Search for Lepton-Flavor-Violating Tau Decays at the B-factories

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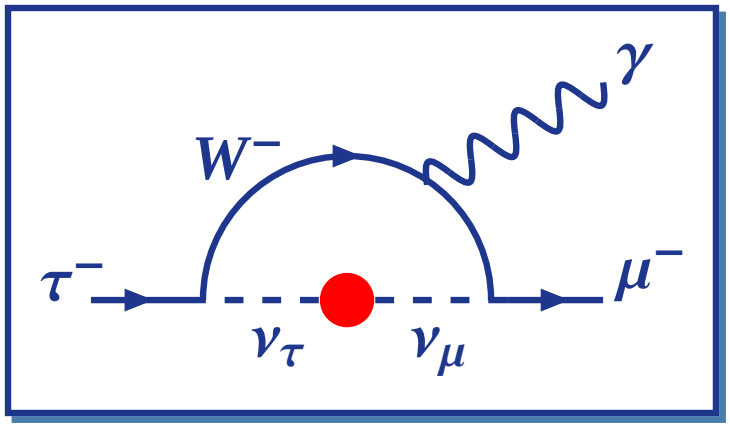
(on behalf of the *BABAR* collaboration)

Neutrino mixing observations → also Charged Lepton Flavour is Violated

$\tau \to \mu\gamma$ LFV from neutrino mixing

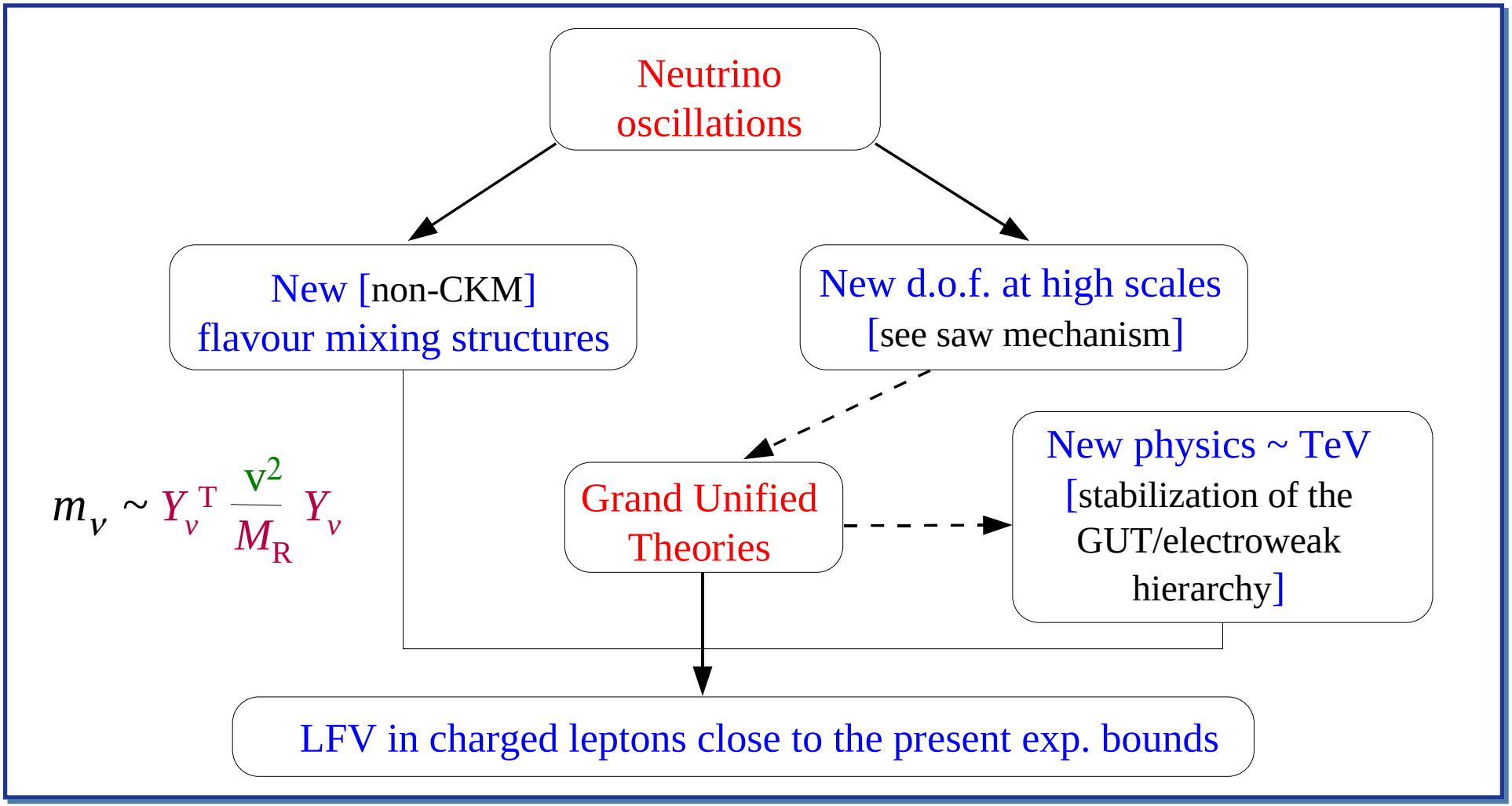


- however, neutrino-mixing induced LFV rates heavily suppressed and unobservable

  according to PRD 16 (1977) 1444:

  - $\dfrac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \dfrac{3\alpha}{32\pi}\dfrac{\Delta m^2_{\nu 12}}{M^2_W}\sin^2\theta_{21}\cos^2\theta_{21}$
  - for $\Delta m_{\nu 32} = 3{\cdot}10^{-3}\,eV$ and maximal mixing $\mathrm{BF}(\tau \to \mu\gamma) \approx O\left(10^{-54}\right)$

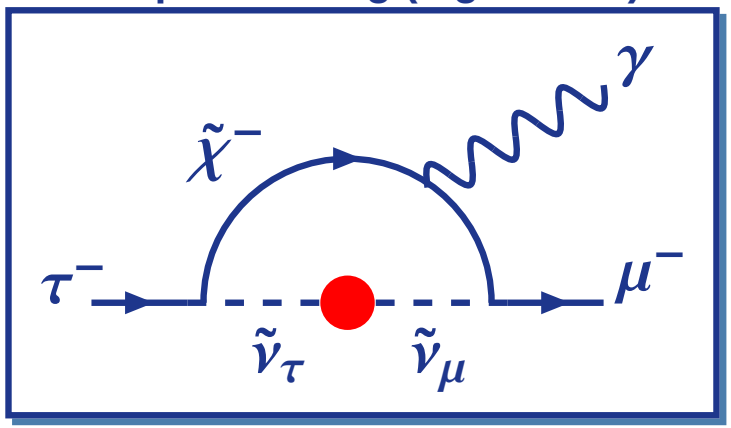
Neutrino mixing → viable NP theory models → LFV up to accessible rates



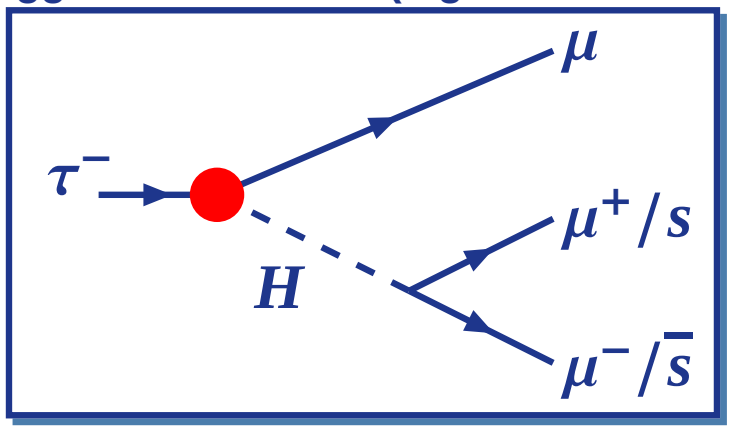
from G. Isidori, seminar at Super-B meeting, Frascati, September 2010

LFV expectations from New Physics models

s-lepton mixing (e.g. MSSM)



Higgs mediated LFV (e.g. NUHM SUSY)



