The 3rd International Joint Workshop on the Standard Model and Beyond and the 11th KIAS Workshop on Particle Physics and Cosmology

Complementarity of μTRISTAN and Belle II in searches for CLFV.

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arXiv:2307.11369

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Overview

Flavour Triality

CLFV Tau decays at Belle II

Next-to-leading order Constraints

Phenomenology at μTRISTAN (arXiv:2307.11369)

Flavour Triality

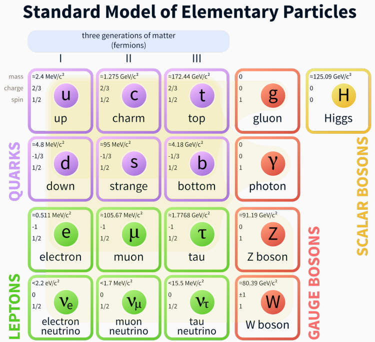
Why three families of quarks and leptons?

Explain the observed mixing patterns.

Fermion mass hierarchy.

Neutrino masses.

Charged Lepton Flavour Violation



Charged Lepton Flavour Violation

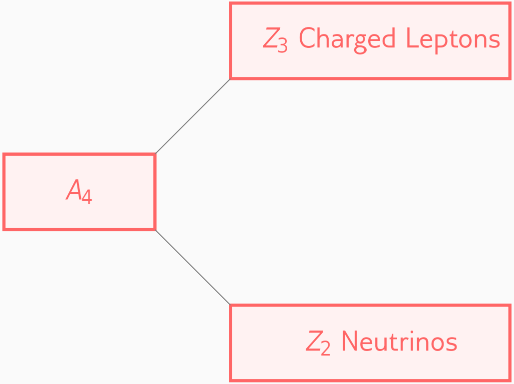
- Charged Lepton Flavour Violation (CLFV) has not yet been observed.
- Neutrino oscillations show no individual lepton numbers L_e, L_μ, and L_τ conservation.
- Several BSM models predict CLFV.
- Experimental bounds are stringent, especially on electron-muon CLFV.
  - $\mu \to e\gamma$ at MEG,
  - $\mu \to eee$ at Mu3e
  - $\mu N \to \mu N$ at COMET, Mu2e and DeeMe
- CLFV involving τ:
  - Data are less constraining;
  - Belle II future sensitivity will increase significantly.

Lepton Triality avoids $\mu \leftrightarrow e$ conversions and allows CLFV tau decays.

Lepton Triality

Motivated by flavour structure models A_4 group can explain the quark and lepton mixing angles.
Tribimaximal mixing of neutrino flavours

Altarelli, Feruglio (2006)
He, Keum, Volkas (2006)
hep-ph/0601001
Ma,(2010) 1006.3524



Lepton Triality

A_4 is generated by S and T Elements

$$T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega^2 & 0 \\ 0 & 0 & \omega \end{pmatrix}$$

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix}$$

Z_3 Lepton sector

$L \to \omega^T L$ and $e_R \to \omega^T e_R$,
$\omega = e^{\frac{2\pi i}{3}}$

H, quarks are singlets under triality

$\mathcal{L}_Y = y_{e_i} \bar{L}_i e_{R_i} H + h.c.$
$\mathcal{L}_Y$ is diagonal under Z_3

Triality sums modulo 3

$\mu^- \rightarrow e^- \gamma$ $\Delta T \neq 0$ ✗

$T=2$ $T=1$

$\tau^- \rightarrow \mu^+ e^- e^-$ $\Delta T = 0$ ✓

$T=3$ $T=-2$ $T=1$ $T=1$

$e \rightarrow T = 1$

$\mu \rightarrow T = 2$

$\tau \rightarrow T = 3$

Mediators of flavour triality transform under Z_3 as:

$k_1 \sim \omega,$

$k_2 \sim \omega^2,$

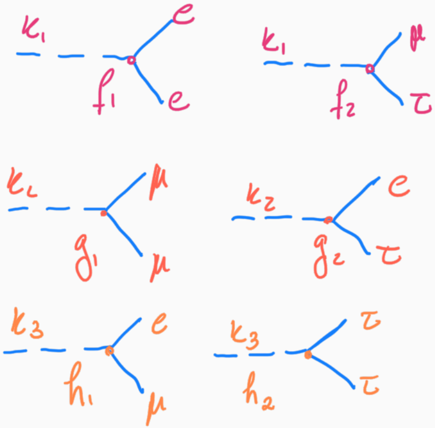
$k_3 \sim 1,$

Models T = 1, 2, 3 for the doubly charged singlet k_i

$$\mathcal{L}_{k_1} = \frac{1}{2}\left(2f_1\overline{(\tau_R)^c}\mu_R + f_2\overline{(e_R)^c}e_R\right)k_1 + \mathrm{h.c.}$$

