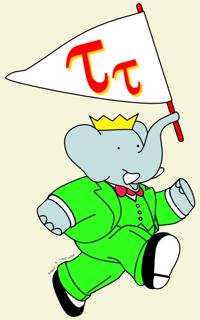
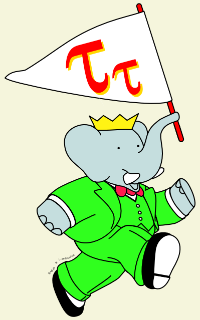


Measurement of the
Tau Lepton Lifetime
with *BABAR*



Alberto Lusiani

INFN and Scuola Normale Superiore
Pisa

(for the *BABAR* Collaboration)

Tau 04

International workshop on
Tau Lepton Physics

Nara new public hall, Nara, Japan September 14-17, 2004

Motivation: check Lepton Universality

$$\tau_\tau = \tau_\mu \left(\frac{g_\mu}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 \mathcal{B}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau) \frac{f(m_e^2/m_\mu^2) r^\mu_{RC}}{f(m_e^2/m_\tau^2) r^\tau_{RC}}$$

$$\tau_\tau = \tau_\mu \left(\frac{g_e}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 \mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau) \frac{f(m_e^2/m_\mu^2) r^\mu_{RC}}{f(m_\mu^2/m_\tau^2) r^\tau_{RC}}$$

where

$f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x$ (phase space ratios)

$r^\ell_{RC} =$ EW radiative corrections, ≈ 1

Ratios of couplings on PDG 2004: $\approx \boxed{1 \pm 0.2\%}$

Data Sample

- BABAR has collected 244 fb^{-1}
- This analysis: **80.0 $\mathbf{fb}^{-1}$** (1999-2002)
- Cross-section $\sigma(\tau^+\tau^-) \approx \sigma(B\overline{B}) \approx$ **1 nb**
- $\approx$ 71.2 million $e^+e^- \to \tau^+\tau^-$ events

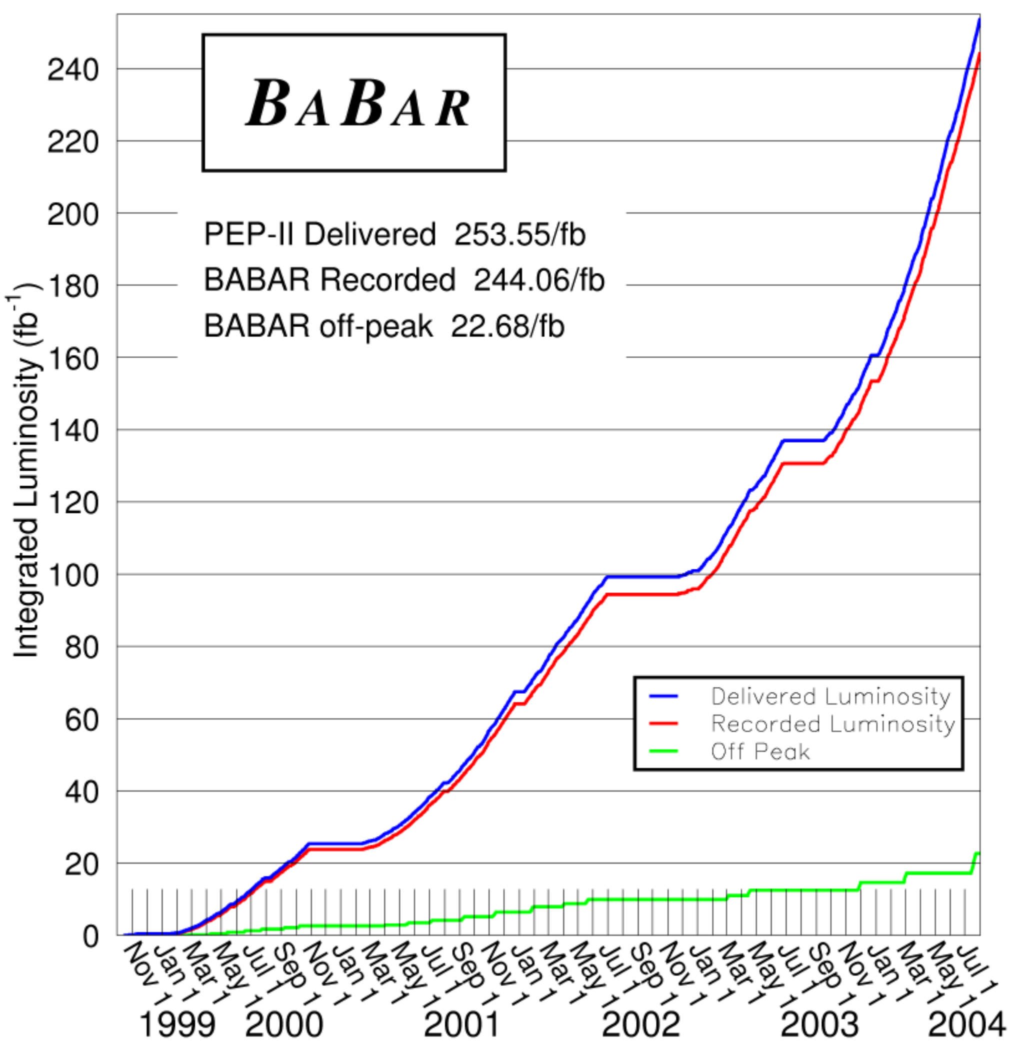
Monte Carlo samples

Roughly 2$\times$ data integrated luminosity:

- signal $\tau^+\tau^-$ (`KoralB`)
- light quarks: $u\overline{u}, d\overline{d}, s\overline{s} = q\overline{q}$
- heavy quarks: $c\overline{c}$, $B\overline{B}$

All results are preliminary

PEP-II performance: Oct 1999 – Jul 2004

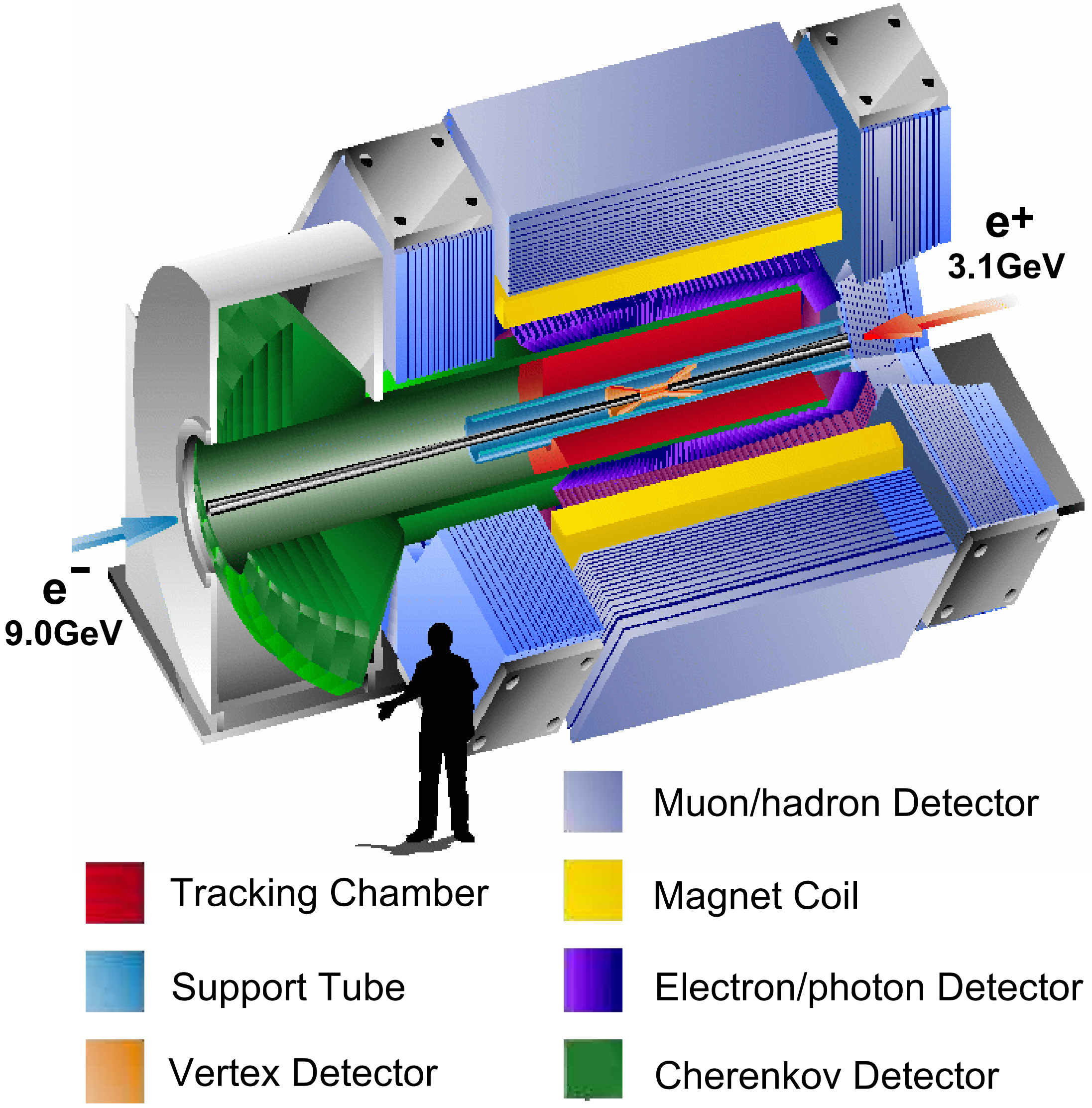


PEP-II at SLAC

- Asymmetric collider at $\Upsilon(4S)$ peak
- $\Upsilon(4S)$ boost $\beta\gamma \approx 0.56$

