Fundamental Symmetries and EIC

(Probing BSM physics at the EIC)

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Theory for EIC in the next decade

September 22$^{\text{th}}$ 2022

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

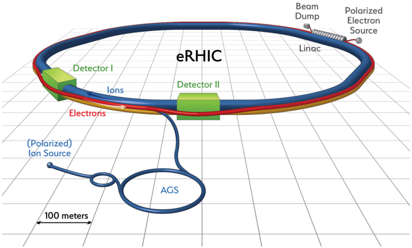
Finding BSM: the precision frontier

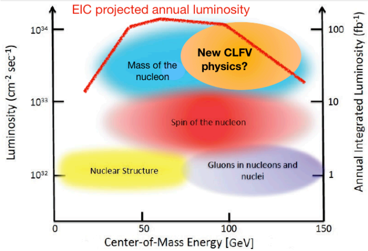
Majorana demonstrator

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

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

The Electron-Ion Collider: an intensity frontier machine?





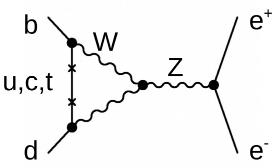
from A. Deshpande, hacked by C. Lee

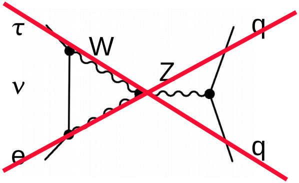
- EIC will deliver a lot of data!
  1000 times more than HERA (at a smaller $\sqrt{s}$)
- with additional unique possibility to polarize e and proton beams

can we look for rare/BSM processes?
can it be competitive with LHC/low energy probes?

Charged lepton flavor violation

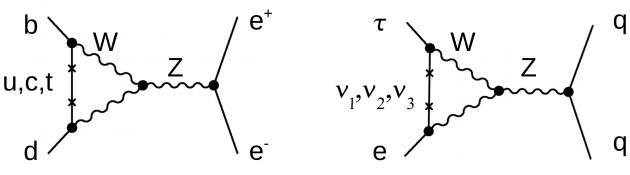
Charged lepton flavor violation





- 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
  $\Longrightarrow$ lepton family (LF) is exactly conserved

Charged lepton flavor violation



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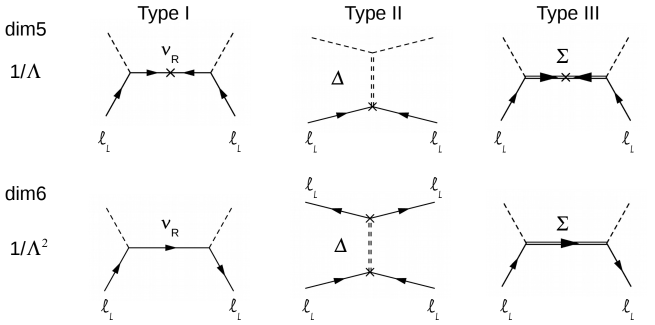
but neutrino have masses!

- 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

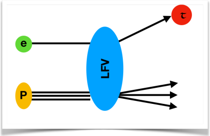


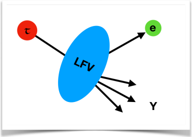
- . . . however, models that explain m_ν usually introduce new CLFV at tree or loop level

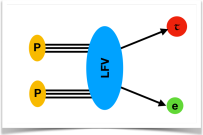
e.g. type I, II and III see-saw
A. Abada, C. Biggio, F. Bonnet, M. B. Gavela, T. Hambye, '08

- 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

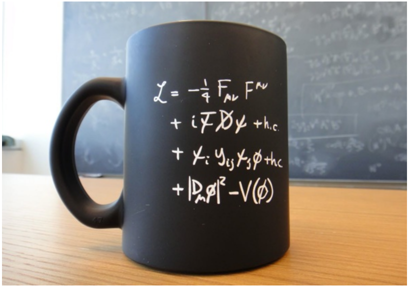
$\tau \leftrightarrow e$ transitions

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

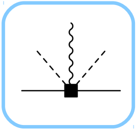
The Standard Model Effective Field Theory



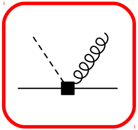
- SM fields, no new light degrees of freedom (e.g. no ν_R)
- local $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance
- organize them in a power counting based on canonical dimension

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

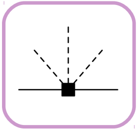
SMEFT for CLFV



vector/axial currents



dipole

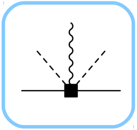


Yukawa

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

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

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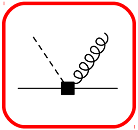
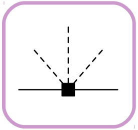
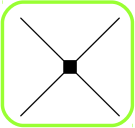

dipole


Yukawa

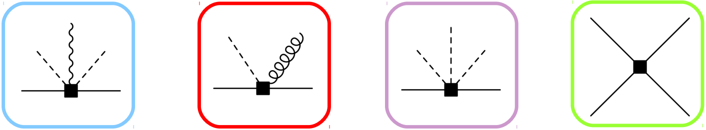

four-fermion

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

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

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

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

- assume generic quark flavor structures

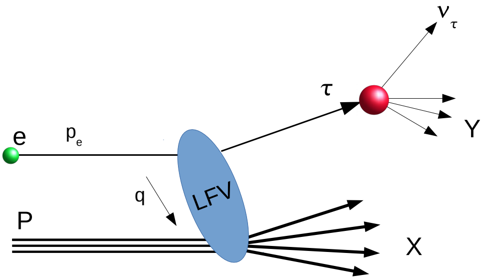
$$[C_{Ld}]_{\tau e} = \begin{pmatrix} [C_{Ld}]_{dd} & [C_{Ld}]_{ds} & [C_{Ld}]_{db} \\ [C_{Ld}]_{sd} & [C_{Ld}]_{ss} & [C_{Ld}]_{sb} \\ [C_{Ld}]_{bd} & [C_{Ld}]_{bs} & [C_{Ld}]_{bb} \end{pmatrix}$$

