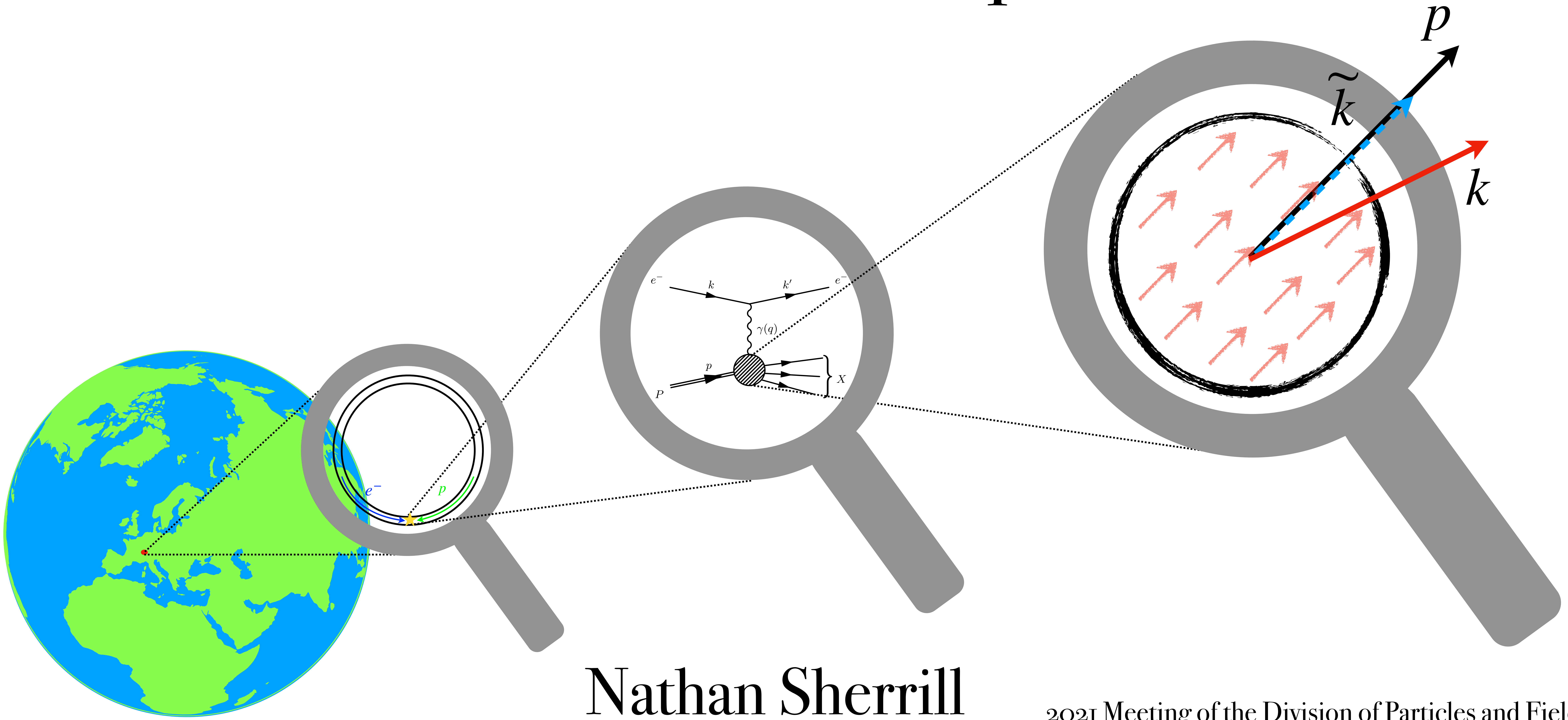
Lorentz violation in the quark sector



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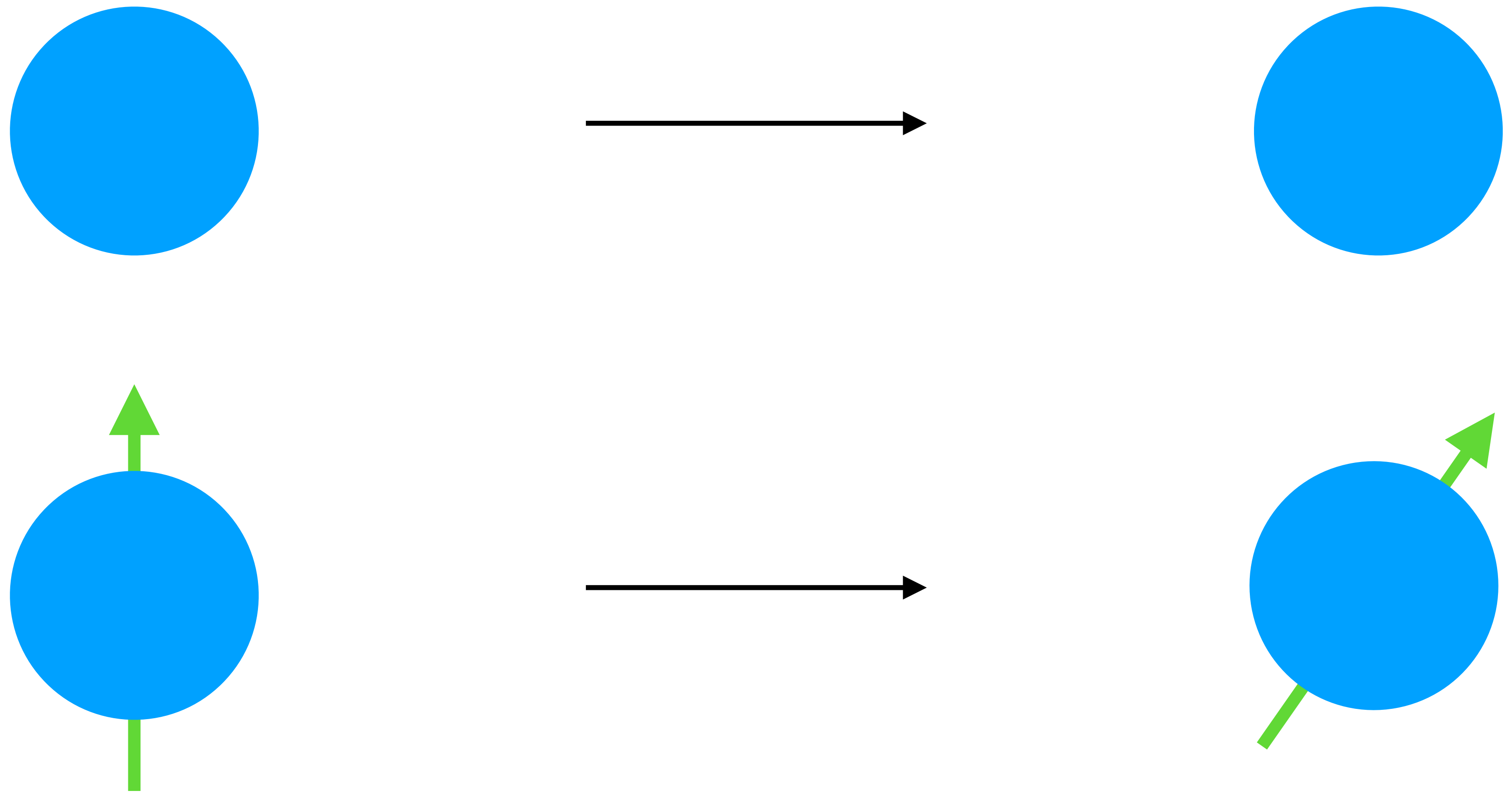
Symmetry and symmetry breaking

- 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, $SU(2)_L$, gauge symmetry, ...; CPT, Lorentz symmetry (?)