Model	Reference	expected LFV BRs
SUSY Higgs	PLB 549 (2002) 159 PLB 566 (2003) 517	10^{-10} – 10^{-7}
SUSY heavy Majorana neutrinos	PRD 66 (2002) 034008	10^{-10} – 10^{-9}
Nonuniversal Z'	PLB 547 (2002) 252	10^{-9} – 10^{-8}
SUSY $SO(10)$	NPB 649 (2003) 189 PRD 68 (2003) 033012	10^{-10} – 10^{-8}
mSUGRA Seesaw	EPJ C14 (2002) 319 PRD 66 (2002) 115013	10^{-9} – 10^{-7}
SM with heavy Dirac neutrinos	PRD 62 (2000) 036010 NP B437 (1995) 491	10^{-6}

Tau LFV searches are complementary to muon LFV searches

relative strength of tau vs. muon LFV discriminates between two most natural NP mechanisms

$$A(l_i \to l_j \gamma) = a\,[Y_e Y_\nu^{+} Y_\nu]_{ij} + b\,[Y_U^{+} Y_U Y_D]_{ij}$$

PMNS mixing structure

dominant if $M_R > 10^{12}$ GeV $\Rightarrow$ $B(\mu \to e\gamma) \sim 10^{-13}\,(M_R/10^{12}\text{GeV})\,(\Lambda/10\,\text{TeV})^4$

CKM mixing structure

dominant if $M_R < 10^{12}$ GeV $\Rightarrow$ $B(\mu \to e\gamma) \sim 10^{-13}\,(\Lambda/10\,\text{TeV})^4$

$$B(\tau \to \mu\gamma) : B(\tau \to e\gamma) : B(\mu \to e\gamma) \sim \lambda^{-6} : \lambda^{-4} : 1 \sim 10^4 : 500 : 1$$

$$B(\tau \to \mu\gamma) : B(\tau \to e\gamma) : B(\mu \to e\gamma) \sim [500\text{–}10] : 1 : 1$$

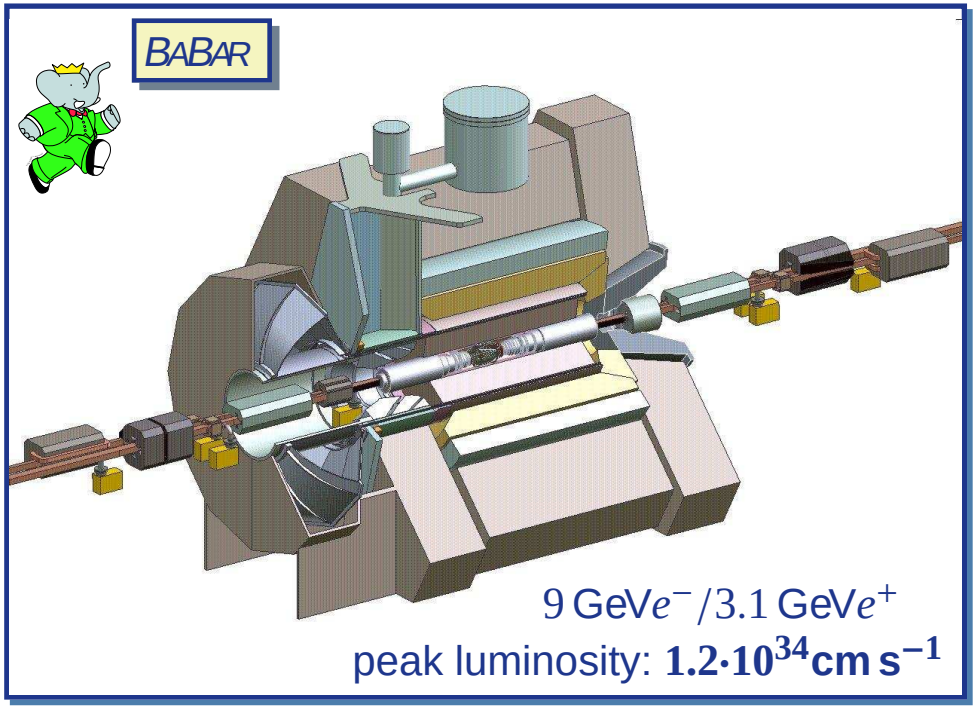
from G. Isidori, seminar at Super-B meeting, Frascati, September 2010

Brief status of Lepton Flavor Violation searches

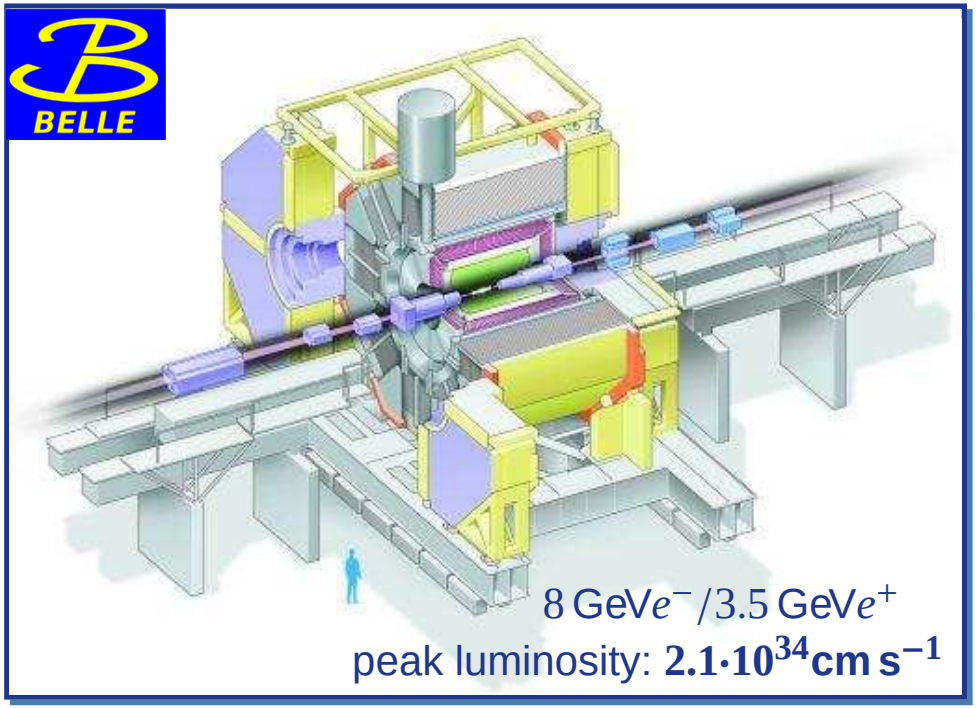
- tau LFV
  - past: CLEO explored up to BRs $\sim 10^{-6}$
  - **present: B-factories are completing exploration up to BRs $\sim 10^{-8}$**
  - future: Super Flavor Factories can explore up to BRs $\sim 10^{-10}$
  - **$\tau \to \mu\gamma$ is the most sensitive channel for most mainstream NP models**
- muon LFV
  - past: LAMPF, MEGA, BF($\mu \to e\gamma$) $< 1.2 \cdot 10^{-11}$ at 90% CL
  - past: SINDRUM II, BF($\mu \to e$ in nucleon field) $< 7 \cdot 10^{-13}$ at 90% CL
  - **present: MEG, BF($\mu \to e\gamma$) $< 1.5 \cdot 10^{-11}$ at 90% CL, (sensitivity $6 \cdot 10^{-12}$)**
  - future: MEG will soon reach sensitivity $\sim 10^{-13}$
  - future: Mu2E and COMET/PRISM can much increase reach on BF($\mu \to e$ in nucleon field)

B-factories detectors *BABAR* and Belle

- asymmetric colliders at & around $\Upsilon(4S)$ peak ($\sqrt{s} = 10.58$ GeV) $\sigma(\tau^+\tau^-) \approx 0.9\,\text{nb} \approx \sigma(B\bar{B}) \approx 1.1\,\text{nb}$
- similar detectors, but for PID: *BABAR* ⇒ RICH, Belle ⇒ threshold Cherenkov & TOF