- 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



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

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

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

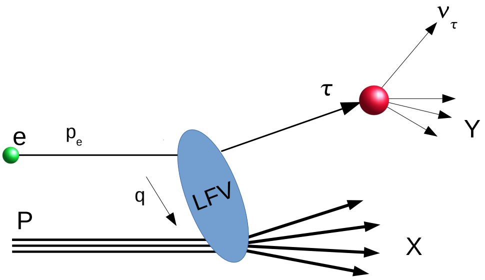
- at tree level

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

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



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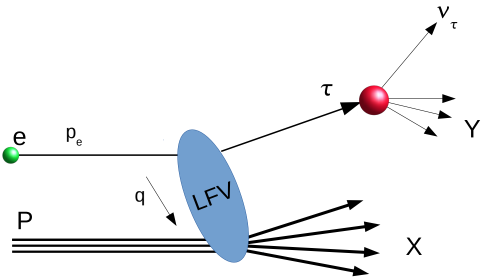
e.g. LL vector like operators

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

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

analogous to Z-exchange DIS



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

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

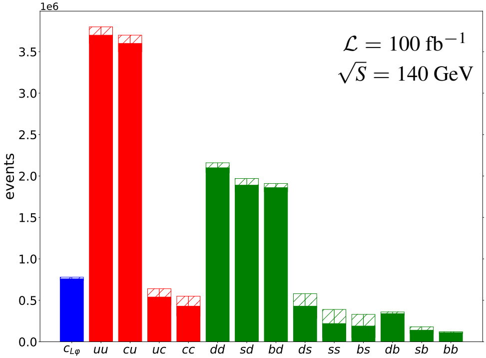
$$\sigma_0 = \frac{\alpha_{\rm em}^2 \pi S x}{Q^4}$$

e.g. scalar/tensor operators

$$\hat{\sigma}^{u_i}_{RR} = F_S\, y^2 \left\{ \left| \left[C^{(1)}_{LeQu}\right]_{\tau e u_i u_i} + 4\left(1-\frac{2}{y}\right)\left[C^{(3)}_{LeQu}\right]_{\tau e u_i u_i} + \frac{Y_u}{2}\,\left[Y'_e\right]_{\tau e}\,\frac{v^2}{m_H^2+Q^2} \right|^2 + \sum_{j\neq i} \left| \left[C^{(1)}_{LeQu}\right]_{\tau e u_j u_i} + 4\left(1-\frac{2}{y}\right)\left[C^{(3)}_{LeQu}\right]_{\tau e u_j u_i} \right|^2 \right\}$$

$$F_S = \frac{1}{4c_w^4 s_w^4}\,\frac{Q^4}{m_Z^4}$$

CLFV Deep Inelastic Scattering



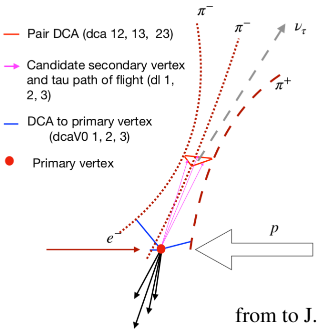
Left handed τ_L, e_L

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

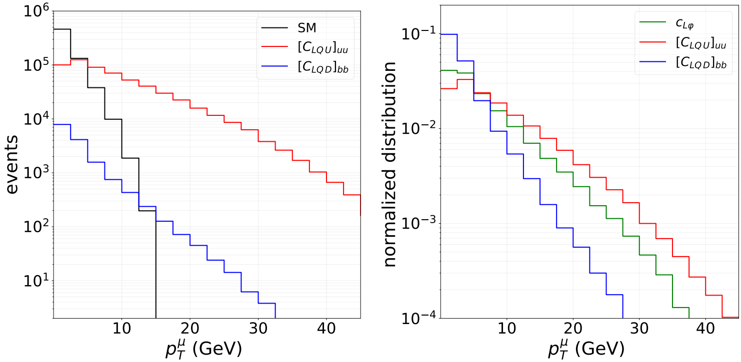
1. $ep \to \tau X \to e + \not{E} + X$
2. $ep \to \tau X \to \mu + \not{E} + X$
3. $ep \to \tau X \to X_h + \not{E} + X$

