Los Alamos NATIONAL LABORATORY

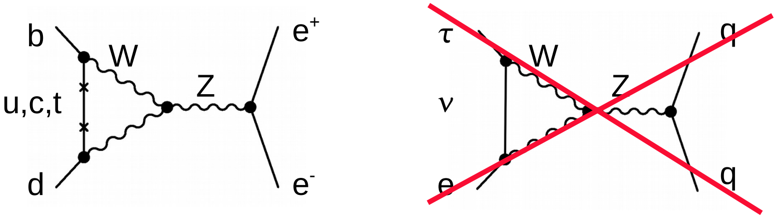
CLFV at the EIC and LHC vs low-energy

Emanuele Mereghetti

Electroweak and Beyond the Standard Model Physics at the EIC
February 14^{th}, 2024, Seattle.

with K. Fuyuto, V. Cirigliano, C. Lee, B. Yan, S. Gonzalez-Solis, F. Delzanno

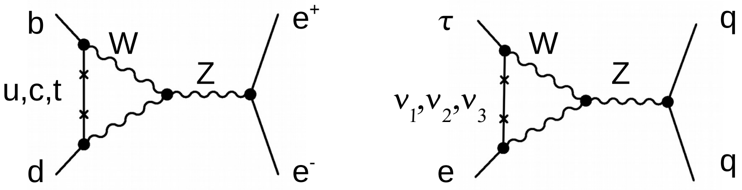
Charged lepton flavor violation



- 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



- mismatch between quark weak and mass eigenstates $\Longrightarrow$ quark family number is not conserved
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- in minimal SM with massless neutrinos, no such mismatch

lepton family (LF) is exactly conserved

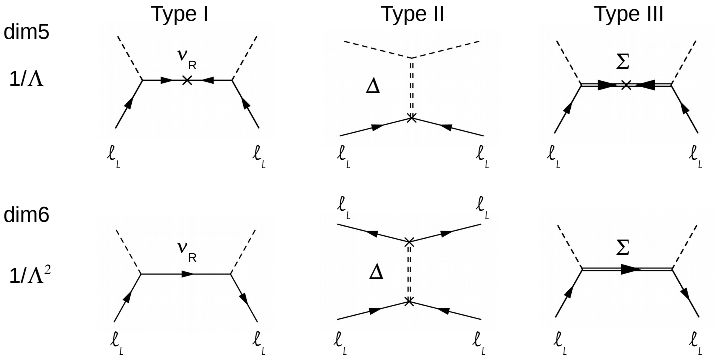
but neutrino have masses!

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

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

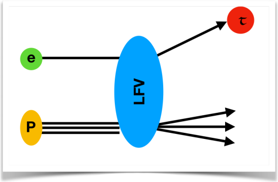
S. Petcov, '77; W. Marciano and A. Sanda, '77

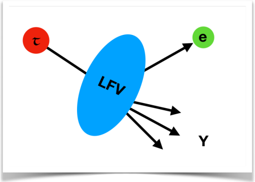
Charged lepton flavor violation

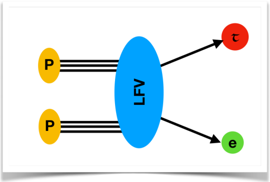


- ... however, models that explain m_ν usually introduce new CLFV at tree or loop level
- e.g. type I, II and III see-saw A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, T. Hambye, '08
- and a variety of models from leptoquarks, to Z′, to SUSY
- CLFV experiments crucial to falsify TeV origin of m_ν

CLFV at low- and high-energy



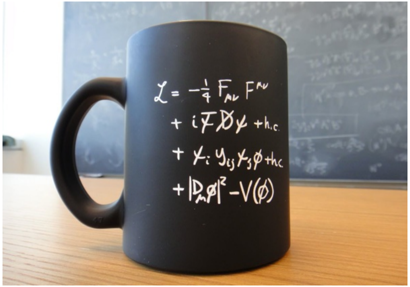




1. μ, τ and meson decays — $\mu \to e\gamma$, $\mu \to 3e$, $\tau \to \ell\gamma$, $\tau \to \ell\pi\pi$, $\tau \to \ell K\pi$, $B \to \pi\tau\ell$, ...
2. pp collisions — $pp \to \ell\ell'$, $h \to \ell\ell'$, $t \to q\tau e$ ...
3. ep collisions — at HERA and the upcoming EIC

M. Gonderinger and M. R. Musolf, '10; HERA collaboration, '11; T. Husek, K. Monsalvez-Pozo, J. Portoles, '20, ...

The Standard Model Effective Field Theory

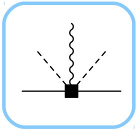


Study CLFV at EIC within EFT framework

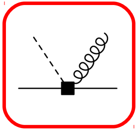
- SM fields, no new light degrees of freedom (but easy to add new particles, e.g. ν_R)
- local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- organize them in a power counting based on canonical dimension

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

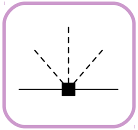
SMEFT for CLFV



vector/axial currents



dipole

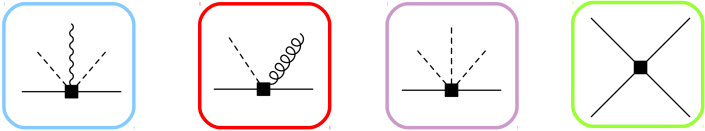


Yukawa

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

$$\begin{aligned}\mathcal{L} &= -\frac{g}{2c_w} Z_\mu \left[\left(c_{L\varphi}^{(1)} + c_{L\varphi}^{(1)} \right)_{\tau e} \bar{\tau}_L \gamma^\mu e_L + c_{e\varphi} \bar{\tau}_R \gamma^\mu e_R \right] - \frac{e}{2v} \left[\Gamma_\gamma^e \right]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R \, F_{\mu\nu} - \left[Y_e' \right]_{\tau e} h \bar{\tau}_L e_R + \text{h.c.} \\ C &= \mathcal{O}\left(\frac{v^2}{\Lambda^2} \right)\end{aligned}$$

