

DIAS - CATCH22+2

Complementarity of μ TRISTAN and Belle II in searches for CLFV.

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arXiv:2307.11369, 2312.09409

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Charged Lepton Flavour Violation (CLFV)

The SM does not predict any mixing pattern in the leptonic sector.

Neutrino oscillations: 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 conversion.

$\mu \rightarrow e\gamma$ at MEG,

$\mu \rightarrow eee$ at Mu3e

$\mu N \rightarrow e N$ at COMET, Mu2e and DeeMe

CLFV involving τ : the data are less constraining.

Lepton Triality allows CLFV, preferably at the 3rd family, avoiding $\mu \leftrightarrow e$ conversions.

Lepton Triality

Motivated by flavour structure models with A_4 discrete symmetry.

He, Keum, Volkas (2006) 0601001, Altarelli, Feruglio (2006) 1006.3524, and Ma,(2010) 1006.3524

Charged Lepton sector with a remaining Z_3 flavour symmetry

$$L \rightarrow \omega^T L \text{ and } e_R \rightarrow \omega^T e_R,$$

$$\omega = e^{\frac{2\pi i}{3}}$$

H, quarks are singlets under triality

\mathcal{L}_Y is diagonal under Z_3

$$e \rightarrow T = 1$$

$$\mu \rightarrow T = 2$$

$$\tau \rightarrow T = 3$$

T = 1, 2, 3 models

A simplified model with a mediator as doubly charged singlet k_i

$$\begin{aligned}k_1 &\sim \omega, \\k_2 &\sim \omega^2, \\k_3 &\sim 1,\end{aligned}$$

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

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

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

Tau Decays at Belle II

Tau CLFV decays:

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

$$\tau \rightarrow e/\mu + l^+l^- \text{ where } l = e/\mu.$$

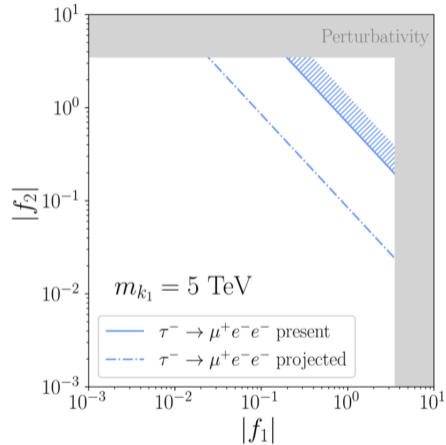
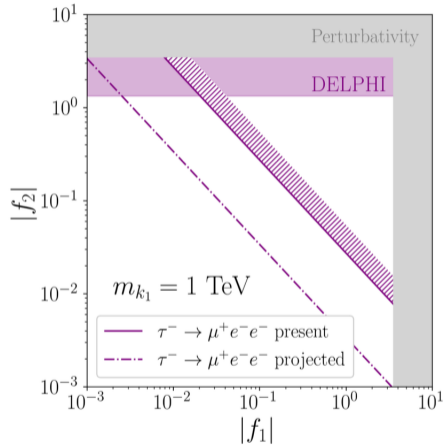
Observable	Present constraint	Projected sensitivity
$\text{BR}(\tau^- \rightarrow \mu^- \mu^- e^+)$	$1.7 \times 10^{-8} *$	$2.6 \times 10^{-10} **$
$\text{BR}(\tau^- \rightarrow \mu^+ e^- e^-)$	$1.5 \times 10^{-8} *$	$2.3 \times 10^{-10} **$

* Belle Collaboration (2010) 1001.3221

** Belle II (2022) 2203.14919

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

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



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

μ TRISTAN

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.

$\mu^+ e^-$ proposal with asymmetric beam energies;

μ^+ beams up to 1 to 3 TeV;

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

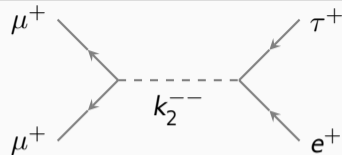
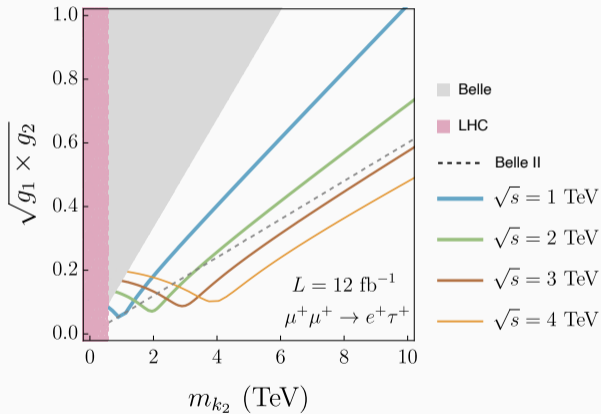
expected luminosity of 100 fb^{-1} per year.

