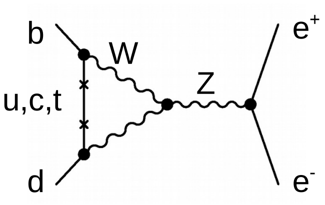
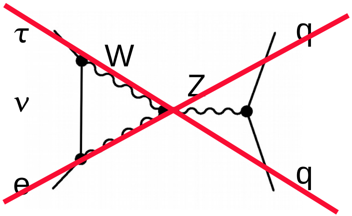
Global Analysis of Lepton Flavor Violating Operators

Emanuele Mereghetti

The 17th International Workshop on Tau Lepton Physics
December 8^{th}, 2023, Louisville.

Charged lepton flavor violation

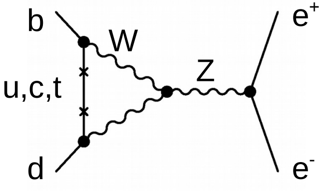


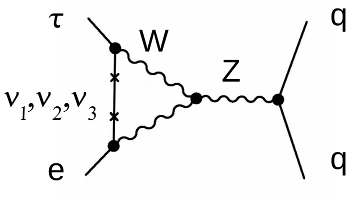


- mismatch between quark weak and mass eigenstates $\Longrightarrow$ quark family number is not conserved
  ✓ visible in several rare $\Delta F = 1$ and $\Delta F = 2$ processes
- in minimal SM with massless neutrinos, no such mismatch

lepton family (LF) is exactly conserved

Charged lepton flavor violation





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  ✓ visible in several rare $\Delta F = 1$ and $\Delta F = 2$ processes
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lepton family (LF) is exactly conserved

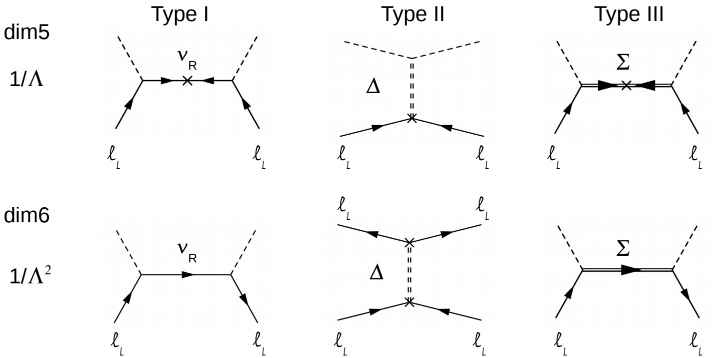
but neutrino have masses!

- LF is broken in neutrino sector
- charged LFV highly suppressed by GIM mechanism

$$\mathrm{BR} \sim \left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-44}$$

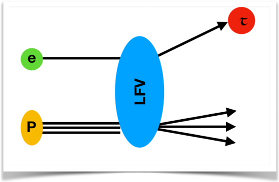
S. Petcov, '77; W. Marciano and A. Sanda, '77

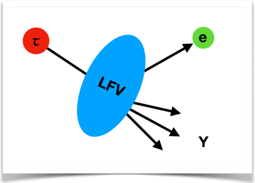
Charged lepton flavor violation

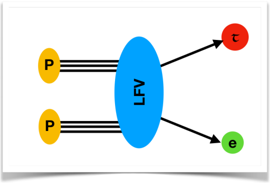


- . . . however, models that explain m_ν usually introduce new CLFV at tree or loop level
- e.g. type I, II and III see-saw A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, T. Hambye, '08
- and a variety of models from leptoquarks, to Z′, to SUSY
- CLFV experiments crucial to falsify TeV origin of m_ν

CLFV at low- and high-energy



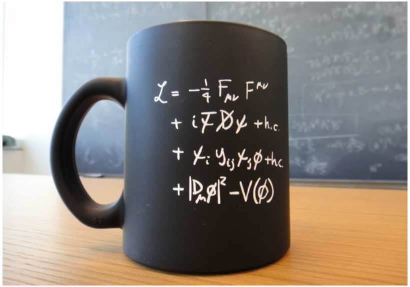




1. μ, τ and meson decays — $\mu \to e\gamma$, $\mu \to 3e$, $\tau \to \ell\gamma$, $\tau \to \ell\pi\pi$, $\tau \to \ell K\pi$, $B \to \pi\tau\ell$, ...
2. *pp* collisions — $pp \to \ell\ell'$, $h \to \ell\ell'$, $t \to q\tau e$ ...
3. *ep* collisions — at HERA and the upcoming EIC

see talks by W. Altmannshofer, M. Ardu, I. Bigaran, J. Heeck, S. Mantry, A. Petrov, ...

