Search for effective Lorentz and CPT violation using ZEUS data[†]

42nd International Conference on High Energy Physics

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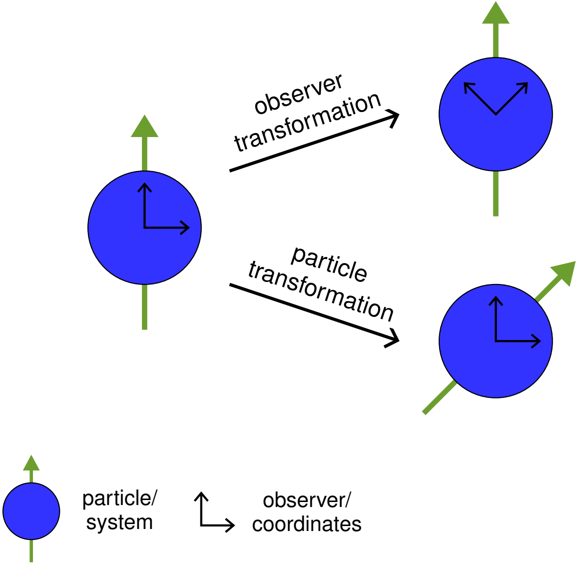
July 19, 2024

[†] PRD 107, 092008 (2023). arXiv:2212.12750

Motivation

Lorentz invariance and effective Lorentz violation

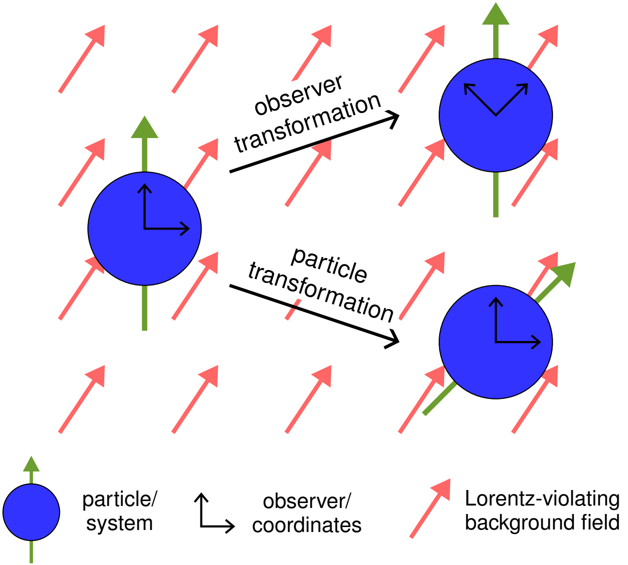
- Lorentz invariance: observer and particle transformations are indistinguishable



Motivation

Lorentz invariance and effective Lorentz violation

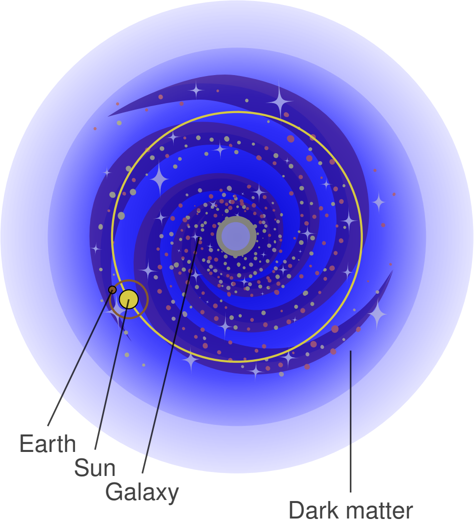
- Lorentz invariance: observer and particle transformations are indistinguishable
- In Lorentz-violating theories, the two transformations lead to measurable differences



Motivation

Lorentz invariance and effective Lorentz violation

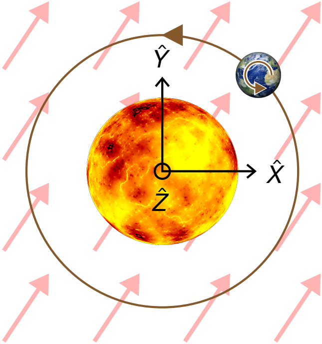
- Lorentz invariance: observer and particle transformations are indistinguishable
- In Lorentz-violating theories, the two transformations lead to measurable differences
- Typical scenario: dark-matter halo in the galactic disk
- Apparent Lorentz-violation due to dark-matter flux through laboratory
- Universe as a whole can still be Lorentz invariant



