Determination of Spin and Parity of the Higgs Boson in Run 1 and Prospects for Run 2 in ATLAS

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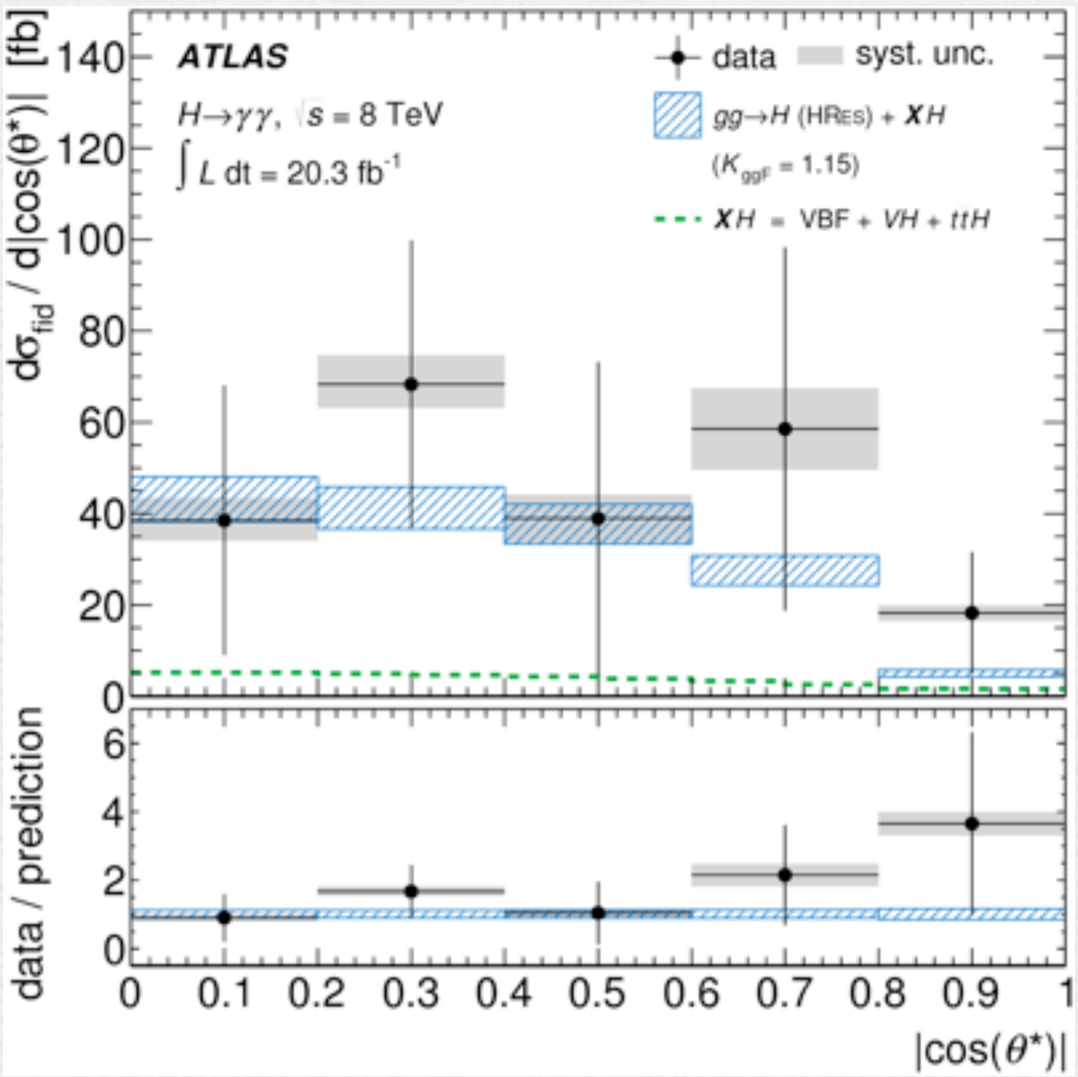
Introduction

