Measurements of $|V_{us}|$ and Searches for Violation of Lepton Universality and for *CPT* Violation in Tau Decays at *BABAR*

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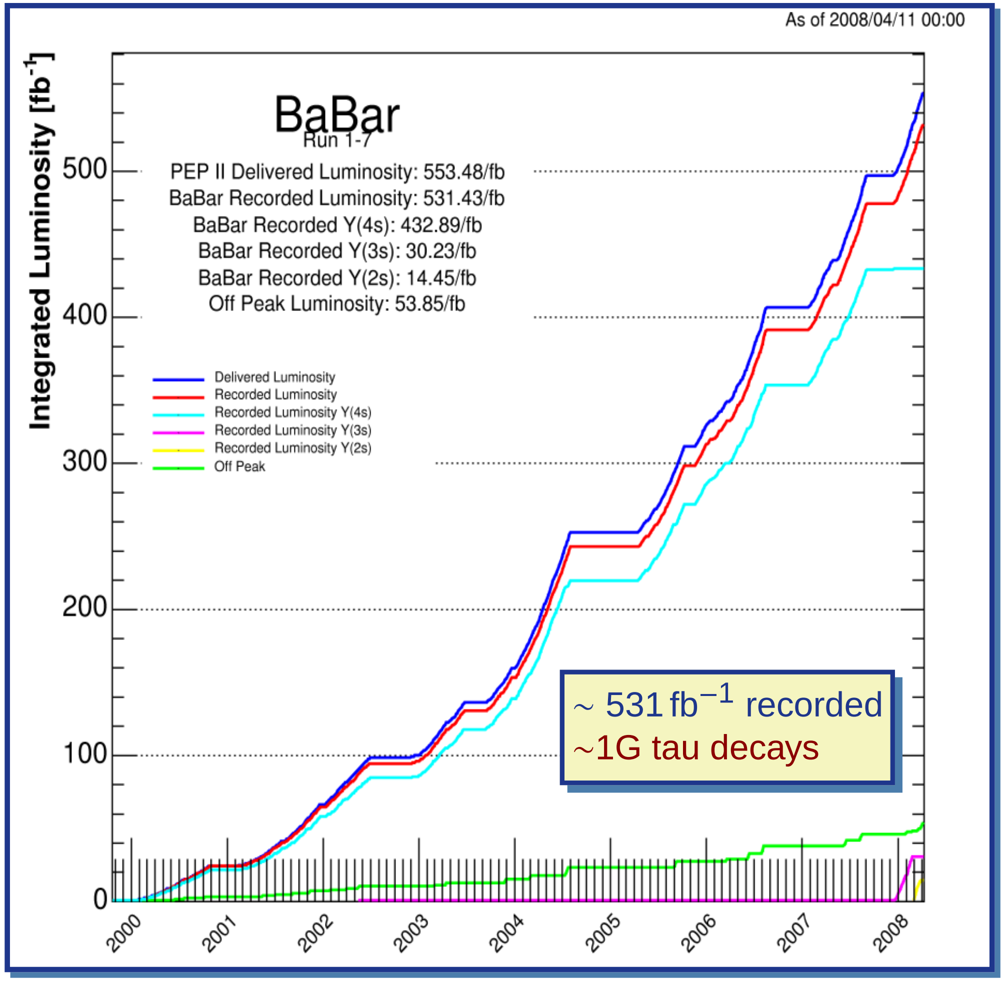
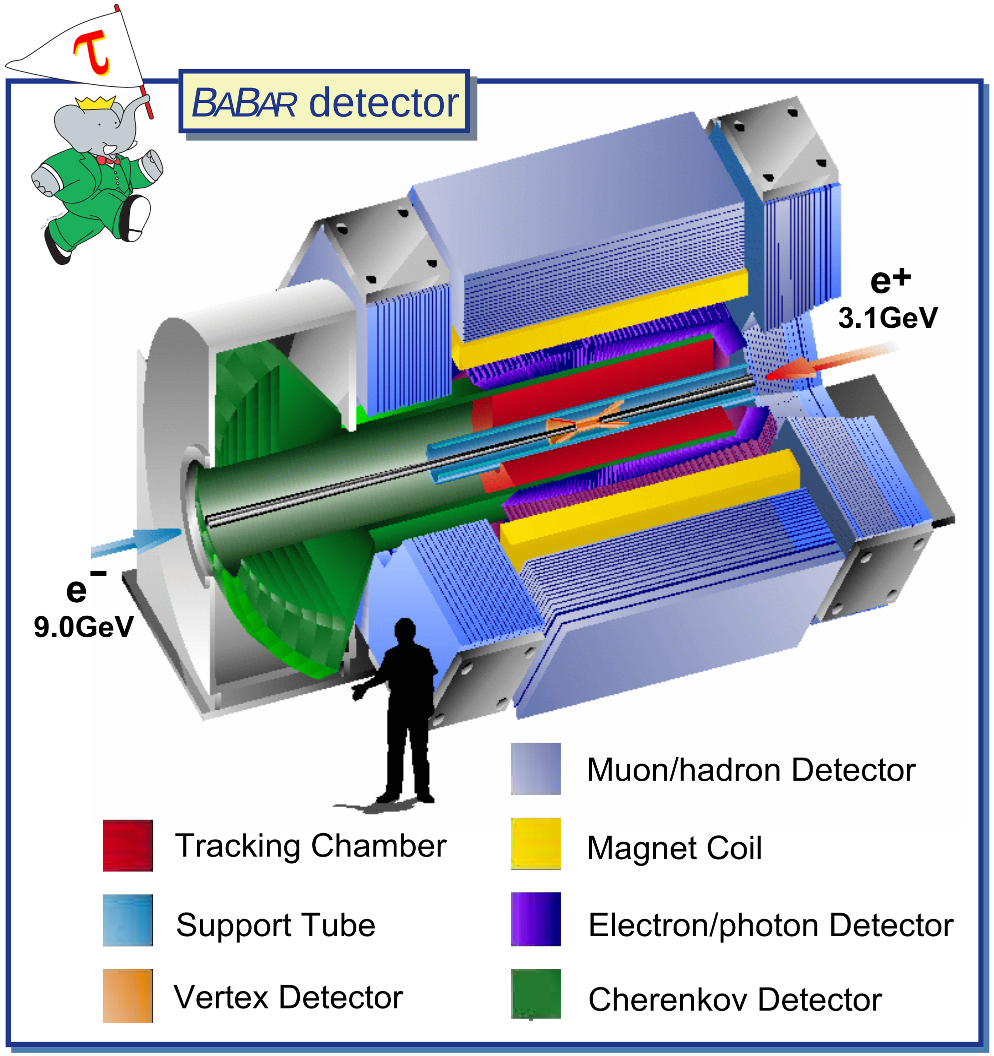
(on behalf of the *BABAR* collaboration)

