Higgs boson searches with tau leptons in CMS

M. Bachtis
University of Wisconsin-Madison
On behalf of the CMS Collaboration

CMS PAS HIG-11-008, HIG-11-009
Introduction

• Tau is the heaviest lepton
  • Higgs couples to mass
  • Violation of lepton universality
    • direct evidence for tau decays of Higgs bosons
• Standard Model (SM)
  • Branching fraction \( (H \rightarrow \tau \tau) \) of ~10% for low Higgs mass
• Minimal Supersymmetric Standard Model (MSSM)
  • Branching fraction \( (\Phi \rightarrow \tau \tau) \) of 10-15% at low \( M_A \)
  • Enhanced at high \( \tan \beta \)
  • Charged Higgs possible
    • \( H^+ \rightarrow \tau \nu \)
• Results are presented for \( H/\Phi \rightarrow \tau \tau \) and \( H^+ \rightarrow \tau \nu \) with 1.1 fb\(^{-1}\) of data
**MSSM (2 doublets/5 Higgs bosons)**

Φ via gluon fusion or associated production with b quarks (σ ~ tan β²)

For $M_{H^+} < M_t$, $t \rightarrow bH$

**SM**

Gluon fusion dominates (irreducible $Z \rightarrow \tau\tau$)

**VBF:** Low cross section $Z \rightarrow \tau\tau$ suppressed

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Hadronic Tau Identification

- Cut based/ using Particle Flow (PF)
- Starts from Jets made of PF candidates
- Creates tau decay mode combinations
  - Reconstructs individual $\rho/\alpha^1$ resonances
  - Introducing strip of EM objects
  - For $\gamma$ conversions
  - Tau energy measured only by the constituents!
- Applies criteria on narrowness, mass and isolation
- Efficiency of ~50% for 20 GeV taus, fakes < 1%
- Efficiency scale factor from data ($\sim 1$ fb$^{-1}$) = 1.00 ± 0.06
- Simple version of the algorithm (using PF) runs on the high level trigger

CMS Preliminary 2010, $\sqrt{s}$=7 TeV, 36 pb$^{-1}$

measured $\tau$ fake rate from jets vs expected $\tau$ efficiency

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VBF $H \rightarrow \tau\tau$ candidate event display

$M_{jj} = 580$ GeV, $\Delta\eta = 3.55$

$\mu P_T = 20$ GeV

$\tau P_T = 69$ GeV

$\text{MET} = 97$ GeV

$\text{jet } P_T = 46$ GeV

$\text{jet } P_T = 177$ GeV

$M_{jj} = 580$ GeV, $\Delta\eta = 3.55$

$\mu P_T = 20$ GeV

$\tau P_T = 69$ GeV

$\text{MET} = 97$ GeV

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$\mu P_T = 20$ GeV

$\tau P_T = 69$ GeV

$\text{MET} = 97$ GeV

$\text{jet } P_T = 46$ GeV

$\text{jet } P_T = 177$ GeV
## Event Preselection

**Analysis is performed using four final states**

<table>
<thead>
<tr>
<th>Final State</th>
<th>Trigger</th>
<th>Offline</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu + \tau )</td>
<td>( \mu(15) + \tau(15/20) )</td>
<td>( \mu , P_T &gt; 15 \text{ GeV}, , \eta &lt; 2.1 ) \small{\text{Opposite charge}}</td>
</tr>
<tr>
<td>E+( \tau )</td>
<td>( e(18) + \tau(20) )</td>
<td>( e , P_T &gt; 20 \text{ GeV}, , \eta &lt; 2.1 ) \small{\text{Opposite charge}}</td>
</tr>
<tr>
<td>E+( \mu )</td>
<td>( \mu(17/8) + e(8/17) )</td>
<td>( \mu , P_T &gt; 20/10 \text{ GeV}, , \eta &lt; 2.1 ) \small{\text{Opposite charge}}</td>
</tr>
<tr>
<td>( \mu + \mu )</td>
<td>( \mu(17) )</td>
<td>( 1^{st} , \mu , P_T &gt; 20 \text{ GeV}, , \eta &lt; 2.1 ) \small{\text{Opposite charge}}</td>
</tr>
</tbody>
</table>

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Neutrinos from taus tend to be collinear to the visible part

