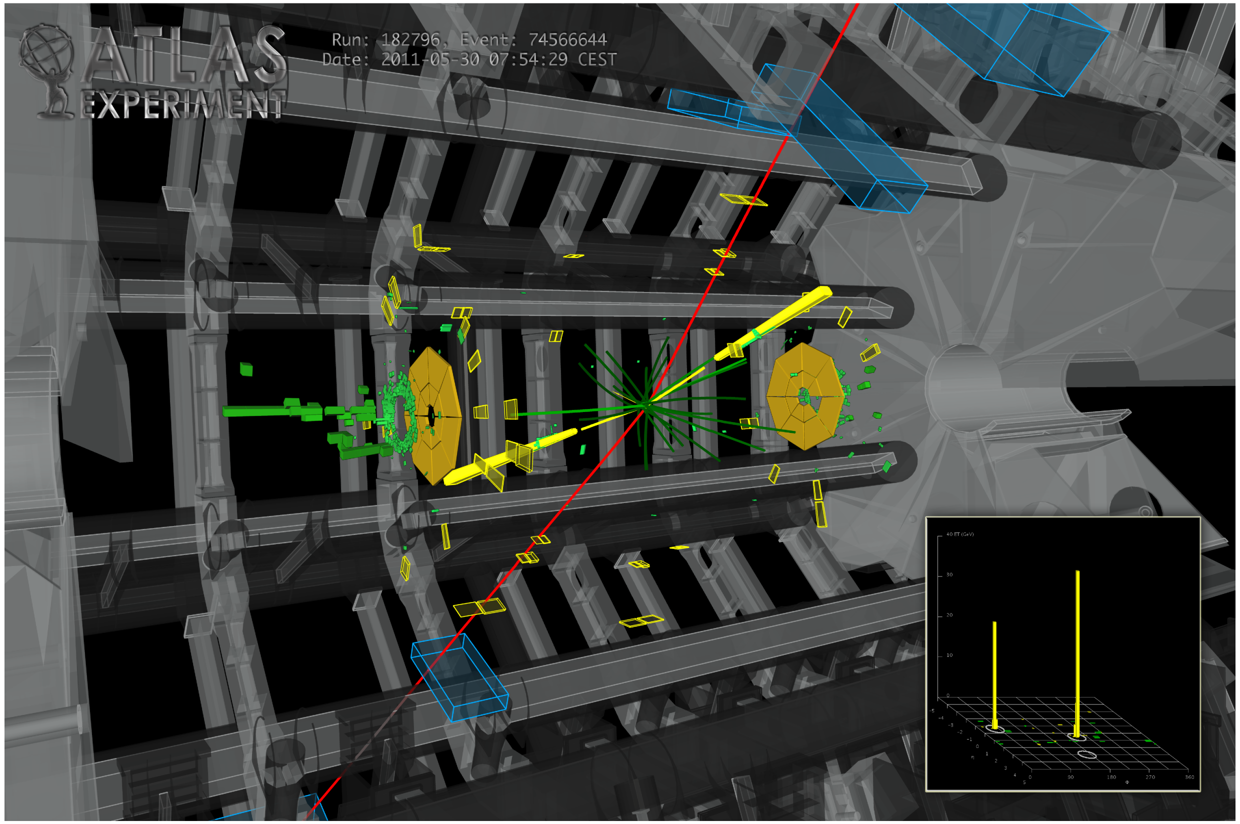
Measurement of the spin and parity of the new boson discovered in ATLAS experiment at the LHC



Kirill Prokofiev

NYU

NEW YORK UNIVERSITY

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

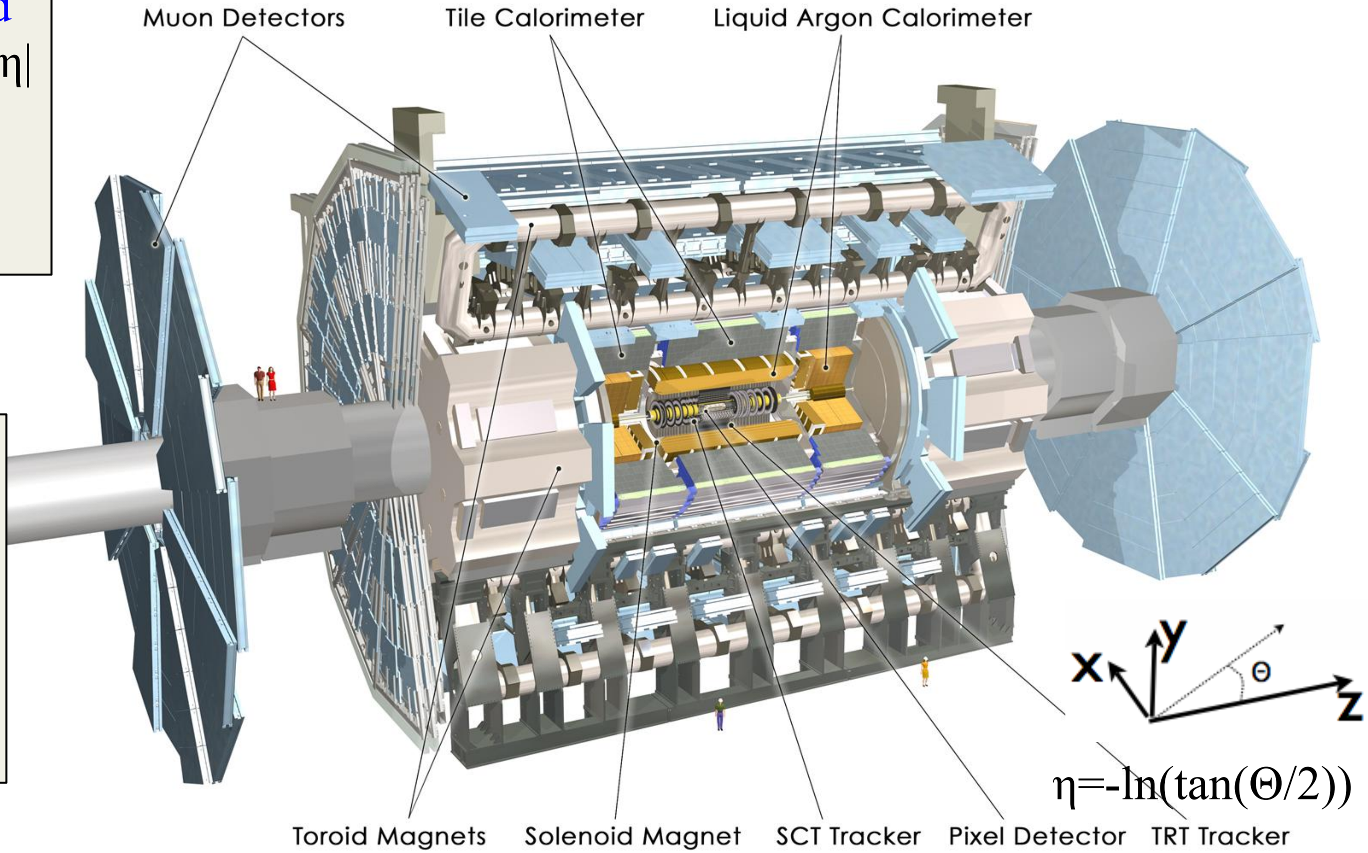
EM Calorimeter: ($|\eta|<4.9$) Pb-LAr accordion structure provides e/γ trigger, identification, measurement **σ/E ~10%√E**

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

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

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

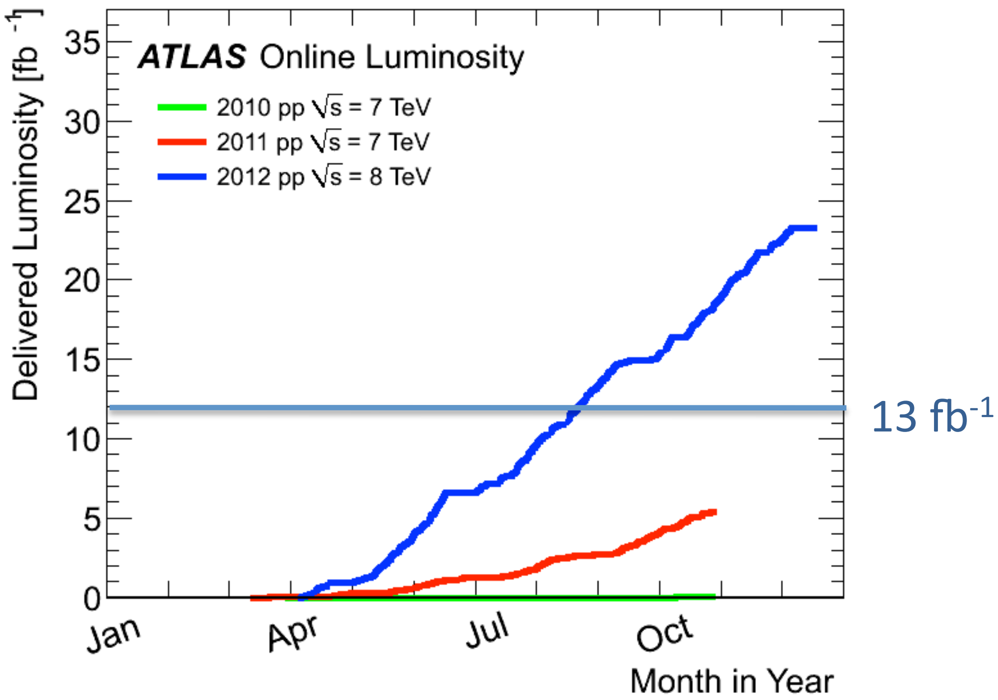
Muon spectrometer: high precision tracking and trigger chambers. $|\eta|$ coverage up to 2.7. Magnetic field produced by 3x8 air-core toroids.



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

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**



ATLAS luminosity detectors calibrated with van der Meer beam separation scans.

