



Dept of Physics
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When CLFV meets SUSY.....



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WHEPP 2019

Lepton number @ Standard Model

- Lepton (also Baryon) **number** is conserved in the Standard Model (SM)

Flavourwise
and the total

- **Accidental** symmetry of the SM Lagrangian

- **Not imposed** but consequence of the particle content, gauge invariance, renormalizability and Lorentz invariance

Example: $\bar{e}_R \ell \ell$

$$\ell \ell : (2, -\frac{1}{6}) \otimes (2, -\frac{1}{6}) \rightarrow (3, -\frac{2}{3}) \oplus (1, -\frac{2}{3})$$

Gauge Invariant ($\Delta L = 1$) operator

Isotriplet and Isosinglet configurations from

Collection of 3 Fermionic fields:

Violates Lorentz Invariance and Renormalizability

Lepton number @ Standard Model

Another example:

$$\frac{\lambda}{M} (\ell^T C i \tau_2 \tau^\alpha \ell) (H^T i \tau_2 \tau_\alpha H)$$

Some coupling

Some mass scale to match Dimensionality requirement

Particle-antiparticle conjugation operator

Pauli spin matrices

(3, -2) (3, 2)

Non-zero neutrino mass

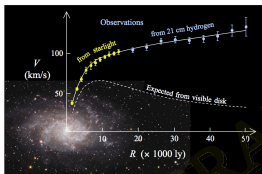
$$m_\nu \approx \lambda \frac{\langle H \rangle^2}{M}$$

Gauge and Lorentz Invariant $\Delta L=2$ operator

It's a d = 5 operator: Non-renormalizable

Limitations of the Standard Model

Non-zero neutrino masses and mixing ►



The Nobel Prize in Physics 2015



Takaaki Kajita



Arthur B. McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

► Galaxy rotation curve inconsistent with Keplerian decline

Gauge-hierarchy problem with Higgs Mass ►

Aesthetic/Cosmetic ?
Brutality of mother Nature ?

Part of a more robust framework like
Supersymmetry (SUSY) ?

► A few others: matter-antimatter asymmetry, too many free parameters, etc...

Beyond the Standard Model with massive neutrinos

No-right handed neutrinos (RHN) in the SM

No Yukawa coupling between Left and Right-handed neutrinos

No Higgs assisted mass generation

How about adding a new term like $Y_\nu \bar{\ell} (\gamma_5 \tau_2 H^*) N_R$, gives $m_D = Y_\nu \langle H \rangle$

A Lorentz invariant, renormalizable and Gauge invariant term iff N_R
is singlet under $SU(3)_c \times SU(2)_L \times U(1)_Y$

If N_R is SM gauge-singlet then how you can forbid a term bilinear in N_R :
A mass term for RHN

Beyond the Standard Model with massive neutrinos

A mass term for RHN: $\frac{1}{2} M_N N_R^T C N_R$?

M_N : A new scale beyond Higgs VEV

A Lorentz invariant, renormalizable, Gauge invariant term as N_R is SM singlet

How to preserve Lepton number conservation now ?

Case-I

N_R has $L = +1$

$$Y_\nu \bar{\ell} (i\tau_2 H^*) N_R$$

Preserves L-number

$$\frac{1}{2} M_N N_R^T C N_R$$

Violates L-number
By two units

Case-II

N_R has $L = 0$

$$\frac{1}{2} M_N N_R^T C N_R$$

Preserves L-number

$$Y_\nu \bar{\ell} (i\tau_2 H^*) N_R$$

Violates L-number
By one unit

Non-zero neutrino mass : Violation of Lepton numbers

Non-zero neutrino mass : Violation of **Lepton** numbers

M_N is arbitrary: Consider $M_N = 0$ with $L(N_R) = +1$ $\blacktriangleright$ $m_D = Y_\nu \langle H \rangle$

Dirac mass term for neutrinos $\blacktriangleright$ Flavour oscillations
No Majorana mass term $\blacktriangleright$ No process like $0\nu\beta\beta$

Violation of L_e, L_μ & L_τ , but not L_{tot}

$M_N \neq 0$ $\blacktriangleright$ Majorana mass for light-neutrinos: $m \approx \frac{m_D^2}{M_N}$

