Electroweak Physics at the EIC

Sonny Mantry
University of North Georgia

Electron-Ion Collider User Group Meeting 2016
UC Berkeley
January, 9th, 2016

Electroweak Physics at the EIC

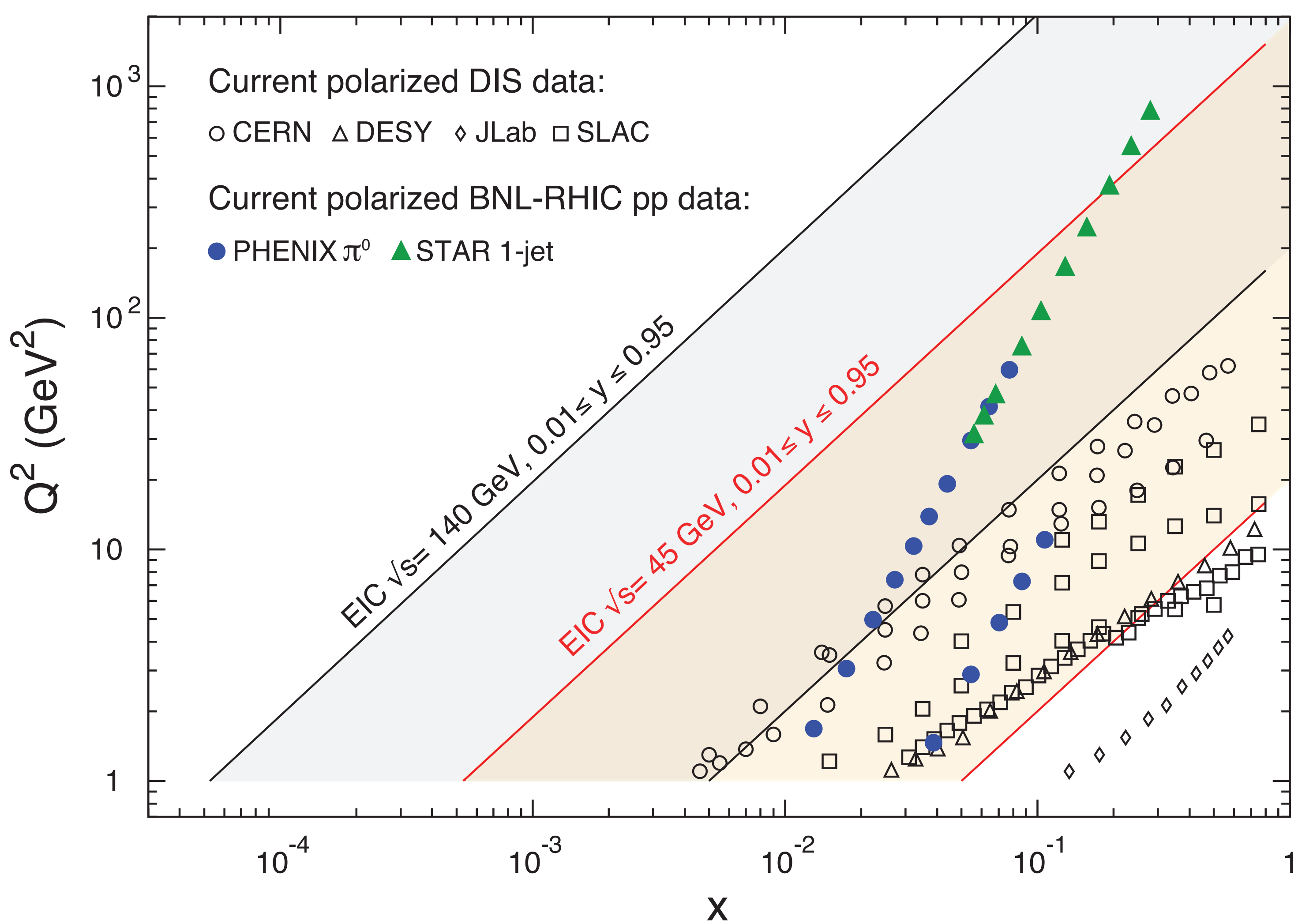
- The EIC is primarily a QCD machine.

- However, electroweak physics at the EIC can play an important role for:

-constraining new physics via precision measurements of electroweak couplings
-lepton flavor violation searches
-nucleon spin structure

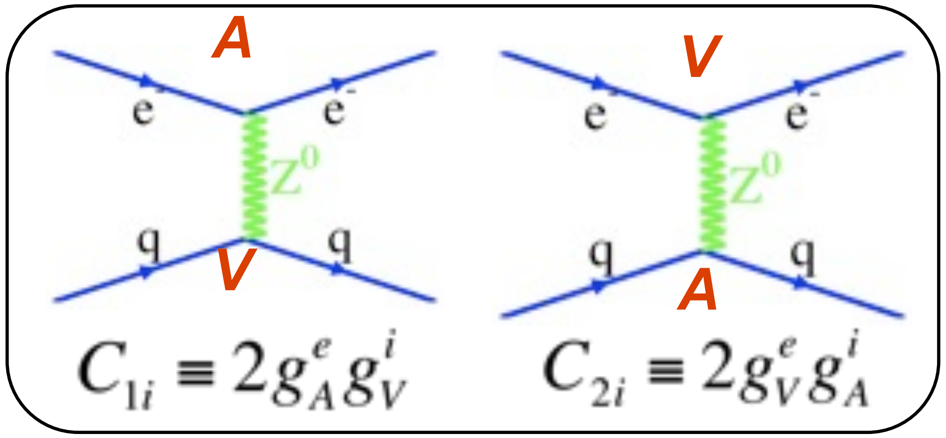
- This is facilitated by:

-high luminosity
-wide kinematic range
-polarized beams
-range of nuclear targets



Precision Measurements of the Weak Neutral Current Couplings

Precision Measurements of the Weak Neutral Current Couplings



- For $Q^2 << (M_Z)^2$ limit, electron-quark scattering via the weak neutral current is mediated by contact interactions:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^\mu\gamma_5 e\left(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\right) + \bar{e}\gamma^\mu e\left(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d\right)\right]$$

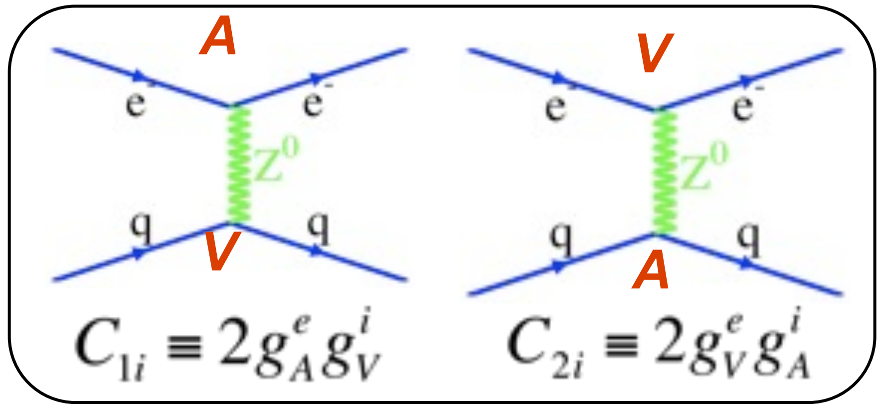
- At tree-level in the SM:

$$C_{1u}^{\text{tree}} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W, \qquad C_{1d}^{\text{tree}} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W,$$
$$C_{2u}^{\text{tree}} = -\frac{1}{2} + 2\sin^2\theta_W, \qquad C_{2d}^{\text{tree}} = \frac{1}{2} - 2\sin^2\theta_W \quad .$$

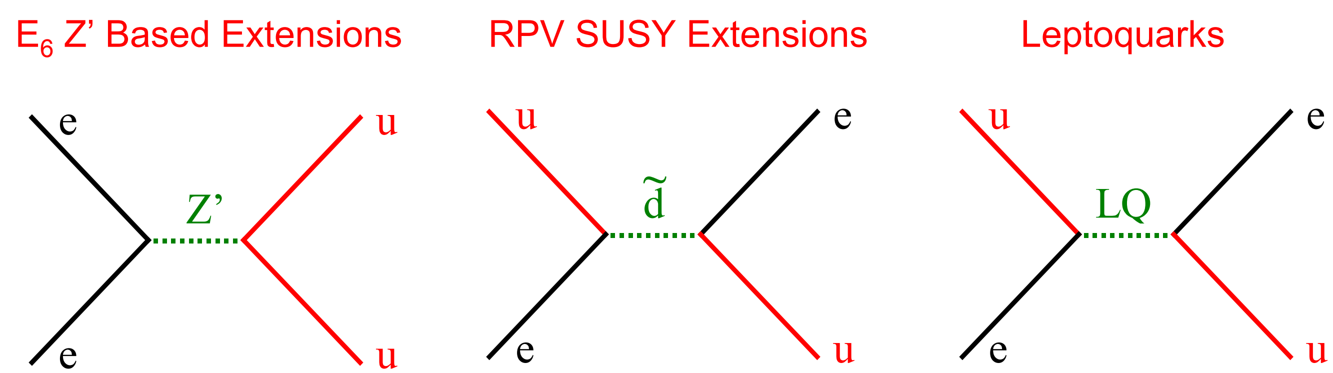
- These tree level values are modified by radiative corrections:

$$C_{1q} = 2\hat{\rho}_{NC} I_3^e \left(I_3^q - 2Q_q\hat{\kappa}\sin^2\hat{\theta}_W\right) - \frac{1}{2}\hat{\lambda}_1^q$$
$$C_{2q} = 2\hat{\rho}_{NC} I_3^q \left(I_3^e - 2Q_e\hat{\kappa}\sin^2\hat{\theta}_W\right) - \frac{1}{2}\hat{\lambda}_2^q$$

New Physics Effects



+



- New physics effects will shift the values of the effective C_{iq} coefficients:

$$\frac{g_{AV}^{eq}}{2v^2}\bar{e}\gamma^\mu\gamma^5 e\bar{q}\,\gamma_\mu q \rightarrow \left[\frac{g_{AV}^{eq}}{2v^2} + \frac{4\pi}{(\Lambda_{AV}^{eq})^2}\right]\bar{e}\gamma^\mu\gamma^5 e\bar{q}\,\gamma_\mu q$$

- Thus, precision measurements of the WNC couplings (or weak mixing angle), constrains new physics.

Precision Measurements of the Weak Neutral Current Couplings

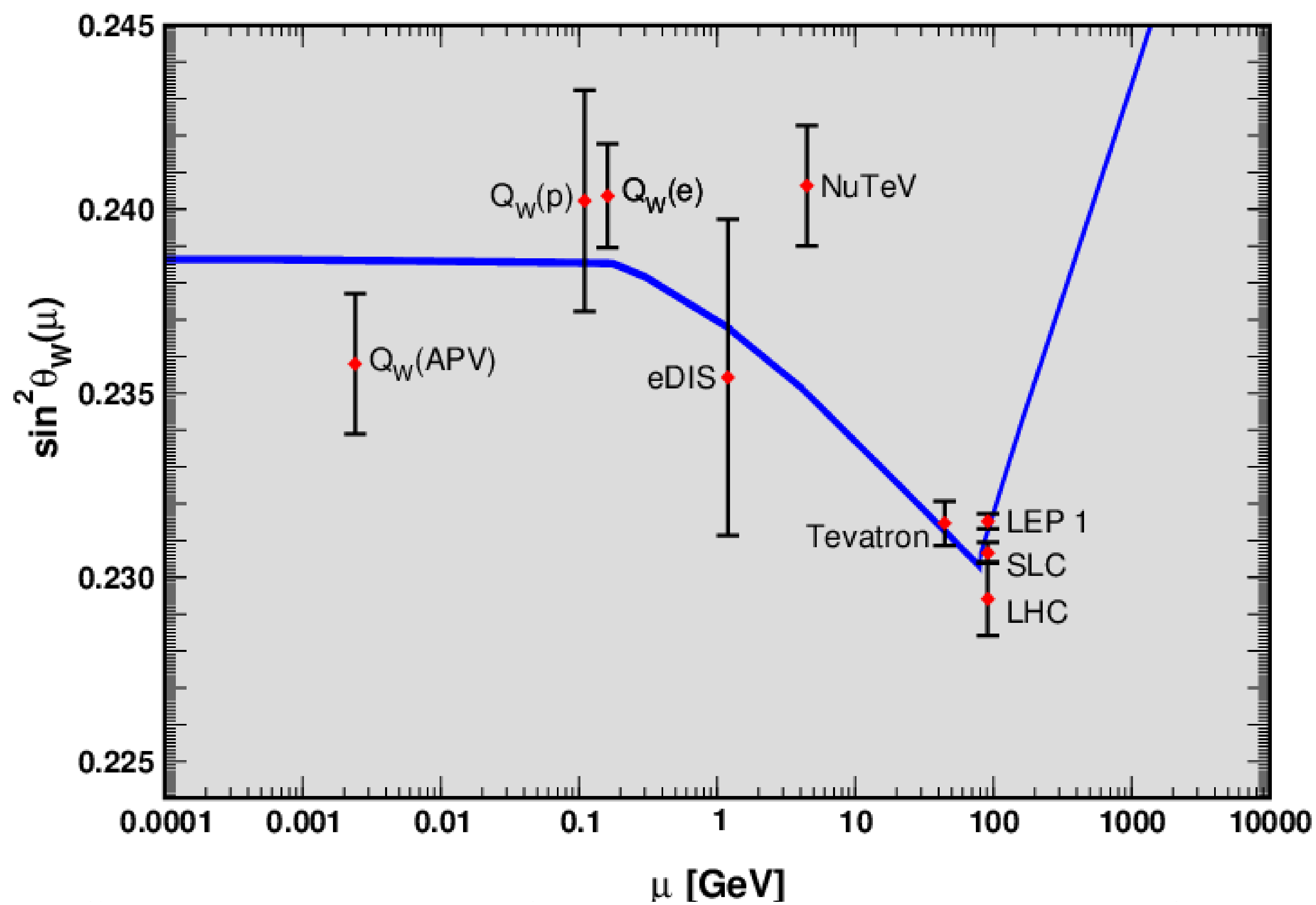
- New physics reach from various precision experiments and the combination of couplings they constrain:

Experiment	Λ	Coupling
Cesium APV	9.9 TeV	$C_{1u} + C_{1d}$
E-158	8.5 TeV	C_{ee}
Qweak	11 TeV	$2C_{1u} + C_{1d}$
SoLID	8.9 TeV	$2C_{2u} - C_{2d}$
MOLLER	19 TeV	C_{ee}
P2	16 TeV	$2C_{1u} + C_{1d}$

[K.kumar, et.al. Ann.Rev.Nucl.Part.Sci. 63 (2013) 237-267]

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\Big[\bar{e}\gamma^\mu\gamma_5 e\big(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\big) + \bar{e}\gamma^\mu e\big(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d\big)\Big]$$

Precision Measurements of the Weak Mixing Angle



[PDG]

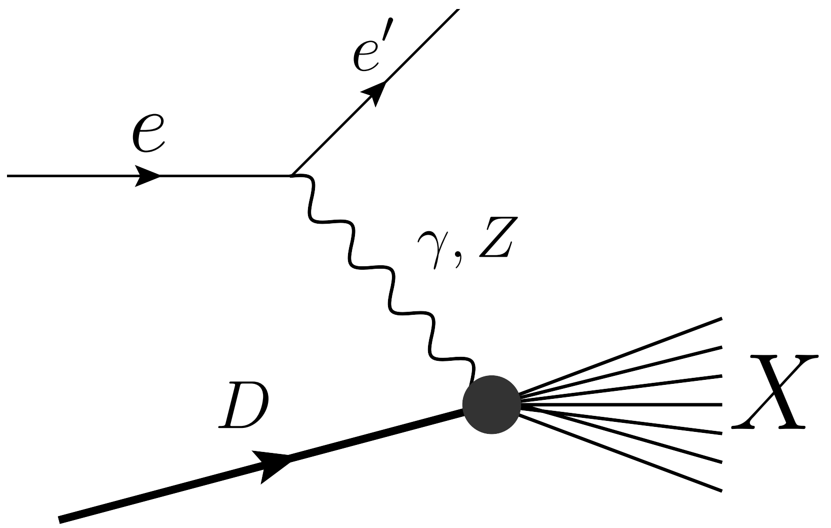
- Deviations from SM predictions can be hints for new physics

- Wide kinematic range and high luminosity of the EIC can provide many more measurements of the weak mixing angle along this curve.