- 5 different luminosity detectors.
- In 2011: **d$\mathcal{L}/\mathcal{L}$ ~3.9%.** In 2012: **d$\mathcal{L}/\mathcal{L}$ ~3.6%.**

Only data sets approved for the CERN Council Week 2012 (up to approximately 13 fb^{-1} collected at √s=8 TeV) are shown in this presentation.

arXiv::11012185v1

ATLAS-CONF-2011-116

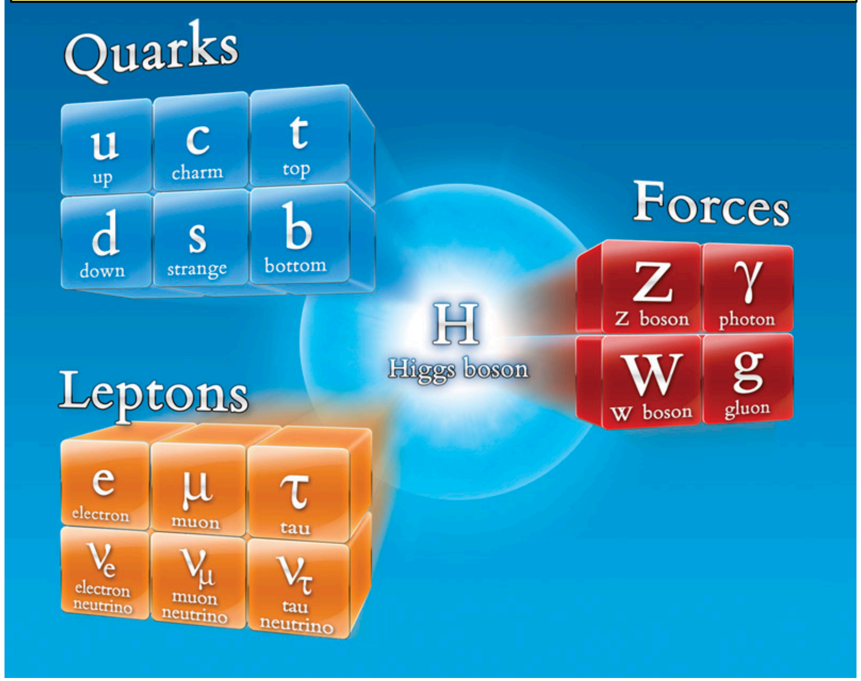
Standard Model Higgs boson

- 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 147< m_H<179 GeV region.

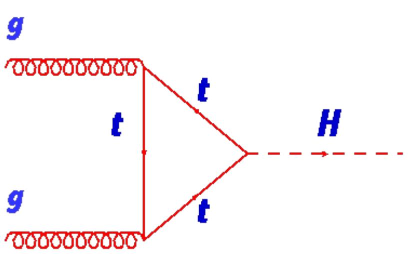
Indirect limits come from the precision measurements of electroweak observables.



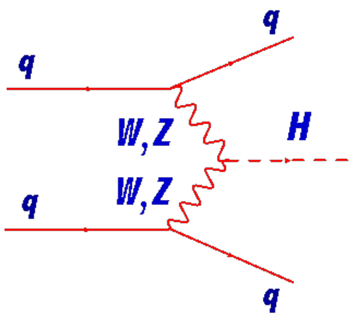
arXiv::1203.3774

Standard Model Higgs searches at LHC

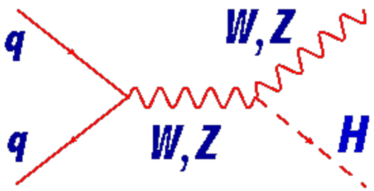
Gluon-gluon fusion

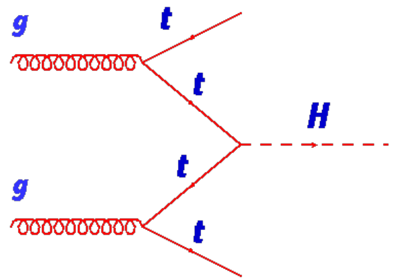


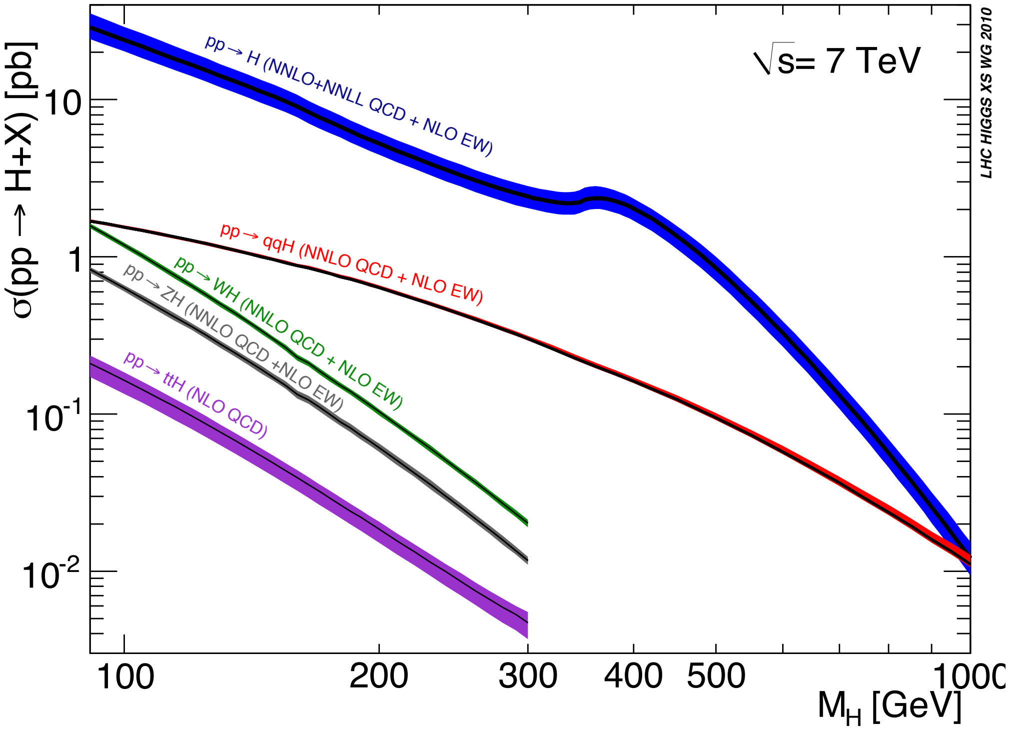
Vector boson fusion

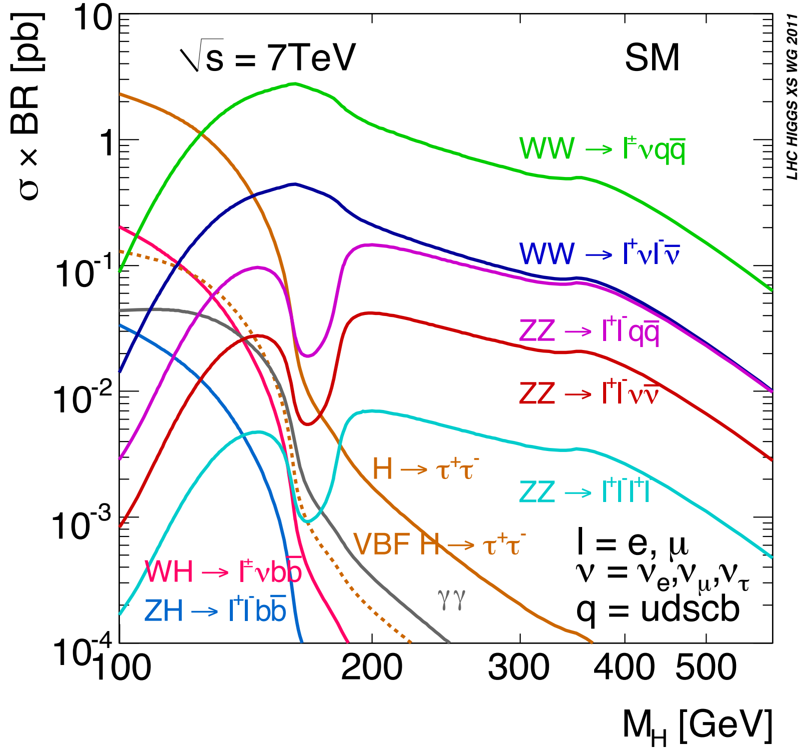


Associated production









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		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.6	[1]
$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, 2-jet VH$\}$	4.8	[5]
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{T,\tau\tau} > 100$ GeV, $VH\}$	4.6	[7]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{T,\tau\tau} > 100$ GeV, 2-jet$\}$	4.6	
	$\tau_{had}\tau_{had}$	$\{$1-jet, 2-jet$\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	4.6	[8]
	$W \to \ell\nu$	$p_T^W \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
	$Z \to \ell\ell$	$p_T^Z \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	13	[6]
$H \to \gamma\gamma$	–	12 categories $\{p_{Tt} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, 2-jet VH$\}$	13	[5]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{$0-jet, 1-jet$\}$	13	[9]
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{T,\tau\tau} > 100$ GeV, $VH\}$	13	[7]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{T,\tau\tau} > 100$ GeV, 2-jet$\}$	13	
	$\tau_{had}\tau_{had}$	$\{$1-jet, 2-jet$\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	13	[8]
	$W \to \ell\nu$	$p_T^W \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	
	$Z \to \ell\ell$	$p_T^Z \in \{<50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	

- Individual channels where the searches were performed for the latest ATLAS combined result . The final result is the combination of all considered modes.
- Search performed in the range m_H = 110 – 600 GeV.

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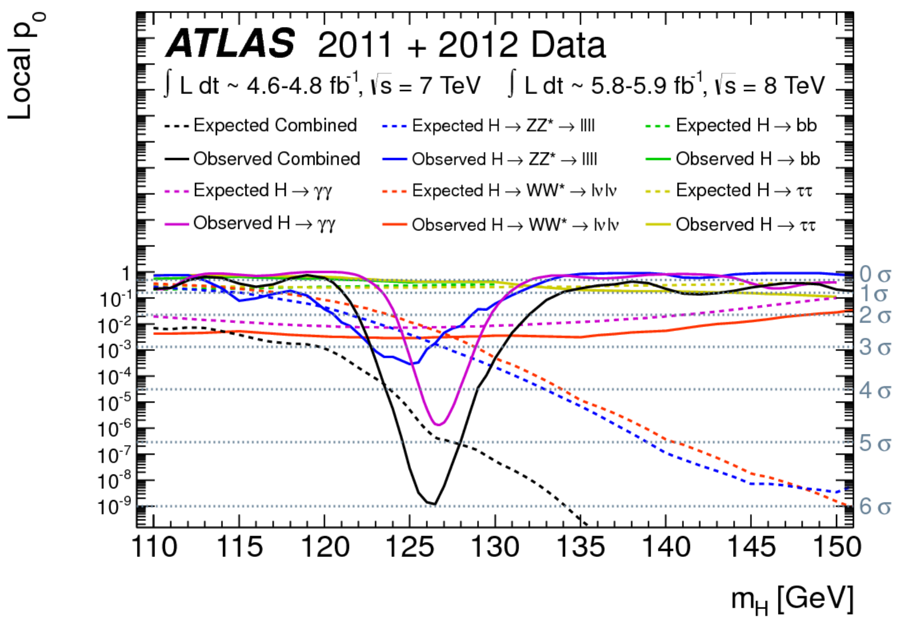
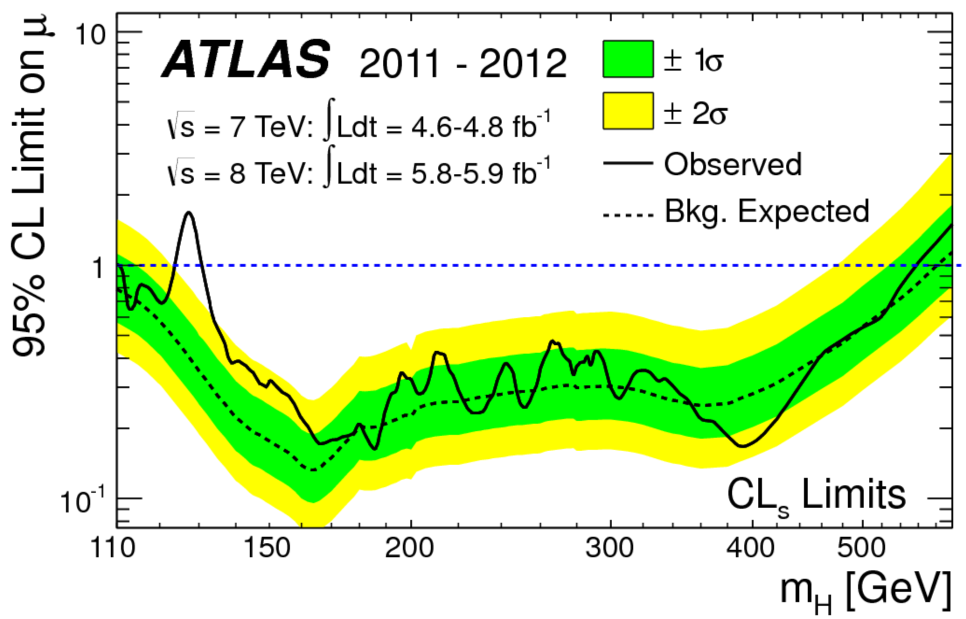
Discovery of the new resonance

- 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 $H \rightarrow \tau^+\tau^-$.