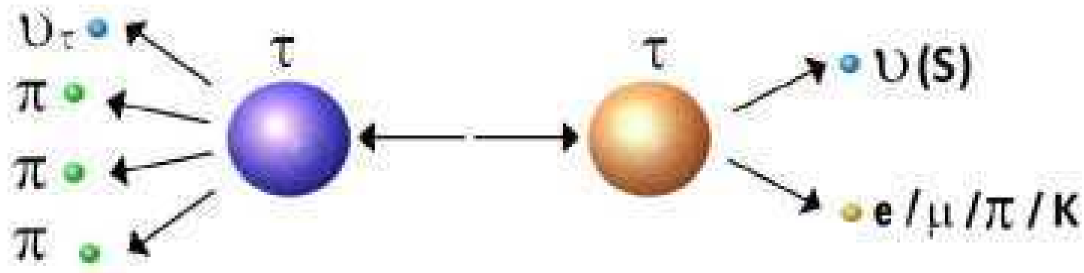
BABAR is a Tau Factory, $\sigma(\tau^+\tau^-) \approx 0.9\,\text{nb} \approx \sigma(B\overline{B}) \approx 1.1\,\text{nb}$





Measurement of tau → 1-prong BRs, with 1-prong = e, μ, π, K

- absolute BRs precision limited by luminosity and PID uncertainties → measure BR ratios
- events with 3-prongs on the tag side and 1-prong on the signal side



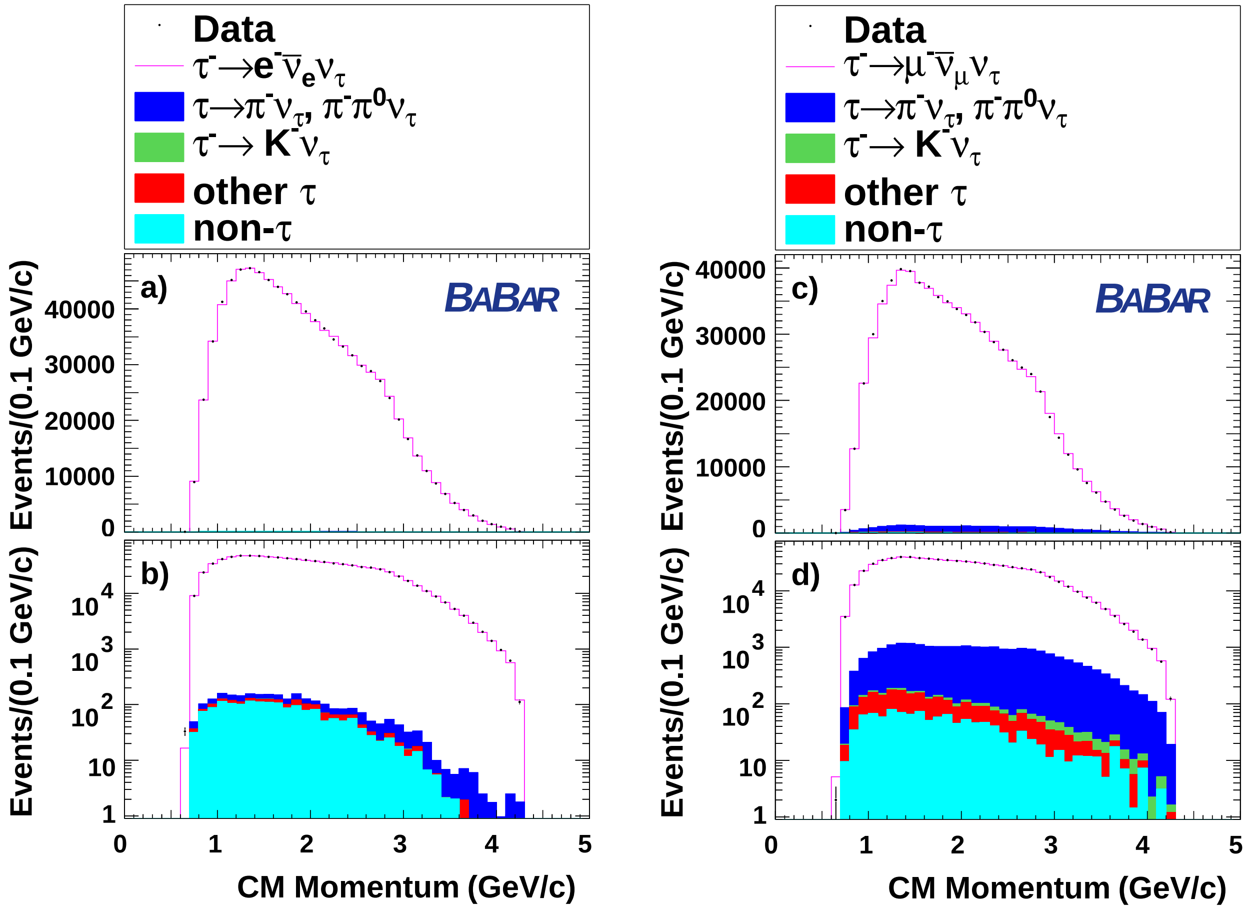
- measure $\frac{\text{BF}(\tau \to \mu\nu\bar{\nu})}{\text{BF}(\tau \to e\nu\bar{\nu})}$ $\frac{\text{BF}(\tau \to \pi\nu)}{\text{BF}(\tau \to e\nu\bar{\nu})}$ $\frac{\text{BF}(\tau \to K\nu)}{\text{BF}(\tau \to e\nu\bar{\nu})}$ $\frac{\text{BF}(\tau \to K\nu)}{\text{BF}(\tau \to \pi\nu)}$
- some systematic uncertainties approximately cancel (luminosity, efficiency)
- 467 fb^{-1} data sample
- limiting systematics
  - PID
  - background suppression (esp. $K\nu$ mode)
  - detector response (drift chamber, EMC)
- **arXiv:0912.0242 [hep-ex]** accepted by PRL

BF($\tau \to \mu\nu\bar{\nu}$), BF($\tau \to e\nu\bar{\nu}$)

BABAR arXiv:0912.0242 [hep-ex]