BABAR Detector

- SVT: 5-layer double-side-readout
- Drift Chamber: 40 stereo layer
- DIRC (PID): 144 quartz bars, 11k PM
- EMC: 6580 CsI(TI) crystals
- Magnet: 1.5 T solenoid
- IFR: iron / RPC



Analysis

Selection

- high purity, sacrificing efficiency

Mean Decay Length

- reconstruct transverse decay length λ_τ^t
- $\lambda_\tau = \lambda_\tau^t / \sin\theta_{\text{3-prong}}$ (approx: $P_\tau \parallel P_{\text{3-prong}}$)
- no weight based on λ_τ estimated errors
- weight to equalize ϕ acceptance in 60 bins
- average λ_τ measurements $\longrightarrow \langle\lambda_\tau\rangle$
- $\langle\lambda_\tau\rangle$ stat. error: variance in 100 sub-samples

Mean Lifetime

- $\langle P_\tau\rangle$ from MC, using beam energies
- $\langle\tau_\tau\rangle = \langle\lambda_\tau\rangle \dfrac{M_\tau}{\langle P_\tau\rangle}$
- subtract measurement bias using MC

Hadronic backgrounds

- light quarks: $u\overline{u}, d\overline{d}, s\overline{s} = q\overline{q}$
- heavy quarks: $c\overline{c}$, $B\overline{B}$
- contamination from MC, with checks on data
- decay length distribution from MC
- $\longrightarrow$ subtract lifetime bias

Bhabha and two-photon backgrounds

- determine contamination from data
- decay length from data control samples
- $\longrightarrow$ subtract lifetime bias

Blind analysis

All quantities in CM system

(unless otherwise noted)

Selection of Signal Candidates

Select $\tau^+\tau^-$ events with:

- **(1-prong decay)** $\tau_1 \rightarrow e^- + X$
- **(3-prong decay)** $\tau_3 \rightarrow$ 3-prong $+ X'$

→

- Require 3-1 topology
- 1-prong: track id. as $e^\pm$, no photon
- 3-prong: no track id. as $e^\pm$, no γ conv.

Further reject Bhabha, two-photon, $q\bar{q}$, $c\bar{c}$, $B\bar{B}$

→

Requirements on:

- Min. & max. **thrust**
- Min. **charged** particles **energy (E_{ch})**
- Min. $E_{\text{miss}} = \sqrt{s} - E_{\text{ch}} - E_{\text{photons}}$
- Min. $\sin\alpha = \left[P_T / \left(\sqrt{s} - E_{\text{ch}}\right)\right]$
- Min. & max. 1-prong momentum $P_{\text{1-prong}}$

Event quality

→

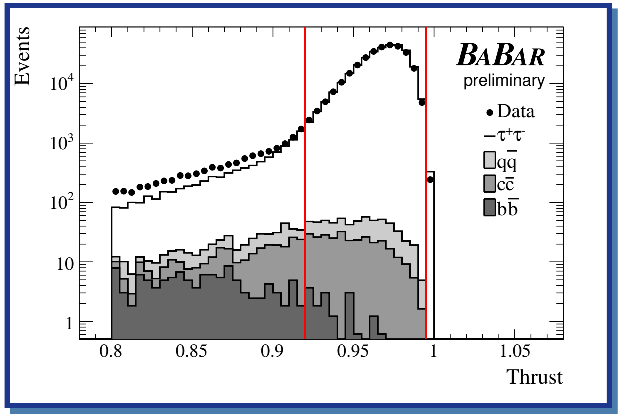
- $\geq$6 SVT hits on all 3-prong tracks
- 3-prong vertex fit $P(\chi^2) > 1\%$
- $\sigma(\lambda_\tau) < 700\ \mu$m
- Trim away very small fraction of improbable measured λ_τ $(2 \cdot 10^{-5})$

Kinematic cuts
after all other cuts

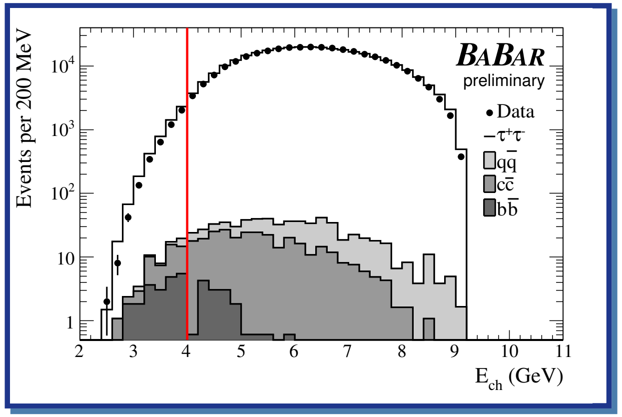
Efficiency on MC:

- all produced $\tau^+ \tau^-$: **0.44%**
- (CLEO 1996 had: 2.54%)
- $\tau^+\tau^- \rightarrow$ eX+3-prong: **7.78%**

