2019 Meeting of the Division of Particles & Fields

Searching for Lorentz violation in high-energy colliders

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Other talks on Lorentz and CPT violation

Nathan Sherrill

"High-energy hadronic processes in the presence of Lorentz violation"

Monday, 5:08 pm

Shillman 335

Benjamin Edwards

"Nonminimal CPT violation in neutral-meson oscillations"

Thursday, 4:18 pm

Shillman 335

Outline

- Lorentz violation and the Standard-Model Extension (SME)
- Gauge-covariant operators
- QED extension
- Experiment: light-by-light scattering
- QCD+QED extension
- Experiment: Deep-Inelastic Scattering (DIS)

Outline

- **Lorentz violation and the Standard-Model Extension (SME)**
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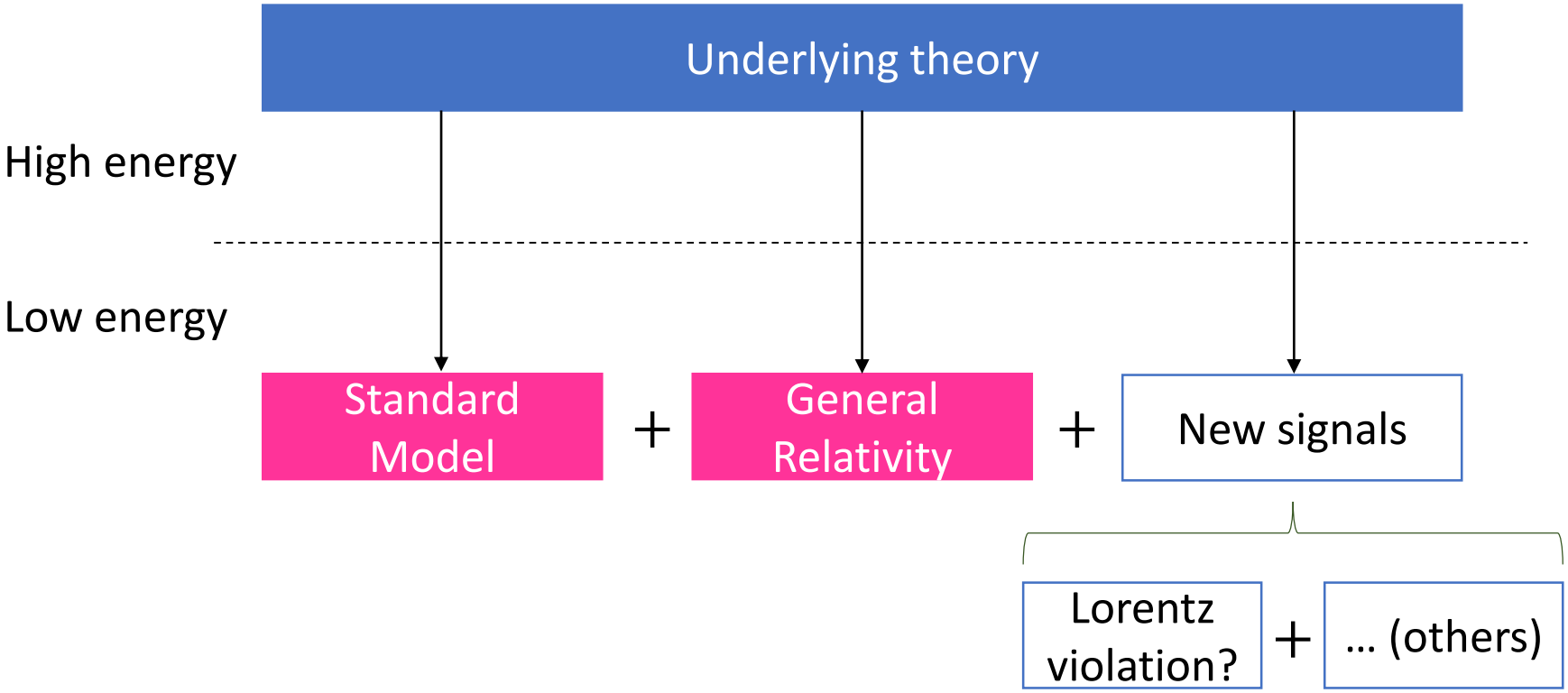
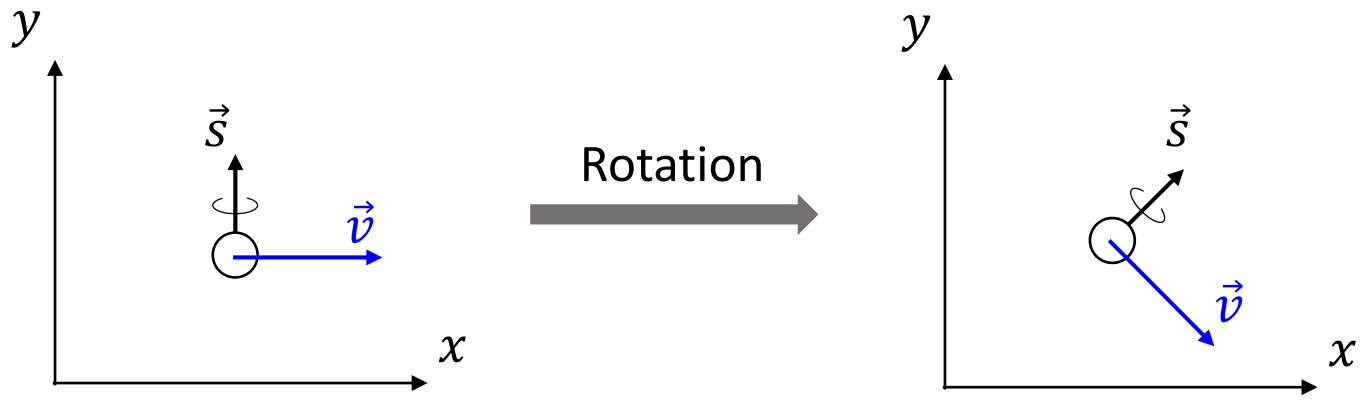
Unification of the Standard Model and General Relativity

- Testing Lorentz violation can shed light on the underlying theory



Lorentz symmetry

- Experimental results are independent
  of the orientation and velocity of the laboratory
- Lorentz transformation: 3 rotations and 3 boosts
- A fundamental symmetry in physics
- Must be precisely tested in experiments



Standard-Model Extension (SME)

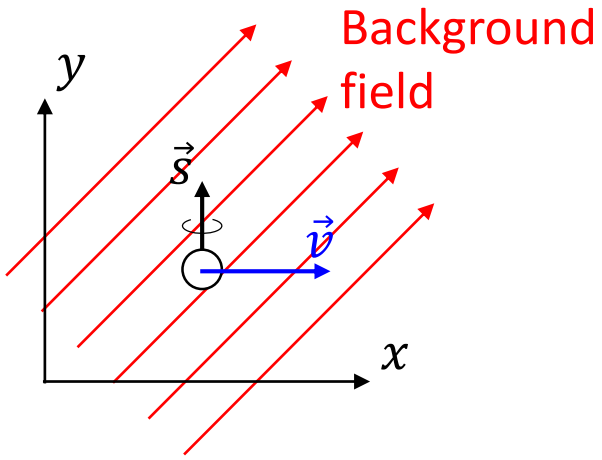
- Studies Lorentz violation in context of effective field theory

