CLFV Decays at *BABAR*

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1st Conference on Charged Lepton Flavour Violation

Lecce

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Outline

- Most of what we know about the τ (87 pages in PDG 2012) comes from τ pair samples produced in e^+e^- annihilation
- τ decays provide an excellent laboratory for CLFV studies, in particular searches for gen 3→ gen 2 and gen 3→gen 1 CLFV
  - Even at current sensitivity, observed branching fraction patterns (or limits) serve to discriminate between New Physics models

- I will discuss CLFV limits from *BABAR* in
  - τ decays $\quad \sigma_{\tau\bar{\tau}}(10.58\,\text{GeV}) = 0.92\,\text{nb} \quad 488\times 10^6\ \tau\bar{\tau}$ pairs
    - $\tau \to \ell\gamma$
    - $\tau \to \ell\ell\ell$
    - $\tau \to \ell\pi^0,\ \ell\eta, \ell\eta', \ell\omega, \ell K_S^0, \ell\rho^0, \ell K^{*0}, \ell\bar{K}^{*0}, \ell\phi$
    - $\tau \to \ell h h'$
    - $\tau^- \to \Lambda\pi^-, K^- \quad \bar{\Lambda}\pi^-, K^-$
  - $\Upsilon(3S) \to e^{\pm}\tau^{\mp},\ \mu^{\pm}\tau^{\mp}$

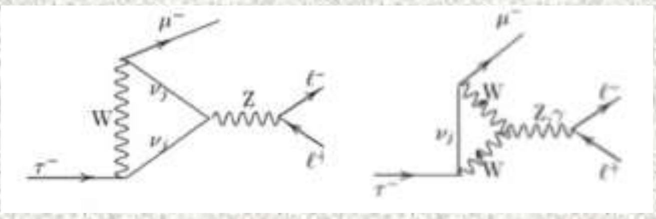
Lepton Flavor Violation in example BSM models

- Neutrino-less τ decays: optimal hunting ground for non-Standard Model LFV effects
- Topologies are similar to those of τ hadronic decays
- Current limits (down to ~ 10^{-8}), or limits anticipated at next generation e^+e^- colliders, directly confront many New Physics models

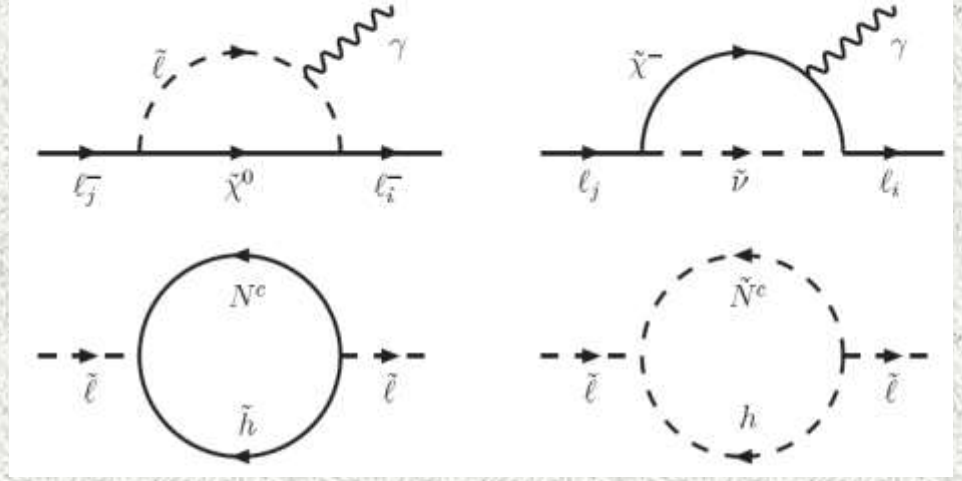
		$\tau \to \mu\gamma$	$\tau \to \ell\ell\ell$
SM + ν mixing	Lee, Shrock, PRD 16 (1977) 1444 Cheng, Li, PRD 45 (1980) 1908	Undetectable	
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549 (2002) 159 Brignole, Rossi, PLB 566 (2003) 517	10^{-10}	10^{-7}
SM + heavy Maj ν_R	Cvetic, Dib, Kim, Kim , PRD66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	Yue, Zhang, Liu, PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649 (2003) 189 Fukuyama, Kikuchi, Okada, PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA + Seesaw	Ellis, Gomez, Leontaris, Lola, Nanopoulos, EPJ C14 (2002) 319 Ellis, Hisano, Raidal, Shimizu, PRD 66 (2002) 115013	10^{-7}	10^{-9}

Search for charged lepton flavor violation - motivation

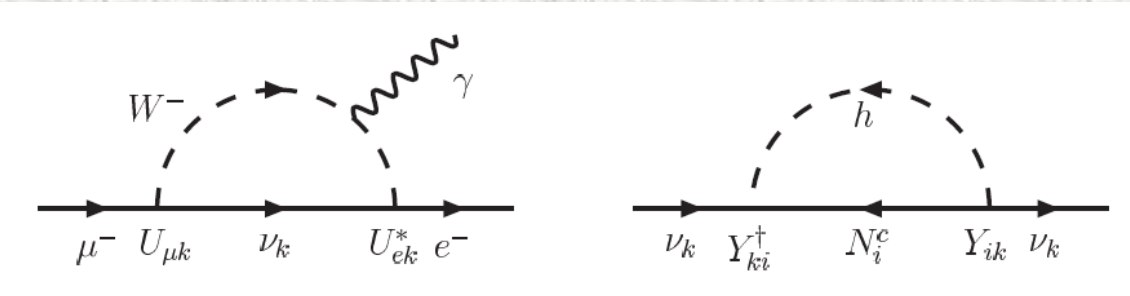
- Neutrino oscillations are *prima facie* evidence for neutral lepton flavor violation
- The obvious next question is whether there is charged lepton flavor violation ?
  - CLFV is too small to measure in the Standard Model,



but can reach observable levels in several channels in Standard Model extensions



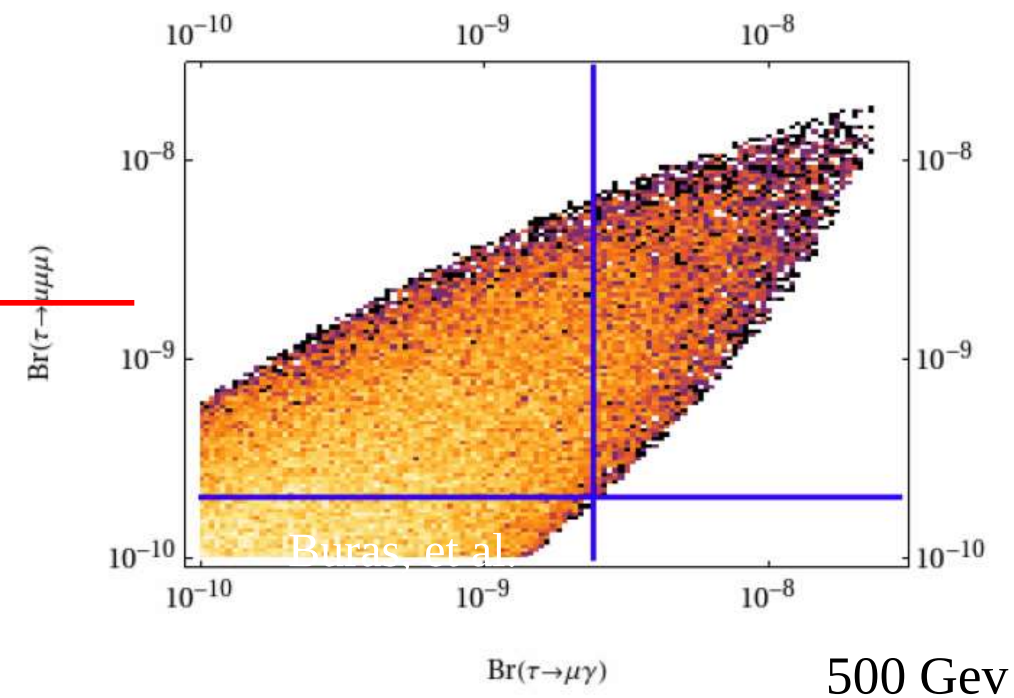
- μ to *e* conversion
- $\mu \to e\gamma$, $\tau \to \mu\gamma, e\gamma$
- $\mu \to eee$, $\tau \to 3\ell$
- $\tau \to h\ell$



- The sensitivity of particular modes to CLFV couplings is model-dependent
- Comparison of branching fractions/conversion rate is model-diagnostic

LFV branching fraction ratios are model discriminators

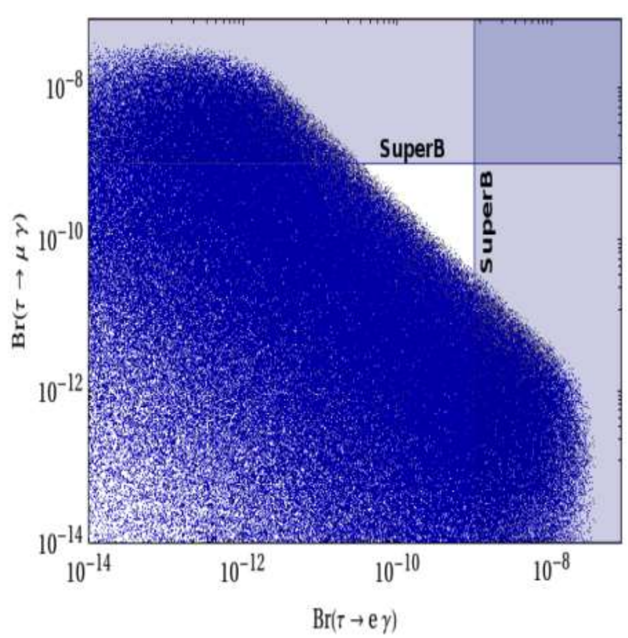
ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2.0$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$



There are correlations in the $\tau \to \mu\gamma$ and $\ell\ell\ell$ branching fractions

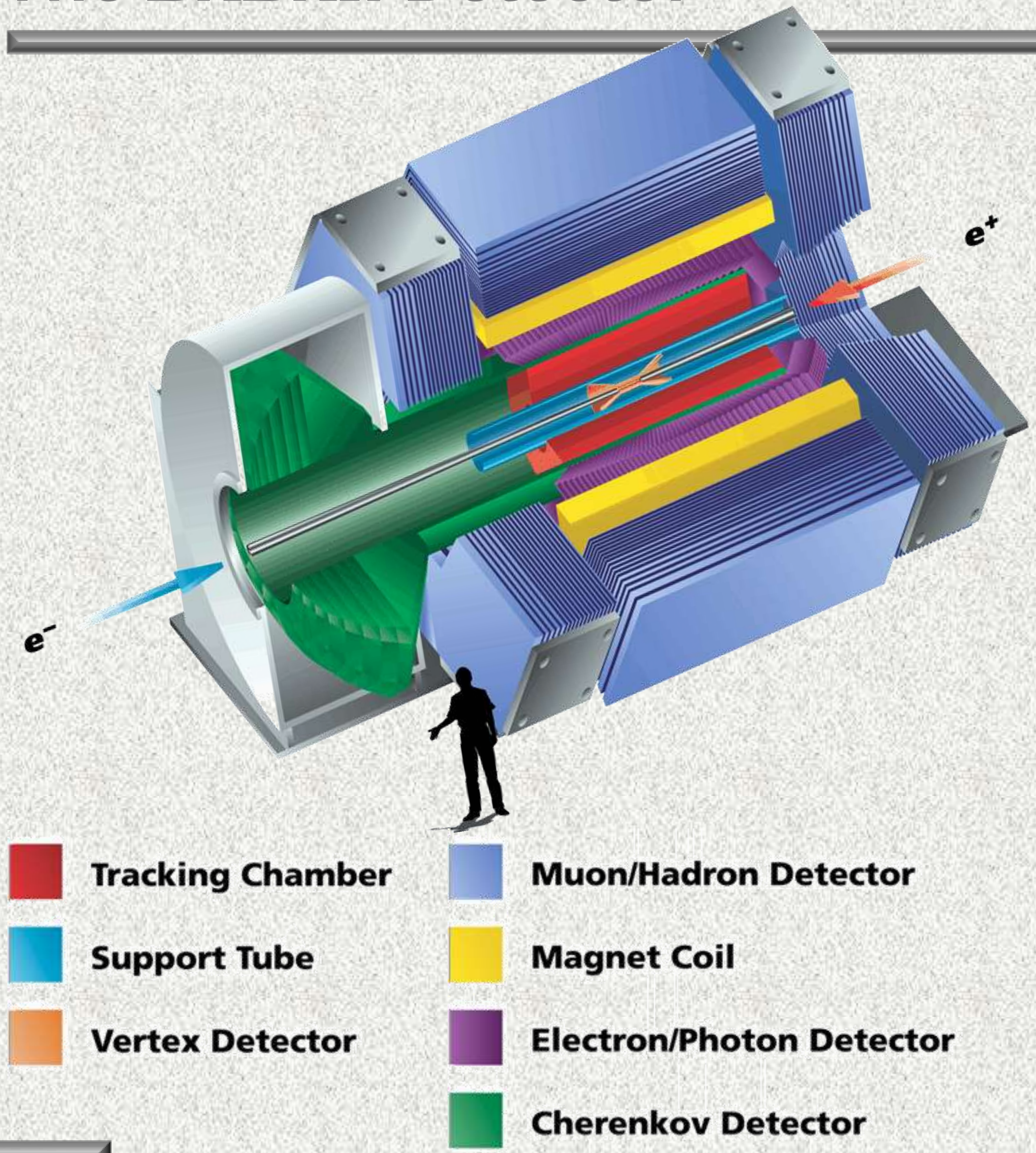
Blanke, Buras, Duling, Recksiegel & Tarantino, Acta Phys. Polon. B41, 657 (2010)

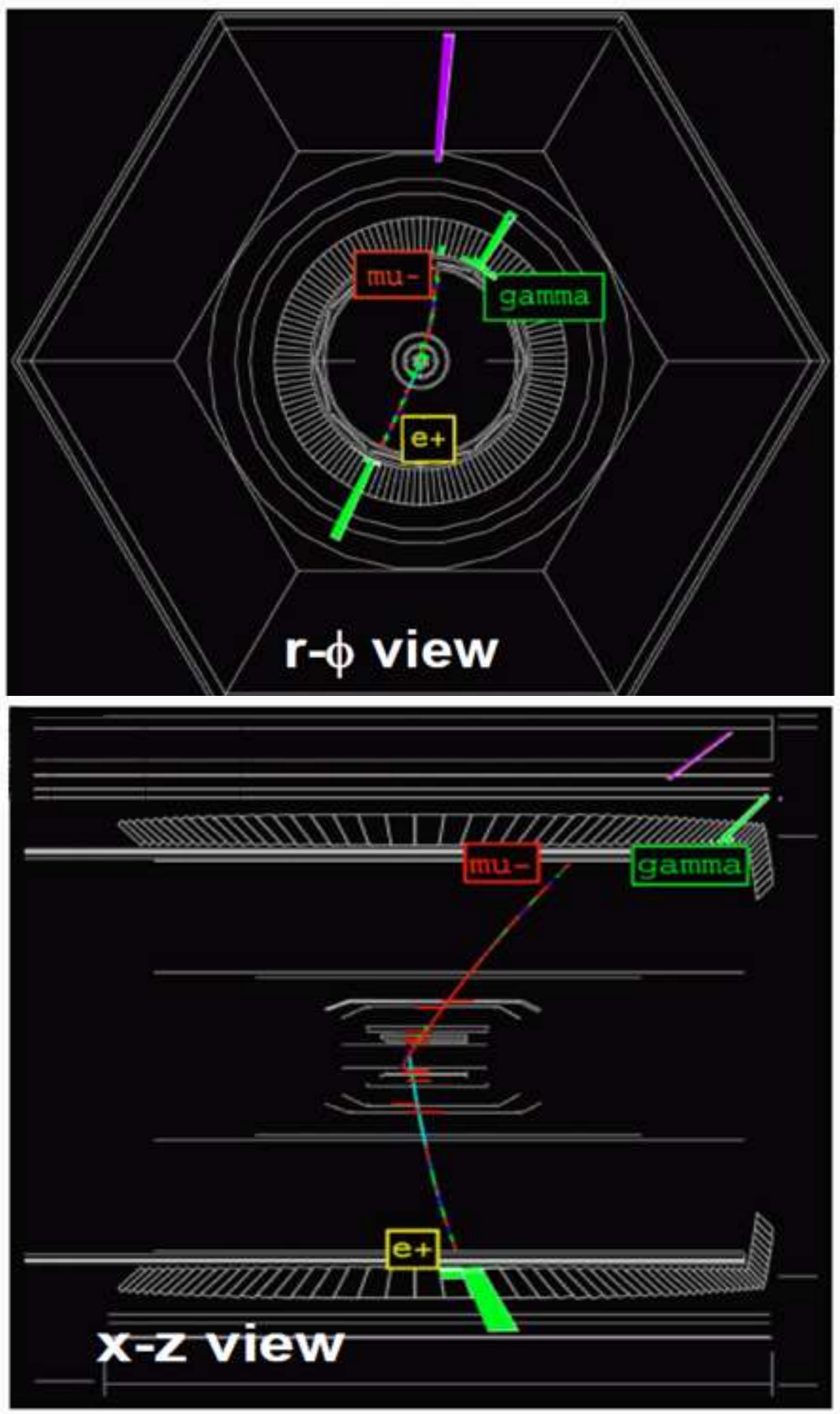
$\mathcal{B}(\tau \to \mu\gamma)$ *vs.* $\mathcal{B}(\tau \to e\gamma)$ in a general fourth generation scenario (Buras)



$\mathcal{B}(\tau \to \mu\gamma)$ *vs.* $\mathcal{B}(\tau \to e\gamma)$ are anti-correlated. Seeing both modes would be evidence against a fourth generation

