Searches of CLFV: the EIC vs. low-energy experiments

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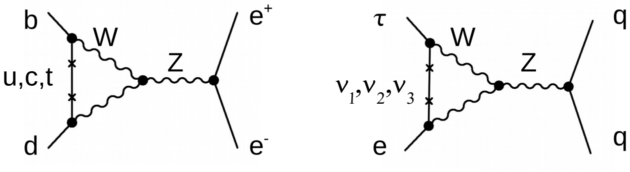
EW&BSM Working Group Meeting, March 14th 2023

with V. Cirigliano, **K. Fuyuto**, C. Lee, **B. Yan** `arXiv:2102.06176`
+ S. Gonzalez-Solis and F. Delzanno *in preparation*

Los Alamos National Laboratory

Charged lepton flavor violation



- mismatch between quark weak and mass eigenstates

  $\Longrightarrow$ quark family number is not conserved
- same mismatch for charged leptons, but suppressed by neutrino masses!

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

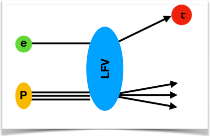
S. Petcov, ‘77; W. Marciano and A. Sanda, ‘77

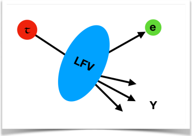
- . . . however, models that explain m_ν usually introduce new CLFV

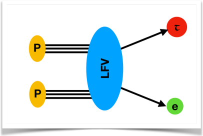
  e.g. type I, II and III see-saw   A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, T. Hambye, ‘08

CLFV experiments crucial to falsify TeV origin of m_ν

CLFV at low- and high-energy







- $\mu \leftrightarrow e$ transitions well constrained at low-energy (hopeless?)
- $\mu \leftrightarrow \tau$ interesting, but not for EIC

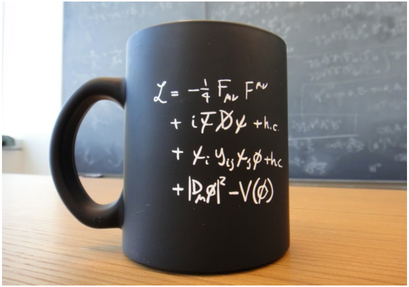
$\tau \leftrightarrow e$ transitions

1. τ and meson decays $\tau \to e\gamma, \tau \to e\pi\pi, \tau \to eK\pi, B \to \pi\tau e, \ldots$
2. pp collisions $pp \to e\tau, h \to \tau e, t \to q\tau e \ldots$
3. & the upcoming EIC

M. Gonderinger and M. Ramsey-Musolf; V. Cirigliano *et al.*; J. Zhang, S. Mantry, *et al.*;

and two Snowmass white papers 2203.13199, 2203.14919

The Standard Model Effective Field Theory



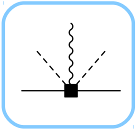
- SMEFT convenient framework to compare different probes

. . . with some caveats . . .

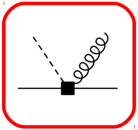
- SM fields, no new light degrees of freedom (e.g. no ν_R)
- local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- organize them in a power counting based on canonical dimension

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

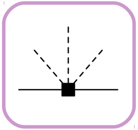
SMEFT for CLFV



vector/axial currents



dipole

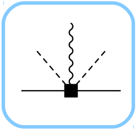


Yukawa

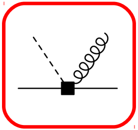
1. LFV Z couplings, & γ, Z dipole and Yukawa couplings

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

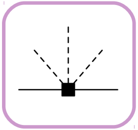
$$- \left[Y'_e \right]_{\tau e} h \bar{\tau}_L e_R + \text{h.c.} \qquad C = \mathcal{O}\left(\frac{v^2}{\Lambda^2} \right)$$



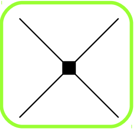
vector/axial currents



dipole



Yukawa

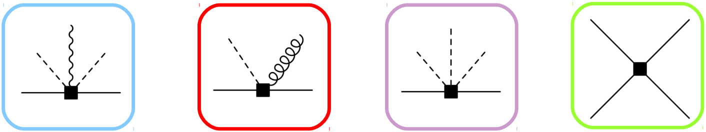


four-fermion

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

   7 Vector/Axial: $C_{L,Q}^{(1,3)}$, C_{eu}, C_{ed}, C_{Lu}, C_{Ld}, C_{Qe}

   3 Scalar/Tensor: C_{LedQ}, $C_{LeQu}^{(1,3)}$



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

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

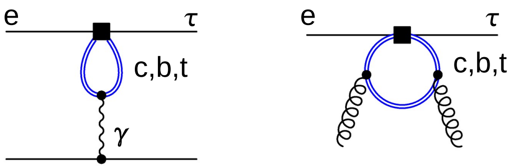
- assume generic quark flavor structures

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

- total of 126 complex coefficients
- for EIC study, equivalent to heavy LQ exchange

