Tau Properties and Lepton Flavor Violation

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Fundamental Physics at the Intensity Frontier
November 30 – December 2, 2011
Rockville, MD
http://www.intensityfrontier.org/

Heavy Quarks
Conveners: Joel Butler (FNAL), Zoltan Ligeti (LBNL), Ritchie Patterson (Cornell) and Jack Ritchie (Texas)

Charged Leptons
Conveners: Brendan Casey (FNAL), Yuval Grossman (Cornell) and Aaron Roodman (SLAC)

Neutrinos
Conveners: Andre deGouvea (Northwestern), Kevin Pitts (Illinois), Kate Scholberg (Duke) and Sam Zeller (FNAL)

Hidden Sector Photons, Axions, and WISPS
Conveners: Juan Collar (Chicago), Rouven Essig (Stonybrook) and John Jaros (SLAC)

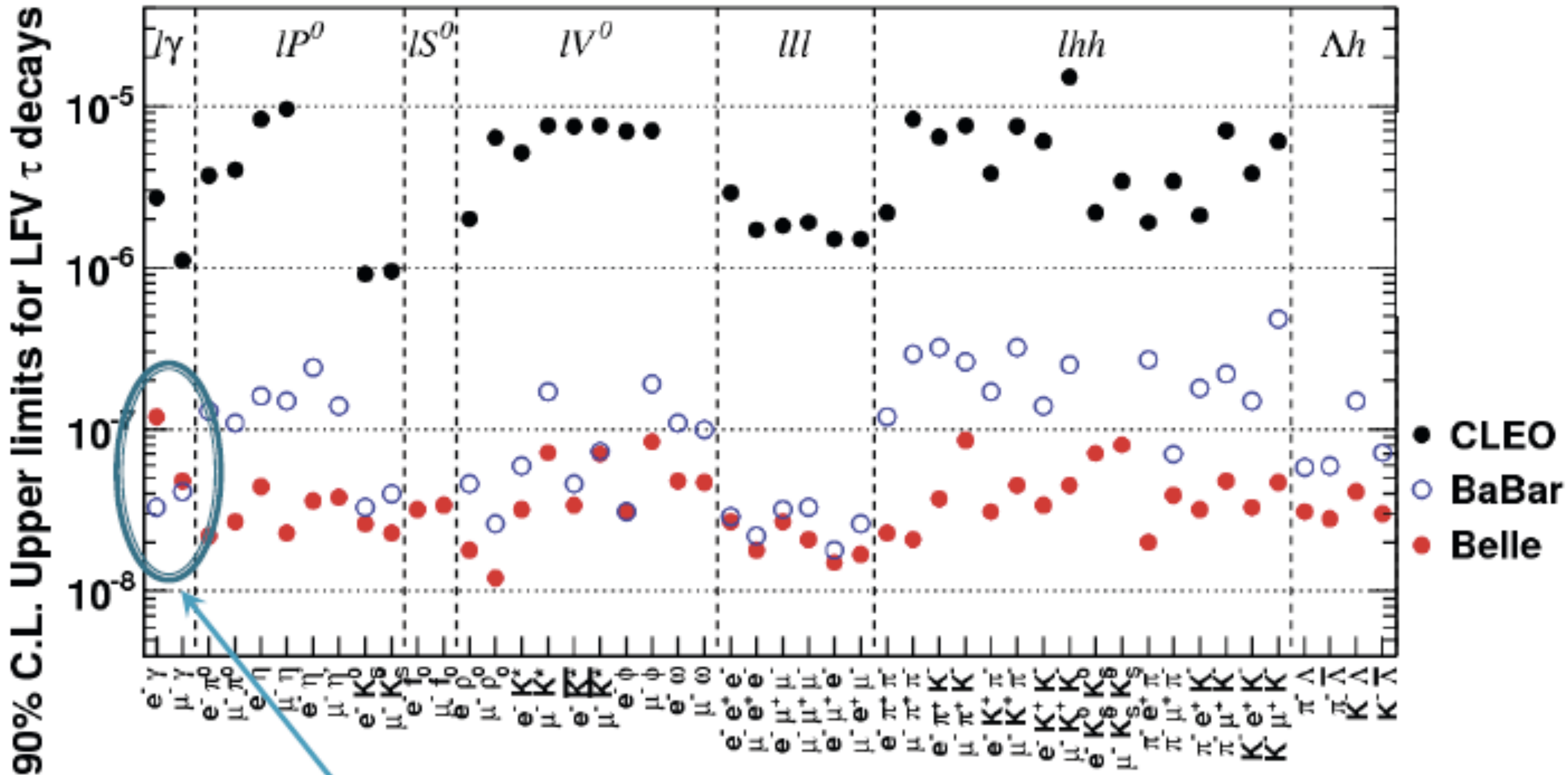
Proton Decay
Conveners: Chip Brock (Michigan State), Chang-Kee Jung (Stonybrook) and Carlos Wagner (ANL and UofC)

Nucleons / Nuclei / Atoms
Conveners: Wick Haxton (Berkeley), Zheng-Tian Lu (ANL) and Michael Ramsey-Musolf (Wisconsin)

Report: arXive:1205.2671

K.Hayasaka ICHEP 2012

Upper Limits on τ LFV Decays



The remaining mode are $\tau \rightarrow \mu\gamma$ and $e\gamma$!

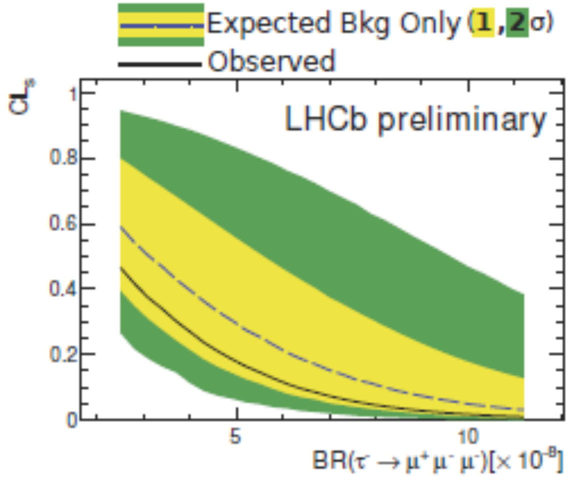
Previously, a 545 fb^{-1} data subsample was analyzed.

Mathieu Perrin-Tarrin (LHCb) ICHEP 2012

Results

- Preliminary upper limits 95 (90)% C.L. extracted using the $\mathrm{CL_s}$ method

$$\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 7.8\ (6.3) \times 10^{-8}$$



- Results comparable with Belle PLB 687 (2010) 139, arXiv:1001.3221
  $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^-) < 2.1 \times 10^{-8}$ at 90% C.L.

New Physics at Tau decays

- Tau decays provide various opportunities to search for new interactions in clean ways.
- Tau may be special because it belongs to the third generation.
- Tau Lepton Flavor Violation searches are particularly interesting because of its connection to neutrino mass generation and/or supersymmetry.

Naïve scaling of there lepton processes

g-2

$$\Delta(g-2)_i \propto m_i^2$$

Current precision
$a_e : 0.7\text{ppb},\ a_\mu : 0.6\text{ppm}$
$-0.052 < a_\tau < 0.013$

Muon g-2 is most sensitive to New Physics.

EDM

$$d_i \propto m_i$$

Current bounds
eEDM $O(10^{-27})$
μEDM $O(10^{-19})$
τEDM $O(10^{-17})$

Electron is most constraining.

LFV

$$B(l_j \to l_j X) \propto (m_i)^0$$

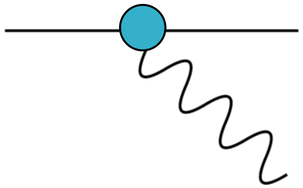
Current bounds
$B(\mu LFV) < O(10^{-13}) - O(10^{-11})$
$B(\tau LFV) < O(10^{-8}) - O(10^{-7})$

No apparent lepton mass dependence.
Sensitive to flavor mixing structure.

Many examples of exceptional cases.