$$\mathcal{L}_{k_2} = \frac{1}{2}\left(2g_1\overline{(\tau_R)^c}e_R + g_2\overline{(\mu_R)^c}\mu_R\right)k_2 + \mathrm{h.c.}$$

$$\mathcal{L}_{k_3} = \frac{1}{2}\left(2h_1\overline{(\mu_R)^c}e_R + h_2\overline{(\tau_R)^c}\tau_R\right)k_3 + \mathrm{h.c.}.$$



CLFV Tau decays at Belle II

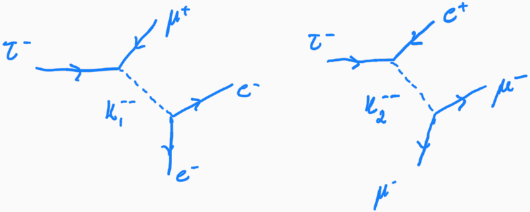
Tau Decays

Bigaran, He, Schmidt, Valencia, Volkas, (2022) 2212.09760.

Tau CLFV decays:

$\tau \to e/\mu + \gamma$,

$\tau \to e/\mu + l^+ l^-$ where $l = e/\mu$.



Observable	Present constraint	Projected sensitivity
$BR(\tau^- \to \mu^- \mu^- e^+)$	1.7×10^{-8} *	2.6×10^{-10} **
$BR(\tau^- \to \mu^+ e^- e^-)$	1.5×10^{-8} *	2.3×10^{-10} **

*** Belle Collaboration (2010) 1001.3221**

**** Belle II (2022) 2203.14919**

SMEFT

$$\mathcal{L}_{6,LFV} = C^{ll}(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L) + C^{ee}(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R) + C^{le}(\bar{L}\gamma_\mu L)(\bar{e}_R\gamma^\mu e_R)$$

$$C^{VRR}_{ee,1312} = \frac{f_1 f_2}{4m_{k_1}^2}$$

$$BR(\tau^\pm \to \mu^\mp e^\pm e^\pm) = \frac{f_1^2 f_2^2}{64 G_F^2 m_{k_1}^4} BR(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$$

$$C^{VRR}_{ee,2321} = \frac{g_1 g_2}{4m_{k_2}^2}$$

$$BR(\tau^\pm \to \mu^\pm \mu^\pm e^\mp) = \frac{g_1^2 g_2^2}{64 G_F^2 m_{k_2}^4} \tilde{I}\left(\frac{m_\mu^2}{m_\tau^2}\right) BR(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$$

Present bounds from Belle:

$\sqrt{f_1 \times f_2} < 0.17 \frac{m_{k1}}{TeV}$

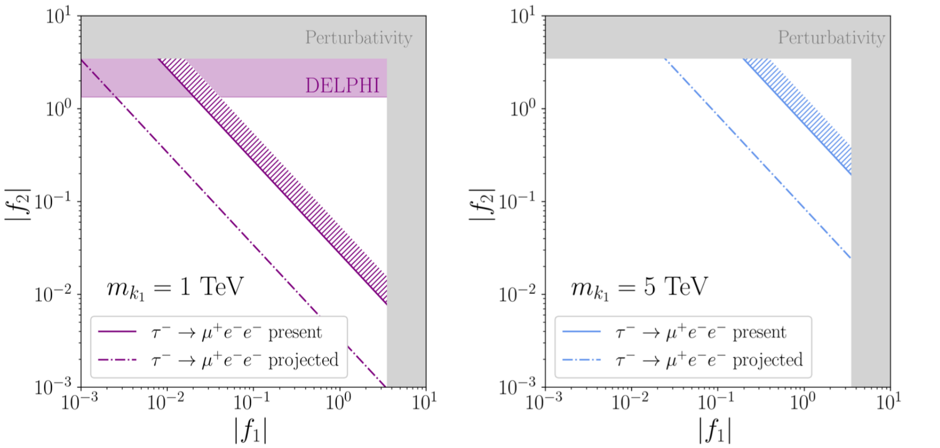
$\sqrt{g_1 \times g_2} < 0.17 \frac{m_{k2}}{TeV}$

Prediction for future sensitivity from Belle II:

$\sqrt{f_1 \times f_2} < 0.06 \frac{m_{k1}}{TeV}$

$\sqrt{g_1 \times g_2} < 0.06 \frac{m_{k2}}{TeV}$

Belle II sensitivity on CLFV tau decays from Triality T=1



Bigaran, He, Schmidt, Valencia, Volkas, (2022) 2212.09760.

