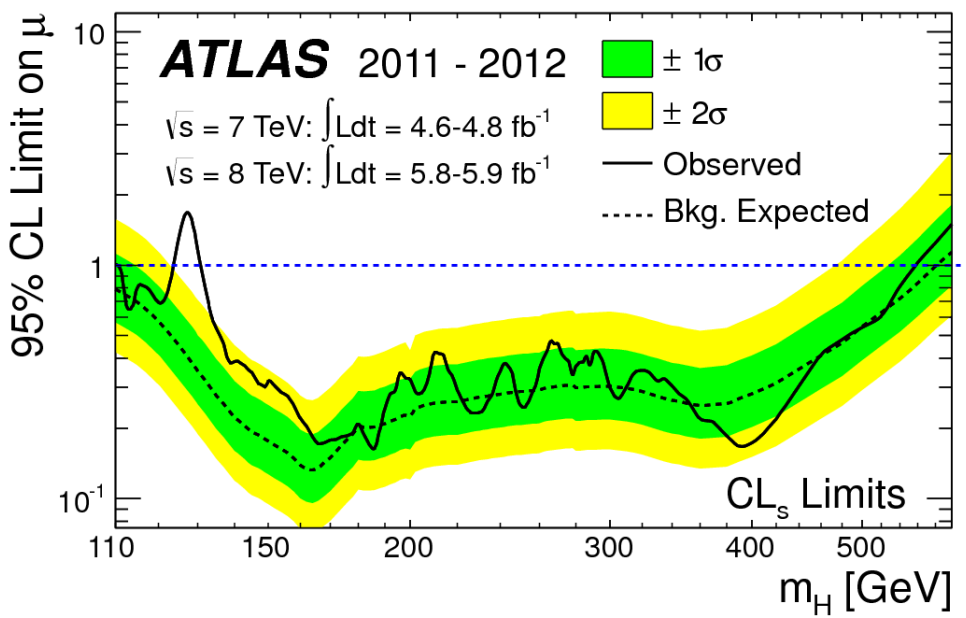
The ID provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at $\eta = 0$.
Coverage: $|\eta| < 2.5$ (2.0 for TRT)
Allows for accurate track and vertex reconstruction.
Resolution goal: $\sigma_{pT} / p_T = 0.05\%\ p_T \oplus 1\%$



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

$$
\begin{aligned}
A(X \to V_1 V_2) = \Lambda^{-1} \Big[& \underline{2 g_1 X_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu}_{\alpha}} \\
& + 2 g_2 X_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} X_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\
& + g_4 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} X_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 X_{\mu\nu} \left(\underline{2 g_5 \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}} + 2 g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} (\varepsilon_1^{*\nu} \varepsilon_2^{*\alpha} - \varepsilon_1^{*\alpha} \varepsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} (\varepsilon_1^* \varepsilon_2^*) \right) \\
& + g_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} X_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 X_{\mu\alpha} \tilde{q}^\alpha \varepsilon_{\mu\nu\rho\sigma} \left(g_9 \frac{q^\sigma}{\Lambda^2} \varepsilon_1^{*\nu} \varepsilon_2^{*\rho} + g_{10} \frac{q^\rho \tilde{q}^\sigma}{\Lambda^4} (\varepsilon_1^{*\nu} (q \varepsilon_2^*) + \varepsilon_2^{*\nu} (q \varepsilon_1^*)) \right) \Big] \quad (3)
\end{aligned}
$$