$\tau \to e\nu\bar{\nu}$ $P_{\text{1-prong}}$

$\tau \to \mu\nu\bar{\nu}$ $P_{\text{1-prong}}$

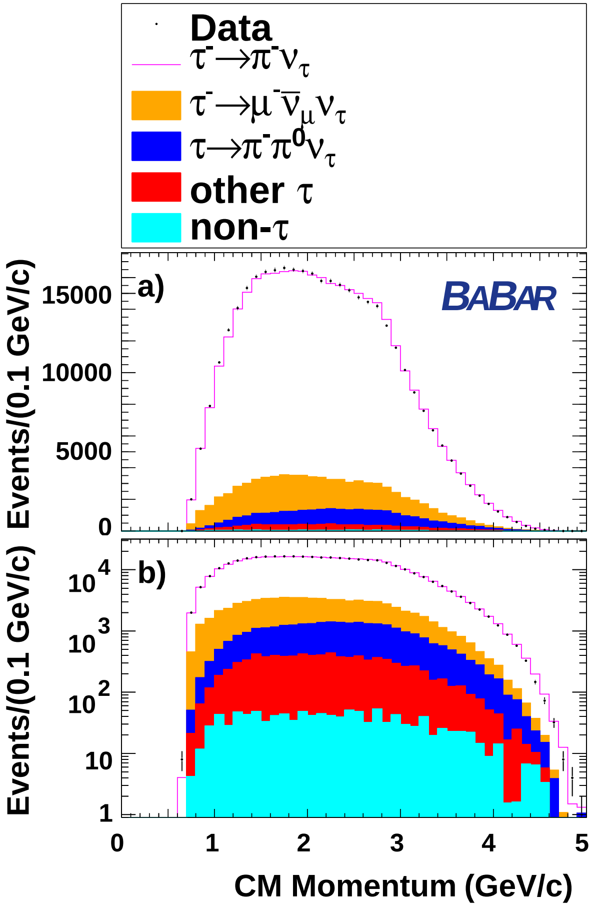


$\tau \to \mu\nu\bar{\nu}$ / $\tau \to e\nu\bar{\nu}$
this work
0.9796 ± 0.0016 ± 0.0036
PDG 2008
0.9725 ± 0.0039

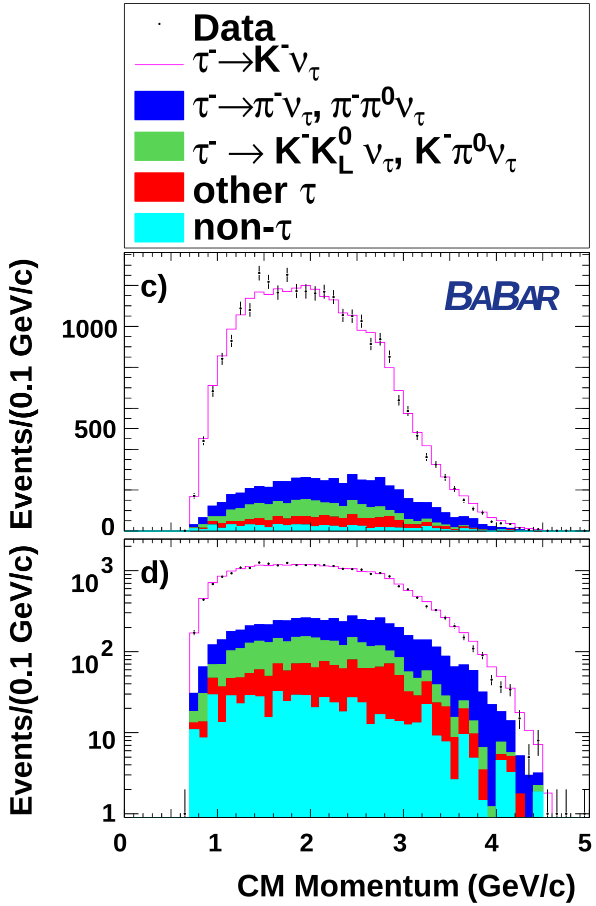
BF($\tau \to \pi\nu$), BF($\tau \to K\nu$)

BABAR arXiv:0912.0242 [hep-ex]

$\tau \to \pi\nu$ $P_{1\text{-prong}}$



$\tau \to K\nu$ $P_{1\text{-prong}}$



$\tau \to \pi\nu \,/\, \tau \to e\nu\overline{\nu}$
$0.5945 \pm 0.0014 \pm 0.0061$

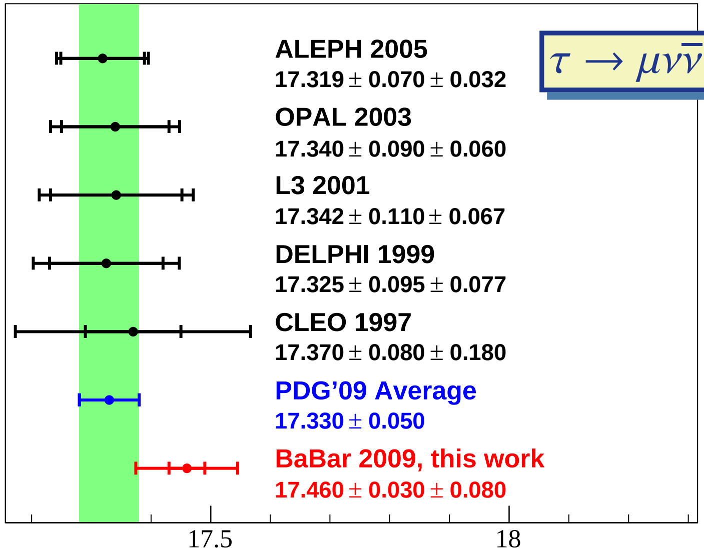
$\tau \to K\nu \,/\, \tau \to e\nu\overline{\nu}$
$0.03882 \pm 0.00032 \pm 0.00057$

$\tau \to K\nu \,/\, \tau \to \pi\nu$
$0.06531 \pm 0.00056 \pm 0.00093$

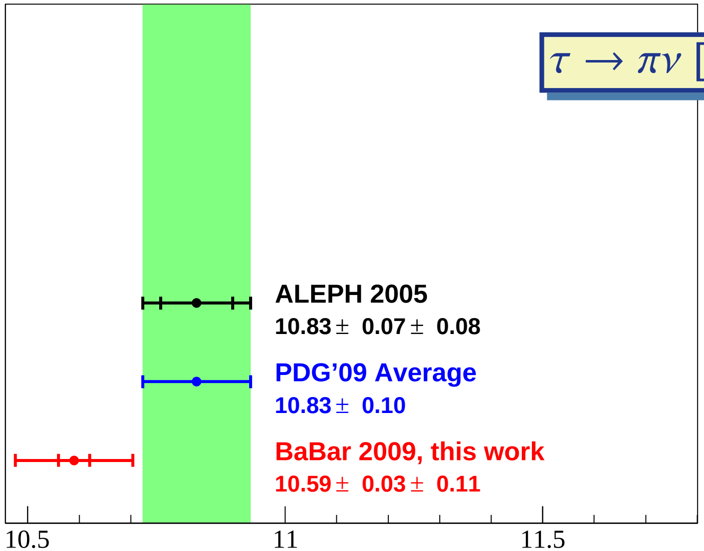
- PDG comparison next page

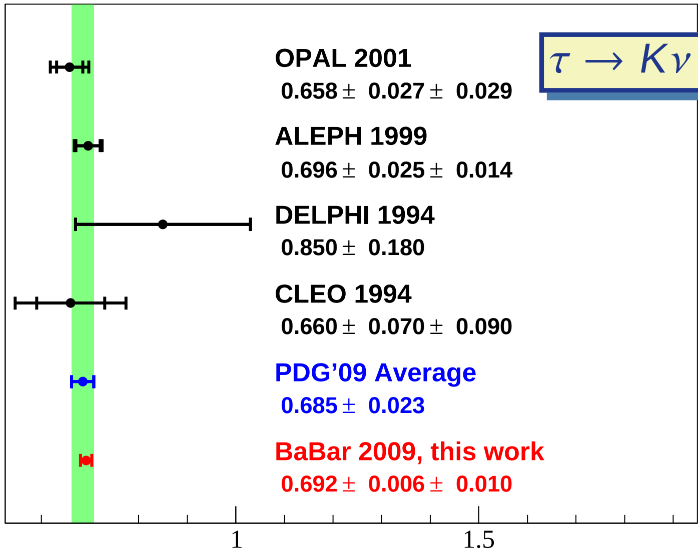
absolute BF($\tau \to \mu\nu\bar{\nu}$), BF($\tau \to \pi\nu$), BF($\tau \to K\nu$)

