Tau Physics at CMS

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On behalf of the CMS Collaboration

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LHC

- pp collisions at $\sqrt{s} = 7$ TeV

- in September 2011 $\approx 2.5$ fb$^{-1}$ delivered

- $\approx 10^7$ taus (Z, W source)
Particle Flow

**TauRec**

$Z \rightarrow \tau\tau$ measurement and tau-ID

**W \rightarrow \tau\nu** observation

Summary
**Tau lepton**

\[ \tau^- \rightarrow W^- \rightarrow e^-, \mu^-, d, \bar{e}, \bar{\mu}, \bar{u} \]

\[ \nu_\tau \]

\( \tau \) properties:
- \( m_\tau = 1.776 \) GeV
- \( c_\tau = 87.11 \mu m \)
- leptonic decay: 35.2%
- hadronic 1 and 3-prong: 63.1%
- significant part of \( \tau \) momentum escapes with neutrino.

Tau lepton is a very suitable tool for studying many physical processes at LHC

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Resonance</th>
<th>Mass, MeV/c²</th>
<th>Branching ratio, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \rightarrow h^- \nu_\tau )</td>
<td></td>
<td></td>
<td>11.6%</td>
</tr>
<tr>
<td>( \tau \rightarrow h^- \pi^0 \nu_\tau )</td>
<td>( \rho )</td>
<td>770</td>
<td>26.0%</td>
</tr>
<tr>
<td>( \tau \rightarrow h^- \pi^0 \pi^0 \nu_\tau )</td>
<td>a1</td>
<td>1200</td>
<td>10.8%</td>
</tr>
<tr>
<td>( \tau \rightarrow h^- h^+ h^- \nu_\tau )</td>
<td>a1</td>
<td>1200</td>
<td>9.8%</td>
</tr>
<tr>
<td>( \tau \rightarrow h^- h^+ h^- \pi^0 \nu_\tau )</td>
<td></td>
<td></td>
<td>4.6%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>63.1%</strong></td>
</tr>
<tr>
<td><strong>Other hadronic decays</strong></td>
<td></td>
<td></td>
<td><strong>1.7%</strong></td>
</tr>
</tbody>
</table>
Particle Flow Algorithm

- Particle Flow (PFlow) combines and links signals coming from different CMS sub-detectors to provide a complete event description.

- As an output PFlow gives a list of reconstructed particle candidates ($e$, $\mu$, $\gamma$, $h^\pm$, $h^0$).

- Tau lepton reconstruction algorithms start from PFlow candidates.
Example of links between tracks and ECAL/HCAL clusters

The link distance is defined as $\Delta R$ in the $(\eta, \phi)$ plane between objects positions. $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$

$\eta = -\ln(tg\frac{\theta}{2})$
Particle Flow Performance

Simulated QCD-multijet events:
PFFlow jet energy response \( \frac{p_T^{\text{rec}} - p_T^{\text{gen}}}{p_T^{\text{gen}}} \) and resolution

Mass of PF photon pair. Agreement for mass within ± 2% of the PDG value

see CMS PAS PFT-10-001
Tau Reconstruction and identification

The main challenge in tau reconstruction is to discriminate between $\tau_{\text{had}}$ and QCD jets.

The experimental signatures of hadronically-decaying taus:

- collimated jet
- low multiplicity (up to three charged hadrons and up to two $\pi^0$'s)
- decay products are isolated (require low detector activity around tau-jet direction)

The best performance in terms of efficiency & fake-rate is achieved by analyzing PFlow jet constituents and building individual decay modes.

Two main algorithms are developed. Presented today: Hadron Plus Strips Algorithm.
Cluster photons within the PFJet into strips accounting for possible broadening due to photon conversions.

Combine charged particles in the jet with strips and reconstruct individual $\tau_h$ decay mode: $\pi^\pm \nu_\tau, \pi^\pm \pi^0 \nu_\tau, (\pi\pi\pi)^\pm \nu_\tau$

Require charged and strips to be contained within a cone $\Delta R = 2.8/P_T$.