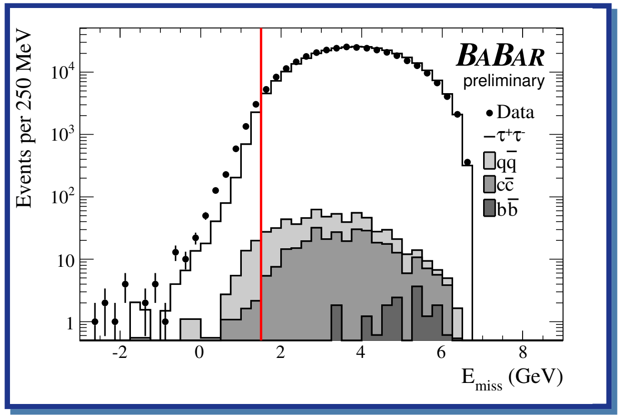
≈ 300k events on data



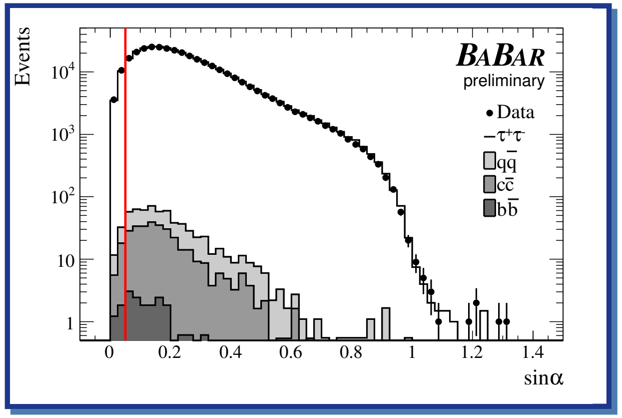
Thrust



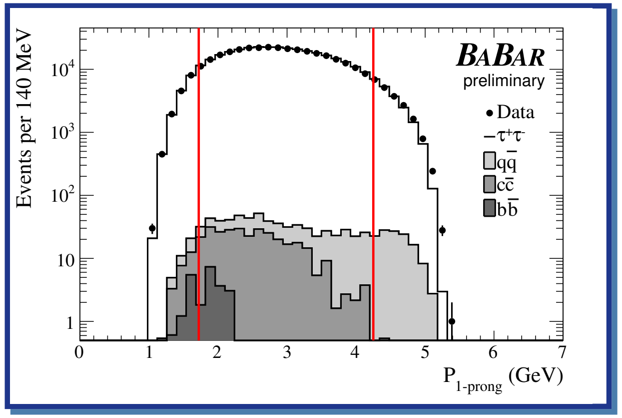
Charged energy



Missing Energy

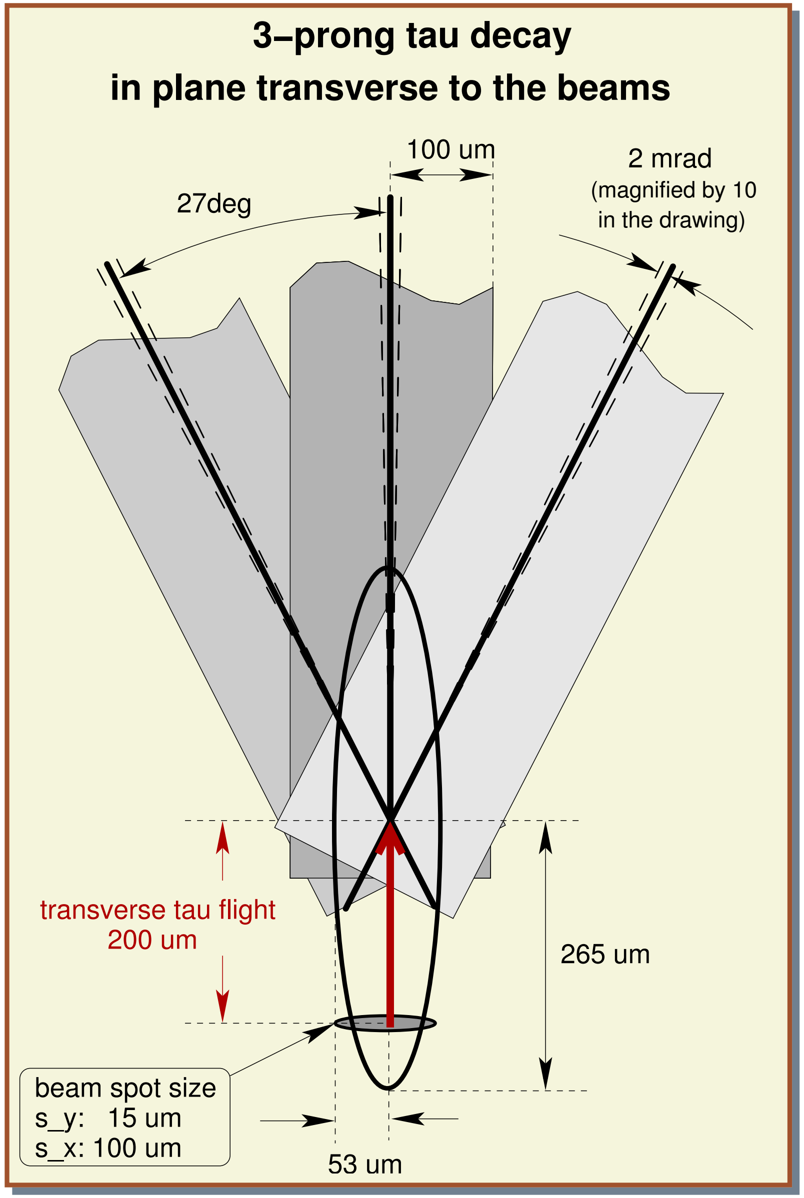


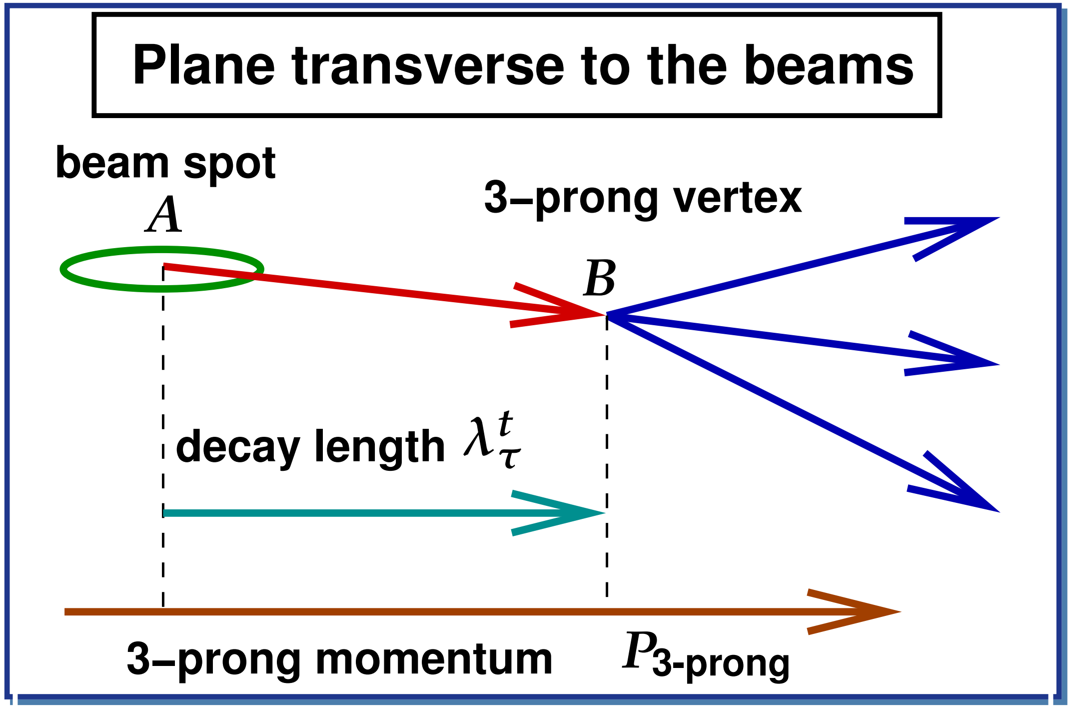
$\sin \alpha$



1-prong momentum

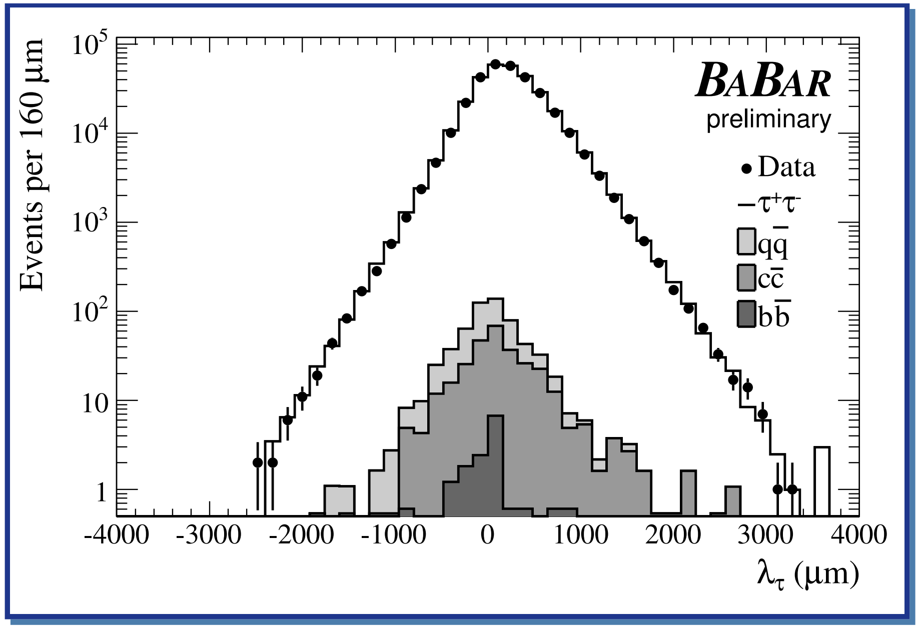
Transverse Decay Length


3–prong tau decay
in plane transverse to the beams

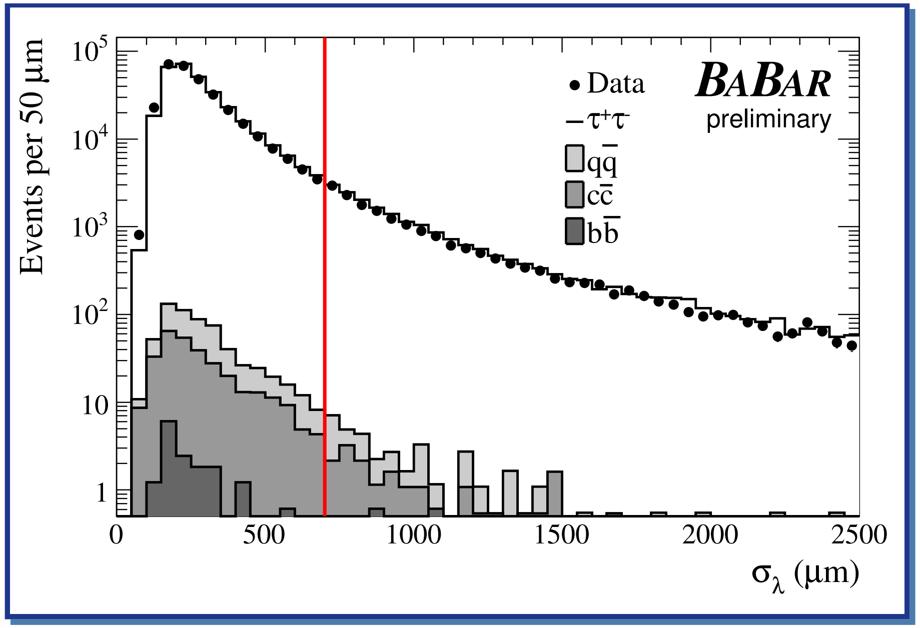


- ◆ Production point ($\vec{A}$): beam spot center
- ◆ Decay point ($\vec{B}$): 3-prong vertex
- ◆ Approx: tau flight direction $\parallel$ $\vec{P}_{\text{3-prong}}$
- ◆ $\lambda^t_\tau = (\vec{B} - \vec{A}) \cdot \hat{P}_{\text{3-prong}}$