Parity-Violating e-D Asymmetry

- Parity-violating e-D asymmetry is a powerful probe of the WNC couplings:

$$A_{\rm PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \simeq \frac{|A_Z|}{|A_\gamma|} \simeq \frac{G_F Q^2}{4\pi\alpha} \simeq 10^{-4} Q^2$$



- The asymmetry can be brought into the form:

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi\alpha}\left[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2} b(x)\right]$$

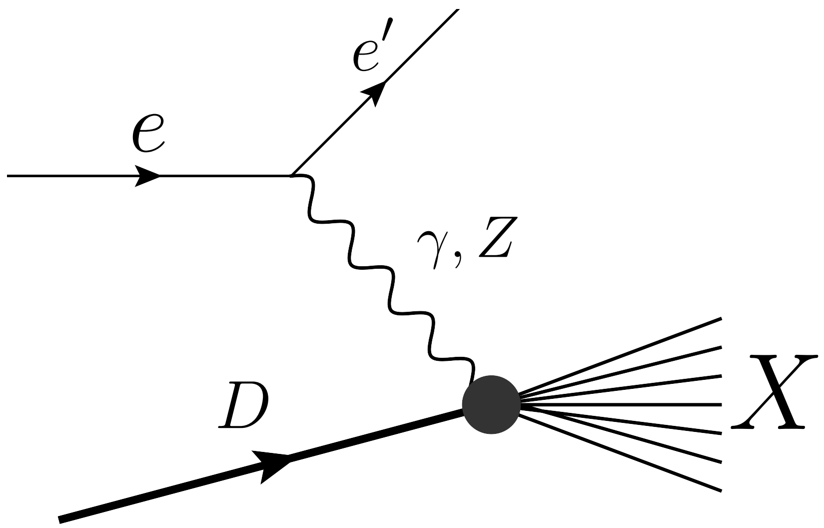
- QPM expressions:

$$a(x) \equiv \Sigma_i f_i(x) C_{1i} q_i / \Sigma_i f_i(x) q_i^2$$

$$b(x) \equiv \Sigma_i f_i(x) C_{2i} q_i / \Sigma_i f_i(x) q_i^2$$

Parity-Violating e-D Asymmetry

- Parity-violating e-D asymmetry is a powerful probe of the WNC couplings:



$$A_{\rm PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \simeq \frac{|A_Z|}{|A_\gamma|} \simeq \frac{G_F Q^2}{4\pi\alpha} \simeq 10^{-4} Q^2$$

- Due to the isoscalar nature of the Deuteron target, the dependence of the asymmetry on the structure functions largely cancels (Cahn-Gilman formula).

$$A^{RL}_{\rm CG} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\left(1 - \frac{20}{9}\sin^2\theta_W\right) + \left(1 - 4\sin^2\theta_W\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

All hadronic effects cancel! → Clean probe of WNC

- e-D asymmetry allows a precision measurement of the weak mixing angle.

Corrections to Cahn-Gilman

- Hadronic effects appear as corrections to the Cahn-Gilman formula

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\tilde{a}_1 + \tilde{a}_2\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$\tilde{a}_j = -\frac{2}{3}(2C_{ju} - C_{jd})\left[1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})\right]$$

New physics

Sea quarks

Charge symmetry violation

Target mass

Higher twist

- Hadronic effects must be well understood before any claim for evidence of new physics can be made.

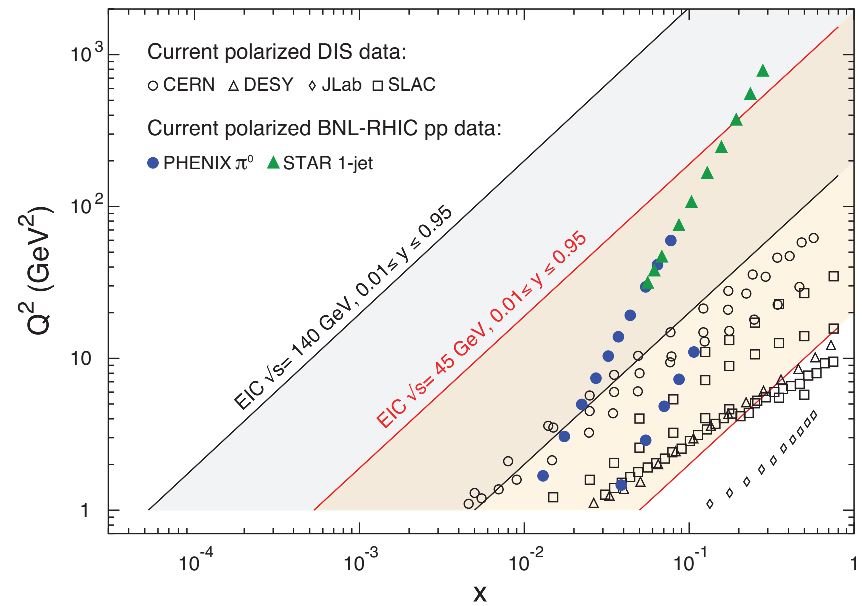
[J.Bjorken, T.Hobbs, W. Melnitchouk; S.Mantry, M.Ramsey-Musolf, G.Sacco; A.V.Belitsky, A.Mashanov, A. Schafer; C.Seng, M.Ramsey-Musolf, ...]

e-D PVDIS at EIC

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi\alpha}\left[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2} b(x)\right]$$

$$a(x) = \frac{6}{5}\left[(C_{1u} - \frac{1}{2}C_{1d}) + \text{corrections}\right]$$

$$b(x) = \frac{6}{5}\left[(C_{2u} - \frac{1}{2}C_{2d})\frac{q(x)-\bar{q}(x)}{q(x)+\bar{q}(x)} + \text{corrections}\right]$$

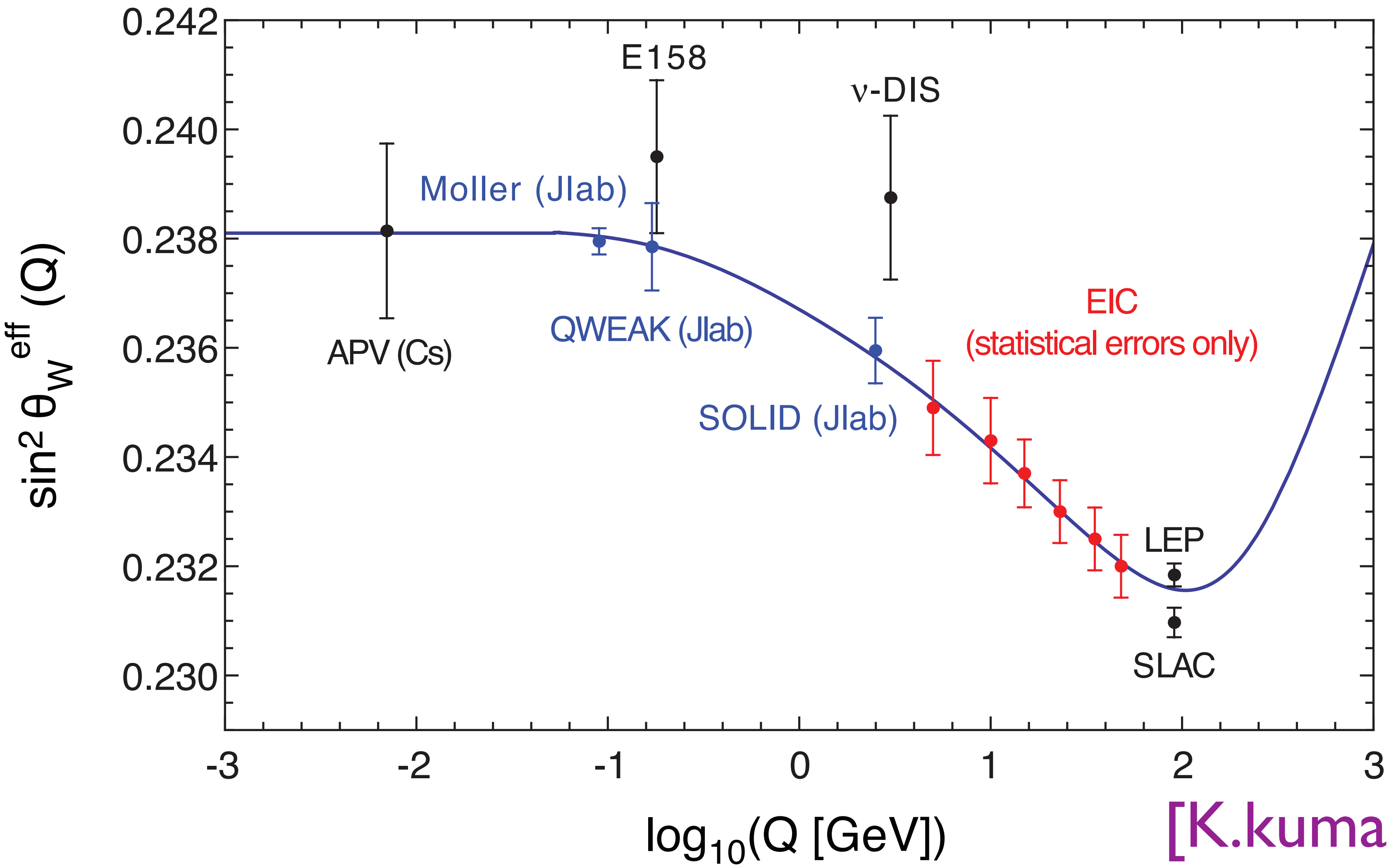


- EIC can make improve on the precision of the WNC couplings.
  - High luminosity:
    - -allows high precision
  - Measurements over wide range of y:
    - -allows clean separation of a(x) and b(x) terms
    - -clean separation of the combinations of WNC couplings:

$$2C_{1u} - C_{1d}, \;\; 2C_{2u} - C_{2d}$$

  - Region of high Q^2:
    - -larger asymmetry
    - -suppress higher twist effects
  - Region of high Q^2 and restrict range of Bjorken-x $0.2 \lesssim x \lesssim 0.5$
    - -suppress sea quark effects

Weak Mixing angle at EIC



[K.kumar, Y.Li, W.Marciano]

- Projected statistical uncertainties on the weak mixing angle at the EIC, for the following conditions:

$$\sqrt{s} \sim 140 \text{ GeV}$$

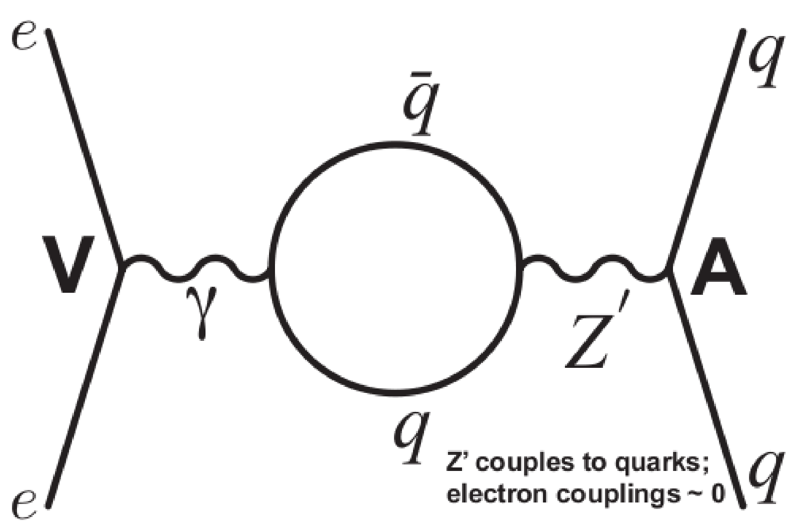
$$\mathcal{L} \sim 200 \text{ fb}^{-1}$$

Leptophobic Z'

- Leptophobic Z's are an interesting BSM scenario for a high luminosity EIC to probe.
- Leptophobic Z's couple very weakly to leptons:

  -difficult to constrain at colliders due to large QCD backgrounds

- Leptophobic Z's only affect the b(x) term or the C_{2q} coefficients in A_{PV}:

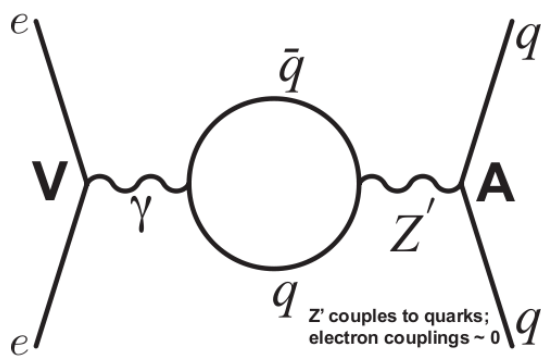


Leptophobic Z' contributes only to the C_{2q} couplings!