(substantial) background from standard NC and CC DIS

- simulate SM & 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

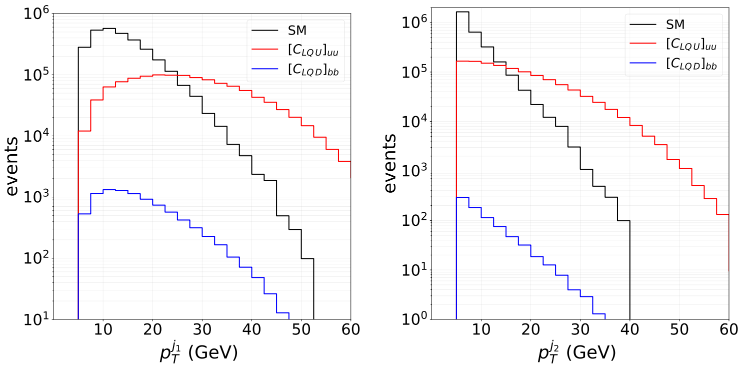
$$p_T^\mu > 10\,\text{GeV}, \quad \not{E}_T > 15\,\text{GeV}, \quad p_T^{j_1} > 20\,\text{GeV}$$

eliminates all SM background

- smaller signal efficiency for Z couplings, heavy quarks

need muon detector?

Hadronic channel



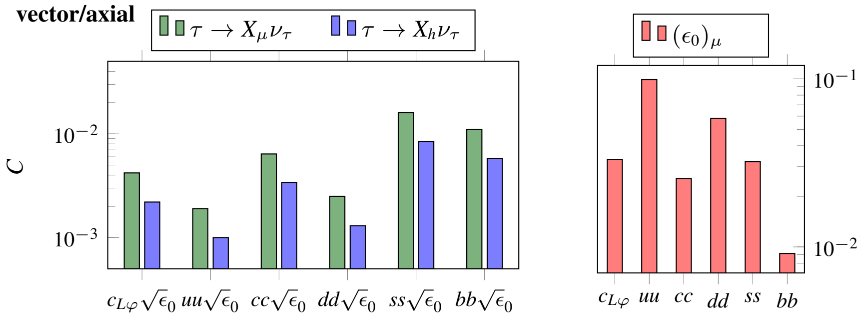
- one "τ-tagged" jet, with 1 or 3 charged tracks, and close in ϕ to $\not{E}_T$
- recoils against a second jet, no charged leptons in final state

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

does not quite kill all SM background

- cuts severely suppress heavy quark signals

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, $n_{\text{obs}} = n_b$

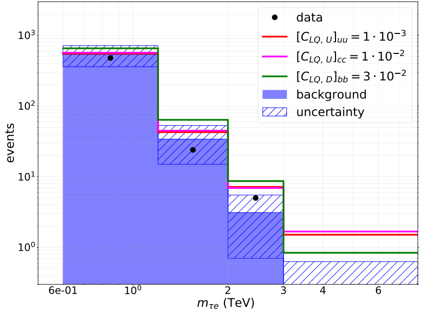
- EIC can probe couplings at the $10^{-3} - 10^{-2}$ level in μ channel

  can improve with "smarter" hadronic channel analysis

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

Complementary probes: LHC and τ decays

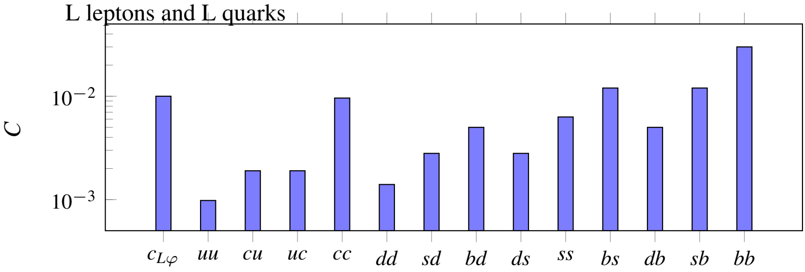
CLFV in high-invariant mass Drell-Yan



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

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



- LHC probes SMEFT coefficients at a similar level as EIC
- 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
- DY sensitive to sum of flavors
  tagging heavy flavors at EIC unique way to identify BSM mechanism
- LHC uniquely sensitive to LFV in Higgs and top FCNC couplings