BABAR



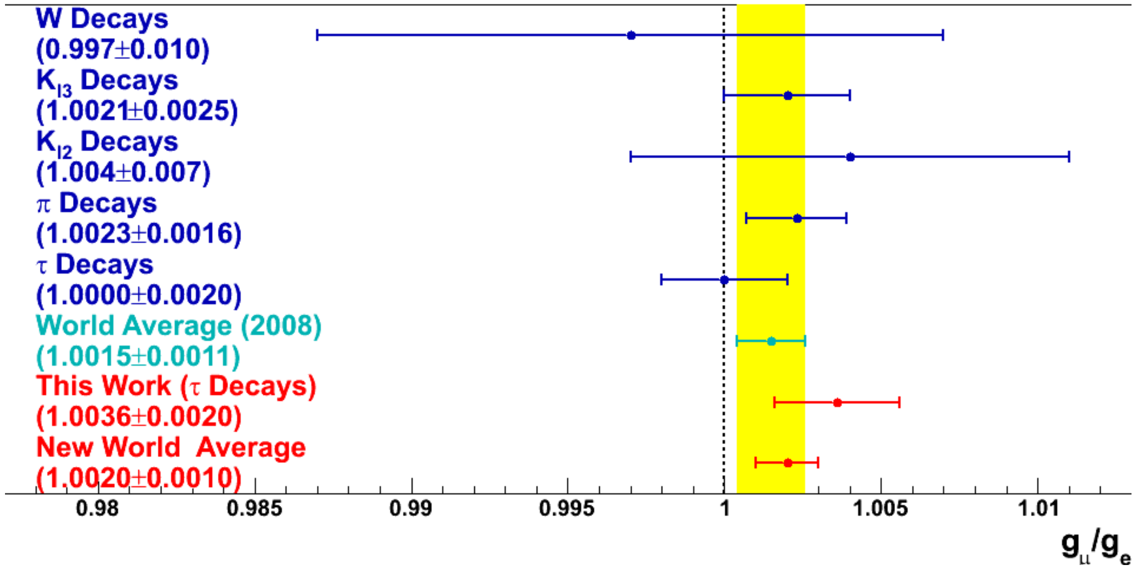
- BABAR arXiv:0912.0242 [hep-ex] PRL acc.
- using BF($\tau \to e\nu\bar{\nu}$) = (17.82 ± 0.05) (PDG 2008)

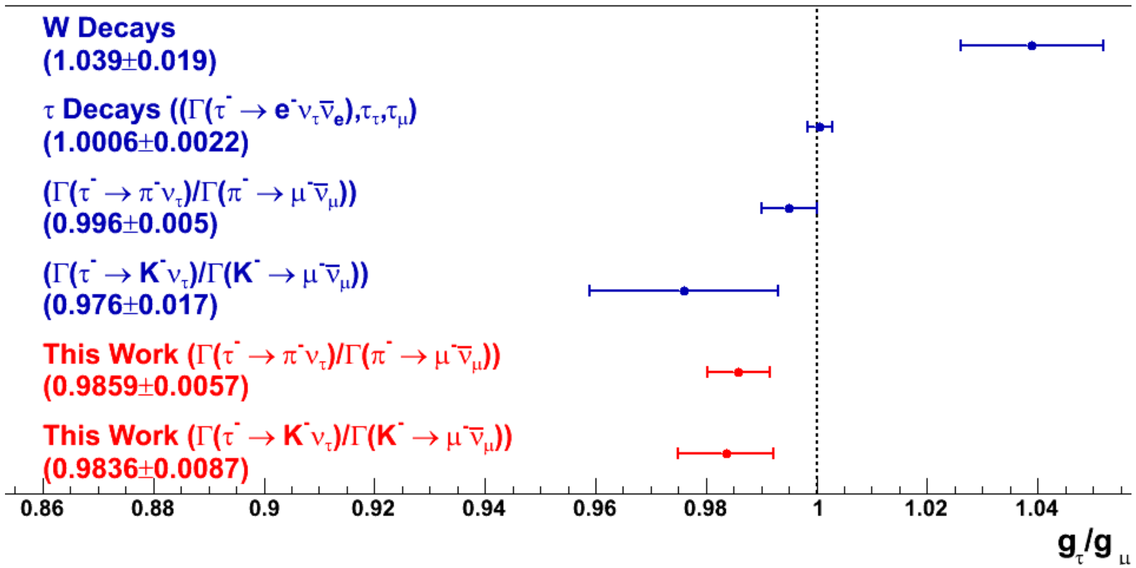




Tau lepton universality tests

BABAR arXiv:0912.0242 [hep-ex] PRL acc.





