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

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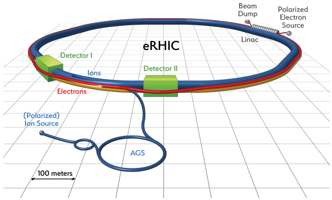
ePIC Collaboration Meeting, January 11$^{th}$ 2023

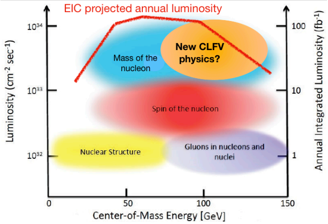
with V. Cirigliano, **K. Fuyuto**, C. Lee, **B. Yan**

arXiv:2102.06176

Los Alamos NATIONAL LABORATORY EST. 1943

# The Electron-Ion Collider: an intensity frontier machine?




from A. Deshpande, hacked by C. Lee

Finding BSM:

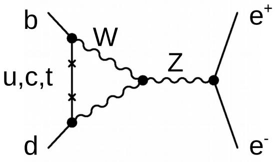
1. directly produce new particles (LHC)
2. search for processes with no/very precise SM background

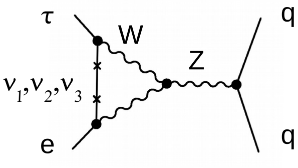
Where does the EIC fit in?

- 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?

# 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!

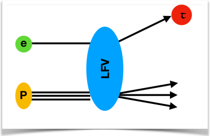
$$\mathrm{BR} \sim \left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-44}$$

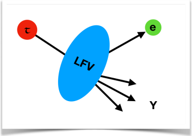
S. Petcov, '77; W. Marciano and A. Sanda, '77

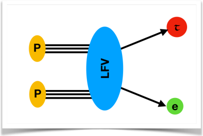
- . . . however, models that explain $m_\nu$ usually introduce new CLFV
  e.g. type I, II and III see-saw  A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, T. Hambye, '08

CLFV experiments crucial to falsify TeV origin of $m_\nu$

# CLFV at low- and high-energy




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

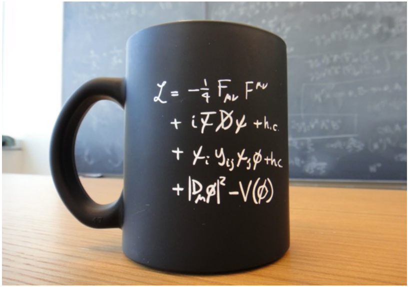
$\tau \leftrightarrow e$ transitions

1. $\tau$ and meson decays $\quad \tau \to e\gamma, \tau \to e\pi\pi, \tau \to eK\pi, B \to \pi\tau e, \ldots$
2. $pp$ collisions $\quad pp \to e\tau, h \to \tau e, t \to q\tau e \ldots$
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

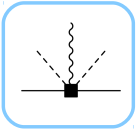



- SMEFT convenient framework to compare different probes

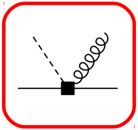
  . . . with some caveats . . .

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

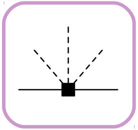
**1.** no CLFV at dim. 4
**2.** GIM suppression at dim. 5, BR $\sim (m_\nu/m_W)^4$



vector/axial currents



dipole



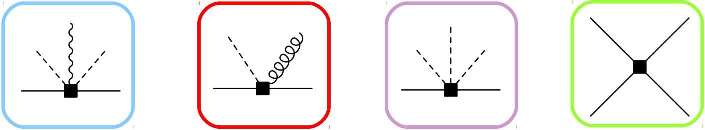
Yukawa

1. LFV $Z$ couplings, & $\gamma$, $Z$ dipole and Yukawa couplings

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

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

# SMEFT for CLFV

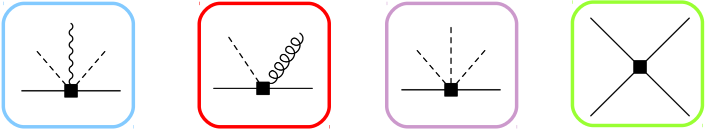


vector/axial currents | dipole | Yukawa | four-fermion

1. LFV $Z$ couplings, & $\gamma$, $Z$ 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, & $\gamma$, $Z$ dipole and Yukawa couplings
2. leptonic and semileptonic interactions

