TAU PHYSICS AT BABAR

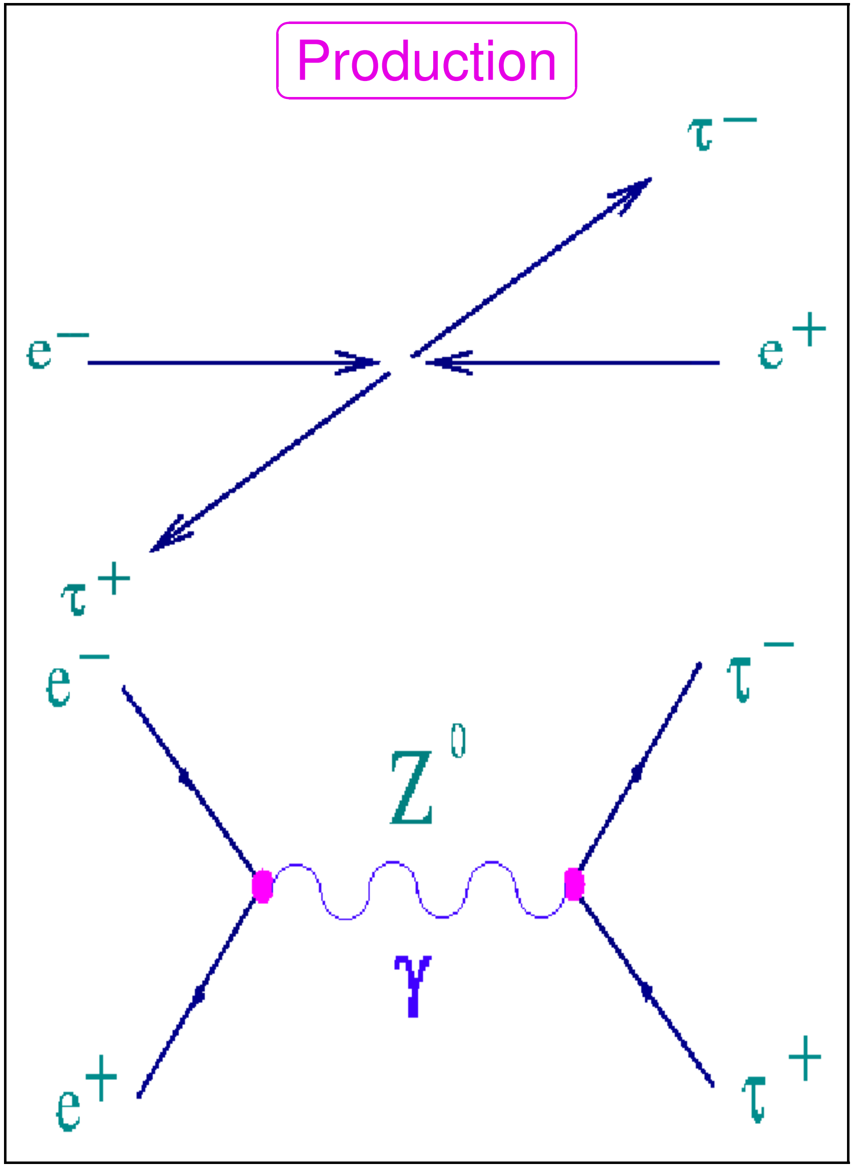
Swagato Banerjee

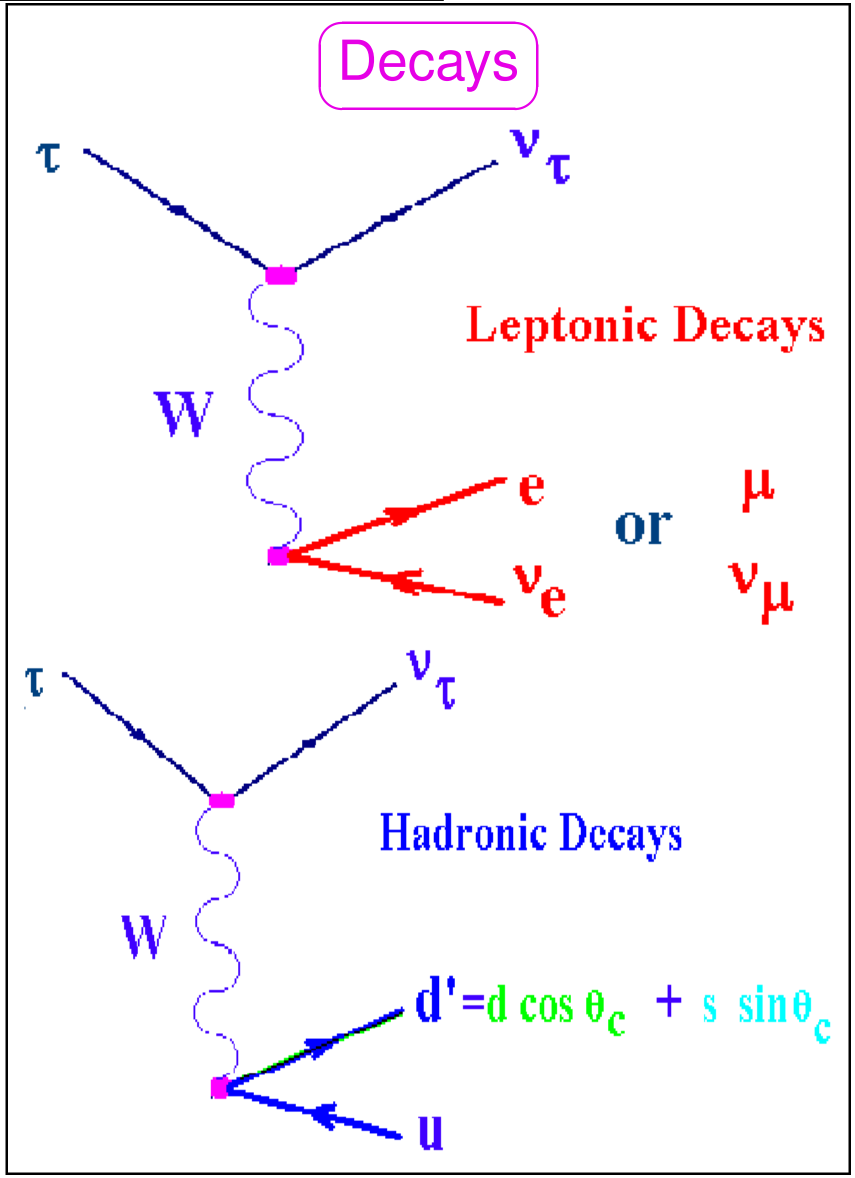
University of Victoria
British Columbia • Canada

On behalf of the BABAR collaboration

DESY Seminar, 16 January 2007

The process: $e^+e^- \rightarrow \tau^+\tau^-$





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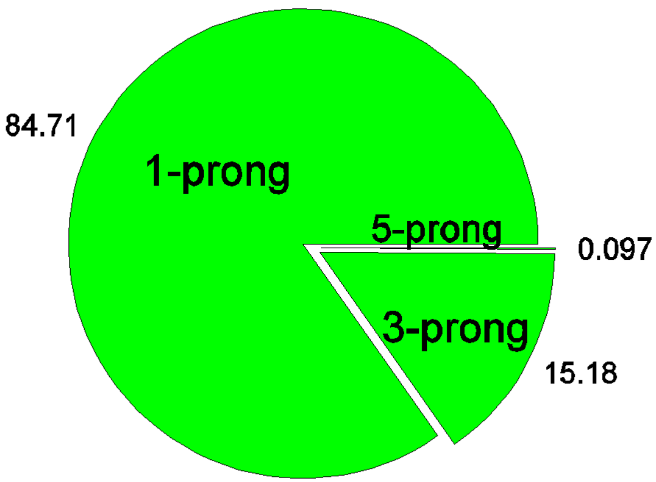
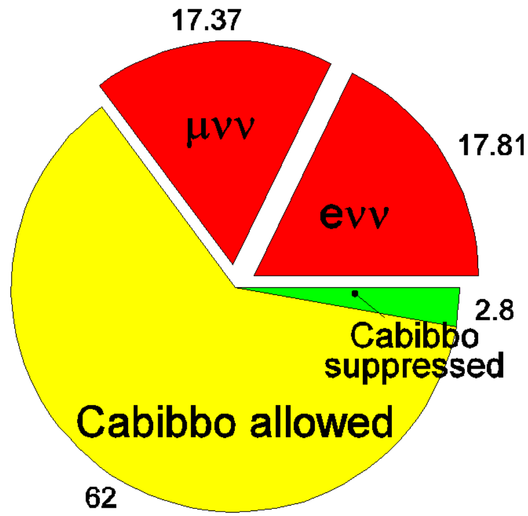
University of Victoria
British Columbia • Canada

τ Branching Fractions (c.f. A. Stahl)

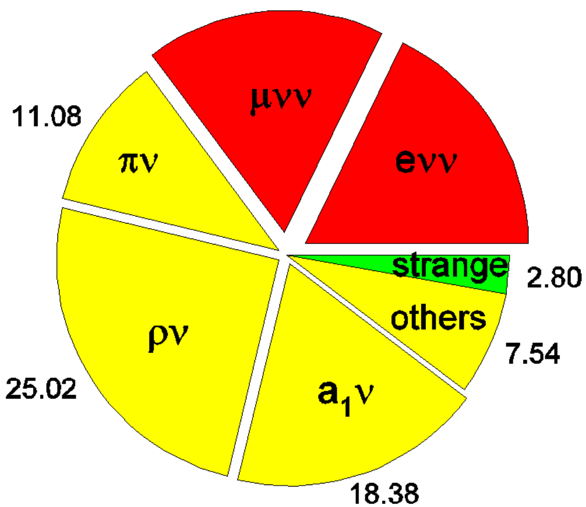
- by topology



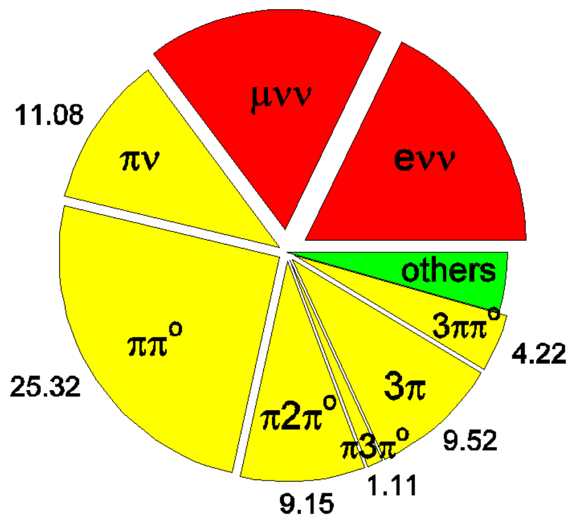
- by leptonic/hadronic



- by resonances



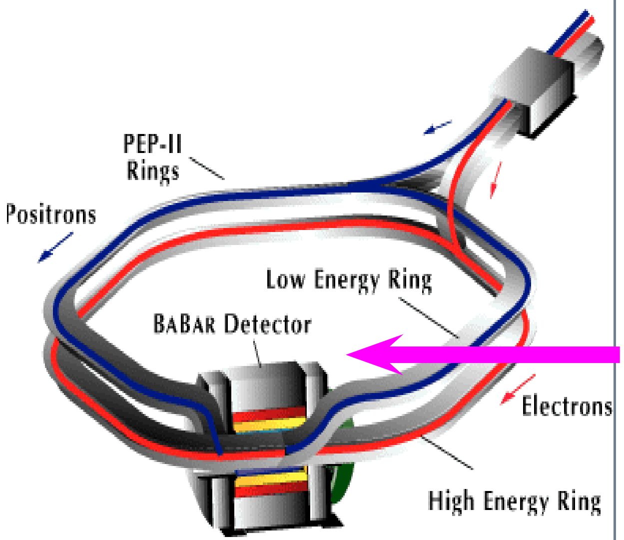
- by exclusive π modes



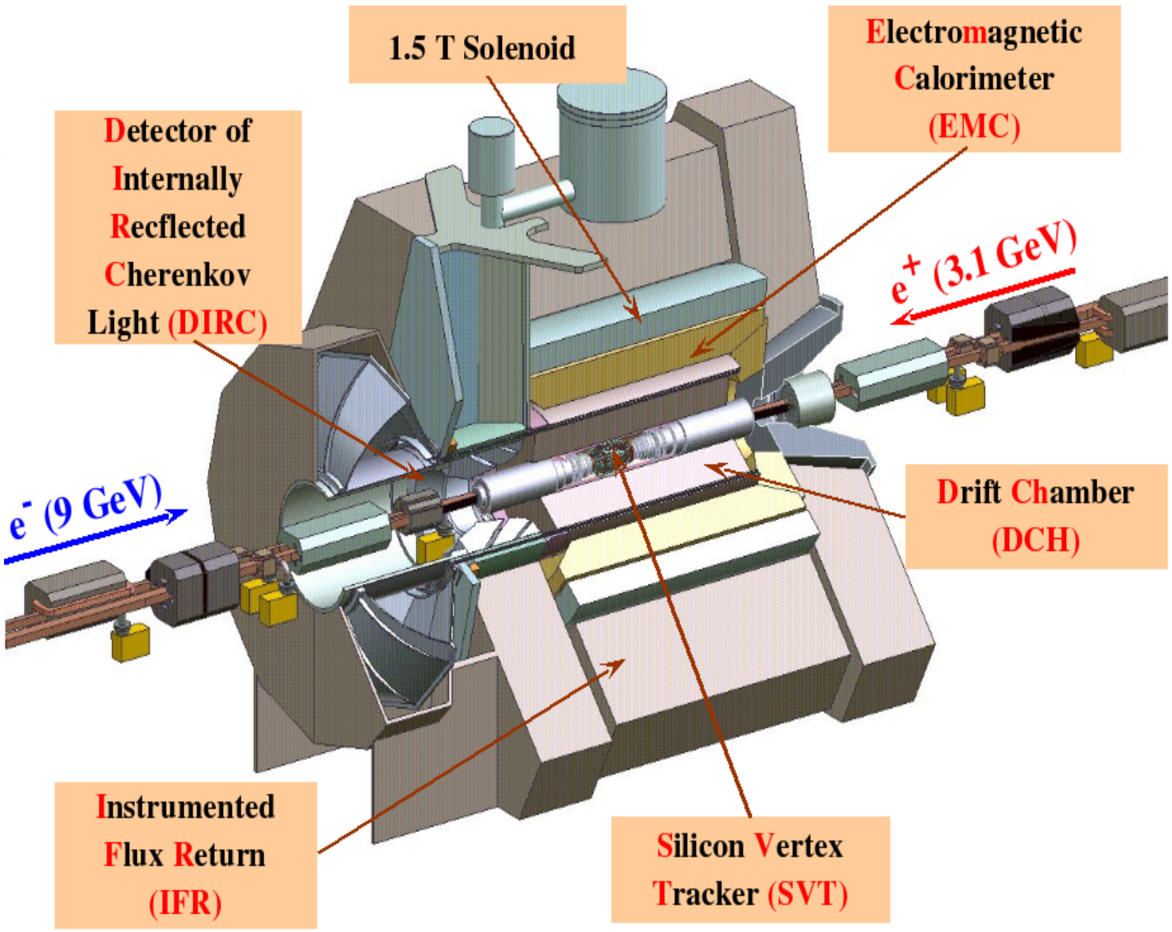
τ Physics at BABAR

- τ-lifetime measurement
  - Tests of CPT, Lepton-universality
- τ-decays with strange quarks
  - Route to world's best measurements of $|V_{us}|$, m_s
  - New decay modes via ϕ resonance observed
- High Multiplicity hadronic states
  - Rich Resonance sub-structures in 3, 5 prong τ decays
  - Limits on τ decaying into 7/8 pions
- Direct Searches for New Physics
  - Lepton Flavor, Lepton Number Violation
    - in decays: $\tau \to \ell\gamma$, $\tau \to \ell\pi^0/\eta/\eta'$, $\tau \to \ell\ell\ell$, $\tau \to \ell hh'$
    - in production: $ee \to \ell\tau$
  - Baryon Number Violation
    - $\tau \to \Lambda\pi/K, \tau \to \bar{\Lambda}\pi/K$
  - CP Violation in lepton sector

SLAC-Based B-Factory: PEP II & BaBar



The BaBar Detector:



S. Banerjee
University of Victoria
British Columbia • Canada

PEP II Records: better than ever

Last update:
August 18, 2006

Peak Luminosity

4 × design

$12.069 \times 10^{33}\ \mathrm{cm^{-2}sec^{-1}}$ August 16, 2006

1722 bunches 2900 mA LER 1875 mA HER

Integration records of delivered luminosity

Best shift (8 hrs, 0:00, 08:00, 16:00)	339.0 $\mathrm{pb^{-1}}$	Aug 16, 2006
Best 3 shifts in a row	910.7 $\mathrm{pb^{-1}}$	Jul 2-3, 2006
Best day	849.6 $\mathrm{pb^{-1}}$	Aug 14, 2006
Best 7 days (0:00 to 24:00)	5.385 $\mathrm{fb^{-1}}$	Jul 27-Aug 3, 2006
Best week (Sun 0:00 to Sat 24:00)	5.111 $\mathrm{fb^{-1}}$	Jul 30-Aug 5, 2006
Peak HER current	1900 mA	Aug 15, 2006
Peak LER current	2995 mA	Oct 10, 2005
Best 30 days	19.315 $\mathrm{fb^{-1}}$	Jul 19 – Aug 17, 2006