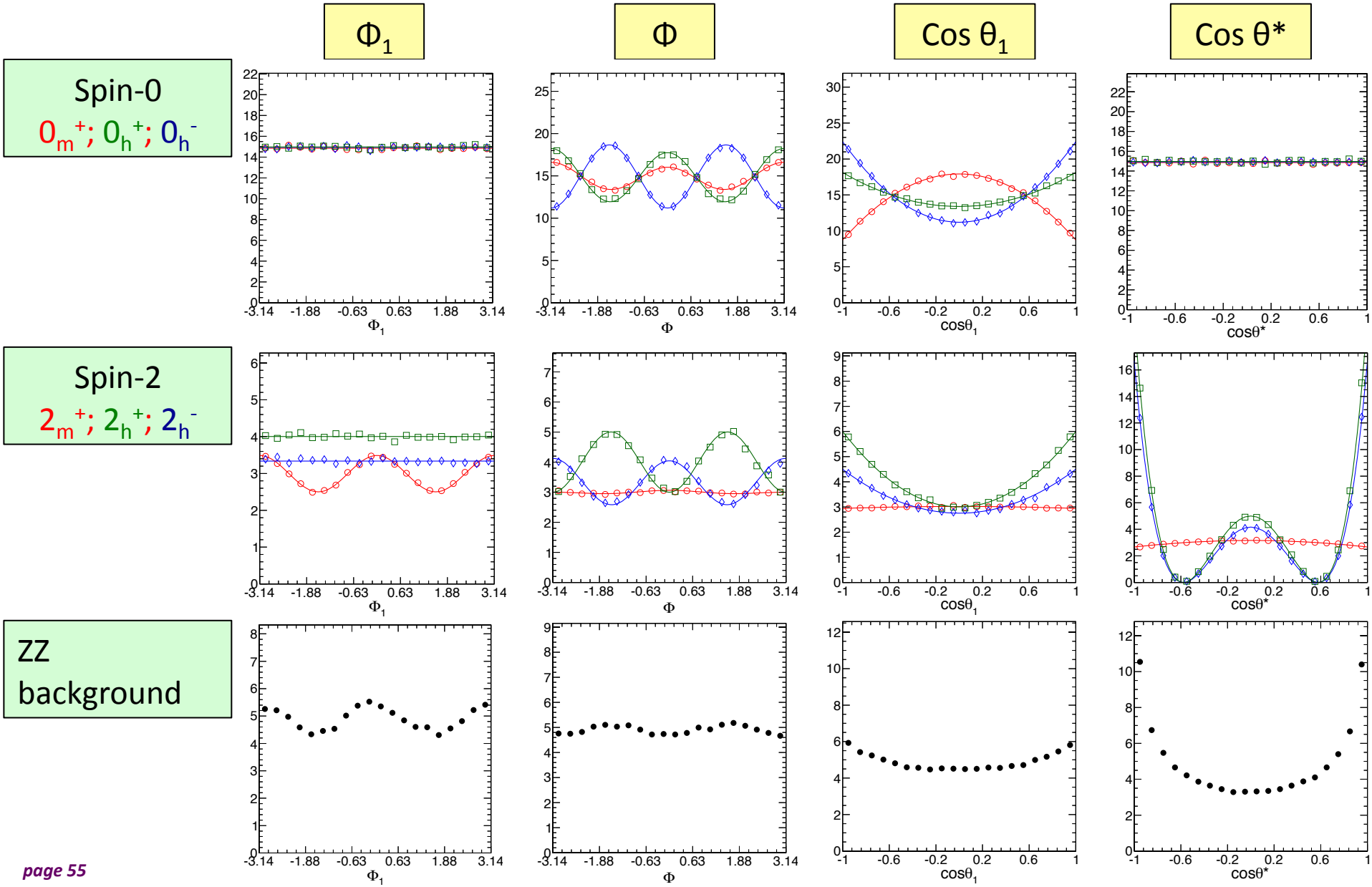
- The interaction of a spin-two particle with a pair of electroweak gauge bosons is described by at least 10 independent tensor couplings.

- 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.