SME	**=**	**Standard Model coupled to General Relativity**	**+**	**All possible modifications**
$\mathcal{L}$	**=**	$\mathcal{L}_0$	**+**	$\mathcal{L}'$

Example: $\mathcal{L}' \supset -a^\mu \overline{\psi}\gamma_\mu\psi$

$a^\mu \rightarrow$ background field
coupling constants
control the size of Lorentz violation

$\overline{\psi}\gamma_\mu\psi \rightarrow$ dynamical field
fermion sector
free propagating term



Colladay, Kostelecký, PRD 55,6760(1997)

Experiments to test the SME

Photon sector:
- Astrophysical birefringence
- Astrophysical dispersion
- CMB polarization
- Laser interferometry
- Microwave, optical resonators
- Cavity oscillators
- Compton scattering

Electron and/or proton sectors:
- Penning trap
- Atom spectroscopy
- K/He magnetometer
- Atomic clock comparison
- 1S-2S transition
- Electron kinematics
- Nuclear binding energy

Gravity sector:
- Gravimetry
- Gravitational waves
- Cosmic ray
- Binary pulsars
- Short-range gravity
- Torsion pendulum
- Atom interferometry

Neutrino sector:
- Neutrino oscillation
- Double beta decay
- Neutrino time-of-flight
- Čerenkov radiation
- Tritium decay

And more…

Kostelecky, Russell, *Data Tables for Lorentz and CPT Violation*, Rev.Mod.Phys. 83.11(2011) updated as arXiv:0801.0287v12(2019)

Current status of SME

- SME includes all possible Lorentz-violating modifications to the SM
- All minimal ($d \leq 4$) terms have been established

Colladay, Kostelecký, PRD 55,6760(1997); PRD 58,116002(1998)
Kostelecký, PRD 69,105009(2004)

- Most nonminimal free-propagation terms have been established

Kostelecký, Mewes, PRD 80,015020(2009); PRD 88,096006(2013);
PRD 85,096005(2012); PLB 779,136(2018)

- Some low-dimension ($d \leq 6$) interaction terms in QED
  have been established

Ding, Kostelecký, PRD 94,056008(2016)

- Unknown:
  1) General terms in QED
  2) General terms in a nonabelian gauge field theory, e.g., QCD

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- **Gauge-covariant operators**
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Constructing gauge-invariant operators

- SME preserves gauge invariance.

All possible modifications to the Standard Model  **All possible gauge-invariant terms**

- Want to find all possible gauge-invariant terms
- Studying gauge-covariant operators is a powerful tool in finding gauge-invariant terms

Kostelecký, Li, PRD 99,056016(2019)

Gauge-covariant operators

- An operator $\mathcal{O}$ is gauge covariant if under the gauge transformation:

$$\mathcal{O} \to U\mathcal{O}U^\dagger$$

- Gauge-covariant operators $\Longrightarrow$ gauge-invariant operators

$$\mathcal{O},\ \mathcal{O}_1,\ \mathcal{O}_2 \qquad\qquad \mathrm{Tr}(\mathcal{O}),\ (\overline{\mathcal{O}_1\psi})\Gamma(\mathcal{O}_2\psi)$$

where $\Gamma \in \{I, i\gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}/2\}$.

- Examples: $F_{\alpha\beta}F^{\alpha\beta} \Longrightarrow \mathrm{Tr}(F_{\alpha\beta}F^{\alpha\beta})$

$$D_\mu \Longrightarrow \overline{\psi}\gamma^\mu D_\mu\psi$$

which are the gauge-invariant terms
in the conventional Lagrange density

Kostelecký, Li, PRD 99,056016(2019)

Constructing gauge-covariant operators

- Basic gauge-covariant operators

1) Gauge strength tensor: $F_{\alpha\beta} \to U F_{\alpha\beta} U^\dagger$

2) Gauge-covariant derivative: $D_\mu \to U D_\mu U^\dagger$

- Any mixture of D and F is gauge covariant
- **Result:** any mixture of D and F can be expressed as a linear combination of operators of form

$$(D_{(n_1)} F_{\mu_1\nu_1})(D_{(n_2)} F_{\mu_2\nu_2}) \cdots (D_{(n_m)} F_{\mu_m\nu_m}) D_{(n_{m+1})}$$

where $D_{(n)}$ means totally symmetric among n indices:

$$D_{(n)} = \frac{1}{n!} \sum D_{\alpha_1} D_{\alpha_2} \cdots D_{\alpha_n}$$

Kostelecký, Li, PRD 99,056016(2019)

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QED extension

QED extension	=	**Conventional QED terms**	+	**All possible modifications**
$\mathcal{L}$	=	$\mathcal{L}_0$	+	$\mathcal{L}'$

- QED extension describes all possible Lorentz-violating signals for photons and fermions involving the electromagnetic interaction
- All minimal and part of the nonminimal terms have been established
- Can apply our general method to QED to get the full QED extension

Colladay, Kostelecký, PRD 55,6760(1997); PRD 58,116002(1998)
Kostelecký, Mewes, PRD 80,015020(2009); PRD 88,096006(2013)
Ding, Kostelecký, PRD 94,056008(2016)

Photon sector

- Conventional term: $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
- Extension:

Component	Expression
$\mathcal{L}_A^{(1)}$	$-(k_A)^\mu A_\mu$
$\mathcal{L}_A^{(3)}$	$\frac{1}{2}(k_{AF})^\kappa \epsilon_{\kappa\lambda\mu\nu} A^\lambda F^{\mu\nu}$
$\mathcal{L}_A^{(4)}$	$-\frac{1}{4}(k_F)^{\kappa\lambda\mu\nu} F_{\kappa\lambda} F_{\mu\nu}$
$\mathcal{L}_A^{(5)}$	$-\frac{1}{4}k^{(5)\alpha\kappa\lambda\mu\nu} F_{\kappa\lambda}\partial_\alpha F_{\mu\nu}$
$\mathcal{L}_A^{(6)}$	$-\frac{1}{4}k_\partial^{(6)\alpha\beta\kappa\lambda\mu\nu} F_{\kappa\lambda}\partial_\alpha\partial_\beta F_{\mu\nu} - \frac{1}{12}k_F^{(6)\kappa\lambda\mu\nu\rho\sigma} F_{\kappa\lambda}F_{\mu\nu}F_{\rho\sigma}$
$\mathcal{L}_A^{(7)}$	$-\frac{1}{4}k_\partial^{(7)\alpha\beta\gamma\kappa\lambda\mu\nu} F_{\kappa\lambda}\partial_\alpha\partial_\beta\partial_\gamma F_{\mu\nu} - \frac{1}{12}k_F^{(7)\alpha\kappa\lambda\mu\nu\rho\sigma} F_{\kappa\lambda}F_{\mu\nu}\partial_\alpha F_{\rho\sigma}$
$\mathcal{L}_A^{(8)}$	$-\frac{1}{4}k_\partial^{(8)\alpha\beta\gamma\delta\kappa\lambda\mu\nu} F_{\kappa\lambda}\partial_\alpha\partial_\beta\partial_\gamma\partial_\delta F_{\mu\nu} - \frac{1}{12}k_{\partial F}^{(8)\alpha\beta\kappa\lambda\mu\nu\rho\sigma} F_{\kappa\lambda}(\partial_\alpha F_{\mu\nu})(\partial_\beta F_{\rho\sigma})$
	$-\frac{1}{48}k_F^{(8)\kappa\lambda\mu\nu\rho\sigma\tau\upsilon} F_{\kappa\lambda}F_{\mu\nu}F_{\rho\sigma}F_{\tau\upsilon}$