The Standard Model Effective Field Theory

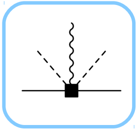


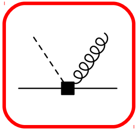
Study CLFV at EIC within EFT framework

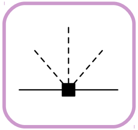
- SM fields, no new light degrees of freedom (but easy to add new particles, e.g. ν_R)
- local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- organize them in a power counting based on canonical dimension

1. no CLFV at dim. 4
2. GIM suppression at dim. 5, BR $\sim (m_\nu / m_W)^4$

SMEFT for CLFV







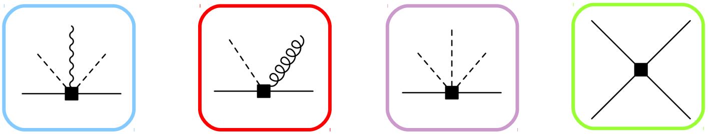
vector/axial currents dipole Yukawa

1. LFV Z couplings, & γ, Z dipole and Yukawa couplings

$$\mathcal{L} = -\frac{g}{2c_w} Z_\mu \left[\left(c^{(1)}_{L\varphi} + c^{(1)}_{L\varphi} \right)_{\tau e} \bar{\tau}_L \gamma^\mu e_L + c_{e\varphi} \bar{\tau}_R \gamma^\mu e_R \right] - \frac{e}{2v} \left[\Gamma^e_\gamma \right]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R F_{\mu\nu} - \left[Y'_e \right]_{\tau e} h \bar{\tau}_L e_R + \text{h.c.}$$

$$C = \mathcal{O}\left(\frac{v^2}{\Lambda^2} \right)$$

SMEFT for CLFV



vector/axial currents | dipole | Yukawa | four-fermion

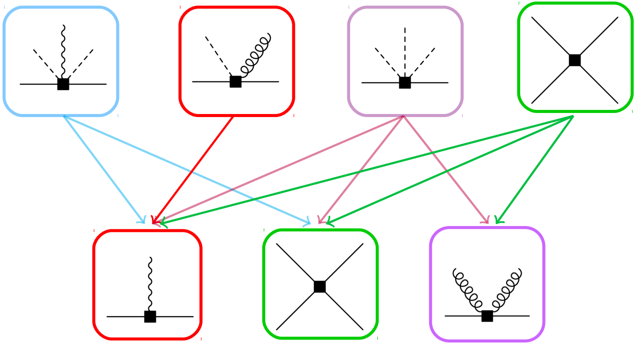
1. LFV Z couplings, & γ, Z dipole and Yukawa couplings
2. leptonic and semileptonic interactions

   7 Vector/Axial: $C^{(1,3)}_{L,Q}$, C_{eu}, C_{ed}, C_{Lu}, C_{Ld}, C_{Qe}
   3 Scalar/Tensor: C_{LedQ}, $C^{(1,3)}_{LeQu}$
   3 purely leptonic: C_{LL}, C_{ee}, C_{Le}

- assume generic quark flavor structures (>120 indep. $\tau \leftrightarrow e$ couplings)

$$[C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

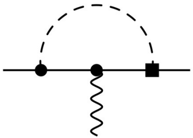
Connecting observables at different scales

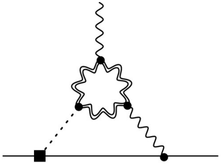


- for μ and τ decays, $\mu \to e$ conversion, integrate heavy particles out
- end up with dipole, leptonic and semileptonic ops. with u, d and s quarks, gluonic ops.