Decay length and its estimated uncertainty



λ_τ



$\sigma(\lambda_\tau)$

Transverse → space decay length: $\lambda_\tau = \lambda^t_\tau / \sin\theta_{\text{3-prong}}$

Lifetime Measurement bias on Monte Carlo

- MC bias on $\langle \tau_\tau \rangle = \left\langle \frac{\lambda^t_\tau}{\sin\theta_{\text{3-prong}}} \right\rangle \frac{M_\tau}{\langle P_\tau \rangle}$: $\quad \mathbf{(0.34 \pm 0.22)\%}$
- Bias components studies using MC truth:
  - Sample $\langle \tau_\tau \rangle$ vs. input $\langle \tau_\tau \rangle$ (selection bias, compatible with zero)
  - $\langle \lambda_\tau \rangle \frac{M_\tau}{\langle P_\tau \rangle}$ vs. $\left\langle \frac{\lambda_\tau M_\tau}{P_\tau} \right\rangle$ (compatible with zero)
  - reconstructed vs. true tau direction ($\approx -1\%$, $\approx$ half ϕ and $\approx$ half θ)
    - **tau decay kinematics effects** $\gg$ tracking effects
    - tau decay B.R. uncertainties $\ll$ total MC stat. error
  - $\langle \lambda^t_\tau \rangle$ vs. true one, on true tau direction ($\approx +1\%$)
    - mostly **tracking $d_0 - \phi_0$ errors correlations**
    - study data vs. MC estimated tracking errors and 3-prong vertex χ^2

      → MC reproduces data within $\approx 5\%$
- MC modeling of $\langle \tau_\tau \rangle$ dependence on event variables extensively studied

→ Systematic effects negligible w.r.t. MC stat. error ($\pm 0.22\%$)

Hadronic backgrounds

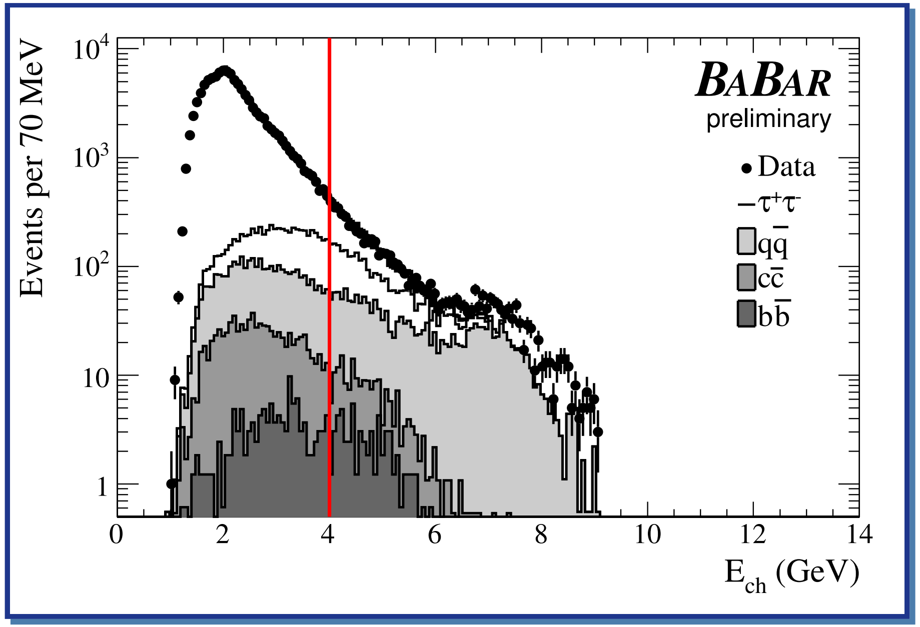
- Before 1-prong electron id., MC predicts data at $M_{\text{3-prong}} > 1.6\,\text{GeV}$ within 10%
- MC underestimates hadron mis-id. into electron
  - checks on data, using electron selector with $>5\times$ higher purity

    → on data, $\Delta \langle \lambda_\tau \rangle = (-60 \pm 71)\%$ of total hadronic bias predicted by MC

→ 100% uncertainty on MC prediction of hadronic contamination

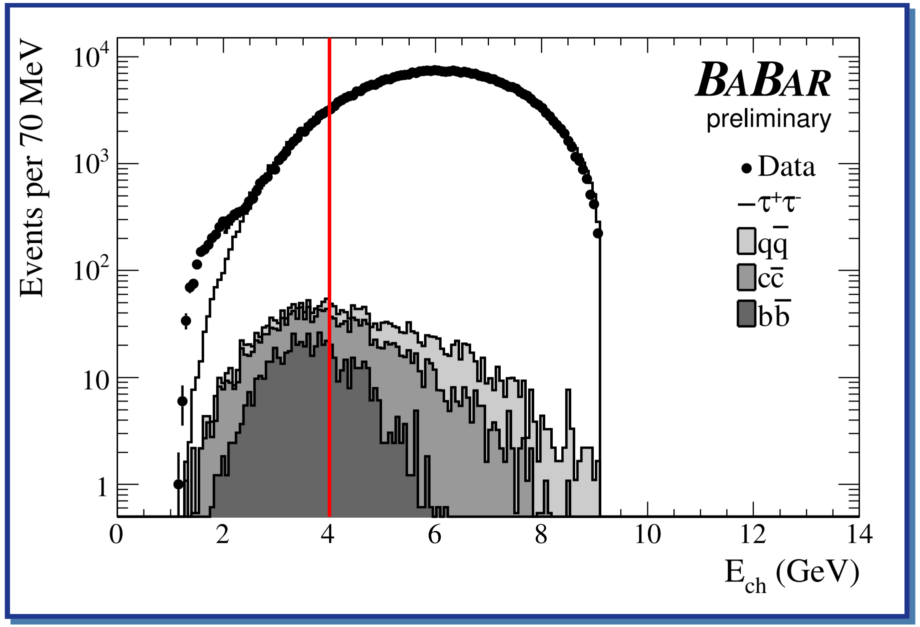
(acceptable since predicted backgrounds are small)

