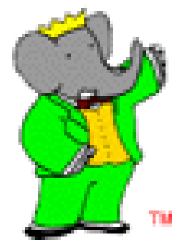
Lepton Flavour Violation in τ decays: Status and Perspectives ...



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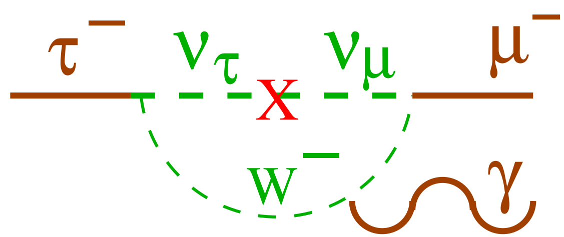
Flavour in the era of the LHC,

Workshop at CERN ($7^{\rm th} - 10^{\rm th}$ Nov 2005)

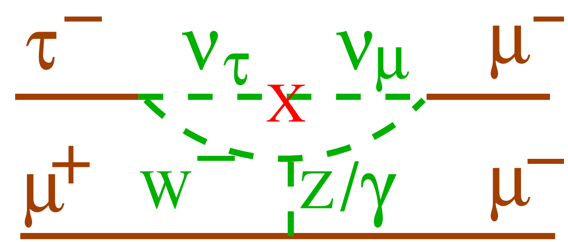
Introduction

- Lepton flavor violation (LFV)
  - not forbidden by SM gauge symmetry
  - most new models explicitly include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
  - SM extended to include finite ν mass and mixing predicts LFV



$\mathcal{B}(\tau \to \mu\gamma) \approx \mathcal{O}(10^{-54})$

PRL95(2005)41802



$\mathcal{B}(\tau \to \mu\mu\mu) \approx \mathcal{O}(10^{-14})$

EPJC8(1999)513

... many orders below experimental sensitivity!

- Observation for LFV $\Rightarrow$

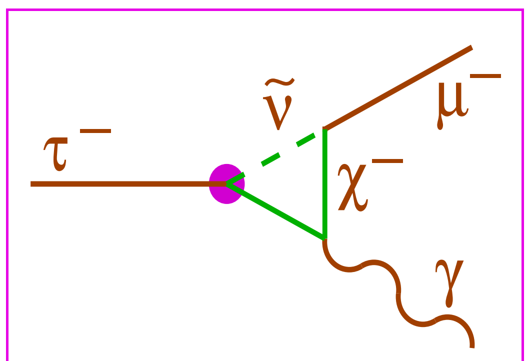
unambiguous signature of new physics

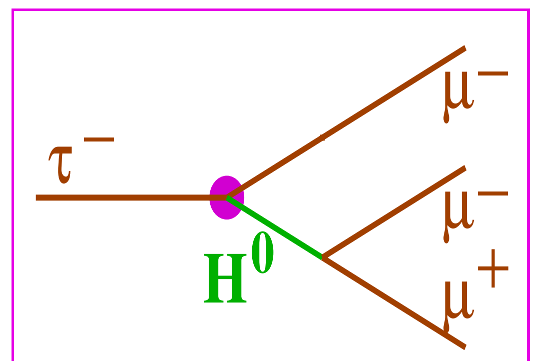
LFV τ decays

- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons
- Some models predict LFV upto existing experimental bounds
- Neutrinoless 2 and 3 body τ decays have different sensitivity

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}	10^{-8}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}

Illustrative scenarios ...





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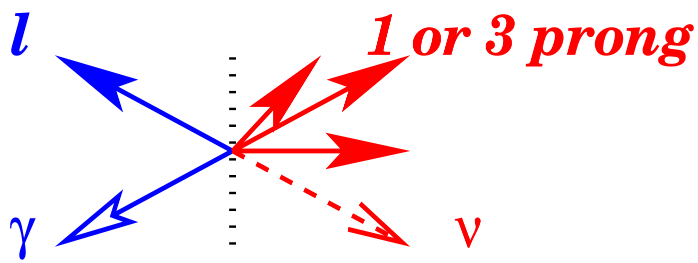
$e^+e^- \to \tau^+\tau^-$ (clean environment)

Search for LFV $\tau \to \ell\gamma$, $\tau \to \ell\ell\ell$, $\tau \to \ell hh'$ decays $(\ell = e, \mu; h = \pi, K)$

- *Divide τ-pair event $\perp$ to thrust axis (CM frame) in 2 hemispheres*

$\tau \to \ell\gamma$

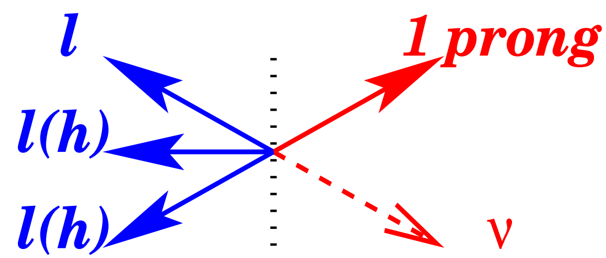


Signal–Side **Tag–Side**

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)

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



Signal–Side **Tag–Side**

Backgrounds:

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

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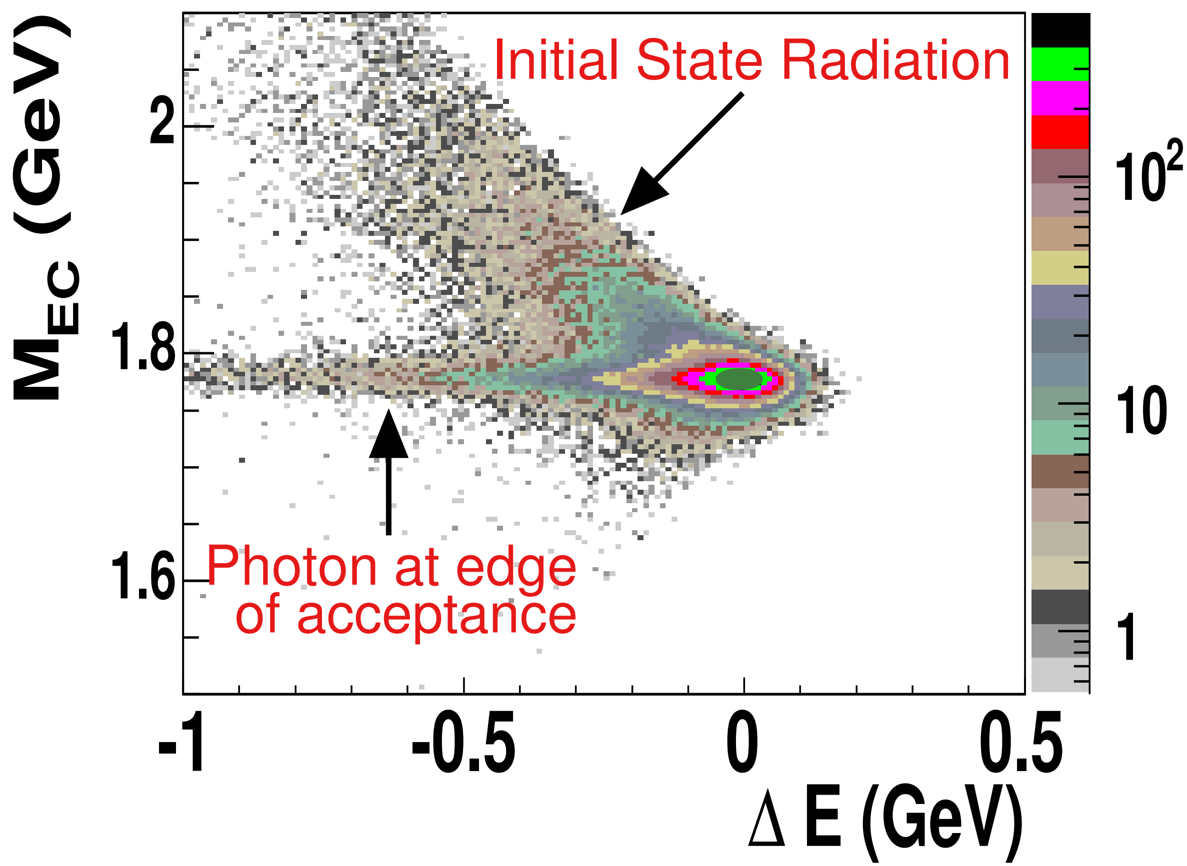
$\tau \to \mu\gamma$

