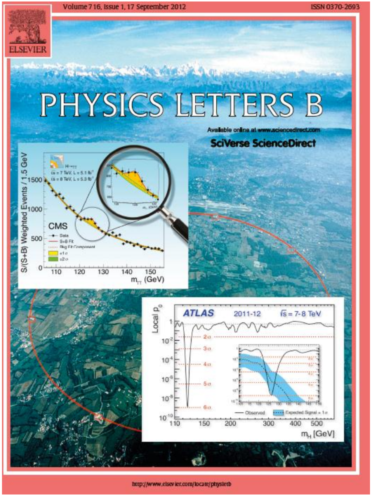
Measurement of the HZZ tensor structure using Higgs to four lepton decays at the ATLAS detector

Katharina Ecker

Max-Planck-Institute for physics

PPSMC Seminar (10.10.2014)



François Englert and Peter Higgs

Is the discovered boson the Standard Model (SM) Higgs boson?

$\Rightarrow$ Property measurements

- Mass measurement:

CMS: $m_H = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$ GeV — CMS-PAS-HIG-14-009

ATLAS: $m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})$ GeV — arXiv:1406.3827 [hep-ex]

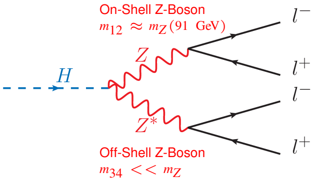
- SM Higgs boson:
  Spin-0 (scalar particle) with CP-even eigenvalue

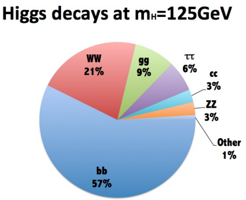
  CP: Parity and charge conjugation combination
- ATLAS and CMS: Discovered boson is with high probability scalar particle (Spin-0)

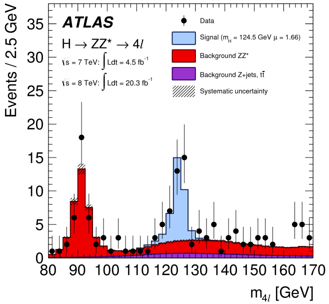
  (Physics Letters B 726 (2013) und 120–144 CMS PAS HIG-14-014).
- Beyond the SM theories (BSM): Mixture of CP-even and CP-odd

$\Rightarrow$ Analysing HZZ tensor structure assuming Spin-0 Higgs boson:
Coupling of Higgs boson to SM particles dependent on its CP-properties

- $H \to ZZ^* \to 4\ell$ ($\ell = \mu, e$):
  - Only consider electrons and muons
  - Final states: 4μ, $4e$, $2e2\mu$







– Small number of events

+ Clear event signature

+ Manageable background

Main bkg: ZZ^* continuum production

+ 4 final state particles can be fully reconstructed

⇒ Channel suited for property measurements

$H \to ZZ^* \to 4\ell$ channel

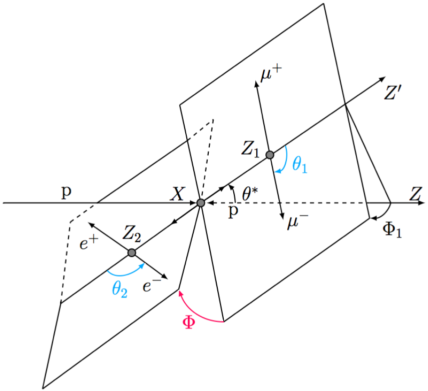
- General amplitude describing interaction of scalar particle and two vector bosons:
  "Spin determination of single-produced resonances at hadron colliders" (arXiv:1001.3396v2)

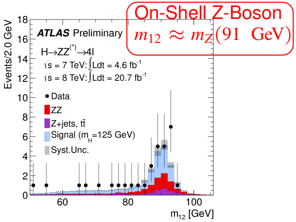
$$A(X \to V_1 V_2) = \mathrm{v}^{-1}[\underbrace{g_1 \cdot M_V^2 \epsilon_1^* \epsilon_2^* + g_2 \cdot f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu}}_{\text{CP-even}} + g_3 \cdot f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + \underbrace{g_4 \cdot f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}}_{\text{CP-odd}}]$$

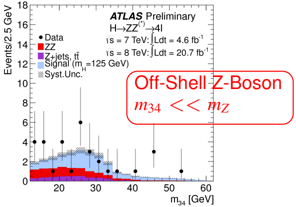
- g_i effective coupling constants: SM g_1=1,$g_{i\neq 1} = 0$
- CP-mixture:
  Simultaniously g_1/g_2 (CP-even) and g_4 (CP-odd).

