OBSERVING $e \to \tau$ LFV via LEPTOQUARKS at the EIC

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Outline

- Introduction
- Leptoquark interactions
- Searches @ HERA: $e^{\pm}p$ collisions
- EIC sensitivity to leptoquark $e \to \tau$
- Updating $\tau \to e\gamma$ limits
- Tevatron and LHC searches
- Concluding remarks

Introduction

- Charged lepton flavor violation is a probe of new physics models
  - SUSY $SO(10)$ GUTs, SSM + RH νs, R-parity violating SUSY
  - RS models in warped extra dimensions
  - LR symmetric models
- Models with leptoquarks also have LFV
  - Pati-Salam $SU(4)_C$
  - GUTs (e.g., $SU(5)$)
  - Technicolor
- Can the EIC observe charged lepton flavor violation? What center of mass energy and luminosity would be needed?
- $e \to \tau$ presently less constrained than $e \to \mu$

Leptoquarks

- Leptoquarks (LQs) are particles which couple leptons and quarks
- LQs come in many different types:
  - Spin: 0 (scalar) or 1 (vector)
  - Fermion number: $|F| = |3B + L| = 0,\ 2$
  - $SU(2)_L$ representation: singlet, doublet, triplet
  - Chirality: L- or R-handed couplings
- Buchmuller-Ruckl-Wyler (BRW) parameterization catalogs all possible types
- 14 LQs in all, assuming L- and R-handed couplings are independent

Interactions

- BRW LQ interactions come from $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant renormalizable Lagrangian:

$$\mathcal{L}_{scalar} = \boldsymbol{\lambda_0^L} \overline{q}_L^C \epsilon l_L \boldsymbol{S_0^L} + \boldsymbol{\lambda_0^R} \overline{u}_R^C e_R \boldsymbol{S_0^R} + \boldsymbol{\tilde{\lambda}_0^R} \overline{d}_R^C e_R \boldsymbol{\tilde{S}_0^R} + \boldsymbol{\lambda_1^L} \overline{q}_L^C \epsilon \vec{\sigma} l_L \boldsymbol{\vec{S}_1^L}$$

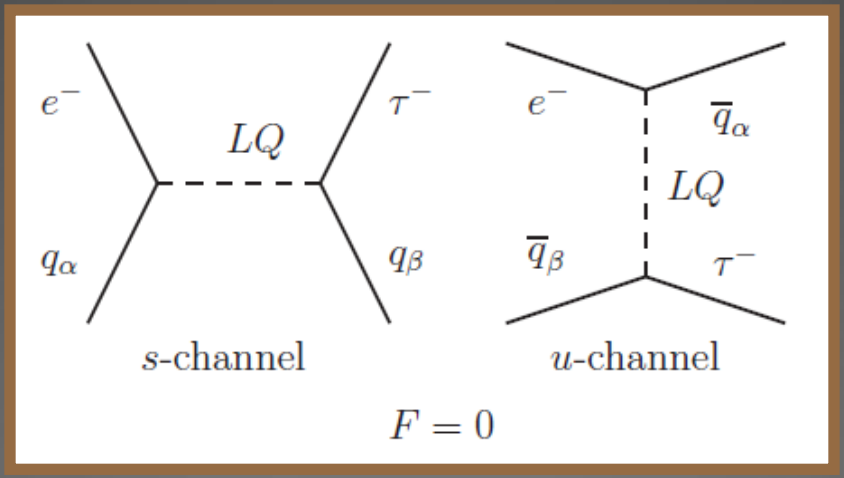
$$+ \boldsymbol{\lambda_{1/2}^L} \overline{u}_R l_L \boldsymbol{S_{1/2}^L} + \boldsymbol{\lambda_{1/2}^R} \overline{q}_L \epsilon e_R \boldsymbol{S_{1/2}^R} + \boldsymbol{\tilde{\lambda}_{1/2}^L} \overline{d}_R l_L \boldsymbol{\tilde{S}_{1/2}^L} + h.c.$$

($\mathcal{L}_{vector}$ is similar)

- LFV arises if the couplings $\boldsymbol{\lambda}$ are matrices in flavor-space with non-zero off-diagonal elements

HERA Searches

- $e^{\pm}p$ collisions at $\sqrt{s} \sim 300\ GeV$
- Search for $e \to \mu$ and $e \to \tau$ BRW LQ events at both ZEUS and H1



