Properties of the Higgs Boson

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On behalf of the CMS and ATLAS Collaborations
One of the goals of the LHC physics program is to unravel the origin of Electroweak symmetry breaking:

Breakthrough: Discovery by CMS and ATLAS of a new boson

With the full Run 1 data (~30/fb) the experiments can test the compatibility of the new boson with the prevailing theory: Standard model Higgs boson

125 GeV: Many available production modes and decay channels to test SM compatibility

FUTURE: 14 TeV SNOWMASS Projections
Standard Model Higgs

free parameter: \(2\sqrt{\mu}=M_H\)

SM Higgs: \(v=\mu/\sqrt{\lambda}=2M_W/g\)

Tree level

\[
V(\phi^+\phi) = \frac{1}{2}(\lambda^2 |\phi|^4 - \mu^2 |\phi|^2)
\]

W, Z

h --- f

\[
g_MW = \frac{gMZ}{\cos \theta_W}
\]

Loop level

Standard

\[
g_M_f = \frac{gM_f}{2M_W}
\]

COMPATIBILITY: Compare the SM prediction to the observed for different quantities:

- signal strength: \(\sigma_{\text{obs}} \times \text{BR}/\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}\)
- coupling scale: \(\kappa \cdot g_{\text{SM}} = g\)

something new?

Presence of non-SM particles in the loop
Combining channels For Mass Measurement

CMS

ATLAS

CMS: $m_H = 125.7 \pm 0.3(sys) \pm 0.3(stat)$

ATLAS: $m_H = 125.5 \pm 0.2(sys)_{+0.5}^{0.6}(stat)$

- For current data: $\Delta m \sim \pm 0.5$ GeV but projections at 300/fb (3000/fb) at 14TeV show $\Delta m \sim 100$ MeV (50 MeV) based on Snolmass projections

- Best fit mass compatible better than 0.1 GeV with the model independent

MODEL DEPENDENT MEASUREMENT

All productions and BR are constrained to the SM predictions.
Combined Signal Strengths

- Simultaneously analyze all selected data across all decay modes and measure the overall deviation from the SM cross-section

ATLAS: Combined $\mu=1.30\pm0.20$

CMS: Combined $\mu=0.80\pm0.14$

- NOW: High sensitivity decay modes basically drive the combination (~15% precision on combined signal strength)
- AT 14TeV: At high luminosity 300/fb, less sensitive decay modes have much smaller uncertainties. The combined signal strength will be even more precise
Production Modes

Combined $\mu=0.80\pm0.14$

- 2D scan: Fermion coupling to Higgs vs. Vector Boson coupling: Each contour is for a different BR/BRSM so difficult to combine
- 1D Scan of ratio: Branching ratio of each decay cancels

ATLAS: $\frac{\mu_{ggF+t\bar{t}H}}{\mu_{VBF+VH}} = 1.2^{+0.7}_{-0.5}$

• Projection of 300/fb to 14TeV predicts a much tighter precision of ~10%
Coupling Scale Factors

Tree level amplitudes:

\[ \sigma \times BR(ii \rightarrow H \rightarrow ff) = \frac{\sigma_f \Gamma_{ff}}{\Gamma_H} \]

\[ \Gamma_{jj} \propto \frac{(m_j \kappa_j)^2}{v^2} \propto \kappa_{jj}^2 \Gamma_{jj}^{SM} \]

channel can be represented as a product of coupling scale factors

Assume: SM tensor structure \( J^P=0^+ \) and SM BR to fermions/Vector bosons:

(common scale factor for all fermions)

\( \kappa_F = \kappa_t = \kappa_b \ldots \)

(common scale factor for all vector bosons)

\( \kappa_V = \kappa_W = \kappa_Z \)

\( \kappa_H = 0.75 \kappa_f^2 \) + \( 0.25 \kappa_V^2 \)

ATLAS \( \kappa_F \in [0.73, 1.07] \) \( \kappa_V \in [1.05, 1.21] \) at 68% C.L.

