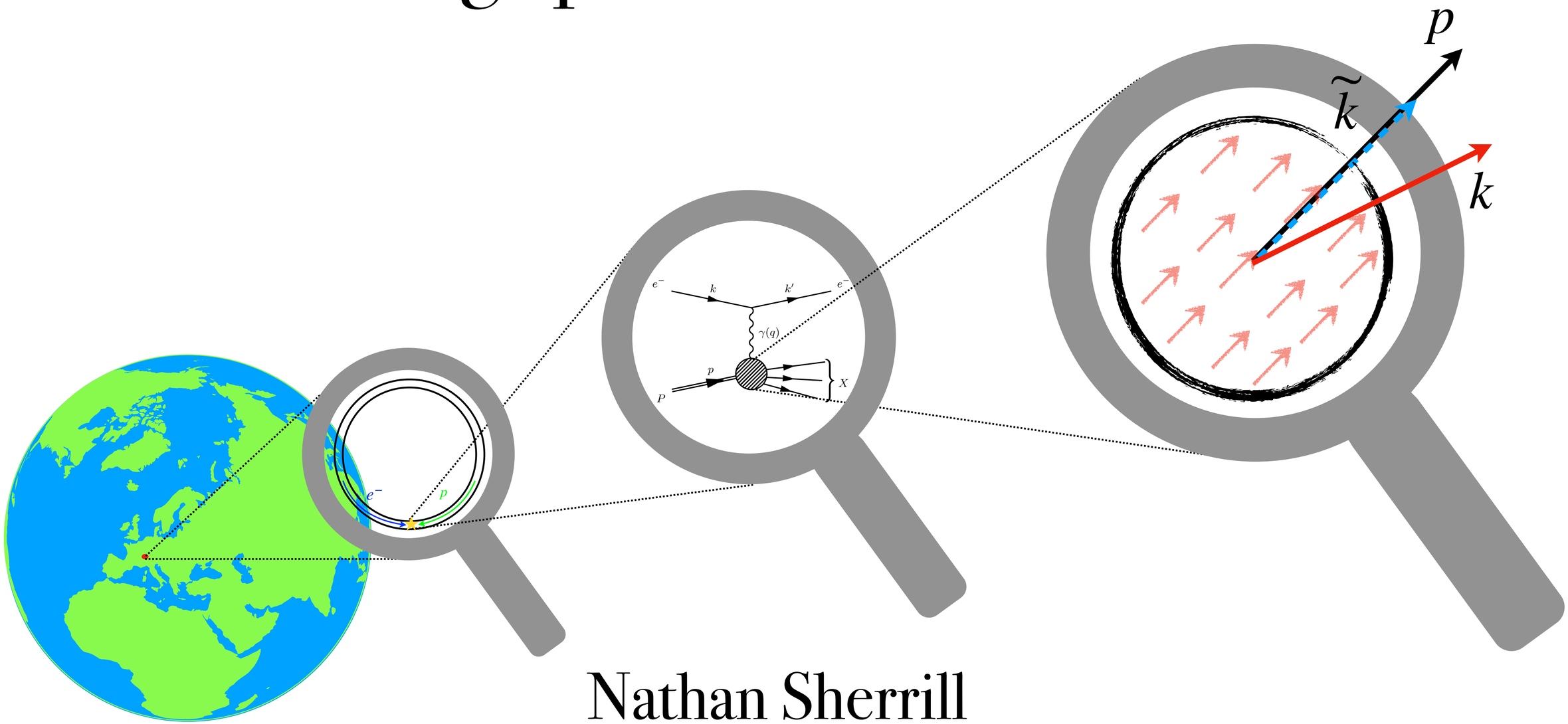
Probing spacetime with colliders



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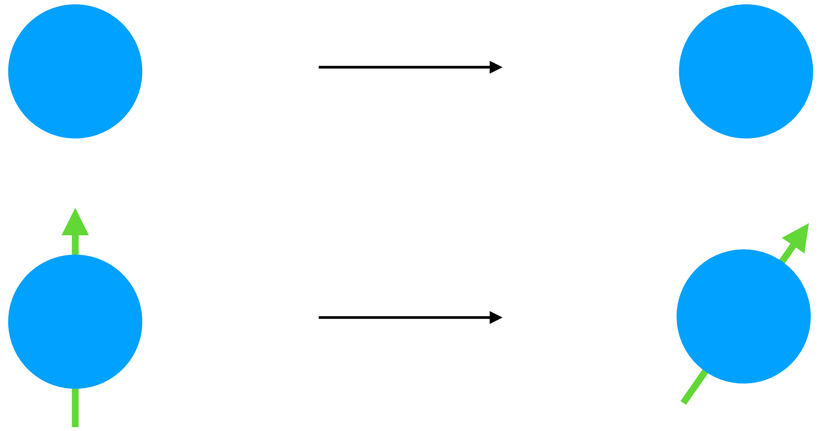
FCC week 2021, FCC-eh session

June 30, 2021

Symmetry and symmetry breaking

- A system possesses a symmetry if it is unchanged under some action



- Fundamental physics is rooted in symmetries

Example: SM symmetries $G_{\text{gauge}} \times G_{\text{Poincaré}}$

- Symmetries are a guiding principle, but often Nature prefers to break them

Examples: C, P, T, $SU(2)_I$, gauge symmetry, ...; CPT, Lorentz symmetry (?)