- α, β are (anti)quark generation indices
- $|F| = 2$ interchanges quarks, antiquarks

Cross Sections

- High mass approximation: $s \ll M_{LQ}^2$
- LQ diagrams reduce to 4-fermion interactions

$$\sigma(F=0)_{scalar} = \frac{s}{32\pi}\left[\frac{\boldsymbol{\lambda_{1\alpha}\lambda_{3\beta}}}{\boldsymbol{M_{LQ}^2}}\right]^2 \left\{\int dxdy\,\frac{1}{2}x\bar{q}_\alpha(x,xs) + \int dxdy\,\frac{(1-y)^2}{2}xq_\beta(x,-u)\right\}$$

- Cross section proportional to s

ZEUS and H1 Limits

- No LFV events observed
- ZEUS and H1 placed upper limits on the ratios $\boldsymbol{\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2}$ for all LQs and all combinations of $\alpha, \beta = 1, 2, 3$
- Some assumptions to get these limits:
  - Only one LQ type dominates cross section
  - LQ $SU(2)_L$ multiplets have degenerate mass
  - Exclude top quark
- S. Chekanov *et al.* (ZEUS), Eur. Phys. J. **C44**, 463 (2005), arXiv:hep-ex/0501070
- A. Aktas *et al.* (H1), Eur. Phys. J. **C52**, 833 (2007), arXiv:hep-ex/0703004

Comparison to Rare Process Limits

- Rare process limits from S. Davidson, D. C. Bailey, and B. A. Campbell, Z. Phys. **C61**, 613 (1994), arXiv:hep-ph/9309310
  - $\tau \to \pi e$, $\tau \to 3e$, meson decays, etc.
- ZEUS limits were generally stronger than rare process limits for couplings with second and third generation quarks
- Units in table: TeV^{-2}

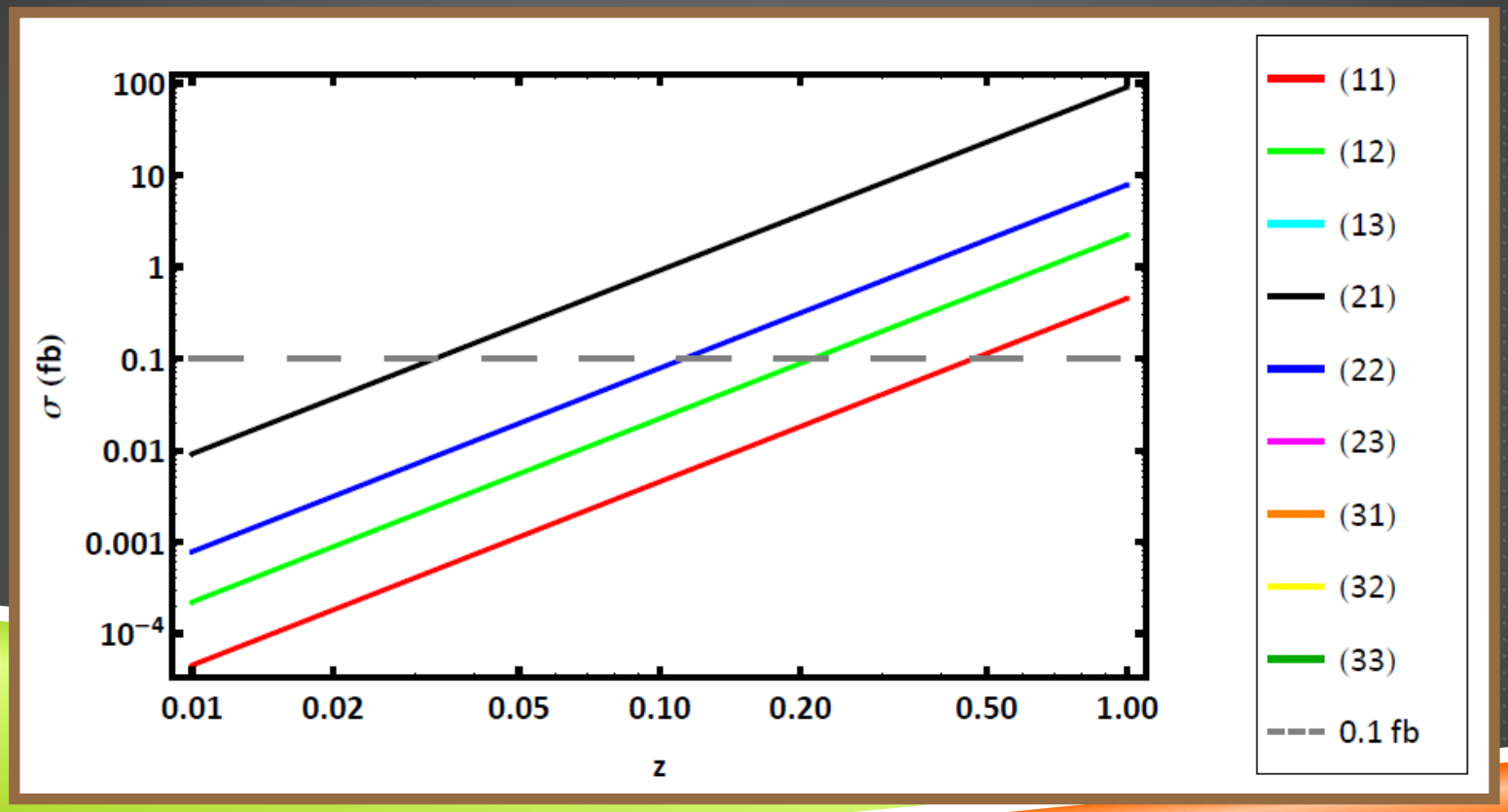
$\alpha\beta$	$S^L_{1/2}$ $e^-\bar{u}$ e^+u	$S^R_{1/2}$ $e^-(\bar{u}+\bar{d})$ $e^+(u+d)$	$\tilde{S}^L_{1/2}$ $e^-\bar{d}$ e^+d
1 1	$\tau \to \pi e$ 0.4 **1.8**	$\tau \to \pi e$ 0.2 **1.5**	$\tau \to \pi e$ 0.4 **2.7**
1 2	**1.9**	$\tau \to Ke$ 6.3 **1.6**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.9**
1 3	*	$B \to \tau\bar{e}$ 0.3 **3.2**	$B \to \tau\bar{e}$ 0.3 **3.3**
2 1	**6.0**	$\tau \to Ke$ 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

