Prospects for new physics in $\tau \to l\mu\mu$ at current and future colliders

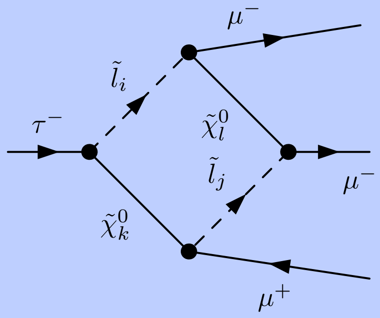
Chris Hays[a], Minimala Mitra[b,c],
Michael Spannowsky[c], and Philip Waite[c]

[a]Oxford University, [b]Indian Institute of Science Mohali,
[c]IPPP Durham

arXiv:1703.04362

25th International Workshop on Deep Inelastic Scattering
4 April 2017

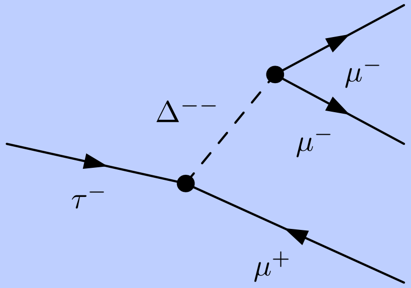
Motivation



Flavour violation observed in the quark and neutrino sectors

No charged lepton flavour violation (LFV) in the SM

Many models predict observable LFV rates, e.g. additional Higgs triplets or supersymmetry



A typical feature of seesaw models for neutrino masses

Current & proposed colliders could improve sensitivity to τ flavour violation by several orders of magnitude

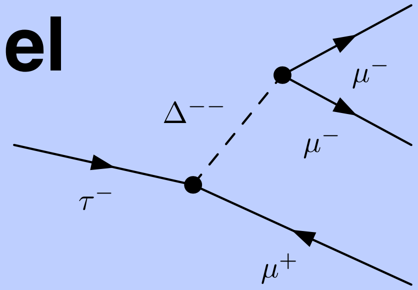
LHC experiments should give the best sensitivity to τ→3μ over the next few years

We investigate the prospects for experimental τ→lμμ constraints and corresponding constraints on parameters in Seesaw Models, the LRSM, and the MSSM

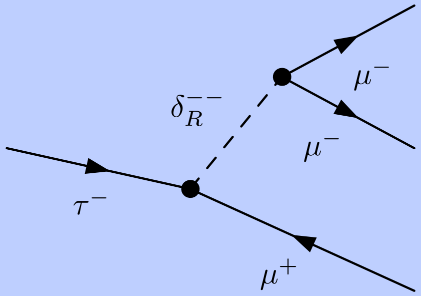
Overview

Collider sensitivity

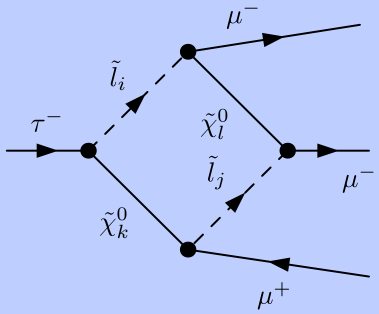
Type-II Seesaw model



Left-right symmetric model



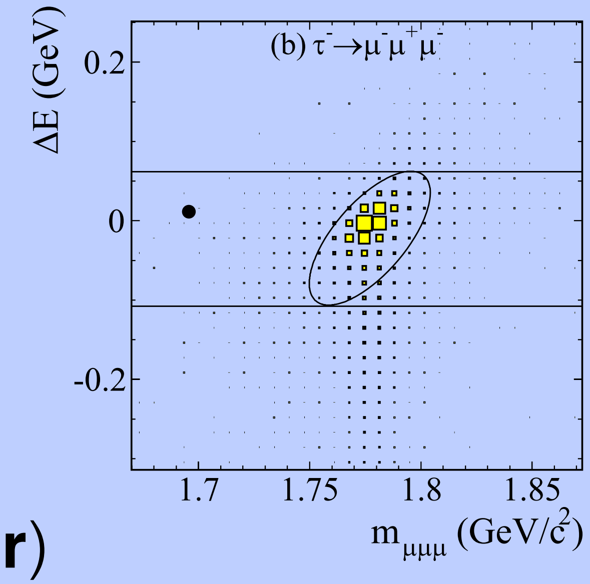
Minimal supersymmetric model



e^+e^- colliders

Best sensitivity is at e^+e^- colliders due to clean environment

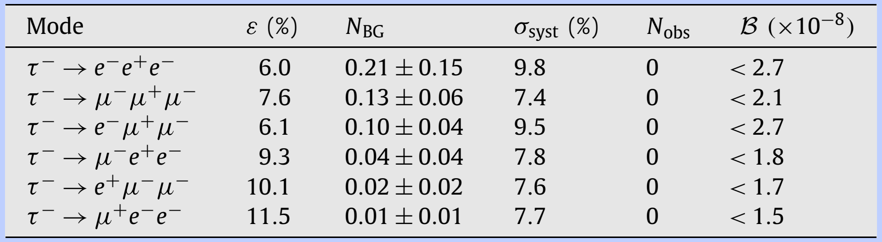
PLB 687, 139 (2010)



Belle and Babar set limits on all six τ➝3l decays
720 million τ-lepton pairs analyzed at Belle, 430 million at BaBar

