Theory Overview

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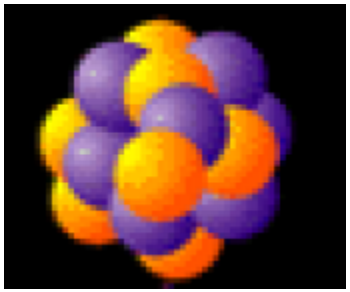
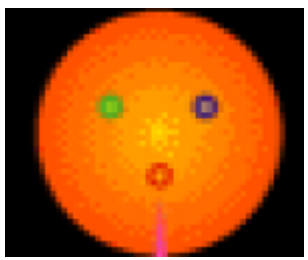
Entering TeV scale physics

MeV



~1930: Discovery of neutrons
Two New forces (strong, weak) are introduced

GeV



~1970: Theory of three interactions based on one additional unknown force (electroweak symmetry breaking)

TeV

~2010: Discovery of a Higgs boson
What is the unknown force?

The equation of the particle physic in the 20th century

The Fermi constant

The Higgs VEV

$$G_F = \frac{1}{\sqrt{2}v^2}$$

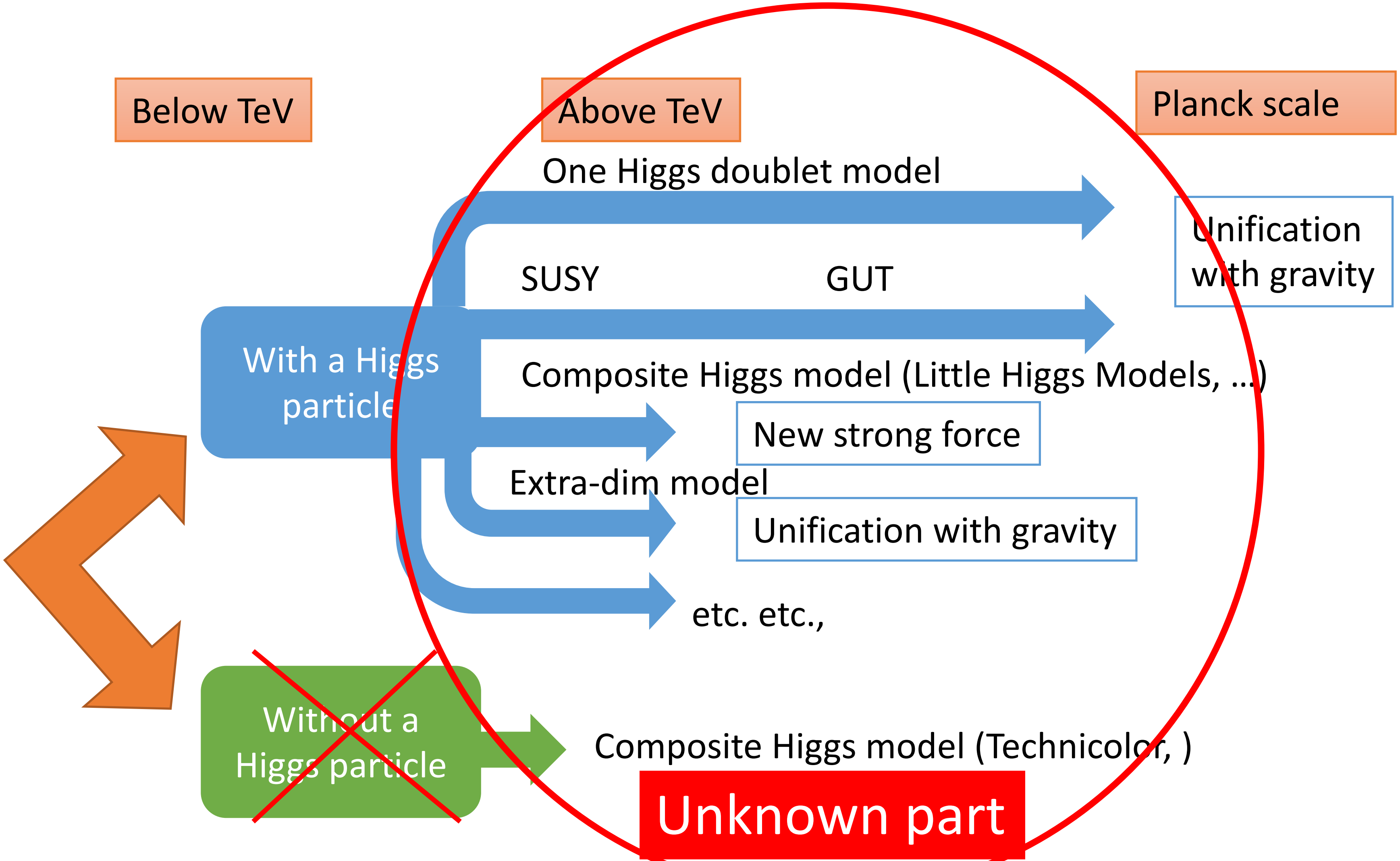
Nambu's Symmetry Breaking

The Higgs vacuum expectation value is determined by the mass and the lifetime of muons

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3},$$

Particle physics after the Higgs discovery

- Enter a new chapter of the particle physics
- The Higgs particle itself is a tool to explore New Physics.
- There are no clear signals beyond the Higgs particle at the LHC experiment.
- Indirect ways to look for new physics becomes more and more important.



Answers to fundamental questions depend on the unknown part.
What is dark matter?
How the matter and anti-matter asymmetry was generated?
Why the neutrino masses are so small? etc.

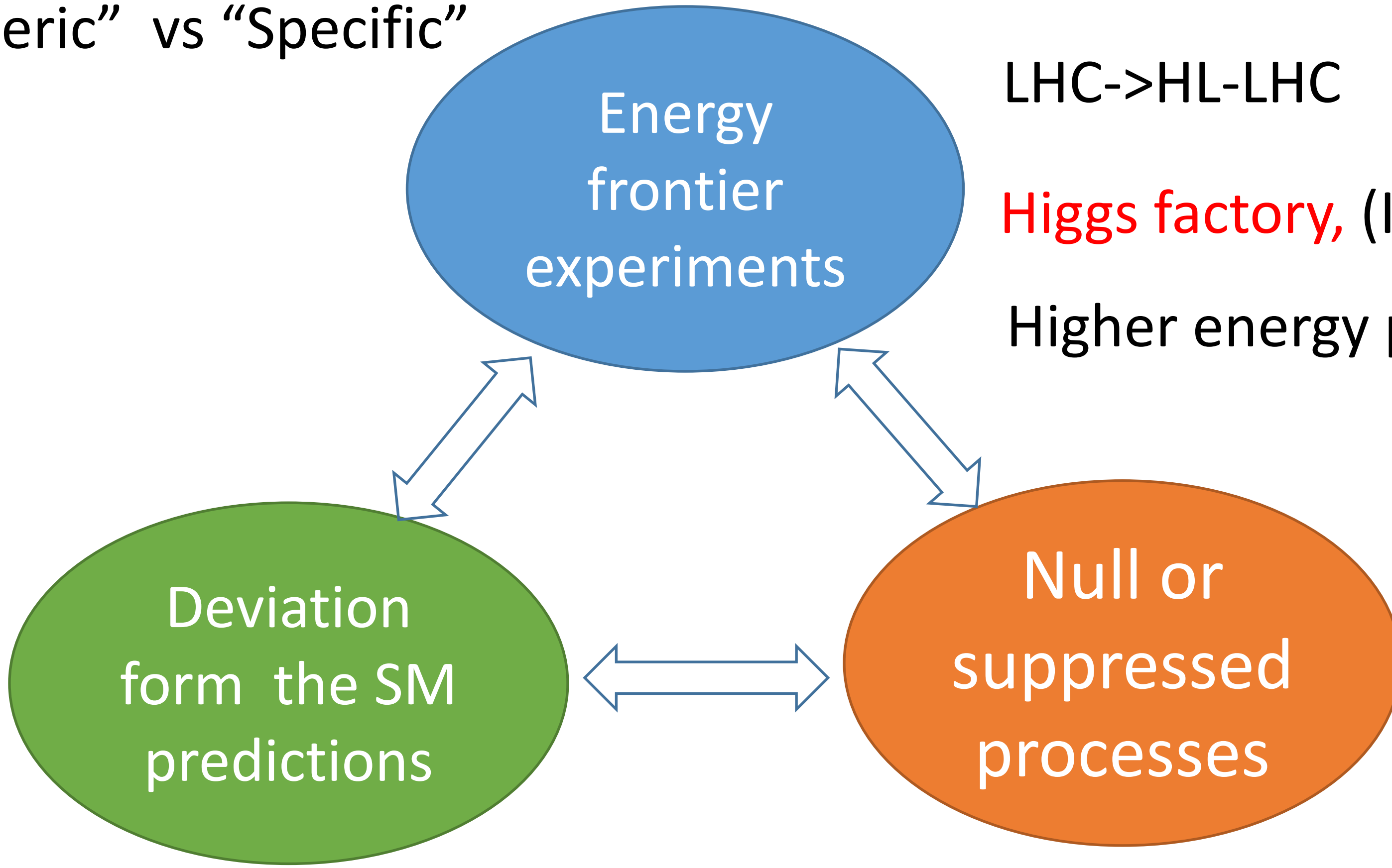
Approaches to new physics

"Generic" vs "Specific"

LHC->HL-LHC

Higgs factory, (ILC, ...)

