Selected electroweak results using $\tau$ leptons at BABAR

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(on behalf of BABAR Collaboration)

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Outline

✓ Some recent results from BABAR on:
  ✓ Lepton Universality test in Y(1S) decays
  ✓ $\text{BR}(\tau^- \rightarrow \bar{K}^0 \pi^- \nu_\tau)$ measurement
  ✓ Precision measurement of:
    ✓ $\tau^-$ mass
    ✓ $\tau^+ - \tau^-$ mass difference
✓ Conclusions

arXiv:0808.1121

FPCP '09

Tau '08
**BABAR data samples**

- PEP-II asymmetric energy $e^+e^-$-collider operating at the Y resonances
- BABAR recorded luminosity

Run 1–6: $Y(4S)$

Run 1-6: $\sim 426 fb^{-1}$

Run 1-5: $\sim 385 fb^{-1}$

- $\sigma(e^+e^- \rightarrow b\bar{b}) @ Y(4S) \sim 1.05 \text{ nb} \Rightarrow \sim 4.4 \cdot 10^8 b\bar{b}$ pairs
- $\sigma(e^+e^- \rightarrow \tau^+\tau^-) @ Y(4S) \sim 0.92 \text{ nb} \Rightarrow \sim 3.9 \cdot 10^8 \tau^+\tau^-$ pairs

BABAR is a $\tau$-factory as well!
Lepton Universality Test

1. Theory

✓ In the SM couplings between gauge bosons and leptons are independent of lepton flavour

✓ SM expectation for $R_{ll'} = \frac{\text{BR}(\Upsilon(1S) \rightarrow l^+ l^-)}{\text{BR}(\Upsilon(1S) \rightarrow l'^+ l'^-)}$ is 1 (except for small lepton-mass effects, $R_{\tau\mu} \sim 0.992$)

✓ NMSSM: deviations of $R_{ll'}$ from SM expectation are possible in the hypothesis of existence of a light pseudo-scalar Higgs boson $A^0$

✓ $A^0$ may mediate the decay chain of the $\Upsilon(1S)$:

\[
\begin{align*}
\Upsilon(1S) & \rightarrow A^0 \gamma, \quad A^0 \rightarrow l^+ l^- \quad (1) \\
\Upsilon(1S) & \rightarrow \eta_b \gamma, \quad \eta_b \rightarrow A^0 \rightarrow l^+ l^- \quad (2)
\end{align*}
\]

✓ If the photon is undetected, the lepton pair would be ascribed to the $\Upsilon(1S)$

✓ It can result in a deviation of $R_{ll'}$ from SM expectation (lepton universality breaking) → NP effect

✓ Effect more evident when one of the leptons is a $\tau$ (up to 10%) → $R_{\tau\mu}$

2. Strategy

✓ 28 fb\(^{-1}\) of data collected at Y(3S) CM energy \(\rightarrow \sim 122 \cdot 10^6\) Y(3S)

✓ Tag Y(1S) exploiting \(Y(3S)\rightarrow Y(1S)\pi^+\pi^-\), \(Y(1S)\rightarrow \tau^+\tau^-\) and \(\mu^+\mu^-\) events:

  ✓ BF\((Y(3S)\rightarrow Y(1S)\pi^+\pi^-)\) \(\sim 5\%\)

  ✓ select \(\tau\) 1-prong decays

  ✓ 4-charged tracks final state topology

✓ Separate selections for \(Y(1S)\rightarrow \tau^+\tau^-\) (D\(\tau\)) and \(\mu^+\mu^-\) events (D\(\mu\))

✓ A multivariate analysis approach in \(\tau^+\tau^-\) channel

✓ Signal extraction efficiencies (estimated on MC simulations):

\[\epsilon_{\mu\mu} \sim 45\%\]

\[\epsilon_{\tau\tau} \sim 17\%\]
3. Signal extraction

✓ Extended and unbinned maximum-likelihood fit:

✓ in $D_\mu$ a 2-dim likelihood based on $\Delta M$ and $M_{\mu^+\mu^-}$

✓ in $D_\tau$ a 1-dim likelihood based on $M_{\pi^+\pi^-\text{reco}}$

$\Delta M = M(\Upsilon(3S)) - M(\Upsilon(1S))$

$M_{\mu^+\mu^-}$ invariant $\mu^+\mu^-$ mass

$M_{\pi^+\pi^-\text{reco}} = \sqrt{s + M_{\pi^+\pi^-}^2 - 2 \cdot s \cdot \sqrt{M_{\pi^+\pi^-}^2 + p_{\pi^+\pi^-}^2} - CM}$

✓ Fit performed simultaneously to the 2 datasets

✓ signal PDFs fixed

✓ bkg PDFs floating

✓ $R_{\tau\mu}$ returned
4. Results

✓ Correction for known differences between data and simulation efficiencies
✓ Systematic uncertainty contributions (up to 2.4%):
  ✓ event selection efficiency;
  ✓ particle identification (for $\mu$ leptons);
  ✓ trigger efficiency;
  ✓ imperfect knowledge of signal and bkg shapes.
✓ BABAR preliminary:

\[
R_{\tau\mu}(\Upsilon(1S)) : 1.009 \pm 0.010 \text{ (stat.)} \pm 0.024 \text{ (syst.)}
\]

[Previous best result: $R_{\tau\mu}(\Upsilon(1S)) : 1.02 \pm 0.02 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$ by CLEO]


✓ Sensitive improvement in precision

No significant deviations w.r.t. SM expectations

Still working to reduce systematics
Measurement of $\text{BF}(\tau^- \rightarrow \bar{K}^0 \pi^- \nu_\tau)$

1. Motivations

✓ Hadronic $\tau$ decays: access to vector (V) and axial-vector (A) spectral functions → insight into QCD dynamics at intermediate scales and test of SM

✓ Hadrons from $\tau$ decays are produced via a W emission

✓ Strangeness changing $\tau$ decays are suppressed relative to Cabibbo-allowed modes

✓ Resonant decay dominates ($K^* \rightarrow K\pi$ for V current, $K_1 \rightarrow K\rho$ or $K^*\pi \rightarrow K\pi\pi$) for A current)

✓ Previous measurements by
  ALEPH
  CLEO
  and OPAL
  (limited by statistics)

✓ Best measurement by BELLE

\[
\text{B}(\tau^- \rightarrow \bar{K}^0 \pi^- \nu_\tau) = (0.808 \pm 0.004(\text{stat.}) \pm 0.026(\text{syst.}))% 
\]

✓ BABAR exploits 385 fb$^{-1}$ of statistics → $\sim 3.5 \cdot 10^8$ events
2. Strategy & result

- Only looking for $\tau^{-} \rightarrow K_{S}^{0} \pi^{-} \nu_{\tau}$ ($K_{S}^{0} \rightarrow \pi^{+}\pi^{-}$) final states
- Event divided in two hemispheres
- Event selection reduces non-$\tau$ bkg, Bhabha and $\mu$-pair events with a converted photon, and $\tau^{-} \rightarrow \pi^{-}\pi^{+}\pi^{-}\nu_{\tau}$ events (rejected at 90% thanks to a cut on $K_{S}^{0}$ flight length significance)
- Main sources of bkg: $\tau^{-} \rightarrow K_{L}^{0}K_{S}^{0} \pi^{-}\nu_{\tau}$ and $\tau^{-} \rightarrow \pi^{0}K_{S}^{0} \pi^{-}\nu_{\tau}$ (additional neutrals undetected)
- After the selection: signal purity $\approx 80\%$ and efficiency $\approx 1.1\%$
- Efficiency corrections needed (due to particle identification and $K_{S}^{0}$ reconstruction efficiency)
- Systematics uncertainty up to 2.72% (main contributions: particle ID and tracking)
- Measurement of the branching fraction (combining e- and $\mu$-tag):

$$\text{BR}(\tau^{-} \rightarrow \bar{K}_{S}^{0} \pi^{-}\nu_{\tau}) = (0.840 \pm 0.004\text{(stat.)} \pm 0.023 \text{ (syst.)})$$

Analysis of the $K_{S}^{0}\pi^{-}$ mass spectrum on-going
Precision measurement of $\tau$ mass and $\tau^+\tau^-$ mass difference

1. Motivations & method

✓ CPT invariance fundamental symmetry of SM

✓ Measurement of differences in mass (or lifetime) between particles and their anti-particles is the most common CPT test