Comparison between μ and τ LFV

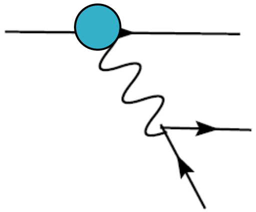
$\mu^+ \to e^+\gamma$

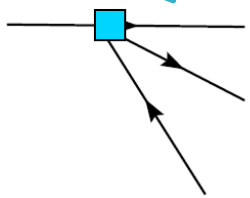


$$-\frac{4G_F}{\sqrt{2}}(m_\mu A_R \bar{\mu}\sigma^{\mu\nu} P_L e F_{\mu\nu} + m_\mu A_L \bar{\mu}\sigma^{\mu\nu} P_R e F_{\mu\nu} + \text{H.c.})$$

$\mu^+ \to e^+\gamma_R$ $\mu^+ \to e^+\gamma_L$

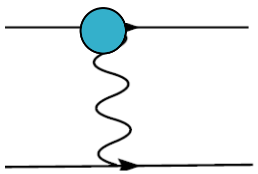
$\mu^+ \to e^+e^+e^-$

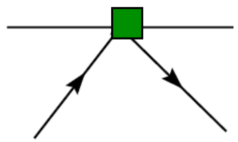




6 additional operators

$\mu^- N \to e^- N$





Various llqq operators

Tau LFV processes

Various flavor structures. Many searches can be carried out simultaneously at e^+e^- colliders.

$$(1)\ \tau \to \mu\gamma, \tau \to e\gamma \quad \longleftrightarrow \quad \mu \to e\gamma$$

$$(2)\ \tau \to lll \quad \longleftrightarrow \quad \mu \to 3e$$

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

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

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

and their CP conjugates

$$(3)\ \tau \to \mu\eta, \mu\pi, \mu\rho, \mu\phi, etc. \quad \longleftrightarrow \quad \mu A \to eA$$

$$\tau \to e\eta, e\pi, e\rho, e\phi, etc.$$

Distinguishing different operators.

Relationship of various LFV branching ratios

If the photon penguin process is dominant, there are simple relations among these branching ratios.

$$\boxed{\begin{aligned} B(\mu \to 3e) &\sim 6.1 \times 10^{-3} B(\mu \to e\gamma) \\ B(\mu Ti \to eTi) &\sim 4.0 \times 10^{-3} B(\mu \to e\gamma) \\ B(\mu Al \to eAl) &\sim 2.6 \times 10^{-3} B(\mu \to e\gamma) \\ B(\tau \to 3\mu) &\sim 2.2 \times 10^{-3} B(\tau \to \mu\gamma) \end{aligned}}$$

In many case of SUSY modes, this is true.
Other cases:
- Additional Higgs exchange diagram (SUSY with large tan β)
- Dominance of tree exchange diagrams (LR symmetric models, etc.)
- Loop-induced but Z-penguin dominance (Little Higgs with T-parity)

“Polarized” tau decay

Tau polarization information is useful for determination of LFV interaction and EDM searches.

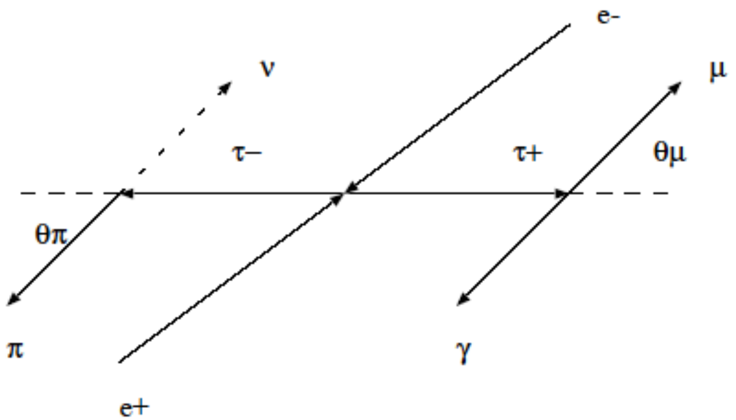
(1) Angular correlation of tau decay products at e^+e^- colliders.

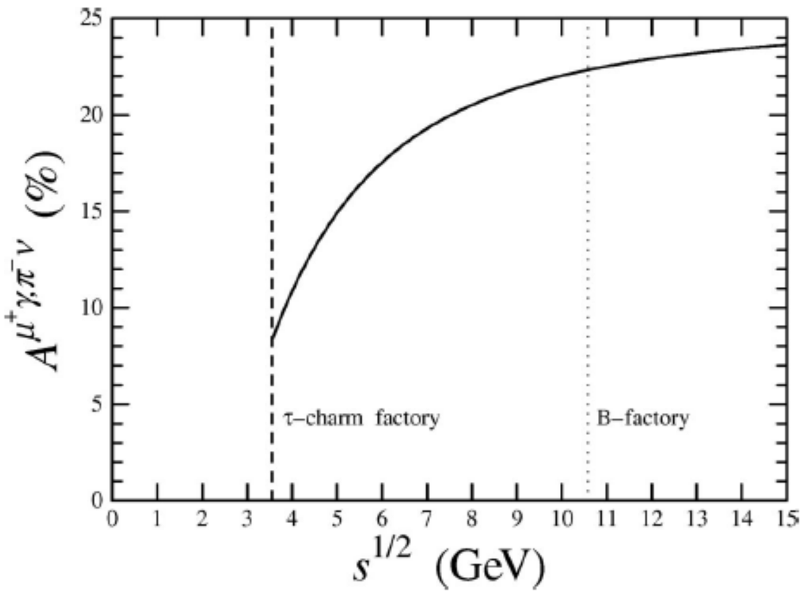
R.Kitano and Y.Okada 2001

Example :

$$\frac{dB(e^+e^- \to \tau^+\tau^- \to \mu^+\gamma + \pi^-\nu)}{d\cos\theta_\mu d\cos\theta_\pi}$$

$$\propto 1 - A_{\tau\to\mu\gamma}\frac{s-2m_\tau^2}{s+2m_\tau^2}\cos\theta_\mu\cos\theta_\pi$$



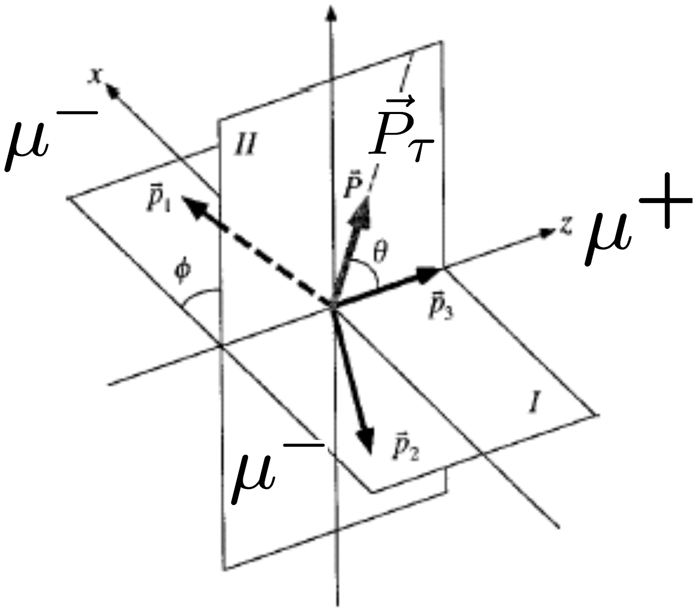


Asymmetry for the SUSY seesaw model (A=−1)

(2) With electron beam polarization, we can extract polarization information only from one side.

(3) At LHC, taus from W decays are polarized. We can use asymmetry observables to distinguish different models in τ->3μ decays.

τ-> 3μ

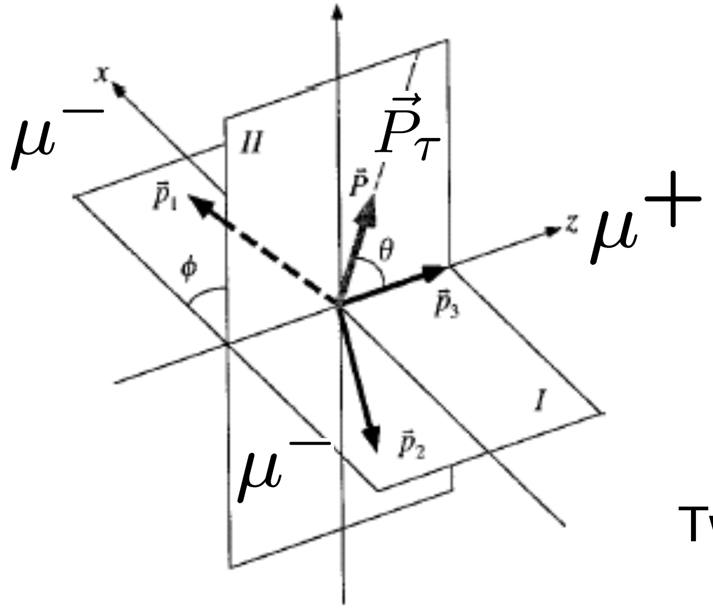


Model	$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\Theta} \propto$ ½+AcosΘ
MSSM with seesaw mechanism	$A = 1/6$
MSSM with R-parity violation:	
"R" ($\lambda_{i22}\lambda^*_{i23} \gg \lambda_{i32}\lambda^*_{i22}$)	$A = 1/6$
"L" ($\lambda_{i22}\lambda^*_{i23} \ll \lambda_{i32}\lambda^*_{i22}$)	$A = -1/6$
Littlest Higgs model with T-parity:	
"Z" ($\bar{Z}^{\prime\tau\mu}_{\rm odd} \gg \bar{Y}^{\prime\tau\mu}_{\mu,\rm odd}$)	$A = 5/18$
"Y" ($\bar{Z}^{\prime\tau\mu}_{\rm odd} \ll \bar{Y}^{\prime\tau\mu}_{\mu,\rm odd}$)	$A = 1/2$
Topcolor-assisted technicolor:	
"Z" ($m_{\pi_t} \gg m_{Z'}$)	$A = -5/14$
"P" ($m_{\pi_t} \ll m_{Z'}$)	$A = 0$
Models with doubly charged Higgs bosons:	
Higgs-triplet model	$A = 1/2$
Zee-Babu model	$A = -1/2$