Motivation

Sun-centred frame and sidereal oscillations

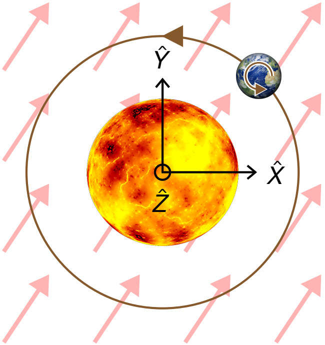
- Movement of sun around galactic centre is negligible
  → consider sun-centred frame (SCF)
- Position of earth irrelevant due to translational invariance
  → consider just rotation of earth



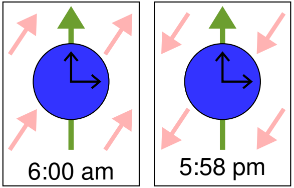
Motivation

Sun-centred frame and sidereal oscillations

- Movement of sun around galactic centre is negligible
  → consider sun-centred frame (SCF)
- Position of earth irrelevant due to translational invariance
  → consider just rotation of earth
- Laboratory system is connected to SCF via time-dependent Lorentz transformation
- Time-independent effects in SCF lead to time-dependent effects in laboratory frame
  → measurable effective Lorentz violation
- Look for periodic effects with sidereal period of $T_\mathrm{p} = 23\,\mathrm{h}\,56\,\mathrm{min}$



Perspective of earth-based observer:



Motivation
Theory
SME
DIS
DIS under SME
Experiment
Analysis
Summary

Theoretical overview
Standard-Model Extension

- **Standard-Model Extension** (SME): effective field theory to parameterise Lorentz- and CPT-violating effects[†]
- Contains all terms that break Lorentz invariance, about half of them break CPT
- Consider extensions to Fermion part of Lagrangian:

$$
\begin{aligned}
\mathcal{L}_\psi &= \frac{1}{2}\overline{\psi}\left(i\not{D} + \hat{Q}\right)\psi + \text{h.c.} \\
\hat{Q} &= -\boxed{a^\mu}\gamma_\mu - \boxed{b^\mu}\gamma_5\gamma_\mu + \dots && \text{CPT odd, renormalisable} \\
&\quad + \boxed{c^{\mu\nu}}\gamma_\mu iD_\nu + \boxed{d^{\mu\nu}}\gamma_5\gamma_\mu iD_\nu + \dots && \text{CPT even, renormalisable} \\
&\quad - \frac{1}{2}\boxed{a^{(5)\mu\nu\lambda}}\gamma_\mu(iD_\nu iD_\lambda + iD_\lambda iD_\nu) + \dots && \text{CPT odd, non-renormalisable} \\
&\quad + \dots
\end{aligned}
$$

- So far, almost no constraints on the quark-sector coefficients
- Here: focus on dominant renormalisable and non-renormalisable coefficients of light-quark flavours: $c_f^{\mu\nu}$ and $a_f^{(5)\mu\nu\lambda}$

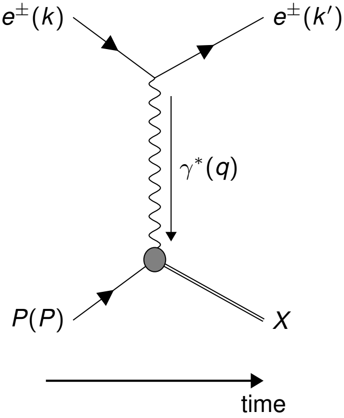
[†] PRD 55, 6760 (1997), arXiv:`hep-ph/9703464`;
PRD 58, 116002 (1998), arXiv:`hep-ph/9809521`;
PRD 69, 105009 (2004), arXiv:`hep-th/0312310`;
PRD 103, 024059 (2021), arXiv:`2008.12206`

Theoretical overview
Deep inelastic scattering

- Deep inelastic scattering (DIS): electron-proton scattering at high momentum transfer Q^2
- Kinematic quantities:

$$Q^2 = -q^2 = -(k - k')^2$$

$$x = \frac{Q^2}{2P \cdot q}$$



Theoretical overview
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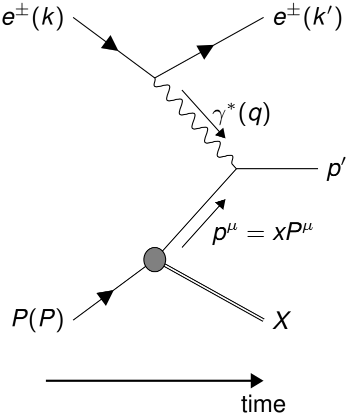
- Here: consider DIS at leading order ($\mathcal{O}(\alpha_s^0)$), i.e. the quark-parton model
- Asymptotically free quarks allow direct access to couplings

