Experimental prospects for rare tau decays

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FLAVOUR IN THE ERA OF THE LHC

a Workshop on the interplay of flavour and collider physics

March 2007
CERN

Outline

- Status of LFV limits from B-factories
- Projections: 10^{36} SuperB Flavour Factory
- Status of LHC studies of LFV from tau decays (thanks to Thomas Kress, Manuel Giffels, L. Perchalla, Achim Stahl (CMS) and Mikhail Shapkin LHCb)
- comments on Lepton Universality from tau decays

LFV predictions very model dependent (see talks on Tuesday of this meeting)

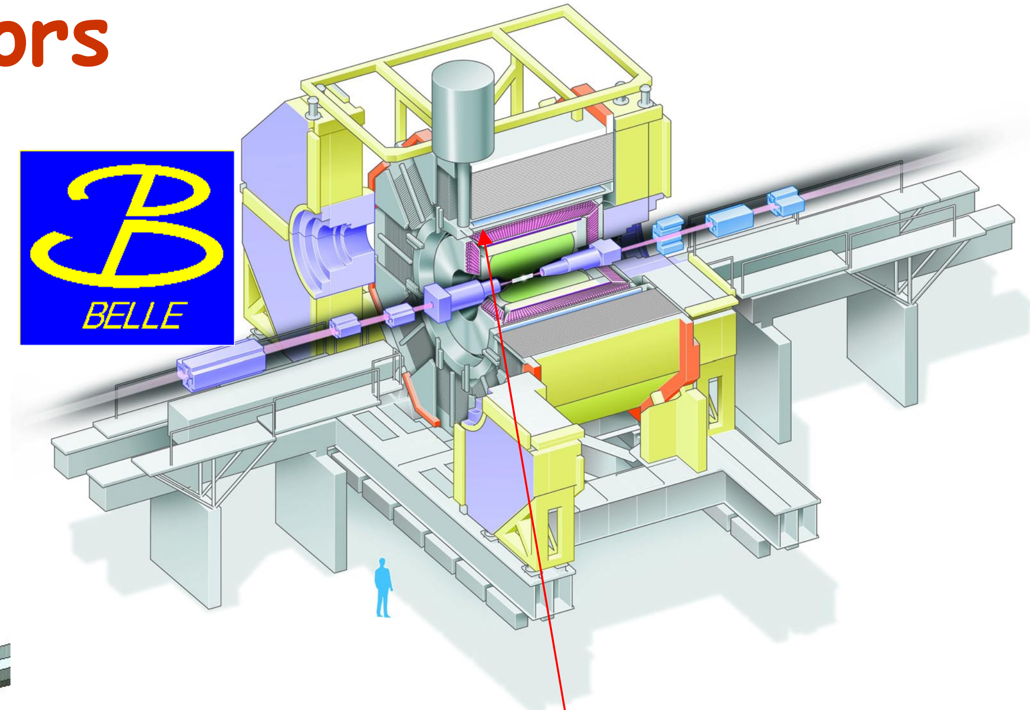
- specific models give LFV process rates
- a single LFV process will not determine the underlying mechanism
- Strategy: combine results from different measurements – complementarity
  - all μ-e LFV processes: radiative decays, μ–e conversion
  - all tau decay channels
    - ☞ many models correlate between various LFV, so e.g. $\mu\to e\gamma$, $\tau\to\mu\gamma$ and $\tau\to e\gamma$ needed
  - K & B LFV decays
  - neutrino oscillations
  - g-2, EDMs
  - direct production at colliders and LHC
  - ...

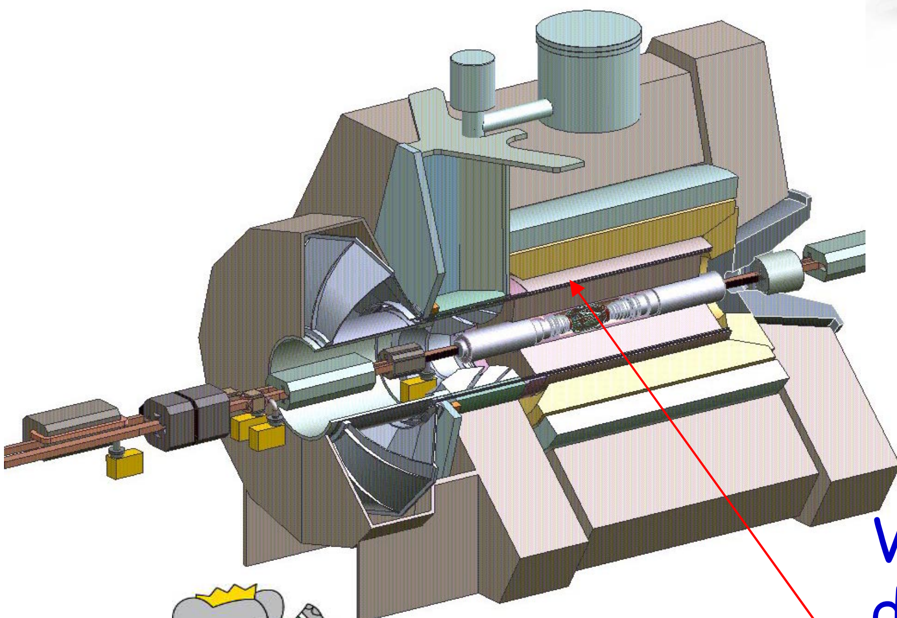
B-Factory Detectors

Both operating at $\Upsilon(4S)$

Belle: 8 GeV e^-/3.5 GeV e^+

BaBar: 9 GeV e^-/3.1 GeV e^+





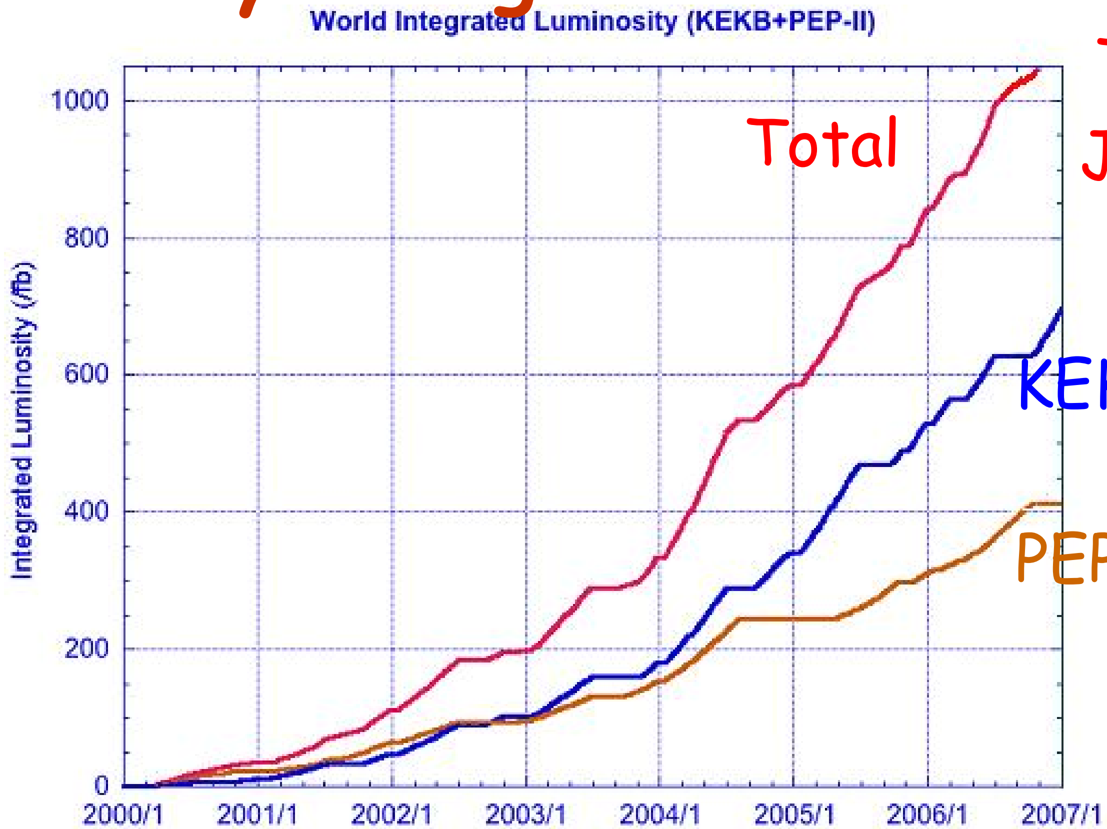
BaBar

Very similar detectors; main difference is in PID:

BaBar: Ring-imaging Cherenkov

Belle: Threshold Cherenkov and TOF

B-factory Integrated luminosity



Total Recorded to Jan 2007 is 1.1 ab^{-1}

$e^+e^- \rightarrow \tau^+\tau^-$ cross section ~0.9nb

Total sample > 10^9 $\tau^+\tau^-$ events

→ search for new physics in rare/forbidden decays

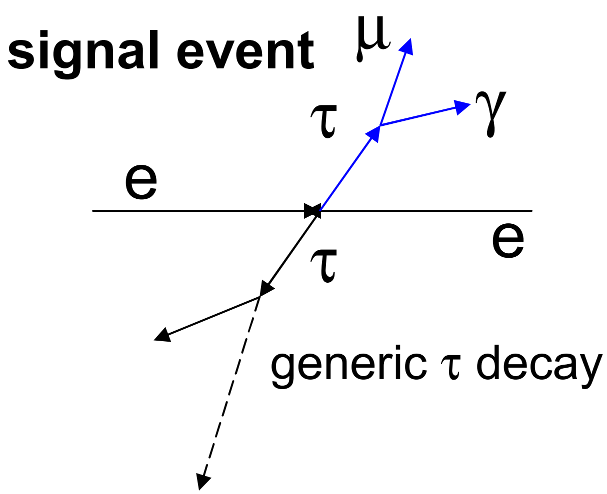
General event Selection Approach

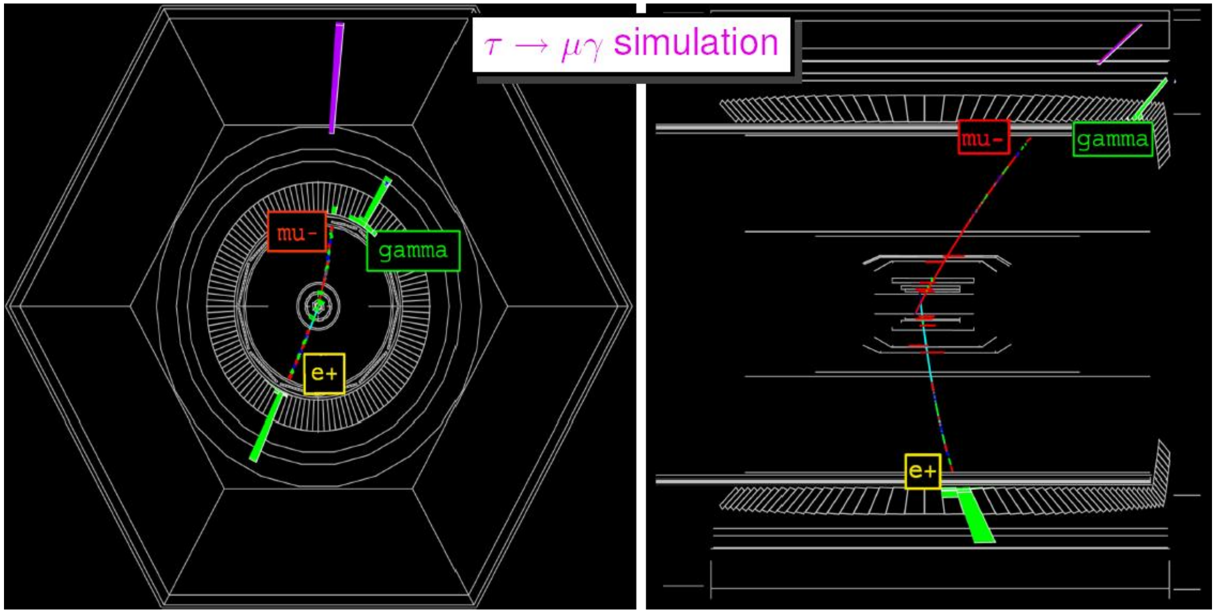
Divide event into hemispheres in the centre-of-mass

- generic τ decay hemisphere: 1-prong (e, μ, π, ρ) or 3 prong τ decay depending on signal and dominant non-τ backgrounds

  [$e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to$ hadrons, $\gamma\gamma$]

  e.g. avoid electron tag for $\tau \to e\gamma$ to minimize Bhabha backgrounds
- All searches are 'blind';MC used to optimize selection for 'best expected limit' $\to$ small no. of background events and $\varepsilon \sim$ 2-10%