Two-photon contamination in charged energy distribution



$\gamma\gamma$-enhanced control sample

- invert 1-prong PID, $\sin\alpha$, min.thrust
- release min.1-prong P

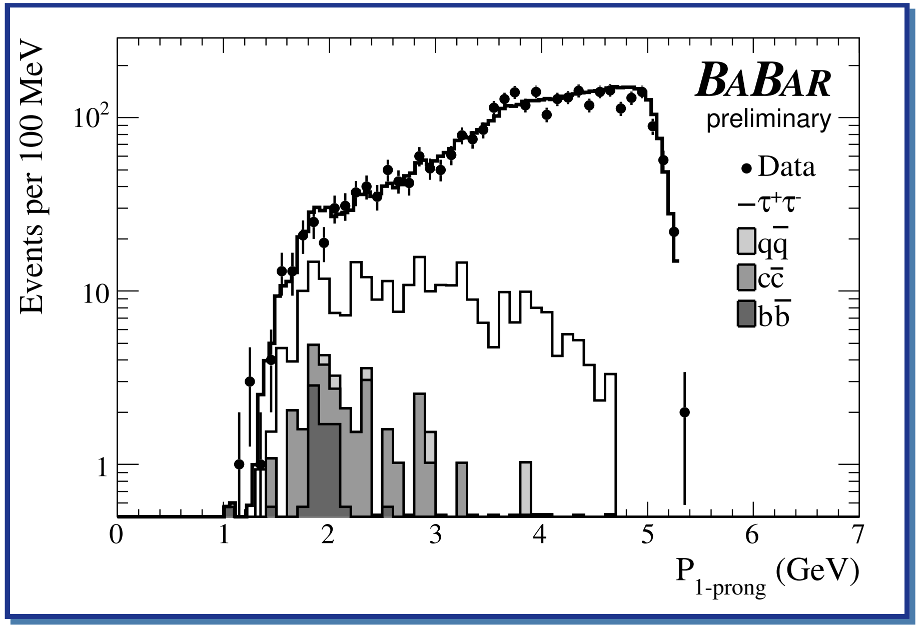


$\gamma\gamma$ contamination fit

- release min.thrust, $\sin\alpha$, min.1-prong P

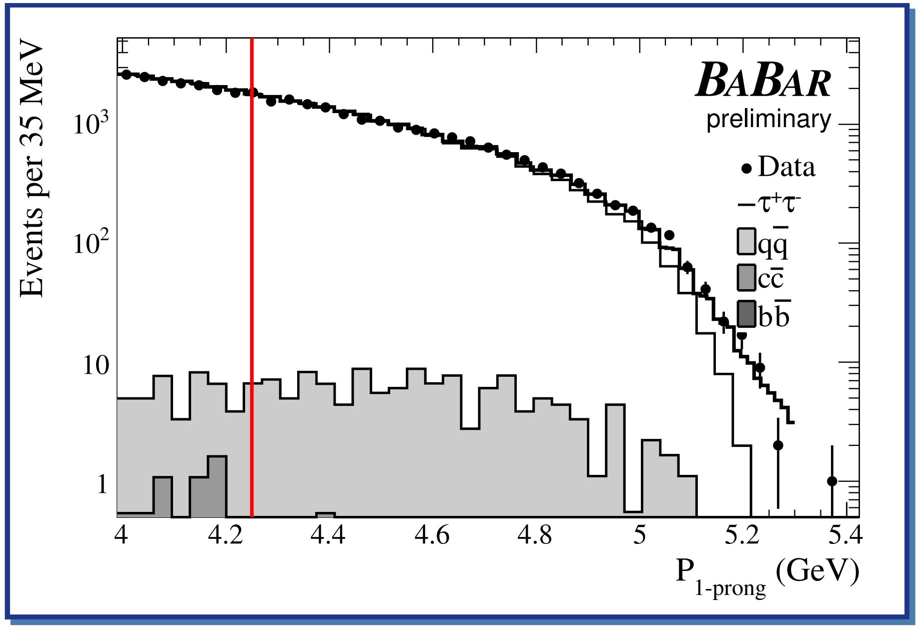
- Upper limit to two-photon contamination from data: $<0.038\%$

Bhabha contamination in 1-prong momentum distribution



Bhabha-enhanced control sample

- ◆ invert 3-prong electron PID veto



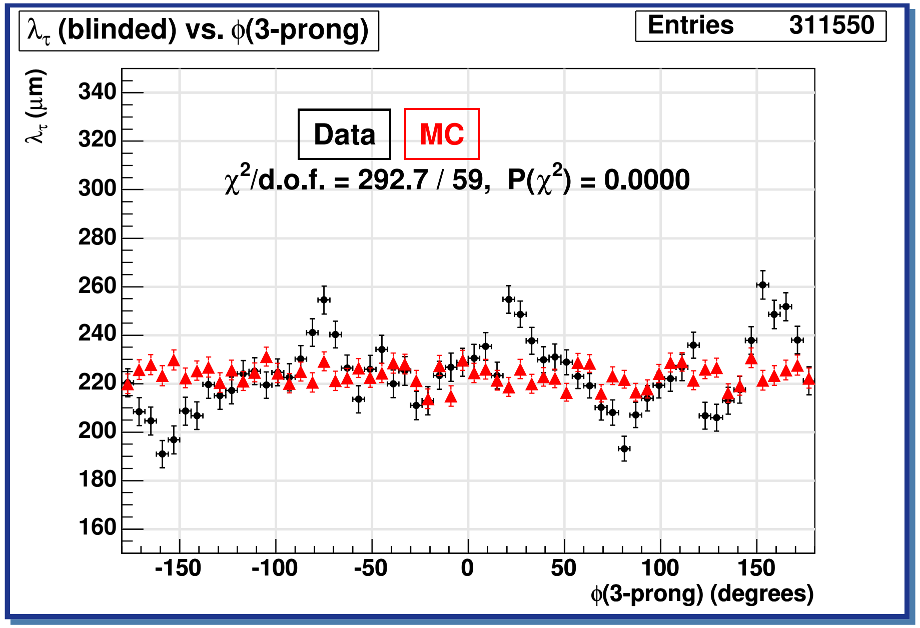
Bhabha contamination fit

- ◆ Bhabha contamination from data: $[0.390 \pm 0.043\,(\text{stat.}) \pm 0.010\,(\text{syst.})]\,\%$

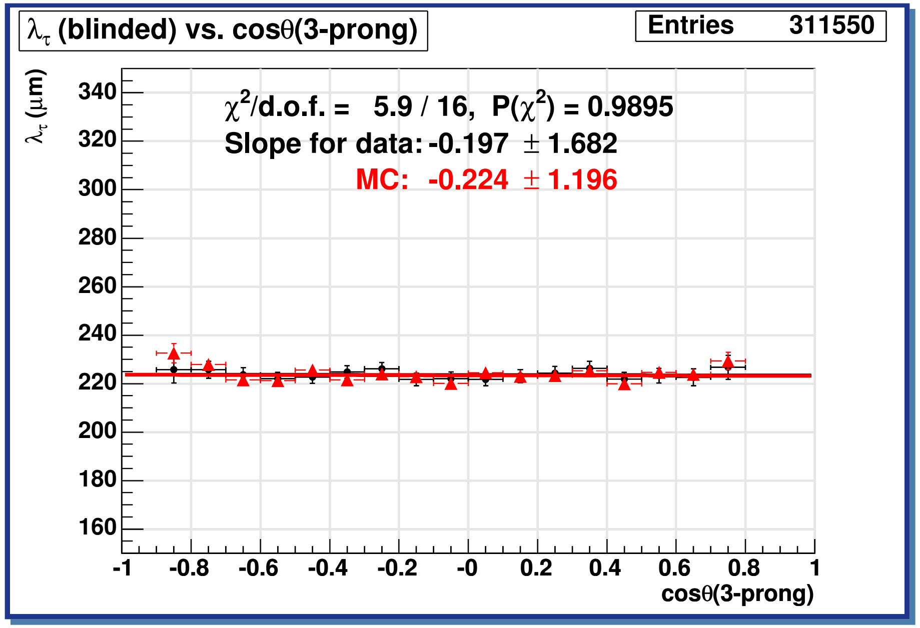
Background biases and uncertainties

background	contamination (%)			$\langle\lambda_i\rangle$ (μm)	bias on $\langle\lambda_\tau\rangle$
$q\overline{q}$	0.099	± 0.004	± 0.099	-11.18 ± 14.92	-0.104 ± 0.113
$c\overline{c}$	0.091	± 0.004	± 0.091	174.74 ± 23.02	-0.025 ± 0.045
$B\overline{B}$	0.005	± 0.001	± 0.005	43.42 ± 66.89	-0.004 ± 0.007
two-photon	0.000	± 0.000	± 0.038	59.73 ± 49.00	0.000 ± 0.030
Bhabha	0.390	± 0.043	± 0.010	55.04 ± 12.64	-0.295 ± 0.066
Total					-0.428 ± 0.142

Decay length vs. azimuthal and polar angle



(blinded) decay length vs. ϕ



(blinded) decay length vs. $\cos\theta$

- azimuthal variations in data related to alignment
- on all other event variables: **no significant variation** & MC matches data

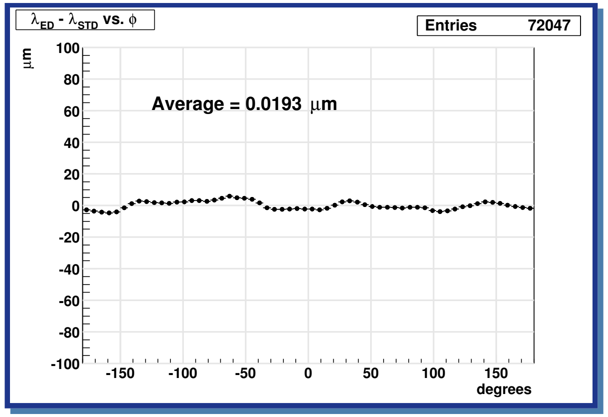
Azimuthal mean decay length variations

- **Common property of high precision tau lifetime measurements**

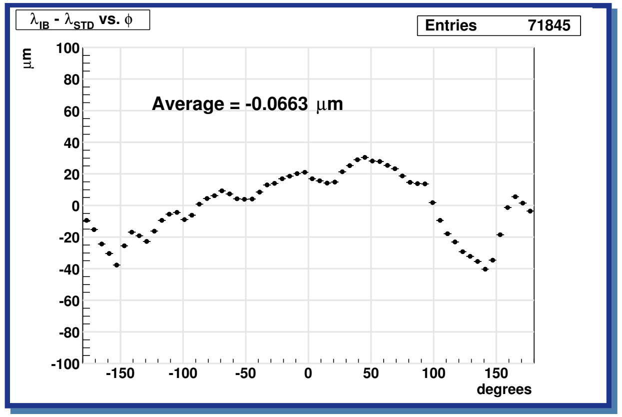
  (S. R. Wasserbaech, Nucl. Phys. B (Proc. Suppl.) **76**, 107 (1999) `[arXiv:hep-ex/9811037]`)
  - Typical size at LEP: $10\,\mu$m$/87\,\mu$m (impact parameter)
    - related to vertex detector local alignment
    - related systematic uncertainty set to $\approx 0.1\%$
  - Observed in CLEO (1996)
- **This measurement**:
  - uncertainties on SVT alignment estimated on data ⟶ misalignment files
  - alignment systematics comparing misaligned to perfect MC