- By how much could the EIC decrease these limits?
- Suppose $\sqrt{s} = 90\ GeV$ and $10\ fb^{-1}$ integrated luminosity
  - $\Rightarrow e \to \tau$ events could be seen for $\sigma \gtrsim 0.1\ fb$
- A given cross section corresponds to a particular number for the ratio $\boldsymbol{\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2}$
- $\sigma = 0.1\ fb$ gives numbers for $\boldsymbol{\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2}$ that are a factor of 2 to almost 2 orders of magnitude smaller, relative to the HERA (or rare process) limits
  - Exact decrease depends on type of LQ, quark generations α, β
- EIC can do better than HERA with lower energies because it will have higher luminosity (ZEUS limits: $130\ pb^{-1}$)

Example

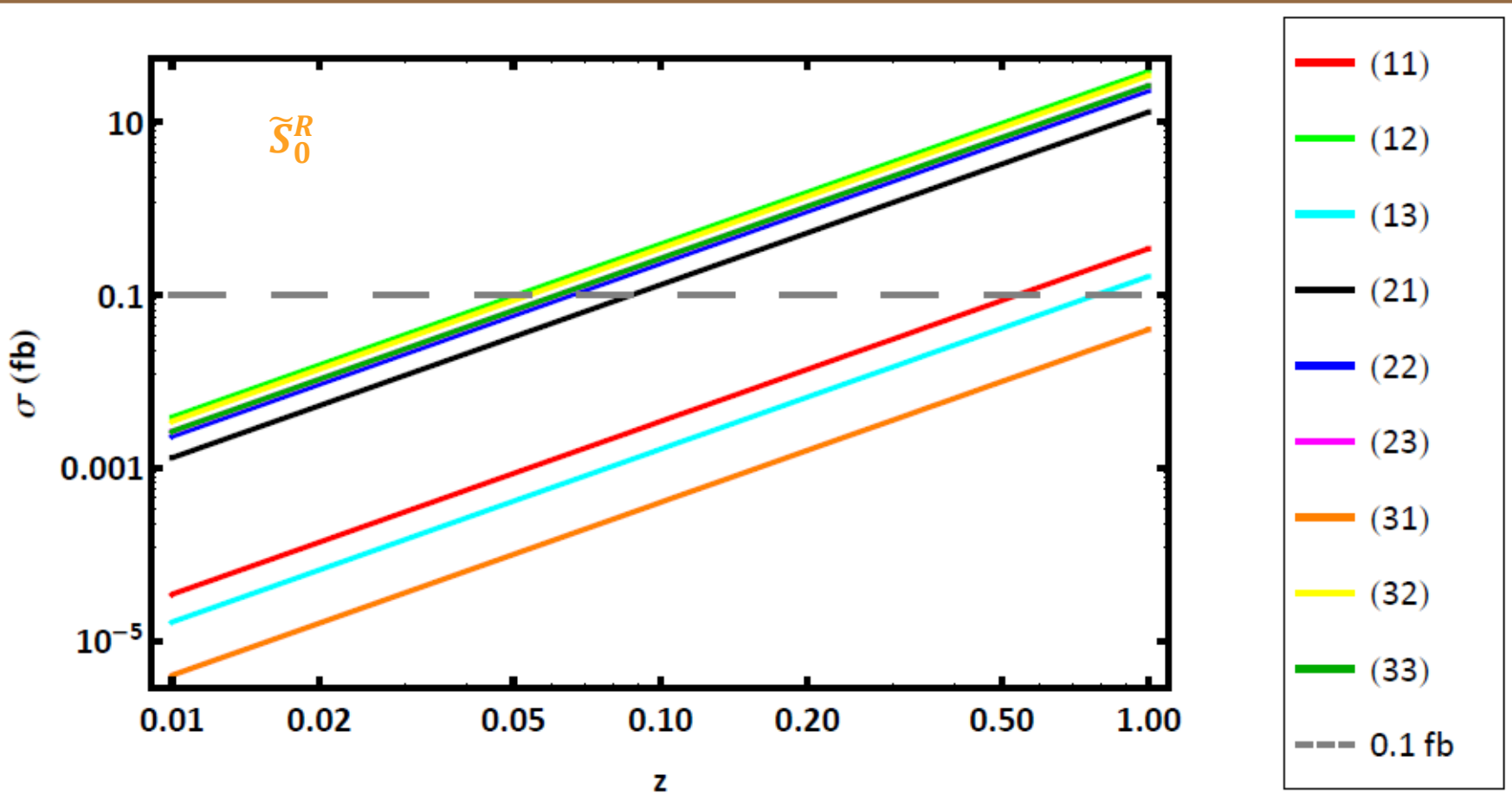
- LQ = $S^L_{1/2}$ (couples only to top quark in third generation)
- z = fractional decrease in $\lambda_{1\alpha}\lambda_{3\beta}/M^2_{LQ}$ ($z = 1 \Leftrightarrow$ HERA limit)
- All cross sections calculated with MSTW 2008 proton p.d.f.s



Comments

- Present limits involving first generation quarks are more stringent and harder to improve upon (despite p.d.f. enhancement)
- Conversely, p.d.f. suppression does not prohibit searching for leptoquark couplings to higher generation quarks
- EIC could probe smaller $\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2$ ratios and push down limits with more luminosity
  - Generally need $100 - 1000\ fb^{-1}$ to reach an order of magnitude improvement in first quark generation ratios
- Higher $\sqrt{s}$ will increase cross sections ⇒ EIC can probe smaller LQ ratios with the same luminosity