Symmetry and symmetry breaking

- The past two decades have seen an explosion of interest in Lorentz and CPT tests

$$\mathcal{L}_{\rm LV} \sim \frac{\lambda}{M^k}\langle T\rangle \cdot \bar{\psi}\Gamma(i\partial)^k\chi + \text{h.c.}$$

V. A. Kostelecký, S. Samuel (1989)

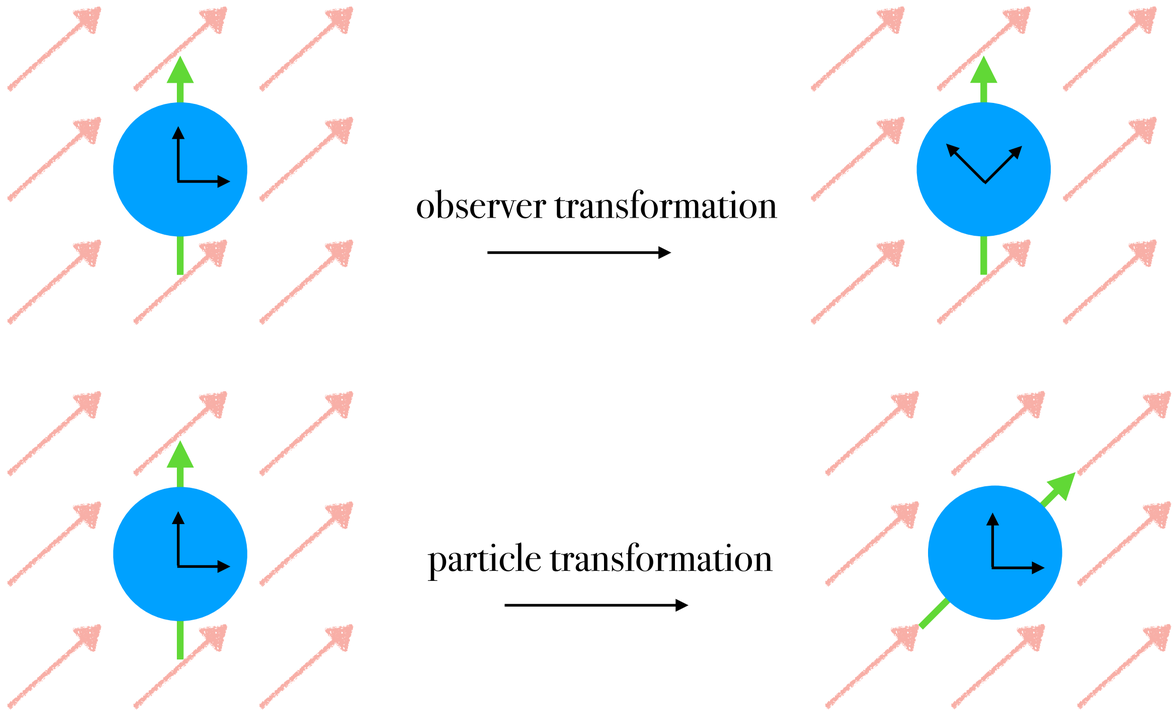
V. A. Kostelecký, R. Potting (1991, 1995)

- These terms have special properties

$$\mathcal{L}_a \supset -a_\mu\bar{\psi}\gamma^\mu\psi$$

$$[a_\mu] = \text{GeV}$$

- Background breaks rotation invariance



$$\mathcal{L}_a \to \mathcal{L}_a$$

$$\mathcal{L}_a \to \mathcal{L}'_a \neq \mathcal{L}_a$$

The Standard-Model Extension (SME)

- The Lorentz- and CPT-violating framework grounded in effective field theory is the Standard-Model Extension (SME)

D. Colladay, V. A. Kostelecký, (1997, 1998)
V. A. Kostelecký, (2004)

$$S_{\mathrm{SME}} = S_{\mathrm{SM}} + S_{\mathrm{GR}} + S_{\mathrm{LV}}$$

$$\mathcal{L}_{\mathrm{LV}} = \sum_i k_{i\mu\nu\ldots} \mathcal{O}_i^{\mu\nu\ldots}$$

Contains <u>all possible</u> terms that break Lorentz and CPT symmetry consistent with the particle/field content of the SM and GR

CPTV implies LV in realistic EFT

O. W. Greenberg, (2002)

- Numerous constraints have been placed to date

- <u>The QCD and electroweak sectors are very unexplored!</u>

Table D40. Gluon sector, $d = 4$

Combination	Result	System	Ref.
$\lvert k^{TT}\rvert$	$< 10^{-21}$	Various	[291]*
$\lvert k^{TJ}\rvert$	$< 10^{-19}$	"	[291]*
$\lvert k^{JK}\rvert$	$< 10^{-27}$	"	[291]*
$\lvert k^{XX}\rvert, \lvert k^{YY}\rvert$	$< 10^{-27}$	"	[291]*
$\lvert k^{ZZ}\rvert$	$< 10^{-20}$	"	[291]*
$\lvert k^{a}\rvert$ for $a = 1, 2, 8, 9, 10$	$< 10^{-34}$	Astrophysics	[291]*
$\lvert k^{a}\rvert$ for $a = 3, 4, 5, 6, 7$	$< 10^{-35}$	"	[291]*
$\lvert \tilde{\kappa}_{\mathrm{tr}}^{\mathrm{QCD}}\rvert$	$< 2 \times 10^{-13}$	"	[171]*

Data Tables for Lorentz and CPT Violation, V. A. Kostelecký, N. Russell, arXiv:0801.0287v14

Prospective HERA and EIC bounds

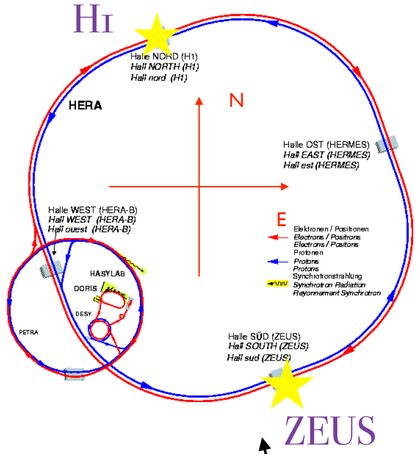
- DIS has been studied in the context of HERA and EIC data
- Dominant renormalizable effects for massless valence quarks

$$\mathcal{L} = \sum_{f=u,d} \frac{1}{2}\bar{\psi}_f(\eta^{\mu\nu} + c_f^{\mu\nu} + \gamma_5 d_f^{\mu\nu})\gamma_\mu i\overleftrightarrow{D}_\nu \psi_f$$