[M.Alonso-Gonzalez, M.Ramsey-Musolf;
M.Buckley,M.Ramsey-Musolf]

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi\alpha}\left[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2} b(x)\right]$$

Leptophobic Z'



Leptophobic Z' contributes only to the C_{2q} couplings!

[M.Alonso-Gonzalez, M.Ramsey-Musolf; M.Buckley,M.Ramsey-Musolf]

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi\alpha}\left[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2} b(x)\right]$$

- Measurements over wide range of Q^2 and y at EIC:

  -allows clean separation of a(x) and b(x) terms

  -clean separation of the combinations of WNC couplings:

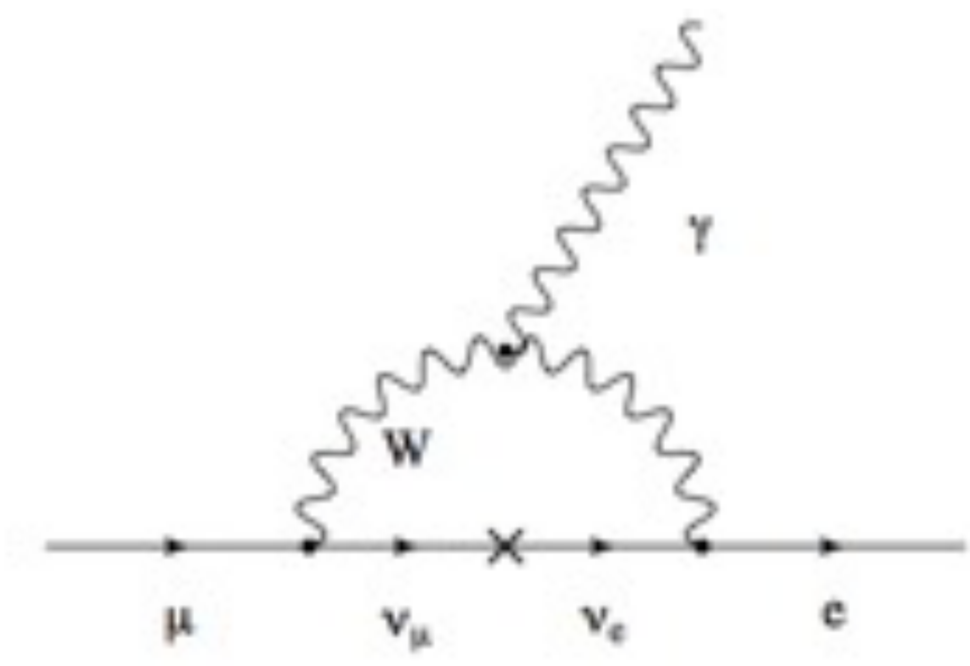
  $2C_{1u} - C_{1d}$, $\boxed{2C_{2u} - C_{2d}}$ → Only this combination is affected by leptophobic Z's

- JLab would be sensitive to leptophobic Z's with mass less than 150 GeV.
- EIC can match the 12 GeV JLab measurement with ~ 75 fb^{-1} .
- EIC can improve by a factor of 2 or 3 at 100 fb^{-1} .

Lepton Flavor Violation

Lepton Flavor Violation

- Discovery of neutrino oscillations indicate that neutrinos have mass!
- Neutrino oscillations imply Lepton Flavor Violation (LFV).
- LFV in the neutrinos also implies Charged Lepton Flavor Violation (CLFV):



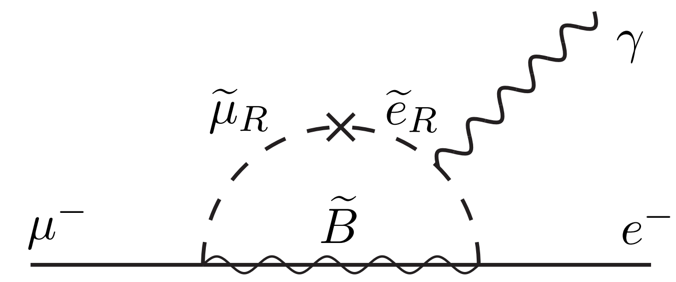
$$\mathrm{BR}(\mu \to e\gamma) < 10^{-54}$$

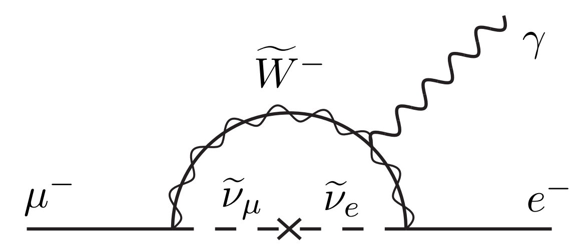
However, SM rate for CLFV is tiny due to small neutrino masses

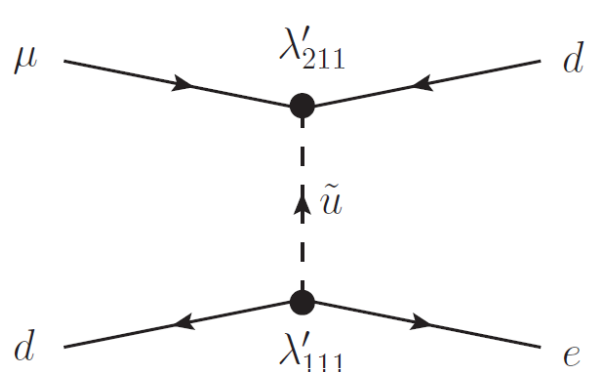
- No hope of detecting such small rates for CLFV at any present or future planned experiments!

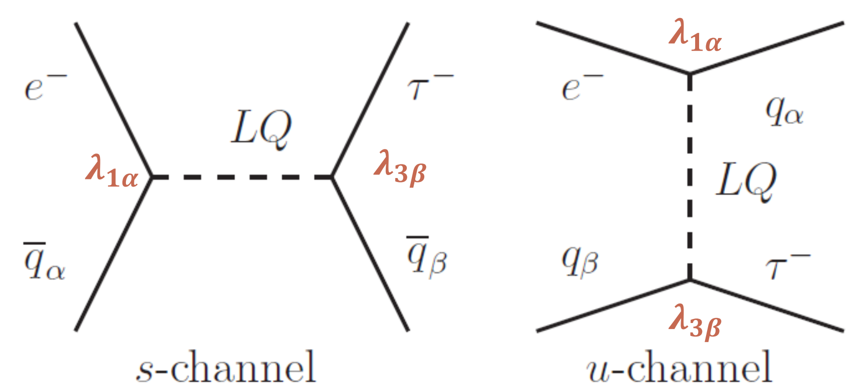
Lepton Flavor Violation in BSM

- However, many BSM scenarios predict enhanced CLFV rates:
  - SUSY (RPV)
  - SU(5), SO(10) GUTS
  - Left-Right symmetric models
  - Randall-Sundrum Models
  - LeptoQuarks
  - ...









- Enhanced rates for CLFV in BSM scenarios make them experimentally accessible.

Enhancement of CLFV in Minimal Flavor Violation Scenario

- In the absence of Yukawa couplings, the SM has a global symmetry in the quark sector:

$$SU(3)_Q \times SU(3)_U \times SU(3)_D$$

- In the absence of Yukawa couplings, the SM has a global symmetry in the lepton sector:

$$SU(3)_L \times SU(3)_E$$

- These global symmetries are broken by the Yukawa matrices:

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_U^{ij} \bar{Q}_L^i \epsilon \phi^* u_R^j - \lambda_D^{ij} \bar{Q}_L^i \phi d_R^j - \lambda_e^{ij} \bar{L}_L^i \phi e_R^j + h.c.$$

- Basic idea of Minimal Flavor Violation is that the flavor structure of the new physics is also governed entirely by these Yukawa matrices:

-allows a natural explanation of small FCNCs observed in the SM.

[Chivukula,Georgi;Buras et. al,
D'Ambrosio,Giudice,Isidori;
Cirigliano,Grinstein,Isidori,Wise]

Enhancement of CLFV in Minimal Flavor Violation Scenario

- MFV realized via a spurion analysis.

- If we assume the quark Yukawa matrices transform as:

$$\lambda_U \sim (3, \bar{3}, 1)$$
$$\lambda_D \sim (3, 1, \bar{3})$$
under $$SU(3)_Q \times SU(3)_U \times SU(3)_D$$

- And the lepton Yukawa matrices as:

$$\lambda_e \sim (\bar{3}, 3)$$ under $$SU(3)_L \times SU(3)_E$$

- Then the SM is invariant under these global symmetries.

- Construct higher dimension operators encoding new physics out of SM fields and the spurions and require them to be invariant under the global symmetries. This is MFV.

Minimal Flavor Violation with Majorana Neutrino Mass

- Non-zero neutrino mass already points to physics beyond the SM.

- Lepton sector with a Majorana mass generating effective operator:

$$\mathcal{L}_{\rm Sym.Br.} = -\lambda_e^{ij}\, \bar{e}_R^i (H^\dagger L_L^j) - \frac{1}{2\Lambda_{\rm LN}}\, g_\nu^{ij} (\bar{L}_L^{ci} \tau_2 H)(H^T \tau_2 L_L^j) + {\rm h.c.}$$

- Dimension-5 operator that generates Majorana neutrino mass violates lepton number and is suppressed by the scale of lepton number violating physics:

$$\Lambda_{\rm LN}$$

- Generalize MFV to include Majorana neutrino mass effect by treating g_ν^{ij} as another spurion field that transforms as:

$$g_\nu^{ij} \sim (6,1) \quad \text{under} \quad SU(3)_L \times SU(3)_E$$

Minimal Flavor Violation with Majorana Neutrino Mass

- Lepton sector with a Majorana mass generating effective operator:

$$\mathcal{L}_{\mathrm{Sym.Br.}} = -\lambda_e^{ij}\,\bar{e}_R^i(H^\dagger L_L^j) - \frac{1}{2\Lambda_{\mathrm{LN}}}\,g_\nu^{ij}(\bar{L}_L^{ci}\tau_2 H)(H^T\tau_2 L_L^j) + \mathrm{h.c.}$$

After EWSB

$$\to -v\lambda_e^{ij}\,\bar{e}_R^i e_L^j - \frac{v^2}{2\Lambda_{\mathrm{LN}}}\,g_\nu^{ij}\,\bar{\nu}_L^{ci}\nu_L^j + \mathrm{h.c.}$$

Neutrino mass matrix

- Using global $SU(3)_L \times SU(3)_E$ symmetry to rotate to charged lepton mass basis:

PMNS matrix

$$\lambda_e = \frac{m_\ell}{v} = \frac{1}{v}\,\mathrm{diag}(m_e, m_\mu, m_\tau)\ ,$$

$$g_\nu = \frac{\Lambda_{\mathrm{LN}}}{v^2}\,\hat{U}^* m_\nu \hat{U}^\dagger = \frac{\Lambda_{\mathrm{LN}}}{v^2}\,\hat{U}^*\mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})\hat{U}^\dagger$$

Minimal Flavor Violation with Majorana Neutrino Mass

[Cirigliano, Grinstein, Isidori, Wise]

- The following spurion combination becomes useful for constructing dimension six operators:

$$\Delta = g_\nu^\dagger g_\nu = \frac{\Lambda_{\rm LN}^2}{v^4}\ \hat{U} m_\nu^2 \hat{U}^\dagger$$

- It transforms as:

$$\Delta \ \sim (8,1) \quad \textbf{under} \qquad SU(3)_L \times SU(3)_E$$

- In terms of neutrino mass squared differences and mixing angles:

$$\begin{aligned}
\Delta_{\mu e} &= \frac{\Lambda_{\rm LN}^2}{v^4}\frac{1}{\sqrt{2}}\left(s\,c\,\Delta m_{\rm sol}^2 \pm s_{13}\,e^{i\delta}\,\Delta m_{\rm atm}^2\right)\\
\Delta_{\tau e} &= \frac{\Lambda_{\rm LN}^2}{v^4}\frac{1}{\sqrt{2}}\left(-s\,c\,\Delta m_{\rm sol}^2 \pm s_{13}\,e^{i\delta}\,\Delta m_{\rm atm}^2\right)\\
\Delta_{\tau \mu} &= \frac{\Lambda_{\rm LN}^2}{v^4}\frac{1}{2}\left(-c^2\,\Delta m_{\rm sol}^2 \pm \Delta m_{\rm atm}^2\right)
\end{aligned}$$

Minimal Flavor Violation

- In the absence of Yukawa couplings

$$\begin{array}{ll} (8,1) & \Delta, \lambda_e^\dagger\lambda_e, \Delta^2, \lambda_e^\dagger\lambda_e\Delta, \ldots \\ (\bar{3},3) & \lambda_e, \ \lambda_e\Delta, \ \lambda_e\lambda_e^\dagger\lambda_e \ , \ldots \\ (1,8) & \lambda_e\lambda_e^\dagger, \ \lambda_e\Delta\lambda_e^\dagger \ , \ldots \end{array}$$

- Leading invariant dimension six LFV operators built out of Δ and $\lambda_e\Delta$

[Cirigliano,Grinstein,Isidori,Wise]

$$O_{LL}^{(1)} = \bar{L}_L\gamma^\mu\Delta L_L \ H^\dagger iD_\mu H$$
$$O_{LL}^{(2)} = \bar{L}_L\gamma^\mu\tau^a\Delta L_L \ H^\dagger\tau^a iD_\mu H$$
$$O_{LL}^{(3)} = \bar{L}_L\gamma^\mu\Delta L_L \ \bar{Q}_L\gamma_\mu Q_L$$
$$O_{LL}^{(4d)} = \bar{L}_L\gamma^\mu\Delta L_L \ \bar{d}_R\gamma_\mu d_R$$
$$O_{LL}^{(4u)} = \bar{L}_L\gamma^\mu\Delta L_L \ \bar{u}_R\gamma_\mu u_R$$
$$O_{LL}^{(5)} = \bar{L}_L\gamma^\mu\tau^a\Delta L_L \ \bar{Q}_L\gamma_\mu\tau^a Q_L$$

$$O_{RL}^{(1)} = g' H^\dagger\bar{e}_R\sigma^{\mu\nu}\lambda_e\Delta L_L \ B_{\mu\nu}$$
$$O_{RL}^{(2)} = g H^\dagger\bar{e}_R\sigma^{\mu\nu}\tau^a\lambda_e\Delta L_L \ W_{\mu\nu}^a$$
$$O_{RL}^{(3)} = (D_\mu H)^\dagger\bar{e}_R\lambda_e\Delta D_\mu L_L$$
$$O_{RL}^{(4)} = \bar{e}_R\lambda_e\Delta L_L \ \bar{Q}_L\lambda_D d_R$$
$$O_{RL}^{(5)} = \bar{e}_R\sigma^{\mu\nu}\lambda_e\Delta L_L \ \bar{Q}_L\sigma_{\mu\nu}\lambda_D d_R$$
$$O_{RL}^{(6)} = \bar{e}_R\lambda_e\Delta L_L \ \bar{u}_R\lambda_U^\dagger i\tau^2 Q_L$$
$$O_{RL}^{(7)} = \bar{e}_R\sigma^{\mu\nu}\lambda_e\Delta L_L \ \bar{u}_R\sigma_{\mu\nu}\lambda_U^\dagger i\tau^2 Q_L$$

$$\boxed{\Lambda_{\mathrm{LFV}}}$$

LFV scale determines dimension six operators and is independent of lepton number violating scale that generates neutrino mass