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



$\tau \to \mu\gamma$ simulation

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

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

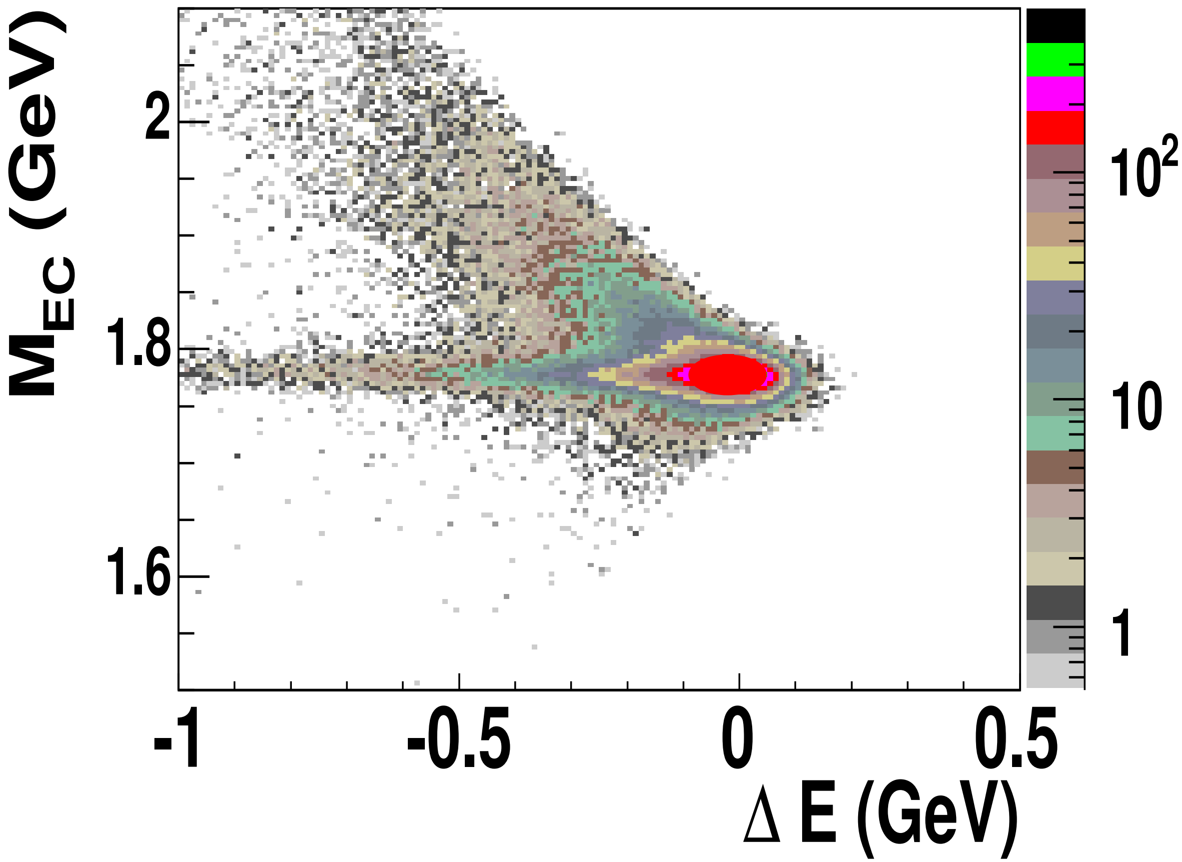
M_{EC} ($\sigma \sim 9$ MeV)

Beam energy constrained mass after vertexing

γ at μ $_{\mathrm{POCA(XY)}}$

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

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



$\tau \to \mu\gamma$ simulation

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

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

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

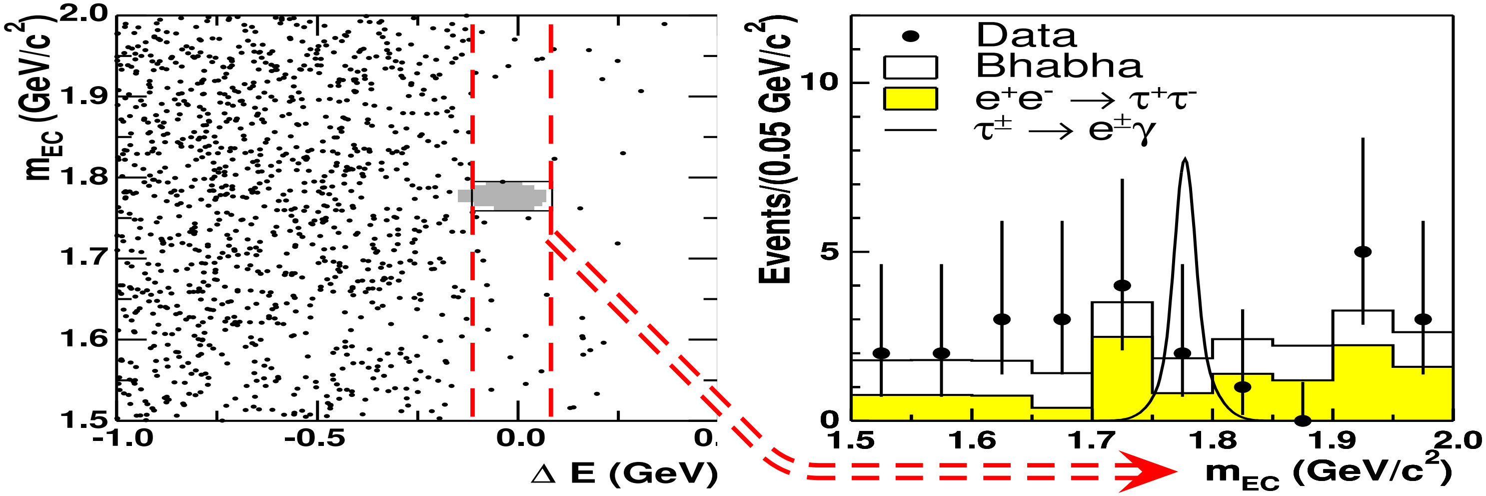
Beam energy constrained mass after vertexing