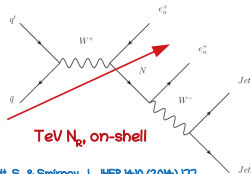
Seesaw mechanism: Minkowski, P., Phys.Lett. 67B (1977) 421-428;
Yanagida, T., Prog.Theor.Phys. 64 (1980) 1103; Mahapatra, R. N. and Senjanovic, G.,
Phys.Rev.Lett. 44 (1980) 912; Schechter, J. and Valle, J. W. F.,
Phys.Rev. D22 (1980) 2227

Majorana mass term for neutrinos $\blacktriangleright$ $\nu - \bar{\nu}$ oscillations

Non-zero $0\nu\beta\beta$, Unique collider signatures $\blacktriangleright$

Violation of L_{tot} also

Pic courtesy: Lindner, M., Schmidt, S., & Smirnov, J., JHEP 1410 (2014) 177



Consequence of broken Lepton number

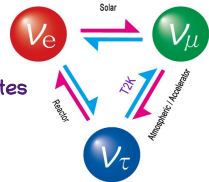
Massive neutrinos: Mass basis and flavour basis are no longer the same

- Non-trivial leptonic mixing : PMNS matrix (It's like leptonic CKM)

Pontecorvo, 1957, 1967, Maki, Nakagawa, Sakata, 1962

Neutrinos change their flavours during propagation

Neutrino Oscillations ► Flavour states are composition of mass states



QM analogue ► Any arbitrary states can be written as a linear combination of the eigen states

When neutrinos oscillate.....

Think about this process: $\mu \rightarrow e \gamma$

$\Delta L = 0$ but $\Delta L_e = 1$ & $\Delta L_\mu = 1$

Non-zero branching fraction only for non-zero neutrino mass



Flavour states are linear combination of mass eigen states

Given $M_W \sim 80$ GeV and neutrino mass ~ 0.1 eV, this $\text{Br} \sim 10^{-5+}$ too small to detect

Aghanim, N. et. al. Planck 2018 results, 1807.06209
Aker, M. et. al. KATRIN, Phys.Rev.Lett. 123 (2019) 221802

Experiment Challenge: Current sensitivity (MEG) $\sim 4.2 \times 10^{-13}$, Eur.Phys.J. C76 (2016) no.8, 4-34
Projected sensitivity (MEG II) $\sim 6.0 \times 10^{-14}$, Eur.Phys.J. C78 (2018) no.5, 380

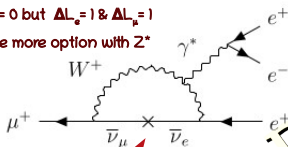
Too small to detect or too soon to detect ?

When neutrinos oscillate.....

Think about another process: $\mu \rightarrow eee$

$\Delta L = 0$ but $\Delta L_e = 1$ & $\Delta L_\mu = 1$

One more option with Z^*



Non-zero branching fraction only for non-zero neutrino mass

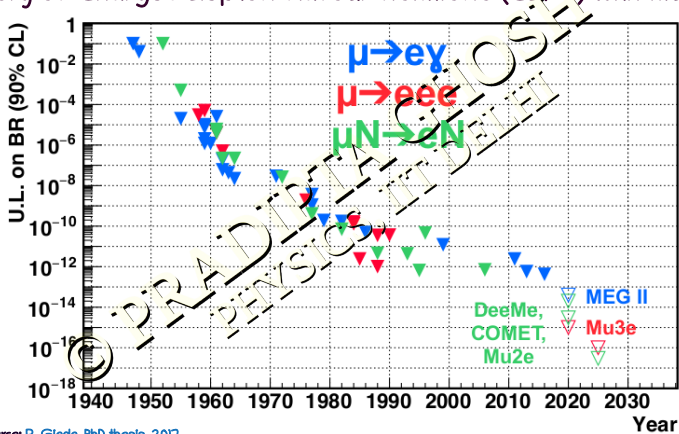
BR even smaller. ◀ Additional vertex of γ conversion

Flavour states are linear combination of mass eigen states

Experiment Challenge: Current sensitivity (SINDRUM) $\sim 1.0 \times 10^{-12}$, Nucl.Phys. B299 (1988) 1-6
Projected sensitivity (Mu3e) $\sim 10^{-15(16)}$, Blondel, A. ArXiv: 1301.6113

Too small to detect or too soon to detect ?

