Lepton flavour violation: a phenomenological bird’s-eye view

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TH Inside!

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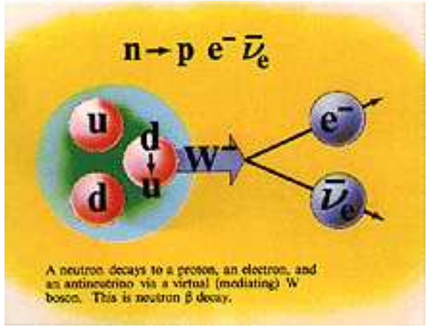
“GT2 - Journées de Prospectives LPC”   20 February 2013

- **Lepton flavour violation: SM and beyond**

Neutral leptons in the SM: a brief history

- **ν birth:** **"Rescue" conservation of energy** in nucleus beta decay $\quad n \to p + e^- + \bar{\nu}_e$



"I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. ... electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle... The continuous beta spectrum would then become understandable..."

Pauli, 1930

- **Enter the "neutrino":** following the discovery of the "neutron" in 1933 by Chadwick, Pauli postulates the **existence of a "massless neutrino"**

- **Electron neutrino:** detected in **1956** by **Cowan** and **Reines**

- **Muon neutrino:** discovery in **1962** by **Lederman, Schwartz** and **Steinberger**

- **3 neutrino families:** Z boson **decay width, CERN 1983**

- **Tau neutrino:** direct evidence in **2000** by **DONUT** team

- **Lepton sector of the SM:** although many pieces of the puzzle have been found, we are far from understanding the "neutrino misteries"

Neutrino sources ⇒ the discovery of ν oscillation

- **Neutrino sources** have been experimentally and observationally explored,
  huge impact for particle & astroparticle physics and astronomy!

  Laboratory: reactors, accelerators

  Cosmic rays: atmospheric neutrinos ($\nu_{@}$), ultra-high energy neutrinos

  Astrophysical: solar neutrinos ($\nu_{\odot}$), supernovae

- **A puzzling and surprising discovery: the solar $\boldsymbol{\nu_e}$ and atmospheric $\boldsymbol{\nu_\mu}$ fluxes...**

  Solar neutrino problem: detection of **only 1/3 of expected flux of solar $\boldsymbol{\nu_e}$'s**

  Atmospheric neutrino problem: detection of $\boldsymbol{\nu_e \sim \nu_\mu}$ (expected $\boldsymbol{\nu_e \sim 2\,\nu_\mu}$)

- **Unsettling hypotheses:**

  "Unexpected" production of ν_α: *do charged currents violate lepton flavours?*

  "Disappearance" of propagating ν_α: *do neutrinos oscillate?*

Neutrino oscillations: massive states, leptonic mixing!

- A simple solution to both problems! Illustrative 2-family example

  Two **massive states** ($\Delta m_\nu \neq 0$) related to flavour eigenstates as $\nu_\alpha = U_{\alpha i}\,\nu_i$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

- What is the **story of a relativistic neutrino**, produced (e.g.) in muon decay??

  (i) Production of **weak eigenstate** at $t=0$: $|\nu_{t=0}\rangle = |\nu_\mu\rangle = \cos\theta\,|\nu_2\rangle + \sin\theta\,|\nu_3\rangle$

  (ii) Travel distance L to the **detector**, during which it *oscillates*

$$|\nu(t)\rangle = \cos\theta e^{-iE_2 t}|\nu_2\rangle + \sin\theta e^{-iE_3 t}|\nu_3\rangle$$

  (iii) At the detector, it produces μ in **charged current** scattering, with probability

$$\mathcal{P}^{2\nu}_{\mu\to\mu}(L,t) = |\langle\nu_\mu|\nu(t)\rangle|^2 = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_\nu\, L}{4E}\right) \quad \neq 1$$

- Oscillations: **if and only if** neutrinos are **massive** and **mix!**

- **Huge breakthrough of SuperKamiokande in 1998** $\Rightarrow$ **Physics beyond SM!**

A first look at flavours in the SM

- **Quark sector:**

The SM electroweak interactions preserve u, d, etc flavours

After EWSB, there is a **misalignment** of physical and interaction eigenstates

Quark flavour violated by **charged current** interactions $V_{ij}^{\text{CKM}}\, W^{\pm}\, \bar{q}_i\, q_j$

Observed in many oscillation/decay processes: **very good agreement with SM!**

[see Nazila's talk next week on beyond SM contributions...]

- **Lepton sector:**

Original SM formulation only includes ν_L (no ν_R, no Higgs triplet)

$m_{\nu_i} = 0$ - **to all orders!** [accidental $U(1)_{B-L}$ symmetry]

Strict **conservation** of total lepton number (L) and lepton flavours (L_i)

Revisiting the SM lepton sector: leptonic mixing

- **A new lepton sector:** flavour violated in **charged current** interactions

Just as in the quark sector, **misalignment** of physical and interaction eigenstates

Misalignement of mass and $SU(2)_L$ states parametrized by **"mixing matrix"** *(à la V_{CKM})*

- **Pontecorvo-Maki-Nakagawa-Sakata matrix:** U_{PMNS}

$$\mathcal{L}^{\text{lepton}}_{\text{charged}} = U_{\text{PMNS}}\, \bar{\ell}_L\, W^{\pm}\, \nu_L \; + \text{h.c.}$$

$$(\nu_e,\, \nu_\mu,\, \nu_\tau) \overset{U_{\text{PMNS}}}{\leftrightsquigarrow} (\nu_1,\, \nu_2,\, \nu_3)$$

$$|\nu_\alpha\rangle = U^*_{\alpha i}\, |\nu_i\rangle$$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{-i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{-i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{-i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{-i\delta} & c_{23}\, c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_1} & 0 \\ 0 & 0 & e^{i\phi_2} \end{pmatrix}$$

- U_{PMNS} : **3 angles**

Solar	$\theta_{12},\, \theta_\odot$	**CPV phases**	Dirac	δ
Atmospheric	$\theta_{23},\, \theta_{@}$		Majorana	$\phi_{1,2}$
Reactor	$\theta_{13},\, \theta_{\text{Chooz}}$			

Revisiting the SM lepton sector: oscillation data

- A huge number of **facilities devoted** to determining **ν-data!**

  SuperK, K2K, MINOS, OPERA, KamLAND, SNO, MiniBoone,
  Chooz, Double Chooz, Daya Bay, Reno,...

- Status of U_{PMNS} (Summer 2012):

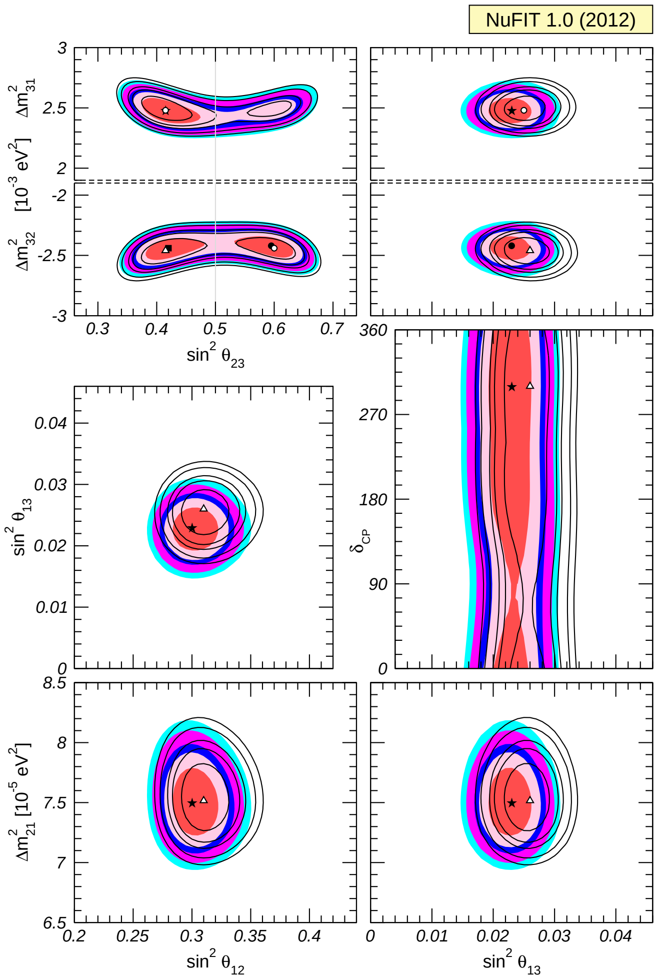
$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix} .$$

$$\boldsymbol{\theta_{23} \approx \pi/4 \pm \pi/40}\,, \qquad \boldsymbol{\theta_{12} \approx \pi/6}\,, \qquad \boldsymbol{\theta_{13} \approx 0.15\ (8.6^\circ)}$$

Large mixing! ... quite different scenario from quark mixing! Recall that

$$\theta_{23} \rightsquigarrow V_{cb} \simeq 0.04\,, \qquad \theta_{12} \rightsquigarrow V_{us} \simeq 0.225\,, \qquad \theta_{13} \rightsquigarrow V_{ub} \simeq 0.004$$

Revisiting the SM lepton sector: oscillation data



	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	0.31 ± 0.013	$0.27 \to 0.35$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	33.9 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	$0.41^{+0.030}_{-0.029} \oplus 0.60^{+0.020}_{-0.026}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	$40.1^{+2.1}_{-1.7} \oplus 50.7^{+1.1}_{-1.5}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$	0.025 ± 0.0023	$0.018 \to 0.033$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$	$9.2^{+0.42}_{-0.45}$	$7.7 \to 10.$
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$	298^{+59}_{-145}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$	$7.50^{+0.205}_{-0.160}$	$7.04 \to 8.12$
$\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	$-2.47^{+0.073}_{-0.064}$	$-2.68 \to -2.25$

- **Global ν fits: www.nu-fit.org**
- **Oscillation data:** typically $\theta_{ij} \leftrightsquigarrow \Delta m^2_{ij}$

- **What about neutrino masses??**

Revisiting the SM lepton sector: massive neutrinos

- **Oscillation data:** only **two squared-mass differences ...**

$$\Delta m^2_{12} = \Delta m^2_{\odot} \approx 7.5 \times 10^{-5}\ \text{eV}^2$$
$$\Delta m^2_{23} = \Delta m^2_{@} \approx \pm 2.4 \times 10^{-3}\ \text{eV}^2$$

- What about the **mass hierarchy?**

  Normal: $m_{\nu_1} < m_{\nu_2} \ll m_{\nu_3}$ **or** **Inverted:** $m_{\nu_3} \ll m_{\nu_1} \lesssim m_{\nu_2}$

  Data from PINGU (Icecube upgrade)? large scale reactors? long baseline?