V. A. Kostelecký, E. Lunghi, A. R. Vieira, (2017)

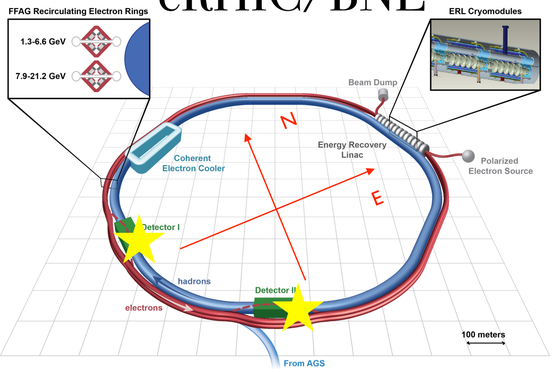
E. Lunghi, N. Sherrill, (2018)

HERA



EIC Yellow Report, arXiv:2103.05419

eRHIC/BNL



Main results

- Best expected constraints at 10^{-5}–10^{-6} levels
- Expected EIC constraints up to two orders of magnitude more stringent than expected constraints from HERA data

Sidereal analysis of HERA data *in progress*

E. Lunghi, N. Sherrill,
ZEUS Collaboration

- (Unpolarized) electromagnetic cross section independent of parity-violating effects (can be constrained instead on the Z pole in the Drell-Yan process @ LHC)

E. Lunghi, N. Sherrill, A. Szczepaniak, A. R. Vieira, (2021)

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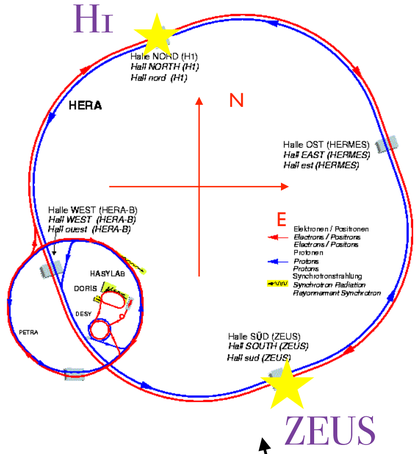

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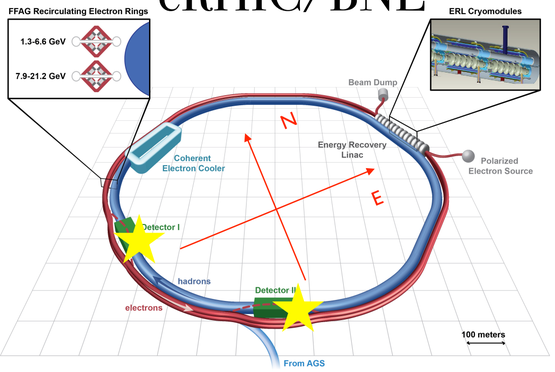

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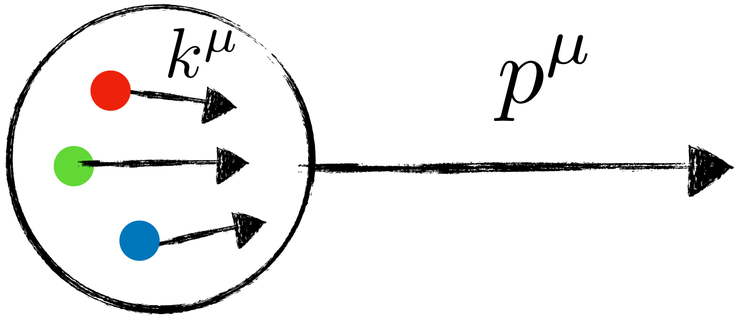
Lorentz- and CPT-violating parton model

- Standard partonic picture at large energies:



$$k^\mu \simeq \xi p^\mu$$

- Quarks modified by Lorentz- and CPT-violating operators

$$\mathcal{L}_\psi = \frac{1}{2}\bar{\psi}(\gamma^\mu i D_\mu + \widehat{\mathcal{Q}})\psi + \text{h.c.}$$

V. A. Kostelecký, M. Mewes, (2013)
V. A. Kostelecký, Z. Li, (2019)

$$\begin{aligned}\frac{1}{2}\bar{\psi}\widehat{\mathcal{Q}}\psi \supset &- a^\mu\bar{\psi}\gamma_\mu\psi - b^\mu\bar{\psi}\gamma_5\gamma_\mu\psi + \cdots \\ &+ c^{\mu\nu}\bar{\psi}\gamma_\mu iD_\nu\psi + d^{\mu\nu}\bar{\psi}\gamma_5\gamma_\mu iD_\nu\psi + \cdots \\ &- a^{(5)\mu\alpha\beta}\bar{\psi}\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi + \cdots\end{aligned}$$

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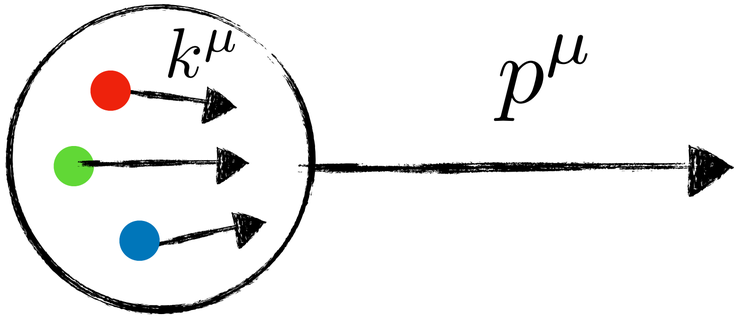

$$k^\mu \simeq \xi p^\mu$$

Do Lorentz-violating effects change this picture?