Future lepton Colliders

Model	Process	Lepton Collider
T=1	$\mu^+ e^- \rightarrow e^+ \tau^-$	μ TRISTAN
T=1	$e^+ e^- \rightarrow e^+ e^-$	$e^+ e^-$
T=1	$e^- e^- \rightarrow e^- e^-$	-
T=1	$e^- e^- \rightarrow \tau^- \mu^-$	-
T=2	$\mu^+ \mu^+ \rightarrow \tau^+ e^+$	μ TRISTAN
T=2	$\mu^+ \mu^+ \rightarrow \mu^+ \mu^+$	μ TRISTAN
T=2	$\mu^+ e^- \rightarrow \tau^+ \mu^-$	μ TRISTAN
T=2	$\mu^+ \mu^- \rightarrow \mu^+ \mu^-$	$\mu^+ \mu^-$
T=3	$\mu^+ e^- \rightarrow \mu^+ e^-$	μ TRISTAN
T=3	$\mu^+ e^+ \rightarrow \tau^+ \tau^+$	-

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

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



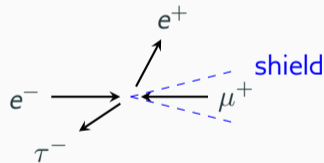
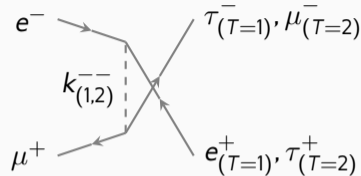
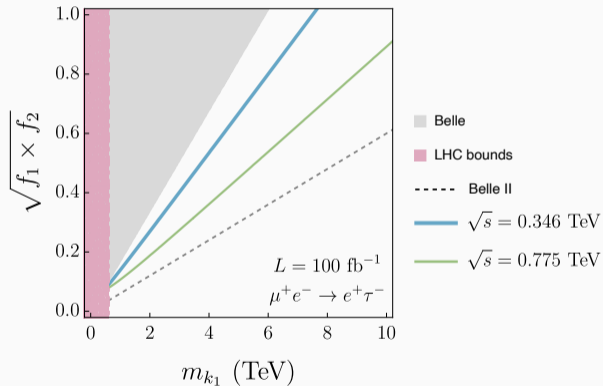
90% C.L. contour
 assuming no background
 $N = 2.44$;

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

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

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

CLFV u-channel at $\mu^+ e^-$



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

Summary Table

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

Next-to-leading order Constraints

G.L. Schmidt, Valencia, Volkas (2023) 2312.09409

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

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

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

$$Z \rightarrow l^+ l^-, \text{ with } l = e, \mu, \tau$$

$$H \rightarrow \gamma\gamma$$

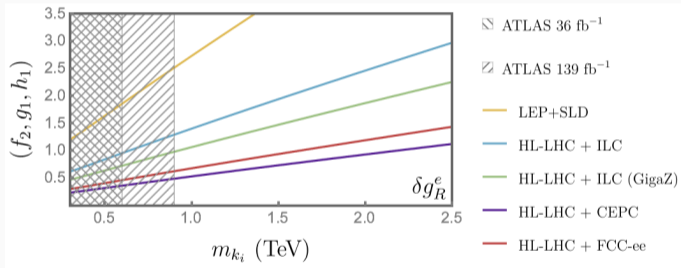
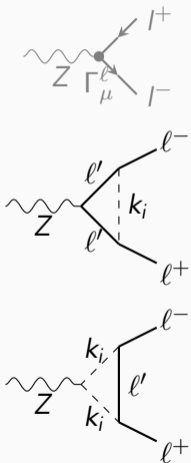
$$H \rightarrow Z\gamma$$

The relevant non-Yukawa interaction terms in the potential are:

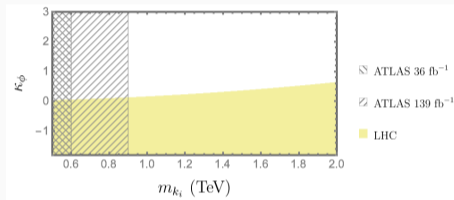
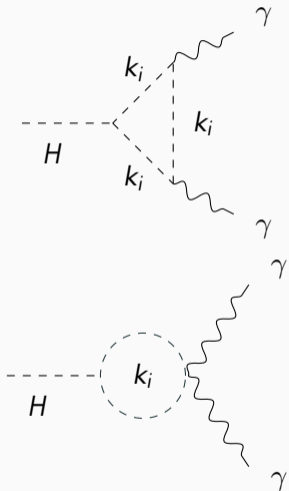
$$\mathcal{L} \supset |D_\mu k_i|^2 - m_{k_i}^2 k_i^\dagger k_i - \frac{\lambda_k}{2} (k_i^\dagger k_i)^2 - \kappa_\phi \left(\phi^\dagger \phi - \frac{v^2}{2} \right) k_i^\dagger k_i - \frac{\lambda}{2} \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2$$

where $D_\mu = \partial_\mu + i2e(A_\mu - \tan \theta_W Z_\mu)$

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



$$H \rightarrow \gamma\gamma$$

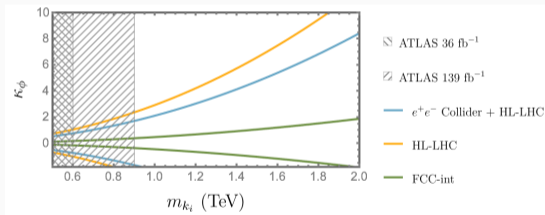


$$R_{\gamma\gamma} = \frac{\Gamma(H \rightarrow \gamma\gamma)}{\Gamma(H \rightarrow \gamma\gamma)_{SM}}$$

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

(ATLAS arXiv:2207.00092 [hep-ex])

$$H \rightarrow \gamma\gamma$$



Future Collider projected sensitivity

$$R_{\gamma\gamma} = \kappa_\gamma^2$$

Orange: HL-LHC (6 ab¹ of data)

$$\Delta\kappa_\gamma = 1.8\%$$

Blue: future e⁺e⁻ collider (240 GeV, 5 ab¹ of data) combined with HL-LHC $\Delta\kappa_\gamma = 1.3\%$

Green: the integrated FCC program (ee, eh and hh) $\Delta\kappa_\gamma = 0.29\%$

(Snowmass 2021 arXiv:2209.07510 [hep-ex])

$$H \rightarrow Z\gamma$$

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

$$R_{Z\gamma} = 2.2 \pm 0.7$$

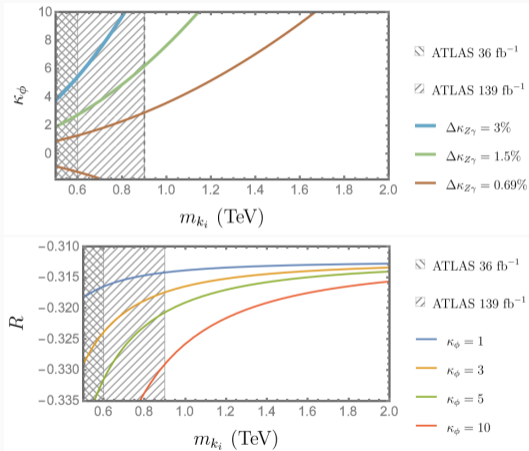
(ATLAS and CMS arXiv:2309.03501 [hep-ex])

$$\Delta\kappa_{Z\gamma} = 9.8\%$$

(Snowmass ATL-PHYS-PUB-2022-018, 2022.)

Compared to $R_{\gamma\gamma}$:

$$R = \frac{R_{Z\gamma} - 1}{R_{\gamma\gamma} - 1}$$



Summary

Lepton Flavour Triality avoids CLFV bounds from muon decays while allowing tau CLFV interactions;

Belle II predictions of tau CLFV decays.

μ TRISTAN

$\mu^+\mu^+$ collider

Resonances searches

μ TRISTAN μ^+e^- collider

Next-to-leading order results from $Z \rightarrow l^+l^-$, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$

Thank you!

Backup slides

Direct Searches of doubly charged scalar with CLFV:

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

Lepton scattering (DELPHI):

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

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

Flavour-violating Z decays:

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

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

anomalous magnetic moment \rightarrow too small.

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

Include 3 RH sterile Neutrinos

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

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

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.

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

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

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

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

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

Present bounds from Belle:

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

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

Prediction for future sensitivity from Belle II:

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

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