M.Giffels, J.Kallarackal, M.Kramer, B.O'Leary and A.Stahl, 2008

A variety of asymmetries

τ−> 3μ

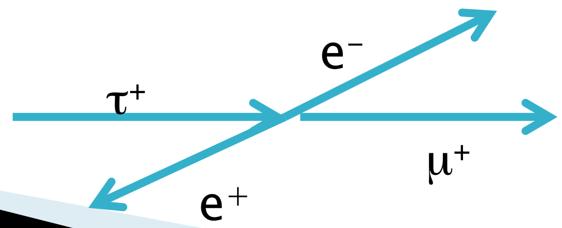


$$A_{P_1} = \frac{N(P_z > 0) - N(P_z < 0)}{N(P_z > 0) + N(P_z < 0)}$$
$$A_{P_2} = \frac{N(P_x > 0) - N(P_x < 0)}{N(P_x > 0) + N(P_x < 0)}$$
$$A_T = \frac{N(P_y > 0) - N(P_y < 0)}{N(P_y > 0) + N(P_y < 0)}$$

Two parity-odd and one T-odd asymmetries

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

Forward-backward asymmetry and FB P-odd FB T-odd asymmetries can be defined.



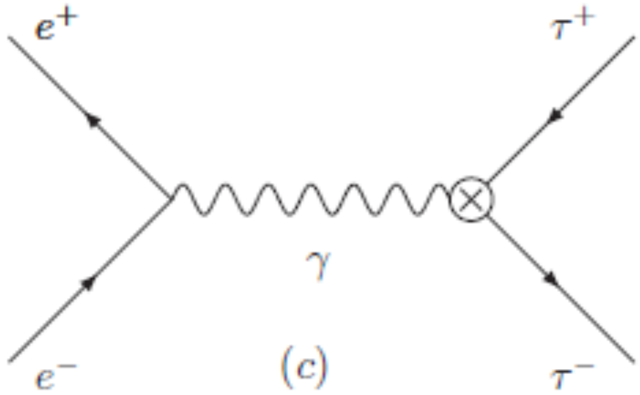
A_{FB} :Energy asymmetry of e^-e^+ in the tau rest frame.

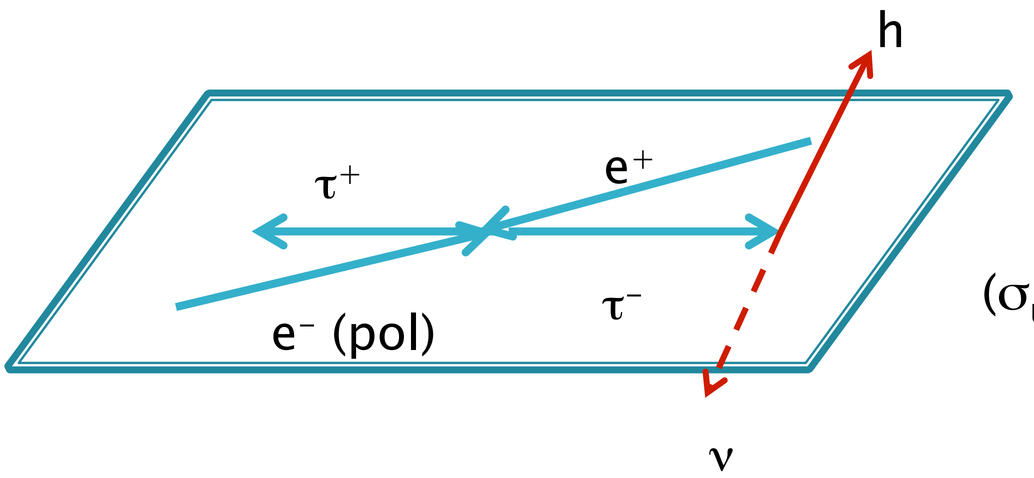
Tau EDM using beam polarization

J.Bernabeu, G.A.Gonzalez-Sprinberg, and J.Vidal, 2006

Using beam polarizations, tau EDM measurement can be done by only looking at one side.

$$e^+e^-(pol) \to \gamma \to \tau^+\tau^- \to h^+\bar{\nu}_\tau h^-\nu_\tau$$





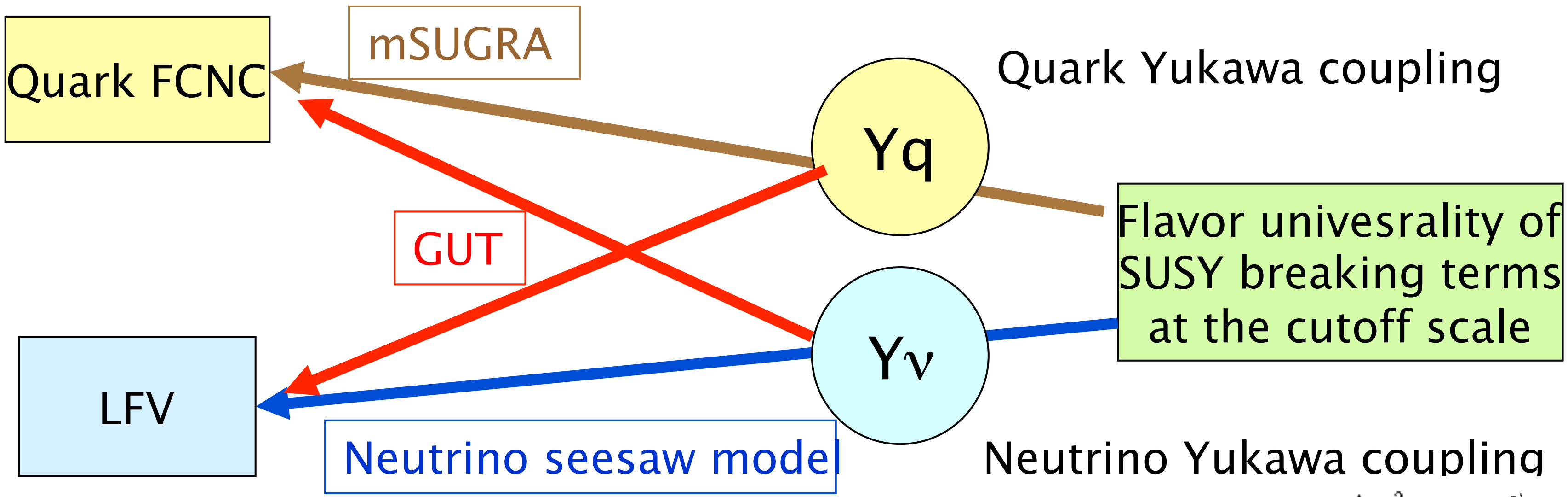
$$(\sigma_{up}-\sigma_{down})|_{\lambda=1}-(\sigma_{up}-\sigma_{down})|_{\lambda=-1}$$
$$\propto d_\tau$$

New physics examples

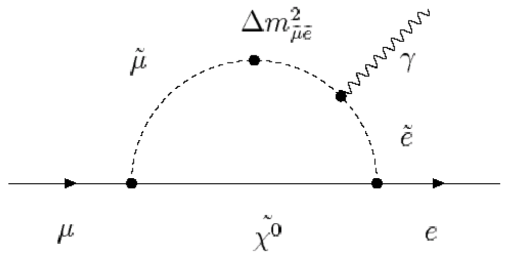
(1) SUSY GUT/Seesaw models

LFV is a probe to interactions at very high energy scales

Quark and neutrino Yukawa coupling constants at the GUT/ Seesaw scale can induce large flavor off-diagonal terms in sqaurk/slepton mass matrices.