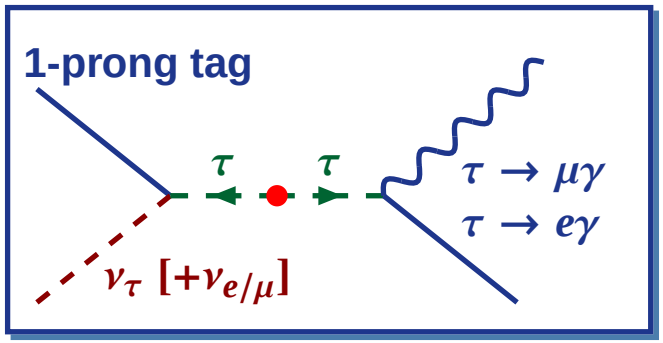
$\int Ldt \approx \mathbf{531\,fb^{-1}}$ recorded

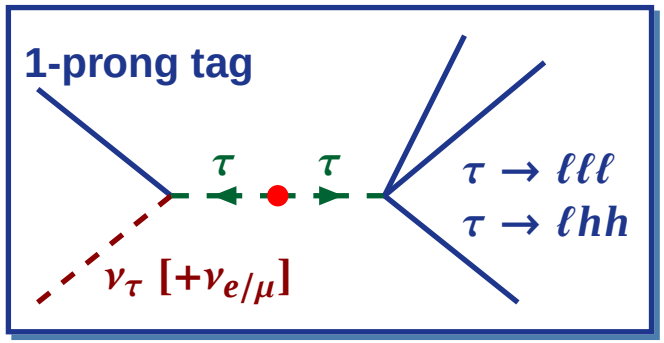


$\int Ldt \approx \mathbf{1040\,fb^{-1}}$ recorded, ended June 2010

LFV searches: typical selection requirements

- select large thrust low-multiplicity events
- **signal side** hemishpere: require tracks and neutrals coming from LFV decay
- **tag side** hemishpere: must be compatible with standard tau decay (1- or sometimes 3-prong)
  - missing transverse momentum
  - total invariant mass including neutrals < tau mass
- total visible energy: less than **di-lepton** events, larger than **two-photon** events





LFV searches: analysis strategy

neutrinoless tau decay in signal side

→ in the center-of-mass system:

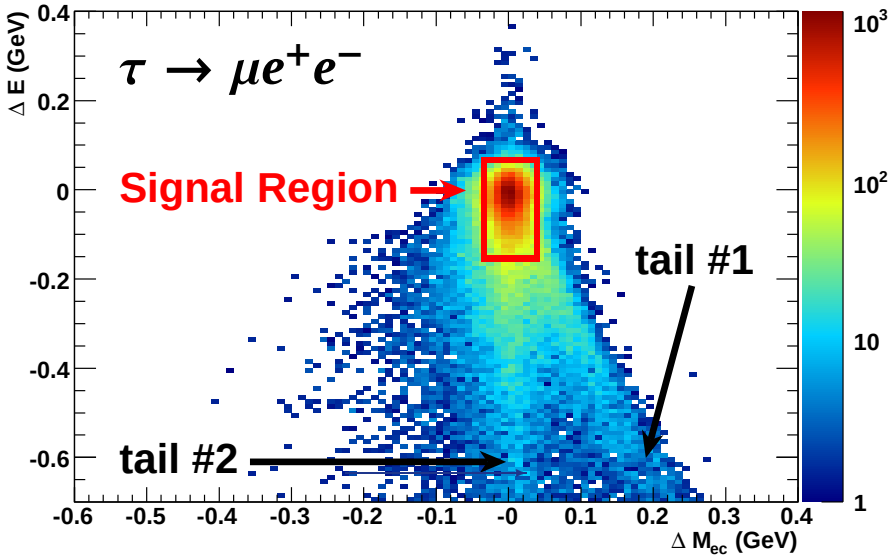
$\Delta M = M_{\text{reco}} - M_\tau = 0 \pm \sigma(\Delta M)$ (10–20 MeV)

$\Delta E = E_{\text{reco}} - \sqrt{s}/2 = 0 \pm \sigma(\Delta E)$ (~40 MeV)

M_{EC} **= energy-constrained refitted mass**

(improved resolution for signal events)

MC signal in $\Delta E - \Delta M$ plane (CM system)



typical analysis

- select signal candidates
- blind analysis, i.e. optimize without looking at data in Signal Region
- estimate background in SR
- estimate signal efficiency in SR
- finally, count N(candidates) – N(exp.bkg) in SR
- **BF(LFV)** = $\dfrac{N\text{(candidates)} - N\text{(exp.bkg)}}{2 \cdot \mathcal{L} \cdot \sigma_{\tau\tau} \cdot \varepsilon}$
- if BF ≈ 0, compute upper limits

signal smeared by resolution and radiation

tail #1 radiation before tau decay

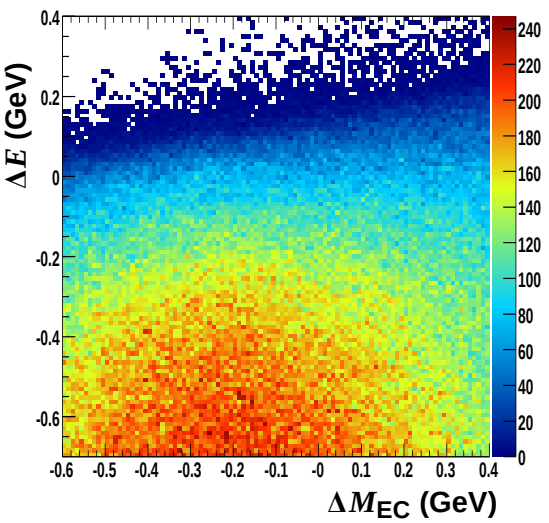
- ► Initial & Final State Radiation (ISR&FSR)

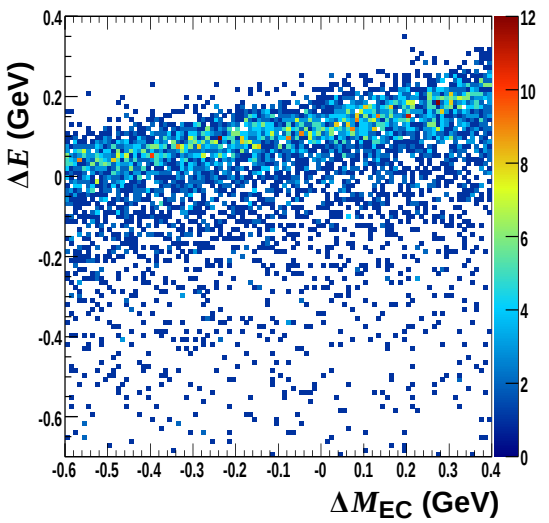
tail #2 radiation after tau decay

- ► tau decay products final state radiation
- ► ~recovered for energy-constrained mass

Typical backgrounds for LFV violating tau decays

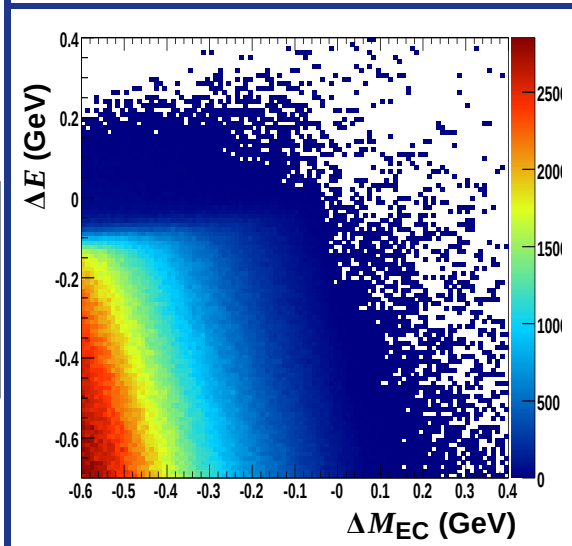
$q\bar{q}$ $(uds, c\bar{c}, b\bar{b})$
($b\bar{b}$ is negligible)
ΔM: no M_τ peak
$\Delta E < 0$

