Combination of results on the Higgs in ATLAS

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On behalf of the ATLAS collaboration
• $m_H$ from $m(\gamma\gamma)$ and $m(4$ leptons$)$

• Signal strength with respect to SM : global ($\mu$), per channel ($\mu_i$)

• Production modes: Vector Boson Fusion (+ VH) / gluon fusion ( + tt )

• Higgs couplings

*ATLAS-CONF-2013-014*
Statistical method

- All results from profiled likelihood method

\[ \Lambda(\mu) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} \]

- \( \mu \) : parameter(s) of interest
- \( \theta \) : nuisance parameters

- Global likelihood maximum: \( \mu \) and \( \theta \) adjusted for max L

- \( L(\hat{\mu}, \hat{\theta}(\mu)) \) tested \( \mu \) point: \( \theta \) adjusted for max L at this \( \mu \) point

- \( -2 \ln \Lambda(\mu) \) follows \( \chi^2 \) distribution with n d.o.f. \((\mu_1,...,n) \Rightarrow P(\chi^2 > x)\)... 

- Nuisance parameters \( \theta \) prob.dist.functions: Gauss, LogNormal, Poisson ...

- Also explored: cases with a « rectangular » pdf for some systematic uncertainties
**Mass systematic uncertainties: 4 leptons and γγ**

- **4 leptons**
  - Dominated by 4 muons (best resolution, less background)
    - Muon momentum-scale uncertainty: 0.2% (from Z, J/ψ → µµ)
  - electron E-scale => see below

- **γγ**
  - Per category systematic uncertainties:
    - method ~ 0.3 % : *(mainly from Z → ee MC/data)*
    - material in front of calorimeter: ~ 0.3%, up to 0.7%
    - relative calibration presampler/calorimeter: ~ 0.1%

    In each of the above: extrapolation in $E \oplus$ transfer from $e$ to $\gamma$

  - Additional (global) syst uncertainties:
    - E1/E2, linearity, lateral leakage, conversion fraction … 0.32%

- Global mass systematic uncertainty: 0.55% = 0.7 GeV
Mass measurement from $\gamma\gamma$ and 4 leptons

- $\mu_{\gamma\gamma}$ and $\mu_{4l}$ treated as independent nuisance parameters

- $m_H$ : parameter of interest

- **Full data sample:**
  2011 (4.8 fb$^{-1}$) + 2012 (20.7 fb$^{-1}$)

- **Result:**  $m_H = 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (sys) GeV

  
  
  Council Dec 2012 : $m_H = 125.2 \pm 0.3$ (stat) $\pm 0.6$ (sys) GeV  $(4.7$ fb$^{-1} + 13$ fb$^{-1})$
Mass difference: $m_{\gamma\gamma} / m_{4l}$

- Parameters of interest: $m_{\gamma\gamma}$, $m_{4l}$ (independent)
- Small correlation due to the common EM-scale in $\gamma\gamma$ and $ee$ in 4 leptons
  - in 4 leptons: $m_{4e} = 126.2 \pm 1.5$, $m_{4\mu} = 123.8 \pm 0.8$
  - pulls EM-scale down by 0.3 %
  - $m_{\gamma\gamma}$ here 0.4 GeV lower than single channel value

Quantify consistency:
- parameter of interest: $\Delta m_H = m_{gg} - m_{4l}$

\[ \Rightarrow \Delta m_H = 2.3^{+0.6}_{-0.7} \text{ (stat)} \pm 0.6 \text{ (sys)} \text{ GeV} \]

2.4 $\sigma$ from $\Delta m_H = 0$ (p = 1.5%)

Also: set E-scale, $e/\gamma$ pdf’s to rectangular $[\pm 1 \sigma]$

(material models, calo samplings calibration...)

\[ \Rightarrow \ p = 8\% \]
• Parameter of interest: $\mu$ (global)

$\Rightarrow \mu = 1.43 \pm 0.16 \text{ (stat)} \pm 0.14 \text{ (sys)}$

$\mu_\text{Council Dec 2012} = 1.35 \pm 0.19 \text{ (stat)} \pm 0.15 \text{ (sys)}$

• Consistency tests
  – global $\mu$ with SM: 3%
    • 11% with rectangular QCD scale and parton dist functions
  – $5\mu_i$ with SM: 8%
  – $5\mu_i$ with 1.43: 32%

• $\mu, m_H$ contours
  – $\gamma\gamma$
  – $4l$
  – combined

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at $m_H = 125.5$

$[124.5-126.5]: \mu \pm 4\%$
Higgs production modes

- Through $t$ coupling
  - fermion masses...

