ATLAS+CMS Combined Measurement of the Higgs Boson Properties

Eric Feng (CERN)
on behalf of the ATLAS and CMS Collaborations

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Introduction

- Higgs boson is a window into possible new phenomena like SUSY
- ATLAS and CMS have measured together its mass, which is a free parameter, to be about 125 GeV
- Angular distributions consistent with spin 0 and even parity
  - In SUSY, CP is generally violated through loops so 125 GeV state could be CP admixture of light h and heavy A/H
- Crucial to measure Higgs couplings as major deviations predicted in BSM models like SUSY
  - Two Higgs doublets modify direct couplings to massive particles
  - Superpartners modify loop-induced couplings to gluons & photons
  - Higgs may decay invisibly to LSP (dark matter candidate)
- Describe today final ATLAS+CMS combined Run 1 measurements of Higgs couplings that have just been submitted to JHEP: http://arxiv.org/abs/1606.02266
  - Denote 125 GeV state as “H” (not “h”) and will clarify whenever referring explicitly to heavy Higgs instead
Combination of channels

- Combined fit of measurements from all major Higgs production and visible decay modes measured by ATLAS and CMS
  - Include numerous correlations in theory uncertainties, background estimates, experimental systematics, etc (4200 nuisance parameters)
- Production modes mediated by fermions (ggF, ttH) or vector bosons (VBF, VH)
- Measure rates in “units” of SM value: \( \mu_i = \frac{\sigma_i}{\sigma_{i,SM}} \) (SM: \( \mu_i=1 \))
- Measure couplings in “units” of SM value: \( \kappa_i^2 = \frac{\sigma_i}{\sigma_{i,SM}} \) (SM: \( \kappa_i=1 \))
From rates to couplings

- Similarly for branching ratios in main decay modes $\gamma\gamma$, $ZZ$, $WW$, $\tau\tau$, $bb$, $\mu\mu$

- Total width characterized with scale factor: $\kappa_H^2 = \Sigma \kappa_i^2 / (1 - B_{BSM})$
- $B_{BSM}$ is BR for BSM (invisible or undetected) decays

- Example:

\[
(\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}
\]

- Photon and gluon loop-induced couplings can be resolved if desired:

\[
\kappa_\gamma^2 = 1.59\kappa_W^2 - 0.66\kappa_W \kappa_t + 0.07\kappa_i^2
\]

- Relations would be modified if new particles like stops, staus, etc enter loops, so can also consider $\kappa_g$ and $\kappa_g$ as “effective” couplings to be less model-dependent
• ATLAS + CMS combined mass measurement: $m_H = 125.09 \pm 0.24$ GeV
• Using high-resolution $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels

**Mass**

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**ATLAS and CMS**

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS + CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$126.02 \pm 0.51$ GeV ($124.68 \pm 0.34$ GeV)</td>
<td>$124.70 \pm 0.34$ GeV ($124.39 \pm 0.31$ GeV)</td>
<td>$125.07 \pm 0.29$ GeV ($125.00 \pm 0.25$ GeV)</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>$124.51 \pm 0.52$ GeV ($124.29 \pm 0.52$ GeV)</td>
<td>$125.59 \pm 0.45$ GeV ($125.49 \pm 0.42$ GeV)</td>
<td>$125.09 \pm 0.24$ GeV ($125.04 \pm 0.21$ GeV)</td>
</tr>
</tbody>
</table>

**Statistical uncertainty still dominates and can be further reduced in future**
Spin and parity

- Various spin-2 and spin-1 models, as well as a large pseudoscalar fraction, in $H\rightarrow VV$ decays are independently disfavored by both CMS & ATLAS data.
- Thus in couplings analysis, assume single narrow spin-0 CP-even resonance with mass of 125.09 GeV.

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**EPJC 75 (2015) 476**
Production and decay rates

- No significant deviation in rates observed in any individual channel of production and decay
  - Mild excesses for ttH (multileptons) and ZH in decay modes with large statistical uncertainties
- Gluon fusion measurements, e.g. in H->WW decays, starting to approach SM theory uncertainties
  - Overall measured rate for Higgs production and decays dominated by theory uncertainty on inclusive cross-section
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Experimentally robust: Small backgrounds and experimental uncertainties
Ratios of rates or couplings

- Treat all production & decay rates independently to minimize model dependence
  - Measured ratios of them wrt $\sigma(ggF)$ and BR($H\rightarrow ZZ$) to cancel out systematic uncertainties: consistent with SM, again with large stat. unc. in $ttH$ and $ZH$
  - Re-fit fewer couplings to actual particles as ratios to $Z$ and gluon, $\lambda_{ij} = \kappa_i/\kappa_j$

