Search for Second-Class Currents in the Decay $\tau^- \to \pi^- \omega \nu_\tau$

The *BaBar* Collaboration

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- Event selection
- Background events
  - Non-resonant background events
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  - Resonant $\tau^+ \tau^-$ background events
- Efficiency
- Result and final fit
- Systematic uncertainties
- Results and conclusions

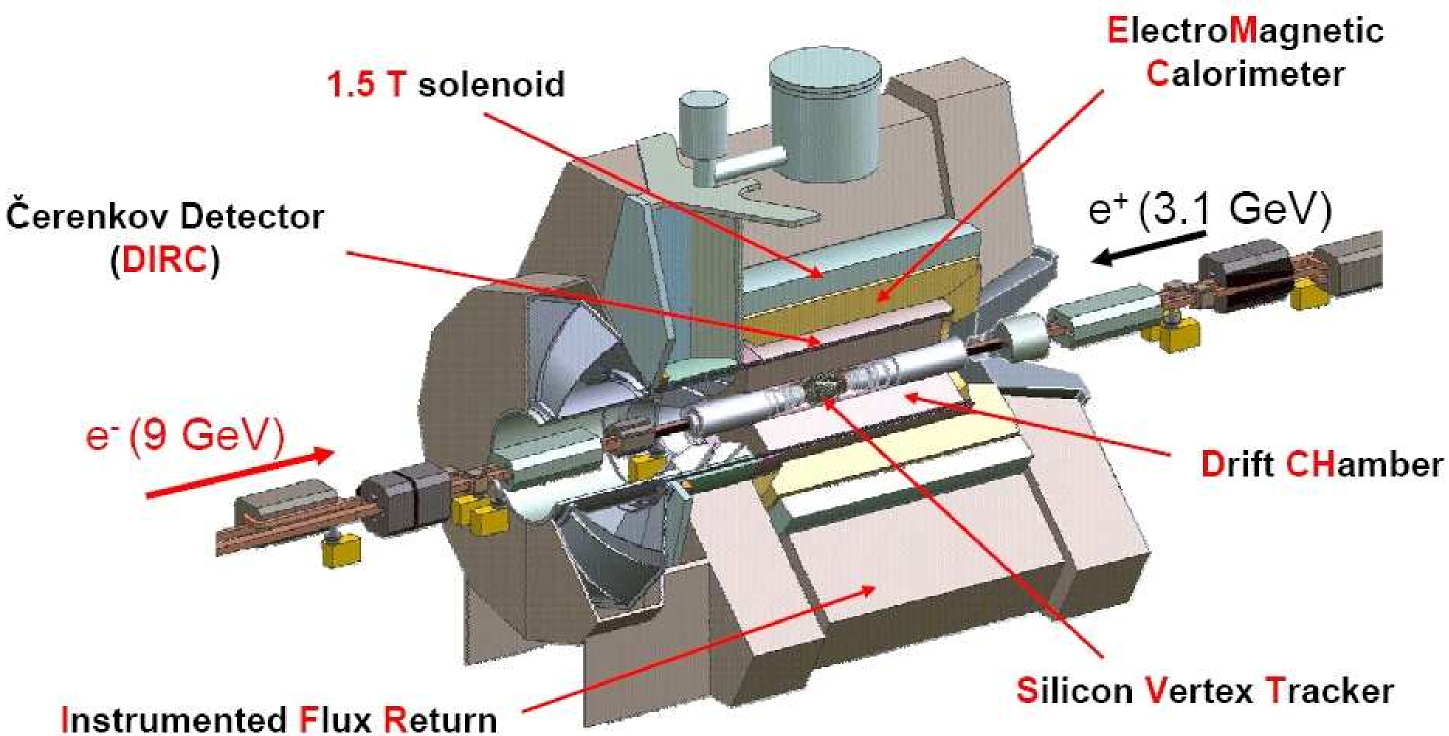

Figure 1: Schematic view of the *BABAR* detector.

- Weak currents can be classified dependent on their G-parity
  S. Weinberg, Phys. Rev. **112** (1958).
  - G-parity is an extension of charge conjugation to include strong isospin multiplets as eigenstates:
    $\hat{G} = \hat{C}e^{i\pi\hat{I}_2}$.
- Classify them as:
  - First-class (FCC), with $PG(-1)^J = +1$ ($J^{PG} = 0^{++}, 0^{--}, 1^{+-}, 1^{-+}$),
  - Second-class (SCC), with $PG(-1)^J = -1$ ($J^{PG} = 0^{+-}, 0^{-+}, 1^{++}, 1^{--}$).
- Previous searches for second-class currents in τ decays and nuclear β decay
  - No confirmed evidence of second-class currents.
- In the Standard Model, the decay constants associated with SCC are proportional to the u–d quark mass difference.