CMS \( \kappa_F \in [0.61, 1.33] \) \( \kappa_V \in [0.74, 1.06] \) at 95% C.L.
Custodial symmetry: \( W/Z \) coupling to Higgs: \( gZ/gW \approx 1 \)

- Issue is \( \Gamma_{\gamma\gamma} \) depends on \( \kappa W \)
- CMS and ATLAS: Decouple the event rate of \( H \rightarrow \gamma\gamma \) from \( \kappa w/\kappa z \) by introducing additional free parameters in the likelihood

**Probe Loop Corrections:**

\( H \rightarrow \gamma\gamma \quad gg \rightarrow H \)

- Scenario 1 New particles contribute negligibly to the total width: \( \Gamma_{\text{total}} = \Gamma_{\text{SM}} \)
  - Fit \( \kappa g \) \( \kappa \gamma \)
- Scenario 2 Allow new particles to contribute to the total width: \( \Gamma_{\text{total}} = \Gamma_{\text{SM}} + \Gamma_{\text{BSM}} \)
  - Fit \( \kappa g, \kappa \gamma, \Gamma_{\text{BSM}} \)
SUMMARY: Couplings and Total Width

- Ratios of couplings requires no assumption on the total width
- Can include total width including extra contributions:
  \[ \Gamma_H = \Gamma_{SM} + \Gamma_{BSM} \]
  \[ BR_{SM} = \frac{\Gamma_{BSM}}{\Gamma_H} \]
- For 300/fb at 14TeV the statistical uncertainty are below 1%
- Theory systematics most important: QCD scale, pdf uncertainties, BR uncertainties
Spin Hypothesis Test

- Test Spin $0^+$ SM Higgs Hypothesis vs a Spin $2^+_M$ hypothesis.
  - Spin $2^+_M$ use graviton model simulation produced via gluon fusion and quark-antiquark (giving different polarization)

ZZ: Fully reconstructed 4-lepton final state:

WW: Not a fully reconstructed final state but have angles computed from the 2 leptons

MVA classifier is trained with final state observables

**ZZ predictions:**

Rules out $0^-$

Confirms not $1$

(pure gg $2m^+$)

(pure qq $2m^+$)

CMS WW/ZZ Combination: Exclude $2^+_m$ for pure ggH model at $2.84\sigma$
Combined Spin Tests

\( \gamma \gamma \) CS frame: use angle between the photons in the collins-soper frame: Spin 0\(^{+}\) the angular distribution is isotropic as opposed to spin 2

\( \gamma \gamma \) sensitive at low qq’ admixture

WW sensitive at high qq’ admixture

**ATLAS: WW, ZZ, \( \gamma \gamma \)**

- Expected exclusion of spin 2\(^{+} \text{m} \) depends onqq’ very weakly
- Data is consistent with 0\(^{+} \) and 2\(^{+} \text{m} \) is excluded at 99.9 % confidence level
New Studies

Use high signal yield mode: H→γγ to probe kinematic properties of production/decay:

- Extract a signal yield for bins of a kinematic variable
- correct yield for acceptance x efficiency, resolution etc. to compare to theory predictions
- (Left) Compare data to simulation (NLO and NNLO for ggH) Chi2: NLO=0.55 and NNLO=0.39.
- (Right) signal strength in bins of CS angle offers a potentially model independent spin measurement

Flavor changing neutral current: t→c(u)H

- Very good indicator of new physics
- Select tt events with one top in fully hadronic or 1lepton channel
- Use H→γγ search selection
- Br(t→c(u)H)<0.83% (0.53% expected) at 95% confidence
• How compatible is the new boson with the Standard Model?
• Measured properties all compatible with the SM Higgs:
  • Combined signal strengths across all decay modes and also for the different production modes are compatible with SM production
  • Couplings do not deviate from the SM predictions. Custodial symmetry is preserved
  • Data is consistent with $0^+$ spin hypothesis
  • No strong sign of $\Gamma_{BSM}$
• Starting to probe differential signal strengths and directly search for new physics (Flavor Changing Neutral Current)
• All of the above measurements will be much more precise at 14TeV with more data and also smaller theoretical uncertainties
• PUBLIC TWIKI: CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
  ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
Additional Material
Test Statistic

\[ q_\mu = -2 \log \frac{L(\mu, \theta_\mu)}{L(\hat{\mu}, \hat{\theta})} \]