SMEFT for CLFV



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

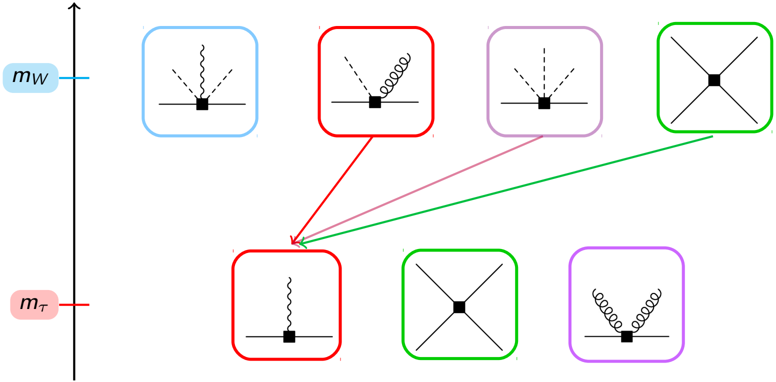
1. LFV Z couplings, & γ, Z dipole and Yukawa couplings
2. leptonic and semileptonic interactions

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

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

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

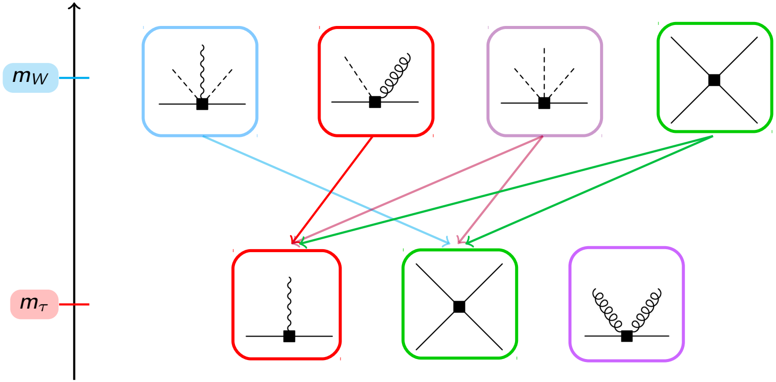
Connecting observables at different scales



- for μ and τ decays, $\mu \to e$ conversion, integrate heavy particles out
- end up with γ dipole operator

$$\mathcal{L} = -\frac{e}{2v}\bar{e}_L^p \left[\Gamma\right]_{pr} \sigma^{\mu\nu} e_R^r F_{\mu\nu}$$

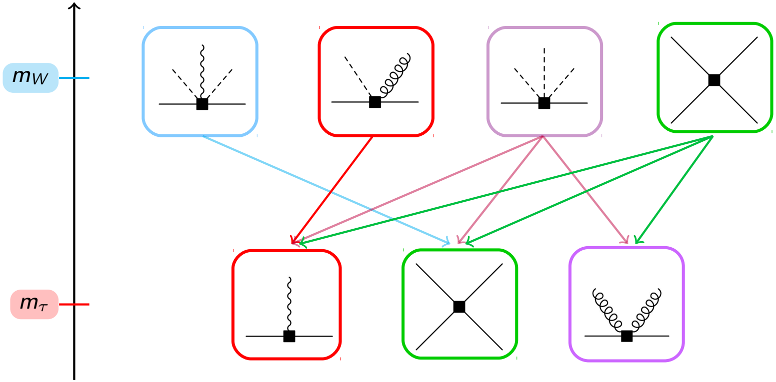
Connecting observables at different scales



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

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} L^{\Gamma}_{prst} \bar{e}^p \Gamma e^r \; \bar{e}^s \Gamma e^t - \frac{4G_F}{\sqrt{2}} C^{\Gamma}_{prst} \bar{e}^p \Gamma e^r \; \bar{q}^s \Gamma q^t$$

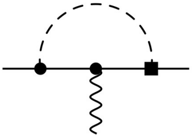
Connecting observables at different scales

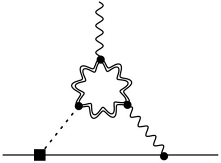


- for μ and τ decays, $\mu \to e$ conversion, integrate heavy particles out
- and gluonic operators

$$\mathcal{L} = \frac{\alpha_s}{4\pi v^3} GG \bar{e}^p \left[C_{GG}\right]_{pr} e^r + \dots$$

Connecting observables at different scales (running is important)



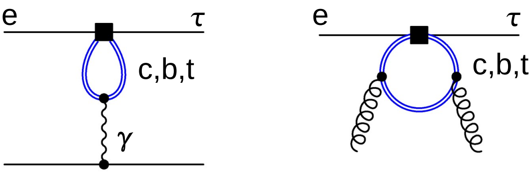


Lepton bilinears

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

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

Connecting observables at different scales (running is important)



Semileptonic operators

- light-quark 4-fermion operators $\Longrightarrow$ tree level matching ✓
- 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.

$$\Gamma^e_\gamma(\mu = 2\,\mathrm{GeV}) = -0.46\left[C^{(3)}_{LeQu}\right]_{tt} + 6.5\cdot 10^{-4}\left[C^{(1)}_{LeQu}\right]_{tt} - 2.0\cdot 10^{-3}\left[C^{(3)}_{LeQu}\right]_{cc} + 2.9\cdot 10^{-6}\left[C^{(1)}_{LeQu}\right]_{cc}$$

Constraints on $\tau \rightarrow e$ 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)						✓	
$J/\psi \to \tau e$				✓																		✓
$\Upsilon \to \tau e$					✓																	
	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

- 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)																	
$\tau \to e\pi^0$							✓ (tree)										✓ (tree)					
$\tau \to e\eta, \eta'$						✓ (tree)		✓ (tree)								✓ (tree)		✓ (tree)	✓ (loop)	✓ (loop)		
$\tau \to e\pi^+\pi^-$		✓ (tree)		✓ (loop)	✓ (loop)						✓ (tree)		✓ (tree)	✓ (loop)	✓ (loop)						✓ (tree)	
$\tau \to eK^+K^-$	✓ (tree)	✓ (tree)	✓ (tree)	✓ (loop)	✓ (loop)						✓ (tree)		✓ (tree)	✓ (loop)	✓ (loop)						✓ (tree)	
$J/\psi \to \tau e$				✓ (tree)																		✓ (tree)
$\Upsilon \to \tau e$					✓ (tree)																	
	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	cu	
$\tau \to eK_S^0$						✓ (tree)										✓ (tree)						
$\tau^- \to e^- K\pi$	✓ (tree)										✓ (tree)											
$B^0 \to e\tau$							✓ (tree)										✓ (tree)					
$B^+ \to \pi^+ e\tau$		✓ (tree)										✓ (tree)										
$B^+ \to K^+ e\tau$			✓ (tree)										✓ (tree)									