    ⟶ no mean decay length statistically significant shift within 0.1%
  - additional checks on data confirm MC studies
  - **misalignment files reproduce size of variations**
  - present evidence on alignment related systematic uncertainty $\approx 0.1\%$

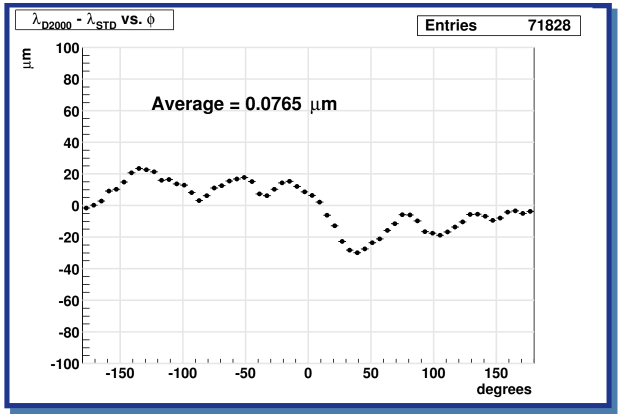
Misaligned MC reproduces size of azimuthal variations



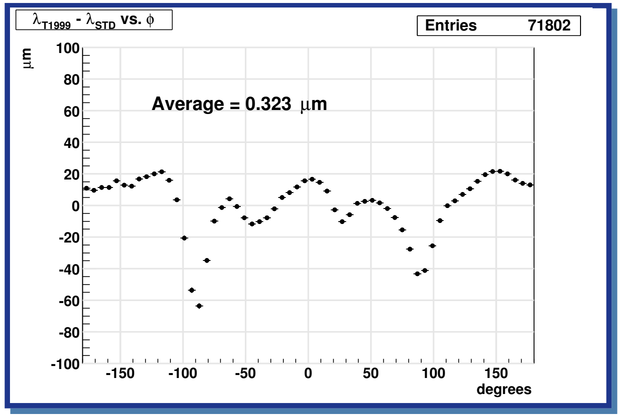
EllipsData



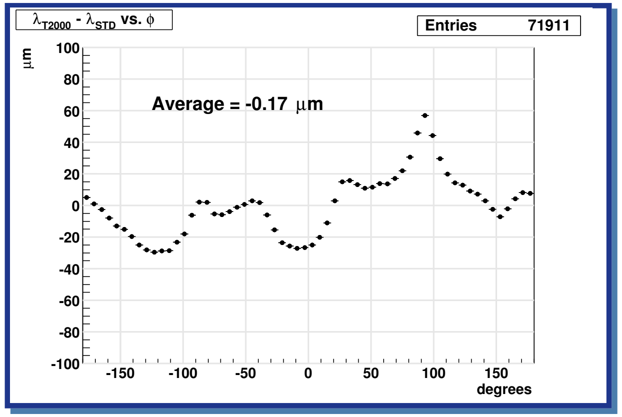
InnerBias



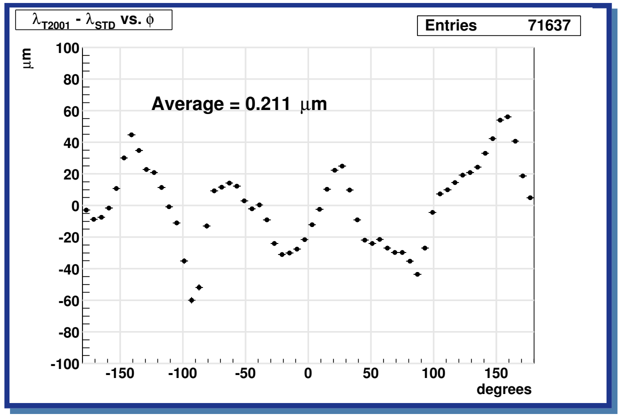
Diff2000



Time1999



Time2000



Time2001

Uncertainty on simulation of mean tau momentum

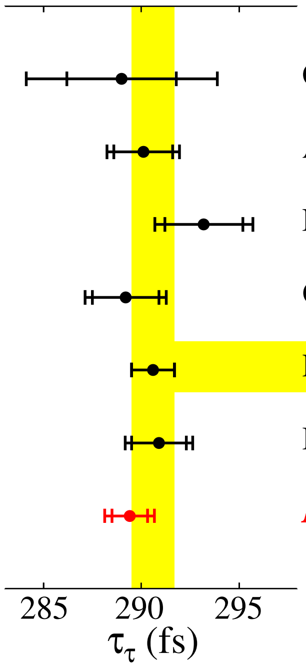
- Compare **Koralb** (1st order) vs. **KK2f** (2nd order plus exponentiation)
- Compare **Koralb** prediction of muon $\langle P \rangle$ on $e^+e^- \to \mu\mu\gamma$ data events
- → uncertainty on $\langle P_\tau \rangle$ set to $\boxed{\Delta \langle P_\tau \rangle \,/\, \langle P_\tau \rangle = 0.1\%}$

Biases and uncertainties summary

Systematic error source	$\Delta\tau_\tau/\tau_\tau(\%)$ bias ± error
Measurement bias	0.336 ± 0.220
Background	-0.428 ± 0.142
Detector alignment and length scale	± 0.111
Beam spot position	± 0.043
Beam spot size	± 0.044
Beam energies and boost direction	± 0.043
Simulation of tau IFR/FSR energy loss	± 0.100
Tau mass	± 0.006
Total	-0.092 ± 0.310

Results

$$\boldsymbol{\tau_\tau = 289.40 \pm 0.91\,(\textbf{stat.}) \pm 0.90\,(\textbf{syst.})\ \textbf{fs}}$$ **preliminary**



CLEO 1996	289.0 ± 2.8 ± 4.0 fs
ALEPH 1997	290.1 ± 1.5 ± 1.1 fs
L3 2000	293.2 ± 2.0 ± 1.5 fs
OPAL 1996	289.2 ± 1.7 ± 1.2 fs
PDG 2004	290.6 ± 1.1 fs
DELPHI 2003, subm.	290.9 ± 1.4 ± 1.0 fs
BABAR 2004, prelim.	289.40 ± 0.91 ± 0.90 fs

Supersedes the *BABAR* preliminary result presented at Moriond 2003, based on a $30\,\text{fb}^{-1}$ sub-sample:

$$\mathbf{290.8 \pm 1.5\,(stat.) \pm 1.6\,(syst.)\ fs}.$$

The two results are compatible within $\Delta\tau_\tau = 0.8\sigma$ (statistical errors only).

Charge Asymmetry: $$\frac{\tau_{\tau-} - \tau_{\tau+}}{\tau_{\tau-} + \tau_{\tau+}} = [0.12 \pm 0.32]\ \%$$

preliminary,
no dedicated
systematic studies yet

Lepton Universality

BABAR 2004 prelim. + PDG 2004 W.A.

assuming no syst. error correlation

$$\boxed{\tau_\tau = 290.09 \pm 0.83\,\mathrm{fs}}$$

Using PDG 2004 world averages

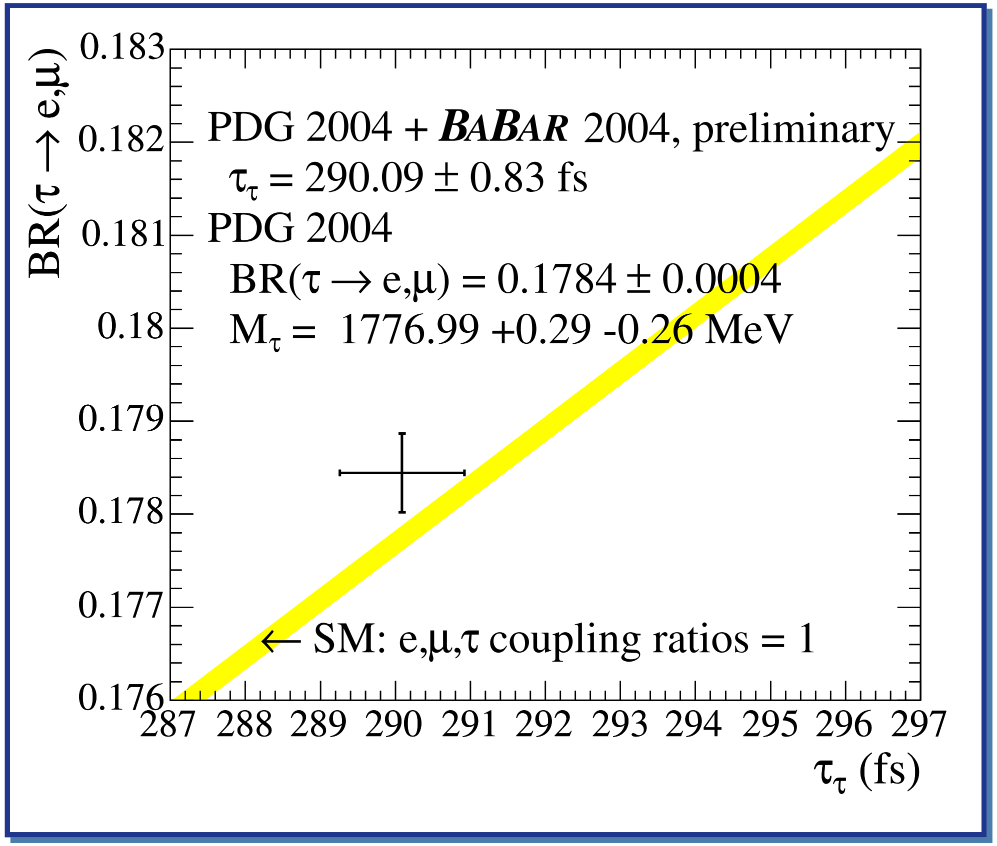
$$\boxed{\frac{g_\mu}{g_\tau} = 0.9981 \pm 0.0022}$$

