Standard Model of Particle Physics

Higgs Properties

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Big thank you to Prof. S. Lai!
(this is inspired by his lecture)
New particle = SM Higgs boson?

- Interesting mass range, but: What is the mass exactly?
- Observed $H \to$ bosons, what about fermions?
- Spin & couplings?
- Production modes?
Mass Distributions

• High mass resolution: only $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ \rightarrow 4l$ matter

• Low resolution:
  - $H \rightarrow \tau \tau$ and $H \rightarrow WW \rightarrow l\nu l\nu$ suffer from final state neutrinos
  - $H \rightarrow bb$ measured in jets (less precise than photons and leptons)
Mass Distributions

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Measuring the mass: Calibration of inputs

Good understanding the energy/momentum scale for photons, electrons and muons is critical!

- use $Z \rightarrow \mu\mu/ee$, $J/\Psi \rightarrow \mu\mu/ee$ for $\mu$ and $e$ calibration

- also usable for photons + $Z \rightarrow ll\gamma$

- in-depth calorimeter knowledge
The mass spectra

- Use maximum likelihood estimator for $m_H$

- NB: Each channel has more than 1 category (2 plots = simplification!)
ATLAS results

ATLAS measurement (stat. limited!)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass measurement [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$125.98 \pm 0.42$ (stat) $\pm 0.28$ (syst) $= 125.98 \pm 0.50$</td>
</tr>
<tr>
<td>$H \rightarrow ZZllll$</td>
<td>$124.51 \pm 0.52$ (stat) $\pm 0.06$ (syst) $= 124.51 \pm 0.52$</td>
</tr>
<tr>
<td>Combined</td>
<td>$125.36 \pm 0.37$ (stat) $\pm 0.18$ (syst) $= 125.36 \pm 0.41$</td>
</tr>
</tbody>
</table>
CMS ATLAS combination

![Graphs showing mass distributions for ATLAS and CMS combined results for $m_H$ and $m_{\gamma\gamma}-m_{Z'}$]
Mass measurements and electro weak vacuum stability?

Extrapolation to planck scale: is the electro weak vacuum stable? Depends critically on values of $m_{\text{top}}$ and $m_H$.

Still consistent with stable vacuum
Need more precise measurements, e.g. ILC

if meta-stable, maybe life-time of EWV longer than age of universe???
Couplings to bosons AND fermions?

Observation of new particle by ATLAS/CMS decaying to $\gamma\gamma$, $ZZ$, $WW$ (all bosons)

- particle is a boson
- particle couples to vector bosons
- coupling to fermions only indirectly seen in loops:

Search for $H\to ff$ important to establish direct Higgs to fermion couplings!
**H→ff searches**

*Advantage*: large branching ratios

*Disadvantage*: $bb$ and $\tau\tau$ are hard to distinguish from jet background

Use more distinct production processes to decrease backgrounds

**WH/ZH production for $H\rightarrow bb$**

- leptonic or neutrino decay products of W/Z reduce backgrounds

**VBF production for $H\rightarrow \tau\tau$**

- VBF jets (forward & separated) help distinguish signal from background
CMS $H \rightarrow bb$

Main decay modes:
$WH \rightarrow l\nu b$, $ZH \rightarrow l^+l^-bb$, $ZH \rightarrow \nu\nu bb$

Require: 2 b-tagged jets and 1 lepton + $E_T^{miss}$ or oppositely charged lepton pair in $Z$ mass window or large $E_T^{miss}$

Split in categories of $p_T^V (V=W/Z)$, exploit differing signal to background ratios

In each category use BDT to separate signal from background, using $m_{bb}$, $p_T^V$, b-tagging, angular separation
CMS $H \rightarrow bb$

“Hint of a signal” corresponds to $2.1\sigma$

Signal strength $\mu = 1.0 \pm 0.5$
ATLAS $H \rightarrow \tau\tau$

Exploit:
Production ggF and VBF
All tau decay combinations

- categorize events into categories sensitive to ggF and VBF production
- build boosted decision tree based on kinematic variables to separate signal from background
Event categories

VBF category
• 2 high $p_T$ jets
• large separation in $\eta$
• better S/B ratio

Boosted category
• sensitive to ggF events with extra jets
• Higgs at higher $p_T$ to balance jets = “boosted” = taus closer together
Di-tau mass reconstruction