The *BABAR* Detector

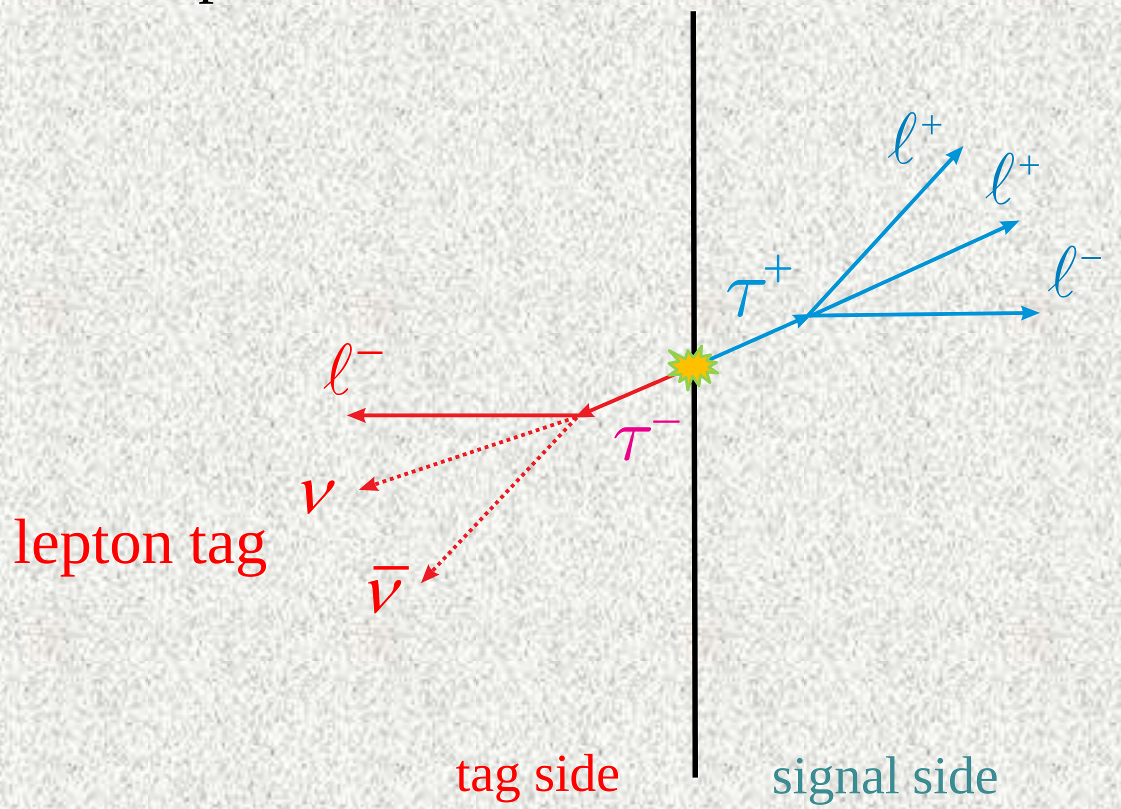


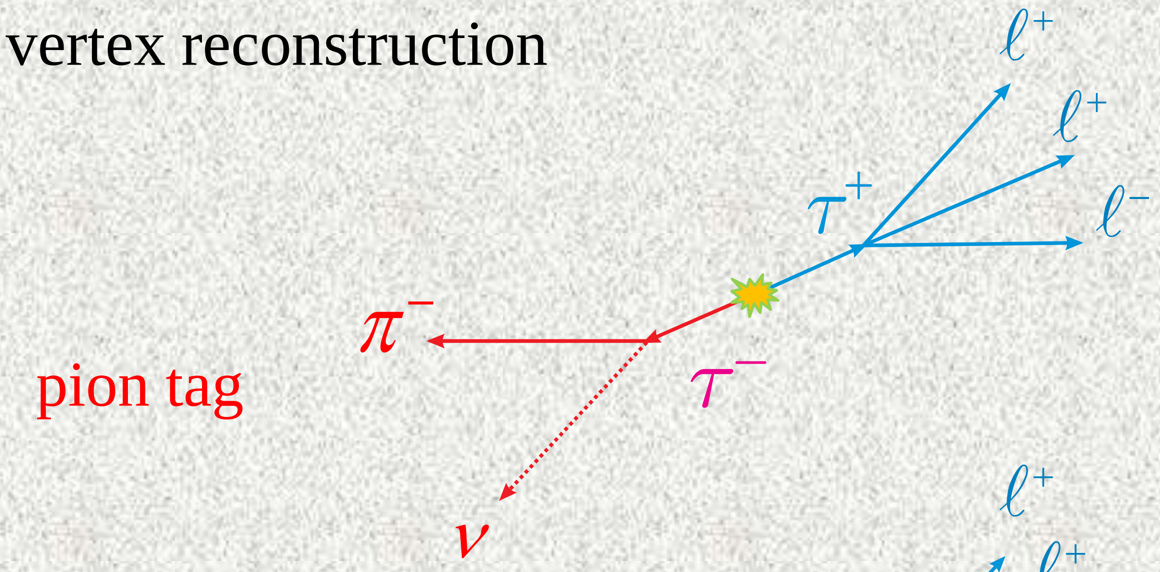


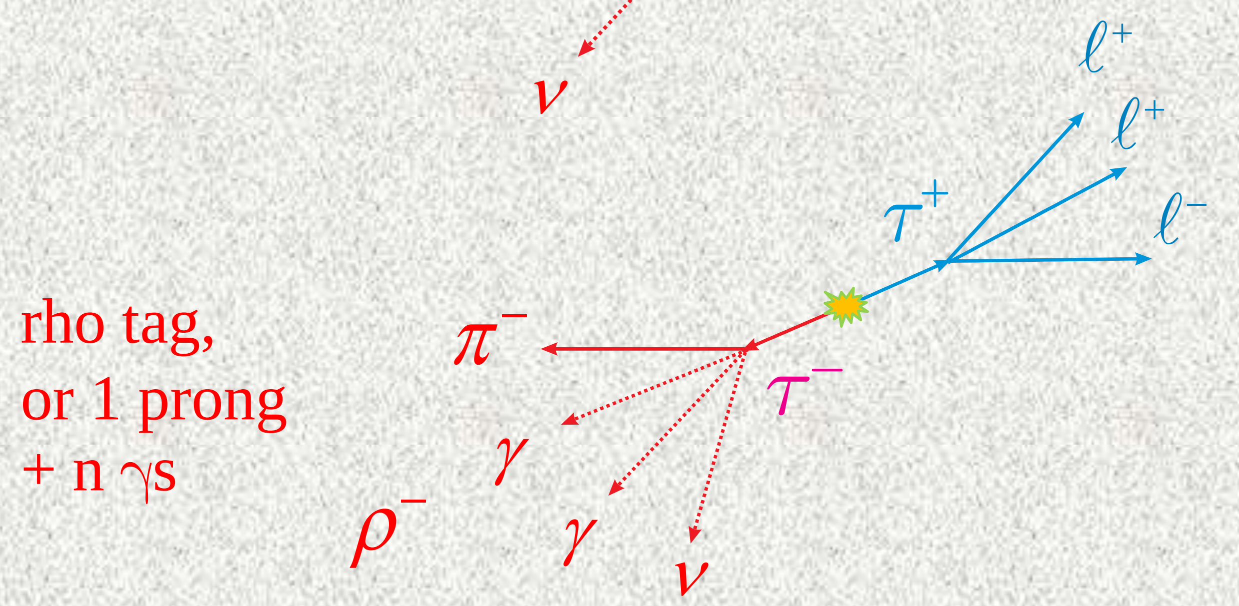
Simulation
$\tau^- \to \mu^- \gamma$ with $\tau^- \to e^+ \nu \bar{\nu}$ tag

Searching for τ LFV

- Analysis performed in the CM system
  - Signal: back-to-back high momentum pairs $E = \sqrt{s/2}$
- Divide events into two hemispheres (tag side and signal side), defined by the thrust axis, and require high thrust
- Good solid angle coverage is needed, since there is missing momentum from one or two neutrinos on the **tag** side
- No neutrinos, thus no missing energy, on the signal side
- Achievable spatial resolution does not allow for vertex reconstruction
- Example: $\tau \longrightarrow \ell\ell\ell$ search







Event selection requirements

- Particle identification (PID) requirement
- Event variables
  - Thrust (high for τ decay products)
  - Net charge zero, and appropriate topology (multiple topologies can be merged)
  - Missing momentum within the detector acceptance different from zero and pointing to the tag side
  - Mode-dependent # of neutrals in each hemisphere
- Optional:
  - Mass of intermediate meson (if available)
  - Specific tag side decay modes (e, μ, π, ρ tag)
- Searches optimized to yield lowest expected upper 90% CL upper limit
  - Assume that any observed events in the signal box are compatible with extrapolated background expectation

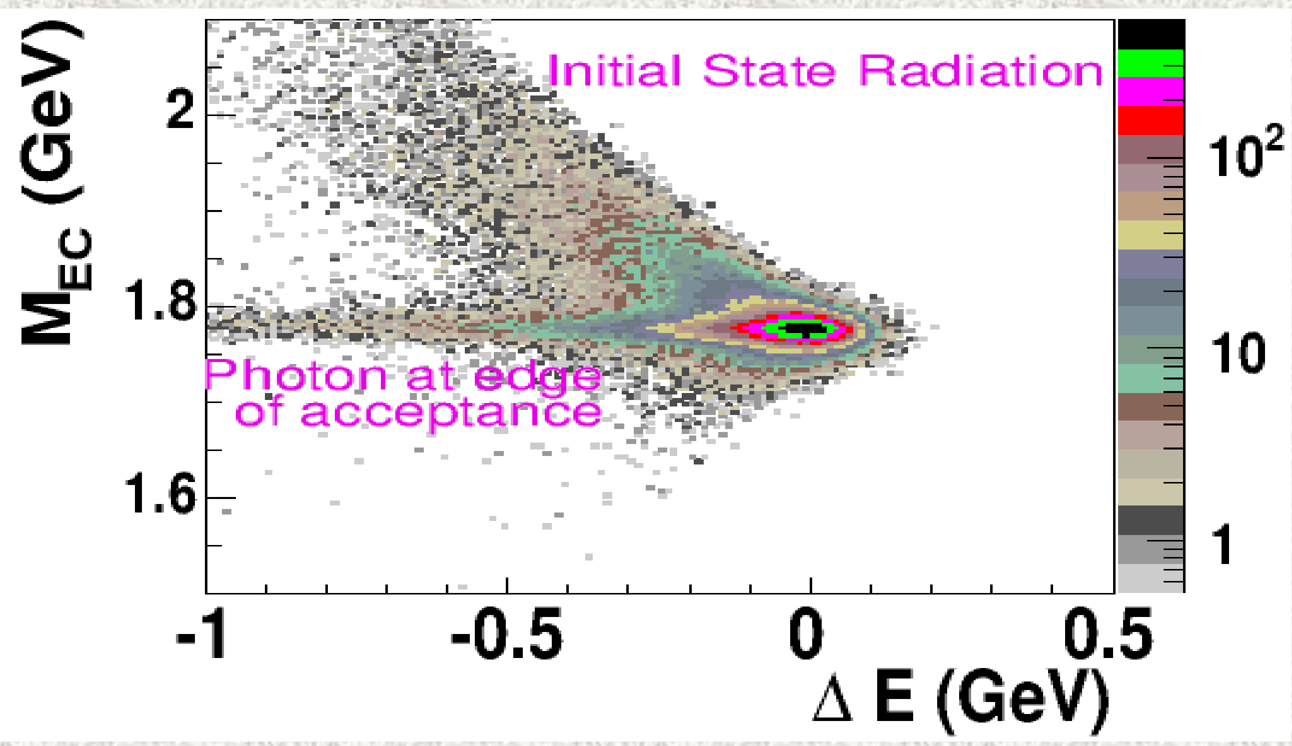
Signal reconstruction

- There are no neutrino(s) on the signal side, so attempt full reconstruction
- Required energy-constrained mass from the kinematic fit to have energy √s/2
- Resolution is broadened by radiative effects

$$\Delta E \equiv E^*_{rec} - E_{beam} \approx 0$$

$$\Delta M_{ec} \equiv M_{ec} - m_\tau \approx 0 \qquad \sigma(\Delta M_{ec}) \simeq 8-20\,\text{MeV}$$

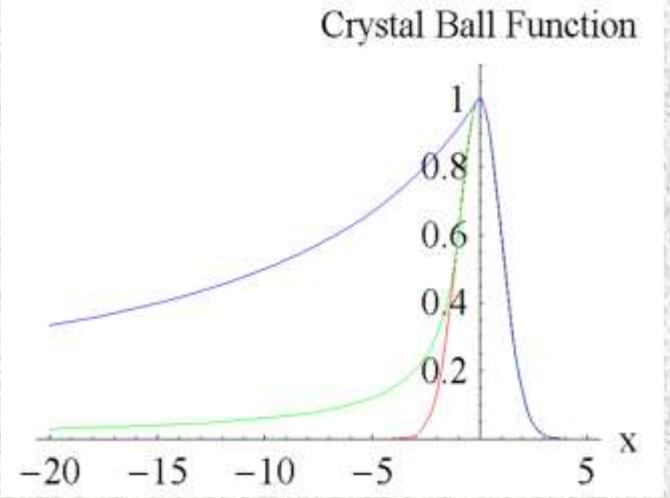
- We define a **blinded signal box**, optimized for each mode, within
- A **grand signal box**, from which background is extrapolated from into the blinded signal box region
- Signal efficiency is calculated using Monte Carlo with flat two/three-body phase space



BABAR Signal MC

Background estimation

- There are two primary sources of background
  - τ (other topologies)
    - veto on π, K_S, γ conversions and unassociated neutral energy
  - Non τ
    - Bhabhas, dimuons, two-photon and $q\bar{q}$ events
    - Discriminate on thrust and missing transverse momentum



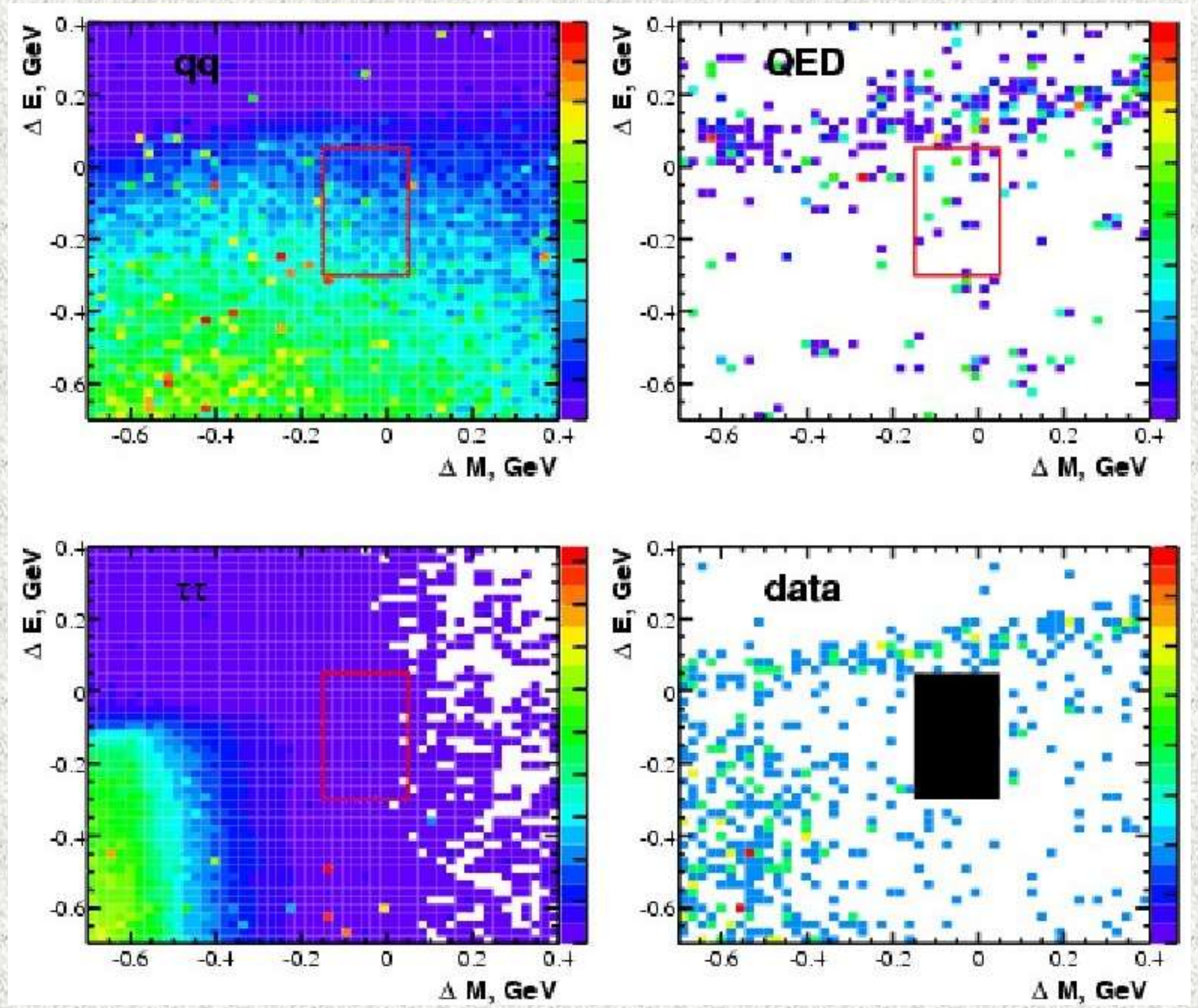
- Use a two-dimensional pdf (ΔM, ΔE) for each background mode
  - Third order polynomial, bifurcated Gaussian and Crystal Ball functions
  - Include correlations between variables
  - Make efficient use of the Monte Carlo for PID selection:
    - Use product of track weights, rather than event rejection
    - Each MC track on the signal side is weighted with the probability of the (mis)identification efficiency in data for the truth-matched particle
    - This is a much more efficient use of MC statistics
- Determines shape of each background component pdf by fit to the MC
- Normalize on Grand Signal Box using an unbinned maximum likelihood fit of the summed pdfs to the data
- Extrapolate background contribution to the signal box