Next-to-leading order Constraints

Next-to-leading order Constraints

$$\mathcal{L}_{k_1} = \frac{1}{2}\left(2f_1\overline{(\tau_R)^c}\mu_R + f_2\overline{(e_R)^c}e_R\right)k_1 + \text{h.c.}$$
$$\mathcal{L}_{k_2} = \frac{1}{2}\left(2g_1\overline{(\tau_R)^c}e_R + g_2\overline{(\mu_R)^c}\mu_R\right)k_2 + \text{h.c.}$$
$$\mathcal{L}_{k_3} = \frac{1}{2}\left(2h_1\overline{(\mu_R)^c}e_R + h_2\overline{(\tau_R)^c}\tau_R\right)k_3 + \text{h.c.}.$$

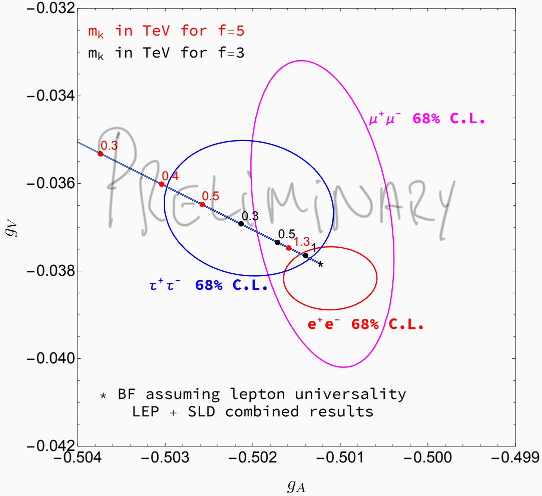
Potential: $\mathcal{L} \supset |D_\mu k_i|^2 + \kappa_i\,\phi^\dagger\phi\,k_i^\dagger k_i$ where
$D_\mu = \partial_\mu + i\,2e\,(A_\mu - \tan\theta_W Z_\mu)$

$Z \to l^+ l^-$, with $l = e, \mu, \tau$

$H \to \gamma\gamma$

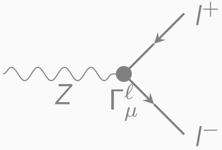
$H \to Z\gamma$

$Z \to l^+ l^-$, with $l = e, \mu, \tau$



$$\Gamma^{\ell}_{\mu} = -\, 2^{1/4} G_F^{1/2} M_Z \, \gamma_\mu \, [(r_\ell + \delta r_\ell) P_R + (l_\ell + \delta l_\ell) P_L],$$

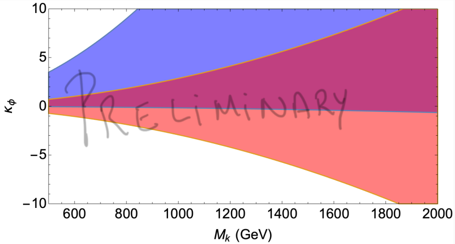
$g_A = (g_L - g_R)/2$ and $g_V = (g_L + g_R)/2$



PRELIMINARY

$H \to \gamma\gamma$

PRELIMINARY



$$R_{\gamma\gamma} = \frac{\Gamma(H\to\gamma\gamma)}{\Gamma(H\to\gamma\gamma)_{SM}}$$

Blue: $R_{\gamma\gamma} = 1.088^{+0.095}_{-0.09}$

(ATLAS arXiv:2207.00092 [hep-ex])

Red: Projected sensitivity with 3000 fb^{-1} at the HL-LHC, $\Delta\kappa_\gamma = 1.8\%$

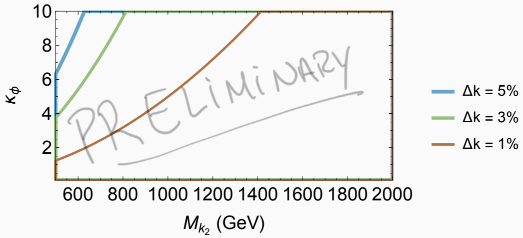
(Snowmass arXiv:1902.10229 [hep-ex])

$H \to Z\gamma$

$0.8 < R_{Z\gamma} < 1.15$

$R_{Z\gamma} = 2.2 \pm 0.7$ (ATLAS and CMS arXiv:2309.03501 [hep-ex])

$\Delta\kappa_{Z\gamma} = 9.8\%$ (Snowmass ATL-PHYS-PUB-2022-018, 2022.)