M. Gonderinger and M. Ramsey-Musolf, '10; J. Zhang, S. Mantry, *et al.*, '22

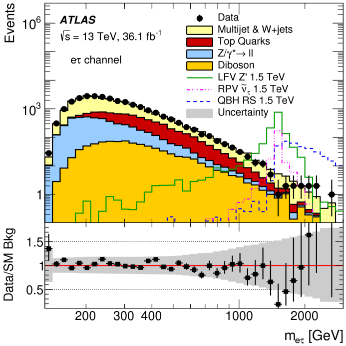
Low-energy EFT (LEFT) for CLFV



- below EW scale, only photon dipole, 4-fermion and $GG\tau e$ are relevant
- loop effects are important

1. Z couplings, γ dipole, 4-fermion operators with light quark match at tree level,
2. vector/axial operators with heavy quarks run onto light-quark at one loop
   10^{-2}-10^{-3} suppression, but only vector contribute
3. tensor operators run onto dipole, proportional to m_q
4. scalar match onto dim-7 GG operators, further suppressed by Λ_{QCD}/m_q

LHC observables



ATLAS arXiv:1807.06573

observable	operator	coeff.	flavor
$pp \to e\tau$	4-fermion	$C^{(1,3)}_{L,Q}$, C_{eu}, C_{ed}, C_{Lu}, C_{Ld}, C_{Qe}, $C^{(1,3)}_{LeQu}$, C_{LedQ}	all
$Z \to e\tau$	Z vector & dipole	$c^{(1,3)}_{L\varphi}$, Γ^e_Z	–
$h \to e\tau$	Yukawa	$Y_{\tau e}$, $Y_{e\tau}$	–
$t \to qe\tau$	4-fermion	$C^{(1,3)}_{L,Q}$, C_{eu}, C_{ed}, C_{Lu}, C_{Ld}, C_{Qe}, $C^{(1,3)}_{LeQu}$, C_{LedQ}	tq

- same list for $e \to \mu$, with somewhat better sensitivity

Low-energy observables. $\Delta F = 0$

Decay mode	BR (90% C.L.)	Decay mode	BR (90% C.L.)
$\tau^- \to e^-\gamma$	$< 3.3 \times 10^{-8}$	$\mu^- \to e^-\gamma$	$< 4.2 \times 10^{-13}$
$\tau^- \to e^-e^+e^+$	$< 2.7 \times 10^{-8}$	$\mu^- \to e^-e^+e^-$	$< 1.0 \times 10^{-12}$
$\tau^- \to e^-\mu^+\mu^-$	$< 2.7 \times 10^{-8}$	$\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}$	$< 6.1 \cdot 10^{-13}$
$\tau^- \to e^-\pi^0$	$< 8.0 \times 10^{-8}$	$\mu\,\mathrm{Au} \to e\,\mathrm{Au}$	$< 7.0 \cdot 10^{-13}$
$\tau^- \to e^-\eta$	$< 9.2 \times 10^{-8}$	$\pi^0 \to e^\pm\mu^\mp$	$< 3.6 \times 10^{-10}$
$\tau^- \to e^-\eta'$	$< 1.6 \times 10^{-7}$		
$\tau^- \to e^-\pi^+\pi^-$	$< 2.3 \times 10^{-8}$		
$\tau^- \to e^-K^+K^-$	$< 3.4 \times 10^{-8}$		

- sensitive to operators with u, d, s at tree level
- sensitive to heavy quarks via RGE effects
- in the τ sector, several channels with similar sensitivity
  $\Longrightarrow$ constraints on most spin/isospin combinations
- μ bounds stronger, but fewer channels
- $\mu \to e$ conversion mostly sensitive to scalar/vector,
  weaker sensitivity to axial, pseudoscalar and tensor