- Enhanced rates for CLFV in BSM scenarios make them experimentally accessible.

$$\mathcal{L} = \frac{1}{\Lambda_{\mathrm{LFV}}^2}\sum_{i=1}^{5} c_{LL}^{(i)}O_{LL}^{(i)} + \frac{1}{\Lambda_{\mathrm{LFV}}^2}\left(\sum_{j=1}^{2} c_{RL}^{(j)}O_{RL}^{(j)} + \mathrm{h.c.}\right)$$

Minimal Flavor Violation

[Cirigliano,Grinstein,Isidori,Wise]

- CLFV lepton decay in MFV:

$$B_{\ell_i \to \ell_j \gamma} = 384\pi^2 e^2 \, \frac{v^4}{\Lambda_{\rm LFV}^4} \, |\Delta_{ij}|^2 \, \left| c_{RL}^{(2)} - c_{RL}^{(1)} \right|^2$$

- CLFV muon to electron conversion in MFV:

$$\begin{aligned} B_{\mu\to e}^{A} \;\; = \;\; & \frac{32\, G_F^2\, m_\mu^5}{\Gamma_{\rm capt}^A} \, \frac{v^4}{\Lambda_{\rm LFV}^4} \, |\Delta_{\mu e}|^2 \, \Bigg| \left(\left(\frac{1}{4} - s_w^2 \right) V^{(p)} - \frac{1}{4} V^{(n)} \right) \, (c_{LL}^{(1)} + c_{LL}^{(2)}) \\ + \;\; & \frac{3}{2} (V^{(p)} + V^{(n)}) \, c_{LL}^{(3)} + (V^{(p)} + \frac{1}{2} V^{(n)}) \, c_{LL}^{(4u)} + (\frac{1}{2} V^{(p)} + V^{(n)}) \, c_{LL}^{(4d)} \\ + \;\; & \frac{1}{2} (-V^{(p)} + V^{(n)}) \, c_{LL}^{(5)} - \frac{eD}{4} (c_{RL}^{(2)} - c_{RL}^{(1)})^* \Bigg|^2 \, , \end{aligned}$$

Minimal Flavor Violation

[Cirigliano,Grinstein,Isidori,Wise]

- For the choice $c_{RL}^{(2)} = c_{LL}^{(3)} = 1$ with all other Wilson coefficients vanishing, we get:

$$B_{\mu\to e\gamma} = 8.3\times 10^{-50}\left(\frac{\Lambda_{\rm LN}}{\Lambda_{\rm LFV}}\right)^4 \qquad B_{\mu\to e} = \left(\frac{\Lambda_{\rm LN}}{\Lambda_{\rm LFV}}\right)^4 \begin{cases} 6.6\times 10^{-50} & \text{for Al} \\ 19.6\times 10^{-50} & \text{for Au}\end{cases}$$

Huge enhancement factor when:

$$\Lambda_{\rm LN} \gg \Lambda_{\rm LFV}$$

- In MFV scenario, a large disparity between lepton number violation and lepton flavor violation scales will produce enhanced CLFV rates.

- For example:

$$\Lambda_{\rm LN} \sim 10^9 \Lambda_{\rm LFV} \longrightarrow \begin{cases} B_{\mu\to e\gamma} = \mathcal{O}(10^{-13}) \\ B_{\mu\to e} = \mathcal{O}(10^{-13}) \end{cases}$$

Charged Lepton Flavor Violating Processes

- Many CLFV processes are being searched for in hopes of discovering BSM signals:

$$\mu + N \to e + N \qquad (\mu \to e \text{ conversion in nuclei})$$

$$\left.\begin{array}{l} \mu \to e\gamma \\ \tau \to e\gamma \\ \tau \to \mu\gamma \\ \mu \to 3e \\ \tau \to 3e \end{array}\right| \qquad \text{(rare CLFV decays)}$$

Charged Lepton Flavor Violation Limits

- Present and future limits:

Process	Experiment	Limit $(90\%\ C.L.)$	Year
$\mu \to e\gamma$	MEGA	$Br < 1.2 \times 10^{-11}$	2002
$\mu + Au \to e + Au$	SINDRUM II	$\Gamma_{conv}/\Gamma_{capt} < 7.0 \times 10^{-13}$	2006
$\mu \to 3e$	SINDRUM	$Br < 1.0 \times 10^{-12}$	1988
$\tau \to e\gamma$	BaBar	$Br < 3.3 \times 10^{-8}$	2010
$\tau \to \mu\gamma$	BaBar	$Br < 6.8 \times 10^{-8}$	2005
$\tau \to 3e$	BELLE	$Br < 3.6 \times 10^{-8}$	2008
$\mu + N \to e + N$	Mu2e	$\Gamma_{conv}/\Gamma_{capt} < 6.0 \times 10^{-17}$	2017?
$\mu \to e\gamma$	MEG	$Br \lesssim 10^{-13}$	2011?
$\tau \to e\gamma$	Super-B	$Br \lesssim 10^{-10}$	$>$ 2020?

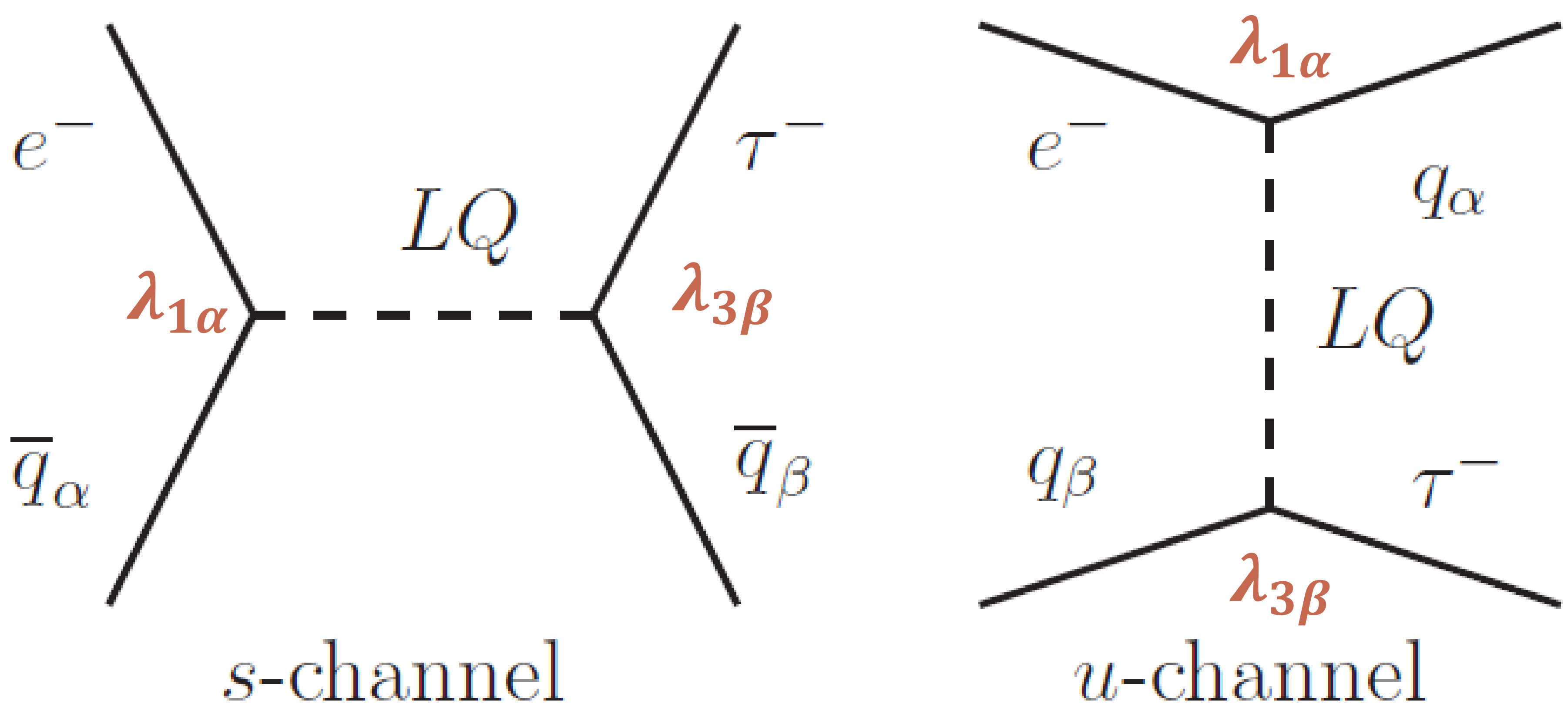
- Note that CLFV(1,2) is severely constrained. Limits on CLFV(1,3) are weaker by several orders of magnitude.
- Limits on CLFV(1,2) are expected to improve even further in future experiments.

CLFV in DIS

- The EIC can search for CLFV(1,3) in the DIS process:

$$ep \to \tau X$$

- Such a process could be mediated, for example, by leptoquarks:



CLFV limits from HERA

- The H1 and ZEUS experiments have searched for the CLFV process and set limits:

$$ep \to \tau X$$

$$\sqrt{s} \sim 320 \text{ GeV}$$

$$\mathcal{L} \sim 0.5 \text{ fb}^{-1}$$

- High luminosity EIC could surpass the best limits set by HERA :

$$ep \to \tau X$$

$$\sqrt{s} \sim 90 \text{ GeV}$$

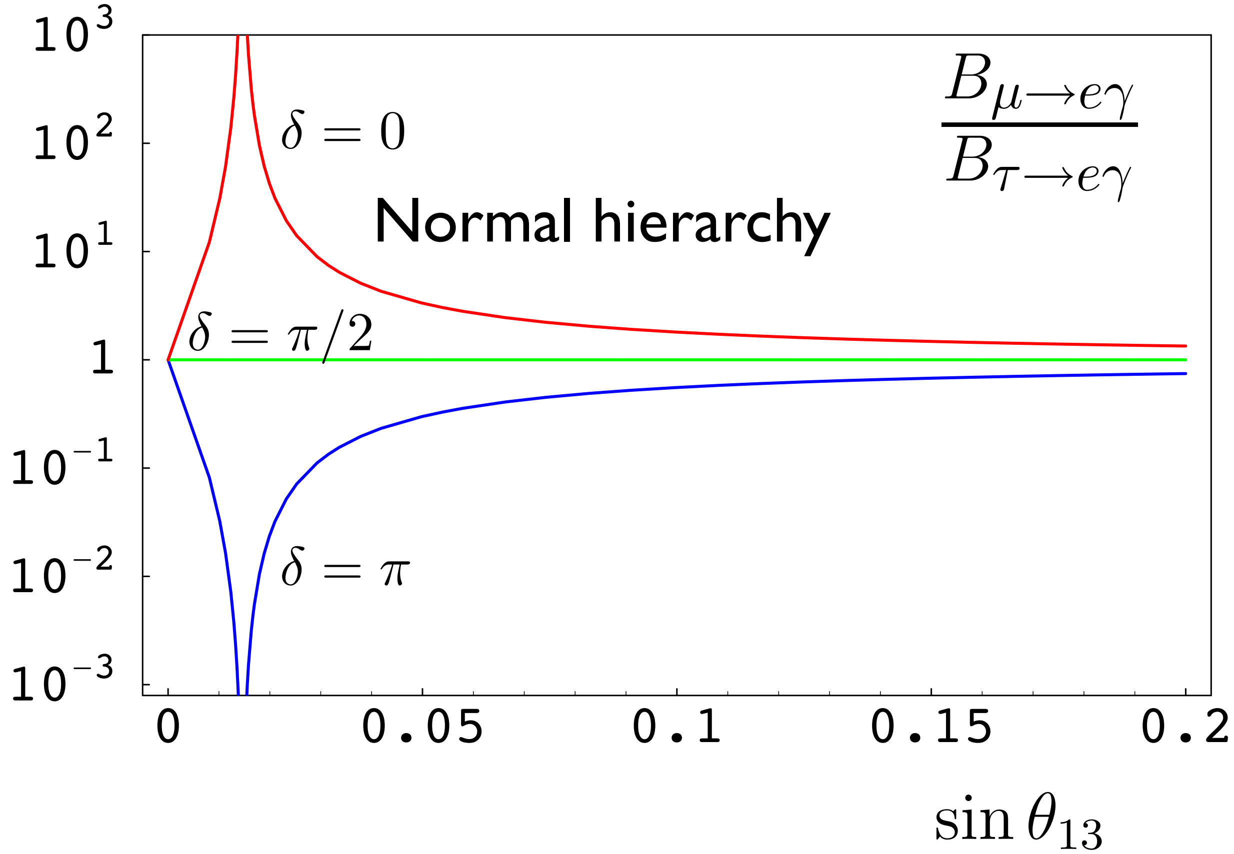
$$\mathcal{L} \sim 10 \text{ fb}^{-1}$$

- At $\mathcal{L} \sim 100 - 200 \text{ fb}^{-1}$ the EIC could compete or surpass the current limits from $\tau \to e\gamma$

- Given the stringent limits on CLFV(1,2), is there theoretical motivation for an EIC search of CLFV(1,3) ?