Phenomenology at μTRISTAN (arXiv:2307.11369)

μTRISTAN

Hamada, Kitano, Matsudo, Takaura and Yoshida, (2022) 2201.06664

Ultracold muon technology from g-2 at J-PARC

$\mu^+\mu^+$ proposal $\sqrt{s} = 2$ TeV;

1 TeV μ^+ beams;

expected luminosity of 12 fb^{-1} per year.

μ^+e^- proposal with asymmetric beam energies;

μ^+ beams up to 1 to 3 TeV;

e^- beams from Tristan at 30 to 50 GeV;

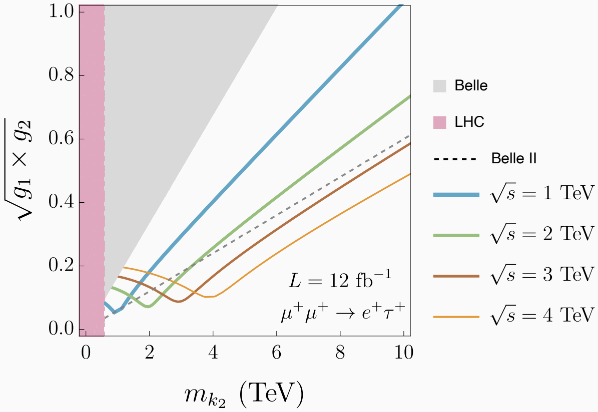
expected luminosity of 100 fb^{-1} per year.

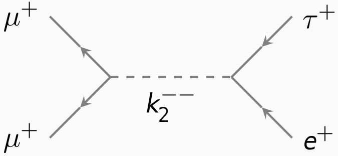
Future lepton Colliders

Model	Process	Lepton Collider
T=1	$\mu^+ e^- \to e^+ \tau^-$	μTRISTAN
T=1	$e^+ e^- \to e^+ e^-$	$e^+ e^-$
T=1	$e^- e^- \to e^- e^-$	-
T=1	$e^- e^- \to \tau^- \mu^-$	-
T=2	$\mu^+ \mu^+ \to \tau^+ e^+$	μTRISTAN
T=2	$\mu^+ \mu^+ \to \mu^+ \mu^+$	μTRISTAN
T=2	$\mu^+ e^- \to \tau^+ \mu^-$	μTRISTAN
T=2	$\mu^+ \mu^- \to \mu^+ \mu^-$	$\mu^+ \mu^-$
T=3	$\mu^+ e^- \to \mu^+ e^-$	μTRISTAN
T=3	$\mu^+ e^+ \to \tau^+ \tau^+$	-

G.L, Schmidt, Valencia, Volkas (2023) 2307.11369

CLFV s-channel at $\mu^+\mu^+$



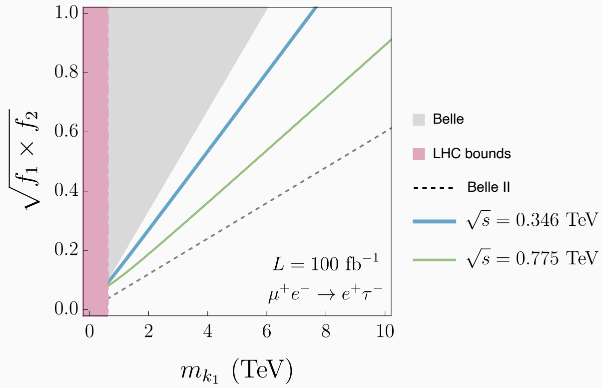


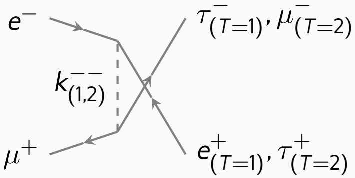
90% C.L. contour
assuming no background
N = 2.44;

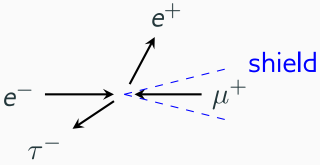
$$\sqrt{g_1 g_2} \lesssim 0.15 \left(\frac{N}{Ls}\right)^{\frac{1}{4}} \frac{m_{k_2}}{\text{TeV}}$$