- Not the case for W+jets and TTBar
- Define $P_\zeta$ variables (introduced in CDF)
  - Project visible di-tau transverse momentum vector and MET in the bisector axis of the visible products
  - Request collinearity between visible and missing $E_T$ part
Topological requirements

- Neutrinos from taus tend to be collinear to the visible part
  - Not the case for W+jets and TTBar
- Define $P_\zeta$ variables (introduced in CDF)
  - Project visible di-tau transverse momentum vector and MET in the bisector axis of the visible products
  - Request collinearity between visible and missing $E_T$ part
## Event Categorization

Analysis is performed using four categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Conditions</th>
</tr>
</thead>
</table>
| **MSSM(b-tag)** | Require less than 2 jets with \(P_T > 30 \text{ GeV}\)  
Require at least one b-tagged jet with \(P_T > 20 \text{ GeV}\) |
| **SM(VBF)** | Require exactly two jets with \(P_T > 30 \text{ GeV}\), opposite \(\eta\)  
Require \(\Delta \eta(jj) > 3.5\), \(M(jj) > 350 \text{ GeV}\) |
| **MSSM(No b-tag)** | Require less than two jets with \(P_T > 30 \text{ GeV}\)  
Require no b-tagged jets with \(P_T > 20 \text{ GeV}\) |
| **SM(No VBF)** | Require less than two jets with \(P_T > 30 \text{ GeV}\)  
OR two jets failing VBF criteria |
Categorization related variables

- Events / 1.00
- CMS Preliminary
- $1.1 \text{ fb}^{-1}$
- $\tau_\mu \tau_\mu$
- $\tau_\tau$
- $\bar{t}t$
- Electroweak
- Fakes

- Events / 1.00
- CMS Preliminary
- $1.1 \text{ fb}^{-1}$
- $\tau_\tau$
- $\bar{t}t$
- Electroweak
- Fakes

- Events / 0.30
- CMS Preliminary
- $1.1 \text{ fb}^{-1}$
- $\tau_\mu \tau_\mu$

- Events / 0.40
- CMS Preliminary
- $1.1 \text{ fb}^{-1}$
- $\tau_\tau$
- $\bar{t}t$
- Electroweak
- Fakes

- Events / 20.00
- CMS Preliminary
- $1.1 \text{ fb}^{-1}$
- $\tau_\mu \tau_\mu$

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Visible Mass after all requirements ($\mu + \tau$)

**No b-tag**

- **Background**
  - No-VBF: $15544 \pm 685$
  - VBF: $14.2 \pm 4.0$

- **Observed**
  - No-VBF: $15988$
  - VBF: $18$

**No b-tag**

- **Background**
  - No-VBF: $14514 \pm 640$
  - VBF: $193 \pm 13$

- **Observed**
  - No-VBF: $15067$
  - VBF: $243$

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Visible Mass after all requirements (e+τ)

**MSSM**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>No-VBF</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No b-tag</td>
<td>9980 ± 302</td>
<td>10787</td>
</tr>
<tr>
<td>VBF</td>
<td>5.9 ± 2.5</td>
<td>7</td>
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</tbody>
</table>

**SM**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>No btag</th>
<th>Btag</th>
</tr>
</thead>
<tbody>
<tr>
<td>No VBF</td>
<td>9398 ± 320</td>
<td>10283</td>
</tr>
<tr>
<td>VBF</td>
<td>105 ± 9</td>
<td>101</td>
</tr>
</tbody>
</table>
Visible Mass after all requirements (e+\mu)

| No b-tag |  | b-tag |
|----------|------------------|
| **No-VBF** | Background: 4251 ± 151 | Obs.: 4517 |
|                | VBF: 6.7 ± 0.9 | **2** |
| **No btag** | 3643 ± 131 | **3942** |
| **Btag**     | 150 ± 12        | **143** |

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Visible Mass after all requirements ($\mu+\mu$)

<table>
<thead>
<tr>
<th>Category</th>
<th>No-VBF</th>
<th>VBF</th>
<th>No b-tag</th>
<th>Btag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>17392 $\pm$ 117</td>
<td>17596</td>
<td></td>
<td></td>
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<tr>
<td>Obs.</td>
<td>17596</td>
<td>103</td>
<td>15711</td>
<td>479</td>
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</tbody>
</table>

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Background estimation and systematics

- \( Z \rightarrow \tau\tau \) and \( \text{TTbar} \) : irreducible
  - Estimated from CMS \( \sigma(Z) / \sigma(\text{ttbar}) \)