Symmetry and symmetry breaking

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

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

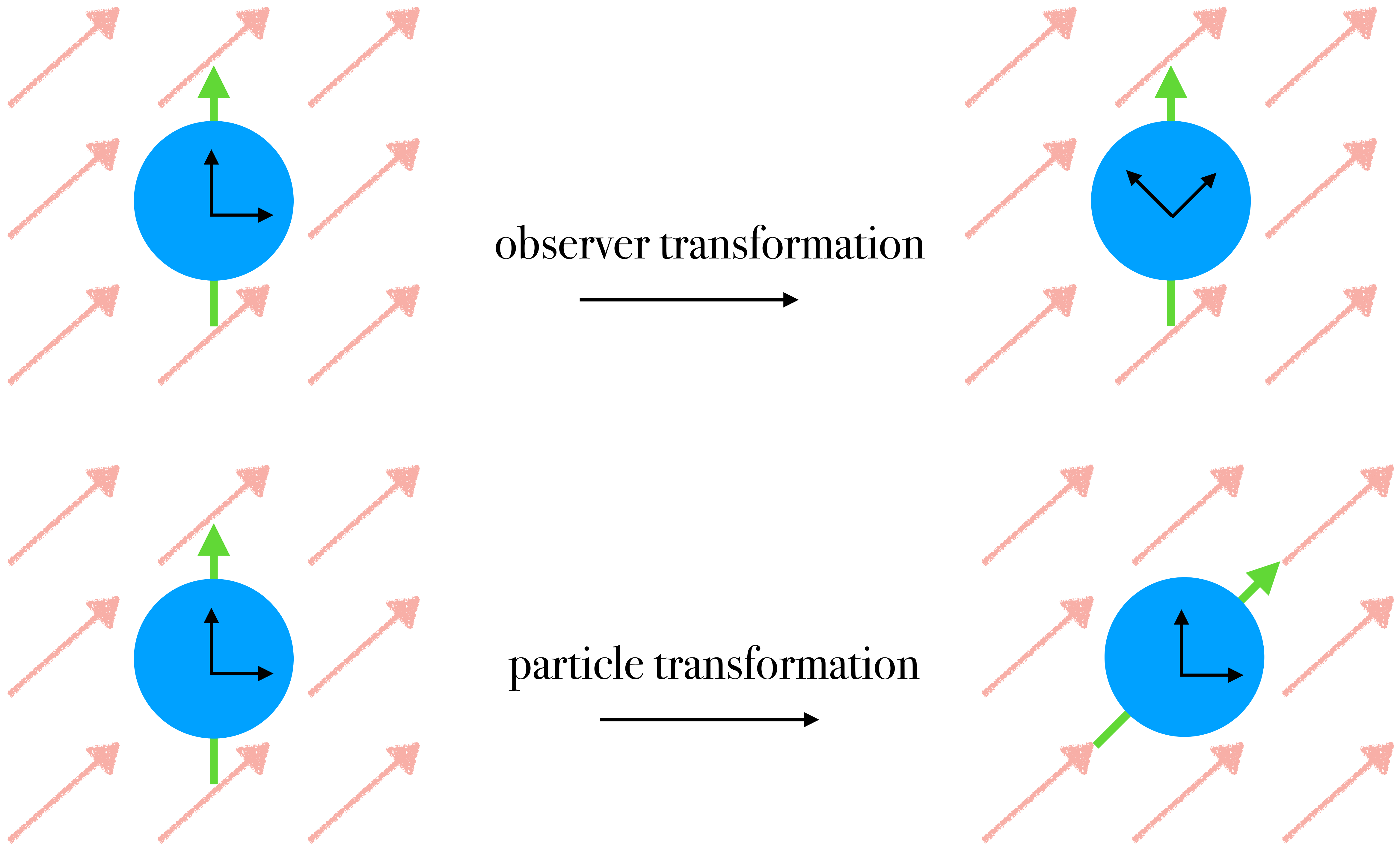
V. A. Kostelecký, S. Samuel (1989)
V. A. Kostelecký, R. Potting (1991, 1995)

- 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)

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

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

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

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]*
$\lvert \tilde{\kappa}_{\text{tr}}^{\text{QCD}}\rvert$	$< 2 \times 10^{-13}$	"	[171]*

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

Prospective HERA and EIC bounds

- Deep inelastic scattering (DIS) has been studied in the context of HERA and EIC data

