Charged Lepton Flavor Violation at the EIC

Emanuele Mereghetti

with V. Cirigliano, **K. Fuyuto**, C. Lee and **B. Yan**.

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Los Alamos NATIONAL LABORATORY EST. 1943

Finding BSM: the energy frontier

1. smash protons as hard as you can and see what comes out

- create new particles and/or
  study their effects on rare processes

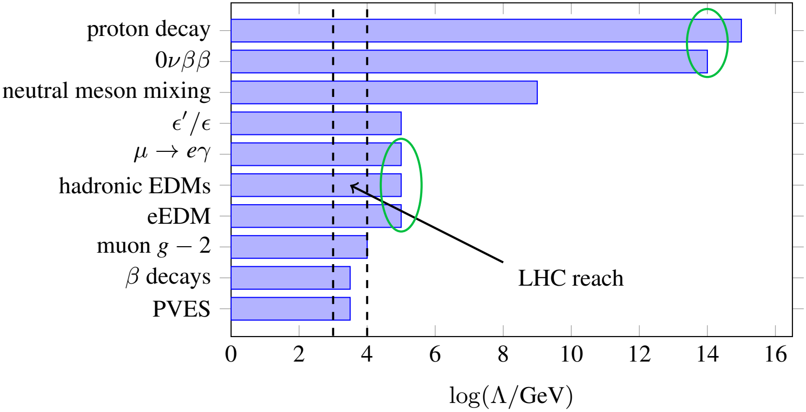
Finding BSM: the precision frontier

Majorana demonstrator

2. search for processes with no/very precisely known SM background

- electric dipole moments
- kaon physics
- rare B decays, $b \to s\gamma$
- muon and electron $g - 2$
- neutrinoless double β decay
- lepton flavor violation $\mu \to e\gamma$

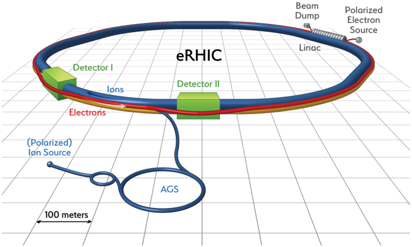
Finding BSM: the precision frontier

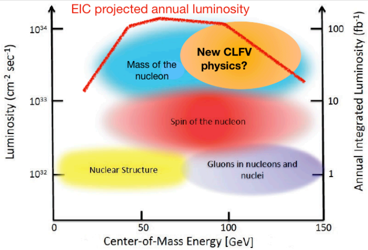


- competitive and complementary to the energy frontier

especially when probing violation of SM symmetries

The Electron-Ion Collider: an intensity frontier machine?



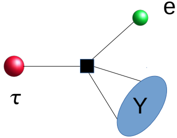


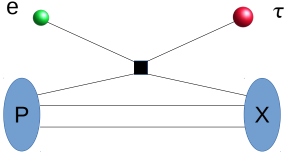
from A. Deshpande, hacked by C. Lee

- EIC received CD-1 in Summer '21, beginning project design
- can deliver a lot of data!
  1000 times more than HERA
- with additional unique possibility to polarize e and proton beams

can we look for rare/BSM processes?

The Electron-Ion Collider: an intensity frontier machine





E.g. $\tau \leftrightarrow e$ from heavy new physics

$$\mathcal{L} \sim \frac{1}{\Lambda^2} \tau \Gamma e \, \bar{q} \Gamma q \qquad \Lambda \gg 246 \text{ GeV}$$

LFV τ decays at B factories

$$N_\tau^{\text{decay}} = \epsilon_d N_\tau \tau_\tau \Gamma_{\tau \to eY},$$
$$\Gamma_{\tau \to eY} \sim \frac{m_\tau^3 \Lambda_{\text{QCD}}^2}{\Lambda^4}$$

"BSM" τs at the EIC

$$N_\tau^{\text{scattering}} = \epsilon_s \mathcal{L} \, \sigma_{ep \to \tau X},$$
$$\sigma_{ep \to \tau X} \sim \frac{S}{\Lambda^4}$$

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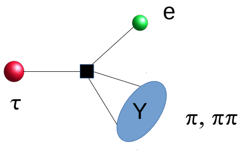