Yes! Many models predict CLFV(1,3) >> CLFV(1,2)

- For example, in Minimal flavor violation:



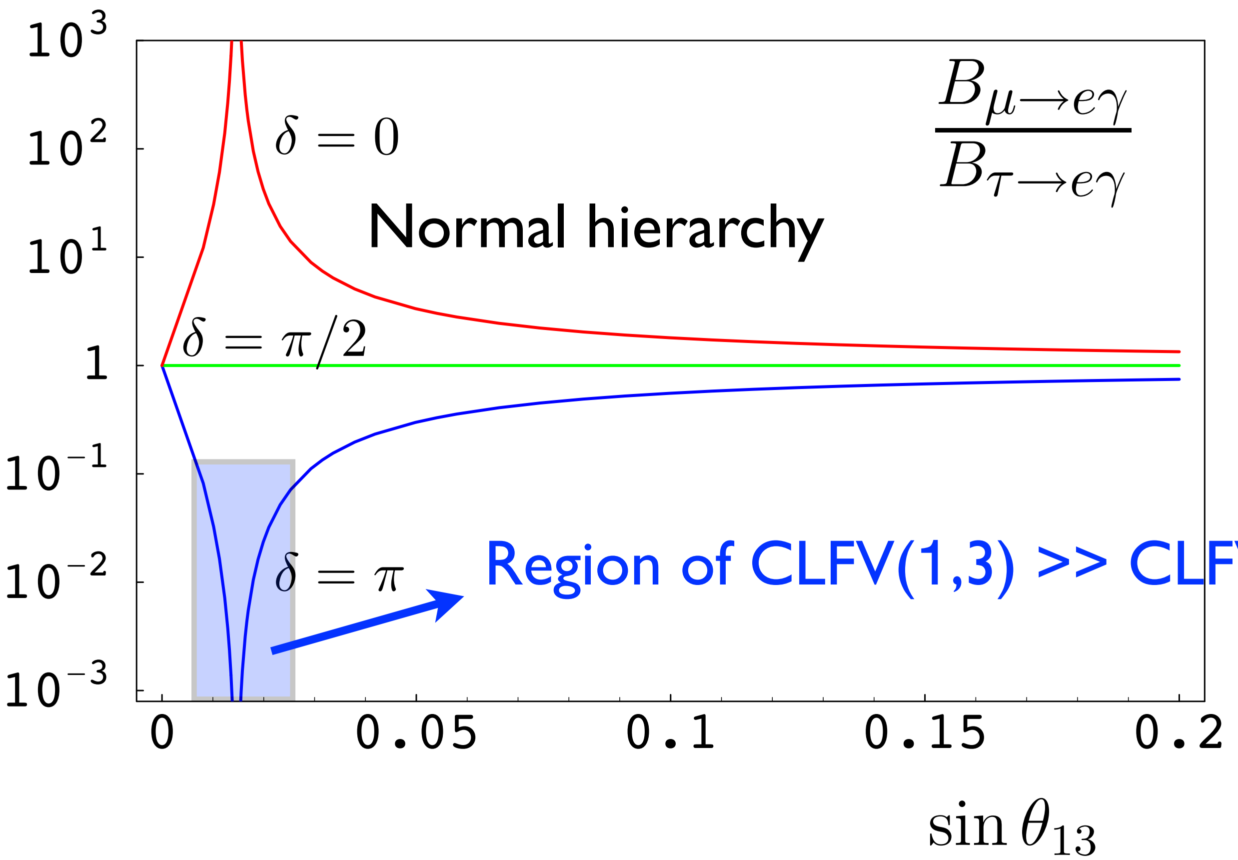
$$\frac{\mathrm{Br}(\mu \to \mathrm{e}\gamma)}{\mathrm{Br}(\tau \to \mathrm{e}\gamma)} = \left|\frac{\Delta_{\mu e}}{\Delta_{\tau e}}\right|^2$$

$$= \left|\frac{\sin\theta_{\mathrm{sol}}\ \cos\theta_{\mathrm{sol}}\ \Delta m^2_{\mathrm{sol}} \pm \sin\theta_{13} e^{i\delta} \Delta m^2_{\mathrm{atm}}}{-\sin\theta_{\mathrm{sol}}\ \cos\theta_{\mathrm{sol}}\ \Delta m^2_{\mathrm{sol}} \pm \sin\theta_{13} e^{i\delta} \Delta m^2_{\mathrm{atm}}}\right|^2$$

- Given the stringent limits on CLFV(1,2), is there theoretical motivation for an EIC search of CLFV(1,3) ?

Yes! Many models predict CLFV(1,3) >> CLFV(1,2)

- For example in Minimal flavor violation:



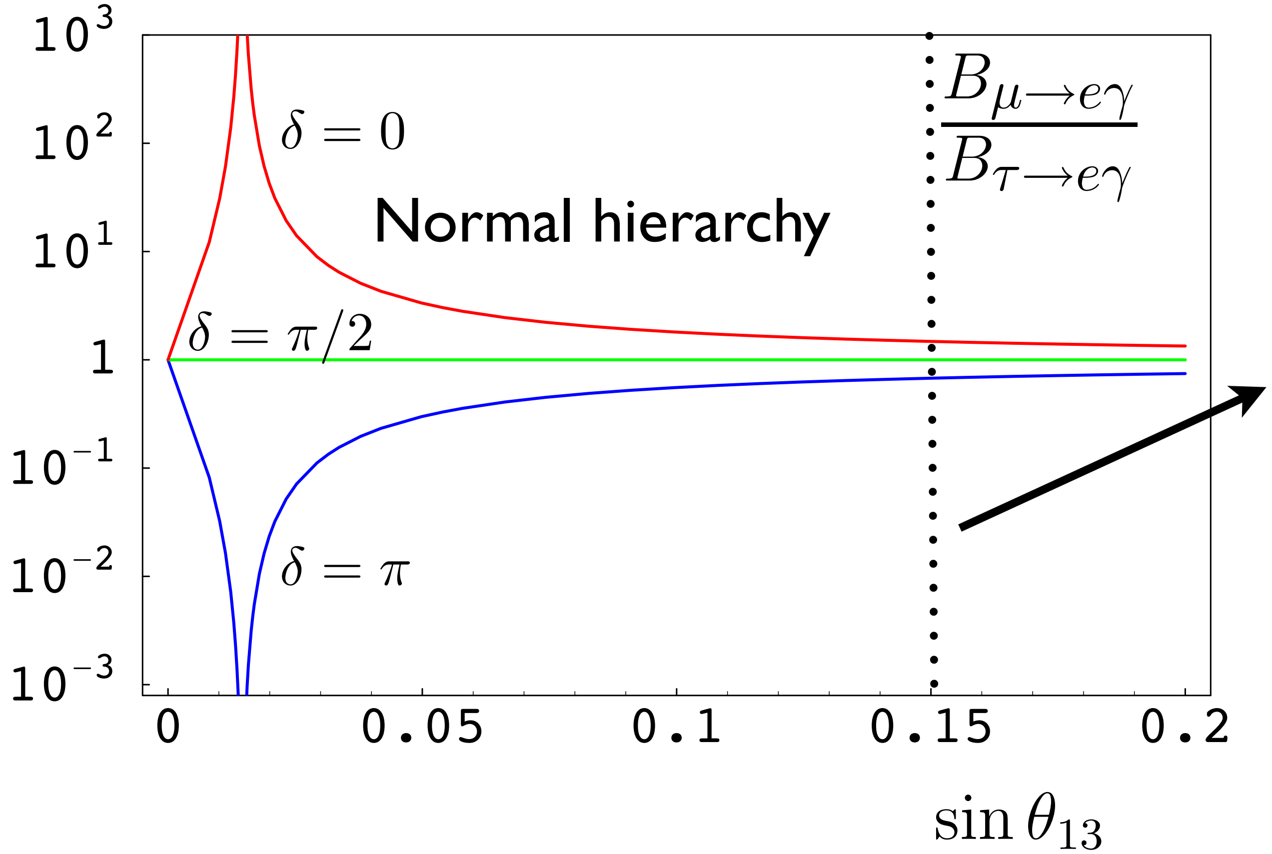
$$\frac{\mathrm{Br}(\mu\to \mathrm{e}\gamma)}{\mathrm{Br}(\tau\to \mathrm{e}\gamma)} = \left|\frac{\Delta_{\mu e}}{\Delta_{\tau e}}\right|^2$$

$$= \left|\frac{\sin\theta_{\rm sol}\ \cos\theta_{\rm sol}\ \Delta m^2_{\rm sol} \pm \sin\theta_{13}e^{i\delta}\Delta m^2_{\rm atm}}{-\sin\theta_{\rm sol}\ \cos\theta_{\rm sol}\ \Delta m^2_{\rm sol} \pm \sin\theta_{13}e^{i\delta}\Delta m^2_{\rm atm}}\right|^2$$

- Given the stringent limits on CLFV(1,2), is there theoretical motivation for an EIC search of CLFV(1,3) ?

Yes! Many models predict CLFV(1,3) >> CLFV(1,2)

- For example in Minimal flavor violation:



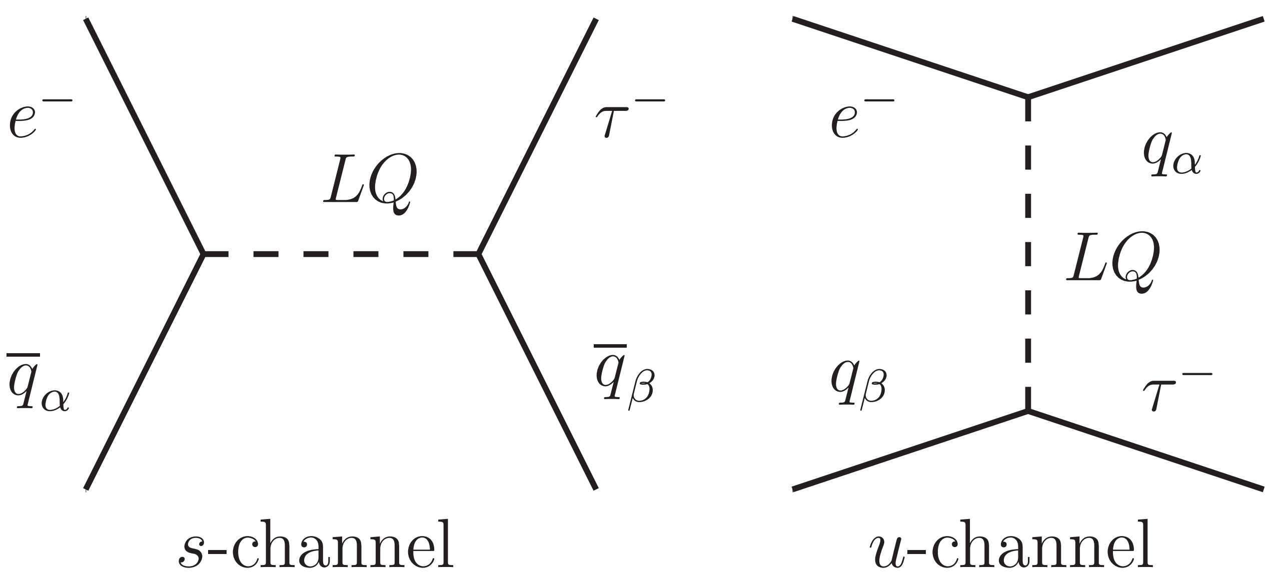
Although current value of $\sin\theta_{13}$ indicates CLFV(1,3) ~ CLFV(1,2) in MFV for rare decays.

However, other scenarios can still predict CLFV(1,3) >> CLFV(1,2).

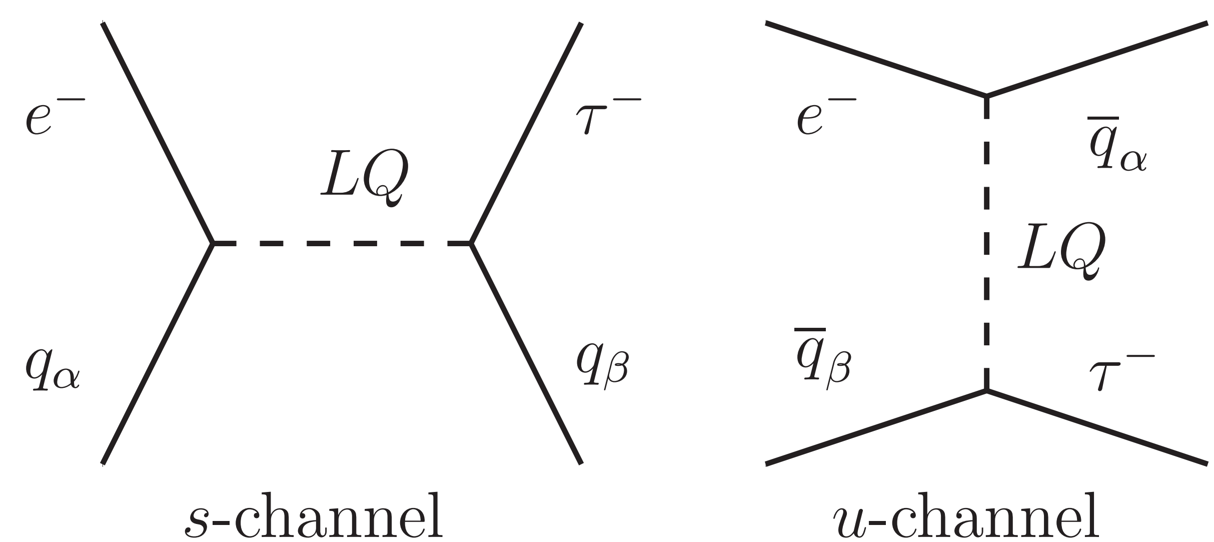
CLFV mediated by Leptoquarks

- Detailed theoretical study of $ep \to \tau X$ has been performed in the Leptoquark framework [M.Gonderinger, M.Ramsey-Musolf]

$$\mathcal{L}_{scalar} = \lambda_0^L \overline{q}_L^C \epsilon l_L S_0^L + \lambda_0^R \overline{u}_R^C e_R S_0^R + \tilde{\lambda}_0^R \overline{d}_R^C e_R \tilde{S}_0^R + \lambda_1^L \overline{q}_L^C \epsilon \vec{\sigma} l_L \vec{S}_1^L$$
$$+ \lambda_{1/2}^L \overline{u}_R l_L S_{1/2}^L + \lambda_{1/2}^R \overline{q}_L \epsilon e_R S_{1/2}^R + \tilde{\lambda}_{1/2}^L \overline{d}_R l_L \tilde{S}_{1/2}^L + h.c.$$