$$\mathcal{L} = -\frac{e}{2v}\bar{e}_L^p \left[\Gamma\right]_{pr} \sigma^{\mu\nu} e_R^r F_{\mu\nu} - \frac{4G_F}{\sqrt{2}} L^{\Gamma}_{prst} \bar{e}^p \Gamma e^r \; \bar{e}^s \Gamma e^t - \frac{4G_F}{\sqrt{2}} C^{\Gamma}_{prst} \bar{e}^p \Gamma e^r \; \bar{q}^s \Gamma q^t + \frac{\alpha_s}{4\pi v^3} GG \bar{e}^p \left[C_{GG}\right]_{pr} e^r + \dots$$

Connecting observables at different scales

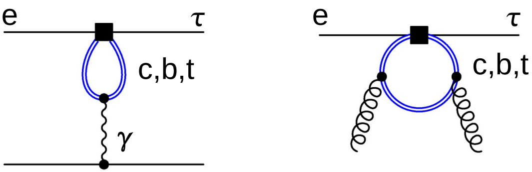




- Z couplings, photon dipoles and light-quark 4-fermion operators $\Longrightarrow$ tree level matching ✓
- Z dipole & Higgs coupling run and match onto γ dipole at one or two loops ✓

$$\left[\Gamma_\gamma^e\right]_{\tau e}(\mu = 2\,\mathrm{GeV}) = \left(\left[\Gamma_\gamma^e\right]_{\tau e} - 2.0 \cdot 10^{-2}\,[\Gamma_Z^e]_{\tau e} - 6.0 \cdot 10^{-5}\,(Y')_{\tau e} \right)(\mu = 1\,\mathrm{TeV}).$$

Connecting observables at different scales



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- vector/axial t operators, vector b and c operators run into light quark ops. via penguins ✓

$$C^{eu}_{\mathrm{VLV}}(\mu = 2\,\mathrm{GeV}) = \left(-10[C_{LQ,U} - C_{Lu}]_{tt} - 2.0[C_{LQ,U} + C_{Lu}]_{tt} + 3.0[C_{LQ,D} + C_{Ld}]_{bb} - 6.8[C_{LQ,U} + C_{Lu}]_{cc}\right) \cdot 10^{-3}$$

$$C^{eu}_{\mathrm{VLA}}(\mu = 2\,\mathrm{GeV}) = \left(-27[C_{LQ,U} - C_{Lu}]_{tt}\right) \cdot 10^{-3}$$

× very suppressed contribs. from axial b and c ops

- scalar/tensor operators run into dipole and match onto dim-7 glue ops.

Constraints on $\tau \to e$ transitions

τ and B CLFV decays

Decay mode	V					A					S					P					T	
	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	u	c
$\tau \to e\gamma$																					✓ (loop)	✓ (loop)
$\tau \to e\ell^+\ell^-$				✓ (loop)	✓ (loop)																	
$\tau \to e\pi^0$							✓															
$\tau \to e\eta, \eta'$						✓		✓								✓		✓	✓ (loop)	✓ (loop)		
$\tau \to e\pi^+\pi^-$		✓		✓ (loop)	✓ (loop)						✓		✓	✓ (loop)	✓ (loop)						✓	
$\tau \to eK^+K^-$	✓	✓	✓	✓ (loop)	✓ (loop)						✓		✓	✓ (loop)	✓ (loop)						✓	
	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	cu	
$\tau \to eK_S^0$						✓										✓						
$\tau^- \to e^-K\pi$	✓										✓											
$B^0 \to e\tau$							✓										✓					
$B^+ \to \pi^+e\tau$		✓										✓										
$B^+ \to K^+e\tau$			✓										✓									

✓ = tree ✓ (loop) = loop

- τ branching ratios in the $\sim 10^{-7}$-10^{-8} range
- non-perturbative input mostly under control (some model dep. in K^+K^-)

A. Celis, V. Cirigliano, E. Passemar, '14, V. Cirigliano, A. Crivellin, M. Hoferichter, '18
E. Passemar *private comm.*, K. Beloborodov, V. Druzhinin, S. Serednyakov, '19

- B branching ratios $\sim 10^{-5}$
- f_B, $f_{+,0}(B \to \pi, K)$ well determined from LQCD