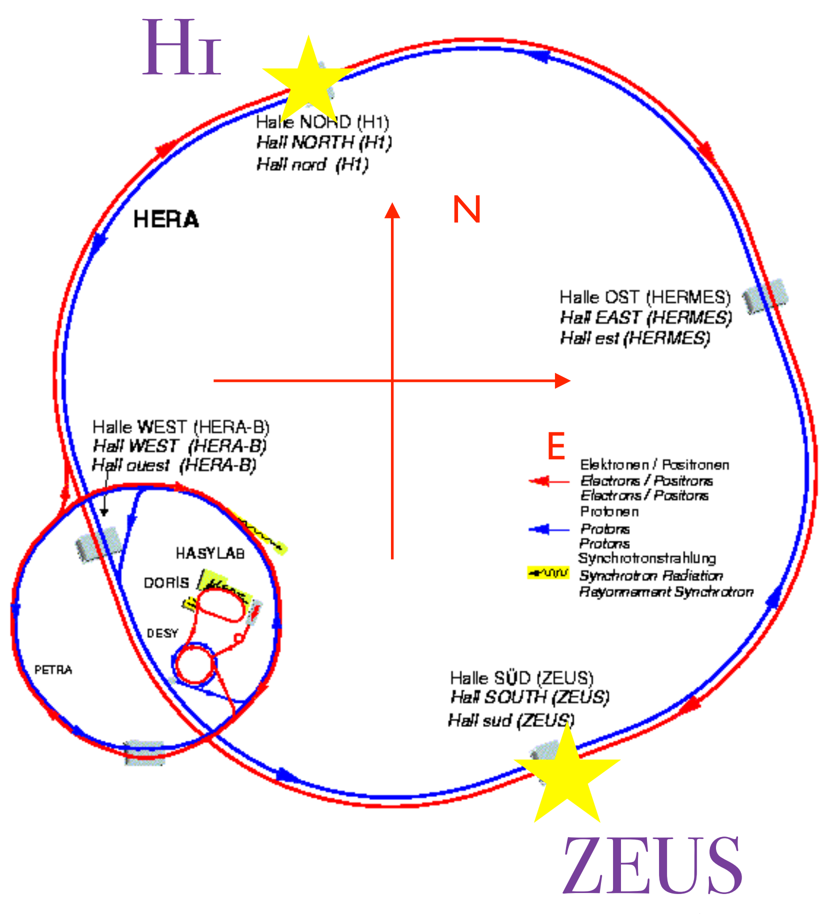
V. A. Kostelecký, E. Lunghi, A. R. Vieira, (2017)

E. Lunghi, N. Sherrill, (2018)

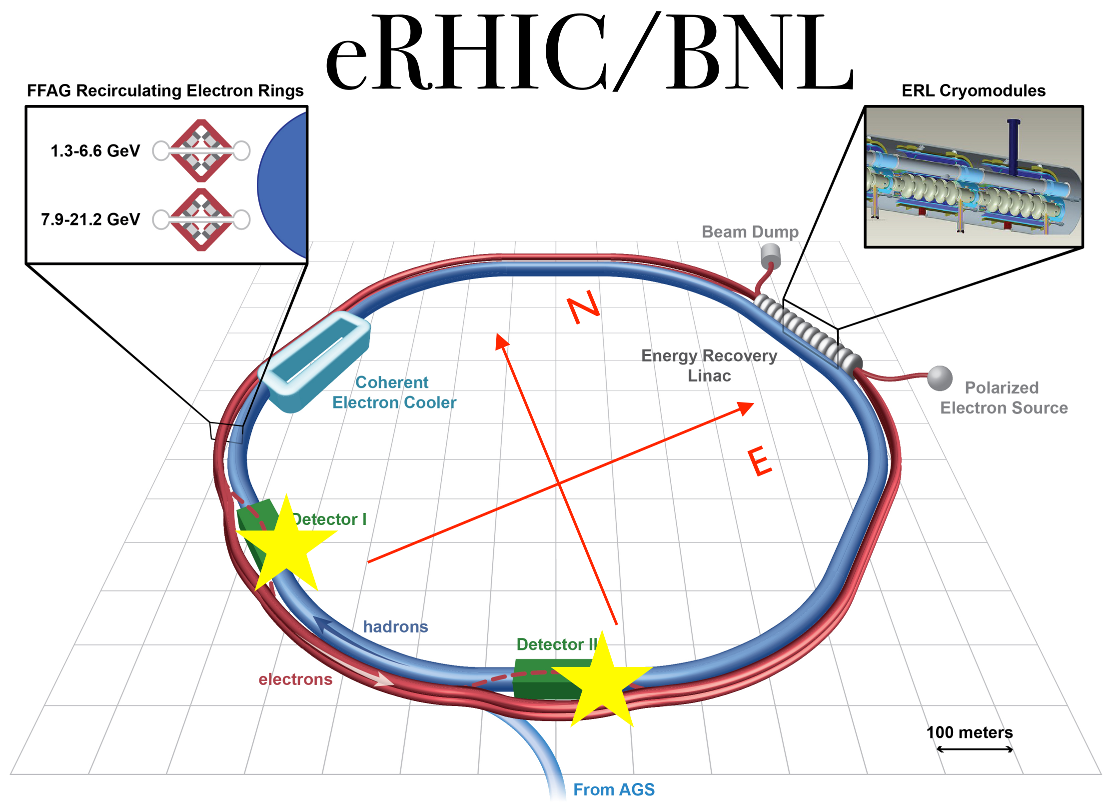
- Dominant renormalizable effects for massless valence quarks