$F = 0$



$|F| = 2$

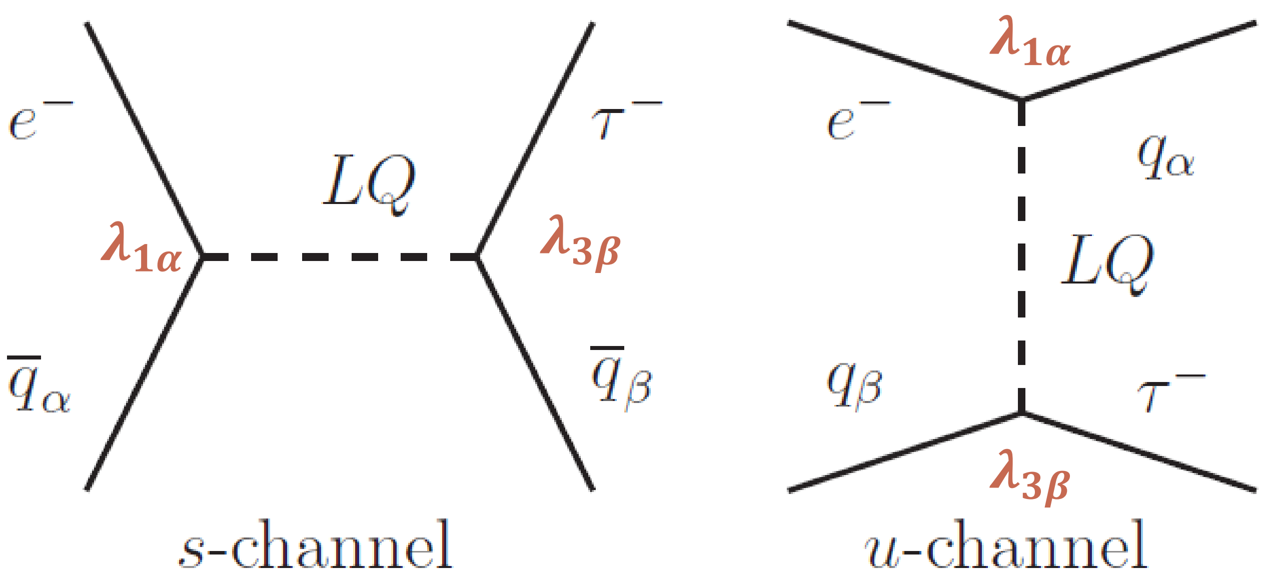
$$F = 3B + L$$

CLFV mediated by Leptoquarks

- Cross-section for $ep \to \tau X$ takes the form:

$$\sigma_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2} \right]^2 \left\{ \int dx dy \; x\bar{q}_\alpha (x, xs) \, f(y) + \int dx dy \; x q_\beta (x, -u) \, g(y) \right\}$$

$$f(y) = \begin{cases} 1/2 & (\text{scalar}) \\ 2(1-y)^2 & (\text{vector}) \end{cases} , \quad g(y) = \begin{cases} (1-y)^2/2 & (\text{scalar}) \\ 2 & (\text{vector}) \end{cases}$$



$F = 0$

- HERA set limits on the ratios $\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}$.
  - all LQs
  - all combinations of quark generations (no top quarks)
  - degenerate masses assumed for LQ multiplets

[S. Chekanov et.al (ZEUS), A.Atkas et.al (H1)]

- Comparison of HERA limits with limits from other rare CLFV processes:

  [S.Davidson, D.C. Bailey, B.A.Campbell]

- HERA limits that are stronger are highlighted in yellow.

- HERA limits are generally better for couplings with second and third generations.

$\alpha\beta$	$S^L_{1/2}$ $e^-\bar{u}$ e^+u	$S^R_{1/2}$ $e^-(\bar{u}+\bar{d})$ $e^+(u+d)$	$\tilde{S}^L_{1/2}$ $e^-\bar{d}$ e^+d
1 1	$\tau \to \pi e$ 0.4 **1.8**	$\tau \to \pi e$ 0.2 **1.5**	$\tau \to \pi e$ 0.4 **2.7**
1 2	**1.9**	$\tau \to K e$ 6.3 **1.6**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.9**
1 3	*	$B \to \tau\bar{e}$ 0.3 **3.2**	$B \to \tau\bar{e}$ 0.3 **3.3**
2 1	**6.0**	$\tau \to K e$ 6.3 **4.1**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **5.2**
2 2	$\tau \to 3e$ 5 **10**	$\tau \to 3e$ 8 **5.6**	$\tau \to 3e$ 17 **6.5**
2 3	*	$B \to \tau\bar{e}X$ 14 **8.1**	$B \to \tau\bar{e}X$ 14 **7.8**

EIC Sensitivity

- How much can the EIC improve upon HERA limits?

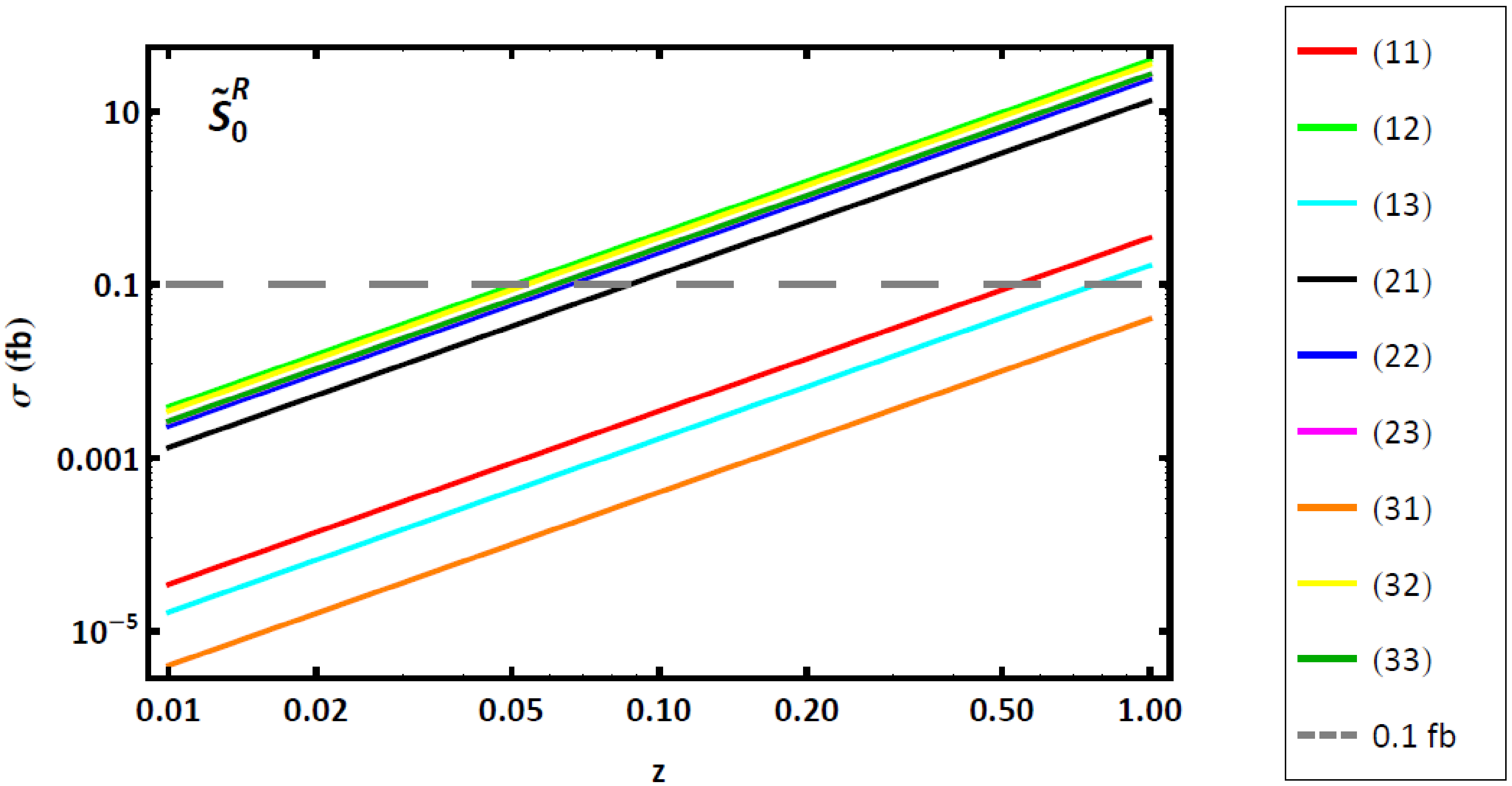
- Study was done for EIC at a center of mass energy of 90 GeV

[M.Gonderinger, M.Ramsey-Musolf]

- At 10 fb^{-1} of luminosity, a cross-section of 0.1 fb yields order one events.

- This cross-section of 0.1 fb corresponds to a typical size of $\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}$ that is about a factor of 2 to almost 2 orders of magnitude smaller, compared to the HERA limits.

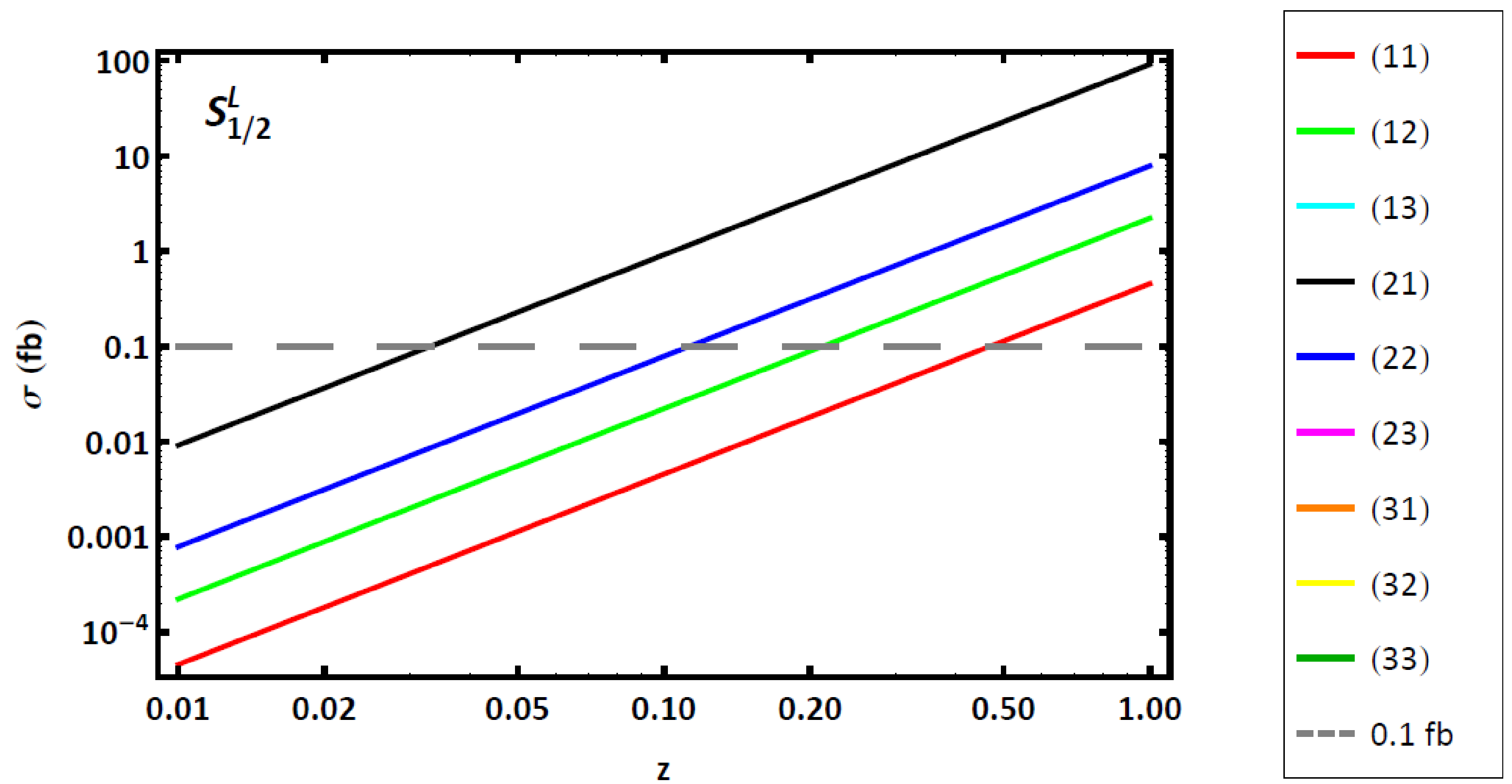
EIC Sensitivity



$$z = \frac{(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)}{[(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)]_{\text{HERAlimit}}}$$

[M.Gonderinger, M.Ramsey-Musolf]

- Present limits involving first generation quarks are harder to improve upon.
- Limits can be improved upon for couplings involving higher generation quarks.
- Larger center of mass energy will increase the cross-section, giving better limits.

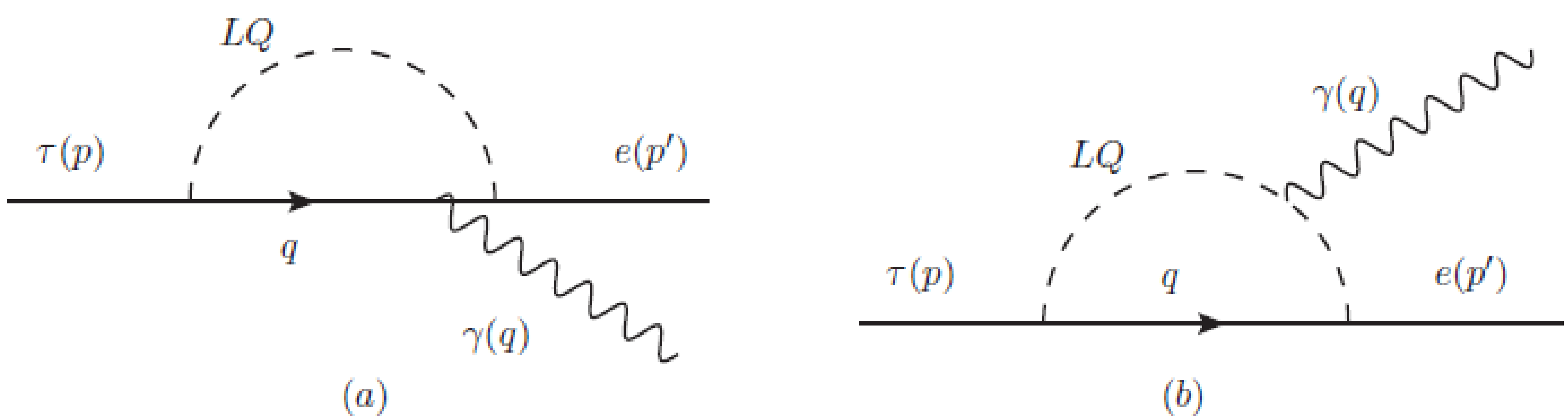


- Of course, higher luminosity will also give better limits.