Most isolated decay “hypothesis” with compatible visible mass is given preference.
Matching efficiency between generated taus and reconstructed by HPS loose working point ( >80% for all three channels )

Expected reconstruction efficiency for three “working-points” defined by isolation thresholds
- loose
- medium
- tight
Hadron Plus Strips Algorithm (HPS)

The tau fake-rate from jets in three different samples.

- QCDj: jet $p_T > 15$ GeV, $|\eta| < 2.5$
- QCD$\mu$: non-iso $\mu$, MET < 40 GeV
- Wj: iso $\mu$, MET > 50 GeV

**HPS “loose” efficiency $\approx 50\%$ at 1% fake-rate**
**$Z \rightarrow \tau \tau$ and tau-ID estimation**

- two nearly back-to-back taus
- tag&probe with 4 combinations:
  - $\tau_\mu \tau_{had}$
  - $\tau_e \tau_{had}$
  - $\tau_e \tau_\mu$
  - $\tau_\mu \tau_\mu$
- $\tau_{had} \tau_{had}$ difficult but doable
**Z → ττ and tau-ID estimation (CMS PAS TAU-11-001)**

The reco and ID efficiency of tau algorithm is obtained from data using a tag&probe approach.

**Preselection**

- only one iso μ with $p_T > 15$ GeV, $|\eta| < 2.1$
- iso tau-jet candidate with $p_T > 20$ GeV, $|\eta| < 2.3$
- leading track within tau-jet with $p_T > 5$ GeV

**Efficiency**

- apply TauID
- fit visible $\mu\tau_{jet}$ invariant mass using signal and background templates

$$
\epsilon = \frac{N^Z\rightarrow \tau\tau_{pass}}{N^Z\rightarrow \tau\tau_{pass} + N^Z\rightarrow \tau\tau_{fail}}
$$

\[ M_T(\mu, E_T^{miss}) = \sqrt{2p_T^{\mu}E_T^{miss}(1 - \cos \Delta \phi)} \]
The reco and ID efficiency of tau algorithm is obtained from data using a tag&probe approach.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Fit data</th>
<th>Expected MC</th>
<th>DATA/MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>TaNC “loose”</td>
<td>0.76 ± 0.20</td>
<td>0.72</td>
<td>1.06 ± 0.30</td>
</tr>
<tr>
<td>TaNC “medium”</td>
<td>0.63 ± 0.17</td>
<td>0.66</td>
<td>0.96 ± 0.27</td>
</tr>
<tr>
<td>TaNC “tight”</td>
<td>0.55 ± 0.15</td>
<td>0.55</td>
<td>1.00 ± 0.28</td>
</tr>
<tr>
<td>HPS “loose”</td>
<td>0.70 ± 0.15</td>
<td>0.70</td>
<td>1.00 ± 0.24</td>
</tr>
<tr>
<td>HPS “medium”</td>
<td>0.53 ± 0.13</td>
<td>0.53</td>
<td>1.01 ± 0.26</td>
</tr>
<tr>
<td>HPS “tight”</td>
<td>0.33 ± 0.08</td>
<td>0.36</td>
<td>0.93 ± 0.25</td>
</tr>
<tr>
<td>HPS “loose”</td>
<td>combined fit [4]</td>
<td>0.94 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>HPS “loose”</td>
<td>$\tau \tau$ to $\mu \mu, ee$ fit [4]</td>
<td>0.96 ± 0.07</td>
<td></td>
</tr>
</tbody>
</table>
Measurement of $Z \rightarrow \tau \tau$ cross section with $36 \text{pb}^{-1}$ combining 4 channels: $	au_{\mu} \tau_{\text{had}}$ channel, $\tau_{\tau} \tau_{\text{had}}$ channel, $\tau_{\mu} \tau_{\mu}$ channel and $\tau_{\mu} \tau_{\mu}$ channel.

**Selection of $\tau l \tau_{\text{had}}$**

- single lepton trigger
- iso $\mu$ or $e$ with $p_T > 15 \text{ GeV}$ and $|\eta| < 2.1$
- associated $\tau$ oppositely charged
- $p_T^{\tau} > 20 \text{ GeV}$ and $|\eta| < 2.3$
- $E_T^{\text{miss}}$ and $M_T(l, E_T^{\text{miss}}) < 40 \text{ GeV}$

**Lepton isolation:**

sum of transverse momentum of tracks, photons and neutrals within a cone of $\Delta R = 0.4/0.3$ divided by lepton $p_T$ is required to be less that $0.1/0.08$. 