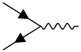


Theoretical overview

Impact of Standard-Model Extension on DIS

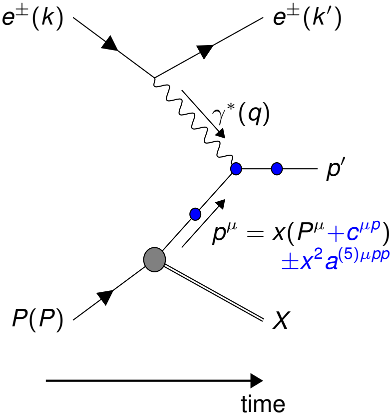
- First studies have computed the impact of the SME on DIS[†]
- In presence of SME operators, quark propagators and couplings get modified

$$= \frac{i}{(g^{\mu\nu}+c^{\mu\nu}+a^{(5)\mu\nu\lambda}p_\lambda)\gamma_\mu p_\nu}$$



$$= -ie(g^{\mu\nu}+c^{\mu\nu}+a^{(5)\mu\nu\lambda}p_\lambda)\gamma_\mu$$

- x is no longer the ratio between p and P



$$p^\mu = x(P^\mu + c^{\mu p}) \pm x^2 a^{(5)\mu pp}$$

[†] PLB 769, 272 (2017), arXiv:`1610.08755`;
PRD 98, 115018 (2018), arXiv:`1805.11684`

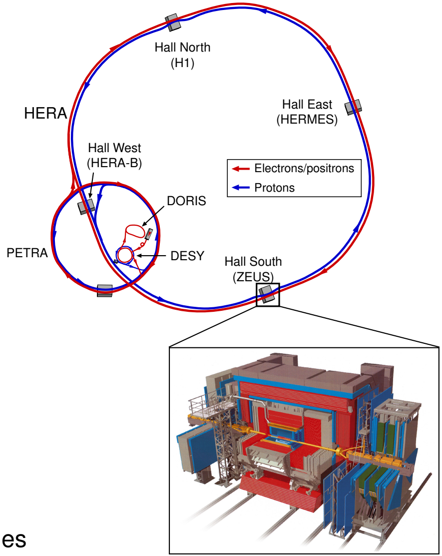
Experiment
HERA and ZEUS

HERA accelerator

- World's only lepton-hadron collider so far
- Located at DESY in Hamburg, Germany
- Two run periods:
  - HERA I: 1992 – 2000
  - HERA II: 2003 – 2007
- Circular collider of length 6336 m
- Collide electrons/positrons at 27.5 GeV with protons at 920 GeV $\rightarrow \sqrt{s} = 318$ GeV

ZEUS detector

- General purpose particle detector
- Integrated luminosity during HERA II: 372 pb^{-1}
- High-resolution uranium-scintillator calorimeter allows precise measurement of hadronic energies



Analysis
Strategy

- Temporal phase $\varphi \in [0, 1]$ for a given period T_p

$$\varphi(T) = \frac{\mathrm{Mod}(T, T_\mathrm{p})}{T_\mathrm{p}}$$

- Start with time-dependent DIS event count

$$\int_\mathrm{PS} \mathrm{d}x\,\mathrm{d}Q^2 \frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\varphi}$$

Analysis

Strategy

Search for effective Lorentz violation

Florian Lorkowski
2024-07-19

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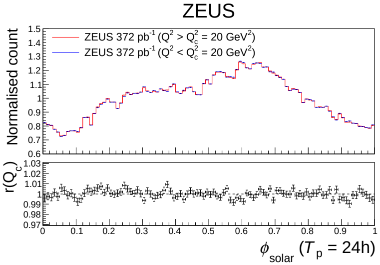
$$\int_\mathrm{PS} \mathrm{d}x\, \mathrm{d}Q^2 \frac{\mathrm{d}N}{\mathrm{d}x\, \mathrm{d}Q^2\, \mathrm{d}\varphi}$$

- Normalised event count is easier to model and less sensitive to systematic uncertainties

$$\frac{\displaystyle\int \mathrm{d}x\, \mathrm{d}Q^2 \frac{\mathrm{d}N}{\mathrm{d}x\, \mathrm{d}Q^2\, \mathrm{d}\varphi}}{\displaystyle\int \mathrm{d}x\, \mathrm{d}Q^2\, \mathrm{d}\varphi \frac{\mathrm{d}N}{\mathrm{d}x\, \mathrm{d}Q^2\, \mathrm{d}\varphi}}$$

