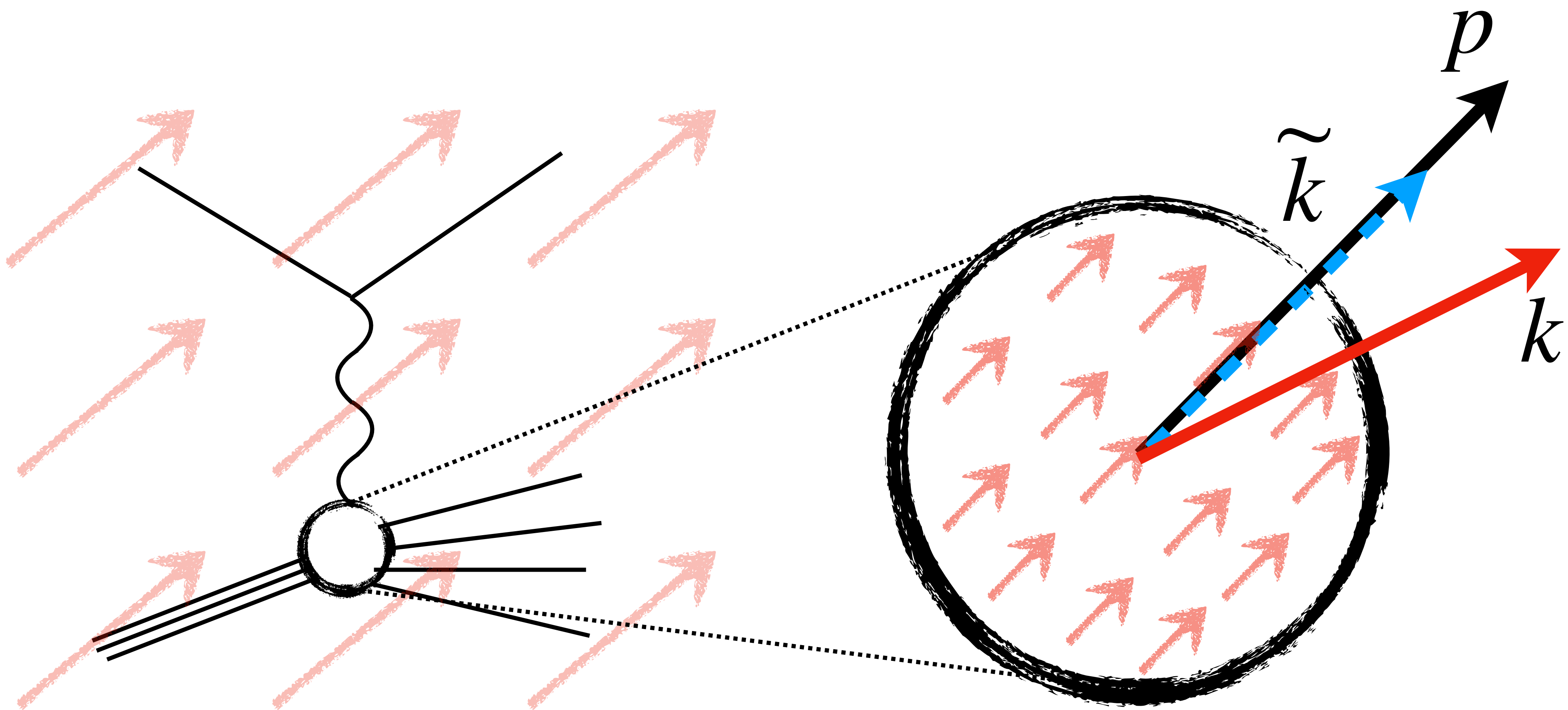
Lorentz violation analysis with ZEUS data



Nathan Sherrill
Indiana University

ZEUS meeting, January 2020

http://www.indiana.edu/~iucss/

In collaboration with Enrico Lunghi

Talk overview

What is Lorentz violation?

How to search for Lorentz violation?

Effects on high-energy hadrons

Application: deep inelastic scattering

Estimates for colliders

An analysis with real data

Based on: arXiv:1911.04002; PRD **98**, 115018 (2018); PLB **769**, 272 (2017)

What is Lorentz violation?

Lorentz invariance: the laws of physics are the same for all inertial observers

$\Rightarrow$ Experimental results do not depend on the orientation of the laboratory/system or its velocity through space

Consider operators

$$\mathcal{O}^{\mu\nu\cdots} \supset \bar{\psi}\gamma^{\mu}\psi, \;\; \bar{\psi}\gamma^{\mu} iD^{\nu}\psi, \;\; \cdots$$

$$\mathcal{L}_{\rm LI} \not\supset \mathcal{O}^{\mu\nu}$$

Make scalars by contracting with objects possessing Lorentz indices!