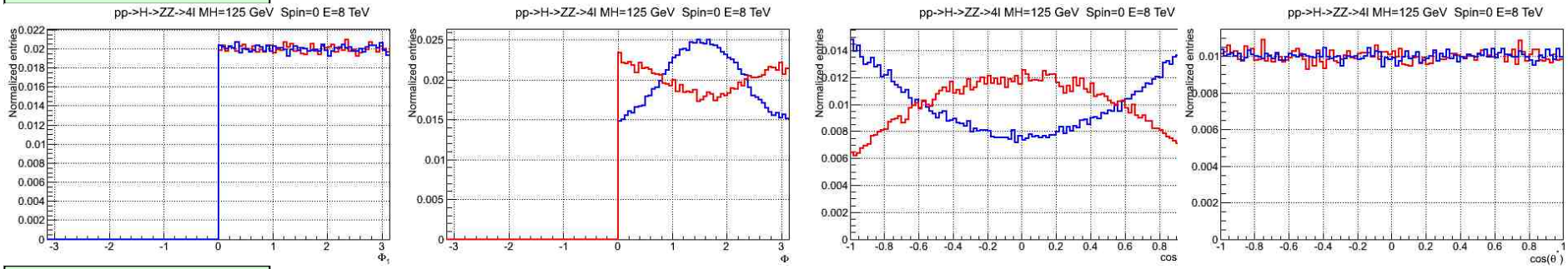


Distributions of the Spin/CP sensitive variables

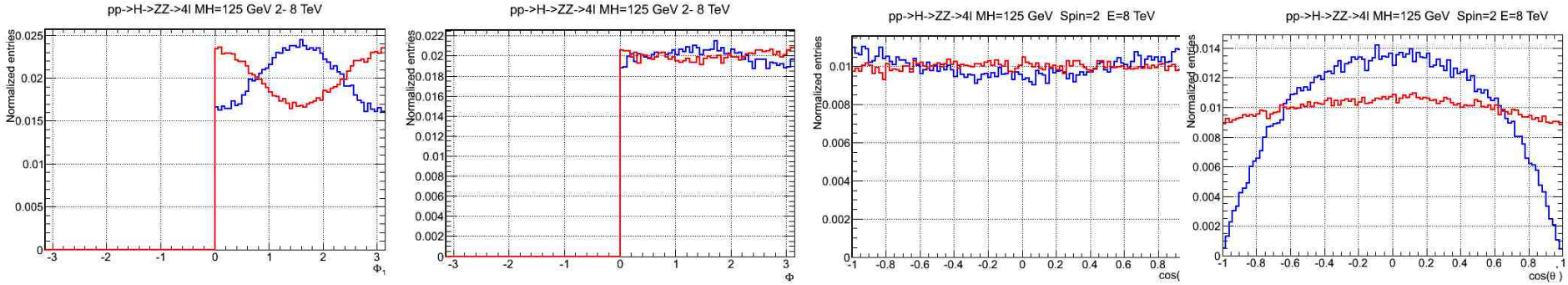
Examples of signal and background distributions at the generator level.

Spin-0: 0^+; 0^-

Φ_1 | Φ | Cos θ_1 | Cos θ^*

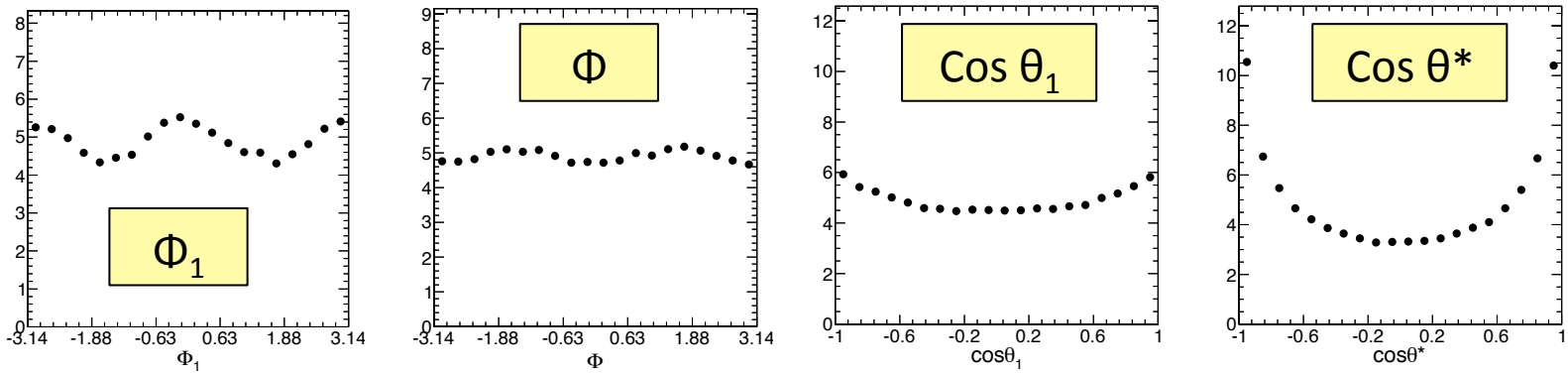


Spin-2: 2_m^+; 2^-



ZZ background

arXiv: 1208.4018v1

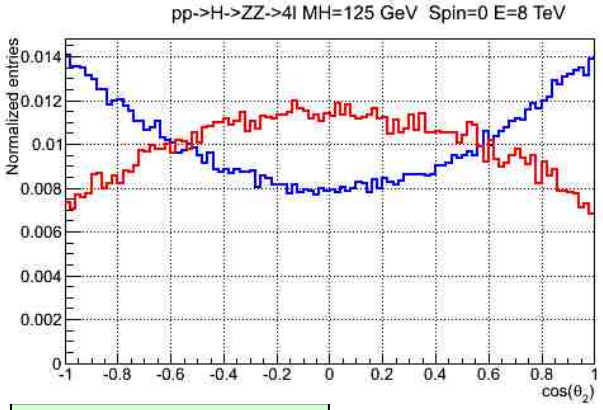


Distributions of the Spin/CP sensitive variables

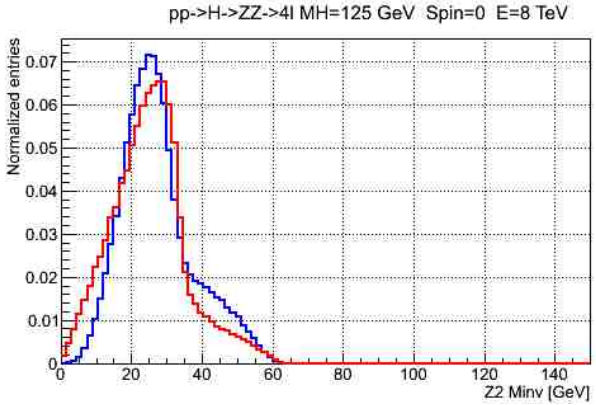
Examples of signal and background distributions at the generator level.