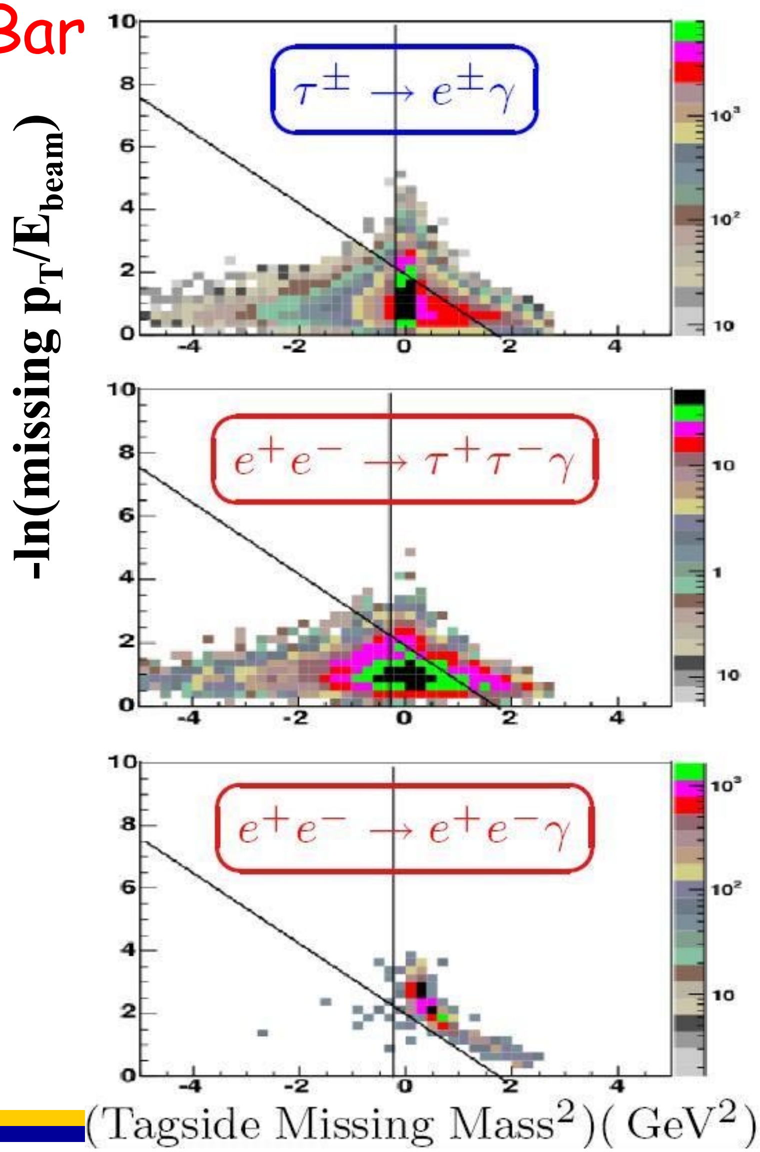




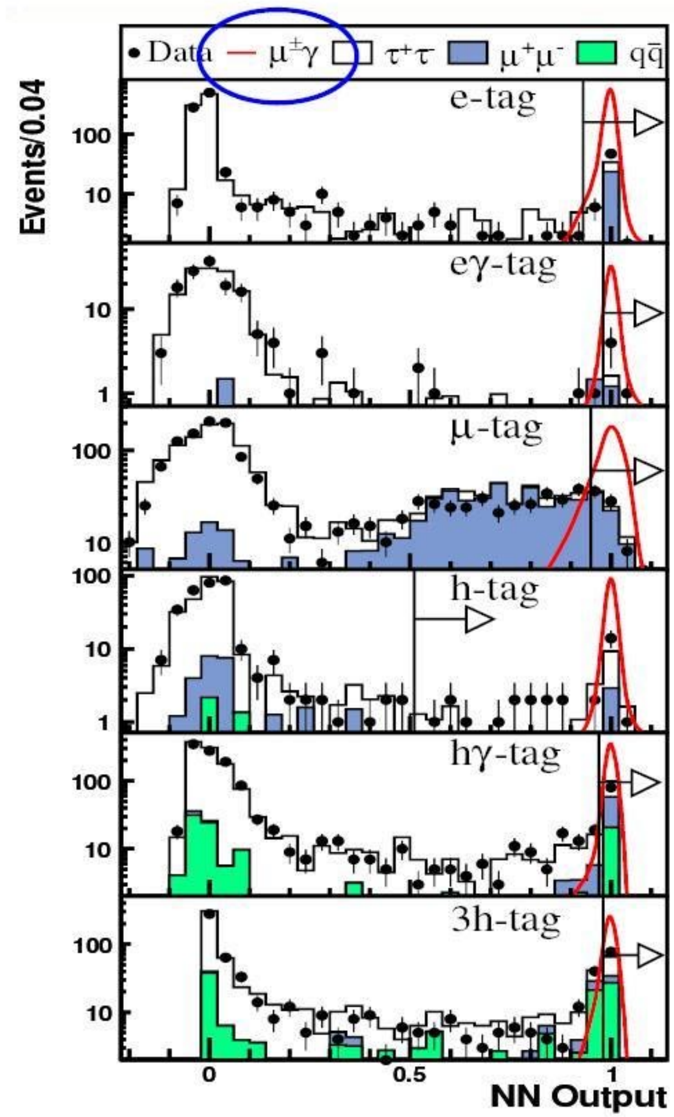
UVic

BaBar

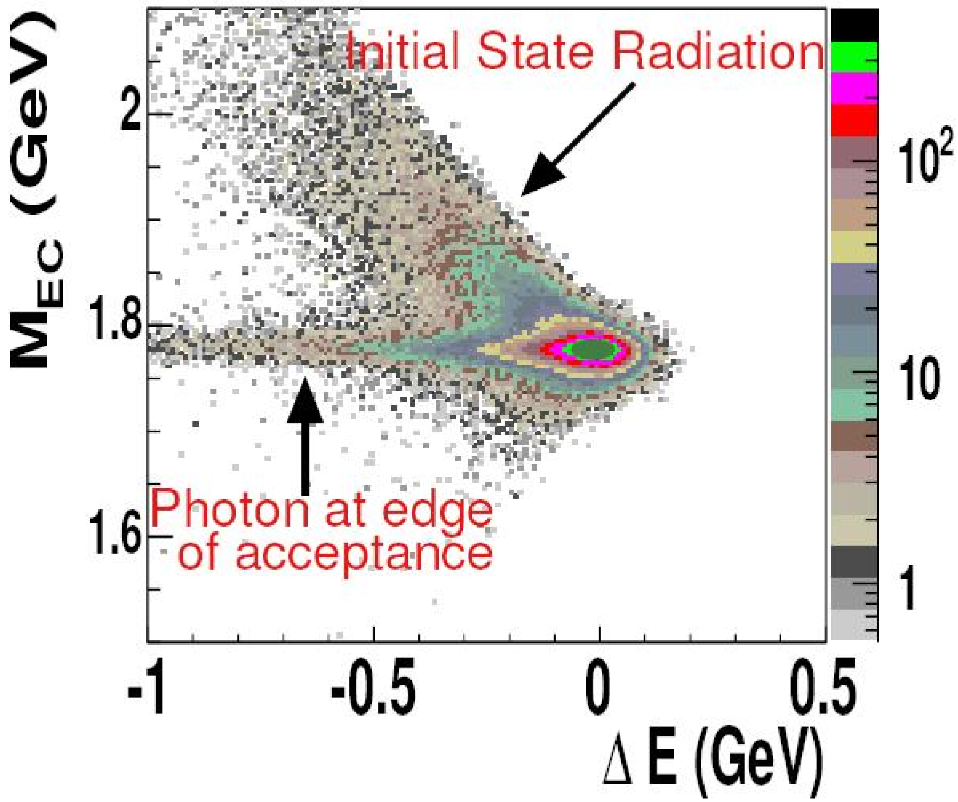
cut based selection



Neutal Net based selection



Signal: no neutrinos → powerful mass and beam energy information



signal region typically defined as 2σ box or ellipse

mass: $m_{\mu\gamma} = m_\tau$

Babar uses beam energy constrained mass & γ vertex at μ point of closest approach to beamspot in x,y

$\sigma(M_{EC})$~9MeV

(cf no mass or vertex constraint σ~24MeV)

Beam Energy:

$\Delta E = E_{\mu\gamma} - E_{beam} \sim 0$

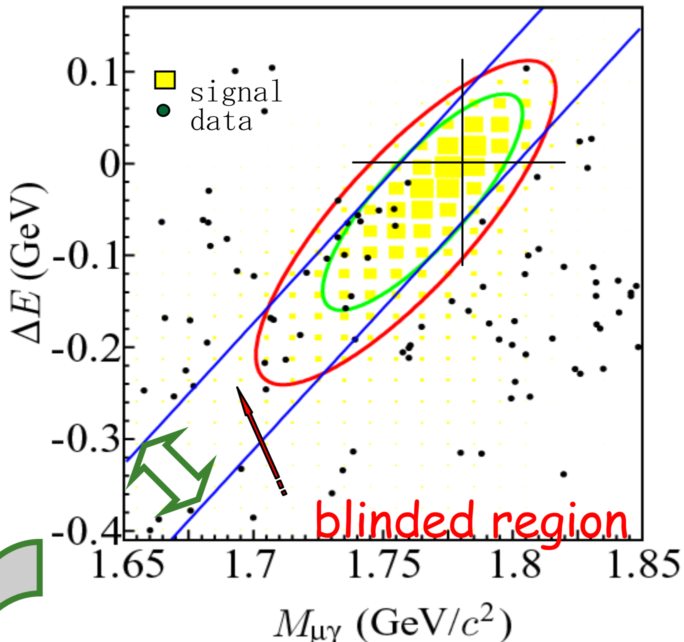
σ (ΔE)~50MeV

UVic

Efficiency for searches typically have the following components:

		cum.
trigger	90%	
acceptance/reconstruction	70%	63%
topology (1vs1, 1 vs 3: hemispheres)	70%	44%
Particle ID	50%	22%
Cuts	50%	11%
Signal-Box	50%	~5%

Preliminary Belle result on $\tau \to \mu\gamma$



94 events in 535 fb^{-1}

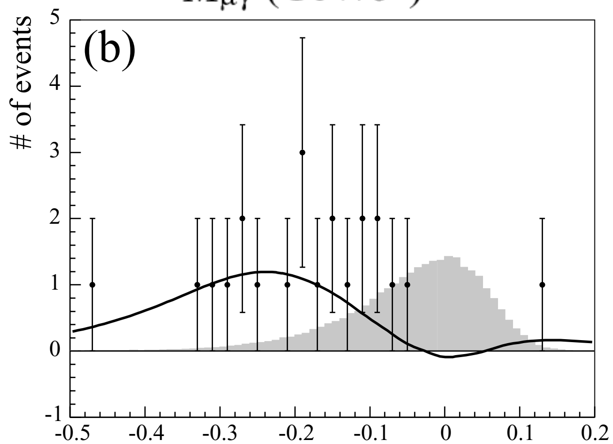
within 2σ ellipse, eff=5.1%

UEML fit in 2σ projected band

signal events = -3.9 (P(n$\leq$-3.9)=25%)

background evts=13.9

2σ projection



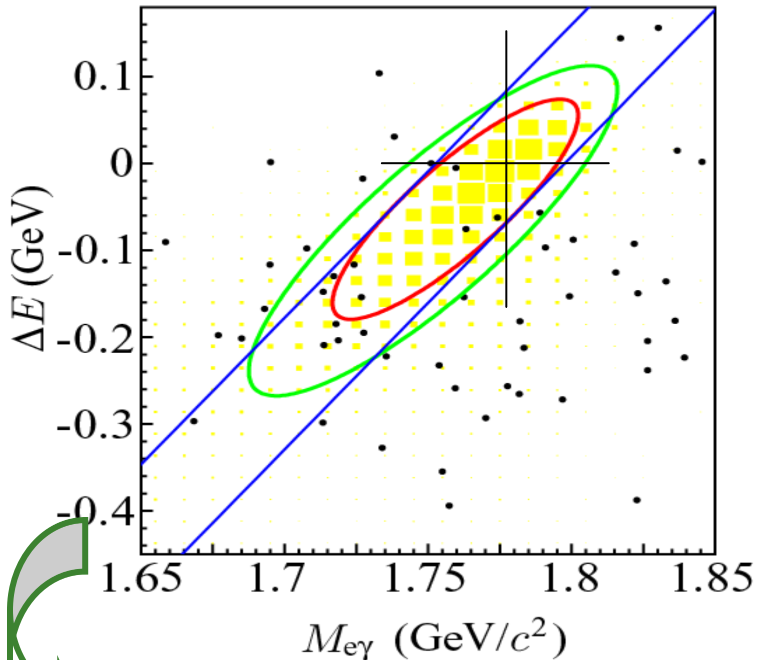
Unbinned Extended Maximum Likelihood fit