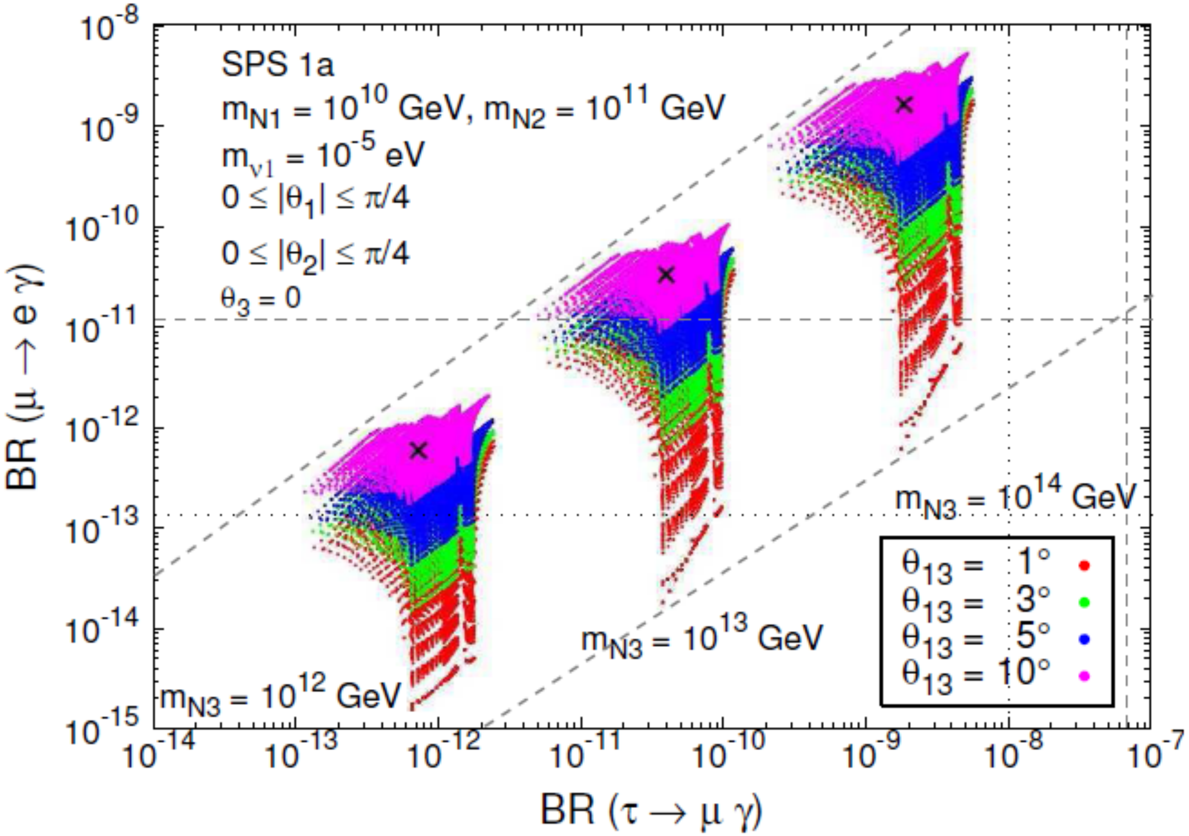


L.J.Hall,V.Kostelecky,S.Raby,1986;A.Masiero, F.Borzumati, 198



Predicted branching ratios depend on the light neutrino masses and mixings, heavy neutrino masses and Yukawa couplings as well as SUSY parameters.

SUSY seesaw model



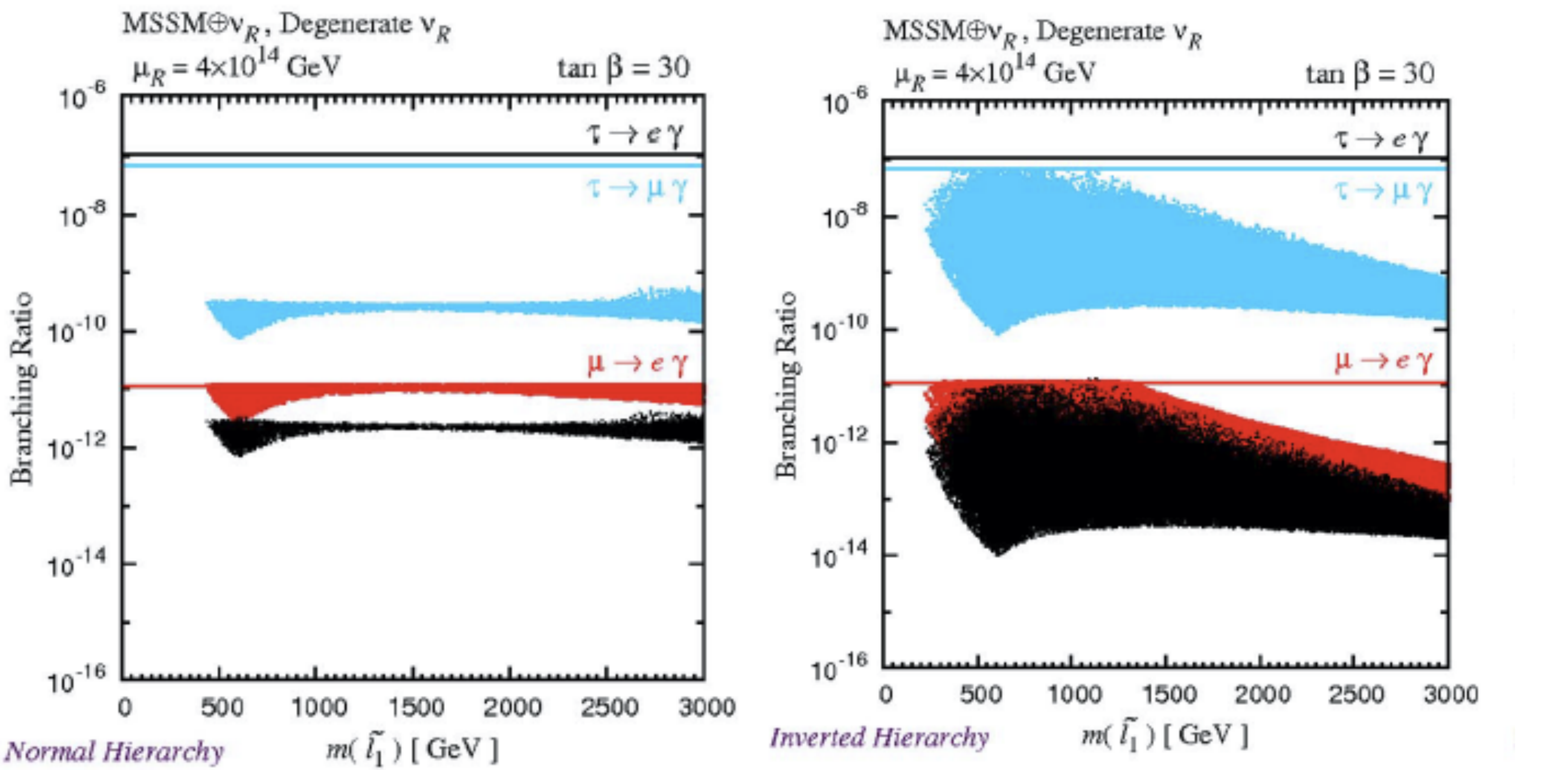
With the constraint of successful thermal leptogenesis