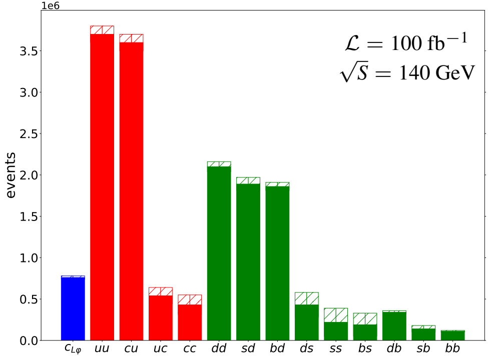
Low-energy observables. $\Delta F = 1$

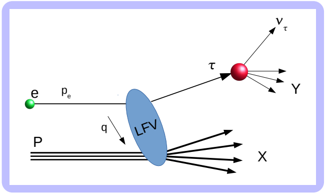
	Decay mode	BR (90% C.L.)	Decay mode	BR (90% C.L.)
sd	$\tau^- \to e^- K_S^0$	$< 2.6 \times 10^{-8}$	$K_L^0 \to e^\pm \mu^\mp$	$< 4.7 \times 10^{-12}$
	$\tau^- \to e^- \pi^+ K^-$	$< 3.7 \times 10^{-8}$	$K_L^0 \to \pi^0 e^\pm \mu^\mp$	$< 7.6 \times 10^{-11}$
	$\tau^- \to e^- \pi^- K^+$	$< 3.1 \times 10^{-8}$	$K^+ \to \pi^+ e^+ \mu^-$	$< 6.6 \times 10^{-11}$
bd	$B^0 \to e^\pm \tau^\mp$	$< 2.8 \times 10^{-5}$	$B^0 \to e^\pm \mu^\mp$	$< 1.0 \times 10^{-9}$
	$B^+ \to \pi^+ e^+ \tau^-$	$< 7.4 \times 10^{-5}$	$B^+ \to \pi^+ e^\pm \mu^\mp$	$< 1.7 \times 10^{-7}$
	$B^+ \to \pi^+ e^- \tau^+$	$< 2.0 \times 10^{-5}$		
bs	$B^+ \to K^+ e^+ \tau^-$	$< 4.3 \times 10^{-5}$	$B^+ \to K^+ e^- \mu^+$	$< 6.4 \times 10^{-9}$
	$B^+ \to K^+ e^- \tau^+$	$< 1.5 \times 10^{-5}$	$B_s \to e^\pm \mu^\mp$	$< 5.4 \times 10^{-9}$
cu			$D^0 \to e^\pm \mu^\mp$	$< 1.3 \times 10^{-8}$
			$D^+ \to \pi^+ e^+ \mu^-$	$< 2.1 \times 10^{-7}$
			$D^+ \to \pi^+ e^- \mu^+$	$< 2.2 \times 10^{-7}$

- channels with different parity probe different Dirac structures
- no sensitivity to $\tau e\, cu$ interactions

CLFV Deep Inelastic Scattering & EIC sensitivity

CLFV Deep Inelastic Scattering





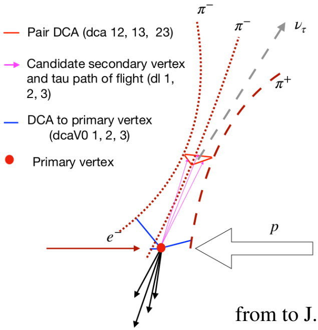
Left handed τ_L, e_L

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 QCD corrections



from to J. Zhang

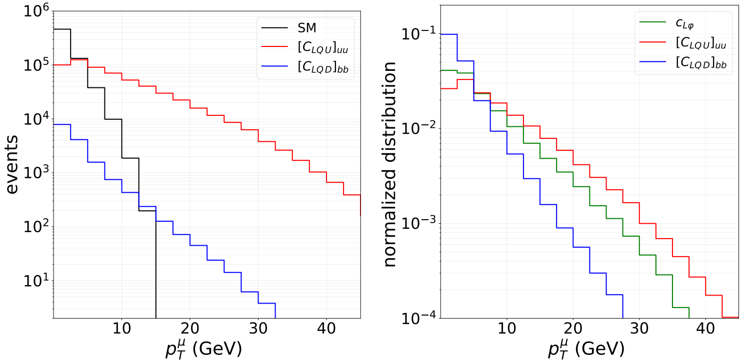
1. $ep \to \tau X \to e + \not{E} + X$
2. $ep \to \tau X \to \mu + \not{E} + X$
3. $ep \to \tau X \to X_h + \not{E} + X$

(substantial) background from standard NC and CC DIS

- simulate 10^9 SM & 10^6 SMEFT events with `Pythia8` + `Delphes` for EIC

thanks to Miguel Arratia!

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

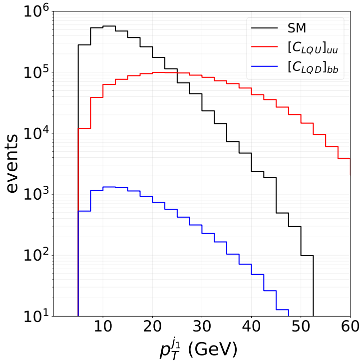
$$p_T^\mu > 10\,\text{GeV}, \quad \not{E}_T > 15\,\text{GeV}, \quad p_T^{j_1} > 20\,\text{GeV}$$

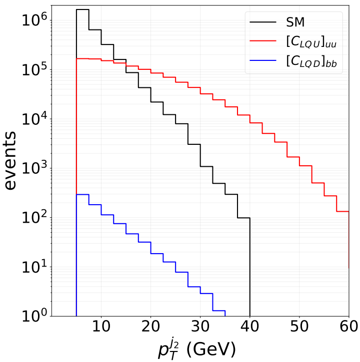
eliminates all SM background

- smaller signal efficiency for Z couplings, heavy quarks

need muon detector?