$$\boxed{\frac{g_e}{g_\tau} = 0.9979 \pm 0.0023}$$

Assuming $g_e = g_\mu = g_{e,\mu}$:

$$\boxed{\frac{g_{e,\mu}}{g_\tau} = 0.9980 \pm 0.0019}$$

SM prediction



Summary and prospects

- ◆ A preliminary measurement of the tau lifetime has been obtained using $80.0\,\mathrm{fb}^{-1}$ of data collected by *BABAR*
  - ▶ agrees with the PDG 2004 world average and SM predictions
  - ▶ improves on previous measurements, LEP heritage → B-factories
- ◆ Future improvements are possible:
  - ▶ statistical error (more data, more efficient selection)
  - ▶ systematic error
    - higher MC statistics → smaller measurement bias error
    - more studies on hadron mis-identification to electrons
    - replace `KoralB` with `KK2f` → smaller error on $\langle P_\tau \rangle$
    - additional studies of detector alignment effects on data

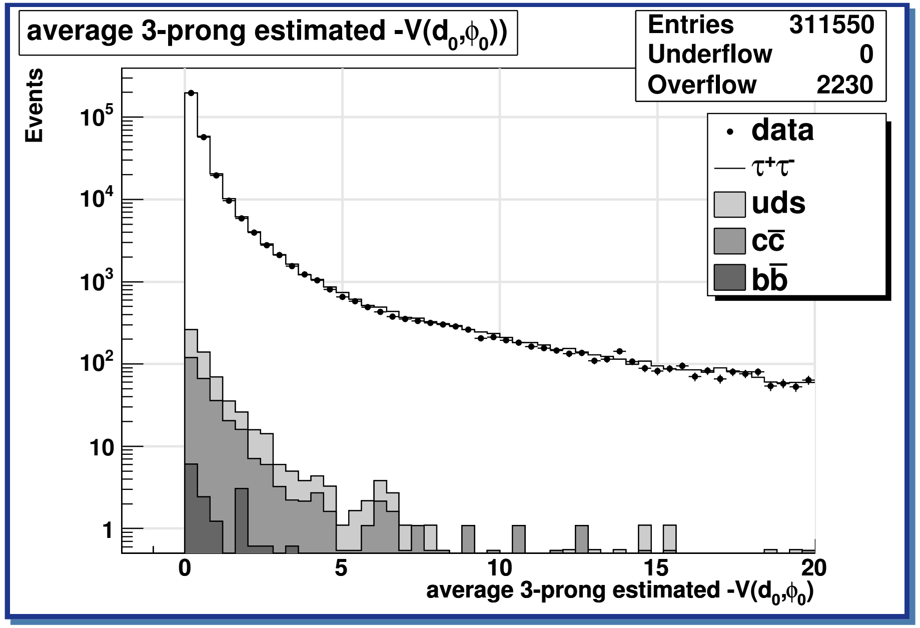
BACKUP SLIDES

Lifetime Measurement bias on Monte Carlo

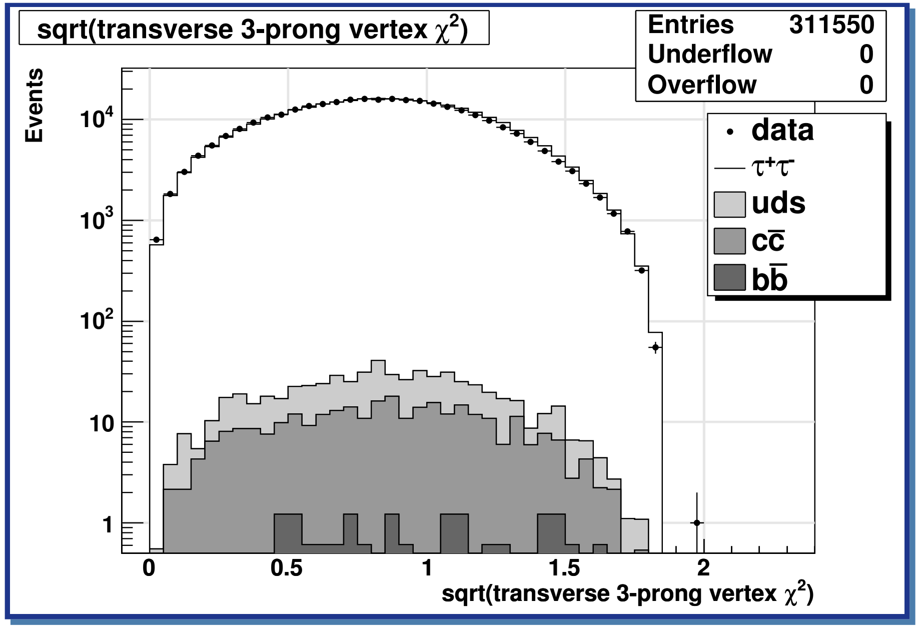
bias contribution	bias (%)
lifetime measurement	0.336 ± 0.220
• selection	-0.029 ± 0.127
• tau momentum reconstruction	0.016 ± 0.010
• decay length reconstruction	0.350 ± 0.179
– tau polar angle reconstruction	-0.529 ± 0.007
– tau azimuthal angle reconstruction	-0.666 ± 0.001
– reconstruction on the true tau direction	1.295 ± 0.170
(because of correlations, contributions do not add up exactly)	

- ◆ Uncertainties from tau branching fractions negligible
- ◆ MC models tracking residuals & error correlations to $\approx 5\%$

Simulation of tracking error correlations



Covariance matrix $V(d_0, \phi_0)$



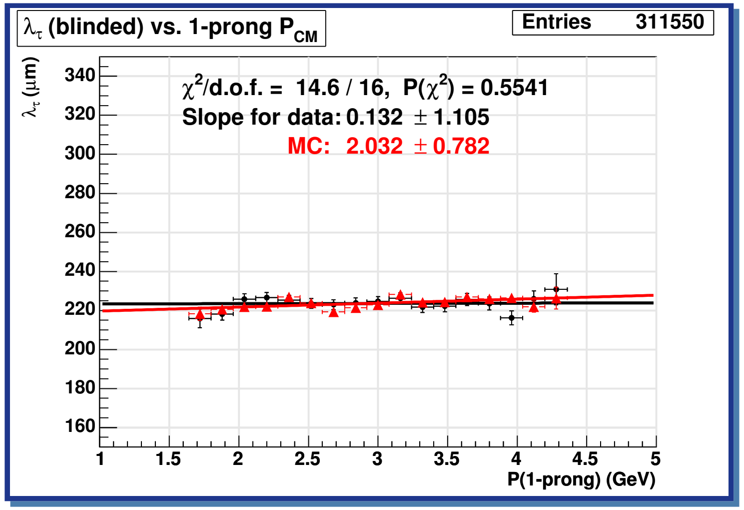
sqrt(transverse 3-prong vertex χ^2)

- Average estimated tracking error correlations simulated to $(2.5 \pm 1.1)\%$
- $\left\langle \frac{\text{MC actual}}{\text{MC estimated}} \right\rangle \cdot \left\langle \frac{\text{data estimated}}{\text{data actual}} \right\rangle$ errors $= 1 + (2.3 \pm 0.2)\%$

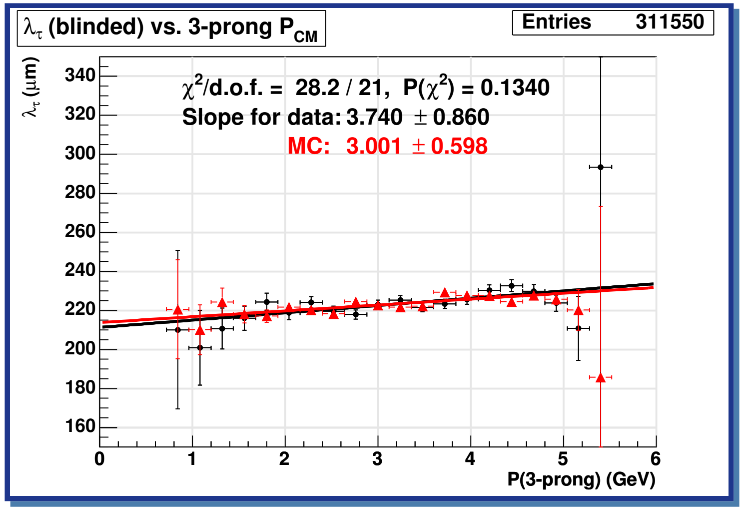
Simulation of decay length measurement bias