- assume generic quark flavor structures

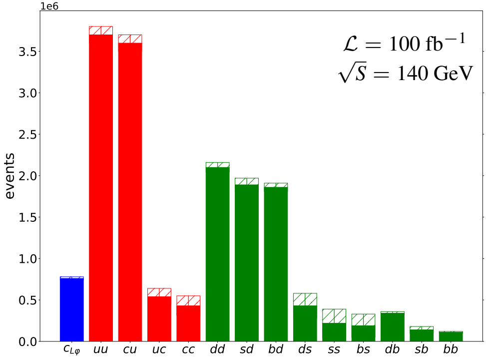
$$[C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

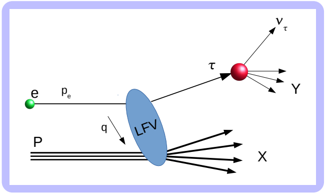
- and integrate out the top quark

run (strongly) onto dipoles, $Z$ couplings, and match onto $\bar{\tau} e G_{\alpha\beta} G^{\alpha\beta}$ ops.

# CLFV Deep Inelastic Scattering & EIC sensitivity

# CLFV Deep Inelastic Scattering




Left handed $\tau_L$, $e_L$

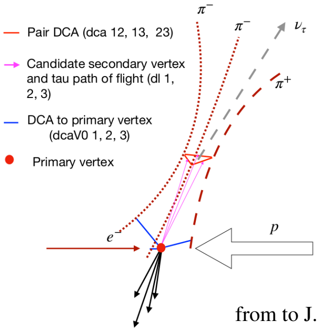
Left handed $u_L$, $d_L$

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

# $\tau$ at the EIC




from to J. Zhang

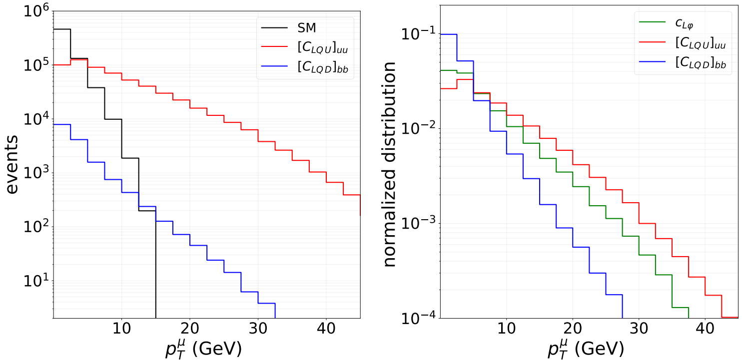
1. $ep \to \tau X \to e + \not{E} + X$
2. $ep \to \tau X \to \mu + \not{E} + X$
3. $ep \to \tau X \to X_h + \not{E} + X$

(substantial) background from standard NC and CC DIS

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

thanks to Miguel Arratia!

# Muon channel




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

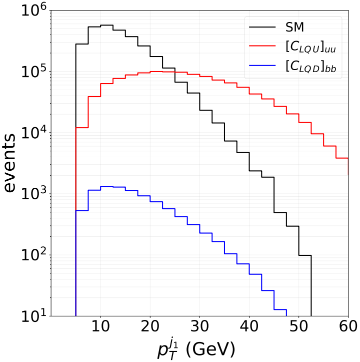
$$p_T^\mu > 10\,\text{GeV}, \quad \not{E}_T > 15\,\text{GeV}, \quad p_T^{j_1} > 20\,\text{GeV}$$

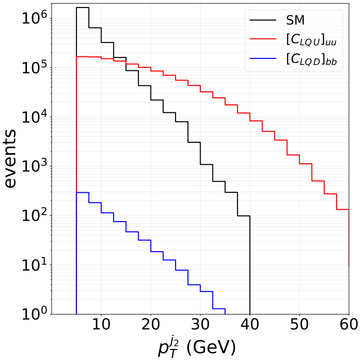
eliminates all SM background

- smaller signal efficiency for $Z$ couplings, heavy quarks

need muon detector?