V. A. Kostelecký, E. Lunghi, N. Sherrill, A. R. Vieira, (2020)

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Lorentz- and CPT-violating parton model

- Explicit calculations carried out for spin-independent and flavor-diagonal effects

$$\mathcal{L} = \sum_{f=u,d} \tfrac{1}{2}\bar{\psi}_f i\gamma^\mu \overleftrightarrow{D}_\mu \psi_f + \tfrac{1}{2} c_f^{\mu\nu} \bar{\psi}_f \gamma_\mu i \overleftrightarrow{D}_\nu \psi_f - \tfrac{1}{2} a_f^{(5)\mu\alpha\beta} \bar{\psi}_f \gamma_\mu i D_{(\alpha} i D_{\beta)} \psi_f + \text{h.c.}$$

- Modified Dirac equation and dispersion relation

$$[(\eta^{\mu\nu} + c_f^{\mu\nu})\gamma_\mu i\partial_\mu - a_f^{(5)\mu\alpha\beta}\gamma_\mu i\partial_\alpha i\partial_\beta]\psi_f = 0$$

$$\widetilde{k}^2 = k^2 + \mathcal{O}(\text{coefficients}) = 0$$

$$\Rightarrow E^2 = |\vec{k}|^2 + \mathcal{O}(\text{coefficients})$$

- Consequence: standard parton-model relation no longer holds

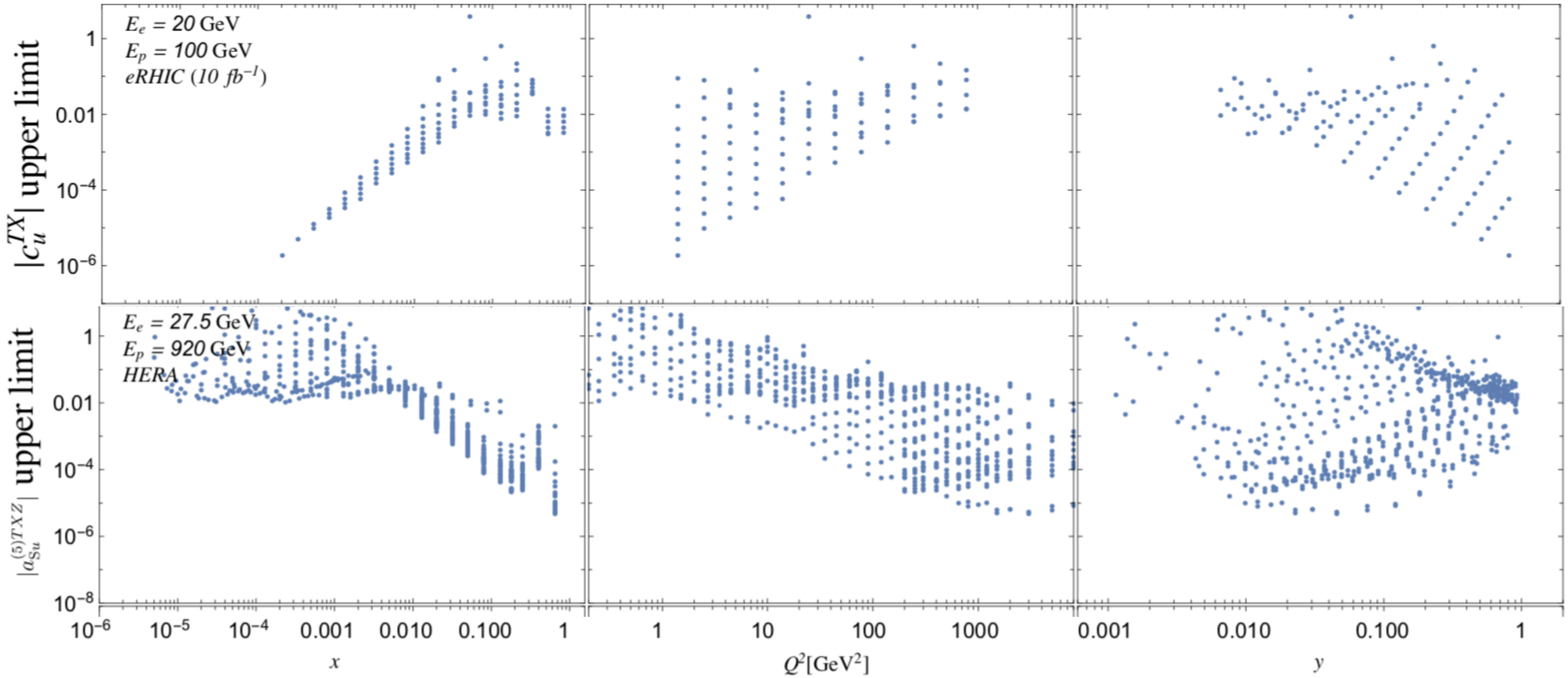
$$k^\mu \neq \xi p^\mu$$

- Factorization requires the following *covariant* relationship

$$\boxed{\widetilde{k}^\mu = \xi p^\mu}$$

The resulting factorization theorem is consistent with the OPE and Ward identities

Lorentz- and CPT-violating parton model



- Renormalizable coefficients: sensitivity at <u>low x</u> !
- Nonrenormalizable effects: $\sigma_{a^5} \propto f_f(x) - f_{\bar{f}}(x)$ $\longrightarrow$ Sea contributions dominate at low x, so CPT violation leads to a weakening of bounds!