**Graph:**

- 36 pb$^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
- $Z \rightarrow \tau \tau \rightarrow \tau_{\mu} \tau_{\text{had}}$
- Events / (10 GeV)
- CMS

**Legend:**

- data
- $Z \rightarrow \tau \tau$
- $W + \text{jets}$
- EWK+$t\bar{t}$
- QCD
**Z → ττ cross section measurement**

**QCD background estimation from data**

ABCD method OS/SS and lepton isolation

\[ N_A = N_B \frac{N_C}{N_D} \]

EWK and t\(\bar{t}\) from MC

**W + jets contribution:**
- extrapolated from W dominated region (\(M_T > 60 \text{ GeV}\))
- shape from MC

Results for \(Z \rightarrow τ_1 τ_{had}\): visible invariant mass for \(τ_μ τ_{had}\) and \(τ_e τ_{had}\) channels.

![Graphs showing visible invariant mass distributions for Z → ττ → τ_μτ_{had} and Z → ττ → τ_eτ_{had} channels.](image-url)
Z → ττ cross section measurement

Selection for τµτµ:
- two oppositely charged muons with p_T > 19 GeV and p_T > 10 GeV within |η| < 2.1
- E_T^{miss} < 50 GeV
- Δφ_{µµ} > 2
- multivariate likelihood to suppress DY.

Selection for τeτµ:
- p_T^{e,µ} > 15 GeV with |η| < 2.1
- opposite charge
- M_T(e, E_T^{miss}) < 50 GeV
- M_T(µ, E_T^{miss}) < 50 GeV

[Histograms showing event distributions for Z → ττ → τµτµ and Z → ττ → τeτµ]
Z → ττ cross section measurement

Total cross section:

\[
\sigma(pp \to ZX) \times B(Z \to \tau^+\tau^-) = \frac{N}{A\epsilon B'L}
\]

- \( A \) geometrical acceptance
- \( N = N_{fit}(1 - f_{out}) \) corrected fraction of signal events outside the generator-level mass window

Measured values:

<table>
<thead>
<tr>
<th>Final state</th>
<th>( \sigma(pp \to ZX) \times B(Z \to \tau^+\tau^-) ) nb</th>
<th>stat.</th>
<th>syst.</th>
<th>lumi.</th>
<th>( \tau ) ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_\mu \tau_{had} )</td>
<td>0.83</td>
<td>0.07</td>
<td>0.04</td>
<td>0.03</td>
<td>0.19</td>
</tr>
<tr>
<td>( \tau_e \tau_{had} )</td>
<td>0.94</td>
<td>0.11</td>
<td>0.03</td>
<td>0.04</td>
<td>0.22</td>
</tr>
<tr>
<td>( \tau_e \tau_\mu )</td>
<td>0.99</td>
<td>0.12</td>
<td>0.06</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>( \tau_\mu \tau_\mu )</td>
<td>1.14</td>
<td>0.27</td>
<td>0.04</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Main systematic uncertainties
- Tau ID 24%
- \( A \) 3.5%
**Z → ττ cross section measurement**

combined result:

\[ \sigma_{CMS}^{comb}(pp \to ZX) \times B(Z \to \tau\tau) = 1.00 \pm 0.05(\text{stat}) \pm 0.08(\text{syst}) \pm 0.04(\text{lumi}) \text{ nb} \]

\[ \sigma_{theor} = 0.972 \pm 0.042 \text{ nb} \]

Total cross section of \(Z \to \tau\tau\) in consistent with theoretical expectation and with result recently published by the ATLAS Collaboration:

\[ \sigma_{ATLAS}^{comb}(pp \to ZX) \times B(Z \to \tau\tau) = 0.97 \pm 0.07(\text{stat}) \pm 0.06(\text{syst}) \pm 0.03(\text{lumi}) \text{ nb} \]