Another Example



Updating $\tau \to e\gamma$ Limits

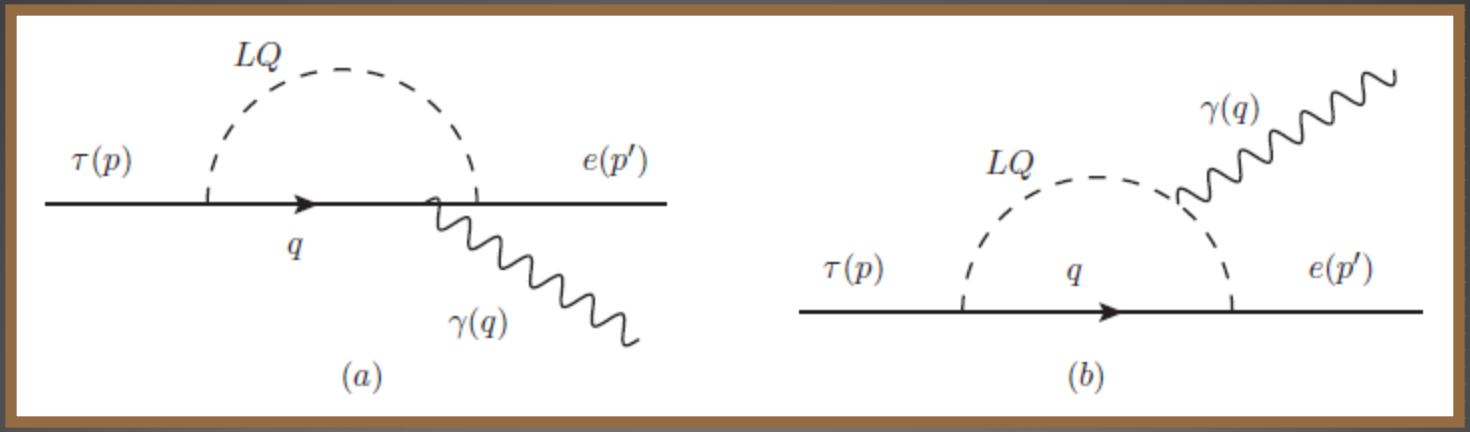
- The rare process limits cited by ZEUS and H1 included a relatively weak upper limit on $\tau \to e\gamma$ decay, so $\tau \to e\gamma$ was not relevant
- $\Gamma(\tau \to e\gamma)$ upper bound has since decreased:

$$\frac{\Gamma(\tau \to e\gamma)}{\Gamma_{total}} \leq 1.1 \times 10^{-7}$$

- B. Aubert *et al.* (BABAR), Phys. Rev. Lett. **96**, 041801 (2006), arXiv:hep-ex/0508012

Leptoquark Loops

- $\tau \to e\gamma$ decays via leptoquark loops:



- These diagrams are proportional to $\boldsymbol{\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2}$ with $\alpha = \beta$
  - $\tau \to e\gamma$ limits are only relevant for these "quark-diagonal" cases

Loop Calculations

- General form for $\tau \to e\gamma^*$ amplitude:

$$\mathcal{M}(\tau \to e\gamma^*) = e\epsilon^{*\nu}\overline{u}_e(p')[(q^2\gamma_\nu - q\cdot\gamma q_\nu)(A_1^L P_L + A_1^R P_R) + im_\tau q^\alpha \boldsymbol{\sigma_{\nu\alpha}}\left(\boldsymbol{A_2^L} P_L + \boldsymbol{A_2^R} P_R\right)]u_\tau(p)$$

- For a real photon with $q^2 = 0$:

$$Br(\tau \to e\gamma) \equiv \frac{\Gamma(\tau \to e\gamma)}{\Gamma(\tau \to e\overline{\nu}_e\nu_\tau)} = \frac{48\pi^3\alpha_{EM}}{G_F^2}\left(\left|\boldsymbol{A_2^L}\right|^2 + \left|\boldsymbol{A_2^R}\right|^2\right) \leq 6.16 \times 10^{-7}$$

Example

- Calculate $\boldsymbol{A_2^{L,R}}$ coefficients in the limit $m_e, m_q \to 0,\ m_\tau/M_{LQ} \ll 1$
- For $\boldsymbol{\widetilde{S}_0^R}$, the result is:

$$\boldsymbol{A_2^R} = 0$$

$$\boldsymbol{A_2^L} = -\frac{1}{32\pi^2}\left(Q_{d^c} + \frac{Q_{LQ}}{2}\right)\sum_{\alpha=1}^{3}\left(\frac{\boldsymbol{\lambda_{1\alpha}\lambda_{3\alpha}}}{\boldsymbol{M_{LQ}^2}}\right)$$