Higher energy pp collider



LHCb, SuperKEKB/Belle II,
Kaon rare decays, muon g-2 ...

EDM, LFV, ...

Why do we believe "new things"?

LHC =TeV physics
=Electroweak
symmetry breaking

Something beyond the known three gauge interaction is necessary.

Other puzzles

Origin of the neutrino mass

Baryon number of the Universe

Dark matter

....

Lepton number violation

Lepton flavor violation

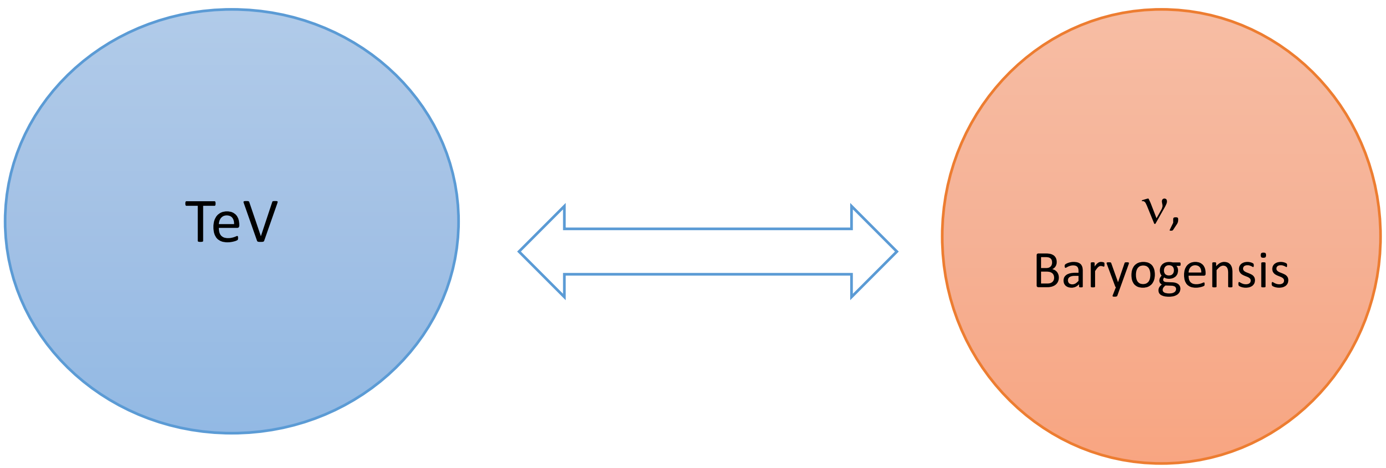
New CP violation

Relevant scale is unknown.

An important role of Lepton Flavor Violation and EDM searches

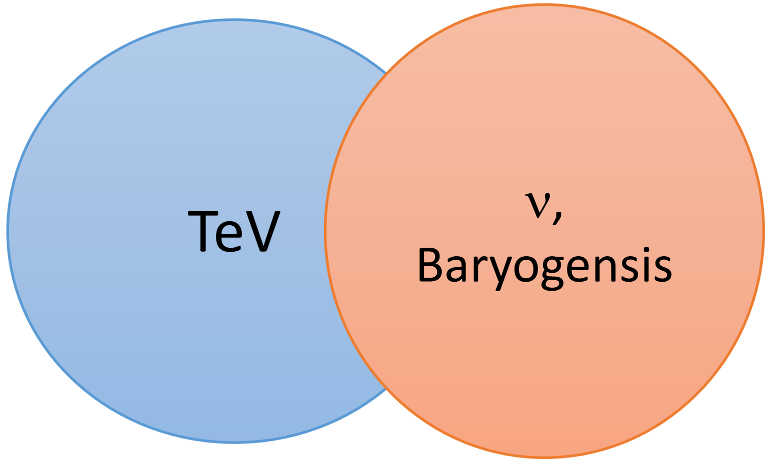
- EDM and LFV searches can provide a hint on the relationship between two scales.

If two scales are well separated,
EDMs and LFV are suppressed.



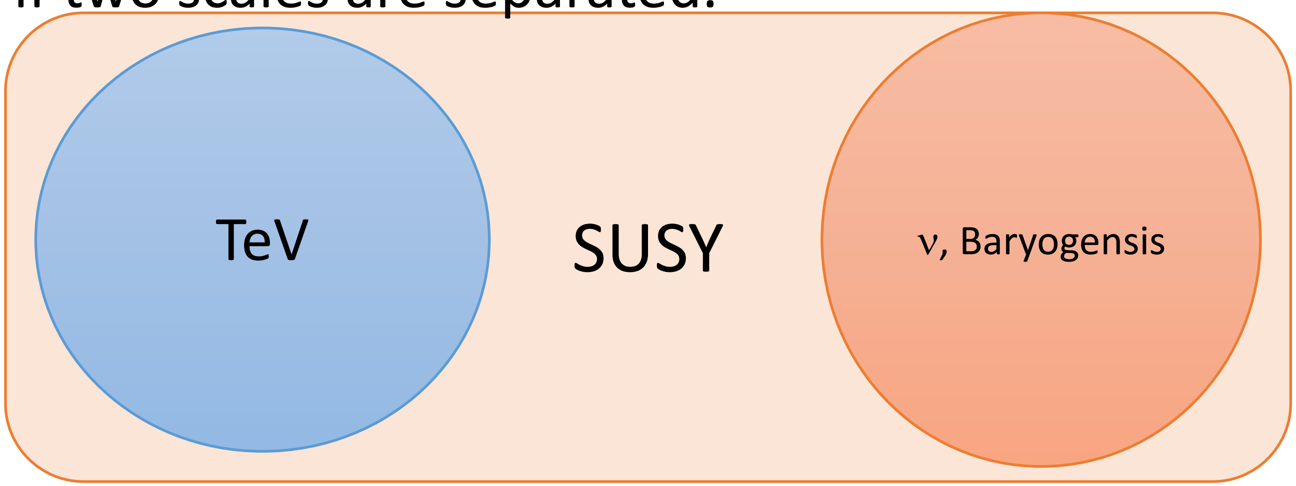
Seesaw neutrino model
Leptogenesis

If two scales are close, large EDMs and LFV are expected.



Example:
Neutrino mass from loop.
Electroweak baryogenesis

In supersymmetric models, large EDMs and LFV are expected even if two scales are separated.



Existence /absence of EDMs and LFV is a clue to fundamental problems such as neutrino mass generation and baryongenesis.

Three lepton processes: Naïve scaling

g-2

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

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

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

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

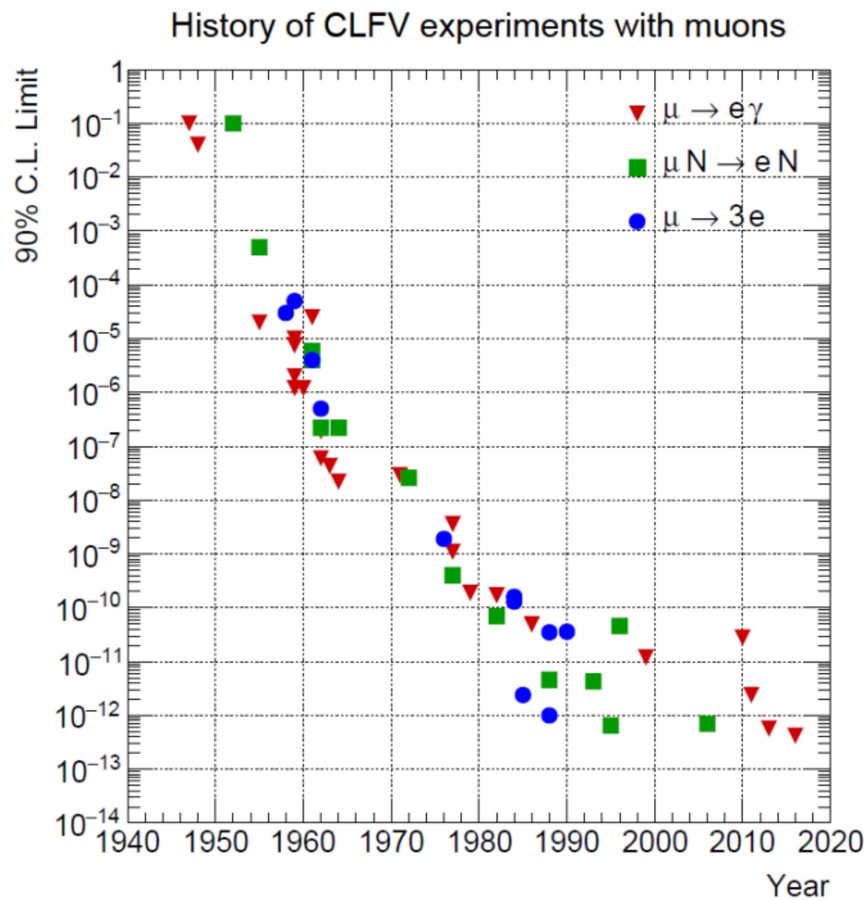
Current bounds
$B(\mu LFV) < O(10^{-13}) - O(10^{-11})$
$B(\tau LFV) < O(10^{-8}) - O(10^{-7})$

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

<u>Many examples of exceptional cases.</u>

Lepton Flavor Violation in Charge Lepton processes

- LFV in charged lepton processes is negligibly small for the Standard Model with simple seesaw neutrinos or Dirac neutrinos.
- Observation of the cLFV is a clear evidence of new physics.