Previous results and predictions

- ✏ The decay $\tau^- \to b_1^-(1235)\nu_\tau \to \pi^-\omega\nu_\tau$ would be a SCC with $J^{PG} = 1^{++}$ (axial-vector current).
- ✏ The decay $\tau^- \to \pi^-\omega\nu_\tau$ also occurs through a FCC with $J^{PG} = 1^{-+}$ (vector current) — $\mathcal{B}(\tau^- \to \pi^-\omega\nu_\tau) \sim 2\%$ (PDG).
- ✏ Limits are placed in terms of

$$\frac{N^{\pi\omega}(\text{non-vector})}{N^{\pi\omega}(\text{vector})}.$$

- ✏ Current limits are from
  - ➙ CLEO: $< 6.4\%$ at the 95% CL
    K. E. Edwards *et. al.*, Phys. Rev. D**61**, 072003 (2000),
  - ➙ ALEPH: $< 8.6\%$ at the 95% CL
    D. Buskulic *et. al.* , Zeit. Phys. C**74**, 263 (1997).
- ✏ No theoretical predictions for the level of SCC in this decay.

Data sample

- On-peak data from Run 1 to Run 5, $347 fb^{-1}$ (319 million $\tau^+ \tau^-$ pairs).

MC sample

- $e^+e^- \to \tau^+\tau^-$ simulated by KK2F, τ decays by TAUOLA, $q\bar{q}$ by EvtGen, FSR by Photos, detector simulation uses GEANT4
- Generic $\tau^+ \tau^-$ MC includes:
  - ➙ $\tau^- \to \pi^-\omega\nu_\tau$ with $J^{PG} = 1^{+-}$,
  - ➙ $\tau^- \to \pi^-\pi^0\omega\nu_\tau$ — main background.

Analysis Method (1)

- Reconstruct $\tau^- \to \pi^- \omega \nu_\tau$, where $\omega \to \pi^+\pi^-\pi^0$.
- Obtain the $\cos\theta_{\omega\pi}$ spectrum for $\tau^- \to \pi^- \omega \nu_\tau$ decays, where $\theta_{\omega\pi}$ is defined as the angle between the π^- and the normal to the ω decay plane in the ω rest frame (Fig. 2).
- The FCC has $J^P = 1^-$ and $L = 1$.
- The SCC has $J^P = 1^+$ and $L = 0, 2$ or $J^P = 0^-$ and $L = 1$.
- The different $J^P(L)$ combinations produce different angular distributions (Fig. 3).

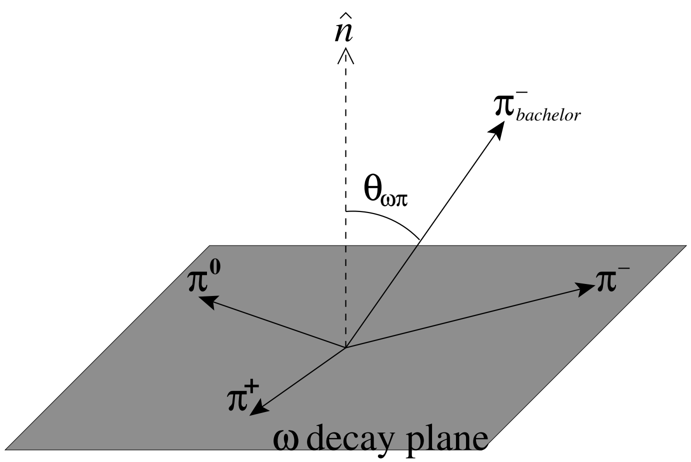

Figure 2: Definition of the angle $\theta_{\omega\pi}$.