s(90% CL) = 2.0 events

Br<4.5x10^{-8} at 90%C.L

hep-ex/0609049

Preliminary Belle result on $\tau \to e\gamma$



20 events within 5σ in 535 fb^{-1}

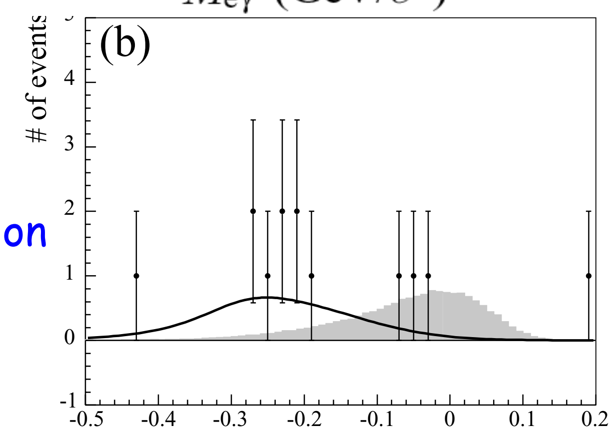
within 2σ ellipse, eff=3%

UEML in 2σ projected band

signal events = -0.14 (P($n \leq -0.14$)=48%)

background evts=5.14

2σ projection



s(90% CL) = 3.34 events

Br<1.2x10^{-7} at 90%C.L

hep-ex/0609049

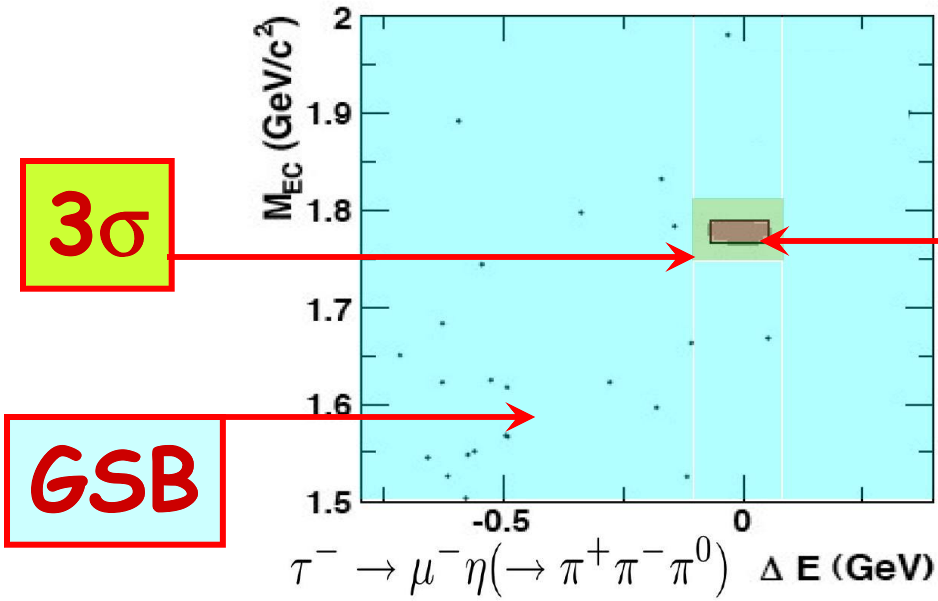
Unbinned Extended Maximum Likelihood fit

NEW $\tau\rightarrow\ell\pi^0/\eta/\eta'$ (ℓ=e or μ)

BaBar

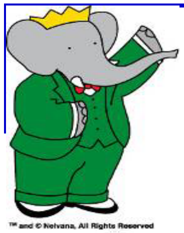
For each of the 6 channels, fit background shapes from MC with an unbinned maximum likelihood fit to (M_{ec} vs ΔE)

Overall normalization taken from data



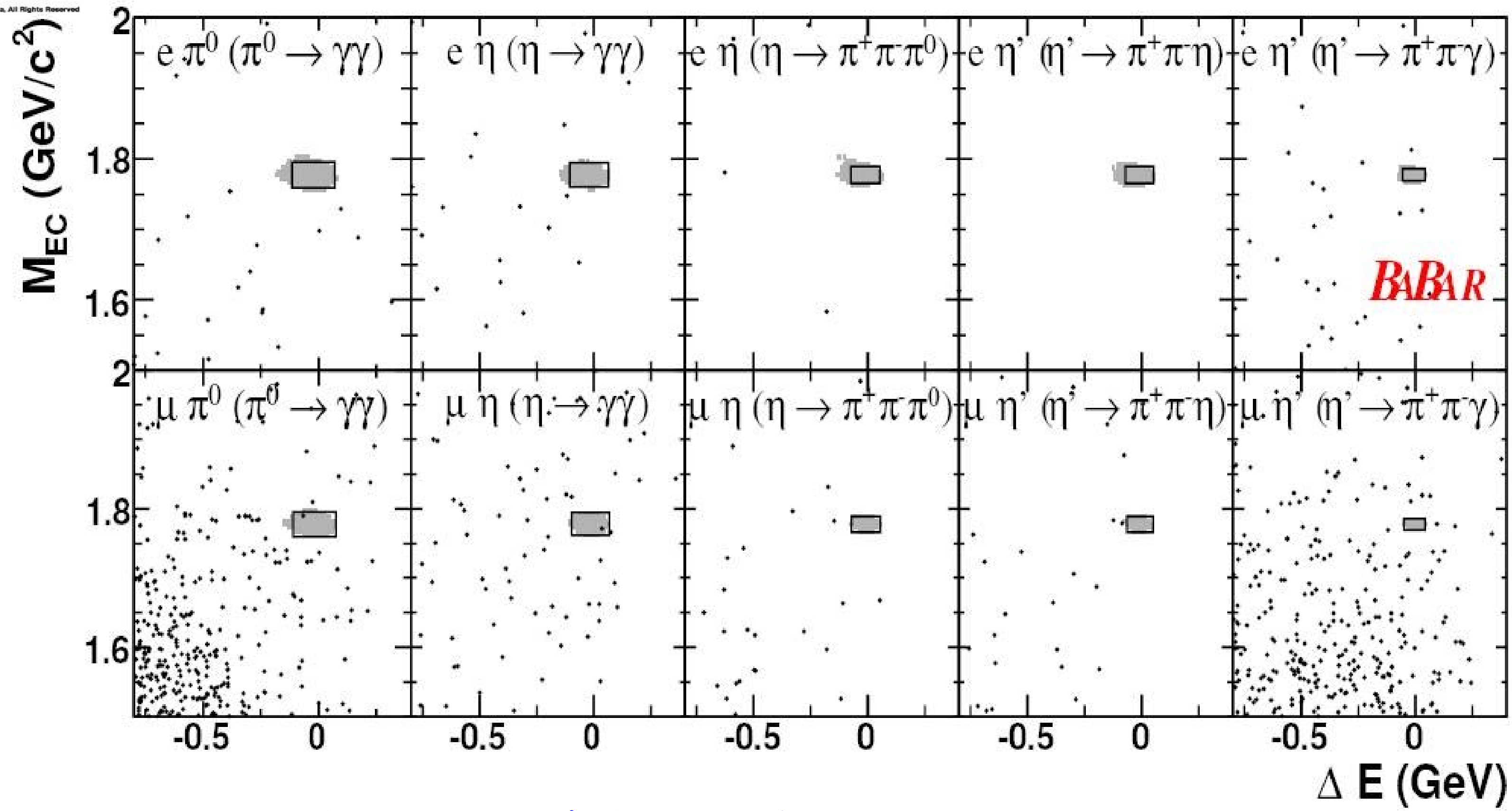
$$N_{2\sigma}^{data} = \frac{\int_{2\sigma} PDF_{tot}}{\int_{GSB-3\sigma} PDF_{tot}} \times N_{GSB-3\sigma}^{data}$$

NEW $\tau \to \ell\pi^0/\eta/\eta'$



BaBar

hep-ex/0610067 PRL 98.061803 (2007)



expected background/channel ~ 0.1-0.3

Total expected background=3.1, Observed=2

Summary of $\tau \to \ell$ Pseudo Scalar 90%CL Upper Limits

τ^- Decay Mode	Belle * Phys.Lett.B639:159-164,2006 hep-ex/0609013		BaBar PRL 98.061803 (2007)	
	Br 10^{-7}	Lum. fb^{-1}	Br 10^{-7}	Lum. fb^{-1}
$e^- K^0_s$	<0.56*	281		
$\mu^- K^0_s$	<0.49*	281		
$\mu^- \pi^0$	<1.2	401	<1.1	339
$\mu^- \eta$	<0.65	401	<1.5	339
$\mu^- \eta'$	<1.3	401	<1.4	339
$e^- \pi^0$	<0.8	401	<1.3	339
$e^- \eta$	<0.92	401	<1.6	339
$e^- \eta'$	<1.6	401	<2.4	339

Summary of 90%CL Upper Limits on LFV τ decays

Channel	Belle		BaBar	
	Br (10^{-7})	$\mathcal{L}$ (fb^{-1})	Br (10^{-7})	$\mathcal{L}$ (fb^{-1})
$\mu^-\gamma$	<0.5*	535	<0.7	232
$\mu^-\pi^0$	<1.2*	401	<1.1	339
$\mu^-\eta$	<0.7*	401	<1.5	339
$e^-\gamma$	<1.2*	535	<1.1	232
$e^-\pi^0$	<0.8*	401	<1.3	339
$e^-\eta$	<0.9*	401	<1.6	339
$\ell\ell\ell$	<(2-4)	87	<(1-3)	92
$\ell hh'$	<(2-16)	158	<(1-5)	221

*** Preliminary**

Combining BaBar and Belle: Sw. Banerjee Tau06 hep-ex/0702017

- efficiency combined from weighted luminosity
- Add no. events observed in data, Nobs(data)
- Add no. expected background events, b
- Obtain 90%CL Cousins & Highland Upper Limit*:
  - Poisson distributed toy MC with mean (s+b)
  - signal: $s=2\mathcal{L}\sigma_{\tau\tau}BR_{UL}(\varepsilon\pm\sigma_{\varepsilon})$
  - expected background: $b\pm\sigma_b$
  - s & b are each Gaussian distributed

vary BR_{UL} until 10% of toy MCs yield # events < Nobs(data)

the 'expected upper limit' obtained setting s=0 for Poisson distributed values of 'Nobs' for expected background b

* Cousins-Highland NIM A320, 331 (1992), Barlow CPC 149 97 (2002)

Combining BaBar and Belle: Sw. Banerjee Tau06 hep-ex/0702017

	$\mathcal{L}$	ε	Background events		$\mathcal{B}^{90}_{\mathrm{UL}}$ $(\times 10^{-8})$	
	(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

Combining BaBar and Belle: Sw. Banerjee Tau06 hep-ex/0702017

Channel	BaBar		Belle		BaBar & Belle	
	$B^{90}_{\rm UL}$ (10^{-8})	$\mathcal{L}$ (fb^{-1})	$B^{90}_{\rm UL}$ (10^{-8})	$\mathcal{L}$ (fb^{-1})	$B^{90}_{\rm UL}$ (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 tau decays: how far can we go?

