DIAS - CATCH22+2

Complementarity of μTRISTAN 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.

$$\begin{cases} \mu \to e\gamma \text{ at MEG,} \\ \mu \to eee \text{ at Mu3e} \\ \mu N \to \mu N \text{ at COMET, Mu2e and DeeMe} \end{cases}$$

CLFV involving τ: the data are less constraining.

Lepton Triality allows CLFV, preferably at the 3^{rd} 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

$e \to T = 1$
$\mu \to T = 2$
$\tau \to T = 3$

$L \to \omega^T L$ and $e_R \to \omega^T e_R$,
$\omega = e^{\frac{2\pi i}{3}}$
H, quarks are singlets under triality
$\mathcal{L}_Y$ is diagonal under Z_3

$\mu^- \to e^- \gamma$ ✗

$T=2$ $T=1$

$\tau^- \to \mu^+ e^- e^-$ sums modulo 3 ✓

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

T = 1, 2, 3 models

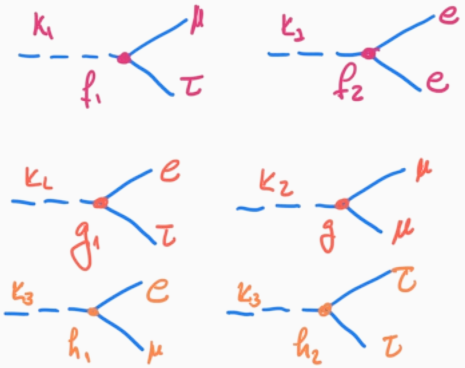
A simplified model with a mediator as doubly charged singlet k_i

$$k_1 \sim \omega,$$
$$k_2 \sim \omega^2,$$
$$k_3 \sim 1,$$

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

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

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



Tau CLFV decays:

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

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

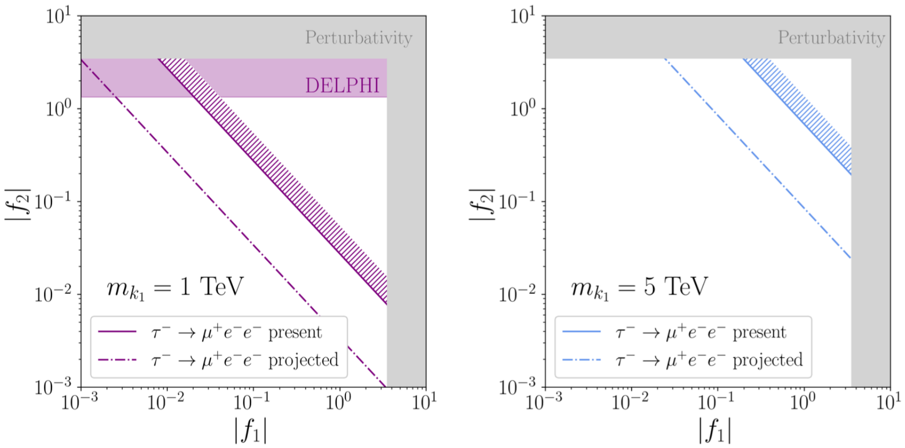
Observable	Present constraint	Projected sensitivity
$BR(\tau^- \to \mu^-\mu^-e^+)$	1.7×10^{-8} *	2.6×10^{-10} **
$BR(\tau^- \to \mu^+e^-e^-)$	1.5×10^{-8} *	2.3×10^{-10} **

*** Belle Collaboration (2010) 1001.3221**

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

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.

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.