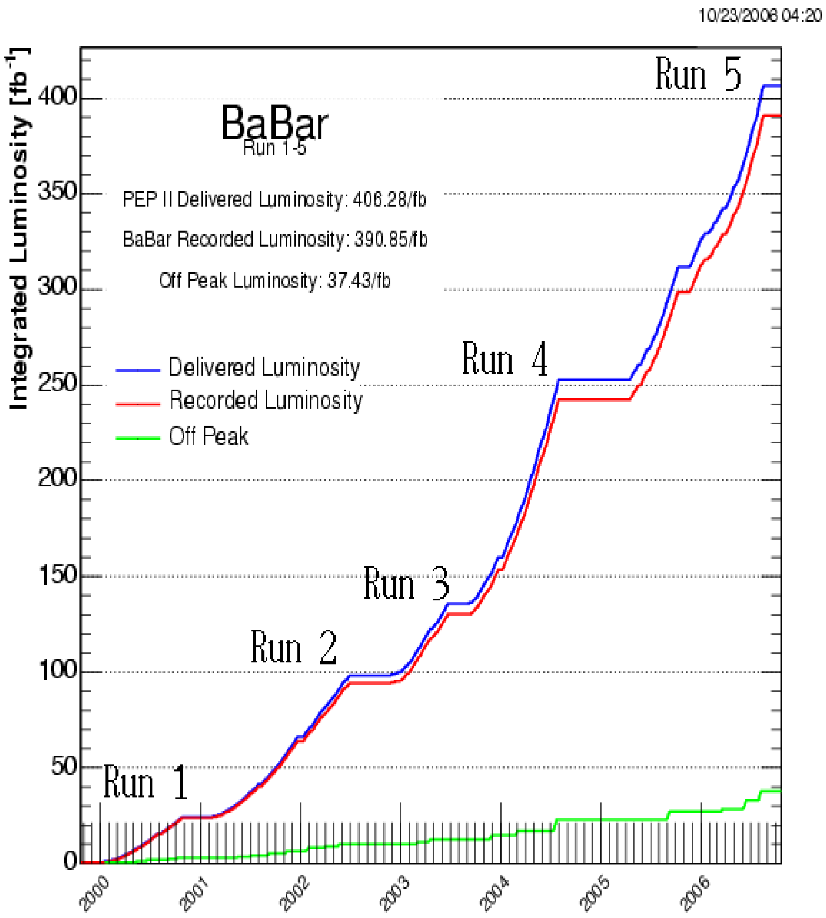
BaBar: a τ-Factory

- B-Factories are also τ-factories

$$\sqrt{s} = 10.58\ \mathrm{GeV}\ (\Upsilon(4S)):$$
$$\sigma(e^+e^- \to B\bar{B}) = 1.1\ \mathrm{nb}$$
$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.9\ \mathrm{nb}$$

Experiment	# of τ-pairs
LEP	3×10^5
CLEO	1×10^7
BaBar	3×10^8

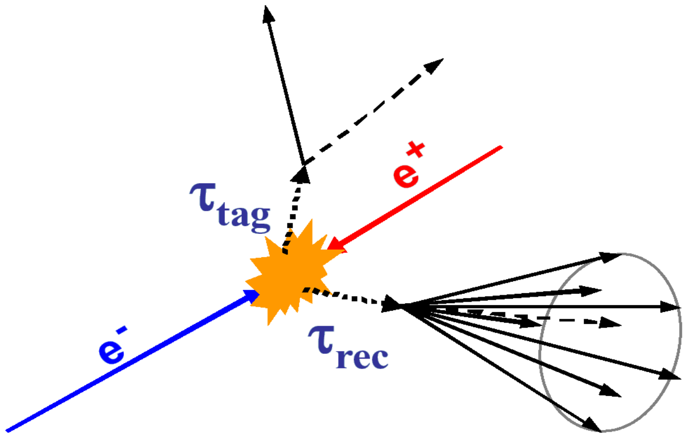
- Precision measurements:
  - systematics limited
  - on-going efforts
- Ideal for search of rare decays



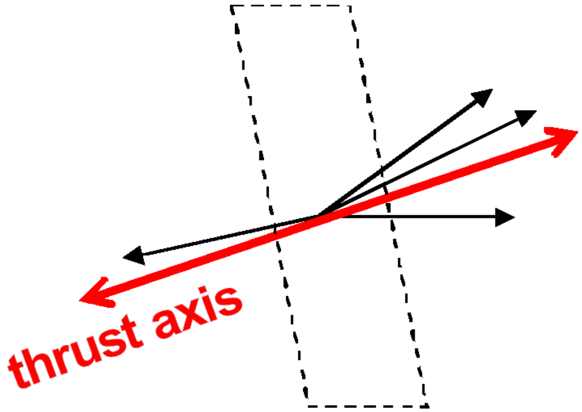
By end of data-taking (Sep 2008):
$\mathcal{L} = 2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}, \int \mathcal{L} > 900\ \mathrm{fb}^{-1}$

τ-pair events at BABAR

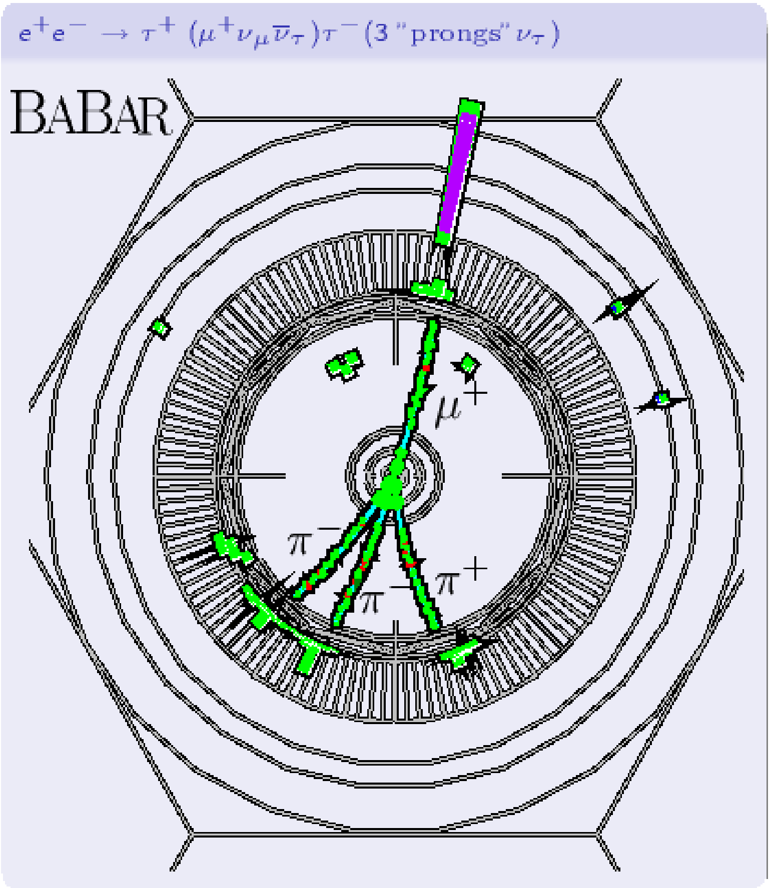
- Well separated in space



- Divide event into 2 hemispheres in CM frame $\perp$ to thrust axis



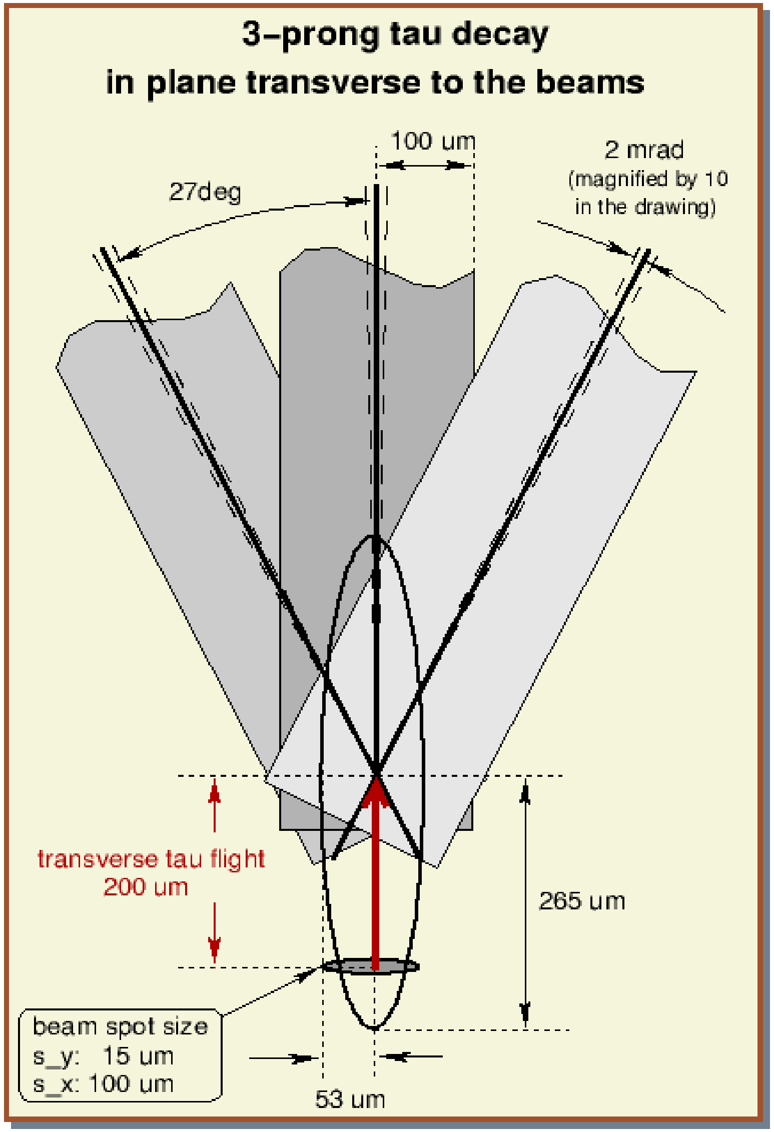
☛ unique signature:
Leptonic + Hadronic decay



☞ most analyses use leptonic tags

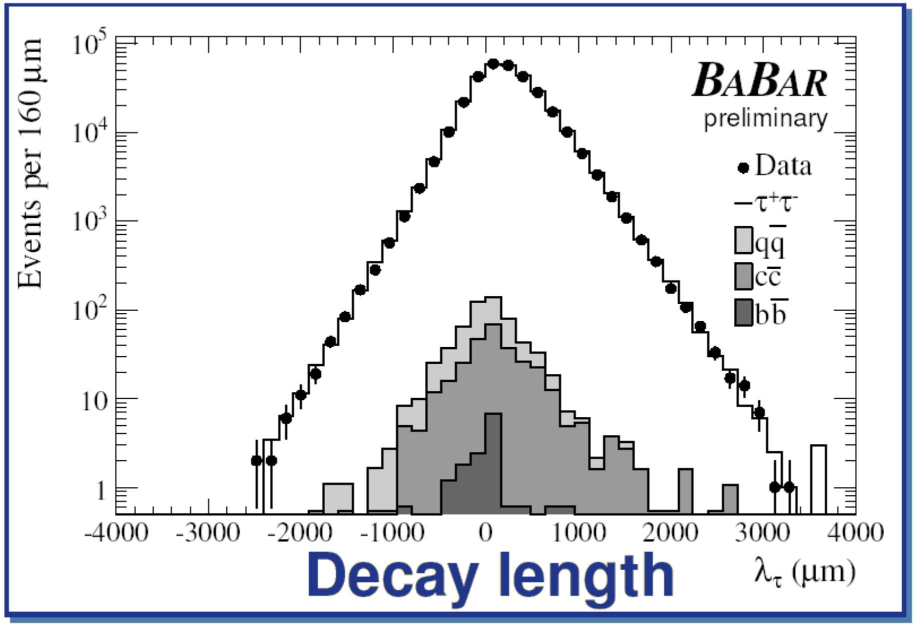
S. Banerjee
University of Victoria
British Columbia • Canada

τ-Lifetime



BaBar (Preliminary): $\mathcal{L} = 80\,\text{fb}^{-1}$ (Tau04, Nara)

Nucl.Phys. B (Proc.Suppl.) 144 (2005) 105



$\tau_\tau = (289.40 \pm 0.91_{\text{stat}} \pm 0.90_{\text{syst}})\text{fs}$

PDG06: $\tau_\tau = (290.6 \pm 1.0)\text{fs}$

Test of CPT:

$\frac{\tau_{\tau^-} - \tau_{\tau^+}}{\tau_{\tau^-} + \tau_{\tau^+}} = (0.12 \pm 0.32_{\text{stat}} \pm X_{\text{syst}})\%$

S. Banerjee
University of Victoria
British Columbia • Canada

τ-Lifetime $\Rightarrow$ Lepton Universality

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

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

where

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

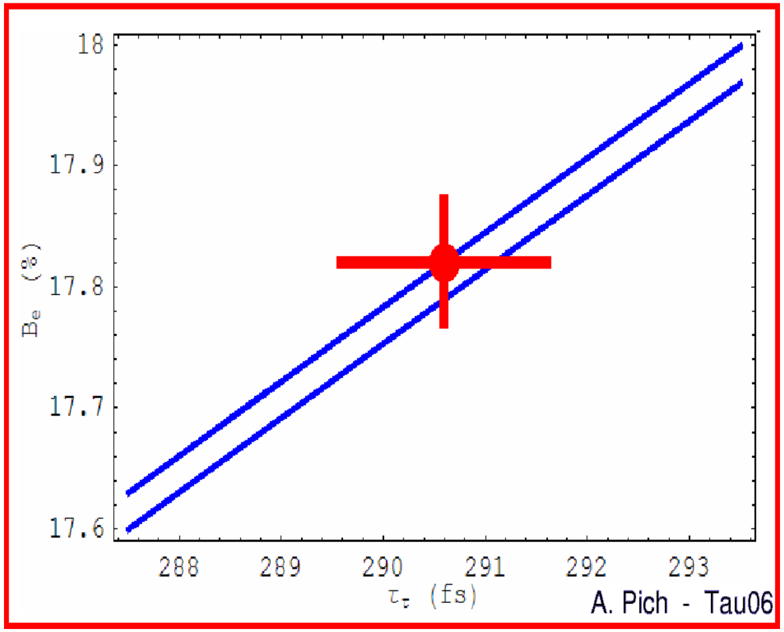
$$r^\ell_{RC} = \text{EW radiative corrections, } \approx 1$$

➥ Expect:

$$B_e = \frac{B_\mu}{(0.972564 \pm 0.000010)} = \frac{\tau_\tau}{(1632.1 \pm 1.4)\text{fs}}$$

➠ PDG06:

$$\frac{B_\mu}{B_e} = (0.9725 \pm 0.0039)$$



S. Banerjee
University of Victoria
British Columbia • Canada

Lepton Universality

- Charged Current Universality:

A.Pich, Tau06

	$\lvert g_\tau / g_e \rvert$
$B_{\tau\to\mu}\, \tau_\mu / \tau_\tau$	1.0004 ± 0.0023
$B_{W\to\tau} / B_{W\to e}$	1.036 ± 0.014

	$\lvert g_\mu / g_e \rvert$
$B_{\tau\to\mu} / B_{\tau\to e}$	1.0000 ± 0.0020
$B_{\pi\to\mu} / B_{\pi\to e}$	1.0017 ± 0.0015
$B_{K\to\mu} / B_{K\to e}$	1.012 ± 0.010 Fiorini
$B_{W\to\mu} / B_{W\to e}$	0.997 ± 0.010

	$\lvert g_\tau / g_\mu \rvert$
$B_{\tau\to e}\, \tau_\mu / \tau_\tau$	1.0004 ± 0.0022
$\Gamma_{\tau\to\pi} / \Gamma_{\pi\to\mu}$	0.996 ± 0.005
$\Gamma_{\tau\to K} / \Gamma_{K\to\mu}$	0.979 ± 0.017
$B_{W\to\tau} / B_{W\to\mu}$	1.039 ± 0.013

- Ratio of Neutral/Charged Current events in muon (anti)neutrino – nucleon scattering measured $g_L^2 = 0.30005 \pm 0.00137$, which is 3σ < SM prediction: $g_L^2 = 0.3042$ "NuTev anomaly"
- Loinaz et.al., hep-ph/0210193: $\mathrm{G_F} = \mathrm{G}_\mu(1+\varepsilon), \varepsilon = 0.003$
- τ-decays: most promising place to look for violation $\sim \mathcal{O}(10^{-3})$

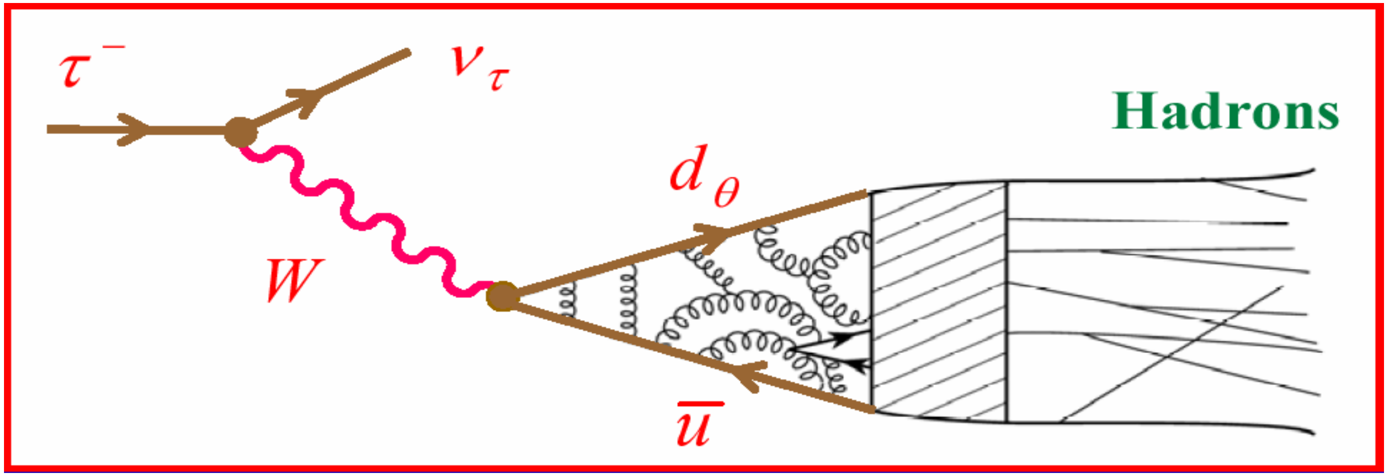
S. Banerjee
University of Victoria
British Columbia • Canada