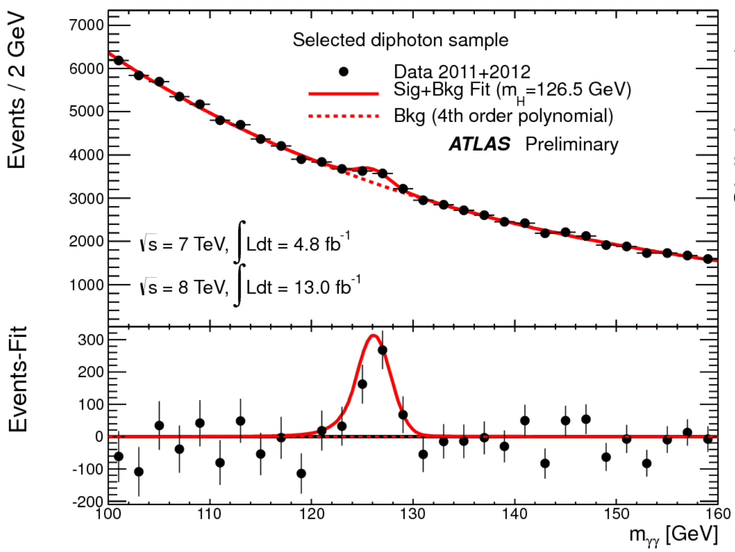
- Excess with local (global) significance of 5.9σ (5.1σ) driven by the $ZZ^{(*)}$, $\gamma\gamma$ and $WW^{(*)}$ decays. M_H = 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV.

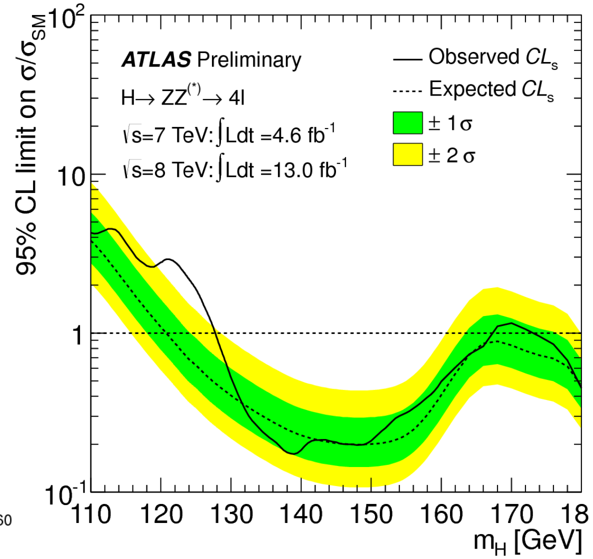


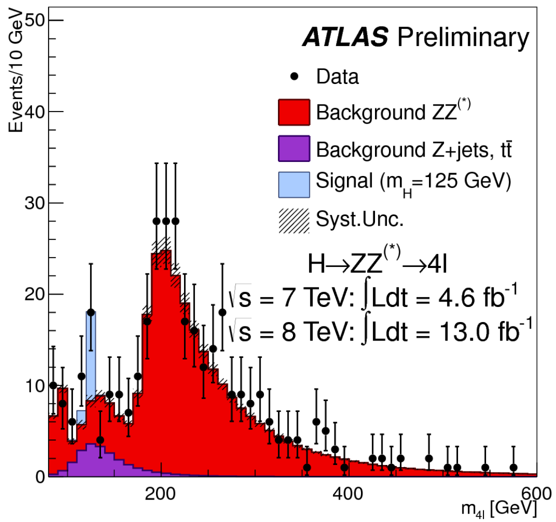


Current status of the new resonance

- In November- December 2012, the discovery results were updated with higher luminosity.
- Up to 13 fb^{-1} in ZZ, γγ, and WW decay channels.
- The resonance remains.
- Individual local significance of excess reached 4.1, 6.1 and 2.8 standard deviations respectively.

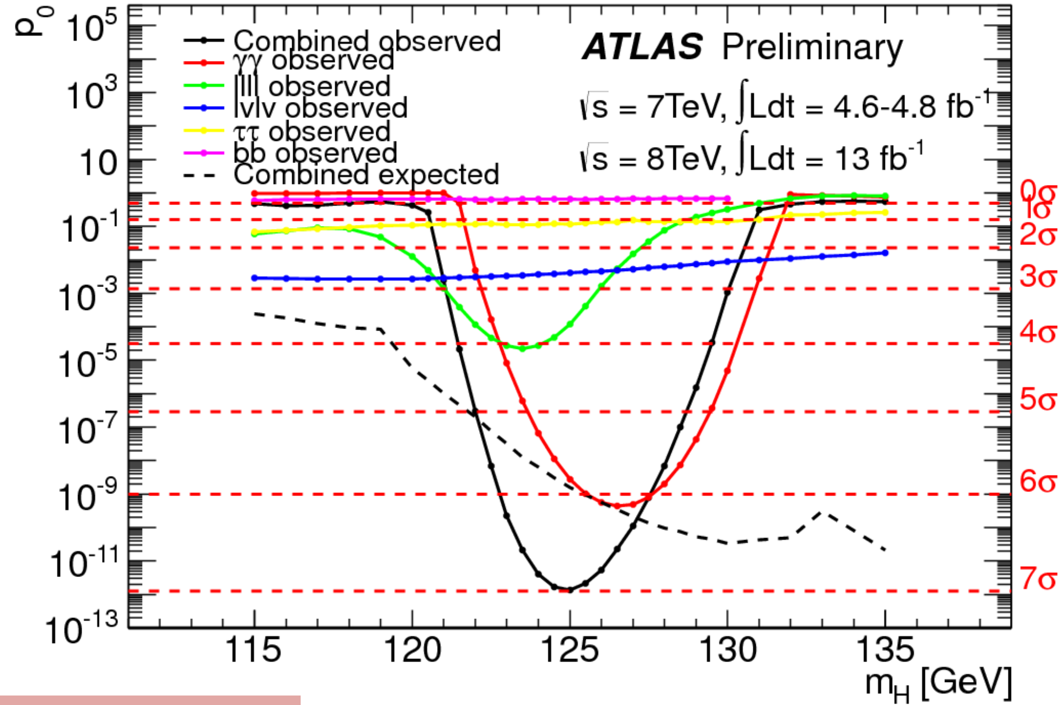


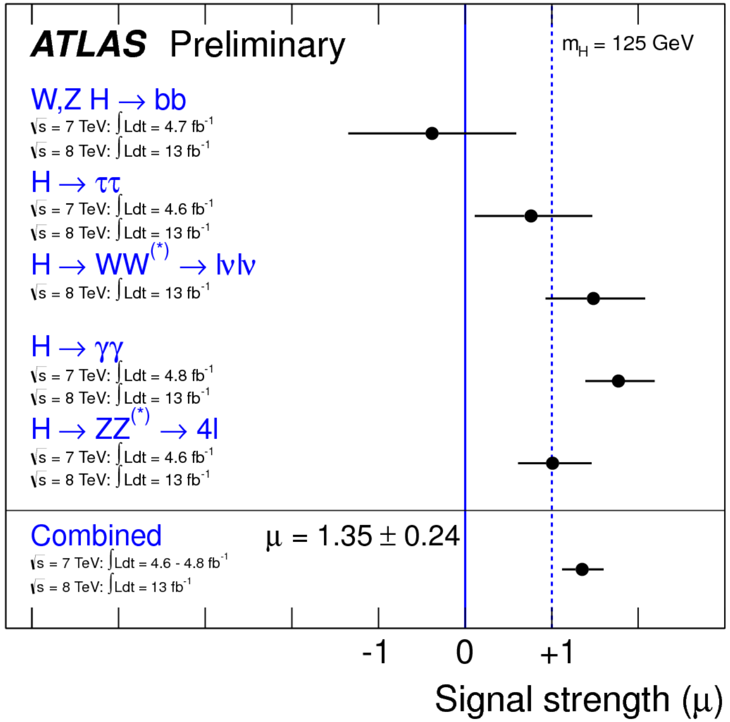




Current status of the new resonance

- Combined local significance including all the channels reaches 7 standard deviations.
- Main contributors: WW, ZZ, γγ
- Combined signal strength μ=1.35±0.24. Consistent with the Standard Model expectation.





ATLAS-CONF-2012-170

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)

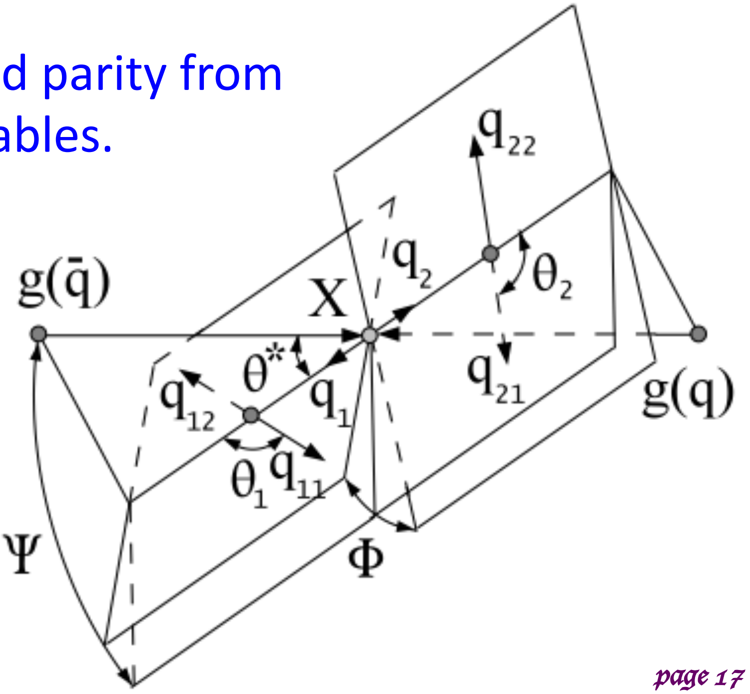
Direct Spin and Parity measurements

- A new Higgs-like resonance produced in pp collisions by both ATLAS and CMS.