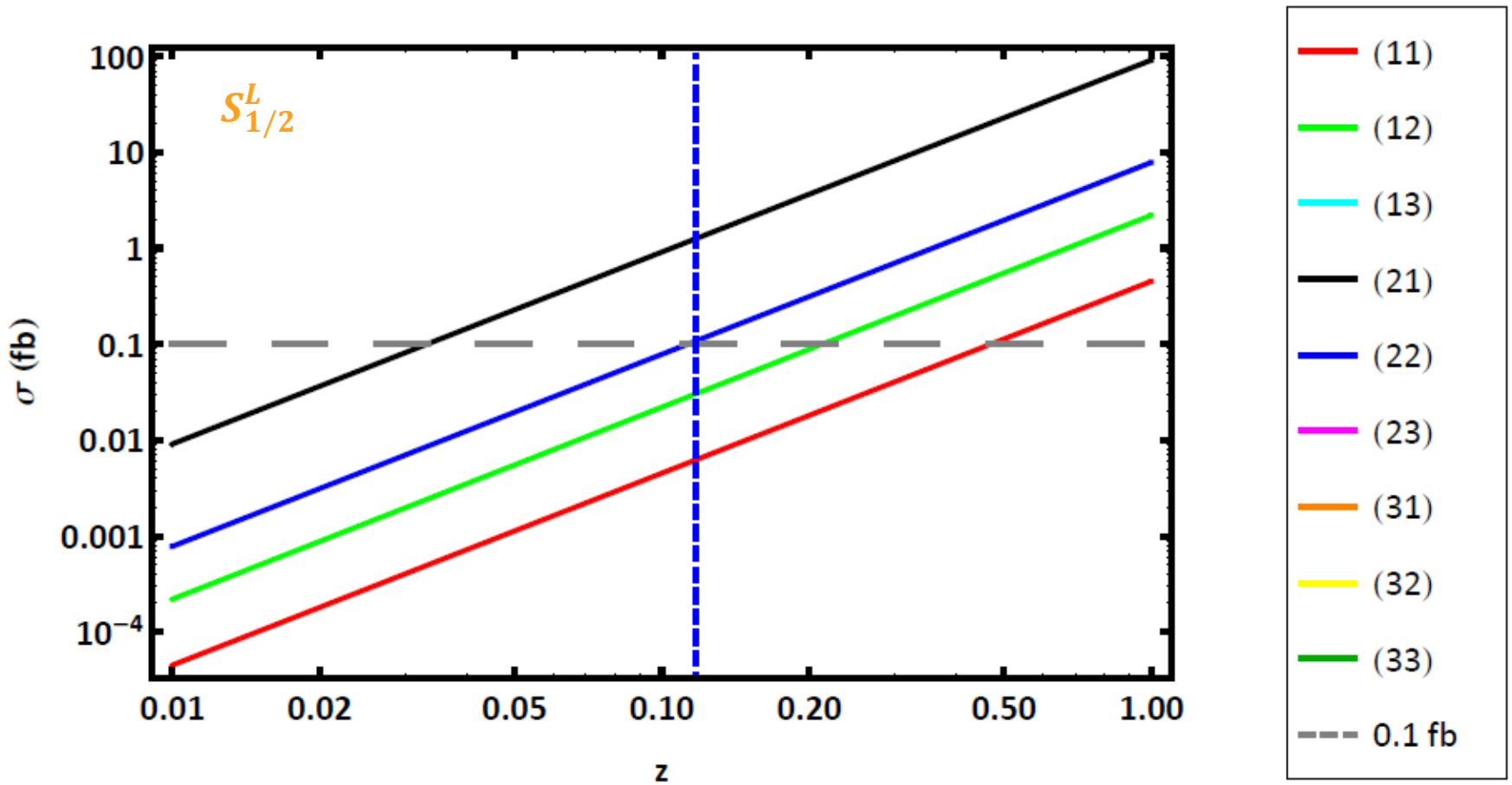
- The result involves a sum over $\boldsymbol{\lambda_{1\alpha}\lambda_{3\alpha}/M_{LQ}^2}$ — how can limits for each individual quark generation α be extracted?