Signal and background characteristics

example: $\tau^- \to \ell^- \ell^+ \ell^-$

$q\bar{q}$ (uds, $c\bar{c}$)
($b\bar{b}$ negligible)

uniform Δm,
$\Delta E < 0$



Bhabha di-muon

uniform Δm
$\Delta E \approx 0$

$\tau^+\tau^-$ backgrounds

$\Delta m < 0$
$\Delta E < 0$

$\tau^- \to \ell^- \ell^+ \ell^-$
signal candidates

Upper limit calculation

- Number of signal candidates, with error, $N_{x\ \mathrm{sel}}$ (efficiency, luminosity, cross-section)

$$N_{\tau\ \mathrm{sel}} = \varepsilon \cdot 2(\mathcal{L} \cdot \sigma_{\tau\tau})$$

- Expected background with error, N_{bkg}
- Number of observed events, N_{obs}

$$\mathcal{B}(\tau \to \ell X) = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{N_{\tau\ \mathrm{sel}}} = \frac{N_{\mathrm{sig}}}{N_{\tau\ \mathrm{sel}}}$$

$$\sum_{n=0}^{N_{\mathrm{obs}}} \mathcal{P}_{\mathrm{Poisson}}(n, \mu^{\mathrm{UL}}) = \alpha = 0.1\ (90\%\mathrm{CL})$$

$$\mathrm{UL}_{90\%\mathrm{CL}}\left[\mathcal{B}(\tau \to \ell X)\right](N_{\mathrm{obs}}) = \frac{\mu^{\mathrm{UL}} - N_{\mathrm{bkg}}}{N_{\tau\ \mathrm{sel}}}$$

- Uncertainties on $N_{x\ \mathrm{sel}}$ and N_{bkg}, Monte Carlo trials and parameters smeared with a Gaussian of appropriate width:
  - Technique of Cousins and Highland NIM A **320**, 321 (1992)
  - Barlow CPC **149,** 97 (2002) or POLE D **67,** 012002 (2003), Narsky arXiv:physics0507143v1
- **Expected UL** is defined as the mean UL, assuming we observe a number of events distributed as the expected background:

$$\mathrm{UL}^{\mathrm{exp}}_{90\%\mathrm{CL}} = \sum_{n=0}^{\infty} \mathcal{P}_{\mathrm{Poisson}}(n, N_{\mathrm{bkg}})\mathrm{UL}_{90\%\mathrm{CL}}(n)$$

Optimized in the event selection

Systematics

- **# of signal candidates**
  - Luminosity and cross-section **0.7-1%**
- **Efficiency**
  - Agreement between data and MC
    - PID: **1-8.5%**
    - Tracking efficiency: **1-1.7%**
    - K_S efficiency: **4.5%**
    - Track momentum and photon energy resolution: **6.5%**
- **Background**
  - Data statistics and background modelling: **20-70%**

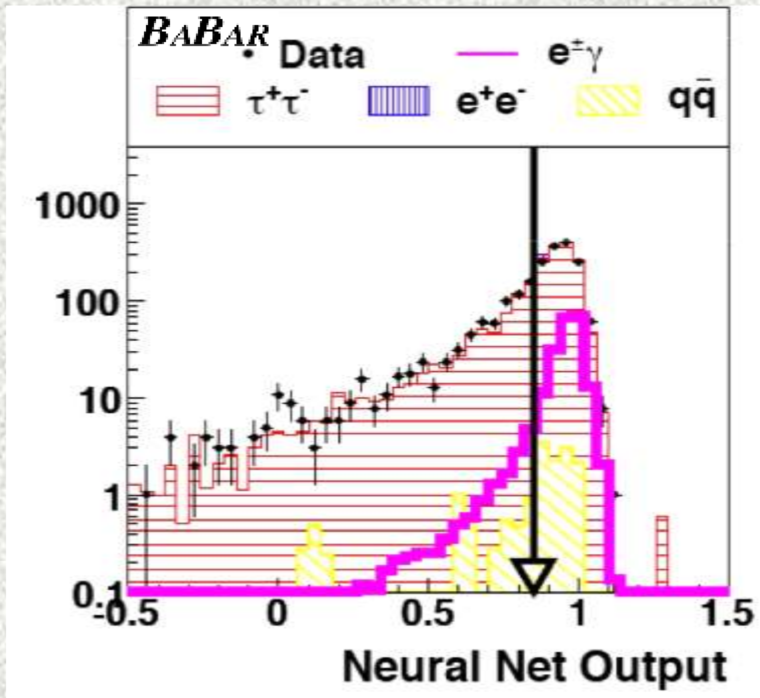
Correlation with the final UL value

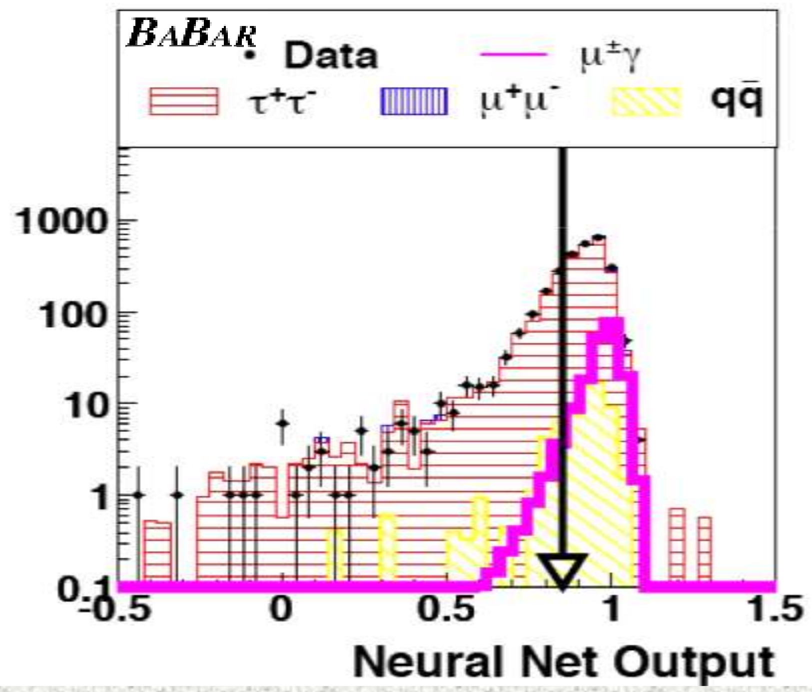
Medium

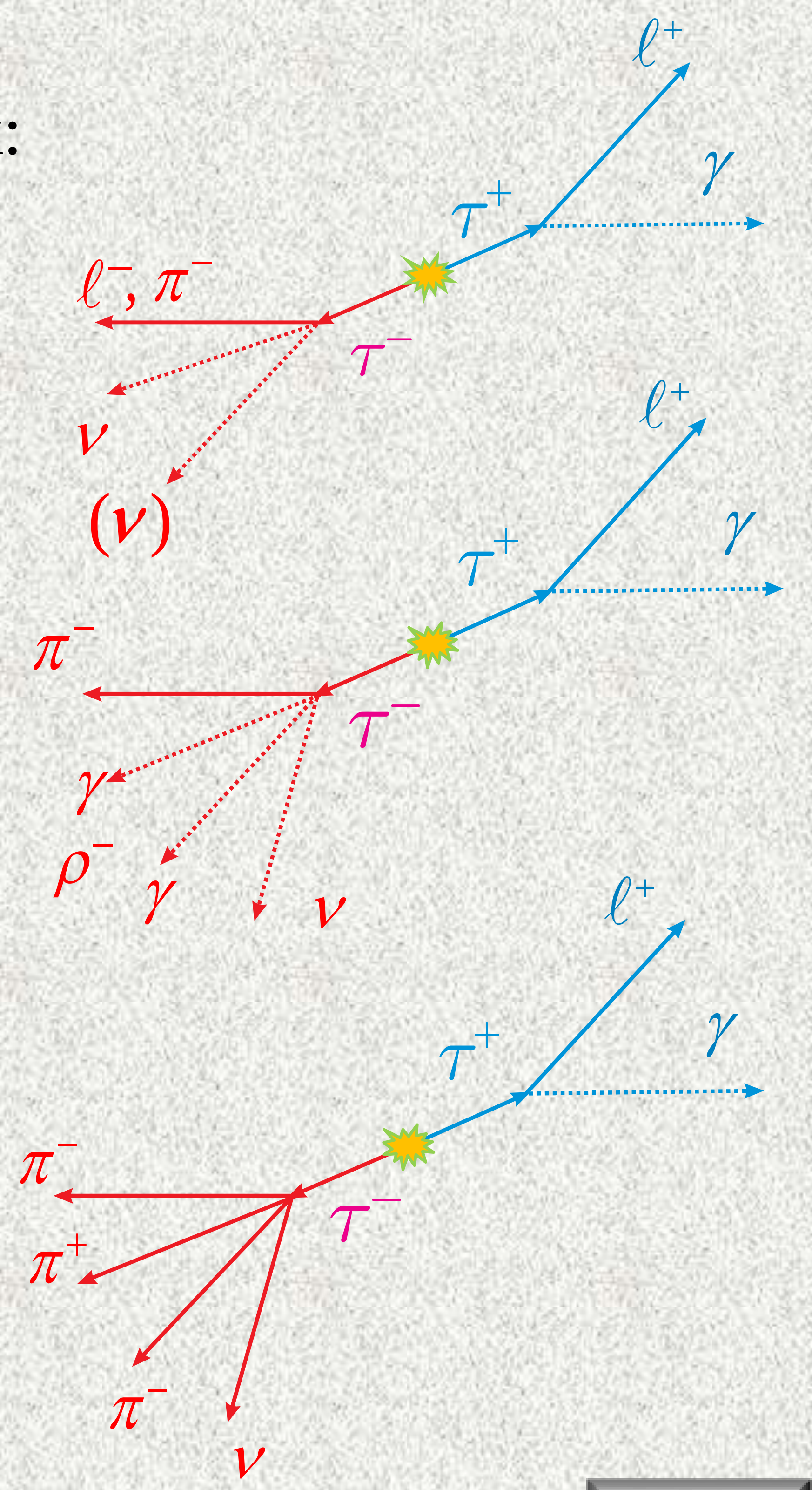
Small

$\tau \rightarrow \ell\gamma$

- Use five tag modes (e, μ, π, ρ, $3h$)
- Cut-based initial selection, followed by neural network:
  - total tag-side momentum
  - $\cos\theta_{recoil}$
  - lepton-photon opening angle
  - missing p_t
  - ΔE_γ (*w.r.t.* expected energy for e^+e^- and $\mu^+\mu^-$ evts)
  - $\cos\theta_{\ell\gamma}$

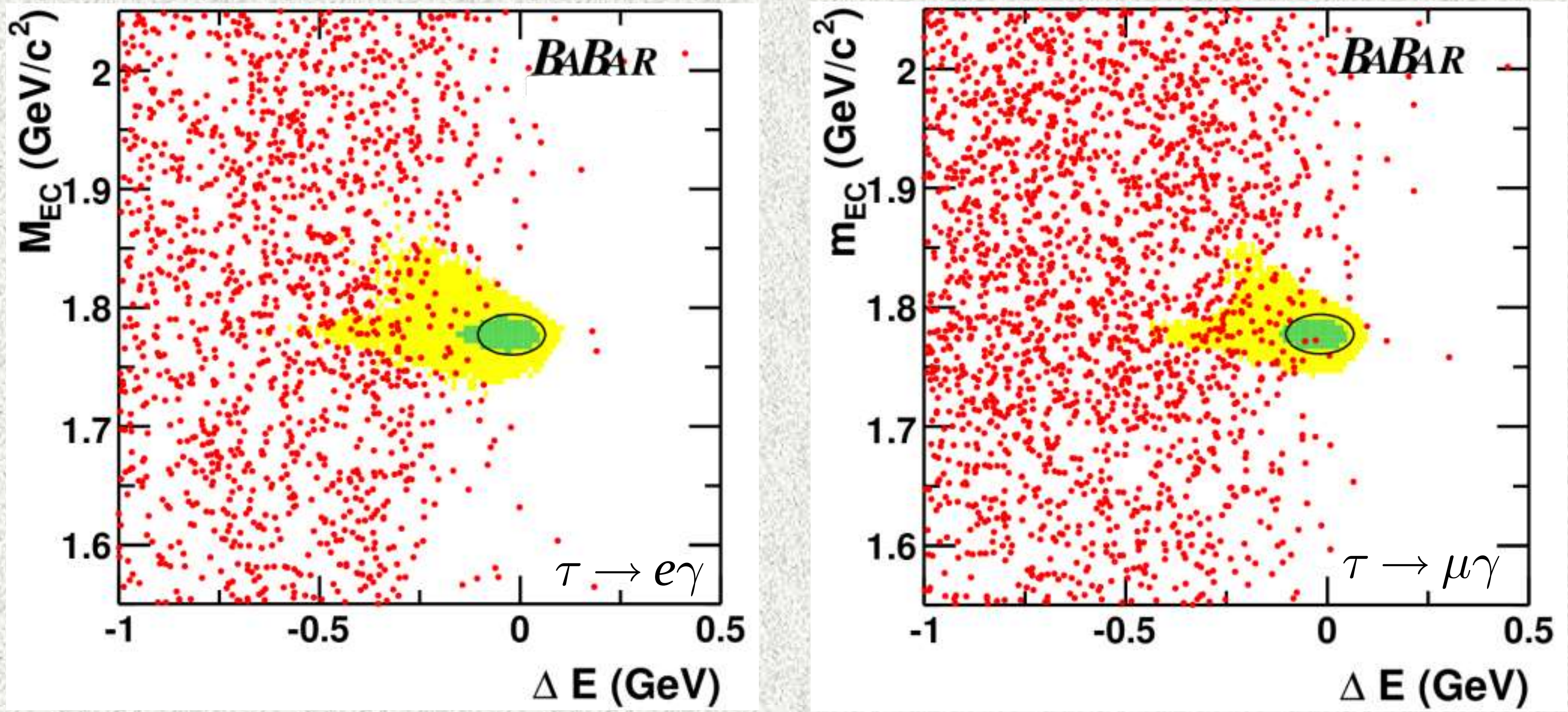






$\tau \to \ell\gamma$

Integrated luminosity corresponds to 482M pairs (2*S*+3*S*+4*S* data)

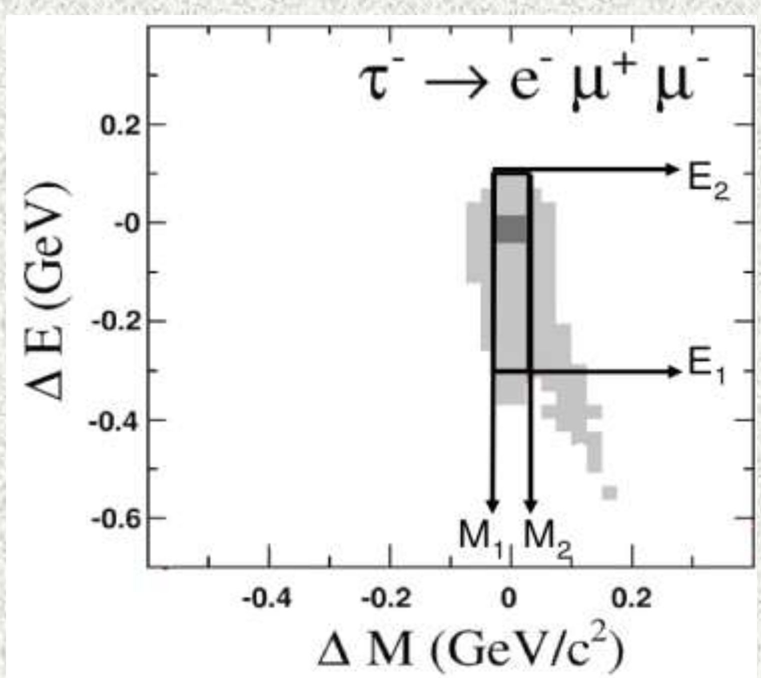


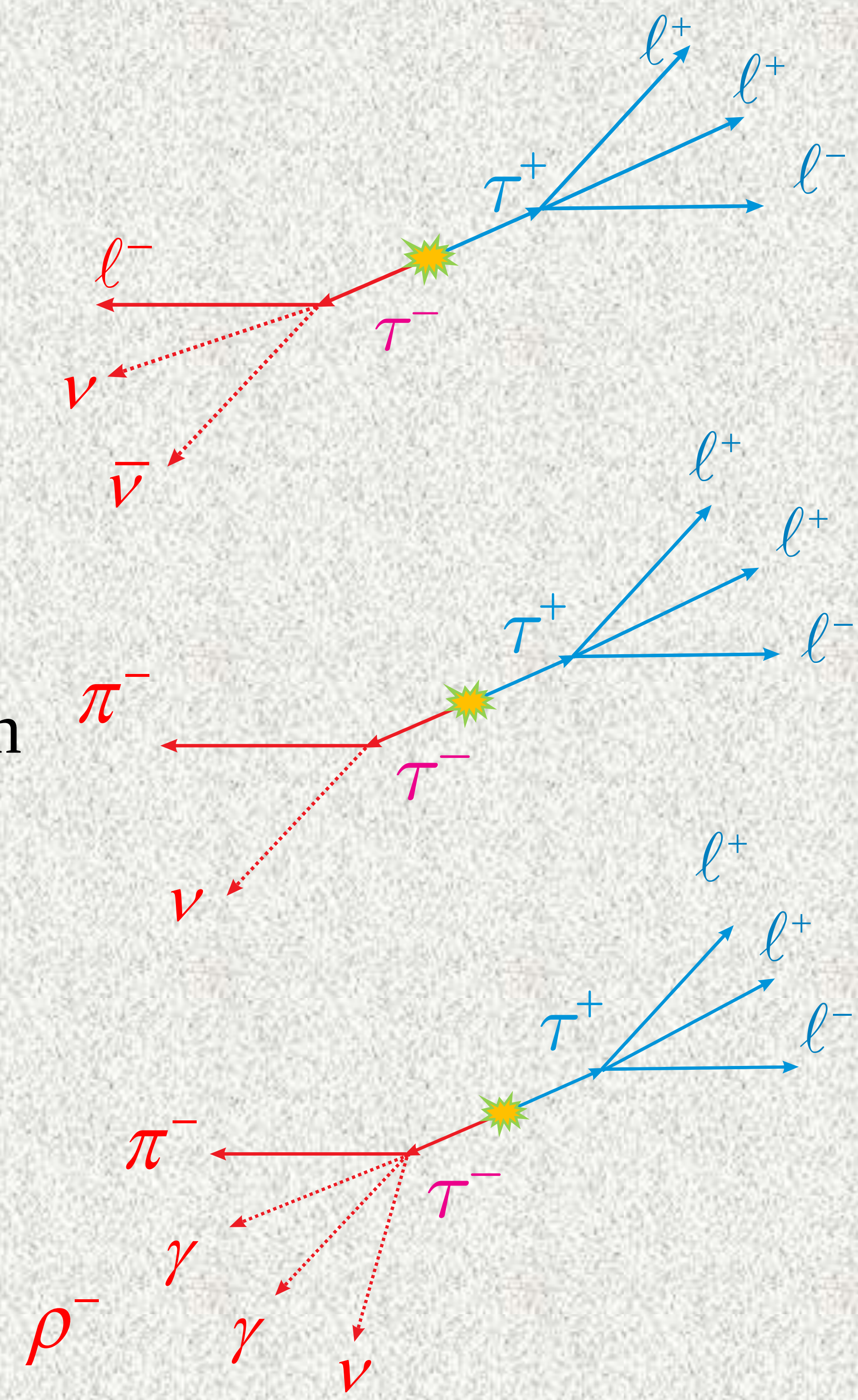
Mode	$\epsilon(\%)$	$\sigma_{\rm syst}(\%)$	$N_{\rm bkg}$	$N_{\rm obs}$	$UL_{90}^{\rm obs}(10^{-8})$
$e\gamma$	3.9	13	1.6 ± 0.5	0	3.3
$\mu\gamma$	6.1	8.2	3.6 ± 0.6	2	4.4