- Possible production mechanisms which can be responsible for the observation in WW, ZZ and γγ:
  - gluon-gluon fusion (spin-0,2)
  - and/or qqbar production (spin-1,2).

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

- Observables (ZZ):
  - Angular distributions of decay products in the resonance rest frame.
  - Invariant masses of the gauge bosons.



arXiv:1001.3396

arXiv:1208.4018

Present spin studies in ATLAS

- 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 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.

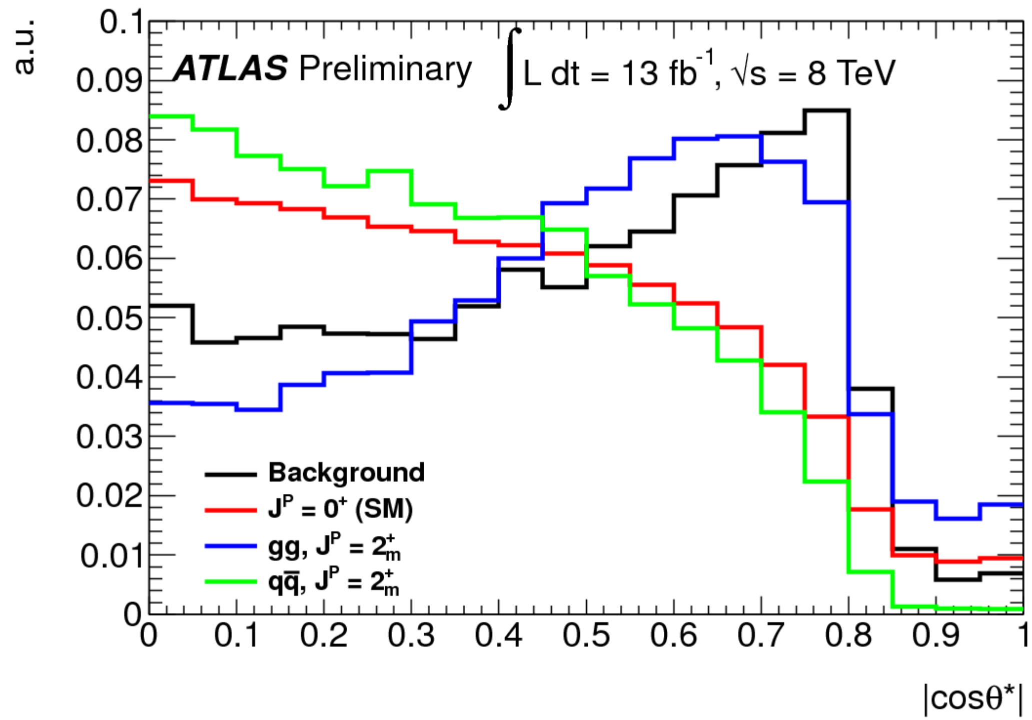
- Spin and parity hypotheses considered: 0^+, 0^-, graviton-like tensor with minimal couplings 2_m^+, pseudo-tensor 2^-.
  - 2_m^+ and 2^- production. gg->X: g_1=1; qq->X: ρ_{12}=1.
  - 2_m^+ decay $g_1=g_5=1$.
  - 2^- decay: $g_8=g_9=1$.

- 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.
  - For the 2012 studies, ATLAS used the JHU generator.

Two photon decay channel

13 fb^{-1} at 8 TeV

- Study based on the single discriminating variable: production angle: |cos θ*|.
- Considered models: 0^+ and 2^+_m
- Both qqbar and ggF production mechanisms are considered for the 2^+_m state.
- Various mixtures of two production mechanisms
- No categorization: 123.8 GeV<$m_{\gamma\gamma}$<128.6 GeV



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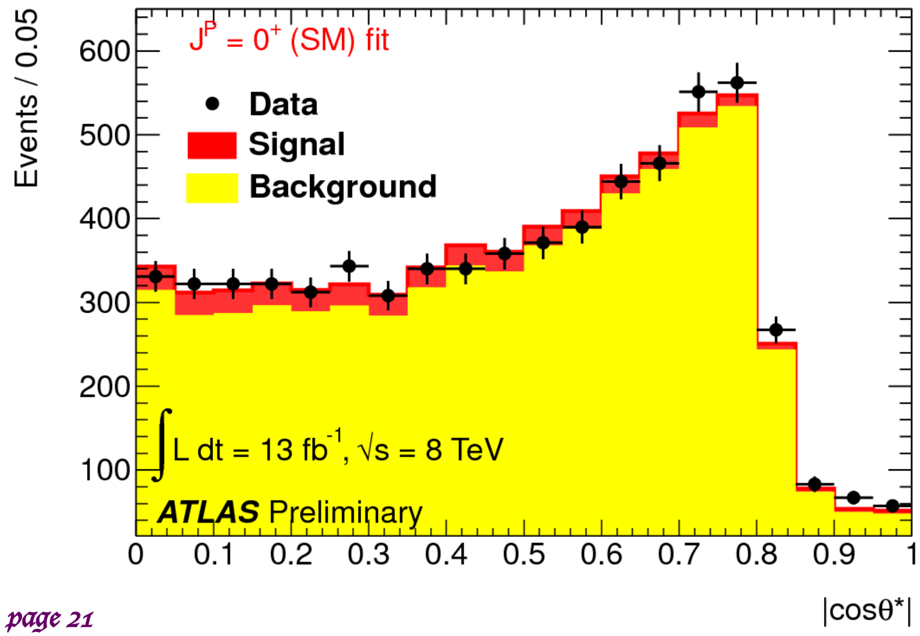
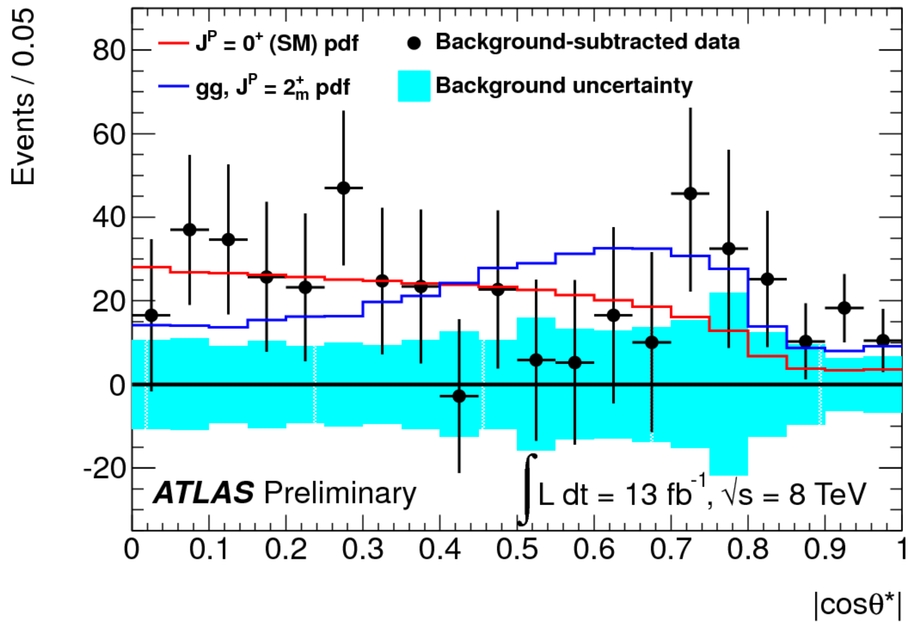
Two photon decay channel

13 fb^{-1} at 8 TeV

- 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.





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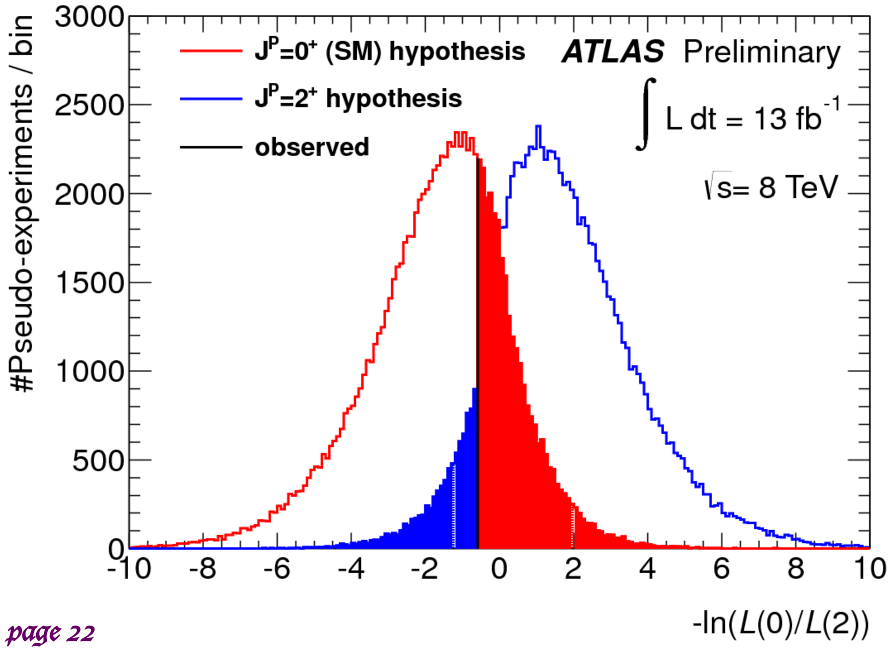
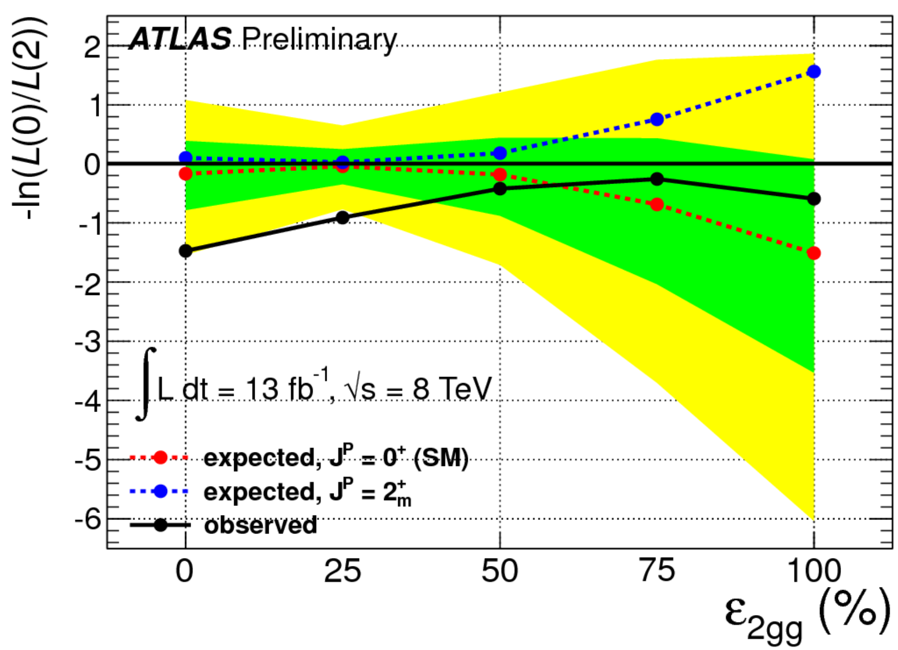
Two photon decay channel