Due to undetected neutrinos mass met fully constrained.
Need to infer through $E_{\text{miss}}$

**Missing Mass calculator (MMC)**
- Assumes $E_{\text{miss}}$ only due to neutrinos
- takes into account the most probable neutrino kinematics to reconstruct di-tau mass

**Typical resolution for $Z \rightarrow \tau \tau$**

<table>
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<tr>
<th>channel</th>
<th>mass resolution</th>
</tr>
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<tbody>
<tr>
<td>lep-lep</td>
<td>16%</td>
</tr>
<tr>
<td>lep-had</td>
<td>16%</td>
</tr>
<tr>
<td>had-had</td>
<td>14%</td>
</tr>
</tbody>
</table>

MMC mass is the most separating in BDT
BDT outputs

Clear excess of data above background prediction

Excess consistent with SM Higgs prediction
Results

Significant excess of events seen across all datasets, channels, categories observed (expected) significance corresponds to $4.5\sigma$ ($3.5\sigma$) best fit signal strength is $\mu = \sigma/\sigma_{SM} = 1.42^{+0.44}_{-0.38}$

CMS: $3.2\sigma$ ($3.7\sigma$) evidence for $H \rightarrow \tau\tau$ decays

CMS/ATLAS combination: $5.5\sigma$  
$\rightarrow$ Discovery!
Signal strength summary

- Signal strength $\mu = \text{measured}/\text{SM}$
- All channels seem to be consistent with the SM expectation

Global ATLAS+CMS:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07} \text{(stat)}^{+0.04}_{-0.04} \text{(expt)}^{+0.03}_{-0.03} \text{(thbgd)}^{+0.07}_{-0.06} \text{(thsig)}$$
Higgs production

Observed @ 5.4\(\sigma\)

not yet @ 5\(\sigma\)
Higgs boson coupling scale factors

Measurements so far are always mixing different production processes, production and decay, and tree vs loop level Higgs couplings, e.g.:

production & decay mix fermion/boson & tree/loop mix

Can separate out effects by using coupling scale factors $\kappa_i$

\[
g_{Hff} = \frac{\sqrt{2m_f}}{v}, \quad g_{HVV} = \frac{2m_V^2}{v} \quad \Rightarrow \quad g_{Hff} = \kappa_f \cdot \frac{\sqrt{2m_f}}{v}, \quad g_{HVV} = \kappa_V \cdot \frac{2m_V^2}{v}
\]

SM: $\kappa_i = 1$
Scale factors

Introduce parameter $\kappa_i$, $\kappa_f$ parametrizing new physics

Example: $ggH \rightarrow \gamma\gamma$

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

$$(\sigma \cdot BR)(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

Also useful to fix parameters to same value:

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_V = \kappa_\tau = \kappa_t$$

E.g. to test boson vs fermion
Higgs boson couplings

Define $\kappa_V$ positive: most processes are not sensitive to relative sign of $\kappa_F$

Destructive interference in $H\rightarrow\gamma\gamma$ decay loop breaks degeneracy
Higgs boson couplings

Define $\kappa_V$ positive: most processes are not sensitive to relative sign of $\kappa_F$

Destructive interference in $H \to \gamma\gamma$ decay loop breaks degeneracy
Higgs boson coupling

\[ \lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} \]
Higgs boson coupling

- Test down-type to up-type fermion coupling
Non-SM contributions?

Effective Higgs-gluon or Higgs-photon couplings can be altered by non-SM contributions in loops.