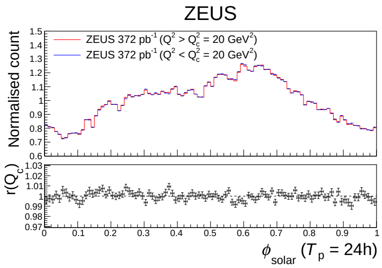
- However: instantaneous luminosity not constant throughout a solar day; higher luminosity over night (midnight $\hat{=}\ \varphi_\mathrm{solar} \approx 0.5$)

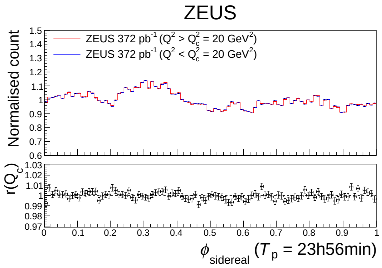


Analysis

Strategy

- Effect cancels over long enough periods if $T_\mathrm{p} \neq 24\mathrm{h}$, but measurement time is not long enough
- To correct for this effect, need instantaneous luminosity ($\mathcal{O}(1\mathrm{min})$ resolution), but this is not available





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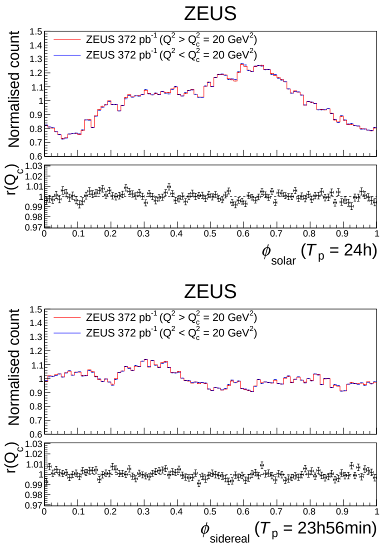
- Effect cancels over long enough periods if $T_\mathrm{p} \neq 24\mathrm{h}$, but measurement time is not long enough
- To correct for this effect, need instantaneous luminosity ($\mathcal{O}(1\,\mathrm{min})$ resolution), but this is not available
- Instead, consider double-ratio of two different phase space regions, PS_1 and PS_2

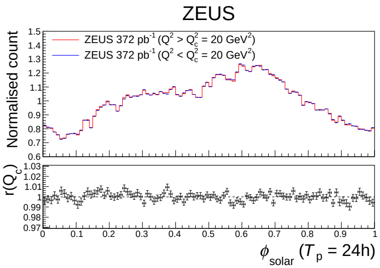
$$\frac{\left(\int_{\mathrm{PS}_1} \mathrm{d}x\,\mathrm{d}Q^2\,\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\varphi}\right) \Big/ \left(\int_{\mathrm{PS}_1} \mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\varphi\,\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\varphi}\right)}{\left(\int_{\mathrm{PS}_2} \mathrm{d}x\,\mathrm{d}Q^2\,\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\varphi}\right) \Big/ \left(\int_{\mathrm{PS}_2} \mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\varphi\,\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\varphi}\right)}$$

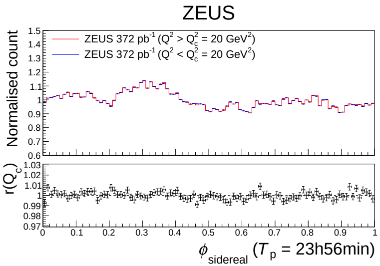
- Less statistics, but luminosity dependence cancels
- All known sources of systematic uncertainty cancel