✓ = 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)						✓	
$J/\psi \to \tau e$				✓					×	×												✓
$\Upsilon \to \tau e$					✓				×	×												
	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	cu	
$\tau \to eK^0_S$						✓										✓						
$\tau^- \to e^- K\pi$	✓										✓											
$B^0 \to e\tau$							✓										✓					
$B^+ \to \pi^+ e\tau$		✓										✓										
$B^+ \to K^+ e\tau$			✓										✓									

✓ = 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 $q^{(0)}$	V $q^{(1)}$	V s	V c	V b	A $q^{(0)}$	A $q^{(1)}$	A s	A c	A b	S $q^{(0)}$	S $q^{(1)}$	S s	S c	S b	P $q^{(0)}$	P $q^{(1)}$	P s	P c	P b	T u	T 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)						✓	
$J/\psi \to \tau e$				✓					✗	✗												✓
$\Upsilon \to \tau e$					✓				✗	✗												

	V ds	V db	V sb	V cu	A ds	A db	A sb	A cu	S ds	S db	S sb	S cu	P ds	P db	P sb	P cu	T cu
$\tau \to eK_S^0$					✓								✓				
$\tau^- \to e^-K\pi$	✓								✓								
$B^0 \to e\tau$						✓								✓			
$B^+ \to \pi^+ e\tau$		✓								✓							
$B^+ \to K^+ e\tau$			✓								✓						

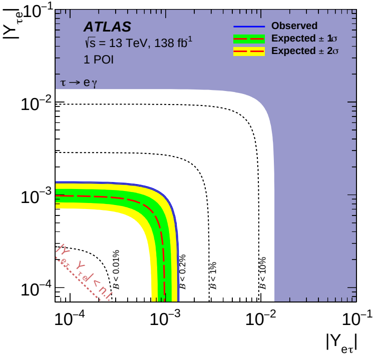
✓ = tree ✓ = loop

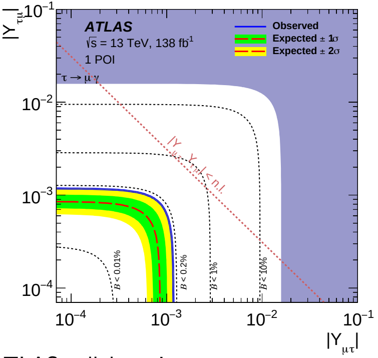
3. strong constraints on ds, sd from $\tau \to eK$, $\tau \to eK\pi$

- 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

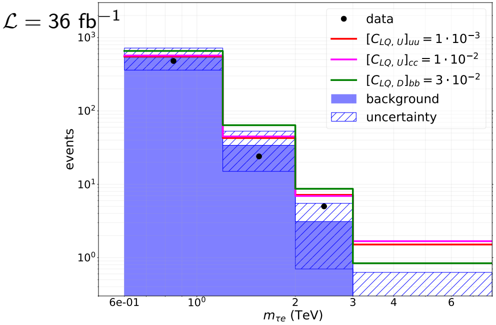
$$\mathrm{BR}(Z \to e\tau) < 5.0 \cdot 10^{-6} \Longrightarrow \left| c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)} \right| < 7.8 \cdot 10^{-3}$$

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

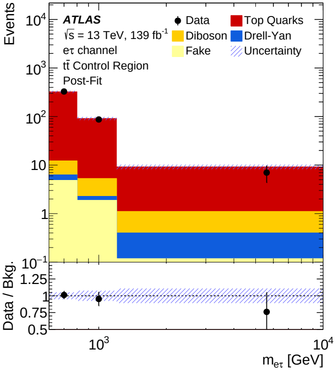
$$\mathrm{BR}(H_0 \to e\tau) < 2.0 \cdot 10^{-3} \Longrightarrow \left| Y'_{e\tau,\,\tau e} \right| < 1.3 \cdot 10^{-3}$$

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

High invariant mass CLFV Drell-Yan



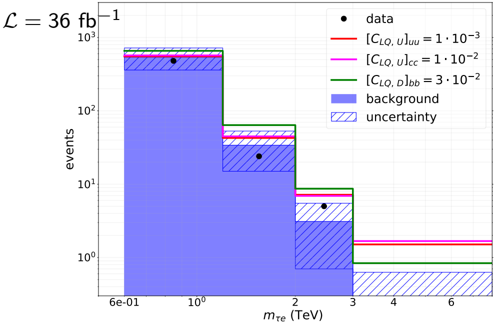
ATLAS arXiv:1807.06573



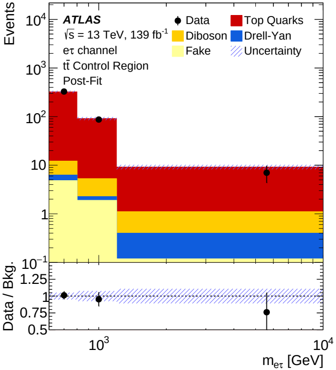
ATLAS arXiv:2307.08567

- 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



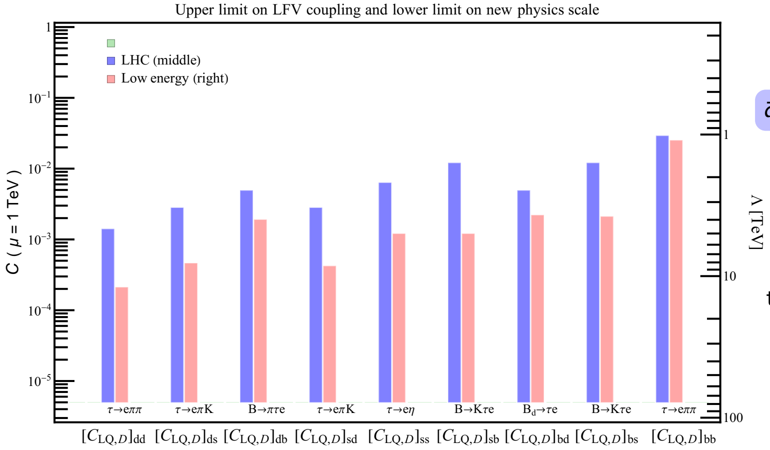
ATLAS arXiv:1807.06573



ATLAS arXiv:2307.08567

- 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 ‘22 and ‘23 ATLAS and CMS analysis with full luminosity and better backgrounds

