Latest CMS Higgs

Dmytro Kovalskyi (UCSB)
Discovery

- New particle with ~125 GeV mass
- $5\sigma$ discovery claim from both ATLAS and CMS
- Tevatron: 2.9$\sigma$ excess for Higgs from 115 to 130 GeV
$H \rightarrow ZZ \rightarrow 4 \ell$


TWiki: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki](https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki)
Golden Channel - Signal is Strong

CMS preliminary

- Data
- $m_H = 126$ GeV
- $Z\gamma^*, ZZ$
- $Z+X$

$\sqrt{s} = 7$ TeV: $L = 5.1$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $L = 19.6$ fb$^{-1}$
HZZ Analysis Details

- New with respect to November 2012
  - event categorization based on jet multiplicity
    - probe qqH, VH and ttH production mechanisms
  - improved background estimation methods

- Selection requirements
  - Muon/electron min Pt: 5/7 GeV
  - \( m_{Z1} \in [40, 120] \text{ GeV}; \ m_{Z2} \in [12, 120] \text{ GeV} \)
  - Loose ID and isolation requirements
  - 3D impact parameter significance < 4

- Background estimations
  - \( ZZ, Z\gamma^* \) - irreducible (from Monte Carlo)
    - POWHEG, Madgraph (alternative)
  - \( Z + \) fakes - reducible (data-driven methods)
Signal Strength

- Observed/expected signal significance: $6.7\sigma / 7.2\sigma$
- Cross-section with respect to SM: $\frac{\sigma}{\sigma_{SM}} = 0.91 \pm 0.30 - 0.24$
Mass measurement inputs:

- per-event m_{4\ell}
- per-event mass error
- kinematic discriminant

m = 125.8 \pm 0.5 \text{ (stat.)} \pm 0.2 \text{ (syst.)}
Higgs Production

- **Higgs enriched distributions**
  - $m_{4l}$ in $[121.5, 131.5]$ GeV, signal purity ~ 3:1

- **Category I**: Events with fewer than two jets
  - VBF contribution is 5%

- **Category II**: Events with at least two jets.
  - VBF contribution is 20%
Hypothesis Testing

Table 3: List of models used in analysis of spin-parity hypotheses corresponding to the pure states of the type noted. The expected separation is quoted for two scenarios, when the signal strength for each hypothesis is pre-determined from the fit to data and when events are generated with SM expectation for the signal yield ($\mu=1$). The observed separation quotes consistency of the observation with the $0^+$ model or $J^P$ model, and corresponds to the scenario when the signal strength is pre-determined from the fit to data. The last column quotes $\text{CL}_s$ criterion for the $J^P$ model.

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>production</th>
<th>comment</th>
<th>expect ($\mu=1$)</th>
<th>obs. $0^+$</th>
<th>obs. $J^P$</th>
<th>$\text{CL}_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>$gg \rightarrow X$</td>
<td>pseudoscalar</td>
<td>$2.6\sigma$ ($2.8\sigma$)</td>
<td>$0.5\sigma$</td>
<td>$3.3\sigma$</td>
<td>$0.16%$</td>
</tr>
<tr>
<td>$0^+$</td>
<td>$gg \rightarrow X$</td>
<td>higher dim operators</td>
<td>$1.7\sigma$ ($1.8\sigma$)</td>
<td>$0.0\sigma$</td>
<td>$1.7\sigma$</td>
<td>$8.1%$</td>
</tr>
<tr>
<td>$2^+_{mgg}$</td>
<td>$gg \rightarrow X$</td>
<td>minimal couplings</td>
<td>$1.8\sigma$ ($1.9\sigma$)</td>
<td>$0.8\sigma$</td>
<td>$2.7\sigma$</td>
<td>$1.5%$</td>
</tr>
<tr>
<td>$2^+_{mq\bar{q}}$</td>
<td>$q\bar{q} \rightarrow X$</td>
<td>minimal couplings</td>
<td>$1.7\sigma$ ($1.9\sigma$)</td>
<td>$1.8\sigma$</td>
<td>$4.0\sigma$</td>
<td>$&lt;0.1%$</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$q\bar{q} \rightarrow X$</td>
<td>exotic vector</td>
<td>$2.8\sigma$ ($3.1\sigma$)</td>
<td>$1.4\sigma$</td>
<td>$&gt;4.0\sigma$</td>
<td>$&lt;0.1%$</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$q\bar{q} \rightarrow X$</td>
<td>exotic pseudovector</td>
<td>$2.3\sigma$ ($2.6\sigma$)</td>
<td>$1.7\sigma$</td>
<td>$&gt;4.0\sigma$</td>
<td>$&lt;0.1%$</td>
</tr>
</tbody>
</table>