Hadronic τ decays

- $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{Hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = N_C + \mathcal{O}(\alpha_s)$

  $R_\tau = \frac{1 - B_e - B_\mu}{B_e} = (3.639 \pm 0.011)$ [PDG06]

- Initial state represents perfect QCD vacuum



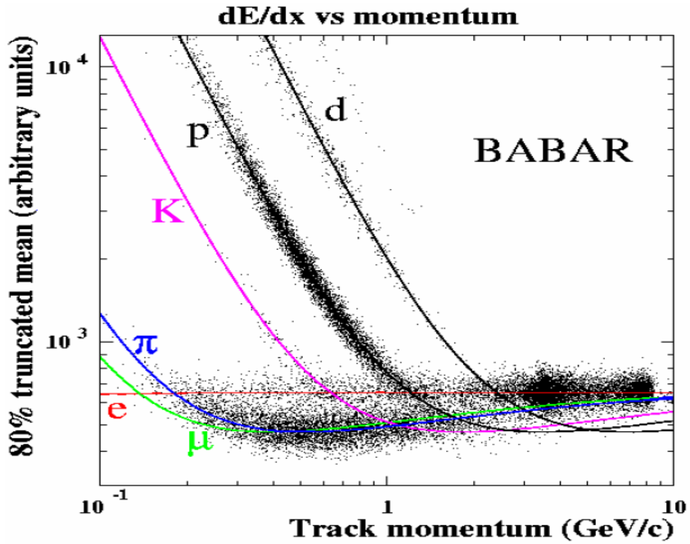
- $\tau^- \to h^- \nu_\tau$ probes hadronic $V - A$ current:
  $\langle h^- | \bar{d}_\theta \gamma^\mu (1 - \gamma_5) u | 0 \rangle$, where $d_\theta = \cos\theta_C d + \sin\theta_C s$
  $\Rightarrow$ Cabibbo allowed non-strange and suppressed strange decays

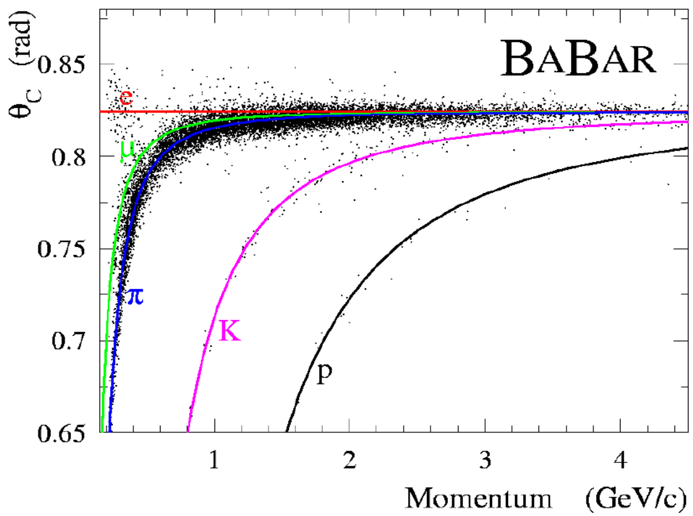
- Ideal for measurements of fundamental quantities: $|V_{us}|$, m_s, α_s

- Several resonance (sub-)structure waiting to be observed

τ-decays with strange quarks

- Excellent K/π separation using dEdx, Cherenkov angle



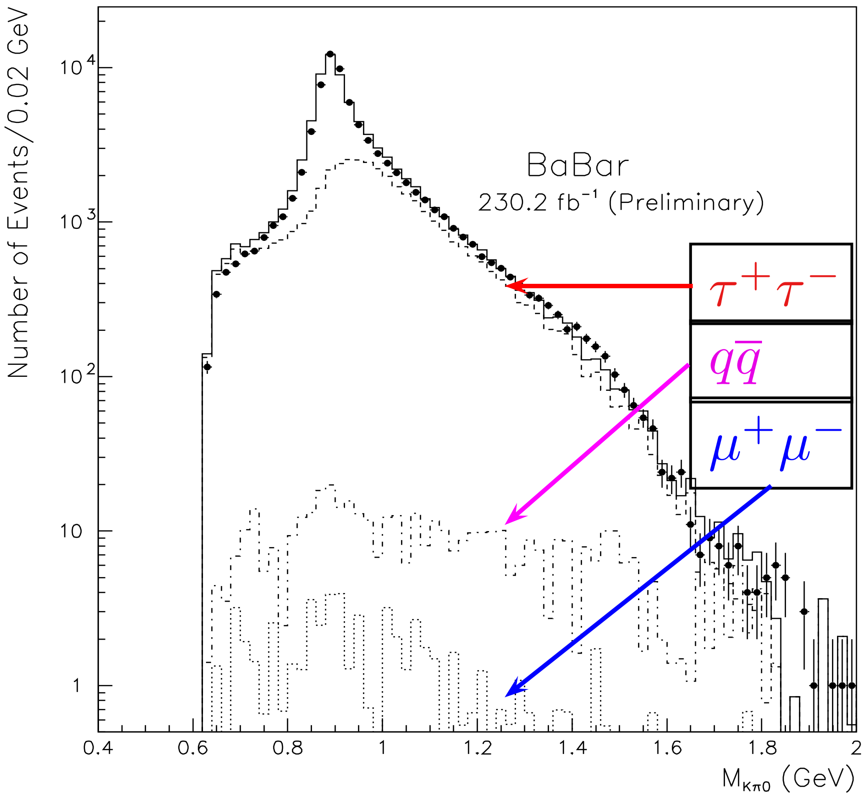


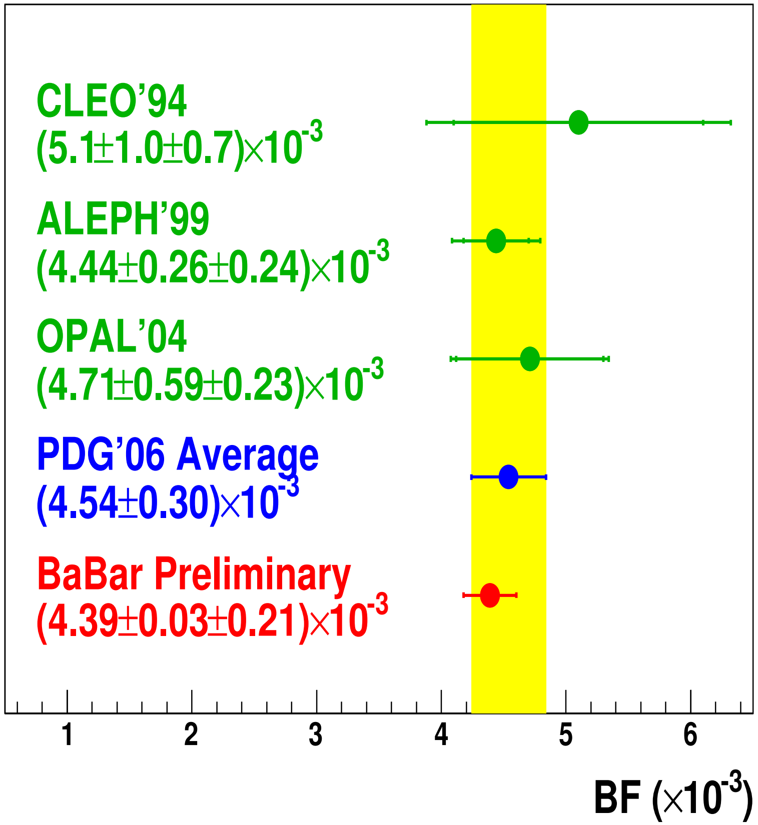
- Inclusive study of strange spectral functions from final states with net strangeness of unity (contributing to $\sim$ 3% of all τ decays)
  $\Rightarrow$ Route to world's best measurements of:
  $|V_{us}| \sim \mathcal{O}(1\%)$ [presently from 3-body leptonic kaon decays],
  $m_s \sim 10\,\mathrm{MeV}$ [presently from Lattice QCD]

- Preliminary $\mathcal{B}(\tau^- \to K^-\pi^0\nu_\tau)$, $\mathcal{B}(\tau^- \to K^-\pi^-\pi^+\nu_\tau)$ reported with better precision than world average (Tau06, Pisa)

$\tau^- \to K^-\pi^0\nu_\tau$ events (Tau06, Pisa)

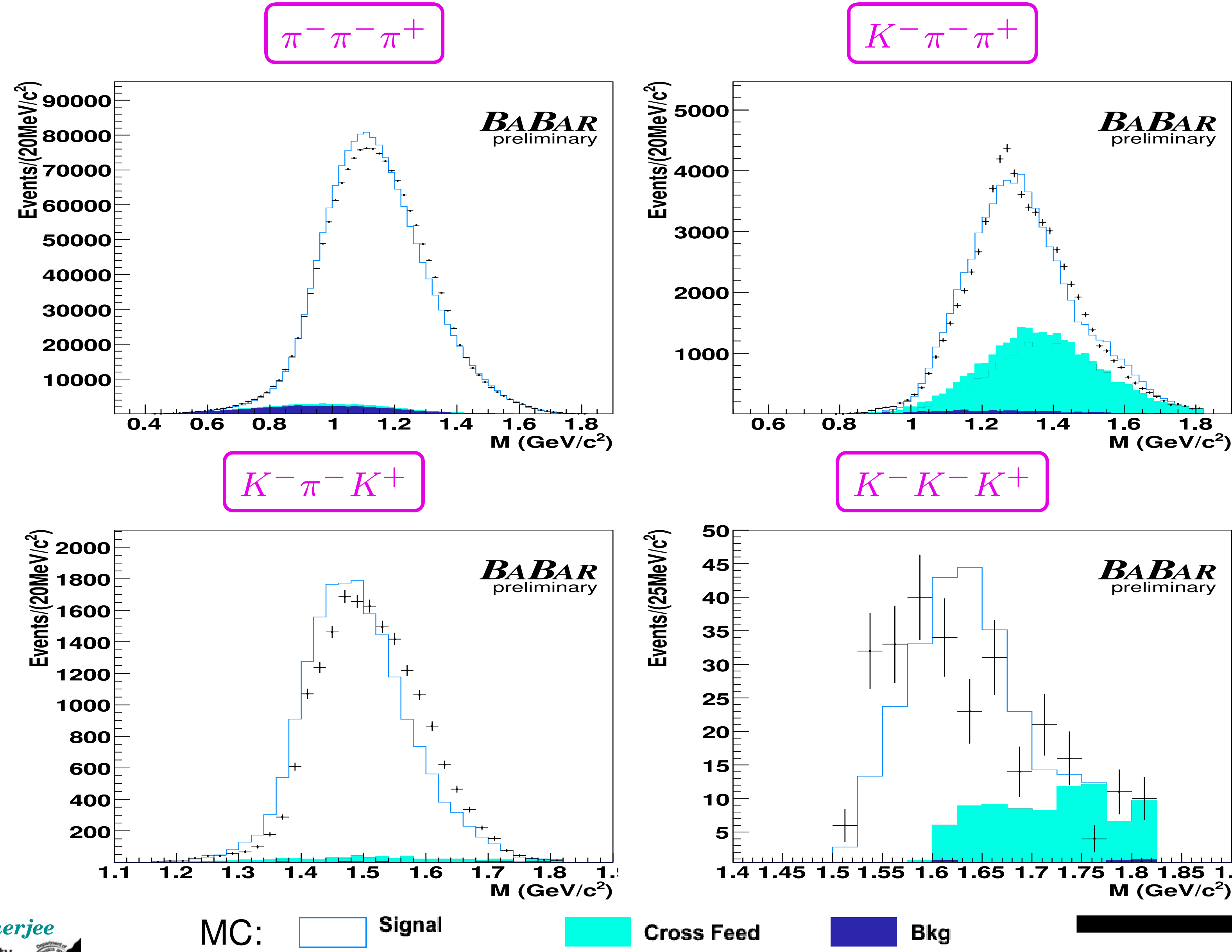
- 78K e/μ-tagged events: $\tau^+\tau^-$ mostly; $q\bar{q}$, $\mu^+\mu^-$ small
- Background sources: K/π mis-ID, π^0 reconstruction in-efficiency





S. Banerjee
University of Victoria
British Columbia • Canada

1.7M e/μ-tagged $\tau^- \to h^- h^- h^+ \nu_\tau$ decays



S. Banerjee
University of Victoria
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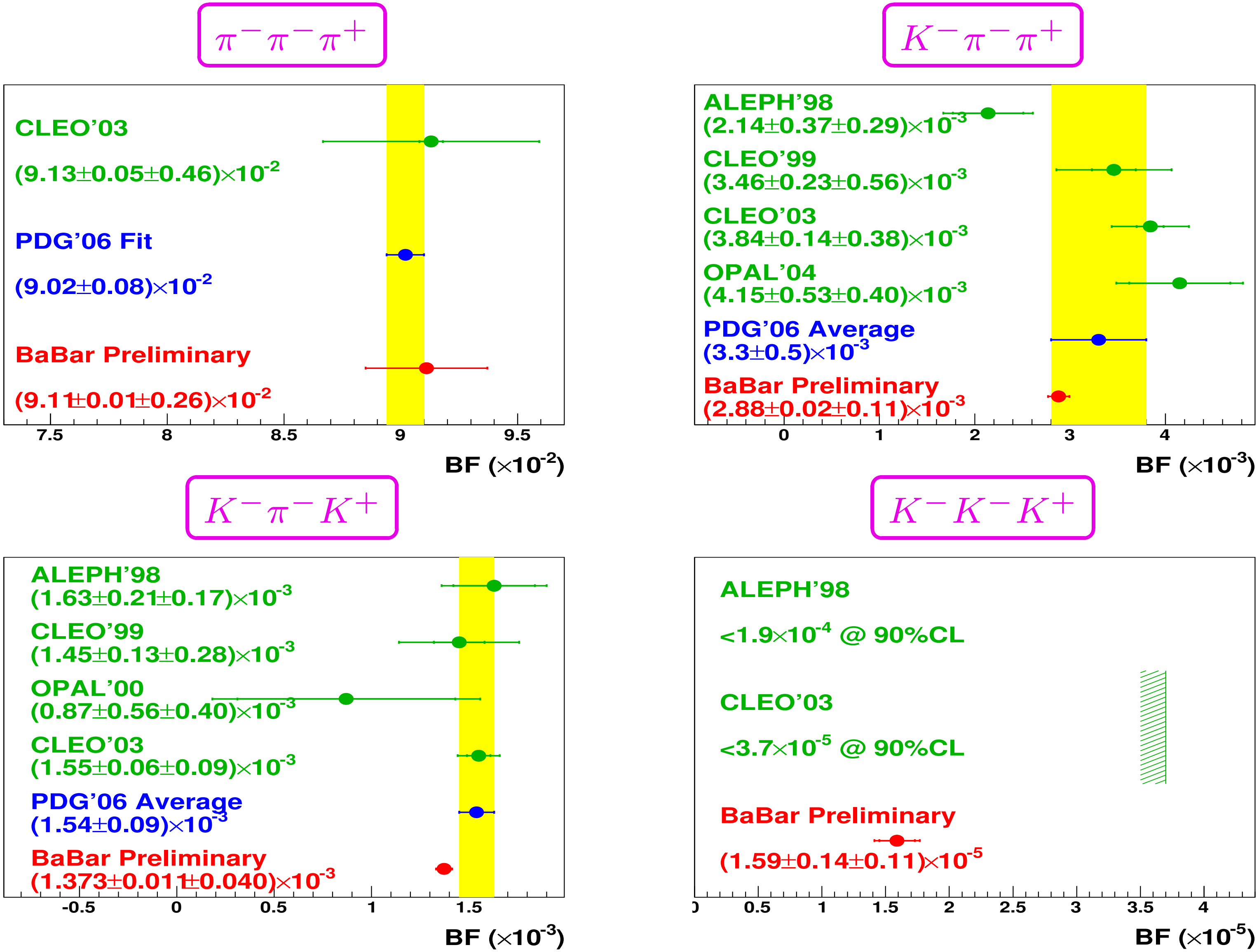
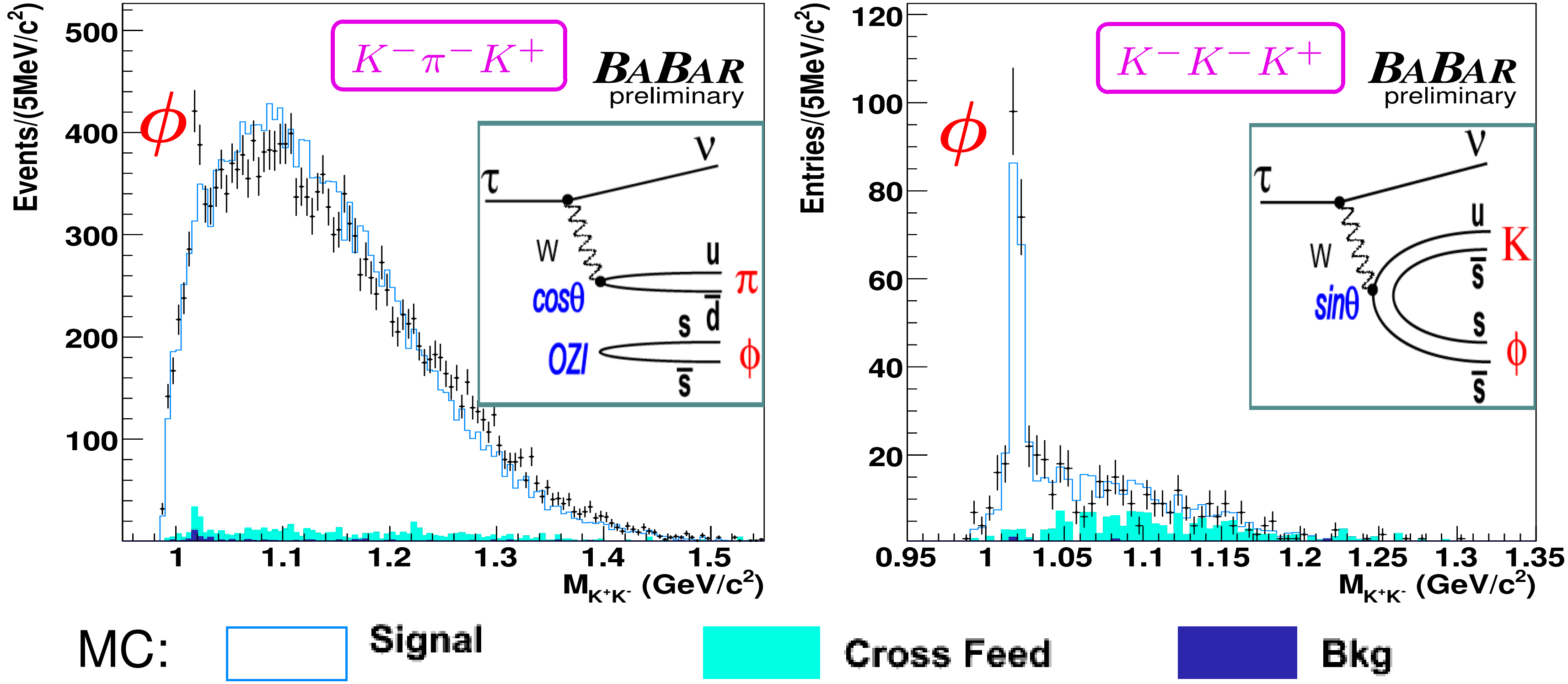
$\tau^- \rightarrow h^- h^- h^+ \nu_\tau$ (Tau06, Pisa)



