Tau Mass Measurement

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Motivation: Tau Mass

Measuring the Tau Mass ($M_\tau$)

- Parameter needed to check lepton universality
- Current value: $1776.84 \pm 0.17$ MeV (PDG 2008)
  - Dominated by the BES and KEDR measurement at the tau production threshold
  - BES result: $1776.96^{+0.18+0.25}_{-0.21-0.17}$ MeV [PRD 53, 20 (1996)]
  - KEDR result: $1776.81^{+0.25}_{-0.23} \pm 0.15$ MeV [Nucl. Phys. Proc. Suppl. 169, 125 (2007)]
- Belle’s current result uses a pseudomass endpoint method
- Belle result: $1776.61 \pm 0.13$ (stat) $\pm 0.35$ (sys) MeV [PRL 99, 011801 (2007)]
Motivation: CPT Test

Test CPT Theorem: \( \frac{M(\tau^+) - M(\tau^-)}{M_{\text{Average}}} = 0 \)

- Can only be tested where \( \tau^+ \) and \( \tau^- \) can be individually reconstructed
- Current limit: \(< 2.8 \times 10^{-4}\) at 90% CL (PDG 2008)
  - Belle Collaboration pseudomass end-point measurement
    [PRL 99, 011801 (2007)]
  - First performed by the Opal Collaboration:
    \(< 3.0 \times 10^{-3}\) at 90% CL (PDG 2008)
    [PLB 492, 23 (2000)]
Over 532 fb⁻¹ of data collected, of which 432 fb⁻¹ is at the Υ(4S) center of mass energy.

This analysis uses 98% of the available data taken at the Υ(4S) center of mass energy.

≈389 million τ⁺τ⁻ pairs
Event Reconstruction

• Well-separated in space

• Divide event into 2 hemispheres in CM frame \( \perp \) to thrust axis

• Unique signature:
Leptonic + hadronic decay

\[
e^+e^- \rightarrow \tau^+ (\mu^+ \nu_\mu \bar{\nu}_\tau) \tau^- (2\pi^- \pi^+ \nu_\tau)
\]
We set $\theta = 0$ to get a lower bound on $M_{\tau}$.

\[ M_{\tau}^2 = M_h^2 + 2(E_\tau - E_h)(E_h - P_h \cos \theta) \quad \text{with } m_\nu = 0 \]

We set $\theta = 0$ to get a lower bound on $M_{\tau}$.

\[ M_{\text{pseudo}} \equiv \sqrt{M_h^2 + (E_{CM} - 2E_h)(E_h - P_h)} \leq M_{\tau} \]
Event Selection

- Require lepton on the tag side
- Require 3 tracks that pass loose pion criteria and are not identified as kaons, protons, or leptons on the signal side
- Require < 5 neutrals and the total neutral energy < 300 MeV, on the signal side, to reduce $\tau^- \rightarrow 2\pi^- \pi^+ \pi^0$ background
- Signal Region:
  $1.68 \leq M_{\text{Pseudo}} \leq 1.86 \text{ (GeV)}$
- Signal efficiency ~2.0% in signal region
- Purity ~96% in signal region
Mass Extraction Procedure

- $p_1$ is the effective endpoint parameter
- $p_1 \neq M_\tau$
- Endpoint, and $p_1$, shift linearly with the generated $M_\tau$
- Use MC to determine relationship between $p_1$ and $M_\tau$

Empirical Fit Function

$$(p_3 + p_4 x) \tan^{-1}\left(\frac{x - p_1}{p_2}\right) + p_5 + p_6 x$$

MC Generators: kk2f & Tauola
Calibration of Track Momentum Reconstruction

- We calibrate the track momentum reconstruction in order to correctly reconstruct some well known reference masses (PDG 2008), following the method developed in the $\Lambda_c$ mass measurement at BaBar [PRD 72 052006 (2005)]
- We use this method to correct the measured value of $p_1$ as well as calculate a systematic uncertainty on $M_\tau$
- The reference masses used in this analysis are the $K^0_s$ and $D^\pm$ masses
- After adjusting the detector material and B-Field to fit the reference masses, we refit the tau event tracks to get a better calibrated momentum measurement which we use to fit for $p_1$ and therefore $M_\tau$
Correction and Systematic Uncertainty of the Momentum Reconstruction

<table>
<thead>
<tr>
<th>Detector Parameter</th>
<th>$\Delta M_\tau$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased SVT Material</td>
<td>+0.31</td>
</tr>
<tr>
<td>Increased Solenoid Field</td>
<td>+0.11</td>
</tr>
<tr>
<td>Increased Bending Magnet Field</td>
<td>+0.21</td>
</tr>
<tr>
<td>$M_\tau$ Momentum Reconstruction Correction</td>
<td>+0.63</td>
</tr>
<tr>
<td>$M_\tau$ Momentum Reconstruction Uncertainty</td>
<td>0.39</td>
</tr>
</tbody>
</table>