For $\sqrt{s} = 2$ TeV:

$$\sqrt{g_1 g_2} \lesssim 0.17 \frac{m_{k_2}}{\text{TeV}} \; .$$

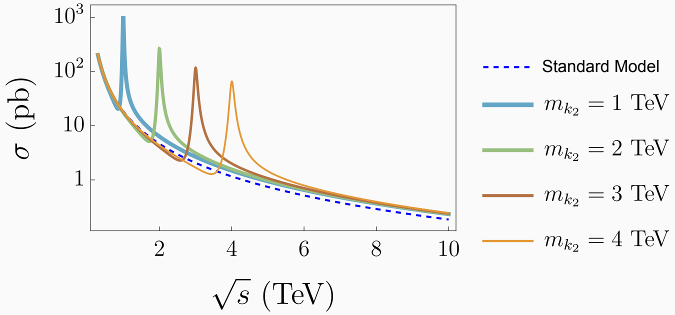


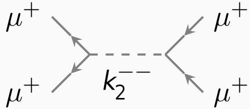




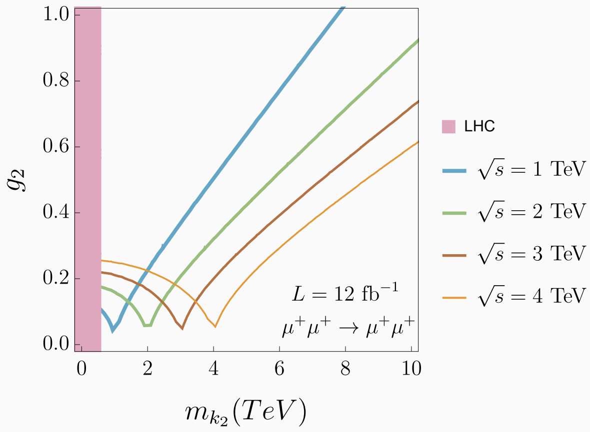
$$\sqrt{f_1 f_2} \lesssim 0.13 \frac{m_{k_1}}{\text{TeV}}$$

Resonances in elastic scattering $\mu^+\mu^+ \to \mu^+\mu^+$





Resonances in elastic scattering $\mu^+\mu^+ \to \mu^+\mu^+$



90% C.L. contour;

SM contributions as background;