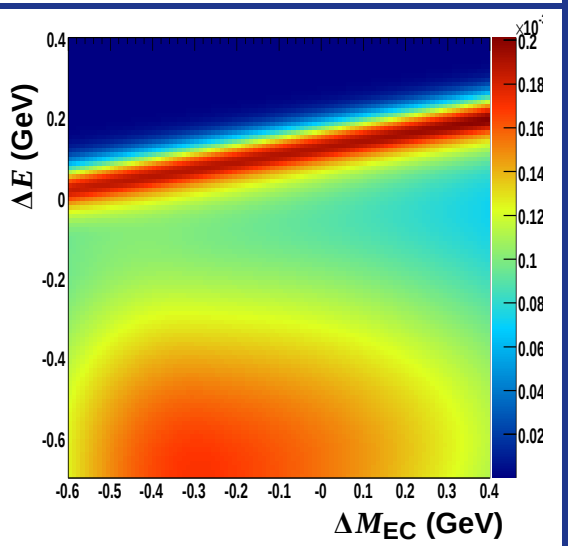




Bhabha, di-muon
ΔM: no M_τ peak
$\Delta E \approx 0$ band

$\tau^+\tau^-$, **two-photon**
$\Delta M < 0$
$\Delta E < 0$





expected bkg PDF
(from sidebands fit)

Status of *BABAR*

- end of data taking April 2008
- published analyses of ~full data sample for $\tau \to \mu/e\gamma$ and $\tau \to \ell\ell\ell$
- published results exists for other channels use samples less than but comparable to full data sample
  - ► only moderate improvements expected by updating to full data sample

Status of Belle

- end of data taking June 2010
- recent publications on ~full data sample: $\tau \to \ell K^0_S$ (671 fb^{-1}), $\tau \to \ell\ell\ell$ (782 fb^{-1})
- **recent preliminary results on ~full data sample: $\tau \to \ell P^0$ (901 fb^{-1}) and $\tau \to \ell V^0$ (854 fb^{-1})**
- progressing towards analysis of full data sample on $\tau \to \mu/e\gamma$ and other hadronic channels

see HFAG-Tau for updated references at

http://www.slac.stanford.edu/xorg/hfag/tau/HFAG-TAU-LFV.htm

Belle preliminary results on LFV searches presented at Tau 2010 – new

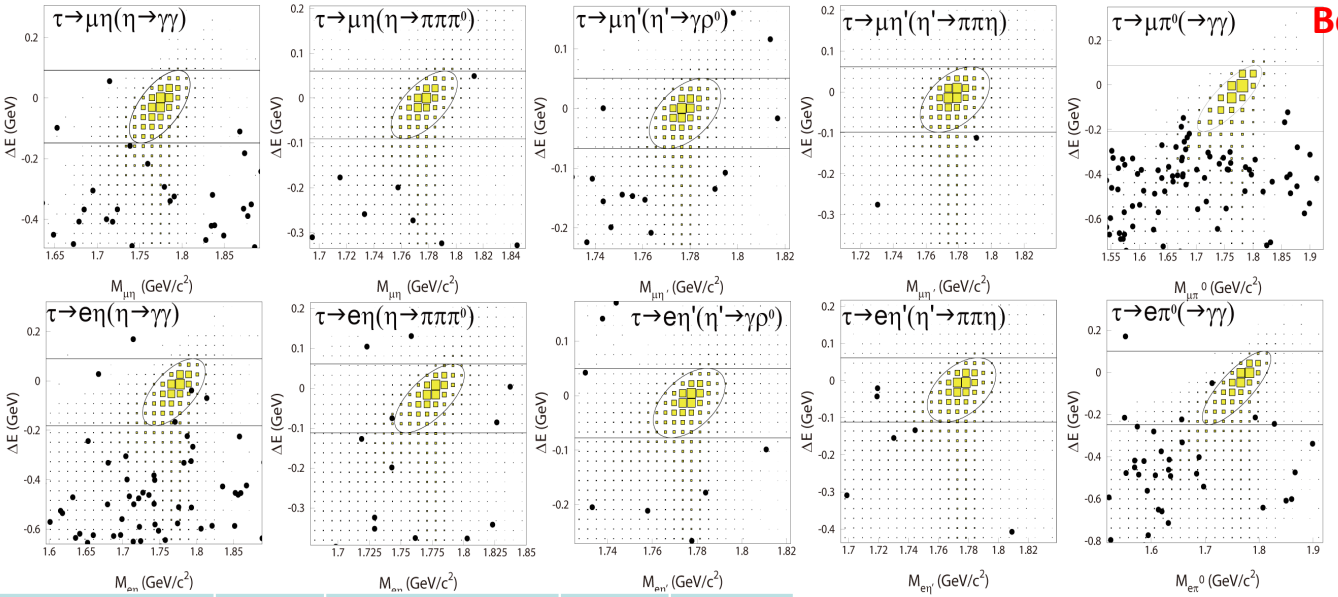
$\tau \to \ell P^0$, $P^0 = \pi^0, \eta, \eta'$ 901 fb^{-1} (previous Belle search 401 fb^{-1})

$\tau \to \ell V^0$, $V^0 = \rho, K^{*0}, \omega, \phi$ 854 fb^{-1} (previous Belle search 543 fb^{-1})

- η, η' modes:
  - mass constraint used
  - reconstructed both in $\gamma\gamma$ and in $\pi^+\pi^-\pi^0$ decay modes
- selection optimized mode-by-mode
  - **optimized for smallest expected BR evidence with 99% CL** (typical Belle strategy)
  - neural network for $\tau \to \mu\eta$
  - improved Bhabha rejection
- **improved efficiency and background suppression** w.r.t. Belle former searches on same channels

LFV search for $\tau \to \ell P^0$, $P^0=\pi^0, \eta, \eta'$

BELLE prelim. $901\ \text{fb}^{-1}$ K.Inami, Tau10

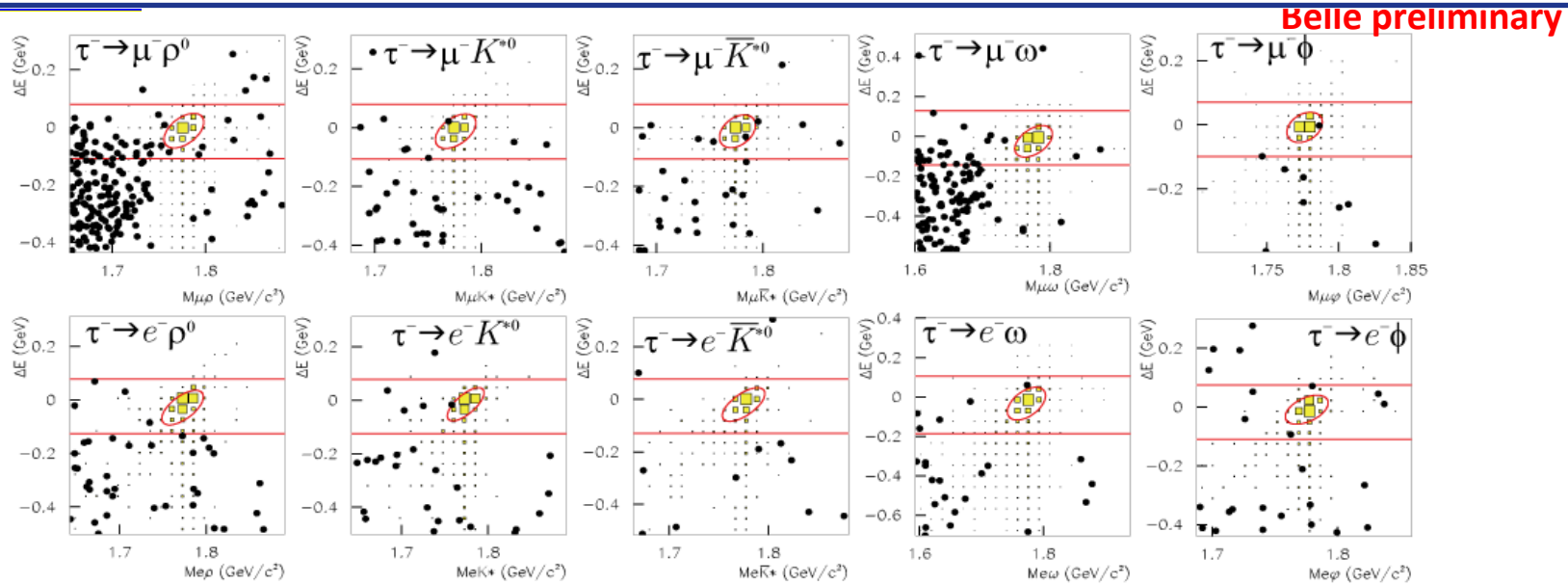


→(2.1-4.4) times more stringent results than previous Belle result (401fb^{-1})