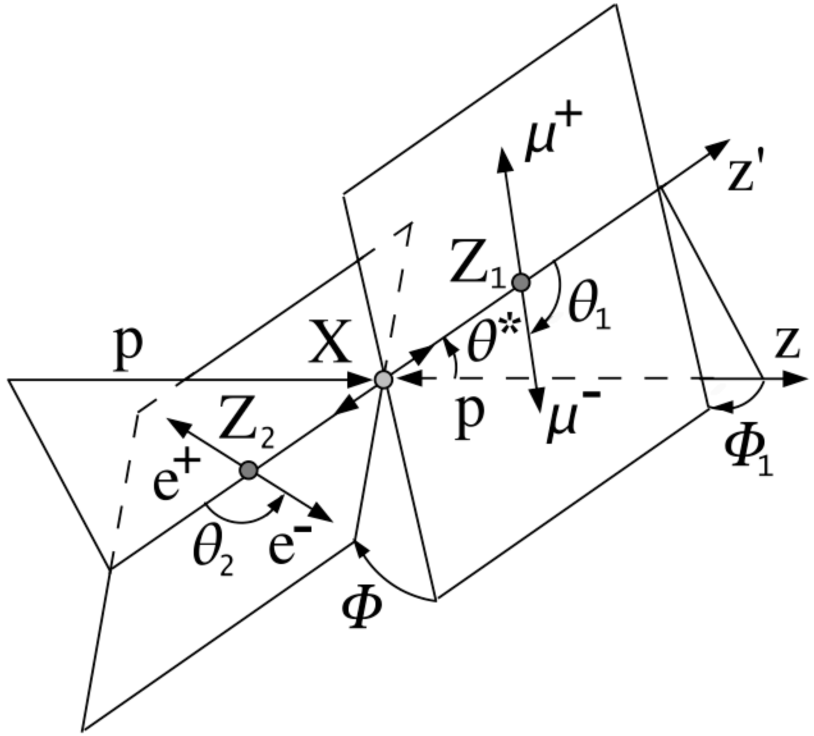
- Expected p_0-value for 2^+_m (100% ggF) : 3.4% (1.8σ)
- Observed p_0-value for 0^+ hypothesis: 29% (0.55 σ)
- Observed p_0-value for 2^+_m (100% ggF) hypothesis: 8.4% (1.4 σ)
- qqbar scan: no discrimination power for 75% qq and higher fractions in two-photon channel.





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-, 2_m+ (graviton –like tensor with min. couplings), 2-.

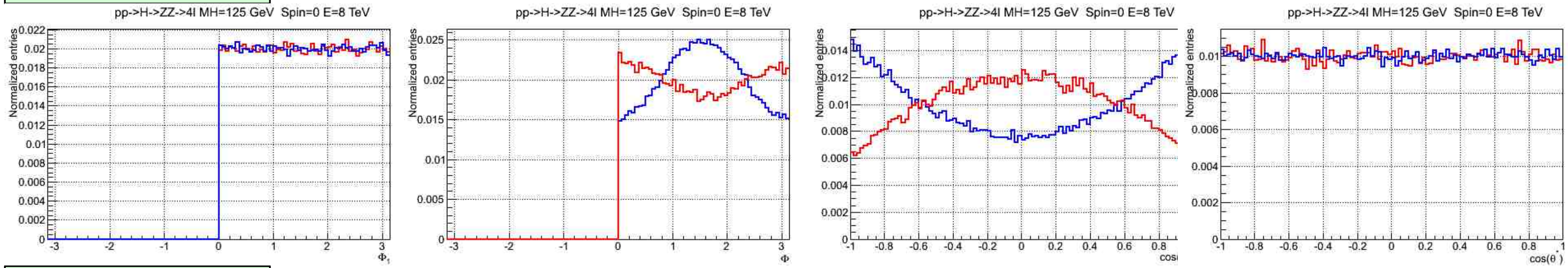
4.6 fb^{-1} at 7 TeV and 13 fb^{-1} at 8 TeV

Distributions of the Spin/CP sensitive variables

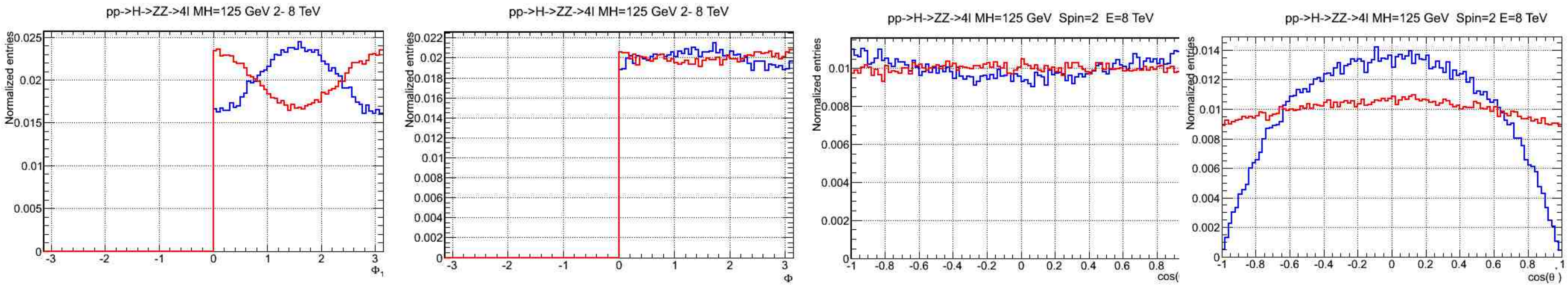
Examples of signal and background distributions at the generator level.

Spin-0: 0^{+}; 0^{-}

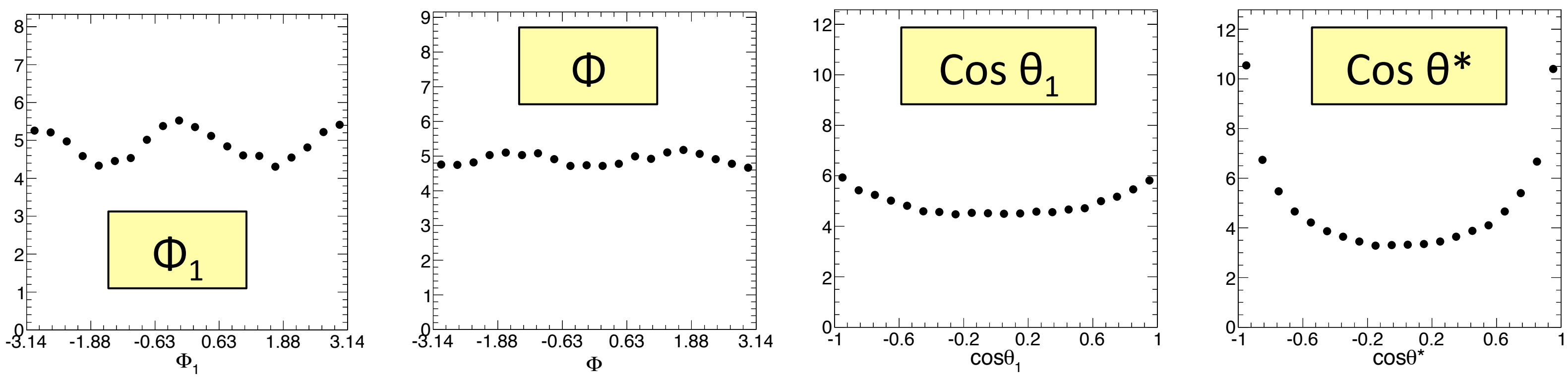
Φ_1 | Φ | Cos θ_1 | Cos θ^*



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



ZZ background



arXiv: 1208.4018v1

Distributions of the Spin/CP sensitive variables

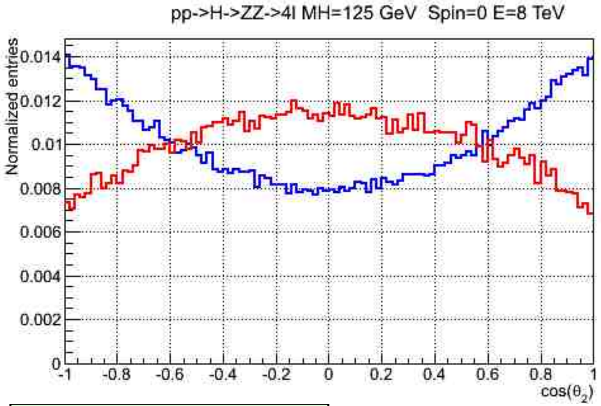
Examples of signal and background distributions at the generator level.