Spin-0: 0^+; 0^-

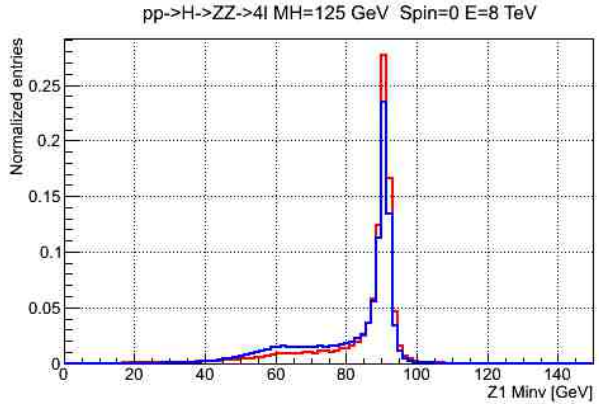
Cos θ_2



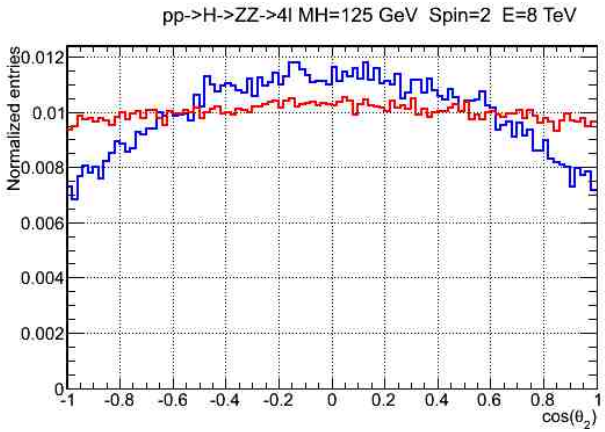
m_{Z2}

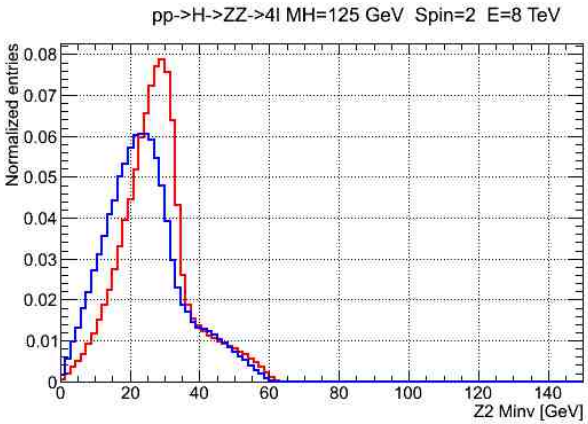


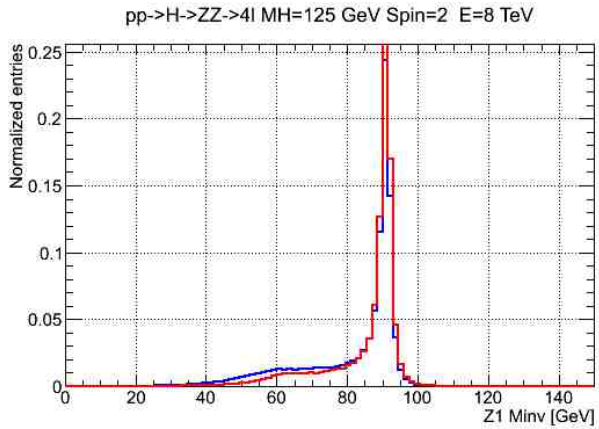
m_{Z1}