Standard Model

- $G_F = \dfrac{g}{4\sqrt{2}M_W^2}$
- $g = g_e = g_\mu = g_\tau$

***W* decays**

- ALEPH, DELPHI, L3, OPAL

***τ* decays**

- ALEPH, DELPHI, L3, OPAL, CLEO

pion decays

- TRIUMF, PSI

kaon decays

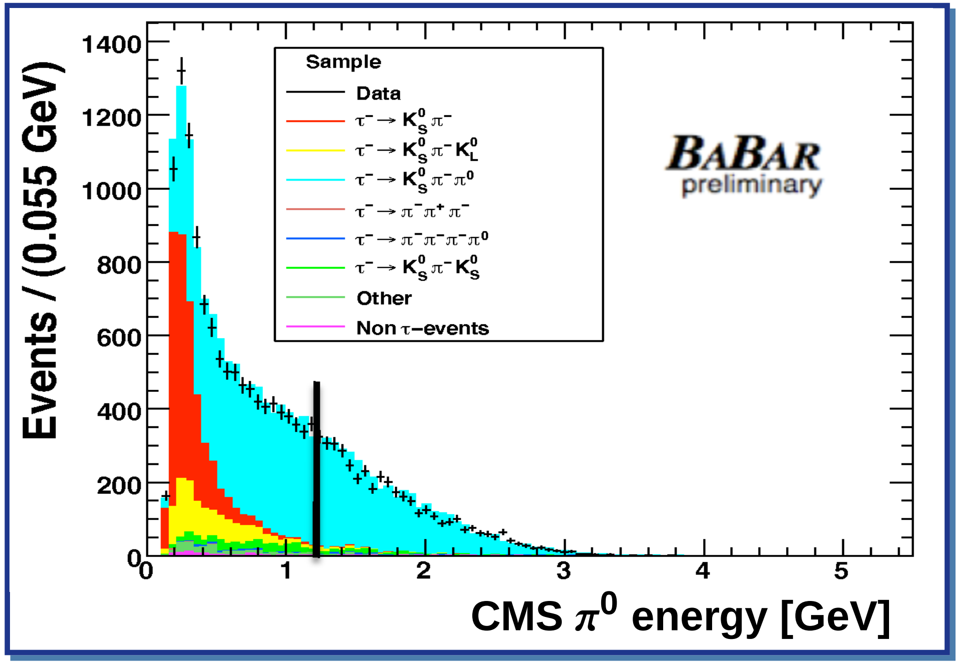
- KLOE

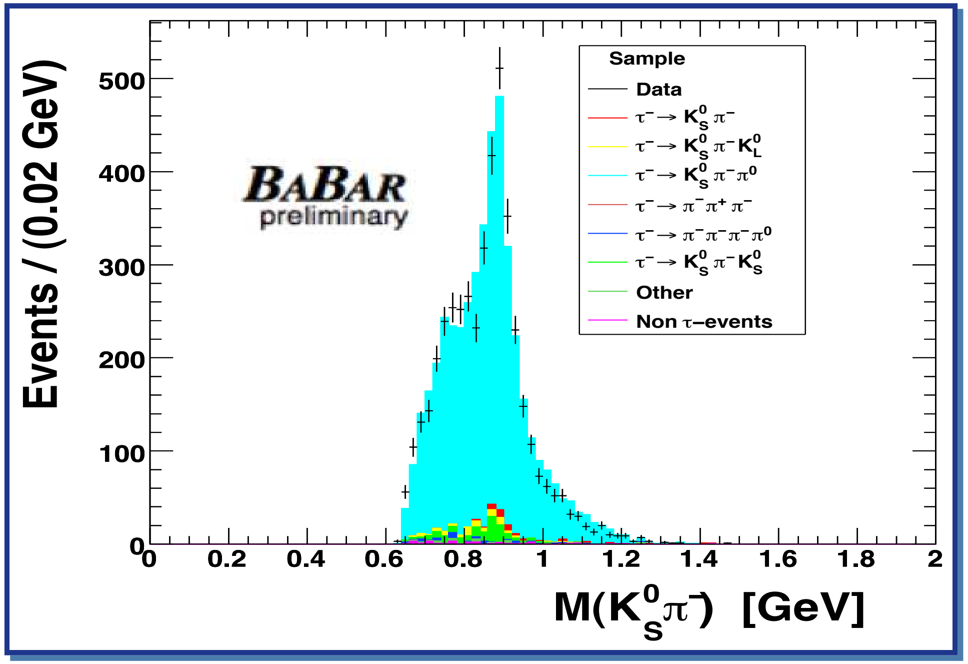
tau, pion, kaon numbers from
A.Pich, arXiv:0806.2793

BF($\tau \to K_S \pi \pi^0 \nu$)

BABAR

S.Paramesvaran, APS-DPF 2009, prelim.





- select single e/μ against $K_S \pi \pi^0$
- require high π^0 energy in CM system
  - → high signal purity ($\sim$ 93%)
- π^0 trajectory within 90° of $K_S \pi$ momentum

- MC tau decay form factors form factors (Tauola) tuned on real data
- dominant systematic is π^0 eff. (3.3% relative)

BF($\tau \to K_S \pi \pi^0 \nu$) = [0.342 ± 0.006 (stat.) ± 0.015 (syst.)] %

4.7% precision, was 10.4% in PDG 2009

Methods for obtaining $|V_{us}|$

$K_{\ell 3}$	$\Gamma(K_{\ell 3}) = [\lvert V_{us}\rvert\, f_+(0)]^2 \times \langle\text{well known constants}\rangle$
$K_{\ell 2}$ (K/π)	$\frac{\Gamma(K_{\ell 2})}{\Gamma(\pi_{\ell 2})} = \left\lvert\frac{V_{us}}{V_{ud}}\right\rvert^2 \frac{f_K^2}{f_\pi^2} \times \langle\text{well known constants}\rangle$
tau K/π	$\frac{\Gamma(\tau \to K\nu)}{\Gamma(\tau \to \pi\nu)} = \left\lvert\frac{V_{us}}{V_{ud}}\right\rvert^2 \frac{f_K^2}{f_\pi^2} \times \langle\text{well known constants}\rangle$
$\tau \to K\nu$ exclusive	$\text{BF}(\tau^- \to K^-\nu_\tau) = \frac{G_F^2 f_K^2 \lvert V_{us}\rvert^2 m_\tau^3 \tau_\tau}{16\pi\hbar}\left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{EW}$
$\tau \to X_s\nu$ inclusive	$\frac{R_{\tau,s}}{\lvert V_{us}\rvert^2} = \frac{R_{\tau,V+A}}{\lvert V_{ud}\rvert^2} - \delta R_{\tau,\text{SU3 breaking}}$
unitarity	$\lvert V_{us}\rvert^2 = 1 - \lvert V_{ud}\rvert^2 - \lvert V_{ub}\rvert^2$

- partial cancellation of theory errors in f_K/f_π
- $\delta R_{\tau,\text{SU3 breaking}}$ = SU(3) symmetry breaking correction, computed with data & QCD with OPE/FESR [see e.g. E.Gamiz *et al.*, arXiv:hep-ph/0612154v1, E.Gamiz *et al.*, POS(KAON)08 (2008)]

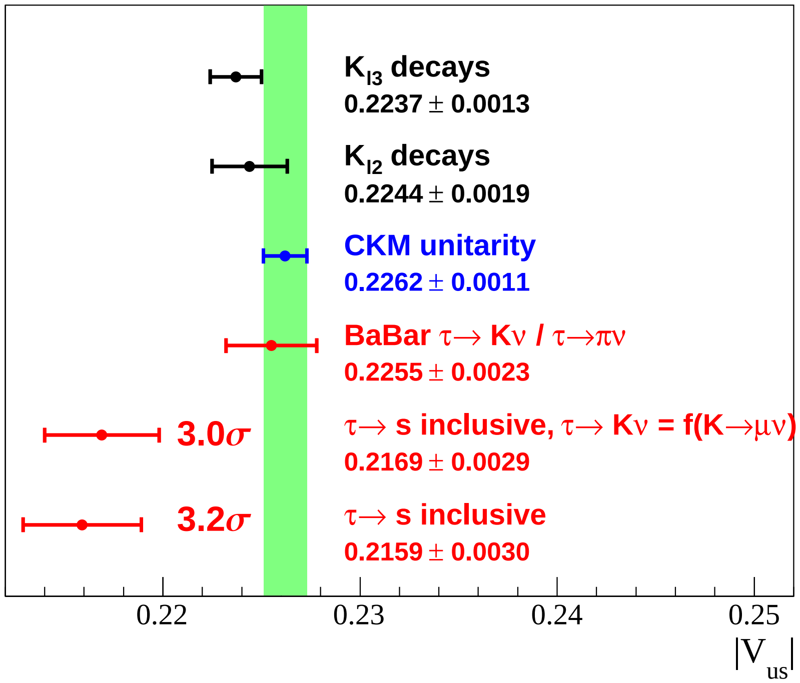
$|V_{us}|$ from $\tau \to X_s \nu$ inclusive is theoretically cleanest