⇒ Probing for CP-admixtures in decay amplitude by measuring CP-sensitive variables

- $H \to 4\ell$ event is fully characterized by 8 parameters:
  1. 3 invariant mass distributions: $m_{4\ell}$, m_{12}, m_{34}
  2. 3 decay angles: $\cos\theta_1$, $\cos\theta_2$, Φ
  3. 2 production angles: $\cos\theta^*$, Φ_1







- CP-sensitive variables: Z-boson masses m_{12} & m_{34} and decay angles $\cos\theta_1$, $\cos\theta_2$, Φ

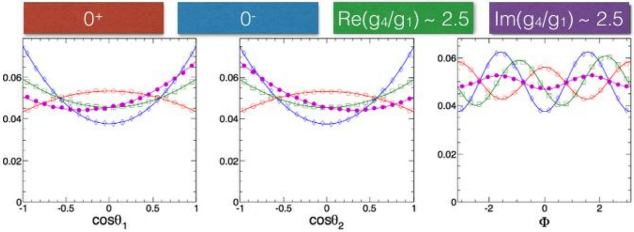
- Example of distributions of CP-sensitive variables for different configuration of effective coupling constants g_i:

$$\text{SM } \{g_1 = 1, g_2 = 0, g_4 = 0\} \to 0^+$$

$$\text{Pure CP-odd}\{g_1 = 0, g_2 = 0, g_4 = 1\} \to 0^-$$

$$\text{CP-mixture}\{g_1 = 1, g_2 = 0, g_4 = 2.5\} \to \mathrm{Re}(g_4/g_1) \sim 2.5$$

$$\text{CP-mixture}\{g_1 = 1, g_2 = 0, g_4 = 2.5i\} \to \mathrm{Im}(g_4/g_1) \sim 2.5$$



- Limited discrimination power of single variables:
  ⇒ Taking into account correlations between variables by using Matrix Element Method

- Use MC event generator (here: JHU) to calculate matrix elements (ME) describing $X \to ZZ^* \to 4\ell$ decays (X is spin-0 particle), for example:

$$\begin{aligned} \mathrm{ME}\ 0^+: &\quad \mathrm{ME}\ (g_1 = 1, g_2 = 0, g_4 = 0) \\ \mathrm{ME}\ 0^-: &\quad \mathrm{ME}\ (g_1 = 0, g_2 = 0, g_4 = 1) \\ \mathrm{ME}\ \text{CP-mixture}: &\quad \mathrm{ME}\ (g_1 = 1, g_2 = 1, g_4 = 1) \end{aligned}$$

  By using full simulation, truth values can be matched to reconstructed values
- Use all four-momenta of four final state (FS) leptons (p_1, p_2, p_3, p_4) as input to ME:

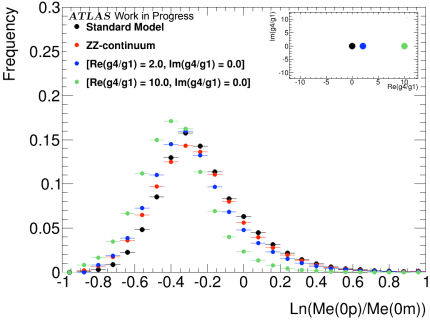
$$|\mathrm{ME}\,(\,0^+|p_1, p_2, p_3, p_4)|^2$$

  Probability that 0^+ particle decayes into FS with specific 4ℓ-kinematic (p_1, p_2, p_3, p_4)
- Building discriminants sensitive to couplings by dividing "probabilities", for example sensitive to $|g_4|$:

$$\ln \frac{|\mathrm{ME}\,(\,0^+|p_1, p_2, p_3, p_4)|^2}{|\mathrm{ME}\,(\,0^-|p_1, p_2, p_3, p_4)|^2}$$

- We want to measure amount of g_2 and g_4 relative to SM coupling g_1:
  $\boxed{g_2/g_1}$ and $\boxed{g_4/g_1}$
- Combining CP-sensitive variables to one discriminant using matrix element method $\rightarrow$ discriminants sensitive to $|g_i|/g_1$, $\mathrm{Re}\,(g_i)/g_1$ and $\mathrm{Im}\,(g_i)/g_1$