a_μ

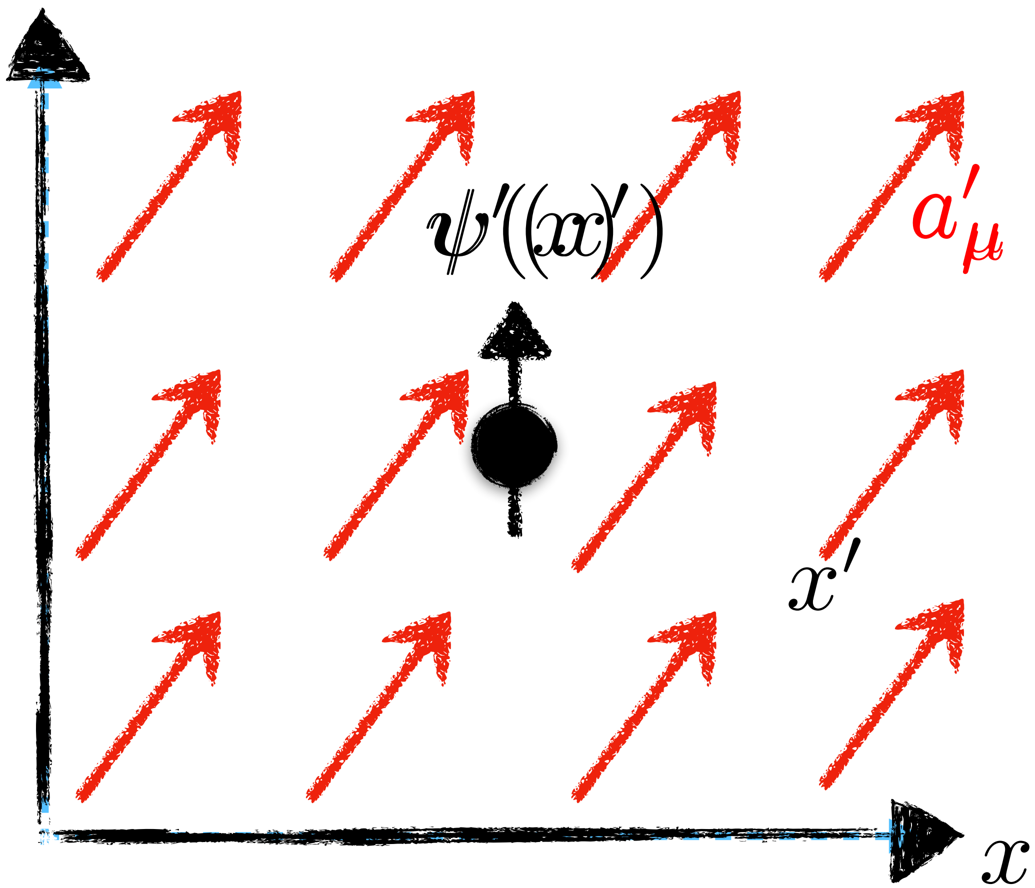
E.g. $\mathcal{L}_a \supset -a_\mu \bar{\psi}\gamma^{\mu}\psi, \quad [a_\mu] = [\mathrm{GeV}]$

Here a_μ is a fixed background vector field filling all of spacetime

What is Lorentz violation?

What effects are induced by $\mathcal{L}_a$?

An *observer* Lorentz transformation (OLT) is a coordinate transformation



$$a^\mu \to \Lambda^\mu{}_\nu a^\nu$$

$$\psi(x) \to \psi'(x') = S\psi(x)$$

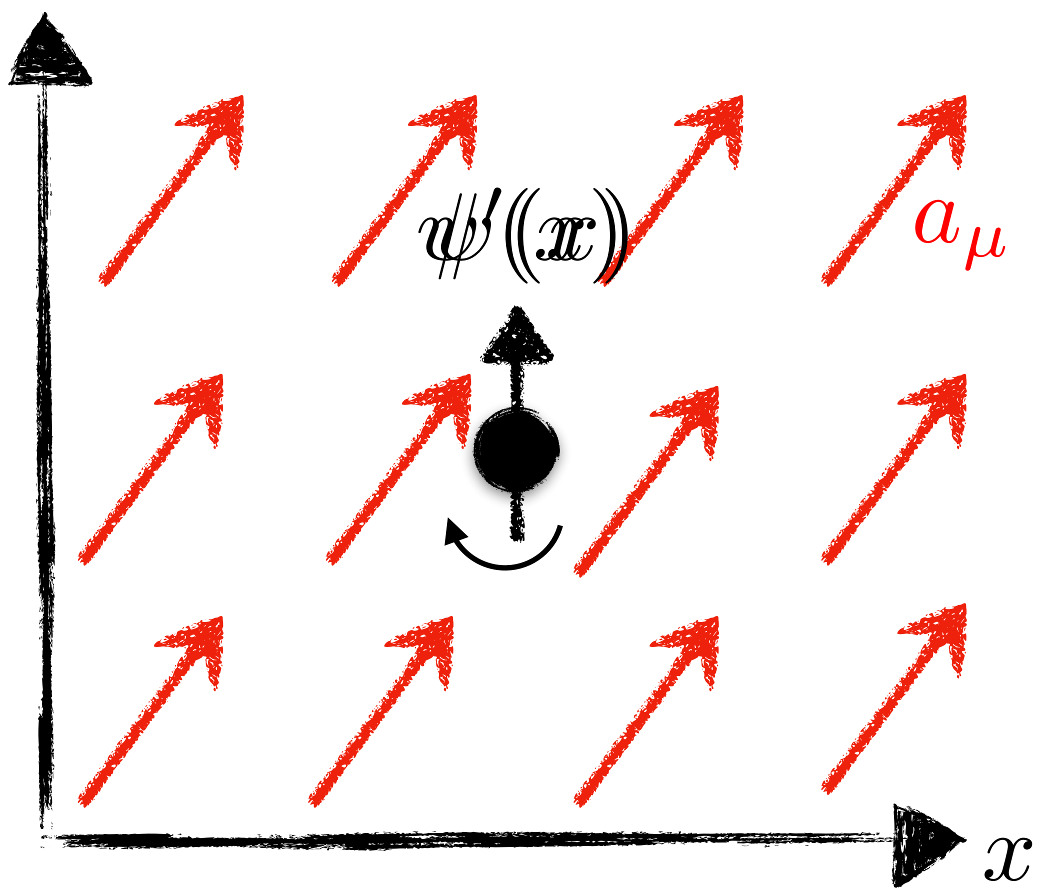
$$-a_\mu \bar{\psi}\gamma^\mu\psi \to -a_\mu \bar{\psi}\gamma^\mu\psi$$