BR_{90}^{UL} depends on backgrounds:

In absence of signal, for large N_{bkg} : $N_{90}^{UL} \sim 1.64 \times \sqrt{N_{bkg}}$

For N_{bkg}~0 and no events observed, $N_{90}^{UL} \sim 2.3 + 1.2 \times \sqrt{N_{bkg}}$

(Feldman&Cousins)

Analyses usually keep handful of events:

expected limit not improved much if alot of signal efficiency lost

Trivial to project expectations if same analyses used:

Limits scale $\sim \sqrt{N_{bkg}} / \mathcal{L} \sim 1/\sqrt{\mathcal{L}}$ for large N_{bkg}

Gives a worst case scenerio:

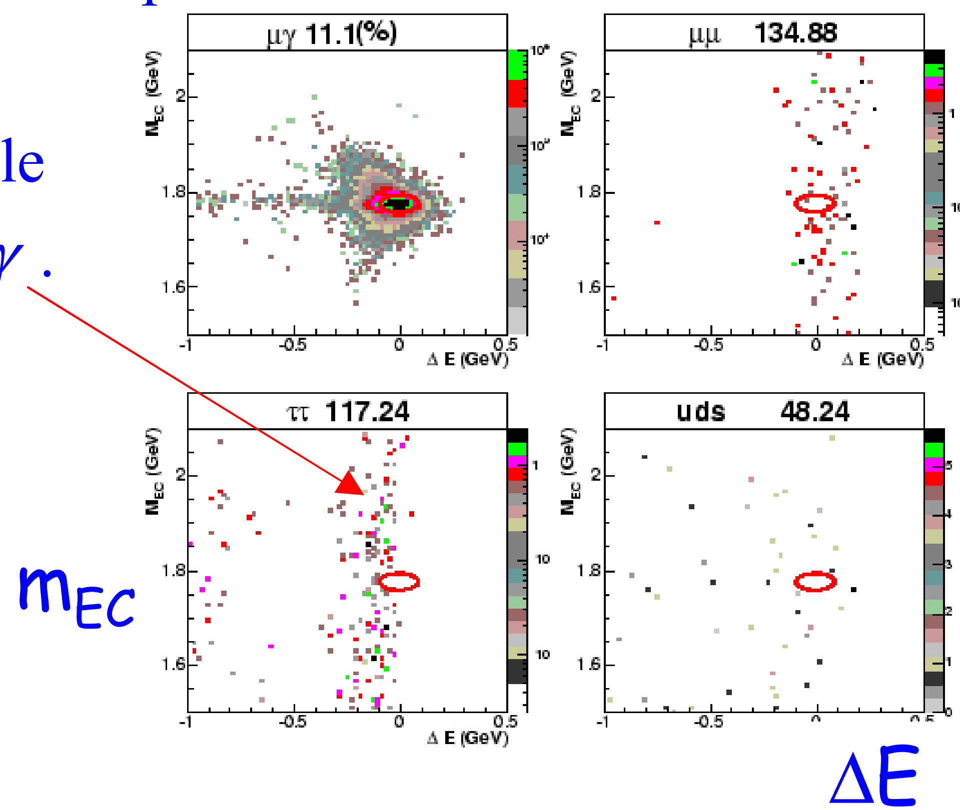
Combining Babar & Belle assuming comparable

sensitivities, this drops to ~$4x10^{-8}$ for ~$1ab^{-1}$ per exp't.

LFV in tau decays $\tau \rightarrow \mu\gamma$

More realistic scenerio: analysis developed with little efficiency loss but all background is solely the irreducible background from $\tau \rightarrow \mu\nu\nu + ISR\gamma$.

This represents ~1/5 of the Babar background.



LFV in tau decays $\tau \rightarrow \mu\gamma$

Limit then determined by scaling reduced background by $\mathcal{L}$

Gives scenerio for expected limits with

irreducible backgrounds of ~1-2x10^{-8} for 1/ab (Babar+Belle)

For a SuperB factory with 100x luminosity, this leads to ~2-3x10^{-9}

NB: Not clear how to do this without some efficiency losses

- **dropping mu-tag - significant efficiency loss**
- **using lifetime information – improved vertexing helps!**
- **more refined tagging analysis**

LFV in tau decays $\tau \rightarrow \mu\gamma$

Can reduce 'irreducible' background by improving mass resolution.

Increase EM Calorimeter granularity:

photon direction is a resolution limiting factor.

e.g. if $\mu\gamma$ mass resolution improves from 8.9MeV to 6MeV,

the irreducible background scenario limit could improve by 25%.

Can also include γ polar angle as a discriminating variable

LFV in tau decays $\tau \rightarrow \ell\ell\ell$, $\tau \rightarrow \ell hh'$, $\tau \rightarrow \ell\eta/\eta'$

Situation different for neutrinoless 3-prong decays: no significant irreducible background (analogous QED radiative decays are suppressed by another α factor and lepton masses) … negligible effect
Backgrounds are at O(1) event per mode level.

With no change to the analyses
$1ab^{-1}$ expected 90%CL UL ~$3\text{-}9\times10^{-8}$ 1 expt

Best case scenario analysis with no 'irreducible' backgrounds, so expected limits could scale as $\mathcal{L}$… get limits for $1ab^{-1}$ of ~10^{-8}

For SuperB, with $75ab^{-1}$, expected limit ~2×10^{-10}

Summary of SuperB Projections of benchmark LFV decays

Probing 10^{-10}–10^{-9}

75 ab^{-1}	BR 90%CL UL ($\times10^{-9}$)
$\tau \to \mu\gamma$	2
$\tau \to e\gamma$	2
$\tau \to \mu\mu\mu$	0.2
$\tau \to eee$	0.2
$\tau \to \mu\eta$	0.4
$\tau \to e\eta$	0.6
$\tau \to \ell K^0_S$	0.2

Early (1997) ATLAS Study of $\tau \to \mu\gamma$

(L. Serin, R. Stroynowski ATLAS Phys-97-114)

Study Based on fast MC

Source of taus: Drell-Yan $qq' \to W \to \tau\nu$

$\sim 2\text{x}10^8$ for $10fb^{-1}$

Selection:

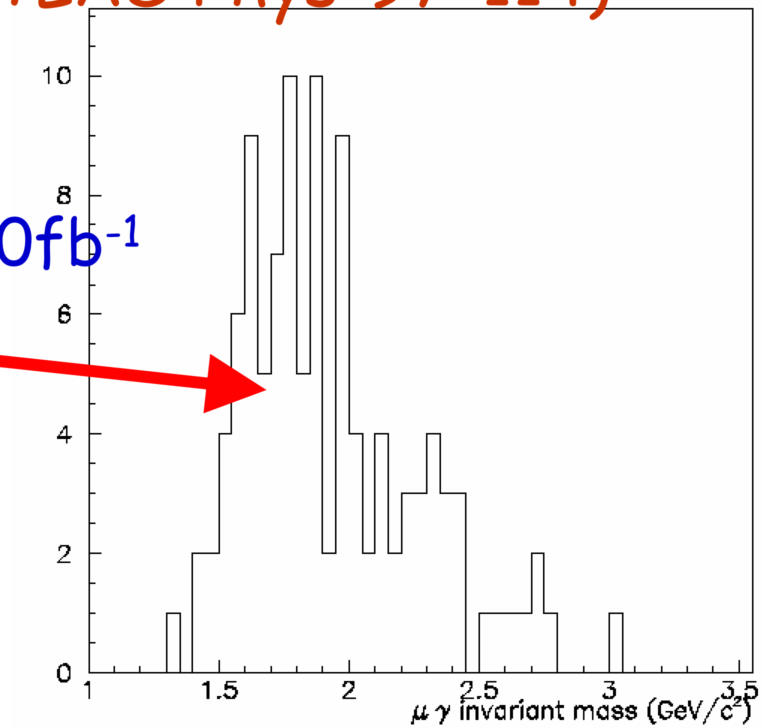
- $|\eta|<2.5$ for both $\mu\gamma$
- $10<P_T(\mu)<20$GeV
- $E_T(\gamma)>20$GeV
- $\sqrt{(\Delta\eta^2+\Delta\phi^2)}>0.08$
- $M(\mu\gamma)$ with 2σ of $M\tau$ ($\sigma\sim 20$MeV)

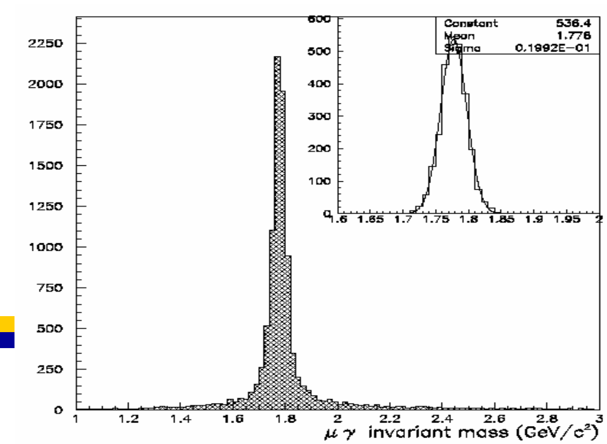
UVic

Early ATLAS Study of $\tau \to \mu\gamma$
(L. Serin, R. Stroynowski ATLAS Phys-97-114)

- Main background is $W \to \tau\nu\gamma \to \mu\nu\nu\gamma$: 17evt/ 10fb^{-1}
- Efficiency ~5%
- 90%CL UL~1x10^{-6} for 10fb^{-1}

Not competitive with B-factories





LHCb Study of $\tau \rightarrow \mu\mu\mu$

(M. Shapkin, Tau06 proceedings)

At LHC, main sources of τ leptons are:

- $B^0/B^{\pm}/B_s \rightarrow X \tau\nu_\tau$ (Br = 2.5 %)
- $D_s \rightarrow X \tau\nu_\tau$ (Br ~ 7.5 %)

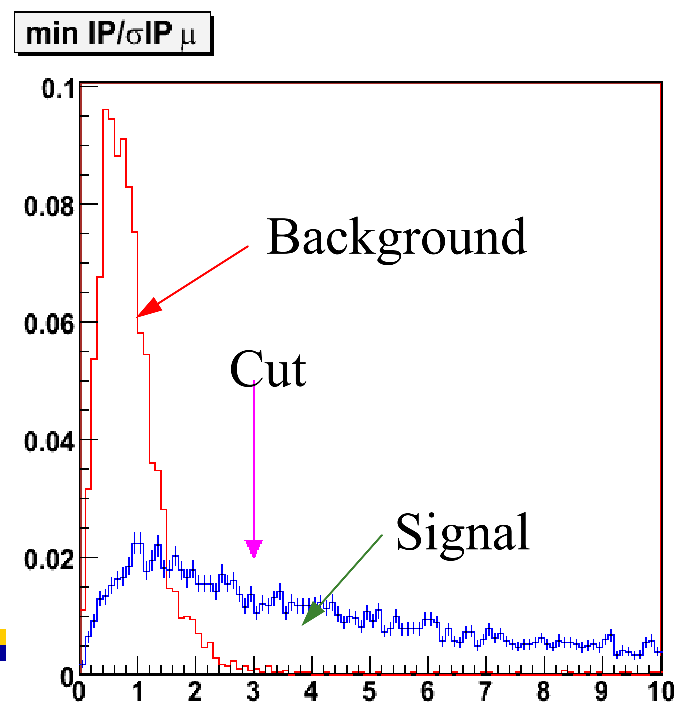
  D_s from B decays & produced in c-quark fragmentation

After 1 LHCb year: $\int L dt = 2\ fb^{-1}$,
$\varepsilon \approx 0.35$ $N_\tau(\mathrm{LHCb}) = 70 \times 10^9$

LHCb Study of $\tau \to \mu\mu\mu$

(M. Shapkin, Tau06 proceedings)