Lorentz- and CPT-violating parton model

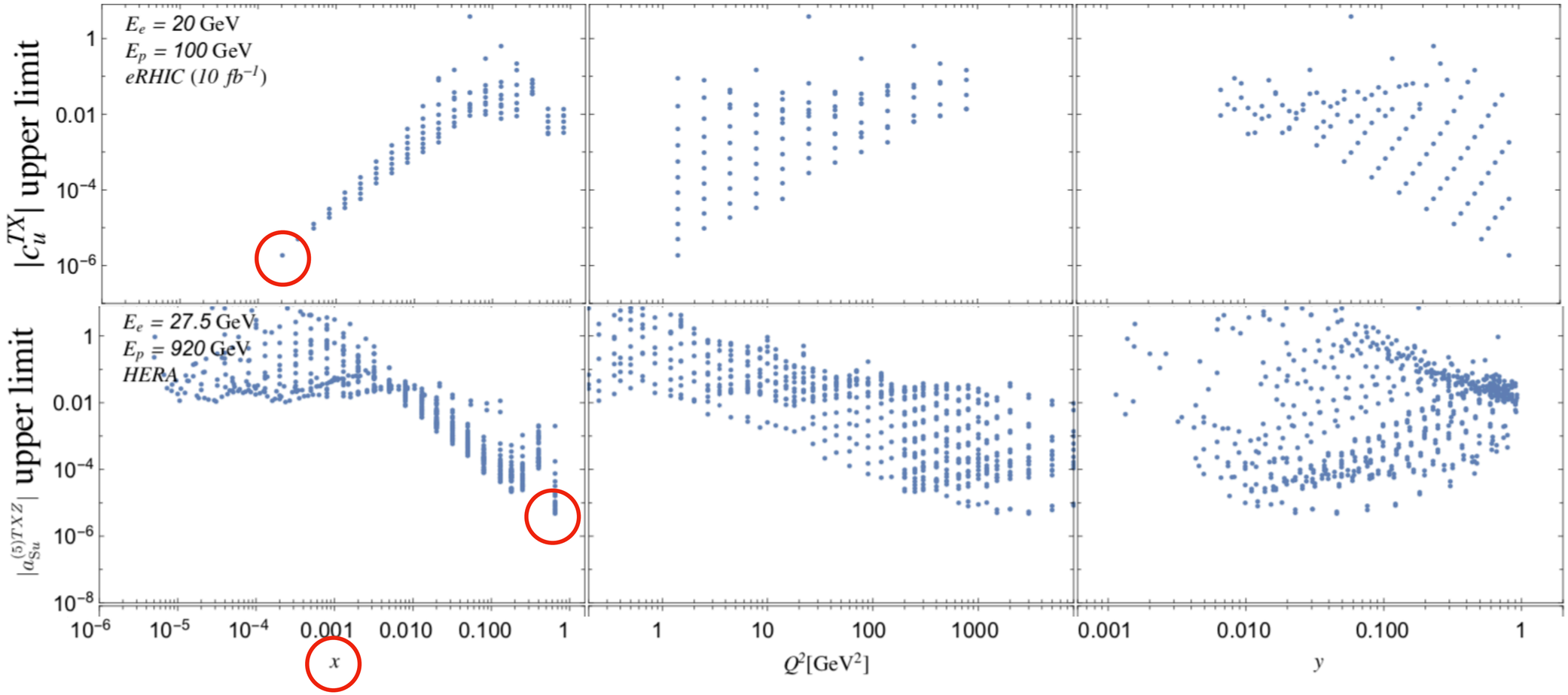


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TABLE IV. Terms of low mass dimension $d \leq 6$ in the Lagrange density for QCD and QED with multiple flavors of quarks.