Very low background, ≲0.1 events
Good selection efficiency, 7.6-10.1%

Current upper limits on B(τ➝3μ): **2.1×10^{-8}** (**Belle**) & **3.3×10^{-8}** (**BaBar**)



Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to e^-e^+e^-$	6.0	0.21 ± 0.15	9.8	0	< 2.7
$\tau^- \to \mu^-\mu^+\mu^-$	7.6	0.13 ± 0.06	7.4	0	< 2.1
$\tau^- \to e^-\mu^+\mu^-$	6.1	0.10 ± 0.04	9.5	0	< 2.7
$\tau^- \to \mu^-e^+e^-$	9.3	0.04 ± 0.04	7.8	0	< 1.8
$\tau^- \to e^+\mu^-\mu^-$	10.1	0.02 ± 0.02	7.6	0	< 1.7
$\tau^- \to \mu^+e^-e^-$	11.5	0.01 ± 0.01	7.7	0	< 1.5

Belle-II will have 50x the luminosity in 2025

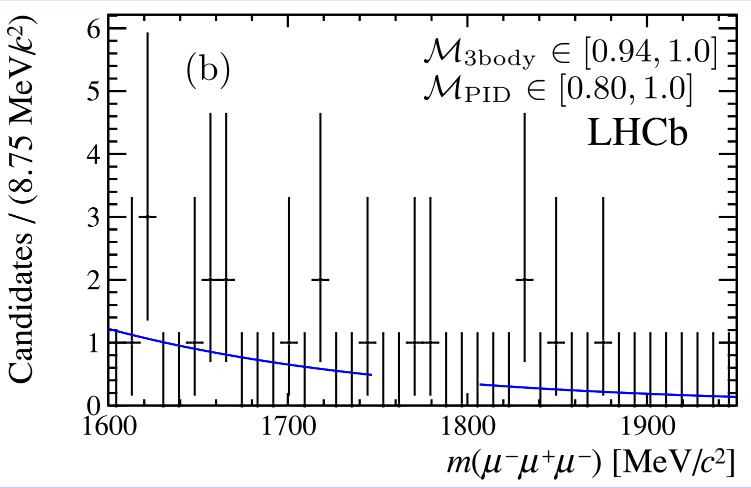
Our conservative projection scales the background by 50

$$\mathcal{B}(\tau^- \to \ell^-\ell^+\ell^-) < \frac{s_{90}}{2N_{\tau\tau}\varepsilon}$$

Our optimistic projection maintains the current background levels assuming additional rejection and a 10% loss in acceptance

Projected range of limits on B(τ➝3μ) is **(4.7-10) x 10^{-10}** at **Belle-II**

Hadron colliders



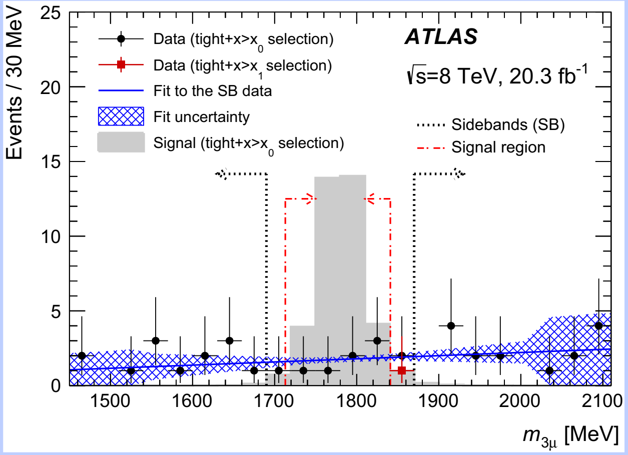
JHEP 02 (2015) 121

LHCb constraint of $B(\tau \to 3\mu) <$ **4.6×10^{-8}** with 7 & 8 TeV data

Inclusive τ cross section is 85 μb
300 billion τ-leptons produced in 3 fb^{-1} of data

Misidentification and $D_s \to \eta(\to \mu\mu\gamma)\mu\nu$ backgrounds important
Fit $m_{3\mu}$ in 30-35 bins of id and event classifiers

HL-LHC: τ-leptons yields increase by factors of 15 (luminosity) & 1.8 (cross section)
We estimate LHCb constraints will be in the range **$(1.5\text{-}11) \times 10^{-9}$**



EPJC 76, 232 (2016)

ATLAS constraint of $B(\tau \to 3\mu) <$ **3.8×10^{-7}** with 8 TeV data

Use W boson decays with BDT to reduce background to 0.2 events

HL-LHC to provide a factor of >100 luminosity and 1.6 in cross section
Backgrounds and triggering will be a substantial challenge

We estimate the ATLAS limits on $B(\tau \to 3\mu)$ will be in the range **$(1.8\text{-}8.9) \times 10^{-9}$**

Future circular colliders

100 TeV pp collider would have a W boson cross section ~7x that of the LHC

Assuming a similar background rejection and efficiency to ATLAS, we project B(τ→3μ) constraints in the range **(3-30) x 10^{-10}** for 3 ab^{-1} of luminosity

Proposed circular **e^+e^- collider** could have a run at the Z-boson resonance

55 ab^{-1} of luminosity at four interaction points would provide 300 trillion τ-lepton pairs