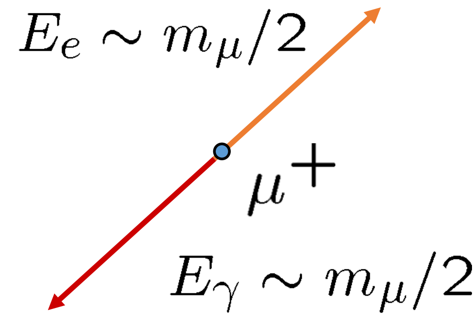


From arXive:1801.04688

Three muon LFV processes

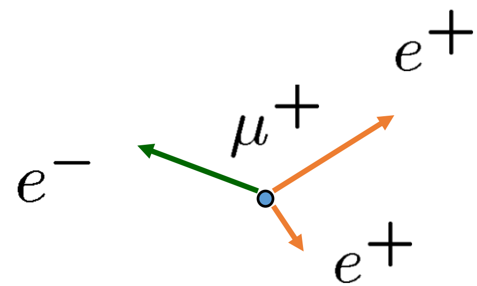
$$\mu^+ \rightarrow e^+\gamma$$

$B < 4.2 \times 10^{-13}$ (MEG)



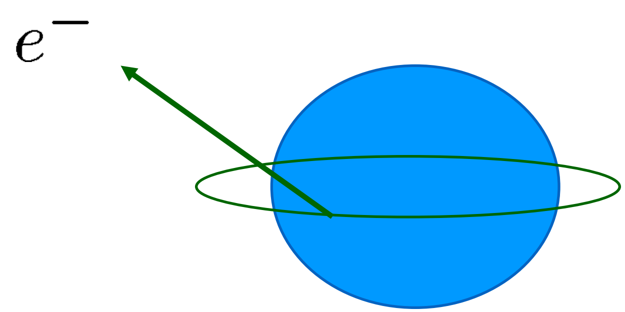
$$\mu^+ \rightarrow e^+e^+e^-$$ (SINDRUM)

$$B < 1.0 \times 10^{-12}$$



$$\mu^- A \rightarrow e^- A$$ (SINDRUMII)

$$B < 7 \times 10^{-13} (Au)$$



$$E_e \sim m_\mu - E_{1sBinding}$$

Tau LFV processes

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

(1) $\tau \to \mu\gamma, \tau \to e\gamma$ ⟷ $\mu \to e\gamma$

(2) $\tau \to lll$ ⟷ $\mu \to 3e$

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

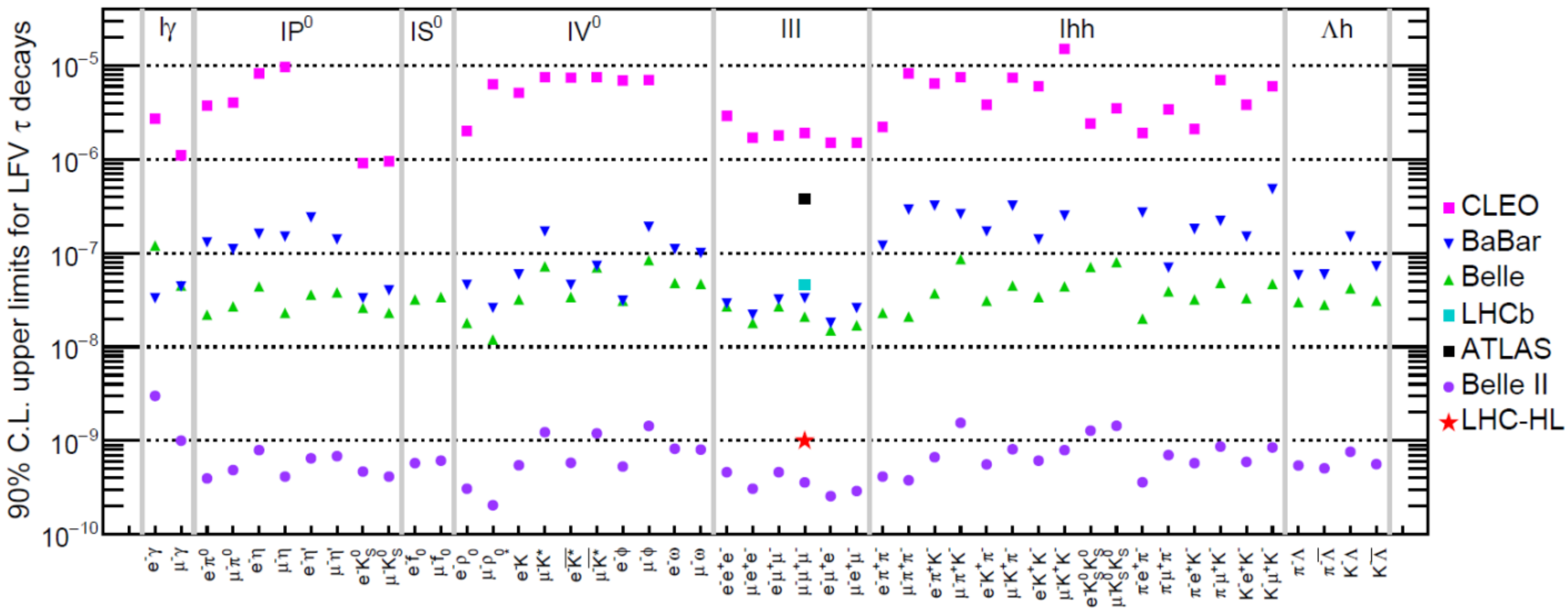
and their CP conjugates

(3) $\tau \to \mu\eta, \mu\pi, \mu\rho, \mu\phi, etc.$ ⟷ $\mu A \to e A$

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

Distinguishing different operators.

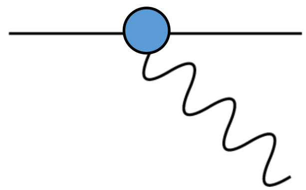
Tau LFV bounds and prospects



From arXiv:1812.07638

Effective interactions

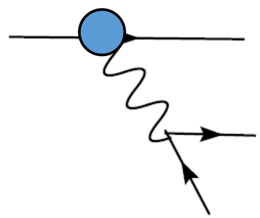
$\mu^+ \to e^+\gamma$

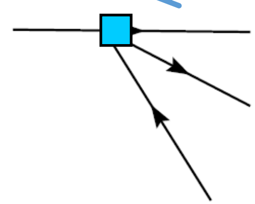


$$-\frac{4G_F}{\sqrt{2}}(m_\mu A_R \overline{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L \overline{\mu}\sigma^{\mu\nu}P_R e F_{\mu\nu} + \text{H.c.})$$

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

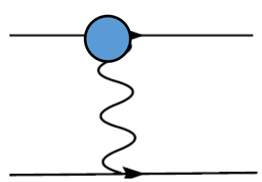
$\mu^+ \to e^+e^+e^-$

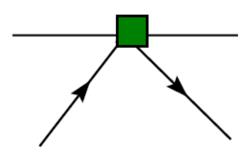




6 additional operators

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





Various llqq operators

Relations between different LFV branching ratios

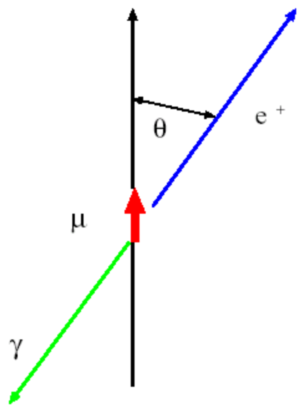
If the photon penguin process is dominant, there are simple relations among these branching ratios.