- What about the **absolute mass scale?**

  - Tritium decays ($^3\text{H} \rightarrow {}^3\text{H} + \bar{\nu}_e + e^-$): $m_{\nu_e} \lesssim 2.2$ eV
  - **Cosmology:** m_ν is a parameter in cosmological fits! (recombination, DM, ...)

    CMB data $\sum m_{\nu_i} < 0.3 \rightarrow 1$ **eV** [WMAP, HST+LSS, Planck+EUCLID,...]

    Formation of cosmic structures: $\sum m_{\nu_i} < 0.65$ **eV**

    Z-bursts (UHE-peV cosmic rays) $m_\nu^{\text{th}} > 0.25$ eV

  - ... other possibilities?? ...

Revisiting the SM lepton sector: massive neutrinos

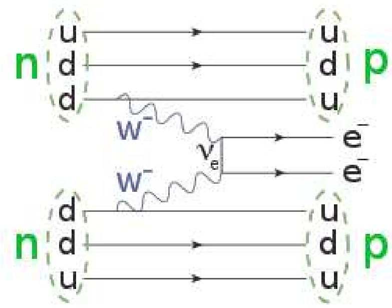
- **Neutrinos are Dirac fermions ($\nu^c \neq \nu$):**

$$-\mathcal{L}^{\text{lepton}}_{\text{mass}} = Y^\ell\,\bar{L}\,\phi\,e_R + Y^\nu\,\bar{L}\,\tilde{\phi}\,\boldsymbol{\nu_R} + \text{h.c.} \qquad L_{SU(2)} = (\nu_L, \ell_L)^T,\ \phi \rightsquigarrow H^{SM}$$

After EWSB, Dirac mass term $\rightsquigarrow$ $m_D^\nu = Y^\nu\,v \quad m_{\nu_i} \lesssim 1$ **eV** $\Rightarrow Y^\nu \lesssim \mathbf{10^{-11}}$

- **Neutrino spectrum: 3 light** mass eigenstates

- **Neutrinos are Majorana fermions ($\nu^c = \nu$):**



$\Rightarrow$ **Experimental** confirmation: **observation** of **$0\nu2\beta$ decay**

$\Rightarrow$ Add **new states** to the SM content: usually 3 $\boldsymbol{\nu_R}$

$$-\mathcal{L}^{\text{neutrino}}_{\text{mass}} = Y^\nu\,\bar{L}\,\tilde{\phi}\,\boldsymbol{\nu_R} + M_R\,\boldsymbol{\bar{\nu}_R}\,\boldsymbol{\nu^c_R} + \text{h.c.} \quad \rightsquigarrow \quad m_D^\nu\,\bar{\nu}_L\,\boldsymbol{\nu_R} + M_R\,\boldsymbol{\bar{\nu}_R}\,\boldsymbol{\nu^c_R} + \text{h.c.}$$

M_R allowed by **Lorentz & gauge** invariance; renormalisable;
not related to SM dynamics; **violates** total **lepton number** L : $\Delta L = 2$

- **Neutrino spectrum: 6 Majorana** mass eigenstates!

Revisiting the SM lepton sector: seesaw mechanism

- $-\mathcal{L}^{\text{lepton}}_{\text{mass}} = Y^\ell \, \bar{L}\, \phi\, e_R + Y^\nu \, \bar{L}\, \tilde{\phi}\, \nu_R + \frac{1}{2}\, \bar{\nu}_R\, M_R\, \nu_R^c + \text{h.c.}$ $[Y^\ell = Y_\ell^{\text{diag}}$ and $M_R = M_R^{\text{diag}}]$
- After EW symmetry breaking, an effective neutrino mass matrix M^ν $[6\times 6]$

$$M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$m_D \to$ **Dirac** mass matrix; $m_D = v Y^\nu$

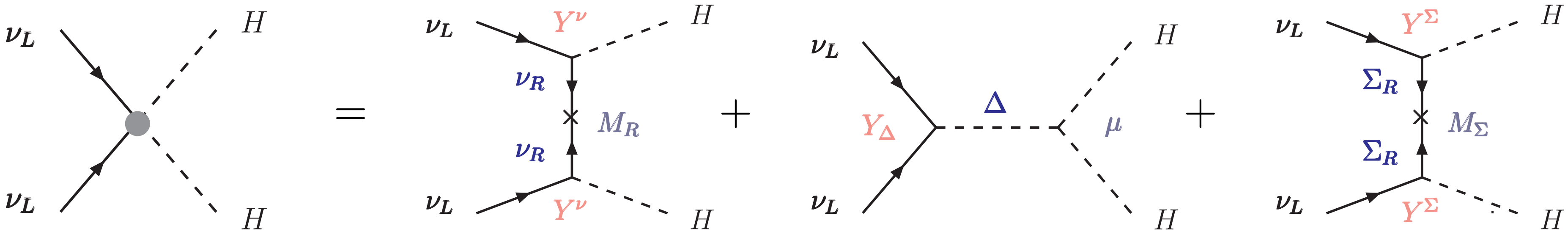
$M_R \to$ **Heavy neutrino** mass matrix - diag (m_{R_i})

- **Seesaw equation:** $m_\nu^{\text{light}} = -m_D\, M_R^{-1}\, m_D^T$

$m_D \ll M_R$

$M_R \sim$ few TeV $\Rightarrow$ $Y^\nu \sim Y^\ell$

$$Y^\nu \sim 1 \Rightarrow M_R \sim \mathcal{O}(10^{15}\ \text{GeV})$$



$\frac{1}{\Lambda} L\, L\, H\, H$ — "Seesaw mechanism"

ν_R (fermion singlet) — **Type I**

Δ (scalar triplet) — **Type II**

Σ_R (fermion triplet) — **Type III**

A second look at flavour violation in the SM

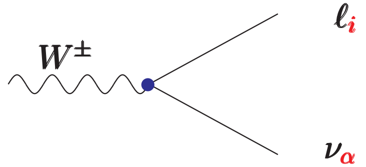
- **Quark sector:** **flavour violated** by **charged current** interactions $V_{ij}^{\text{CKM}}\, W^\pm\, \bar{q}_i\, q_j$

  Observed in many oscillation/decay processes: **very good agreement with SM!**

- **Lepton sector:** **neutral** & **charged** **lepton flavours strictly conserved**

  $\Rightarrow$ **Extend the SM** to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$ [$\text{SM}_{m_\nu} =$ "ad-hoc" m_ν, U_{PMNS}]

  Charged currents violate lepton flavour!

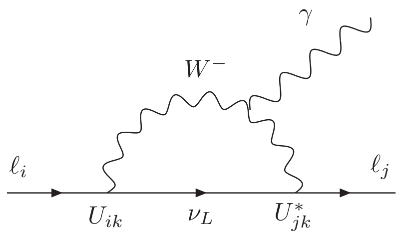


$\bullet \propto U_{\alpha i}^{\text{PMNS}}$

$m_\nu \neq 0$

$\nu_\alpha = \sum_i U_{\alpha i} \nu_\beta$

SM_{m_ν} - **cLFV possible??**



$$\text{BR}(\mu \to e\gamma) \propto \left| \sum U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \sim 10^{-54}$$

Possible - **yes...** but **not observable!!**

- **"Observable" cLFV $\Rightarrow$ New Physics in the lepton sector - beyond SM_{m_ν}**

- **Lepton flavour violation: Observables and facilities**

Lepton Flavour Violation: Observables

- Many **candidate observables!** *(No SM theoretical background!)*
  - **Rare leptonic decays and transitions**
  - Leptonic angular distributions ; P- and T-odd asymmetries
  - **Meson decays: violation of lepton flavour universality, LFV final states**

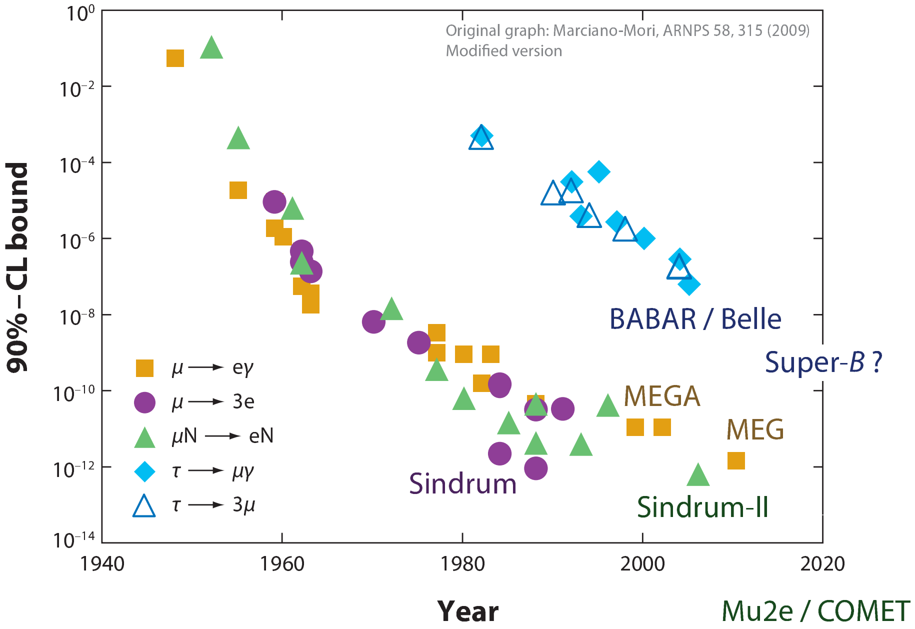
    lepton Number violating decays
  - **Rare (new) heavy particle decays (typically model-dependent):**

