

Searches for Lorentz violation in DIS with ZEUS at HERA

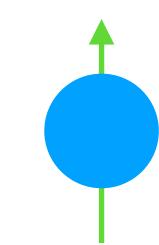
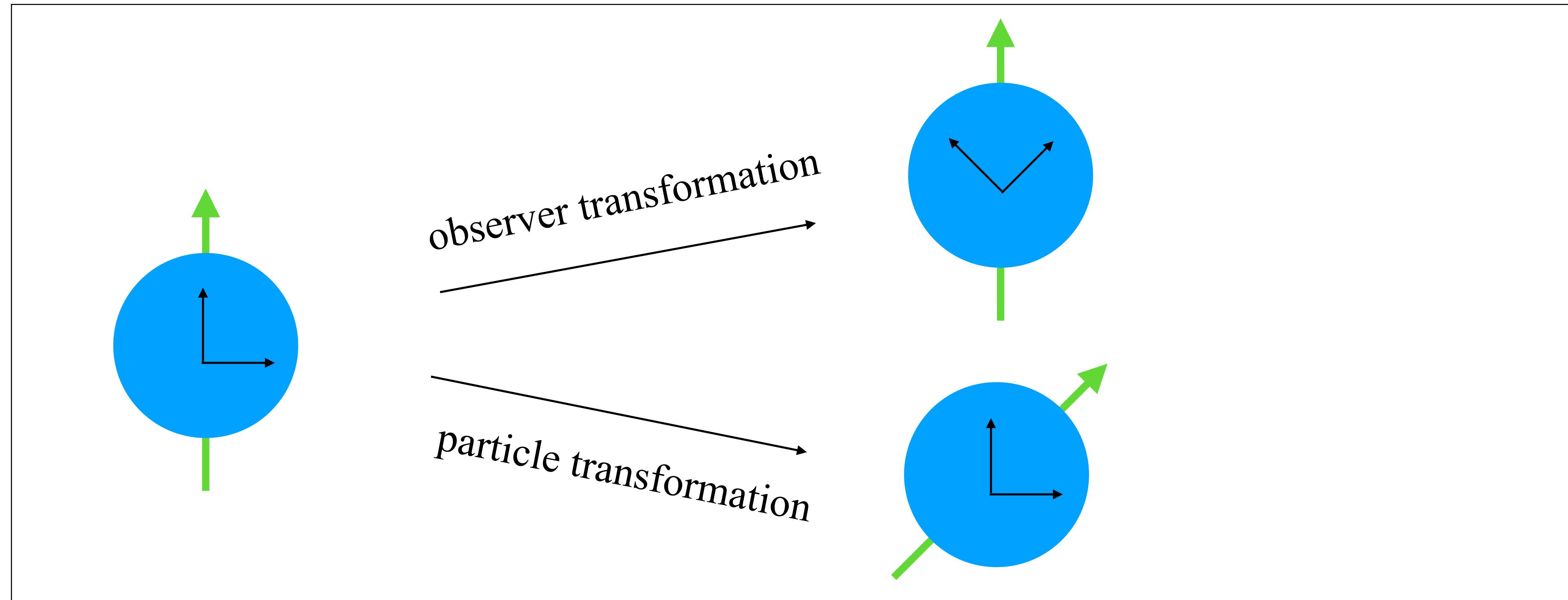
Nathaniel Sherrill
University of Sussex

Based on
arXiv:2212.12750

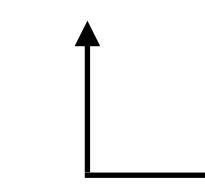
Probing space-time properties (LIV/NC) at HEP experiments
Belgrade, 29/5/2023

Observer vs. particle transformations

In Lorentz-*invariant* theories **observer** and **particle** transformations have indistinguishable effects



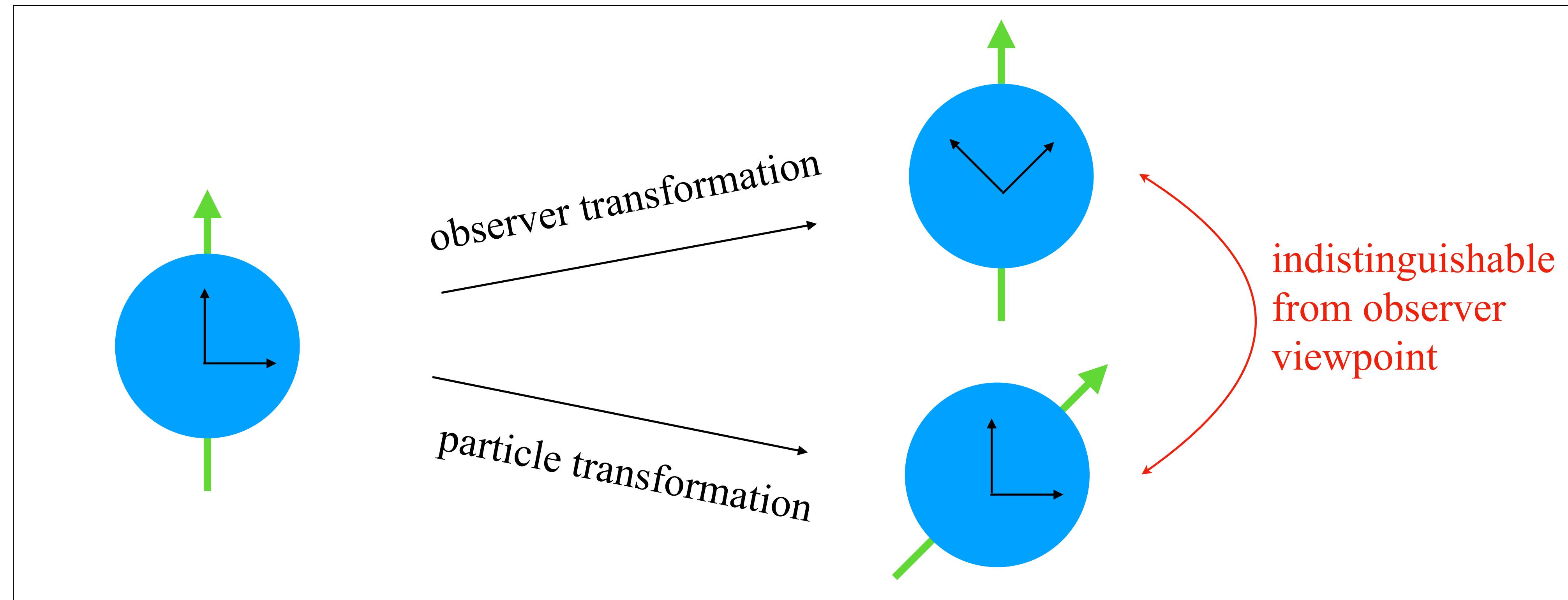
= particle/system

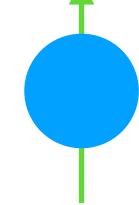


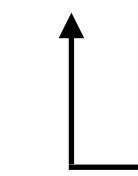
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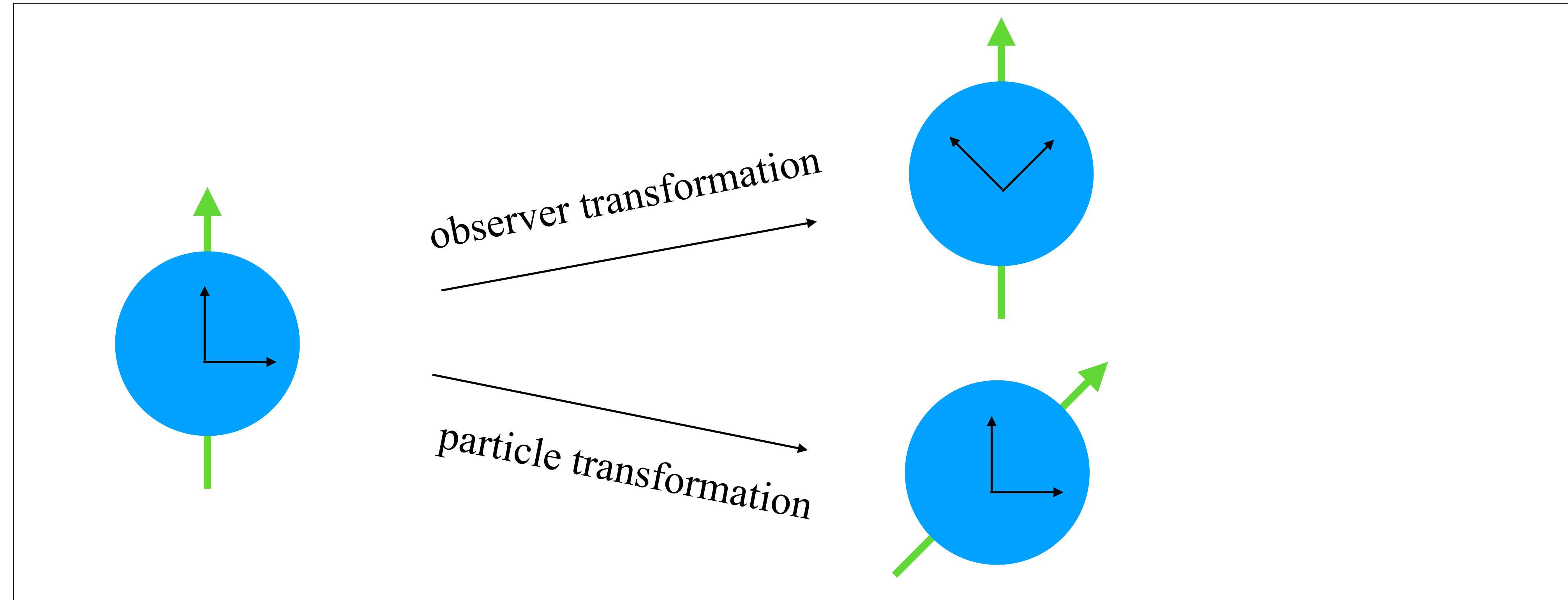