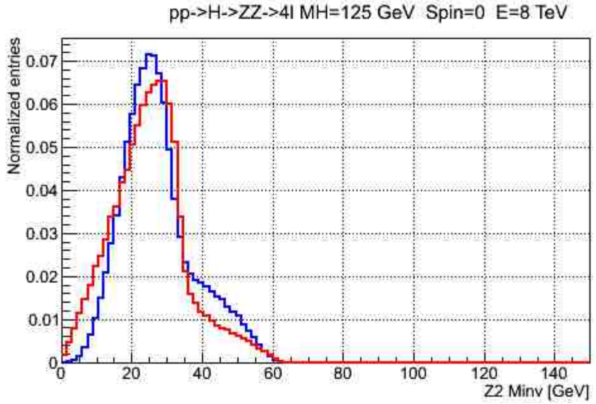
Spin-0: 0^+; 0^-

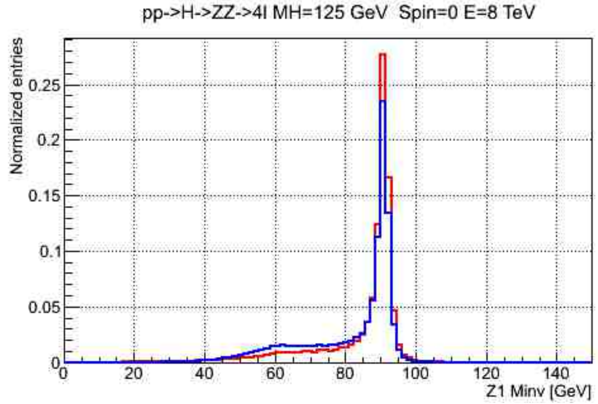
Cos θ_2

m_{Z2}

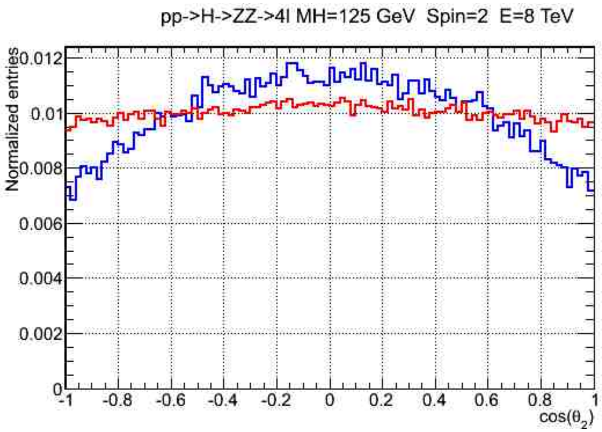
m_{Z1}

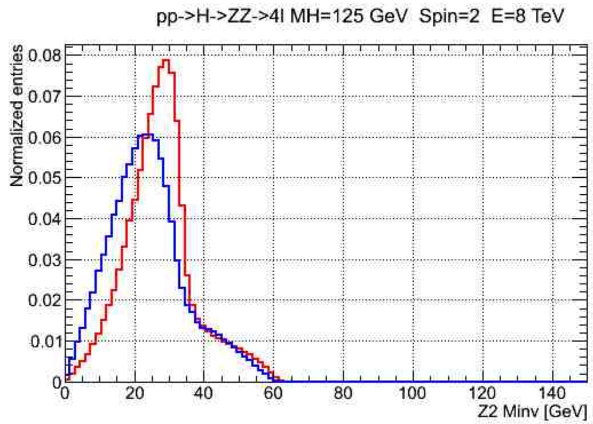


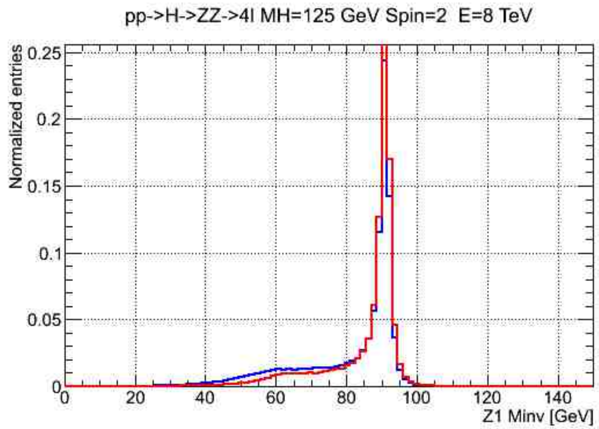




Spin-2: 2_m^+; 2^-



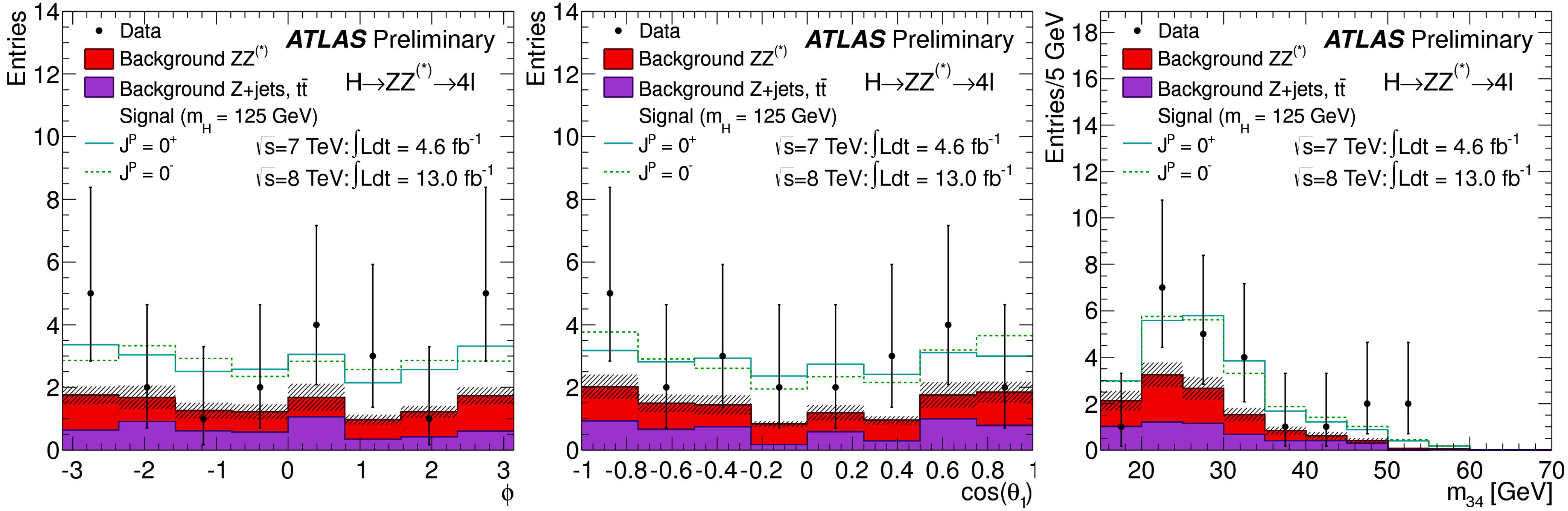




Four lepton decay channel

- Standard 4l cut-based selection (same as used for the discovery analysis).
  - Spin/Parity – dependent quantities are reconstructed.
  - Signal region: 115 GeV – 130 GeV.

- Spin and parity sensitive variables after all selection cuts compared to the signal and background Monte Carlo models.



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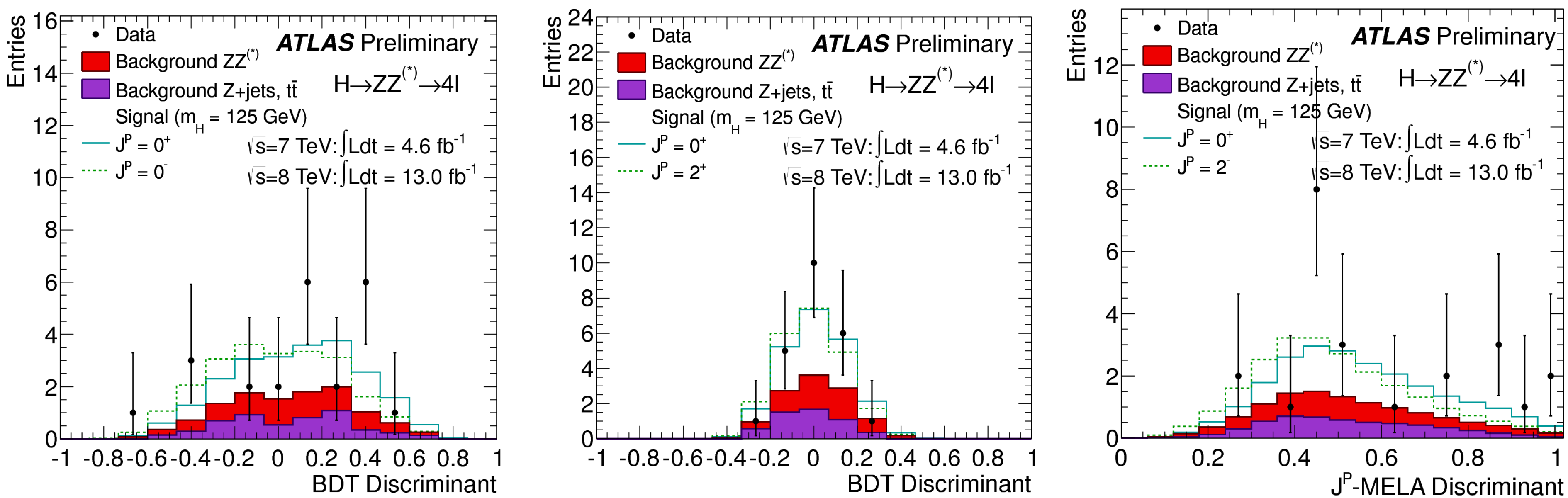
Four lepton decay channel

Two complimentary methods allow for mutual cross-checks and extend each others results.

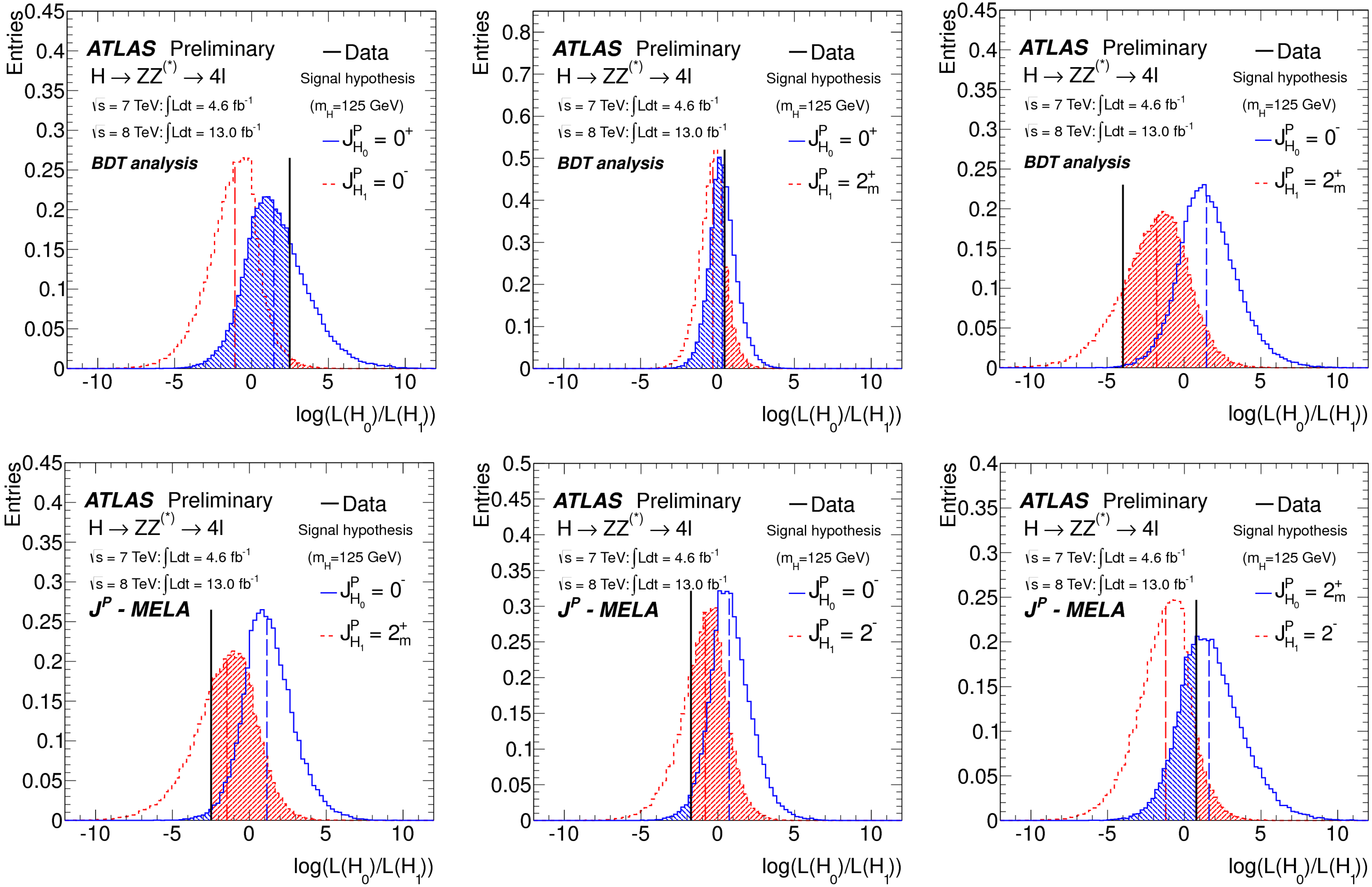
- BDT analysis: discriminants trained to separate pairs of different Spin/CP states. Training on signal MC only.
- Full Simulation MC events after full reconstruction and selection are used for training.
- Background: from full sim (ZZ) and from control regions (others).