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

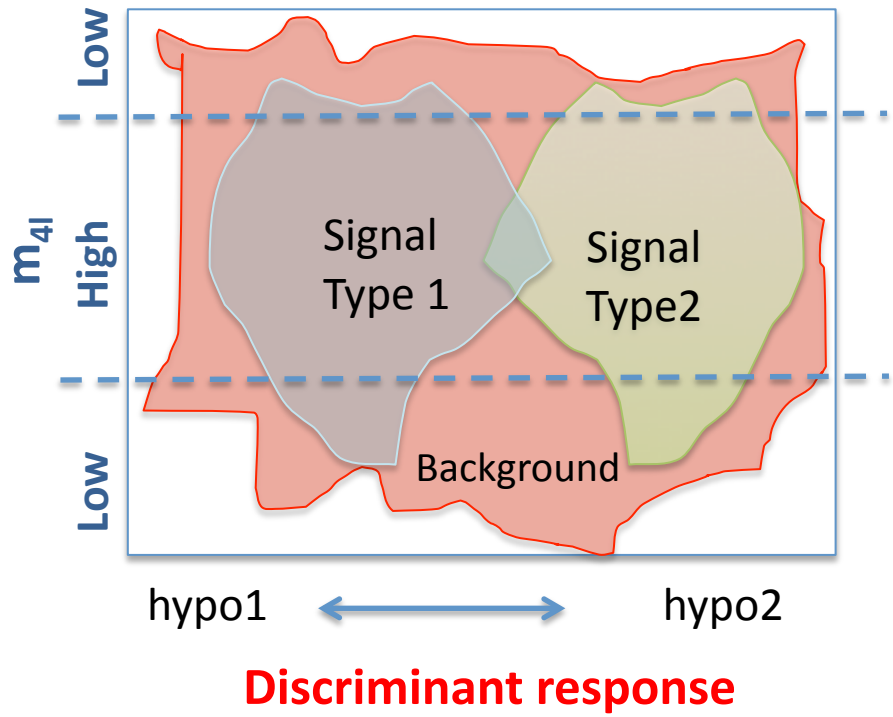






Analysis structure

- 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.

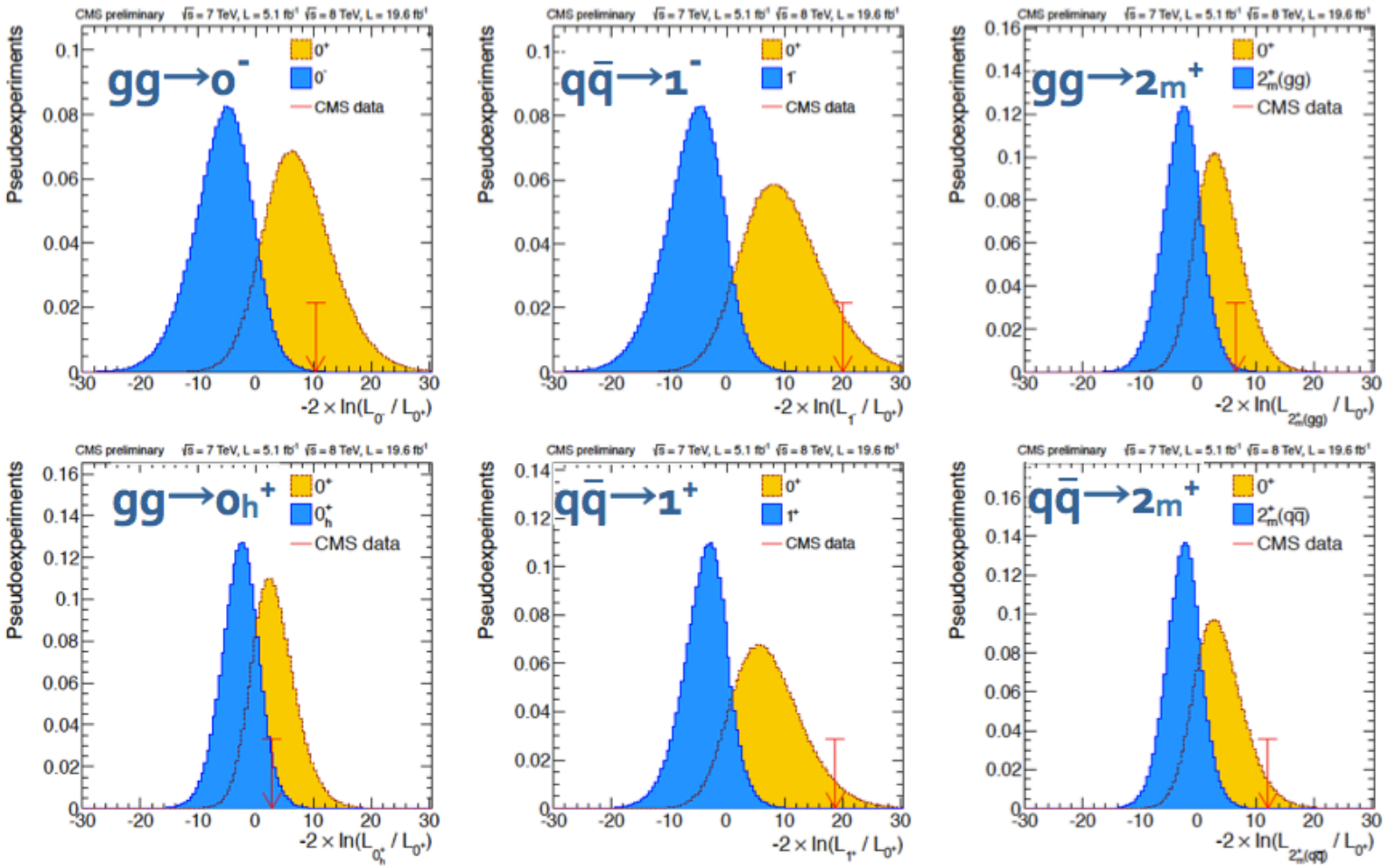
Moriond results (ZZ)