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Dirac spinor sector

- Conventional term: $\frac{1}{2}\overline{\psi}(\gamma^\mu i\partial_\mu - m_\psi)\psi + \text{h.c.}$
- Extension:

Component	Expression
$\mathcal{L}_\psi^{(3)}$	$-im_5\overline{\psi}\gamma_5\psi - a^\mu\overline{\psi}\gamma_\mu\psi - b^\mu\overline{\psi}\gamma_5\gamma_\mu\psi - \frac{1}{2}H^{\mu\nu}\overline{\psi}\sigma_{\mu\nu}\psi$
$\mathcal{L}_\psi^{(4)}$	$\frac{1}{2}c^{\mu\alpha}\overline{\psi}\gamma_\mu iD_\alpha\psi + \frac{1}{2}d^{\mu\alpha}\overline{\psi}\gamma_5\gamma_\mu iD_\alpha\psi$
	$+\frac{1}{2}e^\alpha\overline{\psi}iD_\alpha\psi + \frac{1}{2}if^\alpha\overline{\psi}\gamma_5 iD_\alpha\psi + \frac{1}{4}g^{\mu\nu\alpha}\overline{\psi}\sigma_{\mu\nu}iD_\alpha\psi + \text{h.c.}$
$\mathcal{L}_{\psi D}^{(5)}$	$-\frac{1}{2}m^{(5)\alpha\beta}\overline{\psi}iD_{(\alpha}iD_{\beta)}\psi - \frac{1}{2}im_5^{(5)\alpha\beta}\overline{\psi}\gamma_5 iD_{(\alpha}iD_{\beta)}\psi$
	$-\frac{1}{2}a^{(5)\mu\alpha\beta}\overline{\psi}\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi - \frac{1}{2}b^{(5)\mu\alpha\beta}\overline{\psi}\gamma_5\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi$
	$-\frac{1}{4}H^{(5)\mu\nu\alpha\beta}\overline{\psi}\sigma_{\mu\nu}iD_{(\alpha}iD_{\beta)}\psi + \text{h.c.}$
$\mathcal{L}_{\psi F}^{(5)}$	$-\frac{1}{2}m_F^{(5)\alpha\beta}F_{\alpha\beta}\overline{\psi}\psi - \frac{1}{2}im_{5F}^{(5)\alpha\beta}F_{\alpha\beta}\overline{\psi}\gamma_5\psi$
	$-\frac{1}{2}a_F^{(5)\mu\alpha\beta}F_{\alpha\beta}\overline{\psi}\gamma_\mu\psi - \frac{1}{2}b_F^{(5)\mu\alpha\beta}F_{\alpha\beta}\overline{\psi}\gamma_5\gamma_\mu\psi - \frac{1}{4}H_F^{(5)\mu\nu\alpha\beta}F_{\alpha\beta}\overline{\psi}\sigma_{\mu\nu}\psi$

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- (Continued)

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Component	Expression
$\mathcal{L}^{(6)}_{\psi D}$	$\frac{1}{2}c^{(6)\mu\alpha\beta\gamma}\overline{\psi}\gamma_\mu iD_{(\alpha}iD_\beta iD_{\gamma)}\psi + \frac{1}{2}d^{(6)\mu\alpha\beta\gamma}\overline{\psi}\gamma_5\gamma_\mu iD_{(\alpha}iD_\beta iD_{\gamma)}\psi$
	$+\frac{1}{2}e^{(6)\alpha\beta\gamma}\overline{\psi}iD_{(\alpha}iD_\beta iD_{\gamma)}\psi + \frac{1}{2}if^{(6)\alpha\beta\gamma}\overline{\psi}\gamma_5 iD_{(\alpha}iD_\beta iD_{\gamma)}\psi$
	$+\frac{1}{4}g^{(6)\mu\nu\alpha\beta\gamma}\overline{\psi}\sigma_{\mu\nu}iD_{(\alpha}iD_\beta iD_{\gamma)}\psi + \text{h.c.}$
$\mathcal{L}^{(6)}_{\psi F}$	$\frac{1}{4}c_F^{(6)\mu\alpha\beta\gamma}F_{\alpha\beta}\overline{\psi}\gamma_\mu iD_\gamma\psi + \frac{1}{4}d_F^{(6)\mu\alpha\beta\gamma}F_{\alpha\beta}\overline{\psi}\gamma_5\gamma_\mu iD_\gamma\psi$
	$+\frac{1}{4}e_F^{(6)\alpha\beta\gamma}F_{\alpha\beta}\overline{\psi}iD_\gamma\psi + \frac{1}{4}if_F^{(6)\alpha\beta\gamma}F_{\alpha\beta}\overline{\psi}\gamma_5 iD_\gamma\psi + \frac{1}{8}g_F^{(6)\mu\nu\alpha\beta\gamma}F_{\alpha\beta}\overline{\psi}\sigma_{\mu\nu}iD_\gamma\psi + \text{h.c.}$
$\mathcal{L}^{(6)}_{\psi\partial F}$	$-\frac{1}{2}m_{\partial F}^{(6)\alpha\beta\gamma}(\partial_\alpha F_{\beta\gamma})\overline{\psi}\psi - \frac{1}{2}im_{5\partial F}^{(6)\alpha\beta\gamma}(\partial_\alpha F_{\beta\gamma})\overline{\psi}\gamma_5\psi$
	$-\frac{1}{2}a_{\partial F}^{(6)\mu\alpha\beta\gamma}(\partial_\alpha F_{\beta\gamma})\overline{\psi}\gamma_\mu\psi - \frac{1}{2}b_{\partial F}^{(6)\mu\alpha\beta\gamma}(\partial_\alpha F_{\beta\gamma})\overline{\psi}\gamma_5\gamma_\mu\psi - \frac{1}{4}H_{\partial F}^{(6)\mu\nu\alpha\beta\gamma}(\partial_\alpha F_{\beta\gamma})\overline{\psi}\sigma_{\mu\nu}\psi$
$\mathcal{L}^{(6)}_{\psi\psi}$	$k_{SS}(\overline{\psi}\psi)(\overline{\psi}\psi) - k_{PP}(\overline{\psi}\gamma_5\psi)(\overline{\psi}\gamma_5\psi) + ik_{SP}(\overline{\psi}\psi)(\overline{\psi}\gamma_5\psi)$
	$+(k_{SV})^\mu(\overline{\psi}\psi)(\overline{\psi}\gamma_\mu\psi) + (k_{SA})^\mu(\overline{\psi}\psi)(\overline{\psi}\gamma_5\gamma_\mu\psi) + \frac{1}{2}(k_{ST})^{\mu\nu}(\overline{\psi}\psi)(\overline{\psi}\sigma_{\mu\nu}\psi)$
	$+i(k_{PV})^\mu(\overline{\psi}\gamma_5\psi)(\overline{\psi}\gamma_\mu\psi) + i(k_{PA})^\mu(\overline{\psi}\gamma_5\psi)(\overline{\psi}\gamma_5\gamma_\mu\psi) + \frac{1}{2}i(k_{PT})^{\mu\nu}(\overline{\psi}\gamma_5\psi)(\overline{\psi}\sigma_{\mu\nu}\psi)$
	$+\frac{1}{2}(k_{VV})^{\mu\nu}(\overline{\psi}\gamma_\mu\psi)(\overline{\psi}\gamma_\nu\psi) + \frac{1}{2}(k_{AA})^{\mu\nu}(\overline{\psi}\gamma_5\gamma_\mu\psi)(\overline{\psi}\gamma_5\gamma_\nu\psi) + (k_{VA})^{\mu\nu}(\overline{\psi}\gamma_\mu\psi)(\overline{\psi}\gamma_5\gamma_\mu\psi)$
	$+\frac{1}{2}(k_{VT})^{\lambda\mu\nu}(\overline{\psi}\gamma_\lambda\psi)(\overline{\psi}\sigma_{\mu\nu}\psi) + \frac{1}{2}(k_{AT})^{\lambda\mu\nu}(\overline{\psi}\gamma_5\gamma_\lambda\psi)(\overline{\psi}\sigma_{\mu\nu}\psi) + \frac{1}{8}(k_{TT})^{\kappa\lambda\mu\nu}(\overline{\psi}\sigma_{\kappa\lambda}\psi)(\overline{\psi}\sigma_{\mu\nu}\psi)$