Phys. Rev. Lett. **104,** 021802 (2010)

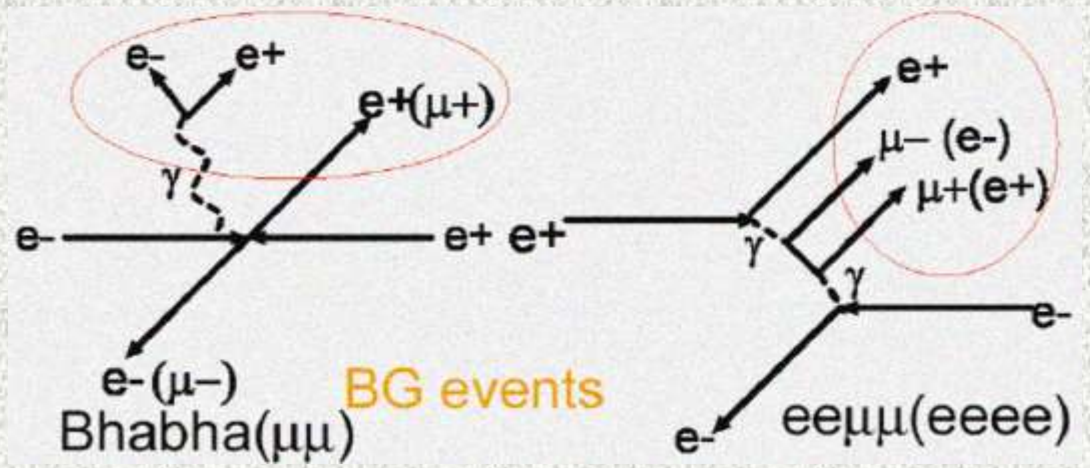
$\tau \to \ell\ell\ell$

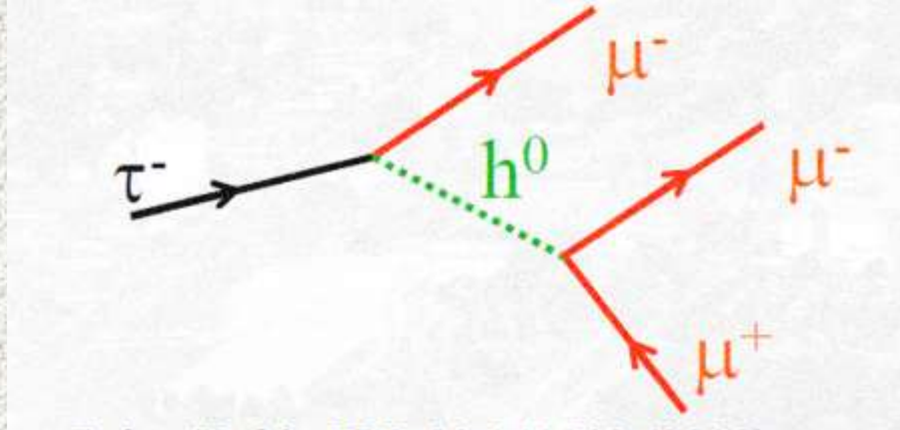
- Six decay modes
- PID applied for all the 3 tracks on signal side
- No specific x decays selected on tag side
- ΔM_{EC} , ΔE
- Signal box size optimized for each mode
- Backgrounds categories:
  - Combinatorial *uds*, flat mass distribution
  - QED radiative events





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





Babu, Kolda PRL 89 241802 (2002)

$$B(\tau^- \to 3\mu) \cong 1\times10^{-7} \times \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100\ \mathrm{GeV}}{m_{h^0}}\right)^4$$

Event selection is optimized separately for each signal mode accounting for different background compositions

$\tau\to\ell\ell\ell$ Signal Mode	$\mu^-\mu^+\mu^-$	$e^-e^+e^-$	$\mu^-e^+e^-$ $e^-\mu^+\mu^-$	$\mu^+e^-e^-$ $e^+\mu^-\mu^-$
Dominant Background	ττ uds eeμμ	Bhabha eeee ττ	eeμμ ττ μμ	ττ uds

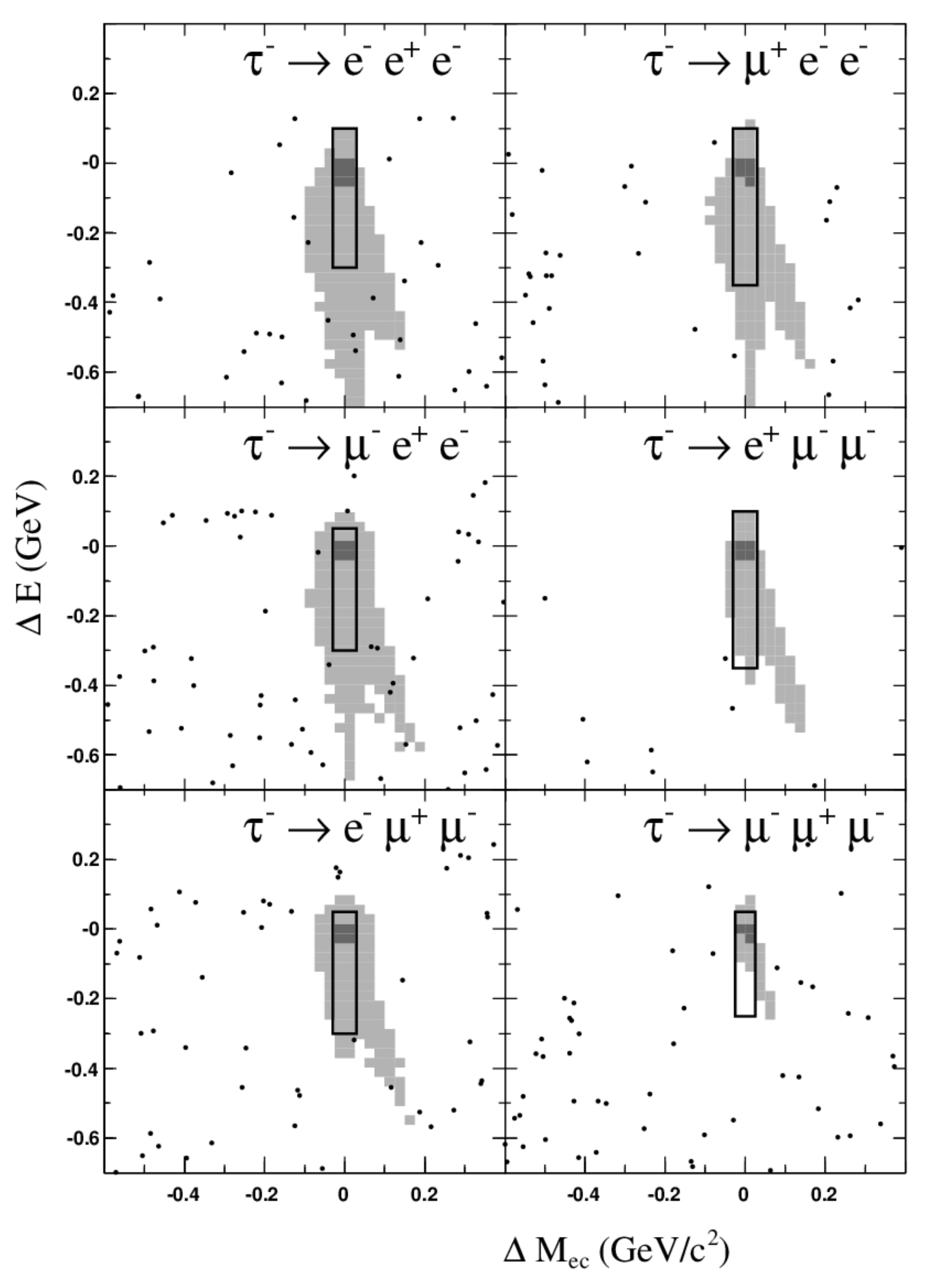
$\tau \to \ell\ell\ell$

- Integrated luminosity: 468 fb^{-1}

  430M τ pairs

Mode	$\epsilon(\%)$	$\sigma_{\text{syst}}(\%)$	N_{bkg}	N_{obs}	$UL_{90}^{\text{obs}}(10^{-8})$
$e^-e^+e^-$	8.6	2.3	0.12 ± 0.02	0	2.9
$e^-e^+\mu^-$	8.8	5.7	0.64 ± 0.19	0	2.2
$e^-\mu^+e^-$	12.6	5.5	0.34 ± 0.12	0	1.8
$e^-\mu^+\mu^-$	6.4	6.2	0.54 ± 0.14	0	3.2
$\mu^-e^+\mu^-$	10.2	5.9	0.03 ± 0.02	0	2.6
$\mu^+\mu^-\mu^+$	6.6	9.0	0.44 ± 0.17	0	3.3

Phys. Rev. **D81**, 111101 (2010)

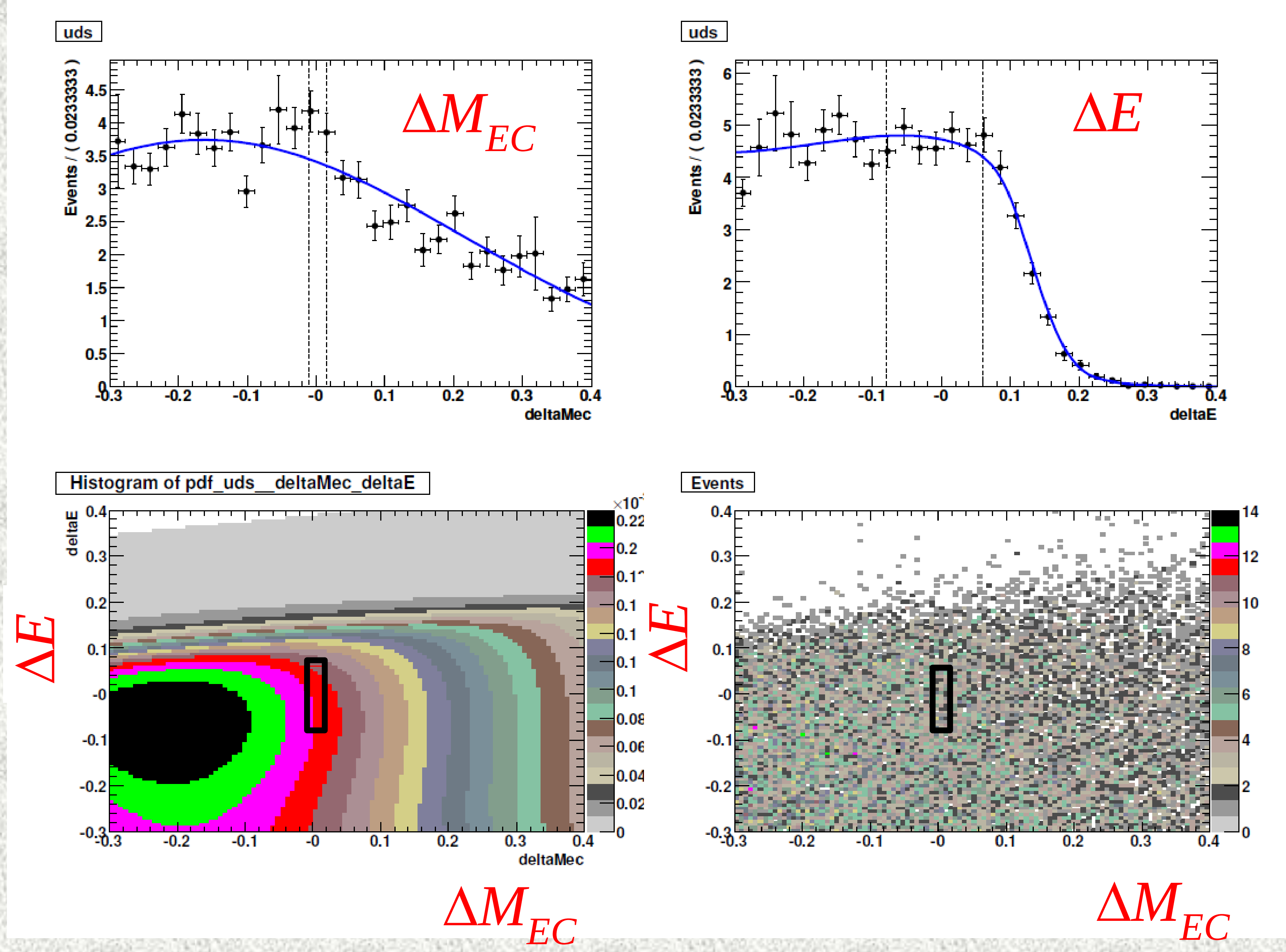


$\tau \to \ell(\rho^0, K^{*0}, \overline{K}^{*0}, \phi)$

$V^0 \to h^+ h^-$

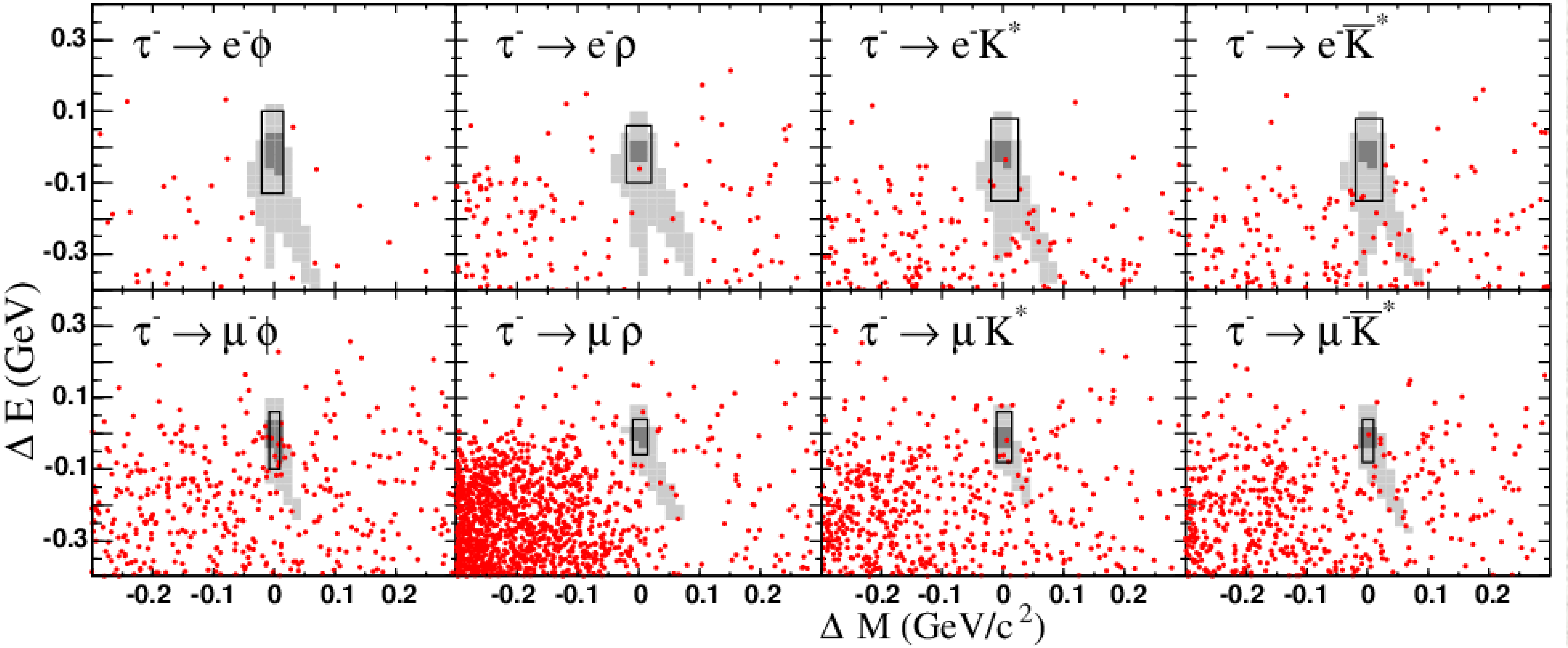
- Cut on meson mass
- No specific decays selected on tag side
- $\Delta M_{EC}, \Delta E$
- Signal box size optimized for each mode

- Residual backgrounds after selection:
  - $c\bar{c}$, modes with a true meson and a misidentified pion: peaked on ΔM_{EC} at D and D_S mass
  - Continuum *uds* with low multiplicity, flat
  - Bhabha: negligible