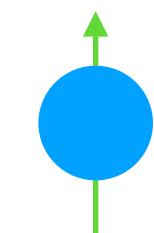
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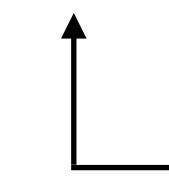
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Observer vs. particle transformations

In Lorentz-*violating* theories **observer** and **particle** transformations are generically *inequivalent*

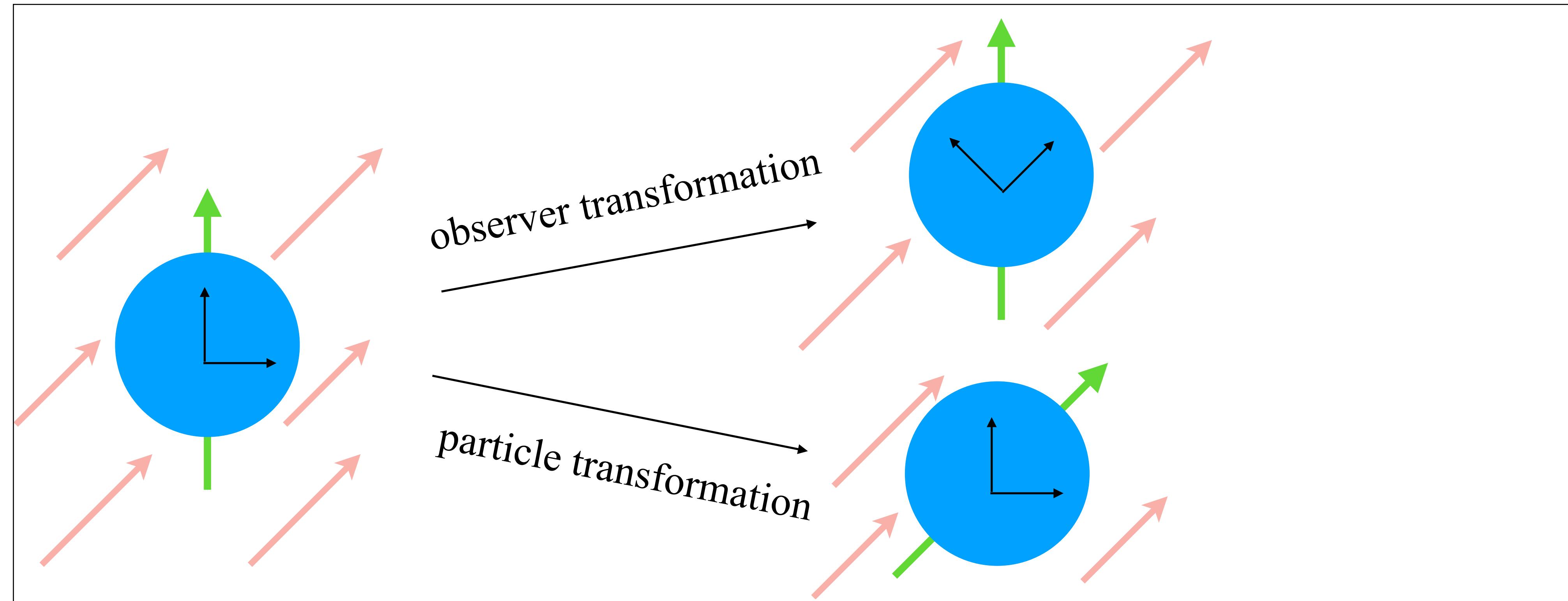


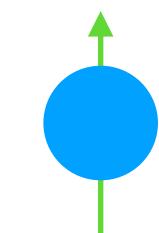
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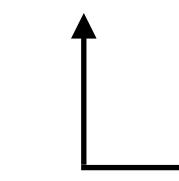
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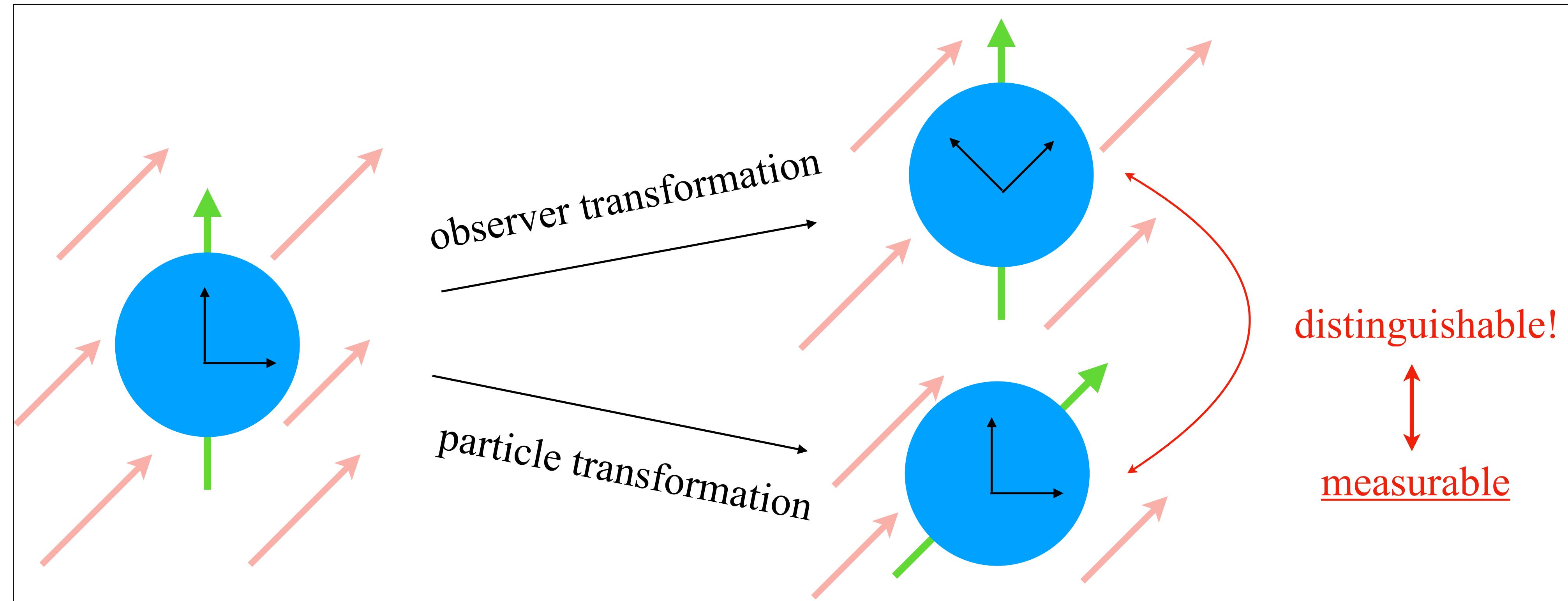
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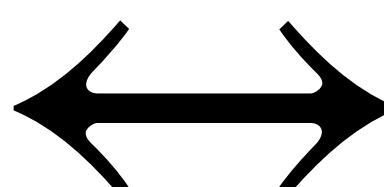
SME constraints

Some coefficients are strongly constrained

$$\mathcal{L}'_{\text{photon}} \supset \frac{1}{2}(k_{AF}^\kappa)\epsilon_{\kappa\lambda\mu\nu}A^\lambda F^{\mu\nu}$$

$$\mathcal{L}'_{\text{matter}} \supset c_\psi^{\mu\nu}\bar{\psi}\gamma_\mu i\partial_\nu\psi$$

$$\mathcal{L}'_{\text{neutrino}} \supset -(a_L)_{\beta ab}\bar{L}_a\gamma^\beta L_b$$



$$|(k_{AF})^\mu| \lesssim 10^{-43} \text{ GeV}$$

$$|c_\psi^{\mu\nu}| \lesssim \begin{cases} 10^{-20}, & \psi = e \\ 10^{-19}, & \psi = p, n \end{cases}$$

$$|(a_L)_{\beta\mu\tau}| \lesssim 10^{-23} \text{ GeV}$$

Others not so much, e.g.

$$\mathcal{L}'_{\text{top}} \supset c_t^{\mu\nu}\bar{t}\gamma_\mu i\partial_\nu t \iff |c_t^{\mu\nu}| \lesssim 10^{-4}$$