Summary of existing constraints

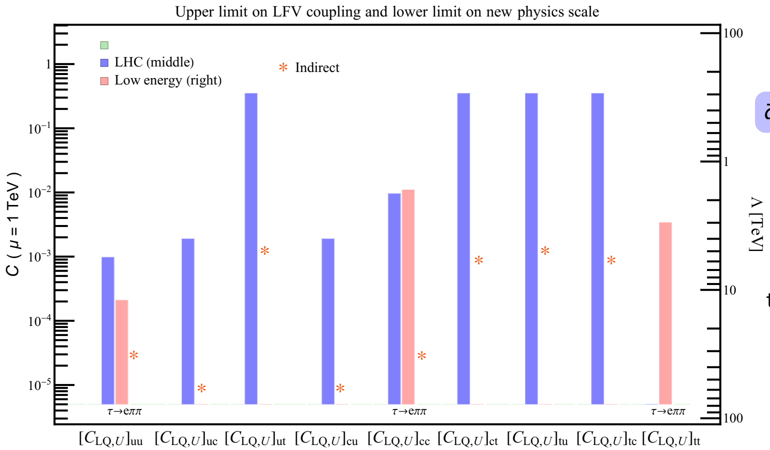


$\bar{q}_L' \gamma^\mu q_L \, \bar{\tau}_L \gamma_\mu e_L$

thanks to K. Fuyuto!

- all channels with *d*-type quarks sector well constrained by low-energy
- LHC in striking distance in *db*, *ss*, and better in *bb* channel

Summary of existing constraints



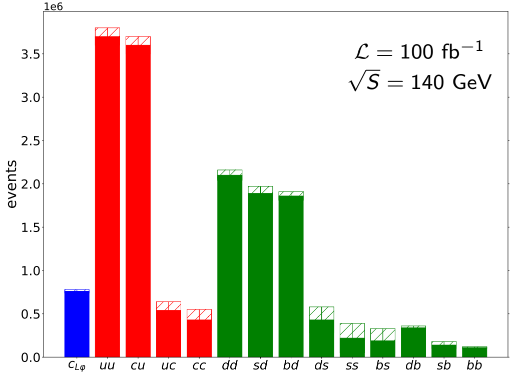
$\bar{q}'_L \gamma^\mu q_L \, \bar{\tau}_L \gamma_\mu e_L$

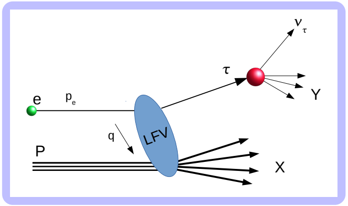
thanks to K. Fuyuto!

- strong constraints on $t\bar{t}$ couplings from $\tau \to e\pi\pi$
- more fragmentary info for u-type FCNC operators
- similar results for other Lorentz structures

CLFV at the EIC

CLFV Deep Inelastic Scattering



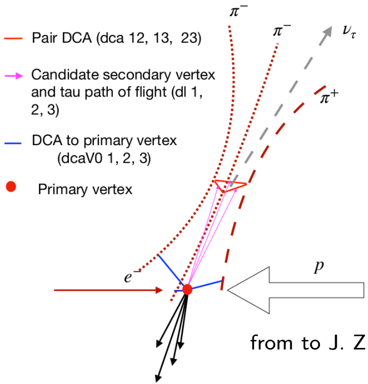


Left handed τ_L, e_L
Left handed u_L, d_L

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, need NLO corrections
- is a NLO + parton shower framework needed/available for EIC?

τ at the EIC



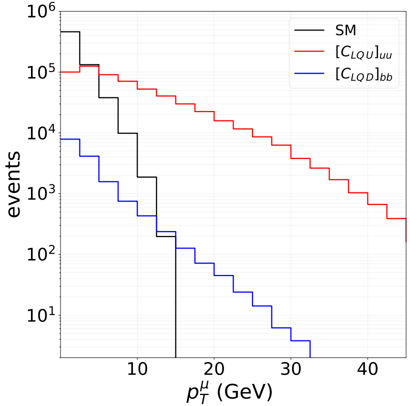
from to J. Zhang

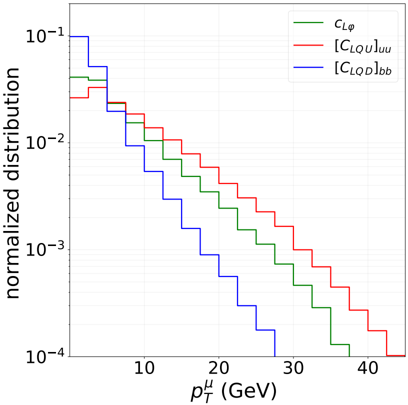
1. $ep \to \tau X \to e + \not{E} + X$
2. $ep \to \tau X \to \mu + \not{E} + X$
3. $ep \to \tau X \to X_h + \not{E} + X$

- (substantial) background from standard NC and CC DIS
- generate 10^8 SM & 10^6 SMEFT events with `Pythia8` + `Delphes` for EIC

using `Delphes` card by M. Arratia and S. Sekula

Muon channel





- too much background in e channel, μ channel much more promising!
- in SM, μ come from hadron decays, typically at small p_T

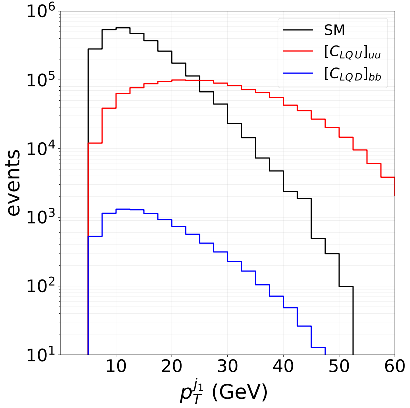
$$p_T^\mu > 10\,\mathrm{GeV}, \quad \not{E}_T > 15\,\mathrm{GeV}, \quad p_T^{j_1} > 20\,\mathrm{GeV}$$

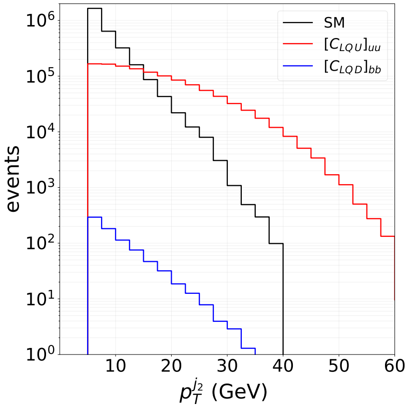
eliminates all SM background

- smaller signal efficiency for Z couplings, heavy quarks

? assumed same performance for muon and electrons, realistic?