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

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)

Muon polarization and LFV processes

- If the muon is polarized, we can define a P-odd asymmetry for μ -> e γ and T-odd and P-odd asymmetries for μ->3e. These asymmetries are useful to discriminate different models.



$$\frac{dB(\mu^+ \to e^+\gamma)}{d\cos\theta} \propto 1 + A_{\mu\to e\gamma} P_\mu \cos\theta$$

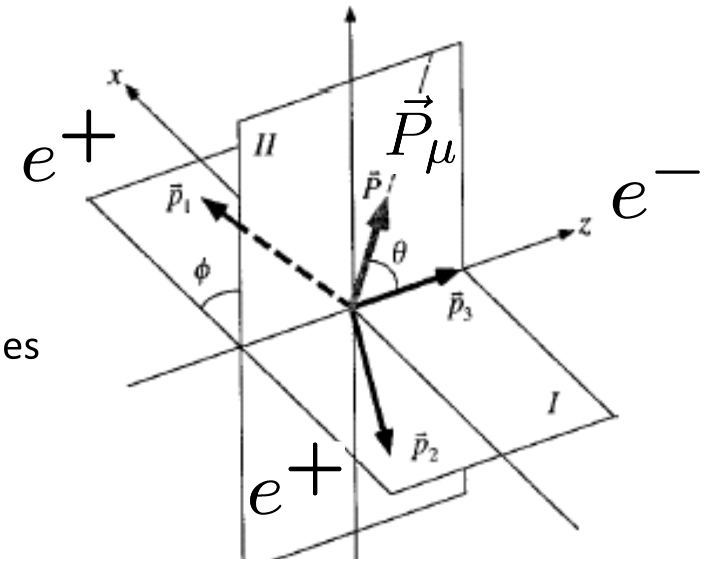
Example :A= -1 for the SUSY seesaw model

Left-handed slepton mixing =>

$$\mu^+ \to e^+\gamma_R \Rightarrow (1-\cos\theta) \text{ distribution}$$

μ–> 3e

Two P-odd and
one T-odd asymmetries



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

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

$$A_T = \frac{N(P_y>0)-N(P_y<0)}{N(P_y>0)+N(P_y<0)}$$

μ->e γ and μ->3e asymmetries in SUSY models

P and T-odd asymmetries in minimal SUSY GUT models

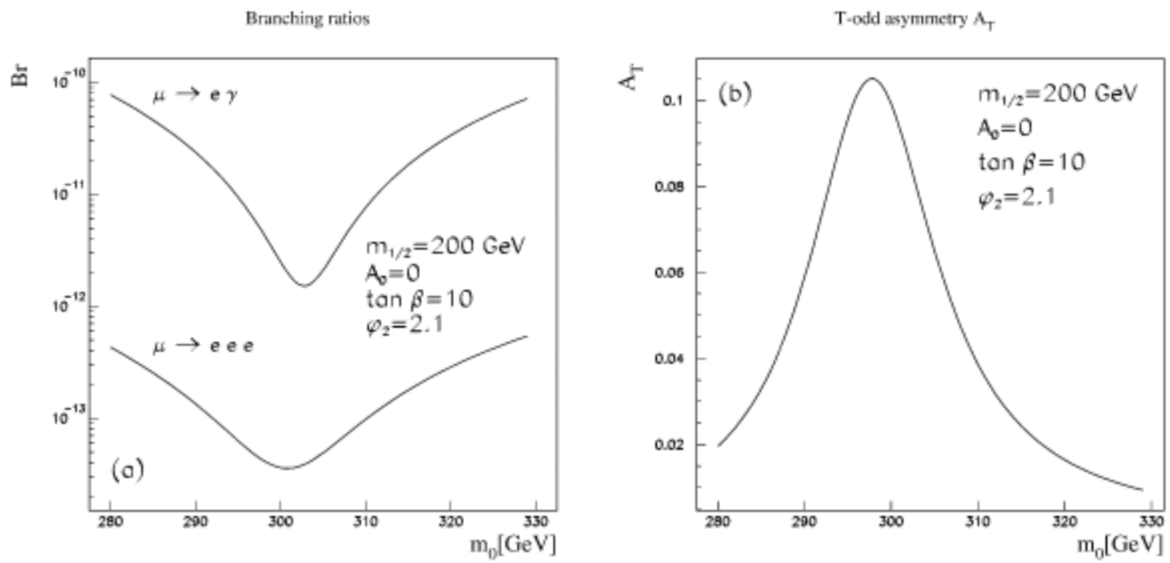
	SU (5)	SO (10)
$A_{\mu\to e\gamma}$	+100%	-100% − +100%
A_{P_1}	-30% − +40 %	$\simeq -A_{\mu\to e\gamma}/10$
A_{P_2}	-20% − +20 %	$\simeq -A_{\mu\to e\gamma}/6$
$\|A_T\|$	$\lesssim$15%	$\lesssim$ 0.01%

Y.Okada,K.Okumura,and Y.Shimizu, 2000

The T-odd asymmetry can be 10 % level for some parameter space of the SU(5) SUSY GUT and the SUSY seesaw model.

Information on lepton sector CP violation

T-odd asymmetry in the SUSY seesaw model



J.Ellis,J.Hisano,S.Lola, and M.Raidal, 2001

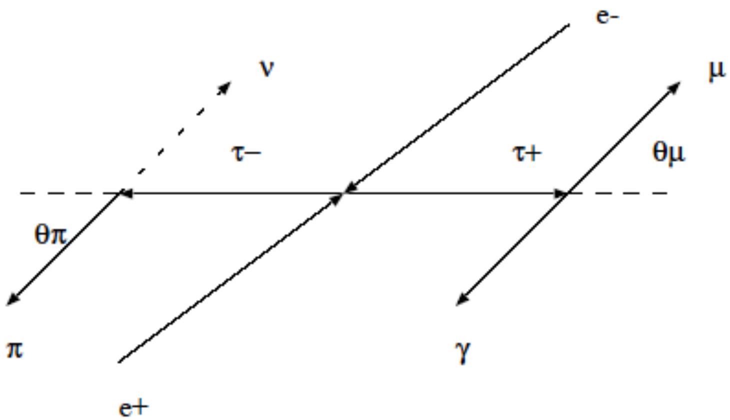
“Polarized” tau decay

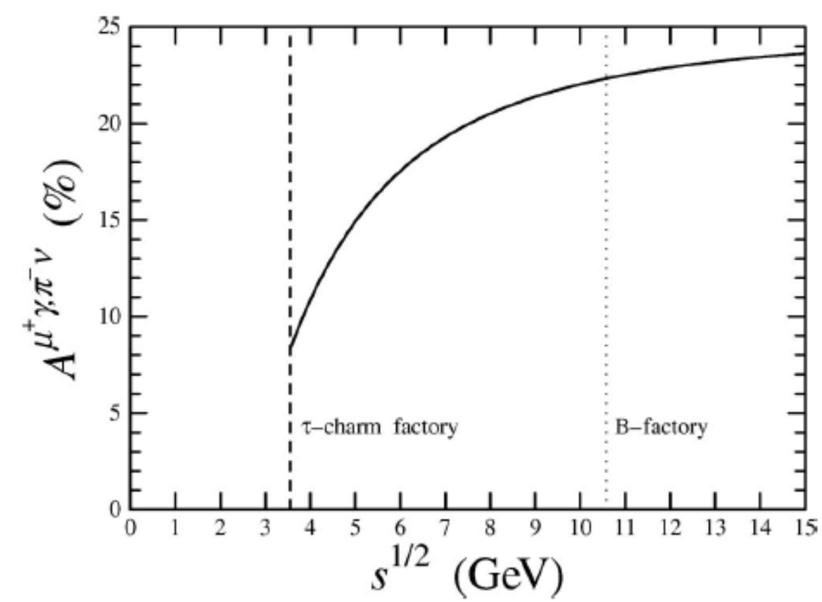
- Angular correlation of tau decay products at e^+e^- colliders.