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

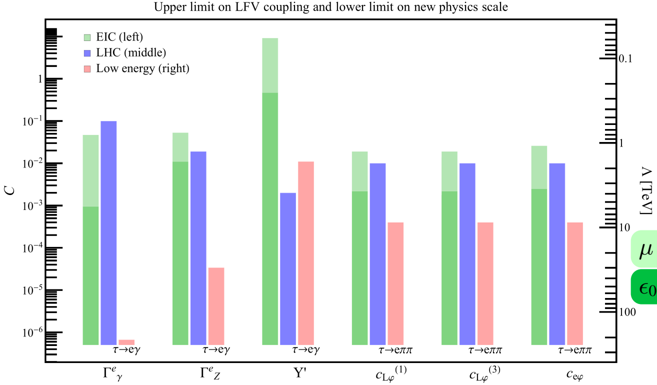
✓ = tree ✓ (loop) = loop

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

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



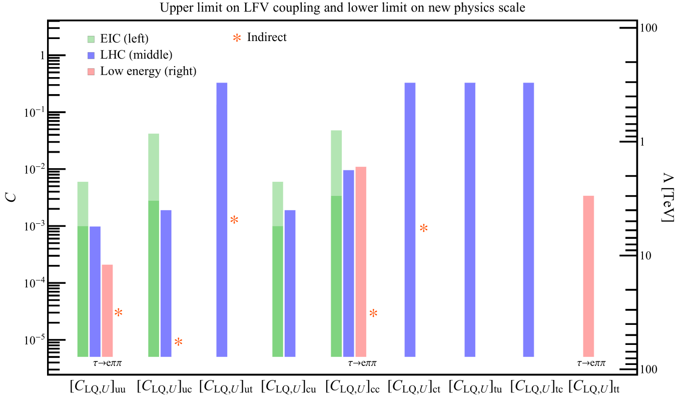
μ analysis

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

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

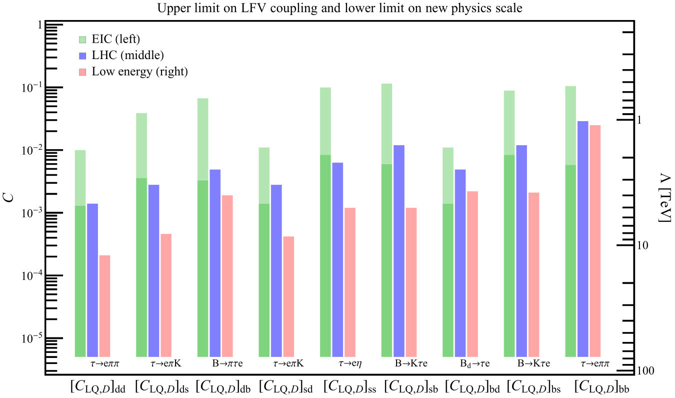
- no competition on γ and Z dipole operators
- strong direct LHC bound on Y'
- $\tau \to e\pi\pi$ dominates Z couplings

High-energy vs low-energy: four-fermion



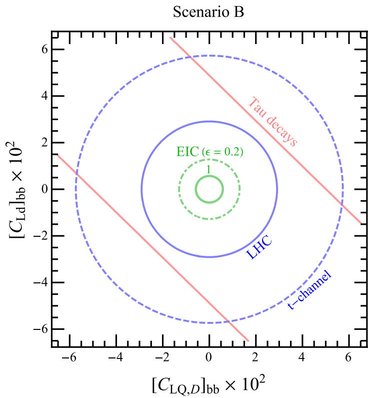
- **uu** $\tau \to e\pi\pi$ stronger by ~ 5,
  EIC and LHC competitive with $\tau \to e\pi$
- **cc** low-energy loop suppressed, EIC can do better than LHC
- **tt** surprisingly strong constraints from τ decays
- EIC & LHC crucial for off-diagonal

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

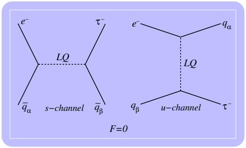


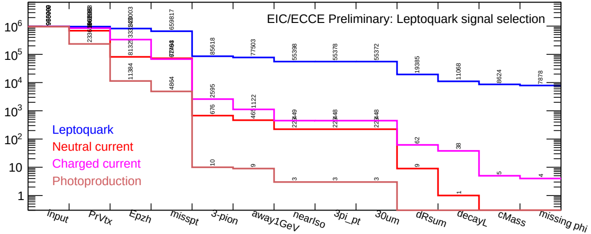
$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, [C_{LQ\,D}]_{bb})$$

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

- 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

CLFV and leptoquarks





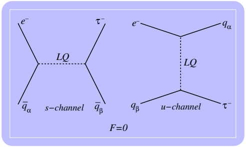
J. L. Zhang, S. Mantry *et al* (ECCE collaboration), ‘22

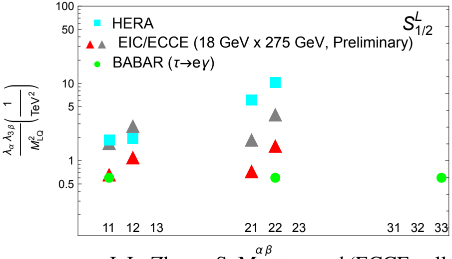
EIC sensitivity can be interpreted in terms of UV models (e.g. leptoquarks)

- dedicated ECCE study of the “3-prongs” mode

$$\tau \to \nu_\tau h^- h^- h^+ + \text{neutrals} \qquad (\text{BR} \sim 15\%)$$

- features of the τ jet (besides naive p_T cuts) further suppress SM backgrounds
- competitive limits on LQ scenarios





J. L. Zhang, S. Mantry *et al* (ECCE collaboration), '22

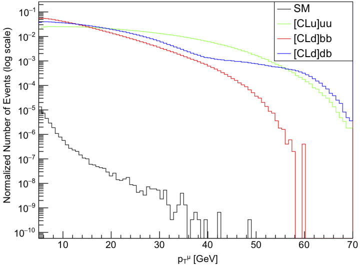
EIC sensitivity can be interpreted in terms of UV models (e.g. leptoquarks)

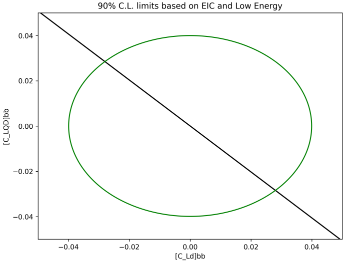
- dedicated ECCE study of the "3-prongs" mode

$$\tau \to \nu_\tau h^- h^- h^+ + \text{neutrals} \qquad (\text{BR} \sim 15\%)$$

- features of the τ jet (besides naive p_T cuts) further suppress SM backgrounds
- competitive limits on LQ scenarios