- hypothesis \( \mu, \theta_\mu \) model of uncertainty
- Denominator maximized Likelihood
- Example of Signal + Background hypothesis testing:
  - Red psuedo-data (statistical toys) of signal + background (expected signal predicted by SM cross-section)
  - Blue psuedo-data (statistical toys) background only
  - Observed value is the value that minimizes the the above ratio in data (value of \( \mu, \theta \) most compatible with the data known as the best fit values)
  - Distribution of test statistics follows a \( \chi^2 \) distribution: \( p \)-value obtained by integrating from the obs value to inf. Used to compute the confidence interval

\[ CL_s = \frac{p_s}{1-p_b} \]

- CLs quantifies the significance of the observed value (consistent with a fluctuating background? Or an excess consistent with signal hypothesis
- Can include more than one hypothesis value (increase ndof in the chi2). Here there are two hypotheses variables included in the likelihood: mass, \( \sigma_{\text{obs}}/\sigma_{\text{SM}} \) (signal strength based on SM cross-section)
- CLs corresponding to 68% is the contour around the best fit values (cross)
14TEV PROJECTIONS

• Based on SNOWMASS studies:
  • Extrapolate from current dataset to 300/fb (3000/fb) at 14TeV with the present level of detector performance
  • 2 Scenarios for projected uncertainties:
    • SCENARIO 1: all systematic uncertainties are left unchanged
    • SCENARIO 2: Theoretical uncertainties scale by 1/2 and other systematic uncertainties scale by 1/sqrt(Luminosity) (more optimistic scenario)
Higgs Doublets

- In two Higgs Doublet models the yukawa couplings of fermions to neutral Higgs can be substantially modified
  - MSSM check $u,d$ coupling ratio

- Also in more general scenarios leptons can virtually decouple from the Higgs so test lepton/quark coupling ratio
  - one is within the 68% CL for both

Wednesday, August 14, 2013
8.4 Results

Figure 7: The SM extracted signal yield as a function of $|\cos(\theta^*)|$ for the $+m$ expectation (red line), the $+m$ expectation with gluon/fusion production only (blue line), the $+m$ expectation with quark/antiquark annihilation production only (green line), the $+m$ expectation with half gg, half qq production (magenta line) and the observation (black points).

Table 5: The $\chi^2$ compatibility of the $+m$ and $-m$ models with the observation.

- $\chi^2$ vs $+m$ signal plus background hypothesis with $68%$ gg
- $\chi^2$ vs $+m$ signal plus background hypothesis with $68%$ qq
- $\chi^2$ vs $+m$ signal plus background hypothesis with $68%$ gg, $50%$ qq

The separation between the two models and the data is extracted using the test statistic defined as twice the negative ratio of the likelihoods for the $+m$ signal plus background hypothesis and the $-m$ signal plus background hypothesis when performing a simultaneous fit of all twenty event classes together.

The distribution of this test statistic is shown in Fig. 8 for pseudoexperiments generated with an overall signal yield which is extracted from a fit to the data for the $+m$ hypothesis (orange) and the $-m$ hypothesis (blue) for gluon/fusion production only (left) and quark/antiquark annihilation production only (right). The observed value is shown as the red arrow. The CL S of the observation for the gluon/fusion only spin/¯ production is 6%-96% whilst for the quark/antiquark production it is 6%-96%. Consequently, neither of these spin/¯ models can be excluded.

The previous two tests are both performed assuming that the $-m$ state is produced entirely by either gluon/fusion or quark/antiquark annihilation. A further three points, with mixtures of gg and $q\bar{q}$ spin/¯ production, have been tested such that the overall yield of the $-m$ signal is...
Agreement at low statistics is fair:

\[ \chi^2/\text{ndof} \quad p\text{-value} \]

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\[ \chi^2/\text{ndof} \quad p\text{-value} \]

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