τ→	Eff. %	N_{BG}^{exp}	$N_{obs.}$	UL $\times 10^{-8}$
μη(→γγ)	8.2	0.63±0.37	0	3.6
μη(→πππ^0)	6.9	0.23±0.23	0	8.6
μη(comb.)				**2.3**
eη(→γγ)	7.0	0.66±0.38	1	8.2
eη(→πππ^0)	6.3	0.69±0.40	0	8.1
eη(comb.)				**4.4**
μη'(→ππη)	8.1%	$0.00^{+0.16}_{-0.00}$	0	10.0
μη' (→ρ^{0}γ)	6.2%	0.59±0.41	0	6.6
μη' (comb.)				**3.8**
eη' (→ππη)	7.3%	0.63±0.45	0	9.4
eη' (→ρ^{0}γ)	7.5%	0.29±0.29	0	6.8
eη' (comb.)				**3.6**
μπ^0(→γγ)	4.2%	0.64±0.32	0	**2.7**
eπ^0(→γγ)	4.7%	0.89±0.40	0	**2.2**

LFV search for $\tau \to \ell V^0$, $V^0 = \rho, K^{*0}, \omega, \phi$

BELLE prelim. $854\,\text{fb}^{-1}$ K.Inami, Tau10



$\tau^- \to$	Eff.	N_{BG}^{exp}	$N_{obs.}$	UL $\times 10^{-8}$	$\tau^- \to$	Eff.	N_{BG}^{exp}	$N_{obs.}$	UL $\times 10^{-8}$
$e^-\rho^0$	7.6%	0.29 ± 0.15	0	**1.8**	e^-K^{*0}	4.4%	0.39 ± 0.14	0	**3.2**
$\mu^-\rho^0$	7.1%	1.48 ± 0.35	0	**1.2**	μ^-K^{*0}	3.4%	0.53 ± 0.20	1	**7.2**
$e^-\phi$	4.2%	0.47 ± 0.19	0	**3.1**	$e^-\overline{K^{*0}}$	4.4%	0.08 ± 0.08	0	**3.4**
$\mu^-\phi$	3.2%	0.06 ± 0.06	1	**8.4**	$\mu^-\overline{K^{*0}}$	3.6%	0.45 ± 0.17	1	**7.0**
$e^-\omega$	2.9%	0.30 ± 0.14	0	**4.8**	$\mu^-\omega$	2.4%	0.72 ± 0.18	0	**4.7**

2010/9/13 Tau2010

UL for $\tau \to \mu\rho^0$ is the most stringent among all the τ-LFV decays 12

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

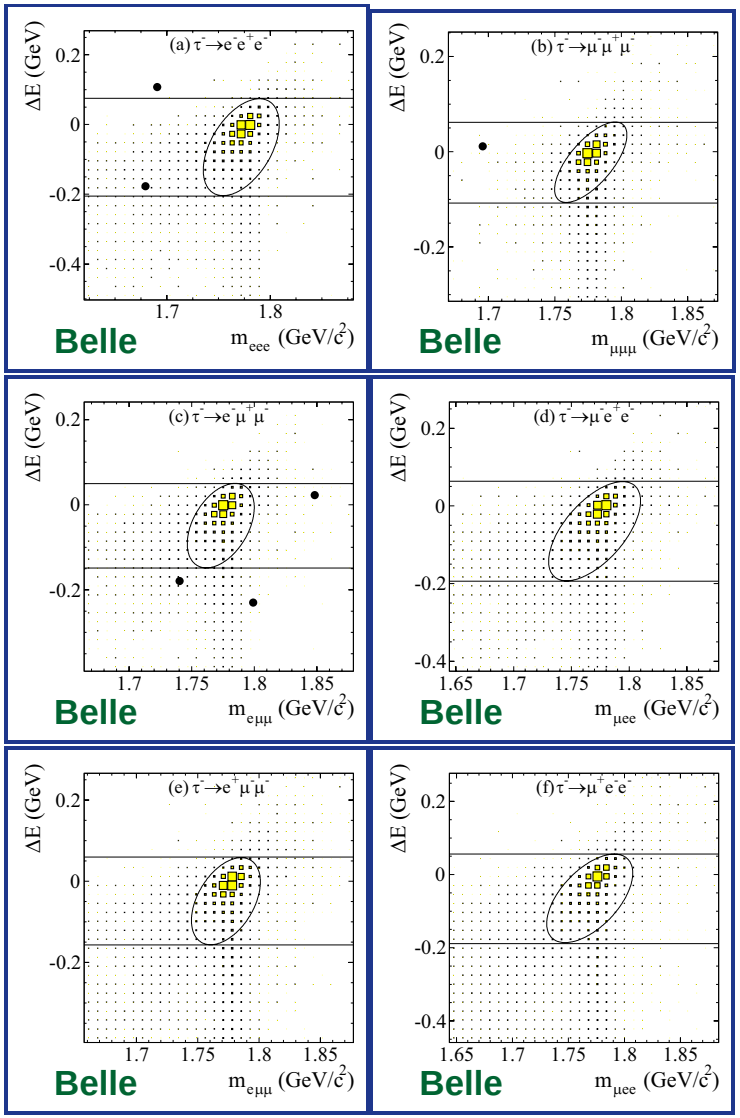
BELLE

$782\,\text{fb}^{-1}$

PLB 687 139 (2010)

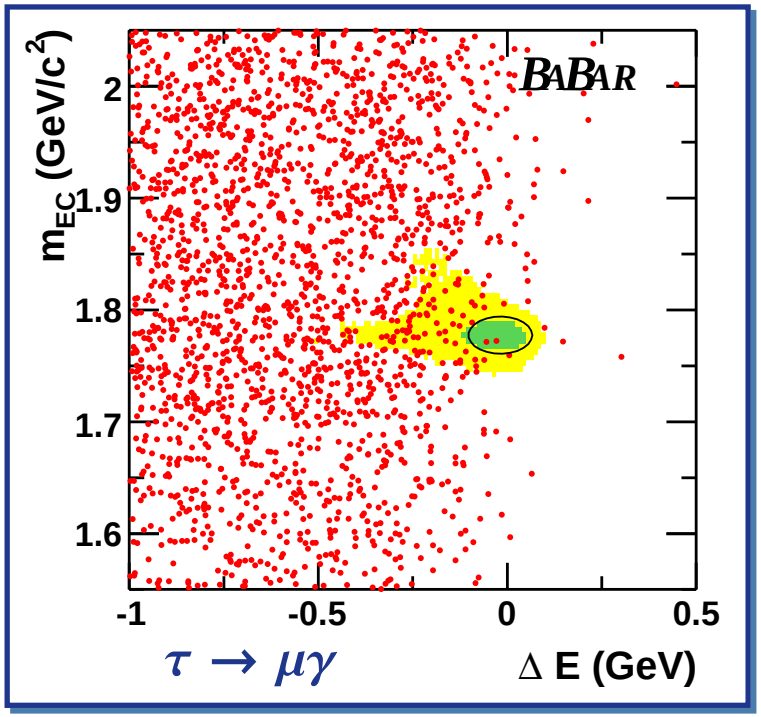
- **very small expected backgrounds**
  with good efficiency
- optimized for smallest BR with 99% significance
- 90% CL frequentistic upper limits with POLE