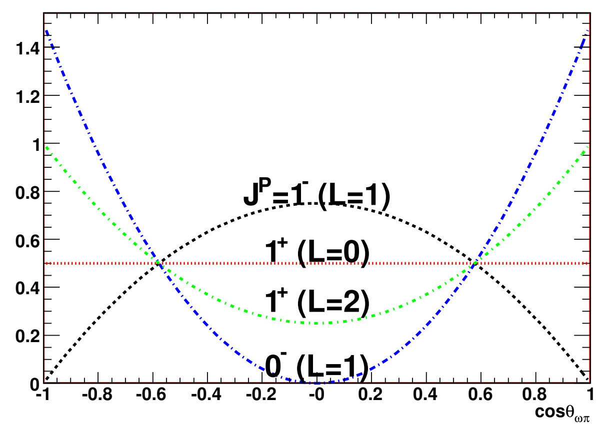

Figure 3: Angular distributions for different $J^P(L)$ states. Normalization of functions is arbitrary.

ANALYSIS METHOD (2)

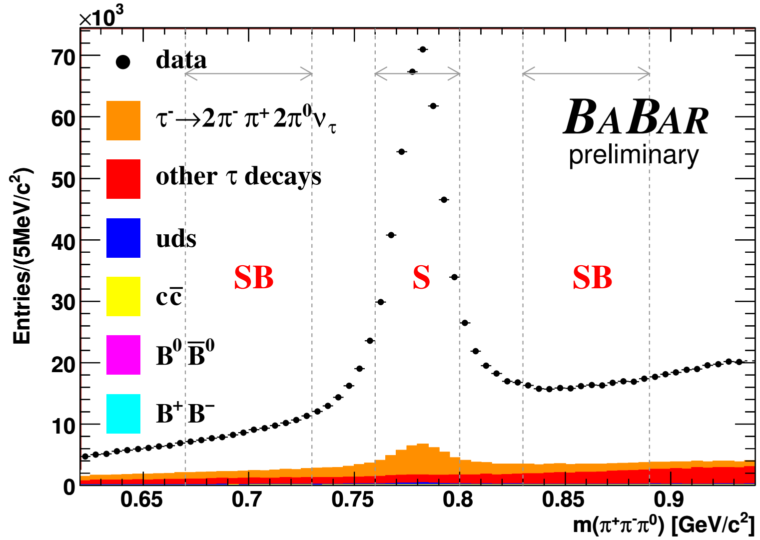

Figure 4: $m(\pi^+\pi^-\pi^0)$ spectrum with one π^0 requirement with Signal and SideBand regions marked.

- Obtain $\cos\theta_{\omega\pi}$ spectrum for data in signal region.
- Subtract contribution from combinatoric backgrounds using sidebands.
- Subtract contribution from $\tau^+ \tau^-$ and $q\bar{q}$ backgrounds using a combination of data and MC.
- Correct for any variation in efficiency as a function of $\cos\theta_{\omega\pi}$.
- Fit this final $\cos\theta_{\omega\pi}$ spectrum to obtain a SCC measurement.

SELECTION CRITERIA

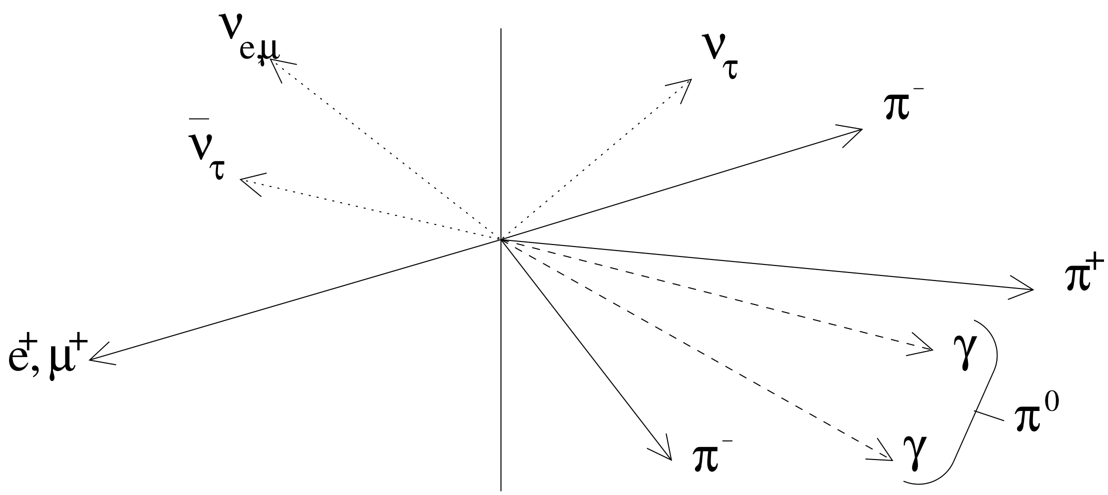

Figure 5: Required topology.