γ at μ $_{\text{POCA(XY)}}$

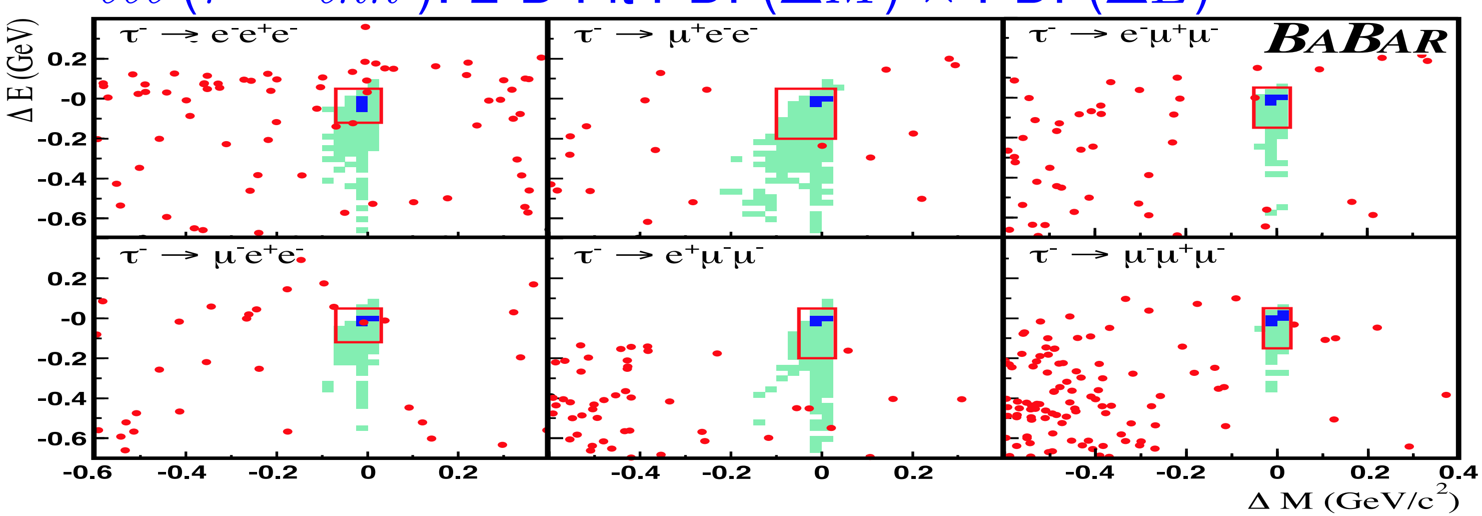
☛ Blinded Region: $\pm$ 3 σ around ($\langle\Delta E\rangle$, $\langle M_{EC}\rangle$)

Background estimation

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



- $\tau \to \ell\ell\ell$ ($\tau \to \ell h h'$): 2-D Fit PDF(ΔM) × PDF(ΔE)



Upper Limit

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

- $N_{\rm UL}^{90}$: 90% C.L. Upper Limit for $(N_{\rm obs}, N_{\rm bkg})$ from Data
- ε: high statistics signal MC simulated for different Data-taking periods

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

- $N_\tau = 2 \times \mathcal{L} \times \sigma_{\tau^+\tau^-}$
  - $\sigma_{\tau^+\tau^-}(10.6\,{\rm GeV}) \sim 0.89\ nb$
  - $\rm L \sim 250\ fb^{-1}$ (BaBar Summer 2005)

$\Rightarrow\ N_\tau \sim 4.5 \times 10^8$

B-Factories: Status

Channel	BaBar		Belle	
	$B^{90}_{\rm UL}$ (10^{-7})	$\mathcal{L}$ (fb^{-1})	$B^{90}_{\rm UL}$ (10^{-7})	$\mathcal{L}$ (fb^{-1})
$\tau \to \mu\gamma$	0.7	232.2	3.1	86.3
	PRL95(2005)41802		PRL92(2004)171802	
$\tau \to e\gamma$	1.1	232.2	3.9	86.7
	hep-ex/0508012 (sub PRL)		PLB613(2005)20	
$\tau \to \mu\mu\mu$	1.9	91.5	2.0	87.1
	PRL92(2004)121801		PLB589(2004)103	
$\tau \to eee$	2.0	91.5	3.5	87.1
	PRL92(2004)121801		PLB589(2004)103	
$\tau \to \ell\ell\ell$	(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	
$\tau \to \ell\pi^0/\eta/\eta'$			(2-10)	153.8
			PLB622(2005)218	
$\tau \to \ell K^0_S$			(0.5-0.6)	281
			hep-ex/0509014	

B-Factories: Projections

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

- $\tau \to \mu\gamma$ search: Optimize: $N^{90}_{\rm UL}/\varepsilon$
  - Sensitivity: $B^{90}_{\rm UL} \sim 1.2 \times 10^{-7}$ (BaBar, 232.2 fb^{-1})
-

	No Background	With Background
$N^{90}_{\rm UL}$	$2.3 \times \sqrt{N_{\rm obs}} \sim \mathcal{O}(1)$	$\sqrt{\mathcal{L}}$
$B^{90}_{\rm UL}$	$\propto 1/\mathcal{L}$	$\propto 1/\sqrt{\mathcal{L}}$

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

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

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

$\tau \to \mu\gamma$: LHC expectations

- Energy of τ not known, Mass(daughters) $\sim$ m$_\tau$

- Signal
  - $qq \to W \to \tau(\to \mu\gamma)\nu$
    $\sigma \times \mathcal{B}$ = 14.8 nb
    $\Rightarrow N_\tau \sim 1.5 \times 10^8$
    (for 10 fb^{-1} low luminosity 1yr data)