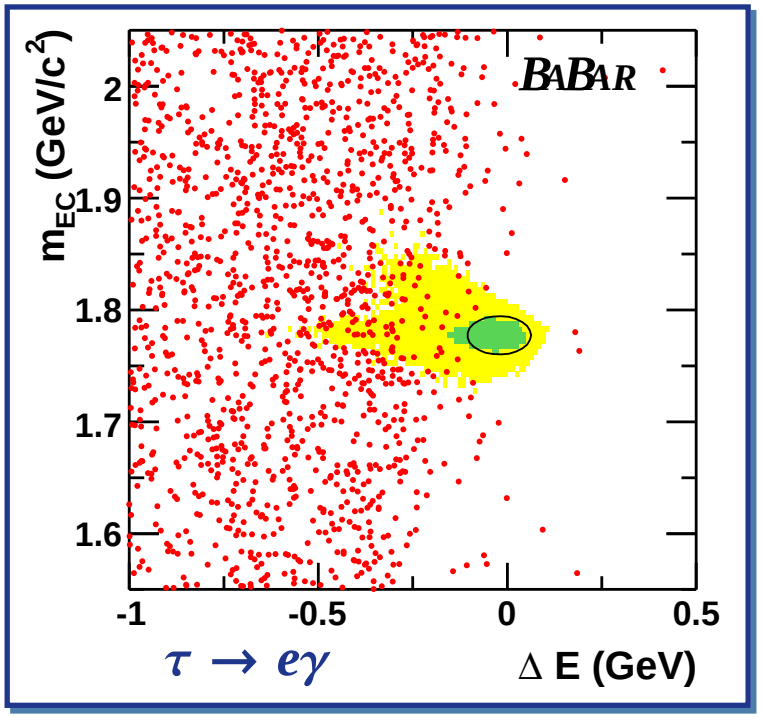
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^-e^+e^-$	6.0	0.21±0.15	9.8	0	<2.7
$\tau^- \to \mu^-\mu^+\mu^-$	7.6	0.13±0.06	7.4	0	<2.1
$\tau^- \to e^-\mu^+\mu^-$	6.1	0.10±0.04	9.5	0	<2.7
$\tau^- \to \mu^-e^+e^-$	9.3	0.04±0.04	7.8	0	<1.8
$\tau^- \to e^+\mu^-\mu^-$	10.1	0.02±0.02	7.6	0	<1.7
$\tau^- \to \mu^+e^-e^-$	11.5	0.01±0.01	7.7	0	<1.5



LFV $\tau \to \mu\gamma$ and $\tau \to e\gamma$

BABAR | 531 fb^{-1} | PRL 104 021802 (2008)





- efficiency: 6.1% ± 0.5%
- events, expected: 3.9 ± 0.3, found (2σ): 2
- 2σ $\Delta M - \Delta E$ box, freq. UL (POLE / F&C)
- **BF < 4.4·10^{-8} (90%CL)** exp.UL 9.8·10^{-8}
- *BABAR*/232 fb^{-1}: 6.8e−8, Belle/535 fb^{-1}: 4.5e−8

- efficiency: 3.9% ± 0.3%
- events, expected: 1.6 ± 0.3, found (2σ): 0
- 2σ $\Delta M - \Delta E$ box, freq. UL (POLE / F&C)
- **BF < 3.3·10^{-8} (90%CL)** exp.UL 8.2·10^{-8}
- *BABAR*/232 fb^{-1}: 1.1e−7, Belle/535 fb^{-1}: 1.2e−7

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

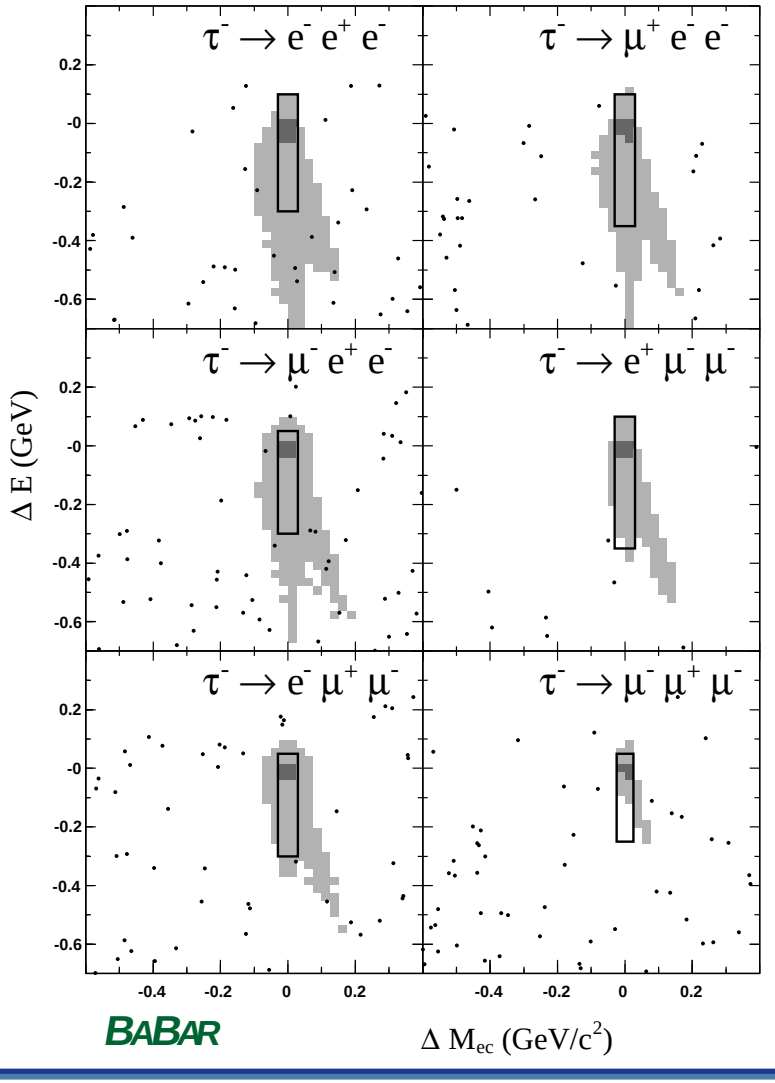
BABAR

468 fb^{-1}

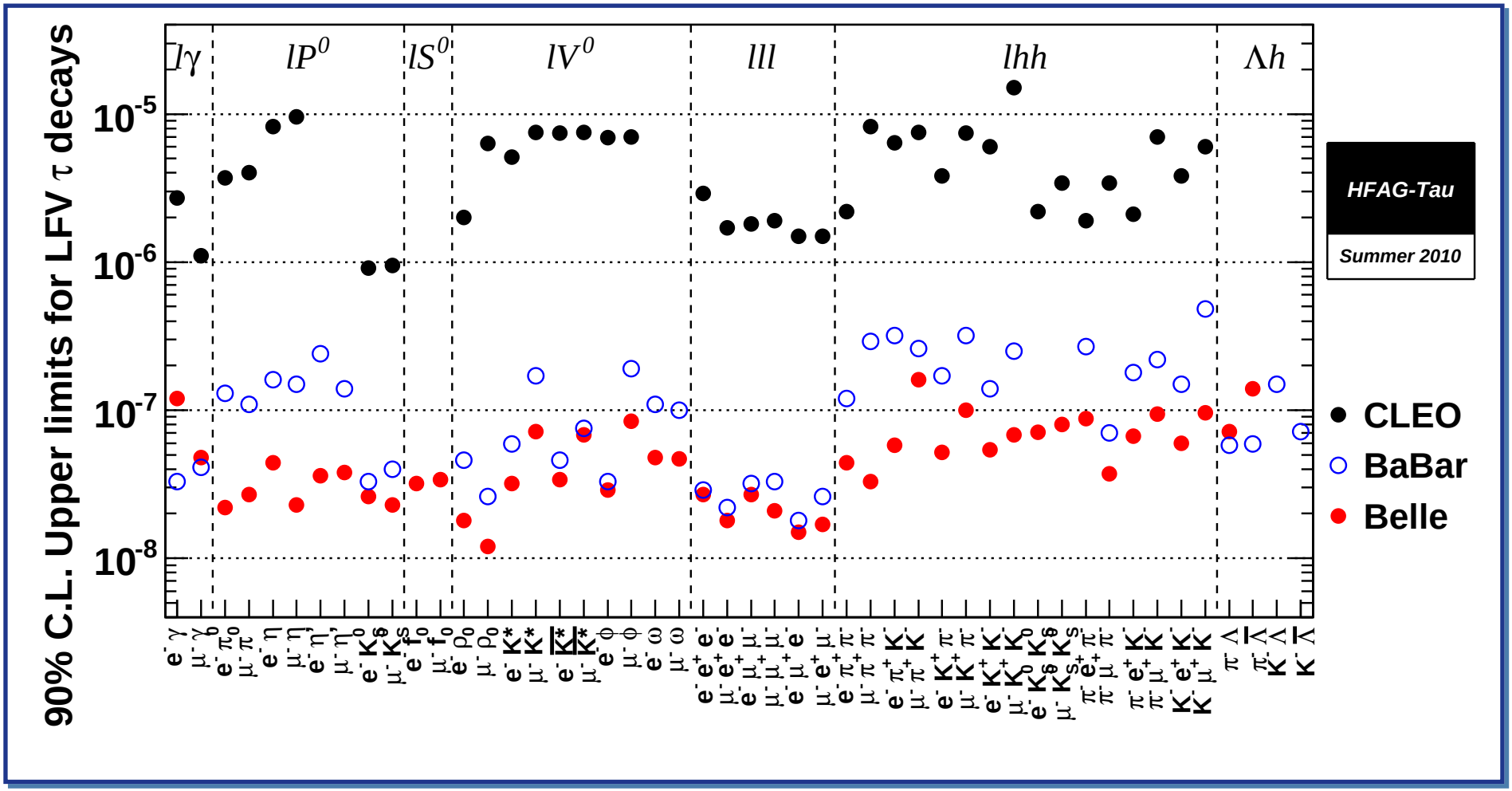
PRD 81 111101 (2010)