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

μ^+ beams up to 1 to 3 TeV;

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

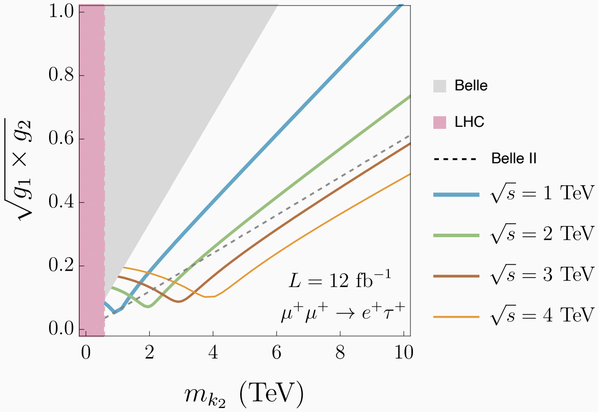
expected luminosity of 100 fb^{-1} per year.

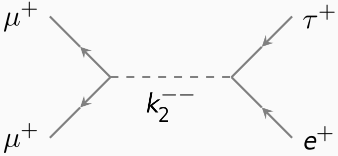
Future lepton Colliders

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





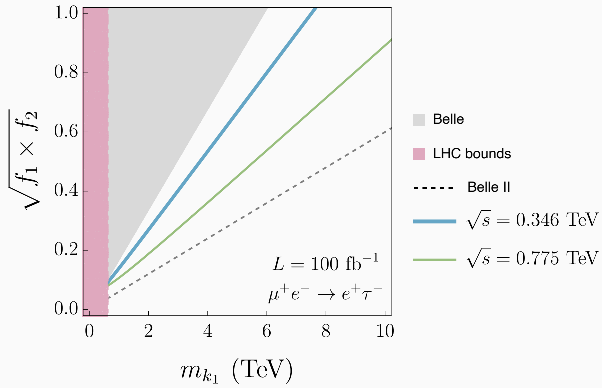
90% C.L. contour
assuming no background
N = 2.44;

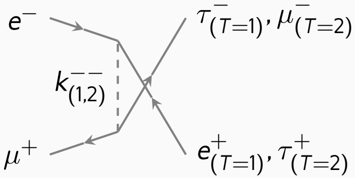
$$\sqrt{g_1 g_2} \lesssim 0.15 \left(\frac{N}{Ls}\right)^{\frac{1}{4}} \frac{m_{k_2}}{\mathrm{TeV}}$$

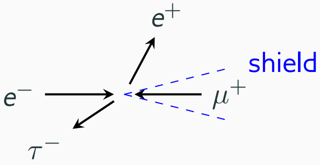
For $\sqrt{s} = 2$ TeV:

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

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







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

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 fb^{-1}
Belle	$\tau^- \to e^+ \mu^- \mu^-$	$\sqrt{g_1 g_2} \lesssim 0.17 \frac{m_{k_2}}{\mathrm{TeV}}$	782 fb^{-1}
Belle II	$\tau^- \to \mu^+ e^- e^-$	$\sqrt{f_1 f_2} \lesssim 0.06 \frac{m_{k_1}}{\mathrm{TeV}}$	50 ab^{-1}
Belle II	$\tau^- \to e^+ \mu^- \mu^-$	$\sqrt{g_1 g_2} \lesssim 0.06 \frac{m_{k_2}}{\mathrm{TeV}}$	50 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 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 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 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 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 fb^{-1}, $(E_e, E_\mu) = (30, 1000)$ GeV

Next-to-leading order Constraints

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

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

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

$H \to \gamma\gamma$

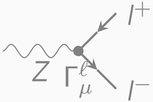
$H \to Z\gamma$

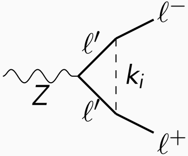
The relevant non-Yukawa interaction terms in the potential are:

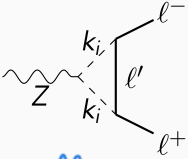
$$\mathcal{L} \supset |D_\mu k_i|^2 - m_{k_i}^2 k_i^\dagger k_i - \frac{\lambda_k}{2}(k_i^\dagger k_i)^2 - \kappa_\phi\left(\phi^\dagger\phi - \frac{v^2}{2}\right)k_i^\dagger k_i - \frac{\lambda}{2}\left(\phi^\dagger\phi - \frac{v^2}{2}\right)^2$$

where $D_\mu = \partial_\mu + i\,2e\,(A_\mu - \tan\theta_W Z_\mu)$

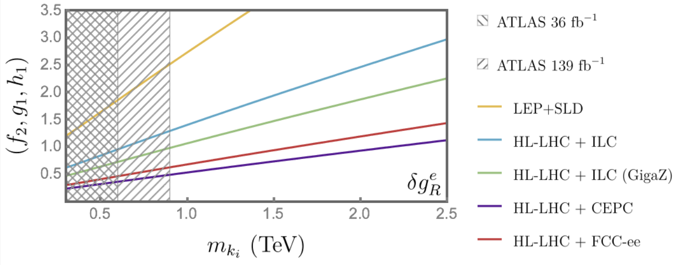
$Z \to l^+ l^-$, with $l = e, \mu, \tau$





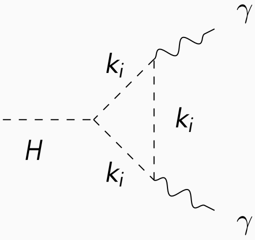


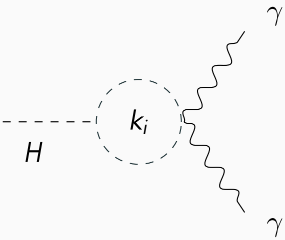
+ self energies

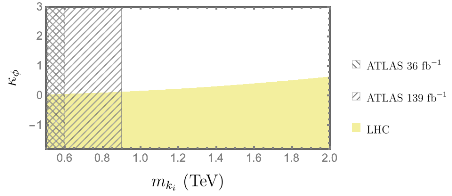


$\boxed{\delta g^{\mu}_R, \ \delta g^{\tau}_R}$

$H \to \gamma\gamma$





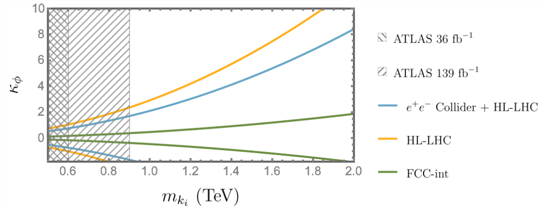


$$R_{\gamma\gamma} = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to \gamma\gamma)_{SM}}$$

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

(ATLAS arXiv:2207.00092 [hep-ex])

$H \to \gamma\gamma$



Future Collider projected sensitivity

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

Orange: HL-LHC (6 ab^1 of data) $\Delta\kappa_\gamma = 1.8\%$

Blue: future e$^+$e collider (240 GeV, 5 ab^1 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])

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

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

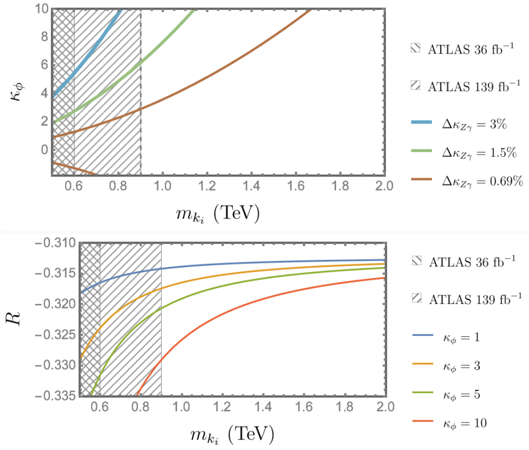
(ATLAS and CMS arXiv:2309.03501 [hep-ex])

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

(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.
- μTRISTAN
  - $\mu^+\mu^+$ collider
  - Resonances searches
  - μTRISTAN μ^+e^- collider
- Next-to-leading order results from $Z \to l^+l^-$, $H \to \gamma\gamma$, $H \to Z\gamma$

Thank you!

Backup slides

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.

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.

SMEFT

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

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

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

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

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

SMEFT

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:

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

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