(arxiv: 1108.2016v1)
W → τν candidate:
- isolated jet
- large $E_T^{miss}$

$m_{vis} = 0.87$ GeV
\( W \rightarrow \tau \nu \) observation

**Selection for analysis with 18.4 pb\(^{-1}\)**

- \( \tau_h + E_{\text{miss}} \) trigger
- \( \tau_h \) with \( p_T > 30 \text{ GeV} + p_T^{\text{lead.track}} > 15 \text{ GeV} \)
- \( e/\mu \) veto
- \( E_T^{\text{miss}} > 35 \text{ GeV} \)
- \( R_{HT} = p_T^{\tau}/\Sigma jet p_T > 0.65 \)

**Background estimate:**

- **EWK** from simulation
- **QCD** estimated from data.

**ABCD method with**

\[ R_{HT} \] and \( E_T^{\text{miss}} \)

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**Signal Region**

- \( R_{HT} > 0.65 \)
- \( E_T^{\text{miss}} < 35 \text{ GeV} \)

**Background Regions**

- A
- B
- C
- D

**Events / (5 GeV)**

**CMS Preliminary**

\( L = 18.4 \text{ pb}^{-1} \)
\( \sqrt{s} = 7 \text{ TeV} \)

- Data
- Wtaunu
- QCD
- Wenu
- ZJet
- Wmumu
Selection for analysis with $18.4 \text{ pb}^{-1}$

- $\tau_h + E_{\text{miss}}$ trigger
- $\tau_h$ with $p_T^{\tau} > 30 \text{ GeV}$ + $p_T^{\text{leadtrack}} > 15 \text{ GeV}$
- $e/\mu$ veto
- $E_T^{\text{miss}} > 35 \text{ GeV}$
- $R_{HT} = p_T^{\tau}/\Sigma jet p_T > 0.65$

Background estimate:
- **EWK** from simulation
- **QCD** estimated from data.
  ABCD method with $R_{HT}$ and $E_T^{\text{miss}}$

Observation:
- 372 events in data selected
- $174 \pm 3$ expected signal from MC
- $217 \pm 20$ observed signal with no systematics assessed!

CMS PAS EWK-11-002
Summary I

- Advanced tau reconstruction algorithm has been developed and successfully commissioned with data collected.

- HPS shows a good performance in terms of efficiency vs. fake-rate. With an efficiency of $\approx 50\%$ only a few percent fake-rate from QCD jets.

- Tau ID efficiency is measured with a precision of $24\%$ (today $6\%$).

- The $Z \rightarrow \tau\tau$ cross section is measured in four channels:
  \[ \sigma_{comb}(pp \rightarrow ZX) \times B(Z \rightarrow \tau^+\tau^-) = 1.00 \pm 0.05(\text{stat}) \pm 0.08(\text{syst}) \pm 0.04(\text{lumi}) \text{ nb} \]
  in good agreement with SM expectation as well as with $Z \rightarrow ll$ cross section.

- Clear signal is observed for $W \rightarrow \tau_{had}\nu$ in $18\text{pb}^{-1}$.

- Many other interesting results with tau in a wide range of physics are already available.
Summary II

— Search for Neutral Higgs Bosons Decaying to Tau Pairs with $1.6 \text{ fb}^{-1}$
  (CMS PAS HIG-11-020)

— First measurement of the $t\bar{t}$ production cross section in the dilepton channel
  with $1.09 \text{ fb}^{-1}$
  (CMS PAS TOP-11-006)

— Measurement of the WW, WZ and ZZ cross section with $1.1 \text{ fb}^{-1}$
  (CMS PAS EWK-11-010)

— Search for new physics with same-sign isolated dilepton with $0.98 \text{ fb}^{-1}$
  (CMS PAS SUS-11-010)

— Search for New Ditau Resonances with $36 \text{ pb}^{-1}$
  (CMS PAS EXO-10-022)
Particle Flow

TauRec

$Z \rightarrow \tau \tau$ measurement and tau-ID

$W \rightarrow \tau \nu$ observation

Summary
signal objects from “shrinking-cone” tau algorithm

consider gammas pair with mass closest to $m_{\pi^0}$ as $\pi^0$ candidate

ensemble of neural networks to decide one of the five decay modes
### Z$\rightarrow\tau\tau$ cross section measurement

