The Standard Model at the LHC

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\( p \rightarrow \star \rightarrow p \sqrt{s} = 8 \text{ TeV} \)
LHC and Luminosity

2011 peak luminosity 3.65 nb⁻¹/s: ~37 W->lv events/s

<table>
<thead>
<tr>
<th>year</th>
<th>√s [TeV]</th>
<th>L [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>0.9-2.36</td>
<td>10⁻¹¹</td>
</tr>
<tr>
<td>2010</td>
<td>7</td>
<td>0.05</td>
</tr>
<tr>
<td>2011</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>2012</td>
<td>8</td>
<td>15?</td>
</tr>
</tbody>
</table>
The Price for high Luminosity: Pileup

\[ \mu = \frac{n_1 n_2}{2\pi \sum_x \sum_y \sigma_{inel}} \]
Outline

Inelastic interactions

Jets

W and Z bosons

Top quark

Higgs Boson
- Growth with energy as anticipated
Jet Cross Sections

- Data well described by SM prediction both for light and heavy flavor jets
W and Z boson production

- Experimental Precision 4.1%
  - Luminosity: 3.4%, other: 2.2%
W and Z boson production

CMS Preliminary

$\gamma^*/Z \rightarrow \mu\mu$

4.5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV

Data (μ, 4.5 fb$^{-1}$ in 2011)

NNLO, FEWZ+MSTW08

$1/\sigma_{Z} \cdot d\sigma/dM(\mu\mu)$ [GeV$^{-1}$]

$M(\mu\mu)$ [GeV]

Combined $ee+\mu\mu$

- Data 2010
- RESBOS
- FEWZ $O(\alpha_s^3)$
- PYTHIA

$|\eta| < 2.4$

$p_T > 20$ GeV

$66$ GeV $< m_\ell < 116$ GeV

ATLAS

$\int L dt = 33-36$ pb$^{-1}$

$Z \rightarrow l^+l^-$

Theory/Data

CMS preliminary

4.7 fb$^{-1}$ at $\sqrt{s} = 7$ TeV

$IYI=0-1$

$p_T(e) > 35$ GeV

$W \rightarrow e\nu$

CMS preliminary

840 pb$^{-1}$ at $\sqrt{s} = 7$ TeV

Electron Charge Asymmetry

$MCFM$: CT10, HERAPDF1.5, MSTW2008LO, NNPDF2.2 (NLO)

theory bands: 68% C.L.
Tau polarisation in W decays

\[ P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1.06 \pm 0.04 \text{ (stat)} \pm 0.05 \text{ (syst)} \]

- Interesting handle for new physics searches
W/Z + Jets Production

Z + n jets

W + n jets

\( \sigma(Z + n \text{ jets}) \)

\( \sigma(W + n \text{ jets}) \) [pb]

\[ \int L dt = 36 \text{ pb}^{-1} \]

Anti-\( k_T \) jets, \( R=0.4 \)

\( p_T^{\text{jet}} > 30 \text{ GeV}, |y|^{\text{jet}}<4.4 \)
Top Quark: Inclusive Cross Section

- Experimental precision 6%!
The top quark: a closer look
Higgs Production at the LHC

$LHC$ Higgs Cross Section Working Group

$\sqrt{s} = 7$ TeV

$\sigma(pp \to H+X) \ [pb]$ vs $M_H \ [GeV]$
Cross Section x Branching Ratio

- Low mass region:
  - $ZZ^* \rightarrow 4$ leptons
  - $\gamma\gamma$
  - $WW \rightarrow l\nu l\nu$
  - $\tau\tau$
  - $WH \rightarrow Wbb$
H-$\rightarrow$WW-$\rightarrow$llll Search

- For $m_H=$130 GeV: $\sigma \times BR = 170$ fb $\Rightarrow$ 850 events / 5 fb$^{-1}$
- Main backgrounds:
  - WW, ttbar and Drell-Yan production
  - Understanding of $E_T^{\text{miss}}$ and low $p_T$ jets critical
- Simple cut based analysis done by both ATLAS and CMS
  - CMS also does multivariate analysis
Final discriminating variable is
- ATLAS: transverse mass of leptons and $E_{t}^{\text{miss}}$: $m_t$
- CMS has 2 analysis: $m_t$ or Boosted Decision Tree Classifier

Data agree with background expectation
- CMS excludes 129<m_H<270 GeV
  – Expected 127<m_H<270 GeV
- ATLAS excludes 130<m_H<260 GeV
  – Expected 127<m_H<234 GeV
Higgs decaying to two photons

- \( \sigma \times BR = 43 \text{ fb} \Rightarrow 215 \text{ evts/5fb}^{-1} \text{ for } m_H = 120 \text{ GeV} \)
  - 70 events expected after reconstruction and event selection

- But large background from prompt diphoton events and from jets with leading \( \pi^0 \)'s
  - Signal/Background \( \approx 3\% \) (\( \approx 70/2300 \))
Rejection of $\pi^0 \rightarrow \gamma\gamma$ Background

- Fine segmentation of strip layer in LAr calorimeter in $\eta$-direction
  - Designed to reject precisely this background
  - Also used to estimate background composition

- $71 \pm 5\%$ of background from irreducible prompt diphoton production
ATLAS Analysis Strategy

- Events with two isolated photon candidates selected:
  - $E_T(\gamma_1)>40$ GeV
  - $E_T(\gamma_2)>25$ GeV
- Isolation cut:
  - $E_T<5$ GeV in 0.4 cone around photon
- Divide sample into 9 categories:
  - Converted versus unconverted
  - High $p_T(\gamma\gamma)$ versus low $p_T(\gamma\gamma)$
  - Different $\eta$ regions