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

Spin-parity: test statistics



NEW

WW spin measurement for Moriond

- The spin analysis leverages the *WW* rate measurement
  - Same object selections, background samples, many shared systematic uncertainties.
  - Analysis uses the 0-jet *e/μ* channel only.

- Candidate events are selected with two opposite-charge, different flavor leptons.

- Topological pre-selections optimized to increase acceptance for a spin-2 particle.

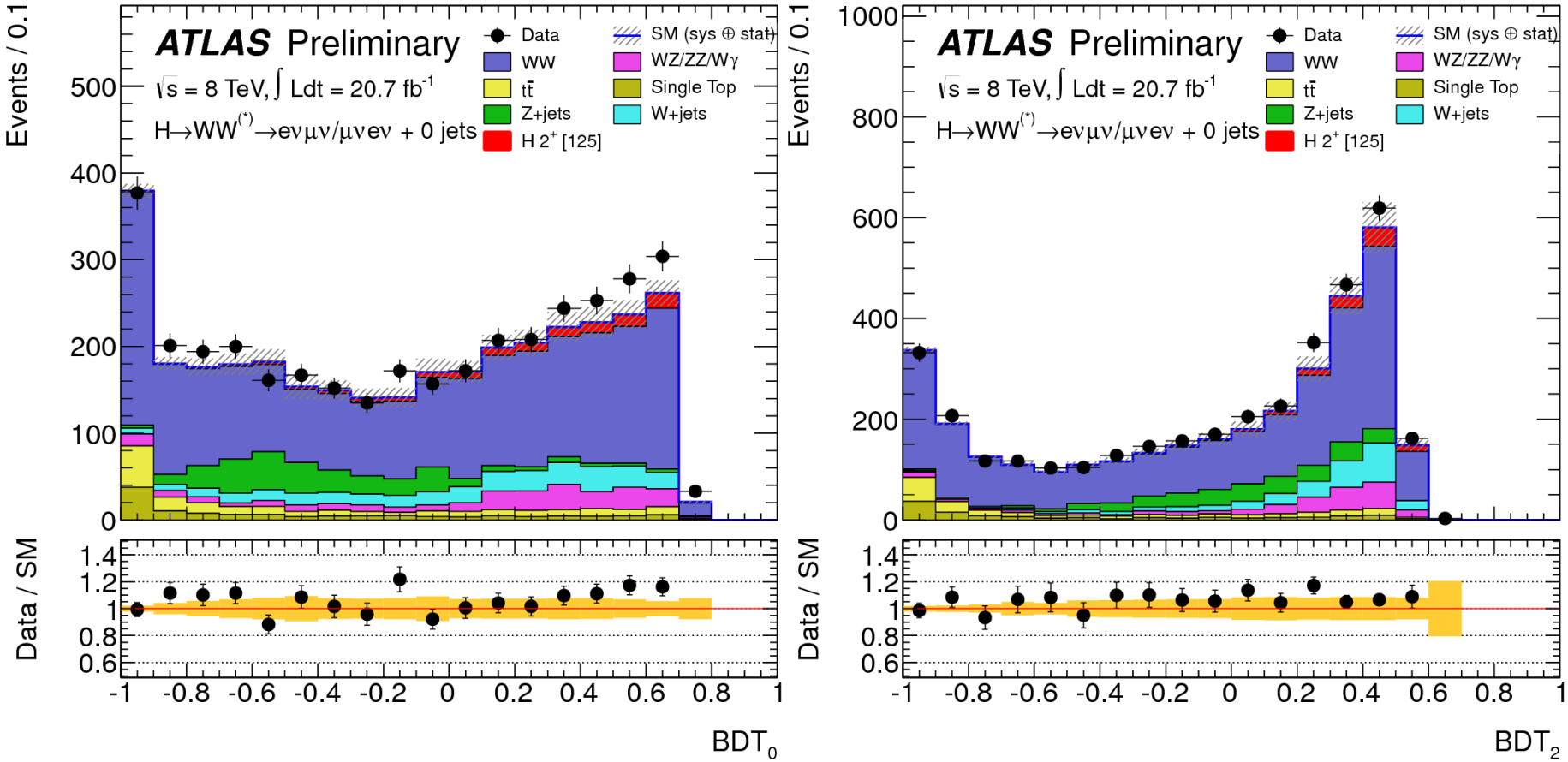
event pre-selection

variable	spin	rate
$E_{\mathrm{T,rel}}^{\mathrm{miss}}$	> 20 GeV	> 25 GeV
$p_{\mathrm{T}}^{\ell\ell}$	> 20 GeV	> 30 GeV
$m_{\ell\ell}$	< 80 GeV	< 50 GeV
$\Delta\phi_{\ell\ell}$	< 2.8	< 1.8