- ✏ Divide events into two hemispheres using thrust and require a 1-3 topology with at least one π^0 candidate (100 MeV/c^2 $< m(\gamma\gamma) <$160 MeV/c^2) on the 3-prong side.
- ✏ Event level cuts (thrust, energy etc.) to select $\tau^+ \tau^-$ events.
- ✏ 1-prong charged track required to pass electron or muon selection criteria.
- ✏ 3-prong charged tracks required to pass pion selection criteria.

- Make two final samples, one for looking at the signal $\tau^- \rightarrow \pi^- \omega \nu_\tau$ decays, the other for studying the main background, $\tau^- \rightarrow \pi^- \pi^0 \omega \nu_\tau$. For the signal sample:
  - Require only one π^0 in the signal hemisphere,
  - No left over photons in the signal hemisphere that are not associated with a charged track,
  - $m(\pi^- \pi^+ \pi^- \pi^0) < 1.777\ \mathrm{GeV/c^2}$.
- For the $\tau^- \rightarrow \pi^- \pi^0 \omega \nu_\tau$ sample:
  - Reconstruct two unique π^0 candidates (no common photons) in the signal hemisphere.
  - $m(\pi^- \pi^+ \pi^- \pi^0 \pi^0) < 1.777\ \mathrm{GeV/c^2}$.
- Final selection rates are:
  - 2.96% for $\tau^- \rightarrow \pi^- \omega \nu_\tau$ in one π^0 sample,
  - 0.70% for $\tau^- \rightarrow \pi^- \pi^0 \omega \nu_\tau$ in one π^0 sample,
  - 1.26% for $\tau^- \rightarrow \pi^- \pi^0 \omega \nu_\tau$ in two π^0 sample,

- Use sidebands in data to model $\cos\theta_{\omega\pi}$ for combinatoric backgrounds in the signal region (Fig. 6).
- Use MC to model ω resonance in $q\bar{q}$ backgrounds:
  - Compare data and MC events with $m(\pi^-\pi^+\pi^-\pi^0) > 2.1$ GeV/c^2 to check the $q\bar{q}$ events have the correct normalization.
  - Use sideband sideband subtraction on the $q\bar{q}$ MC to obtain $\cos\theta_{\omega\pi}$ spectra for ω resonant events (Fig. 7).

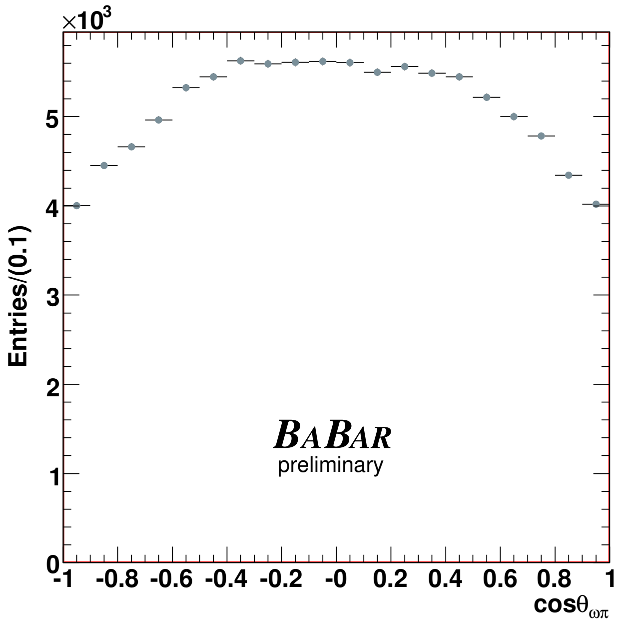

Figure 6: $\cos\theta_{\omega\pi}$ spectrum for data sidebands.