S. Banerjee
University of Victoria
British Columbia • Canada

New decay modes via ϕ resonance



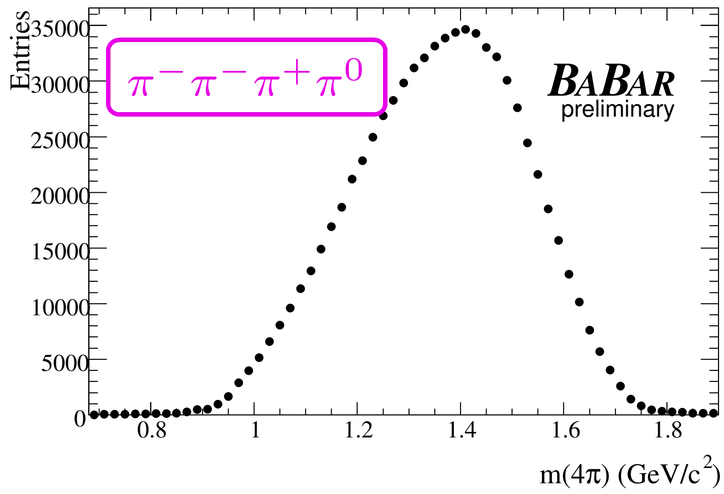
- FIRST MEASUREMENTS of $\pi^-\phi$ and inclusive $K^-K^-K^+$ states:
  $\mathcal{B}(\tau^- \to \pi^-\phi\nu_\tau) = (3.49 \pm 0.55 \pm 0.32) \times 10^{-5}$ (Significance: 5.5σ)
  $\mathcal{B}(\tau^- \to K^-\phi\nu_\tau) = (3.48 \pm 0.20 \pm 0.26) \times 10^{-5}$ (Significance: 10.6σ)
- $\tau^- \to K^-\phi\nu_\tau$ consistent with saturating $\tau^- \to K^-K^-K^+\nu_\tau$ channel
- Consistent with Belle: $\mathcal{B}(\tau^- \to K^-\phi\nu_\tau) = (4.06 \pm 0.25 \pm 0.26) \times 10^{-5}$

S. Banerjee
University of Victoria
British Columbia • Canada

3 prong τ-decays via ω resonance

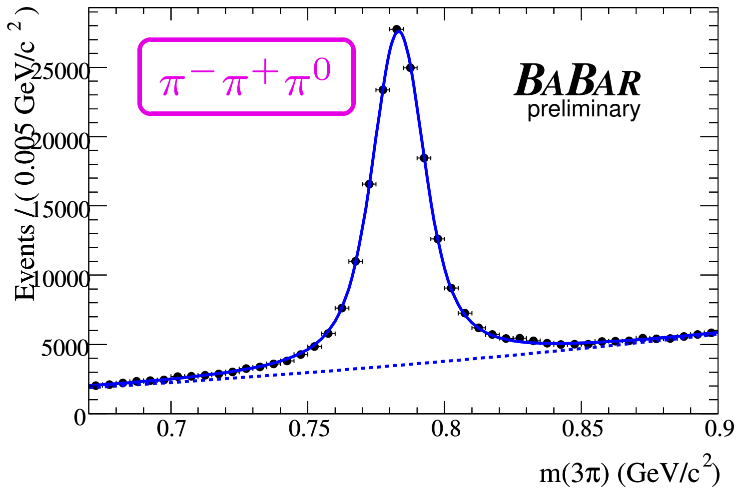
- BaBar (Preliminary, Tau06):
  $\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau) =$
  $(4.39 \pm 0.01 \pm 0.21) \times 10^{-2}$

  PDG06 Average (Aleph, CLEO):
  $(4.55 \pm 0.13) \times 10^{-2}$



- BaBar (Preliminary, Tau06):
  $\mathcal{B}(\tau^- \to \pi^-\underbrace{\pi^-\pi^+\pi^0}_{\omega}\nu_\tau) =$
  $(1.97 \pm 0.01 \pm 0.10) \times 10^{-2}$

  PDG06 Average (Aleph, CLEO):
  $(1.92 \pm 0.07) \times 10^{-2}$

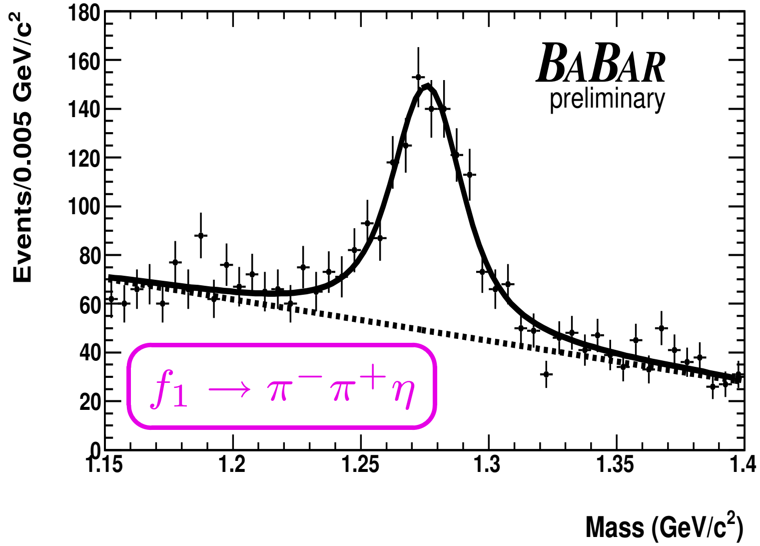


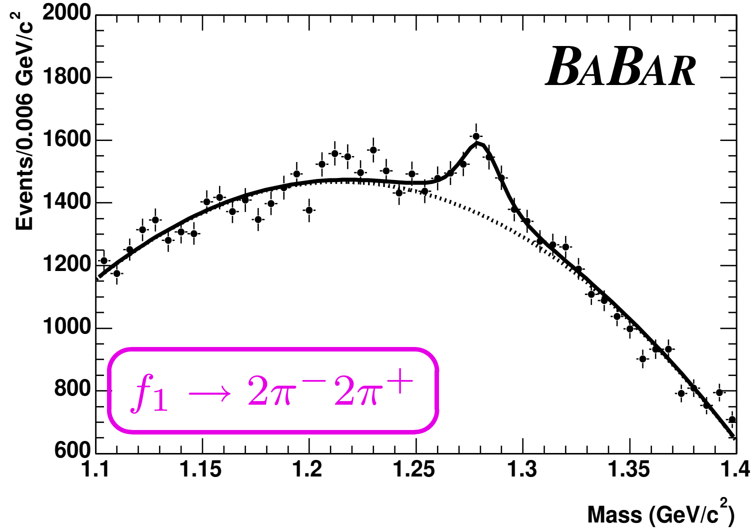
3 & 5 prong τ-decays via f_1 resonance

- BABAR (Preliminary, Tau06):
  (1260 ± 56) $\eta \to \gamma\gamma$ candidates
  $\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau) =$
  $(1.84 \pm 0.09 \pm 0.13) \times 10^{-4}$
  PDG06: $(2.3 \pm 0.5) \times 10^{-4}$

- BABAR (Preliminary, Tau06):
  $\mathcal{B}(\tau^- \to \pi^-\underbrace{\pi^-\pi^+\eta}_{f_1(1285)}\nu_\tau) =$
  $(3.83 \pm 0.32 \pm 0.20 \pm 1.18) \times 10^{-4}$

- BABAR, PRD72(2005)072001:
  $\mathcal{B}(\tau^- \to \pi^- f_1\nu_\tau)$
  = $(3.9 \pm 0.7 \pm 0.5) \times 10^{-4}$
  using $f_1(1285) \to \pi^-\pi^-\pi^+\pi^+$
  in 5 prong τ decays





S. Banerjee
University of Victoria
British Columbia • Canada

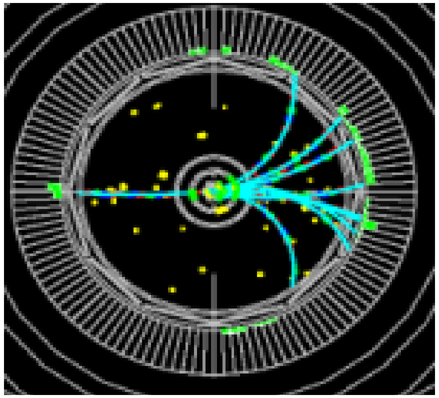
Rich Resonance Substructure

- Ratio of Branching Fractions (BaBar Preliminary, Tau06):
  - $R\left(\frac{\tau^- \to \pi^- \omega \to \pi^- \pi^- \pi^+ \pi^0 \nu_\tau}{\tau^- \to \pi^- \pi^- \pi^+ \pi^0 \nu_\tau}\right) = 0.400 \pm 0.002 \pm 0.006$
  - $R\left(\frac{\tau^- \to \pi^- f_1 \to \pi^- \pi^- \pi^+ \eta \nu_\tau}{\tau^- \to \pi^- \pi^- \pi^+ \eta \nu_\tau}\right) = 0.723 \pm 0.012 \pm 0.042$
- $J^{PG} = 0^{+-}$ current: $\tau^- \to \pi^- \underbrace{\pi^- \pi^+ \pi^0}_{\eta} \nu_\tau$, $\tau^- \to \pi^- \underbrace{\pi^- \pi^+ \eta}_{\eta'} \nu_\tau$
  - 2^{nd} Class Currents (Weinberg, 1958) waiting to be discovered
  - Suppressed by G-parity conservation
  - Expected at the level of isospin breaking $m_u \neq m_d$
  - We see no evidence of $\pi^- \eta'$ signal in $\tau^- \to \pi^- \pi^- \pi^+ \eta \nu_\tau$
  - BaBar Preliminary, Tau06:
    $\mathcal{B}(\tau^- \to \pi^- \eta' \nu_\tau) < 1.2 \times 10^{-5}$ @ 90% C.L.
    CLEO: Upper Limit = 7.4×10^{-5} @ 90% C.L.

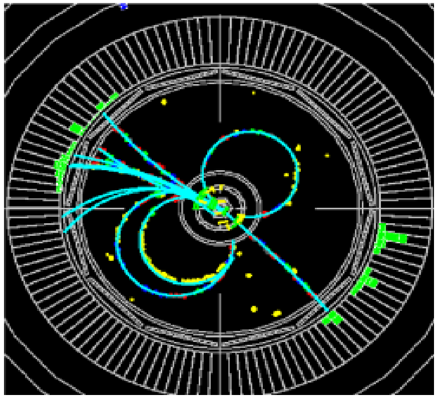
τ decays with 7 or 8 pion final states

- $\mathcal{B}(\tau \to 7\pi\nu) = \underbrace{\text{dynamics}}_{10^{-3}} \times \underbrace{\text{phasespace}}_{6\times10^{-6}} \times \mathcal{B}(\tau \to 5\pi\nu) \approx 6 \times 10^{-12}$ Nussinov-Purohit, PRD65 (2002) 034018
- Resonance sub-structures may enhance multi-pion final states.

1-7 topology simulation



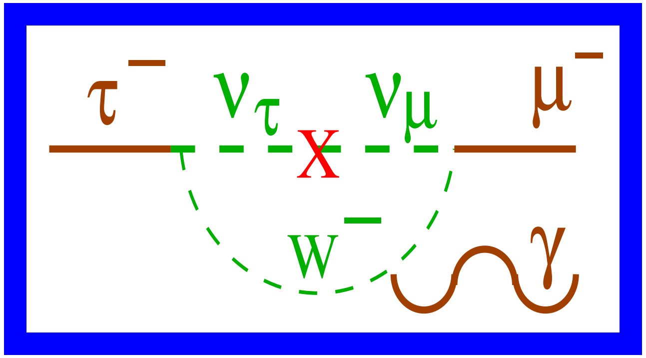
Spoilers: Looping tracks



- BaBar, PRD72 (2005) 012003 ($\mathcal{L} = 232.2\,\text{fb}^{-1}$):
  - $\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+ (\pi^0) \nu_\tau) < 3.0 \times 10^{-7}$ (CLEO (1997): 2.4×10^{-6})
  - $\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+ \nu_\tau) < 4.3 \times 10^{-7}$
  - $\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau) < 2.5 \times 10^{-7}$
- BaBar, PRD74 (2006) 011103 ($\mathcal{L} = 232.2\,\text{fb}^{-1}$):
  - $\mathcal{B}(\tau^- \to 3\pi^- 2\pi^+ 2\pi^0 \nu_\tau) < 3.4 \times 10^{-6}$ (CLEO (1994): 1.1×10^{-4})
  - $\mathcal{B}(\tau^- \to \pi^- 2\omega \nu_\tau) < 5.4 \times 10^{-7}$

Search for New Physics

- Lepton flavor violation (LFV)
  - not forbidden by SM gauge symmetry
  - most new models naturally include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
- Now we have clear indication that ν's have finite mass
  $\Rightarrow$ Lepton Flavor is violated in Nature: but by how much?
- SM extended to include finite ν mass and mixing predicts LFV



$\mathcal{B}(\tau^{\pm} \rightarrow \mu^{\pm}\gamma)$[Lee-Shrock, Phys. Rev. D **16**, 1444 (1977)]

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\mathrm{mix}}\mathcal{B}(\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau)$

With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ (θ_{mix} : max)

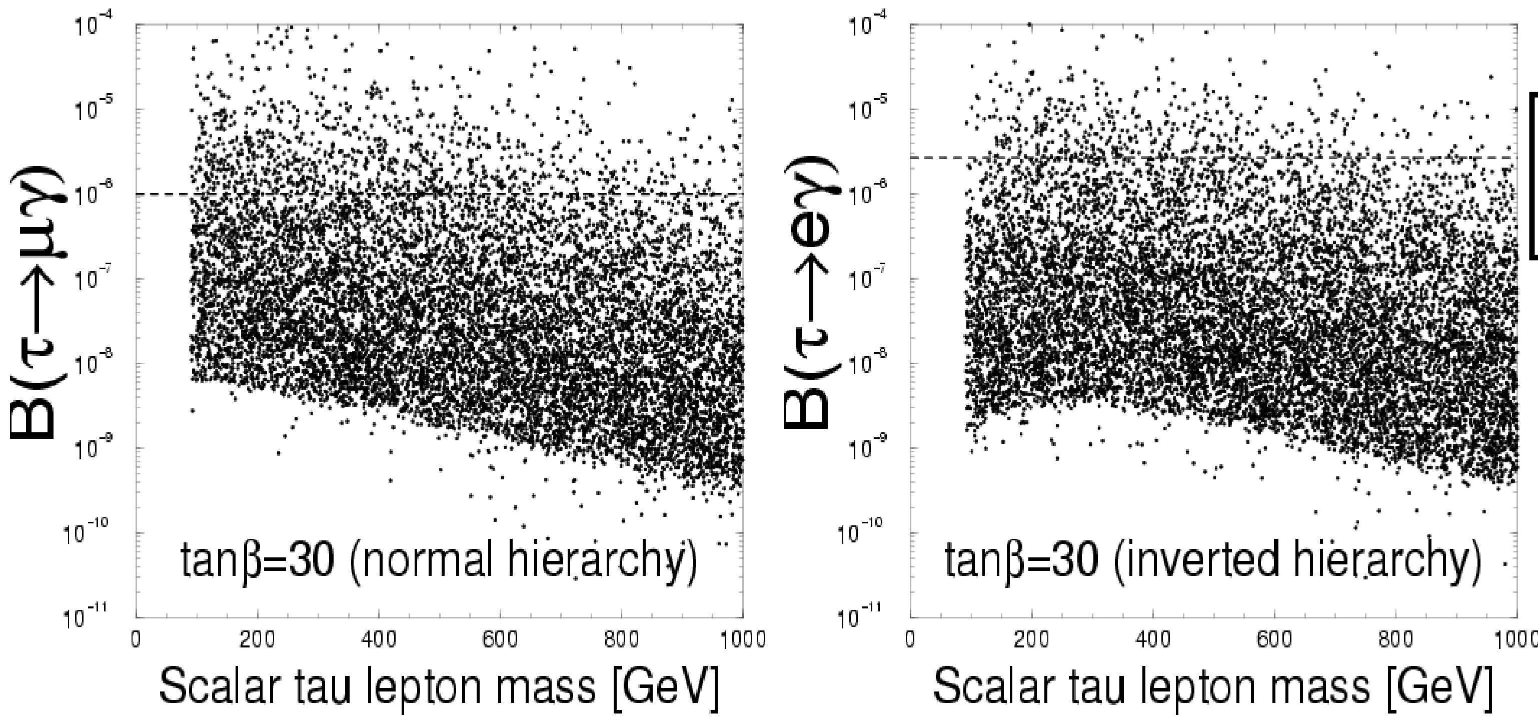
... many orders below experimental sensitivity!