S.Antusch,E.Arganda, M.J.Herrero,and A.M.Teixeira. 2006

SUSY seesaw model

Normal hieararchy

Inverse hierarchy case

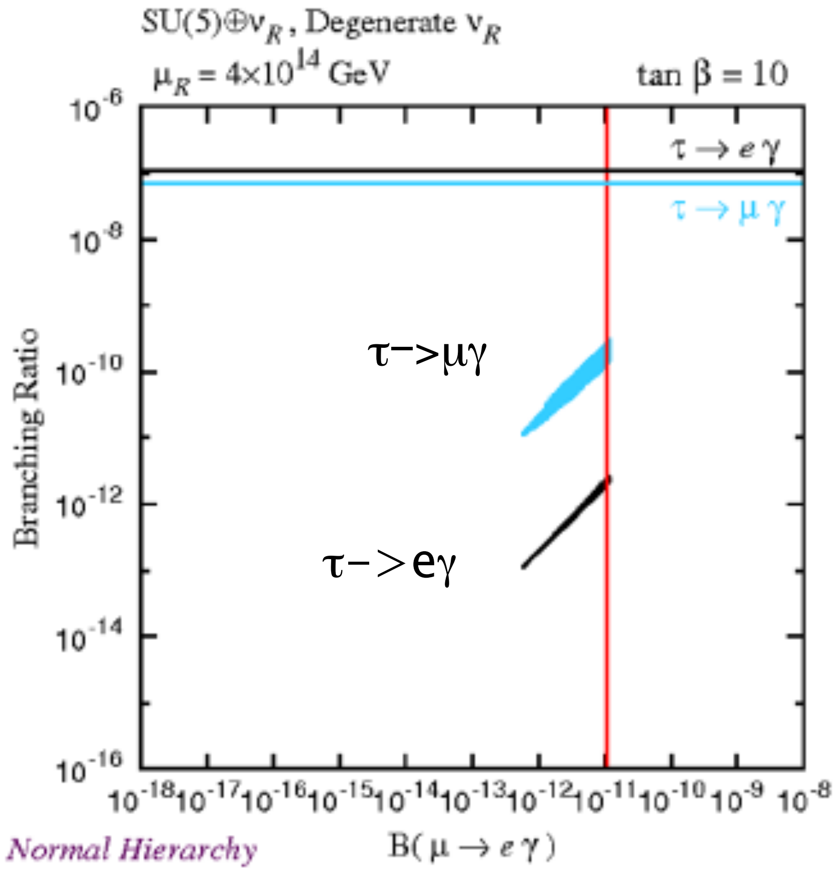


T.Goto, Y.Okada, T.Shindou, and M.Tanaka, 2008

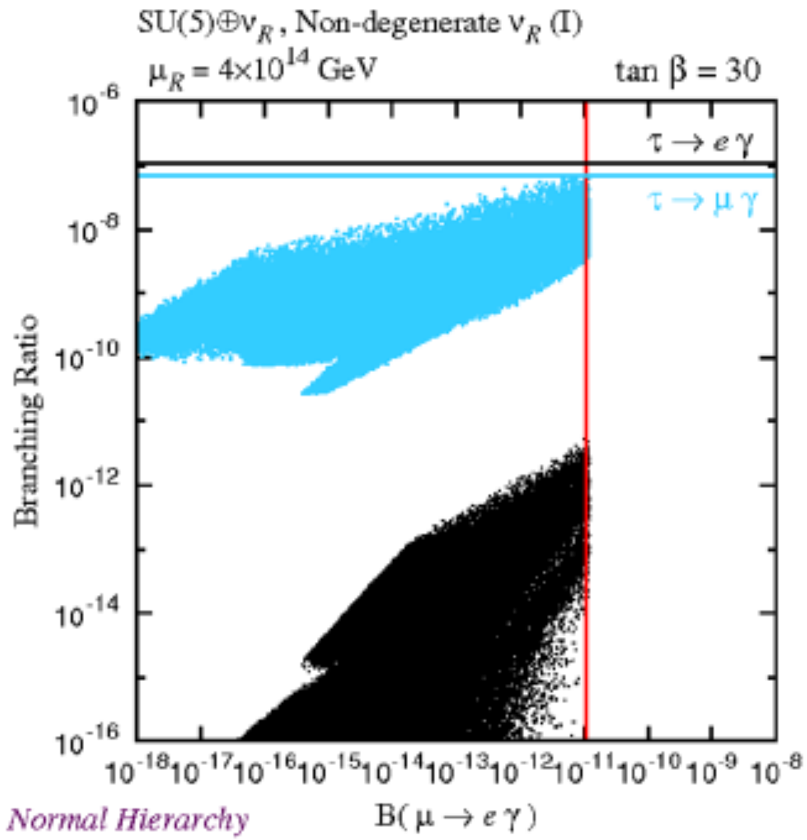
SU(5) SUSY GUT with seesaw neutrinos

correlation between $\tau \to \mu(e)\,\gamma$ and $\mu \to e\gamma$

Degenerate Heavy neutrino masses



The case where the 1-2 component of Y_ν is suppressed

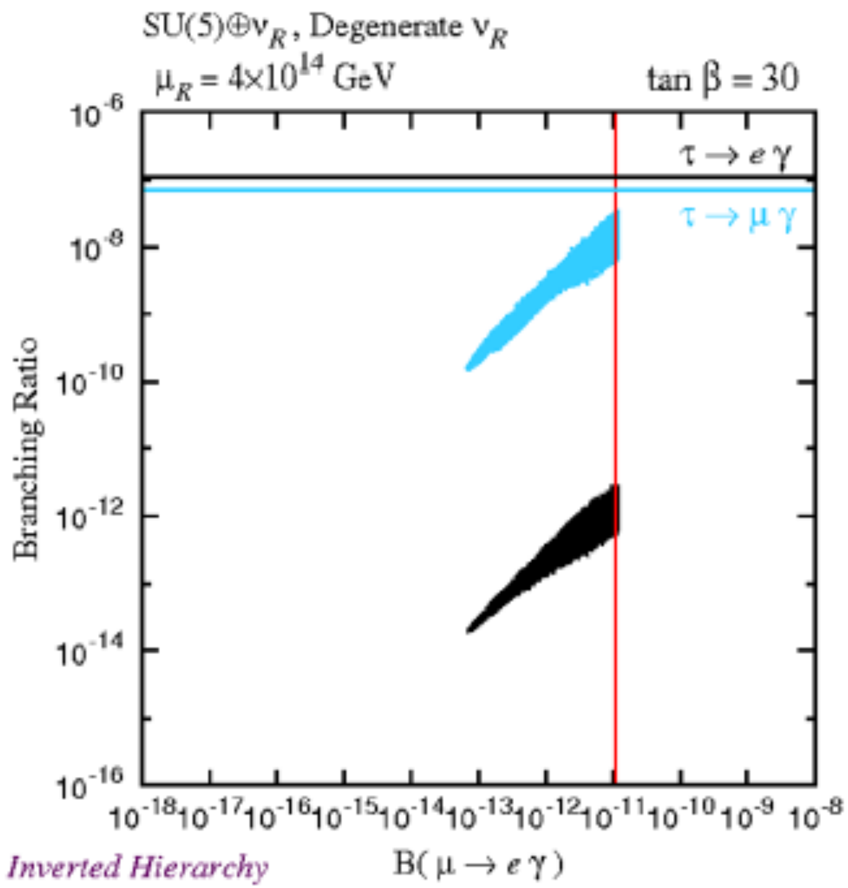


B($\mu \to e\gamma$)

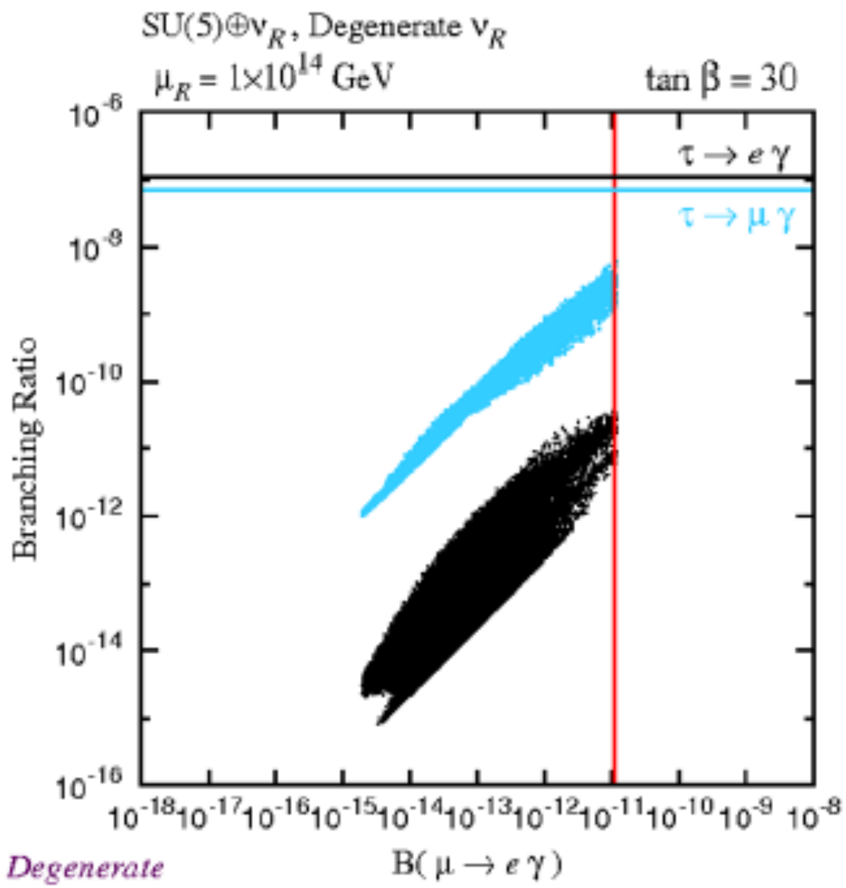
T.Goto, Y.Okada, T.Shindou, and M.Tanaka, 2008