τ and B CLFV decays

Decay mode	V					A					S					P					T	
	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	u	c
$\tau \to e\gamma$																					✓ (loop)	✓ (loop)
$\tau \to e\ell^+\ell^-$				✓ (loop)	✓ (loop)																	
$\tau \to e\pi^0$							✓										✓					
$\tau \to e\eta, \eta'$						✓		✓								✓		✓	✓ (loop)	✓ (loop)		
$\tau \to e\pi^+\pi^-$		✓		✓ (loop)	✓ (loop)						✓		✓	✓ (loop)	✓ (loop)						✓	
$\tau \to eK^+K^-$	✓	✓	✓	✓ (loop)	✓ (loop)						✓		✓	✓ (loop)	✓ (loop)						✓	
	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	cu	
$\tau \to eK_S^0$						✓										✓						
$\tau^- \to e^- K\pi$	✓										✓											
$B^0 \to e\tau$							✓										✓					
$B^+ \to \pi^+ e\tau$		✓										✓										
$B^+ \to K^+ e\tau$			✓										✓									

✓ = tree ✓ = loop

1. uu, dd, ss components of all Dirac structures well constrained by multiple channels

- V isoscalar $uu + dd$ gives small and uncertain contrib. to $\tau \to eKK$

τ and B CLFV decays

Decay mode	V					A					S					P					T	
	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	u	c
$\tau \to e\gamma$																					✓ (loop)	✓ (loop)
$\tau \to e\ell^+\ell^-$				✓ (loop)	✓ (loop)				✗	✗												
$\tau \to e\pi^0$							✓		✗	✗							✓					
$\tau \to e\eta, \eta'$						✓		✓	✗	✗						✓		✓	✓ (loop)	✓ (loop)		
$\tau \to e\pi^+\pi^-$		✓		✓ (loop)	✓ (loop)				✗	✗	✓		✓	✓ (loop)	✓ (loop)						✓	
$\tau \to eK^+K^-$	✓	✓	✓	✓ (loop)	✓ (loop)				✗	✗	✓		✓	✓ (loop)	✓ (loop)						✓	
	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	cu	
$\tau \to eK_S^0$						✓										✓						
$\tau^- \to e^-K\pi$	✓										✓											
$B^0 \to e\tau$							✓										✓					
$B^+ \to \pi^+ e\tau$		✓										✓										
$B^+ \to K^+ e\tau$			✓										✓									

✓ = tree ✓ (loop) = loop

2. bb, cc vectors run into light quark V via penguins

- bb, cc S, P match onto dim 7 gluonic operators
- no constraints on axial cc or bb components

need $\eta_c \to e\tau$, $\eta_b \to e\tau$!

τ and B CLFV decays

Decay mode	V					A					S					P					T	
	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	u	c
$\tau \to e\gamma$																					(✓)	(✓)
$\tau \to e\ell^+\ell^-$				(✓)	(✓)				×	×												
$\tau \to e\pi^0$							✓		×	×							✓					
$\tau \to e\eta, \eta'$						✓		✓	×	×						✓		✓	(✓)	(✓)		
$\tau \to e\pi^+\pi^-$		✓		(✓)	(✓)				×	×	✓		✓	(✓)	(✓)						✓	
$\tau \to eK^+K^-$	✓	✓	✓	(✓)	(✓)				×	×	✓		✓	(✓)	(✓)						✓	
	ds	db	sb	cu		ds	db	sb	cu		ds	db	sb	cu		ds	db	sb	cu		cu	
$\tau \to eK_S^0$						✓										✓						
$\tau^- \to e^- K\pi$	✓										✓											
$B^0 \to e\tau$							✓										✓					
$B^+ \to \pi^+ e\tau$		✓										✓										
$B^+ \to K^+ e\tau$			✓										✓									