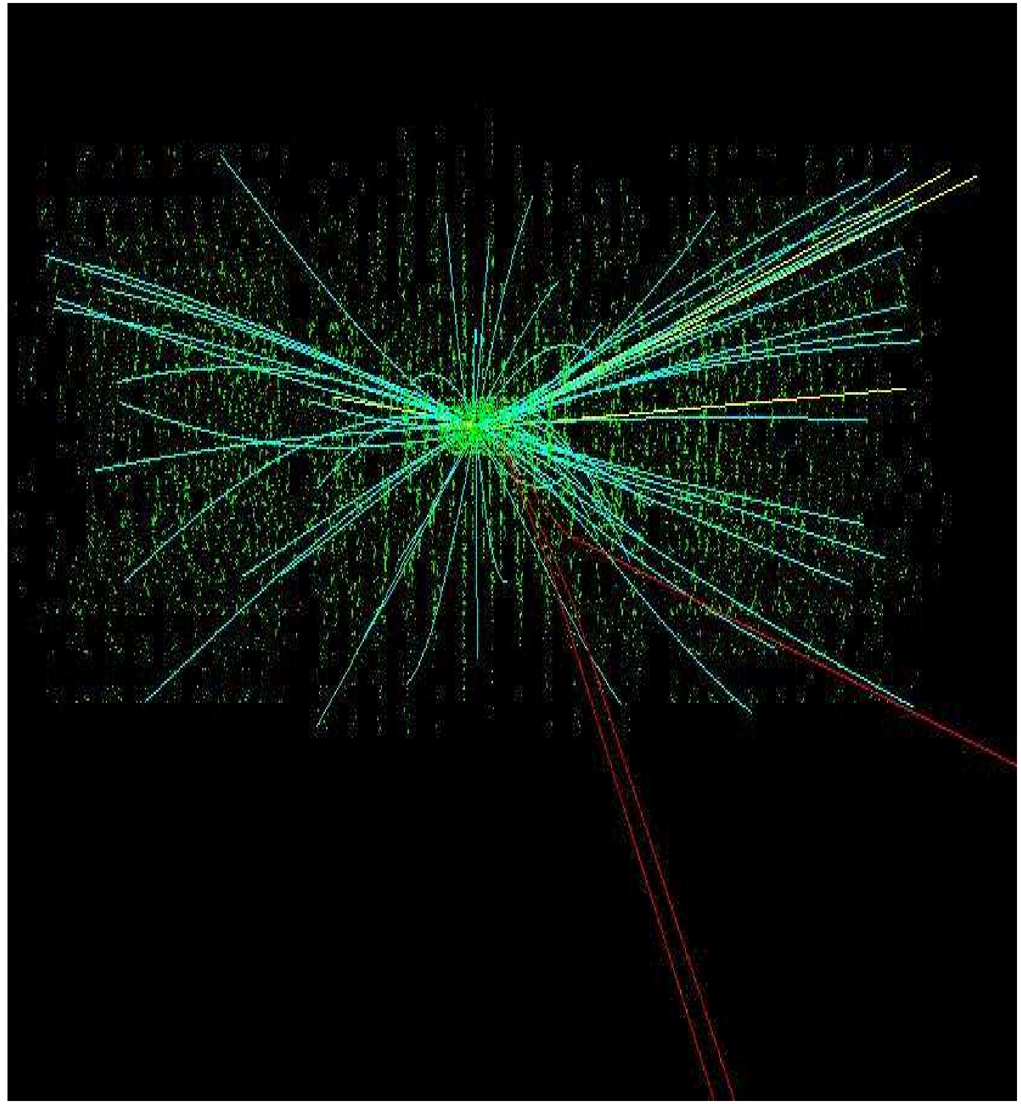
- Backgrounds
  - FSR
    - $qq \to W \to \mu\nu\gamma$
    - $qq \to W \to \tau(\to \mu\nu\bar{\nu})\nu\gamma$
  - Radiative production
    - $qq \to W\gamma \to \mu\nu\gamma$

- L. Serin and R. Stroynowski (ATL-PHYS-97-114):
  - ε = 5.4%, N_{bkg} = 17 events/yr (10 fb^{-1})
  - Sensitivity $\mathcal{B}(\tau \to \mu\gamma)$ = (2.3 $\times \sqrt{N_{bkg}}$) / ($N_\tau \times \varepsilon$) $\sim$ 10^{-6}
  - For 30 fb^{-1} data : $\mathcal{B}(\tau \to \mu\gamma) <$ 0.6 $\times$ 10^{-6}
- E. Barberio (SMU, 2002):
  - Signal: $Z \to \tau\tau$ decays $\Rightarrow N_\tau = 2 \times \mathcal{L} \times \sigma \times \mathcal{B}$
  - For 30 fb^{-1} data : $\mathcal{B}(\tau \to \mu\gamma) <$ 0.5 $\times$ 10^{-7}

$\tau \to \mu\mu\mu$: LHC expectations

- Event Signature:
  - 3 prong vertex
  - μ ID
  - m($\mu\mu\mu$) $\sim$ m$_\tau$

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}



CMS Simulation

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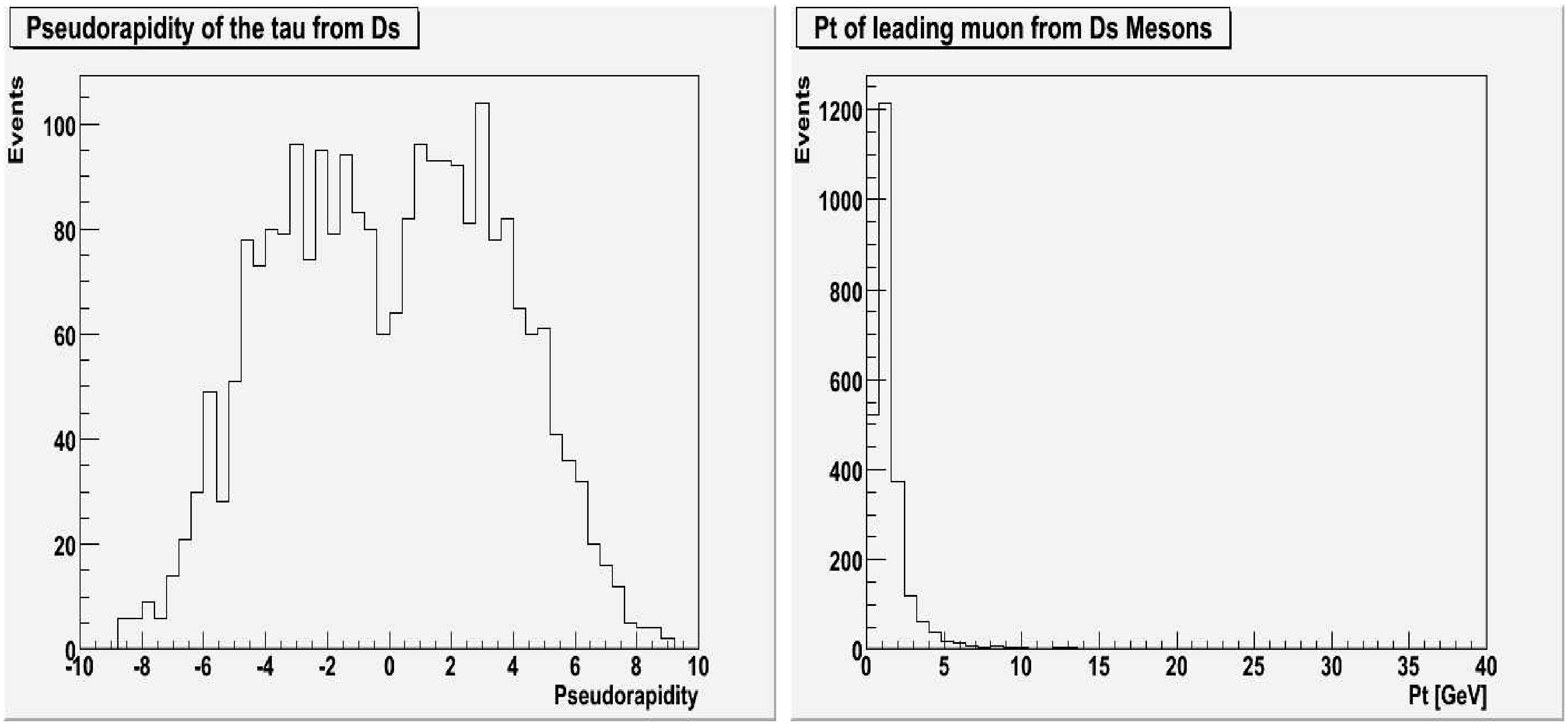
$\tau \to \mu\mu\mu$: LHC expectations