# Hadronic channel



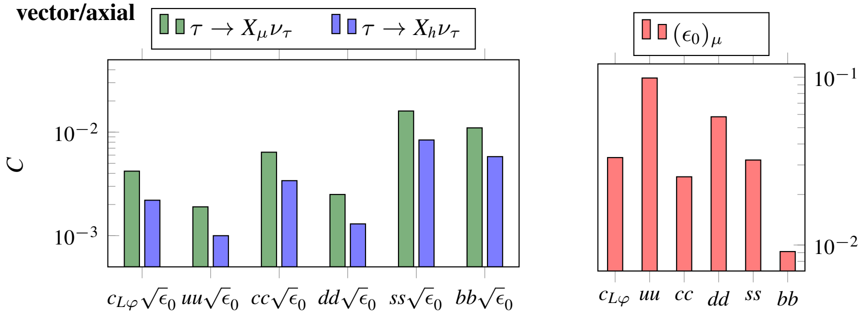

- one "$\tau$-tagged" jet, with 1 or 3 charged tracks, and close in $\phi$ to $\not{E}_T$
- recoils against a second jet, no charged leptons in final state

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

does not quite kill all SM background

- cuts severely suppress heavy quark signals

# EIC sensitivity to CLFV




- $\epsilon_{n_b}$: 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, $n_{\text{obs}} = n_b$

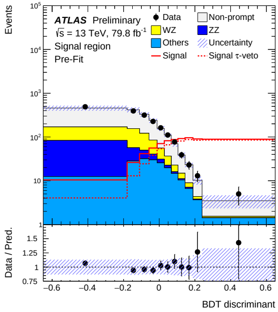
- EIC can probe couplings at the $10^{-3} - 10^{-2}$ level in $\mu$ channel

  can improve with "smarter" hadronic channel analysis

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

# Complementary probes: the LHC

# $Z$, Higgs and Top decays




ATLAS-CONF-2018-044

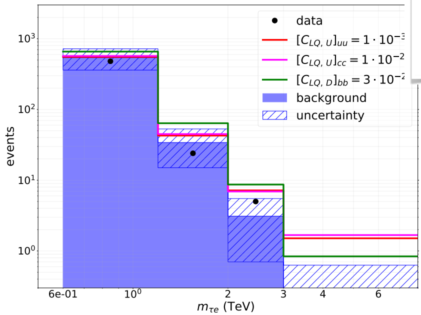
1. $Z \to \tau e$: studied at LEP and LHC, % level constraints on $c_{L\varphi}$, $c_{e\varphi}$
2. $H \to \tau e$: strong constraints ATLAS and CMS

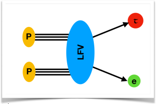
$$\left|Y'_{e\tau,\,\tau e}\right| < 2.0 \cdot 10^{-3}$$

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



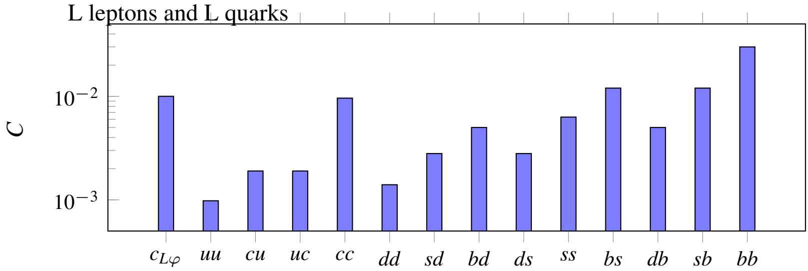




$\mathcal{L} = 36 \text{ fb}^{-1}$

ATLAS $pp \to \tau e$, $\tau \to$ hadrons
`arXiv:1807.06573`

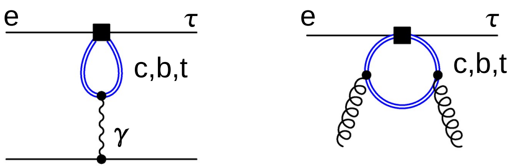
- if $\Lambda \gtrsim 3 - 4$ TeV, use same SMEFT operators as EIC
- simulate SMEFT operators at NLO in QCD (POWHEG + Pythia8 + Delphes)
- signal from four-fermion enhanced at large $m_{\tau e}$, indep. of Lorentz structure