Hadronic channel



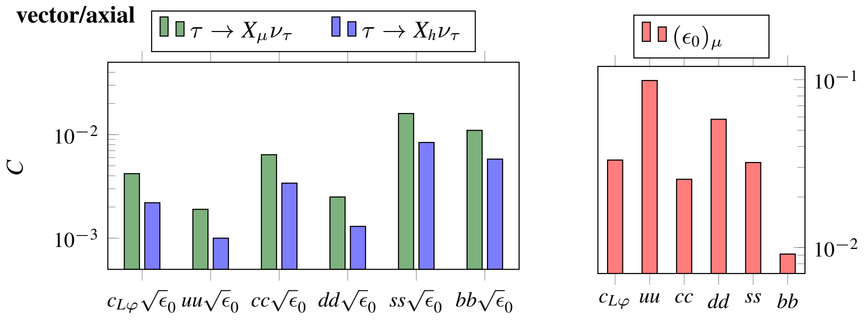


- one "τ-tagged" jet, with 1 or 3 charged tracks, and close in ϕ to $\not{E}_T$
- recoils against a second jet, no charged leptons in final state

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

does not quite kill all SM background

- cuts severely suppress heavy quark signals



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

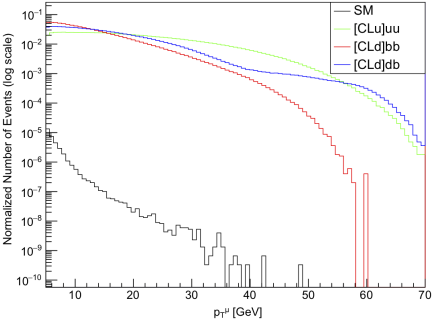
At EIC with $\mathcal{L} = 100$ fb^{-1}, $\sqrt{S} = 140$ GeV, $n_{\rm obs} = n_b$

- 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. $C_{cu} \sim C_{uu}$

$e \to \mu$ conversion at the EIC



thanks to F. Delzanno

- similar (simpler) analysis for $e \to \mu$ operators

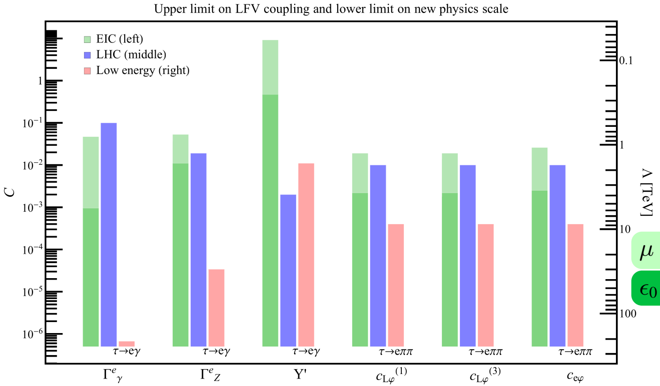
  assuming μ reconstruction as good as electron
- generate 3×10^9 SM events, and 5×10^6 events for each BSM operator
- select events with no electron with $p_T^e > 5$ GeV and

$$p_T^\mu > 20\,\text{GeV}, \quad p_T^{j_1} > 20\,\text{GeV}, \quad 2 < |\Delta\phi| < 4$$

we find

$$\epsilon_{\text{SM}} = 3.2 \times 10^{-8} \qquad \epsilon_{\text{SMEFT}} \in \{0.30, 0.05\}$$

High-energy vs low-energy: dipole, Yukawa and Z



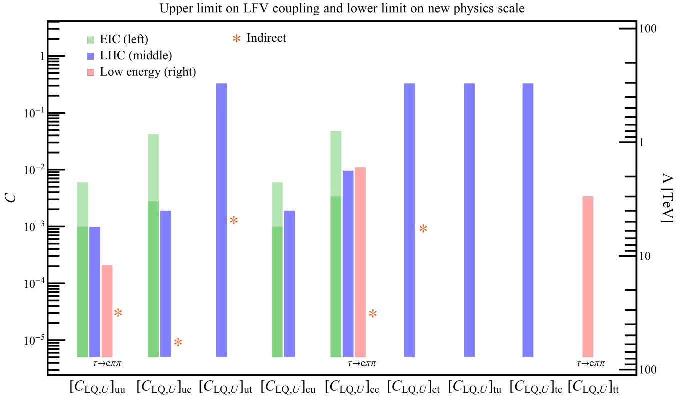
μ analysis

$\epsilon_0 = 1$ in $\tau \to X_h \nu_\tau$

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

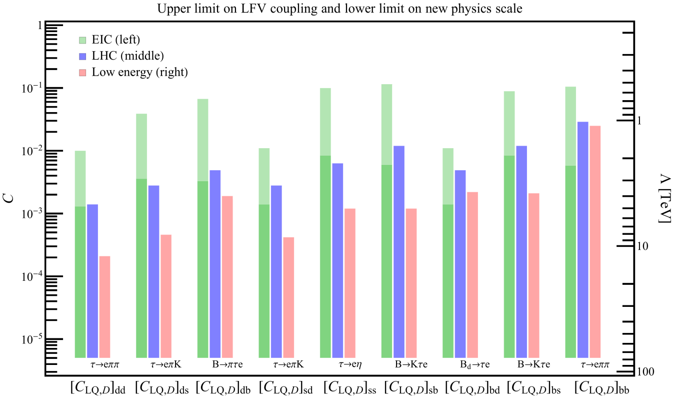
- no competition on γ and Z dipole operators
- strong direct LHC bound on Y'
- $\tau \to e\pi\pi$ dominates Z couplings