History of Charged Lepton flavour violations (CLFV) with muon.....



Pic. source: R. Glada, PhD thesis, 2017

Why beyond the Standard Model (BSM) to study CLFV

CLFV needs non-zero neutrino masses ► ν SM

Branching ratios are too small to detect with ν SM, even at 2030

$$Br(\mu \rightarrow e \gamma) \sim 10^{-34}$$

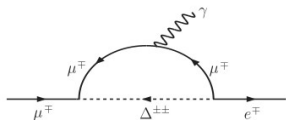
Present sensitivity: $< 4.2 \times 10^{-13}$ MEG collab. Eur.Phys.J. C76 (2016) no.8, 434

SUSY is a well known BSM framework that overpowers SM's shortcomings

New parameters in the theory : New sources of CLFV

CFLV experiments can help us to probe SUSY parameter space

CLFV in BSM theories: SUSY is **not** the chosen one



◀ $\mu \rightarrow e \gamma$

$\tau \rightarrow \mu \mu \mu, \mu e e, \mu \mu e$

▶



CLFV in models with **doubly charged scalar Δ^{++}**

Pic courtesy: Chakraborty, J., Ghosh, P., Mondal, S., & Srivastava, T., Phys.Rev. D93 (2016) no.11, 115004

CLFV in SUSY

Just like the vSM we can try with RHN in SUSY models ► small $\text{Br} \dots$ NOT the 1st choice

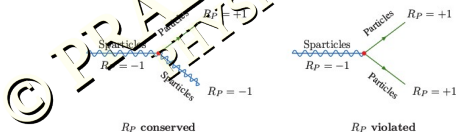
Let's try something that is purely SUPERSYMMETRIC

Violation of R-parity:

$$R_P = (-1)^{3B+L+2s}$$

L = Lepton number
B = Baryon number
s = Spin

$R_P = +1$ for SM particles, $R_P = -1$ for Sparticles



R_P broken ► Lightest SUSY particle (LSP) unstable.... Decaying dark matter ?

$R_p V$ in SUSY

Gives rise to Epsilon-problem:
de Carlos, B., & White, P. L.,
Phys.Rev. D55 (1997) 4222-4239

$$W_{R_p V} = W_{R_p C}^{MSSM} + \frac{1}{2} \lambda_{ijk} \hat{L}_i \cdot \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \cdot \hat{Q}_j \hat{D}_k^c + \frac{1}{2} \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c - \epsilon_i \hat{L}_i \cdot \hat{H}_u$$

$\Delta L = 1$

$\Delta L = 1$

$\Delta B = 1$

$\Delta L = 1$

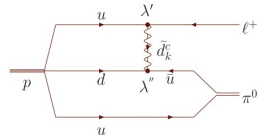
$$\epsilon_{\alpha\beta} \epsilon_i \hat{L}_i^a \hat{H}_u^b$$

SU(2) structure with $\epsilon_{\alpha\beta}$

Similar terms in Soft-SUSY breaking Lagrangian:

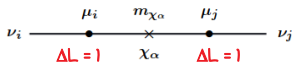
$$-\mathcal{L}_{soft}^{R_p V} = -\mathcal{L}_{soft}^{R_p C} + \frac{1}{2} (A_1 \lambda)_{ijk} \tilde{L}_i \tilde{L}_j \tilde{E}_k^c + (A_2 \lambda')_{ijk} \tilde{L}_i \tilde{Q}_j \tilde{D}_k^c + \frac{1}{2} (A_3 \lambda'')_{ijk} \tilde{U}_i^c \tilde{D}_j^c \tilde{D}_k^c - (B\epsilon)_i \tilde{L}_i \tilde{H}_u$$

Simultaneous presence of L and B violating operators are forbidden: fast proton decay ►