$e \to \mu$ conversion





thanks to F. Delzanno

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

  assuming μ 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

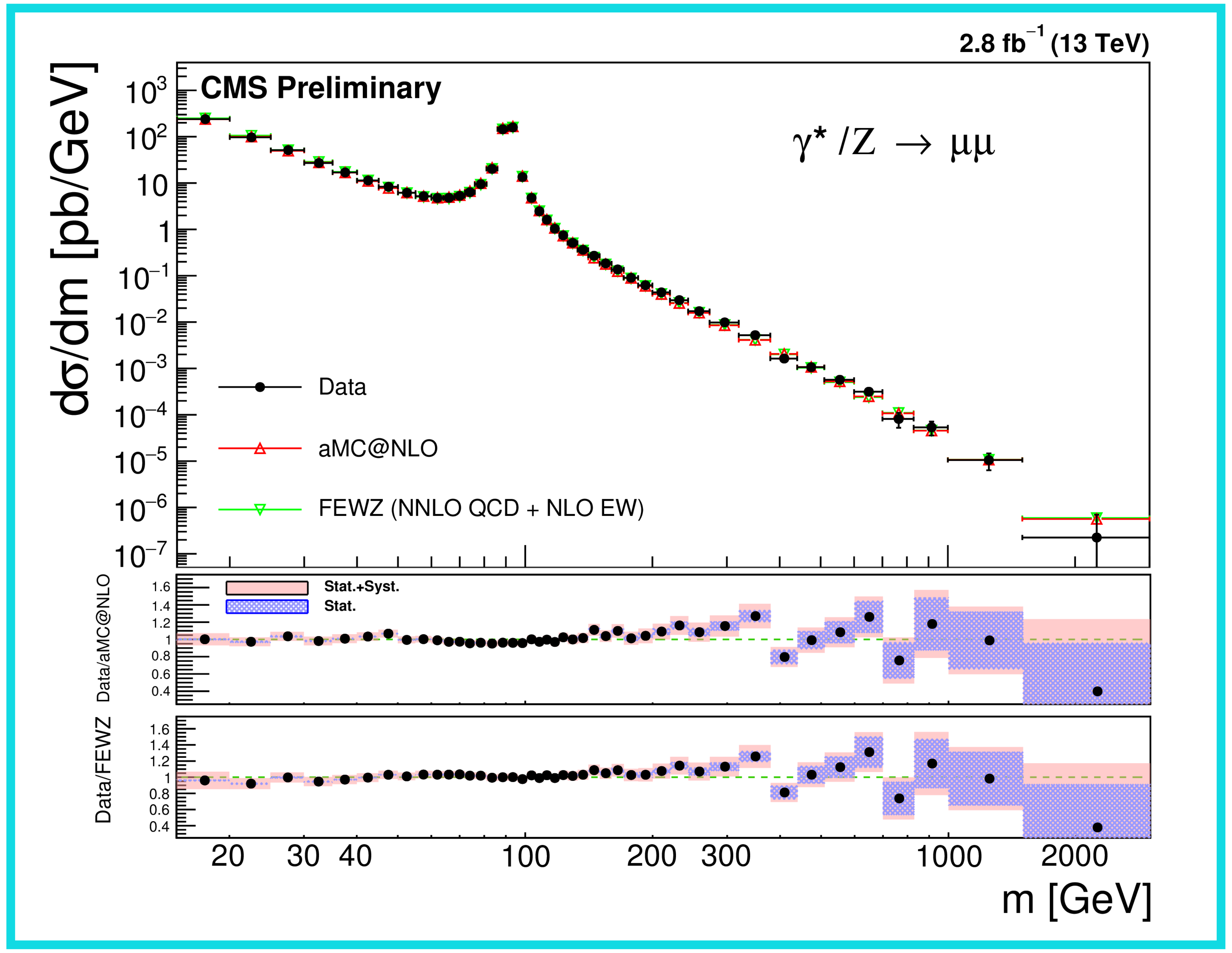
$$\bar{\mu}_{L,R}\gamma^{\mu}e_{L,R}\,\bar{b}\gamma_{\mu}\gamma_5 b$$