- Observation for $\mathrm{LFV} \Rightarrow$ unambiguous signature of new physics

S. Banerjee
University of Victoria
British Columbia • Canada

LFV τ decays

- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons
- Some models predict LFV upto existing experimental bounds
- eg. SUSY models: non-diagonal slepton mass matrix $\Rightarrow$ LFV
- Normal (Inverted) hierarchy for slepton $\Rightarrow \tau \rightarrow \mu\gamma$ ($\tau \rightarrow e\gamma$)



$\sim \mathcal{O}(10^{-6})$ (CLEO '00)

(J. Ellis, J. Hisano, M. Raidal and Y. Shimizu, Phys. Rev. D **66** (2002) 115013)

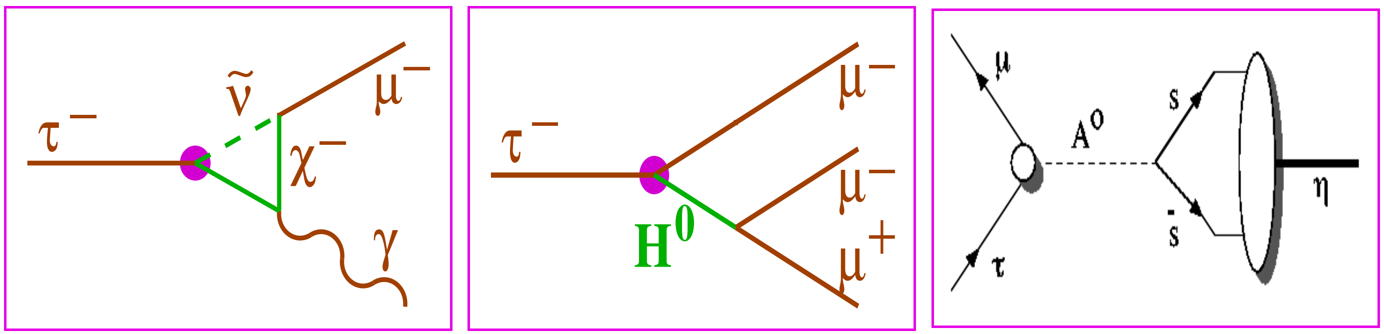
LFV τ **decays**

- Neutrinoless 2 and 3 body τ decays have different sensitivity

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
SM+ν-mixing (PRL95(2005)41802,EPJC8(1999)513)	10^{-54}	10^{-14}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
SM+Heavy Majorana $\nu_{\rm R}$ (PRD66(2002)034008)	10^{-9}	10^{-10}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}

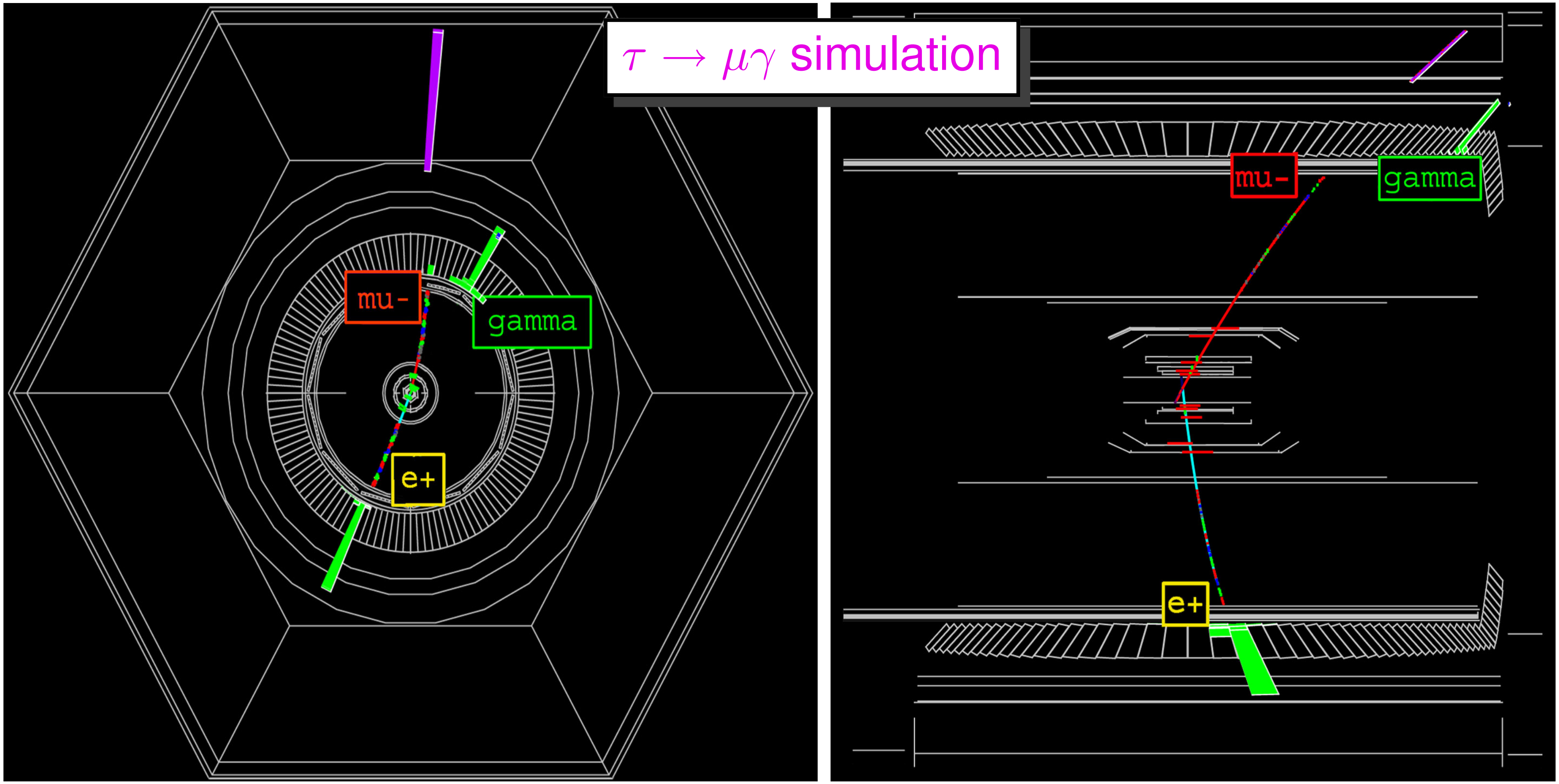
MSSM+seesaw (PRD66 (2002) 057301) $\mathcal{B}(\tau \to \mu\gamma)$: $\mathcal{B}(\tau \to \mu\mu\mu)$: $\mathcal{B}(\tau \to \mu\eta)$ = 1.5 : 1 : 8.4

Illustrations:



☞ Search for $\tau \to \ell\gamma/\pi^0/\eta/\eta'$, $\tau \to \ell\ell\ell$, $\tau \to \ell hh'$ $(\ell = e, \mu; h = \pi, K)$

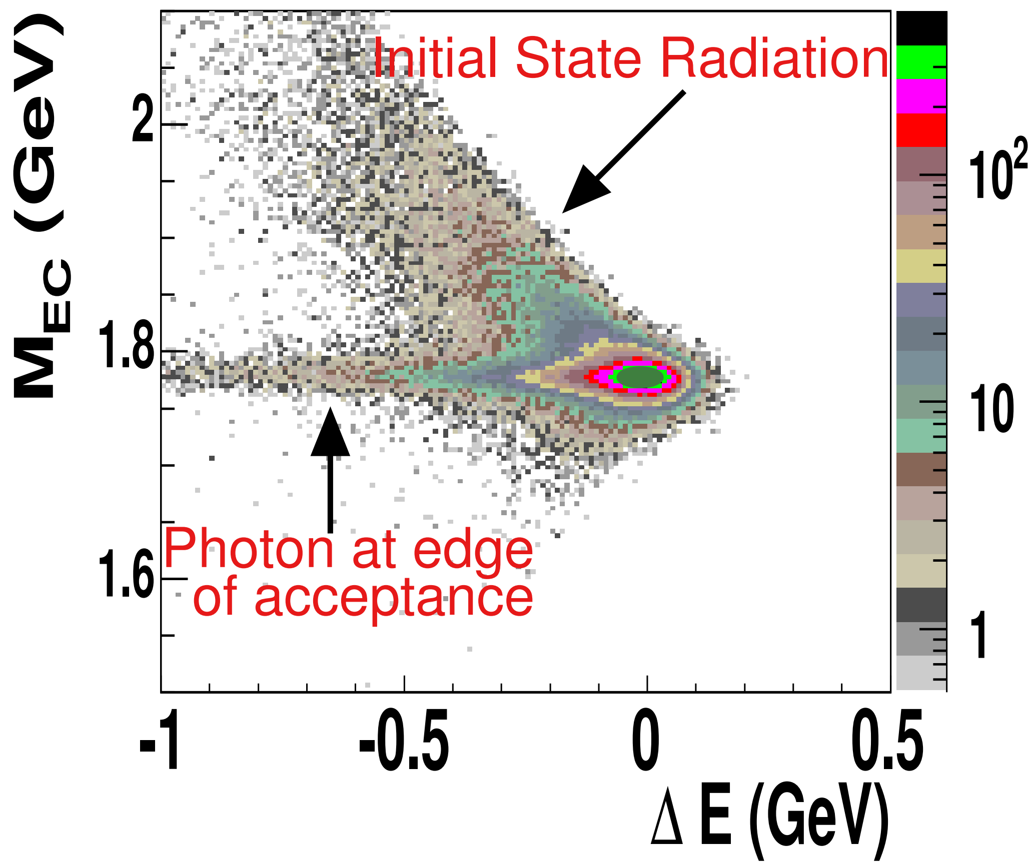
Signal Characteristics



- $m_{\mu\gamma} \sim m_\tau$
- CM Frame: $\Delta E = \sqrt{P_\mu^2 + m_\mu^2} + E_\gamma - \sqrt{s}/2 \sim 0$

Signal Characteristics

- (Energy, Mass)$_{\rm daughters} \sim (\frac{\sqrt{s}}{2}$, m$_\tau$) (upto resolution & radiation)



$\tau \rightarrow \mu\gamma$ simulation

$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$

$\sigma(\Delta E) \sim 50\,\rm MeV$

M$_{\rm EC}$ ($\sigma \sim$ 9 MeV)

Beam energy constrained mass after vertexing

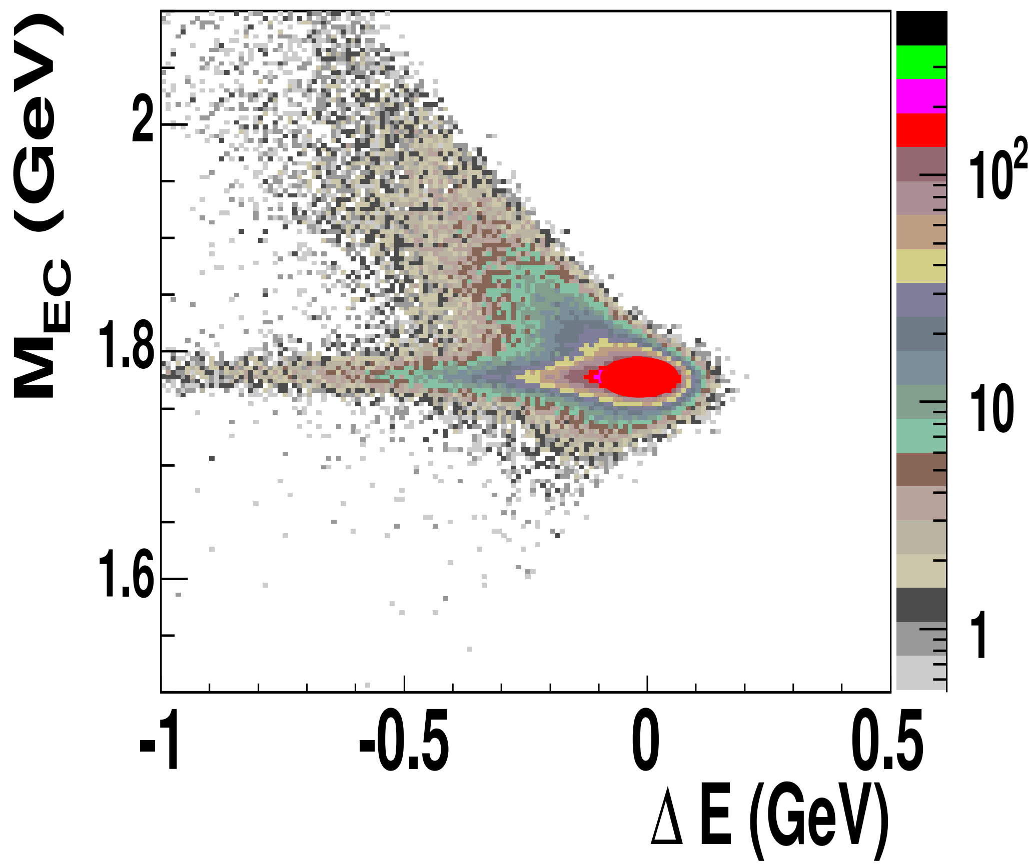
γ at μ POCA(XY)

[Inv. mass: $\sigma \sim$ 24 MeV]

☞ Signal Region: $\pm$ 2 σ around ($\langle\Delta E\rangle$, $\langle M_{EC}\rangle$)

Signal Characteristics

- (Energy, Mass)$_{\rm daughters} \sim (\frac{\sqrt{s}}{2}$, m$_\tau$) (upto resolution & radiation)



$\tau \rightarrow \mu\gamma$ simulation

$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$

$\sigma(\Delta E) \sim 50\,\mathrm{MeV}$

M$_{\rm EC}$ ($\sigma \sim$ 9 MeV)

Beam energy constrained mass after vertexing

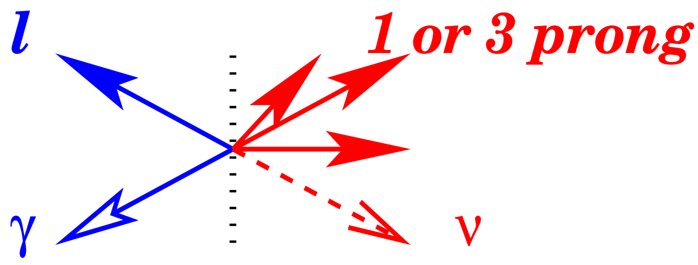
γ at μ $_{\rm POCA(XY)}$

[Inv. mass: $\sigma \sim$ 24 MeV]

☛ Blinded Region: $\pm$ 3 σ around ($\langle\Delta E\rangle$, $\langle M_{EC}\rangle$)

$e^+e^- \to \tau^+\tau^-$ (clean environment)

$\tau \to \ell\gamma$

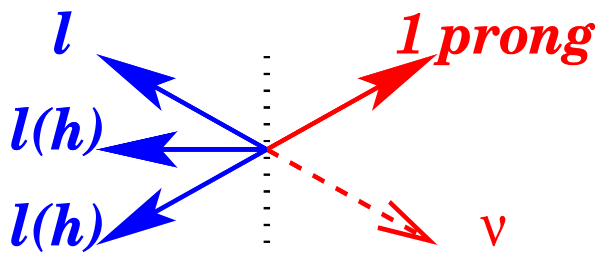


Signal–Side **Tag–Side**

Backgrounds:

- $\tau \to e\gamma$ ($\tau \to \mu\gamma$):
  - Radiative Bhabha (di-muon)
  - $\tau^+\tau^-\gamma(\tau \to \ell\nu\overline{\nu})$
  - $q\overline{q}$ (γ)

$\tau \to \ell\ell\ell$ ($\tau \to \ell h h'$)



Signal–Side **Tag–Side**

Backgrounds:

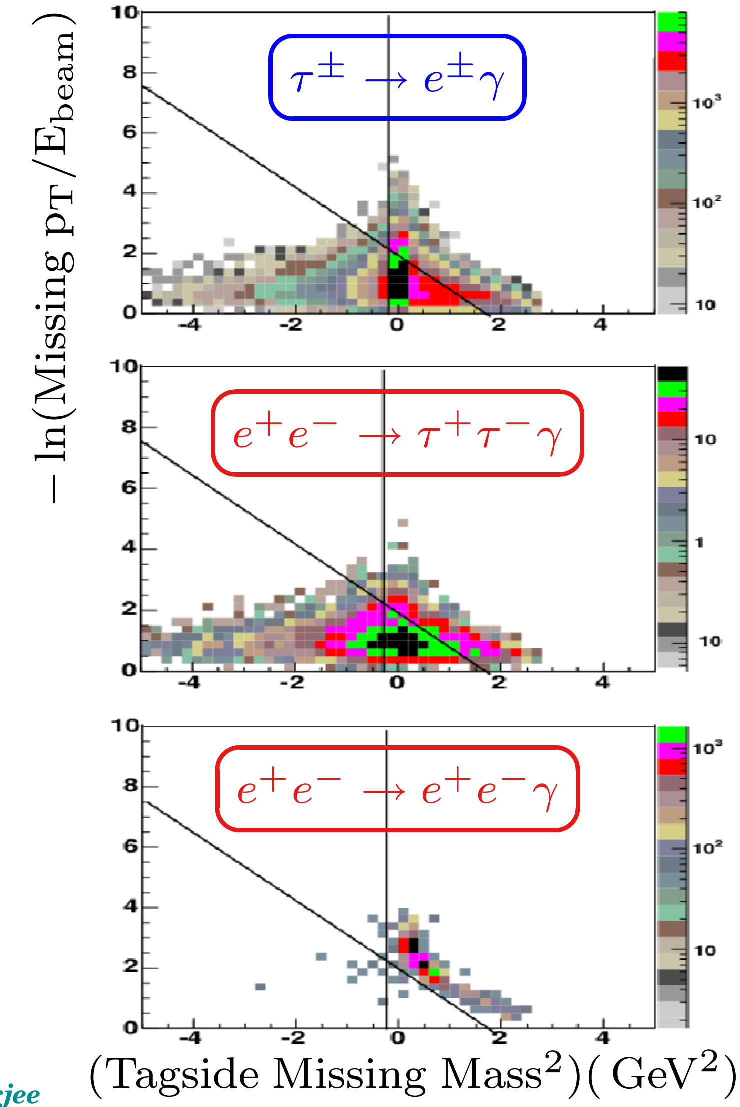
- $\tau^- \to \ell'^-\ell^+\ell^-$:
  - Bhabha, di-muon
- $\tau^- \to \ell^+\ell'^-\ell'^-$, $\tau \to \ell h h'$:
  - $\tau^+\tau^-$, $q\overline{q}$