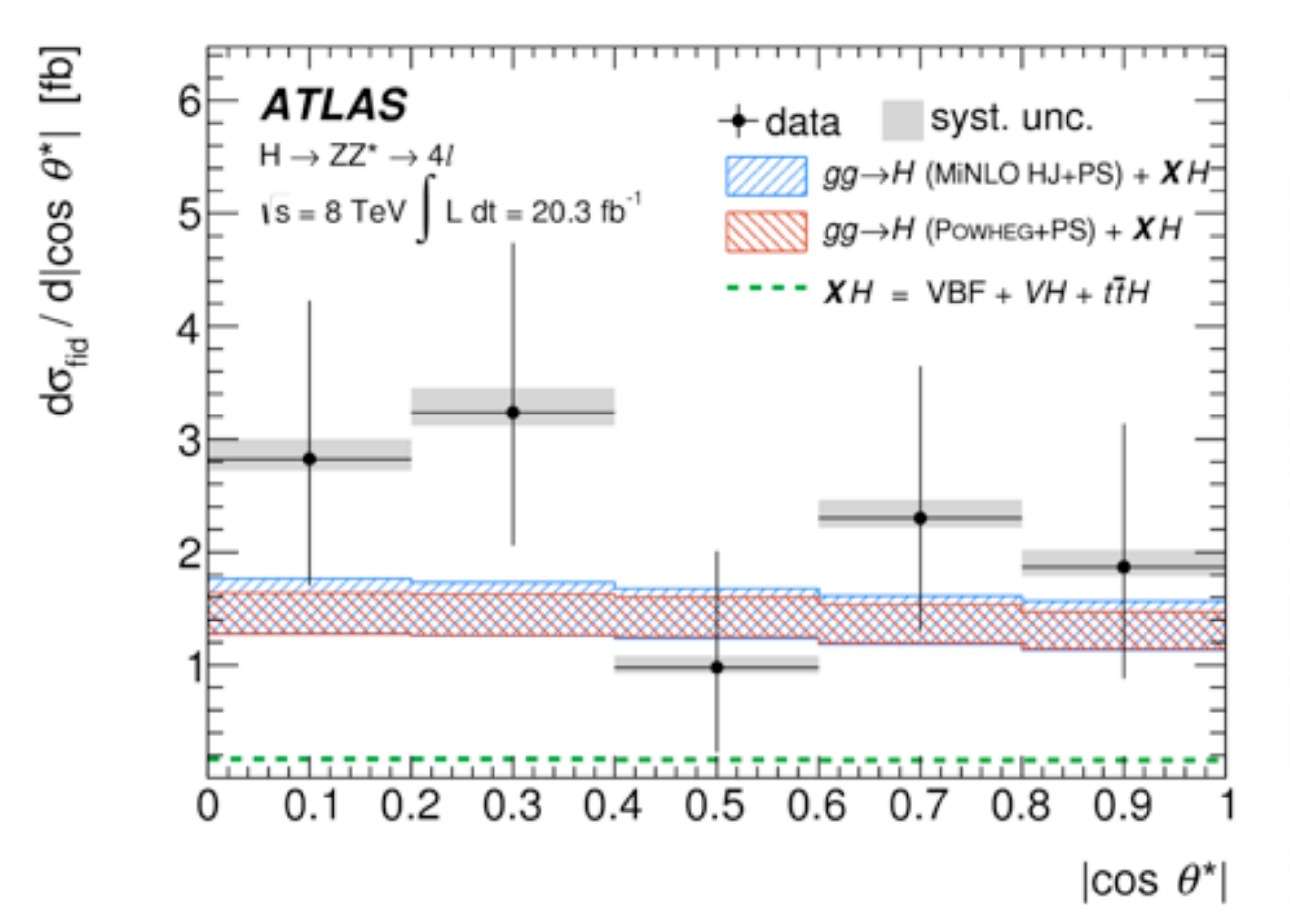
- **spin/parity determination in Run 1**
  - exclusion of alternative spin/parity hypotheses in favour of the SM 0+ hypothesis
    - alternative models: 0-, 1+, 1- and 2+
    - using all 3 bosonic decay channels: γγ, WW and ZZ
  - CMS has published pre-final Run 1 results, ATLAS publications will follow soon

- **spin/parity measurements in Run 2**
  - study of the HVV (V=Z,W) tensor coupling using ZZ, WW decays
    - first results already with run 1 data
  - spin/parity in fermionic channels: $H \to \tau\tau$
  - ... and more