Based on LEP searches, we assume negligible background & 40-80% acceptance, and project B(τ→3μ) limits in the range **(5-10) x 10^{-12}** for such a collider

Experiment	Current	Projected
Belle	2.1×10^{-8}	$(4.7 - 10) \times 10^{-10}$
BaBar	3.3×10^{-8}	–
FCC-ee	–	$(5 - 10) \times 10^{-12}$
LHCb	4.6×10^{-8}	$(1.5 - 11) \times 10^{-9}$
ATLAS	3.8×10^{-7}	$(1.8 - 8.1) \times 10^{-9}$
FCC-hh	–	$(3 - 30) \times 10^{-10}$

	$\tau^\mp \to e^\pm\mu^\mp\mu^\mp$		$\tau^\mp \to e^\mp\mu^\mp\mu^\pm$	
Experiment	Current	Projected	Current	Projected
Belle	1.7×10^{-8}	$(3.4 - 5.1) \times 10^{-10}$	2.7×10^{-8}	$(5.9 - 12) \times 10^{-10}$
BaBar	2.6×10^{-8}	–	3.2×10^{-8}	–
FCC-ee	–	$(5 - 10) \times 10^{-12}$	–	$(5 - 10) \times 10^{-12}$

Type-II Seesaw model

Type-II Seesaw adds a Higgs triplet to the SM doublet:

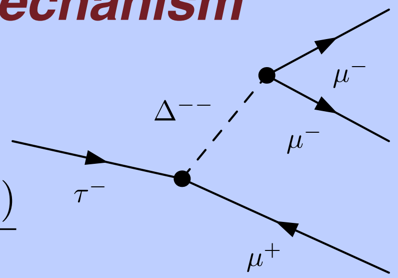
Yukawa terms lead to lepton number violation and LFV:

Neutrino masses are given by $M_\nu = \sqrt{2} Y_\Delta v_\Delta$

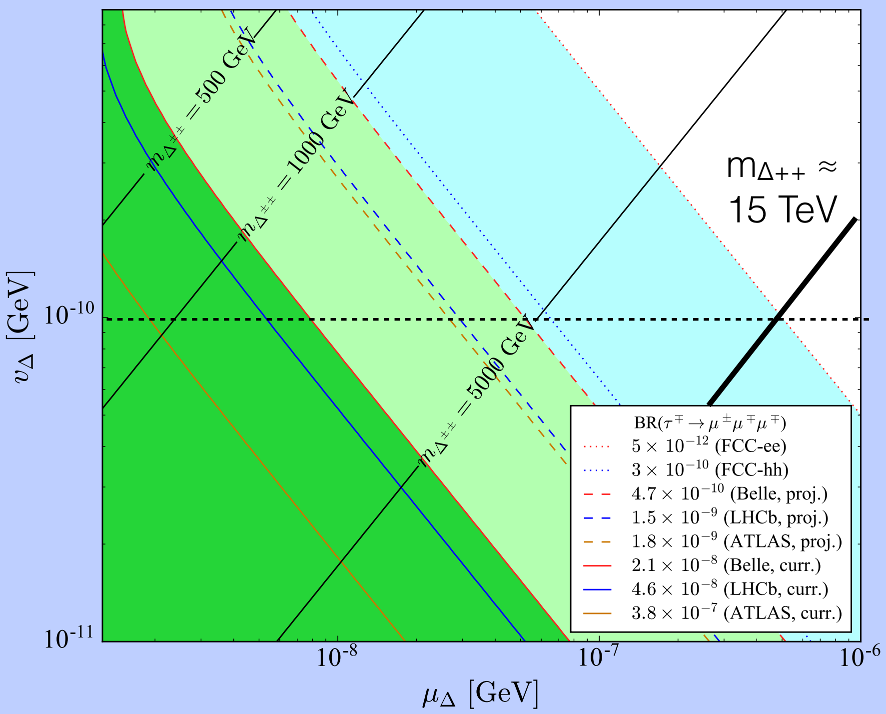
$$v_\Delta = \mu_\Delta v_\Phi^2 / (\sqrt{2} M_\Delta^2)$$

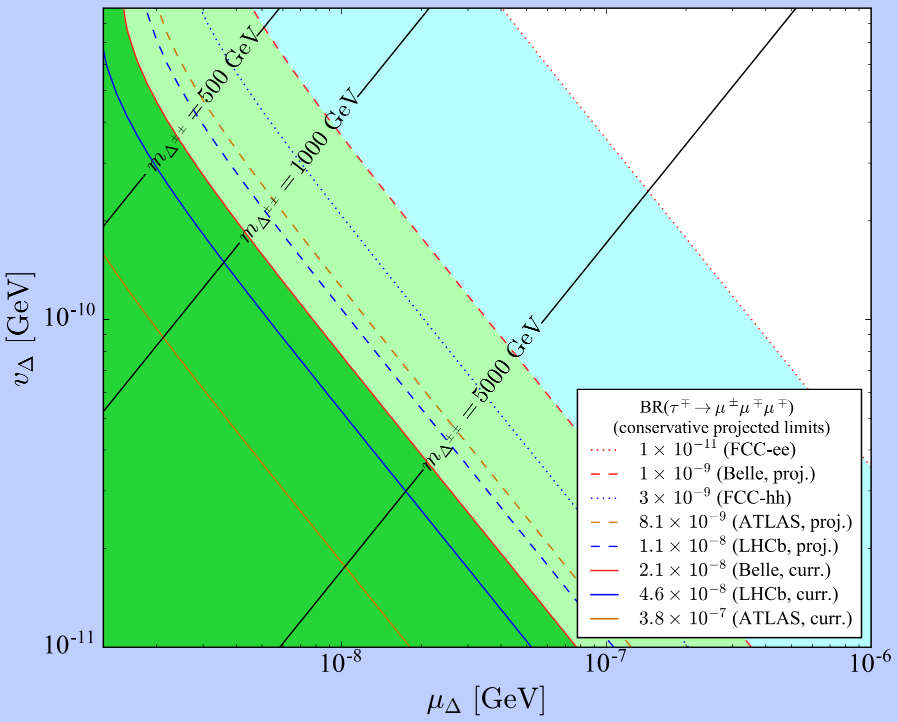
$$V(\Phi, \Delta) = \mu_\Delta \Phi^{\mathrm{T}} i\tau_2 \Delta^\dagger \Phi + \mathrm{h.c.}$$