We sum in quadrature the shift induced separately by the material and B-Field adjustments to determine the uncertainty on $M_\tau$. 
D± Mass Cross Check

<table>
<thead>
<tr>
<th>Detector Parameter</th>
<th>ΔM_D (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased SVT Material</td>
<td>+0.47</td>
</tr>
<tr>
<td>Increased Solenoid Field</td>
<td>+0.30</td>
</tr>
<tr>
<td>Increased Bending Magnet Field</td>
<td>+0.30</td>
</tr>
<tr>
<td>Momentum Reconstruction Correction</td>
<td>+1.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fit</th>
<th>M_D (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>1868.70 ± 0.04</td>
</tr>
<tr>
<td>Corrected</td>
<td>1869.77 ± 0.04</td>
</tr>
</tbody>
</table>

PDG 2008: 1869.62 ± 0.20

D+ → K− π+ π+
**Tau Mass Result**

After Corrections

\[ M_\tau = 1776.68 \pm 0.12 \text{ (stat) MeV} \]
Mass Difference Result

**MC**
\[ \Delta M = M_{\tau^+} - M_{\tau^-} = 0.05 \pm 0.23 \text{ (stat) MeV} \]

**Data**
\[ \Delta M = M_{\tau^+} - M_{\tau^-} = -0.61 \pm 0.23 \text{ (stat) MeV} \]
Absolute $E_{CM}$ Scale Uncertainty

\[ M_{pseudo} \equiv \sqrt{M_h^2 + 2(E_{CM}/2 - E_h)(E_h - P_h)} \]

Propagation of errors:
\[ \sigma(M_\tau) \approx 0.17\sigma(E_{CM}/2) \]

Beam energy is corrected by comparing $m_{ES}$ peak to B mass.
\[ m_{ES} = \sqrt{(E_{CM}/2)^2 - p_B^2} \]
\[ \sigma(E_{CM}/2) = 0.5 \text{ MeV} \]

\[ \sigma(M_\tau) = 0.09 \text{ MeV} \]

\[ \chi^2/\text{NDF} = 1.26/5 \]
\[ a_0 = 1.78 \pm 0.00 \text{ (GeV)} \]
\[ a_1 = 0.16 \pm 0.01 \]
## Systematic Uncertainties on $M_\tau$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>0.09 MeV</td>
</tr>
<tr>
<td>Boost</td>
<td>Negligible</td>
</tr>
<tr>
<td>Resolution</td>
<td>Negligible</td>
</tr>
<tr>
<td>Fit Range</td>
<td>0.05 MeV</td>
</tr>
<tr>
<td>Edge Parameterization</td>
<td>0.05 MeV</td>
</tr>
<tr>
<td>MC Modeling</td>
<td>0.05 MeV</td>
</tr>
<tr>
<td>Neutrino Mass</td>
<td>Negligible</td>
</tr>
<tr>
<td>Limited MC Statistics</td>
<td>0.05 MeV</td>
</tr>
<tr>
<td><strong>Momentum Reconstruction Uncertainty</strong></td>
<td><strong>0.39 MeV</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.41 MeV</strong></td>
</tr>
</tbody>
</table>
Mass Difference Systematic

Measured the mass difference between D masses
Take the weighted average as the uncertainty

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mass Difference (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^- \pi^+ \pi^+$</td>
<td>-0.04 ± 0.03</td>
</tr>
<tr>
<td>$D^+ \rightarrow \phi \pi^+$</td>
<td>-0.09 ± 0.14</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \phi \pi^+$</td>
<td>+0.10 ± 0.07</td>
</tr>
<tr>
<td>Mass Difference Systematic</td>
<td>0.05 ± 0.03</td>
</tr>
</tbody>
</table>
Summary

- \( M_\tau = 1776.68 \pm 0.12 \text{ (stat) } \pm 0.41 \text{ (syst) MeV} \)
- Largest source of uncertainty is that associated with the momentum reconstruction correction
  \( \frac{M(\tau^+) - M(\tau^-)}{M_{\text{Average}}} = (-3.5 \pm 1.3) \times 10^{-4} \)
- 90% Confidence Interval for the mass difference
  \[-5.6 \times 10^{-4} < \frac{M(\tau^+) - M(\tau^-)}{M_{\text{Average}}} < -1.4 \times 10^{-4} \]
Backups
Alternate fit functions

\[ F_1(x) = (p_3 + p_4 x) \frac{x - p_1}{\sqrt{p_2 + (x - p_1)^2}} + p_5 + p_6 x \]

\[ F_2(x) = (p_3 + p_4 x) \frac{-1}{1 + \exp \frac{x - p_1}{p_2}} + p_5 + p_6 x \]

<table>
<thead>
<tr>
<th>Fit</th>
<th>( \Delta M_\tau ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>+0.02</td>
</tr>
<tr>
<td>F2</td>
<td>-0.02</td>
</tr>
</tbody>
</table>