Direct Measurements of Spin

- measure differential x-sections to test directly the compatibility of data with the spin-0 hypothesis
  - as a function of the production angle $|\cos\theta^*|$
  - spin-sensitive: isotropic for spin-0, polynomial for other spin values





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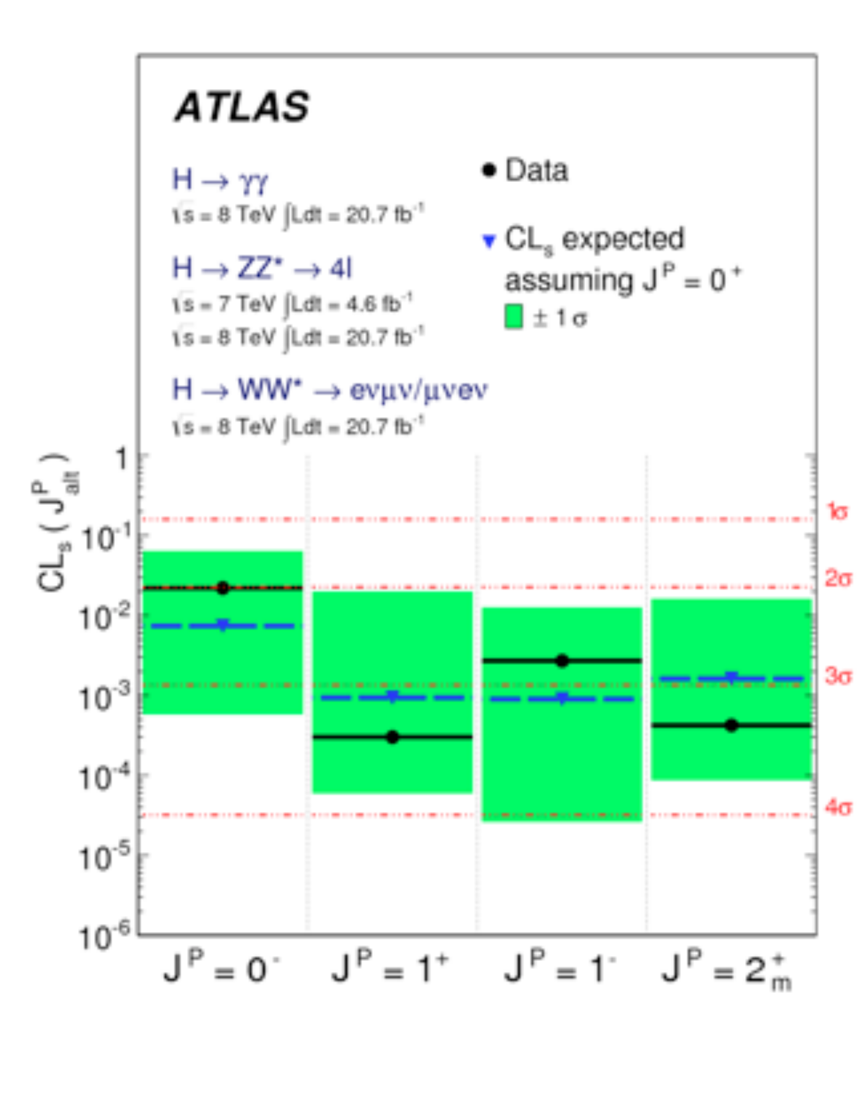
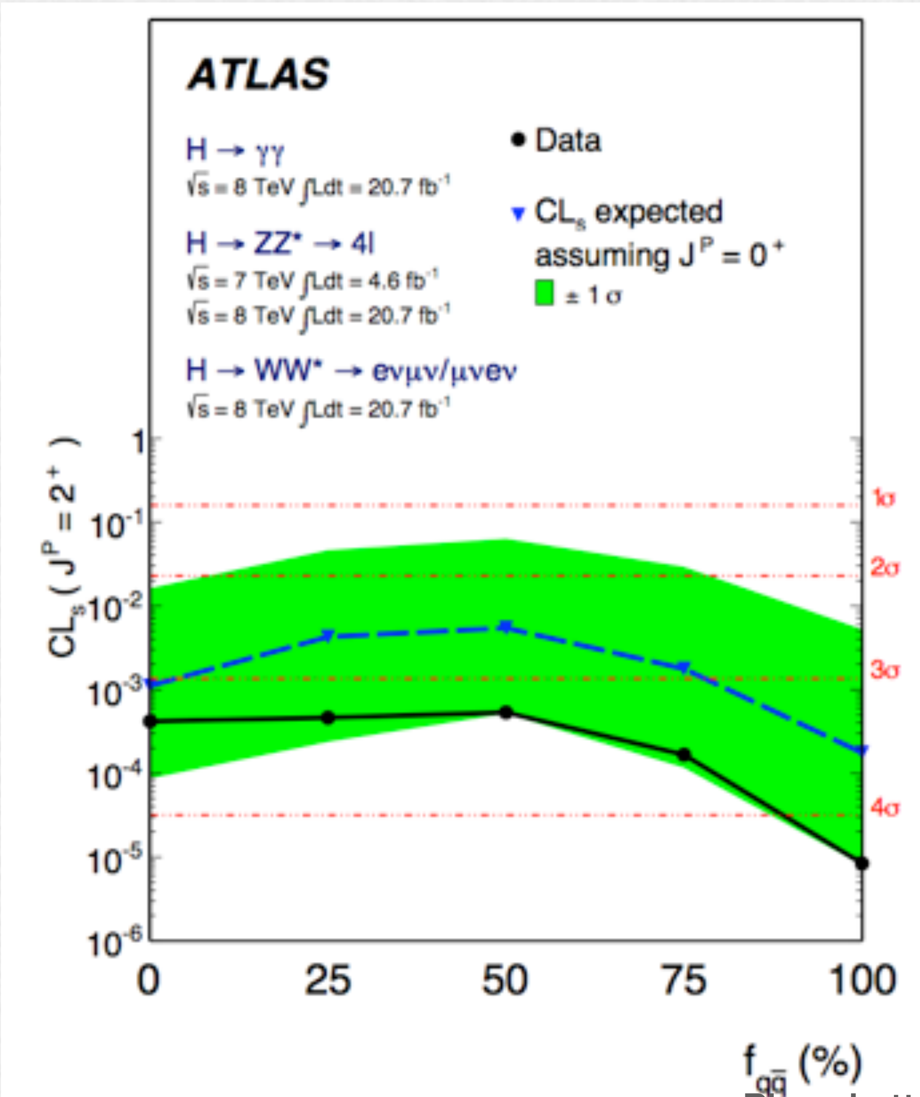
Fixed Hypothesis Tests