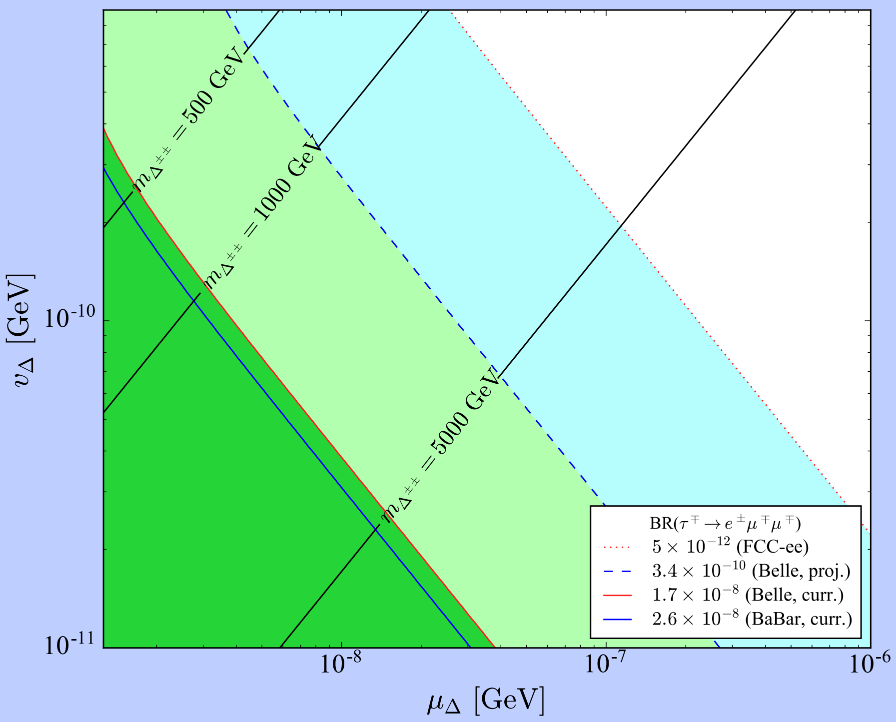
See-saw mechanism



The partial decay width is $\Gamma(\tau^\mp \to \mu^\pm \mu^\mp \mu^\mp) = \frac{m_\tau^5}{192\pi^3} |C_{\tau\mu\mu\mu}|^2 \,, \quad C_{\tau\mu\mu\mu} = \frac{Y_{\tau\mu} Y_{\mu\mu}}{m_{\Delta^{\pm\pm}}^2} = \frac{M_\nu(\tau,\mu) M_\nu(\mu,\mu)}{2 v_\Delta^2 m_{\Delta^{\pm\pm}}^2}$