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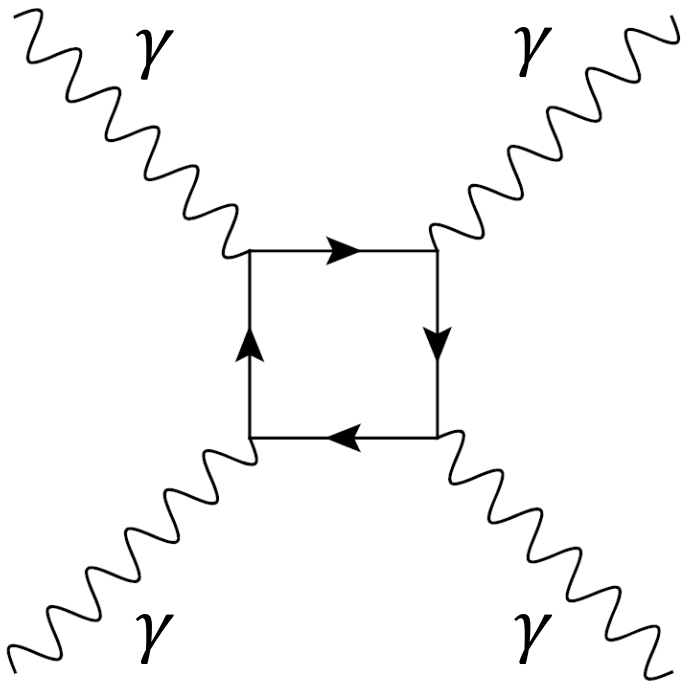
Light-by-light scattering

- Nonlinear effect
  of the electromagnetic field
- Important experimental test of QED
- Experiment done recently at the LHC
- More experiments proposed
- QED extension
  can describe possible deviations
  from Standard-Model prediction



ATLAS, *Nat.Phys.* 13,852(2017); ATLAS-CONF-2019-002
Kostelecký, Li, PRD 99,056016(2019)

The Large Hadron Collider (LHC) at CERN

Image: phys.org/news

ATLAS detector

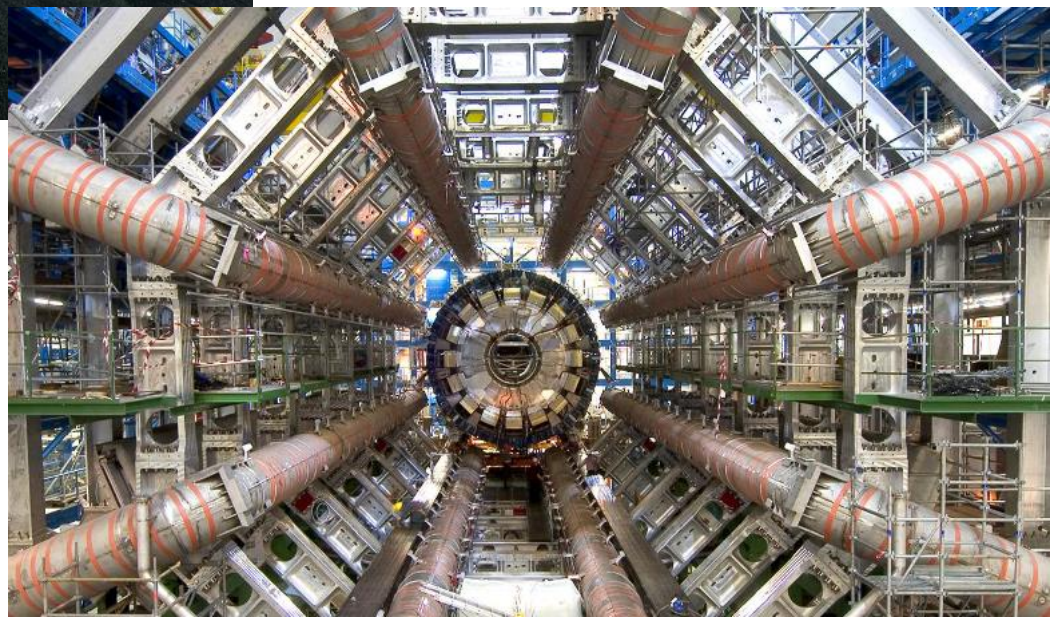


Image: room.eu.com/news

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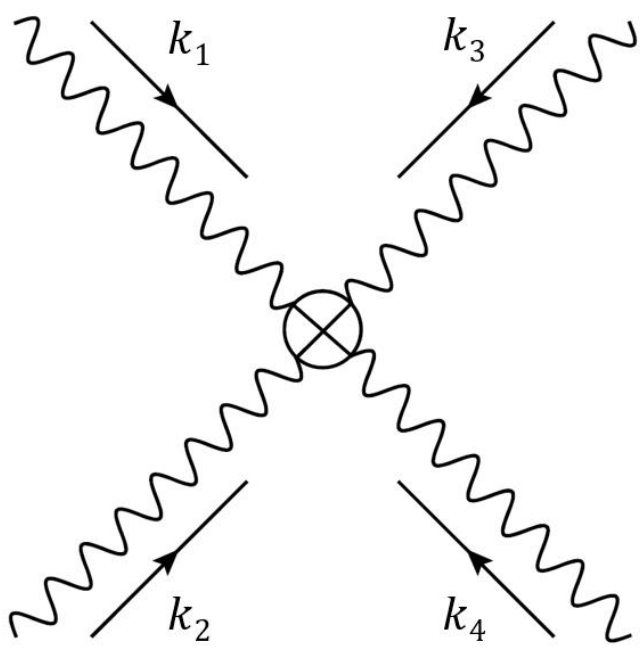
Contributions from SME