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

HERA



EIC Yellow Report, arXiv:2103.05419



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
- Unpolarized electromagnetic exchange independent of parity-violating effects (see Z pole in the Drell-Yan process @ LHC)

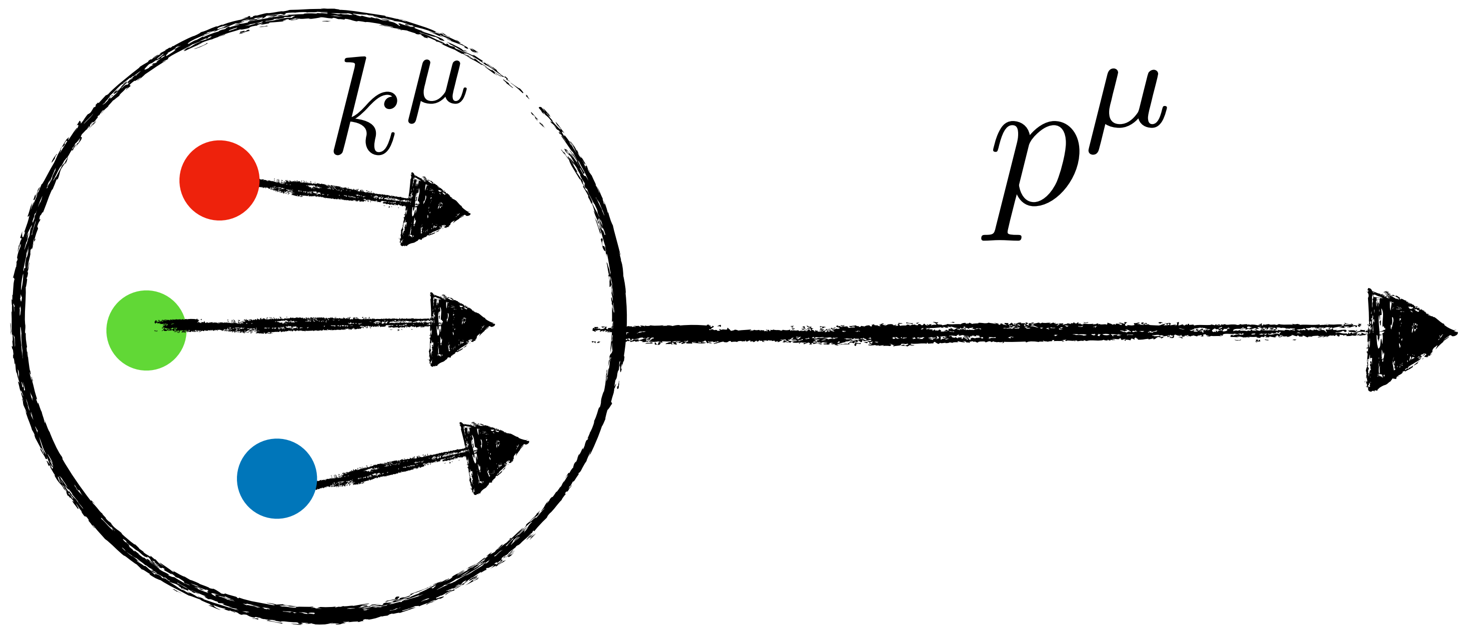
Sidereal analysis of HERA data *in progress*

E. Lunghi, N. Sherrill, ZEUS Collaboration

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

Lorentz- and CPT-violating parton model

- Standard partonic picture at large energies:



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

Do Lorentz-violating effects change this picture?