Unstable, QCD, and EW sectors are comparatively unconstrained/unexplored

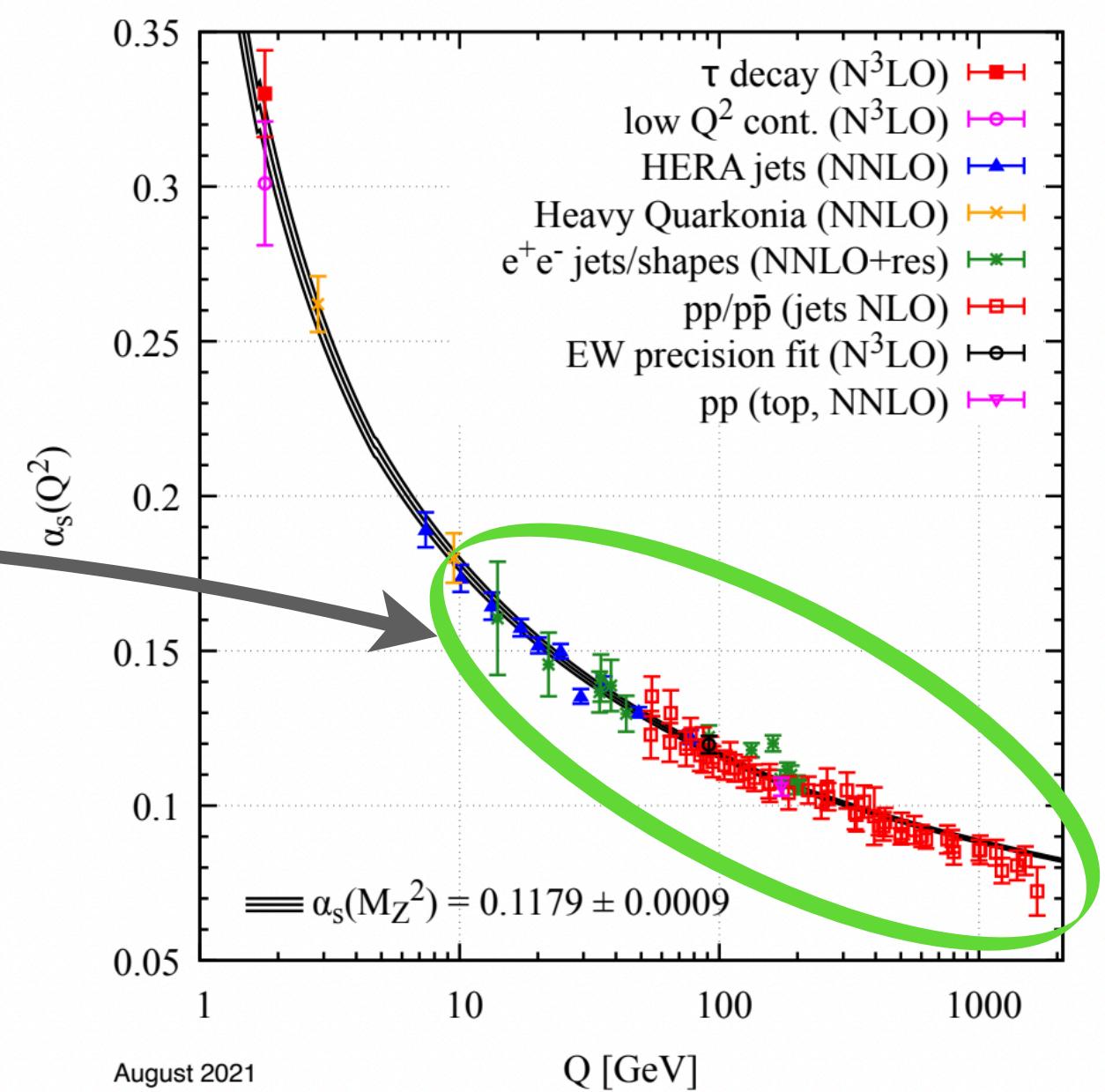
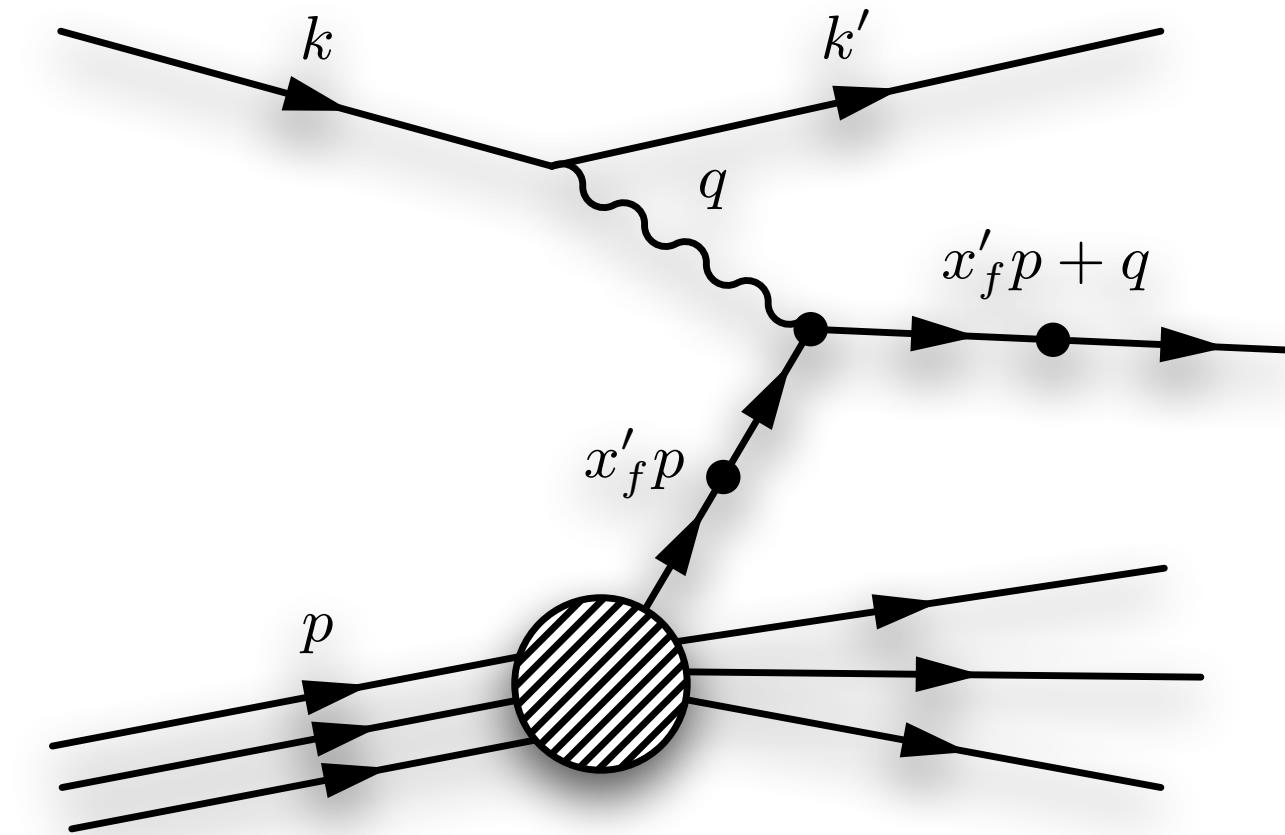
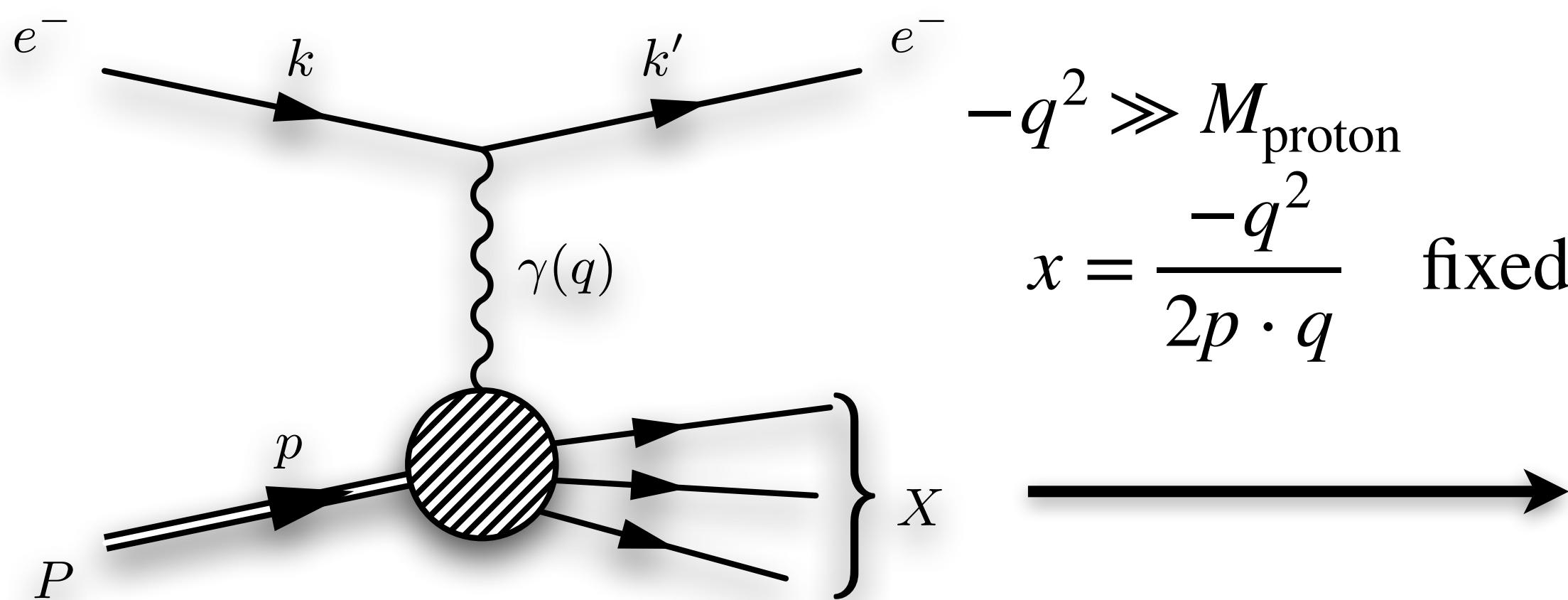
Quark sector