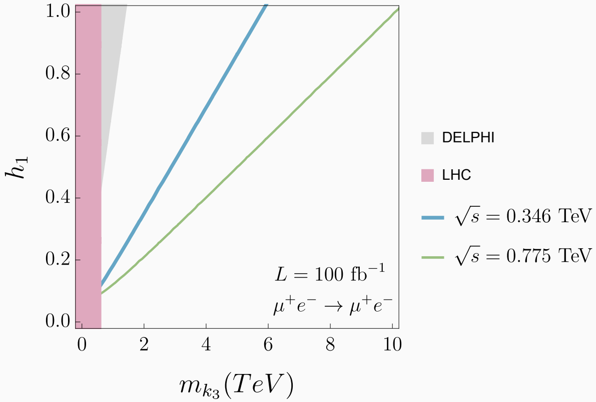
S = 1.64

$$S = \frac{|\sigma - \sigma_{SM}|}{\sqrt{\sigma_{SM}}}\sqrt{L};$$

$$g_2 \lesssim 0.18 \left(\frac{S^2}{Ls}\right)^{1/4} m_k;$$

$$g_2 \lesssim 0.09 \frac{m_{k_2}}{\mathrm{TeV}}.$$

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



$$S = \frac{|\sigma - \sigma_{SM}|}{\sqrt{\sigma_{SM}}}\sqrt{L}\ ;$$

$$h_1 \lesssim 0.17\,\frac{m_{k_3}}{\text{TeV}}\ .$$

Summary Table

Experiment	Process	90% C.L. limit	Assumptions
Belle	$\tau^- \to \mu^+ e^- e^-$	$\sqrt{f_1 f_2} \lesssim 0.17 \frac{m_{k_1}}{\mathrm{TeV}}$	$782\ \mathrm{fb}^{-1}$
Belle	$\tau^- \to e^+ \mu^- \mu^-$	$\sqrt{g_1 g_2} \lesssim 0.17 \frac{m_{k_2}}{\mathrm{TeV}}$	$782\ \mathrm{fb}^{-1}$
Belle II	$\tau^- \to \mu^+ e^- e^-$	$\sqrt{f_1 f_2} \lesssim 0.06 \frac{m_{k_1}}{\mathrm{TeV}}$	$50\ \mathrm{ab}^{-1}$
Belle II	$\tau^- \to e^+ \mu^- \mu^-$	$\sqrt{g_1 g_2} \lesssim 0.06 \frac{m_{k_2}}{\mathrm{TeV}}$	$50\ \mathrm{ab}^{-1}$
DELPHI	$e^+ e^- \to e^+ e^-$	$f_2 \lesssim 1.4 \frac{m_{k_1}}{\mathrm{TeV}}$	
DELPHI	$e^+ e^- \to \mu^+ \mu^-$	$h_1 \lesssim 0.72 \frac{m_{k_3}}{\mathrm{TeV}}$	
DELPHI	$e^+ e^- \to \tau^+ \tau^-$	$g_1 \lesssim 0.66 \frac{m_{k_2}}{\mathrm{TeV}}$	
$\mu^+\mu^+$ collider	$\mu^+ \mu^+ \to \tau^+ e^+$	$\sqrt{g_1 g_2} \lesssim 0.07 \frac{m_{k_2}}{\mathrm{TeV}}$	$12\ \mathrm{fb}^{-1}$, $\sqrt{s} = 2$ TeV
$\mu^+\mu^+$ collider	$\mu^+ \mu^+ \to \mu^+ \mu^+$	$g_2 \lesssim 0.09 \frac{m_{k_2}}{\mathrm{TeV}}$	$12\ \mathrm{fb}^{-1}$, $\sqrt{s} = 2$ TeV
$\mu^+ e^-$ collider	$\mu^+ e^- \to e^+ \tau^-$	$\sqrt{f_1 f_2} \lesssim 0.13 \frac{m_{k_1}}{\mathrm{TeV}}$	$100\ \mathrm{fb}^{-1}$, $(E_e, E_\mu) = (30, 1000)$ GeV
$\mu^+ e^-$ collider	$\mu^+ e^- \to \tau^+ \mu^-$	$\sqrt{g_1 g_2} \lesssim 0.13 \frac{m_{k_2}}{\mathrm{TeV}}$	$100\ \mathrm{fb}^{-1}$, $(E_e, E_\mu) = (30, 1000)$ GeV
$\mu^+ e^-$ collider	$\mu^+ e^- \to \mu^+ e^-$	$h_1 \lesssim 0.17 \frac{m_{k_3}}{\mathrm{TeV}}$	$100\ \mathrm{fb}^{-1}$, $(E_e, E_\mu) = (30, 1000)$ GeV

μTristan

Summary

- Lepton Flavour Triality avoids CLFV bounds from muon decays while allowing tau CLFV interactions;
- Belle II predictions of tau CLFV.
- Next-to-leading order results from $Z \to l^+ l^-$, $H \to \gamma\gamma$, $H \to Z\gamma$
- μTRISTAN
  - $\mu^+\mu^+$ collider
  - Resonances searches
  - μTRISTAN $\mu^+ e^-$ collider

Backup slides

Neutrino Masses

Include 3 RH sterile Neutrinos

T = 1, 2, 3 triality charges $\nu_R \to \omega^T \nu_R$

$-\mathcal{L} \supset y_{\nu i} \bar{L}_i \nu_{Ri} \tilde{H} + \frac{1}{2} M_{ij} (\bar{\nu_{Ri}})^c \nu_{Rj} + h.c.$

M_{ij} is a Majorana mass matrix

Incompatible with neutrino oscillations.

Break Triality with soft-breaking operators or introducing a Singlet complex scalar S (T=1), with non-zero VEV for S.

Type I see-saw, or Type III (triplet).

Bigaran, He, Schmidt, Valencia, Volkas, (2022) 2212.09760.

Observables

Direct Searches of doubly charged scalar with CLFV:

$m_{k_i} \geq 0.6$ TeV (ATLAS).

Lepton scattering (DELPHI):

$\frac{m_{k_1}}{|f_2|} \geq 0.74$ TeV;

$\frac{m_{k_2}}{|g_1|} \geq 1.5$ TeV.

Flavour-violating Z decays:

$BR(Z \to k_1 k_1 \to e^+ e^+ \mu^- \mu^-)$ is highly suppressed;

$BR(Z \to \tau^+ \tau^- \to e^+ e^+ \mu^- \mu^-)$.

anomalous magnetic moment $\to$ too small.

Bigaran, He, Schmidt, Valencia, Volkas, (2022) 2212.09760.