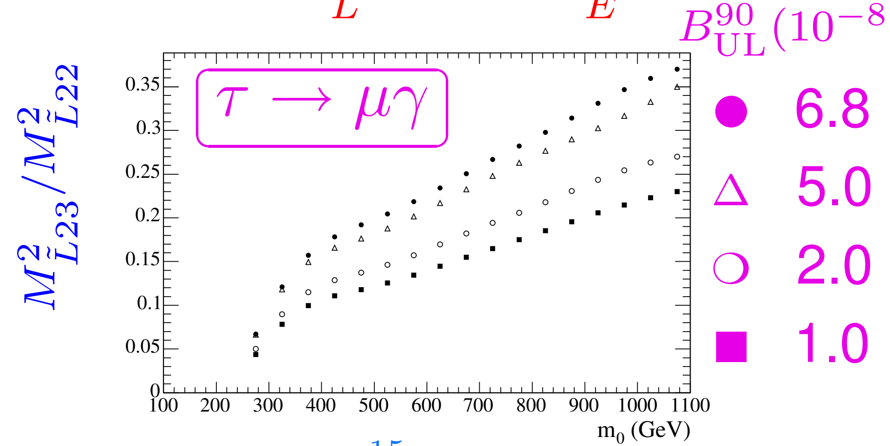


- Level 1 Trigger: single-muon p$_T > 14$ GeV, di-muon p$_T > 3$ GeV
- Backgrounds: $D_S \to \mu\nu\phi$

  $\phi \to \mu\mu$, $\phi \to \mu\mu\gamma$
- $\varepsilon \sim$ 1% (?), $\mathcal{B}(\tau \to \mu\mu\mu)$ < 10^{-10} (A.Stahl, Heraeus School 2005)

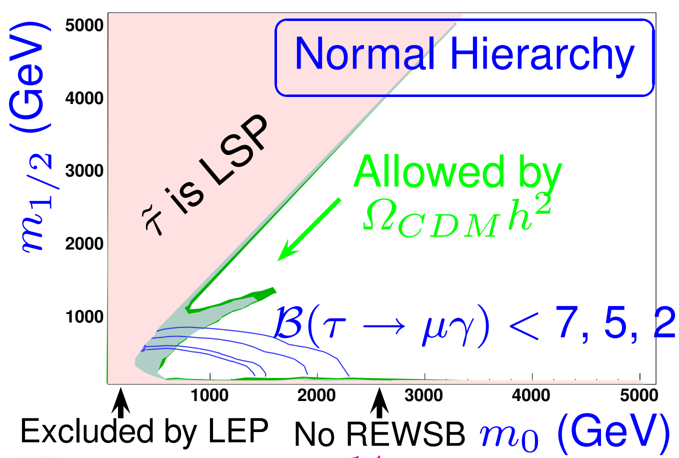
B-Factories Reach (O.Igonkina, SUSY05)

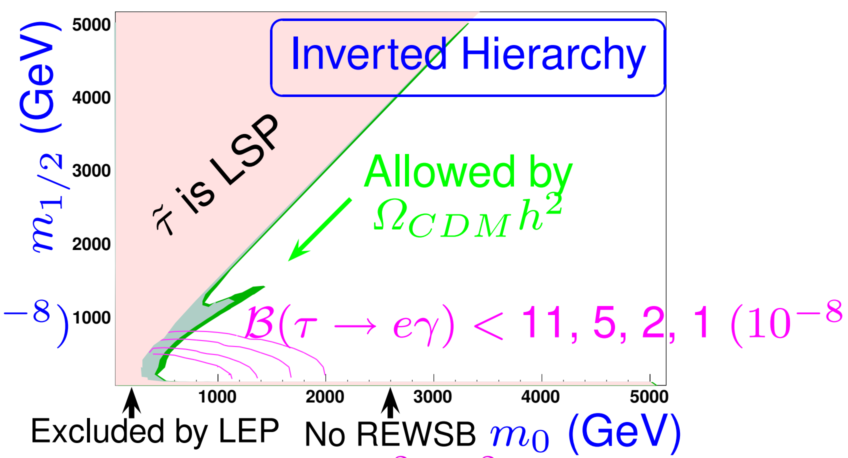
- mSUGRA with off-diagonal elements $\mathcal{L} = -\, M^2_{\tilde{L}} \tilde{L}^* \tilde{L} - M^2_{\tilde{E}} \tilde{E}^* \tilde{E}$
  - Model-independent calculation
    (A.Brignole, A.Rossi, NPB701(2004)3)
  - RGE using SPheno
    (W. Porod, CPC153(2003)275)
  - Cold Dark Matter (WMAP)
    with micrOMEGAs (CPC149(2002)103)



$m_{GUT} = 5 \cdot 10^{15}$ GeV, $\tan\beta = 55$
$\mu > 0,\ A_0 = 0,\ m_{1/2} = 100 + 0.8 \cdot m_0$

- mSUGRA + Seesaw: $\mathcal{L} = Y_\nu L \tilde{H}_2 N_{\rm R}$, $Y_\nu \propto V_{MNS}$ mixing by RGE