Leptoquark Mediated CLFV(1,3) Decays

- Leptoquarks can also mediate the rare decay:

$$\tau \to e\gamma$$



- These diagrams are also proportional to the combination:

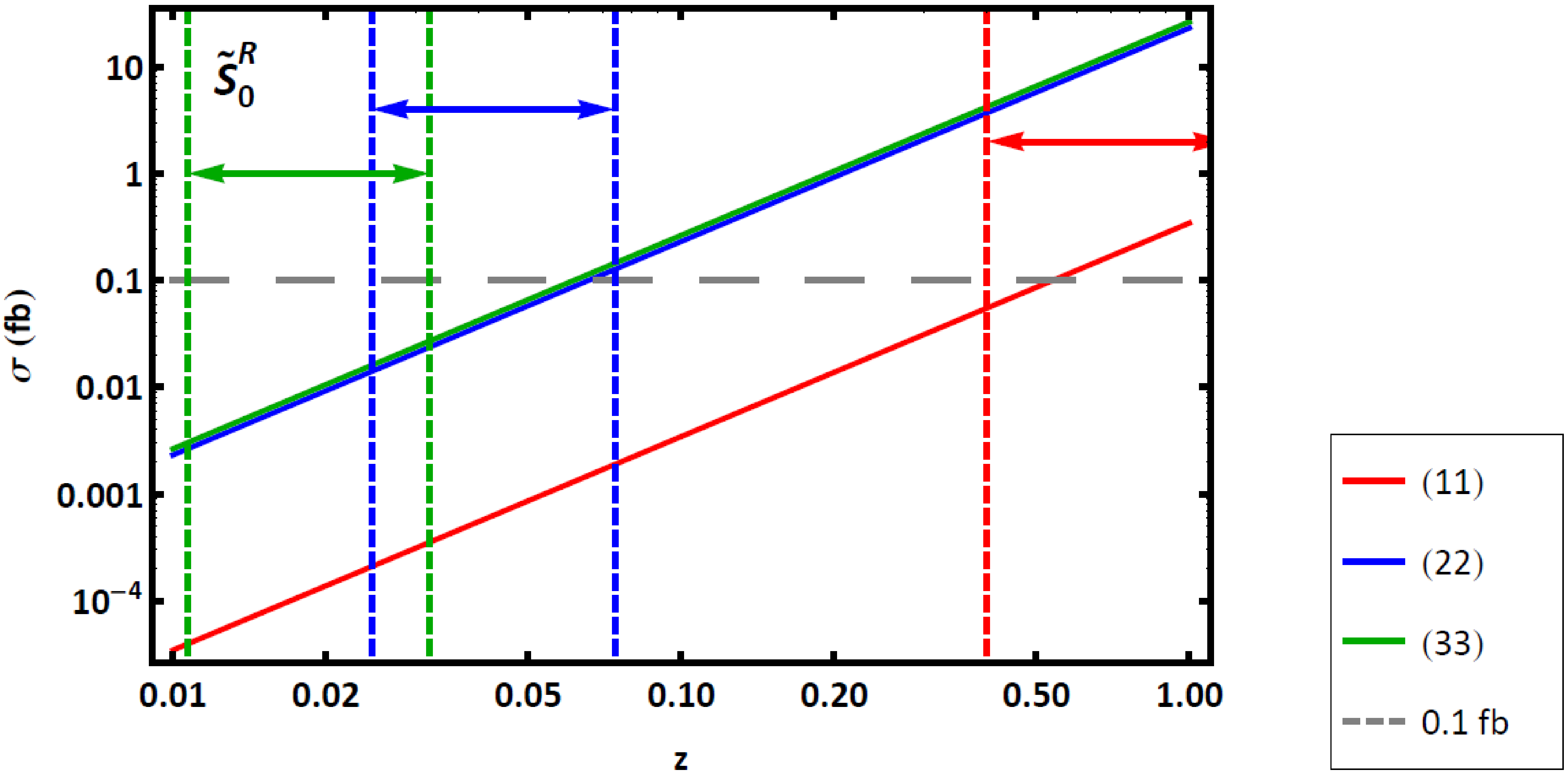
$$\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2} \quad \text{but only for} \quad \alpha = \beta$$

(quark flavor-diagonal case)

EIC Sensitivity

- How does the EIC sensitivity compare to limits from rare decays?

[M.Gonderinger, M.Ramsey-Musolf]



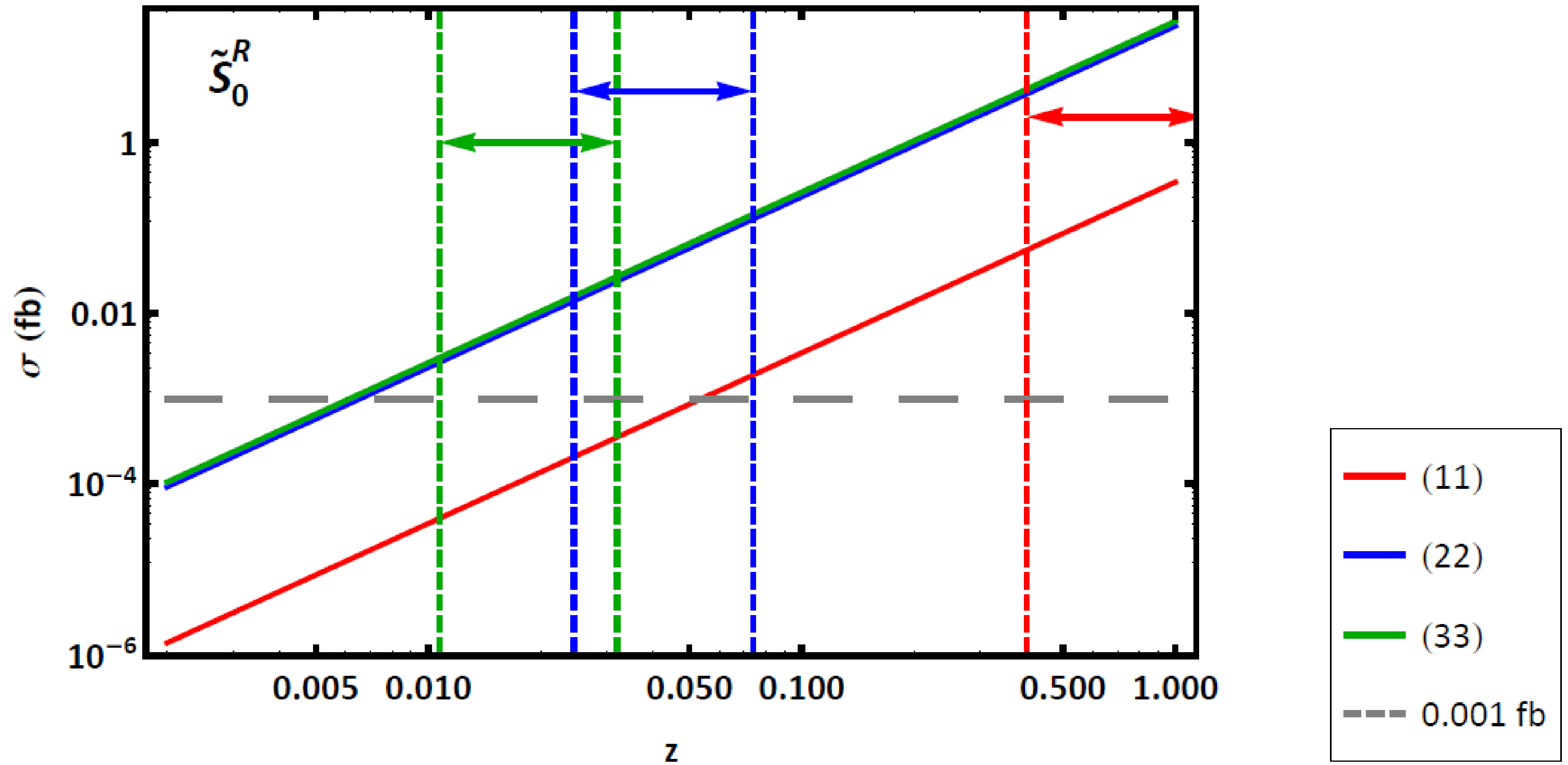
- Vertical dashed lines and horizontal arrows indicate the range of limits from rare decays ("Totalitarian" vs "Democratic" scenarios).

- At 10^{-1}fb, the EIC cannot compete with limits from rare decays.

EIC Sensitivity

- How does the EIC sensitivity compare to limits from rare decays?

[M.Gonderinger, M.Ramsey-Musolf]



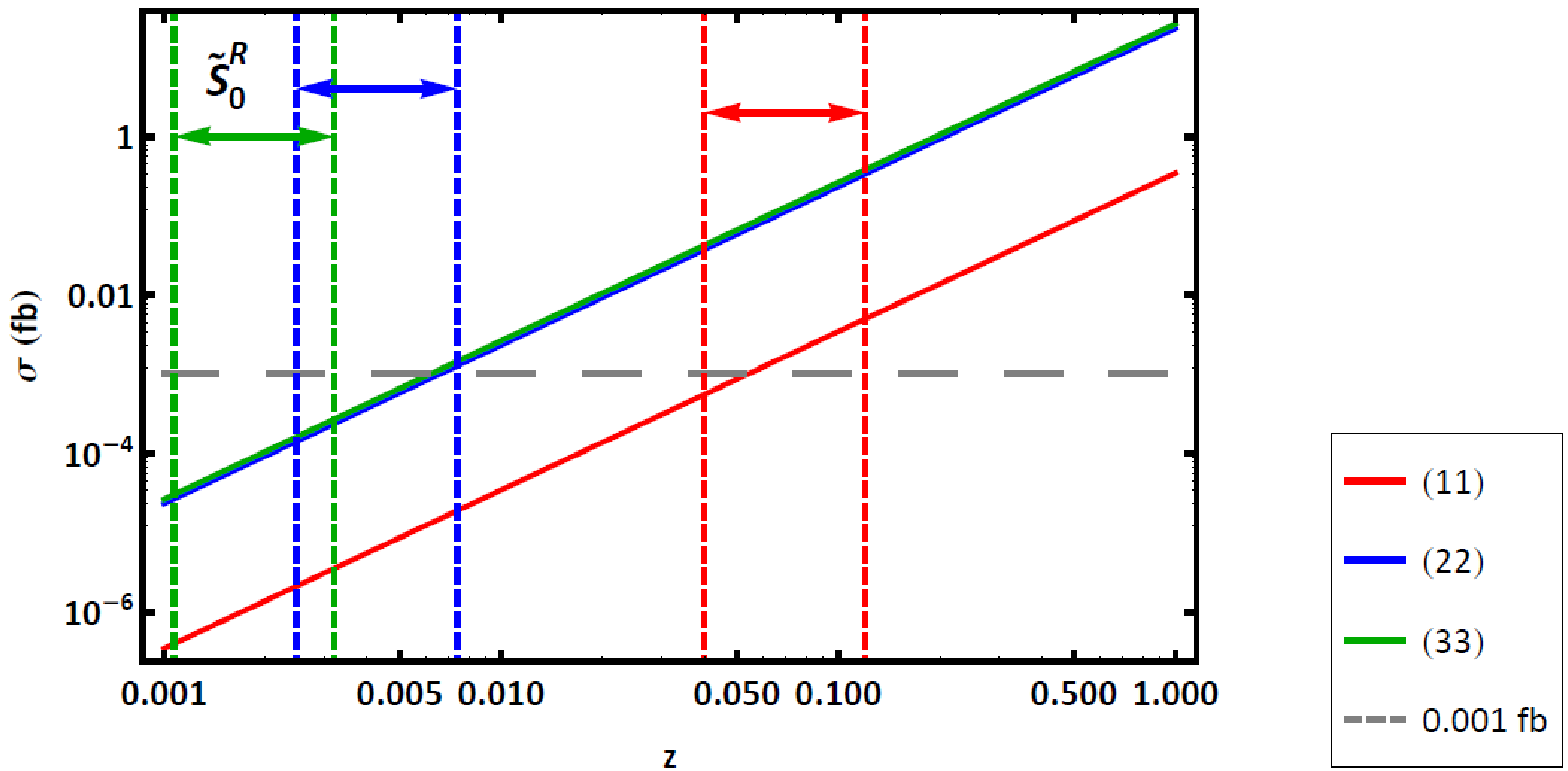
- Vertical dashed lines and horizontal arrows indicate the range of limits from rare decays ("Totalitarian" vs "Democratic" scenarios).

- But at 1000^{-1}fb, the EIC surpasses current rare decay limits.

EIC Sensitivity vs Super-B

- How does the EIC sensitivity compare to limits from rare decays?