High-energy vs low-energy: four-fermion



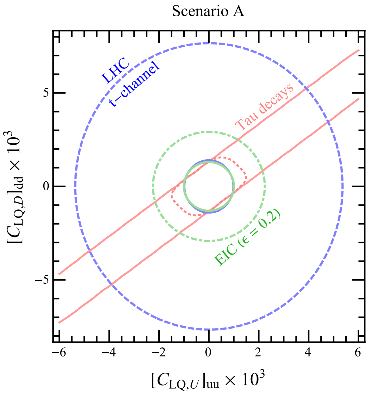
- uu $\tau \to e\pi\pi$ stronger by ~ 5,
  EIC and LHC competitive with $\tau \to e\pi$
- cc low-energy loop suppressed, EIC can do better than LHC
- tt surprisingly strong constraints from τ decays
- EIC & LHC crucial for off-diagonal

High-energy vs low-energy: four-fermion



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

Towards a global fit



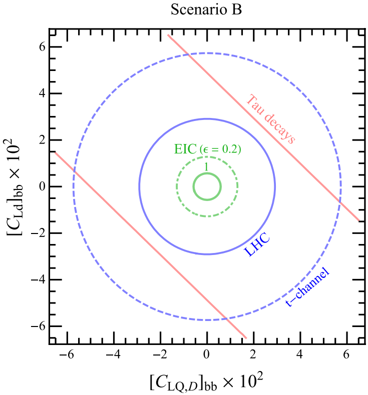
$$C_{LQ\,U} = \mathrm{diag}([C_{LQ\,U}]_{uu}, 0, 0)$$
$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, 0)$$
$$C_{Lu} = \mathrm{diag}([C_{Lu}]_{uu}, 0, 0)$$
$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, 0)$$
$$c_{L\varphi}$$

- $\pi\pi$ mode dominates, can weaken the limits with multiple couplings
- turn on all V/A couplings to L leptons & light quarks
- isoscalar, vector couplings not well constrained,

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

- no cancellation at colliders

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

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

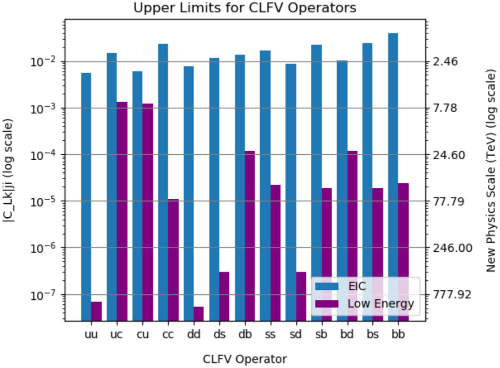
$\mu \to e$ single operator limit.

$C_{LQ,U}$	uu	6.0×10^{-8}	cc	1.1×10^{-5}	tt	3.0×10^{-6}
C_{eu}	uu	6.0×10^{-8}	cc	1.1×10^{-5}	tt	2.3×10^{-6}
C_{Lu}	uu	6.0×10^{-8}	cc	1.1×10^{-5}	tt	2.6×10^{-6}
$C_{LQ,D}$	dd	5.3×10^{-8}	ss	2.3×10^{-5}	bb	2.5×10^{-5}
C_{ed}	dd	5.3×10^{-8}	ss	2.3×10^{-5}	bb	2.4×10^{-5}
C_{Ld}	dd	5.3×10^{-8}	ss	2.2×10^{-5}	bb	2.4×10^{-5}
C_{Qe}	dd	2.9×10^{-8}	ss	1.3×10^{-6}	bb	2.4×10^{-6}
C_{LedQ}	dd	3.5×10^{-9}	ss	5.9×10^{-9}	bb	3.3×10^{-6}
$C^{(1)}_{LeQu}$	uu	7.7×10^{-9}	cc	8.1×10^{-7}	tt	$9.3 \times 10^{-8*}$
$C^{(3)}_{LeQu}$	uu	4.2×10^{-8}	cc	$7.6 \times 10^{-9*}$	tt	$1.3 \times 10^{-10*}$

Table: 90% C.L. upper limits on the quark-flavor-conserving semileptonic operators. " $*$ " represents that the bound is given by $\mu \to e\gamma$, while the rest of operators are constrained by $\mu \to e$ (Al) conversion.