Direct access to Lorentz properties of quarks challenging because of QCD

@ large momentum transfer

- asymptotic freedom
- perturbative QCD
- factorization

Example: deep inelastic scattering (DIS)



<https://pdg.lbl.gov/2021>

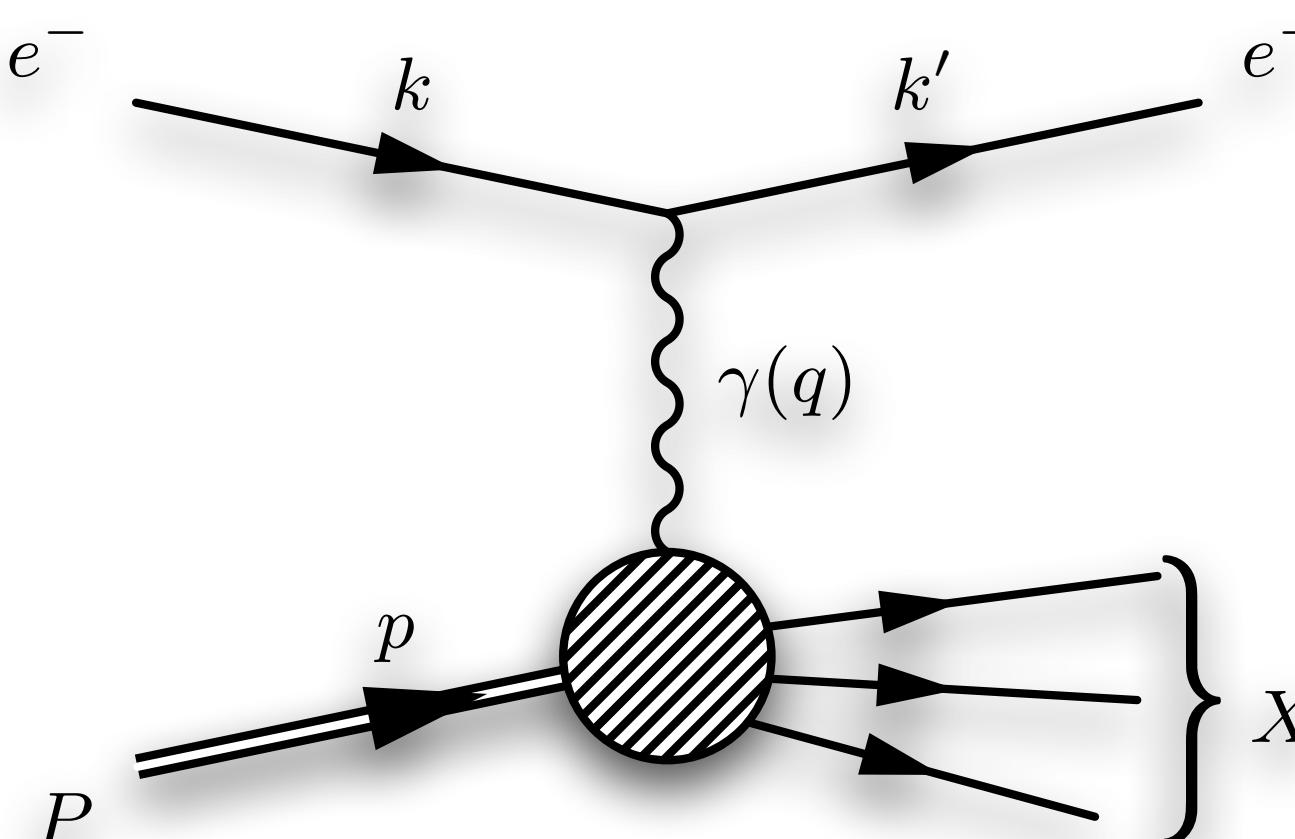
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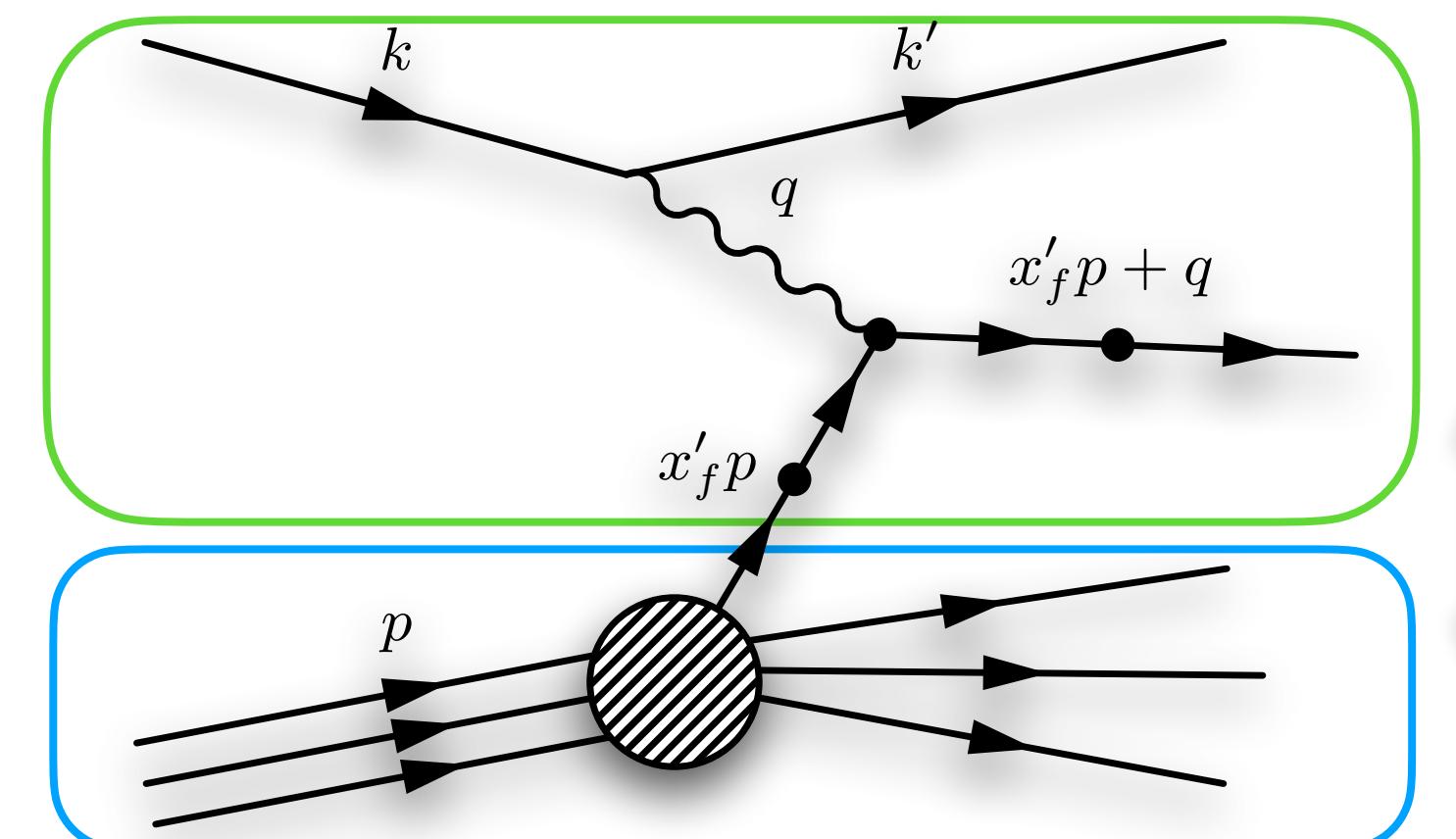
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Example: deep inelastic scattering (DIS)