- Data driven estimation for QCD/W+jets
  - OS/SS+W sideband for \( l+\tau \)
  - Fake rate for \( e+\mu \)

- Constrained fit performed to extract signal cross section or set limit
  - Background and systematic uncertainties as nuisance parameters
  - Shapes from data(QCD) or MC
    - Shape agreement checked in sideband regions
    - MC shapes allowed to vary in the fit

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton ID /trigger</td>
<td>1%</td>
</tr>
<tr>
<td>Tau ID efficiency</td>
<td>6%</td>
</tr>
<tr>
<td>Tau energy scale</td>
<td>3%</td>
</tr>
<tr>
<td>( \sigma(Z \rightarrow \mu\mu/ee) )</td>
<td>3%</td>
</tr>
<tr>
<td>( \sigma(\text{ttbar}) )</td>
<td>12%</td>
</tr>
<tr>
<td>B-Tag Efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>B-Tag Mistag rate</td>
<td>14%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2-5%</td>
</tr>
<tr>
<td>PDFs</td>
<td>3%</td>
</tr>
<tr>
<td>UE/Parton Shower</td>
<td>4%</td>
</tr>
<tr>
<td>QCD Scale</td>
<td>4-12%</td>
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<tr>
<td>Luminosity</td>
<td>6%</td>
</tr>
</tbody>
</table>
MSSM Higgs search results

• No significant excess observed in MSSM search
• Limits set on cross section $\sigma \times \text{BR}(\Phi \rightarrow \tau \tau)$
• Using CLs method
• $\sigma \times \text{BR}$ Limit not model independent
  • MSSM specific
  • $bbH/ggH$ cross section ratio constrained to the ratio in MSSM
    • $\tan \beta = 30$
    • Changes with $M_A$
SM Higgs search results

- Expect to exclude <10x SM at low mass region
- Observed compatible with expectation
- Included in the CMS grand combination
- Achieved much better sensitivity compared to projections
  - Tau ID / Trigger improvements
- Full analysis potential not exploited yet
Light Charged Higgs search
Final states

**Fully Hadronic**
- Trigger
  - $\tau$ ($p_T$ > 40 GeV, $\eta$ < 2.3 (1 prong))
  - At least 3 jets $p_T$ > 30 GeV
  - MET > 70 GeV
  - One b-tag

**$\mu$+\tau**
- Trigger
  - $\mu$ ($p_T$ > 20 GeV, $\eta$ < 2.1)
  - $\tau$ ($p_T$ > 20 GeV, $\eta$ < 2.4)
  - At least 2 jets $p_T$ > 30 GeV
  - MET > 40 GeV
  - One b-tag

**$\mu$+e**
- Trigger
  - $e$ ($p_T$ > 20, $\eta$ < 2.4)
  - At least 2 jets $p_T$ > 30 GeV

$\sqrt{s} = 7$ TeV, 1.08 fb$^{-1}$ CMS Preliminary

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Background estimation

- **Fully hadronic**
  - QCD multijet background from data
  - EWK +tt with real taus estimated with embedding on muon events
  - EWK+ tt with fake taus by simulation

- **μ+τ**
  - QCD estimated by tau fake rate method
  - Other backgrounds from simulation

- **e+μ**
  - Ttbar background dominant
  - Estimated from simulation
Branching fraction limits

**Fully hadronic**

\[ \text{BR}(t \rightarrow bH) \approx 5\%! \]

**μ+τ**

**μ+e**

**Combined**
CMS statement on the MSSM with 1.1 fb$^{-1}$

- $H^+$ contributes at low $M_A$, $H \rightarrow \tau\tau$ drives the sensitivity
- Excluding MSSM at $\tan\beta \sim 15$ for low $M_A$
- Opening new regime at high $M_A$
- Huge improvement wrt the Moriond result
  - B-tagging/tau ID efficiency and more data!
Conclusions

• Results have been presented on SM/MSSM Higgs searches with taus using 1.1 fb$^{-1}$ of CMS data
  - Thanks to the excellent performance of LHC and CMS

• Results set new stringent limits in MSSM parameter space

• First results on SM Higgs in di-tau final state are very promising
Background estimation (l+ ℹ️)