All results are consistent with SM
H → WW → 2 \ell 2ν

PAS (HIG-13-003): http://cdsweb.cern.ch/record/1523673

TWiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13003TWiki
No mass peak due to undetected neutrinos (effectively a counting experiment)

Proper estimation of backgrounds is vital (data driven for more reliable results)

Dominant backgrounds: WW, top, W+jets and Z+jets

Events are categorized by number of jets and lepton final states (ee + μμ, eμ)
Selection

- Leading/trailing lepton Pt: 20/10 GeV
- Stringent lepton identification
- $\min(\text{projected MET, projected track MET}) > 20 \text{ GeV}$ for $ee/\mu\mu$
- DY MVA for $ee/\mu\mu$

2D shape analysis (mll vs mT)

- Optimal sensitivity for low mass Higgs
- Straight-forward interpretation of data

Nothing fundamentally new with respect to November 2012 update
**Signal Strength**

- Signal Strength:
  \[ \mu(125) = 0.76 \pm 0.13 \text{ (stat.)} \pm 0.16 \text{ (syst.)} \]
  
  - Signal Significance (exp/obs): 5.1σ / 4.0σ

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**Latest CMS Higgs Results**

March 15, 2013

Latest CMS Higgs Results - Dmytro Kovalskyi
**WW Background**

- **WW background estimation is critical**
  - Rely on Monte Carlo to reproduce $m_{ll}$
  - CMS cut-based and ATLAS default analyses use high $m_{ll}$ region to predict WW in signal region
  - The ratio $N_{\text{low}}/N_{\text{high}}$ has theory uncertainty $\sim 10\%$
  - Dominant systematics limiting sensitivity
  - B. Holdom (arXiv:1211.2729) points our significant difference in the ratio of $m_{ll}$ in [10-50] over $m_{ll}$ in [80,290]:
    - MCFM: 0.555, MC@NLO-Herwig6: 0.55, POWHEG-Pythia6: 0.60, Herwig++@NLO: 0.625

- **CMS shape analysis relies on the shape**
  - Fit can vary the shape within the uncertainty bounds
  - Data allows to constrain the shape in regions where WW dominates
  - Less extrapolation is needed $\rightarrow$ small systematics

- **Cross-check - compare results using different shapes**
  - The results are very stable (well within systematic uncertainties)
Spin Analysis

HWVV analysis is designed in a way to easily accommodate spin2 hypothesis testing

- The analysis is sensitive only to minimal couplings spin2

- Expected separation for $\mu = 1 - 2.4\sigma$

- For observed signal strength
  - Expected separation of Spin2 from SM: $1.8\sigma$
  - Observed separation of Spin2 from SM: $1.3\sigma$

- Result is consistent with HZZ results
Search for extra Higgs like particles

- Search for second SM Higgs like particle
- Treat the observed boson as a SM background
- No evidence for new particle is found
No public documentation yet

Morion Talk: http://moriond.in2p3.fr/QCD/2013/ThursdayMorning/Ochando.pptx
Higgs to $\gamma\gamma$

**MVA analysis**  
(default)

- Signature: two isolated energetic photons
- Photon Pt: $m_{\gamma\gamma}/3$ / $m_{\gamma\gamma}/4$ GeV
  - for $m_{\gamma\gamma} = 120$: $40/30$ GeV

**Cut-based analysis**  
(cross-check)
H_{\gamma\gamma} Analysis Details

Signal extraction:
- Split events in categories
  - First tag events with large contributions from VBF and associated productions
  - Categorized untagged events by signal purity
  - Fit for a peak in m_{\gamma\gamma} distributions in each category

MVA analysis
- MVA discriminant (BDT) constructed using
  - photon kinematics
    - relative transverse momenta of both photons (p_T/m_{\gamma\gamma})
    - pseudo-rapidities of both photons
    - \cos(\phi_1 \- \phi_2)
  - photon ID MVA score (shower shape, isolation)
  - di-photon mass resolution
    - depends on probability to pick correct primary vertex
- 4 untagged categories with different S/B