# 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 $\sim 2$ 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




Match & run operators from EIC to scales relevant to $\tau/B$ decays

- $Z$ couplings, $\gamma$ dipole, 4-fermion operators with light quark match at tree level, running not important
- vector/axial operators with heavy quarks run onto light-quark at one loop $10^{-2}$-$10^{-3}$ suppression, but only vector contribute
- tensor operators run onto dipole, proportional to $m_q$
- scalar match onto dim-7 $GG$ operators, further suppressed by $\Lambda_{QCD}/m_q$

# B and $\tau$ 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) | | | | | | ✓ | |

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

✓ = tree ✓ (loop) = loop

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

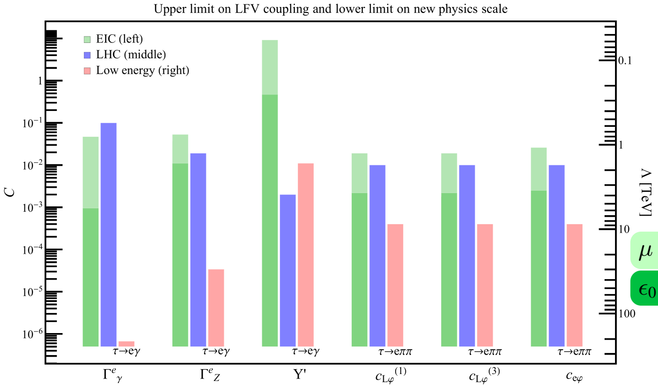
A. Celis, V. Cirigliano, E. Passemar, '14, V. Cirigliano, A. Crivellin, M. Hoferichter, '18
E. Passemar *private comm.*, K. Beloborodov, V. Druzhinin, S. Serednyakov, '19

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

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

see 2203.14919

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



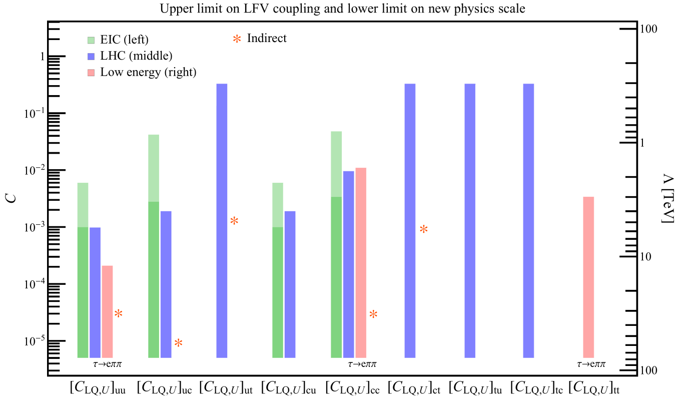

$\mu$ analysis

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

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

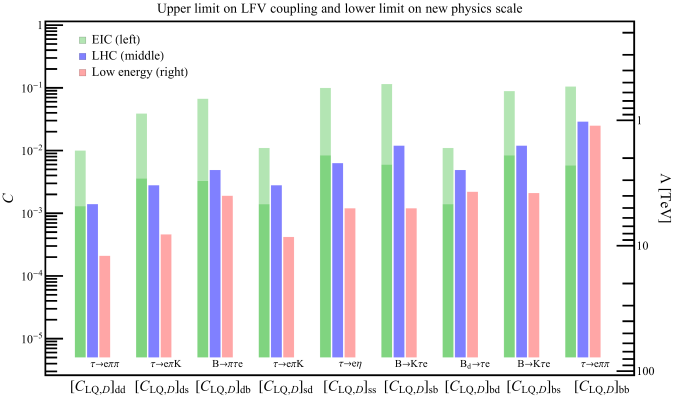
- no competition on $\gamma$ and $Z$ dipole operators
- strong direct LHC bound on $Y'$
- $\tau \to e\pi\pi$ dominates $Z$ couplings