R.Kitano and Y.Okada 2001

Example:

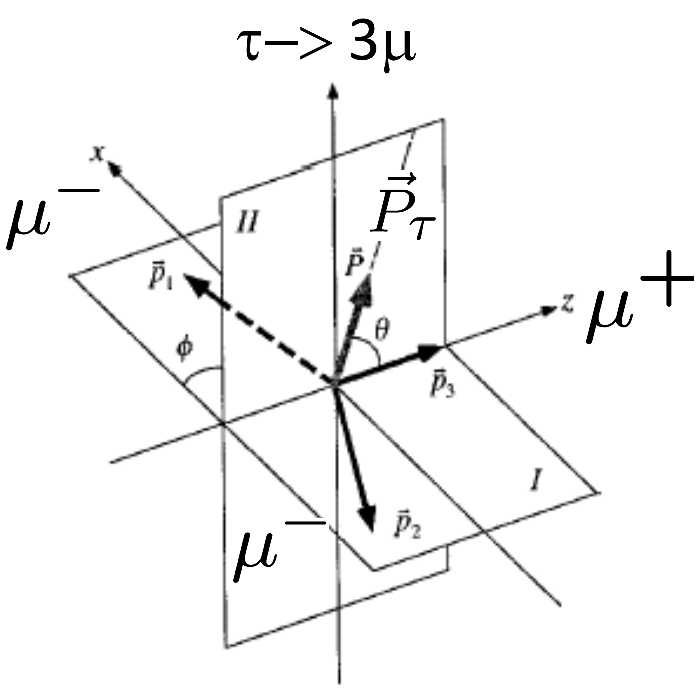
$$\frac{dB(e^+e^- \to \tau^+\tau^- \to \mu^+\gamma + \pi^-\nu)}{d\cos\theta_\mu d\cos\theta_\pi} \propto 1 - A_{\tau\to\mu\gamma}\frac{s-2m_\tau^2}{s+2m_\tau^2}\cos\theta_\mu\cos\theta_\pi$$





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

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



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" ($\bar{Z}^{l\tau\mu}_{\text{odd}} \gg \bar{Y}^{l\tau\mu}_{\mu,\text{odd}}$)	$A = 5/18$
"Y" ($\bar{Z}^{l\tau\mu}_{\text{odd}} \ll \bar{Y}^{l\tau\mu}_{\mu,\text{odd}}$)	$A = 1/2$
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

Calculation of the mu-e conversion rate

- The first calculation of the mu-e conversion rate was done by S. Weinberg and G. Feinberg in 1959.
- O. Shanker made extensive calculations for all interactions based on relativistic wave functions of muon and electrons in 1979.
- A. Czarnecki, W.J. Marciano, and K. Melnikov improved the calculation for selected atoms in 1998.
- Detailed calculations for various nuclei was presented by R. Kitano, M. Koike and Y. Okada in 2002.

Operators relevant to the coherent mu-e conversion

$$\begin{aligned}
\mathcal{L}_{\rm eff}^{(q')} &= -\frac{1}{\Lambda^2}\Bigg[\left(C_{DR} m_\mu\, \bar{e}\sigma^{\rho\nu} P_L \mu + C_{DL} m_\mu\, \bar{e}\sigma^{\rho\nu} P_R \mu\right) F_{\rho\nu} \\
&+ \sum_{q=u,d,s} \left(C_{VR}^{(q)}\, \bar{e}\gamma^\rho P_R \mu + C_{VL}^{(q)}\, \bar{e}\gamma^\rho P_L \mu \right) \bar{q}\gamma_\rho q \\
&+ \sum_{q=u,d,s} \left(C_{SR}^{(q)} m_\mu m_q G_F\, \bar{e} P_L \mu + C_{SL}^{(q)} m_\mu m_q G_F\, \bar{e} P_R \mu \right) \bar{q} q \\
&+ \left(C_{GQR} m_\mu G_F\, \bar{e} P_L \mu + C_{GQL} m_\mu G_F\, \bar{e} P_R \mu \right) \frac{\beta_L}{2 g_s^3} G_a^{\rho\nu} G_{\rho\nu}^a + h.c. \Bigg]
\end{aligned}$$

Photonic dipole

Vector

Scalar

gluonic

The gluonic operator can arise by heavy quark loop diagrams.
The gluonic coupling to a nucleon can be expressed by scalar quark densities in a nucleon.

The μ-e conversion rate is defined

$$B \equiv \frac{\omega(\mu N(A,Z)\rightarrow eN(A,Z))}{\omega(\mu N(A,Z)\rightarrow capture)}$$

Schematically,

$$\omega(\mu N(A,Z) \rightarrow N(A,Z)) \sim |\sum \int d^3x \bar{\psi}_e \Gamma \psi_\mu^{(1S)} \rho^{(p,n)}|^2$$

Calculation goes in the following steps:

(1) Take a matrix element of quark operators in a proton/a neutron state.

(2) Sum over all the protons and neutrons in a nucleus coherently.

(3) Evaluate overlap integrals of the above type.

Theoretical uncertainty depends on a type of operators

(1) Photonic dipole case: Almost no uncertainty
The calculation only depends on the charge distribution in a nucleus, which is precisely known by electron scattering.

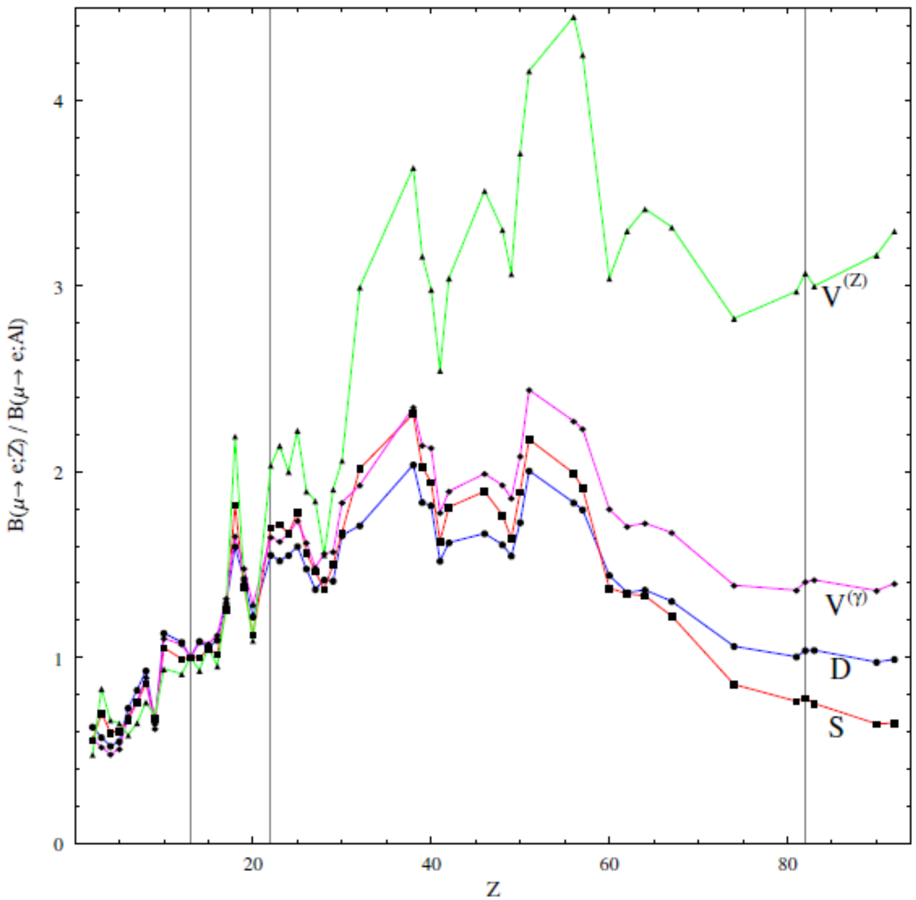
(2) Vector case:
The main uncertainty comes from the neutron density.
Little uncertainty for light nuclei.
Uncertainty is 5% level for heavy nuclei if the proton scattering data is available (ex. Pb).

(3) Scalar case:
An addition source of uncertainty is scalar quark densities in a nucleon.

Lattice QCD calculation reduced uncertainty associated with strange quark scalar density.

V. Cirigliano, R. Kitano, Y. Okada, and P. Tuson, 2009
A. Crivellin, M. Hoferichter and M. Procura, 2014

Atomic number dependence of the mu-e conversion rate for various LFV operators



Z-like vecor

Photon-like vector

Photonic dipole

Higgs-like scalar

Al Ti Pb

- Maximal in the intermediate nuclei.
- Different Z dependence for heavy nuclei.
- Large enhancement in the Z-like vector case (neutron-rich for heavy nuclei).

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

Implications to new physics models

- Observable LFV rates are predicted in many new physics models.
- In particular, the SUSY seesaw model is still a prime candidate producing a large LFV. The predicted rate depends on the scale and the structure of the heavy Majorana neutrino sector.