$$-q^2 \gg M_{\text{proton}}$$

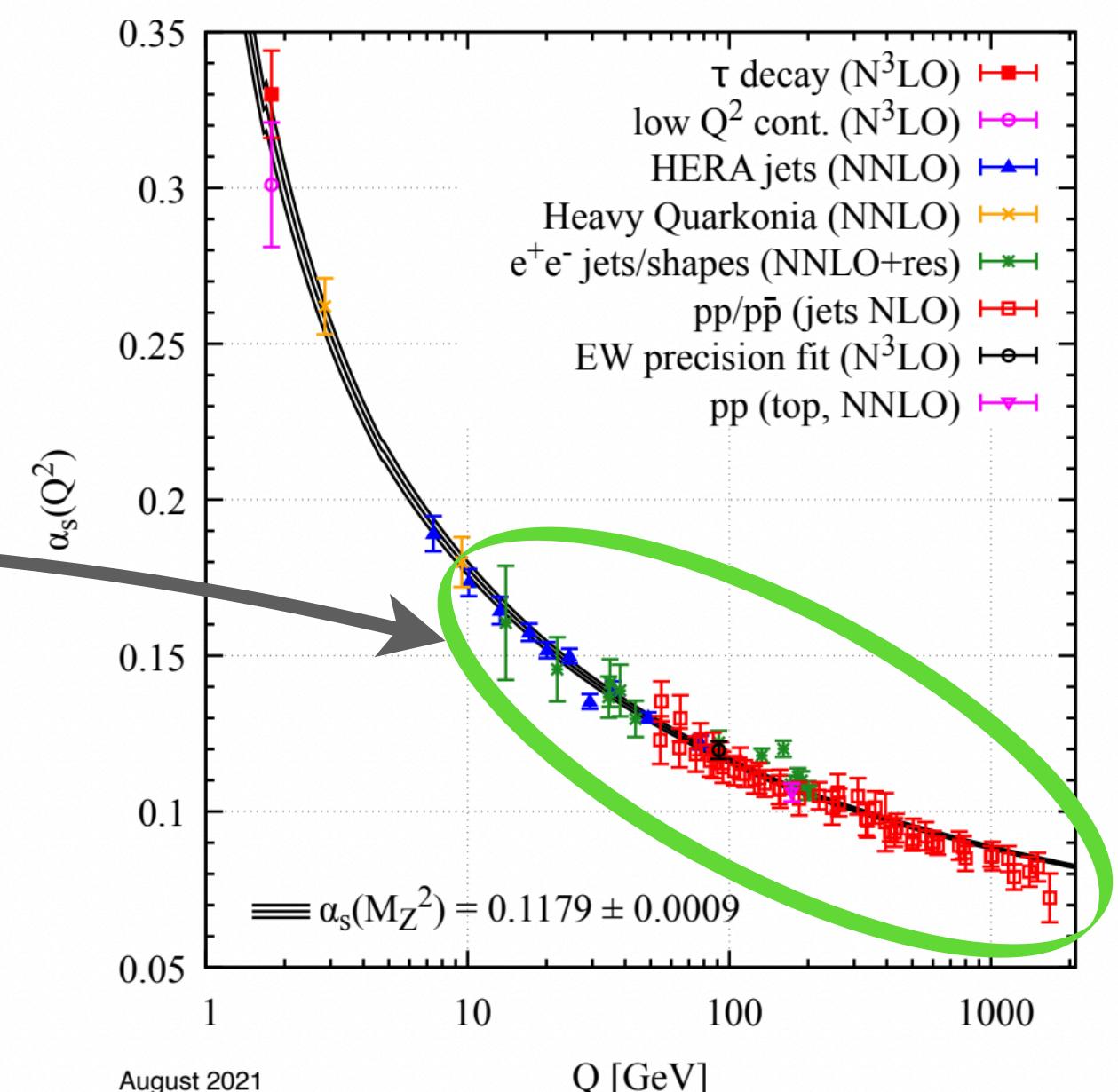
$$x = \frac{-q^2}{2p \cdot q} \quad \text{fixed}$$



<https://pdg.lbl.gov/2021>

factorization

Direct access to parton couplings



Quark sector

QCD + LV operators: can perturbative calculations reliably be performed?

Notion of partons, factorization, PDFs, optical theorem, Ward identities, NLO, ... ?

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First studies: corrections to unpolarized deep inelastic scattering (DIS)

- V. A. Kostelecký, E. Lunghi, A. R. Vieira, PLB **769**, 272 (2017)
- E. Lunghi, NS, PRD **98**, 115018 (2018)

$$\mathcal{L} \supset \sum_{f=u,d} (\eta^{\mu\nu} + \textcolor{red}{c}_f^{\mu\nu} + \gamma_5 \textcolor{red}{d}_f^{\mu\nu}) \bar{\psi}_f \gamma_\mu (i\partial_\nu - e e_f A_\nu) \psi_f$$

Quark sector

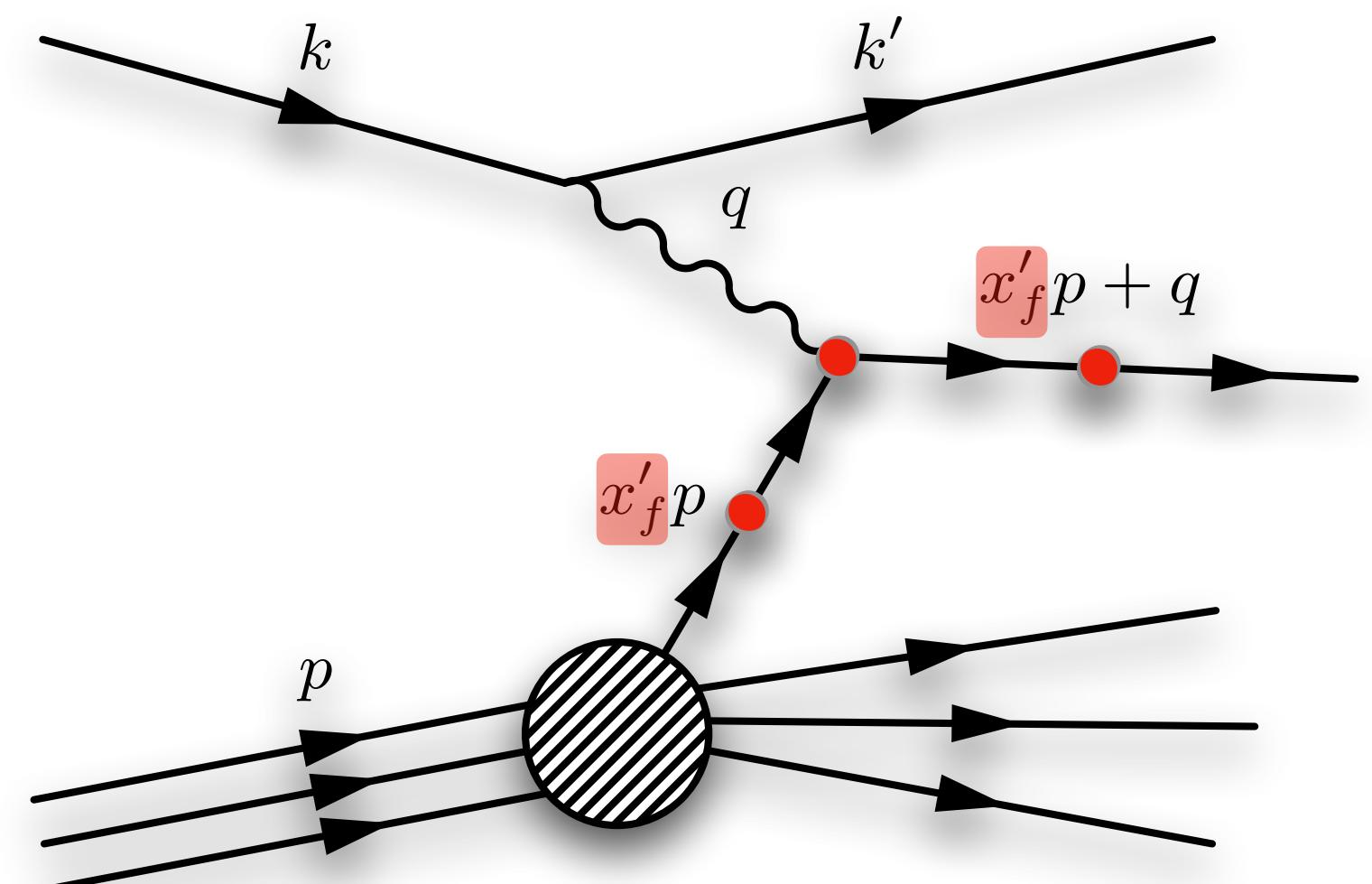
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- Calculated (leading) DIS process with perturbative insertions of quark operators
- Estimated sensitivities for existing/future colliders