    $H \to \tau\mu$, ...

    impact of LFV for new physics searches at colliders, ...
  - CP violation in the leptonic sector

Lepton Flavour Violation: 1947 - 2012

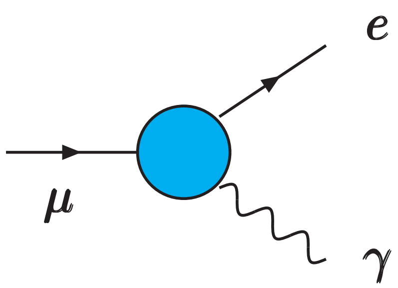
- A world-wide **experimental commitment** for more than **60 years!**



Process	present bound	future	
$\mu \to e\gamma$	2.4×10^{-12}	10^{-14}	MEG at PSI
$\mu \to eee$	1.0×10^{-12}	10^{-14}	Mu3e at PSI
$\mu - e$ (Au)	7×10^{-13}	–	SINDRUM-II
$\mu - e$ (Al)	–	10^{-16}	Mu2e/COMET
$\mu - e$ (Ti)	4.3×10^{-12}	10^{-18}	PRISM
$\tau \to e\gamma$	1.1×10^{-7}	$10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to e\gamma$	3.6×10^{-8}	$10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to \mu\gamma$	4.5×10^{-8}	$10^{-9} - 10^{-10}$	super KEKB/B
$\tau \to \mu\mu\mu$	3.2×10^{-8}	$10^{-9} - 10^{-10}$	super KEKB/B

(super)LHCb??

Lepton Flavour Violation: $\mu \to e\gamma$



- **Event signature:** $E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)

  Back-to-back e^+ - γ ($\theta \sim 180°$); Time coincidence

- **Backgrounds** $\Rightarrow$ prompt physics & accidental

  Prompt: radiative μ decays $\mu \to e\nu_e\nu_\mu\gamma$ (very low E_ν)

  Accidental: positron from $\mu \to e\nu_e\nu_\mu$;

  photon from $\mu \to e\nu_e\nu_\mu\gamma$; photon from in flight e^+e^- annihilation

- **MEG Experiment:** $3 \times 10^7 \mu$/s at **PSI** (Switzerland)

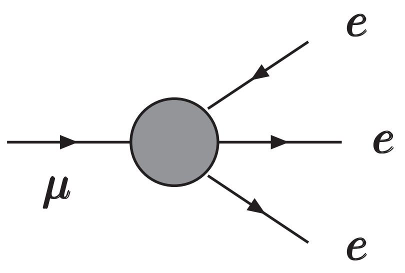
  2.7 ton liquid Xenon scintillation detector (good time, position and energy resolution)

  2009 + 2010 data: 2.4×10^{-12} Upper Limit (90% CL)

  2011 + 2012 data: 10^{-13} Upper Limit (90% CL)

- **MEG II** (proposal to appear 2013): **sensitivity** $\approx \mathbf{10^{-14}}$

Lepton Flavour Violation: $\mu \to eee$



- **Event signature:** $\sum E_e = m_\mu$; $\sum \vec{P}_e = \vec{0}$

  common vertex; Time coincidence

- **Backgrounds** $\Rightarrow$ physics & accidental

  Physics: $\mu \to ee\nu\nu e$ decay (very low E_ν)

  Accidental: positrons from $\mu \to e\nu\nu$;

  electrons from $\mu \to eee\nu\nu$ and/or $\mu \to e\nu\nu\gamma$; ...

- **Mu3e Experiment** at **PSI** (Switzerland)

  Stage I (2014 - 2017): $2 \times 10^8 \mu$/s at ΠE5 muon source

  Stage II (2018 -): $2 \times 10^9 \mu$/s at new muon source

  Future sensitivity: $\approx 10^{-14}$

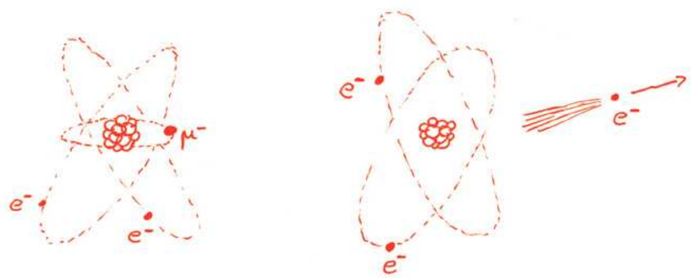
Lepton Flavour Violation: $\mu - e$ conversion in atoms

- Consider the fate of a **1s μ-state in a muonic atom:**

  SM-like muon decay in orbit $\quad \mu^- \to e^- \nu \nu$

  SM-like nuclear muon capture $\quad \mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$

  Beyond SM - neutrinoless muon nuclear capture



$$\mu^- + (A, Z) \to e^- + (A, Z)$$

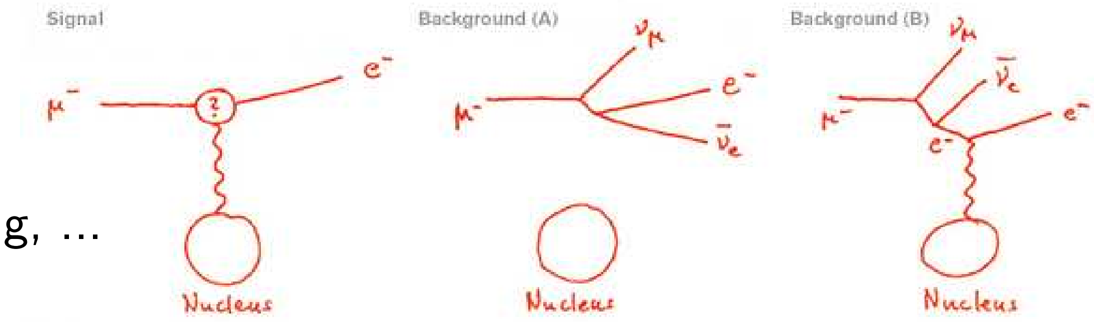
- **Event signature:** single mono-energetic electron

$$E_e \sim 100 \text{ MeV}$$

- **Backgrounds** $\Rightarrow$

  Physics (e.g. muon decay in orbit);

  beam-related; cosmic rays; false tracking, ...



- **SINDRUM-II** at **PSI** (max $10^8 \mu$/s beam intensity): **CR($\mu - e$, Au)** $< 7 \times 10^{-13}$

Improving the bound $\rightsquigarrow \mathcal{O}(10^{-17})$: increase beam intensity $10^{11} \mu$/s (10^7 sec running)

improve background rejection...

Lepton Flavour Violation: $\mu - e$ conversion in atoms

- **Mu2e** at **Fermilab: CR($\mu - e$, Al) <** 10^{-16} (90% CL)

  Reincarnation of MECO at BNL;

  Approved, CDO 2009, CD1 review 2012; *data taking 2019*

- **COMET (E21)** at **J-PARC: CR($\mu - e$, Al) <** 6×10^{-17} (90% CL)

  10^{11} muon stops/s for 56kW proton beam power

  Stage-I approved in 2009

- **DeeMe** at **J-PARC/MLF: CR($\mu - e$, Si) <** 3.5×10^{-14} (90% CL)

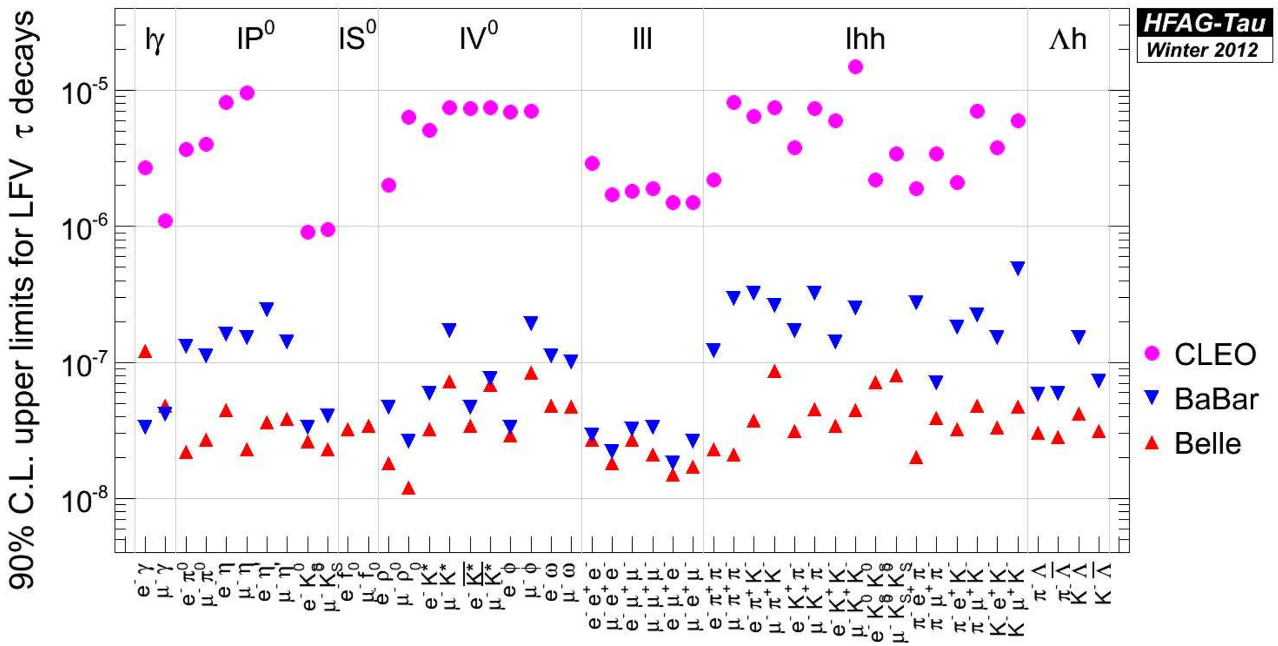
  SiC target; 15×10^{9} muon stopped for 2×10^{7} s running

  quick and not expensive... *not yet stage-I approved...*

Lepton Flavour Violation: τ decays at e^+e^- colliders & LHCb

- **B-factories** are also **τ-factories** (excess of 10^8 in total ...)