*nK**, *uds* MC background

$\tau \to \ell(\rho^0, K^{*0}, \overline{K}^{*0}, \phi)$



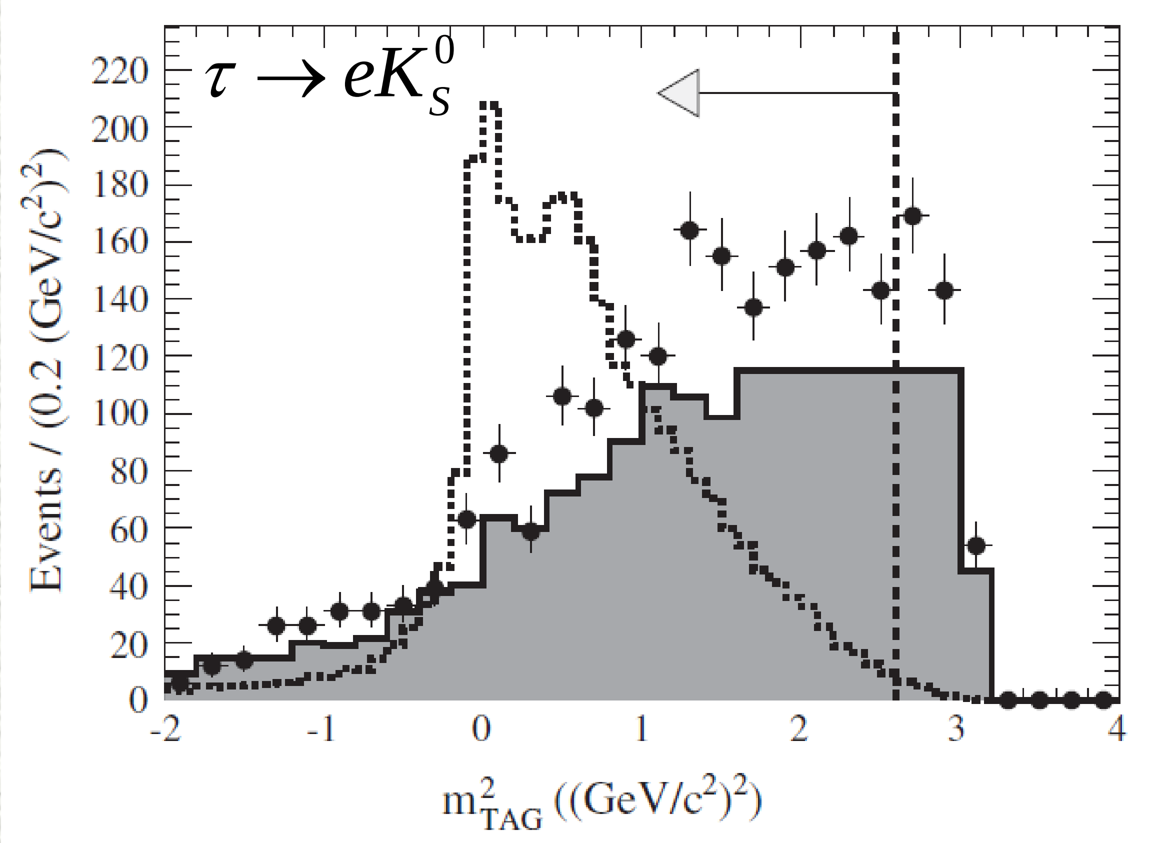
Mode	$\epsilon(\%)$	$\sigma_{\rm syst}(\%)$	$N_{\rm bkg}$	$N_{\rm obs}$	$UL_{90}^{\rm obs}(10^{-8})$
$e\rho^0$	7.31	2.5	1.32 ± 0.19	1	4.3
$\mu\rho^0$	4.52	9.0	2.04 ± 0.21	0	0.8
eK^{*0}	8.00	2.2	1.64 ± 0.29	2	5.6
μK^{*0}	4.57	7.8	1.79 ± 0.25	4	16.7
$e\overline{K}^{*0}$	7.76	2.2	2.76 ± 0.30	2	4.0
$\mu\overline{K}^{*0}$	4.11	7.6	1.72 ± 0.18	1	6.4
$e\phi$	6.43	2.8	0.68 ± 0.14	0	3.1
$\mu\phi$	5.18	5.0	2.76 ± 0.21	6	18.2

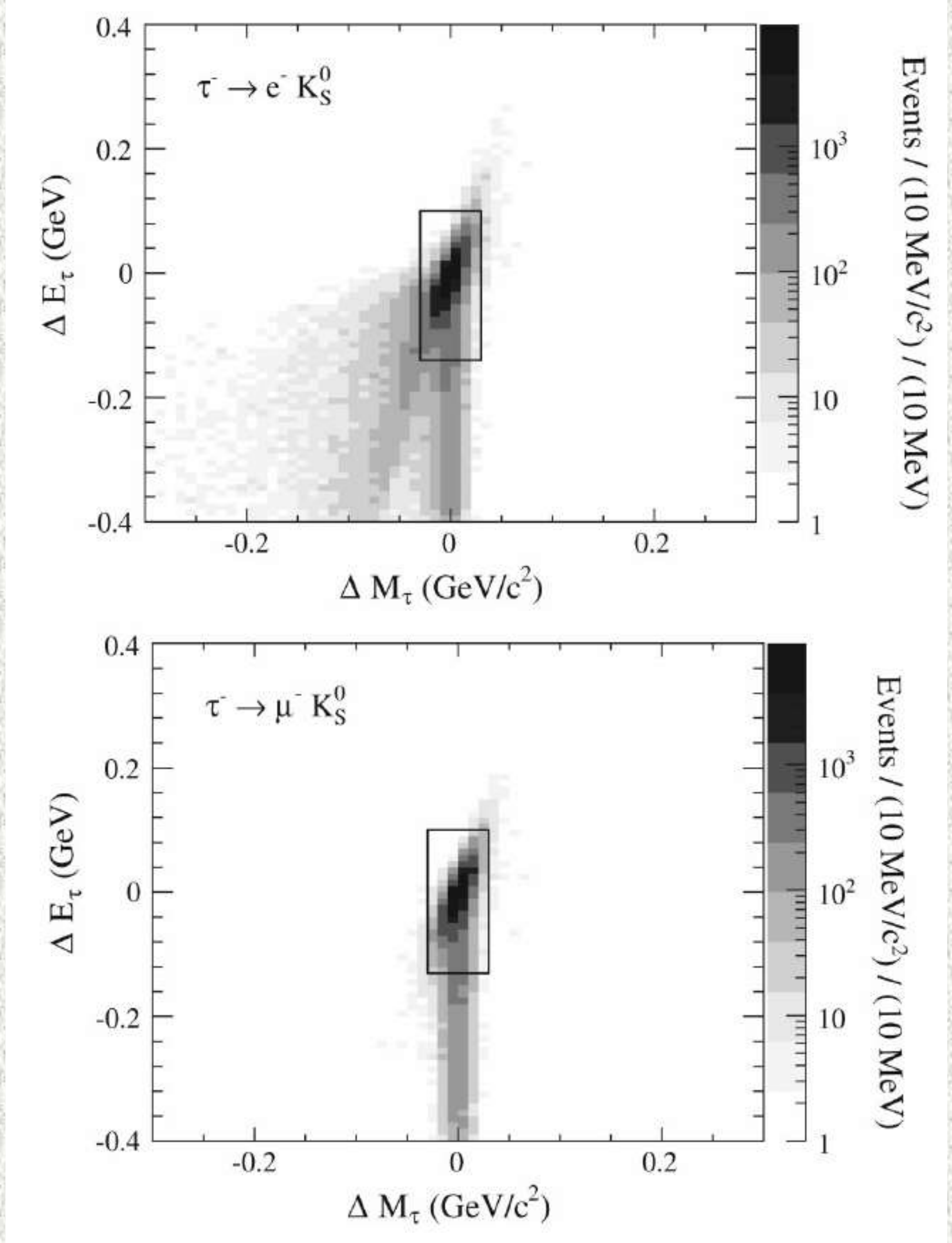
Integrated luminosity: 451 fb^{-1}

415M τ pairs

Phys. Rev. Lett. **103,** 021801 (2009)

$\tau \to \ell K_S$





$B(\tau \to eK_S^0) < 4.8 \times 10^{-8}$

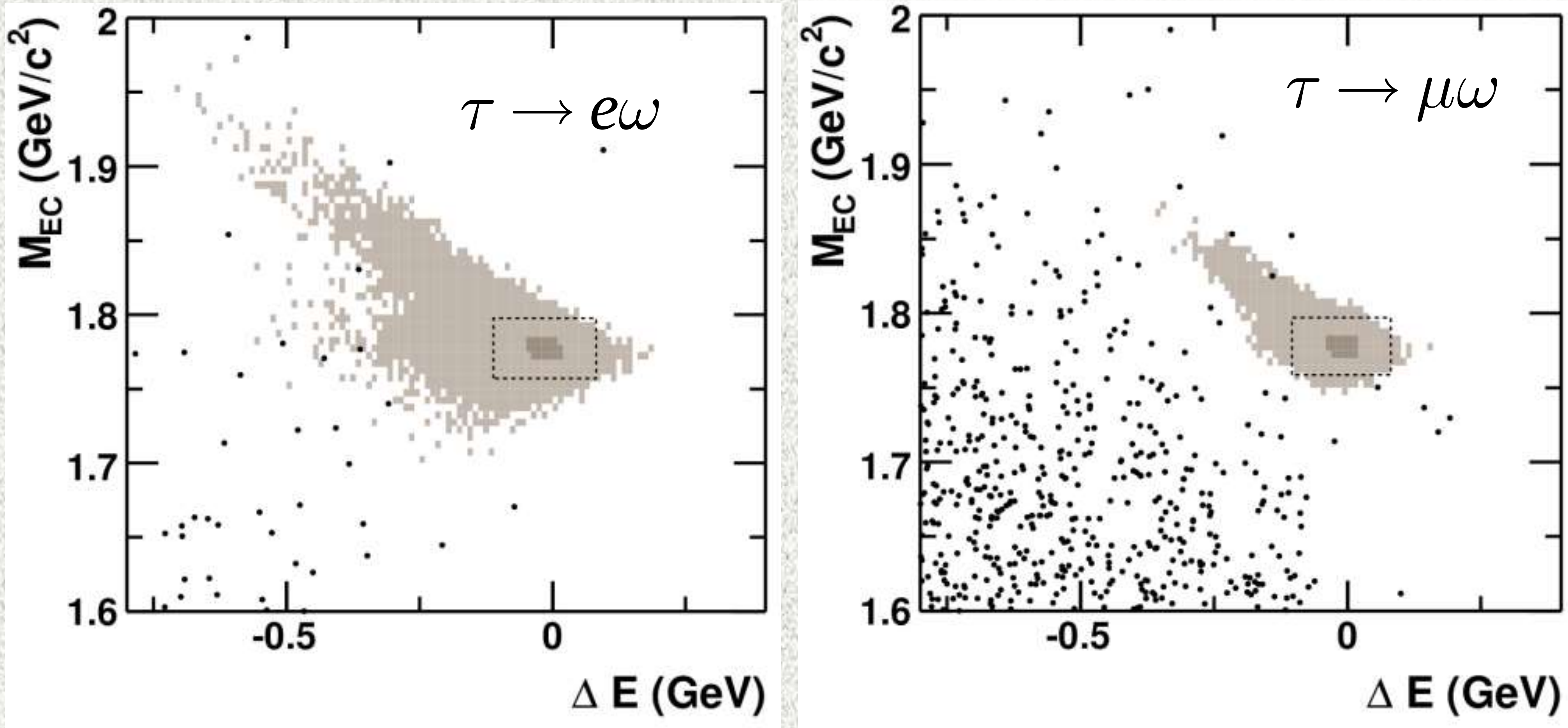
$B(\tau \to \mu K_S^0) < 7.6 \times 10^{-8}$

Integrated luminosity 469 fb^{-1}

Phys. Rev. **D79**, 012004 (2009)

$\tau \to \ell\omega$

- Reconstruct ω in the $\omega \to \pi^+\pi^-\pi^0$ decay mode



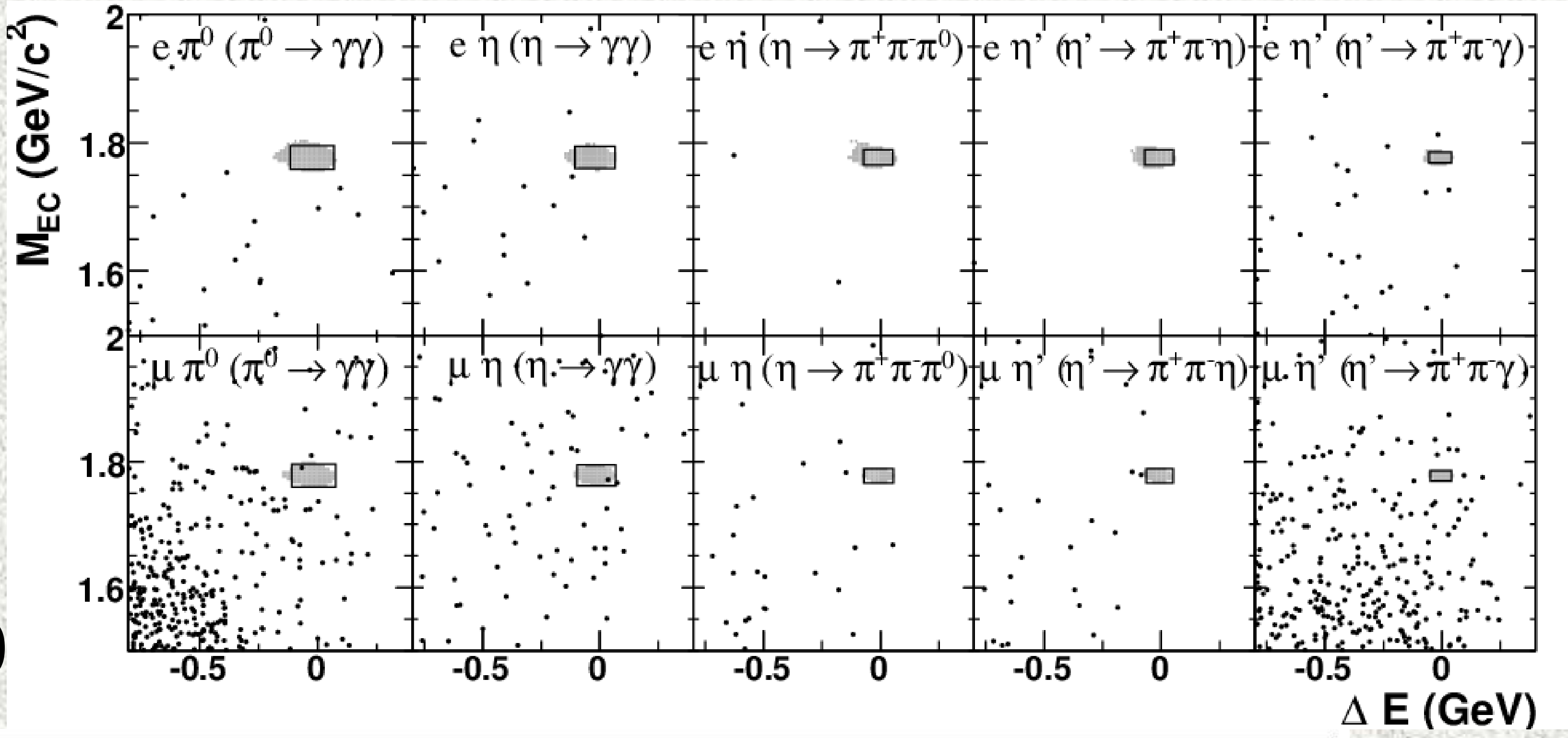
Decay modes	$\hat{m}_{EC}$ MeV/c^2	$\sigma(m_{EC})$ MeV/c^2	$\Delta\hat{E}$ MeV	$\sigma(\Delta E)$ MeV	ε (%)	SB events Exp.	SB events Obs.	UL ($\times 10^{-7}$) Exp.	UL ($\times 10^{-7}$) Obs.
$\tau^\pm \to e^\pm\omega$	1777.4 ± 0.1	6.8 ± 0.1	-14.4 ± 0.3	32.2 ± 0.3	2.96 ± 0.13	0.35 ± 0.06	0	1.4	1.1
$\tau^\pm \to \mu^\pm\omega$	1777.7 ± 0.1	6.4 ± 0.1	-11.2 ± 0.2	30.9 ± 0.3	2.56 ± 0.16	0.73 ± 0.03	0	1.7	1.0

Integrated luminosity 469 fb^{-1} *Phys. Rev. Lett.* **100**, 071802 (2008)

$\tau \to \ell\pi^0, \ell\eta, \ell\eta'$

Integrated luminosity 378 fb^{-1}

Phys. Rev. Lett. **98**, 061803 (2007)