Analysis
Strategy

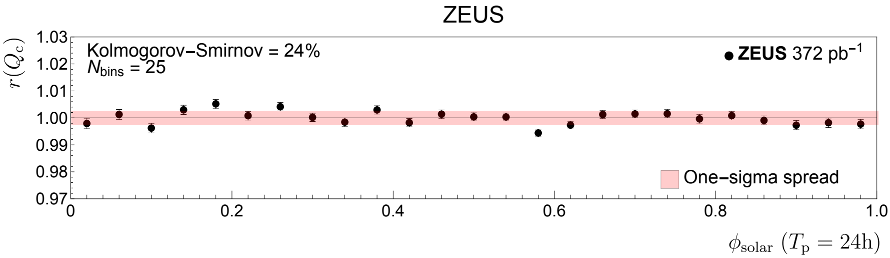
- Identify two scenarios:
  1. $\mathrm{PS}_1 = Q^2 > 20\,\mathrm{GeV}^2$, $\mathrm{PS}_2 = \overline{\mathrm{PS}}_1$:
     negligible sensitivity to Lorentz violation
     $\rightarrow$ control study
  2. $\mathrm{PS}_1 = x > 10^{-3}$, $\mathrm{PS}_2 = \overline{\mathrm{PS}}_1$:
     sensitive to Lorentz violation
     $\rightarrow$ search
- Sensitive to 18 independent *c*-type parameters and 24 $a^{(5)}$-type parameters





Analysis
Control study

- Question: Are there systematic uncertainties remaining?
- Equivalently: is 1σ-spread of points consistent with 1σ-statistical uncertainty?
- Investigate via Kolmogorov-Smirnov (KS): test if numbers are consistent with normal distribution
- Low probabilities ($\lesssim$ 5%) indicate inconsistency, i.e. presence of unknown systematic effects



Analysis

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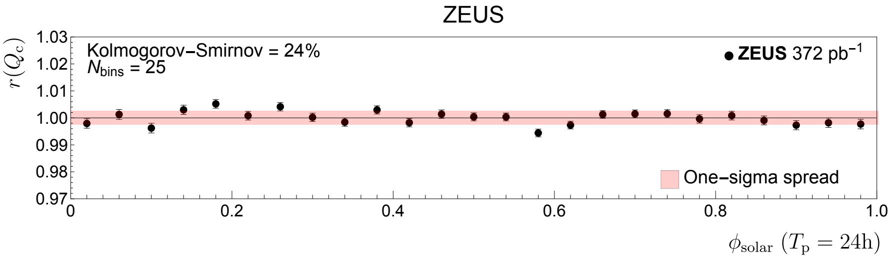
- Investigate via Kolmogorov-Smirnov (KS): test if numbers are consistent with normal distribution
- Low probabilities ($\lesssim 5\%$) indicate inconsistency, i.e. presence of unknown systematic effects
- In control study: large probabilities $\rightarrow$ fluctuations compatible with statistical uncertainties
- Same conclusion when considering different periods T_p or number of bins



Analysis

Systematics

- Control study not sufficient to conclude absence of systematic for search
- Trigger is more sensitive to x (search scenario) than to Q^2 (control study)[†]
  $\rightarrow$ potentially further systematic in search scenario

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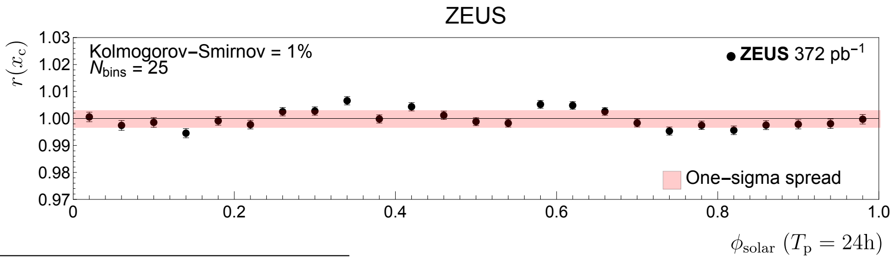
[†] See slide A3

Analysis
Systematics

- Control study not sufficient to conclude absence of systematic for search
- Trigger is more sensitive to *x* (search scenario) than to Q^2 (control study)† $\rightarrow$ potentially further systematic in search scenario
- Observe low KS probabilities in search scenario
- Largest deviation at $T_\mathrm{p} = 24$h $\rightarrow$ hypothesis: previously unknown solar-periodic effect



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Systematics

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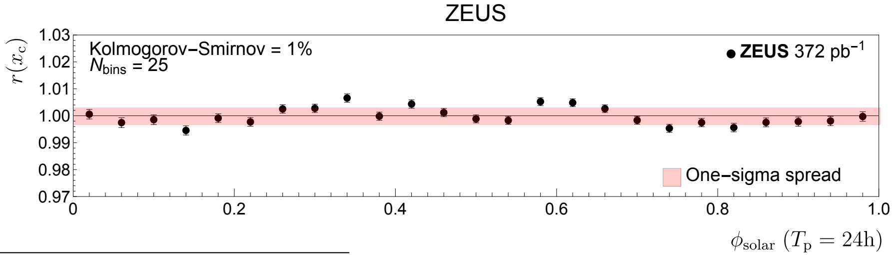
- Trigger is more sensitive to *x* (search scenario) than to Q^2 (control study)[†]
  → potentially further systematic in search scenario
- Observe low KS probabilities in search scenario
- Largest deviation at $T_\mathrm{p} = 24\mathrm{h}$
  → hypothesis: previously unknown solar-periodic effect
- Estimate systematic uncertainty from $T_\mathrm{p} = 24\mathrm{h}\,4\mathrm{min}$