Totalitarianism and Democracy

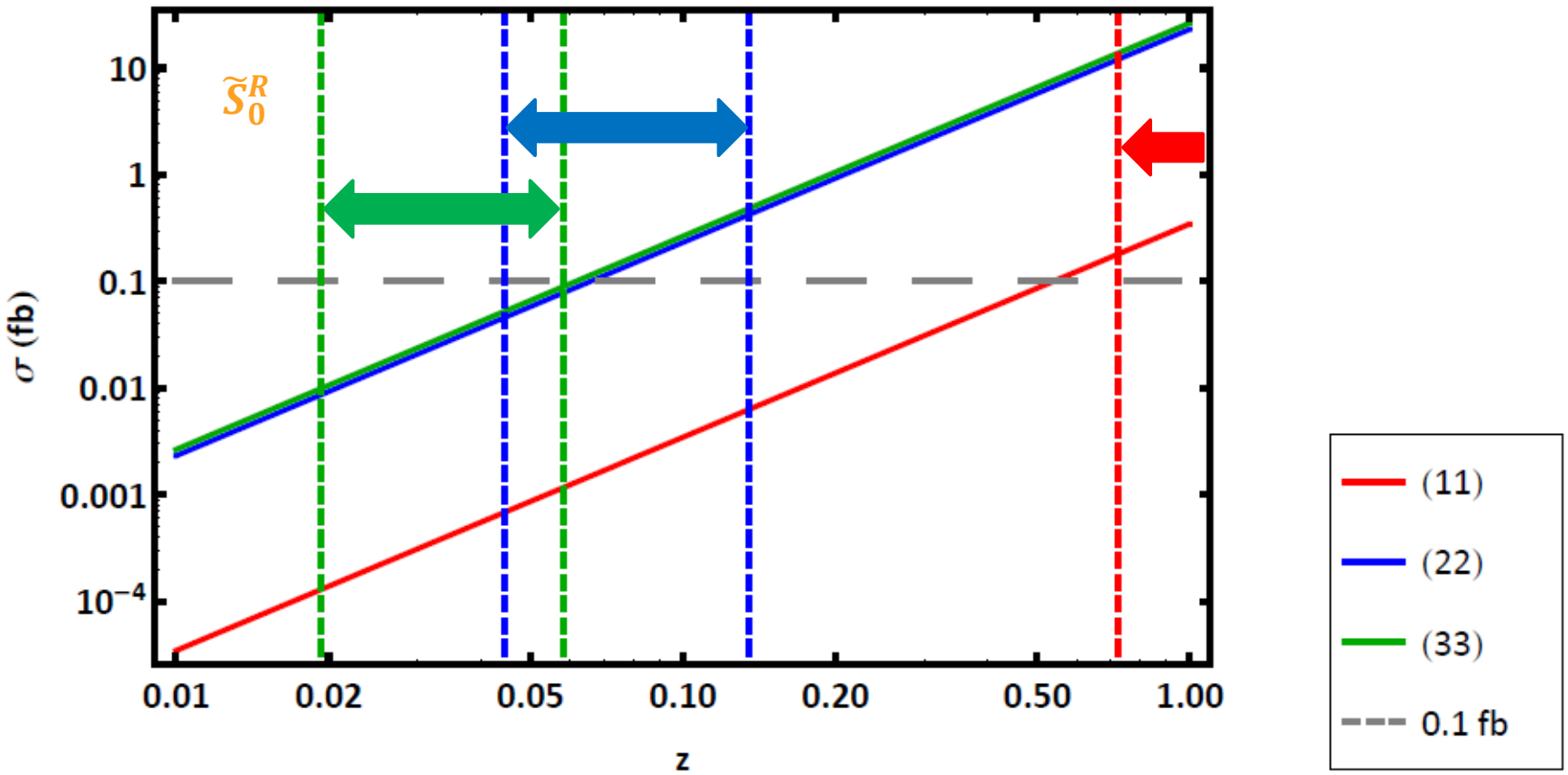
- Two options
- 1) assume a single quark generation saturates the $\tau \to e\gamma$ limit ("totalitarian")
  - This gives a weaker upper limit for each generation
- 2) assume all three generations contribute equally ("democratic")
  - This results in stronger upper limits for each generation

$\tilde{S}_0^R$		Option 1	Option 2
$\lambda_{1\alpha}\lambda_{3\alpha}/M_{LQ}^2$		$0.876\ TeV^{-2}$	$0.29\ TeV^{-2}$
z	$\alpha = 1$	2.19	0.725
	$\alpha = 2$	0.135	0.045
	$\alpha = 3$	0.058	0.019