- Dominant backgrounds: QCD/W+jets
- W extrapolated from low $P_\tau$ region ($P_\tau$ < -40)
  - Separately for OS/SS (6% systematic for extrapolation factor)
- Z +jets backgrounds estimated from CMS measurement corrected for $l \to ℹ️$ and $j \to ℹ️$ fake rates
- TTBar from CMS measurement, Diboson from MC (30% uncertainty)
- In SS region W and other backgrounds are subtracted (QCD remaining)
- QCD extrapolated to OS region by a factor from data (~1.06 ± 5%)
Particle Flow Reconstruction

Particle Flow (PF) algorithm
- Combines information from all sub-detectors
- Provides unique event description
  - Particles

PF candidates used in this analysis
- Tau Identification
- Jet Reconstruction
- Missing $E_T$ reconstruction
- Lepton Isolation

Light version of PF algorithm also running in the High Level Trigger
- Crucial for tau triggers
  - Tau energy measured online with PF
  - Small turn on effects
Acceptance x Efficiency vs mass

- $bb \to \phi$ (MSSM)
- $gg \to \phi$ (MSSM)

BTag Category

- $qq \to H$ (SM)
- $gg \to H$ (SM)

VBF Category

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Tau ID efficiency

<table>
<thead>
<tr>
<th>Uncertainty’s source</th>
<th>HPS combined loose $\Delta \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon Momentum Scale</td>
<td>&lt;&lt; 1%</td>
</tr>
<tr>
<td>$\tau$-Jet Energy Scale</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Track Reconstruction</td>
<td>3.9%</td>
</tr>
<tr>
<td>Track Momentum Scale</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Lead. Track $P_T$ Cut</td>
<td>1%</td>
</tr>
<tr>
<td>Loose Isolation</td>
<td>2.5%</td>
</tr>
<tr>
<td>Jet $\rightarrow \tau_{had}$ Fakes</td>
<td>1.2%</td>
</tr>
<tr>
<td>Lead. Track Corr. Factor</td>
<td>1.7%</td>
</tr>
<tr>
<td>Loose Iso. Corr. Factor</td>
<td>2.1%</td>
</tr>
<tr>
<td>Fit (Statistical Uncertainty)</td>
<td>2.6%</td>
</tr>
<tr>
<td>Sum</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

Tag and probe applied in 1fb$^{-1}$ of data
New uncertainty is 6%!
Triggers are using Particle Flow

Energy of Tau in high level trigger is created only by the PF constituents

- Consistent with offline tau
- Small turn on effects

CMS Preliminary 2011
\( \sqrt{s} = 7 \text{ TeV} \)
\( \int L = 721 \text{ pb}^{-1} \)

LooseisoPFTau20
SM H Limits: Channel by channel

Expected

- $\tau_\mu \tau_h$
- $\tau_e \tau_h$
- $\tau_e \tau_\mu$
- $\tau_\mu \tau_\mu$
- Combined

Observed

- $\tau_\mu \tau_h$
- $\tau_e \tau_h$
- $\tau_e \tau_\mu$
- $\tau_\mu \tau_\mu$
- Combined

Expected $\sigma_{95\% \text{CLs}} / \sigma_{\text{SM}}$

Observed $\sigma_{95\% \text{CLs}} / \sigma_{\text{SM}}$

m$_H$ [GeV]

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MSSM Limits: Channel by channel

Expected

Observed

$\sigma \times BR(\phi \rightarrow \tau \tau)$

$\sigma \times BR(\phi \rightarrow \tau \tau)$

$10^3$

$10^2$

$10^1$

$10^{-1}$

$m_A [\text{GeV}]$

$m_A [\text{GeV}]$

$100$ $150$ $200$ $250$ $300$ $350$ $400$ $450$ $50$

$100$ $150$ $200$ $250$ $300$ $350$ $400$ $450$ $500$

$\tau_\mu \tau_h$
$\tau_e \tau_h$
$\tau_e \tau_\mu$
$\tau_\mu \tau_\mu$

Combined

$\tau_\mu \tau_h$
$\tau_e \tau_h$
$\tau_e \tau_\mu$
$\tau_\mu \tau_\mu$

Combined

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Table 1: The systematic uncertainties (in %) for the backgrounds and the signal from $t\bar{t} \rightarrow H^\pm b H^\mp b$ (HH) and $t\bar{t} \rightarrow W^\pm b H^\mp b$ (WH) processes at $m_{H^\pm}$=80-160 GeV/c^2.