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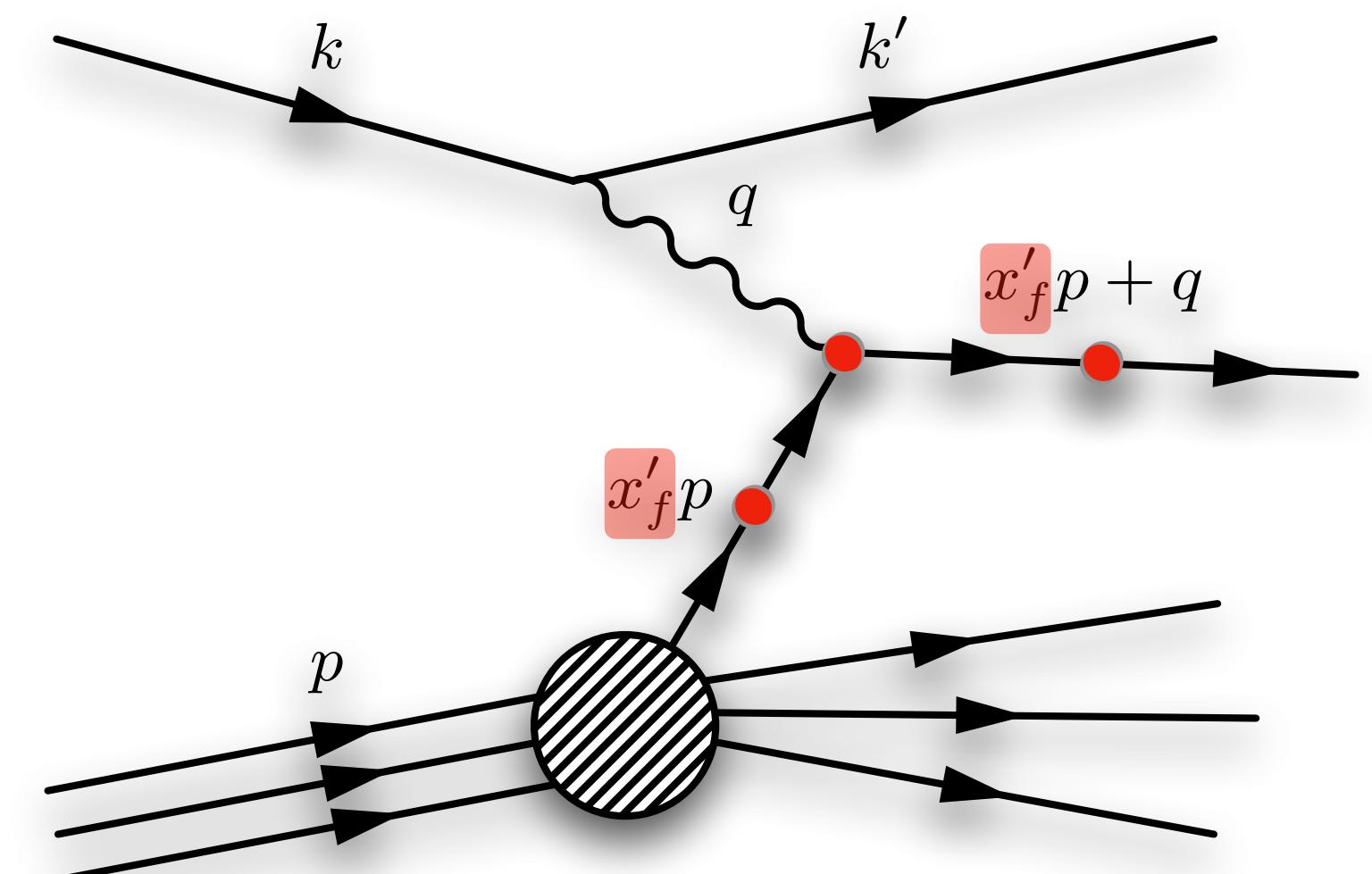
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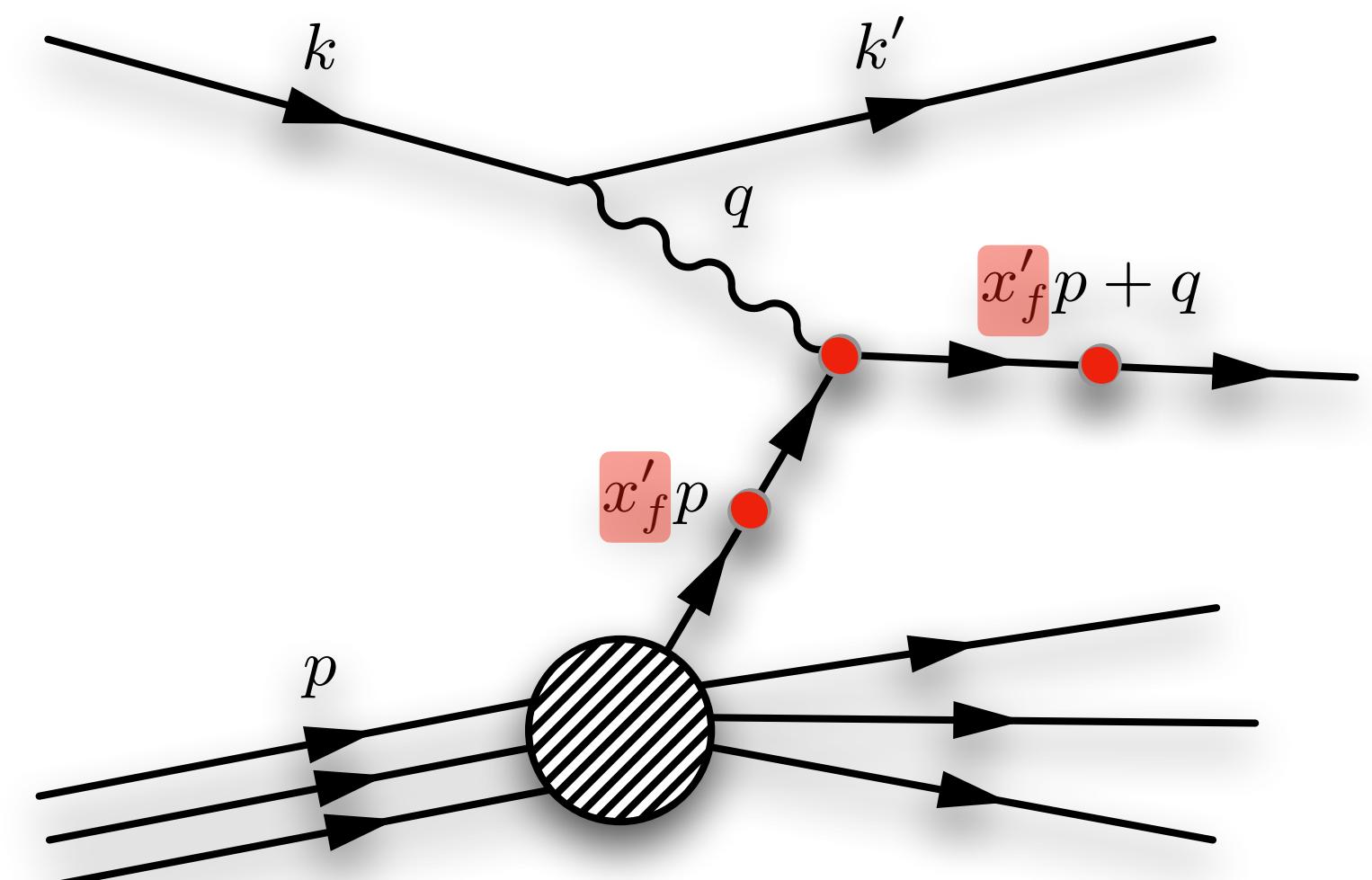
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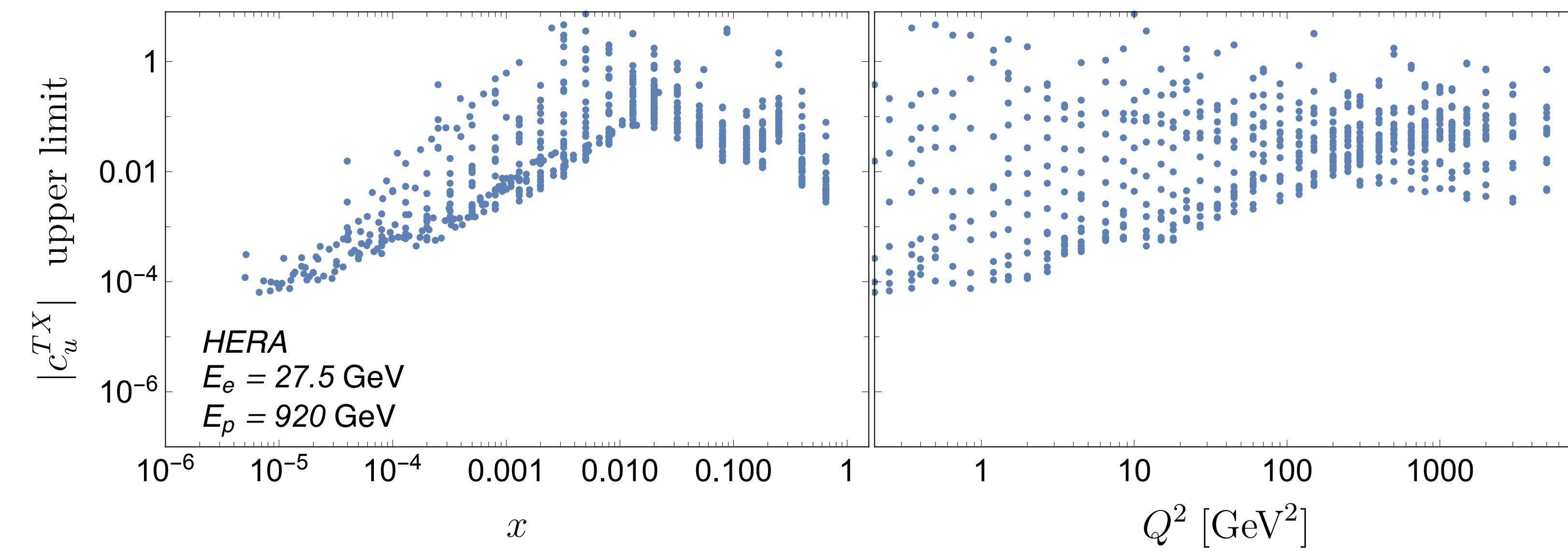
Estimates