- background estimated with 2D ΔM-ΔE fit
- **optimized for smallest expected upper limit**
  → higher backgrounds than Belle
- optimization improved w.r.t. previous pub.
- frequentistic upper limit: POLE (Feldman&Cousins)
- moderate luminosity increase . . .
  but sizeable improvement w.r.t. past paper
  - muon PID 66% → 77%
  - electron PID 89% → 91%
- close/better limits than Belle with smaller statistics

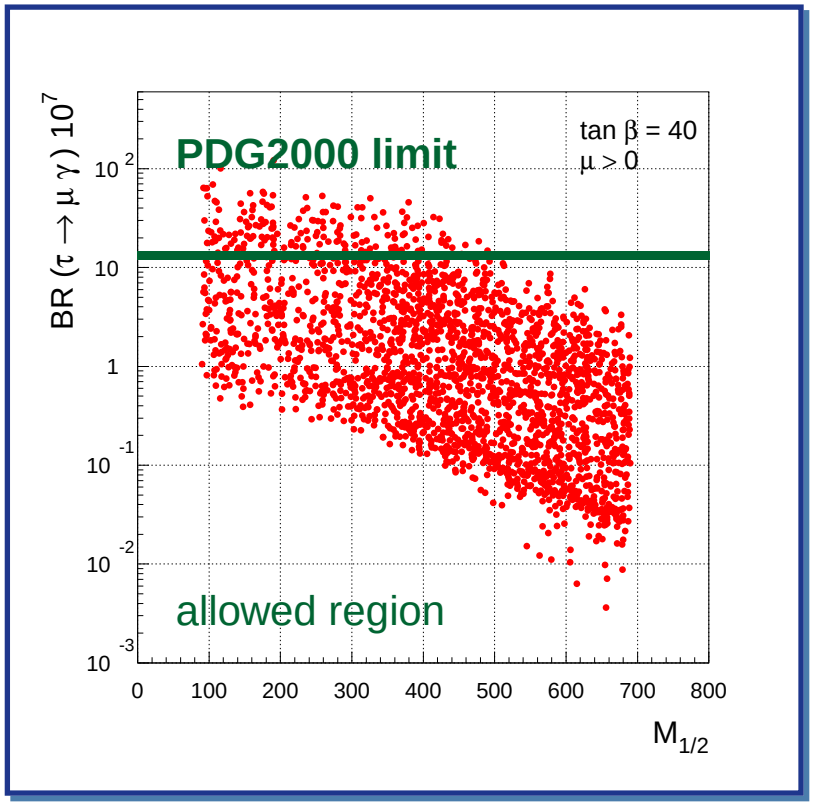
Mode	Eff. [%]	N_{bgd}	UL_{90}^{exp}	N_{obs}	UL_{90}^{obs}
$e^-e^+e^-$	8.6 ± 0.2	0.12 ± 0.02	3.4	0	2.9
$\mu^-e^+e^-$	8.8 ± 0.5	0.64 ± 0.19	3.7	0	2.2
$\mu^+e^-e^-$	12.7 ± 0.7	0.34 ± 0.12	2.2	0	1.8
$e^+\mu^-\mu^-$	10.2 ± 0.6	0.03 ± 0.02	2.8	0	2.6
$e^-\mu^+\mu^-$	6.4 ± 0.4	0.54 ± 0.14	4.6	0	3.2
$\mu^-\mu^+\mu^-$	6.6 ± 0.6	0.44 ± 0.17	4.0	0	3.3

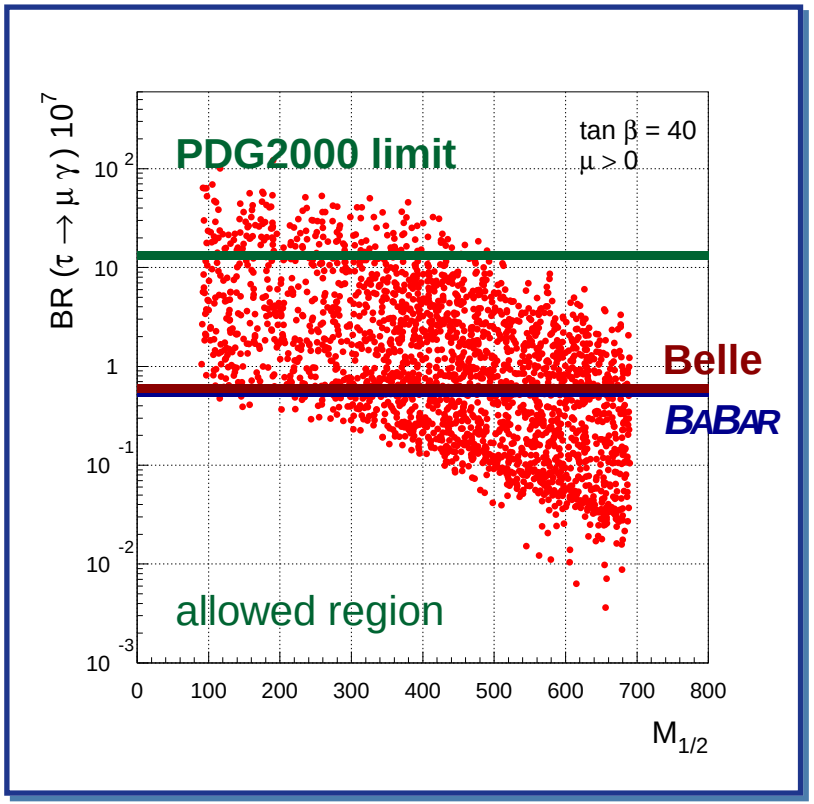


Tau LFV results status (by HFAG-Tau)



B-factories LFV searches do constrain the parameter space of NP models





SUSY SO(10) + seesaw – Masiero et al., NJP 6 (2004) 202

Prospects at the Super Flavour Factories

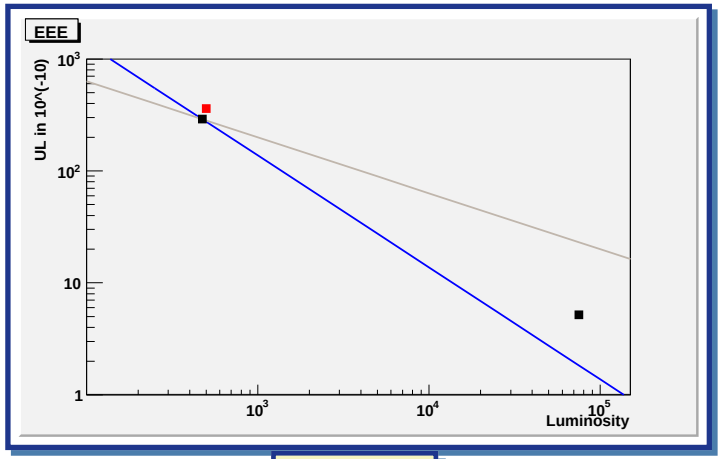
- Belle2 and Super$B$ promise integrated luminosities in the range of $50-75\,\mathrm{ab}^{-1}$
- background limited searches
  - → **repeat analyses optimized for the B-factories**
  - → LFV reach increases $\propto \sqrt{\text{luminosity}}$ i.e. ≈ 10
- background free searches
  - → optimize selection at ~constant efficiency to **expect $\lesssim$1 bkg events**
  - → LFV reach increases $\propto$ luminosity i.e. ≈ 100
- all searches
  - ► reach improves with hermeticity, PID, tracking/neutrals efficiency
  - ► reach worsens with beam background (only modest deterioration expected for nano-beam SFF)