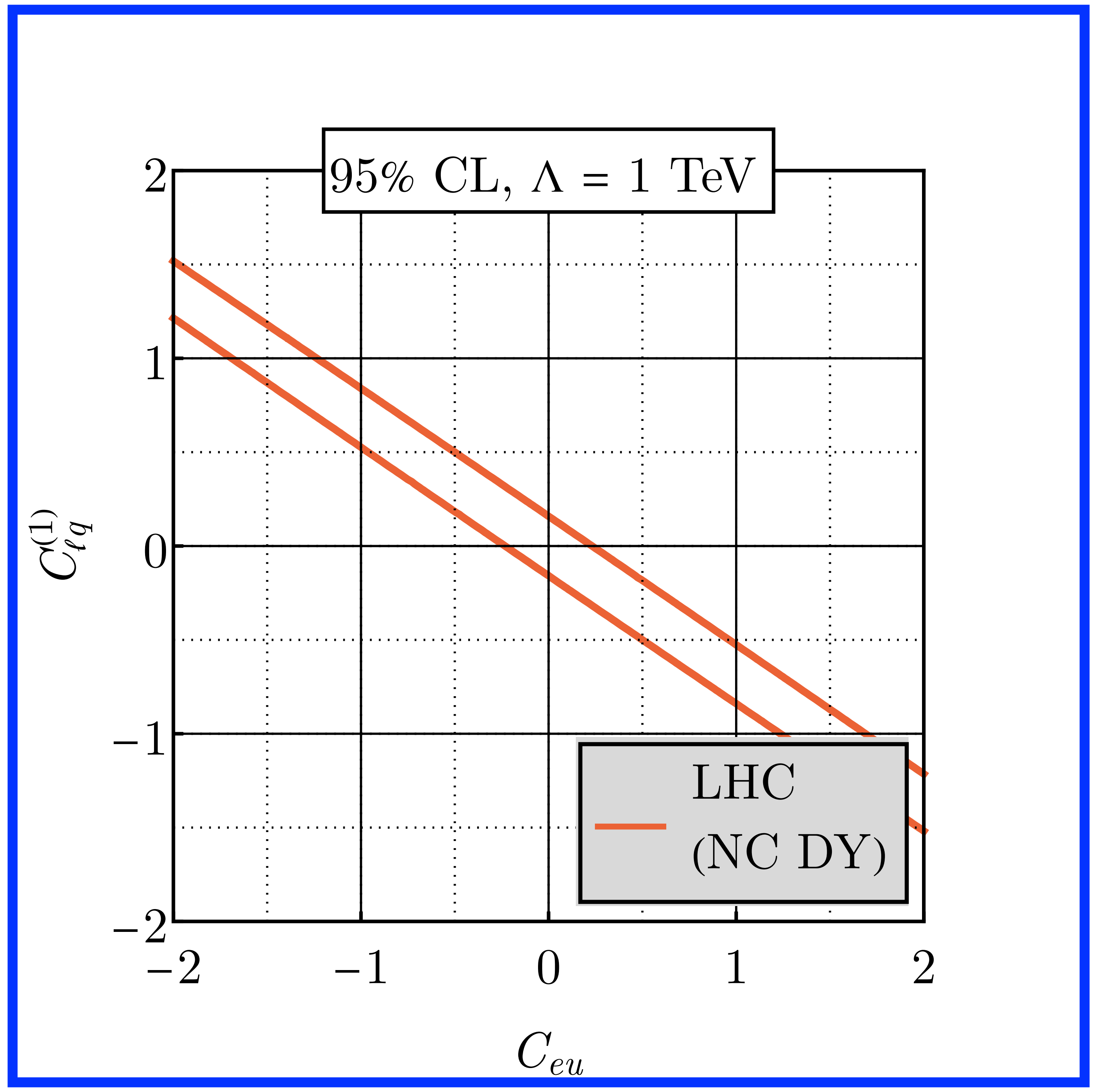
Electroweak physics

R. Boughezal, F. Petriello, D. Wiegand, Removing flat directions in standard model EFT fits;
B. Yan, Z. Yu, C. P. Yuan, The anomalous $Zb\bar{b}$ couplings at the HERA and EIC;
R. Boughezal, *et al*, Neutral-current electroweak physics and SMEFT studies at the EIC;
R. Abdul Khalek, *et al*, Electron Ion Collider for High Energy Physics (Snowmass21);

Blind spots in the LHC BSM coverage

- New semi-leptonic four-fermion interactions appear in numerous extensions of the SM: Z' models, TeV-scale gravity theories, leptoquarks, and many more.
- Strong constraints on them expected from LHC Drell-Yan data, due to very precise theory and small experimental errors.