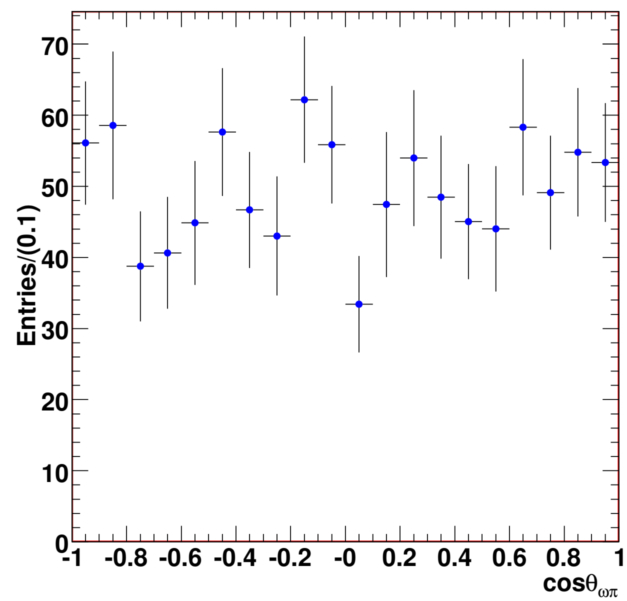

Figure 7: $\cos\theta_{\omega\pi}$ spectrum for ω resonant $q\bar{q}$ events from MC.

- Other τ decays that may be present in the final sample:
  - $\tau^- \to \pi^-\pi^0\omega\nu_\tau$
  - $\tau^- \to K^-\omega\nu_\tau$
  - $\tau^- \to \pi^-\pi^0\pi^0\omega\nu_\tau$
  - $\tau^- \to \pi^-\pi^+\pi^-\omega\nu_\tau$
- Of these, $\tau^- \to \pi^-\pi^0\omega\nu_\tau$ contributes the most events; of the 394,000 ω resonant events in the data, ($\sim$ 5%) from $\tau^- \to \pi^-\pi^0\omega\nu_\tau$, compared to $< 0.2\%$ total for the others ($q\bar{q}$ is $< 0.4\%$).
- $\tau^- \to \pi^-\pi^0\omega\nu_\tau$ events are not well modeled in the MC; both the $\cos\theta_{\omega\pi}$ spectra and the branching fraction are incorrect:
  - The data and MC samples with the requirement of one additional π^0 are used to obtain the correct $\cos\theta$ spectrum for $\tau^- \to \pi^-\pi^0\omega\nu_\tau$ decays.

- Use $m(\pi^+\pi^-\pi^0)$ spectrum with an additional π^0 required (Fig. 8) to correct branching fraction in MC for $\tau^- \to \pi^-\pi^+\pi^-\pi^0\pi^0\nu_\tau$.
- Use $\cos\theta_{\omega\pi}$ spectrum with an additional π^0 required (Fig. 9) to correct angular spectrum in MC for $\tau^- \to \pi^-\pi^+\pi^-\pi^0\pi^0\nu_\tau$.

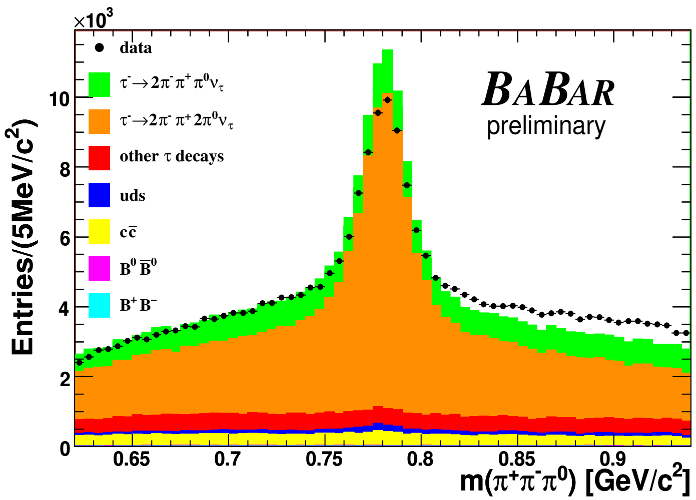

Figure 8: $m(\pi^+\pi^-\pi^0)$ for data and MC with $2\pi^0$ requirement.

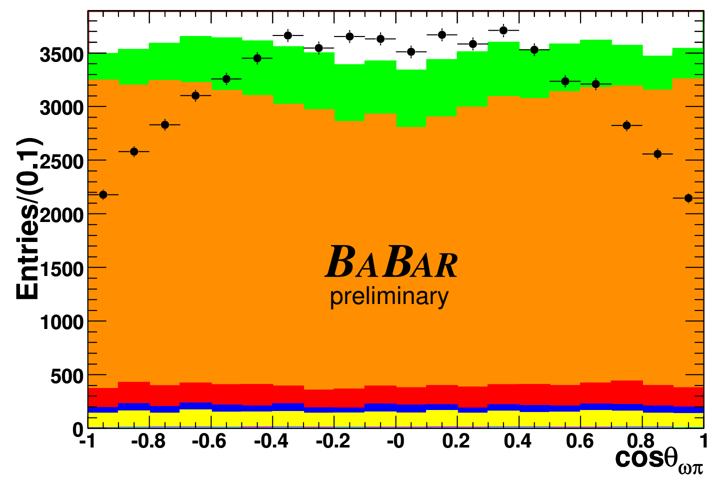

Figure 9: $\cos\theta_{\omega\pi}$ spectra for data and MC with $2\pi^0$ requirement.