  Radiative tau decays ($\tau \to \ell\gamma$) are **background limited;** sensitivity improved by $\mathbf{1/\sqrt{N}}$



- **Super-B factories** will produce $\mathcal{O}(10)$ **times more taus!**

  $\Rightarrow$ **BR($\tau \to \mu\gamma$)** $\sim \mathcal{O}(10^{-9})$ **; BR($\tau \to \mu\mu\mu$)** $\sim \mathcal{O}(10^{-10})$ at 50 ab^{-1}

- **LHCb** searching for **LFV and LNV τ decays;**

  data still a bit less restrictive; present limits expected to improve soon!

Lepton Flavour Violation: meson decays

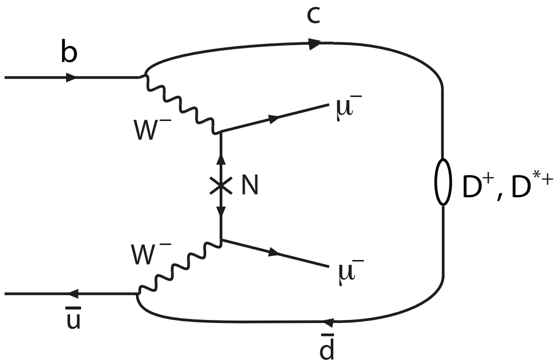
- **Meson decays:** excellent testing grounds for lepton flavour dynamics! Examples...
  - **Lepton Universality Violation in K and π decays**

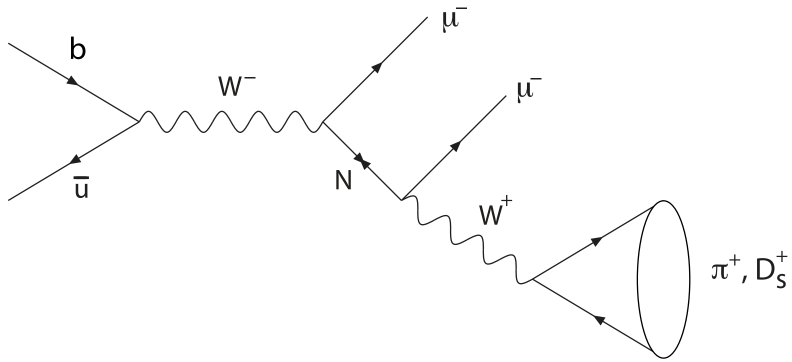
    $R_P = \frac{\Gamma(P \to e\nu)}{\Gamma(P \to \mu\nu)}$ comparison with **SM th predictions** $\Delta r_P = \frac{R_P^{\text{exp}}}{R_P^{\text{SM}}} - 1$

    - **NA62** at **CERN:** $\Delta r_K = (4 \pm 4) \times 10^{-3}$; $\Delta r_\pi = (-4 \pm 3) \times 10^{-3}$

      Future sensitivity: $\delta R_K / R_K \sim 0.1\% \Rightarrow$ measure $\Delta r_K \sim \mathcal{O}(10^{-3})$

  - **Majorana neutrinos and LNV in B meson decays**





Allows to test Majorana ν hypotesis; probe $M_\nu \lesssim 3 - 5$ TeV

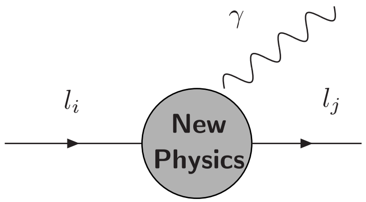
- **LHCb** at **CERN:** (also BaBar, Cleo, Belle)

  BR($B^- \to D^+\mu^-\mu^-$) $< 7 \times 10^{-7}$; BR($B^- \to D^0\pi^+\mu^-\mu^-$) $< 2 \times 10^{-6}$

▶ Lepton flavour violation: New Physics contributions

Lepton Flavour Violation: pheno approach

- What is **required** of a **SM extension** to have **"observable" cLFV?**



$\rightsquigarrow$ **BR($\mu \to e\gamma$)** $= 10^{-12} \times (3\ \text{TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2$

- **cLFV** $\Leftrightarrow$ **New Physics** (beyond SM_{m_ν}) + **Lepton Flavour Mixing**

	New Physics (beyond SM_{m_ν})	+	Lepton Flavour Mixing
cLFV $\Leftrightarrow$	$\Lambda \sim \mathcal{O}(\text{TeV})$		non-negligible $\theta_{\ell_i \ell_j}$
	(testable at colliders ?)		(suggested by neutrino mixing ...)

- **Pheno approaches:**
  - **Effective approach (model-independent)**
  - **Model dependent**

- **One method: Synergy** of **observables**

  peculiar patterns, dominances - **id/exclude candidates...**

cLFV: what are "patterns"?

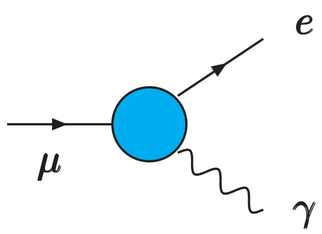
- **New Physics** can **change SM in two ways:**

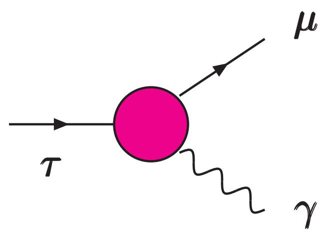
  (i) new sources of **flavour violation** (corrections to SM vertices, or new SM-NP vertices);

  (ii) new Lorentz structure in the four-fermion interaction ⇒ **new effective operators**

- **Consider the following ratios of observables:**

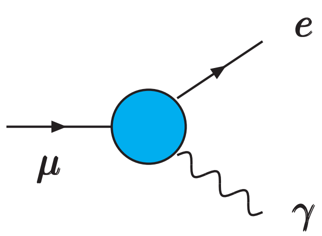
$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{BR}(\tau\to\mu\gamma)}$$

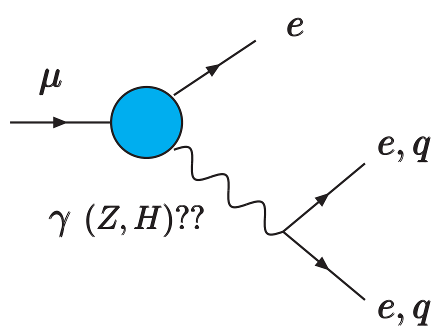




Probe NP flavour structure

$$\frac{\mathrm{BR}(\mu\to e\gamma)}{\mathrm{BR}(\mu\to 3e)}$$





Probe NP operator at work

- **Depending on underlying NP model,** expect **"peculiar ranges for correlation ratios"**

cLFV: the effective approach

- At **higher scales** (TeV? M_{GUT}? M_{Planck}?) additional **"heavy" degrees of freedom**
- **Integrate out "new heavy fields"** (as those required to generate ν masses)

- **Effective Lagrangian: "vestigial" (new) interactions** with **SM fields** at **low-energies**

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \text{higher order (non-renormalisable) terms}$$

[e.g. to break SM $B - L$ accidental symmetry, $m_\nu \neq 0$]

$$\Delta\mathcal{L}^{d\geq 5} \sim \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathcal{C}^n(g, Y, ...) \, \mathcal{O}^n(\ell, q, H, \gamma, ...)$$

Λ : mass **scale of new physics**

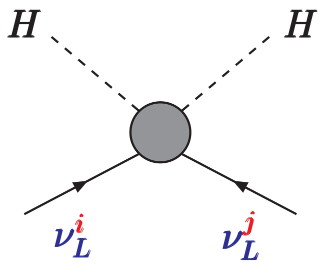
$\mathcal{C}^n$: **dimensionless couplings** - coupling constants, Yukawas, loop factors $((4\pi)^m)$, ...

$\Rightarrow \mathcal{C}^n_{ij}$: *matrices in flavour space!*

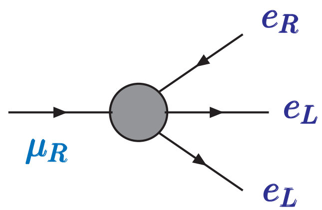
$\mathcal{O}^n$: **"external legs"** of the diagrams - **SM fields only!**

cLFV: the effective approach

$\Delta\mathcal{L}^{d\geq 5} = \quad \mathcal{C}^5_{\text{Weinberg}} \frac{1}{\Lambda} \times$



$+ \ \mathcal{C}^6_{\mu eee} \frac{1}{\Lambda^2} \times$



$+ \ \mathcal{C}^6_{\ell_i \ell_j \gamma} \frac{1}{\Lambda^2} \ \cdots$

- **Dimension 5 $\Delta\mathcal{L}^5$ (Weinberg): neutrino masses** $(\Delta L = 2)$

  Common to all models with Majorana neutrinos [seesaws, radiative (Zee, RpV), ...]

- **Dimension 6 $\Delta\mathcal{L}^6$:** kinetic corrections, **cLFV (dipole and 3-body)**, EW precision, t physics...

  Differs from model to model - used to **disentangle scenarios...**

- **Higher order $\Delta\mathcal{L}^{7,8,..}$:** ν (transitional) magnetic moments, NSI, unitarity violation...

cLFV bounds and $\mathcal{L}^{\text{eff}}$

- Apply **experimental** bounds on **cLFV observables** to **constrain** $\frac{C^6_{ij}}{\Lambda^2}$

  1. hypothesis on **size** of **"new couplings"**
  2. hypothesis on **scale** of **"new physics"**

- **Natural** values of the **couplings** $C^6_{ij} \sim \mathcal{O}(1)$

  $\text{BR}(\mu \to e\gamma)|_{\text{MEG}} \Rightarrow \Lambda \gtrsim 50$ TeV; $\text{BR}(\mu \to 3e) \Rightarrow \Lambda \gtrsim 15$ TeV

  $\text{BR}(\tau \to \ell\gamma) \Rightarrow \Lambda \gtrsim 3$ TeV; $\text{BR}(\tau \to 3\ell) \Rightarrow \Lambda \gtrsim 1$ TeV

  [Davidson, La Thuile '12]

- **Natural scale?** more delicate - **well motivated:** direct discovery, ...