Cut-based analysis
- 4 untagged categories:
  - Barrel / endcap and converted/unconverted from shower shape R9
  - Different mass resolution and S/B among the 4 categories
- 4 MVA analysis has \sim 15\% better sensitivity
Detector Calibration

Photon ID MVA validation on $Z\rightarrow\mu\mu\gamma$

Probability to select correct vertex

Monte Carlo, $p_T(\gamma\gamma)$

Monte Carlo, $N_{vtx}$

Data/MC using $Z\rightarrow\mu\mu$, $p_T(\gamma\gamma)$

Data/MC using $Z\rightarrow\mu\mu$, $N_{vtx}$
ICHEP 2012 vs Moriond 2013

Cross-section: $\sigma / \sigma_{SM} = 1.6 \pm 0.4$
Significance (exp/obs): $2.8\sigma / 4.1\sigma$

Cross-section: $\sigma / \sigma_{SM} = 1.6 \pm 0.4$
Significance (exp/obs): $4.2\sigma / 3.2\sigma$
Comparing Two Analyses

MVA analysis

7+8 TeV: $\sigma/\sigma_{SM} @ 125.0$ GeV = 0.78 $^{+0.28}_{-0.26}$
7 TeV: $\sigma/\sigma_{SM} @ 125.0$ GeV = 1.69 $^{+0.65}_{-0.59}$
8 TeV: $\sigma/\sigma_{SM} @ 125.0$ GeV = 0.55 $^{+0.29}_{-0.27}$

Cut-based analysis

7+8 TeV: $\sigma/\sigma_{SM} @ 124.5$ GeV = 1.11 $^{+0.32}_{-0.30}$
7 TeV: $\sigma/\sigma_{SM} @ 124.5$ GeV = 2.27 $^{+0.80}_{-0.74}$
8 TeV: $\sigma/\sigma_{SM} @ 124.5$ GeV = 0.93 $^{+0.34}_{-0.32}$
What all does it mean?

- Low signal to background ratio a fundamental feature of this channel
  - Uncertainty on signal strength driven by statistical fluctuations of the background
  - Analysis changes can lead to statistical changes due to fluctuations in selected events and their mass
- Correlation between MVA and cut-based measurements is 0.76
  - Estimated using jackknife techniques
- Observed changes in results are all statistically compatible at less than 2σ
- Delay in making results public was caused by additional checks that were requested by CMS Collaboration
  - We found no reasons to believe that either analysis is wrong
  - Results are considered to be solid enough to be made public

<table>
<thead>
<tr>
<th>Test</th>
<th>Signal strength compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVA vs CiC 7+8 TeV</td>
<td>1.5 σ</td>
</tr>
<tr>
<td>MVA vs CiC 8 TeV only</td>
<td>1.8 σ</td>
</tr>
<tr>
<td>Updated MVA vs published (5.3/fb 8TeV)</td>
<td>1.6 σ</td>
</tr>
<tr>
<td>Updated CiC vs published (5.3/fb 8TeV)</td>
<td>0.5 σ</td>
</tr>
</tbody>
</table>
Mass Measurement

**H→ZZ→4l**
- Lepton momentum scale & resolution validated with Z, J/ψ, and γ→ll samples.
- m4l uncertainties due to lepton scale: 0.1% (4µ), 0.3% (4e)

\[
m_H = 125.8 \pm 0.5 \text{ (stat.)} \pm 0.2 \text{ (syst.)}
\]

**H→γγ**
- Systematic errors dominated by overall photon energy scale: 0.47%
  (mostly coming from extrapolation from Z→H and e→γ)

\[
m_H = 125.4 \pm 0.5 \text{ (stat.)} \pm 0.6 \text{ (syst.)}
\]

Measurements in the two channels are well compatible.
\( H \rightarrow \tau \tau \)

No public documentation yet, only talks:

https://indico.in2p3.fr/getFile.py/access?contribId=57&sessionId=6&resId=0&materialId=slides&confId=7411

http://moriond.in2p3.fr/QCD/2013/ThursdayMorning/Puigh.pdf
Analysis Strategy

- **Final states**: $\mu\tau, e\tau, e\mu, \tau\tau, \mu\mu$
- **Mass reconstruction - SVFit**
  - under-constrained ML fit using a matrix element to compute likelihood of the leptonic tau decays
- **Use multivariate regression to avoid PU related resolution degradation**
- **Event Classification**
  - by number of jets and Higgs Pt
Mass Distributions