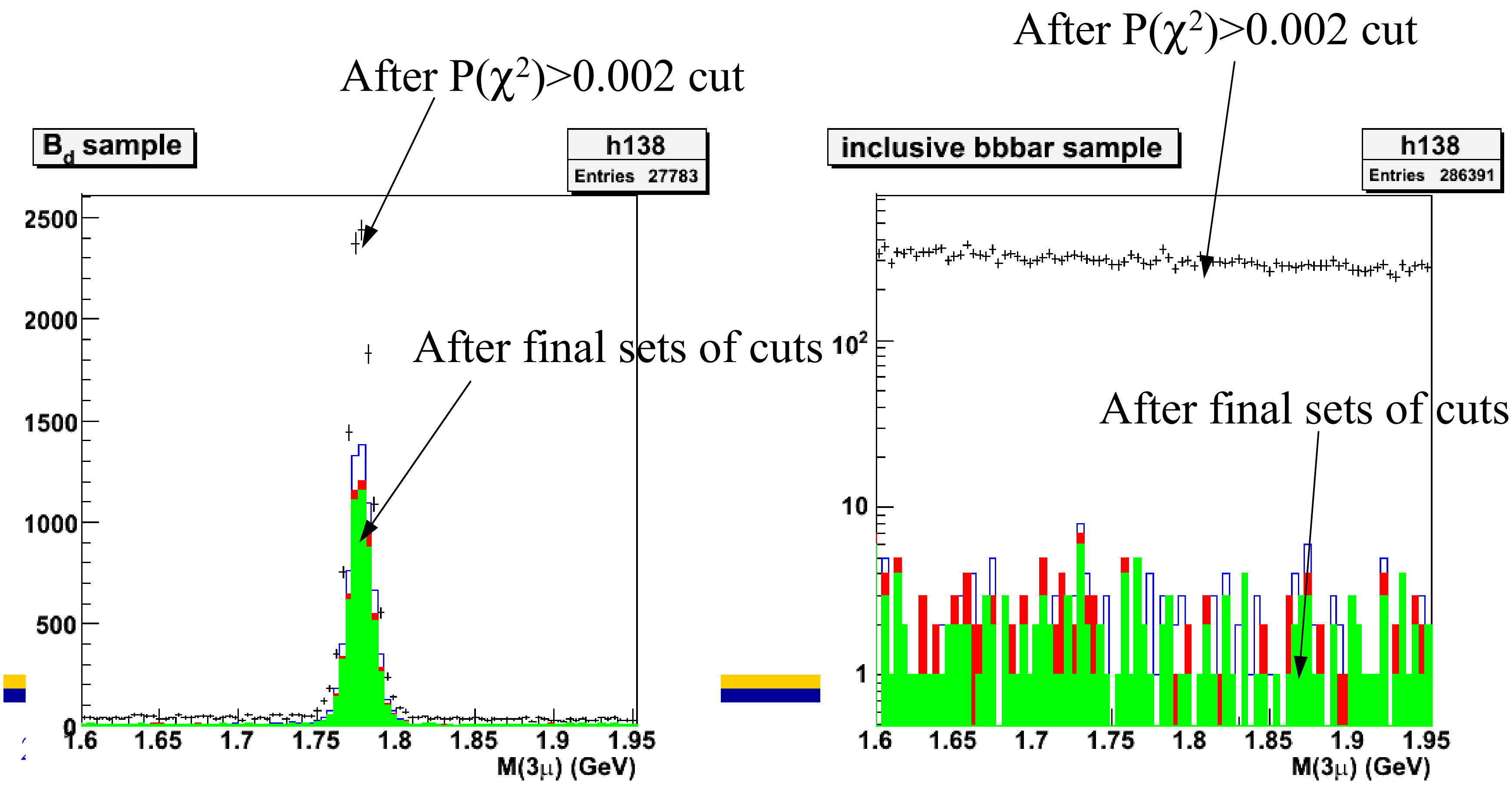
- 3 standard identified muons ($P_t > 0.4$ GeV)
- Common vertex for 3μ $P(\chi^2) > 0.002$
- IP significance: $IP/\sigma_{IP} > 3$ for all μ
- $|V_{3\mu} - V_{Pvtx}|/\sigma > 3$
- $4mm < (Z_{3\mu} - Z_{Pvtx}) < 37mm$
- R_{xy} (between 3μ & Pvtx) $> 0.1mm$



LHCb Study of $\tau \to \mu\mu\mu$

(M. Shapkin, Tau06 proceedings)

M(3μ) for signal and background after different cuts



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LHCb Study of $\tau\rightarrow\mu\mu\mu$
(M. Shapkin, Tau06 proceedings)

- For L_{int} = 2 fb^{-1}: $N_\tau \approx 7 \cdot 10^{10} \cdot \varepsilon$
  inclusive **b** as the main source of background:

  $N_{bg} = 0.5{\cdot}10^{12}\ fb{\cdot}2\ fb^{-1}{\cdot}0.35 \cdot\varepsilon_{bg} = 3.5{\cdot}\ 10^{11} \cdot\varepsilon_{bg}$

- For the mass window of ±10MeV
  - $\varepsilon_{sig} = 4.7\%$; $\varepsilon_{bkg} = 4.6\text{x}10^{-7}$
- For $\int Ldt = 2fb^{-1}$ $N_\tau = 3.5\text{x}10^9$; $N_{bkg} = 1.6\text{x}10^5$

$Br(\tau\rightarrow\mu\mu\mu)<1.2\text{x}10^{-7}$

Initial CMS Study of $\tau \to \mu\mu\mu$

(Perugia: R. Santinelli, M. Biasini, CMS Note 2002/037)

	$N_{events}(/10fb^{-1})$
• $\sigma(pp \to \tau + X) \sim 120\ \mu b$	
❑ $\sigma(pp \to Z \to \tau\tau) = 3nb$	3×10^{7}
❑ $\sigma(pp \to W \to \tau + \nu) = 19nb$	2×10^{8}
❑ $\sigma(pp \to D^{+} \to \tau + \nu + X) \sim 4\mu b$*	4×10^{10}
❑ $\sigma(pp \to B_{x} \to \tau + \nu + X) \sim 24\mu b$*	2.4×10^{11}
❑ $\sigma(pp \to D_{S} \to \tau + \nu + X) \sim 92\mu b$*	1.2×10^{12}

*with large uncertainty

Initial CMS study with GEANT3 simulation & 2002 CMS reconstruction code

UVic

Summary of W,Z, B_x Selection

(Initial CMS Study of $\tau\rightarrow\mu\mu\mu$ CMS Note 2002/037)

- TRIGGER: 2 L1 muons P_T>8GeV and P_T>5 GeV || 1 L1 muon P_T>20GeV
- 3 L3 reconstructed muons with total charge=+/- 1
- $W\rightarrow\tau\nu$:
  - Topological and isolation cuts around 3 muons
  - $E_T$miss > 20GeV
- $Z\rightarrow\tau\tau$:
  - Topological and isolation cuts around 3 muons
  - tag a second tau
  - P_T(3muons) > 20GeV
  - total mass of 2 taus > 70GeV
- $B_x\rightarrow\tau\nu$+X:
  - 3 muons inside b-tagged jet
  - 2nd b-tagged jet opposite signal in azimuth
- No pair of muons with mass ~ $M\phi$ --suppresses $D_s\rightarrow\mu\nu\phi\rightarrow\mu\mu\mu\nu$
- 3 muon mass within 25MeV of $M\tau$ (σ~13MeV)

Summary of W,Z, B_x Reach for $30fb^{-1}$

(Initial CMS Study of $\tau\rightarrow\mu\mu\mu$ CMS Note 2002/037)

- $W\rightarrow\tau\nu$:
  - efficiency ~10%
  - background= 2.4 ± 3
  - 90%CL UL ~ 4×10^{-8}
- $Z\rightarrow\tau\tau$:
  - efficiency ~ 10%
  - background= 1.8 ± 3
  - 90%CL UL ~ 3×10^{-8}
- $B_x\rightarrow\tau\nu+X$:
  - efficiency ~ 2×10^{-5}
  - background=3 ± 3
  - 90%CL UL ~ 2×10^{-7}

New CMS Study of $\tau \to \mu\mu\mu$

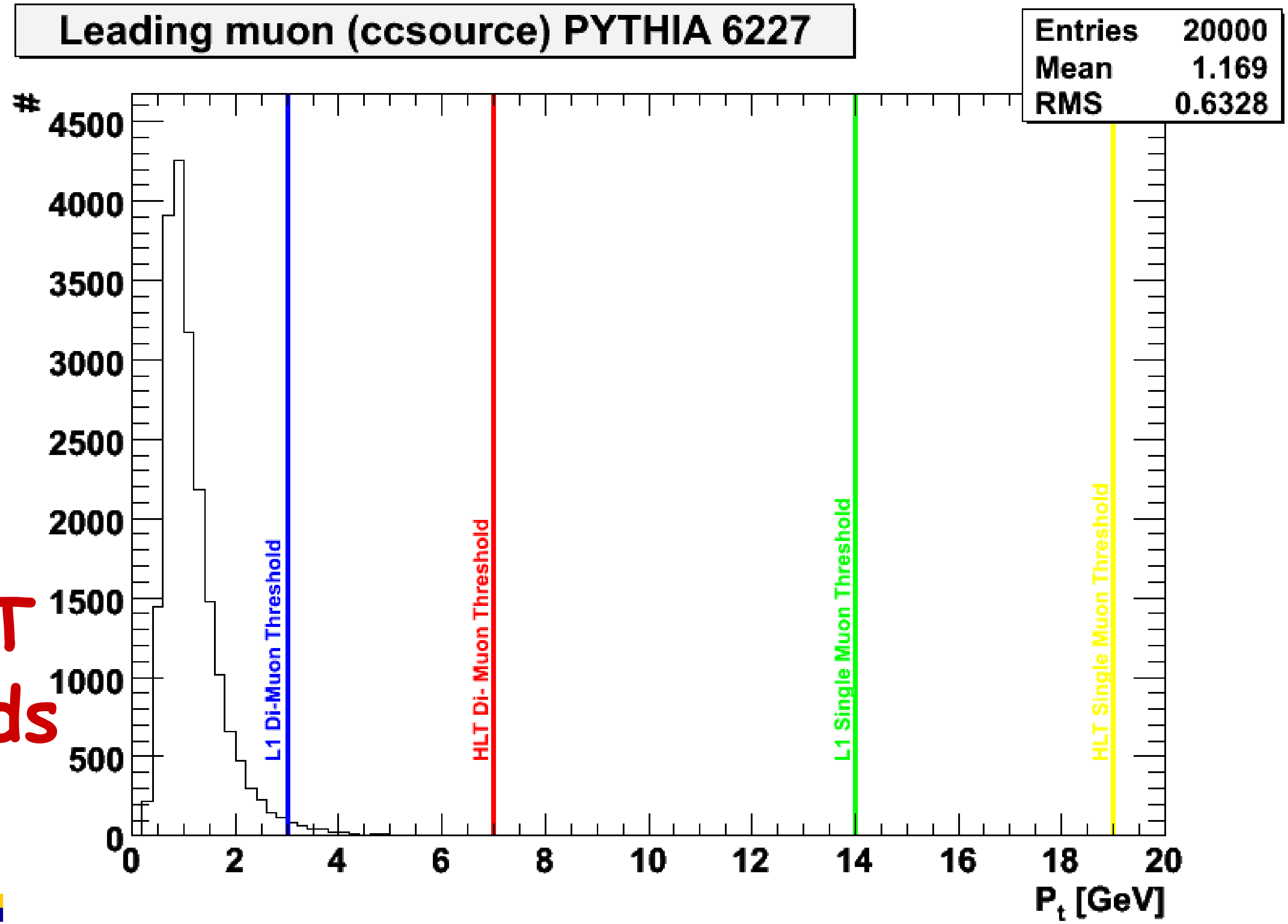
(Aachen: M. Giffels, L. Perchalla, T. Kress, A. Stahl)

- Using GEANT4 and current CMS reconstruction code – more detailed detector & trigger simulation
  - ☞ work in progress
  - Initially looked like D_s was not such a hopeless source of taus
  - gave hope of limits ~10^{-10}
    - ☞ BUT spectrum in Pythia 6.324 was too hard… a bug ☹ …
  - Run Pythia 6.2 and recover similar conclusions of initial study:
    - ☞ must depend on W and Z production

New CMS Study of $\tau \rightarrow \mu\mu\mu$

(Aachen: M. Giffels, L. Perchalla, T. Kress, A. Stahl)

ccbar
e.g.
$D_s \rightarrow \tau\nu X$
$\tau \rightarrow \mu\mu\mu$
L1 & HLT thresholds