Hadronic channel





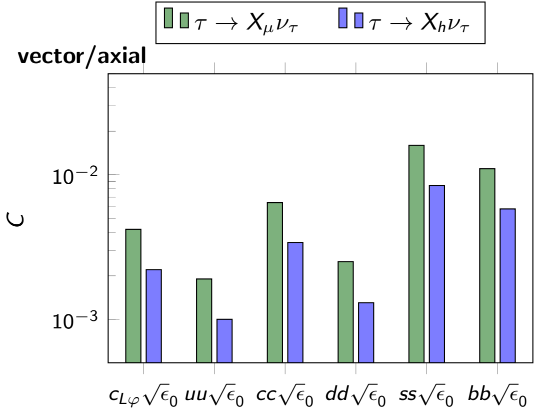
- one "τ-tagged" jet, with 1 or 3 charged tracks, and close in ϕ to $\not{E}_T$
- recoils against a second jet, no charged leptons in final state

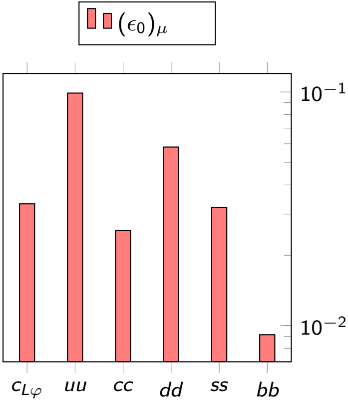
$$p_T^{j_1} > 20\,\mathrm{GeV}, \quad p_T^{j_2} > 15\,\mathrm{GeV}, \quad \not{E}_T > 15\,\mathrm{GeV} \Longrightarrow \epsilon_{SM} = 10^{-5}$$

does not quite kill all SM background

? cuts severely suppress heavy quark signals, can be improved with *b*-tagging?

EIC sensitivity to CLFV





- ϵ_{n_b}: signal efficiency for the cuts to reduce the SM background to n_b events

At EIC with $\mathcal{L} = 100$ fb^{-1}, $\sqrt{S} = 140$ GeV, $n_{\rm obs} = n_b$

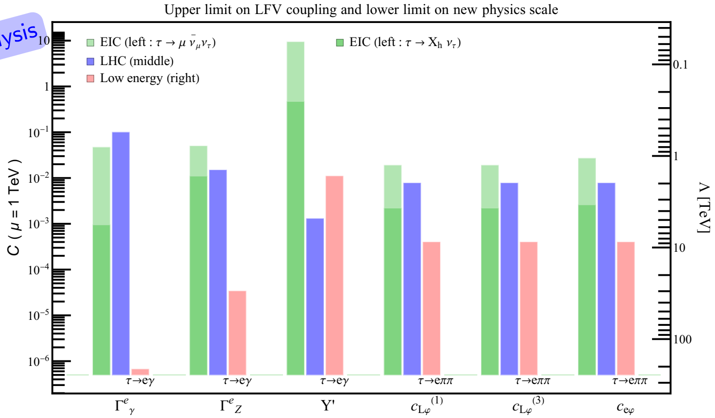
- EIC can probe couplings at the $10^{-3} - 10^{-2}$ level in μ channel

  can improve with "smarter" hadronic channel analysis

- no suppression for off-diagonal, e.g. $C_{cu} \sim C_{uu}$

Constraints on $\tau \leftrightarrow e$ transitions: dipole, Yukawa and Z

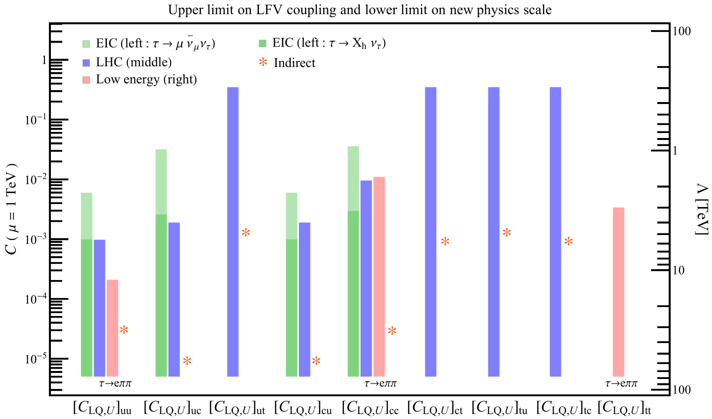
single coupling analysis



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

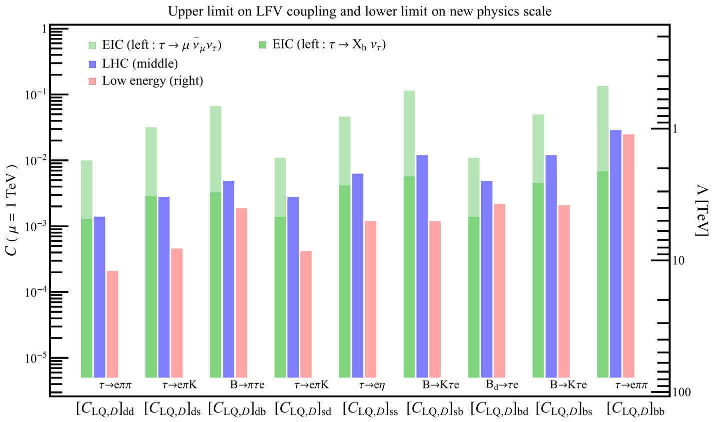
- γ and Z overwhelming constrained by $\tau \to e\gamma$
- strong direct LHC bound on Y'
- $\tau \to e\pi\pi$ dominates Z couplings

Constraints on $\tau \leftrightarrow e$ transitions: four-fermion operators



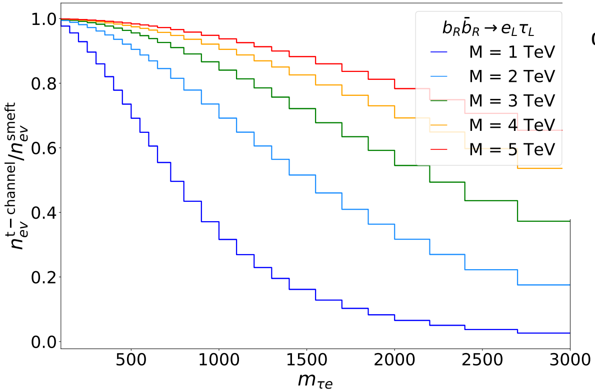
- uu $\tau \to e\pi\pi$ stronger by ~ 5, EIC competitive with $\tau \to e\pi$ & LHC
- cc low-energy loop suppressed, EIC can do better
- tt strong constraints from τ decays
- colliders are only probes of u-type off-diagonal