- Leading-order contribution from SME:

$$-\frac{1}{48}k_F^{(8)\kappa\lambda\mu\nu\rho\sigma\tau\upsilon}F_{\kappa\lambda}F_{\mu\nu}F_{\rho\sigma}F_{\tau\upsilon}\subset\mathcal{L}_g^{(8)}$$

- Many possible Lorentz-violating signals:

1) new contributions
   to the total cross section
   apart from Standard-Model ones
2) sidereal-time dependence
   of the cross section
3) dependence on the location
   and orientation of the laboratory
4) new energy dependence
   of the differential cross section
5) and so on



$$-8i(k_1)_{\mu_1}(k_2)_{\mu_2}(k_3)_{\mu_3}(k_4)_{\mu_4}$$
$$\times k_F^{(8)\mu_1\alpha_1\mu_2\alpha_2\mu_3\alpha_3\mu_4\alpha_4}$$

Constraints

- Experimental result: $70 \pm 24(\text{stat.}) \pm 17(\text{syst.})$ nb
- Standard-Model prediction: 49 ± 10 nb
- Constraints on the Lorentz-invariant and isotropic components of $k_F^{(8)}$:

Limiting case	Coefficient combination	Constraint
Lorentz invariant	$\frac{1}{144}\eta_{\kappa\mu}\eta_{\lambda\nu}\eta_{\rho\tau}\eta_{\sigma\upsilon}k_F^{(8)\kappa\lambda\mu\nu\rho\sigma\tau\upsilon}$	$< 9.5 \times 10^{-8}$ GeV^{-4}
	$\frac{1}{576}\epsilon_{\kappa\lambda\mu\nu}\epsilon_{\rho\tau\sigma\upsilon}k_F^{(8)\kappa\lambda\mu\nu\rho\sigma\tau\upsilon}$	$< 9.5 \times 10^{-8}$ GeV^{-4}
	$\frac{1}{288}\eta_{\kappa\mu}\eta_{\lambda\nu}\epsilon_{\rho\tau\sigma\upsilon}k_F^{(8)\kappa\lambda\mu\nu\rho\sigma\tau\upsilon}$	$< 7.5 \times 10^{-8}$ GeV^{-4}
Isotropic	$\frac{1}{9}\sum_{J,K} k_F^{(8)TJTJTKTK}$	$< 1.2 \times 10^{-7}$ GeV^{-4}
	$\frac{1}{9}\sum_{J<K,L<M} k_F^{(8)JKJKLMLM}$	$< 1.2 \times 10^{-7}$ GeV^{-4}
	$\frac{1}{9}\sum_{J,M,K<L,N<P} \epsilon_{JKL}\epsilon_{MNP}k_F^{(8)TJTMKLNP}$	$< 9.5 \times 10^{-8}$ GeV^{-4}
	$\frac{1}{9}\sum_{J,K<L} k_F^{(8)TJTJKLKL}$	$< 2.3 \times 10^{-7}$ GeV^{-4}
	$\frac{1}{9}\sum_{J,K,L<M} \epsilon_{KLM}k_F^{(8)TJTJTKLM}$	$< 5.6 \times 10^{-8}$ GeV^{-4}
	$\frac{1}{9}\sum_{L,J<K,M<N} \epsilon_{LMN}k_F^{(8)JKJKTLMN}$	$< 5.6 \times 10^{-8}$ GeV^{-4}

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TABLE VIII. Constraints on individual photon coefficients from light-by-light scattering.

Coefficient	Constraint
$k_F^{(8)TXTXTXTX}, k_F^{(8)TYTYTYTY}, k_F^{(8)XZXZXZXZ}, k_F^{(8)YZYZYZYZ}$	$< 1.0 \times 10^{-6}$ GeV^{-4}
$k_F^{(8)TZTZTZTZ}, k_F^{(8)XYXYXYXY}$	$< 5.9 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTXTY}, k_F^{(8)TYTYTYTX}, k_F^{(8)XZXZXZYZ}, k_F^{(8)YZYZYZXZ}$	$< 6.4 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTXTZ}, k_F^{(8)TYTYTYTZ}, k_F^{(8)XZXZXZXY}, k_F^{(8)YZYZYZXY}$	$< 4.9 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTXXY}, k_F^{(8)TYTYTYXY}, k_F^{(8)XZXZXZTZ}, k_F^{(8)YZYZYZTZ}$	$< 5.5 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTXXZ}, k_F^{(8)TYTYTYYZ}, k_F^{(8)XZXZXZTX}, k_F^{(8)YZYZYZTY}$	$< 1.0 \times 10^{-6}$ GeV^{-4}
$k_F^{(8)TXTXTXYZ}, k_F^{(8)TYTYTYXZ}, k_F^{(8)XZXZXZTY}, k_F^{(8)YZYZYZTX}$	$< 5.2 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZTZTX}, k_F^{(8)TZTZTZTY}, k_F^{(8)XYXYXYXZ}, k_F^{(8)XYXYXYYZ}$	$< 3.8 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZTZXY}, k_F^{(8)XYXYXYTZ}$	$< 3.0 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZTZXZ}, k_F^{(8)TZTZTZYZ}, k_F^{(8)XYXYXYTX}, k_F^{(8)XYXYXYTY}$	$< 4.2 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTYTY}, k_F^{(8)XZXZYZYZ}$	$< 5.6 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTZTZ}, k_F^{(8)TYTYTZTZ}, k_F^{(8)XYXYXZXZ}, k_F^{(8)XYXYYZYZ}$	$< 3.6 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXXYXY}, k_F^{(8)TYTYXYXY}, k_F^{(8)TZTZXZXZ}, k_F^{(8)TZTZYZYZ}$	$< 9.7 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXXZXZ}, k_F^{(8)TYTYYZYZ}$	$< 1.1 \times 10^{-6}$ GeV^{-4}
$k_F^{(8)TXTXYZYZ}, k_F^{(8)TYTYXZXZ}$	$< 4.3 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZXYXY}$	$< 2.4 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTYTZ}, k_F^{(8)TYTYTXTZ}, k_F^{(8)XZXZXYYZ}, k_F^{(8)YZYZXYXZ}$	$< 3.4 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTYXY}, k_F^{(8)TYTYTXXY}, k_F^{(8)XZXZTZYZ}, k_F^{(8)YZYZTZXZ}$	$< 4.0 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTYXZ}, k_F^{(8)TYTYTXYZ}, k_F^{(8)XZXZTXYZ}, k_F^{(8)YZYZTYXZ}$	$< 5.2 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTYYZ}, k_F^{(8)TYTYTXXZ}, k_F^{(8)XZXZTYYZ}, k_F^{(8)YZYZTXXZ}$	$< 4.2 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTZXY}, k_F^{(8)TYTYTZXY}, k_F^{(8)YZYZTZXY}, k_F^{(8)XZXZTZXY}$	$< 2.8 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZTXYZ}, k_F^{(8)TZTZTYXZ}, k_F^{(8)XYXYTXYZ}, k_F^{(8)XYXYTYXZ}$	$< 2.8 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTZXZ}, k_F^{(8)TYTYTZYZ}, k_F^{(8)XZXZTXXY}, k_F^{(8)YZYZTYXY}$	$< 5.1 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXTZYZ}, k_F^{(8)TYTYTZXZ}, k_F^{(8)XZXZTYXY}, k_F^{(8)YZYZTXXY}$	$< 2.9 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXXYXZ}, k_F^{(8)TYTYXYYZ}, k_F^{(8)XZXZTXTZ}, k_F^{(8)YZYZTYTZ}$	$< 6.0 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXXYYZ}, k_F^{(8)TYTYXYXZ}, k_F^{(8)XZXZTYTZ}, k_F^{(8)YZYZTXTZ}$	$< 3.0 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTXXZYZ}, k_F^{(8)TYTYXZYZ}, k_F^{(8)XZXZTXTY}, k_F^{(8)YZYZTXTY}$	$< 4.8 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZTXTY}, k_F^{(8)XYXYXZYZ}$	$< 2.9 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZTXXY}, k_F^{(8)TZTZTYXY}, k_F^{(8)XYXYTZXZ}, k_F^{(8)XYXYTZYZ}$	$< 2.3 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZTXXZ}, k_F^{(8)TZTZTYYZ}, k_F^{(8)XYXYTXXZ}, k_F^{(8)XYXYTYYZ}$	$< 3.9 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZXYXZ}, k_F^{(8)TZTZXYYZ}, k_F^{(8)XYXYTXTZ}, k_F^{(8)XYXYTYTZ}$	$< 2.4 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TZTZXZYZ}, k_F^{(8)XYXYTXTY}$	$< 7.3 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTYTZXY}, k_F^{(8)TZXYXZYZ}$	$< 2.2 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTYTZXZ}, k_F^{(8)TXTYTZYZ}, k_F^{(8)TXXYXZYZ}, k_F^{(8)TYXYXZYZ}$	$< 2.9 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTYXYXZ}, k_F^{(8)TXTYXYYZ}, k_F^{(8)TXTZXZYZ}, k_F^{(8)TYTZXZYZ}$	$< 3.2 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTYXZYZ}$	$< 3.4 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTZXYXZ}, k_F^{(8)TYTZXYYZ}$	$< 3.8 \times 10^{-7}$ GeV^{-4}
$k_F^{(8)TXTZXYYZ}, k_F^{(8)TYTZXYXZ}$	$< 3.5 \times 10^{-7}$ GeV^{-4}