Different light neutrino mass hierarchy

Inverse hierarchy case



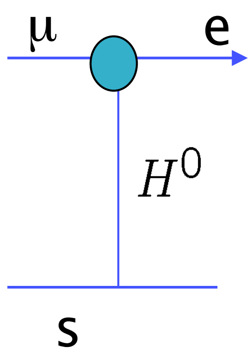
Degenerate case



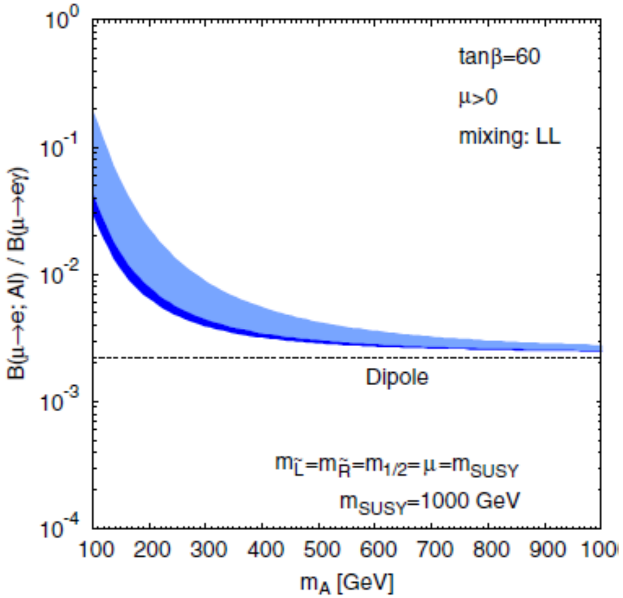
(2) Higgs-mediated LFV in SUSY with large tanβ

For large values of the two Higgs vacuum expectation values (tanβ), a heavy Higgs exchange diagram can be large. Processes like mu-e conversion, τ->3μ, τ->$\mu\eta$, etc become important.

K.Babu, C.Kolda,2002; M.Sher, 2002;R.Kitano,M.Koike,S.Komine, and Y.Okada, 2003

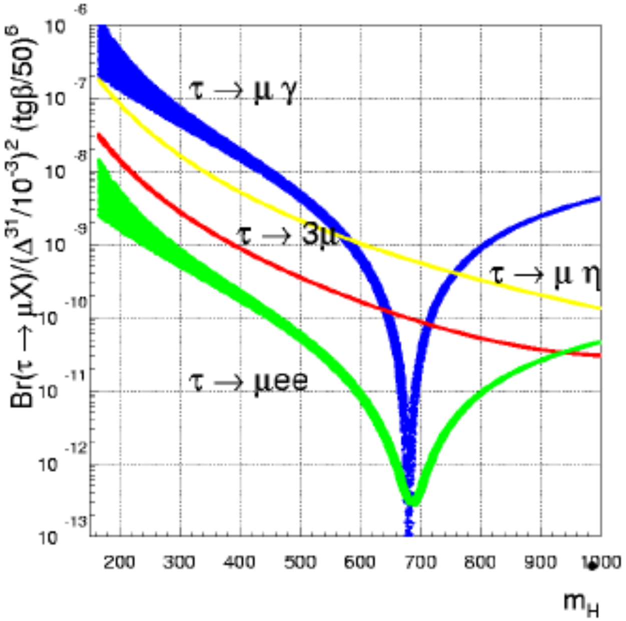


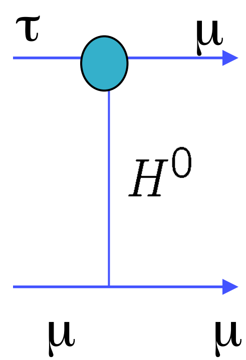
μ-e conv/μ->eγ



V. Cirigliano, R.Kitano, Y.Okada, and P.Tuson, 2009

tau LFV





P.Paradisi,2006

(3)Little Higgs Models with T parity

- The Higgs doublet field is a part of pseudo-NG bosons associated with a symmetry breaking dynamics at about 10 TeV.
- The quadratic divergence of the Higgs mass term is cancelled by extra-gauge bosons and a heavy top quark partner at the one loop level.(A solution to the "little hierarchy problem")

  N.Arkani-Hamed,A.G.Cohen, E.Katz, A.E.Nelson, T.Gregoire and J.G.Wacker,2002

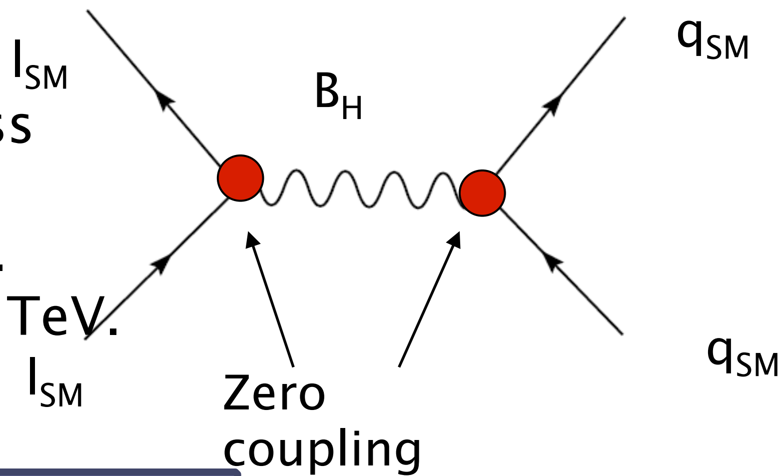
  N.Arkani-Hamed,A.G.Cohen, E.Katz,and A.E.Nelson,2002

- Electroweak precision measurements still put a strong constraints mostly due to tree-level exchange of extra-gauge b

Introduction of T-parity

The original model is extended to possess T-parity, so that no dangerous diagrams exist in terms of electroweak constraints. Masses of new particles can be close to 1TeV.

C.H.Cheng and I.Low,2003

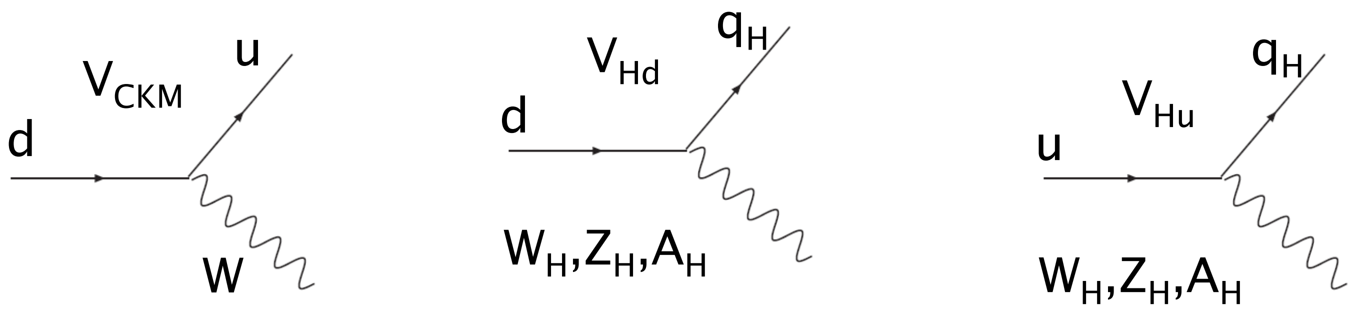


T-odd partners to quark and leptons are introduced

New Flavor mixing matrices

After diagonalization of the fermion mass matrices, flavor changing are induced in the gauge boson-fermion vertexes.

J.Hubisz,S.J.Lee,G.Paz, 2005



$$\boxed{V_{Hu}^{\dagger} V_{Hd} = V_{CKM}}$$

Out of three mixing matrices, two are independent.