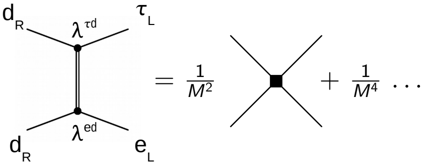
Constraints on $\tau \leftrightarrow e$ transitions: four-fermion operators



- EIC can compete on *bb* component and with *B* decays
  if we improve *b* quark analysis

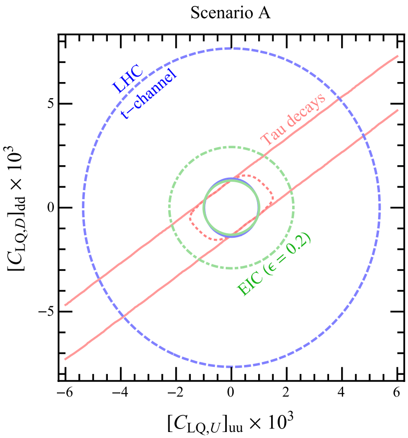
LHC vs EIC, SMEFT vs models





- LHC vs EIC comparison assumes SMEFT is applicable in DY tail (i.e. $\Lambda \gg m_{\tau e}$)
- cross section can be suppressed in BSM models
  e.g. t-channel exchanges with $M \sim 1 - 2$ TeV
- DY bound weaken by a factor of 2 ($M = 2$ TeV) to 5 ($M = 1$ TeV)
- discovery at EIC and null results at LHC could point to specific (lightish) new physics

Beyond single coupling



V/A couplings to L leptons & light quarks

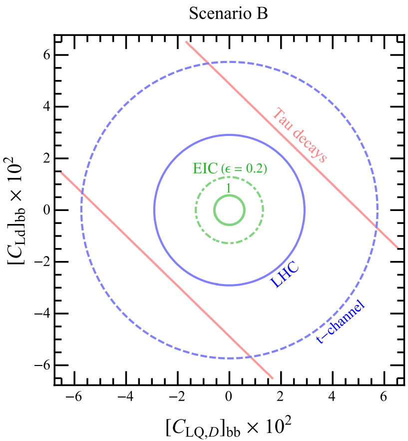
$$C_{LQ\,U} = \mathrm{diag}([C_{LQ\,U}]_{uu}, 0, 0)$$
$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, 0)$$
$$C_{Lu} = \mathrm{diag}([C_{Lu}]_{uu}, 0, 0)$$
$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, 0)$$
$$c_{L\varphi}$$

- $\pi\pi$ mode dominates, can weaken the limits with multiple couplings
- isoscalar, vector couplings not well constrained,

$$[C_{LQ\,U}]_{uu} + [C_{LQ\,D}]_{dd} + [C_{Lu}]_{dd} + [C_{Ld}]_{dd}$$

- no free directions at colliders!

Beyond single coupling



V/A couplings to L leptons & d-type quarks

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

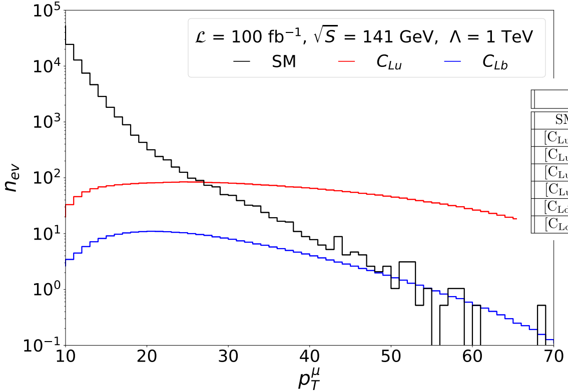
$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, [C_{Ld}]_{bb})$$

- 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

low energy not sufficient to constrain full parameter space
need complementary info!

$e \to \mu$ at the EIC

$e \to \mu$ at the EIC



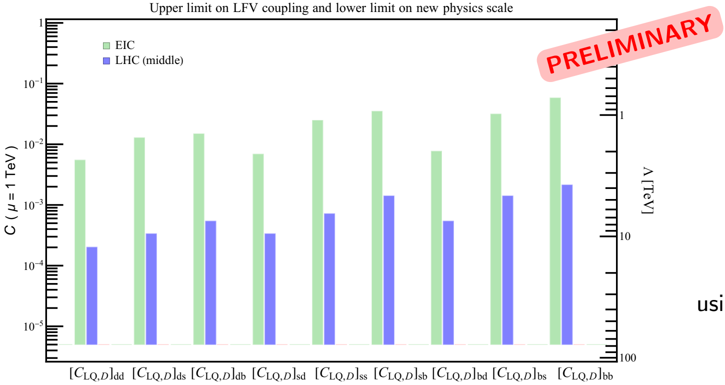
3.4 × 10^9 SM, 5 · 10^6 SMEFT events

	$\epsilon_1(\%)$	$\epsilon_{15}(\%)$		$\epsilon_1(\%)$	$\epsilon_{15}(\%)$
SM	6.097×10^{-4}	3.168×10^{-6}	$[C_{Ld}]_{db}$	44.32618	12.14276
$[C_{Lu}]_{uu}$	59.5736	27.10608	$[C_{Ld}]_{ss}$	57.00858	11.15796
$[C_{Lu}]_{uc}$	53.6548	11.7106	$[C_{Ld}]_{sd}$	58.65418	20.1075
$[C_{Lu}]_{cu}$	58.00442	28.50714	$[C_{Ld}]_{sb}$	40.90006	7.80432
$[C_{Lu}]_{cc}$	49.06806	10.12724	$[C_{Ld}]_{bd}$	48.98402	19.43488
$[C_{Ld}]_{dd}$	59.07366	20.72078	$[C_{Ld}]_{bs}$	45.38408	9.62494
$[C_{Ld}]_{ds}$	58.49876	14.91384	$[C_{Ld}]_{bb}$	35.8322	5.44654

thanks to F. Delzanno

- simpler analysis (still assuming $\mu \sim e \dots$)
- investigated 15 cuts with p_T^μ, p_T^{jet} between 5 and 20 GeV, electron veto between 5 and 10 GeV
- hardest cut leaves about $\sim$ 50 SM events behind
- explored role of b-tagging to allow for softer cuts for heavy flavors