method	theory systematic error for $\lvert V_{us}\rvert$		
K_{l3}	0.58%	from $\Delta\,[f_+(0)]$	arXiv:1004.0886v1 [hep-lat]
K_{l2}	0.50%	from $\Delta\,(f_K/f_\pi)$	arXiv:1005.2323v1 [hep-ph] (FlaviaNet)
$\tau \to X_s \nu$ inclusive	0.47%	from $\Delta\left(\delta R_{\tau,\text{SU3 breaking}}\right)$	E.Gamiz et al., arXiv:hep-ph/0612154v1
$\tau \to X_s \nu$ inclusive	0.23%	from $\Delta\left(\delta R_{\tau,\text{SU3 breaking}}\right)$	E.Gamiz *et al.*, POS(KAON)08 (2008)

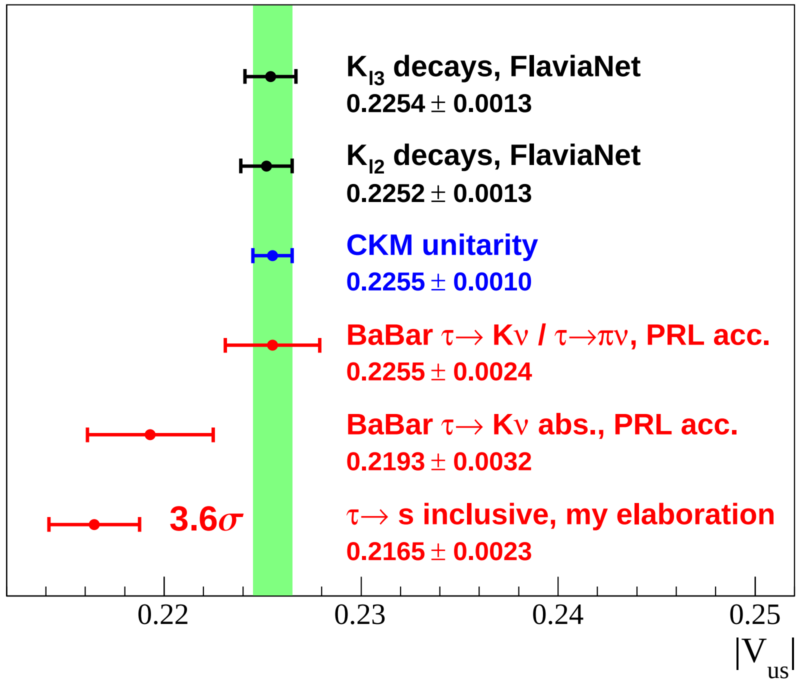
- $|V_{us}|$ from K_{l3} and K_{l2} is already limited by theory uncertainties

Update of tau $|V_{us}|$ measurements

ICHEP 2008, arXiv:0811.1429v3 [hep-ex]



ICHEP 2010



- first $|V_{us}|$ determination using $\tau \to K\nu$ absolute rate
- details on $|V_{us}|$ from $\tau \to X_s\nu$ inclusive on next pages

Some details on the computation of $|V_{us}|$ from $\tau \to X_s\nu$ inclusive

- newly formed HFAG-tau group S.Banerjee, K.Hayasaka, H.Hayashii, A.L., J.M.Roney, B.Shwartz
  - using PDG 2009 measurements inputs plus all **available recent tau preliminary results**
  - taking into account **correlated systematics**, also across experiments
  - no PDG-style S-factors are used, quote CL or χ^2/d.o.f.
  - will release official results soon, including $|V_{us}|$ from tau's
  - here personal elaboration using HFAG tau's inputs and techniques
- **$\tau \to X_s\nu$ measurements list revisited**
  - Rev.Mod.Phys. 78 (2006) 1043 estimates for $\tau \to K3\pi\nu$ & $\tau \to K4\pi\nu$ replaced with results of HFAG unconstrained fit on all measured tau BRs
  - include best complete non overlapping set of modes

ICHEP 2008 $\tau \rightarrow X_s \nu$

hadronic system in $\tau \rightarrow X_s \nu$	BF [%]	References
K^- [from τ decay]	0.690 ± 0.010	PDG 2006 + BABAR 2008 prelim.
[indirect, from $K_{\mu 2}$]	(0.715 ± 0.004)	E.Gamiz *et al.*, PoSKAON:008,2008
$K^-\pi^0$	0.426 ± 0.016	Aubert:2007jh
$\overline{K}^0\pi^-$	0.835 ± 0.022 ($S = 1.4$)	Epifanov:2007rf, Aubert:2008an
$K^-\pi^0\pi^0$	0.058 ± 0.024	Yao:2006px
$\overline{K}^0\pi^0\pi^-$	0.360 ± 0.040	Yao:2006px
$K^-\pi^-\pi^+$	0.290 ± 0.018 ($S = 2.3$)	Aubert:2007mh, Inami:2008kt
$K^-\eta$	0.016 ± 0.001	Inami:2008ar
$(\overline{K}3\pi)^-$ (est'd)	0.074 ± 0.030	Davier:2005xq
$K_1(1270) \rightarrow K^-\omega$	0.067 ± 0.021	Davier:2005xq
$(\overline{K}4\pi)^-$ (est'd)	0.011 ± 0.007	Davier:2005xq
$K^{*-}\eta$	0.014 ± 0.001	Inami:2008ar
$K^-\phi$	0.0037 ± 0.0003 ($S = 1.3$)	Inami:2006vd,Aubert:2007mh
TOTAL using only tau's	2.8447 ± 0.0688	
TOTAL using $K \rightarrow \mu\nu$ to get $\tau \rightarrow K\nu$	(2.8697 ± 0.0680)	

(arXiv:0811.1429v3 [hep-ex])