Neutrino mass m_1=0.1 eV

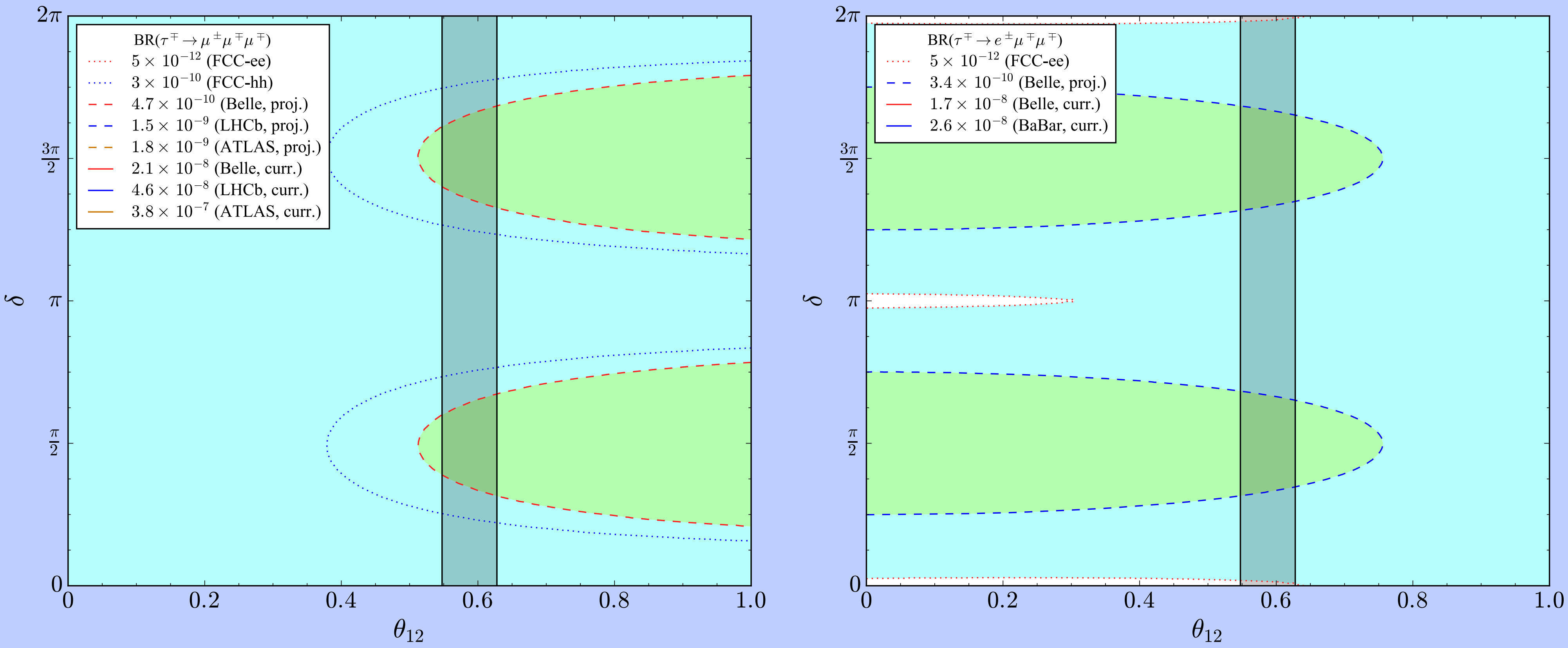
Type-II Seesaw model

Diagonalize neutrino mass matrix with the PMNS matrix $U_{\mathrm{P}}^{\mathrm{T}} M_\nu U_{\mathrm{P}} = M_d$

$$U_{\mathrm{P}} = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -c_{23}\, s_{12} - s_{23}\, s_{13}\, c_{12}\, e^{i\delta} & c_{23}\, c_{12} - s_{23}\, s_{13}\, s_{12}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{23}\, s_{12} - c_{23}\, s_{13}\, c_{12}\, e^{i\delta} & -s_{23}\, c_{12} - c_{23}\, s_{13}\, s_{12}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

δ: Dirac CP violating phase
$\alpha_{1,2}$: Majorana phases

Constraints on δ vs θ_{12} using $v_\Delta = 10^{-10}$ GeV and $m_{\Delta^{++}}$ = 8 TeV or 10.3 TeV:



Future searches sensitive to δ

Left-right symmetric model

The LRSM adds an SU(2)$_R$ Higgs doublet and triplet to the minimal Type-II Seesaw model

$$\begin{aligned} -\mathcal{L}_Y \;=&\; h\bar{\psi}_L\Phi\psi_R + \tilde{h}\bar{\psi}_L\tilde{\Phi}\psi_R + f_L\psi_L^{\mathrm{T}}Ci\tau_2\Delta_L\psi_L \\ &+ f_R\psi_R^{\mathrm{T}}Ci\tau_2\Delta_R\psi_R + \mathrm{h.c.}\ , \end{aligned}$$

$$M_\nu \approx M_L - M_D M_R^{-1} M_D^{\mathrm{T}} = \sqrt{2}v_L f_L - \frac{\kappa^2}{\sqrt{2}v_R} h_D f_R^{-1} h_D^{\mathrm{T}}$$

$$M_R = \sqrt{2}v_R f_R$$

LFV can be mediated by either doubly charged Higgs boson

$$\mathcal{L}_Y = f_L \bar{l}_L^c \delta_L^{++} l_L + f_R \bar{l}_R^c \delta_R^{++} l_R \ + \mathrm{h.c.}$$

The relevant terms of the Higgs potential for doubly charged Higgs boson masses are

$$\begin{aligned} V(\Phi,\Delta_L,\Delta_R) \;=\;& +\rho_1\left[\mathrm{Tr}\left[\Delta_L^\dagger\Delta_L\right]\right]^2 + \rho_1\left[\mathrm{Tr}\left[\Delta_R^\dagger\Delta_R\right]\right]^2 + \rho_3\mathrm{Tr}\left[\Delta_L^\dagger\Delta_L\right]\mathrm{Tr}\left[\Delta_R^\dagger\Delta_R\right] \\ & +\rho_2\mathrm{Tr}\left[\Delta_L\Delta_L\right]\mathrm{Tr}\left[\Delta_L^\dagger\Delta_L^\dagger\right] + \rho_2\mathrm{Tr}\left[\Delta_R\Delta_R\right]\mathrm{Tr}\left[\Delta_R^\dagger\Delta_R^\dagger\right] \\ & +\rho_4\mathrm{Tr}\left[\Delta_L\Delta_L\right]\mathrm{Tr}\left[\Delta_R^\dagger\Delta_R^\dagger\right] + \rho_4\mathrm{Tr}\left[\Delta_L^\dagger\Delta_L^\dagger\right]\mathrm{Tr}\left[\Delta_R\Delta_R\right] \\ & \alpha_1\mathrm{Tr}\left[\Phi^\dagger\Phi\right]\mathrm{Tr}\left[\Delta_L^\dagger\Delta_L + \Delta_R^\dagger\Delta_R\right] + \alpha_3\mathrm{Tr}\left[\Phi\Phi^\dagger\Delta_L\Delta_L^\dagger + \Phi^\dagger\Phi\Delta_R\Delta_R^\dagger\right] + \ \dots \end{aligned}$$