- Measurement bias depends (moderately) on event properties (expect from estimated decay length error, 3-prong opening angles)
- Simulation discrepancies → inaccuracy of simulated measurement bias
- → weight MC events to match data distributions (and viceversa) for:
  - 1-prong momentum
  - 3-prong total momentum
  - cosine of 3-prong momentum polar angle
  - decay length estimated uncertainty
  - sum of sines of 3-prong tracks opening angles
  - $d_0 - \phi_0$ estimated tracking error correlations
  - χ^2 of 3-prong vertex fit in transverse plane
- No decay length shift $> 0.03\%$

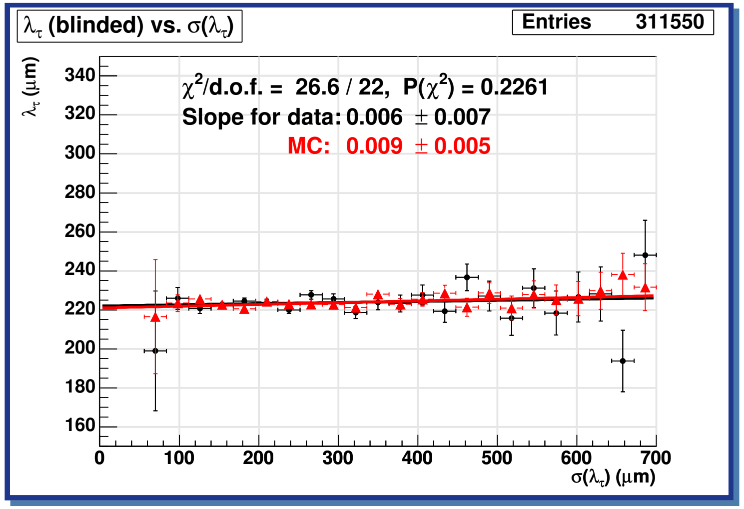
Decay length vs. other variables



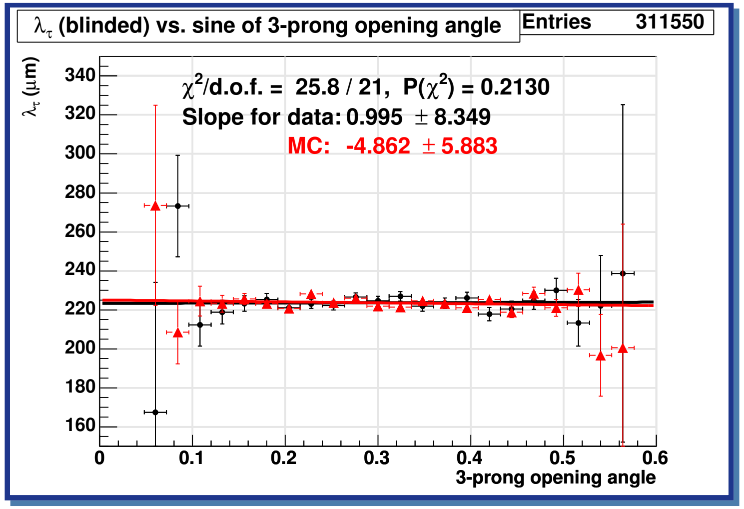
P (1-prong)



P (3-prong)

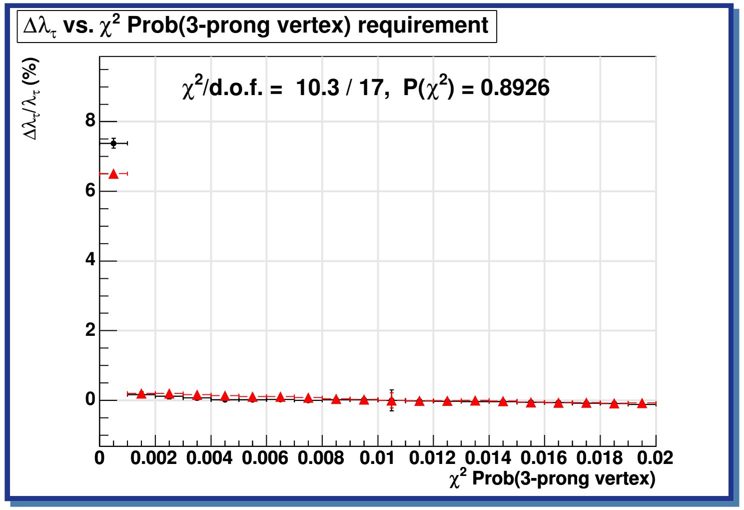


estimated error

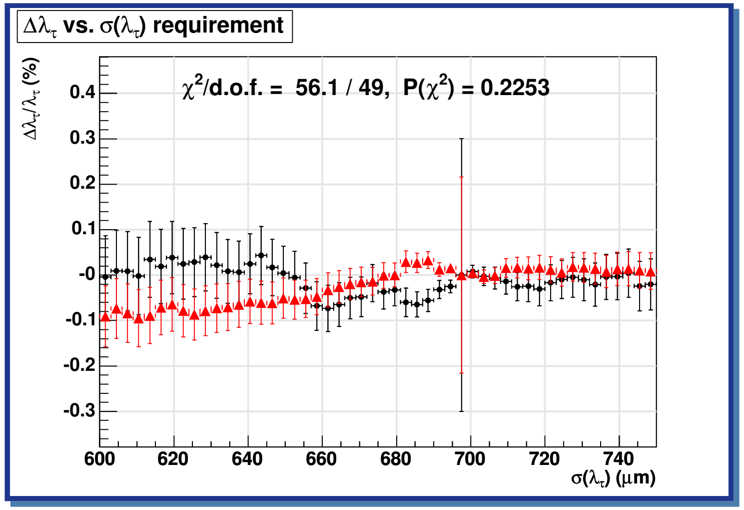


3-prong opening angle

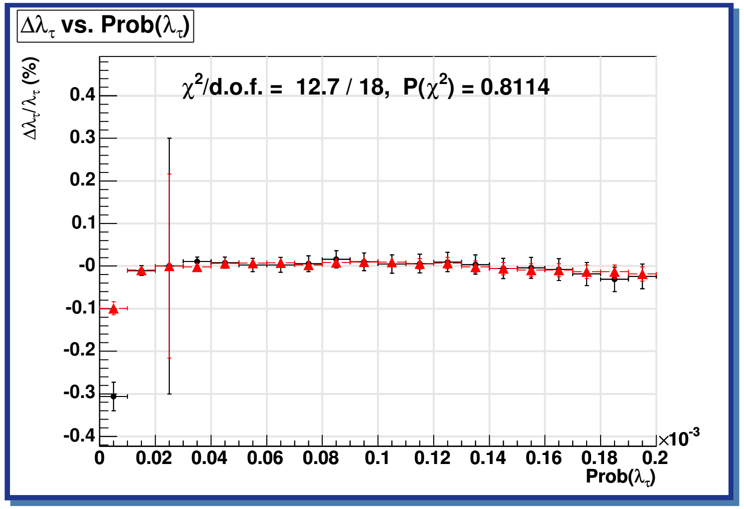
Decay length vs. "quality" requirements and run number



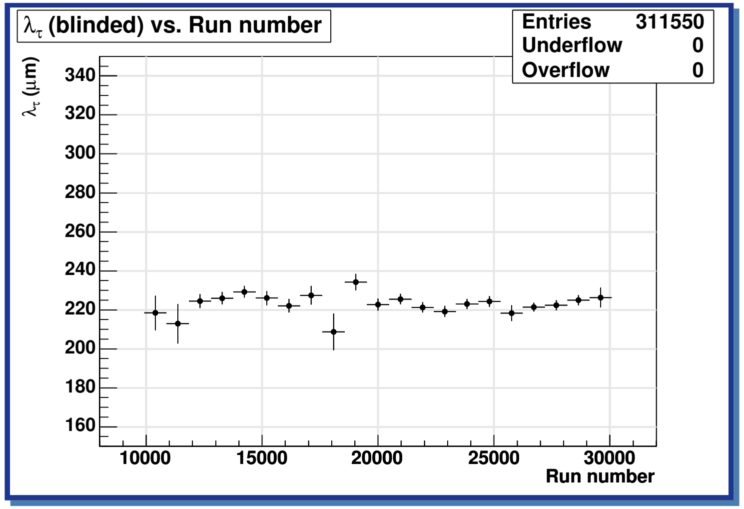
3-prong vertex Prob (χ^2)



Estimated error



Trimming fraction



Run number