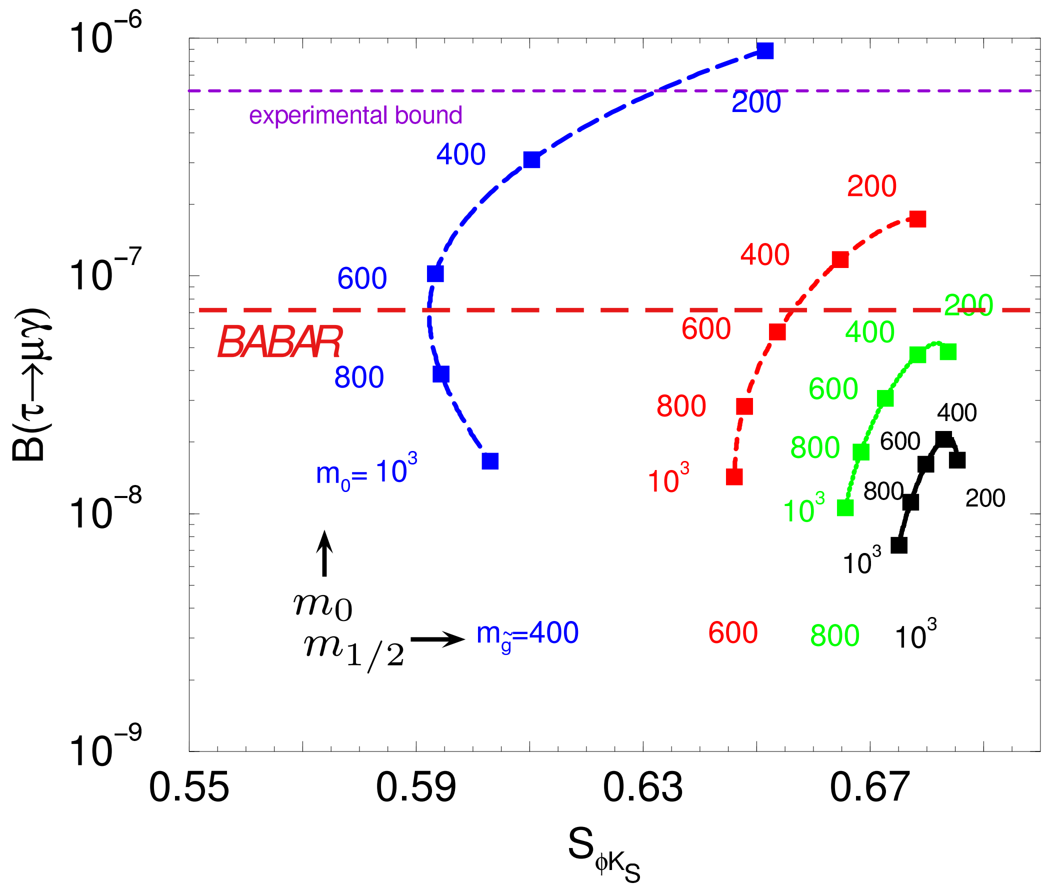




- $m_{\nu_R} = 5 \times 10^{14}$ GeV, $\tan\beta = 55$, $\mu > 0$, $A_0 = 0$, m_0, $m_{1/2}$, $M^2_{\tilde{L}}$, $M^2_{\tilde{E}}$: Diagonal

$\tau \to \mu\gamma$ & $\mathbf{S}_{\phi K_S}$

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



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

$\tan\beta = 10,\ A_0 = 0,$

$m_{\nu_R} = 5 \times 10^{14}\ \mathrm{GeV},$

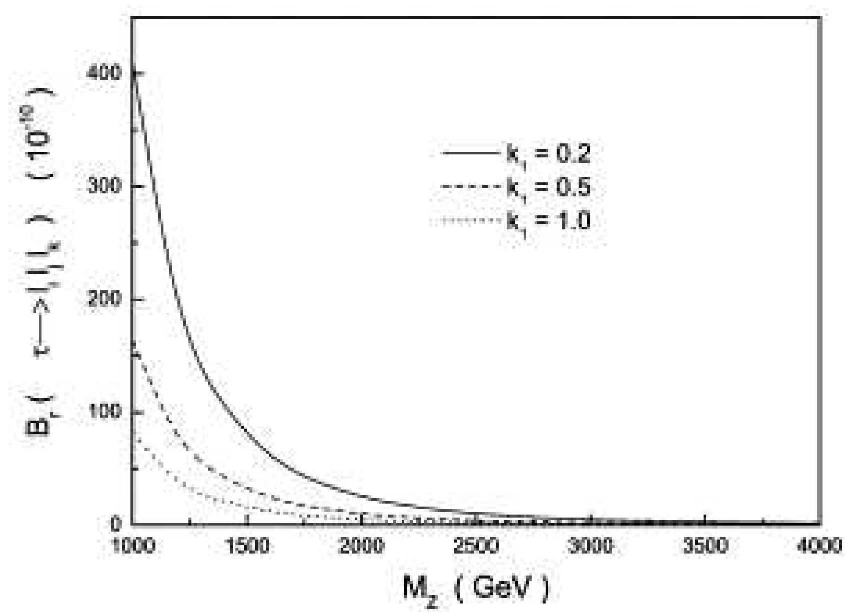
$m_{\nu_\tau} = 5 \times 10^{-2}\ \mathrm{eV}$

- Current measurement: $S(B \to \phi K_S) = 0.47 \pm 0.19$ (HFAG, 2005). More sensitive $\mathcal{B}(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$ exclude some regions.

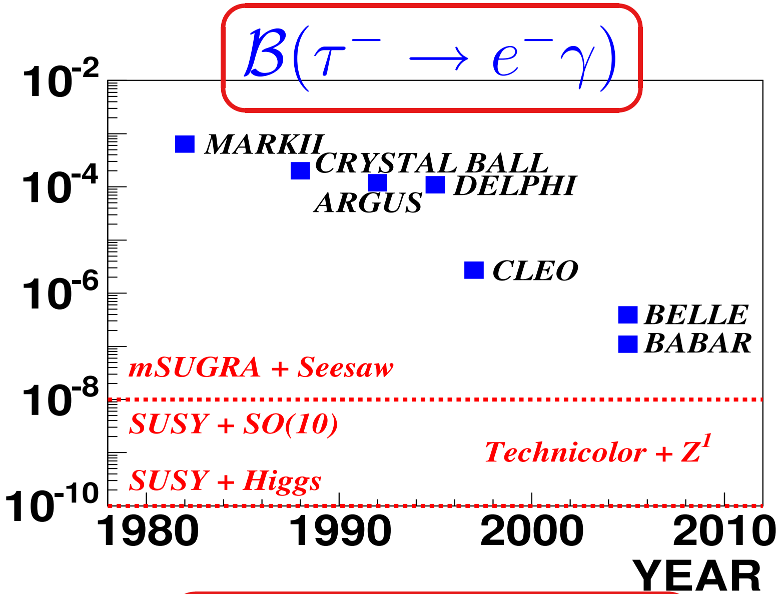
$\tau \to \ell\ell\ell$ predictions

- 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

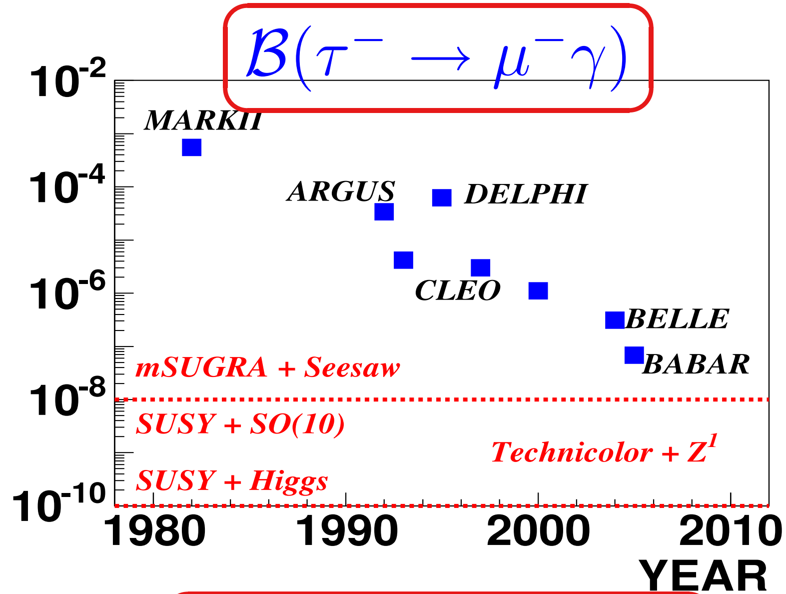
- Non Universal Z' (Technicolor) (C.Yue, Y.Zhang, L.Liu, PLB547(2002)252)
  - $\tau \to \ell\ell\ell$ most sensitive
  - Flavour mixing (k_1) = 0.2, $\mathcal{B}(\tau \to \ell\ell\ell) < 10^{-8}$ $\Rightarrow m_{Z'} < 1.2\ \mathrm{TeV}$