<table>
<thead>
<tr>
<th></th>
<th>HH</th>
<th>WH</th>
<th>QCD</th>
<th>non QCD Type 1</th>
<th>non QCD Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td>$t\bar{t}$</td>
<td>$tW$</td>
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<td>$\tau - p_T^{miss}$ trigger</td>
<td>24-26</td>
<td>24-25</td>
<td>9.6</td>
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<tr>
<td>$\tau$-jet id</td>
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<td>jet, $\ell \rightarrow \tau$ mis-id</td>
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<td>15</td>
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<tr>
<td>JES+JER+MET</td>
<td>13-17</td>
<td>14-19</td>
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<td>$b$-jet tagging</td>
<td>12-15</td>
<td>14-16</td>
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<td>jet $\rightarrow b$ mis-id</td>
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<td>11</td>
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<tr>
<td>QCD stat.+syst.</td>
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<tr>
<td>Non QCD Type 1 stat.</td>
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<td>6.8</td>
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<td>$s_W \rightarrow \tau \rightarrow \mu$</td>
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<tr>
<td>MC stat</td>
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<td>4</td>
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</tr>
</tbody>
</table>
## Systematics $H^+ (\mu+e/\tau)$

### mu+tau channel

<table>
<thead>
<tr>
<th></th>
<th>HH</th>
<th>WH</th>
<th>$t\bar{t}$</th>
<th>$t\bar{t}\ell\ell$</th>
<th>$\tau$ fakes</th>
<th>Single top</th>
<th>VV</th>
<th>DY($\mu\mu$)</th>
<th>DY($\tau\tau$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$-jet id</td>
<td>7.0</td>
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<tr>
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<td>3.0</td>
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<td>8.0</td>
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<td>15.0</td>
<td></td>
</tr>
<tr>
<td>JES+JER+MET</td>
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<td>6.0</td>
<td>5.0</td>
<td>5.0</td>
<td>8.0</td>
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<td>5.0</td>
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### e-mu channel

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<tr>
<th></th>
<th>HH</th>
<th>WH</th>
<th>$t\bar{t}$</th>
<th>DY(ll)</th>
<th>W+jets</th>
<th>Single top</th>
<th>VV</th>
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<tr>
<td>JES+JER+MET</td>
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<td>7.0</td>
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<td>20.0</td>
<td>4.0</td>
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<td>3.4</td>
<td>0.5</td>
<td>3.2</td>
<td>16.0</td>
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</table>
Establishing the standard candles

CMS

$Z \rightarrow \tau\tau$ $^{36\text{ pb}^{-1}\text{ at }\sqrt{s} = 7\text{ TeV}}$

$\sigma(pp \rightarrow ZX) \times BR(Z \rightarrow \tau\tau)$ / $\sigma_{\text{theory}}$ (NNLO)

CMS preliminary

$36\text{ pb}^{-1}\text{ at }\sqrt{s} = 7\text{ TeV}$

CMS $Z \rightarrow ee, \mu\mu$
- $e + \tau_{\text{had}}$
- $\mu + \tau_{\text{had}}$
- $\mu + \mu$
- $e + \mu$

CMS $Z \rightarrow \tau\tau$ (combined)
- D0 Run II 1 fb$^{-1}$, $\mu + \tau_{\text{had}}$
- CDF Run II 0.35 fb$^{-1}$, $e + \tau_{\text{had}}$

CMS hadronic
- TOP-11-007 (L=1.09/fb)
- $136 \pm 20^{+40}_{-40} \pm 8$
  (val = stat. + syst. + lum)

CMS tau dilepton
- TOP-11-008 (L=1.09/fb)
- $149 \pm 24^{+26}_{-26} \pm 9$
  (val = stat. + syst. + lum)

CMS combined
- TOP-11-001 (L=36/fb)
- $158 \pm 18 \pm 6$
  (val = tot. + lum.)

CMS dilepton
- arXiv:1105.5661 (L=36/fb)
- $168 \pm 18^{+14}_{-14} \pm 7$
  (val = stat. + syst. + lum)

CMS +jets
- arXiv:1106.0902 (L=36/fb)
- $173 \pm 14^{+30}_{-29} \pm 7$
  (val = stat. + syst. + lum)

MSTW2008(N)NLO PDF, scale@ PDF(90% C.L.) uncertainty

Top Pair Production Cross Section [pb]