ICHEP 2010 $\tau \to X_s \nu$

hadronic system in $\tau \to X_s \nu$	BF [%]	B-factories contributions
K^-	0.696 ± 0.010	BABAR 2010 PRL accepted
$K^-\pi^0$	0.431 ± 0.015	BABAR 2007
$K^-\pi^0\pi^0(ex.K^0)$	0.060 ± 0.022	
$K^-\pi^0\pi^0\pi^0(ex.K^0,\eta)$	0.044 ± 0.022	
$\overline{K}^0\pi^-$	0.827 ± 0.018	Belle 2008, BABAR 2008
$\overline{K}^0\pi^-\pi^0$	0.349 ± 0.015	BABAR 2009 prelim.
$\overline{K}^0\pi^-\pi^0\pi^0$	0.023 ± 0.023	
$K^0h^-h^+h^-$	0.023 ± 0.020	
$K^-\pi^-\pi^+(ex.K^0)$	0.294 ± 0.007	BABAR 2008, Belle 2010
$K^-\pi^-\pi^+\pi^0(ex.K^0,\eta)$	0.075 ± 0.012	
$K^-\eta$	0.016 ± 0.001	Belle 2009
$K^-\eta\pi^0$	0.0048 ± 0.0012	Belle 2009
$\overline{K}^0\eta\pi^-$	0.0094 ± 0.0015	Belle 2009
$K^-K^+K^-$	0.0022 ± 0.0001	Belle 2006, BABAR 2007
$K^-K^0\overline{K}^0$ from $K^-K^+K^- \cdot \frac{\phi\to K^0\overline{K}^0}{\phi\to K^+K^-}$	0.0015 ± 0.0001	$(K^-\phi, \phi \to K^+K^-$ saturates $K^-K^+K^-)$
TOTAL using only tau's	2.8570 ± 0.0582	error also depends on correlations

(BRs obtained by HFAG unconstrained fit (personal elaboration), χ^2/d.o.f = 155/114)

$|V_{us}|$ from $\tau \to X_s \nu$ inclusive, additional notes

- BF($\tau \to X_{V+A}\nu$) + BF($\tau \to X_s\nu$) = BF($\tau \to X_h\nu$) is set to 1 – BF($\tau \to e\nu\bar{\nu}$)$_{\text{UNIV}}$ – BF($\tau \to \mu\nu\bar{\nu}$)$_{\text{UNIV}}$
  - BF($\tau \to e\nu\bar{\nu}$)$_{\text{UNIV}}$ and BF($\tau \to \mu\nu\bar{\nu}$)$_{\text{UNIV}}$ defined as in Rev.Mod.Phys. 78 (2006) 1043
  - preliminary computation of BF($\tau \to \ell\nu\bar{\nu}$)$_{\text{UNIV}}$ in HFAG-tau context
- $\delta R_{\tau,\text{SU3 breaking}} = 0.240 \pm 0.032$, E.Gamiz et al., arXiv:hep-ph/0612154v1 (conservative theory error)
- $|V_{ud}| = 0.97425 \pm 0.00022$, Towner-Hardy, 2009
- $|V_{us}|$ from Kaons and unitarity from FlaviaNet report arXiv:1005.2323v1 [hep-ph]

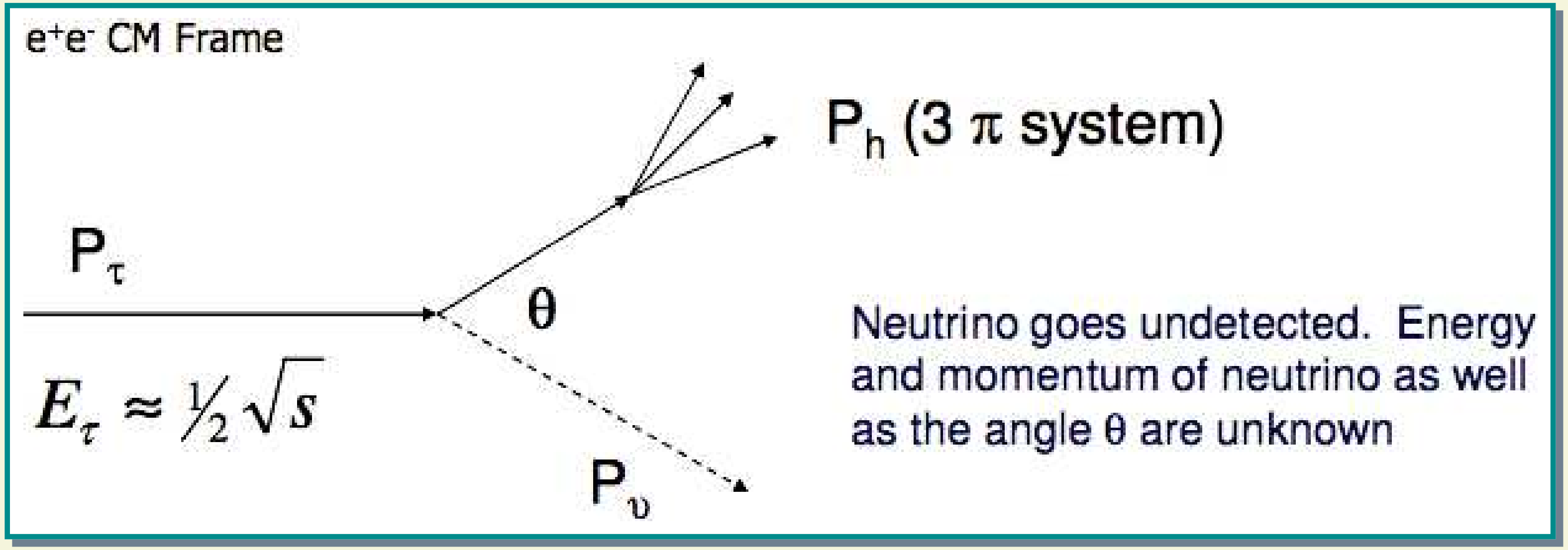
Tau Mass

BABAR PhysRevD.80.092005

- threshold experiments obtain best precision but cannot separately measure $M_{\tau+}$ vs. $M_{\tau-}$
- B-factories systematically dominated, but can test **CPT prediction $M_{\tau+} = M_{\tau-}$**
- select 1-prong vs. 3-prong events (mostly $\tau^- \to \pi^-\pi^+\pi^-\nu$, charge conjugation implied)
- compute tau pseudo-mass

$$M_\tau^2 = M_h^2 + 2(E_\tau - E_h)(E_h - P_h \cos\theta)$$ set $\theta = 0$ to get lowest bound on mass

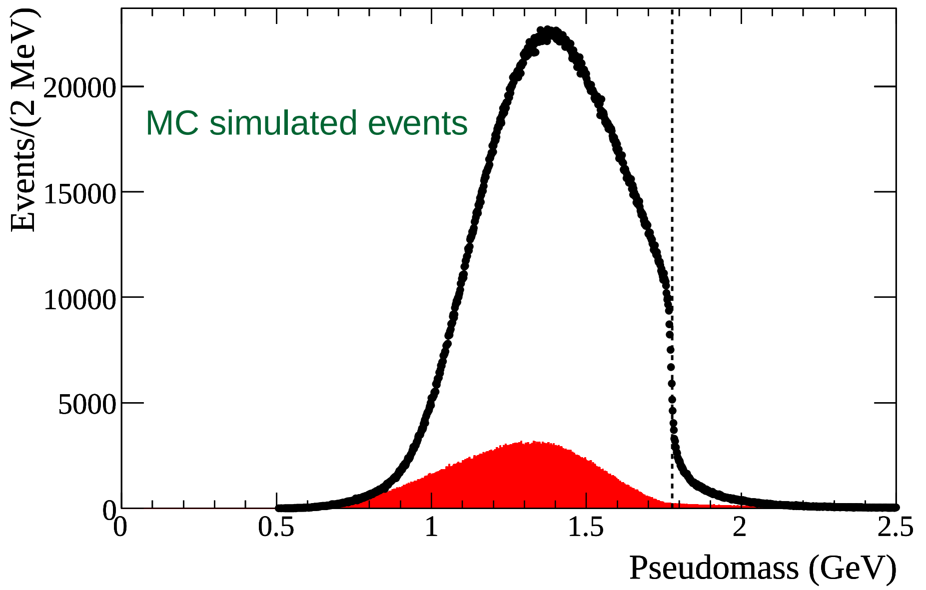
$$M_{\text{pseudo}} = \sqrt{M_h^2 + 2(\sqrt{s} - E_h)(E_h - P_h)} \leq M_\tau$$