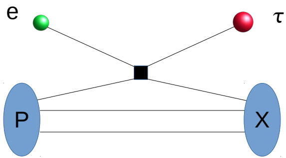

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$$N_\tau^{\text{scattering}} = \epsilon_s \mathcal{L} \, \sigma_{ep \to \tau X},$$

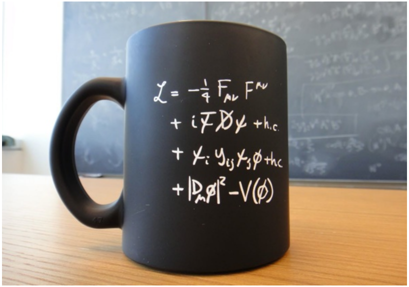
$$\sigma_{ep \to \tau X} \sim \frac{S}{\Lambda^4}$$

- to be competitive $N_\tau^{\text{scattering}} = N_\tau^{\text{decay}}$

$$\epsilon_s \mathcal{L} \sim \epsilon_d N_\tau \frac{(4\pi)^3 v^4 \Lambda_{\text{QCD}}^2}{S m_\tau^2} \sim 10^3 \text{ fb}^{-1}$$

CLFV in the SMEFT

The Standard Model Effective Field Theory

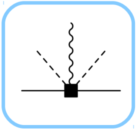


Study CLFV at EIC within EFT framework

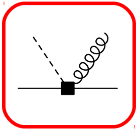
- SM fields, no new light degrees of freedom (e.g. no ν_R)
- local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- organize them in a power counting based on canonical dimension

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

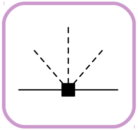
SMEFT for CLFV



vector/axial currents



dipole



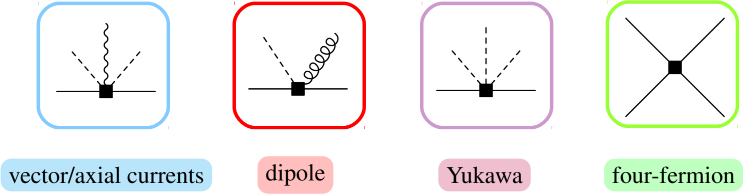
Yukawa

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

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

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

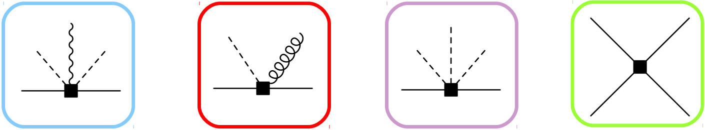
SMEFT for CLFV



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}, $C^{(1,3)}_{LeQu}$



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

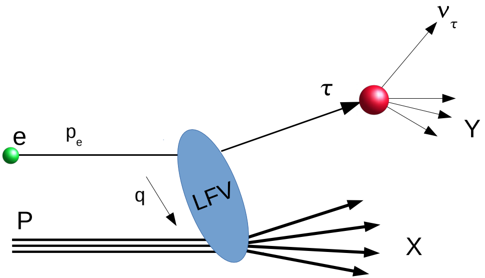
$$[C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

- and integrate out the top quark

$[C^{(3)}_{LeQu}]_{e\tau tt}$, $[C_{eu}]_{e\tau tt}$ runs strongly onto dipoles, Z couplings