Component	Expression
$\mathcal{L}_0$	$\frac{1}{2}\bar{\psi}_A\gamma^\mu iD_\mu\psi_A + \text{H.c.} - \bar{\psi}_A m_{AB}\psi_B - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\text{tr}(G_{\mu\nu}G^{\mu\nu})$
$\mathcal{L}_\psi^{(3)}$	$-im_{5AB}\bar{\psi}_A\gamma_5\psi_B - a^\mu_{AB}\bar{\psi}_A\gamma_\mu\psi_B - b^\mu_{AB}\bar{\psi}_A\gamma_5\gamma_\mu\psi_B - \frac{1}{2}H^{\mu\nu}_{AB}\bar{\psi}_A\sigma_{\mu\nu}\psi_B$
$\mathcal{L}_\psi^{(4)}$	$\frac{1}{2}c^{\mu\alpha}_{AB}\bar{\psi}_A\gamma_\mu iD_\alpha\psi_B + \frac{1}{2}d^{\mu\alpha}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu iD_\alpha\psi_B$ $+\frac{1}{2}e^\alpha_{AB}\bar{\psi}_A iD_\alpha\psi_B + \frac{1}{2}if^\alpha_{AB}\bar{\psi}_A\gamma_5 iD_\alpha\psi_B + \frac{1}{4}g^{\mu\nu\alpha}_{AB}\bar{\psi}_A\sigma_{\mu\nu}iD_\alpha\psi_B + \text{H.c.}$
$\mathcal{L}_{\psi D}^{(5)}$	$-\frac{1}{2}(m^{(5)})^{\alpha\beta}_{AB}\bar{\psi}_A iD_{(\alpha}iD_{\beta)}\psi_B - \frac{1}{2}i(m^{(5)}_5)^{\alpha\beta}_{AB}\bar{\psi}_A\gamma_5 iD_{(\alpha}iD_{\beta)}\psi_B - \frac{1}{2}(a^{(5)})^{\mu\alpha\beta}_{AB}\bar{\psi}_A\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_B$ $-\frac{1}{2}(b^{(5)})^{\mu\alpha\beta}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_B - \frac{1}{4}(H^{(5)})^{\mu\nu\alpha\beta}_{AB}\bar{\psi}_A\sigma_{\mu\nu}iD_{(\alpha}iD_{\beta)}\psi_B + \text{H.c.}$
$\mathcal{L}_{\psi F}^{(5)}$	$-\frac{1}{2}(m^{(5)}_F)^{\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\psi_B - \frac{1}{2}i(m^{(5)}_{5F})^{\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\gamma_5\psi_B$ $-\frac{1}{2}(a^{(5)}_F)^{\mu\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\gamma_\mu\psi_B - \frac{1}{2}(b^{(5)}_F)^{\mu\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\gamma_5\gamma_\mu\psi_B - \frac{1}{4}(H^{(5)}_F)^{\mu\nu\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\sigma_{\mu\nu}\psi_B$
$\mathcal{L}_{\psi G}^{(5)}$	$-\frac{1}{2}(m^{(5)}_G)^{\alpha\beta}_{AB}\bar{\psi}_A G_{\alpha\beta}\psi_B - \frac{1}{2}i(m^{(5)}_{5G})^{\alpha\beta}_{AB}\bar{\psi}_A\gamma_5 G_{\alpha\beta}\psi_B$ $-\frac{1}{2}(a^{(5)}_G)^{\mu\alpha\beta}_{AB}\bar{\psi}_A\gamma_\mu G_{\alpha\beta}\psi_B - \frac{1}{2}(b^{(5)}_G)^{\mu\alpha\beta}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu G_{\alpha\beta}\psi_B - \frac{1}{4}(H^{(5)}_G)^{\mu\nu\alpha\beta}_{AB}\bar{\psi}_A\sigma_{\mu\nu}G_{\alpha\beta}\psi_B$
$\mathcal{L}_{\psi D}^{(6)}$	$\frac{1}{2}(c^{(6)})^{\mu\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_\mu iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \frac{1}{2}(d^{(6)})^{\mu\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \frac{1}{2}(e^{(6)})^{\alpha\beta\gamma}_{AB}\bar{\psi}_A iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B$ $+\frac{1}{2}i(f^{(6)})^{\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_5 iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \frac{1}{4}(g^{(6)})^{\mu\nu\alpha\beta\gamma}_{AB}\bar{\psi}_A\sigma_{\mu\nu}iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \text{H.c.}$
$\mathcal{L}_{\psi F}^{(6)}$	$\frac{1}{4}(c^{(6)}_F)^{\mu\alpha\beta\gamma}_{AB}F_{\beta\gamma}\bar{\psi}_A\gamma_\mu iD_\alpha\psi_B + \frac{1}{4}(d^{(6)}_F)^{\mu\alpha\beta\gamma}_{AB}F_{\beta\gamma}\bar{\psi}_A\gamma_5\gamma_\mu iD_\alpha\psi_B$ $+\frac{1}{4}(e^{(6)}_F)^{\alpha\beta\gamma}_{AB}F_{\beta\gamma}\bar{\psi}_A iD_\alpha\psi_B + \frac{1}{4}i(f^{(6)}_F)^{\alpha\beta\gamma}_{AB}F_{\beta\gamma}\bar{\psi}_A\gamma_5 iD_\alpha\psi_B + \frac{1}{8}(g^{(6)}_F)^{\mu\nu\alpha\beta\gamma}_{AB}F_{\beta\gamma}\bar{\psi}_A\sigma_{\mu\nu}iD_\alpha\psi_B + \text{H.c.}$
$\mathcal{L}_{\psi G}^{(6)}$	$\frac{1}{4}(c^{(6)}_G)^{\mu\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_\mu G_{\beta\gamma}iD_\alpha\psi_B + \frac{1}{4}(d^{(6)}_G)^{\mu\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu G_{\beta\gamma}iD_\alpha\psi_B$ $+\frac{1}{4}(e^{(6)}_G)^{\alpha\beta\gamma}_{AB}\bar{\psi}_A G_{\beta\gamma}iD_\alpha\psi_B + \frac{1}{4}i(f^{(6)}_G)^{\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_5 G_{\beta\gamma}iD_\alpha\psi_B + \frac{1}{8}(g^{(6)}_G)^{\mu\nu\alpha\beta\gamma}_{AB}\bar{\psi}_A\sigma_{\mu\nu}G_{\beta\gamma}iD_\alpha\psi_B + \text{H.c.}$