- single operator limits dominated by $\mu \to e$ conversion
- somewhat weaker for s and heavy flavor, but still very strong
- $\Delta F = 1$ vary between $\sim 10^{-3}$ (cu) to 10^{-6} (bd)

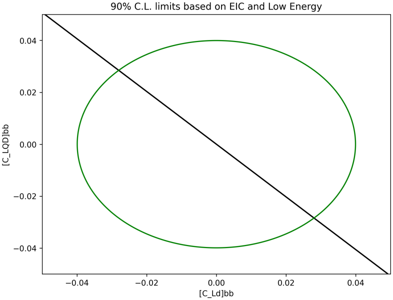
$\mu \to e$ single operator limit.



L leptons, R quarks

- in single coupling analysis, less hopeful than $e \to \tau$
- . . . but smaller number of observables

$e \to \mu$ conversion



thanks to F. Delzanno

- implies unconstrained directions, e.g. b axial couplings

$$[C_{LQ,D} - C_{Ld}]_{bb}\, \bar{\mu}_{L,R}\gamma^{\mu} e_{L,R}\, \bar{b}\gamma_{\mu}\gamma_5 b$$

Future directions

- CLFV can unveil/constrain mechanism for neutrino mass generation
- EIC competitive and complementary to LHC and B factories

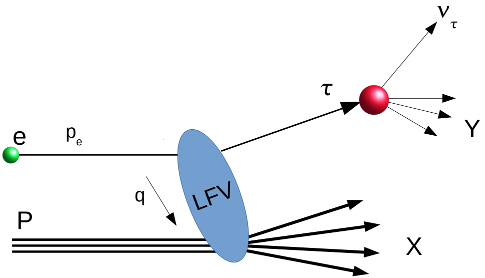
1. Z couplings
2. four-fermion with heavy quarks and quark-flavor-changing ops.

To do:

1. extend the calculation to NLO in QCD, especially for heavy quarks
2. detailed study of the hadronic channel $\tau \to X_h \nu_\tau$
3. detailed study of heavy quark channels
   improve ϵ with b tagging, ...
4. work towards a global fit
5. identify realistic UV models that evade $\mu \to e$ low-energy constraints

Back up

CLFV Deep Inelastic Scattering



$$x = \frac{Q^2}{2P\cdot q}$$

$$y = \frac{P\cdot q}{P\cdot p_e} = \frac{Q^2}{Sx}$$

$$\sigma_0 = \frac{\alpha_{\rm em}^2 \pi S x}{Q^4}$$

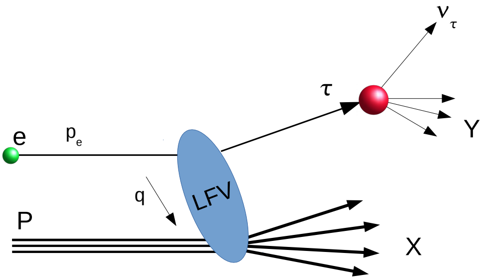
- at tree level

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

λ_e: electron polarization

- all operator info in partonic $\hat\sigma_{LL}$, $\hat\sigma_{LR}$, $\hat\sigma_{RL}$, $\hat\sigma_{RR}$

CLFV Deep Inelastic Scattering



$$x = \frac{Q^2}{2P\cdot q}$$

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$$\sigma_0 = \frac{\alpha_{\rm em}^2 \pi S x}{Q^4}$$

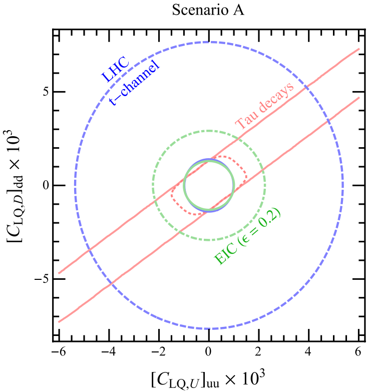
e.g. LL vector like operators

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

$$F_Z = \frac{1}{4 c_w^4 s_w^4} \frac{Q^4}{(Q^2 + m_Z^2)^2}$$

analogous to Z-exchange DIS

Towards a global fit

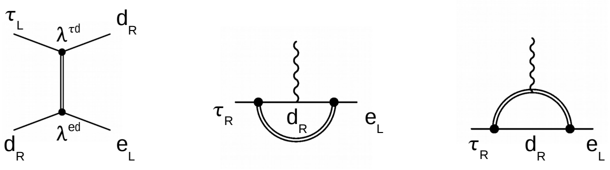


$$
\begin{aligned}
C_{LQ\,U} &= \mathrm{diag}([C_{LQ\,U}]_{uu}, 0, 0) \\
C_{LQ\,D} &= \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, 0) \\
C_{Lu} &= \mathrm{diag}([C_{Lu}]_{uu}, 0, 0) \\
C_{Ld} &= \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, 0) \\
c_{L\varphi} &
\end{aligned}
$$