Example discriminant sensitive to $|g_4|/g_1$: $\ln(\mathcal{M}_{0p}^2/\mathcal{M}_{0m}^2)$



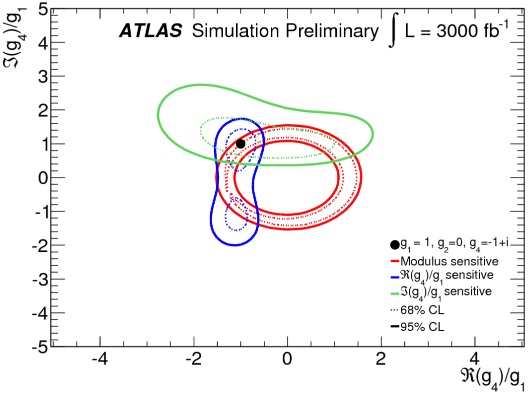
Observable	Sensitivity
$\ln\frac{\|\mathrm{ME}(g_1{=}1,g_2{=}0,g_4{=}0)\|^2}{\|\mathrm{ME}(g_1{=}0,g_2{=}0,g_4{=}1)\|^2}$	$\|g_4\|/g_1$
$\ln\frac{\|\mathrm{ME}(g_1{=}1,g_2{=}0,g_4{=}-1.4{+}1.4i)\|^2}{\|\mathrm{ME}(g_1{=}1,g_2{=}0,g_4{=}1.4{+}1.4i)\|^2}$	$\Re(g_4)/g_1$
$\ln\frac{\|\mathrm{ME}(g_1{=}1,g_2{=}0,g_4{=}1.4{-}1.4i)\|^2}{\|\mathrm{ME}(g_1{=}1,g_2{=}0,g_4{=}1.4{+}1.4i)\|^2}$	$\Im(g_4)/g_1$

Fit model

- Free fit parameters: Effective coupling constants $g_i/g_1 \in \{-5, 5\}$
- Example: Measurement of g_4 by fitting 3 discriminants

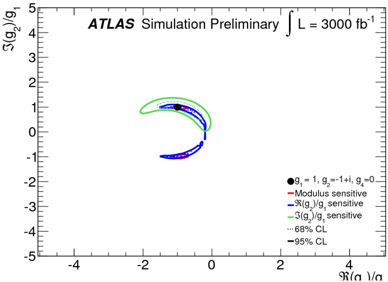
- Three planes within parameter space:
  1. $\{\mathrm{Re}(g_2/g_1), \mathrm{Im}(g_2/g_1)\}$
  2. $\{\mathrm{Re}(g_4/g_1), \mathrm{Im}(g_4/g_1)\}$
  3. $\{|g_4|/g_1, |g_2|/g_1\}$

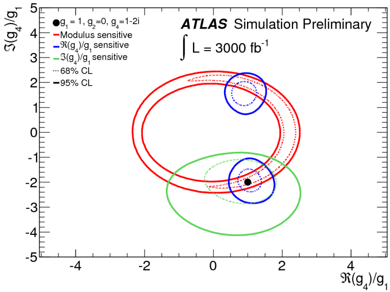
- Fit results: Likelihood bounds for non-SM coupling constants g_2 and g_4

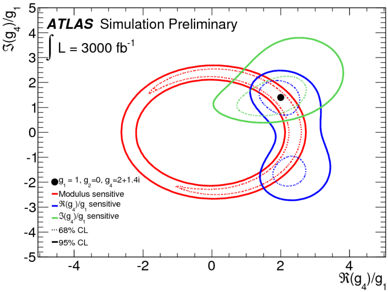


Tests

- Testing method on simulated data:
  - SM: $g_1 = 1, g_2 = 0, g_4 = 0$
  - $g_1 = 1, g_2 = 0, g_4 = 1 - 2i$
  - $g_1 = 1, g_2 = 0, g_4 = -1 + i$
  - $g_1 = 1, g_2 = 0, g_4 = 2 + 1.4i$
  - $g_1 = 1, g_2 = 0, g_4 = 2 + 2i$
  - $g_1 = 1, g_2 = 1 + i, g_4 = 0$
  - $g_1 = 1, g_2 = -1 + i, g_4 = 0$