H->WW->$e\nu_e\mu\nu_\mu$ (ATLAS)

Distributions of BDT_0 and BDT_2 for the signal region superimposed with the Standard Model $J^P=2^+_m$ expectation.

Backgrounds: W+jets, Z/γ->ττ, WW, top.



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: $\cos\vartheta_1$, $\cos\vartheta_2$, ϕ, $\cos\vartheta^*$, ϕ_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.

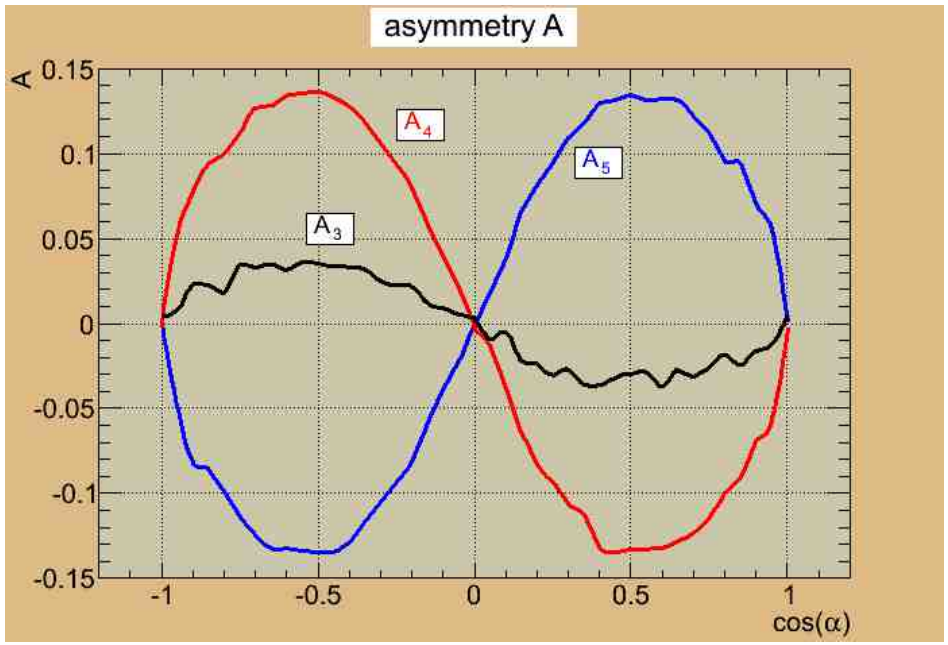
- Calculating the expected exclusion of the CP-mixed hypothesis in favor of the Standard Model 0^+.

H->μμ

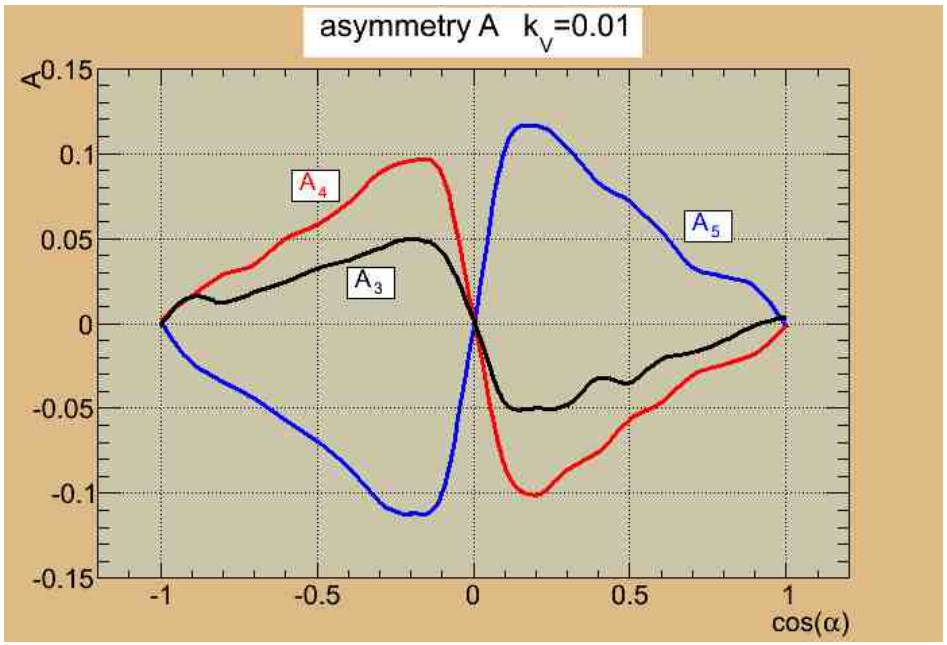
- CP-odd amplitudes are naturally expected to be suppressed in the HVV coupling.
  - The channels containing the HVV coupling in the final state are hence not ideal for the CP-studies.
- Naturally remain the channels where there is no HVV couplings in the final state.
- Studies were done for ttH, H->μμ 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