✓ In BABAR with $\tau$ leptons

✓ Current best values:

\[
M_\tau = (1776.84 \pm 0.17) \text{ MeV/c}^2
\]

\[
\frac{M(\tau^+) - M(\tau^-)}{M_{\text{Average}}} < 2.8 \cdot 10^{-4}
\]  

[PDG '08]

✓ Pseudomass endpoint measurement (ARGUS and BELLE)

✓ For hadronic $\tau$ decays: $\tau^\pm \rightarrow h^\pm \nu_\tau$

(h is the total hadronic system)

\[
M_\tau = \sqrt{M_h^2 + 2(\sqrt{\frac{s}{2}} - E_h^*)(E_h^* - P_h^* \cos \theta^*)}
\]

\[
M_p \equiv \sqrt{M_h^2 + 2(\sqrt{\frac{s}{2}} - E_h^*)(E_h^* - P_h^*)} \leq M_\tau
\]

✓ $M_p = M_\tau(\theta^*=0)$

✓ Sharp kinematic cutoff at $M_p=M_\tau$

✓ Smearing due to ISR/FSR and detector resolution

E. Guido, Univ.&INFN Genova
2. Event selection & signal extraction

✓ 423 fb$^{-1}$ of data collected at the $Y(4S)$ energy

✓ Events well separated in the space:

✓ Select $\tau^\pm \rightarrow \pi^\pm \pi^+ \pi^- \nu_\tau$ [BR~$(8.99\pm0.06)\%$; high signal purity; large statistics in endpoint region]

✓ Leptonic tag

✓ Charged and neutral kaons and protons vetoed

✓ 3 tracks not identified as a lepton on the signal side

✓ Less than 5 photons and total neutral energy < 300 MeV

✓ Signal efficiency ~2.0\% in the signal region

✓ Purity ~96\% in the signal region

✓ To determine the endpoint from $M_\rho$ distribution this empirical fit function is used:

$$F(x) = (p_3 + p_4x)\tan^{-1}\left(\frac{p_1-x}{p_2}\right) + p_5 + p_6x$$

(BELLE)
✓ Relation between $M_p$ endpoint and $M_\tau$ determined with Monte Carlo simulations

✓ Linear relationship with a slope of unity and y-intercept=0 is expected

✓ ISR/FSR and imperfect detector resolution $\rightarrow$ non-zero offset, used to determine $M_\tau$ from the endpoint fit to data

✓ Several cautions to take into account the possible bad reconstruction of tracks momenta

✓ Bias in momentum scale reconstruction is the greatest systematic uncertainty contribution

<table>
<thead>
<tr>
<th>Detector Parameter</th>
<th>$p_1$ Shift (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVT Material +20.0 %</td>
<td>+0.30</td>
</tr>
<tr>
<td>Sol Field +0.02 %</td>
<td>+0.10</td>
</tr>
<tr>
<td>B1/Q1 Field +20.0 %</td>
<td>+0.20</td>
</tr>
<tr>
<td>Correction</td>
<td>+0.60</td>
</tr>
<tr>
<td>Systematic</td>
<td>0.39</td>
</tr>
</tbody>
</table>

$$\chi^2/\text{NDF} = 1.61/1$$
$$a_0 = 1.49 \pm 0.05 \text{ (MeV)}$$
$$a_1 = 0.96 \pm 0.02 \text{ (MeV)}$$

Table 4: Total systematics

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC Statistics</td>
<td>0.05</td>
</tr>
<tr>
<td>Parameterization</td>
<td>0.03</td>
</tr>
<tr>
<td>Fit Range</td>
<td>0.05</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>0.09</td>
</tr>
<tr>
<td>Boost</td>
<td>0.00</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.00</td>
</tr>
<tr>
<td>MC Modeling</td>
<td>0.05</td>
</tr>
<tr>
<td>$\nu_\tau$ Mass</td>
<td>0.00</td>
</tr>
<tr>
<td>$\phi$ Dependence</td>
<td>0.00</td>
</tr>
<tr>
<td>Tracking Bias</td>
<td>0.39</td>
</tr>
<tr>
<td>Total</td>
<td>0.41</td>
</tr>
</tbody>
</table>
3. Result