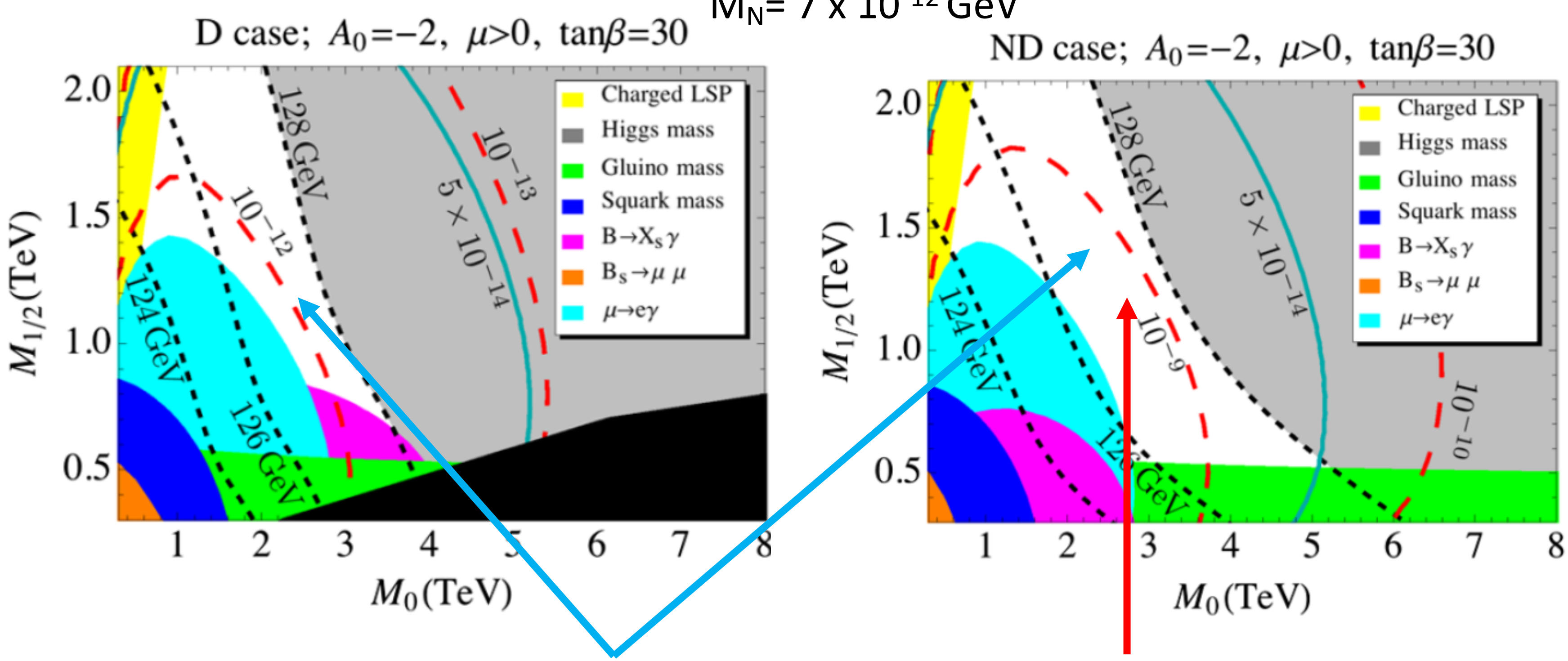
LFV in SUSY seesaw model

T. Goto, Y. Okada, T.Sindou, M.Tanaka and R.Watanabe, 2015

We have updated the prediction of muon and tau LFV processes in the SUSY seesaw Model, takin into account of various experimental results including the Higgs boson mass, SUSY searches at the 8TeV LHC run and θ_{13} in the neutrino experiments.

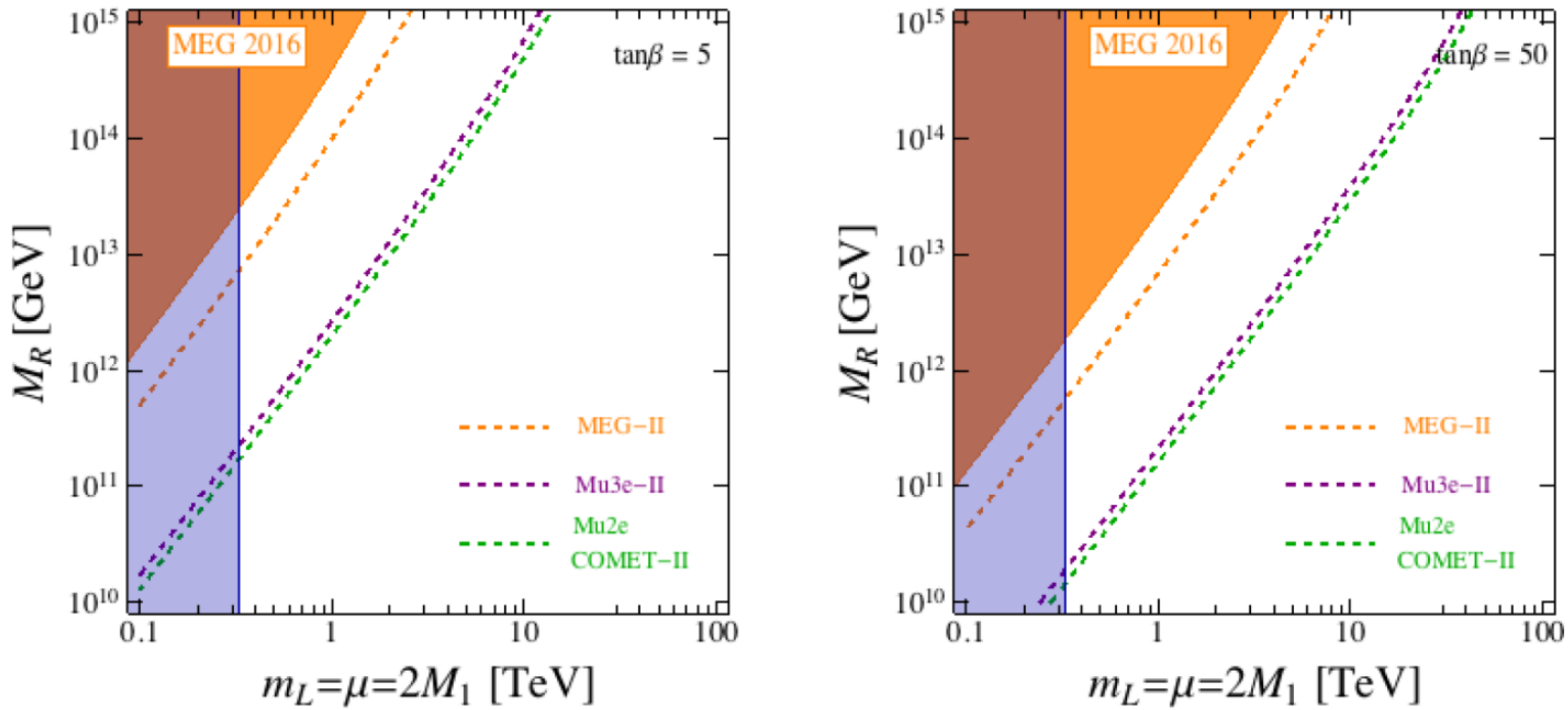
Degenerate case for the Majorana mass matrix   A special non-degenerate case

$M_N = 7 \times 10^{12}$ GeV



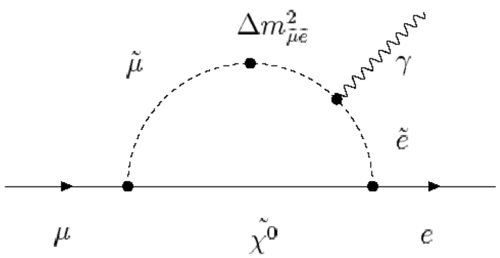
O(10^{-13}) in μ->eγ O(10^{-9}) in τ->$\mu\gamma$

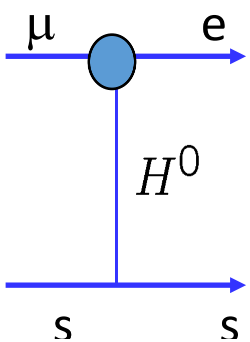
Parameter space covered by LFV searches (Degenerate Majorana neutrinos)



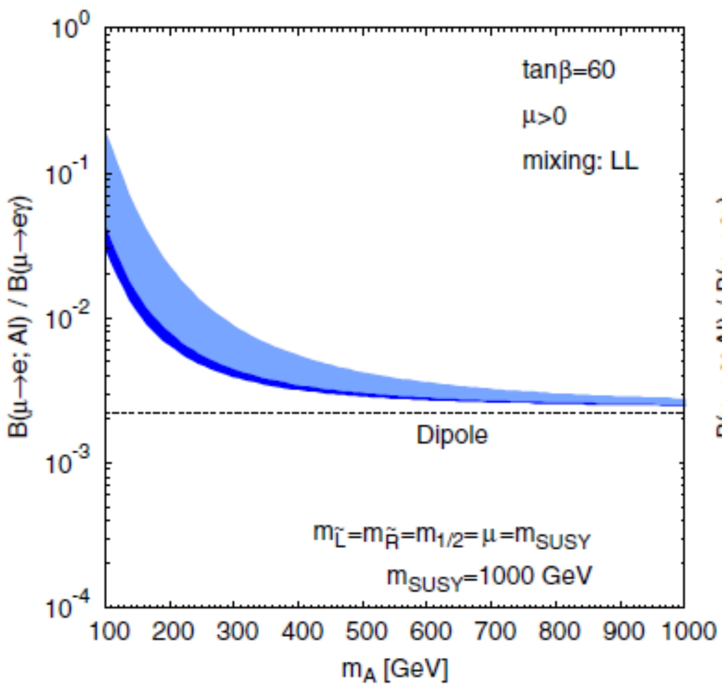
L. Calibbi and G. Signorelli, arXive:1709.00294