Under an OLT the background a_μ transforms like an ordinary four vector

Hence, there is no change in the physics; the background cannot be seen by performing observer transformations (changing coordinates)

What is Lorentz violation?

A *particle* Lorentz transformation (PLT) is a transformation of the physical system



$$a_\mu \to a_\mu$$

$$\psi(x) \to \psi'(x) = S\psi(\Lambda^{-1}x)$$

Net physical effect

$$-a_\mu \bar{\psi}\gamma^\mu\psi \to -\left(\Lambda^{-1}\right)_{\mu\nu} a^\nu \bar{\psi}\gamma^\mu\psi$$

$$\neq -a_\mu \bar{\psi}\gamma^\mu\psi$$

Unlike OLTs, PLTs can produce physical effects as a result of the background

The rotated system obeys a different physical law than the same system with rotated coordinates $\Rightarrow$ Lorentz violation!

How to search for Lorentz violation?

We use a model-independent, effective field theory framework: the Standard-Model Extension (SME)*

*D. Colladay, V. A. Kostelecký, PRD 55, 6760 (1997); PRD 58, 1166002 (1998)
*V. A. Kostelecký, PRD 69, 105009 (2004)

$$\mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{GR}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{LV}}$$

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

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

CPTV $\Rightarrow$ LV in realistic EFT*

- "Coefficients for Lorentz violation"
- Observer Lorentz tensors
- Coupling constants
- Necessarily small (perturbative)
- Experimentally accessible!

*D. Colladay, V. A. Kostelecký, PRD 55, 6760 (1997)
*O. W. Greenberg, Phys. Rev. Lett. 89, 231602 (2002)

How to search for Lorentz violation?

Data Tables for Lorentz and CPT Violation

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January 2020 update of *Reviews of Modern Physics* **83**, 11 (2011) [arXiv:0801.0287]

This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, neutrino, and gravity sectors. Tables presenting definitions and properties are also compiled.

⋮

Table D19. Nonminimal photon sector, $d = 7$

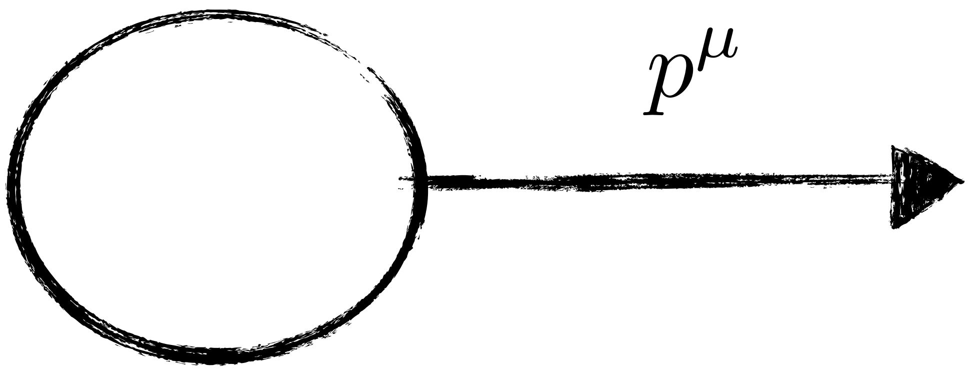
Combination	Result	System	Ref.
$\lvert\sum_{jm} Y_{jm}(110.47°, 71.34°) k^{(7)}_{(V)jm}\rvert$	$< 2 \times 10^{-6}$ GeV^{-3}	Spectropolarimetry	[170]
$\lvert\sum_{jm} Y_{jm}(330.68°, 42.28°) k^{(7)}_{(V)jm}\rvert$	$< 4 \times 10^{-6}$ GeV^{-3}	"	[170]
$\lvert k^{(7)}_{(V)00}\rvert$	$< 6 \times 10^{-6}$ GeV^{-3}	"	[170]
$\lvert\sum_{jm} Y_{jm}(27°, 6°) k^{(7)}_{(V)jm}\rvert$	$< 2 \times 10^{-28}$ GeV^{-3}	Astrophysical birefringence	[171]*

100s of bounds for nearly every major subfield of physics

Much of the QCD sector is yet to be explored!