Similarly, for the lepton sector,

$$\boxed{V_{Hl}^{\dagger} V_{H\nu} = V_{PMNS}}$$

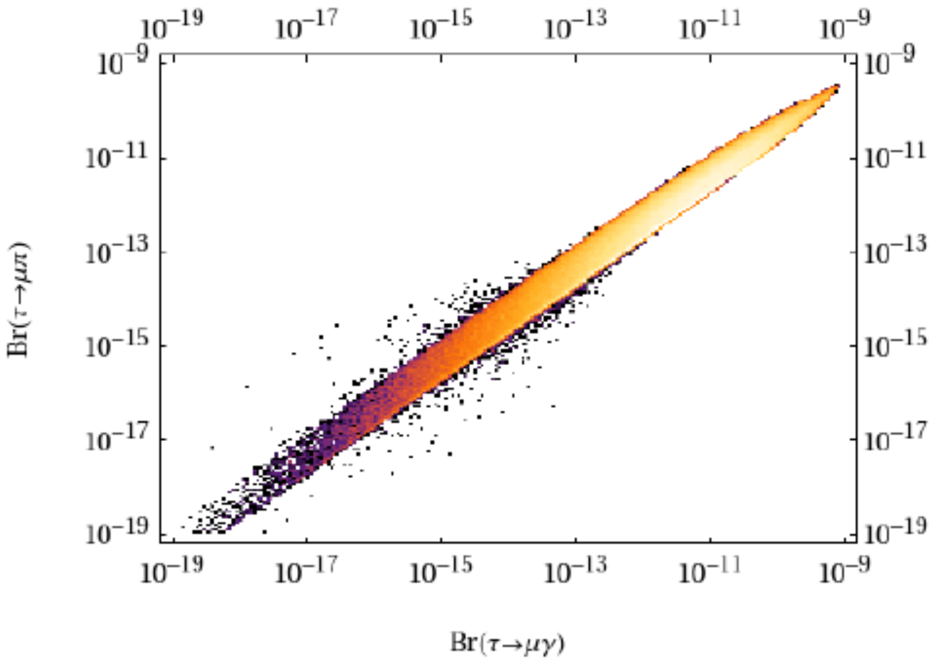
New contributions to quark flavor changing neutral current (FCNC) processes and LFV arise from T-odd particle loop diagrams.

Tau LFV branching ratios

Flavor transition occur only in the left -handed sector.

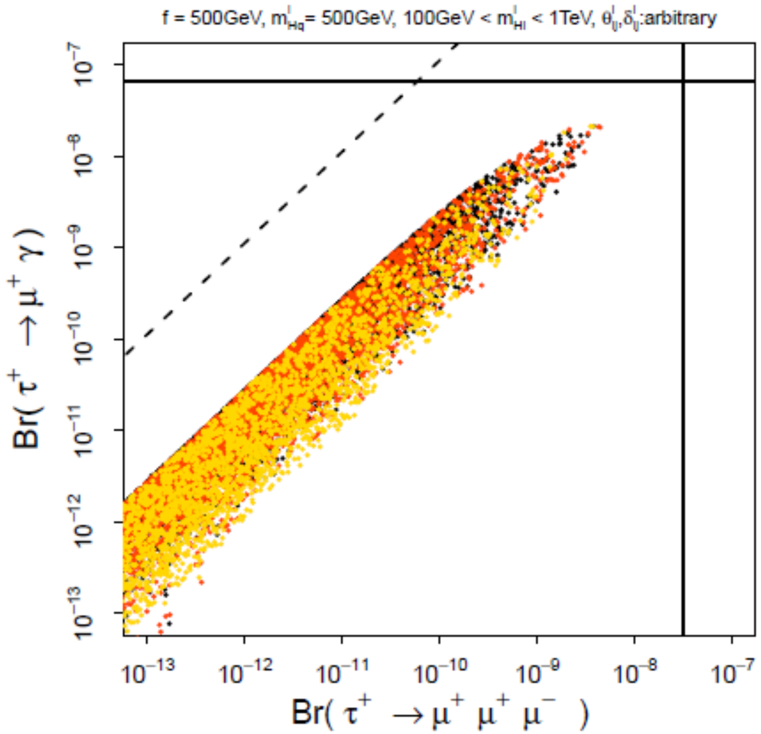
$$\mathcal{L}_{\mathrm{I}} = -\frac{4G_F}{\sqrt{2}}\left[m_\tau A_R^{\mathrm{LHT}}\bar{\tau}_R\sigma^{\mu\nu}\mu_L F_{\mu\nu} + g_{Ll}^{\mathrm{I,LHT}}(\bar{\tau}_L\gamma^\mu\mu_L)(\bar{\mu}_L\gamma_\mu\mu_L) + g_{Lr}^{\mathrm{I,LHT}}(\bar{\tau}_L\gamma^\mu\mu_L)(\bar{\mu}_R\gamma_\mu\mu_R) + \mathrm{H.c.}\right],$$

τ->μπ vs. τ->μγ



M.Blanke, A.J.Buras, B.Duling, S.Recksiegel and C.Tarantino, 2009

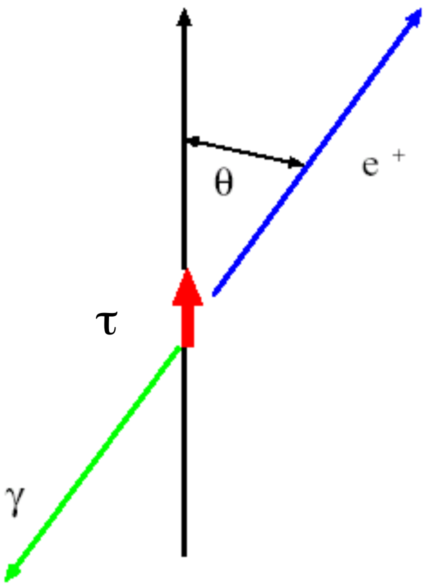
τ->μγ vs. τ->3μ



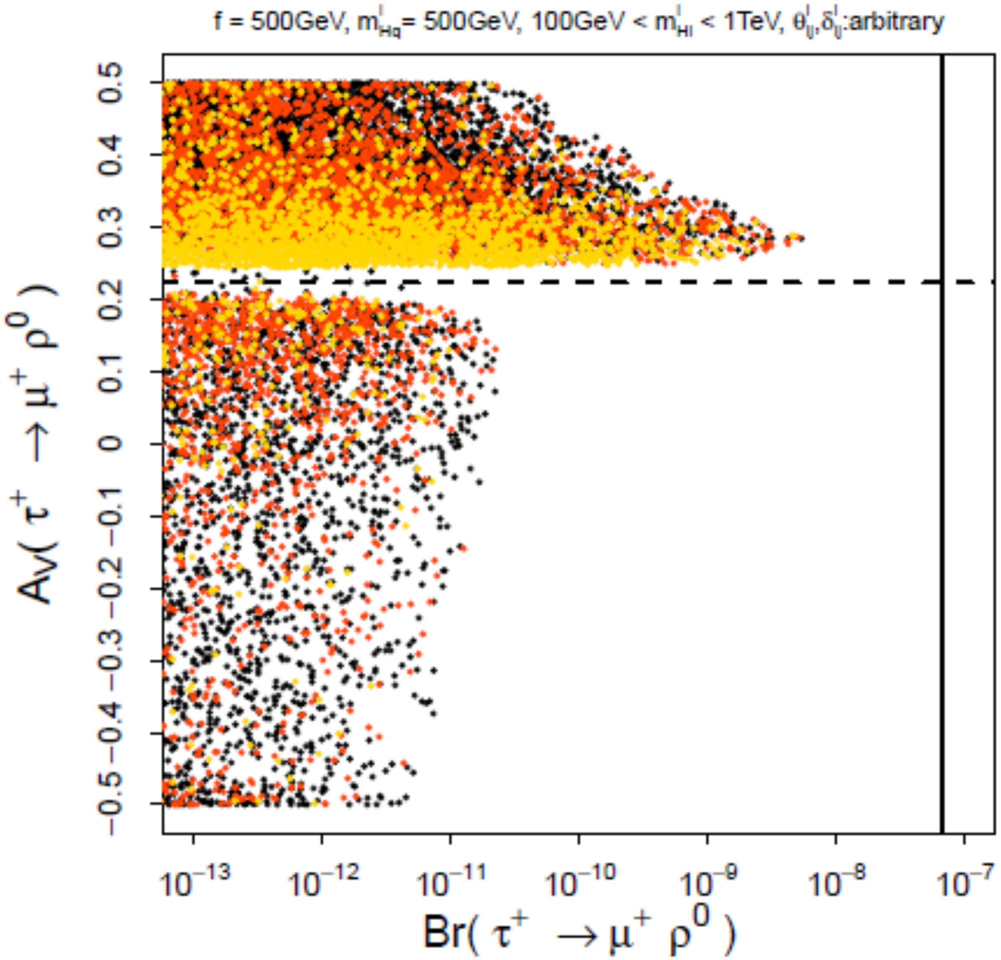
T.Goto, Y.Okada,and Y.Yamamoto,2011

Three Branching ratios are similar.