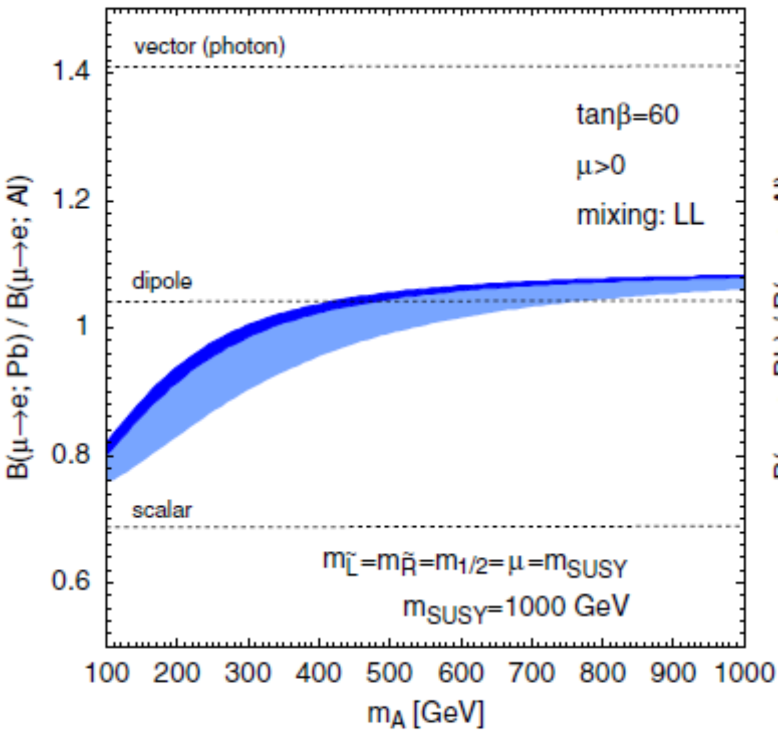
Higgs exchange contribution in SUSY seesaw model with a large “tanβ”





Blue band :
Uncertainty from “y”
Light: 0<y<0.4
Dark:0<y<0.05





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

Neutrino mass from TeV physics and LFV

- If the origin of neutrino mass comes from TeV physics, a large LFV is expected.
- Each model shows a characteristic feature in branching ratios, angular distributions, etc.

Examples

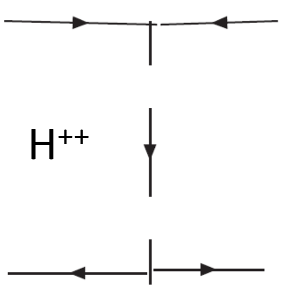
Radiative neutrino mass generation (Zee model, etc)

Low energy seesaw model (singlet neutrino, triplet scalar, triplet fermion)

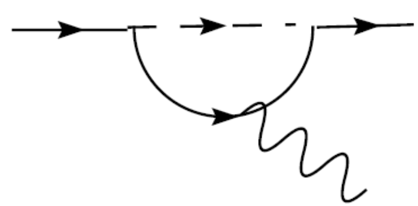
R-parity violating SUSY model

Left-right symmetric model

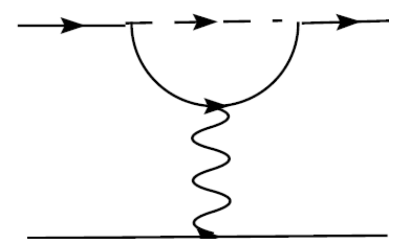
μ->3e



μ ->eγ

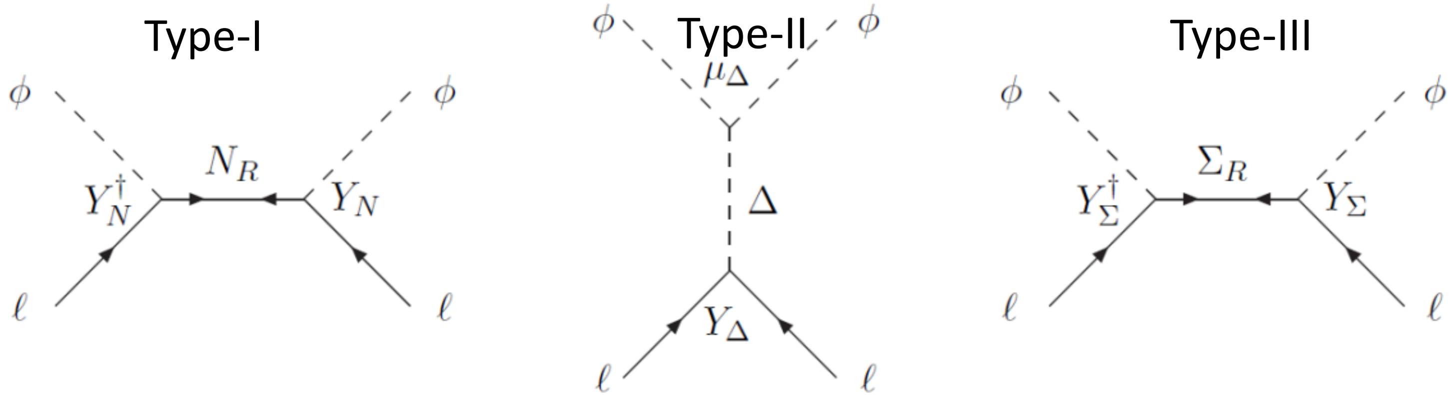


μ-e conv



TeV scale seesaw model and LFV

A. Abada, C. Biggio, F. Bonnet, M.B.Gavela, and T. Hambye, 2007



Non-unitarity in the PMNS matrix

Triplet Higgs coupling

Tree-level LFV coupling

Seesaw relation

$$m_\nu \equiv -\frac{v^2}{2}\, c^{d=5} = -\frac{1}{2}\, Y_N^T \frac{v^2}{M_N} Y_N$$

$$m_\nu = -2 Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$

Inverse seesaw mechanism

$$\begin{pmatrix} 0 & m_{D_1} & 0 \\ m_{D_1} & 0 & M_{N_1} \\ 0 & M_{N_1} & \mu \end{pmatrix} \Longrightarrow m_\nu \sim \mu \frac{Y_1^2 v^2}{M_1^2}.$$

M can be close to the TeV scale with O(1) Yukawa coupling constants

Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\text{BR}(\mu \to eee)}{\text{BR}(\mu \to e\gamma)}$	$\frac{\text{CR}(\mu N \to eN)}{\text{BR}(\mu \to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	$0.1 - 10$
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop*†	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

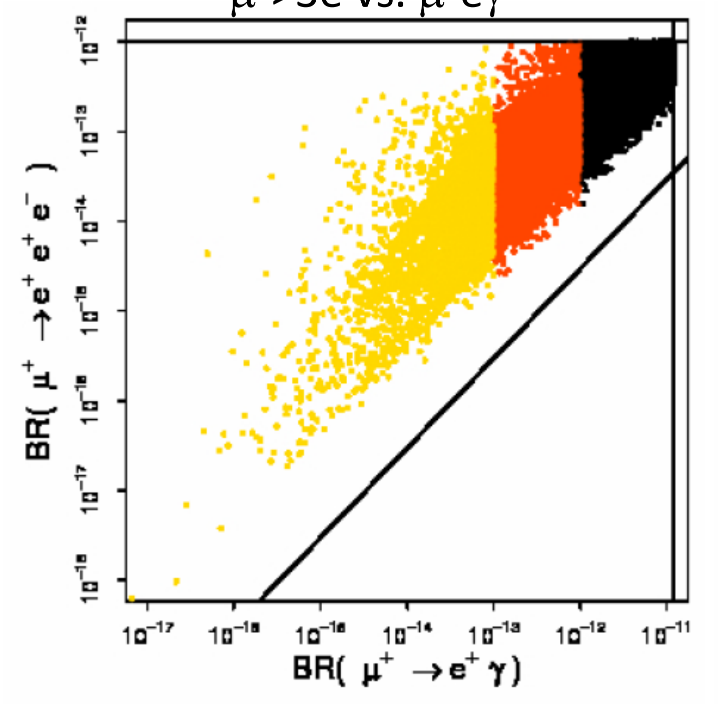
L. Calibbi and G. Signorelli, arXive:1709.00294

Little Higgs Model with T parity

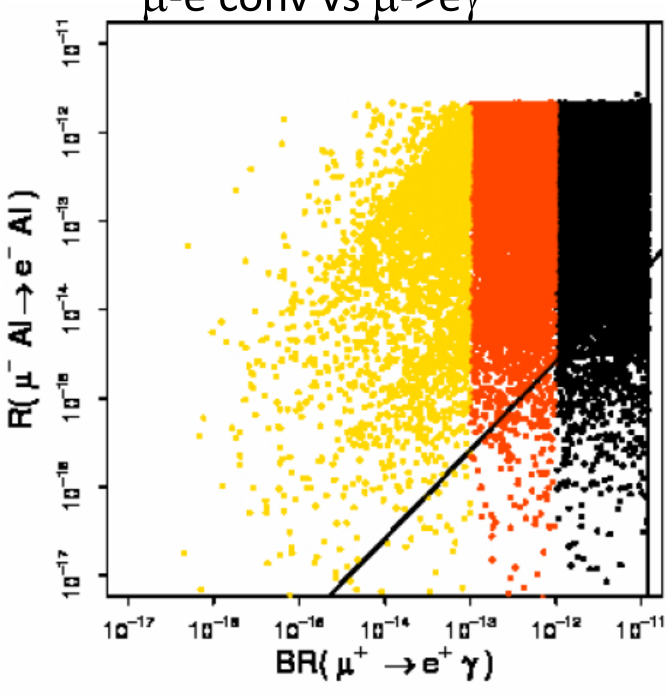
- The Higgs boson is a pseudo Nambu-Goldstone boson of some strong dynamics at ~10 TeV.
- New gauge bosons and a top partner to stabilize the Higgs potential against large radiative corrections without fine-tuning.
- T-odd heavy quarks and leptons are introduced. New flavor mixing matrixes induce FCNC and LFV.