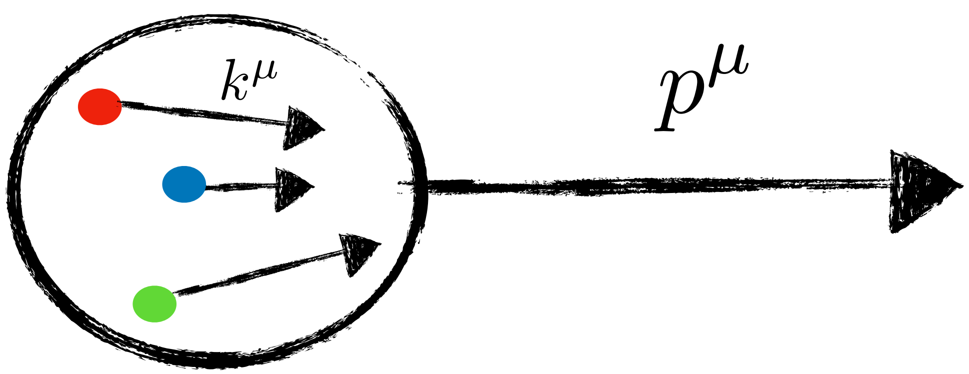
High-energy hadrons

Consider a high-energy hadron



$$p^\mu = \left(p^+, \frac{M^2}{2p^+}, 0_\perp\right), \quad p^+ \gg M$$

The partons have momenta that scale like p^μ



$$k^\mu \sim \left(p^+, \frac{M^2}{2p^+}, M\right) + \mathcal{O}(M/p^+)$$

Fraction of plus momenta is boost invariant, leading to familiar parameterization for high-energy, massless, on-shell partons within hadrons

$$\xi \equiv k^+/p^+$$

$$k^\mu = \xi p^\mu$$

Covariant expression; can be used in any frame

Quark-sector Lorentz-violating effects

Massless quarks modified by Lorentz-violating effects

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

E.g. general modified kinetic terms

$$\begin{aligned}\tfrac{1}{2}\bar{\psi}\widehat{\mathcal{Q}}\psi \supset &- \left(a^{(3)}\right)^{\mu}_{AB}\bar{\psi}_A\gamma_\mu\psi_B - \left(b^{(3)}\right)^{\mu}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu\psi_B + \cdots \\ &+ \left(c^{(4)}\right)^{\mu\nu}_{AB}\bar{\psi}_A\gamma_\mu iD_\nu\psi_B + \left(d^{(4)}\right)^{\mu\nu}_{AB}\bar{\psi}_A\gamma_5\gamma_\mu iD_\nu\psi_B \cdots \\ &- \left(a^{(5)}\right)^{\mu\alpha\beta}_{AB}\bar{\psi}_A\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_B + \cdots\end{aligned}$$

We consider the following (spin-independent, flavor-diagonal) effects

$$\begin{aligned}\mathcal{L} = \sum_{f=u,d} &\tfrac{1}{2}\bar{\psi}_f\gamma^\mu iD_\mu\psi_f + \tfrac{1}{2}(c_f^{(4)})^{\mu\nu}\bar{\psi}_f\gamma_\mu iD_\nu\psi_f \\ &- (a_f^{(5)})^{\mu\alpha\beta}\bar{\psi}_f\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_f + \text{h.c.}\end{aligned}$$

Quark-sector Lorentz-violating effects

Modified Dirac equation

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

Dispersion relation

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

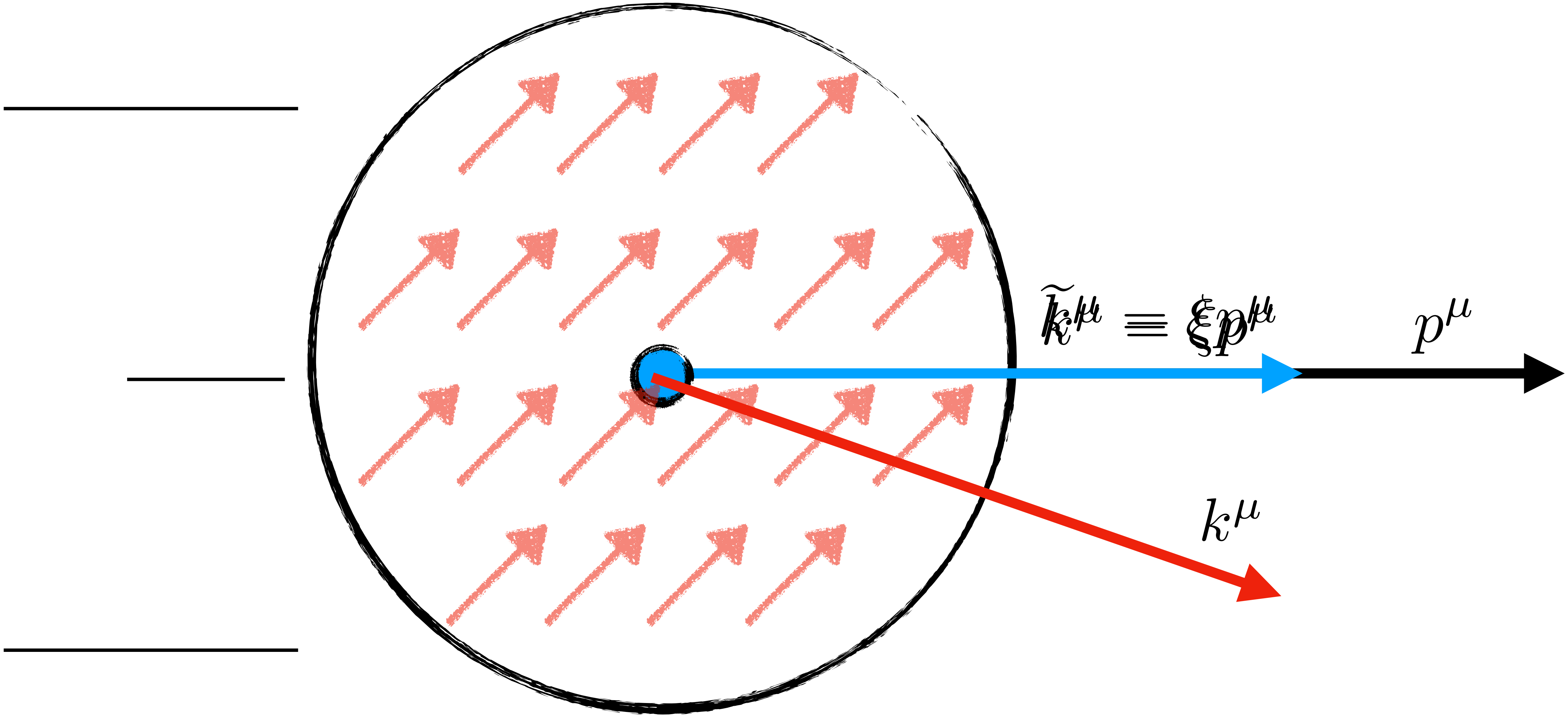
$$E^2 = |\vec{k}|^2 + \mathcal{O}(\text{coefficients})$$