- $\pi\pi$ mode dominates, can weaken the limits with multiple couplings
- turn on all V/A couplings to L leptons & light quarks
- isoscalar, vector couplings not well constrained,

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

- no cancellation at colliders



- leptoquarks are good candidate for BSM (ν masses, B anomalies, ...)

$$\mathcal{L} = \tilde{\lambda}^{\alpha a} \bar{d}_R^{\alpha} \ell_L^a \tilde{S}_{1/2}^{\dagger} + \text{h.c.}$$

can explain ν masses if we add ν_R which interact with LQ

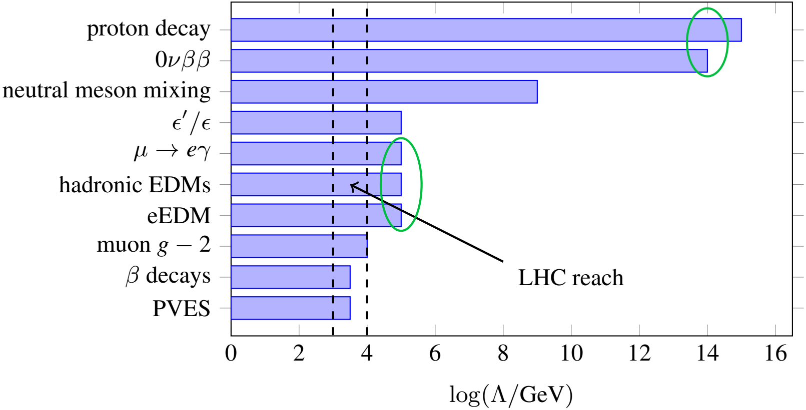
- match onto L-lepton, R d quark operator

$$[C_{Ld}]_{\tau e d_i d_j} = \left(\frac{v}{2M_{LQ}}\right)^2 \left(\tilde{\lambda}^*\right)^{ed_i} \left(\tilde{\lambda}\right)^{\tau d_j}$$

- LQ charges are such that dipole vanishes

$$\left[\Gamma_{\gamma}^{e}\right]_{\tau e} = \left[\Gamma_{\gamma}^{e}\right]_{e\tau} = 0$$

Finding BSM: the precision frontier



- competitive and complementary to the energy frontier

especially when probing violation of SM symmetries

B and τ 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	
$\tau \to eK_S^0$						✓										✓						
$\tau^- \to e^- K\pi$	✓										✓											
$B^0 \to e\tau$							✓										✓					
$B^+ \to \pi^+ e\tau$		✓										✓										
$B^+ \to K^+ e\tau$			✓										✓									

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

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

B and τ 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
$\tau \to e\gamma$																					✓ (orange)	✓ (orange)
$\tau \to e\ell^+\ell^-$				✓ (orange)	✓ (orange)																	
$\tau \to e\pi^0$							✓										✓					
$\tau \to e\eta, \eta'$						✓		✓								✓		✓	✓ (orange)	✓ (orange)		
$\tau \to e\pi^+\pi^-$		✓		✓ (orange)	✓ (orange)						✓		✓	✓ (orange)	✓ (orange)						✓	
$\tau \to eK^+K^-$	✓	✓	✓	✓ (orange)	✓ (orange)						✓		✓	✓ (orange)	✓ (orange)						✓	
	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	ds	db	sb		cu	cu	
$\tau \to eK^0_S$						✓										✓						
$\tau^- \to e^-K\pi$	✓										✓											
$B^0 \to e\tau$							✓										✓					
$B^+ \to \pi^+e\tau$		✓										✓										
$B^+ \to K^+e\tau$			✓										✓									

1. *uu*, *dd*, *ss* well constrained by multiple channels for all Dirac structures
   - V isoscalar $uu + dd$ gives small and uncertain contrib. to $\tau \to eKK$
2. *bb*, *cc* vectors run into light quark V via penguins; S, P match onto *GG* ops.
   - no constraints on axial *cc* or *bb* components

B and τ 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
$\tau \to e\gamma$																					✓	✓
$\tau \to e\ell^+\ell^-$				✓	✓																	
$\tau \to e\pi^0$							✓										✓					
$\tau \to e\eta, \eta'$						✓		✓								✓		✓	✓	✓		
$\tau \to e\pi^+\pi^-$		✓		✓	✓						✓		✓	✓	✓						✓	
$\tau \to eK^+K^-$	✓	✓	✓	✓	✓						✓		✓	✓	✓						✓	

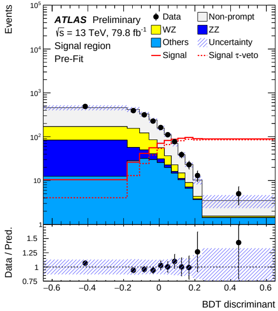
	V				A				S				P				T
	ds	db	sb	cu	ds	db	sb	cu	ds	db	sb	cu	ds	db	sb	cu	cu
$\tau \to eK_S^0$					✓								✓				
$\tau^- \to e^-K\pi$	✓								✓								
$B^0 \to e\tau$						✓								✓			
$B^+ \to \pi^+ e\tau$		✓								✓							
$B^+ \to K^+ e\tau$			✓								✓						