  Example: **discovery of type II seesaw** (scalar triplet) mediator at LHC, $M_\Delta \sim 1$ **TeV**

  $\text{BR}(\mu \to e\gamma)|_{\text{MEG}} \Rightarrow |Y^{\Delta\dagger}_{\mu\mu} Y^{\Delta}_{\mu e} + Y^{\Delta\dagger}_{\tau\mu} Y^{\Delta}_{\tau e}| \lesssim 2 \times 10^{-3}$

  [Abada et al, '07-'09]

- **Can we reconstruct the New Physics Lagrangian?** not likely...

We can **identify operators** (combining distinct observables) and

learn about **flavour structure** (same observable, different flavours)

Models of New Physics

- Model-independent approach is quite "hard"...

  Be prepared! - master **"theoretical expectations"** of **N** models to **falsify** them!

But **"theoretical expectations"** is an *oxymoron:*

different theorists expect **different New Physics** at the **TeV scale** because it is

- motivated by the **naturalness** of the weak scale
- motivated by precision **unification of couplings**
- not motivated, but **why not**
- to their personal **taste or prejudice!**

[Jäger, NA62 Workshop, '09]

- **Here:** consider **examples** of (well motivated?) **models of New Physics**

  $\rightsquigarrow$ with **potentially observable cLFV implications!**

cLFV: models of New Physics

- **SM extensions** introduce **new particles**, **new** flavour violating couplings..
- In the **absence** of cLFV (and other) **signals:**

  ⇒ **constraints on parameter space (scale and couplings)**

- **cLFV observed: compare with peculiar features of given model**

  ⇒ **predictions** for **cLFV observables**

  ⇒ **intrinsic patterns** of **correlations of observables**

- **Examples:**
  - **Generic cLFV extensions** - general MSSM, LHT, RS, 4th generation, ...
  - **cLFV from m_ν**
    - SM seesaw (TeV scale) - type II & inverse seesaw
    - Extended frameworks - SUSY seesaw, GUTs, ...

- **Generic cLFV extensions**

cLFV in Little Higgs models (T-parity)

★ **Higgs** is a **pseudo-Goldstone** boson of **spontaneously broken** global symmetry

▶ SU(5) → SO(5) **(@ TeV scale)**; **augmented gauge group** $[\mathrm{SU}(2)\times\mathrm{U}(1)]^2$

⇒ **new (heavy) gauge bosons** - A_H, Z_H, $W_H^\pm$

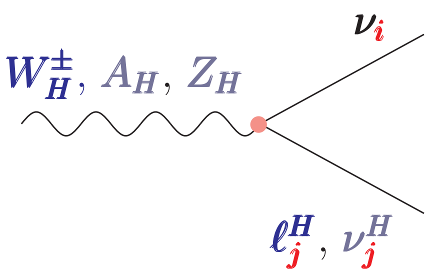
▶ T parity ⇒ prevents contributions to **EW observables** (tree-level)

Lightest T-odd particle stable ⇝ dark matter candidate

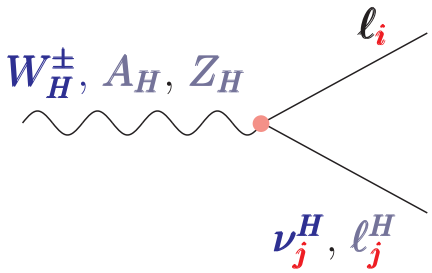
▶ **New scale** as low as **500 GeV** [$f \sim$ decay const of NL sigma model (NG)]

▶ Only **10 new parameters** in flavour sector, only **SM operators relevant**

▶ **Sources of cLFV:** couplings of **leptons** - **mirror leptons - heavy gauge bosons**



$\propto V_{H\nu}$

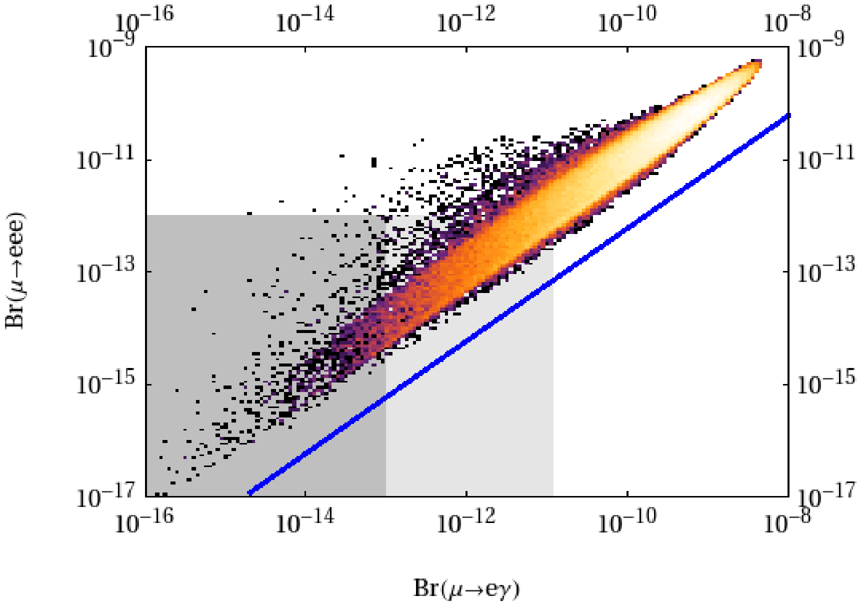


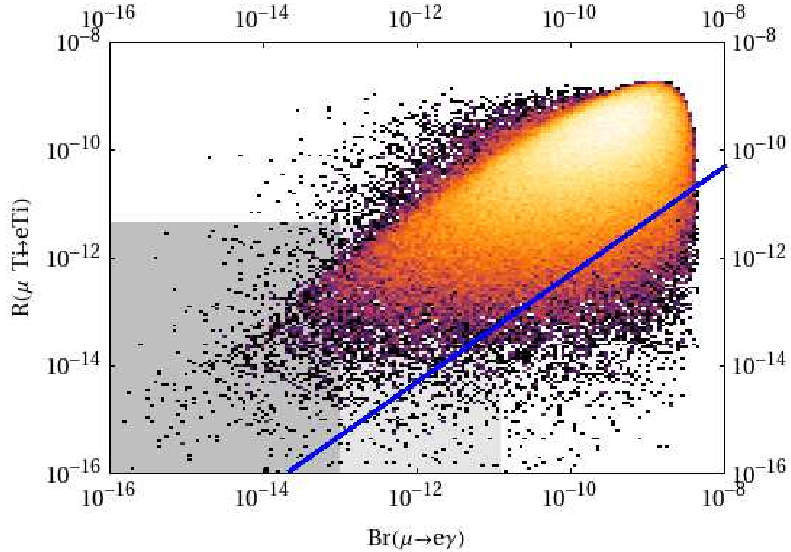
$\propto V_{H\ell}$

$$V_{H\nu}^\dagger V_{H\ell} = U_{\mathrm{PMNS}}^\dagger$$

[Hubisz et al '05; Blanke et al '06-'09; Ray et al '07; Goto et al '09-'11, del Aguila et al '09-'10, ...]

cLFV in Little Higgs models (T-parity): an example





[Blanke et al, 0906.5454]

- **Strong correlation** of some cLFV observables: $\mu \to e\gamma$ **and** $\mu \to 3e$
- **Asymmetries** for **polarised** τ **and** μ decays $\leftrightsquigarrow$ **chirality structure of LHT**

  [Goto et al, 1012.4385]

- Typically **large contributions to cLFV** $\rightsquigarrow$ some **fine-tuning required**

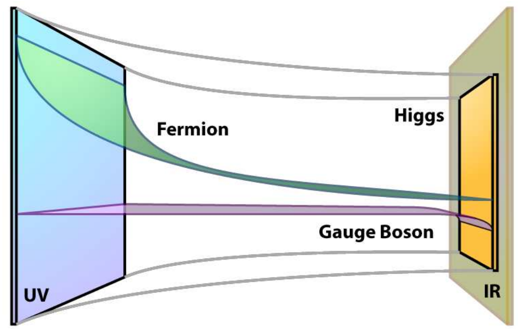
  hierarchical mixing matrices $(V_{H\ell}, V_{H\nu})$, quasi degenerate states, ...