Sidereal signatures: six coefficient combinations induce oscillations

$$\sigma \approx \sigma_{\text{SM}} [1 + c_f^{\mu\nu} f_{\mu\nu}(x, Q^2, T_{\oplus})]$$

Simulated constraints using H1 + ZEUS
neutral-current DIS @ HERA

H. Abramowicz et al.,
Eur. Phys. J. C **75**,
580 (2015)



www.desy.de

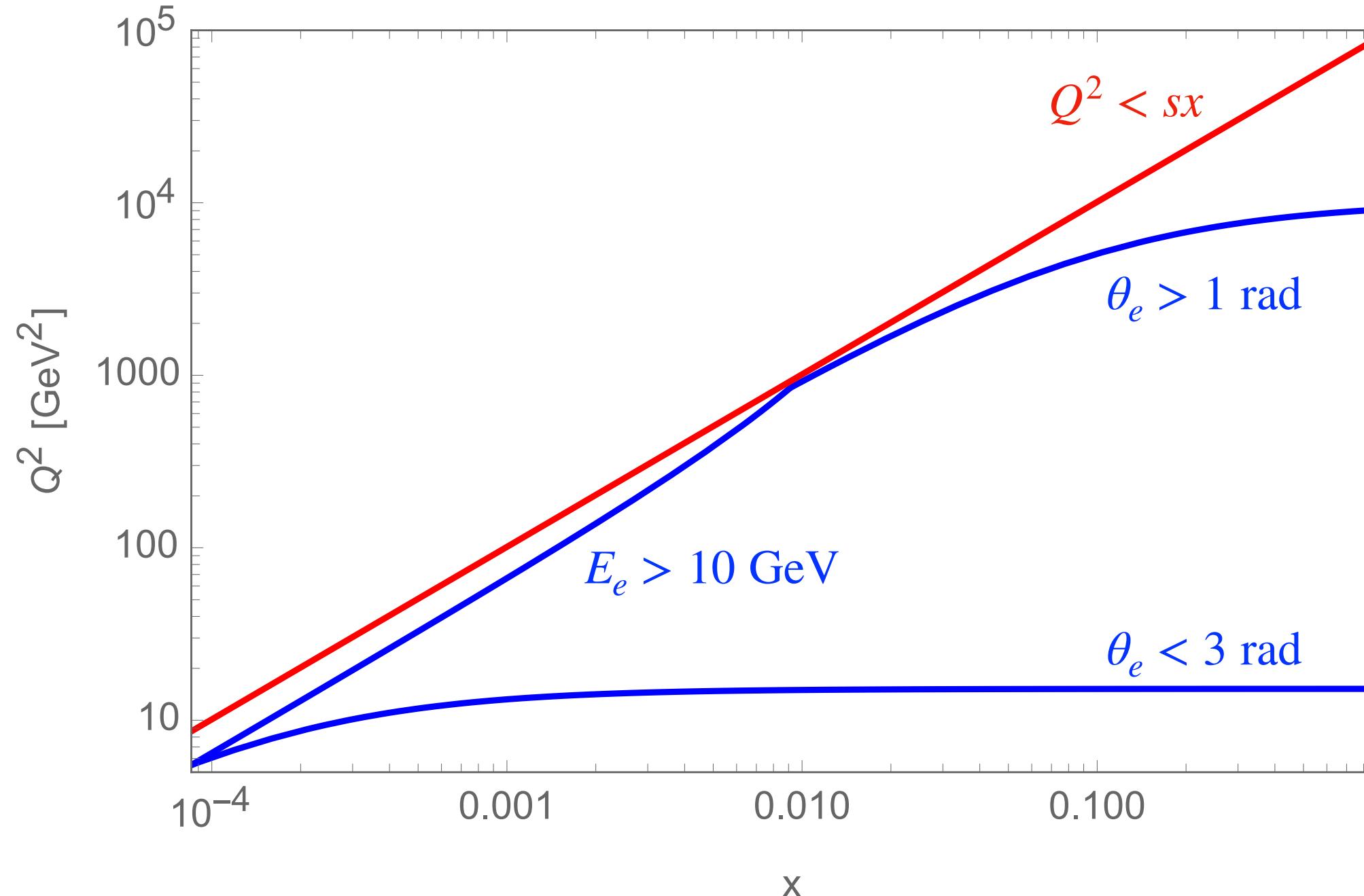
- Most sensitivity @ low x, Q^2
- Larger collision energies favored

ZEUS analysis

ZEUS Collaboration,
PRD 107, 092008 (2023)

Put ideas to test with **time-dependent analysis of (unpolarised) DIS data**

Total # DIS events \approx 45 million
 $x \in [7.7 \times 10^{-5}, 1]$
 $Q \in [2.2, 94] \text{ GeV}$



| Run period | Run range | E_p (GeV) | E_e (GeV) | e charge | lumi (pb^{-1}) | δ (%) |
|-------------------|---------------|-------------|-------------|----------|---------------------------|--------------|
| 2002/03 (no pol.) | 42825 - 44825 | 920 | 27.5 | e^+ | 0.97 | |
| 2003 | 45416 - 46638 | 920 | 27.5 | e^+ | 2.08 | 3.5 |
| 2004 | 47010 - 51245 | 920 | 27.5 | e^+ | 38.68 | 3.5 |
| 2004/05 | 52244 - 57123 | 920 | 27.5 | e^- | 134.16 | 1.8 |
| 2006 | 58181 - 59947 | 920 | 27.5 | e^- | 54.80 | 1.8 |
| 2006/07 | 60005 - 62049 | 920 | 27.5 | e^+ | 117.24 | 1.8 |
| 2007 | 62050 - 62637 | 920 | 27.5 | e^+ | 25.13 | 2.1 |
| 2007 LER | 70000 - 70854 | 460 | 27.5 | e^+ | 13.44 | ? |
| 2007 MER | 71004 - 71401 | 570 | 27.5 | e^+ | 6.33 | ? |