Missing momentum in Signal-side	Signal: ✘	$\tau^+\tau^-$: ✔	e^+e^-, $\mu^+\mu^-$, $q\overline{q}$: ✘
Missing momentum in Tag-side	Signal: ✔	$\tau^+\tau^-$: ✔	e^+e^-, $\mu^+\mu^-$, $q\overline{q}$: ✘

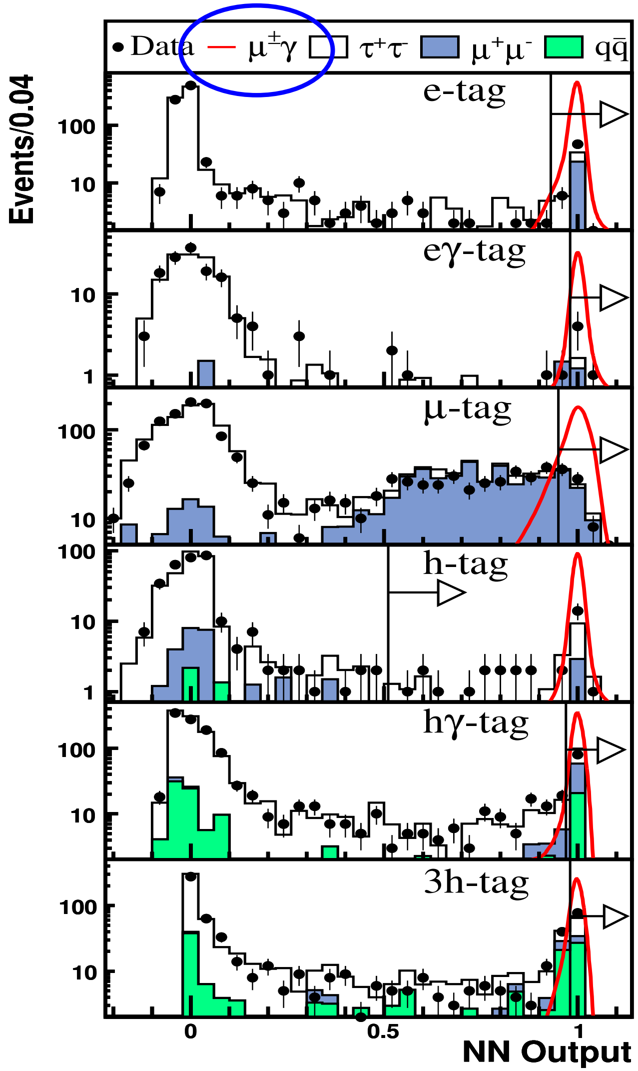
S. Banerjee
University of Victoria
British Columbia • Canada

Signal vs. Background

Cut-based Selection



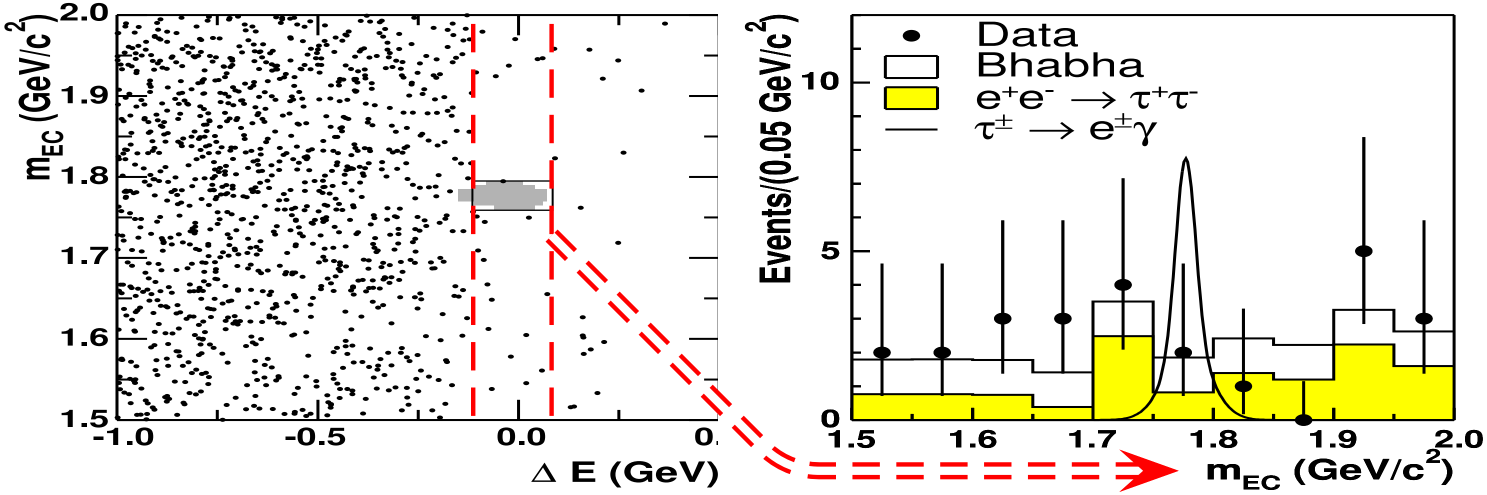
Neural Net / tag-side decay



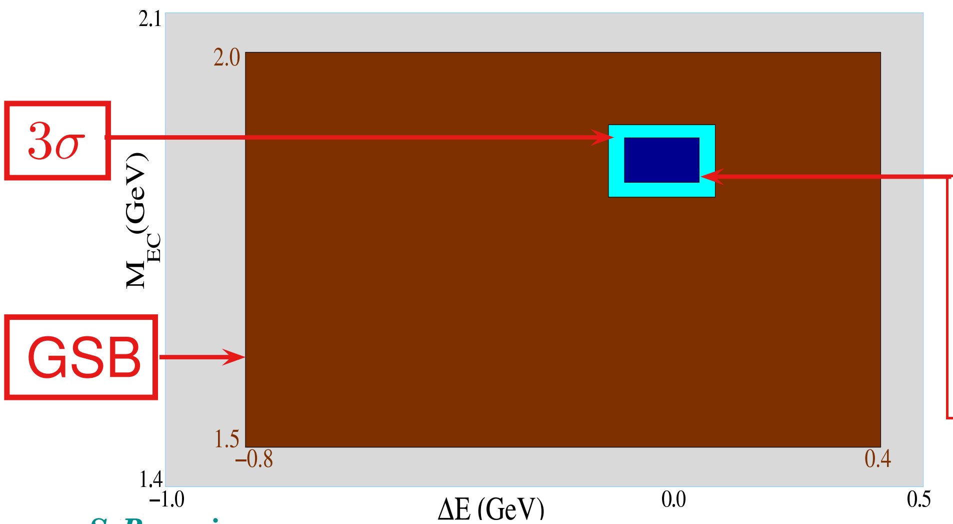
S. Banerjee
University of Victoria
British Columbia • Canada

Background estimation: $\tau \to \ell\gamma / P^0$

- $\tau^\pm \to \ell^\pm\gamma$: Background rate from PDF($m_{\rm EC}$) in $\pm 2\sigma$ band in ΔE



- $\tau^\pm \to \ell^\pm P^0$: Unbinned maximum likelihood fit to $(m_{\rm EC}, \Delta E)$

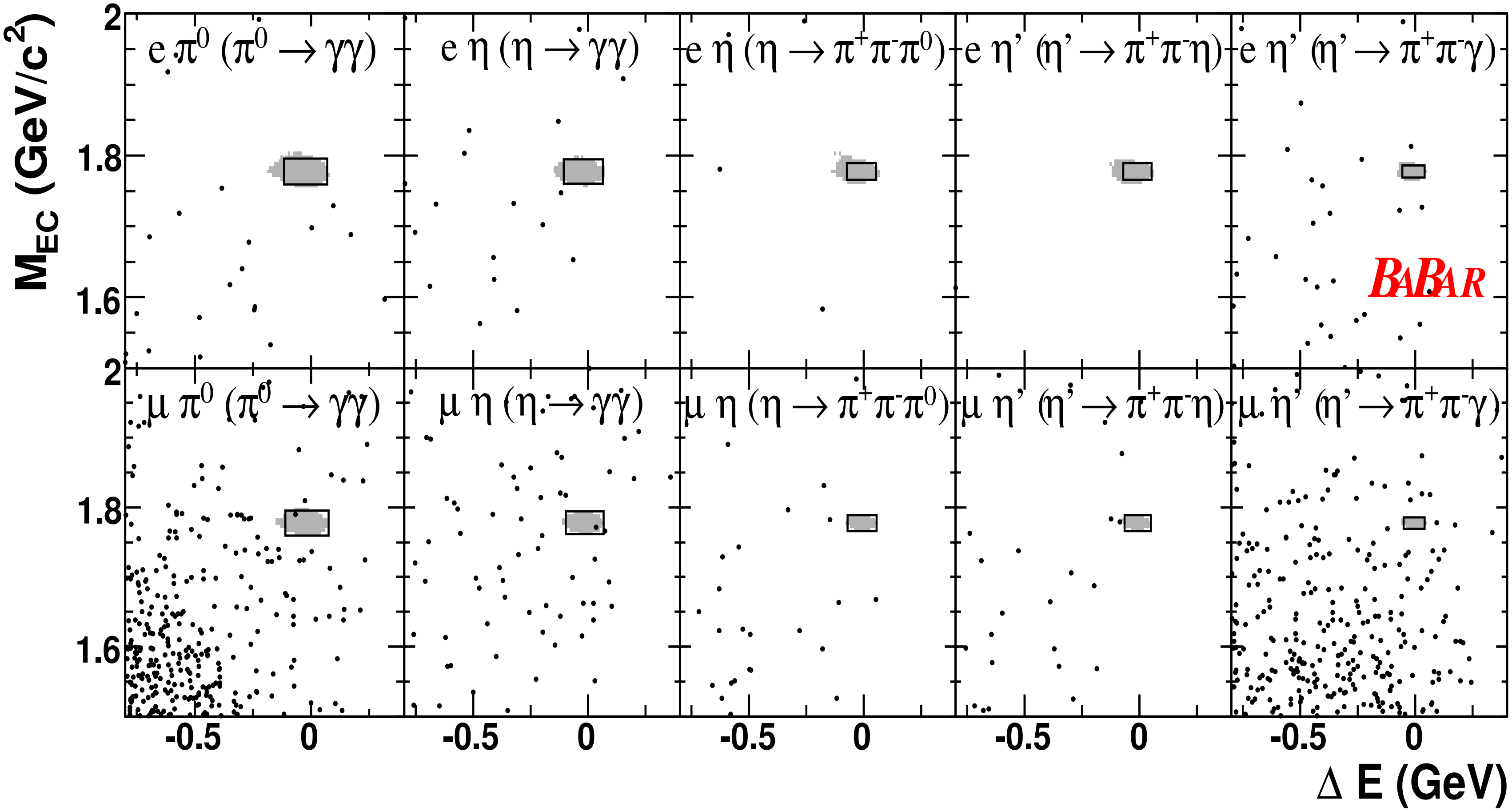


$$N_{2\sigma}^{data} = \frac{\int_{2\sigma} {\rm PDF}_{tot}}{\int_{GSB-3\sigma} {\rm PDF}_{tot}} \times N_{GSB-3\sigma}^{data}$$

S. Banerjee
University of Victoria
British Columbia • Canada

$\tau^{\pm} \rightarrow \ell^{\pm} P^0$

hep-ex/0610067 (subm. to PRL)

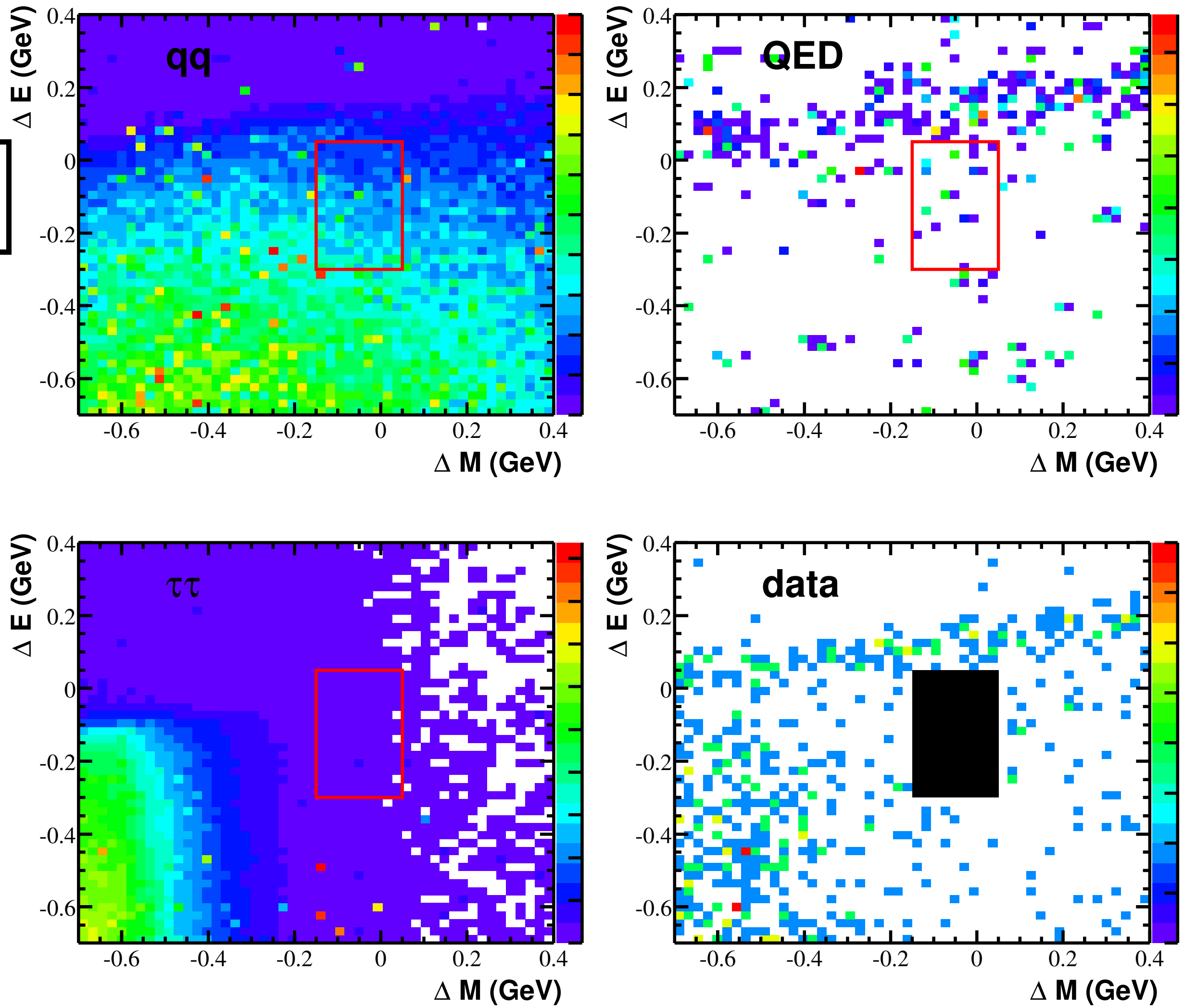


$N_{\rm bkg}$/channel = $(0.1 - 1.3)$, Total expected = 3.1, Observed = 2

Background estimation: $\tau \to \ell\ell\ell, \ell hh'$

$q\bar{q}$: uniform

QED:
$\Delta E \approx 0$



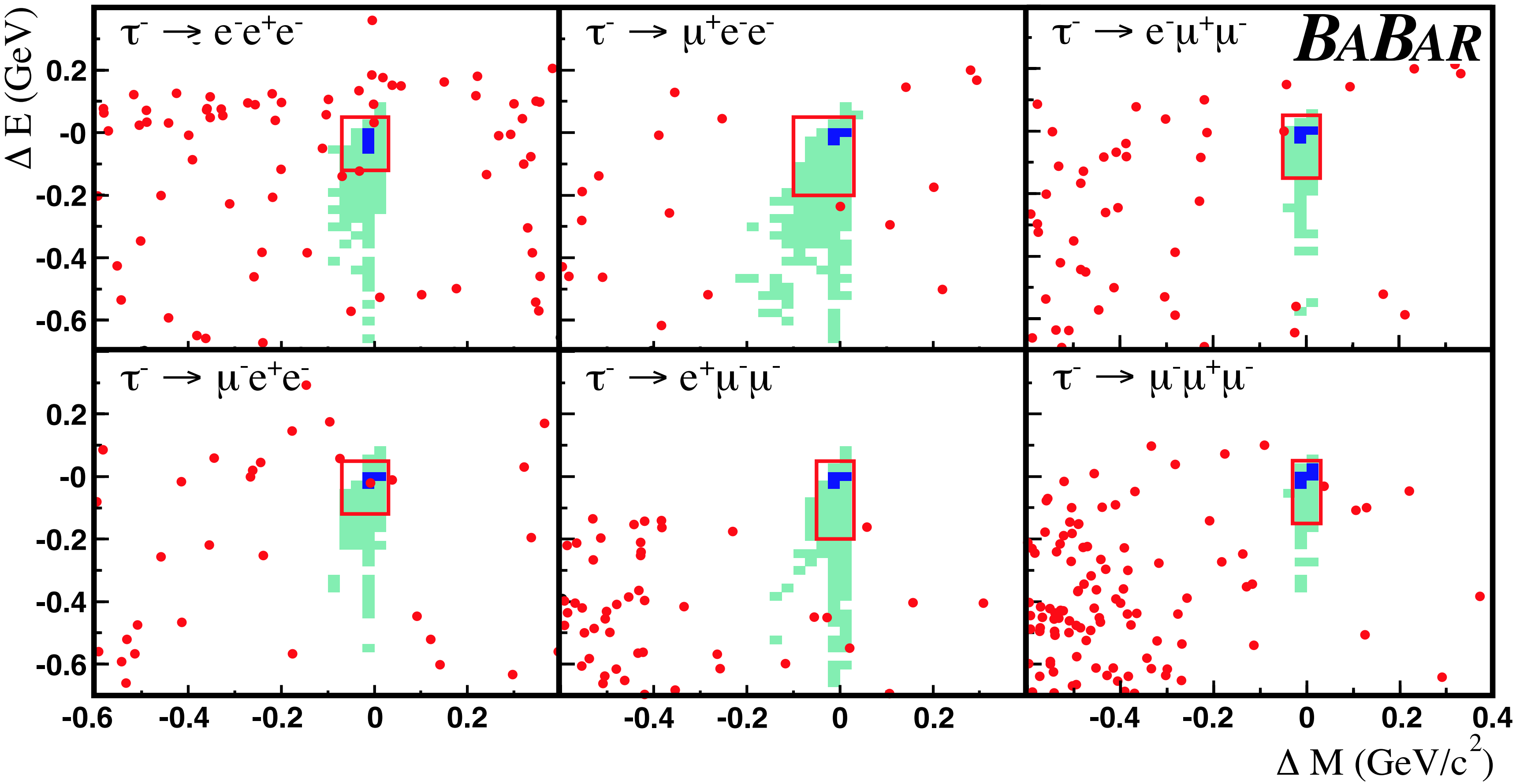
$\tau^+\tau^-$:
$\Delta M \ll 0$
$\Delta E \ll 0$