Several other constraints: See e.g., Barbler, R. et. al. Phys.Rept. 420 (2005) 1-202

Neutrino masses in $R_p V$ SUSY

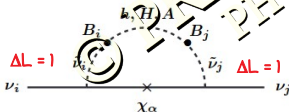
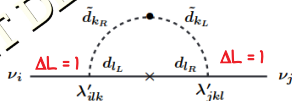


◀ Tree level with bi-linear term

$$m_\nu \approx \frac{\mu_i \mu_j}{m_{\tilde{\chi}}}$$

Loop level with Tri-linear term ▶

$$m_\nu \approx \frac{2 m_d^2}{m_d}$$



◀ Loop level with bi-linear soft-term

$$m_\nu \approx g_2^2 \frac{(B\epsilon)_i (B\epsilon)_j}{\tilde{m}^3}$$

Plc courtesy: Grossman, Y. & Rakshit, S., Phys.Rev. D69 (2004-) 093002

CLFV in $R_p V$ SUSY

$$\tilde{B}, \tilde{W}_3^0 \quad \tilde{H}_u^0, \tilde{H}_d^0$$

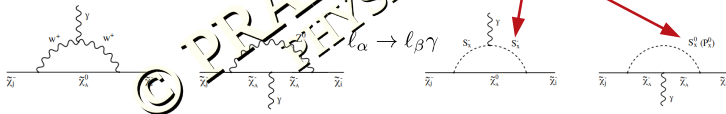
Neutral Gauginos and Higgsinos mix with neutrinos ► Extended neutralino Matrix 7X7 or More

$$\tilde{W}^\pm, \tilde{H}_u^\pm, \tilde{H}_d^\pm$$

Charged Gauginos and Higgsinos mix with Charged leptons ► 5 X 5 chargino mass matrix

Charged Higgses mix with Charged sleptons ► 8 X 8 charged scalar mass matrix

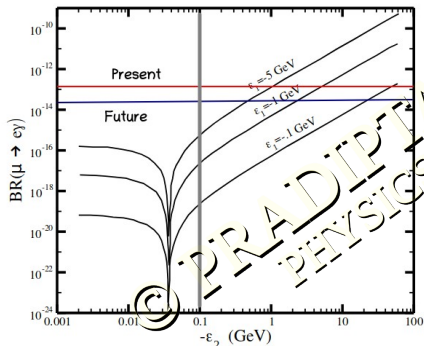
Neutral Higgses mix with Neutral sleptons ► Enlarged CP+, CP- scalar mass matrices



Including LQD ^{c} will increase the number of diagrams, quark-squark channel also

Plc courtesy: Carvalho, D. F. and Gomez, M. E. and Romao, J. C., Phys.Rev. D65 (2002) 093013

CLFV in $R_p V$ SUSY-1



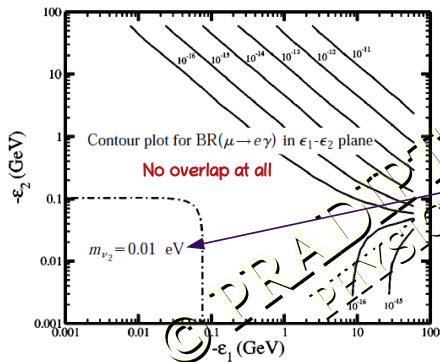
Given the current constraint on the sum of neutrino mass,
Only $\epsilon_1 < 0.1$ GeV is OK.. If μ -parameter is as large as 10^8 GeV... not natural
That however, once again will predict too small Br... hard to detect soon

TeV scale μ -parameter gives $\epsilon_1 \sim 10^4$ GeV which would predict too small Br... hard to detect even in distant future

If SUSY with BRpV is the model for neutrino mass
► CLFV processes will remain beyond experimental reach even in the far future

Plc courtesy: Carvalho, D. F. and Gomez, M. E. and Romao, J. C., Phys.Rev. D65 (2002) 093013