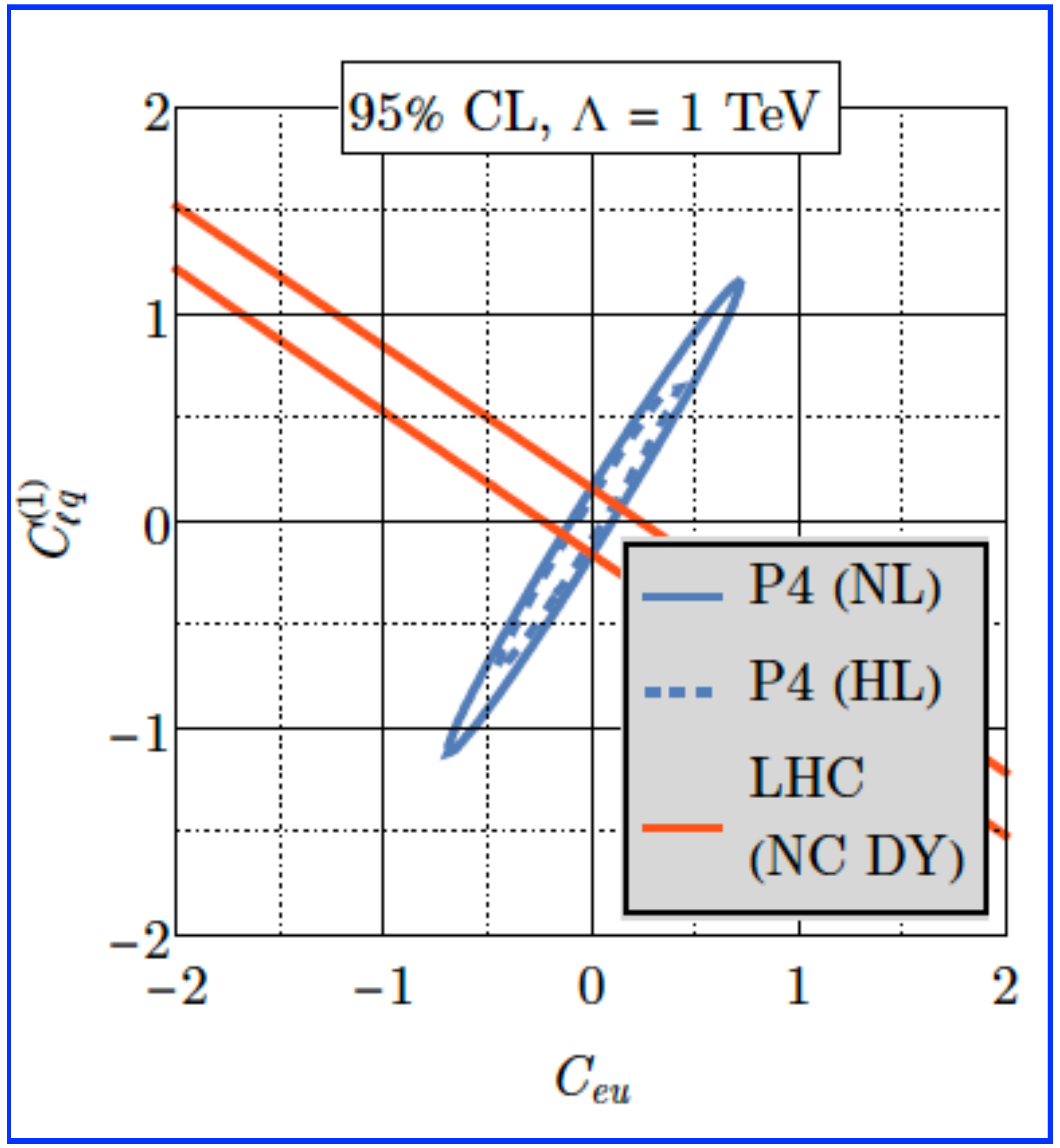
Boughezal, Petriello, Wiegand 2004.00748

Blind spots in the LHC coverage! LHC Drell-Yan invariant mass and rapidity distributions only probe one linear combination of parameters.

$$\mathcal{O}_{lq}^{(1)} : (\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q)$$
$$\mathcal{O}_{eu} : (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$$

Resolving LHC blind spots with the EIC

- The EIC, with the possibility of polarizing both beams, can remove these degeneracies. Excellent opportunity for complementarity with the LHC program!

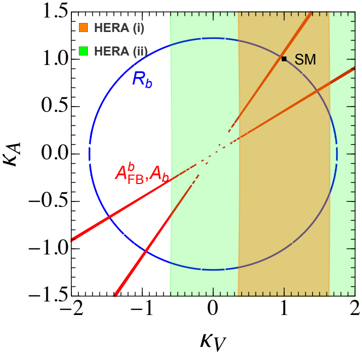


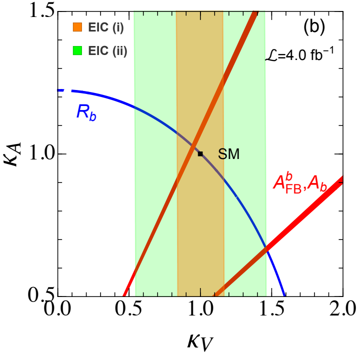
Boughezal et al, 2204.07557

- A fit to simulated parity-violating asymmetries assuming either polarized electrons or protons/deuterons shows that no degeneracies remain in the parameter space after the nominal EIC program.
- The EIC and LHC probes of Wilson coefficients are orthogonal. They can be combined to further strengthen the bounds on the parameter space.

P4 (NL) : 10 GeV x 275 GeV ep, 100 fb^-1
P4 (HL): 10 GeV x 275 GeV ep, 1000 fb^-1

Constraining the $Z\bar{b}b$ coupling





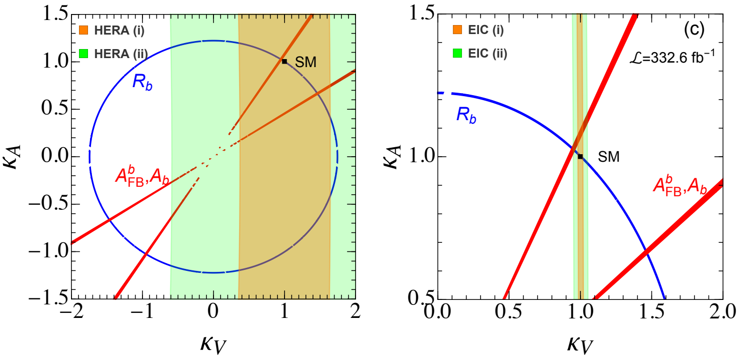
B. Yan, Z. Yu, C. P. Yuan, '21

- long standing 2σ tension in b forward-backward asymmetry at LEP
- LEP/SLC not sufficient to lift the degeneracy in κ_A-κ_V plane
- exploit polarization at e-p colliders

$$A_e^b = \frac{1}{P_e}\frac{\sigma_b^{\text{tot}}(P_e) - \sigma_b^{\text{tot}}(-P_e)}{\sigma_b^{\text{tot}}(P_e) + \sigma_b^{\text{tot}}(-P_e)}$$