Previously Seen

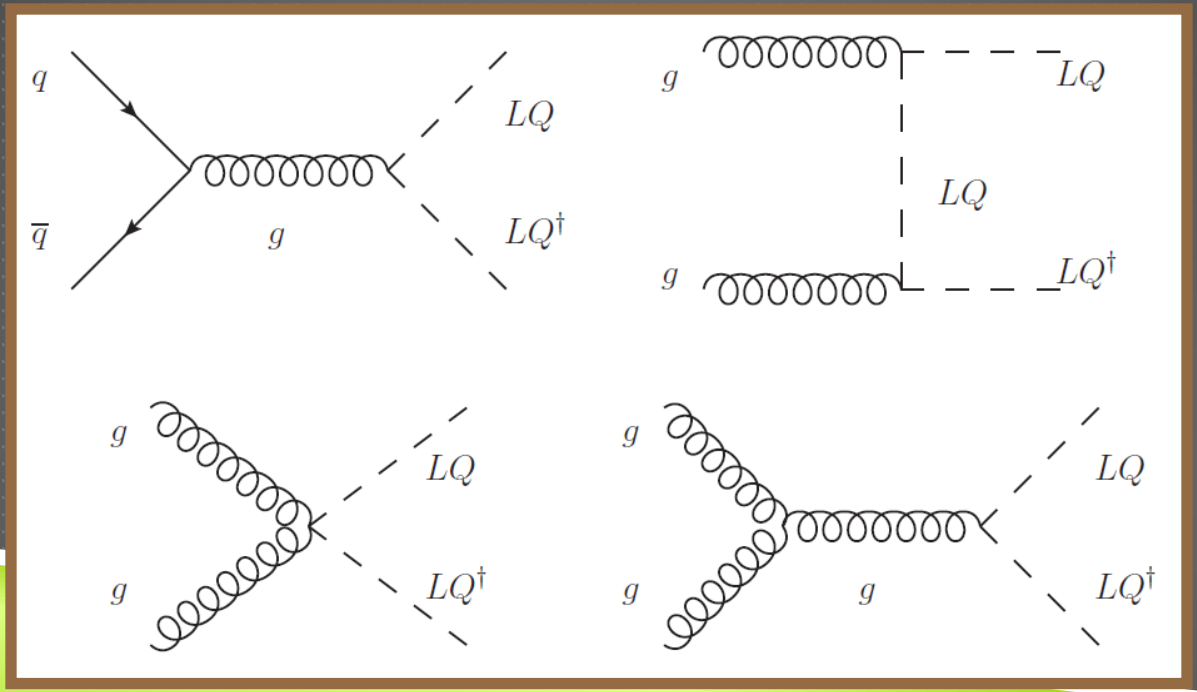


All Three Generations



Tevatron + LHC Searches

- LQs are color triplets ⇒ they participate in strong interactions
- LQ pair production cross section depends only on $\boldsymbol{M_{LQ}}$ and α_S, single production depends also on $\boldsymbol{\lambda}$
- Final states determined by branching fractions to $l^{\pm}q$ and νq



Complementary Searches

- Model-independent analyses (using BRW parameterization) for measuring LQ masses at the Tevatron and LHC can be found in the literature, along with current limits
- A. Belyaev, C. Leroy, R. Mehdiyev, and A. Pukhov, JHEP **09**, 005 (2005), arXiv:hep-ph/0502067
- If Tevatron or LHC measures LQ mass, EIC can measure its LFV couplings

Summary: $e \to \tau$ @ EIC

- HERA and rare processes have placed limits on $\boldsymbol{\lambda_{1\alpha}\lambda_{3\beta}/M_{LQ}^2}$ for BRW leptoquarks
- With $\sqrt{s} = 90\ GeV$ and $10\ fb^{-1}$, EIC can decrease many of these limits by a factor of 2 to almost 2 orders of magnitude
  - Limits involving second (or even third) generation quarks are presently less tightly constrained and will be easier to probe
  - To reach an order of magnitude improvement on first generation quark limits, $100 - 1000\ fb^{-1}$ are needed
- Present HERA limits are already stronger than $\tau \to e\gamma$ limits for first generation quarks; EIC could compete with or surpass $\tau \to e\gamma$ limits for second, third generation quarks
- Higher energies and luminosities will increase the EIC's reach
- EIC leptoquark searches are complementary to Tevatron and LHC searches

Leptoquarks and Beyond

- Feasibility of observing $e \to \tau$ events in a leptoquark framework is worth further study
- Can the EIC observe LFV arising from other non-leptoquark models?
- If $e \to \tau$ events are observed at the EIC, can they be used to discriminate between various models of LFV?