Consistent with SM.
Spin and parity

- SM Prediction for the Higgs boson: $J^P = 0^+$
- Simple Alternate Hypotheses:
  Pseudoscalar: $J^P = 0^-$
  Vector, Pseudovector: $J^P = 1^-, 1^+$
  Tensor/Pseudotensor: $J^P = 2^{+/−}$
- Complex Alternate Hypotheses: admixture state
  i.e. $|\text{Higgs}⟩ = α |\text{even-parity}⟩ + β |\text{odd-parity}⟩$
- Likelihood ratio (based-upon hypotheses) often
  the final test statistic

NB: Particle is a boson, otherwise decays to $γγ$, $ZZ$, $WW$
(conervation of angular momentum)

Landau-Yang Theorem: $S ≠ 1$ if it decays to di-photon
Collins-Soper Frame

- use Higgs boson rest-frame
- define Collins-Soper axis as bisector between two proton vectors
- Collins-Soper angle: between outgoing photon and axis
- minimizes effect of initial state radiation

\[ |\cos \theta^*| = \frac{|\sinh(\Delta \eta_{\gamma\gamma})| \cdot \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}}{\sqrt{1 + (p_T^{\gamma\gamma} / m_{\gamma\gamma})^2}} \]

Before selection:
S=0: isotropic (flat distribution)
S=2: depends on qq/gg fractions

100% gg : \[ \frac{dN}{d \cos \theta^*} = 1 - 6 \cos^2 \theta^* + \cos^4 \theta^* \]
100% q\bar{q} : \[ \frac{dN}{d \cos \theta^*} = 1 - \cos^4 \theta^* \]

\[ s = 8 \text{ TeV} \]
\[ p_T^{\gamma\gamma} < 125 \text{ GeV} \]
Distributions

Check distributions of $p_T^{\gamma\gamma}$ and $|\cos(\theta^*)|$ high $p_T$ category

Use background subtracted distributions
Form LLH ratio for hypothesis
$H \rightarrow ZZ$

Exploit full angular correlations of decay products, very sensitive to spin/parity of parent particle

Combine kinematics into MV-discriminant
train in different hypotheses
For $s=0$, both charged leptons emitted in same direction preferentially —> can be exploited
Hypothesis testing

Form likelihood ratios for different hypothesis vs the SM one.
Use CL$_S$ (see last week) to exclude

**S=2, universal couplings**
all data point to QNs consistent with the SM Higgs boson
non-SM admixture states not fully excluded
Higgs production and ttH

gluon fusion

vector boson fusion (main mode for $H \rightarrow \tau\tau$)
direct access to Higgs-top quark Yukawa coupling

top associated production  W/Z associated production
ATLAS ttH

Higgs and 2 tops in final state —> spectacular signature

Problem: low cross-section, top pair background

95% observed (expected) limits on signal strength

6.7 (4.9) x SM for tt(H→γγ)
4.1 (2.6) x SM for tt(H→bb)
CMS ttH

5 channels: bb, $\tau\tau$, $\gamma\gamma$, WW, ZZ

Run 1

$\mu = 2.8 \pm 1.0$

p-value: $3.4\sigma$
CMS ttH

5 channels: bb, $\tau\tau$, $\gamma\gamma$, WW, ZZ

Run 1

$\mu = 2.8 \pm 1.0$

p-value: $3.4\sigma$

Run 2

$m_H = 125$ GeV

95% CL upper limit on $\mu = \sigma/\sigma_{SM}$
Fat jets for a light Higgs

Hadronic tops with HEPTopTagger, method from HD theory, applied by HD experiment!
Fat jets for a light Higgs

Hadronic tops with HEPTopTagger, method from HD theory, applied by HD experiment!
Higgs self coupling

- Reminder, Higgs potential:
  \[ \mathcal{L}_{\text{Higgs}} = D_\mu \phi^\dagger D^\mu \phi - V(\phi) \]
  \[ V(\phi) = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{2} (\phi^\dagger \phi)^2 \]

- What are the lambdas?

- After electroweak symmetry breaking can be expanded to:
  \[ V = \frac{1}{2} M_h^2 h^2 + \lambda v h^3 + \frac{\tilde{\lambda}}{4} h^4 \]

- SM expectation: \[ \lambda = \tilde{\lambda} = \frac{M_h^2}{2v^2} \sim 0.13 \] needs to be verified
Self coupling

- $h^3$ term might be measurable at the high luminosity LHC, but need 14TeV and 3 ab$^{-1}$ (= 3000 fb$^{-1}$ !!!)

- Measure SM di-Higgs HH production

- Challenges: small cross section (→ need large BR: $bb$, $WW$, $\tau\tau$), large backgrounds
Total cross-section measurement
Differential measurements ($N_{\text{jet}}$)
Differential measurement ($p_{T}^{H}$)