- 2013 analysis results:
  - all spin-2 benchmarks excluded at > 99.9% CL in favour of the SM hypothesis
  - spin 0- excluded at 97.8% CL in favour of the SM hypothesis





Phys. Lett. B 726 (2013)

Tensor structure

- Run 1 data provide evidence for the spin-0 nature of the found Higgs particle with a strong preference for positive parity
  - independent of the assumptions on the coupling strengths to the SM particles (→ analysis based only on angular information)
  - in case of spin-2 independent of the relative fractions of gg/qq production of the spin-2 particle
- the Higgs couplings are completely determined in the SM
  - **need to measure them**
- the BMS theories predict possible anomalous contributions and/or CP-violation in the Higgs sector
  - e.g. 2HDM predicts a scalar (H) and a pseudo-scalar (A) spin-0 particle
    - the observed Higgs h (mass eigenstate) could be a mixture of the CP eigenstates (H+A)
- **a model independent approach: measure the couplings structure and compare to the SM prediction -> two frameworks**

Effective field theory Approach

- effective Lagrangian to describe the interaction of a spin-0 particle with vector bosons

$$
\begin{aligned}
\mathcal{L}_0^{\rm V} = \Big[& \underbrace{c_\alpha \kappa_{\rm SM}}_{\rm SM} \big[\tfrac{1}{2} g_{\rm HZZ}\, Z_\mu Z^\mu + g_{\rm HWW}\, W^{+\mu} W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{\rm H\gamma\gamma} g_{\rm H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{\rm A\gamma\gamma} g_{\rm A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{\rm HZ\gamma} g_{\rm HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{\rm AZ\gamma} g_{\rm AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{\rm Hgg} g_{\rm Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{\rm Agg} g_{\rm Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{\rm HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{\rm AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[\underbrace{c_\alpha \kappa_{\rm HWW}}_{\text{CP-even}}\, W^+_{\mu\nu} W^{-\mu\nu} + \underbrace{s_\alpha \kappa_{\rm AWW}}_{\text{CP-odd}}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big]\Big] X_0
\end{aligned}
$$