**Systematic uncertainties:**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\tau_\mu T_{\text{had}}$</th>
<th>$\tau_e T_{\text{had}}$</th>
<th>$\tau_e T_\mu$</th>
<th>$\tau_\mu T_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>0.2%</td>
<td>3%</td>
<td>0.2%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Lepton identification and isolation</td>
<td>1.0%</td>
<td>1.1%</td>
<td>0.2%</td>
<td>1%</td>
</tr>
<tr>
<td>$\tau_{\text{had}}$ identification</td>
<td>23%</td>
<td></td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>Efficiency of $M_T$ selection</td>
<td>2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likelihood selection efficiency</td>
<td>-</td>
<td></td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Acceptance due to $\tau_{\text{had}}$ energy scale, 3%</td>
<td>3.5%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptance due to e energy scale, 2%</td>
<td>-</td>
<td>1.6%</td>
<td>1.6%</td>
<td></td>
</tr>
<tr>
<td>Acceptance due to $\mu$ momentum scale, 1%</td>
<td>1%</td>
<td>-</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>2%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$\tau_\mu T_{\text{had}}$</th>
<th>$\tau_e T_{\text{had}}$</th>
<th>$\tau_e T_\mu$</th>
<th>$\tau_\mu T_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance $A$</td>
<td>0.13</td>
<td>0.12</td>
<td>0.074</td>
<td>0.16</td>
</tr>
<tr>
<td>Selection efficiency $\epsilon$</td>
<td>0.37</td>
<td>0.23</td>
<td>0.55</td>
<td>0.17</td>
</tr>
<tr>
<td>Mass window correction $f_{\text{out}}$</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Z → ττ cross section measurement

- fit visible mass distributions using shapes from MC or data
- background normalizations correspond to estimated:

<table>
<thead>
<tr>
<th>Source</th>
<th>τμτhad</th>
<th>τeτhad</th>
<th>τeτμ</th>
<th>τμτμ (M_μμ &lt; 70 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z → ℓ⁺ℓ⁻, jet misidentified as τ</td>
<td>6.4 ± 2.4</td>
<td>15.0 ± 6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z → ℓ⁺ℓ⁻, lepton misidentified as τ</td>
<td>12.9 ± 3.5</td>
<td>109 ± 28</td>
<td>2.4 ± 0.3</td>
<td>20.1 ± 1.3</td>
</tr>
<tr>
<td>tt</td>
<td>6.0 ± 3.0</td>
<td>2.6 ± 1.3</td>
<td>7.1 ± 1.3</td>
<td>0.15 ± 0.03</td>
</tr>
<tr>
<td>W → ℓν</td>
<td>54.9 ± 4.8</td>
<td>30.6 ± 3.1</td>
<td>1.5 ± 0.5</td>
<td>2.5 ± 2.5</td>
</tr>
<tr>
<td>W → τν</td>
<td>14.7 ± 1.3</td>
<td>7.0 ± 0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD multijet</td>
<td>132 ± 14</td>
<td>181 ± 23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
<td>1.6 ± 0.8</td>
<td>0.8 ± 0.4</td>
<td>3.0 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>228 ± 16</td>
<td>346 ± 37</td>
<td>14.0 ± 1.8</td>
<td>22.8 ± 2.8</td>
</tr>
<tr>
<td>Total data</td>
<td>517</td>
<td>540</td>
<td>101</td>
<td>58</td>
</tr>
</tbody>
</table>
**Z → ττ cross section measurement**

Likelihood contours for the joint parameter estimation of the cross section and the τ ID.

![Contour plot](image)

DATA/MC correction factor for tau ID efficiency: $0.93 \pm 0.09$. 

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**Note:** The diagram shows a contour plot representing the joint parameter estimation of the cross section and the tau ID efficiency. The plot is labeled with the CMS data at $36 \text{ pb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$. The contours are labeled with 68% and 95% CL confidence levels.
Observed and expected limit on $\sigma_H \times BR(H \to \tau\tau)$ normalized to SM expectation.