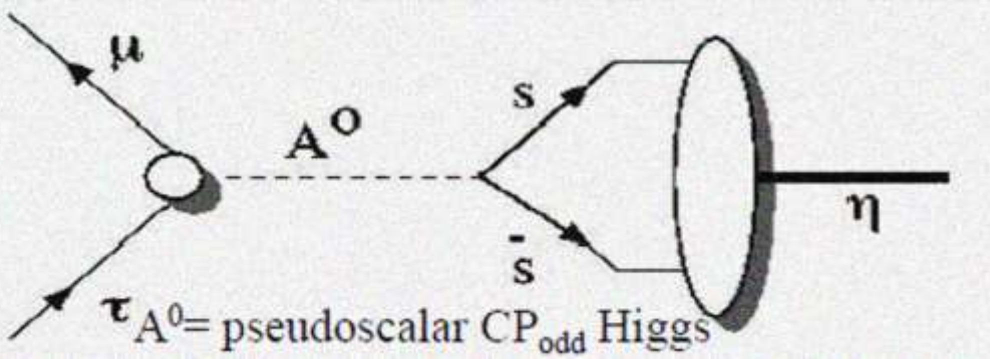


Decay modes	$\sigma(m_{EC})$ MeV/c^2	$\sigma(\Delta E)$ MeV	$\pm3\sigma$ to $\pm11\sigma$ box obs.	exp.	$\pm2\sigma$ box obs.	exp.	$\mathcal{B}$ (%)	ε (%)	UL ($\times 10^{-7}$) obs.	exp.
$\tau^\pm \to e^\pm\pi^0\ (\pi^0 \to \gamma\gamma)$	9.1	46.4	4	5.37 ± 1.14	0	0.17 ± 0.04	98.80 ± 0.03	2.83 ± 0.25	1.3	1.4
$\tau^\pm \to \mu^\pm\pi^0\ (\pi^0 \to \gamma\gamma)$	9.0	46.4	43	40.68 ± 4.32	1	1.33 ± 0.15	98.80 ± 0.03	4.75 ± 0.37	1.1	1.1
$\tau^\pm \to e^\pm\eta\ (\eta \to \gamma\gamma)$	8.5	42.6	4	4.99 ± 1.18	0	0.20 ± 0.05	39.38 ± 0.26	3.59 ± 0.24	2.5	2.8
$\tau^\pm \to e^\pm\eta\ (\eta \to \pi^+\pi^-\pi^0)$	5.9	31.4	0	0.64 ± 0.32	0	0.02 ± 0.01	22.43 ± 0.40	3.17 ± 0.32	5.4	5.5
$\tau^\pm \to e^\pm\eta$					0	0.22 ± 0.05	$\mathcal{B}\varepsilon = 2.12 \pm 0.20$ (%)		1.6	1.9
$\tau^\pm \to \mu^\pm\eta\ (\eta \to \gamma\gamma)$	8.3	40.8	20	17.36 ± 2.12	1	0.67 ± 0.08	39.38 ± 0.26	7.03 ± 0.53	1.9	1.6
$\tau^\pm \to \mu^\pm\eta\ (\eta \to \pi^+\pi^-\pi^0)$	5.6	31.0	3	2.01 ± 0.41	0	0.08 ± 0.02	22.43 ± 0.40	3.67 ± 0.32	4.5	4.8
$\tau^\pm \to \mu^\pm\eta$					1	0.75 ± 0.08	$\mathcal{B}\varepsilon = 3.59 \pm 0.41$ (%)		1.5	1.3
$\tau^\pm \to e^\pm\eta'\ (\eta' \to \pi^+\pi^-\eta)$	5.9	31.0	0	0.14 ± 0.14	0	0.01 ± 0.01	17.52 ± 0.56	3.75 ± 0.27	5.8	5.9
$\tau^\pm \to e^\pm\eta'\ (\eta' \to \rho^0\gamma)$	4.4	24.3	2	2.97 ± 0.54	0	0.11 ± 0.03	29.40 ± 0.90	2.98 ± 0.28	4.2	4.5
$\tau^\pm \to e^\pm\eta'$					0	0.12 ± 0.03	$\mathcal{B}\varepsilon = 1.53 \pm 0.16$ (%)		2.4	2.6
$\tau^\pm \to \mu^\pm\eta'\ (\eta' \to \pi^+\pi^-\eta)$	5.6	29.1	1	2.42 ± 0.47	0	0.07 ± 0.02	17.52 ± 0.56	5.87 ± 0.46	3.6	3.8
$\tau^\pm \to \mu^\pm\eta'\ (\eta' \to \rho^0\gamma)$	4.1	23.1	13	11.06 ± 0.65	0	0.42 ± 0.03	29.40 ± 0.90	3.90 ± 0.46	2.7	3.7
$\tau^\pm \to \mu^\pm\eta'$					0	0.49 ± 0.04	$\mathcal{B}\varepsilon = 2.18 \pm 0.26$ (%)		1.4	2.0

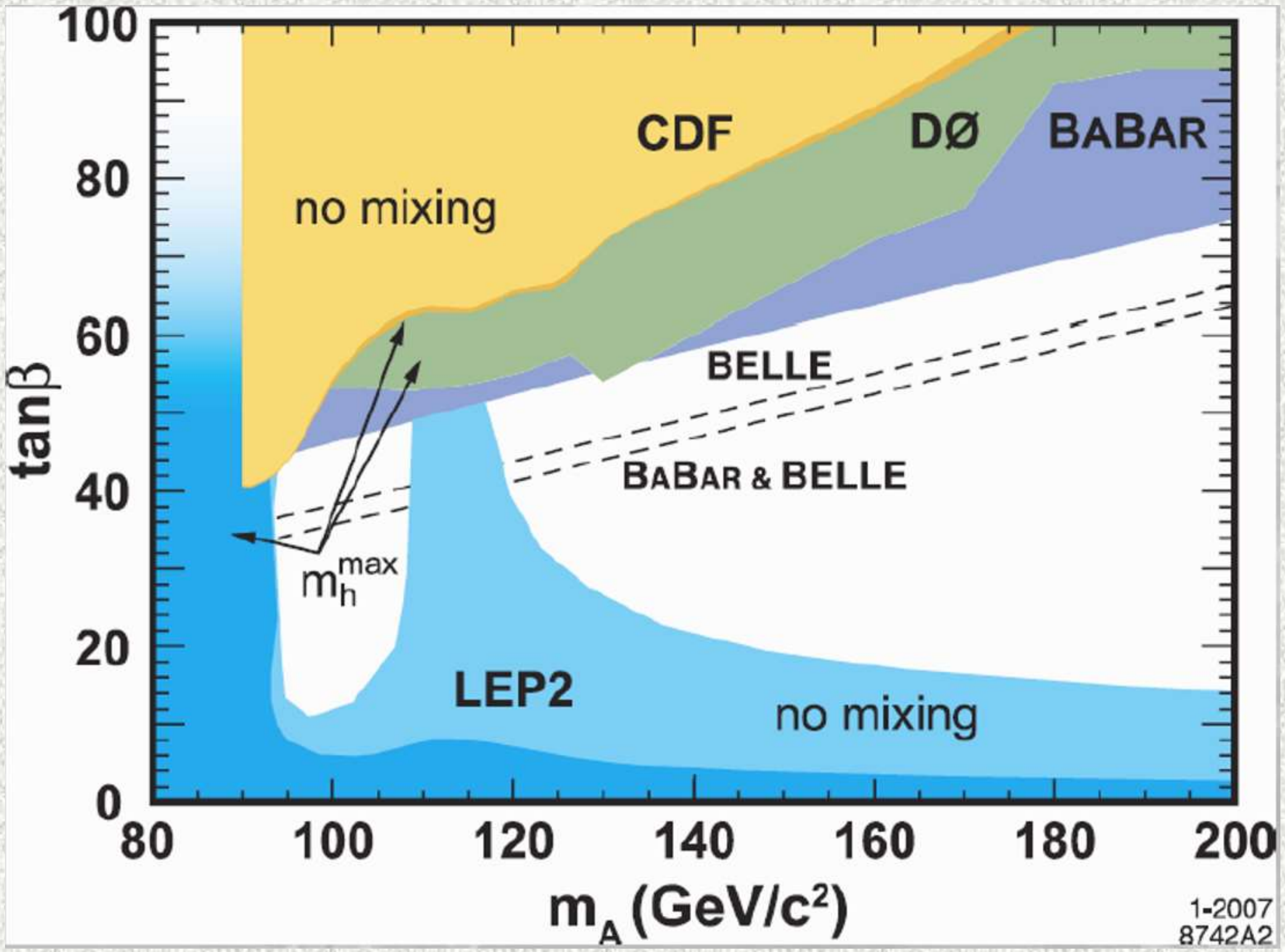
$\tau \rightarrow \ell\eta$

$$B(\tau^- \rightarrow \mu^- \eta) = 0.84 \times 10^{-6} \times \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100\ \text{GeV}}{m_A}\right)^4$$

$\tan\beta = \langle H_u \rangle / \langle H_d \rangle$, A^0= pseudoscalar CP_{odd} Higgs



M. Sher, Phys. Rev D66, 057301 (2002)



(2006)

Exclusion regions in the m_A and $\tan\beta$ plane by different experiments @ 95%CL

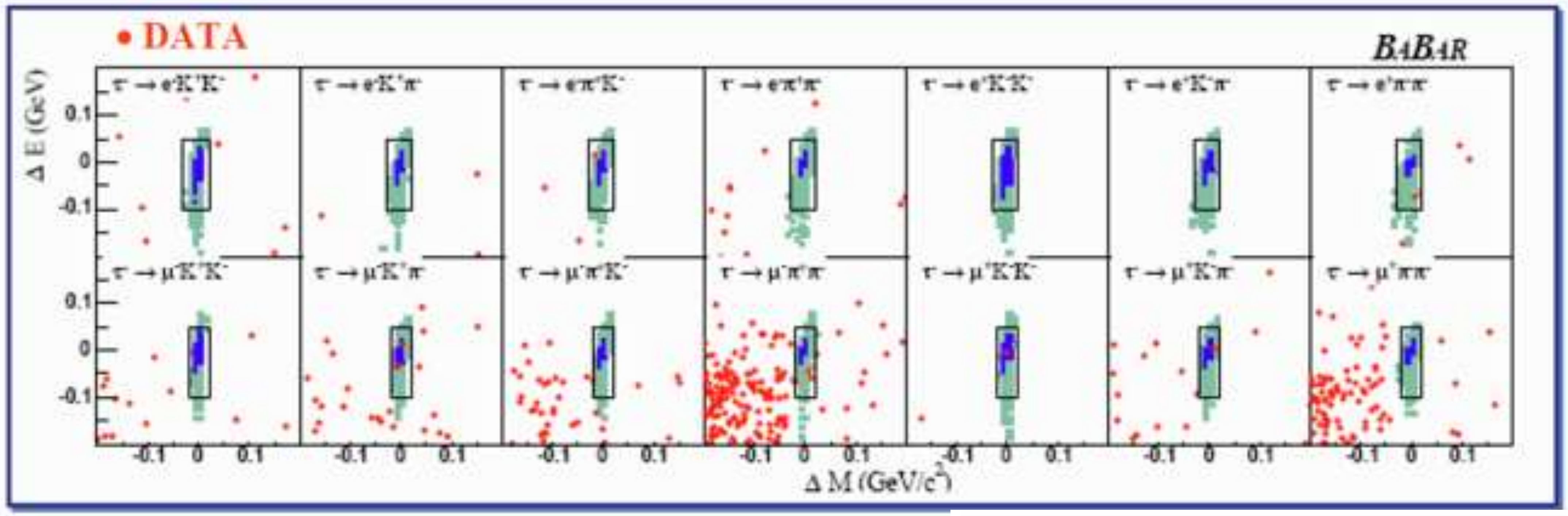
Competitive with the direct Higgs searches at CDF & D0

CDF: $p\bar{p} \rightarrow H \rightarrow \tau^+\tau^-$ (310 fb^{-1})

D0: $p\bar{p} \rightarrow H \rightarrow \tau^+\tau^-$ (325 fb^{-1})

D0: $p\bar{p} \rightarrow H \rightarrow b\bar{b}$ (260 fb^{-1})

$\tau \rightarrow \ell h h'$



Integrated luminosity 221 fb^{-1}

Mode	Efficiency [%]	N_{bgd}	N_{obs}	UL at 90% CL
$e^- K^+ K^-$	3.77 ± 0.16	0.22 ± 0.06	0	$1.4 \cdot 10^{-7}$
$e^- K^+ \pi^-$	3.08 ± 0.13	0.32 ± 0.08	0	$1.7 \cdot 10^{-7}$
$e^- \pi^+ K^-$	3.10 ± 0.13	0.14 ± 0.06	1	$3.2 \cdot 10^{-7}$
$e^- \pi^+ \pi^-$	3.30 ± 0.15	0.81 ± 0.13	0	$1.2 \cdot 10^{-7}$
$\mu^- K^+ K^-$	2.16 ± 0.12	0.24 ± 0.07	0	$2.5 \cdot 10^{-7}$
$\mu^- K^+ \pi^-$	2.97 ± 0.16	1.67 ± 0.29	2	$3.2 \cdot 10^{-7}$
$\mu^- \pi^+ K^-$	2.87 ± 0.16	1.04 ± 0.18	1	$2.6 \cdot 10^{-7}$
$\mu^- \pi^+ \pi^-$	3.40 ± 0.19	2.99 ± 0.41	3	$2.9 \cdot 10^{-7}$
$e^+ K^- K^-$	3.85 ± 0.16	0.04 ± 0.04	0	$1.5 \cdot 10^{-7}$
$e^+ K^- \pi^-$	3.19 ± 0.14	0.16 ± 0.06	0	$1.8 \cdot 10^{-7}$
$e^+ \pi^- \pi^-$	3.40 ± 0.15	0.41 ± 0.10	1	$2.7 \cdot 10^{-7}$
$\mu^+ K^- K^-$	2.06 ± 0.11	0.07 ± 0.10	1	$4.8 \cdot 10^{-7}$
$\mu^+ K^- \pi^-$	2.85 ± 0.16	1.54 ± 0.25	1	$2.2 \cdot 10^{-7}$
$\mu^+ \pi^- \pi^-$	3.30 ± 0.18	1.46 ± 0.27	0	$0.7 \cdot 10^{-7}$

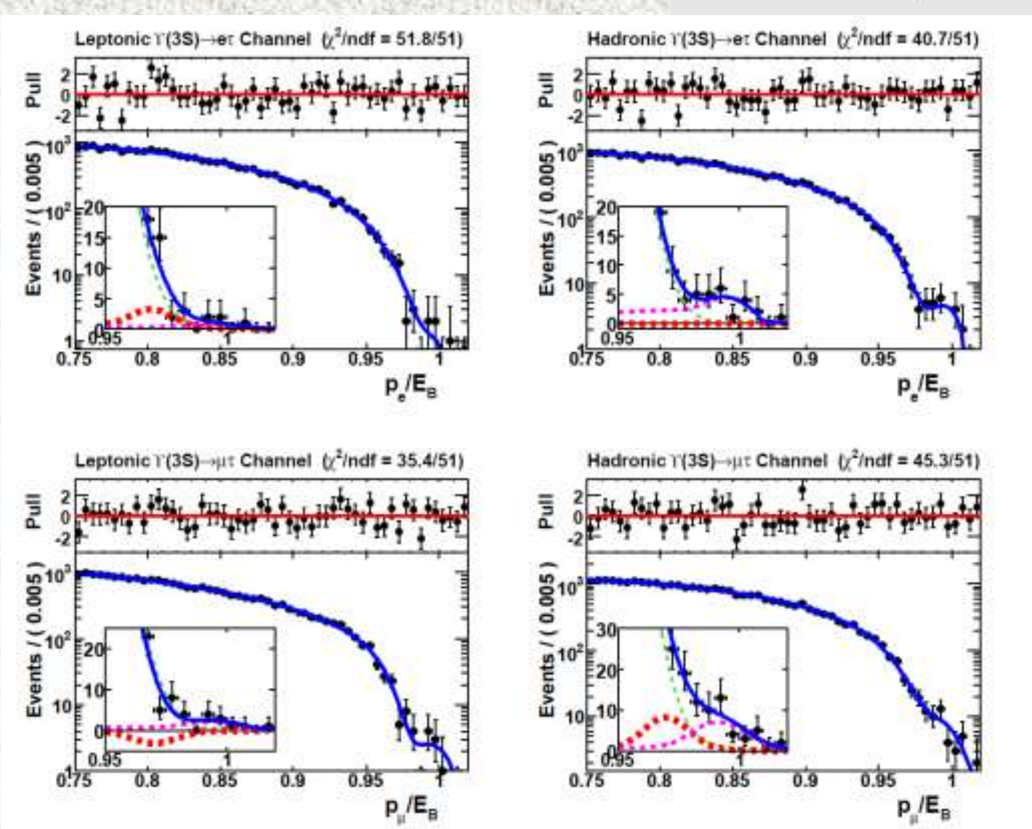
- Many modes studied; selection criteria optimized for best UL for each mode
- Signal efficiency varies from ~2.1-3.8%
- Net signal box yields: background est 0.1-3 events, signal 0-3 events
- Upper limits calculated with Cousins/Highland method
- 90% CL upper limits range from $(0.7 – 4.8) \times 10^{-7}$

Phys. Rev. Lett. **95**, 191801 (2005)

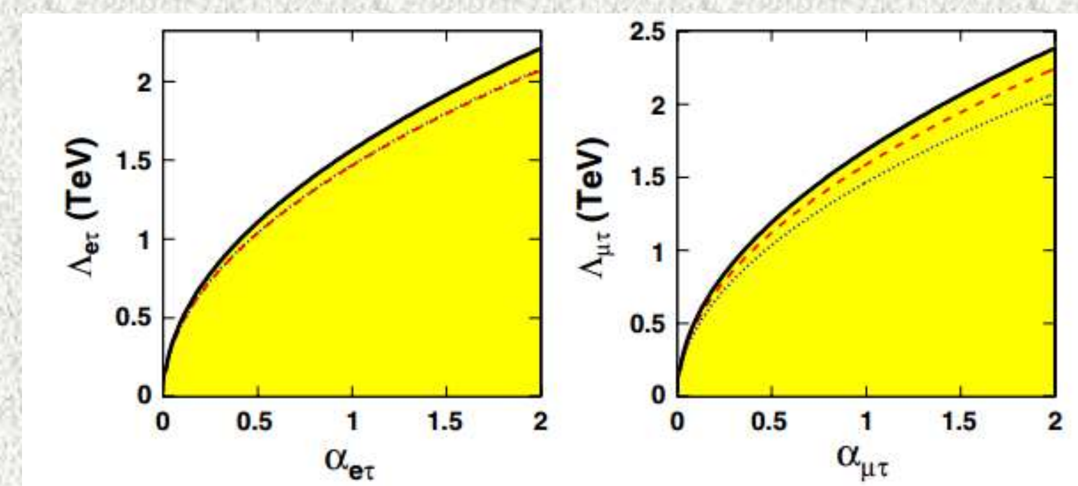
Search for $\Upsilon(2S,3S)\to e^{\pm}\tau^{\mp}$ and $\Upsilon(2S,3S)\to \mu^{\pm}\tau^{\mp}$