The light-cone decomposition no longer necessarily true

$$k^\mu \sim \left(p^+, \frac{M^2}{2p^+}, M\right) + \mathcal{O}(M/p^+)$$

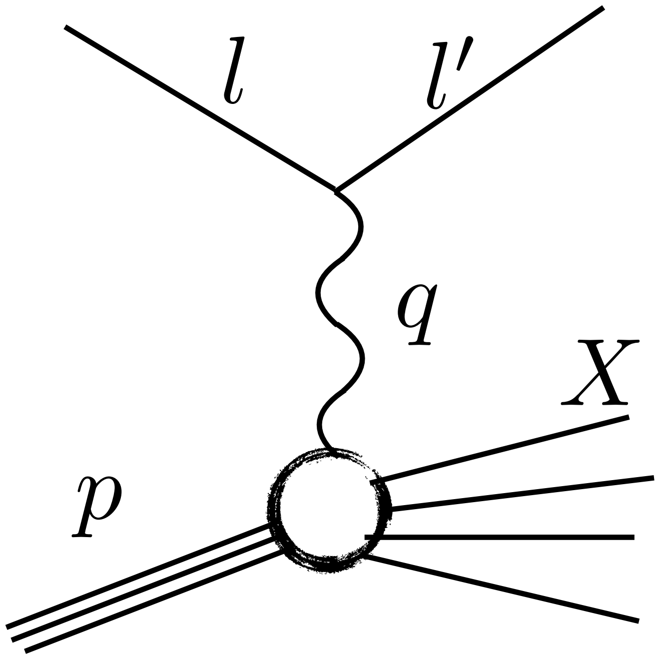
$k^\mu = \xi p^\mu$ is no longer consistent

Instead, for a covariant definition to be retained $\widetilde{k}^\mu = \xi p^\mu$