$\tau^- \to \pi^-\pi^0\omega\nu_\tau$ BACKGROUND (2)

✏ Carry out sideband and background subtractions on the data with the additional π^0 requirement to obtain the correct $\cos\theta_{\omega\pi}$ spectrum for $\tau^- \to \pi^-\pi^0\omega\nu_\tau$ decays, shown in Fig. 10.

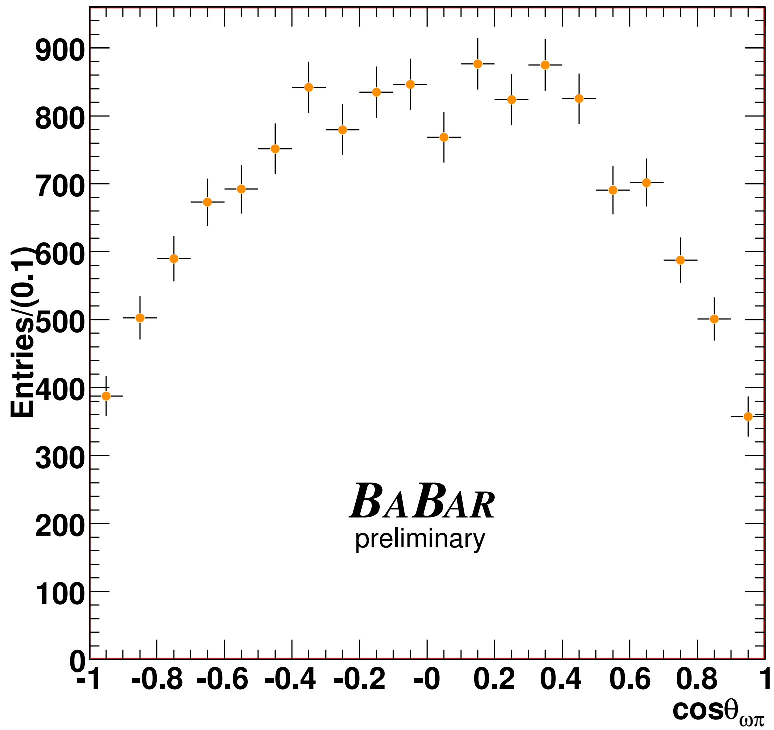

Figure 10: Corrected $\cos\theta_{\omega\pi}$ spectrum for $\tau^- \to \pi^-\pi^0\omega\nu_\tau$ decays.

- The $\cos\theta_{\omega\pi}$ spectrum obtained after the backgrounds have been subtracted off is corrected for any efficiency variation as a function of $\cos\theta_{\omega\pi}$.
- Efficiency histogram is obtained from MC.

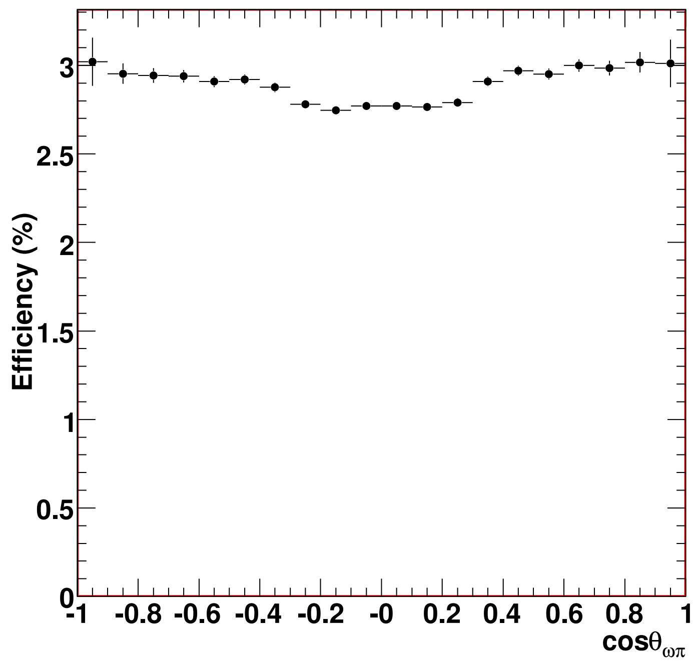

Figure 11: Efficiency as a function of $\cos\theta_{\omega\pi}$ from MC.