Geometric flavour violation: RS warped extra dimensions

★ Embed **4dim space-time** into **5dim AdS space** (extra dim compactified on orbifold)

- **Two branes** (UV, IR) and **bulk** between; $M_{\text{TeV}} = M_{\text{Planck}} e^{-\pi L_5}$
- Localise fields:

  interactions ⇝ overlap of wave functions



- **Geometrical distribution** of **fermions** in bulk:

  hierarchy in 4dim Yukawas for **"anarchic" $\mathcal{O}(1)$ couplings!**

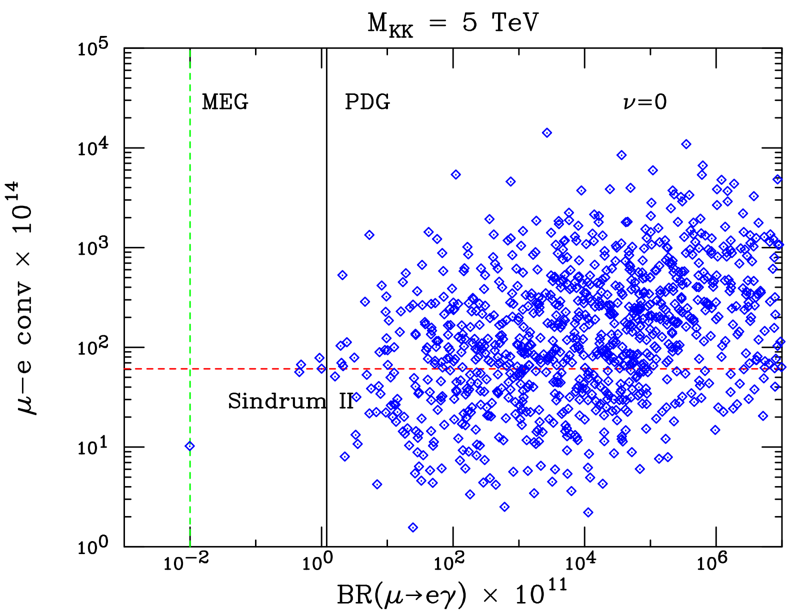
- **Circumvent pheno issues:** enlarge **bulk symmetry** (prevent violation of custodial SU(2));

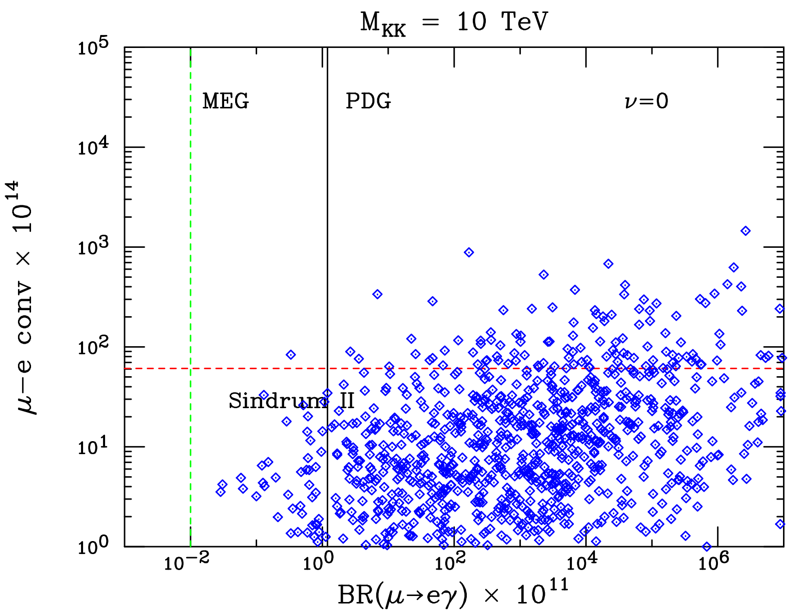
  additional **"rescue" ingredients** to **avoid excessive FCNCs,**

  protect **EW precision observables,** ...

[Burdman '02; Agashe et al '04 -; Csaki et al '08; Blanke et al & Buras et al '08-'09]

Geometric flavour violation: RS warped extra dimensions





[Agashe et al, 0606021]

- cLFV processes mediated by **KK-lepton excitations, new gauge fields**

- **Electroweak precision observables: $M_{KK} \geq 3$ TeV ;**

  cLFV: $M_{KK} \geq 10$ **TeV** (5 TeV only marginally compatible)

- Possible ways out... flavour structure (non-geometrical), increase gauge symmetry, ...

[Very recent... Vempati et al, 1206.4383]

General Minimal Supersymmetric extension of the SM

- **Supersymmetry is broken in Nature:** different masses for SM particles and superpartners

  Generic soft-SUSY breaking terms introduce new sources of flavour violation (q and ℓ)

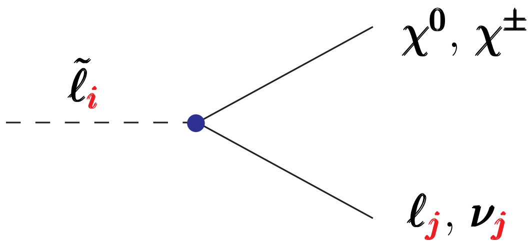
  non-diagonal masses for sleptons and sneutrinos $\quad (M^2_{\tilde{\ell}})_{ij} \neq 0!\quad (M^2_{\tilde{\nu}})_{ij} \neq 0!$

- **Misalignement** of **flavour** and **physical** eigenstates: $\quad R^{\tilde{\ell}\,\dagger}\, M^2_{\tilde{\ell}}\, R^{\tilde{\ell}} = \mathrm{diag}(m^2_{\tilde{\ell}_i}) \quad R^{\tilde{\ell}} \neq 1!$

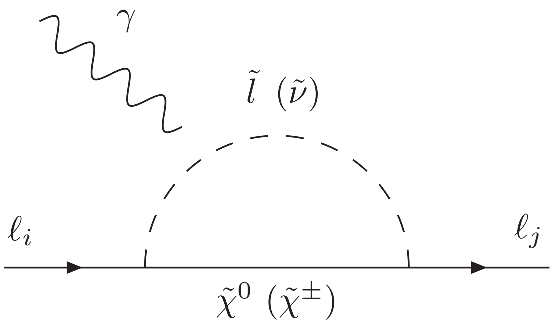
  $\{\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R\} \;\not\leftrightarrow\; \{\tilde{\ell}_1, \dots, \tilde{\ell}_6\}$

  manifest in **neutral** and

  charged **lepton-slepton** interactions



$\bullet \propto R^{\tilde{\ell}}_{ij}$



- Sizable contributions to **cLFV observables** $\propto \delta^{\ell}_{ij} = \frac{(M^2_{\tilde{\ell}})_{ij}}{M^2_{\mathrm{SUSY}}}$

"almost everything is possible - depending on the regime"...

e.g. $\mathbf{BR}(\mu \to e\gamma) \sim \frac{\alpha}{4\pi} \left(\frac{M_W}{M_{\mathrm{SUSY}}}\right)^4 \sin^2\theta_{\tilde{e}\tilde{\mu}} \left(\frac{\Delta m^2_{\tilde{\ell}}}{M^2_{\mathrm{SUSY}}}\right)^2$

[Ellis et al, Hisano et al, Lavignac et al, Raidal et al, Brignole & Rossi, Paradisi, Buras et al, Herrero et al...]

4th generation* - and beyond!

- **Extend the SM** via a **fourth family** of quarks* and **leptons** (Dirac or Majorana νs)

  *LHC excluded...

- **Additional** mixing angles and CP phases in the **lepton sector**

- **Radiative and 3-body decays:** all **as large as** current bounds **(not simultaneously)**

- **Distinctive** patterns for correlations of observables in **SM4**

[Babu, Ma, Hill, Kribbs et al, Soni et al, Eilam et al, Hou et al, Burdman, Rajamaran et al, Lenz et al, Aparici et al, Buras et al, Schmidt et al, ...]

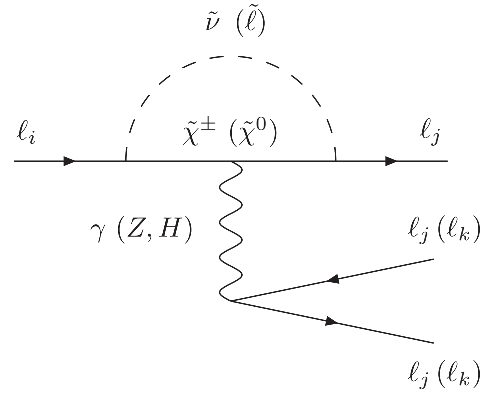
⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆ ⋆

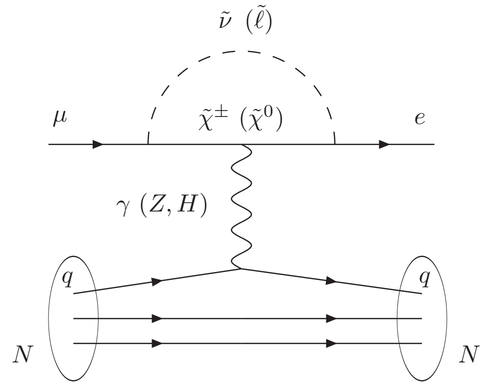
And many other models ... LR symmetric, multiHiggs, Leptoquarks, ...

Comparing predictions - finding fingerprints

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{BR(\mu\to eee)}{BR(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\times10^{-3}$	$\sim 6\times10^{-3}$	$0.06\ldots\mathbf{2.2}$
$\frac{BR(\tau\to eee)}{BR(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\times10^{-2}$	$\sim 1\times10^{-2}$	$0.07\ldots\mathbf{2.2}$
$\frac{BR(\tau\to \mu\mu\mu)}{BR(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\times10^{-3}$	$0.06\ldots0.1$	$0.06\ldots\mathbf{2.2}$
$\frac{BR(\tau\to e\mu\mu)}{BR(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\times10^{-3}$	$0.02\ldots0.04$	$0.03\ldots\mathbf{1.3}$
$\frac{BR(\tau\to \mu ee)}{BR(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\times10^{-2}$	$\sim 1\times10^{-2}$	$0.04\ldots\mathbf{1.4}$
$\frac{BR(\tau\to eee)}{BR(\tau\to e\mu\mu)}$	$0.8\ldots2$	$\mathbf{\sim 5}$	$0.3\ldots0.5$	$1.5\ldots2.3$
$\frac{BR(\tau\to \mu\mu\mu)}{BR(\tau\to \mu ee)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$	$1.4\ldots1.7$
$\frac{CR(\mu Ti\to e Ti)}{BR(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\times10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

[Buras et al, 1006.5356]





- Most **models predict/accommodate** extensive **ranges for observables**

  (no new physics yet discovered, only bounds on new scale!)