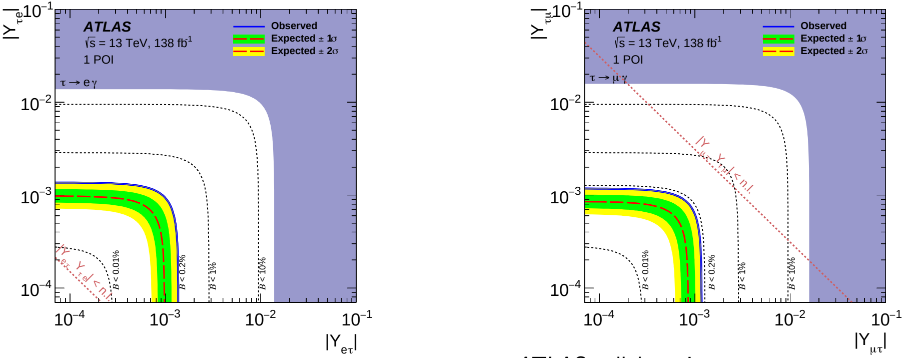
✓ = tree (✓) = loop

3. strong constraints on ds, sd from $\tau \to eK$, $\tau \to eK\pi$

- and on vector/scalar bd, bs ($B \to P\tau e$) and axial/pseudoscalar bd ($B \to \tau e$) components
- no constraints on cu, axial and pseudoscalar sb, bs,

$B_s \to e\tau$ at Belle II and LHCb
$D \to e\tau$ at LHCb and BESIII

Z, Higgs and top decays



ATLAS collaboration, `arXiv:2302.05225`

- $Z \to \tau e$ studied at LEP and LHC, LHC giving strongest bounds

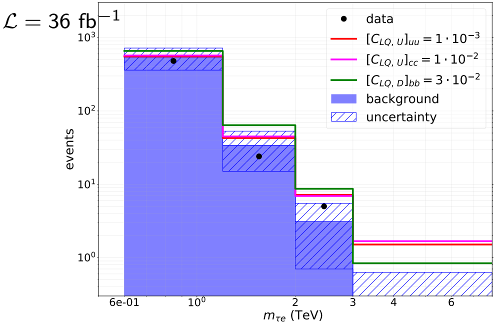
$$\mathrm{BR}(Z \to e\tau) < 5.0 \cdot 10^{-6} \implies \left| c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)} \right| < 7.8 \cdot 10^{-3}$$

- limit on $H \to \tau e$ from LHC

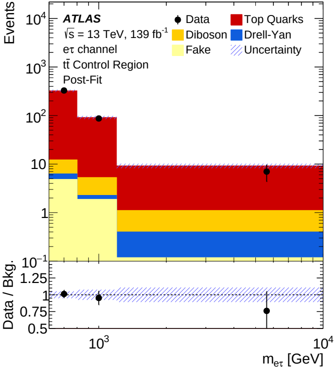
$$\mathrm{BR}(H_0 \to e\tau) < 2.0 \cdot 10^{-3} \implies \left| Y'_{e\tau,\,\tau e} \right| < 1.3 \cdot 10^{-3}$$

- ATLAS looked for $t \to q\ell\ell'$, $C \sim 0.1$ bounds

High invariant mass CLFV Drell-Yan



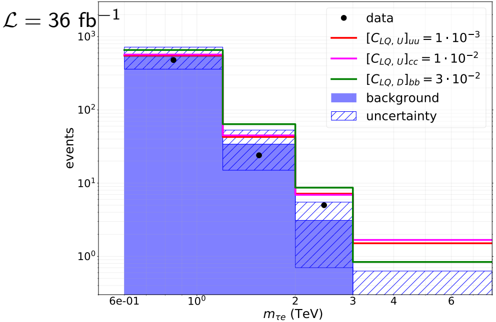
ATLAS `arXiv:1807.06573`



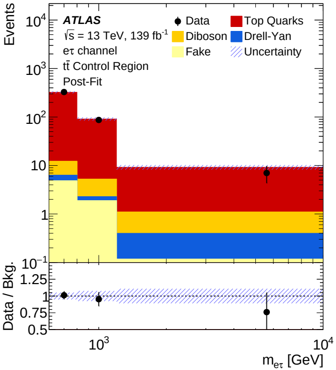
ATLAS `arXiv:2307.08567`

- ATLAS published $pp \to \tau e$ results, with hadronic τ, framed as Z' searches
  6 invariant mass bins from 100 GeV to 3 TeV, compatible with background only
- if $\Lambda \gtrsim 3 - 4$ TeV, can be reframed as constraints on four-fermion operators as at low-energy
- simulate SMEFT operators at NLO in QCD, with `POWHEG` + `Pythia8` + `Delphes`