- Data split in 2 samples (based on the total $3\pi$ charge)
- Both average and separate measurements of $M(\tau^+)$ and $M(\tau^-)$

$$M_\tau = (1776.68 \pm 0.12\text{(stat.)} \pm 0.41\text{(syst.)}) \text{ MeV/c}^2$$

$$\frac{M(\tau^+) - M(\tau^-)}{M_{\text{Average}}} = (-3.5 \pm 1.3) \cdot 10^{-4}$$

- Comparison with previous measurements for average $\tau$ mass and $\tau^+ - \tau^-$ mass difference
Conclusions

✓ BABAR data are a rich harvest for electroweak physics results:
  ✓ several important (and different) tests on SM are possible exploiting
    the data collected

✓ Now finalizing most of the analyses using the full dataset at Y(4S) energy

✓ Y(3S) and Y(2S) datasets will yield important results, in many fields
  but also for electroweak physics

✓ Preliminary results on:
  ✓ Lepton Universality in Y(1S) decays
  ✓ BR(τ⁻→K⁰π⁻ντ) measurement
  ✓ τ mass and τ⁺–τ⁻ mass difference

✓ Final results awaited for soon. Stay tuned!
BACKUP SLIDES
The BABAR detector

**Cherenkov Detector**
Particle identification (PID)
K-π separation >3.4σ for p<3.5GeV/c

**Solenoid 1.5T**

**Instrumented Flux Return**
Muon and neutral hadron identification
μ efficiency >~85%, π mis-id 6-8%, for p>1.5 GeV/c

**Silicon Vertex Tracker**
Vertex reconstruction and tracking + dE/dx.
Efficiency ~ 97%

**Drift Chamber**
Momentum measurement for charged particles + dE/dx.
σ(p_T)/p_T=0.13%p_T⊕0.45%

**Electromagnetic Calorimeter**
Electron and photon energy measurement.
σ(E)/E=1.33%E^{-1/4}⊕2.1%

e^+ (3.1 GeV)
e^- (9 GeV)
Lepton Universality
✓ Likelihood written as:

\[
L_{\text{ext}} = \frac{e^{-N'}(N')^N}{N!} \prod_{i=1}^{N} p_i
\]

where \( p_i \) is:

\[
p_i \equiv N_{\mu} p_{i\mu} (\Delta M, M_{\mu+\mu^{-}}) + N_{\text{bkg}} p_{i\mu} (\Delta M, M_{\mu+\mu^{-}}) + \\
\frac{\epsilon_{\mu}^{D}}{\epsilon_{\mu\mu}} N_{\mu} R_{\tau} p_{i\tau} (M_{\pi^{+}\pi^{-}}) + N_{\text{bkg}} p_{i\tau} (M_{\pi^{+}\pi^{-}})
\]

✓ Asymmetric Gaussian with non-Gaussian tails functional form:

\[
\mathcal{F}(x) = \exp \left\{ -\frac{(x - \mu)^2}{2\sigma^{2}(L, R) + \alpha(L, R)(x - \mu)^2} \right\}
\]

✓ Summary of systematic uncertainties:

<table>
<thead>
<tr>
<th>Source</th>
<th>( \mu^{+}\mu^{-} )</th>
<th>( \tau^{+}\tau^{-} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>event selection</td>
<td>1.5%</td>
<td>—</td>
</tr>
<tr>
<td>PID</td>
<td>0.6%</td>
<td>—</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.18%</td>
<td>— 0.10%</td>
</tr>
<tr>
<td>BGF</td>
<td>negl.</td>
<td>negl.</td>
</tr>
<tr>
<td>P.d.f.‘s parameters</td>
<td>1.7%</td>
<td>—</td>
</tr>
<tr>
<td>Bkg p.d.f.</td>
<td>0.28%</td>
<td>—</td>
</tr>
<tr>
<td>Agreement ( \mu^{+}\mu^{-} ) vs. ( \tau^{+}\tau^{-} ) in MassPiPiReco</td>
<td>—</td>
<td>0.10%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.08%</td>
<td>0.09%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2.4%</td>
<td>—</td>
</tr>
</tbody>
</table>

| Corrections:                   | —                    | 1.020                |
| PID                            | 1.023                | —                    |
| Trigger                        | —                    | 1.020                |
Measurement of $BF(\tau \rightarrow K^0\pi^-\nu_\tau)$
✓ Summary of event selection:

✓ $K_S^0$ reco from 2 oppositely charged tracks with a mass within 25MeV of the PDG value

✓ $K_S^0$ transverse flight length significance $L_{xy}/\sigma_{xy} > 5$ (to reduce (@90% level) the # of $\tau^ {-} \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ events)

✓ $\pi^+ - \pi^-$ nearest point < 0.2 cm (to increase the likelihood they come from a $K_S^0$)

✓ $|\cos \theta_{\text{hel}}| < 0.97$ (to reduce the # of converted $\gamma$)

✓ Event neutral energy < 0.5 GeV and signal side neutral energy < 0.25 GeV (to reduce the # of $\tau^ {-} \rightarrow K_S^0 \pi^0 \pi^- \nu_\tau$ and $\tau^ {-} \rightarrow K_S^0 K_L^0 \pi^- \nu_\tau$ events)

✓ Summary of systematic uncertainties:

Table 2: Summary of the systematic uncertainties as they feed into the measurement of $B(\tau^- \rightarrow K^0 \pi^- \nu_\tau)$

<table>
<thead>
<tr>
<th>Systematic</th>
<th>$e$-tag</th>
<th>$\mu$-tag</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>0.58%</td>
<td>0.58%</td>
<td>0.58%</td>
</tr>
<tr>
<td>$K_S^0$ Efficiency</td>
<td>1.40%</td>
<td>1.40%</td>
<td>1.40%</td>
</tr>
<tr>
<td>PID</td>
<td>1.45%</td>
<td>1.68%</td>
<td>1.50%</td>
</tr>
<tr>
<td>$\mathcal{L} \times \sigma_{\tau\tau}$</td>
<td>0.83%</td>
<td>0.83%</td>
<td>0.83%</td>
</tr>
<tr>
<td>Statistical efficiency error</td>
<td>0.51%</td>
<td>0.56%</td>
<td>0.38%</td>
</tr>
<tr>
<td>MC background statistics</td>
<td>0.28%</td>
<td>0.30%</td>
<td>0.20%</td>
</tr>
<tr>
<td>$\tau$ backgrounds</td>
<td>1.37%</td>
<td>1.37%</td>
<td>1.37%</td>
</tr>
<tr>
<td>Modelling efficiency</td>
<td>0.37%</td>
<td>0.37%</td>
<td>0.37%</td>
</tr>
<tr>
<td>Total</td>
<td>2.73%</td>
<td>2.87%</td>
<td>2.72%</td>
</tr>
</tbody>
</table>
\[
\sqrt{\text{BR}(\tau \rightarrow K^0 \pi^- \nu_\tau)} = 1/2N_{TT} \cdot (N_{data} - N_{bkg})/\epsilon_{\text{sig}}
\]

\[N_{TT} = \sigma_{\tau} \cdot l_{data} = (353.4 \pm 2.3) \cdot 10^6\]

[N_{TT} # of \tau+\tau- pairs in real data; 
N_{data} # of selected ev. in real data; 
N_{bkg} # of bkg ev. estimated on MC; 
\epsilon_{\text{sig}} signal efficiency]
Precision measurement of $\tau$ mass and $\tau^+ - \tau^-$ mass difference
Summary of tracking bias:

Energy loss in material (SVT) underestimation:

- $K_S^0$ control sample (non-zero flight length, useful to probe uncertainty in the detector material looking at the reconstructed $K_S^0$ mass at different decay lengths)

- Several possibilities studied: best option is increasing the amount of SVT material of 20%

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Solenoidal field: very accurately measured (0.02%)

Final beam-bending magnets show a variation in the permeability of 20%

Shifts due to the increased tracking volume material, solenoidal field and final bending magnets in quadrature to determine the systematic due to the tracking bias

Almost all the syst. cancel out when measuring the mass difference

- $\pi^+$ and $\pi^-$ different interaction with the detector material

- Effect evaluated comparing the reconstructed mass of some well measured hadronic resonances ($D^+ \rightarrow K^-\pi^+\pi^-, D^+ \rightarrow \phi\pi^+, D_s^+ \rightarrow \phi\pi^+$)