RESULT AND FINAL FIT

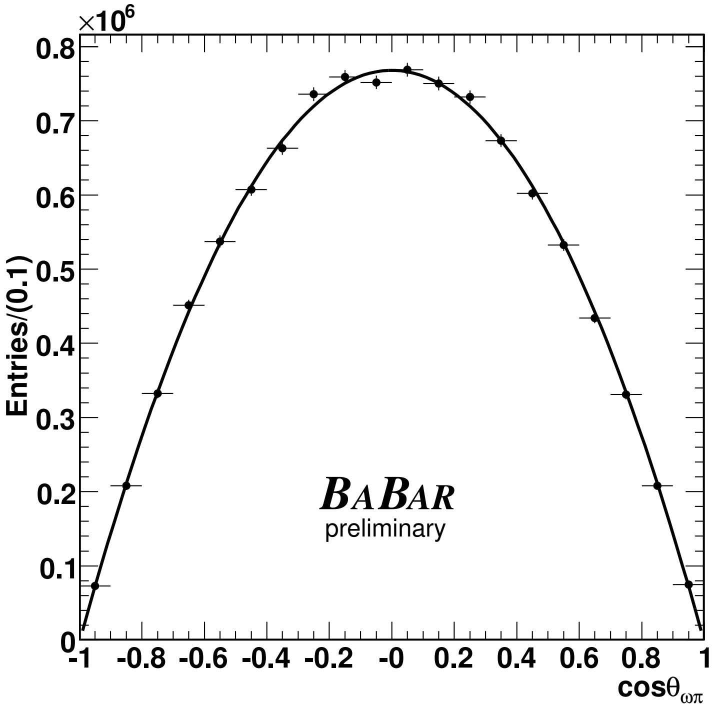

Figure 12: Data fit to find SCC contribution. $\chi^2/dof = 15.4/18$.

arXiv:0807.4900 [hep-ex]

- The final fit uses the function

$$F(\cos\theta_{\omega\pi}) = N[(1-\epsilon)F^{FCC}(\cos\theta_{\omega\pi}) + \epsilon F^{SCC}_{L=0}(\cos\theta_{\omega\pi})],$$

where $F^{FCC}(x) \propto (1-x^2)$ and $F^{SCC}_{L=0}(x) \propto (1)$, to find the second class current fraction, ϵ.

- The result from the fit is $\epsilon = (-5.5 \pm 5.8(\text{stat.})) \times 10^{-3}$.

- Correction applied for $\mathcal{B}(\tau^- \to \pi^-\pi^0\omega\nu_\tau)$ $\sigma_\epsilon = \pm 0.0007$,
- un-modeled resonant τ decays:
  - $\tau^- \to K^-\omega\nu_\tau$,
  - $\tau^- \to \pi^-\pi^+\pi^-\omega\nu_\tau$,
  - $\tau^- \to \pi^-\pi^0\pi^0\omega\nu_\tau$,

  total contribution is $\sigma_\epsilon =^{+0.0000}_{-0.0055}$,
- $q\bar{q}$ normalization $\sigma_\epsilon = \pm 0.0001$,

Total systematic error is $\sigma_\epsilon =^{+0.0008}_{-0.0055}$.

RESULTS AND CONCLUSIONS

- Final result from fit for second-class current contribution is $\epsilon = (-5.5 \pm 5.8(\text{stat.})^{+0.8}_{-5.5}(\text{syst.})) \times 10^{-3}$.
- This sets limits on

$$\frac{N^{\omega\pi}(\text{non-vector})}{N^{\omega\pi}(\text{vector})} = \frac{\varepsilon}{1-\varepsilon}$$

  of 0.69% at 90% C.L. and 0.85% at 95% CL (using a Bayesian scheme).
- Order of magnitude improvement over previous limits.
- Equivalent to $\mathcal{B}(\tau^- \rightarrow \pi^- \omega \nu_\tau(\text{second-class})) < 1.3 \times 10^{-4}$ at 90% C.L.
- Analysis is presented in arXiv:0807.4900 [hep-ex].