![Graph showing ratios of production or decay rates and re-fit of couplings]
• Simple parametrization $[\kappa_V, \kappa_F]$ with unified couplings to vectors (W, Z) or fermions (t, b, \(\tau\), \(\mu\))
  • Probes Two-Higgs-doublet-model (2HDM) Type I i.e.“Fermiophobic”
  • Fewer parameters enables higher-precision test
• No deviation observed wrt SM
• H\(\rightarrow\gamma\gamma\) channel provides sensitivity to relative sign of vector and fermion couplings through interference of loops in decays to photons
Vector and fermion couplings

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Weak boson couplings

- In MSSM (or more generally, 2HDM Type II) W and Z couplings can be reduced away from “alignment limit” of SM-like couplings
- Ratio of W and Z couplings consistent with SM when tested with \( \sim 10\% \) precision
  - Compatible with alignment, but need not imply that additional Higgs bosons are very heavy (decoupling limit)
- No deviation in absolute W and Z couplings either
b-quark coupling

- At large tan $\beta$, large enhancements to b-quark, $\tau$, and muon couplings
- Measured ratio $B(H\to bb)/B(H\to ZZ)$ using independent production & decay rates to reduce model dependence as before
  - Smaller than expected, but consistent with SM within about 2.5$\sigma$
- After relating couplings to particles (fewer parameters), re-fit ratio of b-quark and Z couplings shows similar agreement with $\sim$25% frac. unc.
- Higher-precision tests possible by reducing parameters further as follows
Fermion couplings

- In MSSM / 2HDM Type II $[\kappa_V, \kappa_d, \kappa_u]$, ratio of down-type (b, \(\tau\), \(\mu\)) and up-type (t) fermion couplings is tested with $\sim 10\%$ precision
- No enhancement observed wrt SM, i.e. consistent with alignment limit

- In 2HDM Lepton-Specific $[\kappa_V, \kappa_l, \kappa_q]$, ratio of lepton (\(\tau\), \(\mu\)) and quark couplings (t, b) would be enhanced at large $\tan \beta$
- Also good agreement with SM
Resolving the gluon fusion loop

- Light stops, sbottoms, etc can enhance gluon fusion production (and also $H \rightarrow gg$ decays) via loops
  - Absorb into effective coupling to gluons, $\kappa_g$
- Ratio of direct top ($ttH$) and loop-induced gluon ($ggF$) couplings, with latter dominated by top in SM
  - Mild excess wrt SM (MSSM predicts deficit), but again consistent within uncertainties
- Very mild preference for relative sign of top quark and gluon couplings from $tH$ and $gg \rightarrow ZH$
- Again precision could be improved by tailoring parameters to specific models
Linearized couplings to massive particles, with resolved loops to g and $\gamma$.

- Test non-linearity $\varepsilon$ and “VEV” normalization parameter $M$ (SM: $\varepsilon=0$, $M\sim 246$ GeV).
- All measurements are consistent with mass dependence expected for SM-like Higgs boson.
Invisible or undetected decays

- Higgs boson may decay invisibly to LSP e.g. lightest neutralino, a dark matter candidate
- Branching ratio for invisible or “undetected” (typically due to low signal-to-background, e.g. H->cc) decays can be tested assuming $|\kappa_V| \leq 1$, which is satisfied in MSSM at tree level
  - No excess observed: $B_{BSM} < 34\%$ at 95\% CL
  - Taking $|\kappa_V| \leq 1$ or $B_{BSM} = 0$, all absolute couplings consistent with SM
Conclusions and outlook

• Final combined ATLAS+CMS Run 1 measurements of Higgs boson couplings submitted to JHEP in arXiv:1606.02266
  • Precision usually better by \(\sim 1/\sqrt{2}\) wrt single experiment
  • Gluon fusion measurements approaching precision of SM theory predictions in some cases
• All rates of Higgs production and visible/invisible decay, couplings, and ratios are consistent with SM within 2.5\(\sigma\) or less
  • But plenty of Higgs coupling parameter space left for BSM deviations in future, which in SUSY are often expected to be small
• Significantly higher precision in many channels, particularly \(\text{ttH}\) and \(\text{VH}\) production, anticipated with higher-energy 13 TeV data
  • Run 2 data flowing in rapidly, so stay tuned for exciting updates on future Higgs property measurements!
EXTRA SLIDES