UVic

New CMS Study of $\tau\rightarrow\mu\mu\mu$

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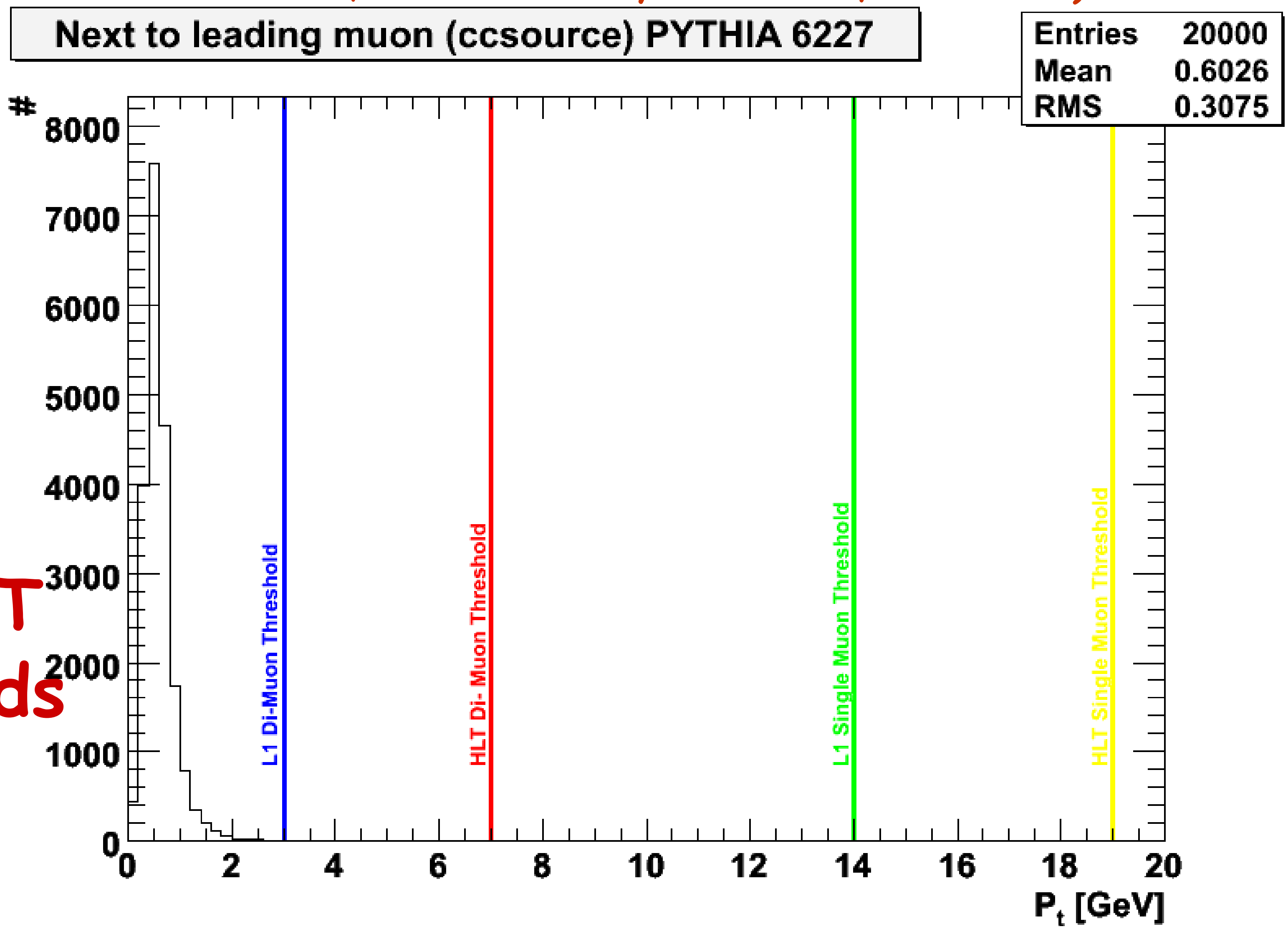
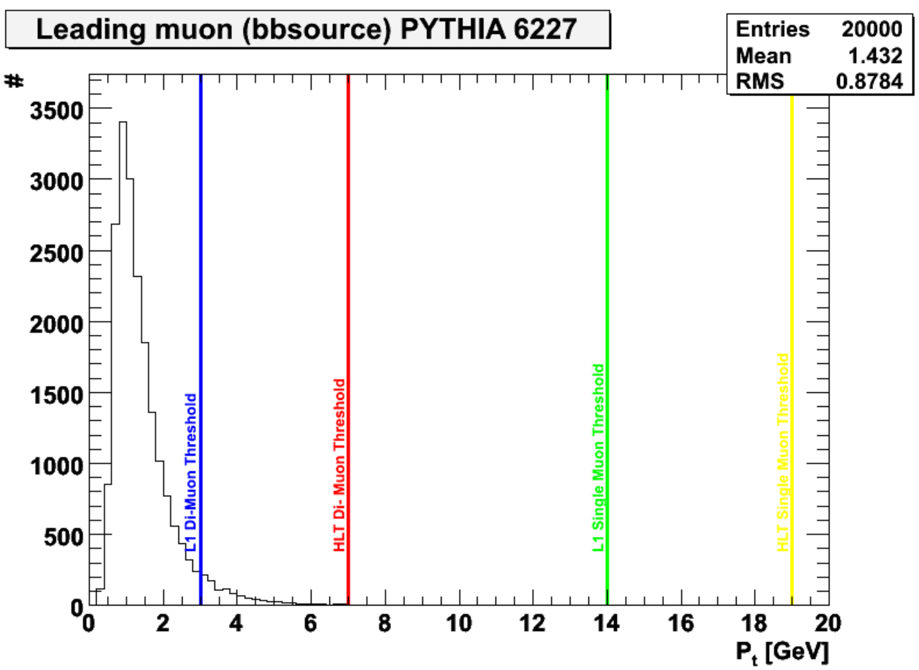


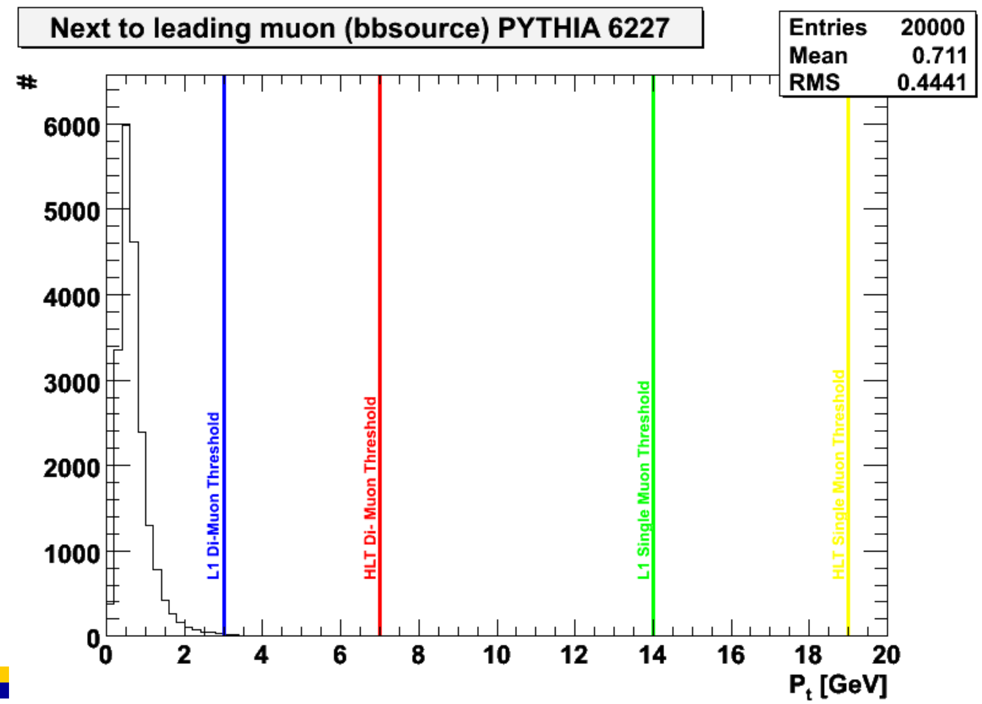
ccbar
e.g.
$D_s\rightarrow\tau\nu X$
$\tau\rightarrow\mu\mu\mu$
L1 & HLT thresholds

New CMS Study of $\tau\to\mu\mu\mu$

(Aachen: M. Giffels, L. Perchalla, T. Kress, A. Stahl)

$B_x\to\tau\nu X$; $\tau\to\mu\mu\mu$
L1 & HLT thresholds
for single muon and two muons

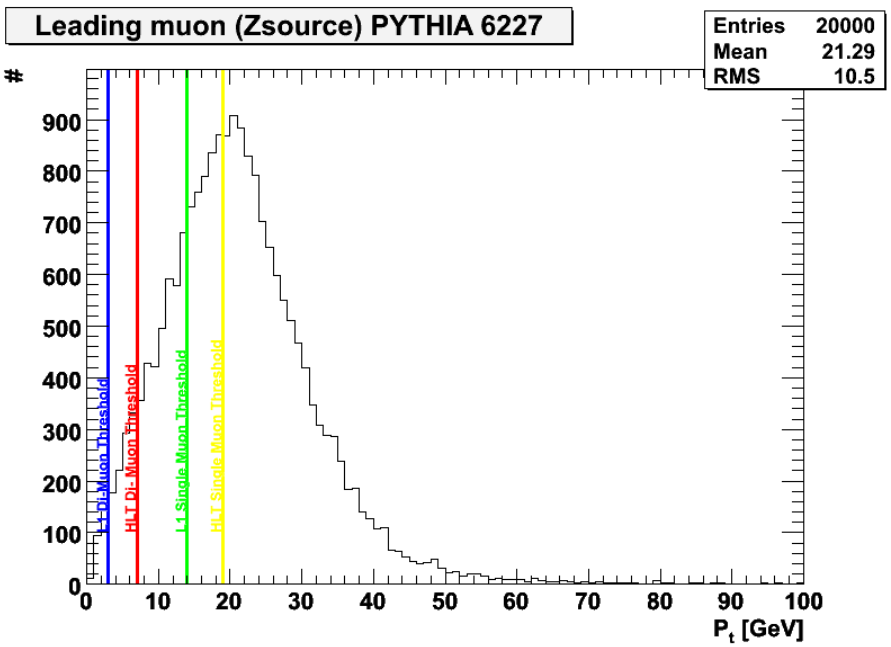


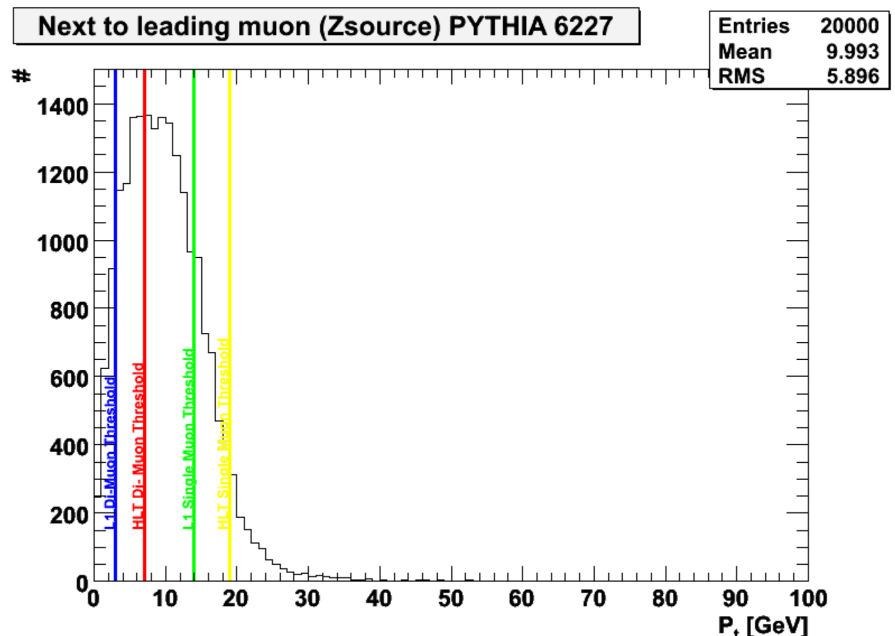


New CMS Study of $\tau \rightarrow \mu\mu\mu$

(Aachen: M. Giffels, L. Perchalla, T. Kress, A. Stahl)

$Z \rightarrow \tau\tau$; $\tau \rightarrow \mu\mu\mu$
L1 & HLT thresholds
for single muon and two muons