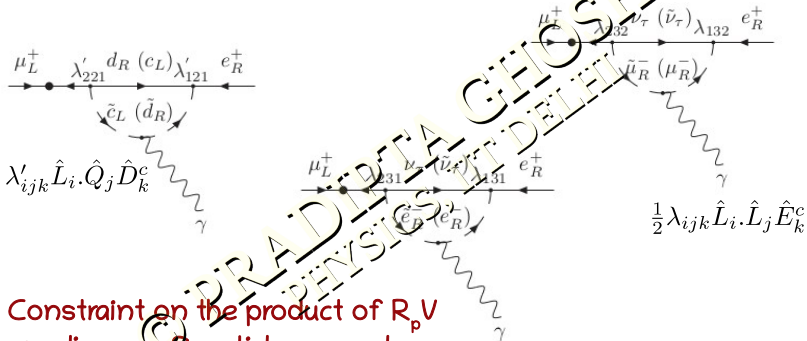
CLFV in $R_p V$ SUSY- I (Contd....)



If SUSY with BRpV is the model for neutrino mass
 ► CLFV processes will remain beyond experimental reach even in the far future

Plc courtesy: Carvalho, D. F. and Gomez, M. E. and Romao, J. C., Phys.Rev. D65 (2002) 093013

CLFV in $R_p V$ SUSY- II (TRpV)



Constraint on the product of $R_p V$ couplings vs sparticle mass plane

Pic courtesy: de Gouvea, A., Lola, S. & Tobe, K., Phys.Rev. D63 (2001) 035004

CLFV in $R_p V$ SUSY- II (Contd....)



CLFV at the tree-level ►

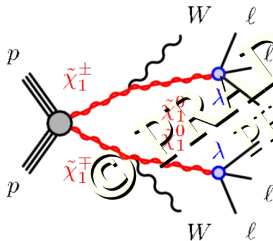
Constraint on the product of $R_p V$ couplings vs S particle mass plane

Pic courtesy: de Gouvea, A., Lola, S. & Tobe, K., Phys.Rev. D63 (2001) 035004

CLFV in $R_p V$ SUSY- I + II (what we should do)

$R_p V$ is instrumental for neutrino mass generation ► tree or loop-level

Some of the $R_p V$ couplings can generate CLFV ► tree or loop-level



New signatures at the LHC from unstable LSP ► multi-lepton, Same-sign leptons, etc.

Need complementary analyses

Plc courtesy: ATLAS-CONF-2016-075

CLFV in SUSY: an example of complementary analysis

RHN superfield with $L = -1$

Singlet superfield with $L = +1$

$$W = W_{MSSM} + \epsilon_{ab} h_\nu^i \hat{L}_i^a \hat{H}_u^b \hat{\nu}^c + M_{B\hat{L}} \hat{L} \hat{S} + \frac{1}{2} \mu_S \hat{S} \hat{S}$$

No Rpv

$\Delta L = +2$

Arina, C., Bazzocchi, F., Fornengo, N., Romao, J. C. & Valle, J. W. F. Phys.Rev.Lett. 101 (2008) 161802
Hirsch, M., Kernreiter, T., Romao, J. C., Villanova del Moral, A., JHEP 1001 (2010) 103

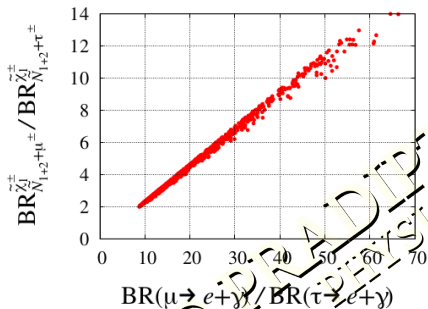
Soft-SUSY breaking part

$$-\mathcal{L}_{\text{soft}} = -\mathcal{L}_{\text{soft}}^{MSSM} + m_{\nu^c}^2 \tilde{\nu}^c \tilde{\nu}^c + m_S^2 \tilde{S}^\dagger \tilde{S} + (\epsilon_{ab} A_{h_\nu}^i \tilde{L}_i^a \tilde{\nu}^c H_u^b + B_{M_R} \tilde{\nu}^c \tilde{S} + \frac{1}{2} B_{\mu_S} \tilde{S} \tilde{S} + \text{h.c.})$$