Require δ$_L^{++}$ to have a large mass since it is larger than neutral Higgs bosons that must have a large mass to avoid flavour changing currents in the quark sector

$$M_{H_1^0}^2 = M_{A_1^0}^2 \approx \alpha_3\frac{v_R^2}{2}\frac{k_+^2}{k_-^2}\ , \qquad M_{H_3^0}^2 = M_{A_2^0}^2 \approx (\rho_3 - 2\rho_1)\frac{v_R^2}{2}$$

$$M_{\delta_L^{\pm\pm}}^2 \approx (\rho_3 - 2\rho_1)\frac{v_R^2}{2} + \alpha_3\frac{k_-^2}{2}$$

Left-right symmetric model

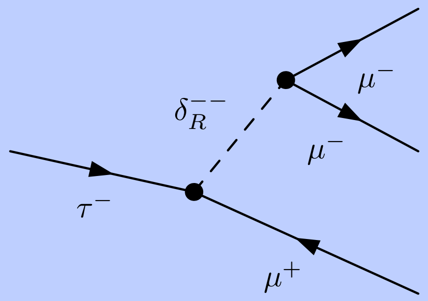
Consider two benchmark scenarios where δ_R^{++} has a somewhat lower mass

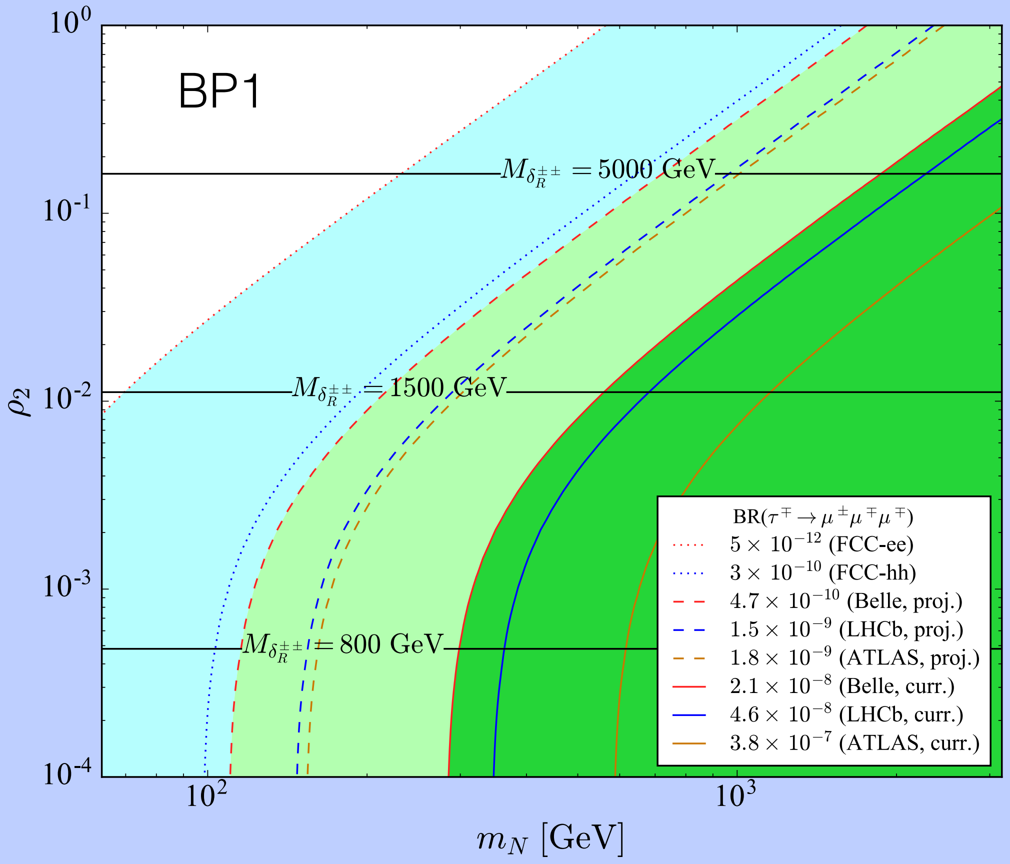
$$M^2_{\delta_R^{\pm\pm}} \approx 2\rho_2 v_R^2 + \alpha_3 \frac{k_-^2}{2}$$