$\mathcal{L}_{\psi\partial F}^{(6)}$	$-\frac{1}{2}(m^{(6)}_{\partial F})^{\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\bar{\psi}_A\psi_B - \frac{1}{2}i(m^{(6)}_{5\partial F})^{\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\bar{\psi}_A\gamma_5\psi_B$ $-\frac{1}{2}(a^{(6)}_{\partial F})^{\mu\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\bar{\psi}_A\gamma_\mu\psi_B - \frac{1}{2}(b^{(6)}_{\partial F})^{\mu\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\bar{\psi}_A\gamma_5\gamma_\mu\psi_B - \frac{1}{4}(H^{(6)}_{\partial F})^{\mu\nu\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\bar{\psi}_A\sigma_{\mu\nu}\psi_B$
$\mathcal{L}_{\psi DG}^{(6)}$	$-\frac{1}{2}(m^{(6)}_{DG})^{\alpha\beta\gamma}_{AB}\bar{\psi}_A(D_\alpha G_{\beta\gamma})\psi_B - \frac{1}{2}i(m^{(6)}_{5DG})^{\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_5(D_\alpha G_{\beta\gamma})\psi_B$ $-\frac{1}{2}(a^{(6)}_{DG})^{\mu\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_\mu(D_\alpha G_{\beta\gamma})\psi_B - \frac{1}{2}(b^{(6)}_{DG})^{\mu\alpha\beta\gamma}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu(D_\alpha G_{\beta\gamma})\psi_B - \frac{1}{4}(H^{(6)}_{DG})^{\mu\nu\alpha\beta\gamma}_{AB}\bar{\psi}_A\sigma_{\mu\nu}(D_\alpha G_{\beta\gamma})\psi_B$
$\mathcal{L}_{\psi\psi}^{(6)}$	$(k_{SS})_{ABCD}(\bar{\psi}_A\psi_B)(\bar{\psi}_C\psi_D) - (k_{PP})_{ABCD}(\bar{\psi}_A\gamma_5\psi_B)(\bar{\psi}_C\gamma_5\psi_D)$ $+i(k_{SP})_{ABCD}(\bar{\psi}_A\psi_B)(\bar{\psi}_C\gamma_5\psi_D) + (k_{SV})^\mu_{ABCD}(\bar{\psi}_A\psi_B)(\bar{\psi}_C\gamma_\mu\psi_D)$ $+(k_{SA})^\mu_{ABCD}(\bar{\psi}_A\psi_B)(\bar{\psi}_C\gamma_5\gamma_\mu\psi_D) + \frac{1}{2}(k_{ST})^{\mu\nu}_{ABCD}(\bar{\psi}_A\psi_B)(\bar{\psi}_C\sigma_{\mu\nu}\psi_D)$ $+i(k_{PV})^\mu_{ABCD}(\bar{\psi}_A\gamma_5\psi_B)(\bar{\psi}_C\gamma_\mu\psi_D) + i(k_{PA})^\mu_{ABCD}(\bar{\psi}_A\gamma_5\psi_B)(\bar{\psi}_C\gamma_5\gamma_\mu\psi_D)$ $+\frac{1}{2}i(k_{PT})^{\mu\nu}_{ABCD}(\bar{\psi}_A\gamma_5\psi_B)(\bar{\psi}_C\sigma_{\mu\nu}\psi_D) + \frac{1}{2}(k_{VV})^{\mu\nu}_{ABCD}(\bar{\psi}_A\gamma_\mu\psi_B)(\bar{\psi}_C\gamma_\nu\psi_D)$ $+\frac{1}{2}(k_{AA})^{\mu\nu}_{ABCD}(\bar{\psi}_A\gamma_5\gamma_\mu\psi_B)(\bar{\psi}_C\gamma_5\gamma_\nu\psi_D) + (k_{VA})^{\mu\nu}_{ABCD}(\bar{\psi}_A\gamma_\mu\psi_B)(\bar{\psi}_C\gamma_5\gamma_\mu\psi_D)$ $+\frac{1}{2}(k_{VT})^{\lambda\mu\nu}_{ABCD}(\bar{\psi}_A\gamma_\lambda\psi_B)(\bar{\psi}_C\sigma_{\mu\nu}\psi_D) + \frac{1}{2}(k_{AT})^{\lambda\mu\nu}_{ABCD}(\bar{\psi}_A\gamma_5\gamma_\lambda\psi_B)(\bar{\psi}_C\sigma_{\mu\nu}\psi_D)$ $+\frac{1}{8}(k_{TT})^{\kappa\lambda\mu\nu}_{ABCD}(\bar{\psi}_A\sigma_{\kappa\lambda}\psi_B)(\bar{\psi}_C\sigma_{\mu\nu}\psi_D)$
$\mathcal{L}_{AG}^{(1)}$	$-(k_A)^\mu A_\mu$
$\mathcal{L}_{AG}^{(3)}$	$\frac{1}{2}(k_{AF})^\kappa\epsilon_{\kappa\lambda\mu\nu}A^\lambda F^{\mu\nu} + (k_3)^\kappa\epsilon_{\kappa\lambda\mu\nu}\text{tr}(G^\lambda G^{\mu\nu} + \frac{2}{3}ig_3G^\lambda G^\mu G^\nu)$
$\mathcal{L}_{AG}^{(4)}$	$-\frac{1}{4}(k_F)^{\kappa\lambda\mu\nu}F_{\kappa\lambda}F_{\mu\nu} - \frac{1}{2}(k_G)^{\kappa\lambda\mu\nu}\text{tr}(G_{\kappa\lambda}G_{\mu\nu})$
$\mathcal{L}_{AG}^{(5)}$	$-\frac{1}{4}k^{(5)\alpha\kappa\lambda\mu\nu}F_{\kappa\lambda}\partial_\alpha F_{\mu\nu} - \frac{1}{2}k_D^{(5)\alpha\kappa\lambda\mu\nu}\text{tr}(G_{\kappa\lambda}D_\alpha G_{\mu\nu})$
$\mathcal{L}_{AG}^{(6)}$	$-\frac{1}{4}k_\partial^{(6)\alpha\beta\kappa\lambda\mu\nu}F_{\kappa\lambda}\partial_\alpha\partial_\beta F_{\mu\nu} - \frac{1}{12}k_F^{(6)\kappa\lambda\mu\nu\rho\sigma}F_{\kappa\lambda}F_{\mu\nu}F_{\rho\sigma}$ $-\frac{1}{2}k_D^{(6)\alpha\beta\kappa\lambda\mu\nu}\text{tr}(G_{\kappa\lambda}D_{(\alpha}D_{\beta)}G_{\mu\nu}) - \frac{1}{6}k_G^{(6)\kappa\lambda\mu\nu\rho\sigma}\text{tr}(G_{\kappa\lambda}G_{\mu\nu}G_{\rho\sigma}) - \frac{1}{4}k_{FG}^{(6)\kappa\lambda\mu\nu\rho\sigma}F_{\kappa\lambda}\text{tr}(G_{\mu\nu}G_{\rho\sigma})$