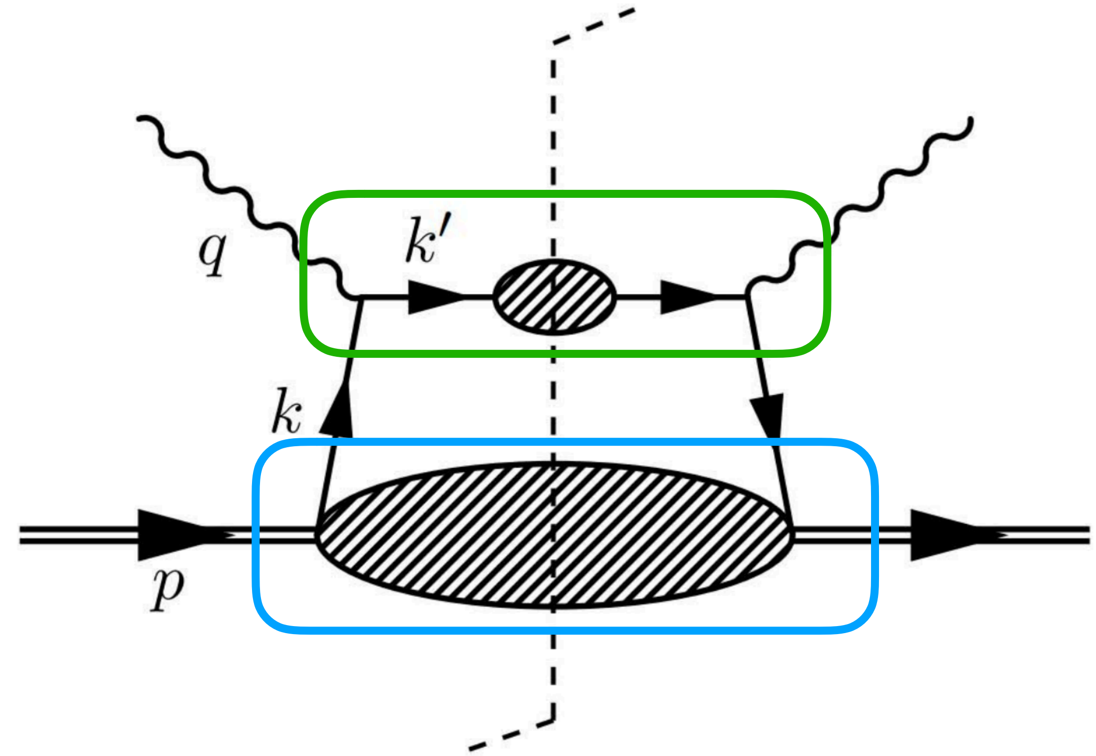
$\widetilde{k}^\mu = \xi p^\mu$
p^μ
k^μ

Application I: deep inelastic scattering (DIS)



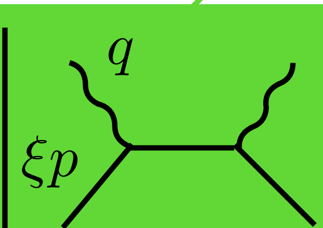
$$T_{\mu\nu} = i\int d^4w e^{iq\cdot w}\langle p,s|\mathrm{T}j^\dagger_\mu(w)j_\nu(0)|p,s\rangle_c$$

$$\sigma \propto L_{\mu\nu}\mathrm{Im}T^{\mu\nu}$$



Factorization in DIS limit most simply shown in frame where $\vec{p}+\vec{q}=\vec{0}$

$$\sigma \sim \int d\xi\, \sigma_{\text{parton}}(\xi) f(\xi) + \text{small corrections}$$

$\sim \left|\right.$  $\left.\right|^2 + \cdots$

$\sim\langle\text{hadron}|\Gamma^+|\text{hadron}\rangle$

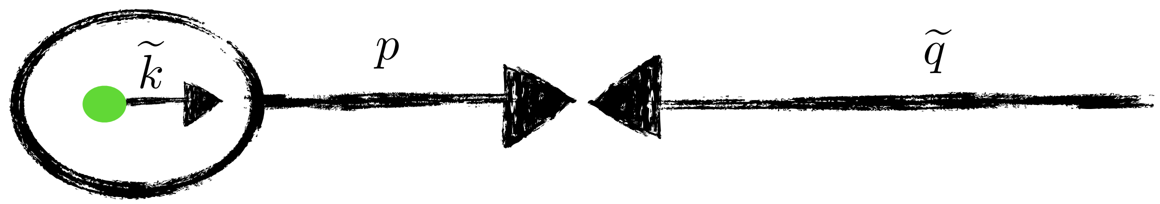
- kinematical corrections
- radiative effects

What happens when Lorentz violation is present?

Application I: deep inelastic scattering (DIS)

In the presence of Lorentz violation, factorization occurs in a modified Breit frame

$$\vec{p} + \vec{\widetilde{q}} = \vec{0} \qquad \widetilde{q} \equiv \widetilde{k + q} - \widetilde{k}$$



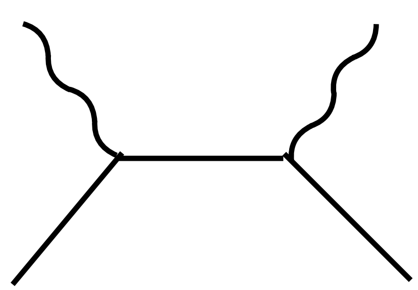
Calculate the imaginary part of internal propagator

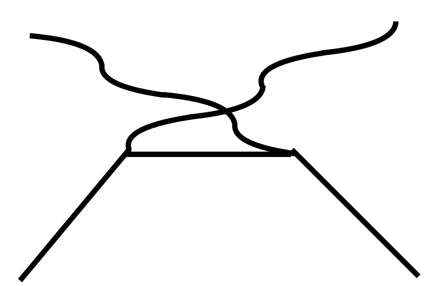
$$\mathrm{Im}\frac{1}{\widetilde{k}^2 + i\epsilon} = -\pi\left[\delta(\widetilde{k}^2)\theta(k^0) + \delta(\widetilde{-k}^{\,2})\theta(-k^0)\right]$$

Quark initiated

Antiquark initiated

Contributes to





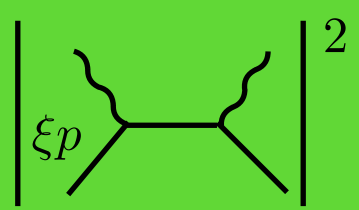
Will focus on quark contribution

Application I: deep inelastic scattering (DIS)

Example: $\mathcal{L}_c \supset \frac{1}{2} c_f^{\mu\nu} \bar{\psi}_f(x) i\gamma_\mu \overleftrightarrow{\partial}_\nu \psi_f(x)$

$$\widetilde{k}_f^\mu = k^\mu + c_f^{\mu\nu} k_\nu$$
$$\widetilde{q}_f^\mu = q^\mu + c_f^{\mu\nu} q_\nu$$