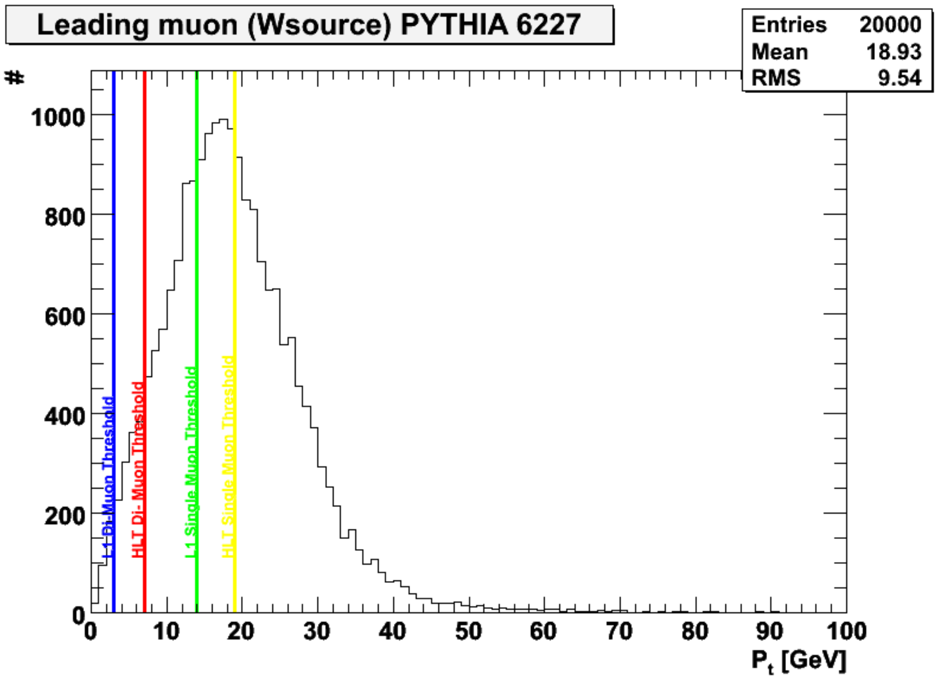


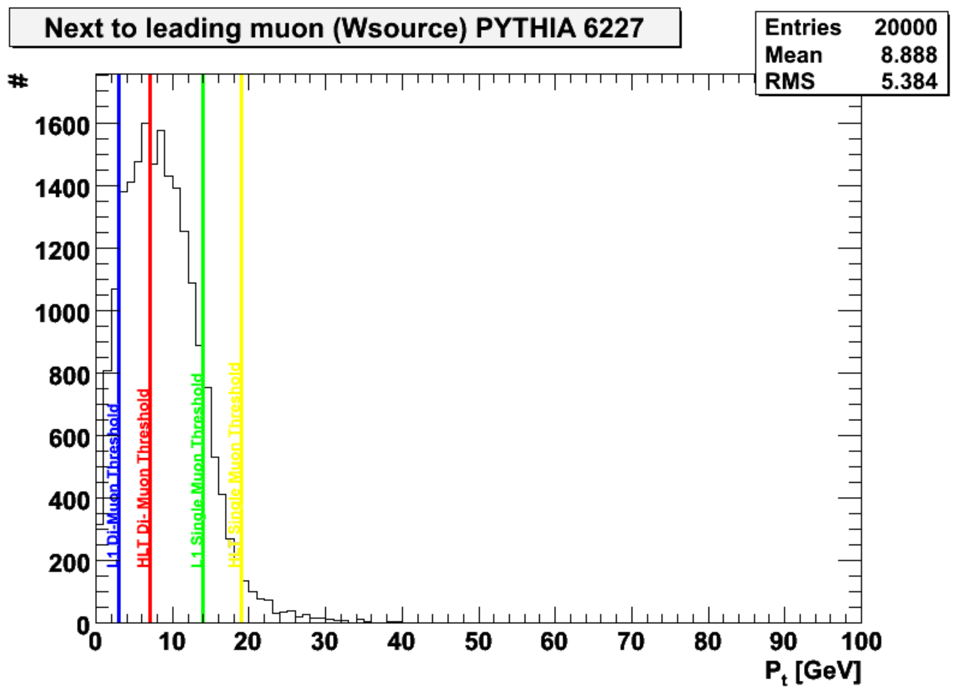


New CMS Study of $\tau \to \mu\mu\mu$

(Aachen: M. Giffels, L. Perchalla, T. Kress, A. Stahl)

$W \to \tau\nu$; $\tau \to \mu\mu\mu$
L1 & HLT thresholds
for single muon and two muons





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Comments on Lepton universality:

- Charged current universality: tau decays

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

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

where

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

- BR($\tau \to e\nu\nu$)= (17.824±0.052)% [0.29%]
- BR($\tau \to \mu\nu\nu$)= (17.331±0.048)% [0.28%]

RATIO OF BRANCHING RATIOS:

- g_μ/g_e=0.9999 ±0.0020 from tau decays
- pion decays: 1.0021±0.0016

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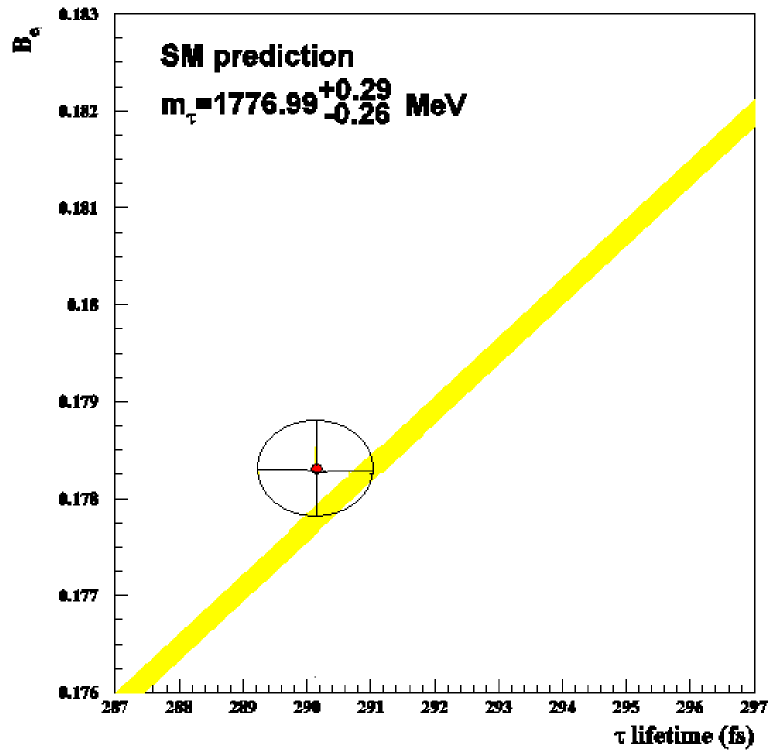
Comments on Lepton universality:

- Charged current
  tau-mu universality



- BR($\tau\to e\nu\nu$)= (17.824±0.052)% [0.29%]
- BR($\tau\to \mu\nu\nu$)= (17.331±0.048)% [0.28%]
  - ☞ e-μ univ:BR($\tau\to e\nu\nu$)= (17.821±0.036)% [0.20%]
- τ_τ= **290.15 ± 0.77 fs [0.27%]**

g_μ/g_τ=0.9982 ±0.0021

B-factories consider measuring leptonic branching ratios at 0.1% level

- Issues of systematic errors:
  - LEP measurements rely on data control samples for establishing the detector response for electrons and muons: same can be done at B-factories
  - Non-tau backgrounds can be controlled at B-factories: trade-off statistics for reduced systematics
  - Cross contamination from other tau decays: use of control samples & may require improved simultaneous measurements of some non-leptonic modes
  - Normalization has been a dominant error at $\Upsilon(4s)$: (no. of produced taus entering the BR denominator)
    - ☞ Normalize to $N_{\mu\mu}$ but requires $\sigma(\tau\tau)/\sigma(\mu\mu)$ at <0.1% level and counting $N_{\mu\mu}$ at 0.1% level

Consider ratio of leptonic branching ratios

- Access Lepton universality… statistical sensitivity… using BELLE figures for yields of e-rho mu-rho decays - ~250k in ~30/fb
- Ratio of BR for 75/ab would have statistics to play-off systematic uncertainties.
- Could reach well below (perhaps x10) better than current 0.2%
- STUDIES WITH CURRENT DATA NEEDED
- Very difficult work understanding lepton ID

Summary

- BaBar and Belle have looked in many channels for evidence of LFV in τ decay: limits have pushed into 10^{-8} zone and parameter space in beyond the SM theories are being eaten
- There is still much data to come – at e.g. BaBar expects $940 fb^{-1}$ and has analysed only a $230\text{-}340 fb^{-1}$ of that… BELLE will collect at least $1000 fb^{-1}$
- SuperB factories will probe $10^{-10} - 10^{-9}$
- LHC experiments ~restricted to $\tau \rightarrow \mu\mu\mu$ and should reach 10^{-8} levels – similar to existing B-factories
- Lepton universality: systematics questions – current B-factories working on this

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additional slides

Summary of $\tau \to \ell\gamma$, $\ell\ell\ell$

τ^- mode	Belle		BaBar	
	Br, 10^{-7}	Lum. fb^{-1}	Br, 10^{-7}	Lum. fb^{-1}
$\mu^-\gamma$	<0.45	535	<0.68	232
$e^-\gamma$	<1.2	535	<1.1	232
$\mu^- e^+ \mu^-$	<2.0	87.1	<1.3	91.5
$\mu^- e^- e^+$	<1.9	87.1	<2.7	91.5
$\mu^-\mu^-\mu^+$	<2.0	87.1	<1.9	91.5
$e^-\mu^-\mu^+$	<3.3	87.1	<2.0	91.5
$\mu^+e^-e^-$	<2.0	87.1	<1.1	91.5
$e^+e^-e^+$	<3.5	87.1	<2.0	91.5

Summary of $\tau \to \ell hh'$ 90%CL Upper Limits

τ^- mode	Belle Phys.Lett.B640:138 144,2006		BaBar PRL95(2005)191801	
	Br, 10^{-7}	Lum. fb^{-1}	Br, 10^{-7}	Lum. fb^{-1}
$e^-\pi^+\pi^-$	<7.3	158	<1.2	221
$e^+\pi^-\pi^-$	<2.0	158	<2.7	221
$e^-\pi^+K^-$	<7.2	158	<3.2	221
$e^-\pi^-K^+$	<1.6	158	<1.7	221
$e^+\pi^-K^-$	<1.9	158	<1.8	221
$e^-K^+K^-$	<3.0	158	<1.4	221
$e^+K^-K^-$	<3.1	158	<1.5	221

Summary of $\tau \to \ell$Vector 90%CL Upper Limits

Phys.Lett.B640:138 144,2006

τ^- mode	Belle		τ^- mode	Belle	
	Br, 10^{-7}	Lum. fb^{-1}		Br, 10^{-7}	Lum. fb^{-1}
$e^-\rho^0$	<6.4	158	$\mu^-\rho^0$	<2.0	158
$e^-K^*(892)^0$	<3.0	158	$\mu^-K^*(892)^0$	<3.9	158
$e^-\overline{K^*}(892)^0$	<4.0	158	$\mu^-\overline{K^*}(892)^0$	<4.0	158
$e^-\phi$	<7.4	158	$\mu^-\phi$	<7.7	158

CP-violation via Dipole Moments

- Baryon asymmetry requires non-SM sources of CPV thus motivating searches for evidence of CPV outside the SM
- Electric Dipole Moment, d, is T,P-odd

  (so under CPT CP-odd): d≠0 → CPV

  d $\vec{E}\bullet\vec{S}$ interaction for spin-½ particle relativistically:

$$H_{T,P-odd} = -d \cdot \vec{E}\bullet\vec{S} / S \quad \rightarrow \quad L = -d \frac{i}{2} \overline{\psi} \sigma^{\mu\nu} \gamma_5 \psi F_{\mu\nu}$$

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CP-violation via Dipole Moments

- EDM can be generalized to Z-fermion and gluon-fermion interactions giving rise to weak dipole (WDM) and chromoelectric dipole moments of fermions
- Neutron EDM: $|d_n|<6\text{x}10^{-26}$ e cm (90%CL) [Harris et al, PRL 82, 904 (1999)]
- Electron EDM via Tl (paramagnetic): $|d_e|<1.6\text{x}10^{-27}$ e cm (90%CL)

  [Regan et al, PRL 88, 071805 (2002)]

  (cf SM: $|d_n^{KM}|\sim 10^{-34}$ e cm & $|d_e^{KM}|<10^{-38}$ e cm)
- In general, dipole moment has s dependence and is complex. (For electron and neutron EDM results, s=0 and EDM is real)

CP-violation via τ Dipole Moments

In light of $d_e < 1.6\text{x}10^{-27}$ e-cm limit is $\sigma(\text{Re}(d_\tau)) = O(10^{-20})$e-cm (100/ab reach) interesting?

If $d_\ell \sim e\frac{m_\ell}{\Lambda^2}$ then $d_\tau^{MIN} \sim 3554 d_e \rightarrow d_e(\text{equiv}) = 3\text{x}10^{-24}$e-cm

missing by ~x2000, less if Λ is different, but > factor 10 'unnatural'.

In multi-Higgs models $d_\ell \sim e\frac{m_\ell^3}{\Lambda^4}$

in this case, $d_\tau^{MIN} \sim 4\text{x}10^{10} d_e \rightarrow d_e(\text{equiv}) = 3\text{x}10^{-31}$e-cm

sensitive to values of Λ of >~60GeV.