CLFV Deep Inelastic Scattering & EIC sensitivity

CLFV Deep Inelastic Scattering



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

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

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

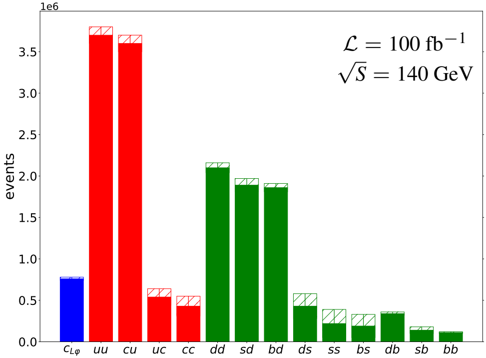
- at tree level

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

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



Left handed τ_L, e_L

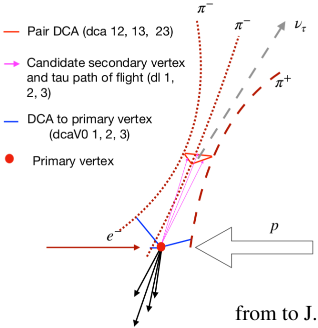
Left handed u_L, d_L

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

- not much sensitivity to Higgs



from to J. Zhang

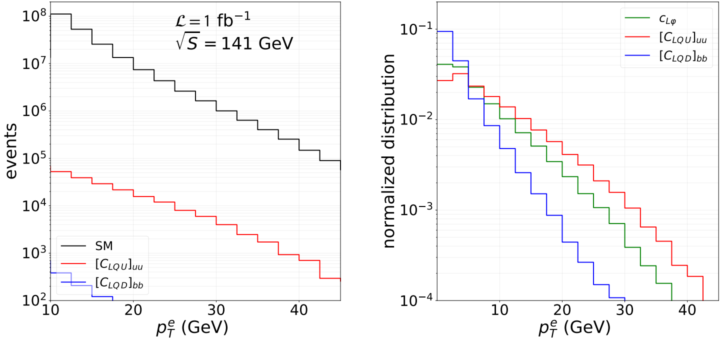
1. $ep \to \tau X \to e + \not{E} + X$
2. $ep \to \tau X \to \mu + \not{E} + X$
3. $ep \to \tau X \to X_h + \not{E} + X$

(substantial) background from standard NC and CC DIS

- simulate SM & SMEFT events with `Pythia8` + `Delphes` for EIC

thanks to Miguel Arratia (UCR)!

Electron channel

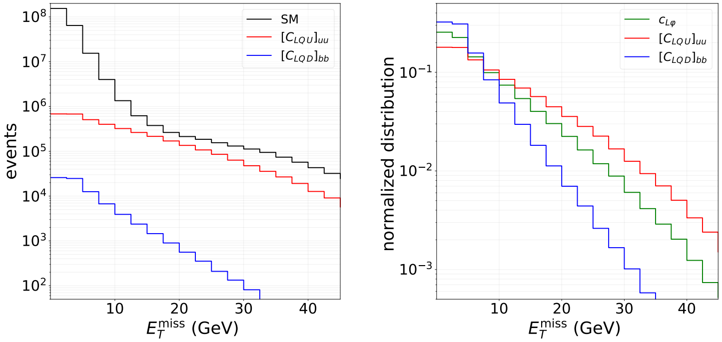


- signal falls slower than SM for u-operators
- Z couplings and c, b more similar to SM
- NC and CC DIS background swamps electron signal

$$p_T^e > 10\,\mathrm{GeV}, \quad \not{E}_T > 15\,\mathrm{GeV}, \quad p_T^{j_1} > 20\,\mathrm{GeV} \Longrightarrow \epsilon_{SM} = 10^{-4}$$

leave behind thousands of SM events

Electron channel



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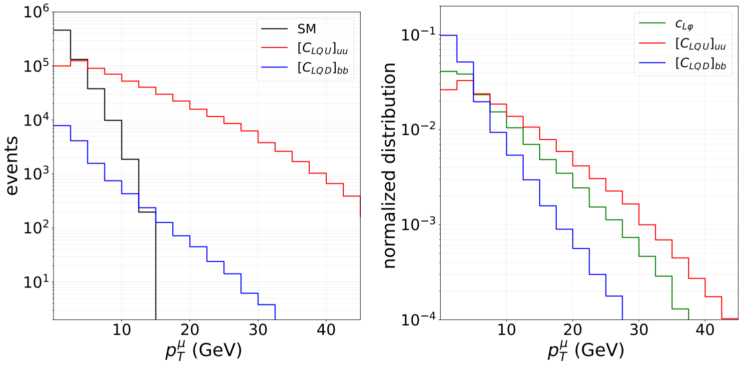
Muon channel



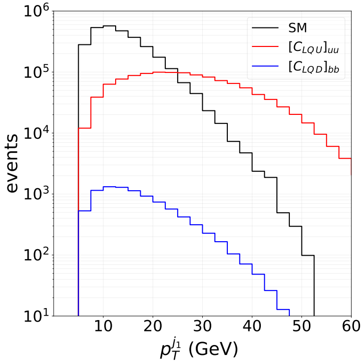
- μ channel much more promising!
- in SM, μ come from hadron decays, typically at small p_T