- But... **Peculiar patterns** to **correlation of observables** (model-specific)

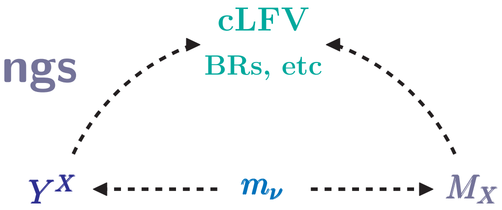
Correlations might allow to **disentagle models of cLFV** in the absence of **discovery of new states!** ... or inability to **identify mechanism of LFV!**

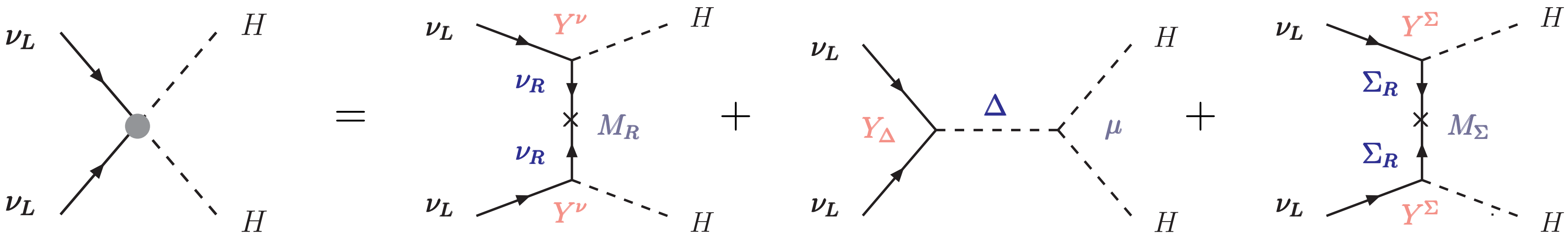
- **cLFV from ν mass generation mechanisms - seesaw**

cLFV and the seesaw mechanism

★ **Seesaw mechanism:** explain **small ν masses** with **"natural" couplings**

via **new dynamics** at **"heavy" scale**

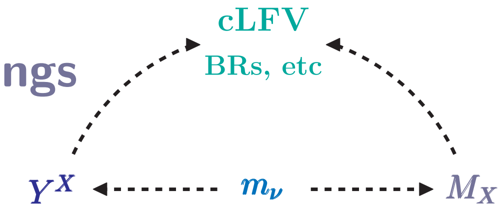




$\frac{1}{\Lambda} L\, L\, H\, H$	ν_R (fermion singlet)	Δ (scalar triplet)	Σ_R (fermion triplet)
"Seesaw mechanism"	**Type I**	**Type II**	**Type III**

cLFV and the seesaw mechanism

★ **Seesaw mechanism:** explain **small ν masses** with **“natural” couplings** via **new dynamics** at **“heavy” scale**



Seesaw	$\tilde{\mathcal{C}}_5$	New Physics scales	$\tilde{\mathcal{C}}_6$	cLFV obs
Fermionic singlet (type I)	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N \sim \mathcal{O}(1) \Rightarrow M_N \approx 10^{15}$ **GeV** $M_N \sim M_{\mathrm{GUT}}$???	$\left(Y_N^\dagger \frac{1}{M_N^\dagger} \frac{1}{M_N} Y_N\right)_{\alpha\beta}$	...
Fermionic triplet (type III)	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	“ ”	$\left(Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma\right)_{\alpha\beta}$	...
Scalar triplet (type II)	$4 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$	$Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \approx$ **TeV** **($\mu_\Delta \ll 1$!)**	$\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y^\dagger_{\Delta\gamma\delta}$	**large BRs !** **constrain model!**

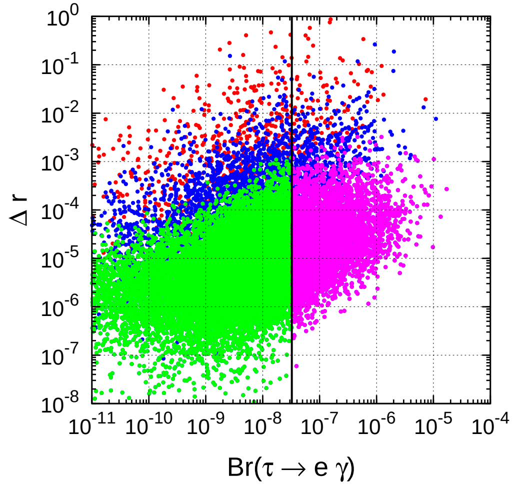
- **Type II seesaw:** **rich phenomenology, predictive** (correlations), **observable cLFV!**
- **cLFV bounds** $\Rightarrow$ **constraints on Y_Δ and M_Δ; $\mu \to eee$: $Y_\Delta \sim \mathcal{O}(1) \Rightarrow M_\Delta \geq 300$ TeV**

  [for a review: 0707.4058]
- **If $M_\Delta \sim$ TeV** (smaller Y_Δ), possible **discovery at LHC**
- **“Inverse seesaw”:** similar decorrelation between m_ν suppression and cLFV - large BRs (?)

[TeV-scale seesaws recent review: Dinh et al 1205.4671]

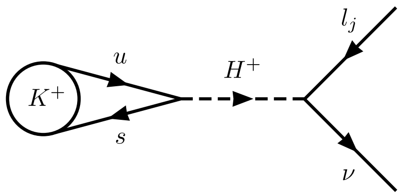
Inverse seesaw: flavour universality violation in kaon decays

- **NA62** expected to probe SM th predictions for Δr_K up to $\mathcal{O}(10^{-3})$
- **Models of new physics** **(2HDM, SUSY, etc)** typically lead to $\Delta r_K < \mathcal{O}(10^{-3,-4})$

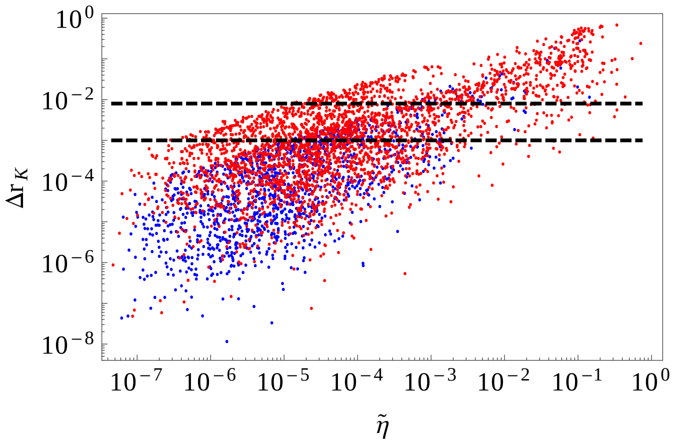


- **Unconstrained MSSM: LFV corrections to $H^+\ell\nu$ vertex**

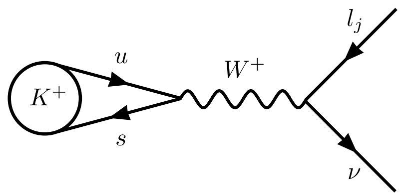
[■ ⇝ viable points]



Maximise Δr_K: explicit LFV δ_{31}^{RR}, low mass regimes



- **Inverse seesaw: corrections to $W^+\ell\nu$ vertex**



$\Delta r_K \sim \mathcal{O}(1)$

Deviation from **"unitarity" of U_{PMNS}** due to **light singlets**

$M_R \in [0.1, 200]$ **MeV**; $M_R \in [1, 10^6]$ **GeV**

- **cLFV from m_ν in extended frameworks**

The supersymmetric seesaw(s) and cLFV

★ **Embed seesaw in the framework** of (otherwise) **flavour-conserving SUSY models**

(cMSSM, supergravity-inspired, etc)

▶ In addition to

Right-handed ν	$\rightsquigarrow$	$\tilde{\nu}_R$	[Type I]
Scalar triplets	$\rightsquigarrow$	**"triplinos"**	[Type II]
Fermion triplets	$\rightsquigarrow$	**"s-triplets"**	[Type III]

with **same couplings, same interactions!**

▶ **mSUGRA-like SUSY seesaw:** Y^ν **unique source of FV** (observables strongly related)

⋆ **low-energies:** $l_j \to l_i \gamma$, $l_j \to 3 l_i$, $\mu - e$ **in Nuclei** $\Rightarrow$ **large rates**

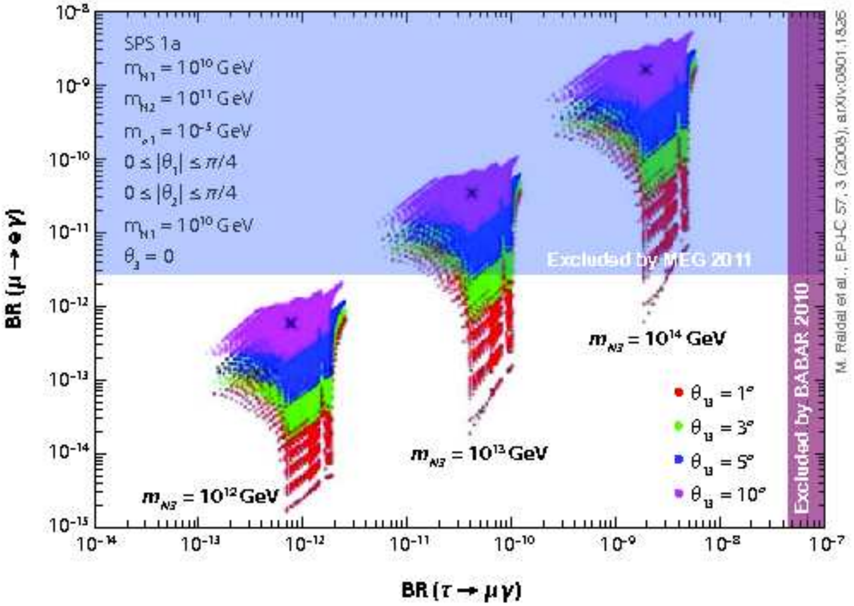
⋆ **high-energies:** study **charged sleptons** from $\chi_2^0 \to \ell^\pm \ell^\mp \chi_1^0$ decays **[LHC, LC]**