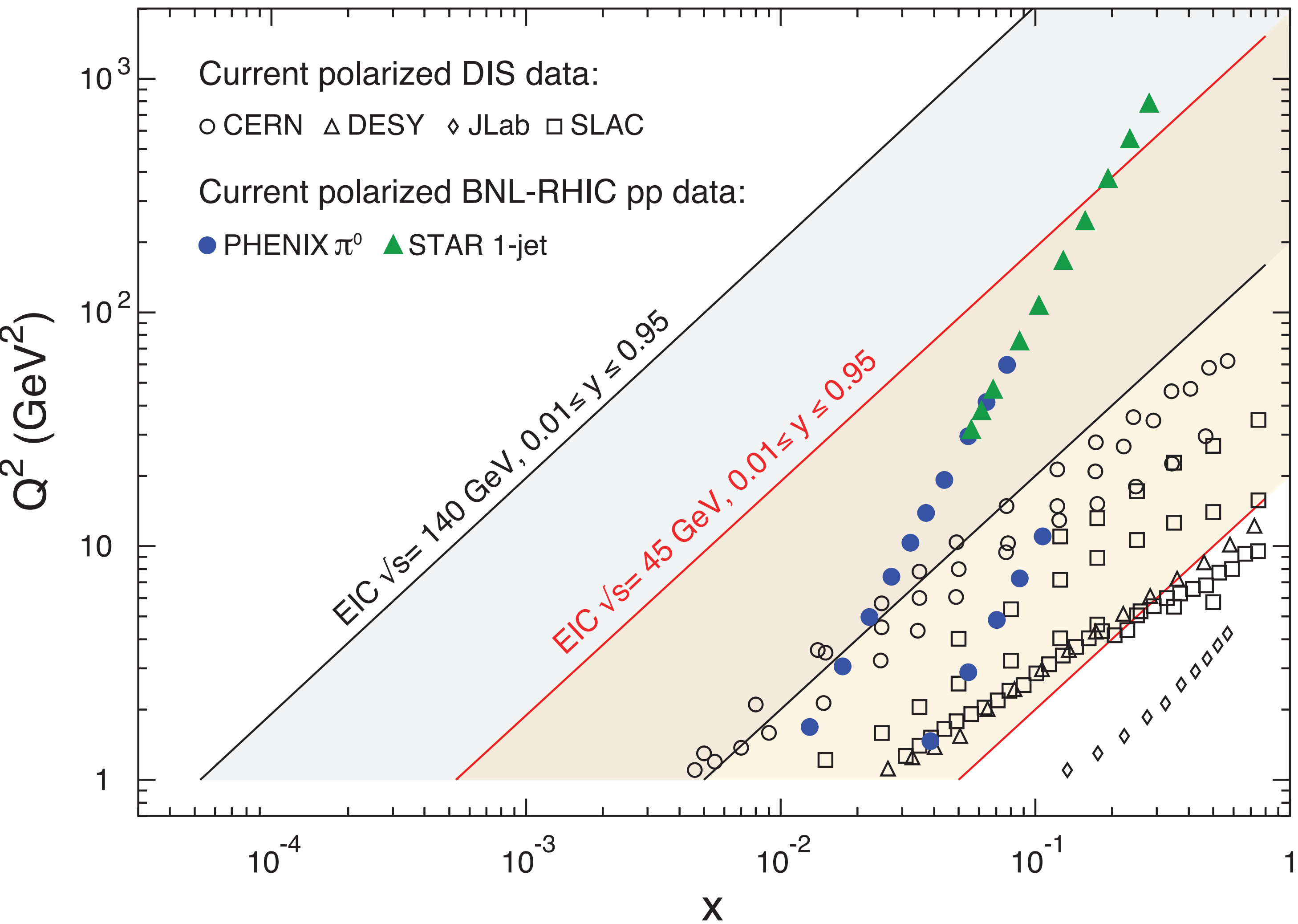
[M.Gonderinger, M.Ramsey-Musolf]

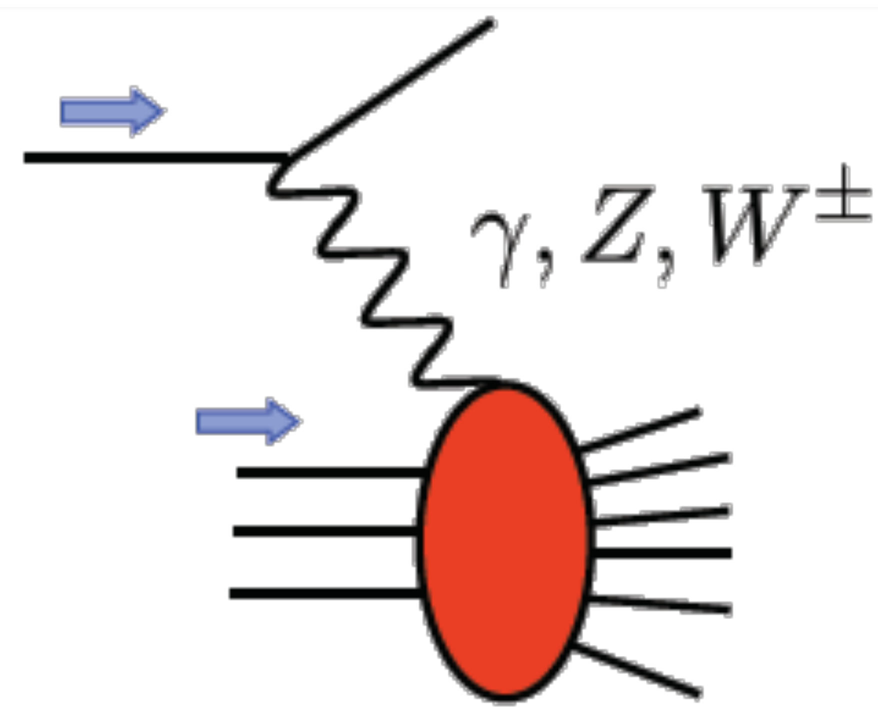


- Vertical dashed lines and horizontal arrows indicate the range of limits from rare decays ("Totalitarian" vs "Democratic" scenarios).
- At 1000^{-1}fb, the EIC could compete with Super-B in for first generation quark couplings but not for higher generation quark couplings.

Electroweak Spin Structure Functions

Electroweak DIS





- At high enough Q^2 , weak boson exchange becomes relevant:

  -NC DIS γ, Z exchange + interference
  -CC DIS W exchange

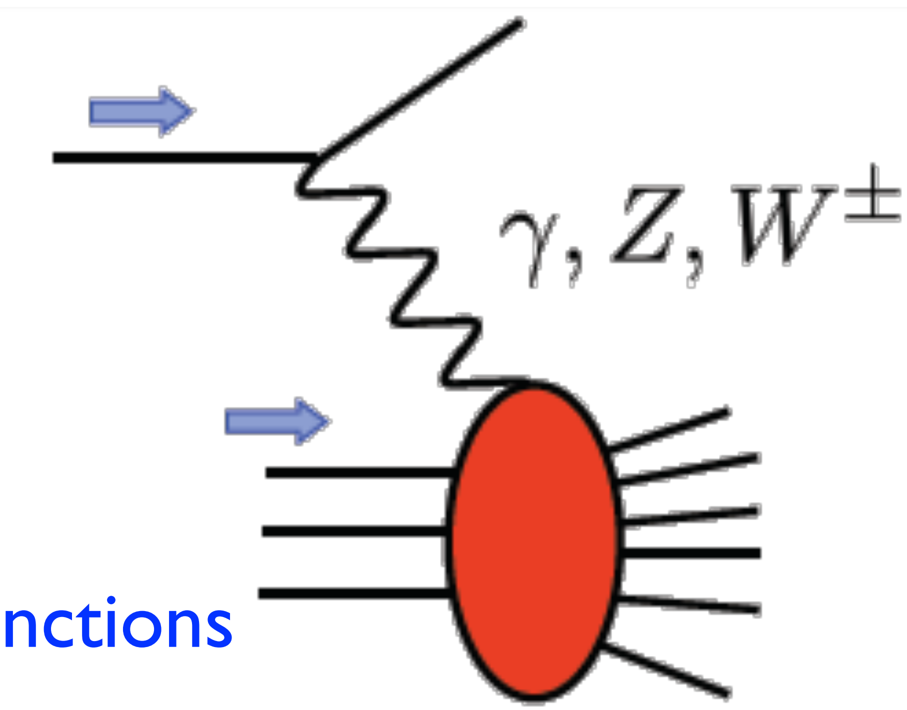
- Corresponding structure functions probe different combinations of PDFs.

NC Target-flip Parity-Violating Asymmetry

- Polarized beam ion beams at EIC provide a new direction for exploring the nucleon spin structure:

Target-flip parity violating asymmetries!

-polarized ^{1}H,^{2}H,^{3}H beams to be used
-new structure functions arise
-new combinations of helicity structure functions



- Polarized nucleon asymmetry (unpolarized electron, polarized hadron):

$$A_{TPV} = \frac{G_F}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^{\gamma Z}} + g_A^e f(y) \frac{g_1^{\gamma Z}}{F_1^{\gamma Z}}\right]$$

- Electroweak structure functions

[Anselmino, Gambino, Kalinoski]

$$g_1^{\gamma Z} = \sum e_q (g_V)_q (\Delta q + \Delta \bar{q})$$

$$g_5^{\gamma Z} = \sum_q e_q (g_A)_q (\Delta q - \Delta \bar{q})$$

NC Target-flip Parity-Violating Asymmetry

- Polarized nucleon asymmetry (unpolarized electron, polarized hadron):

$$A_{TPV} = \frac{G_F}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^{\gamma Z}} + g_A^e f(y) \frac{g_1^{\gamma Z}}{F_1^{\gamma Z}}\right]$$

- Electroweak structure functions in QPM:

$$g_1^{\gamma Z} = \sum e_q (g_V)_q (\Delta q + \Delta\bar{q})$$
$$g_5^{\gamma Z} = \sum_q e_q (g_A)_q (\Delta q - \Delta\bar{q})$$

- These structure functions are complementary to studies of nucleon spin structure:

  -different weighting of helicity structure functions
  -weights do not depend on fragmentation functions

- For example, in the SIDIS structure function, the helicity structure functions are weighted by fragmentation functions, extracted from QCD data:

$$g_1^h(x, Q^2, z) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q(x, Q^2) D_q^h(z, Q^2) + \Delta\bar{q}(x, Q^2) D_{\bar{q}}^h(z, Q^2)\right]$$

CC Target-flip Parity-Violating Asymmetry

- Polarized nucleon asymmetry in CC DIS: [See analysis for EIC: Aschenauer,Burton,Stratmann,Martin,Spiesberger]

$$\frac{d^2\Delta\sigma^{W^-,N}}{dxdy} = \frac{2\pi\alpha_{em}^2}{xyQ^2}\eta\left[2Y_- x g_1^{W^-,N} - Y_+ g_4^{W^-,N} + y^2 g_L^{W^-,N}\right]$$

- Electroweak structure functions in QPM:

$$\begin{aligned} g_1^{W^-,p}(x) &= \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x) , \\ g_5^{W^-,p}(x) &= -\Delta u(x) + \Delta\bar{d}(x) - \Delta c(x) + \Delta\bar{s}(x) \end{aligned}$$

$$g_4^{W^-,N} = 2x g_5^{W^-,N}$$

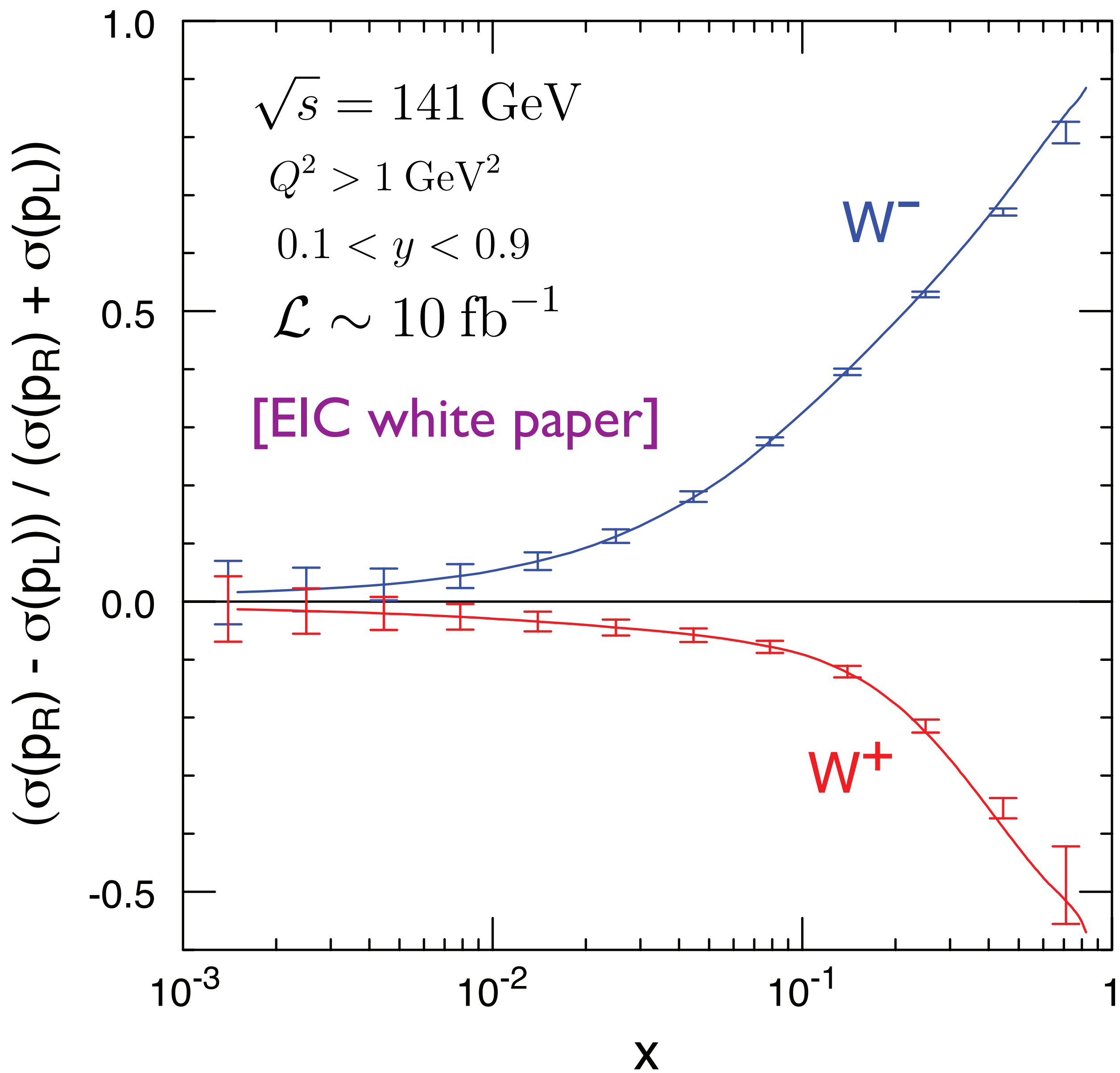
- With a positron beam instead, we obtain new structure functions that give yet another combination of helicity structure functions:

$$\begin{aligned} g_1^{W^+,p}(x) &= \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{c}(x) + \Delta s(x) \\ g_5^{W^+,p}(x) &= \Delta\bar{u}(x) - \Delta d(x) + \Delta\bar{c}(x) - \Delta s(x) \end{aligned}$$

- Once again, a flavor separation of helicity structure functions independent of fragmentation functions can be achieved.

CC Target-flip Parity-Violating Asymmetry

- Size of the polarized nucleon asymmetry in CC DIS for W^+ and W^- exchange:



$$(\sigma(p_R) - \sigma(p_L))/(\sigma(p_R) + \sigma(p_L))$$

- Large asymmetries expected in the region of moderate to large Bjorken-x.

- Measurement of this asymmetry can provide valuable information on nucleon spin structure.

- Electroweak physics at the EIC complements QCD physics at the EIC.

Conclusions

- Electroweak physics at the EIC can play an important role for:

  -constraining new physics via precision measurements of electroweak couplings
  -lepton flavor violation searches
  -nucleon spin structure

- This is facilitated by:

  -high luminosity
  -wide kinematic range
  -polarized beams
  -range of nuclear targets