- Constraints on single components

$$k_F^{(8)YZYZXYXZ} < 3.4 \times 10^{-7}\ \text{GeV}^{-4}$$

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Outline

- Lorentz violation and the Standard-Model Extension (SME)
- Gauge-covariant operators
- QED extension
- Experiment: light-by-light scattering
- **QCD+QED extension**
- Experiment: Deep-Inelastic Scattering (DIS)

QCD+QED extension

QCD+QED extension	=	**Conventional QCD+QED terms**	+	**All possible modifications**
$\mathcal{L}$	=	$\mathcal{L}_0$	+	$\mathcal{L}'$

- QCD+QED extension describes all possible Lorentz-violating signals in strong and electromagnetic interactions
- The minimal terms have seen established, but nonminimal terms for QCD are unknown
- Can apply our general method to get the full QCD+QED extension

Colladay, Kostelecký, PRD 55,6760(1997); PRD 58,116002(1998)

Pure-gauge sector

- Conventional term: $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu})$
- Extension:

Component	Expression
$\mathcal{L}_{AG}^{(1)}$	$-(k_A)^{\mu}A_{\mu}$
$\mathcal{L}_{AG}^{(3)}$	$\frac{1}{2}(k_{AF})^{\kappa}\epsilon_{\kappa\lambda\mu\nu}A^{\lambda}F^{\mu\nu} + (k_3)^{(3)\kappa}\epsilon_{\kappa\lambda\mu\nu}\mathrm{Tr}(G^{\lambda}G^{\mu\nu} + \frac{2}{3}ig_3G^{\lambda}G^{\mu}G^{\nu})$
$\mathcal{L}_{AG}^{(4)}$	$-\frac{1}{4}(k_F)^{\kappa\lambda\mu\nu}F_{\kappa\lambda}F_{\mu\nu} - \frac{1}{2}(k_G)^{(4)\kappa\lambda\mu\nu}\mathrm{Tr}(G_{\kappa\lambda}G_{\mu\nu})$
$\mathcal{L}_{AG}^{(5)}$	$-\frac{1}{4}k^{(5)\alpha\kappa\lambda\mu\nu}F_{\kappa\lambda}\partial_{\alpha}F_{\mu\nu} - \frac{1}{2}k_D^{(5)\alpha\kappa\lambda\mu\nu}\mathrm{Tr}(G_{\kappa\lambda}D_{\alpha}G_{\mu\nu})$
$\mathcal{L}_{AG}^{(6)}$	$-\frac{1}{4}k_{\partial}^{(6)\alpha\beta\kappa\lambda\mu\nu}F_{\kappa\lambda}\partial_{\alpha}\partial_{\beta}F_{\mu\nu} - \frac{1}{12}k_F^{(6)\kappa\lambda\mu\nu\rho\sigma}F_{\kappa\lambda}F_{\mu\nu}F_{\rho\sigma}$
	$-\frac{1}{2}k_D^{(6)\alpha\beta\kappa\lambda\mu\nu}\mathrm{Tr}(G_{\kappa\lambda}D_{(\alpha}D_{\beta)}G_{\mu\nu}) - \frac{1}{6}k_G^{(6)\kappa\lambda\mu\nu\rho\sigma}\mathrm{Tr}(G_{\kappa\lambda}G_{\mu\nu}G_{\rho\sigma})$
	$-\frac{1}{4}k_{FG}^{(6)\kappa\lambda\mu\nu\rho\sigma}F_{\kappa\lambda}\mathrm{Tr}(G_{\mu\nu}G_{\rho\sigma})$

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Quark sector

- Conventional term: $\frac{1}{2}(\overline{\psi}_A\gamma^\mu iD_\mu\psi_A - m_{AB}\overline{\psi}_A\psi_B) + \text{h.c.}$
- Extension:

Component	Expression
$\mathcal{L}_\psi^{(3)}$	$-im_{5AB}\overline{\psi}_A\gamma_5\psi_B - a^\mu_{AB}\overline{\psi}_A\gamma_\mu\psi_B - b^\mu_{AB}\overline{\psi}_A\gamma_5\gamma_\mu\psi_B - \frac{1}{2}H^{\mu\nu}_{AB}\overline{\psi}_A\sigma_{\mu\nu}\psi_B$
$\mathcal{L}_\psi^{(4)}$	$\frac{1}{2}c^{\mu\alpha}_{AB}\overline{\psi}_A\gamma_\mu iD_\alpha\psi_B + \frac{1}{2}d^{\mu\alpha}_{AB}\overline{\psi}_A\gamma_5\gamma_\mu iD_\alpha\psi_B$
	$+\frac{1}{2}e^\alpha_{AB}\overline{\psi}_A iD_\alpha\psi_B + \frac{1}{2}if^\alpha_{AB}\overline{\psi}_A\gamma_5 iD_\alpha\psi_B + \frac{1}{4}g^{\mu\nu\alpha}_{AB}\overline{\psi}_A\sigma_{\mu\nu}iD_\alpha\psi_B + \text{h.c.}$
$\mathcal{L}_{\psi D}^{(5)}$	$-\frac{1}{2}(m^{(5)})^{\alpha\beta}_{AB}\overline{\psi}_A iD_{(\alpha}iD_{\beta)}\psi_B - \frac{1}{2}i(m^{(5)})^{\alpha\beta}_{AB}\overline{\psi}_A\gamma_5 iD_{(\alpha}iD_{\beta)}\psi_B - \frac{1}{2}(a^{(5)})^{\mu\alpha\beta}_{AB}\overline{\psi}_A\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_B$
	$-\frac{1}{2}(b^{(5)})^{\mu\alpha\beta}_{AB}\overline{\psi}_A\gamma_5\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_B - \frac{1}{4}(H^{(5)})^{\mu\nu\alpha\beta}_{AB}\overline{\psi}_A\sigma_{\mu\nu}iD_{(\alpha}iD_{\beta)}\psi_B + \text{h.c.}$
$\mathcal{L}_{\psi F}^{(5)}$	$-\frac{1}{2}(m^{(5)}_F)^{\alpha\beta}_{AB}F_{\alpha\beta}\overline{\psi}_A\psi_B - \frac{1}{2}i(m^{(5)}_{5F})^{\alpha\beta}_{AB}F_{\alpha\beta}\overline{\psi}_A\gamma_5\psi_B$
	$-\frac{1}{2}(a^{(5)}_F)^{\mu\alpha\beta}_{AB}F_{\alpha\beta}\overline{\psi}_A\gamma_\mu\psi_B - \frac{1}{2}(b^{(5)}_F)^{\mu\alpha\beta}_{AB}F_{\alpha\beta}\overline{\psi}_A\gamma_5\gamma_\mu\psi_B - \frac{1}{4}(H^{(5)}_F)^{\mu\nu\alpha\beta}_{AB}F_{\alpha\beta}\overline{\psi}_A\sigma_{\mu\nu}\psi_B$
$\mathcal{L}_{\psi G}^{(5)}$	$-\frac{1}{2}(m^{(5)}_G)^{\alpha\beta}_{AB}\overline{\psi}_A G_{\alpha\beta}\psi_B - \frac{1}{2}i(m^{(5)}_{5G})^{\alpha\beta}_{AB}\overline{\psi}_A\gamma_5 G_{\alpha\beta}\psi_B$
	$-\frac{1}{2}(a^{(5)}_G)^{\mu\alpha\beta}_{AB}\overline{\psi}_A\gamma_\mu G_{\alpha\beta}\psi_B - \frac{1}{2}(b^{(5)}_G)^{\mu\alpha\beta}_{AB}\overline{\psi}_A\gamma_5\gamma_\mu G_{\alpha\beta}\psi_B - \frac{1}{4}(H^{(5)}_G)^{\mu\nu\alpha\beta}_{AB}\overline{\psi}_A\sigma_{\mu\nu}G_{\alpha\beta}\psi_B$

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Component	Expression
$\mathcal{L}^{(6)}_{\psi D}$	$\frac{1}{2}(c^{(6)})^{\mu\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_\mu iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \frac{1}{2}(d^{(6)})^{\mu\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_5\gamma_\mu iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \frac{1}{2}(e^{(6)})^{\alpha\beta\gamma}_{AB}\overline{\psi}_A iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B$
	$+\frac{1}{2}i(f^{(6)})^{\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_5 iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \frac{1}{4}(g^{(6)})^{\mu\nu\alpha\beta\gamma}_{AB}\overline{\psi}_A\sigma_{\mu\nu}iD_{(\alpha}iD_\beta iD_{\gamma)}\psi_B + \text{h.c.}$
$\mathcal{L}^{(6)}_{\psi F}$	$\frac{1}{4}(c^{(6)}_F)^{\mu\alpha\beta\gamma}_{AB}F_{\alpha\beta}\overline{\psi}_A\gamma_\mu iD_\gamma\psi_B + \frac{1}{4}(d^{(6)}_F)^{\mu\alpha\beta\gamma}_{AB}F_{\alpha\beta}\overline{\psi}_A\gamma_5\gamma_\mu iD_\gamma\psi_B$
	$+\frac{1}{4}(e^{(6)}_F)^{\alpha\beta\gamma}_{AB}F_{\alpha\beta}\overline{\psi}_A iD_\gamma\psi_B + \frac{1}{4}i(f^{(6)}_F)^{\alpha\beta\gamma}_{AB}F_{\alpha\beta}\overline{\psi}_A\gamma_5 iD_\gamma\psi_B + \frac{1}{8}(g^{(6)}_F)^{\mu\nu\alpha\beta\gamma}_{AB}F_{\alpha\beta}\overline{\psi}_A\sigma_{\mu\nu}iD_\gamma\psi_B + \text{h.c.}$
$\mathcal{L}^{(6)}_{\psi G}$	$\frac{1}{4}(c^{(6)}_G)^{\mu\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_\mu G_{\alpha\beta}iD_\gamma\psi_B + \frac{1}{4}(d^{(6)}_G)^{\mu\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_5\gamma_\mu G_{\alpha\beta}iD_\gamma\psi_B$
	$+\frac{1}{4}(e^{(6)}_G)^{\alpha\beta\gamma}_{AB}\overline{\psi}_A G_{\alpha\beta}iD_\gamma\psi_B + \frac{1}{4}i(f^{(6)}_G)^{\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_5 G_{\alpha\beta}iD_\gamma\psi_B + \frac{1}{8}(g^{(6)}_G)^{\mu\nu\alpha\beta\gamma}_{AB}\overline{\psi}_A\sigma_{\mu\nu}G_{\alpha\beta}iD_\gamma\psi_B + \text{h.c.}$
$\mathcal{L}^{(6)}_{\psi\partial F}$	$-\frac{1}{2}(m^{(6)}_{\partial F})^{\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\overline{\psi}_A\psi_B - \frac{1}{2}i(m^{(6)}_{5\partial F})^{\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\overline{\psi}_A\gamma_5\psi_B$
	$-\frac{1}{2}(a^{(6)}_{\partial F})^{\mu\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\overline{\psi}_A\gamma_\mu\psi_B - \frac{1}{2}(b^{(6)}_{\partial F})^{\mu\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\overline{\psi}_A\gamma_5\gamma_\mu\psi_B - \frac{1}{4}(H^{(6)}_{\partial F})^{\mu\nu\alpha\beta\gamma}_{AB}(\partial_\alpha F_{\beta\gamma})\overline{\psi}_A\sigma_{\mu\nu}\psi_B$
$\mathcal{L}^{(6)}_{\psi DG}$	$-\frac{1}{2}(m^{(6)}_{DG})^{\alpha\beta\gamma}_{AB}\overline{\psi}_A(D_\alpha G_{\beta\gamma})\psi_B - \frac{1}{2}i(m^{(6)}_{5DG})^{\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_5(D_\alpha G_{\beta\gamma})\psi_B$
	$-\frac{1}{2}(a^{(6)}_{DG})^{\mu\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_\mu(D_\alpha G_{\beta\gamma})\psi_B - \frac{1}{2}(b^{(6)}_{DG})^{\mu\alpha\beta\gamma}_{AB}\overline{\psi}_A\gamma_5\gamma_\mu(D_\alpha G_{\beta\gamma})\psi_B - \frac{1}{4}(H^{(6)}_{DG})^{\mu\nu\alpha\beta\gamma}_{AB}\overline{\psi}_A\sigma_{\mu\nu}(D_\alpha G_{\beta\gamma})\psi_B$
$\mathcal{L}^{(6)}_{\psi\psi}$	$(k_{SS})_{ABCD}(\overline{\psi}_A\psi_B)(\overline{\psi}_C\psi_D) - (k^{(6)}_{PP})_{ABCD}(\overline{\psi}_A\gamma_5\psi_B)(\overline{\psi}_C\gamma_5\psi_D)$
	$+i(k^{(6)}_{SP})_{ABCD}(\overline{\psi}_A\psi_B)(\overline{\psi}_C\gamma_5\psi_D) + (k^{(6)}_{SV})^\mu_{ABCD}(\overline{\psi}_A\psi_B)(\overline{\psi}_C\gamma_\mu\psi_D)$
	$+(k^{(6)}_{SA})^\mu_{ABCD}(\overline{\psi}_A\psi_B)(\overline{\psi}_C\gamma_5\gamma_\mu\psi_D) + \frac{1}{2}(k^{(6)}_{ST})^{\mu\nu}_{ABCD}(\overline{\psi}_A\psi_B)(\overline{\psi}_C\sigma_{\mu\nu}\psi_D)$
	$+i(k^{(6)}_{PV})^\mu_{ABCD}(\overline{\psi}_A\gamma_5\psi_B)(\overline{\psi}_C\gamma_\mu\psi_D) + i(k^{(6)}_{PA})^\mu_{ABCD}(\overline{\psi}_A\gamma_5\psi_B)(\overline{\psi}_C\gamma_5\gamma_\mu\psi_D)$
	$+\frac{1}{2}i(k^{(6)}_{PT})^{\mu\nu}_{ABCD}(\overline{\psi}_A\gamma_5\psi_B)(\overline{\psi}_C\sigma_{\mu\nu}\psi_D) + \frac{1}{2}(k^{(6)}_{VV})^{\mu\nu}_{ABCD}(\overline{\psi}_A\gamma_\mu\psi_B)(\overline{\psi}_C\gamma_\nu\psi_D)$
	$+\frac{1}{2}(k^{(6)}_{AA})^{\mu\nu}_{ABCD}(\overline{\psi}_A\gamma_5\gamma_\mu\psi_B)(\overline{\psi}_C\gamma_5\gamma_\nu\psi_D) + (k^{(6)}_{VA})^{\mu\nu}_{ABCD}(\overline{\psi}_A\gamma_\mu\psi_B)(\overline{\psi}_C\gamma_5\gamma_\mu\psi_D)$
	$+\frac{1}{2}(k^{(6)}_{VT})^{\lambda\mu\nu}_{ABCD}(\overline{\psi}_A\gamma_\lambda\psi_B)(\overline{\psi}_C\sigma_{\mu\nu}\psi_D) + \frac{1}{2}(k^{(6)}_{AT})^{\lambda\mu\nu}_{ABCD}(\overline{\psi}_A\gamma_5\gamma_\lambda\psi_B)(\overline{\psi}_C\sigma_{\mu\nu}\psi_D)$
	$+\frac{1}{8}(k^{(6)}_{TT})^{\kappa\lambda\mu\nu}_{ABCD}(\overline{\psi}_A\sigma_{\kappa\lambda}\psi_B)(\overline{\psi}_C\sigma_{\mu\nu}\psi_D)$