- Through $W/Z$ coupling
  - $W/Z$ masses...
  - unitarity of SM

Can be tested for all modes with VBF sensitivity

Here: $\gamma\gamma$, $ZZ \ (4.8 + 21 \text{ fb}^{-1})$, $\tau\tau \ (4.6 + 13 \text{ fb}^{-1})$
Production modes: VBF+VH / ggF +ttH

- \( \mu_{\text{VBF+VH}} \) versus \( \mu_{\text{ggF+ttH}} \)

includes Branching Ratio

(which might be different in each case)

- Ratio independent of B.R.: can be combined

\[ \Rightarrow \frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 0.9^{+0.7}_{-0.4} \]
Higgs couplings

• For each observed final state, production and decay involve several couplings

• Best example: $\gamma\gamma$
  
  – Production
  
  \[ \sim \kappa_g^2 \left( \kappa_t, \kappa_b, m_H \right) \]

  \[ + \sim \kappa_W^2 \]

  – Decay

  \[ \text{Decay width : } \sim (\kappa_W - 0.2 \kappa_t)^2 \quad [\text{note: interference}] \]

• Need consistent parametrization => LHC-XS-WG

• Ideally: use all production and decay modes to measure all $\kappa$’s

• Reality: some modes are statistically limited, or even invisible ( $\kappa_c$, $\kappa_\mu$...?)

  => Group some $\kappa$’s in order to test salient/important features

ATLAS-CONF-2012-127
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Fermion versus Vector couplings

- Group couplings: $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

- Assume:
  - $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ only through SM particles
  - only SM particles contribute to decay (relaxing this assumption => backup)

  sensitivity to relative sign:
  - only from interference term in $H \rightarrow \gamma\gamma$
  - compatibility with SM: 21%

- With these data, sensitivity to $\kappa_F$ is mostly through top in loops. Will be better with $\tau\tau$, $bb$…

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W and Z couplings ('custodial symmetry')

- group $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- un-group $\kappa_W, \kappa_Z$

- test $\lambda_{WZ} = \kappa_W / \kappa_Z$

$\Rightarrow \lambda_{WZ} = 1.07^{+0.35}_{-0.27}$

Direct contribution: WW and ZZ
Indirect: $\gamma\gamma$ (through W loop)
Contributions from non-SM particles

• Assume all couplings to SM particles $\kappa_i = 1$

• Introduce effective $\kappa_g$, $\kappa_\gamma$, independent (allow additional contributions to loops)

• Assume no contributions to the total width in undetected modes (relaxing this assumption => backup)

$$\kappa_g = 1.1^{+0.2}_{-0.3}; \kappa_\gamma = 1.2^{+0.3}_{-0.2}$$

SM hypothesis: 18%

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Conclusion: ATLAS-Higgs status today

- New high resolution channels $\gamma\gamma$ and 4 leptons (full 2011 + 2012 data)
  
  $m_H = 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (sys) GeV
  
  $\mu = 1.43 \pm 0.16$ (stat) $\pm 0.14$ (sys)

- Signal strengths
  
  $\Rightarrow$ $\Rightarrow$

- Production mode (from $\gamma\gamma$, ZZ, $\tau\tau$): $\mu_{VBF+VH}/\mu_{ggF+ttH} = 0.9\quad^{+0.7}_{-0.4}$

- Higgs couplings (partial dataset)
  
  Compatible with SM hypothesis.

- $\text{BR}(H\to\text{inv.}) < 65\%$ (95\% C.L.)

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The birth of a particle

- A big thank you to all my ATLAS colleagues since the beginning…

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• Most recent documentation

- $\gamma\gamma$: ATLAS-CONF-2013-012
- WW, $\tau\tau$, $bb$: ATLAS-CONF-2012-162
- Previous combination: ATLAS-CONF-2012-170
- Couplings: ATLAS-CONF-2012-127
Per-channel masses in $H \to 4l$

**ATLAS Preliminary $H \to ZZ^{(*)} \to 4l$**

- $\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $\int L dt = 20.7$ fb$^{-1}$

$\hat{m}_H = 124.3 \pm 0.6^{(\text{stat})} \pm 0.5^{(\text{sys})}$ GeV

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$\mu_i$ dependence on assumed $m_H$

$m_H = 124.5$

$m_H = 125.5$

$m_H = 126.5$
$p_0$ plots

- Full 2011 and 2012 statistics:
  - Previous combination
    $\gamma\gamma : 6.1 \sigma \oplus ZZ : 4.1 \sigma \Rightarrow$ global : $7.0 \sigma$

  Present combination
  $\gamma\gamma : 7.4 \sigma \oplus ZZ : 6.6 \sigma \Rightarrow$ global : $? (> 9 \sigma)$

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Fermion versus Vector couplings (2)

- Group couplings: $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
  - Assume: $gg \to H$ and $H \to \gamma\gamma$ only through SM particles

- No assumption on total width:
  
  $\lambda_{FV} = \kappa_F / \kappa_V$; $\kappa_{VV} = \kappa_V \kappa_V / \kappa_H$
Contributions from non-SM particles (2)

- Assume all couplings to SM particles $\kappa_i = 1$
- Introduce effective $\kappa_g, \kappa_\gamma$, independent (allow additional contributions to loops)

- Allowing possible $\text{BR}_{\text{inv, undet}}$ to undetected modes

$\text{BR}_{\text{inv, undet}} < 0.68 \ (68\% \ CL)$
$\text{BR}_{\text{inv, undet}} < 0.84 \ (95\% \ CL)$

SM hypothesis : 35%