# High-energy vs low-energy: four-fermion



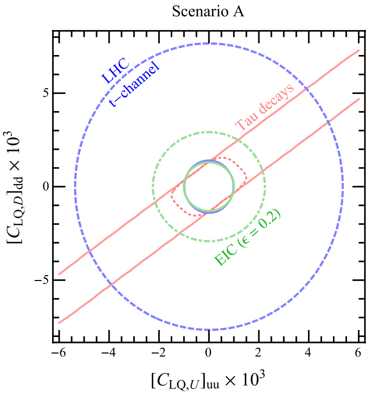

- uu $\tau \to e\pi\pi$ stronger by $\sim 5$,
  EIC and LHC competitive with $\tau \to e\pi$
- cc low-energy loop suppressed, EIC can do better than LHC
- tt surprisingly strong constraints from $\tau$ decays
- EIC & LHC crucial for off-diagonal

# 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



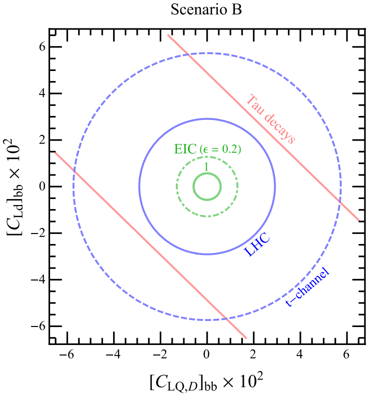

$$C_{LQ\,U} = \mathrm{diag}([C_{LQ\,U}]_{uu}, 0, 0)$$
$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, 0)$$
$$C_{Lu} = \mathrm{diag}([C_{Lu}]_{uu}, 0, 0)$$
$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, 0)$$
$$c_{L\varphi}$$

- $\pi\pi$ 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



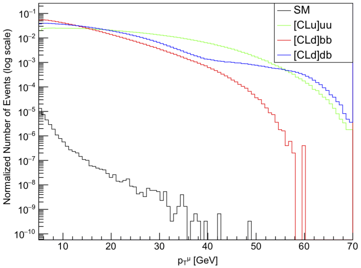

$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, [C_{LQ\,D}]_{bb})$$

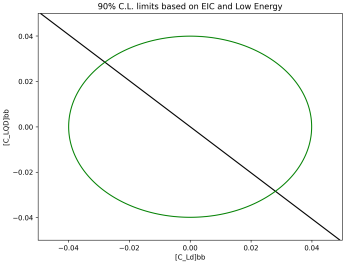
$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, [C_{Ld}]_{bb})$$

- turn on all V/A couplings to L leptons & $d$-type quarks
- contributions to hadronic $\tau$ 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!

# $e \to \mu$ conversion




thanks to F. Delzanno

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

  assuming $\mu$ reconstruction as good as electron
- very strong constraints from $\mu \to e$ conversion in nuclei

  also on heavy flavor operators
- but there are unconstrained directions, e.g. $b$ axial couplings

$$\bar{\mu}_{L,R}\gamma^\mu e_{L,R}\,\bar{b}\gamma_\mu\gamma_5 b$$

# Future directions

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

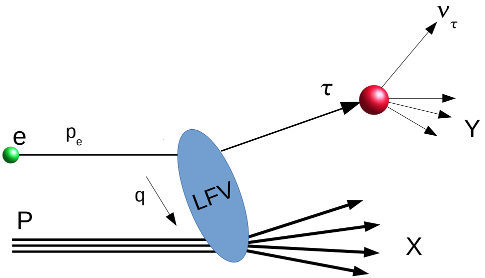
1. Z couplings
2. four-fermion with heavy quarks and quark-flavor-changing ops.

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 $\epsilon$ with $b$ tagging, ...
4. work towards a global fit
5. ...