Summary



$\mathcal{B}(\tau^- \to e^-\gamma)$
MARKII
CRYSTAL BALL
ARGUS
DELPHI
CLEO
BELLE
BABAR
mSUGRA + Seesaw
SUSY + SO(10)
Technicolor + Z'
SUSY + Higgs
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1980
1990
2000
2010
YEAR



$\mathcal{B}(\tau^- \to \mu^-\gamma)$
MARKII
ARGUS
DELPHI
CLEO
BELLE
BABAR
mSUGRA + Seesaw
SUSY + SO(10)
Technicolor + Z'
SUSY + Higgs
10^{-2}
10^{-4}
10^{-6}
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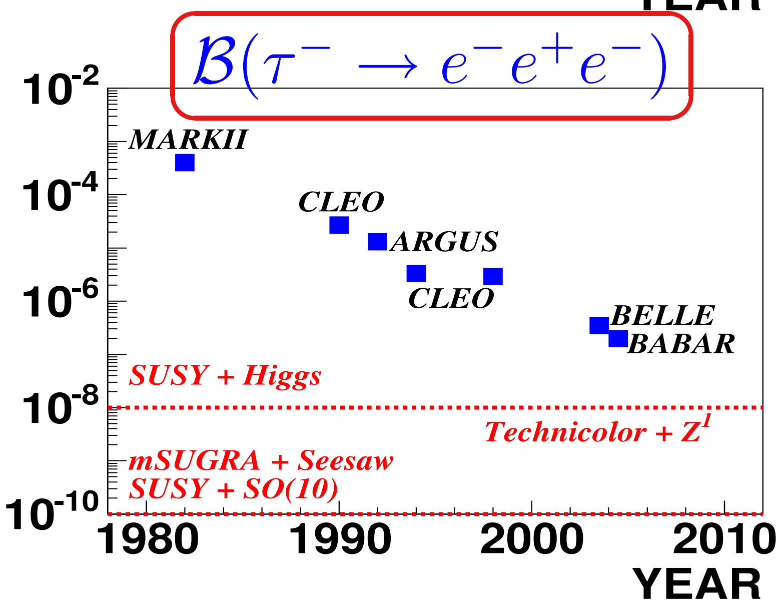
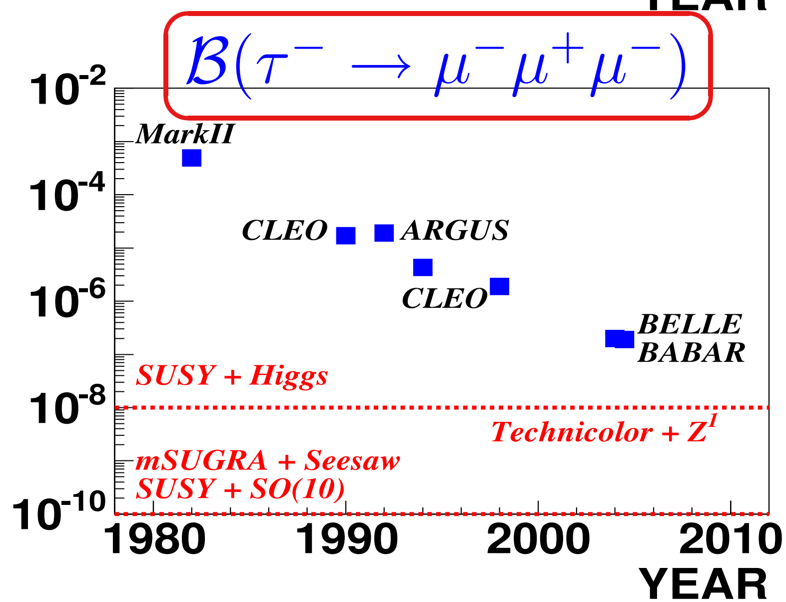
1980
1990
2000
2010
YEAR



$\mathcal{B}(\tau^- \to e^-e^+e^-)$
MARKII
CLEO
ARGUS
CLEO
BELLE
BABAR
SUSY + Higgs
Technicolor + Z'
mSUGRA + Seesaw
SUSY + SO(10)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1980
1990
2000
2010
YEAR