$\mu\tau_h$ (VBF) - one of most sensitive channels

Weighted multi-channel distribution

$\mu\tau_h$ 2 jet (VBF)
Results

Signal significance: $2.9\sigma$

$\sigma/\sigma_{SM} = 1.1 \pm 0.4$
Mass Measurement

CMS Preliminary, $H \rightarrow \tau\tau, L = 24.3 \text{ fb}^{-1}$

$\mu_{\text{best-fit}}$

$\Delta(-\ln L)$

$\sigma$

$1\sigma$

$2\sigma$

$m_H = 120 + 9 - 7 \text{ GeV}$
$H \rightarrow bb$

Last update November 2012

PAS (HIG-12-044): http://cdsweb.cern.ch/record/1493618

TWiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12044TWiki
Analysis Overview

- Hbb events reconstructed only in association with W and Z decaying leptonically
  - Dominant backgrounds: Wjets, Zjets, Top
- Analysis Strategy - use MVA to get best Signal/Background separation
  - rely on boosted W/Z and Higgs
  - b-jet energy regression helps improve resolution

March 15, 2013
Results

- Observed (expected) limit of 2.5 (1.2) x SM at 125 GeV
- Observed (expected) local significance of 2.2\(\sigma\) (2.1\(\sigma\)) for \(m_H = 125\) GeV
- Combined best-fit \(\mu = 1.3^{+0.7}_{-0.6}\)
Expected Sensitivity with 300/fb

CMS Projection

Without theory uncertainties

With theory uncertainties

68%CL

95%CL

Expected uncertainties on Higgs boson signal strength $\mu$

Boxes show current results

H → $\gamma\gamma$
H → ZZ
H → WW
H → $\tau\tau$
H → bb

March 15, 2013

Latest CMS Higgs Results - Dmytro Kovalskyi
Summary

- LHC delivered good quality data
  - ~25/fb of data at 7-8 TeV
  - Higgs results look extremely good
- Signal Strength ($\sigma/\sigma_{SM}$):
  - $H \rightarrow ZZ \rightarrow 4l$: $0.91^{+0.30}_{-0.24}$
  - $H \rightarrow WW \rightarrow 2l2\nu$: $0.76 \pm 0.21$
  - $H \rightarrow \gamma\gamma$: $0.78^{+0.28}_{-0.26}$
  - $H \rightarrow \tau\tau$: $1.1 \pm 0.4$
  - $H \rightarrow bb$: $1.3^{+0.7}_{-0.6}$
- Looks like the new boson is the Standard Model Higgs
Backup Slides
Matrix Element

- 5 angles, $M_{Z1}$, $M_{Z2}$
- transverse momentum of the four-lepton system
Hzz Hypothesis Testing 2

Figure 13: Distributions of $D_{JP}$ with a requirement $D_{bkg} > 0.5$. Distributions in data (points with error bars) and expectations for background and signal are shown. Six alternative hypotheses are tested from top to bottom and left to right: $J^P = 0^-, 0^+_h, 1^-, 1^+_m, 2^+_m(gg), 2^+_m(q\bar{q})$. 

March 15, 2013  Latest CMS Higgs Results - Dmytro Kovalskyi
Figure 14: Distribution of $q = -2 \ln(\mathcal{L}_p / \mathcal{L}_{SM})$ for two signal types ($0^+$ represented by the yellow histogram and alternative $J^P$ hypothesis by the blue histogram) for $m_H = 126$ GeV shown with a large number of generated experiments. The arrow indicates the observed value. Six alternative hypotheses are tested from top to bottom and left to right: $J^P = 0^-, 0^+_h, 1^-, 1^+, 2^+_m, 2^+_m$. 

Latest CMS Higgs Results - Dmytro Kovarskyi
Higgs to bb

- Most challenging channel
  - Higgs is searched in associated production WH, ZH to control QCD bb background
  - Events are categorized by W/Z pt and its decay channel, i.e. ℓ ℓ, vv, ℓ v
  - Dominant backgrounds: V+bjets, Top

March 15, 2013

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Exploring Couplings

Effective Lagrangian approach: SM + “anomalous couplings”

- Kinematic distributions are likely to be modified
- In the simplest model one can looks for deviations only in coupling strength

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

For Standard Model \(\kappa = 1\)