$$\sigma_{\text{syst.}} \approx \sqrt{\sigma^2_{\text{spread}} - \sigma^2_{\text{stat.}}} = 0.16\%$$

- Comparable to statistical uncertainty



[†] See slide A3

Analysis
Results

Coefficient	Lower	Upper
c_u^{TX}	-2.5×10^{-4}	6.6×10^{-5}
c_u^{TY}	-1.7×10^{-4}	9.8×10^{-5}
c_u^{XY}	-3.2×10^{-4}	4.1×10^{-5}
c_u^{XZ}	-5.4×10^{-4}	1.4×10^{-4}
c_u^{YZ}	-3.7×10^{-4}	2.1×10^{-4}
$c_u^{XX} - c_u^{YY}$	-2.1×10^{-4}	2.5×10^{-4}
c_d^{TX}	-7.8×10^{-4}	2.0×10^{-4}
c_d^{TY}	-5.2×10^{-4}	3.0×10^{-4}
c_d^{XY}	-1.6×10^{-3}	2.0×10^{-4}
c_d^{XZ}	-2.7×10^{-3}	7.0×10^{-4}
c_d^{YZ}	-1.8×10^{-3}	1.0×10^{-3}
$c_d^{XX} - c_d^{YY}$	-1.0×10^{-3}	1.2×10^{-3}
c_s^{TX}	-9.6×10^{-4}	2.5×10^{-4}
c_s^{TY}	-6.4×10^{-4}	3.7×10^{-4}
c_s^{XY}	-2.6×10^{-3}	3.3×10^{-4}
c_s^{XZ}	-4.4×10^{-3}	1.2×10^{-3}
c_s^{YZ}	-3.0×10^{-3}	1.7×10^{-3}
$c_s^{XX} - c_s^{YY}$	-1.7×10^{-3}	2.0×10^{-3}

- First experimental constraints on c-type coefficients; first ever constraints on c_s
- Much more stringent constraints on $c_{u/d}$ from theoretical analysis of cosmic rays[†], but with significant model dependence

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[†] PRD 96, 095026 (2017), arXiv:`1702.03171`

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c_d^{TX}	-7.8×10^{-4}	2.0×10^{-4}
c_d^{TY}	-5.2×10^{-4}	3.0×10^{-4}
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- First experimental constraints on c-type coefficients; first ever constraints on c_s
- Much more stringent constraints on $c_{u/d}$ from theoretical analysis of cosmic rays[†], but with significant model dependence
- First ever constraints on $a^{(5)}$-type coefficients
- Possible comparison: effective $a^{(5)}_{\text{proton}}$ coefficients from hydrogen transitions[‡] $\sim 10^{-7} - 10^{-8}\,\text{GeV}^{-1}$

Coefficient	Lower (GeV^{-1})	Upper (GeV^{-1})
$a_{\text{S}u}^{(5)TXX} - a_{\text{S}u}^{(5)TYY}$	-5.1×10^{-7}	4.3×10^{-7}
$a_{\text{S}u}^{(5)XXZ} - a_{\text{S}u}^{(5)YYZ}$	-1.7×10^{-6}	2.0×10^{-6}
$a_{\text{S}u}^{(5)TXY}$	-8.3×10^{-8}	6.5×10^{-7}
$a_{\text{S}u}^{(5)TXZ}$	-2.9×10^{-7}	1.1×10^{-6}
$a_{\text{S}u}^{(5)TYZ}$	-4.3×10^{-7}	7.4×10^{-7}
$a_{\text{S}u}^{(5)XXX}$	-3.9×10^{-7}	1.2×10^{-7}
$a_{\text{S}u}^{(5)XXY}$	-2.3×10^{-7}	1.8×10^{-7}
$a_{\text{S}u}^{(5)XYY}$	-4.6×10^{-7}	9.2×10^{-8}
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$a_{\text{S}d}^{(5)YZZ}$	-5.4×10^{-6}	3.1×10^{-6}