- high-luminosity EIC will falsify the anomaly

Constraining the $Z\bar{b}b$ coupling



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- high-luminosity EIC will falsify the anomaly

Conclusion

EIC's features allow for rich program of BSM searches

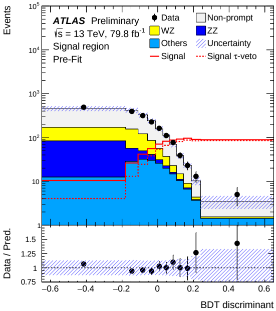
1. charged lepton flavor violation
2. anomalous couplings of Z and W bosons
3. precise extractions of SM couplings
4. extraction of nucleon MEs needed for BSM searches
5. ...

- competitive and complementary to LHC & low-energy probes

definitely worth pursuing!

Back up

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



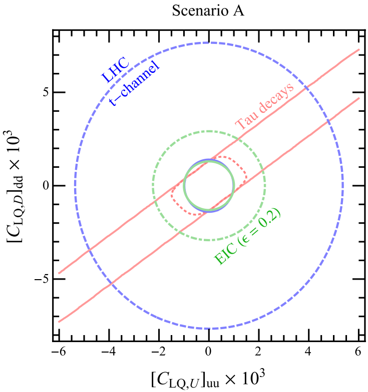
ATLAS−CONF−2018−044

- $Z \to \tau e$ 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



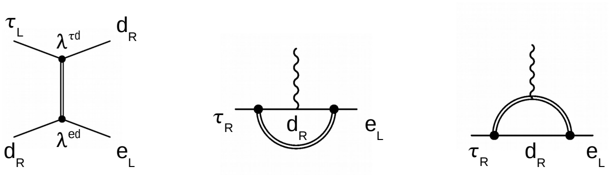
$$C_{LQ\,U} = \mathrm{diag}([C_{LQ\,U}]_{uu}, 0, 0)$$
$$C_{LQ\,D} = \mathrm{diag}([C_{LQ\,D}]_{dd}, [C_{LQ\,D}]_{ss}, 0)$$
$$C_{Lu} = \mathrm{diag}([C_{Lu}]_{uu}, 0, 0)$$
$$C_{Ld} = \mathrm{diag}([C_{Ld}]_{dd}, [C_{Ld}]_{ss}, 0)$$
$$c_{L\varphi}$$

- $\pi\pi$ 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

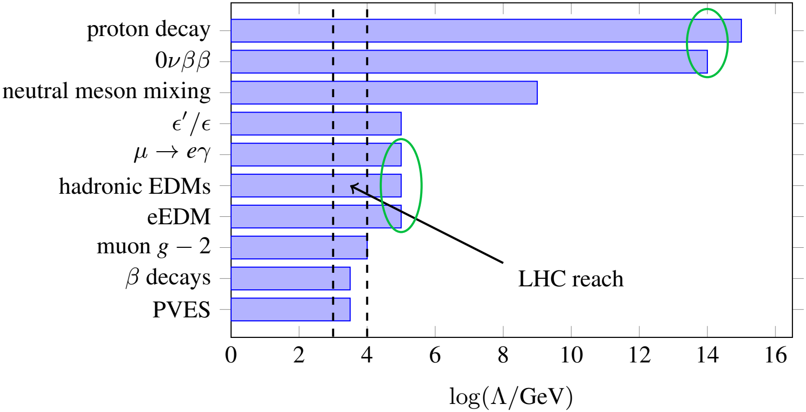
- match onto L-lepton, R d quark operator

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

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

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

B and τ CLFV decays

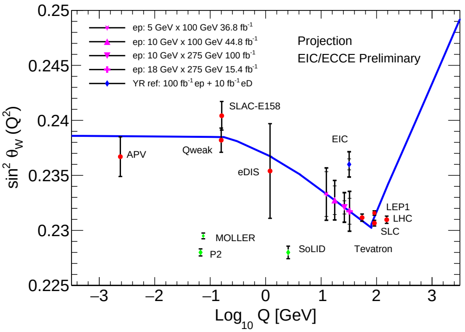
Decay mode	V					A					S					P					T	
	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	$q^{(0)}$	$q^{(1)}$	s	c	b	u	c
$\tau \to e\gamma$																					✓	✓
$\tau \to e\ell^+\ell^-$				✓	✓																	
$\tau \to e\pi^0$							✓										✓					
$\tau \to e\eta, \eta'$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

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



R. Boughezal, *et al.*, '22

- PV asymmetries allow for precise determination of $\sin^2\theta_W$ unpolarized PV asymmetry

$$A_{\mathrm{PV}}^{(e)} = \frac{1}{P_e}\frac{d\sigma^{++} + d\sigma^{+-} - d\sigma^{-+} - d\sigma^{--}}{d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}}$$

- $A_{\mathrm{PV}}^{(e)}$ can be measured at the percent level (dominated by statistics) competitive extraction of $\sin\theta_W$