- Pseudo-MELA: Discriminant based on the full Matrix Element theory calculation for each Spin/CP hypothesis.
- Signal description: analytical calculation.
- Background: from full sim (ZZ) and from control regions (others).



Four lepton decay channel

- Test statistic: ratio of profiled likelihoods.



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Four lepton decay channel

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)	

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.

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 HZZ coupling.

- The magnitude of the CP-mixing in the Higgs sector may vary significantly from model to model.
  - Usually, the expected contributions from Beyond the Standard Model couplings is small.

- Measurement of possible CP-violation in the Higgs sector or anomalous contribution to the HZZ coupling will require large datasets.
  - Question: observing the dominant 0^+ state, can we tell if it has a CP-odd admixture?

arXiv:0708.0458v2

CP-violation in ZZ coupling

- The ways to estimate possible mixing contribution vary from paper to paper.
  - Observables for the Higgs mass lower than two Z masses: 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 HVV vertex.

CP-violation in ZZ coupling

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

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

a_1 and a_2 are associated with coupling of CP-even Higgs to a pair of vector bosons; a_3 is associated with that of a CP-odd Higgs boson.

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.

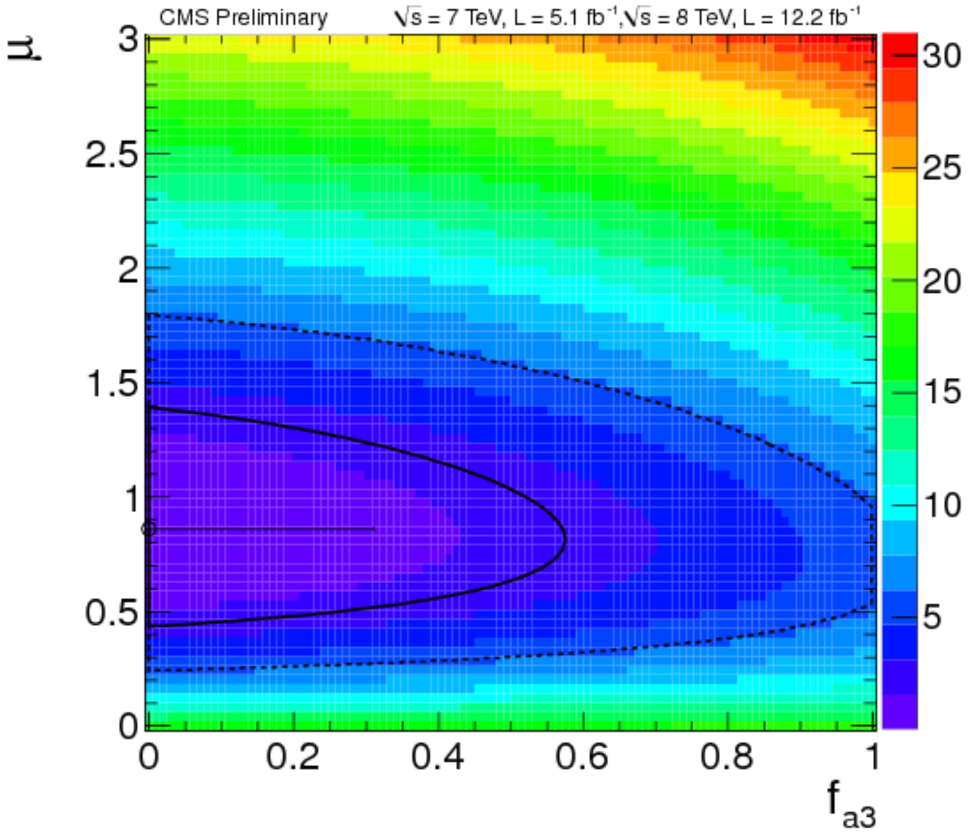
This vertex is in principle valid at all orders of perturbation theory. Contributions from loop corrections will only alter the a_i.

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 (Standard Model) and vary a_3 (The CP-odd coupling constant).

The form factor a_2 is set to 0 to simplify the analysis.

- Generator level Monte Carlo study.
- Monte Carlo: JHU at 14 TeV for the signal and MadGraph for the ZZ background. Pythia showering (AU2 CTEQ6L1).
- Smearing functions to simulate detector resolution effects.
- Trigger and lepton reconstruction efficiencies are accounted for by assigning event weights.

CP-violation in Higgs sector

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

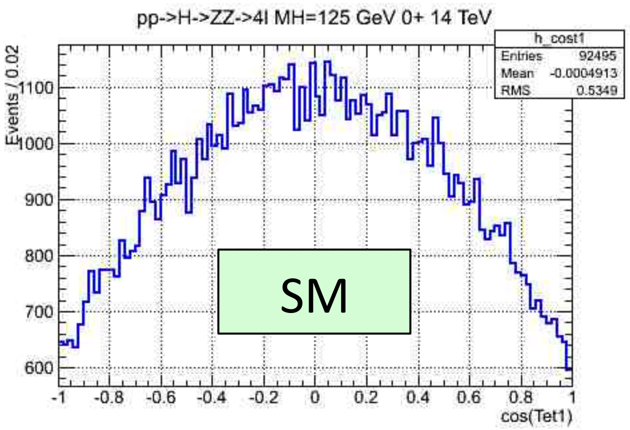
- Analysis: Applying two independent BDT discriminants to separate spin and parity states and to reject the ZZ background.
  - First BDT is trained to separate spin-CP states using angular and mass variables: $\cos\vartheta_1$, $\cos\vartheta_2$, ϕ, $\cos\vartheta^*$, ϕ_1, m_{Z1}, m_{Z2}.
  - Second 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.

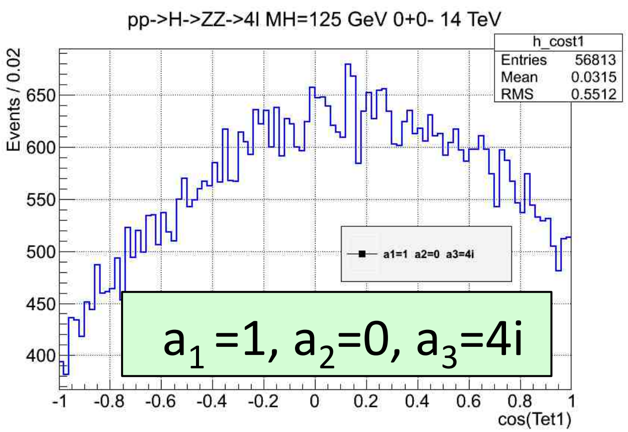
- Calculating the expected exclusion of the CP-mixed hypothesis in favor of the Standard Model 0^+.

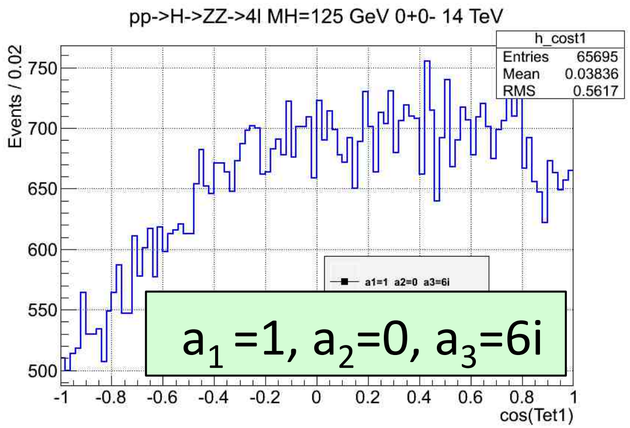
CP-violation in Higgs sector

- 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.







CP-violation in Higgs sector

Expected separation in number of Gaussian σ between the pure 0^+ hypothesis and the mixed hypothesis as a function of a_3.

Signal region: 100 GeV to 150 GeV.

The ZZ background is scaled to the total background expectation.

	Exclusion $a_3 = 6+6i$ wrt 0+	**Exclusion $a_3 = 6i$ wrt 0+**	**Exclusion $a_3 = 4+4i$ wrt 0+**
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

The LHC is approved until 300 fb^{-1}.

Form factors much smaller than presented can be excluded with luminosities higher than planned for the LHC.

Very large CP-violating amplitudes can be excluded with more than 3σ at 100 fb^{-1}. This study is done for the same S/B ratio as we expect now. If the observed signal yield is higher, we can put the limit further.

Summary

- First spin and parity results start appearing in LHC experiments.
  - No decisive conclusion yet, but data start looking more like 0^+.
  - I have only presented ATLAS results, but the CMS results look very much alike.

- 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 both in combinations of channels and in each channel alone.
  - The ATLAS-CMS combination will be possible.
  - 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 a Standard Model Higgs then?

Summary

- CP-violation and tensor structure of the HVV 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 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}).