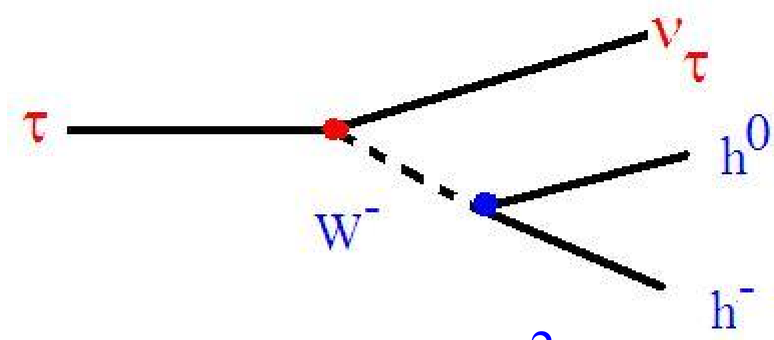
Leptoquark models (Bernreuther et at, PLB 391, 413 (1997) give:

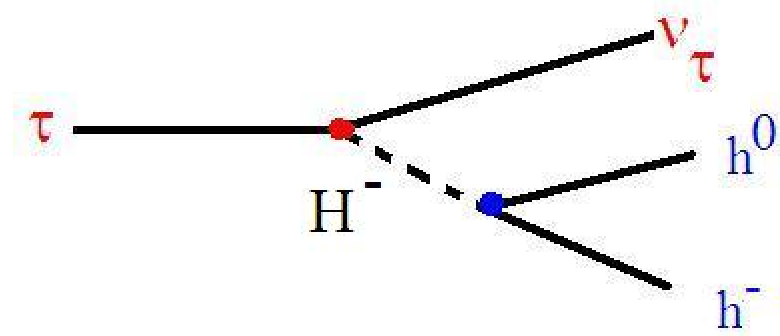
$d_e : d_\mu : d_\tau = m_u^2 m_e : m_c^2 m_\mu : m_t^2 m_\tau = 1 \; : \; 14\text{x}10^6 \; : 4\text{x}10^{12}$

Now generally felt that looking for EDM via CPV tau production un likely to bear fruit of new physics (see also e.g. Tsai PhysLettB 378(1996)

CP-violation in τ Decay

Y.S. Tsai, PRD55, 3172 (1995)





$$F_V = \frac{m_\rho^2}{m_\rho^2 - s - i m_\rho \Gamma_\rho(s)}$$

$$F_S = |\Lambda| e^{i\Theta_{CP}} |f_S| e^{i\delta_S},$$

$$f_S = 1 \text{ or BW(scalar } h^0 h^-)$$

Interference between F_v and F_s because of CPV manifested in τ+ -- τ- decay angle distributions

CP-violation in τ Decay

Unpolarised taus

- Measure BR's of tau decays with >=2 hadrons

e.g. $BR(\tau^- \to \pi^- \pi^0 \nu_\tau) \neq BR(\tau^+ \to \pi^+ \pi^0 \overline{\nu}_\tau)$

(need to understand inelastic final state interactions to interpret an observed CPV)

- Measure CP or T-violating correlations in $\tau^+ \tau^-$ events

CP-violation in τ Decay

Polarised taus

- Use T-odd rotationally invariant products e.g.

$P_Z^\tau \bullet (\vec{p}_{K+} \times \vec{p}_{\pi 0})$ $\quad P_Z^\tau$ component of τ polarization along beam axis averaged over production angle

in τ+ and τ− decays to >=2 hadrons such as :

$$\tau^- \to \pi^- \pi^0 \nu_\tau, \tau^- \to K^- \pi^0 \nu_\tau,$$

$$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau, \tau^- \to K^- \pi^+ \pi^- \nu_\tau$$

various observables

e.g. $f_{\pi 0}(p_{\pi 0}^Z) = \overline{f}_{\pi 0}(-p_{\pi 0}^Z)$

longitudinal π^0 momentum distributions from

$\tau^- \to K^- \pi^0 \nu_\tau$ and $\tau^+ \to K^+ \pi^0 \nu_\tau$

CP-violation in τ Decay

Get polarised taus from beam polarisation:
only one beam needs to be polarised for this

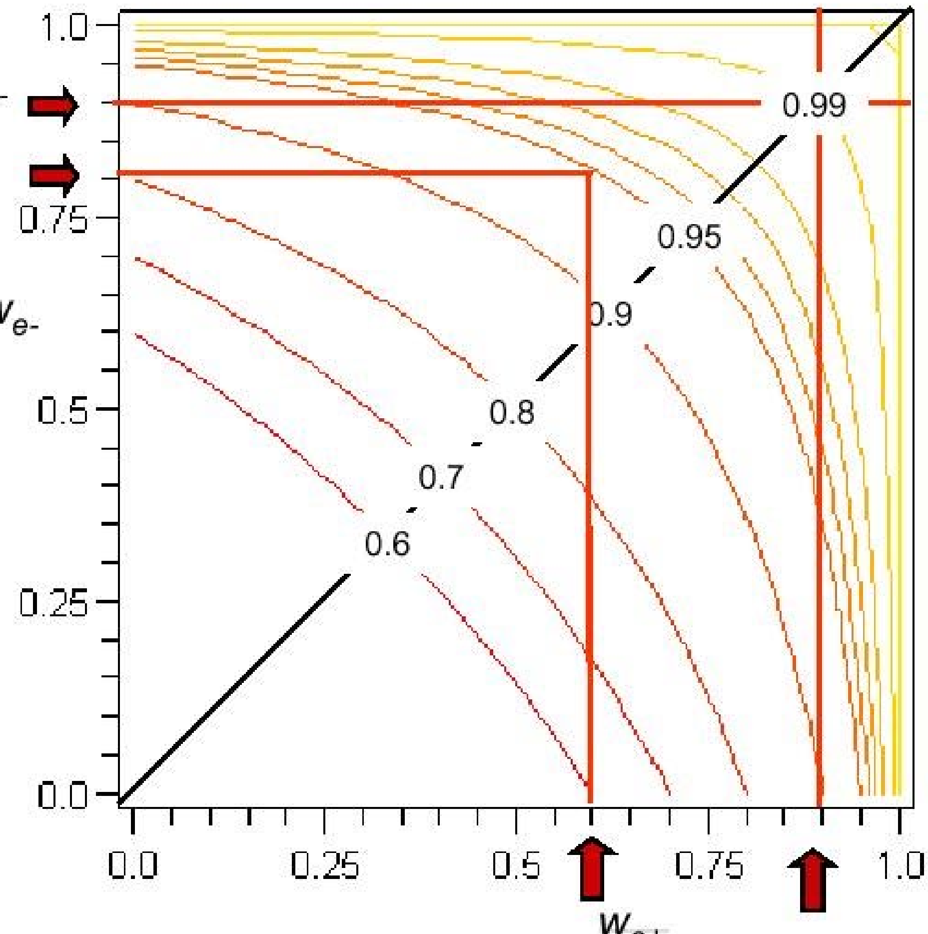
- Longitudinal polarization

$$w_{e^-} = \frac{N_{e^-\rightarrow} - N_{e^-\leftarrow}}{N_{e^-}} \qquad w_{e^+} = \frac{N_{e^+\rightarrow} - N_{e^-\leftarrow}}{N_{e^+}}$$

$$P_z^\tau = (w_{e-} + w_{e+})/(1 + w_{e-}w_{e+})\frac{1+2a}{2+a^2}$$

$a = m_\tau/\sqrt{s}$ (integrated over production angle, same for τ+ and τ- when no CPV in production)

- For $w_{e^-} = 0.8, w_{e^+} = 0$: $P = 0.8$
  while for
  $w_{e^-} = 0.8, w_{e^+} = 0.6$: $P = 0.945$
- For $w_{e^-} = 0.9, w_{e^+} = 0$: $P = 0.9$
  while for
  $w_{e^-} = 0.9, w_{e^+} = 0.9$: $P = 0.994$



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CP-violation in τ Decay

Question: it is better to run at threshold with lower lumi, or at Upsilon(4s) with higher lumi?Tsai gives 'Figure of Merit':

$$FOM = \text{luminosity} \times P_Z^\tau \times \text{ Total Cross section}$$

$$\propto \text{luminosity} \times (w_{e+} + w_{e-}) \times \sqrt{1-a^2}\, a^2 (1+2a)$$

e.g. BEPCII@10^{33} SuperB@10^{36} SuperB(4GeV)@10^{35}

Machine	FOM/FOM BEPCII
BESIII@ $\sqrt{s}$ =4 GeV	1
SBF @ $\Upsilon(4S)$	178
SBF @ $\sqrt{s}$ =4 GeV	100

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Precision measurements of tau properties: CPT and CP

- Tau lifetime
- Tau mass
- Dipole moments

CPT

- **Lifetime:**

  1st CPT on lifetime from BABAR (Lusiani, TAU04)

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

preliminary,
no dedicated
systematic studies yet

THIS TEST WOULD BENEFIT FROM HIGH STATISTICS AS MANY SYSTEMATICS WOULD CANCEL

(care needed in selection to avoid known differences in hadronic interaction cross sections for $\pi+$ & $\pi-$)

Statistical error only goes to 10^{-3} with 1/ab
and 10^{-4} with 100/ab

~ 2nd generation CPT lifetime test:
muon CPT lifetime $(2\pm8)\mathrm{x}10^{-5}$

CPT

- **Lifetime:**

Preliminary tau lifetime work reported by BABAR (Lusiani, TAU04-Nara) gives guide to systematics:

Data sample of: 80/fb

Systematic Errors:

MC statistics selection bias	: 0.22%
Background	: 0.14 – uds 0.11
Alignment&length scale	: 0.11
ISR/FSR simulation	: 0.10
Beam spot position	: 0.04
Beam spot size	: 0.04
Beam energy & boost direction	: 0.04
Tau Mass	: 0.01

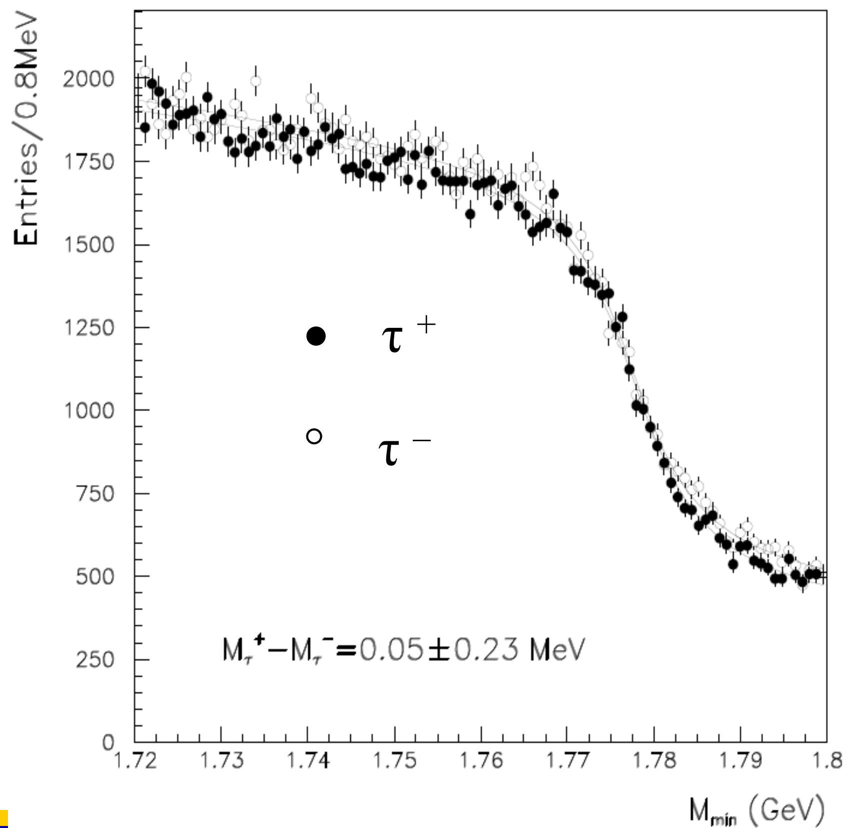
CPT

- **Mass:**

BELLE update TAU06 (see Mikhail Shapkin's talk on Tuesday) using 414/fb

$$m_{\tau-} - m_{\tau+} = (0.05 \pm 0.23 \pm 0.14)\,\mathrm{MeV}$$

$$\left|\frac{m_{\tau-} - m_{\tau+}}{m_\tau}\right| < 2.8\times10^{-4} \ \ @90\%\mathrm{CL}$$



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CPT

- **Mass:**

  BELLE: 0.14MeV systematic error from potential charge asymmetries assessed by comparing response of detector to:

$$D^0 \rightarrow K^- \pi^+ ; \overline{D^0} \rightarrow K^+ \pi -$$

$$\Lambda_c \rightarrow p K^- \pi^+ ; \overline{\Lambda_c} \rightarrow \overline{p} K^+ \pi^+$$

$$D^+ \rightarrow \phi \pi^+ ; D^- \rightarrow \phi \pi^-$$

$$D_S^+ \rightarrow \phi \pi^+ ; D_S^- \rightarrow \phi \pi^-$$

Care needed in interpreting results as CPT assumed in for these modes…

CPT

- **Mass:**

  SUPER-B: 100/ab would yield a statistical error of 0.023MeV on the mass difference ~ 6 x smaller than 0.15MeV systematic error BELLE now quotes.

  (Reach 0.15MeV at 2.3/ab)

To fully exploit 100/ab, would need charge asymmetric momentum scales controlled at 10^{-5} level. VERY CHALLENGING DETECTOR SYSTEMATICS PROBLEM

Would get CPT test to 2×10^{-5} level of sensitivity and would be most sensitive CPT mass difference test after K^0(10^{-18}), proton and electron (10^{-8}).