V. A. Kostelecký, Z. Li, (2019)

- Vast majority of nonrenormalizable effects in QCD and electroweak sectors are unconstrained
- Colliders, especially the FCC, will play an important role in future studies of Lorentz and CPT violation

$$\sigma_d \propto (\text{coefficient}) \times (E_{\text{collider}})^{d-4}$$

Example: gauge-sector effects

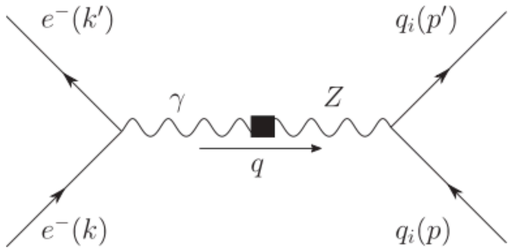
- A recent study has considered Z-boson Lorentz violation for in DIS at future colliders

A. Michel, M. Sher (2019)

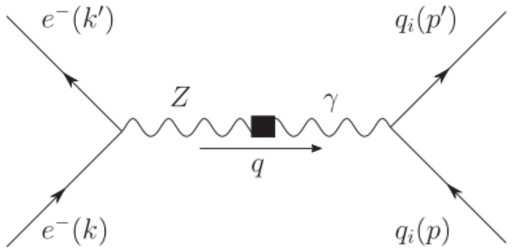
- Electron-quark corrections

$$\left(\frac{d^2\sigma}{dE'd\Omega}\right)_{ep\to eX} = \sum_i \int_0^1 dx f_i(x) \left(\frac{d^2\sigma}{dE'd\Omega}\right)_{eq_i\to eq_i}$$

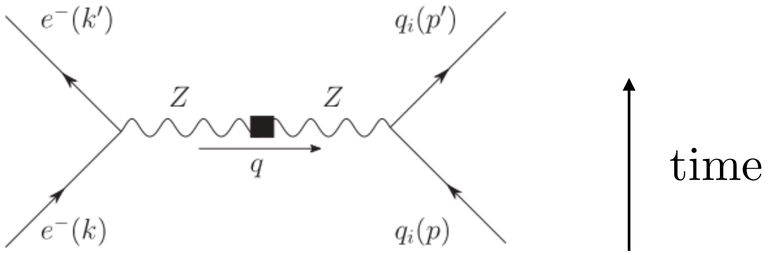
A popular framework for exploring Lorentz violation is the Standard Model extension. This extension contains a large number of parameters that can be bounded in various experiments. Most studies, however, focus on the fermion or photon sector. Here, we consider Lorentz violation in the weak vector boson sector. The strongest bounds come from measurements of the asymmetry in Møller scattering. We study the bounds that can be obtained from future measurements of the parity violating asymmetry in deep inelastic electron-proton scattering at the EIC, the LHeC, and the FCC-eh. For the FCC-eh, the bounds could be substantially improved over current bounds by including timing information.



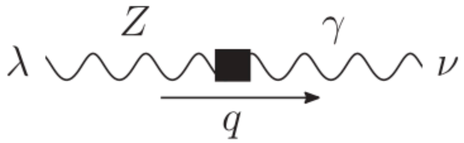
(c) $i\mathcal{M}_{\gamma Z}$



(d) $i\mathcal{M}_{Z\gamma}$

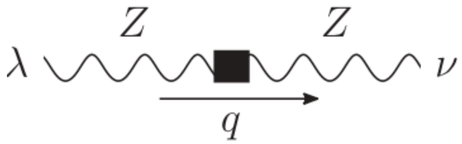


(e) $i\mathcal{M}_{ZZ}$



$$= -2i \tan\theta_W (k_W)_{\kappa\lambda\mu\nu} q^\kappa q^\mu$$

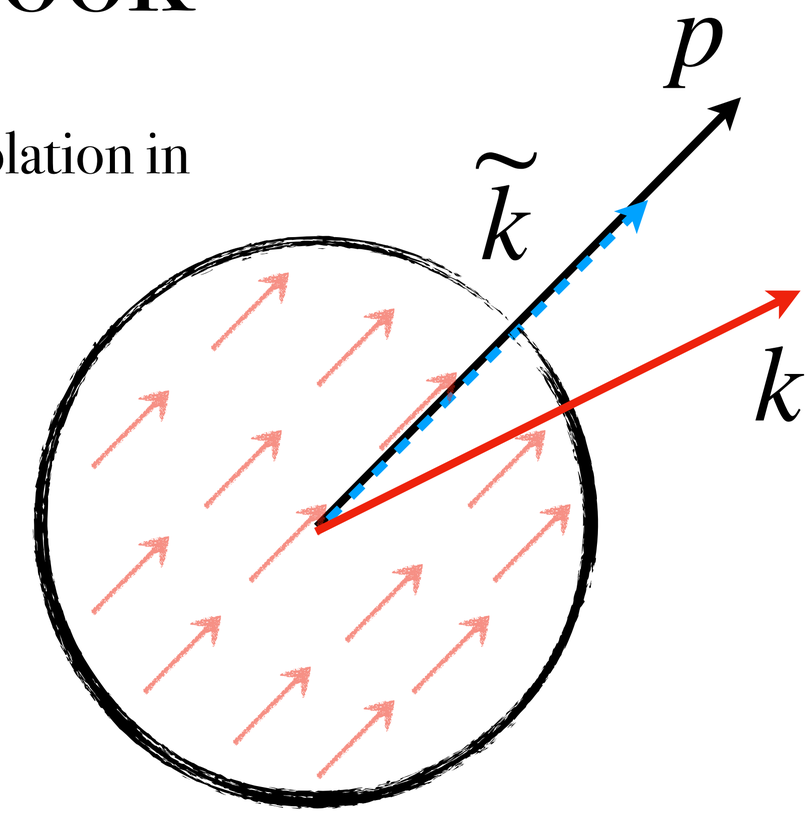
(a)



$$= -2i(1-\tan^2\theta_W)(k_W)_{\kappa\lambda\mu\nu} q^\kappa q^\mu$$

(b)

Conclusions and outlook



- We developed a framework for studying quark-sector Lorentz and CPT violation in collider processes
- Extracted simulated and real constraints on renormalizable and nonrenormalizable coefficients for Lorentz and CPT violation at existing and future colliders
- HERA analysis with ZEUS collaboration underway
- Kinematic reach and increased luminosity of FCC-eh expected to produce improved constraints over HERA/LHC by several orders of magnitude
- Many new theoretical and experimental opportunities available – a great time to get involved!