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



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



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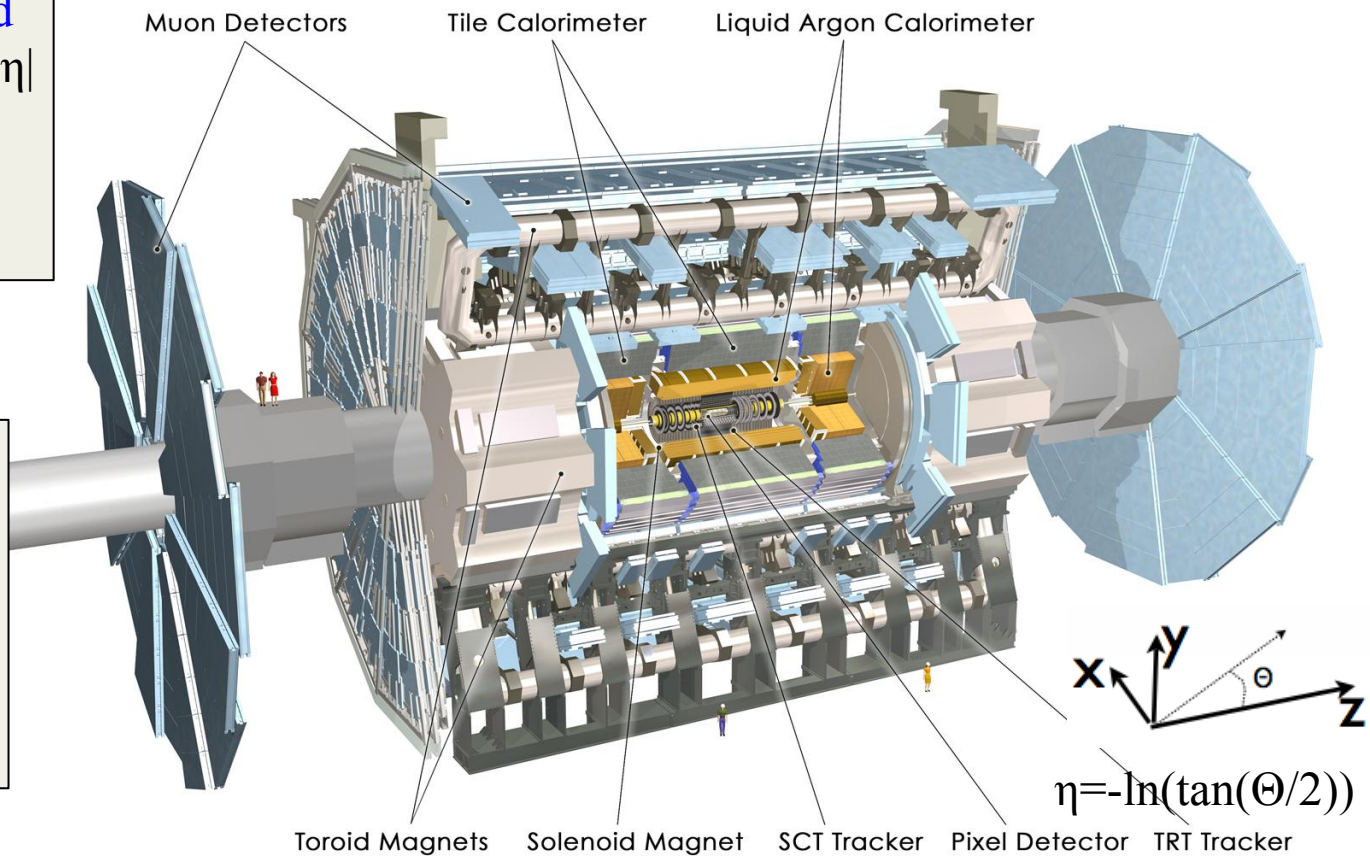

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