BACKUP SLIDE(S)

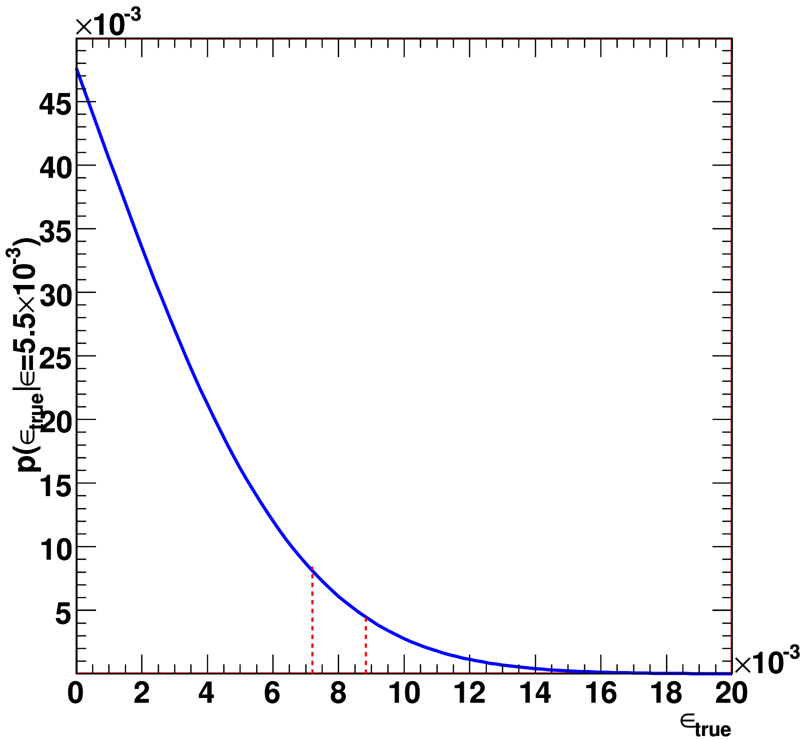

Figure 13: $p(\epsilon_{true}|\epsilon)$ — Bayesian limit.

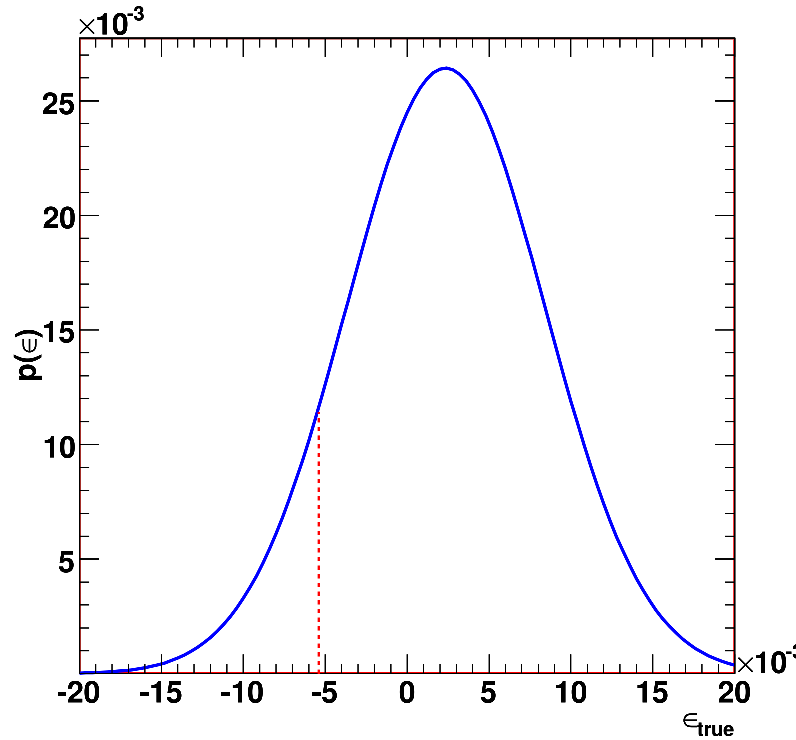

Figure 14: $p(\epsilon)$ — classical limit.

Limits on $N^{\omega\pi}$(non-vector)$/N^{\omega\pi}$(vector):

- ✏ Bayesian limits are 0.69% (90% CL) and 0.85% (95% CL).
- ✏ Classical limits are 0.20% (90% CL) and 0.42% (95% CL).