High invariant mass CLFV Drell-Yan



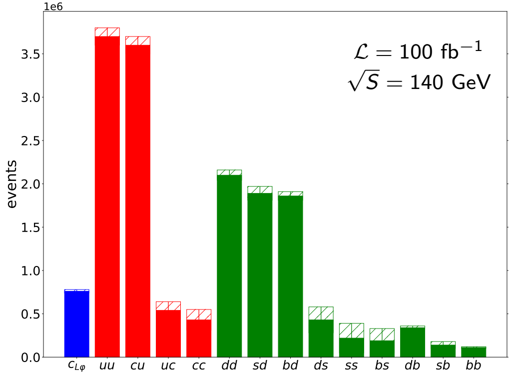
ATLAS arXiv:1807.06573

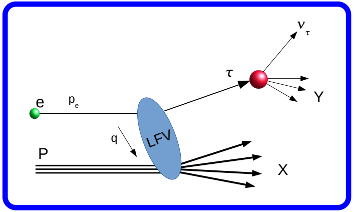


ATLAS arXiv:2307.08567

- no SM background at large $m_{\tau e}$,
- signal from four-fermion enhanced at large $m_{\tau e}$, indep. of Lorentz structure
- $C_{\tau e q_i q_j} \lesssim 10^{-3}$ for valence quarks, $\lesssim 3 \cdot 10^{-2}$ for b quarks
- new '23 ATLAS and CMS analysis with full luminosity and better backgrounds

CLFV Deep Inelastic Scattering





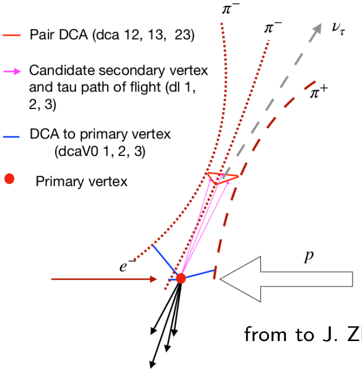
Left handed τ_L, e_L

Left handed u_L, d_L

`NNPDF31_lo_as_0118`

- most cross sections in the 1-10 pb range, for $\Lambda = v$,
- heavy flavors c, b suppressed by factor ten
- large PDF uncertainties for heavy-flavor-initiated processes (NLO QCD corrections will be important)

τ at the EIC



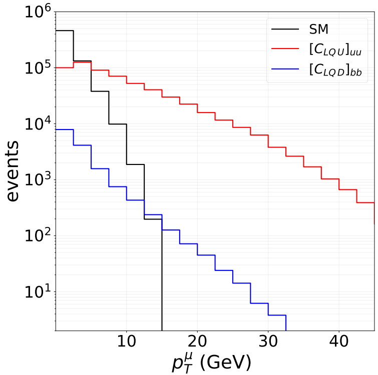
from to J. Zhang

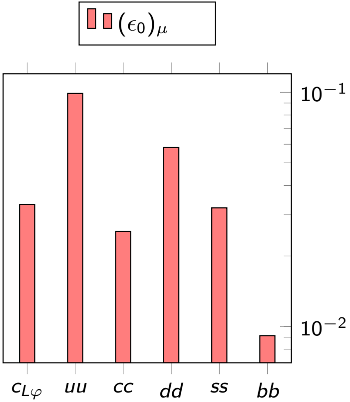
1. $ep \to \tau X \to e + \not{E} + X$
2. $ep \to \tau X \to \mu + \not{E} + X$
3. $ep \to \tau X \to X_h + \not{E} + X$

- (substantial) background from standard NC and CC DIS
- simulate SM & SMEFT events with `Pythia8` + `Delphes` for EIC

thanks to Miguel Arratia (UCR)!