Two body decays



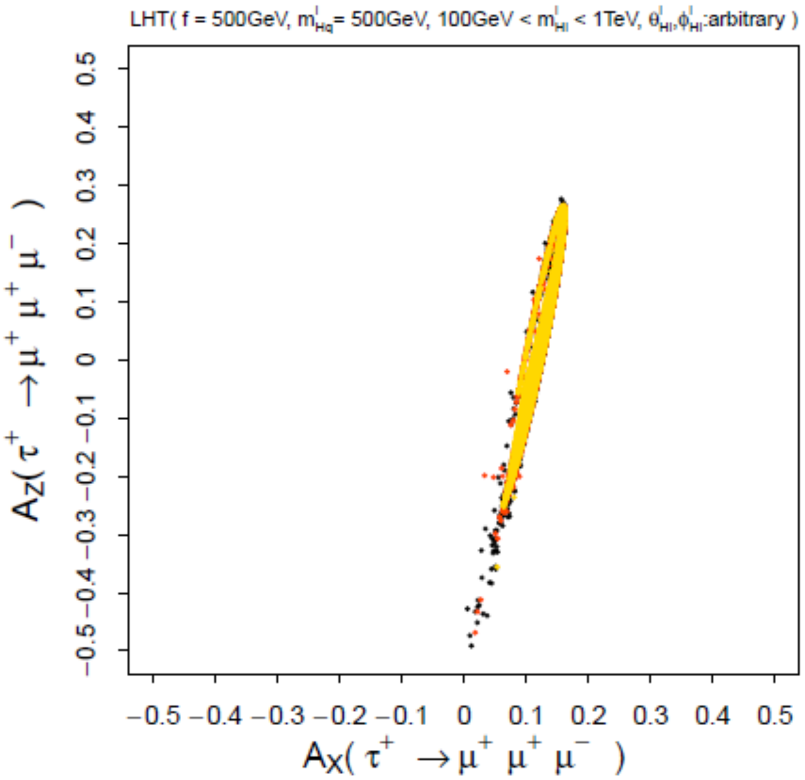
(1−cos θ) for τ−>lγ
(1+cos θ) for τ −>lπ (lη, lη')



T.Goto, Y.Okada,and Y.Yamamoto,2011

Three body decays

(1) $\tau \to 3\mu$ ($\tau \to 3e$)

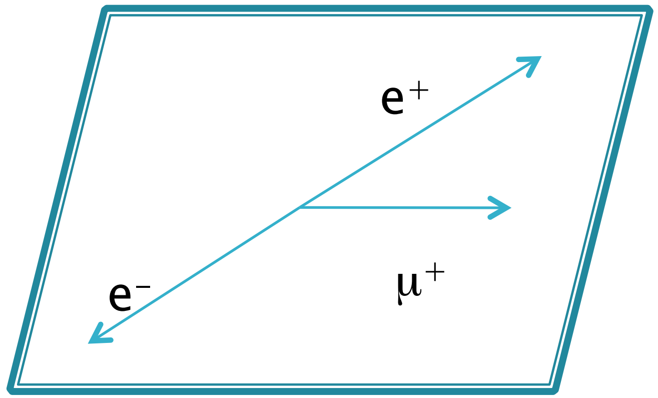


(2) $\tau^+ \to \mu^+ e^+ e^-$ ($\tau^+ \to e^+ \mu^+ \mu^-$)

Forward-backward asymmetries
(with and without polarization)
with respect to final e^+e^- can be defined.

A characteristic relation

$$A_X : A_{FB} : A_{ZFB} = -\frac{4\pi}{35} : -\frac{1}{4} : \frac{1}{8}.$$



(3) $\tau^+ \to \mu^- e^+ e^-$ ($\tau^+ \to e^- \mu^+ \mu^+$)

Small branching ratio ($<10^{-13}$)

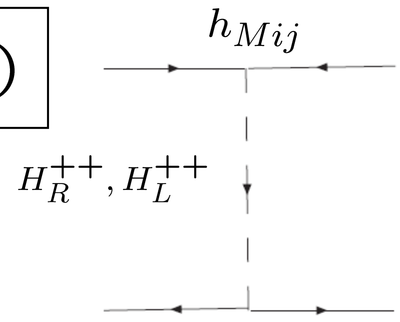
$$A_Z^{\rm III,LHT} = -\frac{1}{2}, \qquad A_X^{\rm III,LHT} = 0, \qquad A_Y^{\rm III,LHT} = 0.$$

T.Goto, Y.Okada,and Y.Yamamoto,2011

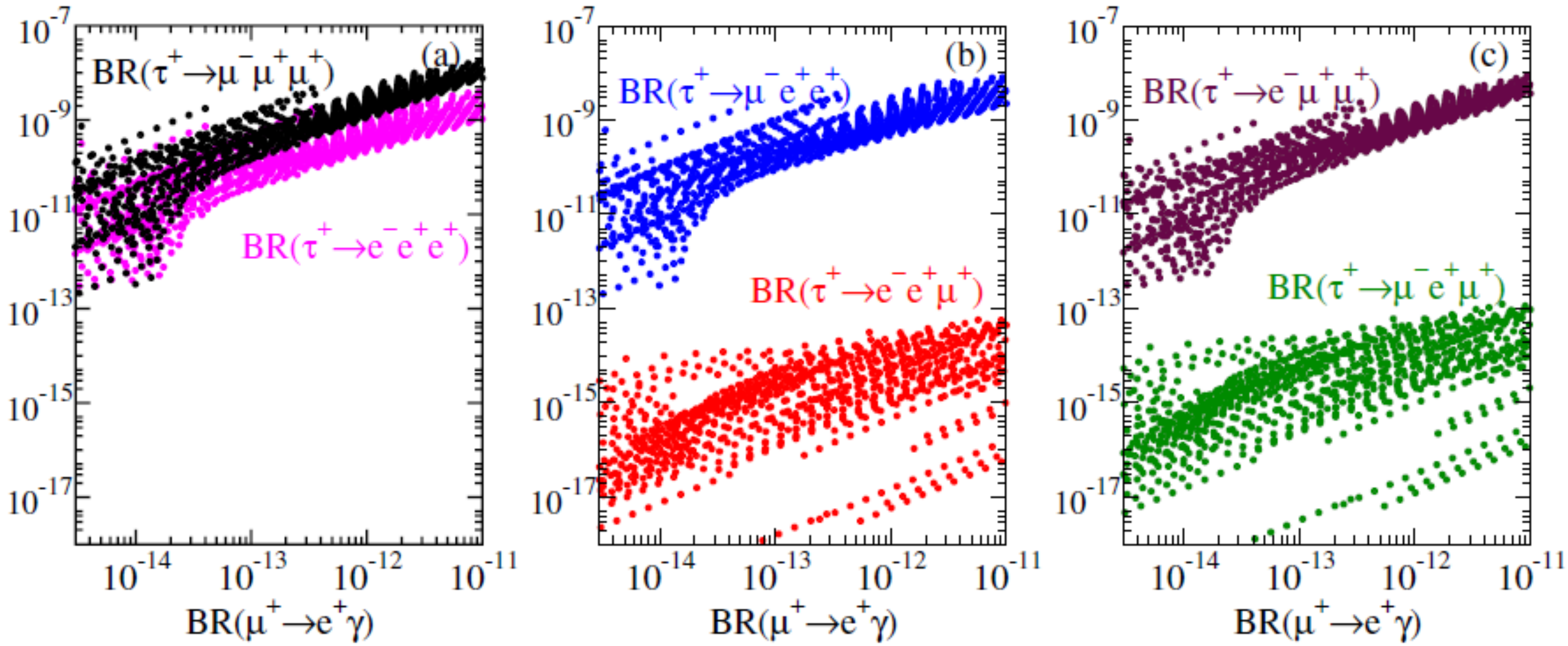
(4) Left-Right symmetric model

Neutrino mass generation at the TeV scale.
Doubly charged Higgs bosons induce LFV processes at the tree level.

$$\boxed{SU(2) \times SU(2) \times U(1) \xrightarrow{v_R} SU(2) \times U(1) \xrightarrow{v_1, v_2} U(1)}$$



$$B(\mu \to 3e) >> B(\mu \to e\gamma), B(\mu A \to eA)$$
$$B(\tau \to lll) >> B(\tau \to l\gamma), B(\tau \to l\eta)$$



A.G.Akeroyd, M.Aoki, and Y.Okada, 2007

New Physics summary

model	Feature
SUSY neutrino/ SUSY GUT	B(τ->lγ)<O(10^{-8}), B(τ->lγ)>> B(τ->3l)
SUSY neutrino with large tan β	B(τ->$\mu\eta$) , B(τ->3l) can be enhanced due to scalar operators
Little Higgs with T-parity	B(τ->lγ) ~B(τ->3l)~B(τ->lπ), Various relations among asymmetries
Left-right symmetric model	B(τ->lll) >> B(τ->lγ), B(τ->lη)

Summary

- Sizable tau LFV arises in many new physics models.
- Pattern of different tau LFV modes and relation to muon LFV are important in distinguishing different models.
- Polarized tau decays are useful in determining LFV interactions and EDM. At e^+e^- colliders, polarization information can be extracted trough angular correlation of decay products of two taus or using electron beam polarization.