- and fermions

$$
\mathcal{L}_0^{\rm f} = -\big[\underbrace{c_\alpha \kappa_{\rm Hff}}_{\text{CP-even}} g_{\rm Hff}\, \bar\psi_{\rm f}\psi_{\rm f} + \underbrace{s_\alpha \kappa_{\rm Aff}}_{\text{CP-odd}} g_{\rm Aff}\, \bar\psi_{\rm f} i\gamma_5 \psi_{\rm f}\big] X_0,
$$

- κ_i - dimensioneless coupling parameters (real) and α is the mixing angle
- SM case: $\cos\alpha = 1$ and $\kappa_{SM} = 1$, CP-odd case: $\cos\alpha = 0$ and $\kappa_{AVV} \neq 0$
- Mixed state $0 < \cos\alpha < 1$ and $\kappa_i \neq 0$

Higgs Characterisation: JHEP 1311 (2013) 043

Anomalous couplings Approach

- generic scattering amplitude to describe the interaction of a spin-0 particle and two spin-1 gauge bosons:

$$A(\mathrm{X}_{J=0} \to \mathrm{VV}) = v^{-1}\left(\underbrace{g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)}}_{\text{CP-even}} \frac{q_\nu q^\alpha}{\Lambda^2} + \underbrace{g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{CP-odd}}\right),$$

CP-even CP-odd

  - g1, g2 and g3 couplings describe the tree-level and loop-induced interaction of a CP-even particle
  - g4 coupling describes the interaction of the CP-odd particle
  - couplings could be complex
  - SM defined as g1=1, g2=g3=g4=0; pure CP-odd state: g1=g2=g3=0, g4=1
  - CP violation if simultaneous presence of g1 or g2 or g3 and g4
- and for fermions:

CP-odd

$$A(\mathrm{X}_{J=0} \to \mathrm{f\bar{f}}) = \frac{m_{\mathrm{f}}}{v} \bar{u}_2 \left(\rho_1 + \rho_2 \gamma_5\right) v_1$$

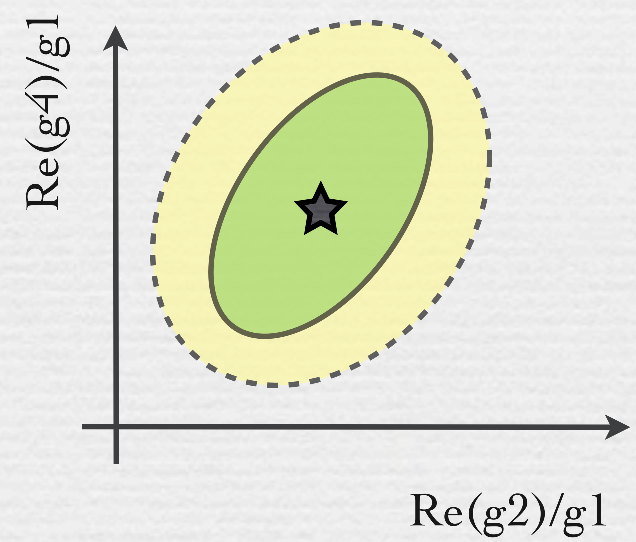
CP-even

- one-to-one matching of parameters is available for EFT and anomalous couplings approaches

Phys.Rev. D86 (2012) 095031

Measurements in the VV channel

- ATLAS measures the ratio of couplings g4/g1 and g2/g1
  - g3 is small and can be neglected in the following discussion
- the following measurements are possible:
  - Re(gi)/g1 -> heavy BSM particles
  - Im(gi)/g1 -> light BSM particles in loops
  - 2D scans e.g. Re(g4)/g1 vs Re(g2)/g1



matching to EFT:

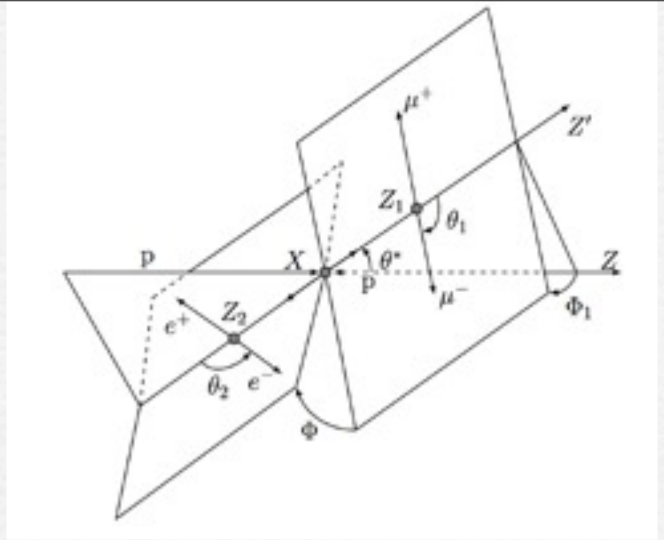
$$\frac{g_4}{g_1} \rightarrow \frac{k_{Aww}}{k_{SM}} \cdot tan\alpha$$

$$\frac{g_2}{g_1} \rightarrow \frac{k_{Hww}}{k_{SM}}$$

for real couplings

- ratio of couplings -> use only the angular information
  - combination of angular and rate information planned for Run 2

Analysis in the ZZ channel



- 2 analyses in the ZZ channel:

ME observable fit

- fit combined observable sensitive to different couplings:

Observable	Sensitivity
$\ln \frac{\lvert ME(g_1=1, g_2=0, g_4=-2+2i)\rvert^2}{\lvert ME(g_1=1, g_2=0, g_4=2+2i)\rvert^2}$	$\Re(g_4)/g_1$
$\ln \frac{\lvert ME(g_1=1, g_2=-1+i, g_4=0)\rvert^2}{\lvert ME(g_1=1, g_2=1+i, g_4=0)\rvert^2}$	$\Re(g_2)/g_1$

- include the 2nd dimension using a BDT to suppress background (BDT is non-sensitive to CP properties)
- for each set of couplings prepare a 2D fit

8D Likelihood fit

- likelihood is defined using the full analytical expression of the ME at LO

$$L(\mu, N_{sig_i}, N_{ZZ_i}, N_{Red_i}, \text{syst}) \propto \sum_i \prod_{events} \left[\mu N_{sig_i} \text{pdf}_{sig_i}\left(\vec{x}, \frac{g_2}{g_1}, \frac{g_4}{g_1}\right) + N_{ZZ_i} \text{pdf}_{ZZ_i}(\vec{x}) + N_{Red_i} \text{pdf}_{Red_i}(\vec{x}) \right]$$

- depends on experimental observables and coupling constants
- detector acceptance and resolution described by parametrisations based on MC simulations
- for each set of couplings a fit is performed

ATL-PHYS_PUB-2013-013

Results in the VV channel

- prospects for g4/g1 and g2/g1 ATLAS measurements:

Luminosity	$\|g_4\|/g_1$	$\Re(g_4)/g_1$	$\Im(g_4)/g_1$	$\|g_2\|/g_1$	$\Re(g_2)/g_1$	$\Im(g_2)/g_1$
300 fb^{-1}	1.03	(-1.01, 1.01)	(-1.02, 1.02)	1.39	(-0.88, 0.38)	(-1.13, 1.13)
3000 fb^{-1}	0.49	(-0.34, 0.26)	(-0.34, 0.48)	0.81	(-0.33, 0.11)	(-0.73, 0.75)

Table 6: Results of the ME-observable fit to the Standard Model signal: the 95% CL exclusion limits for g_4 and g_2 coupling constants at 300 fb^{-1} and 3000 fb^{-1}.

- correspond to the CMS measurement - limits in terms of f_{ai}, ϕ_{ai}
  - in the g_i-parametrisation: $$f_{g_i} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right).$$

- an analysis on Run 1 data will be published soon:
  - **ZZ channel following the anomalous coupling approach**
  - **WW channel following the EFT approach**
  - and their combination

Further Parity studies

- **tree-level CP-odd coupling:**
  - **H->ττ** channel in decay
  - ttH channel in production

Run 2?

- **loop-induced CP-odd coupling:**
  - **gg->H+2j** in production (e.g. in WW,ZZ channels)

Run 2?

  - **VBF**/VH channel in production
    - VBF H->ττ and H->γγ already with Run 1 data?

run 2 - looking forward to many exciting property measurements