$\tau \to \ell\ell\ell$:
after PID &
Preselection

2-dim PDF's: shape from MC/control sample, rate fitted to Data

$\tau \to \ell\ell\ell$

PRL92(2004)121801

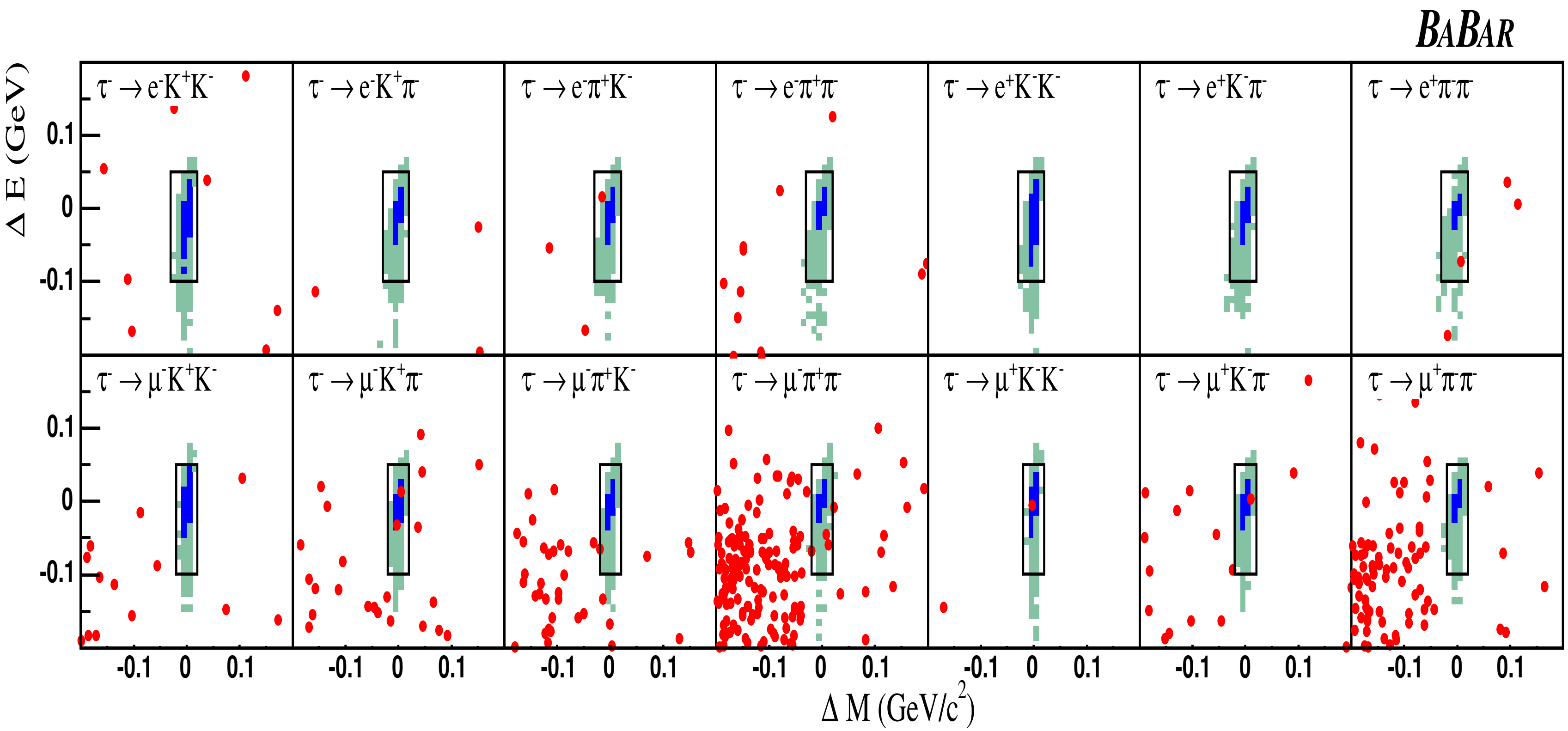


$N_{\rm bkg}$/channel = $(0.2 - 1.5)$, Total expected = 3.4, Observed = 3

$\tau \to \ell h h'$

PRL95(2005)191801

- Lepton Flavor violating modes: $\tau^- \to \ell^- h^+ h'^-$
- Lepton Number violating modes: $\tau^- \to \ell^+ h^- h'^-$



$N_{\rm bkg}$/channel = $(0.1 - 3.0)$, Total expected = 11.3, Observed = 10

No signal found...

Upper Limit: $B^{90}_{\rm UL} = N^{90}_{\rm UL} / (N_\tau \times \varepsilon)$

- ε: *high statistics signal MC simulated for different Data-taking periods*

$\varepsilon =$	Trigger .	Reco .	Topology .	PID .	Cuts .	Signal–Box
	90%	70%	70%	50%	50%	50%
Cumulative:						
	90%	63%	44%	22%	11%	~5%

- $\sigma_{\tau^+\tau^-}(10.6\,\mathrm{GeV}) \sim 0.89\, nb$, $\mathcal{L} \sim 339$ *fb*$^{-1}$ (BABAR *Summer 2006*)

$$\Rightarrow N_\tau = 2 \times \mathcal{L} \times \sigma_{\tau^+\tau^-} \sim 6.0 \times 10^8$$

- $N^{90}_{\rm UL}$: *90% C.L. Upper Limit for* $(N_{\rm obs}, N_{\rm bkg})$ *from Data*
- *Naive Sensitivity :* $N^{90}_{\rm UL} = 2.3 \times \sqrt{N_{\rm bkg}}$, $N_{\rm bkg} \sim \mathcal{O}(1) \Rightarrow B^{90}_{\rm UL} \sim \mathcal{O}(10^{-7})$

B-Factories: Status

Channel	BaBar		Belle	
	$B_{\rm UL}^{90}$ (10^{-7})	$\mathcal{L}$ (fb^{-1})	$B_{\rm UL}^{90}$ (10^{-7})	$\mathcal{L}$ (fb^{-1})
$\tau^\pm \to e^\pm \gamma$	1.1	232.2	1.2	535.0
	PRL96(2006)41801		ICHEP06: hep-ex/0609049	
$\tau^\pm \to \mu^\pm \gamma$	0.7	232.2	0.5	535.0
	PRL95(2005)41802		ICHEP06: hep-ex/0609049	
$\tau^\pm \to e^\pm \pi^0$	1.3	339.0	0.8	401.0
	TAU06: hep-ex/0610067		ICHEP06: hep-ex/0609013	
$\tau^\pm \to \mu^\pm \pi^0$	1.1	339.0	1.2	401.0
	TAU06: hep-ex/0610067		ICHEP06: hep-ex/0609013	
$\tau^\pm \to e^\pm \eta$	1.6	339.0	0.9	401.0
	TAU06: hep-ex/0610067		ICHEP06: hep-ex/0609013	
$\tau^\pm \to \mu^\pm \eta$	1.5	339.0	0.7	401.0
	TAU06: hep-ex/0610067		ICHEP06: hep-ex/0609013	
$\tau \to \ell\ell\ell$	(1-3)	91.5	(2-4)	87.1
	PRL92(2004)121801		PLB589(2004)103	
$\tau \to \ell h h'$	(1-5)	221.4	(2-16)	158.0
	PRL95(2005)191801		NPB(Proc)144(2005)173	

B-Factories: Combinations (Tau06, Pisa)

- Signal and Background PDF parameterizations vary
- Efficiency combined by weighting with luminosity
- Observed & background events added (asymmetric errors averaged)
- 10^6 Toy MC: **Poisson distribution with mean** $(s+b)$ where signal $s = 2\mathcal{L}\sigma_{\tau\tau}\mathcal{B}_{UL}(\varepsilon \pm \sigma_\varepsilon)$, background $(b \pm \sigma_b)$ are Gaussian PDF's
- Vary $\mathcal{B}_{UL}$ till 10% of toy MCs yield # of events $< n_{\rm obs}$ **= # of events observed in the data** $\Rightarrow \mathcal{B}^{90}_{\rm UL}$. Average around expected background $\Rightarrow$ expected limit. [Ref: Cousins-Highland NIM A320, 331 (1992), Barlow CPC 149, 97 (2002)]

	$\mathcal{L}$	ε	Background events		$\mathcal{B}^{90}_{\rm UL}$ $(\times 10^{-8})$	
	(fb^{-1})	(%)	Expected	Observed	Expected	Observed
$\tau^\pm \to e^\pm\gamma$						
BaBar	232.2	4.70 ± 0.29	1.9 ± 0.4	1	12	11
Belle	535.0	2.99 ± 0.13	$5.14^{+2.6}_{-1.9}$	5		12
BaBar & Belle	767.2	3.51 ± 0.13	7.0 ± 2.3	6	12	9.4
$\tau^\pm \to \mu^\pm\gamma$						
BaBar	232.2	7.42 ± 0.65	6.2 ± 0.5	4	12	6.8
Belle	535.0	5.07 ± 0.20	$13.9^{+3.3}_{-2.6}$	10		4.5
BaBar & Belle	767.2	5.78 ± 0.24	20.1 ± 3.0	14	11	1.6

B-Factories: Projections

$$B_{\rm UL}^{90} = N_{\rm UL}^{90}/(N_\tau \times \varepsilon)$$

- $\tau^\pm \to \mu^\pm\gamma$ search: Optimize $N_{\rm UL}^{90}/\varepsilon$ for expected UL @ 90% C.L.
  - Baseline: $B_{\rm UL}^{90} \sim 1.2 \times 10^{-7}$ (BaBar expected @ 232.2 fb^{-1})

	Background free search	Background limited search
$N_{\rm UL}^{90}$	2.3 $\times \sqrt{N_{\rm obs}} \sim \mathcal{O}$(1)	$\sqrt{\mathcal{L}}$
$B_{\rm UL}^{90}$	$\propto 1/\mathcal{L}$	$\propto 1/\sqrt{\mathcal{L}}$

- BaBar, Belle: 1 ab^{-1} each (2008)

$\mathcal{L}$ (ab^{-1})	0.25 (Now)	1.0	50
$B_{\rm UL}^{90}$ (10^{-8})	10	2.5 (5)	0.05 (0.7)

- Super B-Factory:
  - 50 ab^{-1} $\Rightarrow B_{\rm UL}^{90} < \mathcal{O}$ (10^{-10}) / $\mathcal{O}$ (10^{-9}) no/with Background

LHC expectations

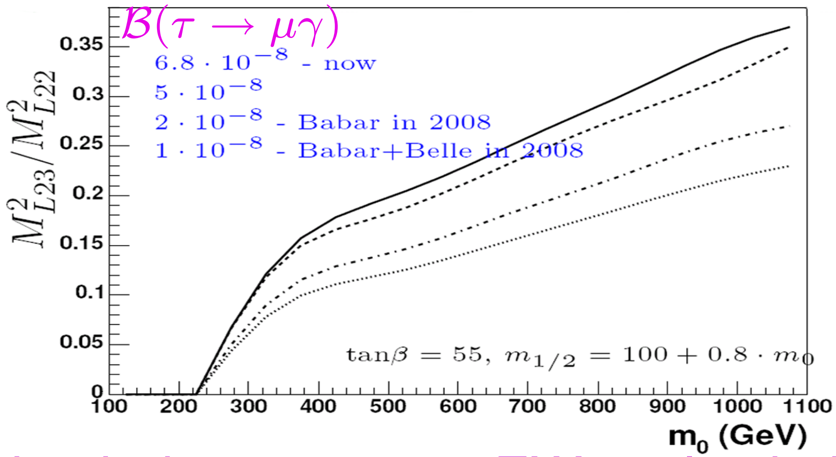
N_τ / yr (low lumi)	
$W \to \tau\nu$	1.5×10^8
$Z \to \tau\tau$	8.0×10^8
$D_S \to \tau X$	1.5×10^{12}
$B^0 \to \tau X$	4.0×10^{11}
$B^\pm \to \tau X$	3.8×10^{11}
$B_S \to \tau X$	7.9×10^{10}

- More tau's...
  More backgrounds
  from ISR/FSR,
  radiative production...
- Cleaner Event Signature:
  - 3 prong vertex
  - μ ID
  - m($\mu\mu\mu$) $\sim$ m$_\tau$

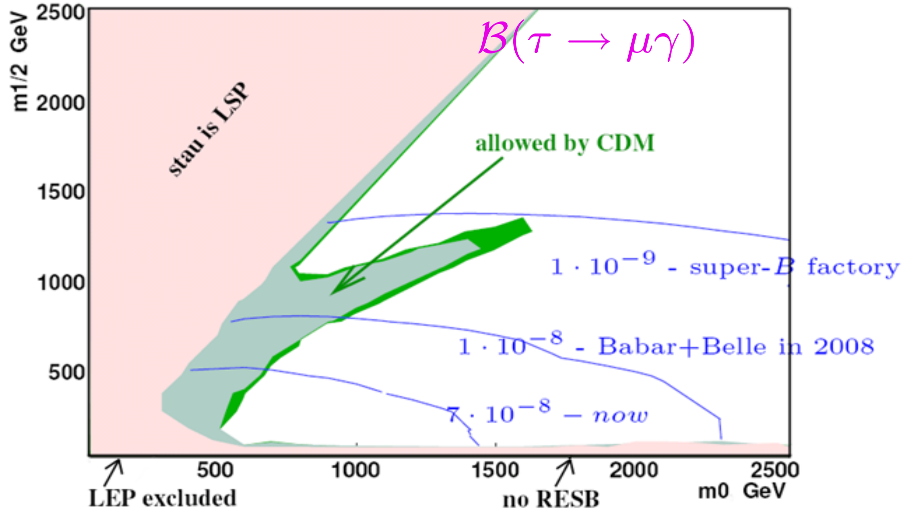
- Signal: $W \to \tau\nu$, Backgrounds: Radiation (L. Serin, R. Stroynowski, 1997)
  - For 30 fb^{-1} data: $\mathcal{B}(\tau \to \mu\gamma) < 0.6 \times 10^{-6}$
- Signal: $Z \to \tau\tau$, Backgrounds: Radiation (E. Barberio, 2002)
  - For 30 fb^{-1} data: $\mathcal{B}(\tau \to \mu\gamma) < 0.5 \times 10^{-7}$
- Signal: $D_S \to \tau X$, Backgrounds: $D_S \to \mu\nu\phi$, $\phi \to \mu\mu(\gamma)$ (A. Stahl, 2005)
  - For 100 fb^{-1} data: $\mathcal{B}(\tau \to \mu\mu\mu) < 10^{-10}$

BABAR Physics Reach Assessment (2005)

- mSUGRA mixing at GUT scale: $\mathcal{L} = -\, M^2_{\tilde{L}} \tilde{L}^* \tilde{L} - M^2_{\tilde{E}} \tilde{E}^* \tilde{E}$
  - Model-independent calculation
    (A.Brignole, A.Rossi, NPB701(2004)3)
  - $m_{GUT} = 5 \cdot 10^{15}$ GeV
    $\mu > 0,\ A_0 = 0$