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

- Quarks modified by Lorentz- and CPT-violating operators

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

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

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

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

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

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

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

- Consequence: standard parton-model relation no longer holds

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

- Factorization requires the following *covariant* relationship

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

Resulting factorization theorems for DIS and Drell-Yan are consistent with the OPE and Ward identities

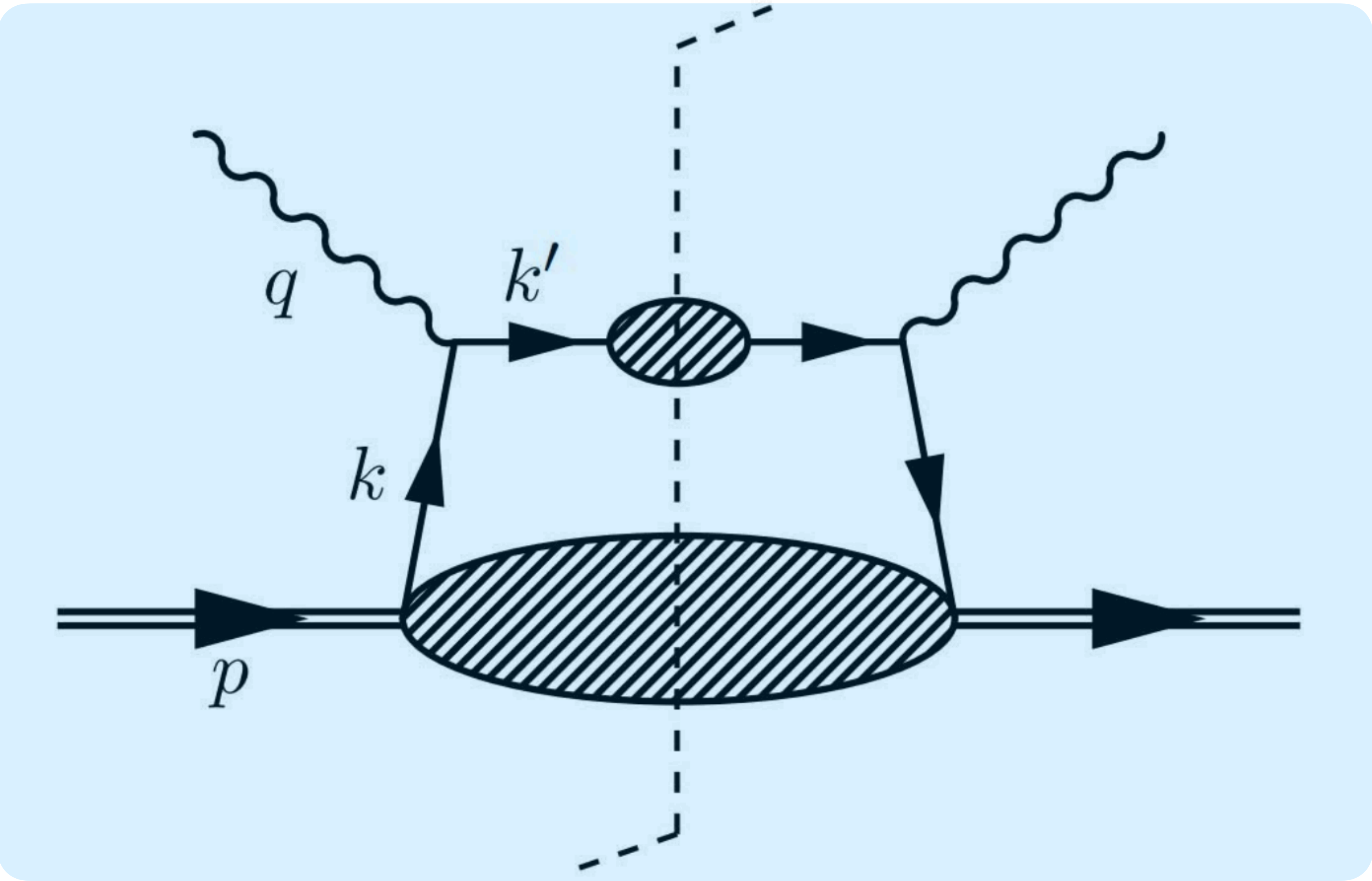
Constraints for DIS and DY process

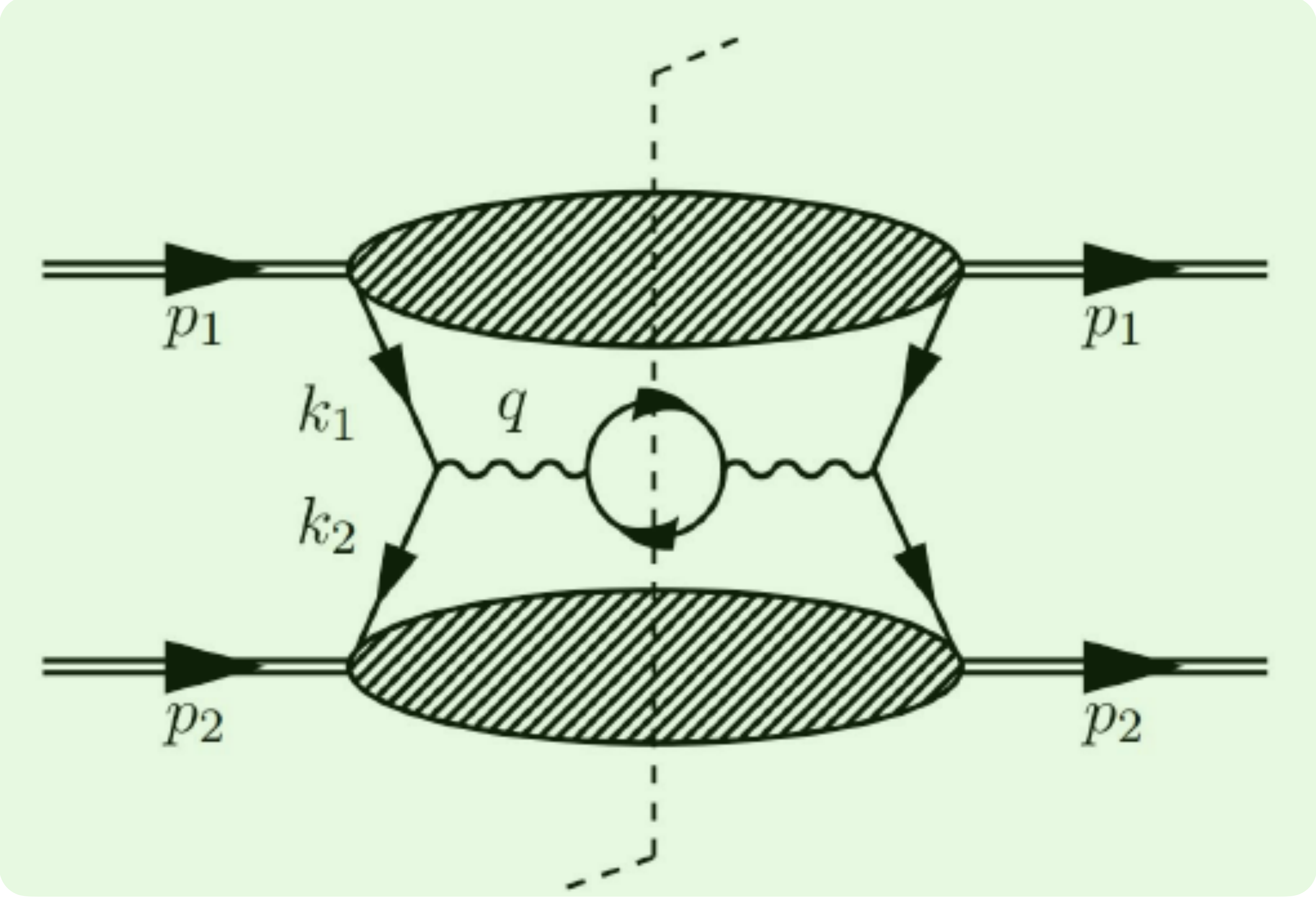
- Comparisons between DIS and DY

	EIC	LHC	
$\lvert c_u^{XX} - c_u^{YY} \rvert$	0.37	15	
$\lvert c_u^{XY} \rvert$	0.13	2.7	$\times 10^{-5}$
$\lvert c_u^{XZ} \rvert$	0.11	7.3	
$\lvert c_u^{YZ} \rvert$	0.12	7.1	
$\lvert a_{\mathrm{S}u}^{(5)TXX} - a_{\mathrm{S}u}^{(5)TYY} \rvert$	2.3	0.015	
$\lvert a_{\mathrm{S}u}^{(5)TXY} \rvert$	0.34	0.0027	$\times 10^{-6}$ GeV^{-1}
$\lvert a_{\mathrm{S}u}^{(5)TXZ} \rvert$	0.13	0.0072	
$\lvert a_{\mathrm{S}u}^{(5)TYZ} \rvert$	0.12	0.0070	

- Renormalizable effects more sensitive to DIS at the EIC; nonrenormalizable more sensitive to DY at the LHC