### Production modes

- \(\sigma_{ggH}/\sigma_{ggH}^{\text{SM}} = \left\{ \begin{array}{l} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g \end{array} \right\} \) (3)
- \(\sigma_{VBF}/\sigma_{VBF}^{\text{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)\) (4)
- \(\sigma_{WH}/\sigma_{WH}^{\text{SM}} = \kappa_W^2\) (5)
- \(\sigma_{ZH}/\sigma_{ZH}^{\text{SM}} = \kappa_Z^2\) (6)
- \(\sigma_{ttH}/\sigma_{ttH}^{\text{SM}} = \kappa_t^2\) (7)

### Detectable decay modes

- \(\Gamma_{WW^{(*)}}/\Gamma_{WW^{(*)}}^{\text{SM}} = \kappa_W^2\) (8)
- \(\Gamma_{ZZ^{(*)}}/\Gamma_{ZZ^{(*)}}^{\text{SM}} = \kappa_Z^2\) (9)
- \(\Gamma_{bb}/\Gamma_{bb}^{\text{SM}} = \kappa_b^2\) (10)
- \(\Gamma_{\tau^{-}\tau^{+}}/\Gamma_{\tau^{-}\tau^{+}}^{\text{SM}} = \kappa_\tau^2\) (11)
- \(\Gamma_{YY}/\Gamma_{YY}^{\text{SM}} = \left\{ \begin{array}{l} \kappa_Y^2(\kappa_b, \kappa_t, \kappa_{\tau}, \kappa_W, m_H) \\ \kappa_Y \end{array} \right\} \) (12)
- \(\Gamma_{Z\gamma}/\Gamma_{Z\gamma}^{\text{SM}} = \left\{ \begin{array}{l} \kappa_{Z\gamma}^2(\kappa_b, \kappa_t, \kappa_{\tau}, \kappa_W, m_H) \\ \kappa_{Z\gamma} \end{array} \right\} \) (13)
Benchmark Parametrization

- A number of parameterizations can be derived with different assumptions
  - LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle (arXiv:1209.0040)

- Simplest model - common scale factor:
  \( K = K_t = K_b = K_T = K_W = K_Z \)
  - ATLAS: \( \kappa = 1.4 \pm 0.3 \)
  - CMS: \( \kappa = 0.87 \pm 0.23 \)

- Scaling of vector boson and fermion couplings
  - Higgs can play a different role in vector boson and fermion sectors

### Boson and fermion scaling assuming no invisible or undetectable widths

<table>
<thead>
<tr>
<th></th>
<th>( H \rightarrow \gamma\gamma )</th>
<th>( H \rightarrow ZZ^* )</th>
<th>( H \rightarrow WW^* )</th>
<th>( H \rightarrow bb )</th>
<th>( H \rightarrow \tau^-\tau^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ggH )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2 (\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2 (\kappa_t)} )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_t)} )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_t)} )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_t)} )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_t)} )</td>
</tr>
<tr>
<td>( t\bar{t}H )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2 (\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2 (\kappa_t)} )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_t)} )</td>
<td>( \frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_t)} )</td>
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<td>( \frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_t)} )</td>
</tr>
<tr>
<td>( VBF )</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>( WH )</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>( ZH )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Spin Study Hypotheses

TABLE I: List of scenarios chosen for the analysis of the production and decay of an exotic $X$ particle with quantum numbers $J^P$. The subscripts $m$ (minimal couplings) and $h$ (couplings with higher-dimension operators) distinguish different scenarios, as discussed in the last column. The spin-zero and spin-one $X$ production parameters do not affect the angular and mass distributions, and therefore are not specified.