Muon channel





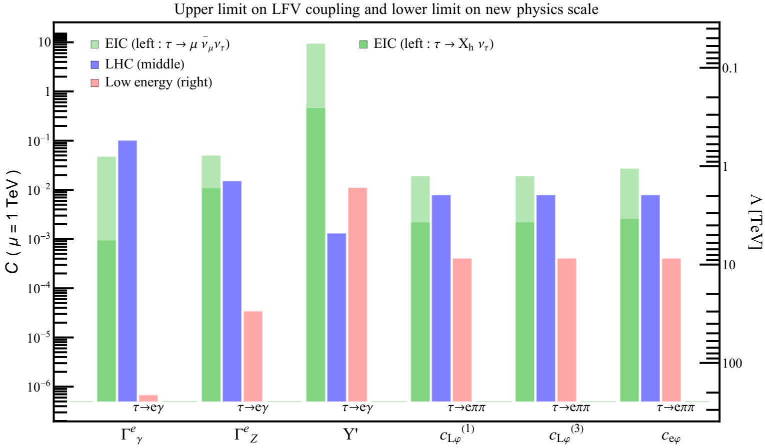
- μ and hadronic channels are the most promising

see S. Mantry's talk

- in SM, μ come from hadron decays, typically at small p_T
- moderate cuts on muon and jet p_T eliminate all SM background
- smaller signal efficiency for Z couplings, heavy quarks

A global look to τ CLFV

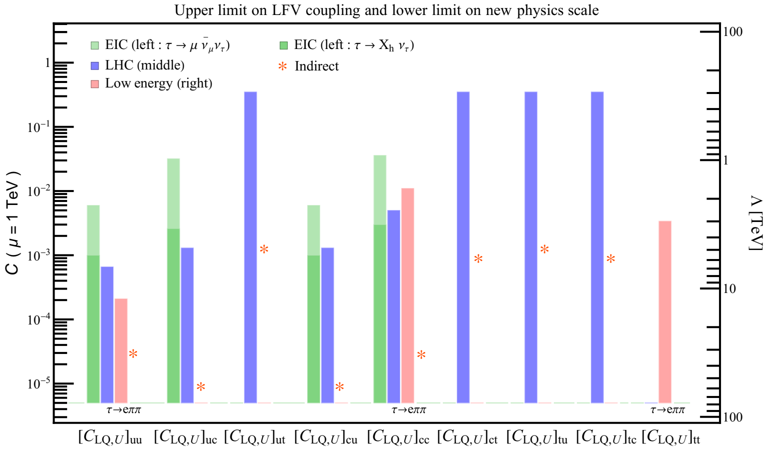
A global look to $\tau \leftrightarrow e$ transitions: dipole, Yukawa and Z



V. Cirigliano, **K. Fuyuto** , C. Lee, EM, **B. Yan**, '21

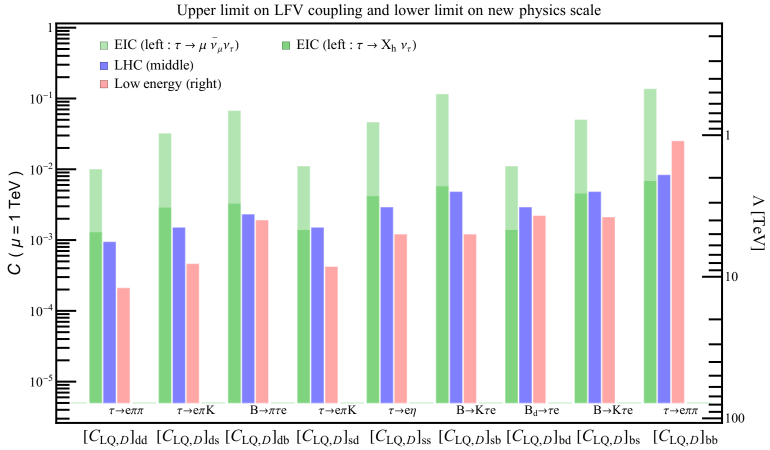
- γ and Z overwhelming constrained by $\tau \to e\gamma$
- strong direct LHC bound on Y'
- $\tau \to e\pi\pi$ dominates Z couplings

A global look to $\tau \leftrightarrow e$ transitions: four-fermion operators



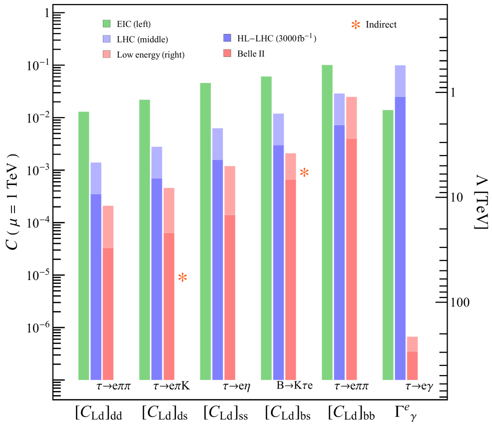
- uu $\tau \to e\pi\pi$ stronger by ~ 3, LHC and EIC competitive with $\tau \to e\pi$
- cc low-energy loop suppressed, LHC and EIC can do better
- tt surprisingly strong constraints from τ decays
- colliders are only probes of u-type off-diagonal