LHC data taking periods

- Large Hadron Collider (LHC) data taking:

	Integrated luminosity $\mathcal{L}$ [fb^{-1}]
LHC Run-I until 2012	$25\ \text{fb}^{-1}$
LHC Run-II until 2018	$\sim 100\ \text{fb}^{-1}$
LHC Run-III until 2022	$\sim 300\ \text{fb}^{-1}$
LHC Upgrade until 2030?	$\sim 3000\ \text{fb}^{-1}$

- Within this talk presented analysis is currently done on Run-I data
  $\Rightarrow$ Publication planned for end of 2014
- For thesis analysis of Run-II is also planned
- Results of sensitivity study for data of $300\ \text{fb}^{-1}$ and 3000fb^{-1} will be presented

- Publication of analysis on LHC Run-I data (2011+2012) end of 2014

⇒ Only allowed to show results of sensitivity studies:

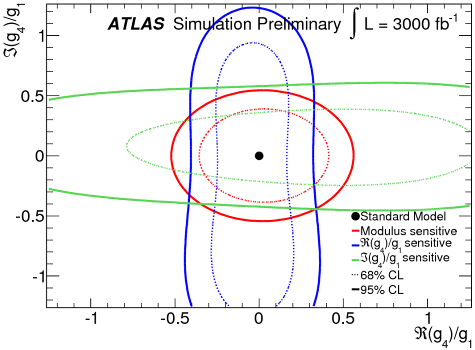
- Sensitivity study for integrated luminosities $300\ \mathrm{fb}^{-1}$ and $(3000\ \mathrm{fb}^{-1})$:

  $|g_2|/g_1 < 1.39$ (0.81) at 95% CL

  $|g_4|/g_1 < 1.03$ (0.49) at 95% CL

  $300\ \mathrm{fb}^{-1}$: End LHC 2022

  $3000\ \mathrm{fb}^{-1}$: Upgrade LHC 2030?



- *"Prospects for measurements of the HZZ vertex tensor structure in $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel with ATLAS" (ATLAS-PHYS-PUB-2013-013)*

Summary

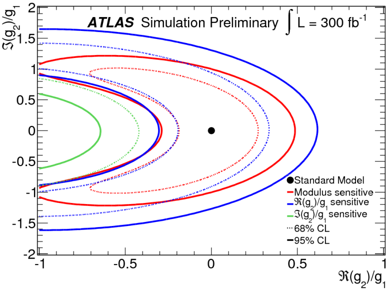
- Discovered boson is with high probability scalar particle (Spin-0)
- Probing HZZ tensor structure for CP-mixing, because CP-mixing is proposed in many BSM
- Sensitivity studies on integrated luminosities of $300\ \text{fb}^{-1}$ and ($3000\ \text{fb}^{-1}$):

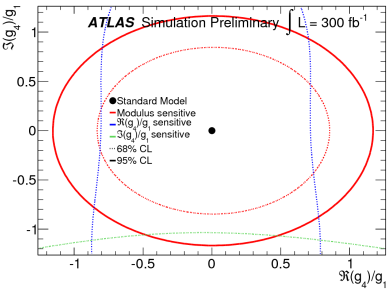
  $|g_2|/g_1 < 1.39$ (0.81) at 95% CL
  $|g_4|/g_1 < 1.03$ (0.49) at 95% CL

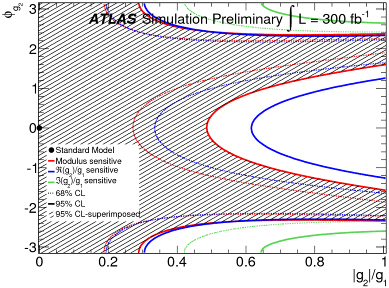
- End of 2014: Publication of HZZ tensor structure measurement using $H \to ZZ^* \to 4\ell$ events in ATLAS data

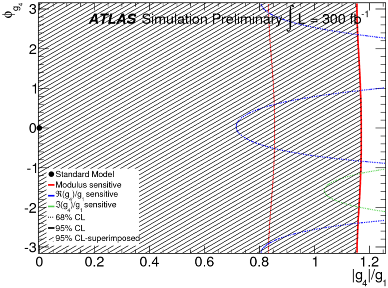
Backup

Result sensitivity study using 300 fb^{-1}









Result sensitivity study for measuring g_2/g_1 using 3000 fb^{-1}