[†] PRD 96, 095026 (2017), arXiv:`1702.03171`

[‡] PRD 92, 056002 (2015), arXiv:`1506.01706`

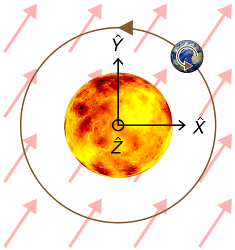
Summary

Summary

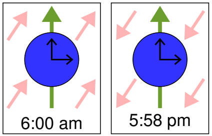
- Lorentz and CPT violation can be investigated using the Standard Model Extension
- Effective Lorentz violation would lead to observable sidereal oscillations
- First search for effective Lorentz violation in quark sector
- Placed constraints on 42 dominant parameters

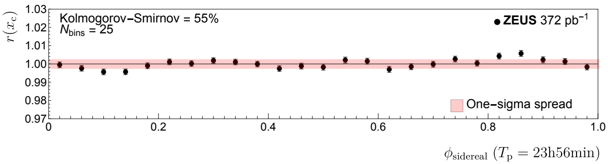
Outlook

- Plans to investigate further coefficients
- Refine systematic study and tighten constraints



Perspective of earth-based observer:





Data sample

Data sample

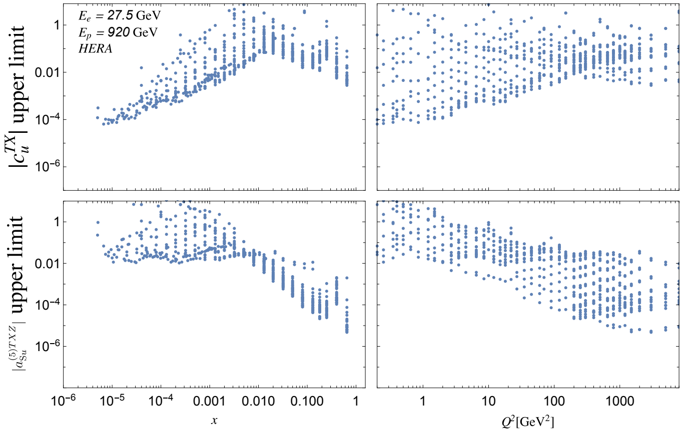
- $E_p = 920\,\text{GeV}$, $E_e = 27.5\,\text{GeV} \to \sqrt{s} = 318\,\text{GeV}$
- Data collected between 2003 and 2007 (HERA II period)
- Integrated luminosity: $372\,\text{pb}^{-1}$

Event selection

- Identify final-state electron with high confidence
- Energy of final-state electron $E_e' > 10\,\text{GeV}$
- $Q^2 > 5\,\text{GeV}^2$
- Scattering angle of final-state electron (relative to incoming proton direction) $\theta_e > 1$
- Energy - longitudinal momentum balance of all detected final-state particles
  $47\,\text{GeV} < E - p_z < 69\,\text{GeV}$

Sensitivity study

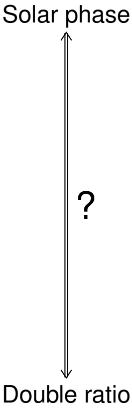
- Sensitivity study has been performed on HERA data[†]
- Plot: each dot is an inclusive DIS data point from HERA; show expected limits from each point
- Significant dependence on kinematic region
- Studies of DIS and Drell-Yan data are complementary



[†] JHEP 04 (2020) 143, arXiv:`1911.04002`

Monte Carlo trigger study

- How could the relation between solar phase and double ratio arise?



Monte Carlo trigger study

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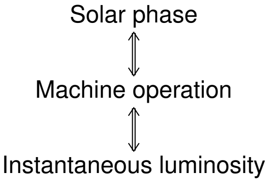

Solar phase
↕
Machine operation
↕
Instantaneous luminosity

Double ratio

- Length of fills of accelerator affects instantaneous luminosity

Monte Carlo trigger study

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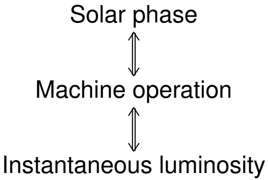

Solar phase

Machine operation

Instantaneous luminosity

Double ratio

- Length of fills of accelerator affects instantaneous luminosity
- Different trigger configurations, based on instantaneous luminosity
- Trigger efficiency might be different in high- and low-*x* regions