- The limits on $B(\tau \to \ell\ell\ell) < (2\text{-}4) \times 10^{-8}$ imply, *e.g.*, $B(\Upsilon(3S)\to \ell^{\pm}\tau^{\mp}) < (3-6)\times 10^{-3}$
- If CLFV originates in the Higgs sector, it could preferentially couple to heavy quarks
- Hence a direct search for $\Upsilon(2S,3S)\to \ell^{\pm}\tau^{\mp}$ in our $\Upsilon(2S,3S)$ samples is well-motivated
- *n.b.* $\Upsilon(2S,3S)\to \ell^{\pm}\tau^{\mp}$ decays are enhanced over $\Upsilon(4S)\to \ell^{\pm}\tau^{\mp}$ decay by $\sim 10^{3}$
- Search channels
  - leptonic $e\tau$ channel: $\Upsilon(3S) \to e^{\pm}\tau^{\mp}$, $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$
  - hadronic $e\tau$ channel: $\Upsilon(3S) \to e^{\pm}\tau^{\mp}$, $\tau^- \to \pi^-\pi^0\nu_\tau/\pi^-\pi^0\pi^0\nu_\tau$
  - leptonic $\mu\tau$ channel: $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$, $\tau^- \to e^-\nu_\tau\bar{\nu}_e$
  - hadronic $\mu\tau$ channel: $\Upsilon(3S) \to \mu^{\pm}\tau^{\mp}$, $\tau^- \to \pi^-\pi^0\nu_\tau/\pi^-\pi^0\pi^0\nu_\tau$

99×10^6 $\Upsilon(2S)$ decays
117×10^6 $\Upsilon(3S)$ decays



	$\mathcal{B}$ (10^{-6})	UL (10^{-6})
$\mathcal{B}(\Upsilon(2S) \to e^{\pm}\tau^{\mp})$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	<3.2
$\mathcal{B}(\Upsilon(2S) \to \mu^{\pm}\tau^{\mp})$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	<3.3
$\mathcal{B}(\Upsilon(3S) \to e^{\pm}\tau^{\mp})$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	<4.2
$\mathcal{B}(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$-0.8^{+1.5+1.4}_{-1.5-1.3}$	<3.1



Phys. Rev. Lett. **104**, 151802 (2010)

Lepton and baryon number violation in τ decay

Can search for *B*, *L* violation, with *B*-*L* conserved or violated

$$\tau^- \to \bar{\Lambda}\pi^-, K^- \quad (\bar{\Lambda} \to \bar{p}\pi^+)$$

	τ^-	$\bar{\Lambda}$	π^-, K^-
B	0	-1	0
L	1	0	0
B-L	-1	-1	0

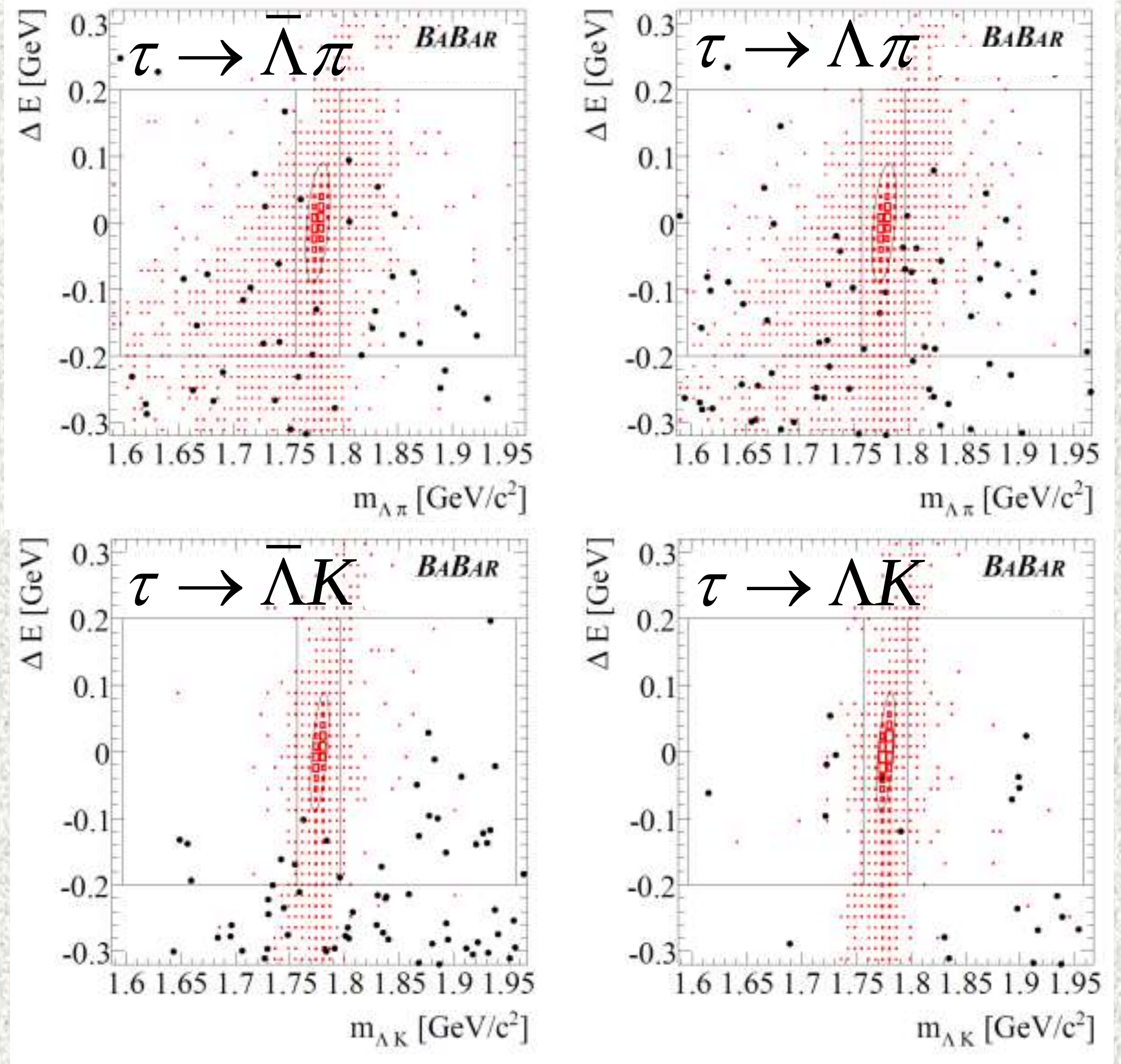
(B-L) conserving

$$\tau^- \to \Lambda\pi^-, K^- \quad (\Lambda \to p\pi^-)$$

	τ^-	Λ	π^-, K^-
B	0	1	0
L	1	0	0
B-L	-1	+1	0

(B-L) violating

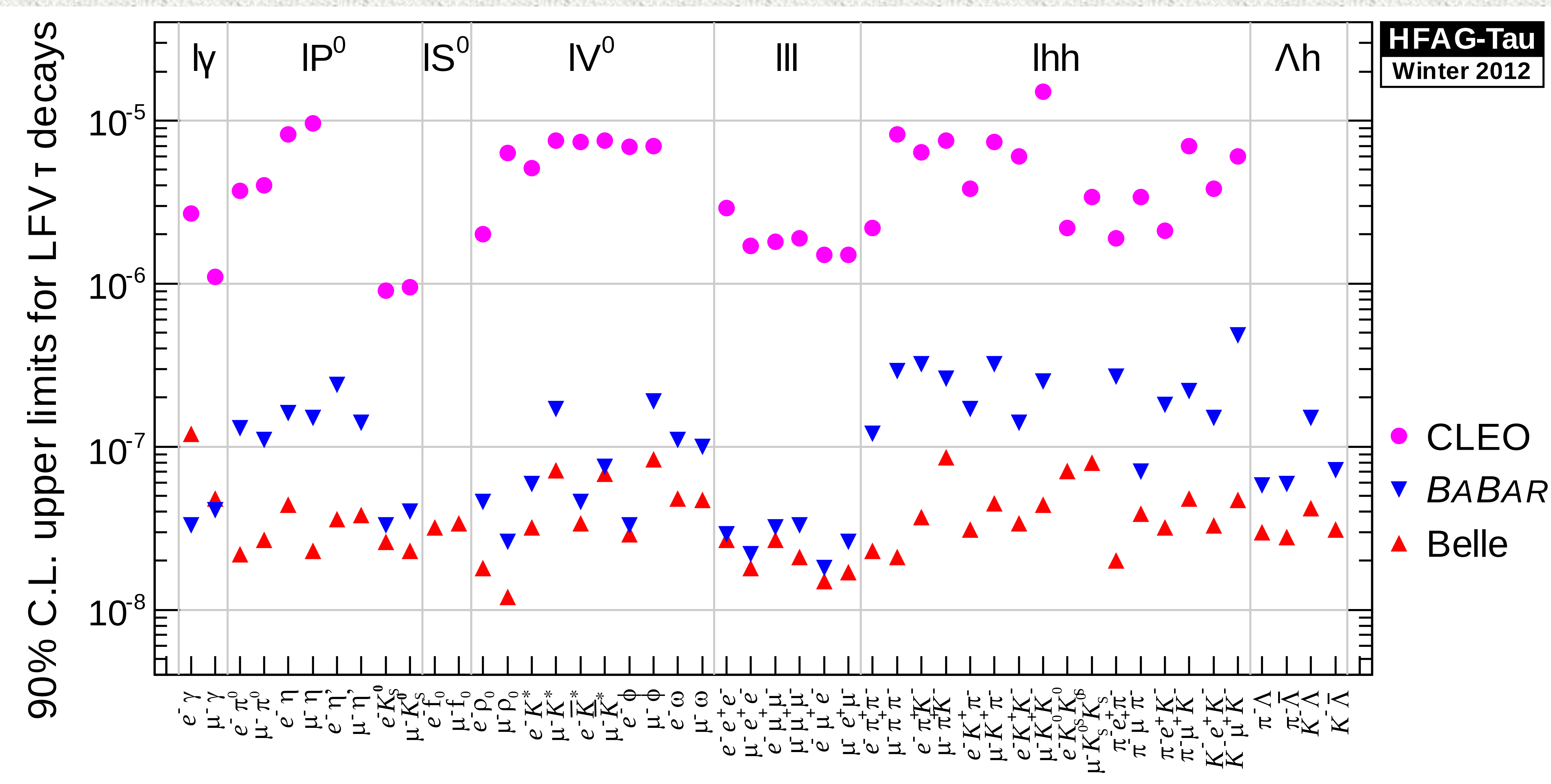
B and *L* violation in τ decay



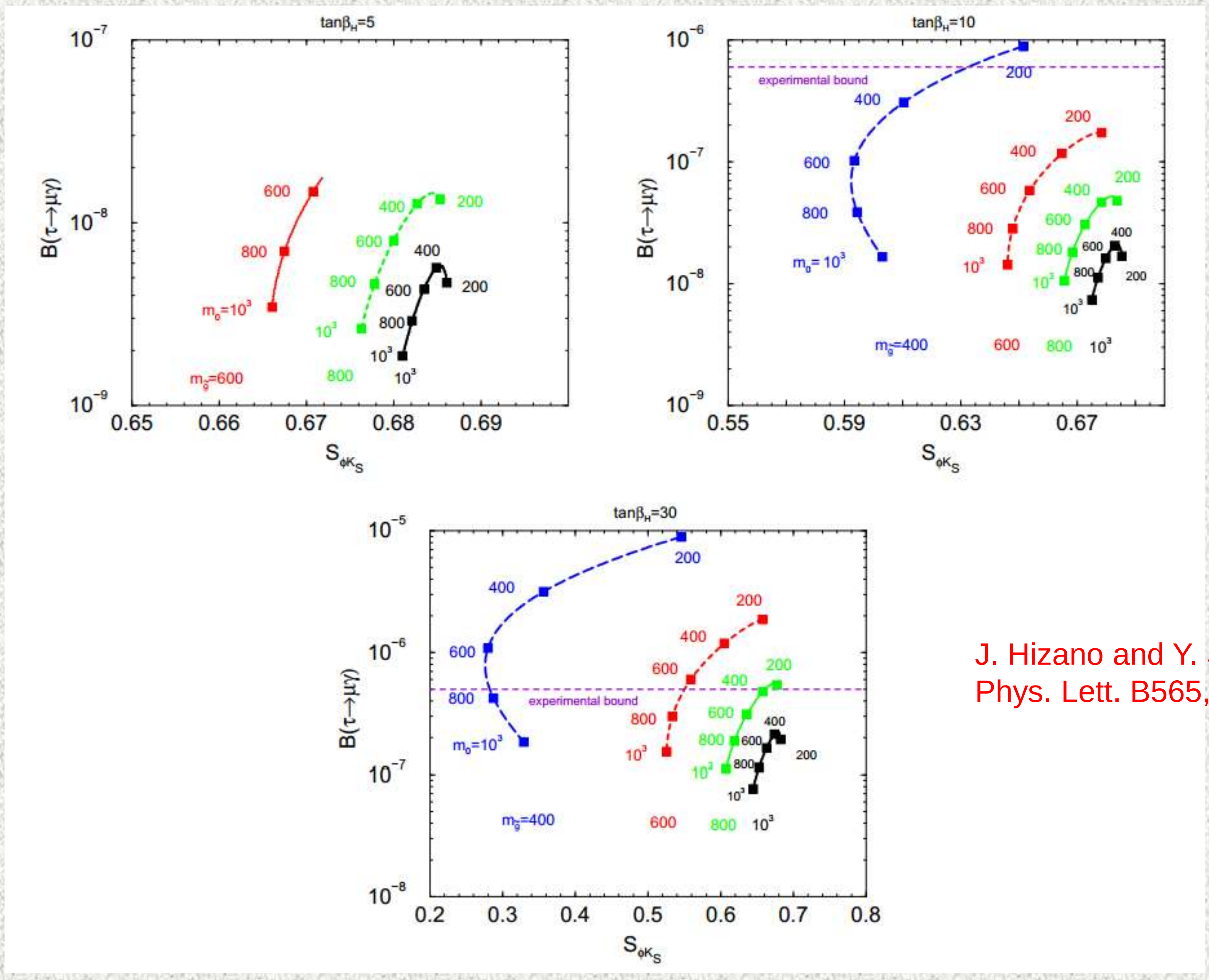
Integrated luminosity
237 fb^{-1} (220 x 10^6 τ pairs)
hep-ex/0607040

Mode	B-L	Eff.(%)	expected bckd	observed bckd	UL@90%CL
$\tau^- \to \bar{\Lambda}\pi^-$	conserve	12.28	0.42±0.42	0	$5.9 \cdot 10^{-8}$
$\tau^- \to \Lambda\pi^-$	violate	12.21	0.56±0.56	0	$5.8 \cdot 10^{-8}$
$\tau^- \to \bar{\Lambda}K^-$	conserve	10.63	0.26±0.26	0	$7.2 \cdot 10^{-8}$
$\tau^- \to \Lambda K^-$	violate	9.47	0.12±0.12	1	$15 \cdot 10^{-8}$