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





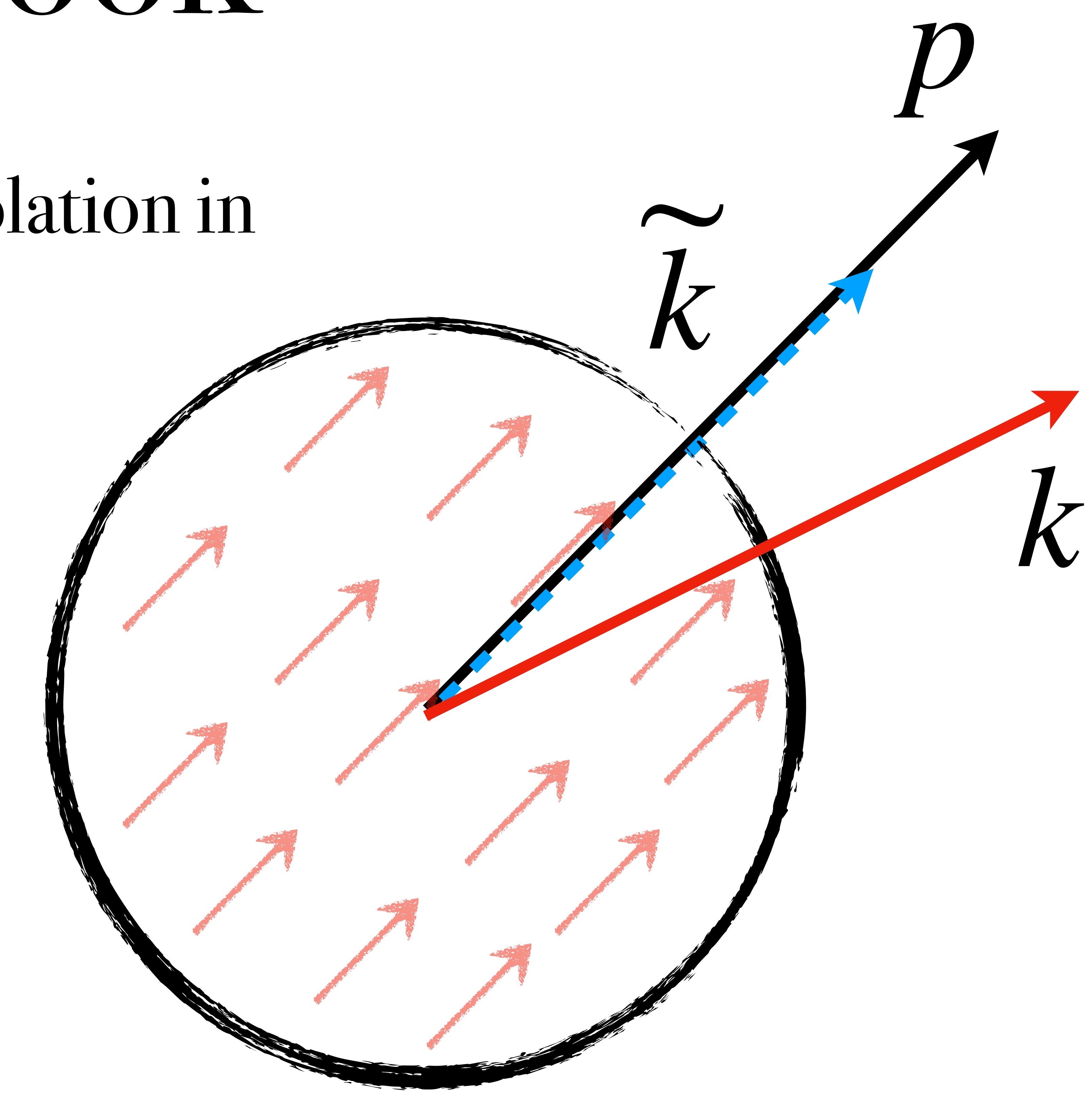
Conclusions and outlook

- 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

- Analysis of HERA neutral-current data w/ZEUS collaboration underway

- Kinematic reach and increased luminosity of future colliders, e.g. the FCC, will improve constraints over HERA/LHC by several orders of magnitude



See, e.g., A. Michel & M. Sher (2019)

- Many new theoretical and experimental opportunities available – a great time to get involved!