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- Lorentz violation and the Standard-Model Extension (SME)
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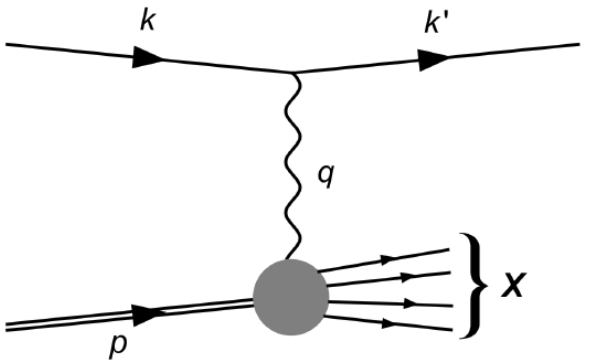
- QCD+QED extension
- **Experiment: Deep-Inelastic Scattering (DIS)**

Deep-inelastic scattering (DIS)

- Key experimental evidence
  for quarks and QCD
- An essential tool
  in the search for new physics
- Can be used to test Lorentz violation
- QCD+QED extension is a framework
  to describe new signals



HERA accelerator, Germany

Image: wikipedia

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SME contributions

- Leading-order spin-independent contribution from nonminimal SME :

$$-\tfrac{1}{2}\sum_f a_f^{(5)\mu\alpha\beta}\overline{\psi}_f\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi_f + \text{h.c.}$$

- Cross section

$$\begin{aligned}\frac{d\sigma}{dxdyd\phi} =& \frac{\alpha^2}{q^4}\sum_f F_{2f}\left[\frac{ys^2}{\pi}\left(1+(1-y)^2\right)\delta_f + \frac{y(y-2)s}{x}x_f\right.\\
&-4[1+(1-y)^2]a_p^{ppp}+4(y-2)a_p^{kpp}-2ya_p^{qpp}\\
&-\frac{4}{x}(4x^2a_f^{ppk}+2xa_f^{pkq}+2xa_f^{qkp}+2xa_f^{kpq}+a_f^{qqk}+a_f^{kqq})\\
&+2y(4x^2a_f^{ppp}+2xa_f^{ppq}+2xa_f^{qpp}+a_f^{qqp}+4xa_f^{ppk}+2a_f^{pkq})\\
&-y^2sg_{\mu\nu}(2xa_f^{(5)\mu\nu p}+a_f^{(5)\mu\nu q})\\
&\left.+\frac{4y}{x}(2xa_f^{kkp}+a_f^{kkq})\right]\end{aligned}$$

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Implications

- Based on some simulations in the KLV'2017 paper for $c^{\mu\nu}$ coefficients, can estimate $a^{(5)\mu\alpha\beta} \lesssim 10^{-7} - 10^{-4}\ \mathrm{GeV}^{-1}$
- Dependence on up to the third-order harmonics of the sidereal time variables
- CPT-odd contribution for proton and antiproton:

$$\left.\frac{d\sigma}{dxdyd\phi}\right|_{e^-p,a} = \left.\frac{d\sigma}{dxdyd\phi}\right|_{e^+p,a} = \left.\frac{d\sigma}{dxdyd\phi}\right|_{e^-\overline{p},-a} = \left.\frac{d\sigma}{dxdyd\phi}\right|_{e^+\overline{p},-a}$$

H1 Collaboration, EPJC 75,580(2015)
Kostelecký, Lunghi, Vieira, PLB 769,272(2017)
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Summary

- The unification of Standard Model and General Relativity
  may lead to small deviations from Lorentz symmetry
- The Standard-Model Extension (SME) is developed
  to study Lorentz violation in the context of effective field theory
- The full QED and QCD+QED extensions are presented in this talk
- Photon-photon scattering gives first constraints
  on $d = 8$ coefficients in QED extension
- Deep-inelastic scattering (DIS) can be used
  to test QCD+QED extension