Lepton Flavor Violation in τ decays - current status

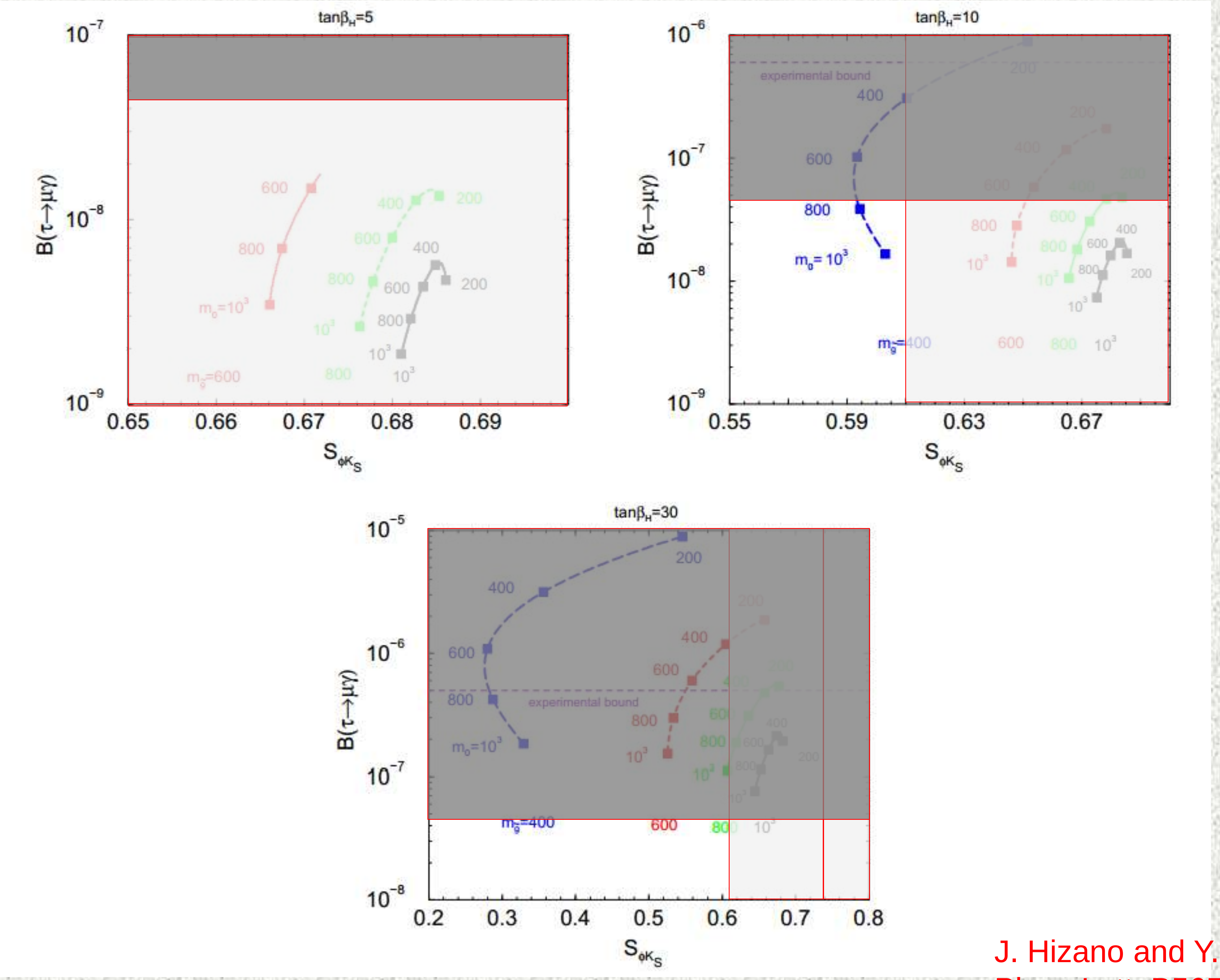


An SU(5) SUSY GUT with right handed neutrinos



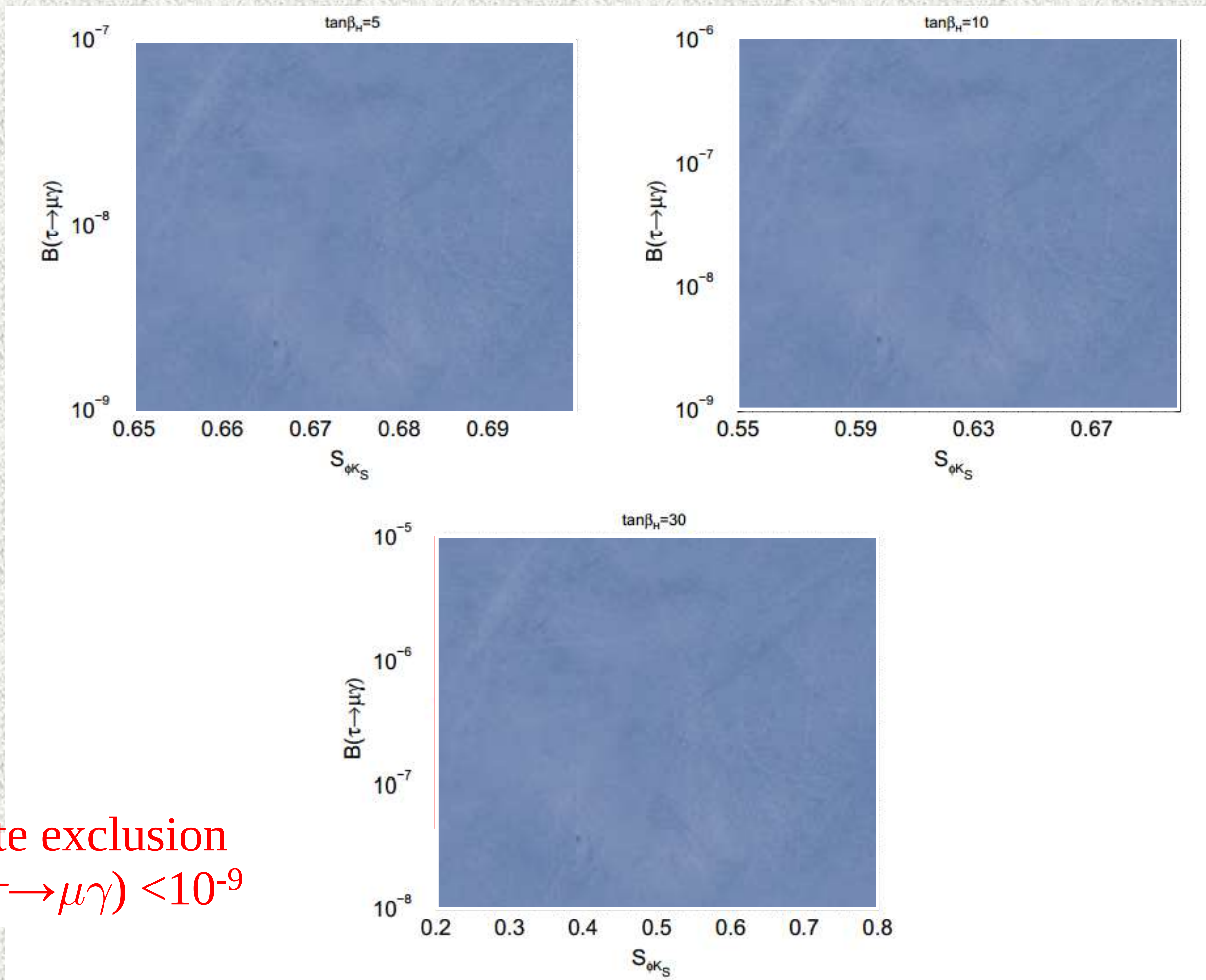
J. Hizano and Y. Shimizu
Phys. Lett. B565, 182 (2003)

An SU(5) SUSY GUT with right handed neutrinos



J. Hizano and Y. Shimizu
Phys. Lett. B565, 182 (2003)

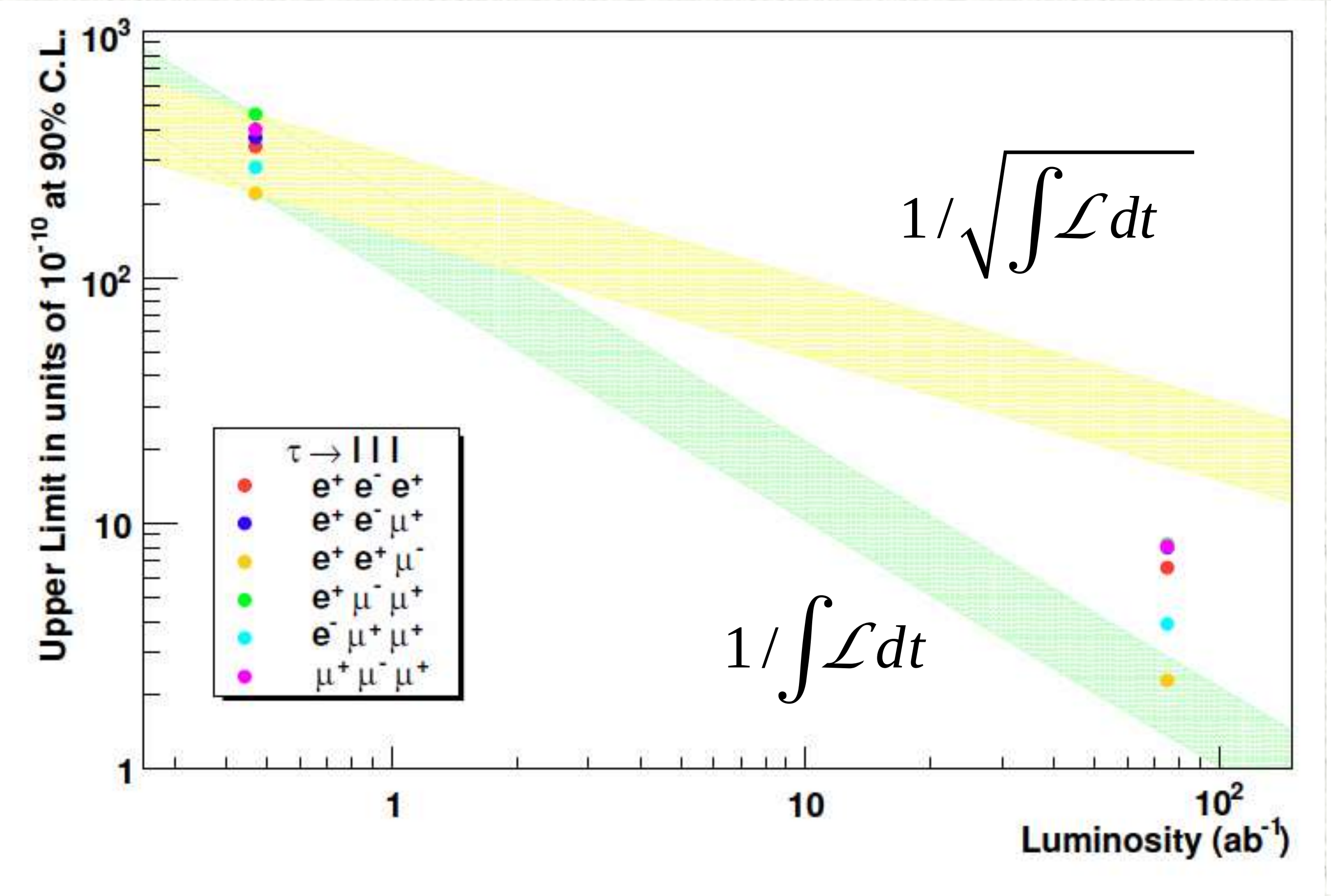
An SU(5) SUSY GUT with right handed neutrinos



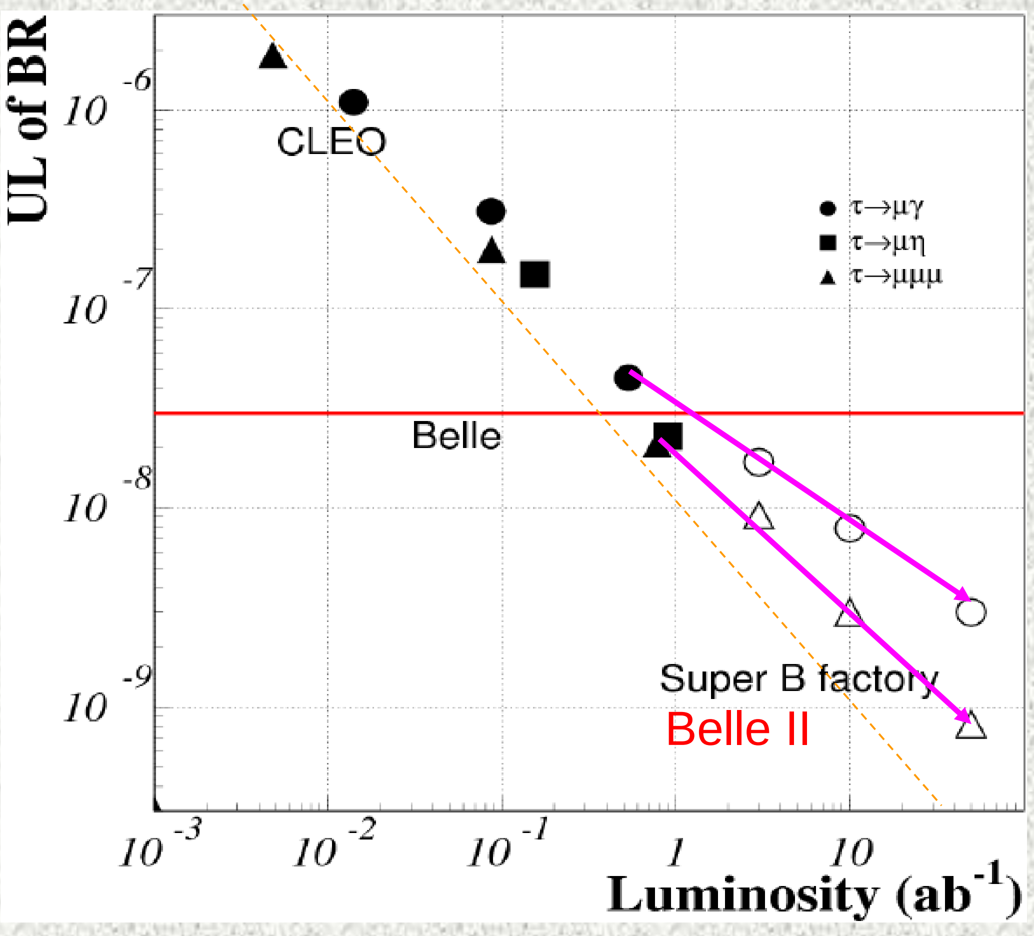
Complete exclusion with $B(\tau\to\mu\gamma) < 10^{-9}$

Sensitivity of τ *LFV* decay searches

- Current branching fraction limits, typically in the several x 10^{-8} range, don't have measurable backgrounds. Is this the case with 100× the data?
- It is difficult to do a realistic Monte Carlo simulation of potential backgrounds at a Super *B* Factory. Preparations for such detailed simulations are underway
- The no-background regime improves as $1/\int \mathcal{L}dt$
- If there are background events, the improvement is $1/\sqrt{\int \mathcal{L}dt}$



~~Super~~*B*



Belle II

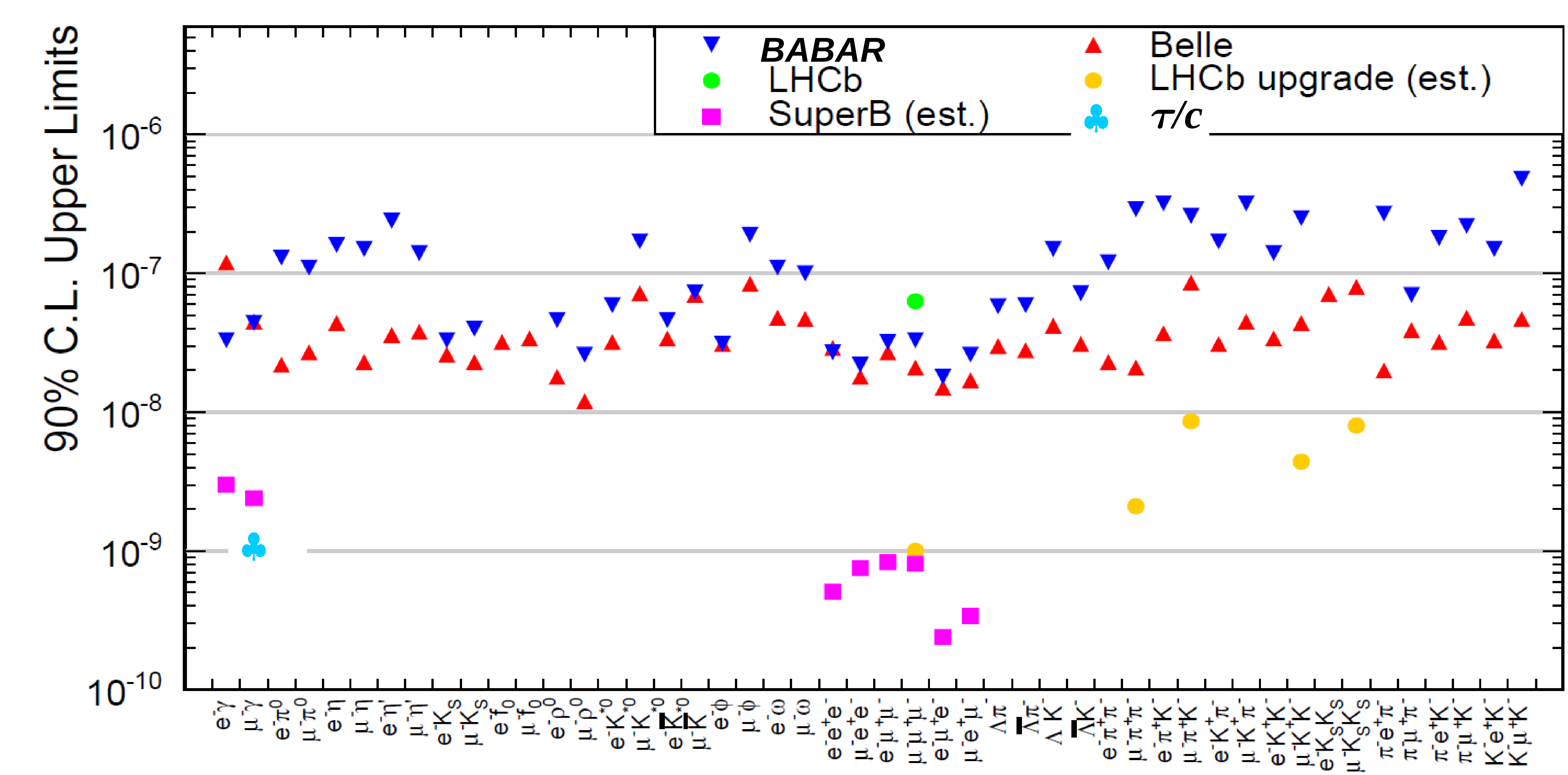
Sensitivity of $\tau \rightarrow \mu\gamma$ searches at B and τ/c factories

- How does sensitivity compare?
  - Assume running on resonance (not optimal for background rejection)
    - $\tau^+\tau^-$ production cross section ~1/*s* : KORALB: σ(3.77)/σ(10.58) = 2.8/0.92 = 3.05
    - Peak luminosity: SuperKEKB: 2 - 8 x10^{35} ; Super τ/c: 10^{35}
    - Integrated luminosity by 2023 : SuperKEKB: 50 ab^{-1}; Super τ/c: 10 ab^{-1}
  - Since there are irreducible backgrounds, *e.g.*, $e^+e^- \rightarrow \tau^+\tau^-\gamma$, sensitivity improves as $1/\sqrt{\int L\,dt}$
    - e^- polarization at τ/c reduces background by a factor of at least two, as at Super*B*|SuperKEKB, assuming SM-type couplings for New Physics

Collider	$\int L\,dt$	e^- polarization	$\tau^+\tau^-$ pairs	90 % CL limit
τ/c @ 3.686, 3.77, 4.17*	10	Y	3.2 x 10^{10}	10^{-9}
SuperKEKB @ $\Upsilon(4S)$	50	N	5 x 10^{10}	~3 x 10^{-9}

*A.V. Bobrov and A.F. Bondar, Nucl. Phys. **B225**, 195 (2012)

Super e^+e^- factory sensitivity directly confronts New Physics models of CLFV



Mode	*BABAR* ($\times 10^{-8}$)	Belle ($\times 10^{-8}$)	Super*B* ($\times 10^{-8}$)
$\tau^\pm \to e^\pm \gamma$	3.3	12	0.3
$\tau^\pm \to \mu^\pm \gamma$	4.4	4.5	0.2
$\tau^\pm \to \mu^\pm \mu^+ \mu^-$	3.3	2.1	0.08
$\tau^\pm \to e^\pm e^+ e^-$	2.9	2.7	0.02

Conclusions

- *BaBar* has performed CLFV searches in a large variety of τ decay modes, as well as in Υ decays (and *B* meson decays)
  - Sensitivity is best in $\tau \to \ell\ell\ell$ modes
  - Current limits already challenge some BSM models
- Sensitivity can be improved by one to two orders of magnitude at a next generation τ/c or *B* factory
  - A polarized e^- beam is advantageous in reducing SM background and also enables study of New Physics couplings in $\tau \to \ell\ell\ell$, as well as searches for a τ EDM and for *CP*V in τ decay