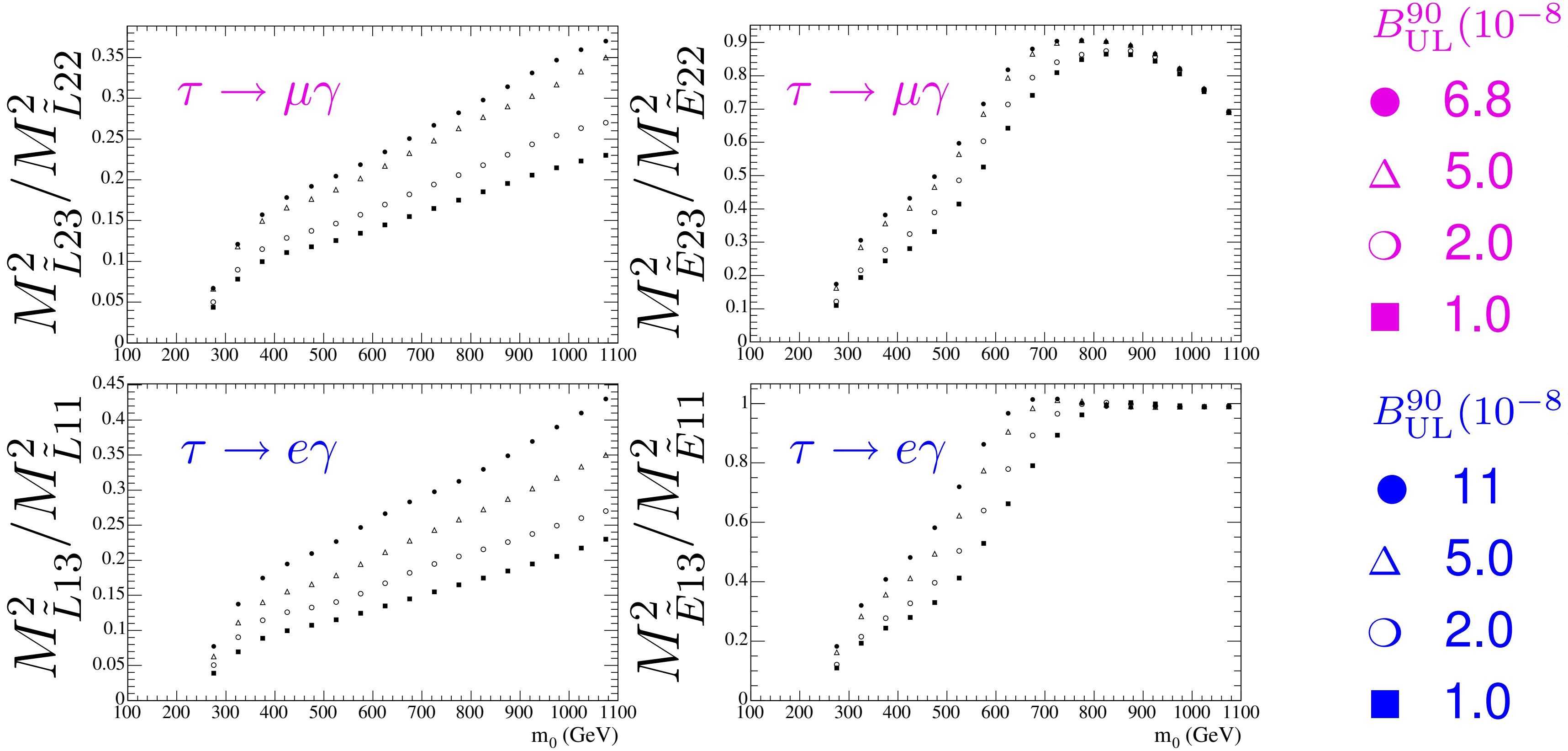


$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$
MarkII
CLEO
ARGUS
CLEO
BELLE
BABAR
SUSY + Higgs
Technicolor + Z'
mSUGRA + Seesaw
SUSY + SO(10)
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1980
1990
2000
2010
YEAR

Backup Slides ...

mSUGRA: mixing at GUT scale

- $\mathcal{L} = -M^2_{\tilde{L}} \tilde{L}^* \tilde{L} - M^2_{\tilde{E}} \tilde{E}^* \tilde{E}$, where $\tilde{L} : (\tilde{\nu}_{\rm L}, \tilde{\ell}_{\rm L})$, $\tilde{E} : (\tilde{\ell}_{\rm R})$

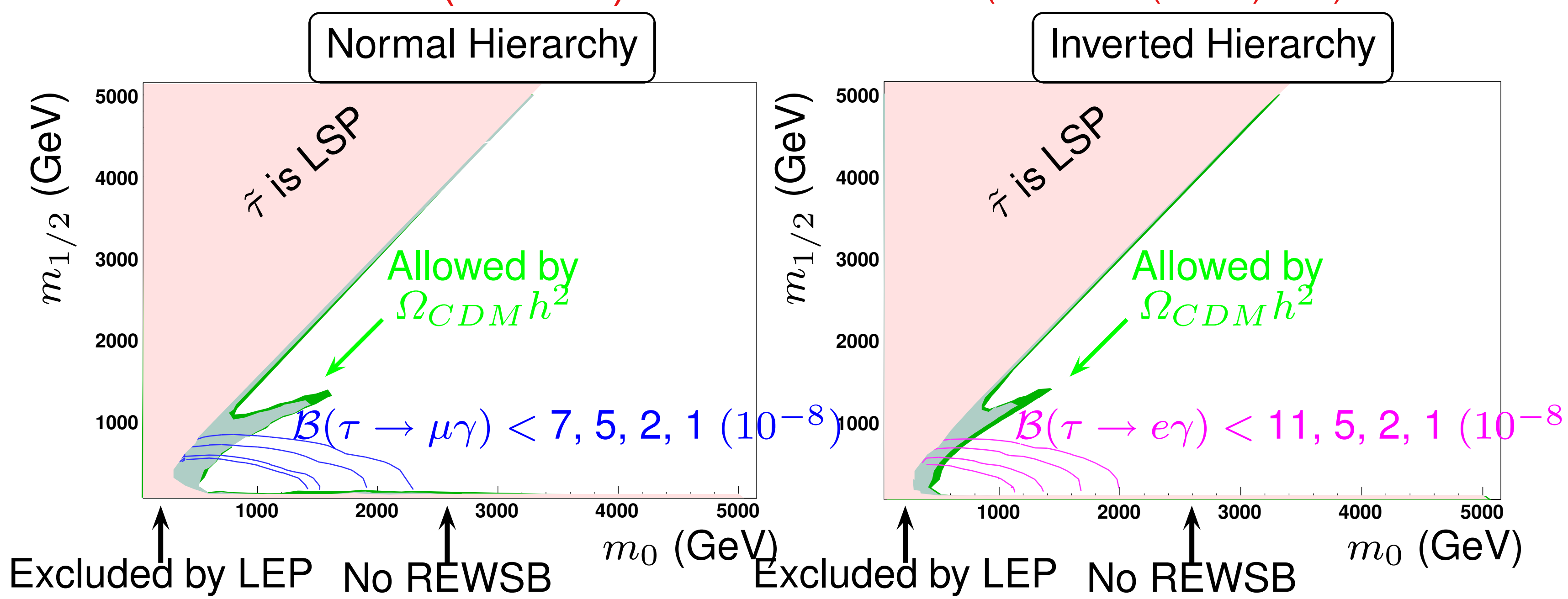


$$m_{GUT} = 5 \cdot 10^{15} \text{ GeV}, \tan\beta = 55, \mu > 0, A_0 = 0, m_{1/2} = 100 + 0.8 \cdot m_0$$

- BaBar Physics Reach Assessment 2005 (O.Igonkina, SUSY05)
  - Model-independent calculation (A.Brignole, A.Rossi, NPB701(2004)3)
  - RGE using SPheno (W. Porod, CPC153(2003)275)

mSUGRA + Seesaw: mixing by RGE

- $\mathcal{L} = Y_\nu L \tilde{H}_2 N_{\rm R}$, where $L : (\nu_{\rm L}, \ell_{\rm L})$, $N_{\rm R} : (\nu_{\rm R})$
  $Y_\nu = V_R V_{MNS}$, $V_{R_{ii}}(\rm m_{\nu_R}) = \sqrt{2 m_{\nu_i} m_{\nu_R}}/v_2$
  V_{MNS}: ν-mixing induces LFV at EW scale via RGE flow
- Global Analysis of ν Data, M.C. Gonzalez-Garcia, hep-ph/0410030
- Cold Dark Matter (WMAP) with micrOMEGAs (CPC149(2002)103)



- $\rm m_{\nu_R} = 5 \times 10^{14}\ GeV$, $\tan\beta = 55$, $\mu > 0$, $A_0 = 0$
- $m_0, m_{1/2}, M^2_{\tilde{L}}, M^2_{\tilde{E}}$: Diagonal