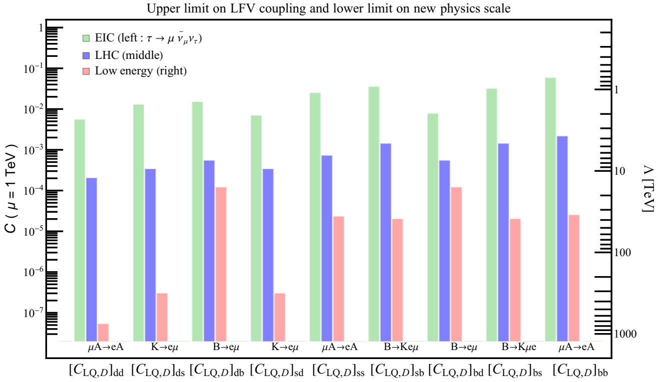
$e \to \mu$ at the EIC vs LHC



using CMS `arXiv:2205.06709`

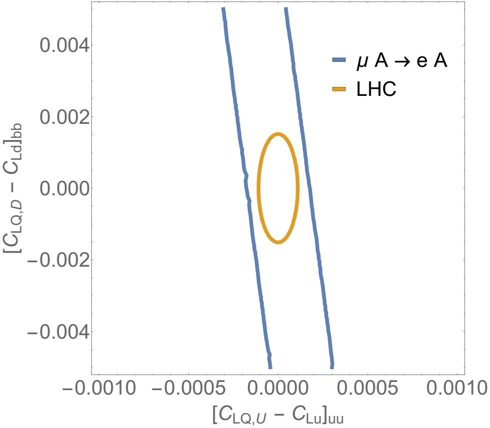
- **if** SMEFT interpretation is valid, LHC stronger by a factor of 10/20
- and pushing in the $\Lambda > 10$ TeV regime

$e \to \mu$ at the EIC vs LHC and low-energy



- in single coupling analysis, low energy provides stronger constraints on $\mu \to e$ interactions
- SI $\mu \to e$ conversion in nuclei constrains *dd*, *ss* and *bb* couplings
- *ss* suppressed by nucleon strange vector form factor, *bb* by electroweak loop, still 100× stronger than LHC/EIC
- *K*, *D* and *B* decays give strong constrains on flavor changing couplings

Multiple couplings



marginalized over
$[C_{LQ,D} - C_{Ld}]_{dd}$
$[C_{LQ,U} + C_{Lu}]_{uu}$

- spin independent and spin dependent $eA \to \mu A$ limits are very strong, but only a few...
- 4 couplings are enough to reveal free directions
- and colliders become competitive on both heavy and light flavors

Conclusion

- CLFV can unveil/constrain mechanisms of neutrino mass generation
- EIC, LHC, B factories and $\mu \to e$ experiments 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, ...
- ? can we get away w/o full detector simulations?
- 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

Backup

The LEFT LNV Lagrangian

- vector-like operators

$$\mathcal{L}_6 = -\frac{4G_F}{\sqrt{2}}\Big(C^{eu}_{\rm VLL}\,\bar{e}_L\gamma^\mu e_L\,\bar{u}_L\gamma_\mu u_L + C^{ed}_{\rm VLL}\,\bar{e}_L\gamma^\mu e_L\,\bar{d}_L\gamma_\mu d_L + C^{eu}_{\rm VRR}\,\bar{e}_R\gamma^\mu e_R\,\bar{u}_R\gamma_\mu u_R$$
$$+ C^{ed}_{\rm VRR}\,\bar{e}_R\gamma^\mu e_R\,\bar{d}_R\gamma_\mu d_R + C^{ue}_{\rm VLR}\,\bar{e}_R\gamma^\mu e_R\,\bar{u}_L\gamma_\mu u_L + C^{de}_{\rm VLR}\,\bar{e}_R\gamma^\mu e_R\,\bar{d}_L\gamma_\mu d_L$$
$$+ C^{eu}_{\rm VLR}\,\bar{e}_L\gamma^\mu e_L\,\bar{u}_R\gamma_\mu u_R + C^{ed}_{\rm VLR}\,\bar{e}_L\gamma^\mu e_L\,\bar{d}_R\gamma_\mu d_R\Big),$$

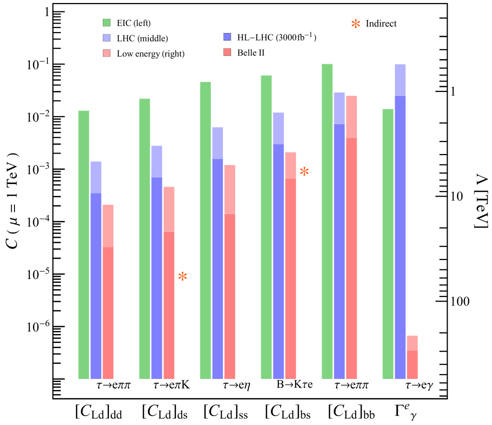
- scalar-tensor type operators

$$\mathcal{L}_6 = -\frac{4G_F}{\sqrt{2}}\Big(C^{eu}_{\rm SRR}\,\bar{e}_L e_R\,\bar{u}_L u_R + C^{ed}_{\rm SRR}\,\bar{e}_L e_R\,\bar{d}_L d_R + C^{eu}_{\rm TRR}\,\bar{e}_L\sigma^{\mu\nu} e_R\,\bar{u}_L\sigma_{\mu\nu} u_R$$
$$+ C^{ed}_{\rm TRR}\,\bar{e}_L\sigma^{\mu\nu} e_R\,\bar{d}_L\sigma_{\mu\nu} d_R + C^{eu}_{\rm SRL}\,\bar{e}_L e_R\,\bar{u}_R u_L + C^{ed}_{\rm SRL}\,\bar{e}_L e_R\,\bar{d}_R d_L\Big) + \text{h.c.}$$

- vector/axial combinations

$$C^{eq}_{\rm VLV} = \frac{1}{2}\left(C^{eq}_{\rm VLR} + C^{eq}_{\rm VLL}\right), \qquad C^{eq}_{\rm VLA} = \frac{1}{2}\left(C^{eq}_{\rm VLR} - C^{eq}_{\rm VLL}\right)$$