1. uu, dd, ss well constrained by multiple channels for all Dirac structures
   - V isoscalar $uu + dd$ gives small and uncertain contrib. to $\tau \to eKK$
2. bb, cc vectors run into light quark V via penguins; S, P match onto GG ops.
   - no constraints on axial cc or bb components
3. 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

Complementary probes: the LHC

Z, Higgs and Top decays



ATLAS−CONF−2018−044

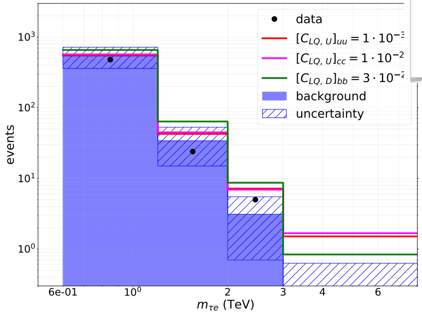
1. $Z \to \tau e$: studied at LEP and LHC, % level constraints on $c_{L\varphi}$, $c_{e\varphi}$
2. $H \to \tau e$: strong constraints ATLAS and CMS

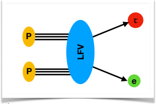
$$\left|Y'_{e\tau,\,\tau e}\right| < 2.0 \cdot 10^{-3}$$

3. search for $t \to q\ell\ell'$ at ATLAS, mostly sensitive to $t \to q\mu e$

- worked with C. A. Gottardo extract $\mathrm{BR}(t \to qe\tau) < 2.2 \cdot 10^{-4}$
- phase space suppression implies weak $\sim 10\%$ bounds

CLFV in high-invariant mass Drell-Yan





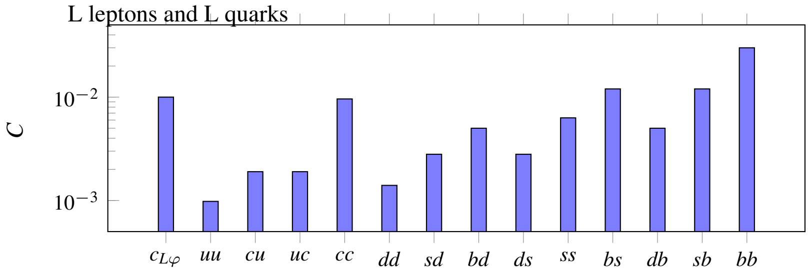
$\mathcal{L} = 36\ \text{fb}^{-1}$

ATLAS $pp \to \tau e$, $\tau \to$ hadrons

arXiv:1807.06573

- if $\Lambda \gtrsim 3 - 4$ TeV, use same SMEFT operators as EIC
- simulate SMEFT operators at NLO in QCD (POWHEG + Pythia8 + Delphes)
- signal from four-fermion enhanced at large $m_{\tau e}$, indep. of Lorentz structure

CLFV at the LHC



- LHC probes SMEFT coefficients at a similar level as EIC

a. bounds from tail of $m_{e\tau}$ distribution, sensitive to SMEFT assumption!
   weaker by ~ 2 if BSM particles in t-channel with $M \sim 1-2$ TeV
b. DY sensitive to sum of flavors
   tagging heavy flavors at EIC unique way to identify BSM mechanism

B and τ 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^-)

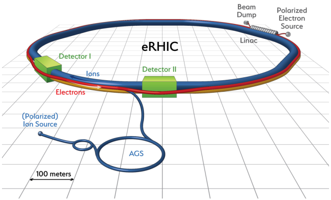
A. Celis, V. Cirigliano, E. Passemar, '14, V. Cirigliano, A. Crivellin, M. Hoferichter, '18
E. Passemar *private comm.*, K. Beloborodov, V. Druzhinin, S. Serednyakov, '19

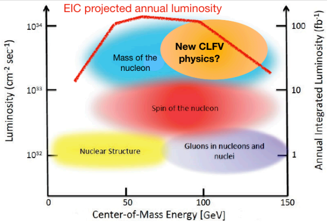
- B branching ratios $\sim 10^{-5}$, decay constants and form factors from LQCD

Belle II will improve τ BR by $\sim 10 - 100$

see 2203.14919

The Electron-Ion Collider: an intensity frontier machine?





from A. Deshpande, hacked by C. Lee

Finding BSM:

1. directly produce new particles (LHC)
2. search for processes with no/very precise SM background

Where does the EIC fit in?

- EIC will deliver a lot of data! 1000 $\times$ HERA
- with additional unique possibility to polarize e and proton beams

look for rare/BSM processes? competitive with LHC/low energy?