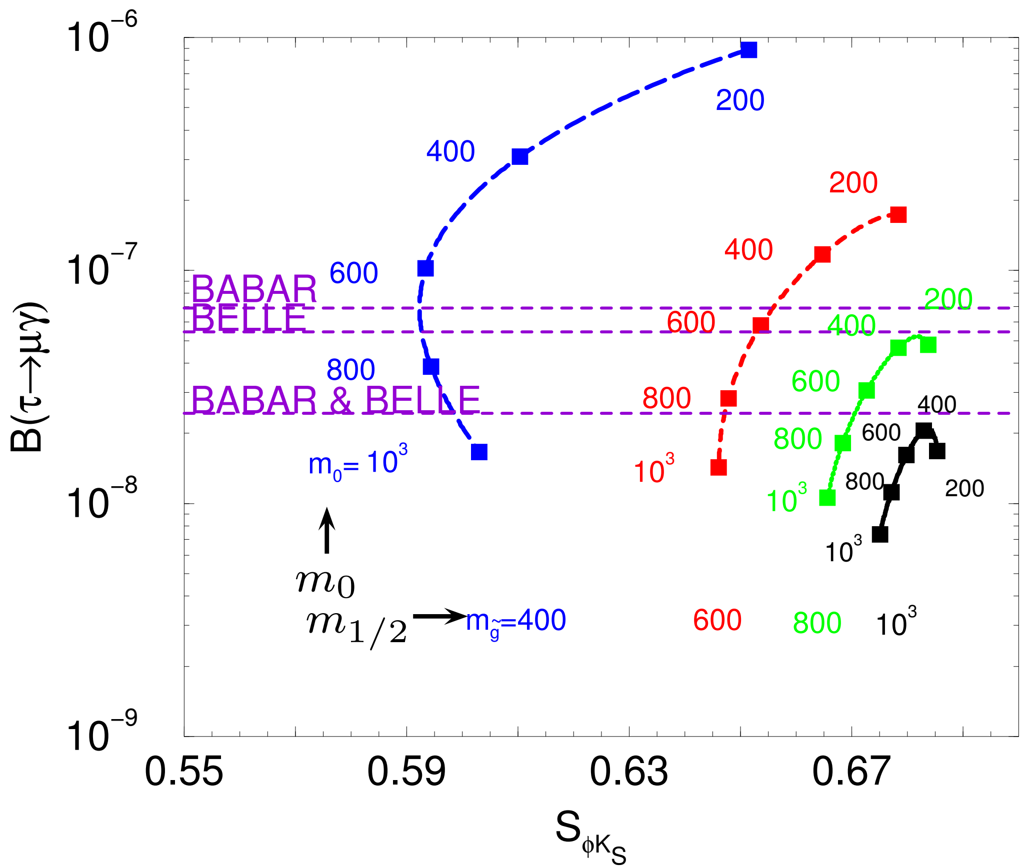
- mSUGRA + Seesaw: ν-mixing induces LFV at EW scale via RGE
  - RGE using SPheno
    (W. Porod, CPC153(2003)275)
  - Cold Dark Matter: WMAP Data Simulation with micrOMEGAs
    (CPC149(2002)103)
  - $m_{\nu_R} = 5 \times 10^{14}$ GeV, $\tan\beta = 55$,
    $\mu > 0,\ A_0 = 0,\ m_0, m_{1/2}$,
    $M^2_{\tilde{L}}, M^2_{\tilde{E}}$: Diagonal



S. Banerjee
University of Victoria
British Columbia • Canada

$\tau \to \mu\gamma$ & $S_{\phi K_S}$

- SUSY SU(5) GUT: Flavor changing right-handed currents $\Rightarrow$ Correlations between CP asymmetry in b-s penguins and $\tau \to \mu\gamma$



J. Hisano, Y. Shimizu (PLB565(2003)183)

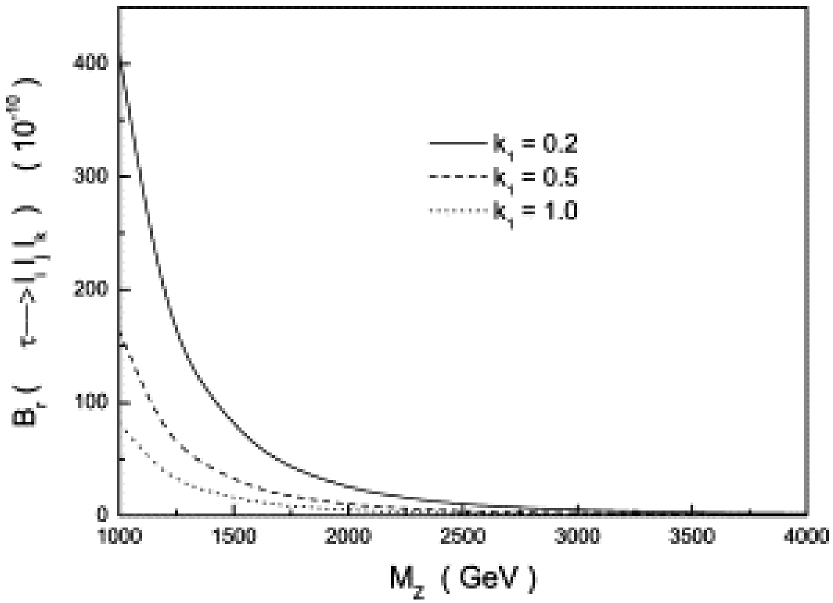
$\tan\beta = 10,\ A_0 = 0,$
$m_{\nu_R} = 5 \times 10^{14}$ GeV,
$m_{\nu_\tau} = 5 \times 10^{-2}$ eV

- Current measurement: $S(B \to \phi K^0) = (0.39 \pm 0.18)$ (HFAG, 2006) More sensitive $\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < 1.6 \times 10^{-8}$ exclude some regions.

$\tau \to \ell\ell\ell$ predictions

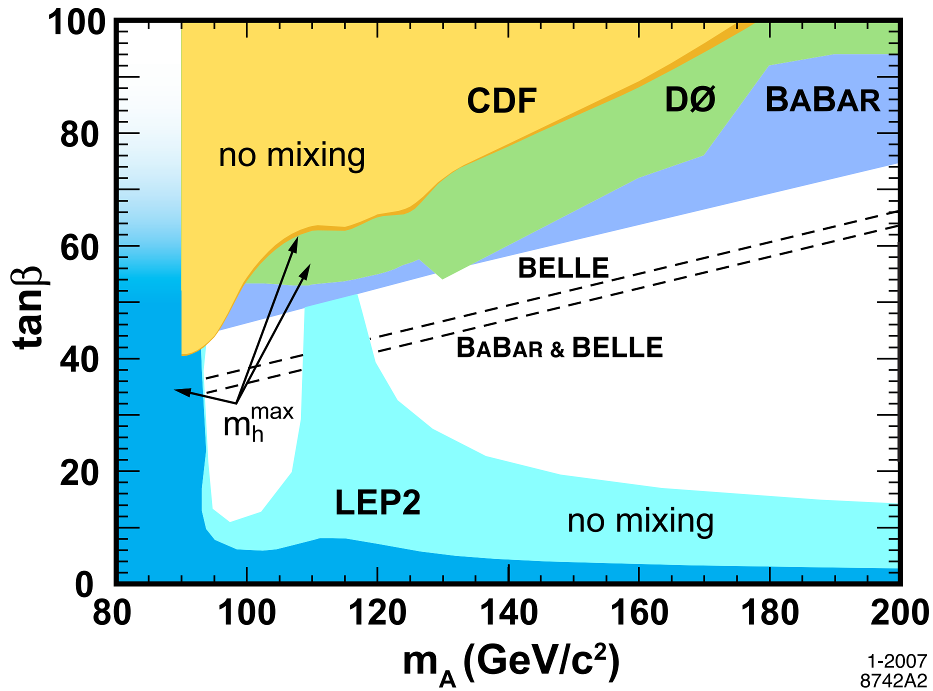
- SUSY + Higgs (A.Brignole, A.Rossi, PLB566(2003)217)
  - $\mathcal{B}(\tau \to 3\mu) \simeq 10^{-7} \times (\frac{\tan\beta}{50})^6 \times (\frac{100GeV}{m_A})^4 \times (\frac{|50\Delta_L|^2+|50\Delta_R|^2}{10^{-3}})$
  - If Higgs light, s-particles $\sim \mathcal{O}(\mathrm{TeV})$, $\tan\beta \sim 50$
    - No direct observation, but $\tau \to \mu\mu\mu$ observable (?)
    - Sensitivity $\sim 10^{-8} - 10^{-10}$ at B-Factories, LHC

- Non Universal Z' (Technicolor) (C.Yue, Y.Zhang, L.Liu, PLB547(2002)252)
  - $\tau \to \ell\ell\ell$ most sensitive
  - Flavor mixing (k_1) = 0.2,
    $\mathcal{B}(\tau \to \ell\ell\ell) < 10^{-8}$
    $\Rightarrow m_{Z'} < 1.2\ \mathrm{TeV}$



Search for Supersymmetric Higgs

- Mixing between left-handed smuons and staus with m_{ν_R} = 10^{14} GeV via seesaw ⇒ $\tau^\pm \to \mu^\pm\eta$ limit translates into exclusion plot in $\tan\beta$ vs. m_A plane (M.Sher, PRD66 (2002) 057301)

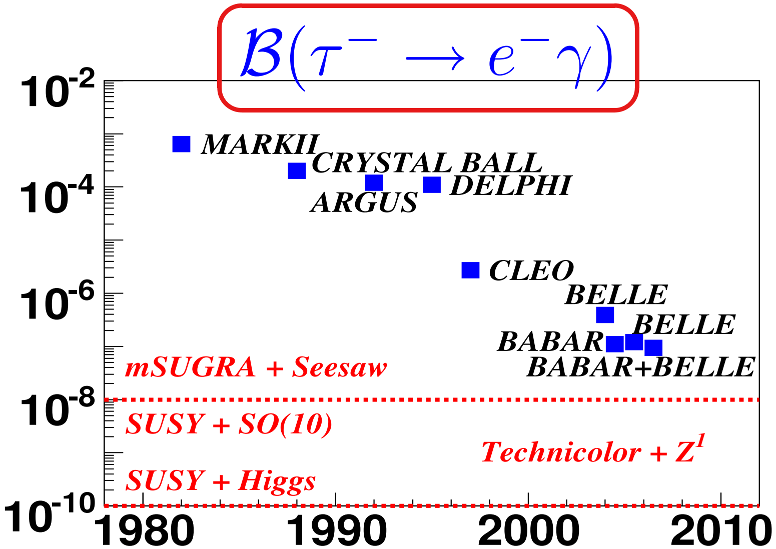


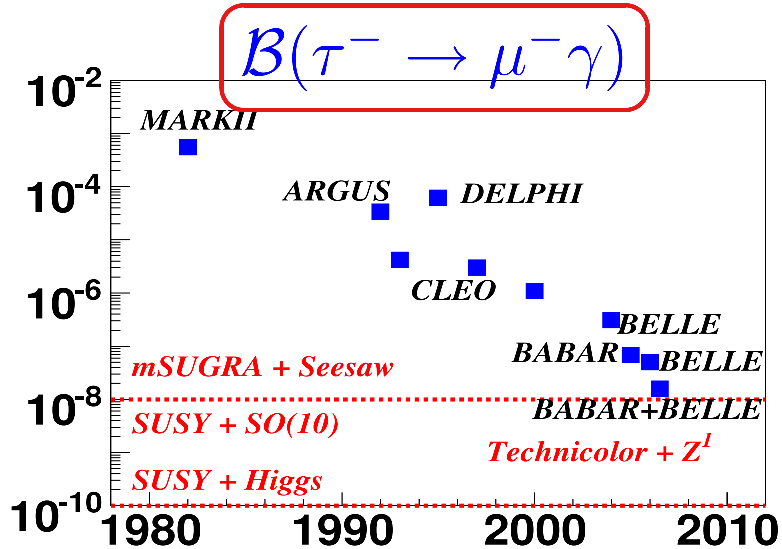
Light and dark shade: $m_h^{\max}$ and no-mixing stop mixing benchmark models
(M. Carena et.al, hep-ph/9912223)

- 95% C.L. from BABAR-BELLE competitive with direct searches at CDF: Higgs $\to \tau^+\tau^-$ (310 pb^{-1}), D0: Higgs $\to b\bar{b}$ (260 pb^{-1}), $\tau^+\tau^-$ (325 pb^{-1}); complementary to region excluded by LEP2

S. Banerjee
University of Victoria
British Columbia • Canada

Summary of Limits on LFV decays





Channel	BaBar		Belle		BaBar & Belle	
	B_{UL}^{90} (10^{-8})	$\mathcal{L}$ (fb^{-1})	B_{UL}^{90} (10^{-8})	$\mathcal{L}$ (fb^{-1})	B_{UL}^{90} (10^{-8})	$\mathcal{L}$ (fb^{-1})
$\tau^\pm \to e^\pm\gamma$	11	232.2	12	535.0	9.4	767.2
$\tau^\pm \to \mu^\pm\gamma$	6.8	232.2	4.5	535.0	1.6	767.2
$\tau^\pm \to e^\pm\pi^0$	13	339.0	8.0	401.0	4.4	740.0
$\tau^\pm \to \mu^\pm\pi^0$	11	339.0	12	401.0	5.8	740.0
$\tau^\pm \to e^\pm\eta$	16	339.0	9.2	401.0	4.5	740.0
$\tau^\pm \to \mu^\pm\eta$	15	339.0	6.5	401.0	5.1	740.0
$\tau^\pm \to e^\pm\eta'$	24	339.0	16	401.0	9.0	740.0
$\tau^\pm \to \mu^\pm\eta'$	14	339.0	13	401.0	5.3	740.0

LFV in $e^+e^- \to \ell^+\tau^-$ production

- Some theories predict sizeable LFV in $e^+e^- \to \ell^+\tau^-$ production, even if stringent limits exist on LFV τ-decays
- J.Bordes, H.-M.Chan, S.T.Tsou, PRD65(2002)093006:

  at $\sqrt{s}$ = 10.58 GeV: $\sigma_{\mu\tau}/\sigma_{\mu\mu} \sim \mathcal{O}(10^{-4})$
- BaBar search: $\mathcal{L}$ = 211 fb^{-1} using $\tau \to \pi^-\nu$, $\tau \to 2\pi^-\pi^+\nu$

$\sqrt{s}$ (GeV)	$\sigma_{\mu\mu}$	$\sigma_{e\tau}/\sigma_{\mu\mu}$	$\sigma_{\mu\tau}/\sigma_{\mu\mu}$	Experiment
10.58	1.1 nb	8.9×10^{-6}	4.0×10^{-6}	BaBar, hep-ex/0607044
29	0.2 nb	1.8×10^{-3}	6.1×10^{-3}	MARKII, 1991
91.2	3.3 nb	2.9×10^{-4}	5.1×10^{-4}	OPAL, 1995
91.2	3.3 nb	6.5×10^{-4}	3.6×10^{-4}	DELPHI, 1997
189	3.2 pb	3.0×10^{-2}	3.7×10^{-2}	OPAL, 2001
192-196	3.0 pb	4.9×10^{-2}	4.0×10^{-2}	OPAL, 2001
200-209	2.7 pb	2.9×10^{-2}	2.4×10^{-2}	OPAL, 2001

Bayon Number Violation

- One of 3 “Sakharov’s conditions” for matter-antimatter asymmetry
- Angular Momentum conservation $\Rightarrow \Delta B = \pm \Delta L$
  In lepton $\rightarrow$ baryon + meson decays $\Rightarrow \Delta(B-L)$ = 0 or 2
- Many SUSY and superstring inspired models predict B, L violation
- $(B-L)$ gives useful hints to the mechanism of baryon instability

Mode	$(B-L)$	BaBar hep-ex/0607040 $\mathcal{L} = 237\,\text{fb}^{-1}$	Belle PLB632(2006)51 $\mathcal{L} = 154\,\text{fb}^{-1}$
$\tau^- \rightarrow \bar{\Lambda}\pi^-$	conserving	5.9×10^{-8}	14×10^{-8}
$\tau^- \rightarrow \Lambda\pi^-$	violating	5.8×10^{-8}	7.2×10^{-8}
$\tau^- \rightarrow \bar{\Lambda}K^-$	conserving	7.2×10^{-8}	
$\tau^- \rightarrow \Lambda K^-$	violating	15×10^{-8}	

CP violation in the lepton sector

- Essential ingredient for matter-antimatter asymmetry
- CP asymmetry $\sim 0.33\%$ expected in $\tau^- \to K^0_S \pi^- \nu_\tau$ decays, because of CP impurity in K^0_S (the observed kaons are the mass and not the flavor eigenstates) (Bigi, Sanda: hep-ph/0506037)
- Sources of CP violation in Standard Model are not enough to explain the matter-antimatter asymmetry in the universe
- τ decays : ideal place to look for new sources of CP violation
- Expected statistical precision with full dataset @ BABAR $\sim$ 0.1%
- Datta, Kiers, London, O'Donnell, Szynkman (hep-ph/0610162): New Physics can contribute to $\tau \to N\pi\nu_\tau$ (N = 3, 4) final states
  - $\tau^- \to a_1 \pi^- \nu_\tau$ (polarization-dependent asymmetry)
  - $\tau^- \to \omega \pi^- \nu_\tau$ (triple product asymmetry)
- Active analyses in BABAR: challenging systematics

Conclusions

- B-Factories are also τ-Factories
- Dataset expected to be doubled by end of data-taking (Sep 2008)
- On-going effort to better understand systematic errors
- Expect lots of more τ-physics with inputs also from ISR studies:
  - τ-Lifetime, Leptonic Branching Fractions, Lepton Universality
  - High precision tests of QCD
    - Measurements of fundamental quantities:
      $|V_{us}|$, m_s, α_s, $(g-2)_\mu$ ...
    - Structure of non-strange and strange hadronic states
    - Resonance sub-structure of hadronic final states
    - Search for second class currents
  - Search for new Physics are getting significantly closer to theoretical predictions on LFV decays $\sim \mathcal{O}(10^{-8})$.
    Please Stay tuned to update of Experiment vs. Theory plots ...
  - Search for CP violation in τ decays

S. Banerjee
University of Victoria
British Columbia • Canada