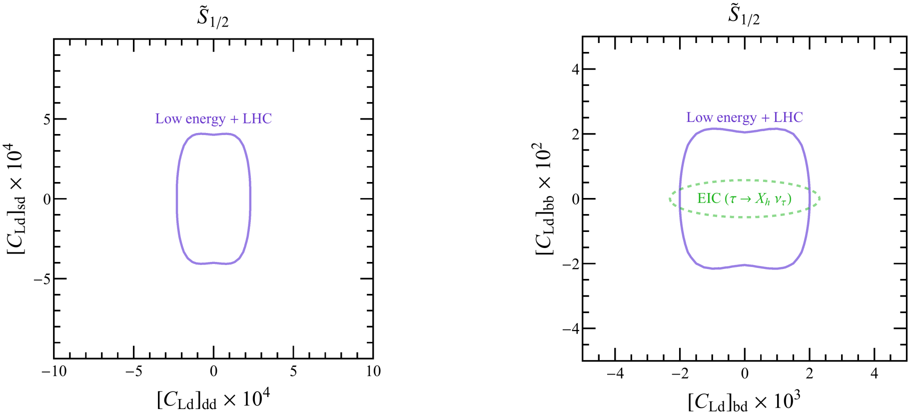
$\tau \leftrightarrow e$ transitions: future projections



thanks to K. Fuyuto
`arXiv:2203.14919`

- Belle-II will improve
- colliders will play an important role in heavy flavor & multi-coupling scenarios

Leptoquark models



marginalized over remaining couplings

- light-quark components severely constrained by low-energy
- EIC and LHC can improve the *b* components

Polarized cross section

- generic form of polarized cross section

$$\frac{1}{\sigma_0}\frac{d\sigma_{\lambda_e\lambda_T}}{dx\,dy} = \frac{1}{2}\sum_a\left[\frac{1-\lambda_e}{2}\left(\hat\sigma^a_{\rm LL}+\hat\sigma^a_{\rm LR}\right)+\frac{1+\lambda_e}{2}\left(\hat\sigma^a_{\rm RL}+\hat\sigma^a_{\rm RR}\right)\right] f_a(x,Q^2).$$
$$+\frac{1}{2}\sum_a\left[\frac{1-\lambda_e}{2}\left(-\hat\sigma^a_{\rm LL}+\hat\sigma^a_{\rm LR}\right)+\frac{1+\lambda_e}{2}\left(-\hat\sigma^a_{\rm RL}+\hat\sigma^a_{\rm RR}\right)\right]\lambda_T\Delta f_a(x,Q^2)\,,$$

- example of u quarks ($F_Z = \frac{1}{c_w^4 s_w^4}\frac{Q^4}{(Q^2+m_Z^2)^2}$)

$$\hat\sigma^{u_i}_{LL} = F_Z\left\{\left|\left[c^{(1)}_{L\varphi}+c^{(3)}_{L\varphi}\right]_{\tau e} z_{u_L} + \frac{Q^2+m_Z^2}{m_Z^2}\left[C_{LQ,\,U}\right]_{\tau e u_i u_i}\right|^2 + \sum_{j\neq i}\left|\frac{Q^2+m_Z^2}{m_Z^2}\left[C_{LQ,\,U}\right]_{\tau e u_j u_i}\right|^2\right\}$$

$$\hat\sigma^{u_i}_{RR} = F_Z\left\{\left|\left[c_{e\varphi}\right]_{\tau e} z_{u_R} + \frac{Q^2+m_Z^2}{m_Z^2}\left[C_{eu}\right]_{\tau e u_i u_i}\right|^2 + \sum_{j\neq i}\left|\frac{Q^2+m_Z^2}{m_Z^2}\left[C_{eu}\right]_{\tau e u_j u_i}\right|^2\right\}$$

$$\hat\sigma^{u_i}_{LR} = F_Z(1-y)^2\left\{\left|\left[c^{(1)}_{L\varphi}+c^{(3)}_{L\varphi}\right]_{\tau e} z_{u_R} + \frac{Q^2+m_Z^2}{m_Z^2}\left[C_{Lu}\right]_{\tau e u_i u_i}\right|^2 + \sum_{j\neq i}\left|\frac{Q^2+m_Z^2}{m_Z^2}\left[C_{Lu}\right]_{\tau e u_j u_i}\right|^2\right\}$$

$$\hat\sigma^{u_i}_{RL} = F_Z(1-y)^2\left\{\left|\left[c_{e\varphi}\right]_{\tau e} z_{u_L} + \frac{Q^2+m_Z^2}{m_Z^2}\left[C_{Qe}\right]_{\tau e u_i u_i}\right|^2 + \sum_{j\neq i}\left|\frac{Q^2+m_Z^2}{m_Z^2}\left[C_{Qe}\right]_{\tau e u_j u_i}\right|^2\right\},$$

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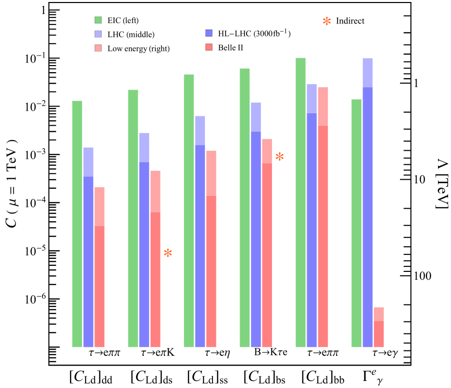

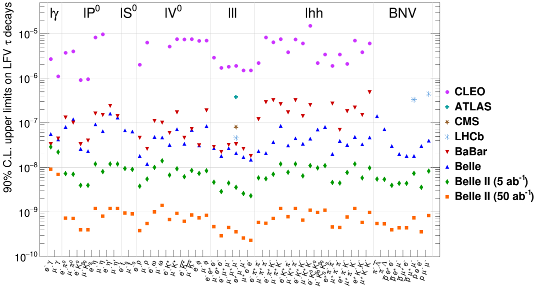

S. Banerjee *et al*, `arXiv:2203.14919`

- Belle-II will improve τ decays BR by a factor of 5 ($\tau \to e\gamma$) to 40 ($\tau \to e\pi\pi$)
- colliders will play an important role in heavy flavor & multi-coupling scenarios