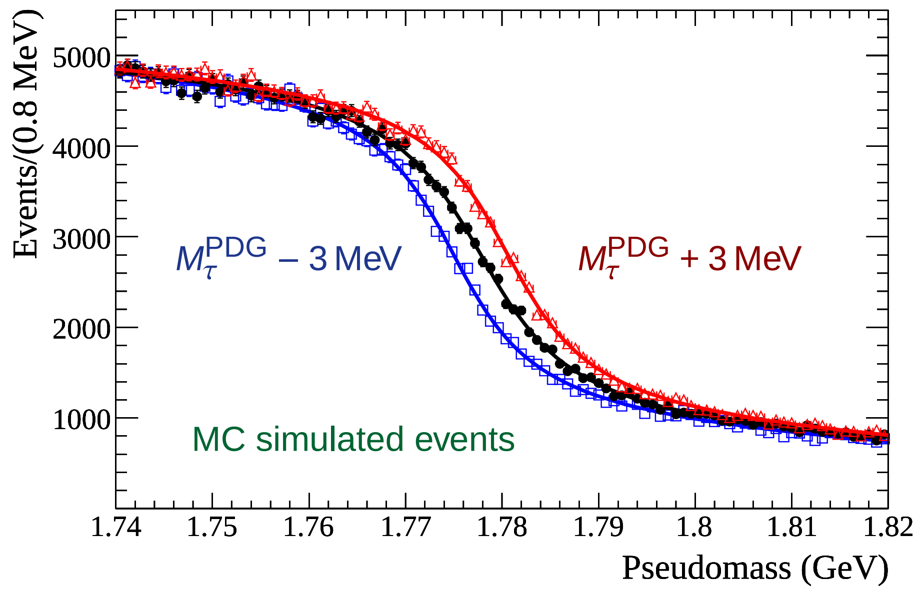
Tau Mass (2)

BABAR PhysRevD.80.092005

- fit endpoint region with $f(m) = (c_3 + c_4 m) \tan^{-1}\left(\frac{m - c_1}{c_2}\right) + c_5 + c_6 m$
- obtain m_τ from c_1 using MC simulation



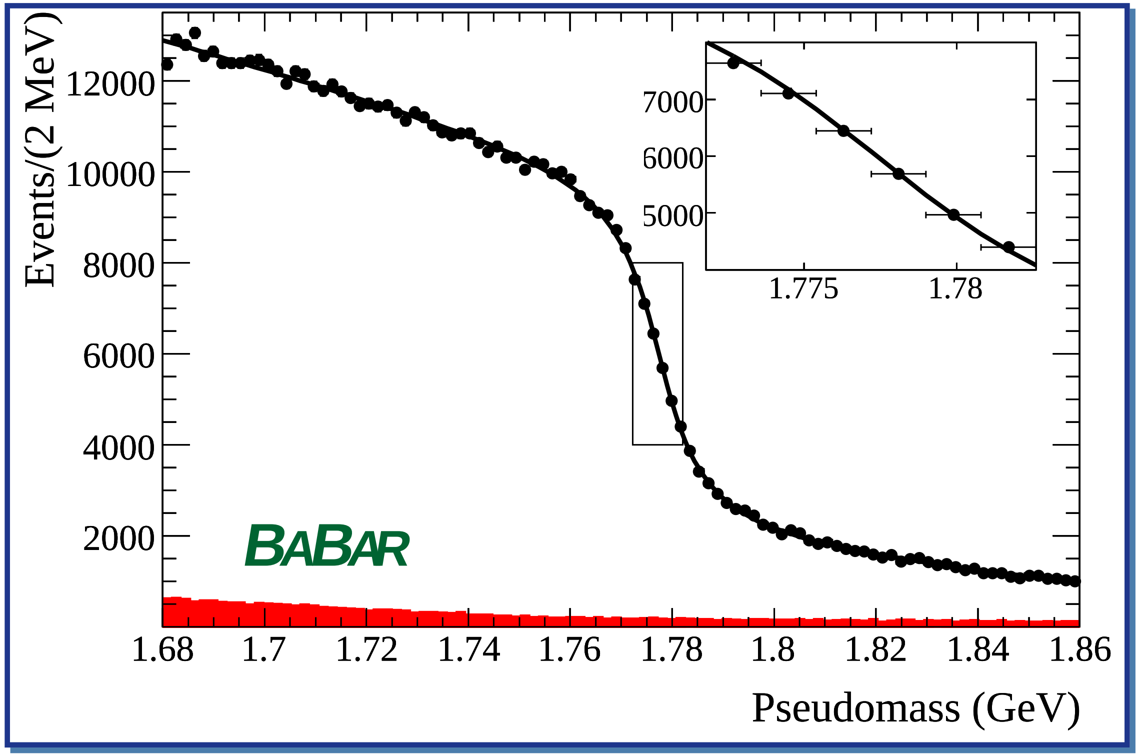
sharp endpoint fall & little background below



endpoint is function of tau mass

Tau Mass – results

BABAR PhysRevD.80.092005



$M_\tau = 1776.68 \pm 0.12\,(\text{stat.}) \pm 0.41\,(\text{syst.})$ MeV

$$\frac{M_{\tau+} - M_{\tau-}}{M_{\text{average}}} = -3.4 \pm 1.3\,(\text{stat.}) \pm 0.3\,(\text{syst.}) \cdot 10^{-4}$$

dominant systematic uncertainty:
absolute momentum measurement
calibrated on Ks and D masses

Conclusions

- measured BF($\tau \to K\nu$) and BF($\tau \to K_S\pi\pi^0\nu$) with better precision than current world averages
- new precise measurements of BF($\tau \to \mu, \pi, K$ + neutrino(s))/BF($\tau \to e$ + neutrino(s))
  - precision comparable or better than existing PDG world averages
  - ⟶ improved charged current lepton universality checks
- computed $|V_{us}|$ with tau's with
  - BF($\tau \to K\nu$)/BF($\tau \to \pi\nu$)
  - BF($\tau \to K\nu$) absolute
  - $\tau \to X_s\nu$ inclusive (observed discrepancy persists)
- HFAG-tau group is finalizing tau world averages, including $|V_{us}|$ determination