J.Hubisz,S.J.Lee,G.Paz, 2005 ;M.Blanke,et al. 2006-2009;
S.Rai Choudhury, et al. 2007;T.Goto, Y.Okada, Y.Yamamoto, 2009
F.del Aguila, J.I.Illana, M.D.Jenkins,2009,2010

μ->3e vs. μ-eγ



μ-e conv vs μ->eγ

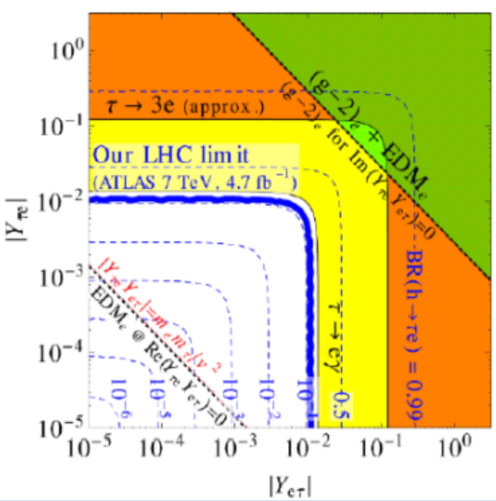


T.Goto, Y.Okada, Y.Yamamoto, 2010

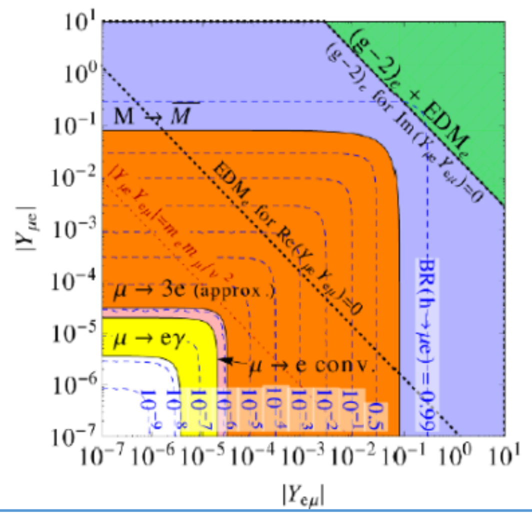
LFV Higgs decay

- Higgs decays provide opportunity to look for LFV interactions.
- Higgs to tau-mu and tau-e modes are promising taking account of rare decay constraints.

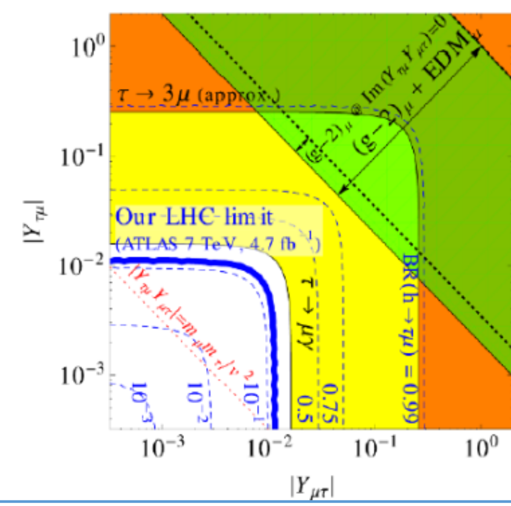
H->τe



H->eμ



H->τμ

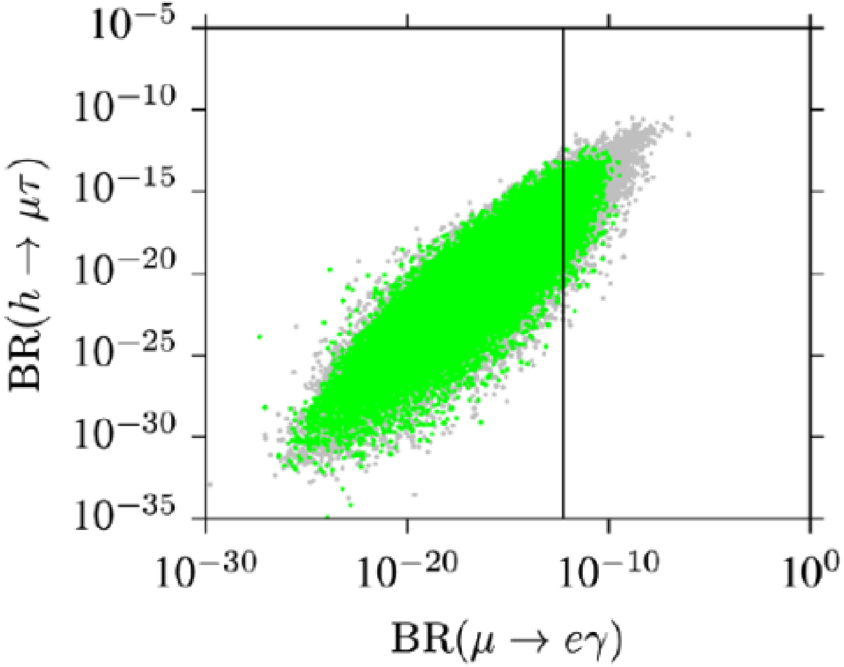


$$\mathcal{L}_Y \supset -Y_{e\mu}\bar{e}_L\mu_R h - Y_{\mu e}\bar{\mu}_L e_R h - Y_{e\tau}\bar{e}_L\tau_R h - Y_{\tau e}\bar{\tau}_L e_R h - Y_{\mu\tau}\bar{\mu}_L\tau_R h - Y_{\tau\mu}\bar{\tau}_L\mu_R h + h.c..$$

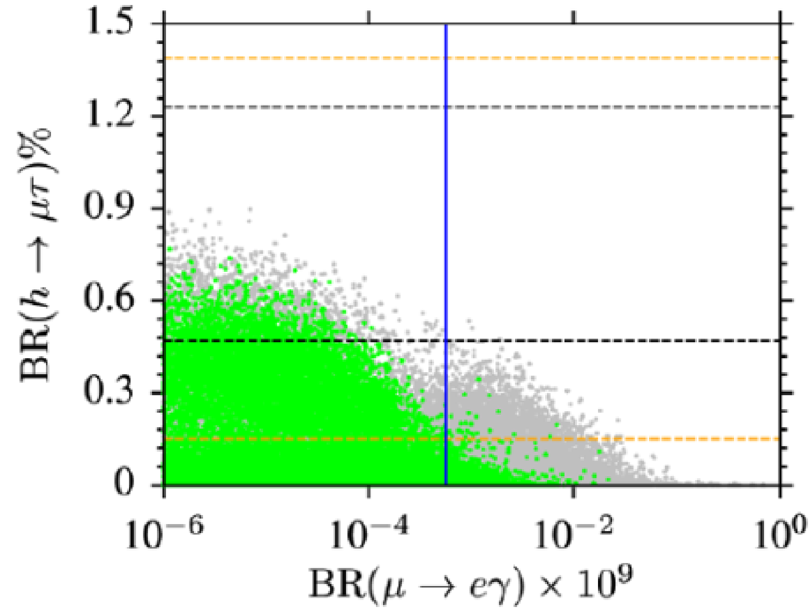
R. Harnik, J. Kopp, and J.Zupan, 2013

SUSY model example

High scale SUSY seesaw model



SUSY B-L model with inverse seesaw
(Low scale seesaw model)



A. Hammad S,. Khalil, and C.S. Un, 2017

Summary

- Particle physics has entered a new era.
- Searches for Lepton Flavor Violation offer prime opportunities to explore new physics in generic ways. This is particularly interesting in views of neutrino and/or SUSY.
- Experimental prospects are bright. There are ongoing and planned muon dedicated experiments as well as tau LFV searches at LHC, LHCb and Belle II.