ATLAS+CMS Combined Measurement of the Higgs Boson Properties

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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, $\mu\mu$

\[ H \rightarrow VV \]
\[ H \rightarrow bb, \tau\tau, \mu\mu \]
\[ H \rightarrow \gamma\gamma \]

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

- Example:

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

- 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:**
  \[ m_H = 125.09 \pm 0.24 \text{ GeV} \]

• Using high-resolution \( H \rightarrow \gamma \gamma \) and \( H \rightarrow ZZ \rightarrow 4l \) channels

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**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 $H\to VV$ 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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- $X(2^+_m) \to ZZ + WW$
- $-2 \ln \left( \frac{L_p}{L_0} \right)$
- CMS: $19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$

**ATLAS**

- Higgs boson couplings
- $H \to ZZ^* \to 4l$
- $\sqrt{s} = 7 \text{ TeV}, 4.5 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$
- $H \to WW^* \to e\nu\mu\nu$

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- CP-odd coupling
- $\left( \frac{\tilde{\kappa}_{AVV}}{\kappa_{SM}} \right) \cdot \tan \alpha$
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

Production and decay rates

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Production & decay rate
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->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, $\lambda_{ij} = \kappa_i/\kappa_j$
• 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
• $H\to\gamma\gamma$ 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 ~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 $B(H-\rightarrow bb)/B(H-\rightarrow ZZ)$ 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->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->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 \( ttH \) and \( VH \) 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