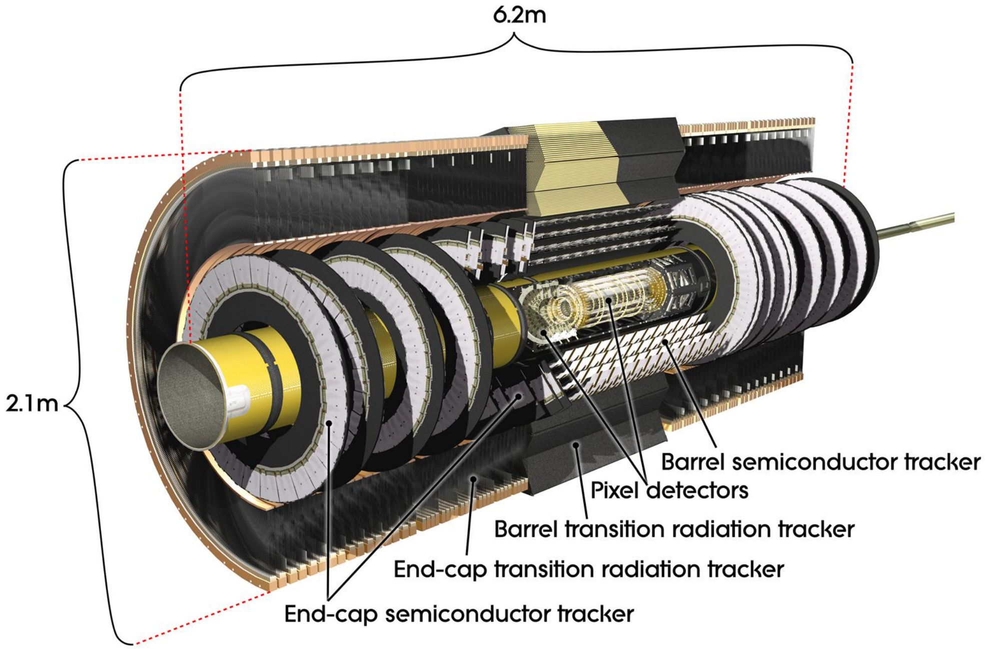
- Further studies (after the re-start of the LHC)
  - Establish the dominant spin and parity in the individual channels (ZZ).
  - Searches for the CP-violation and study of the tensor structure of the HZZ vertex.
  - Likelihood fit to matrix element.
  - Study of asymmetries directly sensitive to different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

Further Higgs studies (LHC and beyond)

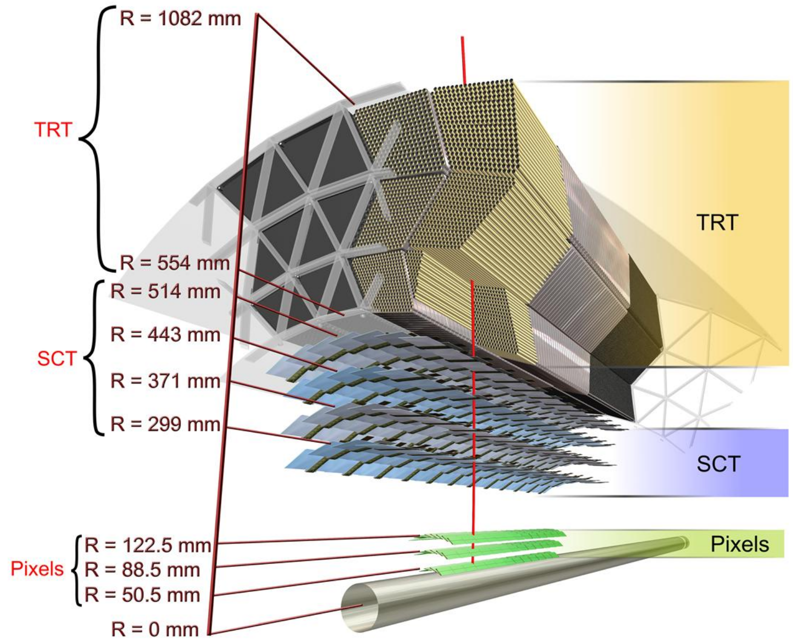
- Important studies which were not discussed in this talk.
- Study of the spin and parity in channels with VBF, VH, ttH production mechanisms.
- Searches for the CP-violation in ttH H->μμ decay.
- Measurements of the Higgs self-couplings.
- Direct searches for additional (heavy) Higgs bosons.

Backup

ATLAS 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

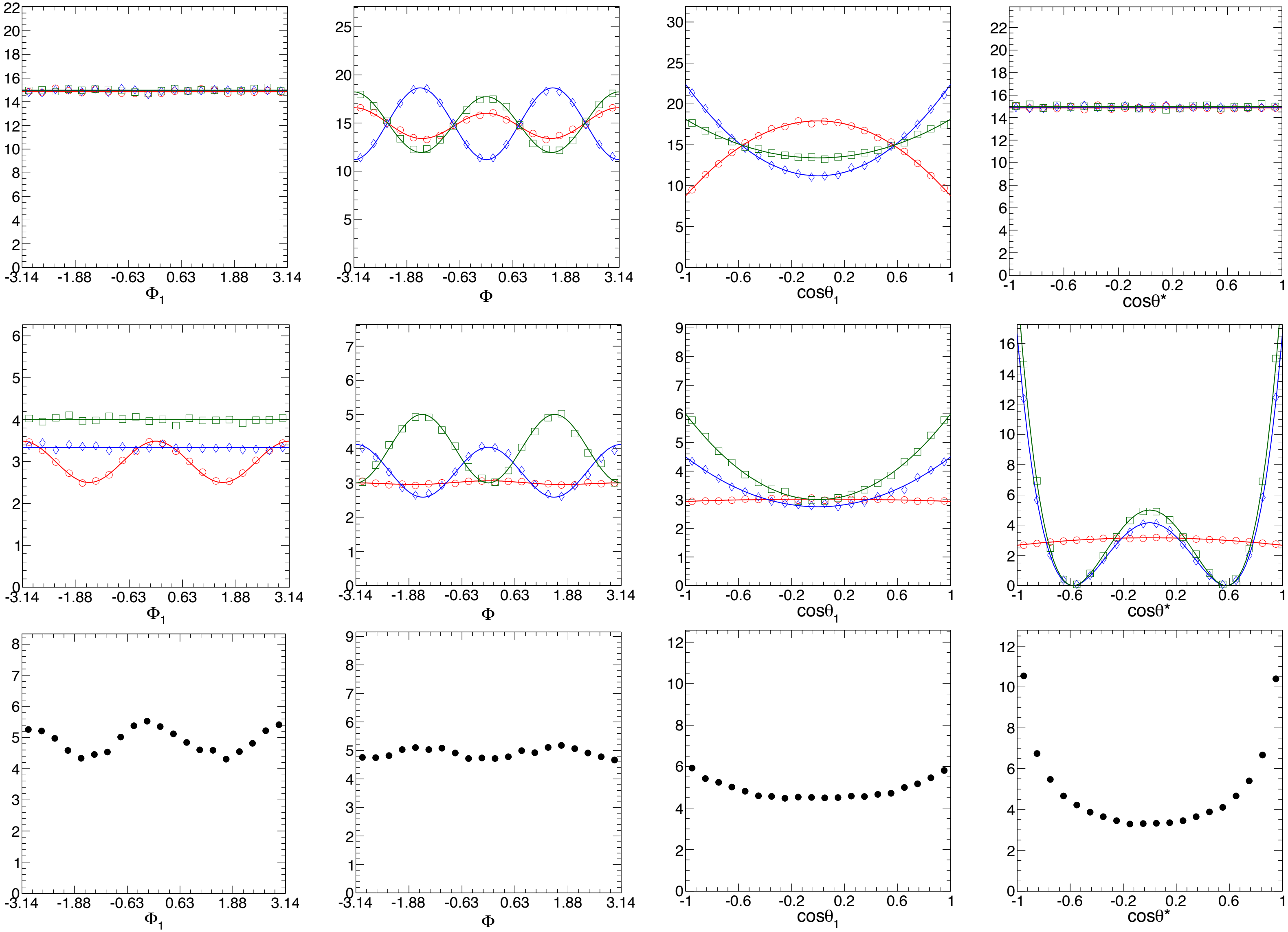


The ID provides around 3 pixel, 8 SCT and 30 TRT measurements per charged track at $\eta = 0$.
Coverage: $|\eta| < 2.5$ (2.0 for TRT)
Allows for accurate track and vertex reconstruction.
Resolution goal: $\sigma_{pT} / p_T = 0.05\%\ p_T \oplus 1\%$

Distributions of the Spin/CP sensitive variables

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

	Φ_1	Φ	$\cos\theta_1$	$\cos\theta^*$
Spin-0: 0_m^+; 0_h^+; 0_h^-				
Spin-2: 2_m^+; 2_h^+; 2_h^-				
ZZ background				



H->μμ

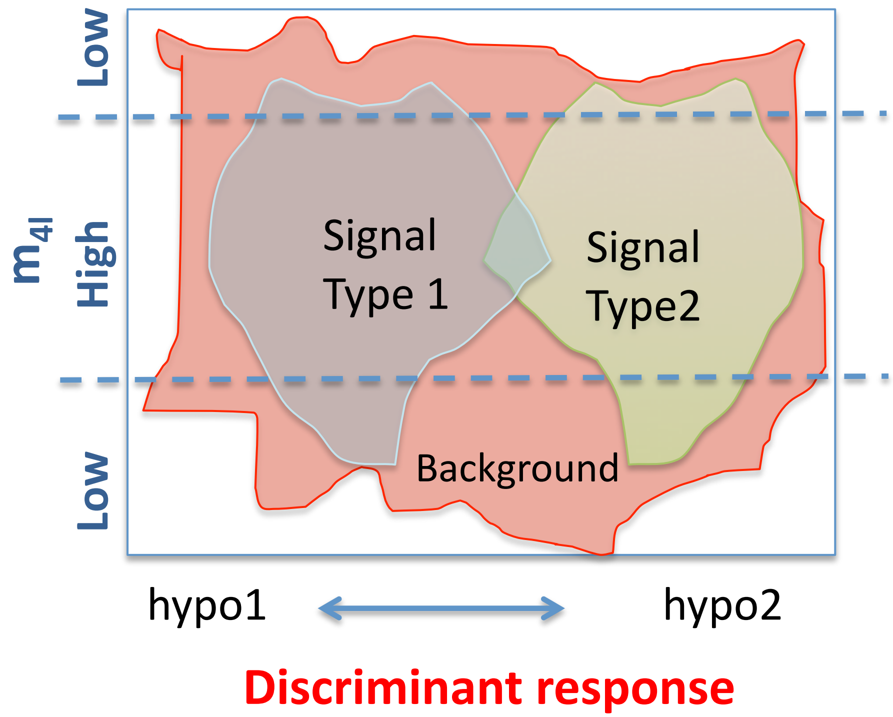
- CP-odd amplitudes are naturally expected to be suppressed in the HVV coupling.
  - The channels containing the HVV coupling in the final state are hence not ideal for the CP-studies.

- 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}.

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.