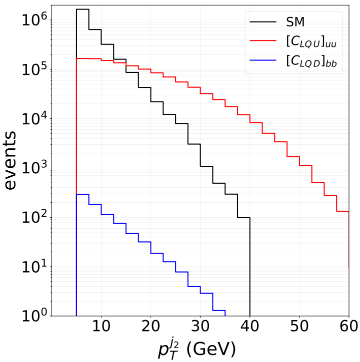
$$p_T^\mu > 10\,\text{GeV}, \quad \not{E}_T > 15\,\text{GeV}, \quad p_T^{j_1} > 20\,\text{GeV}$$

eliminates all SM background

- smaller signal efficiency for Z couplings, heavy quarks

Hadronic channel





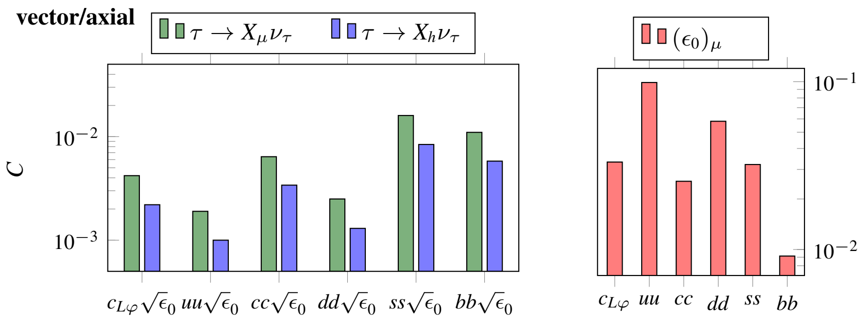
- one "τ-tagged" jet, with 1 or 3 charged tracks, and close in ϕ to $\not{E}_T$
- recoils against a second jet, no charged leptons in final state

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

does not quite kill all SM background

- cuts severely suppress heavy quark signals

EIC sensitivity to CLFV



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

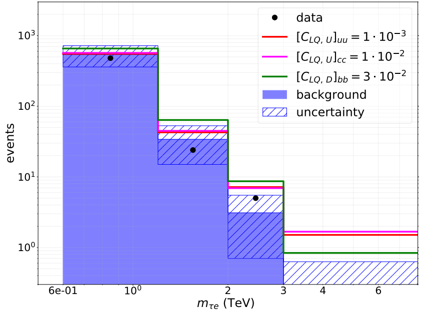
At EIC with $\mathcal{L} = 100\ \text{fb}^{-1}$, $\sqrt{S} = 140$ GeV, $n_{\text{obs}} = n_b$

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

EIC vs high-invariant mass Drell-Yan

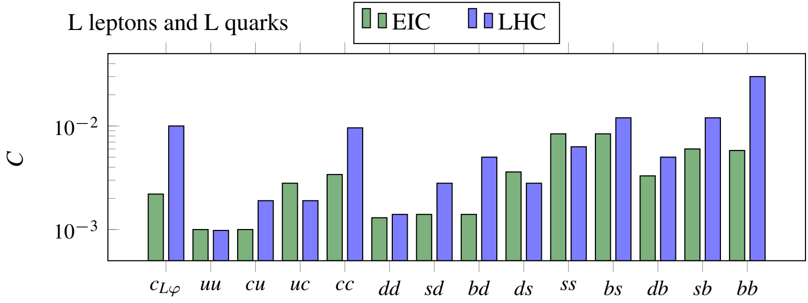


$\mathcal{L} = 36\ \text{fb}^{-1}$

ATLAS $pp \to \tau e$, $\tau \to$ hadrons
arXiv:1607.08079

- 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
- heavy quarks more suppressed compared to EIC

Summary of CLFV at colliders



- EIC with $\mathcal{L} = 100\ \mathrm{fb}^{-1}$ quite competitive with LHC
- ... especially on CLFV Z couplings & 4-fermion with c, b

  but need to improve τ efficiency & theory predictions
- LHC wins on Higgs and top FCNC couplings

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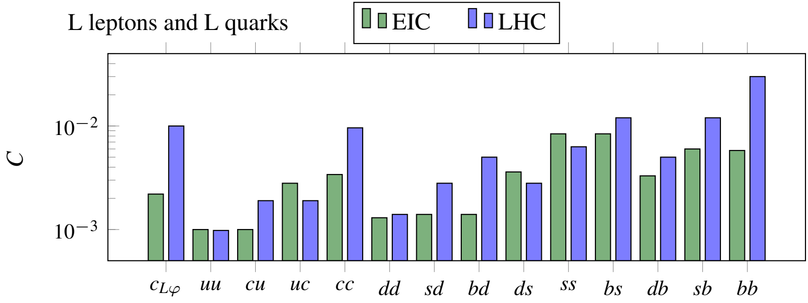