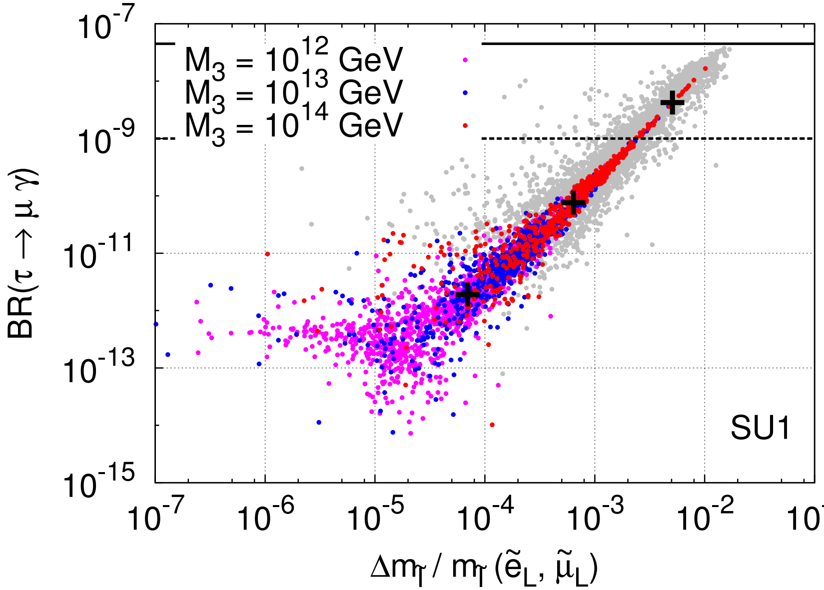
$\Rightarrow$ **sizable** $\tilde{e} - \tilde{\mu}$ **mass differences**, new edges in $m_{\ell\ell}$: $\chi_2^0 \to \tilde{\ell}_X^j \ell_i \to \chi_1^0 \ell_i \ell_i$

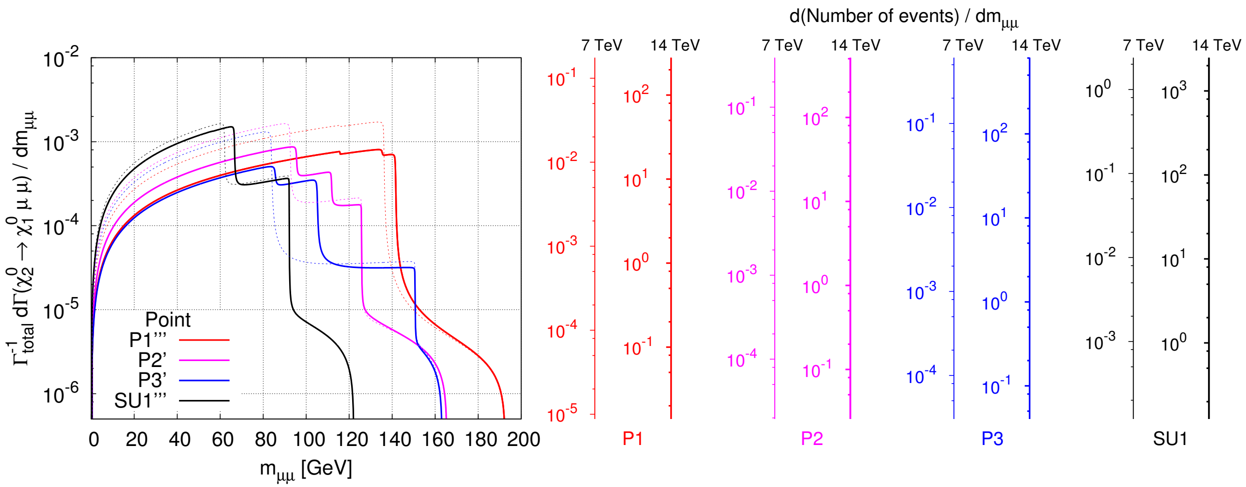
▶ **Even if correlations, etc... - difficult to disentangle from "generic" MSSM cLFV...**

On the other hand $\Rightarrow$ some **scenarios are falsifiable!**

Type I SUSY seesaw cLFV: low- and high-energies







Beyond the type I SUSY seesaw: examples ...

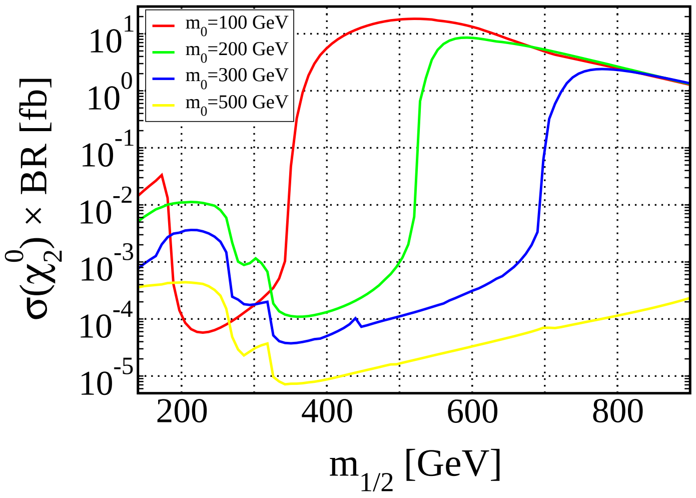
★ **Type II SUSY seesaw**

▶ **More predictive** (up to overal scale) - $(\Delta m^2_{\tilde{L}})_{ij} \propto m^2_{\nu\alpha} U_{\alpha i} U^*_{\beta j}$

correlations between cLFV observables controled by **ν-parameters !**

[Rossi et al, ...]

▶ **Distinctive prospects for cLFV at colliders**

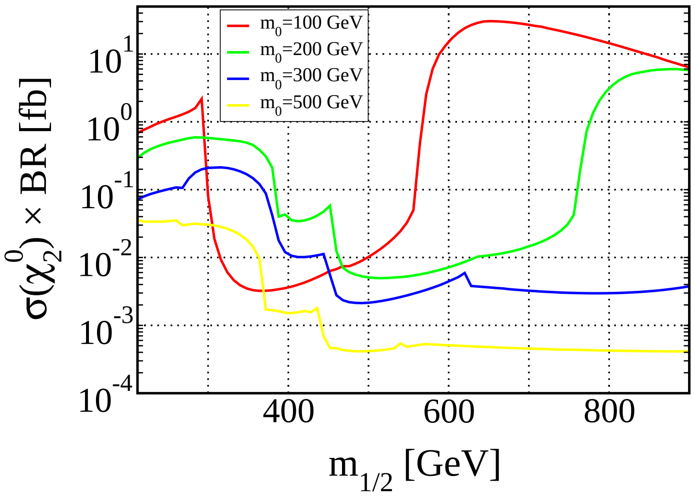


BR($\chi^0_2 \to \mu\tau$)

← Type I SUSY seesaw

Type II SUSY seesaw →

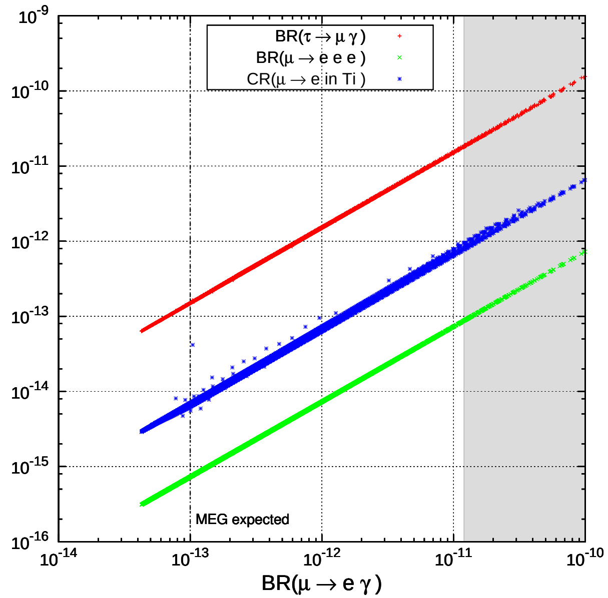
[Esteves et al, 0903.1408]



Beyond the type I SUSY seesaw: examples ...

★ **Supersymmetric Grand Unified Theories**

▶ **Reduce arbitrariness of Y^ν** [SO(10) CKM- and U_{PMNS}-inspired patterns..]



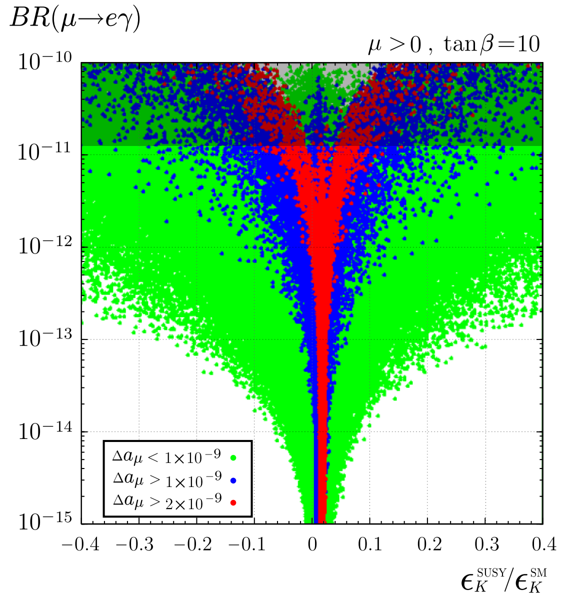
▶ **SO(10) type II example**

(leptogenesis motivated)

highly correlated cLFV observables!

[Calibbi et al, 0910.0377]

▶ **SU(5) + RH neutrinos SUSY GUTs**



correlated CPV and FV observables

in lepton and hadron sectors!

[Buras et al, 1011.4853]

- **Lepton flavour violation: some final words ...**

Lepton Flavour Violation - February 2013

- What is the role of flavour physics in the LHC era?
- Why Lepton flavour Violation?

- We know that there is NP in the lepton sector!

  ... and that minimal SM deviations cannot account for cLFV!

- Neutrino experiments and cLFV searches will offer a "clean", complementary avenue in our quest for New Physics

- *Will the LPC join??*

Find me in room 6210a ....

to discuss lepton flavour violation, neutrinos,

and share other not-so-leptonic flavours !