# Back up

# CLFV Deep Inelastic Scattering




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

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

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

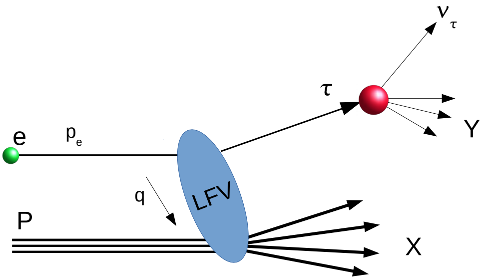
- at tree level

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

$\lambda_e$: electron polarization

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

# CLFV Deep Inelastic Scattering




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

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

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

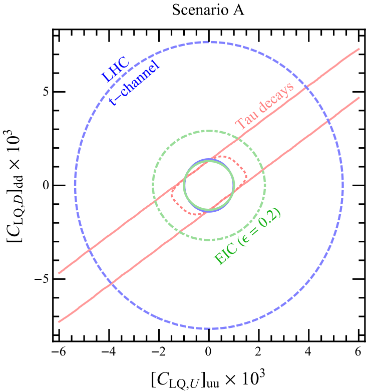
e.g. LL vector like operators

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

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

analogous to $Z$-exchange DIS

# Towards a global fit



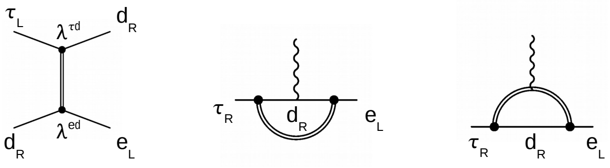

$$
\begin{aligned}
C_{LQ\,U} &= \mathrm{diag}([C_{LQ\,U}]_{uu}, 0, 0) \\
C_{LQ\,D} &= \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, 0) \\
C_{Lu} &= \mathrm{diag}([C_{Lu}]_{uu}, 0, 0) \\
C_{Ld} &= \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, 0) \\
c_{L\varphi} &
\end{aligned}
$$

- $\pi\pi$ 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

## CLFV and leptoquarks




- leptoquarks are good candidate for BSM ($\nu$ 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 $\nu$ masses if we add $\nu_R$ which interact with LQ

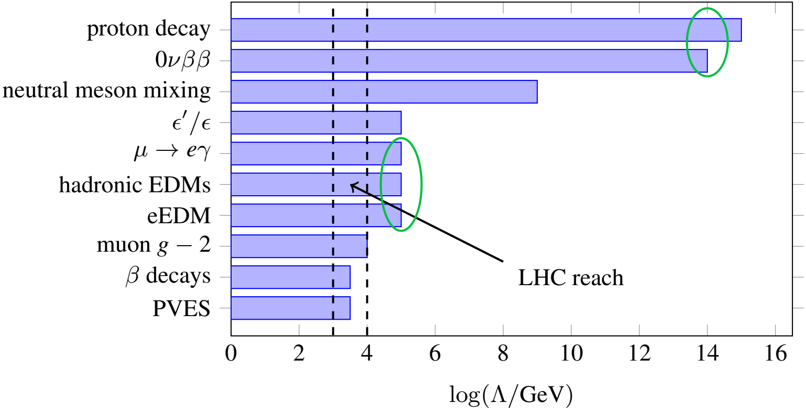
- match onto $L$-lepton, $R$ $d$ quark operator

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

- 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 $\tau$ 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 $\tau$ 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) | | | | | | ✓ | |
| | $ds$ | $db$ | $sb$ | | $cu$ | $ds$ | $db$ | $sb$ | | $cu$ | $ds$ | $db$ | $sb$ | | $cu$ | $ds$ | $db$ | $sb$ | | $cu$ | $cu$ | |
| $\tau \to eK_S^0$ | | | | | | ✓ | | | | | | | | | | ✓ | | | | | | |
| $\tau^- \to e^-K\pi$ | ✓ | | | | | | | | | | ✓ | | | | | | | | | | | |
| $B^0 \to e\tau$ | | | | | | | ✓ | | | | | | | | | | ✓ | | | | | |
| $B^+ \to \pi^+ e\tau$ | | ✓ | | | | | | | | | | ✓ | | | | | | | | | | |
| $B^+ \to K^+ e\tau$ | | | ✓ | | | | | | | | | | ✓ | | | | | | | | | |

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

| Decay mode | $V$ $q^{(0)}$ | $V$ $q^{(1)}$ | $V$ $s$ | $V$ $c$ | $V$ $b$ | $A$ $q^{(0)}$ | $A$ $q^{(1)}$ | $A$ $s$ | $A$ $c$ | $A$ $b$ | $S$ $q^{(0)}$ | $S$ $q^{(1)}$ | $S$ $s$ | $S$ $c$ | $S$ $b$ | $P$ $q^{(0)}$ | $P$ $q^{(1)}$ | $P$ $s$ | $P$ $c$ | $P$ $b$ | $T$ $u$ | $T$ $c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\tau \to e\gamma$ | | | | | | | | | | | | | | | | | | | | | ✓ (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) | | | | | | ✓ | |

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

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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