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but need to improve τ efficiency & theory predictions

- LHC wins on Higgs and top FCNC couplings

! DY limits weaker by ~ 2 if BSM particles in t-channel with $M \sim 1 - 2$ TeV

! DY sensitive to sum of flavors

tagging heavy flavors at EIC unique way to identify BSM mechanism

CLFV at low energy

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)						✓	

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

✓ = 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

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

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

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

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

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

Decay mode	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
$\tau \to eK_S^0$					✓								✓				
$\tau^- \to e^-K\pi$	✓								✓								
$B^0 \to e\tau$						✓								✓			
$B^+ \to \pi^+e\tau$		✓								✓							
$B^+ \to K^+e\tau$			✓								✓						

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

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

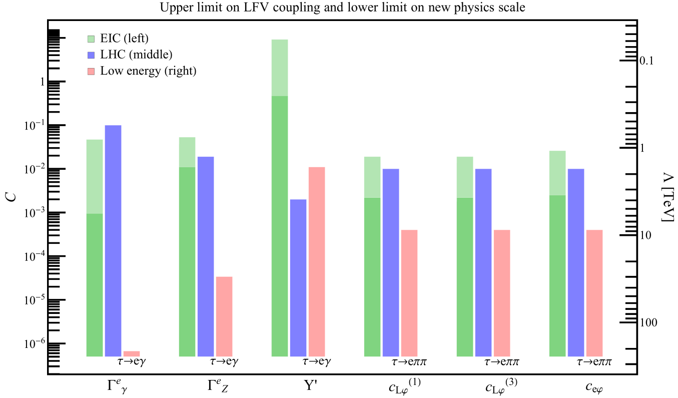
3. strong constraints on ds, sd from $\tau \to eK$, $\tau \to eK\pi$

- 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

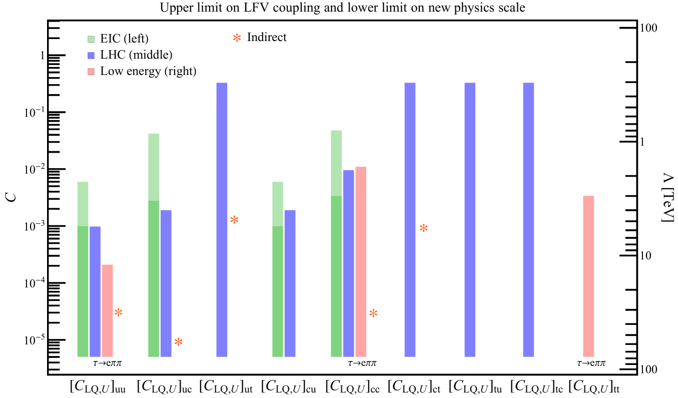
τ CLFV: high- vs. low-energy

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



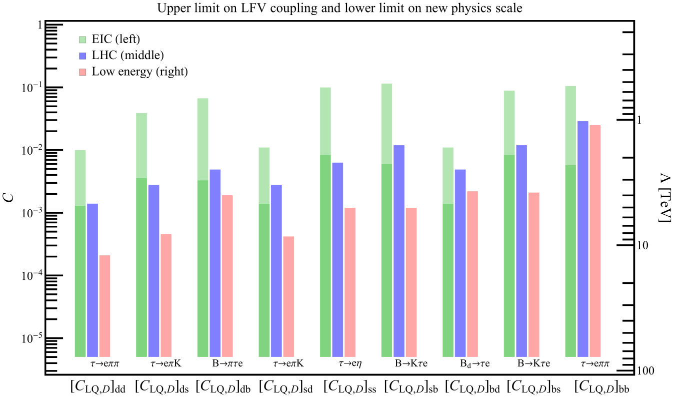
- EIC sensitivity with μ analysis (light green) and $\tau \to X_h \nu_\tau$, assuming $\epsilon_0 = 1$ (dark green)
- no competition on γ and Z dipole operators
- strong direct LHC bound on Y'
- $\tau \to e\pi\pi$ dominates Z couplings