Monte Carlo trigger study

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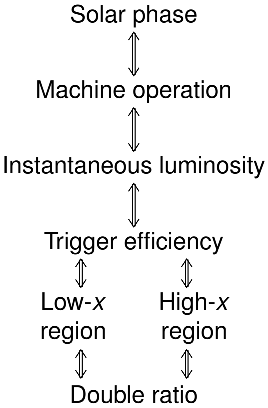
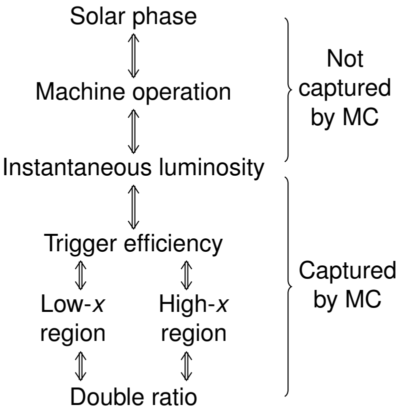

Solar phase
⇕
Machine operation
⇕
Instantaneous luminosity
⇕
Trigger efficiency
⇕ ⇕
Low-*x* region | High-*x* region
⇕ ⇕
Double ratio

- Length of fills of accelerator affects instantaneous luminosity
- Different trigger configurations, based on instantaneous luminosity
- Trigger efficiency might be different in high- and low-*x* regions
- Try to understand effect using Monte Carlo (MC) study
- MC samples capture all known relations between instantaneous luminosity and measured ratio

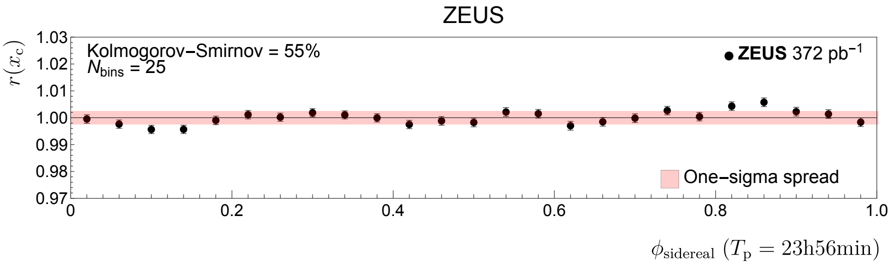
Monte Carlo trigger study

- How could the relation between solar phase and double ratio arise?



- MC events do not have time stamps, as SM calculations have no time-dependence
- Assign time stamps from data events to MC events with similar instantaneous luminosity
  → MC events gain solar phase dependence corresponding to data
- Double ratio in MC is consistent with statistics alone
  → observed systematic effect not accounted for by any known detector effect

Limit extraction



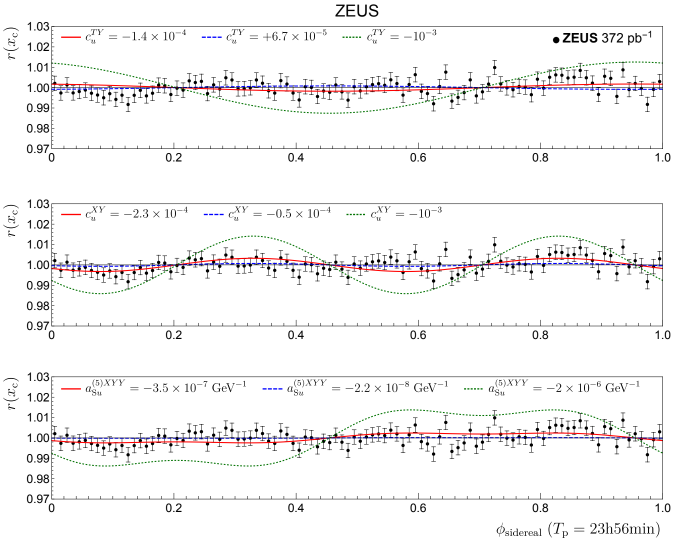
- Calculate χ^2 and *p*-value between measurement and SM prediction ($r \equiv 1$)

$$\chi^2/\text{DOF} = 114/100$$
$$p = 0.16$$

$\rightarrow$ Result consistent with SM

- Limit extraction
  - Consider one of the 42 coefficients at a time
  - Compute *p* as a function of each coefficient
  - Exclude region where $p < 0.05$

Example ratio



- Examples of effect of coefficients
- Blue/red lines: limits
- Green lines: expected double ratio if coefficients were large

- - - - Upper limit
—— Lower limit
⋯⋯ Excluded