2010 Super*B* Physics Report, arXiv:1008.1541v1 [hep-ex]

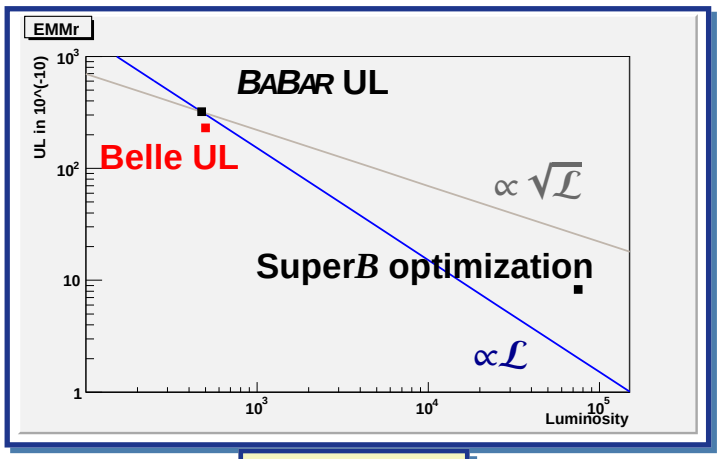
- $\tau \to \ell\gamma$
  - **repeated** last published *BABAR* analysis at Super*B* luminosity
  - estimated gains from improved tracking resolution & photon acceptance
- $\tau \to \ell\ell\ell$
  - **re-optmimized** last published *BABAR* result for Super*B* luminosity
  - neglected expected gains from better tracking resolution
- ~80% electron beam polarization
  - increases experimental reach reach given the LFV interaction
  - facilitates determination of LFV interaction structure

Process	Expected 90% CL upper limit	3σ evidence reach
BF($\tau \to \mu\gamma$)	$2.4 \cdot 10^{-9}$	$5.4 \cdot 10^{-9}$
BF($\tau \to e\gamma$)	$3.0 \cdot 10^{-9}$	$6.8 \cdot 10^{-9}$
BF($\tau \to \ell\ell\ell$)	$2.3–8.2 \cdot 10^{-10}$	$1.2–4.0 \cdot 10^{-9}$

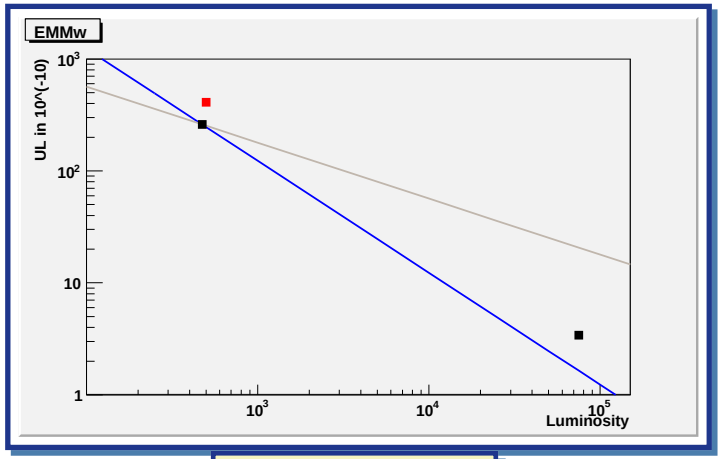
Super$B$ $\tau \to 3\ell$ 90% CM upper limit extrapolations: $\propto \mathcal{L}$ vs. $\propto \sqrt{\mathcal{L}}$ vs. re-optimization



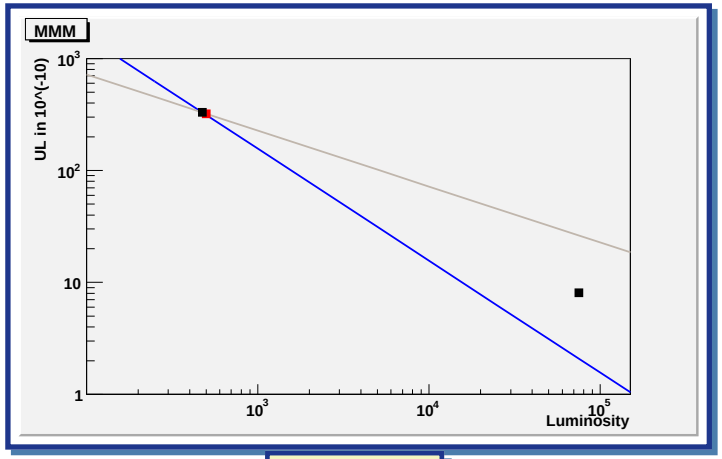
$\tau \to eee$



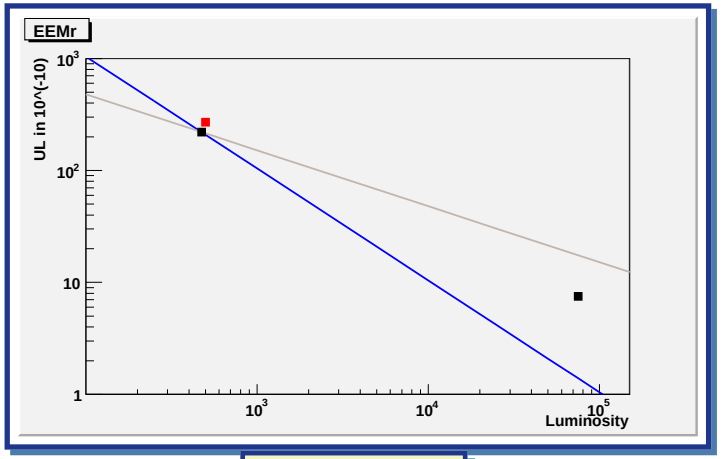
$\tau \to e\mu+\mu-$



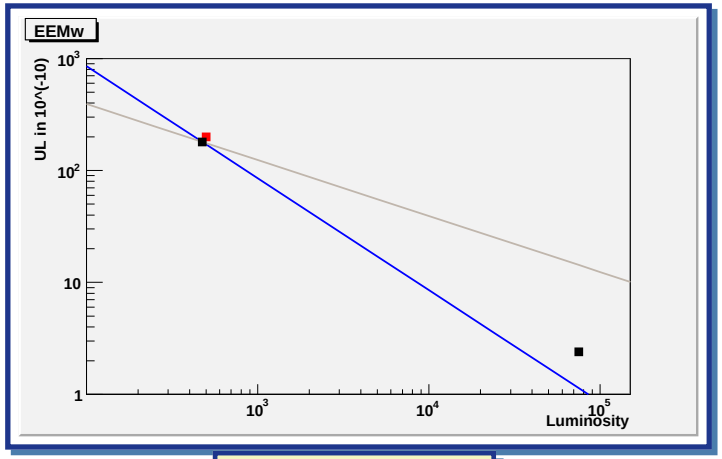
$\tau- \to e+\mu-\mu-$



$\tau \to \mu\mu\mu$



$\tau \to \mu e+e-$



$\tau- \to \mu+e-e-$

Summary

- tau LFV expected up to the experimental sensitivity in many mainstream NP models
- B-factories have found no evidence of tau LFV yet up to BF $\approx 10^{-8}$
  - *BABAR* has published LFV searches on its full statistics or at least on a fair part of it
  - Belle is completing $\tau \to \mu/e\gamma$ on its full data sample
    and has recently produced several preliminary results samples close to its full statistics
- muon LFV searches are active in the present, and improved experiments are planned for the future
- within this decade Super Flavour Factories will explore tau LFV up to BRs = 10^{-9}–10^{-10}