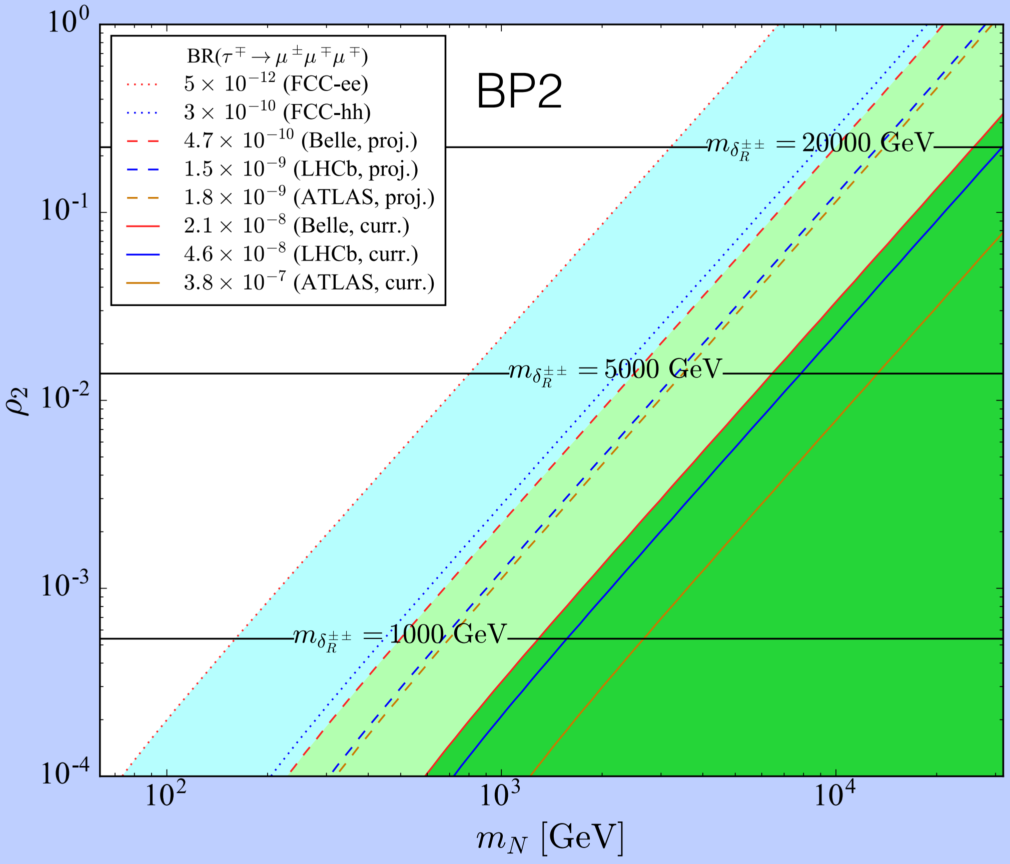
BP1: $\alpha_3 = 18.88\,,\quad v_R = 8.68\ \text{TeV}$

BP2: $\alpha_3 = 1.00\,,\quad v_R = 30.00\ \text{TeV}$

Decay amplitude proportional to $C_{\tau\mu\mu\mu} = \dfrac{f_{R\tau\mu} f_{R\mu\mu}}{M^2_{\delta_R^{\pm\pm}}} \approx \dfrac{M_{R\tau\mu} M_{R\mu\mu}}{2v_R^2 M^2_{\delta_R^{\pm\pm}}} = \dfrac{(V_R^* \widetilde{M}_R V_R^\dagger)_{\tau\mu} (V_R^* \widetilde{M}_R V_R^\dagger)_{\mu\mu}}{2v_R^2 (2\rho_2 v_R^2 + \alpha_3 \frac{k_-^2}{2})}$







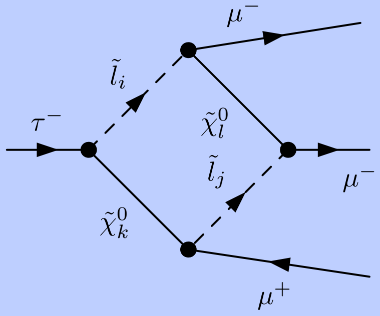
Minimal supersymmetric standard model

Slepton generational mixing is a general feature and can induce LFV

Mass matrices have flavour-violating and flavour-conserving terms

$$M^2_{\tilde{l}\,LL\,ij} = m^2_{\tilde{L}\,ij} + \left(m^2_{l_i} + (-\frac{1}{2} + \sin^2\theta_W) M_Z^2 \cos 2\beta \right) \delta_{ij}$$

$$M^2_{\tilde{l}\,RR\,ij} = m^2_{\tilde{E}\,ij} + \left(m^2_{l_i} - \sin^2\theta_W M_Z^2 \cos 2\beta \right) \delta_{ij}$$