Tree level neutrino mass $\blacktriangleright (m_\nu)_{ij} = \frac{\mu_S m_{D_i} m_{D_j}}{M_R^2 + \sum m_{D_k}^2}$ with $m_D \rightarrow h_\nu \langle H_u \rangle$

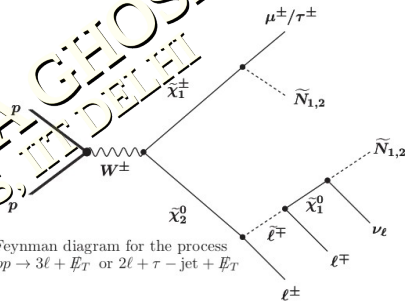
Only one massive neutrino at the tree level $\blacktriangleright$ Loop effects are necessary

CLFV in SUSY: an example of complementary analysis



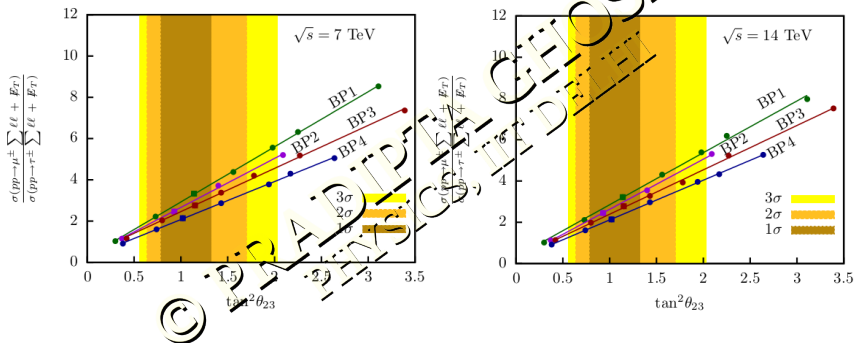
Pic courtesy: Hirsch, M., Kernreiter, T., Romao, J. C., Villanova del Moral, A., JHEP 1001 (2010) 103

Feynman diagram for the process $pp \rightarrow 3\ell + \cancel{E}_T$ or $2\ell + \tau - \text{jet} + \cancel{E}_T$



Pic courtesy: Mondal, S., Biswas, S., Ghosh, P. & Roy, S., JHEP 1205 (2012) 134

CLFV in SUSY: an example of complementary analysis

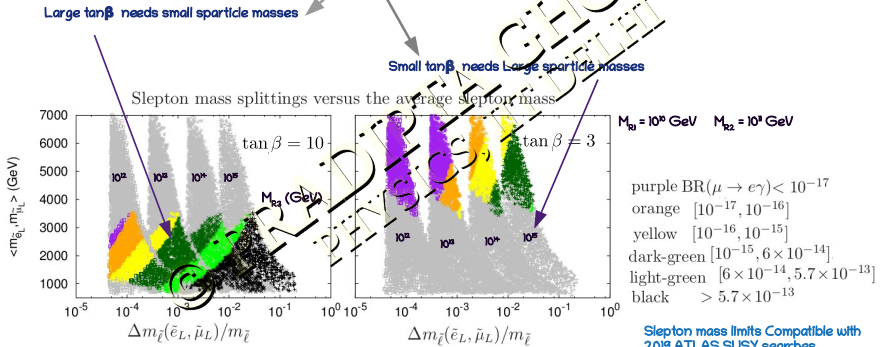


Pic courtesy: Mondal, S., Biswas, S., Ghosh, P. & Roy, S., JHEP 1205 (2012) 134

CLFV in SUSY: another example of complementary analysis

Model: Supersymmetric Type-I seesaw

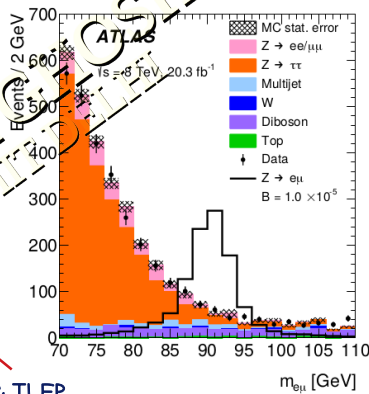
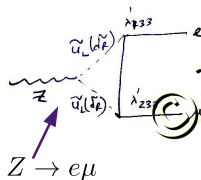
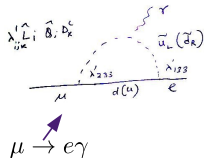
Gray: Wrong Higgs mass