High-energy vs low-energy: four-fermion



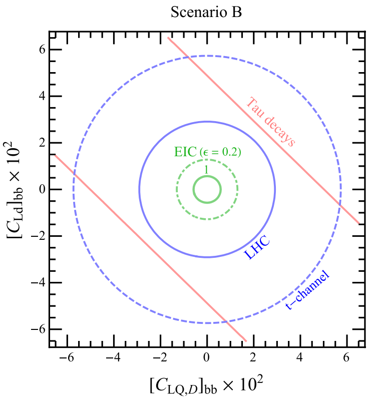
- uu $\tau \to e\pi\pi$ stronger by ~ 5,
  EIC and LHC competitive with $\tau \to e\pi$
- cc low-energy loop suppressed, EIC can do better than LHC
- tt surprisingly strong constraints from τ decays
- EIC & LHC crucial for off-diagonal

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

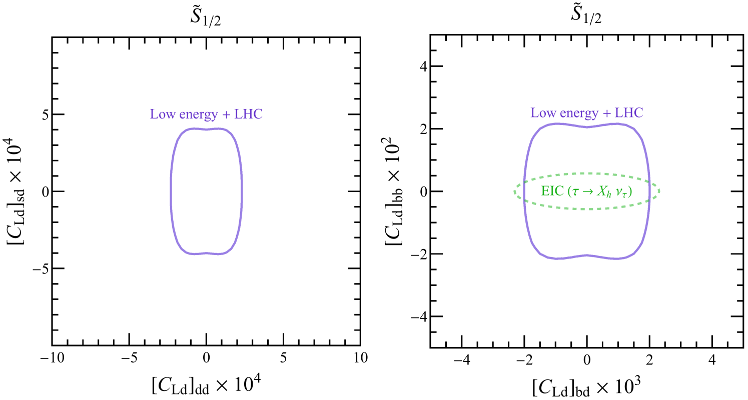


$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, [C_{LQ\,D}]_{bb})$$

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

- 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

CLFV and leptoquarks



marginalized over remaining couplings

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

Future directions

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

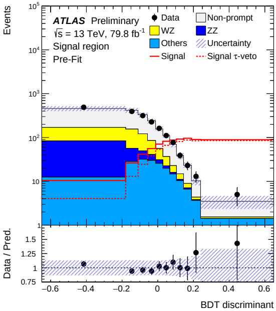
1. Z couplings
2. four-fermion with heavy quarks and quark-flavor-changing ops.

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. do we learn anything from more exclusive final states?
6. what about lepton *number* violation?

Back up

CLFV in Z, H, t decays and Drell-Yan



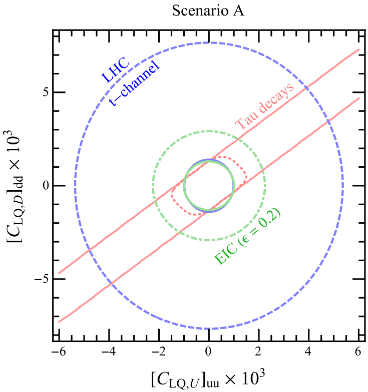
ATLAS−CONF−2018−044

- $Z \to \tau e$ studied at LEP and LHC, % level constraints on $c_{L\varphi}$, $c_{e\varphi}$
- strong constraints on LFV Yukawa from $H \to \tau e$ at ATLAS and CMS

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

- 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

Towards a global fit



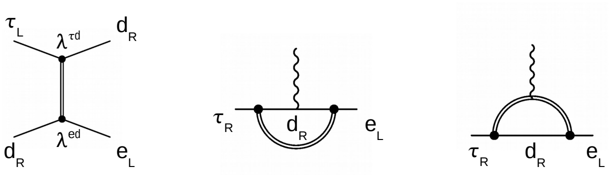
$$C_{LQ\,U} = \mathrm{diag}([C_{LQ\,U}]_{uu}, 0, 0)$$
$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, 0)$$
$$C_{Lu} = \mathrm{diag}([C_{Lu}]_{uu}, 0, 0)$$
$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, 0)$$
$$c_{L\varphi}$$

- $\pi\pi$ 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

CLFV and leptoquarks



- 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

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