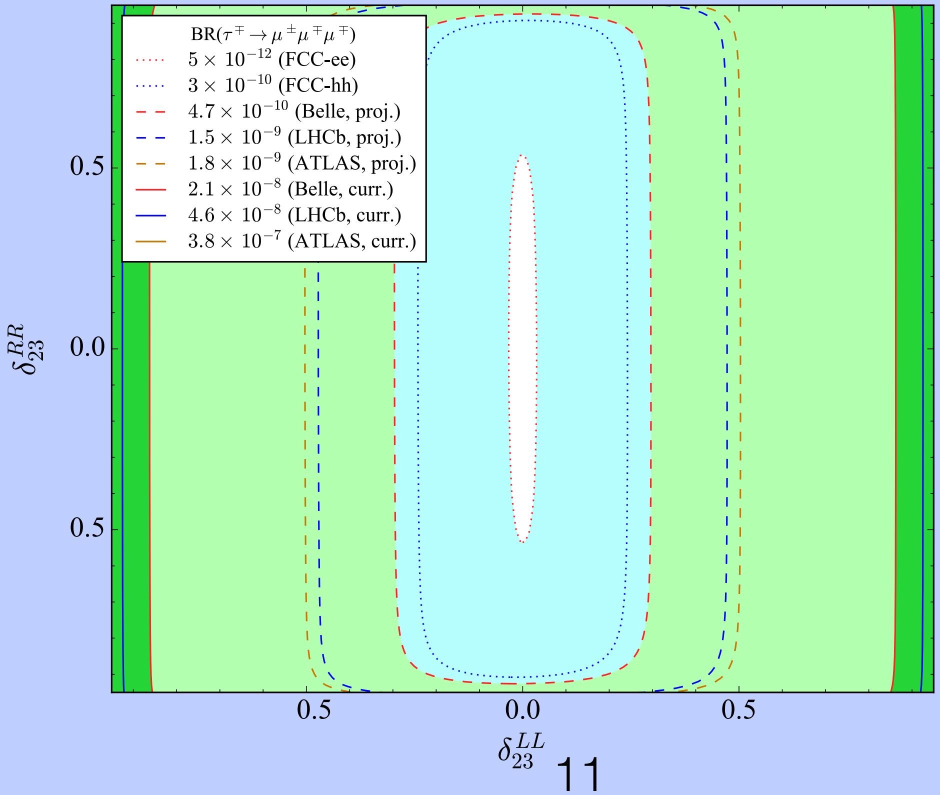


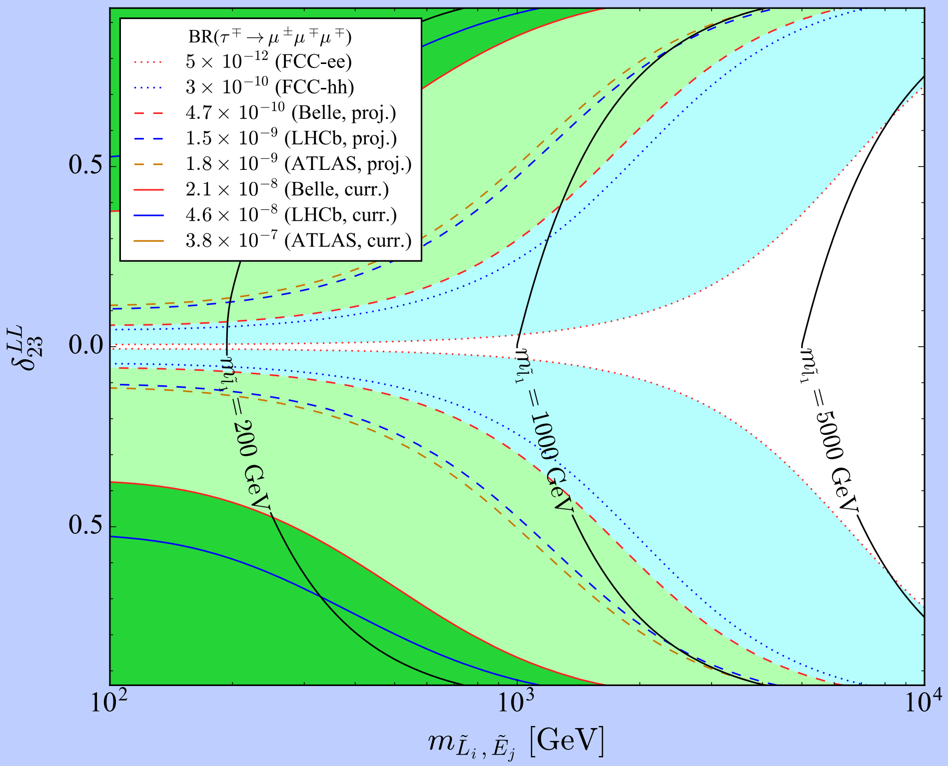
Parametrize off-diagonal entries as $\delta^{AB}_{ij} \equiv \dfrac{M^2_{\tilde{l}\,AB\,ij}}{m_{\tilde{A}_i} m_{\tilde{B}_j}}$

Vary slepton masses:

Benchmark parameters:

$\tan\beta = 10$, $\mu = -100$ GeV ,
$M_A = 1000$ GeV , $M_1 = 250$ GeV ,
$M_2 = 500$ GeV , $M_3 = 2000$ GeV ,
$m_{\tilde{L}_i} = m_{\tilde{E}_j} = 1000$ GeV , $A_\tau = 200$ GeV .





Summary

LFV is a general feature of neutrino seesaw mechanisms and of supersymmetry

Expect ~2 orders of magnitude improvement in $B(\tau\to l\mu\mu)$ in the next decade

LHC should have the best sensitivity to $B(\tau\to 3\mu)$ *for the next few years*
LHC could also be competitive in $B(\tau^-\to e^+\mu^-\mu^-)$

Future circular e^+e^- *collider could improve sensitivity by another two orders of magnitude*

In the **Type-II Seesaw model** Belle-II could probe the CP-violating phase

In the **LRSM**, increasing sensitivity to $B(\tau\to l\mu\mu)$ will probe smaller values of $m_N/m_{\delta R++}$

In the **MSSM** increasing sensitivity to $B(\tau\to l\mu\mu)$ will probe smaller mixing values