Pic courtesy: Figueiredo, A. J. R. & Teixeira, A. M., JHEP 14(01) (2014) 015

CLFV in SUSY: One more example of complementary analysis

TR0V SUSY



LC & TLEP

Pic courtesy: Yang, J. M., Sci.China Phys.Mech.Astron. 53 (2010) 1949-1952

Pic courtesy: ATLAS collab.,
Phys.Rev. D90 (2014) no.7, 072010

CLFV via slepton mixing (RpV)

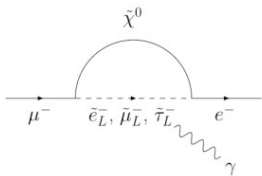
Charged Slepton mass squared matrix (6×6) has LL, RR, LR entries

LL, RR entries contain Lepton mass square, soft-SUSY breaking squared masses and D-term contribution for diagonal terms

LR entries are proportional to lepton mass $\times$ SUSY breaking scale

Soft-SUSY breaking sleptons masses and Lepton Yukawas are not simultaneously diagonal ► **Physical sleptons contain flavour admixing**

CLFV via slepton mixing



This contribution is sensitive to:

$$\frac{A}{m_{\tilde{l}}^2} \left(\frac{\Delta m_{\tilde{l}}^2}{m_{\tilde{l}}^2} \right)^2$$

1. Degeneracy : Controlled by quasi-degenerate Slepton soft masses

2. Alignment : Controlled by assuming Slepton soft masses are almost diagonal in the basis of diagonal lepton Yukawas

3. Decoupling : Controlled by very heavy Sparticles

Whepp2019-26a.pdf

CLFV via slepton sneutrino mixing

Q: What will happen if consider seesaw ?

A: It all depends on Neutrino Yukawa.. $m_\nu \approx \frac{m_D^2}{M_R}$, $m_D = Y_\nu \langle H \rangle$

Option 1: TeV scale seesaw

Pros: TeV scale N_R .. detectable at the LHC.. at least in HL-LHC

Cons: Neutrino Yukawa $\sim 10^{-4}$ ► too small Δm_ν^2

Consequence: Suppressed Br for CLFV processes ► hard to probe

Model example: MSSM with RHN, μ SUSM (Lopez-Fogliani, D. E. & Munoz, C.,
Phys.Rev.Lett. 97 (2006) 041801)

CLFV via slepton sneutrino mixing

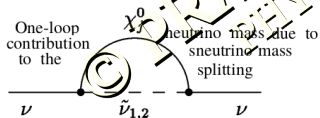
Option II: GUT scale seesaw

Pros: Very heavy ► Hard to detect at man-made colliders

Cons: Neutrino Yukawa $\sim O(1)$ ► $\Delta m_{\tilde{\nu}}^2$ Sizable

Consequence: Enhanced Br for CLFV processes ► chance to probe

Be careful about neutrino mass generation ► $m_{\nu}^{1-loop} \propto \Delta m_{\tilde{\nu}}$



Sneutrino mass splitting

Plc courtesy: Grossman, Y. & Haber, H. E., Phys.Rev.Lett. 78 (1997) 34-38-34-41

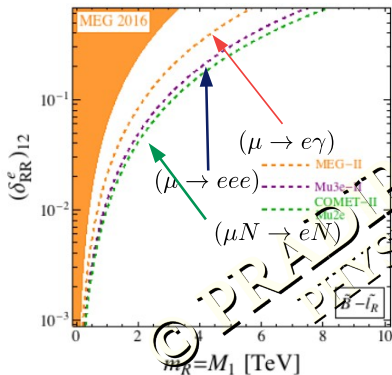
CLFV via slepton mixing

Let's define the normalized off-diagonal parameters:

$$\begin{aligned}
 (\delta_{LL})_{\alpha\beta} &= \frac{(LL)_{\alpha\beta}}{\sqrt{(m_{\tilde{L}}^2)_{\alpha\alpha}(m_{\tilde{L}}^2)_{\beta\beta}}} & (\delta_{RR})_{\alpha\beta} &= \frac{(RR)_{\alpha\beta}}{\sqrt{(m_{\tilde{E}c}^2)_{\alpha\alpha}(m_{\tilde{E}c}^2)_{\beta\beta}}} \\
 (\delta_{LR})_{\alpha\beta} &= \frac{(LR)_{\alpha\beta}}{\sqrt{(m_{\tilde{L}}^2)_{\alpha\alpha}(m_{\tilde{E}c}^2)_{\beta\beta}}}
 \end{aligned}$$

These parameters are tightly constrained from CLFV searches given the SUSY spectrum, $\tan\beta$, etc..

CLFV via slepton mixing



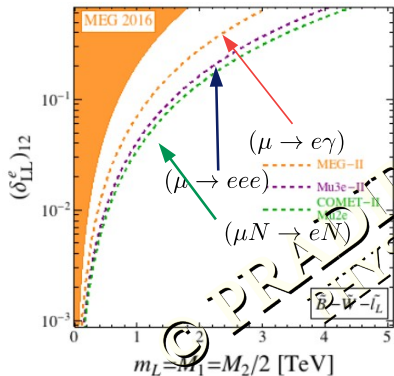
A Bino-like neutralino and RH-sleptons (typically 1st and 2nd gen)... rest of the spectrum decoupled

Complementary LHC searches

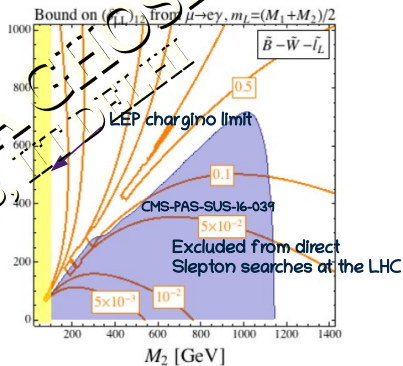
Pic courtesy: Calibbi, L., & Signorelli, G., Riv. Nuovo Cim. 41 (2018) no.2, 71-174

CLFV via slepton mixing

A Bino-like neutralino LSP (half-way between Bino and Wino gen)... rest of the spectrum decoupled



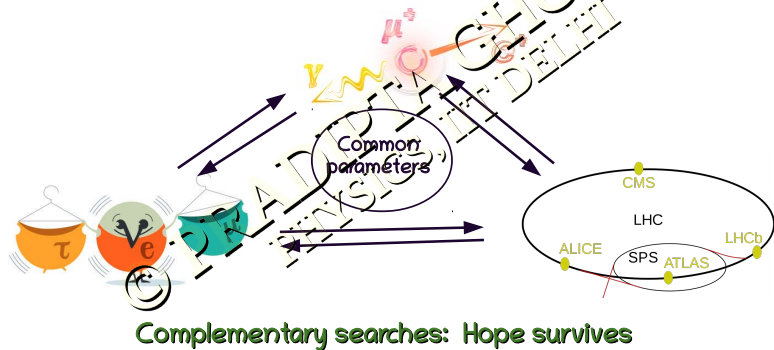
Pic courtesy: Calibbi, L., & Signorelli, G.,
Riv. Nuovo Cim. 41 (2018) no.2, 71-174



Complementary LHC searches
Is more stringent here

CLFV in SUSY: not even covered the tip of the iceberg !!

The take home message





Pankaj & Ruchi ▶



◀ Jaswant & Arjun
(Mentor: Tobias Toll)

Pankaj joins them ▶



IITD HeP-PH group
Computational
facilities

Four node cluster with DELL T-7820
precision workstations

96 (4 X 24) core Intel Xeon Silver
4116 processor

512 GB (4 X 128 GB) DDR4 2666 MHz ECC RAM

8 (4 X 2 GB) NVIDIA quadro P600 graphics

16 TB (4 X 4 TB) HDD

Operating System: Ubuntu 18.04.3 Server edition

Up to one hour power backup facility