<table>
<thead>
<tr>
<th>scenario</th>
<th>$X$ production</th>
<th>$X \rightarrow VV$ decay</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_{m}$</td>
<td>$gg \rightarrow X$</td>
<td>$g_1^{(0)} \neq 0$ in Eq. (9)</td>
<td>SM Higgs boson scalar</td>
</tr>
<tr>
<td>$0^+_{h}$</td>
<td>$gg \rightarrow X$</td>
<td>$g_2^{(0)} \neq 0$ in Eq. (9)</td>
<td>scalar with higher-dimension operators</td>
</tr>
<tr>
<td>$0^-$</td>
<td>$gg \rightarrow X$</td>
<td>$g_4^{(0)} \neq 0$ in Eq. (9)</td>
<td>pseudo-scalar</td>
</tr>
<tr>
<td>$1^+_{m}$</td>
<td>$q\bar{q} \rightarrow X$</td>
<td>$b_2 \neq 0$ in Eq. (16)</td>
<td>exotic pseudo-vector</td>
</tr>
<tr>
<td>$1^+_{h}$</td>
<td>$q\bar{q} \rightarrow X$</td>
<td>$b_1 \neq 0$ in Eq. (16)</td>
<td>exotic vector</td>
</tr>
<tr>
<td>$2^+_{m}$</td>
<td>$g_1^{(2)} \neq 0$ in Eq. (18)</td>
<td>$g_1^{(2)} = g_5^{(2)} \neq 0$ in Eq. (18)</td>
<td>graviton-like tensor with minimal couplings</td>
</tr>
<tr>
<td>$2^+_{h}$</td>
<td>$g_4^{(2)} \neq 0$ in Eq. (18)</td>
<td>$g_4^{(2)} \neq 0$ in Eq. (18)</td>
<td>tensor with higher-dimension operators</td>
</tr>
<tr>
<td>$2^-_{h}$</td>
<td>$g_8^{(2)} \neq 0$ in Eq. (18)</td>
<td>$g_8^{(2)} \neq 0$ in Eq. (18)</td>
<td>“pseudo-tensor”</td>
</tr>
</tbody>
</table>
$\textbf{Higgs } \rightarrow \textbf{WW } \rightarrow 2l2\nu$

- **Higgs Signature:**
  - 2 isolated leptons (electron or muon)
  - large missing energy
- **Sensitivity:** low and high mass
- Highest rate with manageable background
- Counting experiment, no mass peak

Electron  Electron

Missing Energy (neutrinos)
Analysis Challenges

- No mass is reconstructed - essentially a **counting experiment**
- Key selection requirements:
  - lepton $pt > 10$ GeV with tight identification and isolation - **QCD, Wjets**
  - large missing transverse energy (MET) and Z veto - **Drell-Yan**
  - number of jet classification ($Pt > 30$ GeV) and b-quark veto - **Top**
  - kinematics ($m_\ell$, $d\phi$) - **WW**
- Final step selection requirements are optimized for different Higgs mass hypotheses

[Graph showing Cross-section x Branching Ratio (fb) for Wjets, Drell-Yan, Top, WW, Higgs 160]
Analysis Challenges

- No mass is reconstructed - essentially a counting experiment
- Underestimation of any background can lead to a signal like excess!
  - Background estimation is the most important part of the analysis
Wjets

- Jets - main source of fakes
- Requirements: pt, isolation, impact parameter, quality
- Tight → Loose: 10-100 time more fake leptons
- Use QCD sample to measure fake rate: \( \varepsilon = \frac{N_B}{N_A} \)
- Background estimation:
  \[
  N_D = N_C \frac{\varepsilon}{1 - \varepsilon}
  \]

Systematic uncertainty of the method: \( \sim 35\% \)
Missing Energy with PileUp

- **2011 data differs from 2010:**
  - ~8 interactions per bunch crossing
  - larger tails in the missing energy distribution
- **Two different MET variables:**
  - nominal - calorimeter and tracker
  - only tracker based MET
    - not affected by pile up
- **pfMET and trkMET are weakly correlated for backgrounds**
  - use the smaller one for each event
  - minMet>40 (same flavor)
  - minMet>20 (opposite flavor)
Drell-Yan Estimation

- Drell-Yan: $ee/\mu\mu$, but not $e\mu$
- Use $e\mu$ events to subtract backgrounds
- Narrow Z-peak - little background
- Rout/in is measure both in simulation and in data
- Systematic uncertainties can be as large as 100%
Top Background

Jet veto kills top

Remaining top can be tagged:
- soft b-jets
- soft muons

Top tagging eff is \(~50\%\) for 0-jet

Estimate residual top:

\[
N_{top} = N_{tag} \frac{\varepsilon}{1 - \varepsilon}
\]

- Measure \(\varepsilon\) in 1-jet events
- There must be another b-quark
- Systematics \(~20\%-30\%)
**WW Background**

- **WW is an irreducible background** - one order of magnitude larger SM Higgs
- **Kinematics is the main discriminator:**
  - low mass - dPhi, Mll
    - for mH ≤ 130 need to lower lepton pt → larger Wjets background
- above 200GeV - WW and Higgs harder to distinguish
- **Use signal free events to calibrate WW yield**