<table>
<thead>
<tr>
<th>Examples of categories</th>
<th>FWHM (GeV)</th>
<th>Signal</th>
<th>S/BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unc. low pt central</td>
<td>3.4</td>
<td>7.3</td>
<td>0.051</td>
</tr>
<tr>
<td>Unc high pt central</td>
<td>3.3</td>
<td>3.3</td>
<td>0.117</td>
</tr>
<tr>
<td>Conv. Low pt central</td>
<td>3.9</td>
<td>4.7</td>
<td>0.038</td>
</tr>
<tr>
<td>Conv. transition</td>
<td>5.8</td>
<td>5.9</td>
<td>0.014</td>
</tr>
<tr>
<td>Unc. Low pt other</td>
<td>4.1</td>
<td>13.5</td>
<td>0.023</td>
</tr>
<tr>
<td>Conv. Low pt other</td>
<td>4.7</td>
<td>14.0</td>
<td>0.017</td>
</tr>
</tbody>
</table>
CMS Analysis Strategy

- Events with two isolated photons selected
- Events categorized by Boosted Decision Tree (BDT)
  - Each category has different signal/background and resolution
  - Vector-Boson-Fusion is separate category
Diphoton Mass Resolution

**CMS**
\[ \sigma(M) = 1.2 - 2.5 \text{ GeV} \]

**ATLAS**
\[ \sigma(M) = 1.4 - 2.3 \text{ GeV} \]
Overall Diphoton Mass Distribution

Inclusive diphoton sample
- Data 2011
- Background model
- SM Higgs boson $m_H = 120$ GeV (MC)

$\sqrt{s} = 7$ TeV, $\int L dt = 4.9$ fb$^{-1}$

ATLAS Preliminary

CMS preliminary
$\sqrt{s} = 7$ TeV $L = 4.76$ fb$^{-1}$

All Categories Combined

Events / (1 GeV/$c^2$)

$1xSM m_H=120$ GeV

Data
Bkg Model
$\pm 1\sigma$
$\pm 2\sigma$
Overall Diphoton Mass Distribution

\( \sqrt{s} = 7 \text{ TeV} \), \( \int L dt = 4.9 \text{ fb}^{-1} \)

CMS preliminary

All Categories Combined

\( m_{\gamma\gamma} \text{ (GeV/c}^2) \)

\( m_{\gamma\gamma} \text{ [GeV]} \)
Most significant excess
- CMS: $m_H=125$ GeV, global (local) significance 1.6$\sigma$ (2.9$\sigma$)
- ATLAS: $m_H=126$ GeV, global (local) significance 1.5$\sigma$ (2.8$\sigma$)
Diphoton signal about $1\sigma$ stronger than SM expectation in both experiments
H→Z*Z→4 leptons

- 125 GeV Higgs: expect ~2 evts/5 fb⁻¹
- ATLAS Selection:
  - 4 leptons with $p_T > 7$ GeV
    - 2 leptons with $p_T > 20$ GeV
  - Leading dilepton mass:
    - $|m_{12} - m_Z| < 15$ GeV
  - Subleading mass from off-shell $Z$ boson at low mass: $m_{34} > 15$ GeV
  - 4-lepton mass resolution:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>4µ</th>
<th>4e</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>1.5%</td>
<td>1.9%</td>
</tr>
<tr>
<td>CMS</td>
<td>1.1%</td>
<td>2.1%</td>
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</table>
Results of 4-lepton search

- High Signal to Background Ratio: ~1
- Will be very interesting to watch develop in 2012 data!
  - Expect ~8 events / 15 fb\(^{-1}\) per experiment for \(m_H = 125\) GeV
H->4 leptons: cross section limits

- Observed limit agrees with expected limit to within $2\sigma$ over full mass range
Combining the Higgs Search Channels

ATLAS 2011 Preliminary

$\int L \, dt \sim 4.6-4.9 \, fb^{-1}, \sqrt{s}=7 \, TeV$
Combined result of Higgs Searches

- At 95% CL:
  - CMS exclude $127.5 < m_H < 600$ GeV
  - ATLAS exclude $110-117.5$ GeV, $118.5-122.5$ GeV and $129-539$ GeV
Combined result of Higgs Searches

- Local significance of excess 2.5σ (ATLAS) and 2.8σ (CMS)
- Global significance for search window 110-145 GeV:
  - 10% (ATLAS) and 4% (CMS)
Contributions of individual channels

- CMS: excess driven by $\gamma\gamma$
- ATLAS: excess driven by $\gamma\gamma$ and $ZZ^*$
- Overall signal strength consistent with SM
  - But also with 50% difference!
Are the data compatible with SM Higgs boson?

ATLAS Preliminary

- Best fit
- $-2 \ln \lambda(\mu) < 1$
- $\int L dt = 4.7 \, fb^{-1}$
- $\sqrt{s} = 7 \, TeV$

$m_H = 125 \, GeV$

CMS Preliminary

- Combined (68%)
- $\sqrt{s} = 7 \, TeV$
- $L = 4.6-4.8 \, fb^{-1}$

H → bb
H → \tau\tau
H → \gamma\gamma
H → WW
H → ZZ
Conclusions and Outlook

- ATLAS and CMS have made many measurements of SM processes
  - All agree with SM expectation
  - Some of high precision => challenge theoretical calculations
- The SM Higgs boson search has entered it’s last round!
  - Nearly entire range $m_H < 600$ GeV excluded at 95% CL
  - It’s mass is either ~125.5 GeV or it does not exist with SM properties
  - Will find out by the end of this year with ~15 fb$^{-1}$ at $\sqrt{s}=8$ TeV

2012:
Peak L=5.7 x 10$^{33}$ cm$^{-2}$s$^{-1}$
Happy Birthday Savas!