With on-shell parameterization $\widetilde{k} = \xi p$



$$\sim \quad \mathrm{Tr}\left[(\gamma^\mu + c_f^{\alpha\mu}\gamma_\alpha)\frac{1}{(\xi p^\alpha + q^\alpha + c_f^{\alpha\beta} q_\beta)\gamma_\alpha + i\epsilon}(\gamma^\nu + c_f^{\alpha\nu}\gamma_\alpha)\gamma_\beta \xi p^\beta\right]$$

$\langle \mathrm{hadron}|\Gamma^+|\mathrm{hadron}\rangle$

$$\sim \quad f_f(\xi, \cdots) = \int \frac{d\lambda}{2\pi} e^{-i\xi p\cdot n\lambda} \langle p|\bar{\psi}(\lambda \widetilde{n}_f)\frac{\gamma_\mu n^\mu}{2}\psi(0)|p\rangle$$

$$\widetilde{n}_f \to n^\mu + c_f^{\mu\alpha} n_\alpha$$

"Shifted" conventional scenario

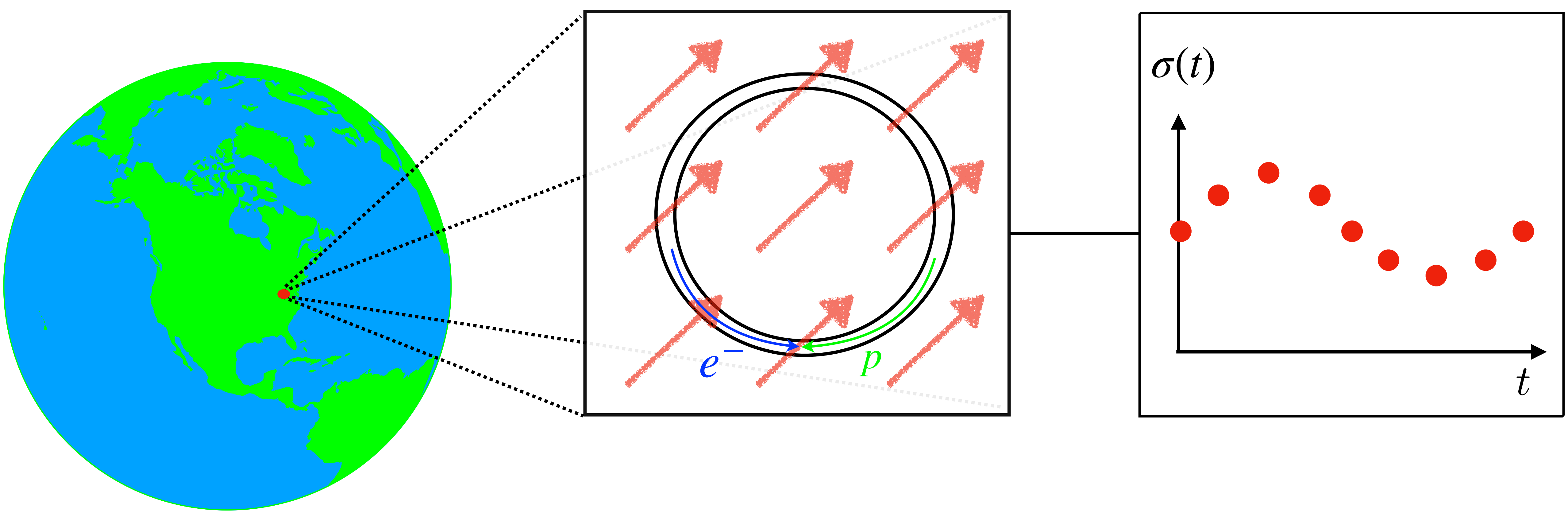
Estimating sensitivities at colliders

Using data from HERA, the LHC, and the future electron-ion collider (EIC) we obtain *estimates* on the sensitivity to the coefficients of interest

Technique relies on coefficient combinations that exhibit sidereal time dependence

$\sim$ **23 hrs 56 mins**

$$\sigma(t) \sim \sigma_{\text{SM}}(1 + c_0 + c_1 \cos(\omega_\oplus T_\oplus) + c_2 \cos(2\omega_\oplus T_\oplus) + \cdots)$$



Coefficients also depend on laboratory colatitude and beam directions!

Estimating sensitivities at colliders

Extract bounds on coefficients: Using H1 and ZEUS combined 644 neutral-current DIS measurements (Eur. Phys. J. C75 (2015)). For each (x,Q) value:

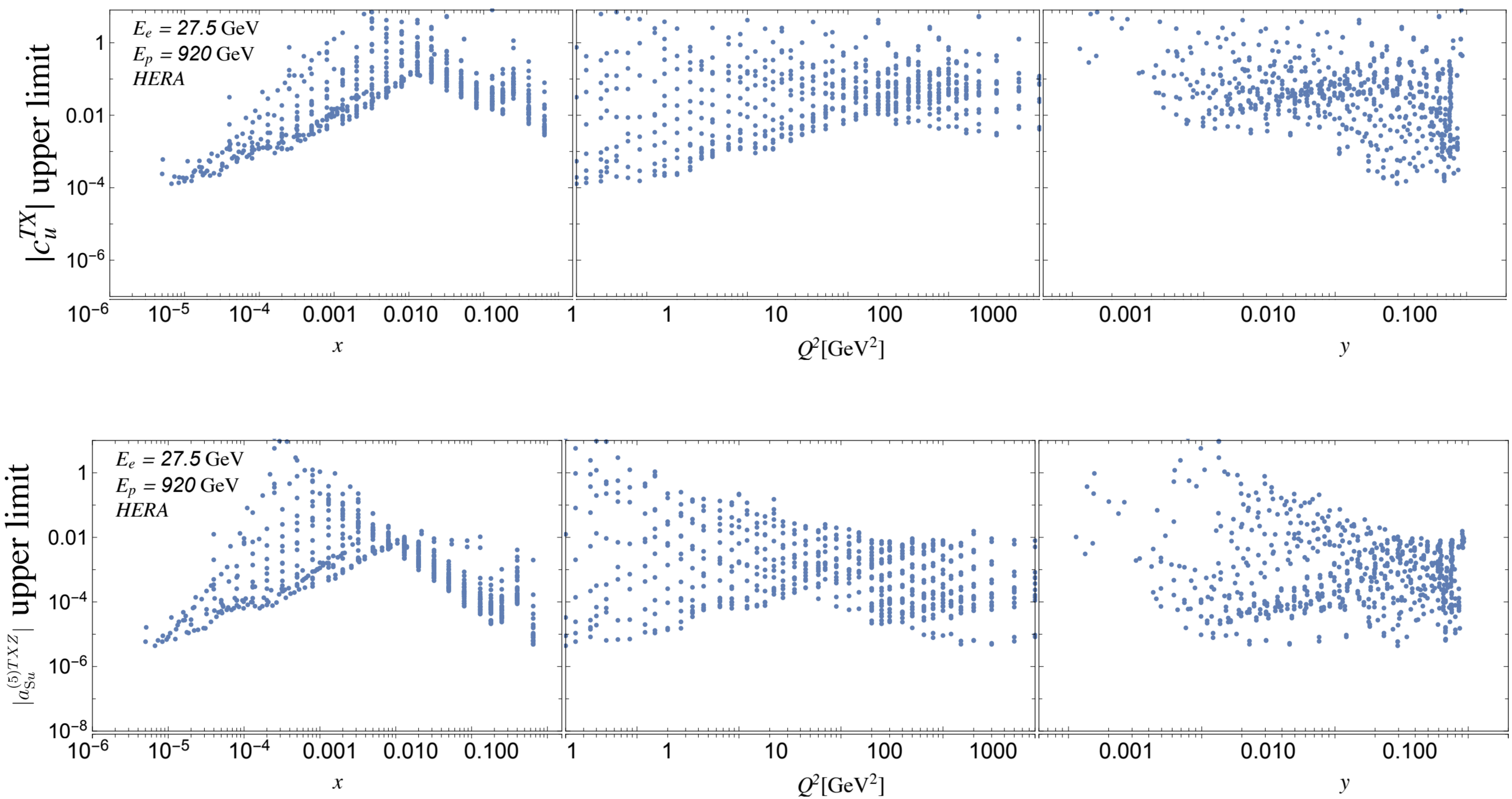
For each (x,Q) value we:

- Integrate the SME cross section into 4 bins of a sidereal day
- Generate 1000 normally-distributed pseudoexperiments about the reported cross section using total uncertainties
- Build chi-square as a function of a single coefficient at a time.

$$\chi_i^2(x, Q^2, c_f^{\mu\nu}) = \sum_{m,n}^{n_{\rm bins}} [\sigma^{\rm SME}(c_f^{\mu\nu}) - \sigma_i^{\rm exp}]_m C_{mn}^{-1} [\sigma^{\rm SME}(c_f^{\mu\nu}) - \sigma_i^{\rm exp}]_n$$

- Minimize and extract 95% CL constraint

Estimating sensitivities at colliders



Generally speaking, region of most sensitivity at low x, low-moderate Q, and higher collision energies

An actual experimental search

36 coefficients for Lorentz violation which contribute to time-dependent effects have not been experimentally bounded

$$c_f^{TX}, c_f^{TY}, \cdots, a_{\mathrm{S}f}^{TXY}, a_{\mathrm{S}f}^{TXZ}, \cdots$$

We have differential cross sections and understand the regions of kinematical sensitivity. Oscillations occur up to the third harmonic in sidereal frequency.

We would like to perform a study of ZEUS neutral-current DIS data for time-dependent effects

What is needed (?):

- Cross sections as functions of (x, Q) in (4-8) bins of sidereal time
- Understanding of systematics: which uncertainties matter over the course of a few hours in a day? E.g., beam luminosity ~ constant?
- Since SME cross section is different in each bin, can construct observables that partially shield against systematics

Recap + Conclusions

A framework has been developed for studying quark-sector Lorentz violation in hadronic processes using the SME

Factorization at the parton level for DIS and the Drell-Yan process

Consistency checks: Approach is consistent with the OPE and Ward identities

Lorentz- and CPT-violating effects on PDFs deduced

Estimated limits for minimal spin-independent coefficients are improved and first determination of nonminimal coefficient sensitivities are placed

Many new experimental opportunities to search for Lorentz and CPT violation in DIS

Thank you!