A global look to $\tau \leftrightarrow e$ transitions: four-fermion operators



- LHC/EIC very competitive on *bb* component
- and with *B* decays
- similar conclusions for scalar/tensor operators

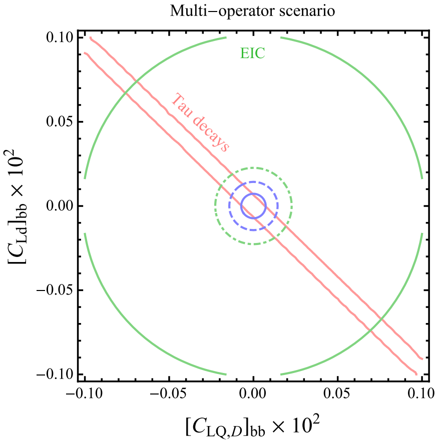
$\tau \leftrightarrow e$ transitions: future projections



thanks to K. Fuyuto
arXiv:2203.14919

- Belle-II will push CLFV scale to $\Lambda \gtrsim 30$ TeV ($\tau \to e\pi\pi$) or $\Lambda \gtrsim 300$ TeV ($\tau \to e\gamma$)
- colliders will play an important role in heavy flavor & multi-coupling scenarios

Towards a global fit

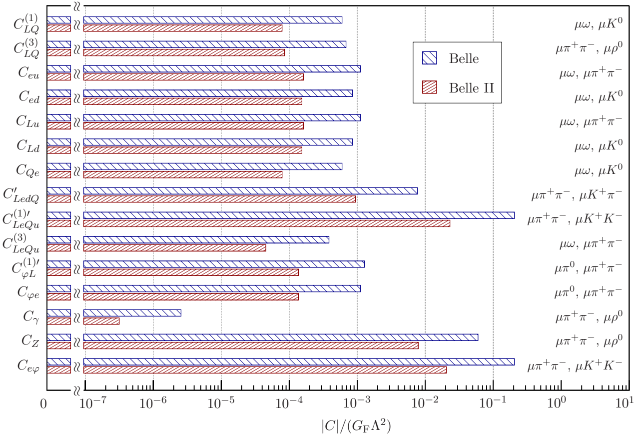


$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, [C_{LQ\,D}]_{bb})$$

$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, [C_{Ld}]_{bb})$$

- turn on all V/A couplings to L leptons & d-type quarks
- contributions to hadronic τ decays cancel for $[C_{Ld}]_{bb} \sim -[C_{LQ\,D}]_{bb}$
- $\tau \to e\ell^+\ell^-$ weaker than current LHC and project EIC
- need collider or η_b decays

$\tau \leftrightarrow \mu$ transitions



T. Husek, K. Monsalvez-Pozo, J. Portoles '20
and in `arXiv:2203.14919`

- very similar discussion for $\mu \to \tau$ transitions
- abundance of flavor-conserving and flavor-changing channels $\Longrightarrow$ strong constraints on light-quark operators

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- heavy flavors and interplay with LHC to be studied

Conclusion

- CLFV can unveil/constrain mechanisms of neutrino mass generation
- B factories, LHC and future *e*-*p* colliders are complementary
  especially for heavy flavors and in multiple-coupling scenarios

To do:

- improve EIC calculations and simulations,
  detailed study of heavy quark channels, improve efficiency with *b* tagging, study $e \leftrightarrow \mu$ transitions, ...
- recast ATLAS and CMS analyses in SMEFT language (alongside to benchmark models)
- perform a real global fit & identify unconstrained direction in $e \leftrightarrow \mu$, $e \leftrightarrow \tau$ and $\mu \leftrightarrow \tau$ interactions
- extend SMEFT studies to include light sterile neutrinos