Relevant coefficients violate rotation invariance

$$c_f^{TX}, c_f^{TY}, c_f^{XZ}, c_f^{YZ}, c_f^{XY}, c_f^{XX-YY}$$

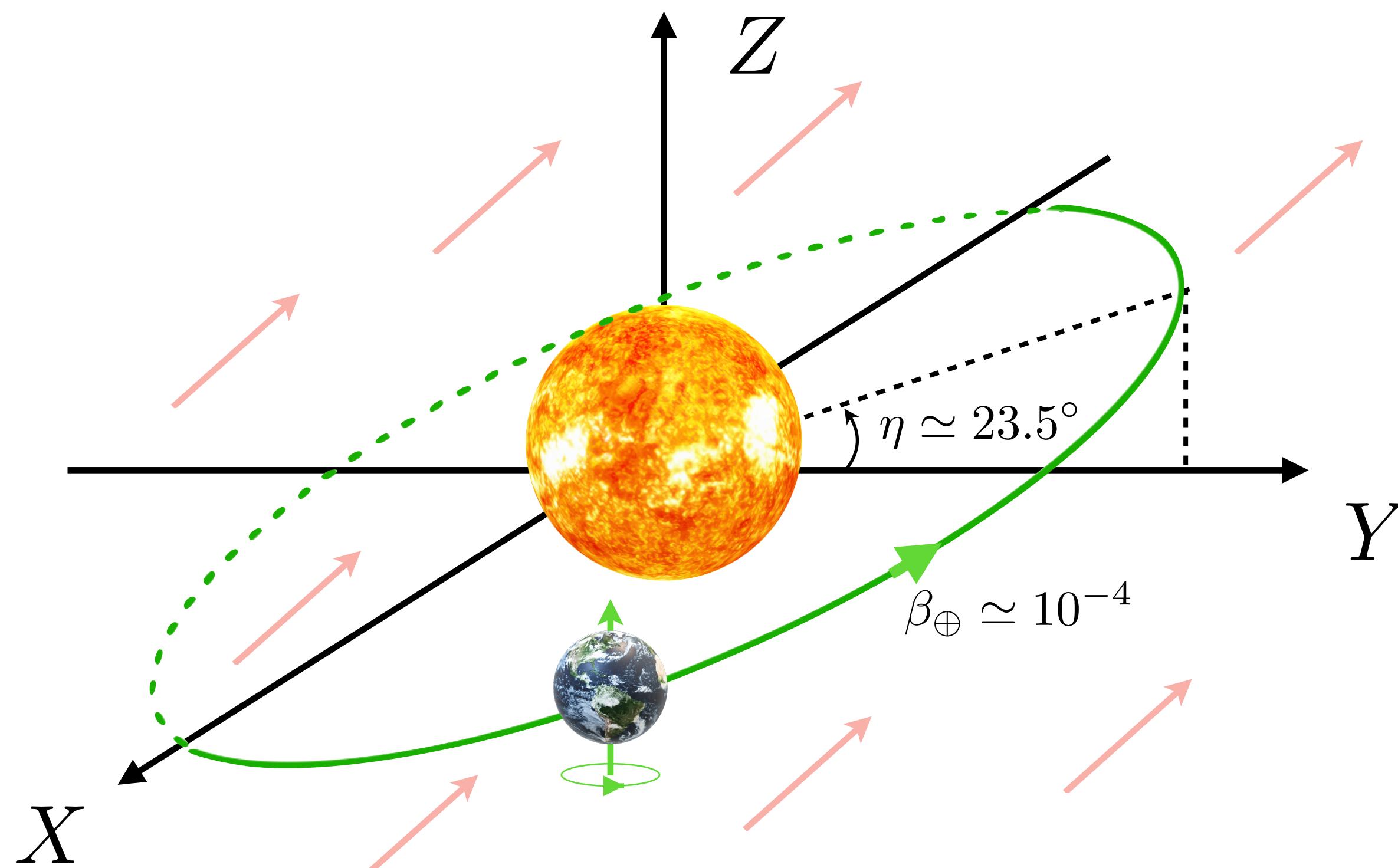
Lorentz violating only

$$a_{\text{Sf}}^{(5)TXX} - a_{\text{Sf}}^{(5)TYY}, a_{\text{Sf}}^{(5)XXZ} - a_{\text{Sf}}^{(5)YYZ}, a_{\text{Sf}}^{(5)TXY}, a_{\text{Sf}}^{(5)TXZ}, a_{\text{Sf}}^{(5)TYZ}, \\ a_{\text{Sf}}^{(5)XXX}, a_{\text{Sf}}^{(5)XXY}, a_{\text{Sf}}^{(5)XYY}, a_{\text{Sf}}^{(5)XYZ}, a_{\text{Sf}}^{(5)XZZ}, a_{\text{Sf}}^{(5)YYY}, a_{\text{Sf}}^{(5)YZZ}$$

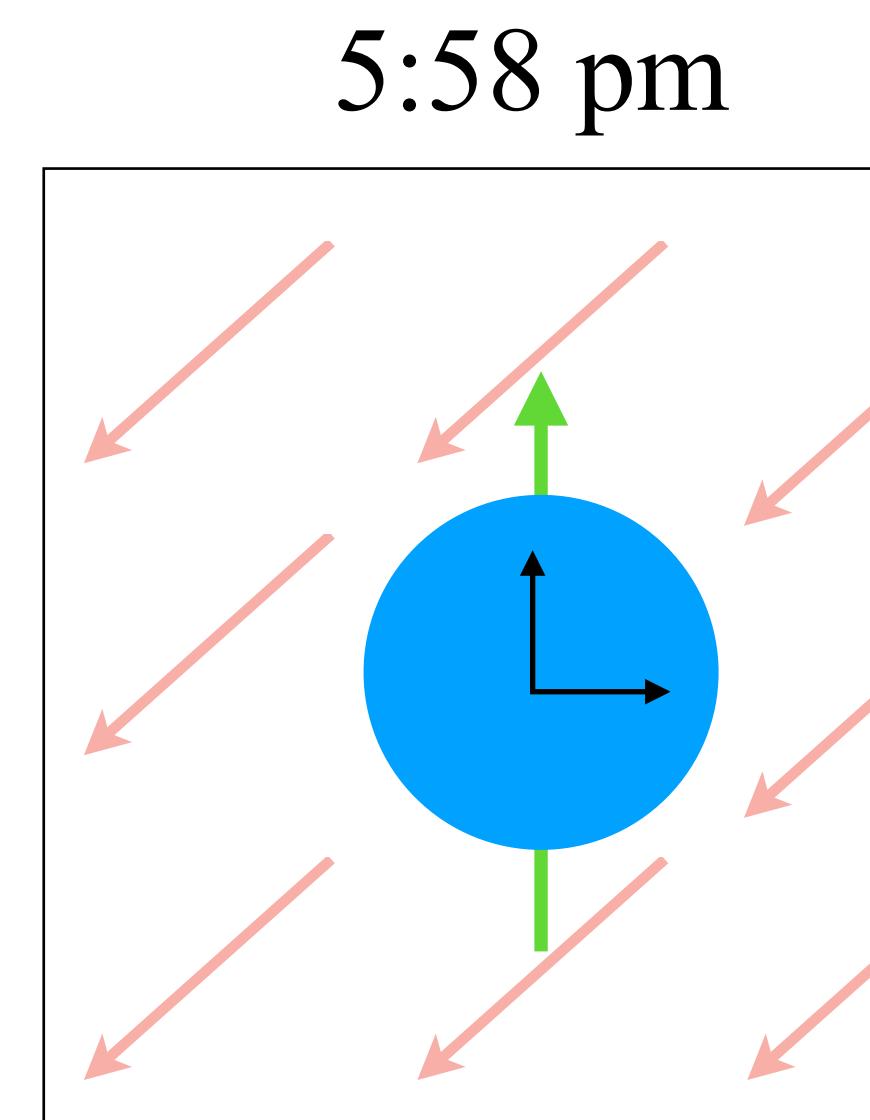
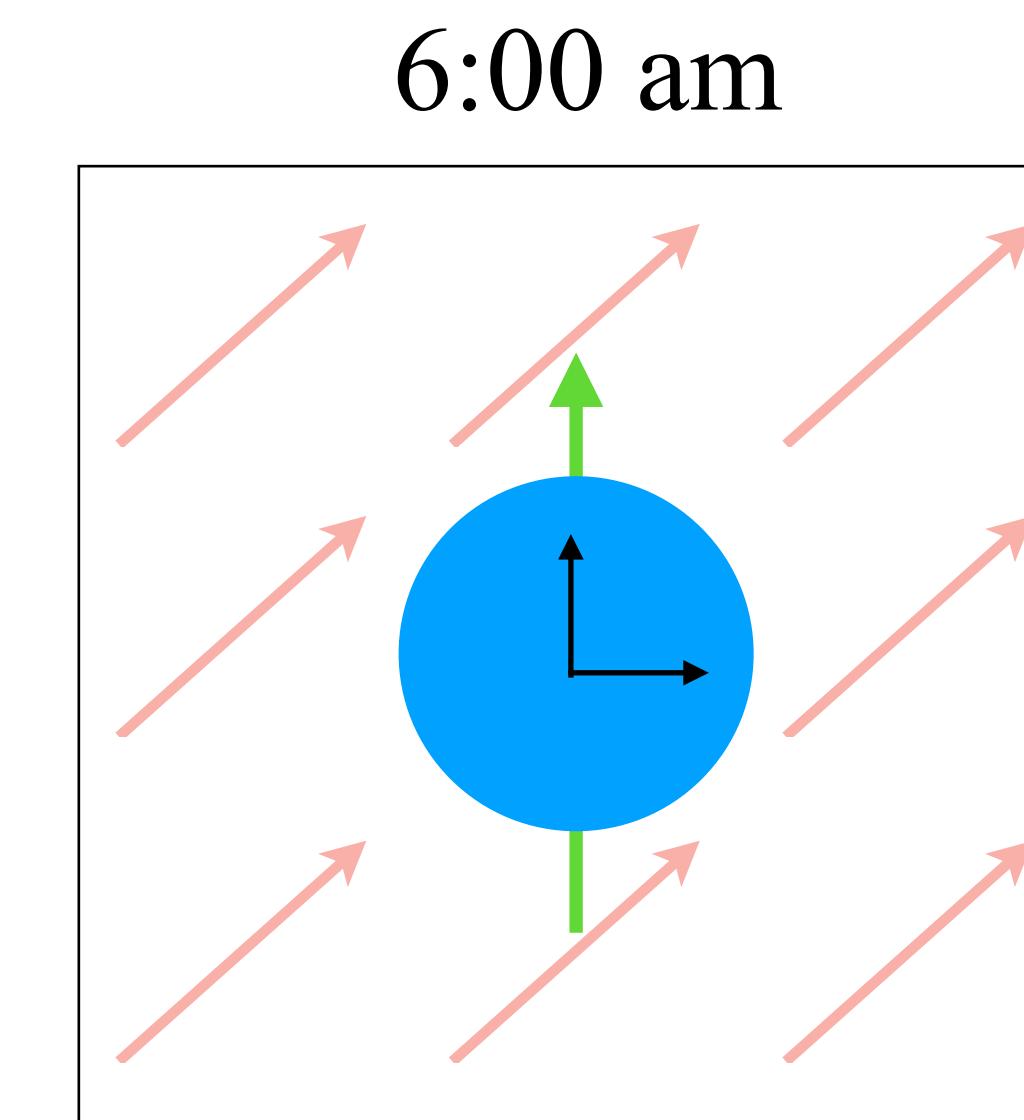
Lorentz and CPT violating

$f = u, d, s$: 42 coeffs. produce time-dependent oscillating signal

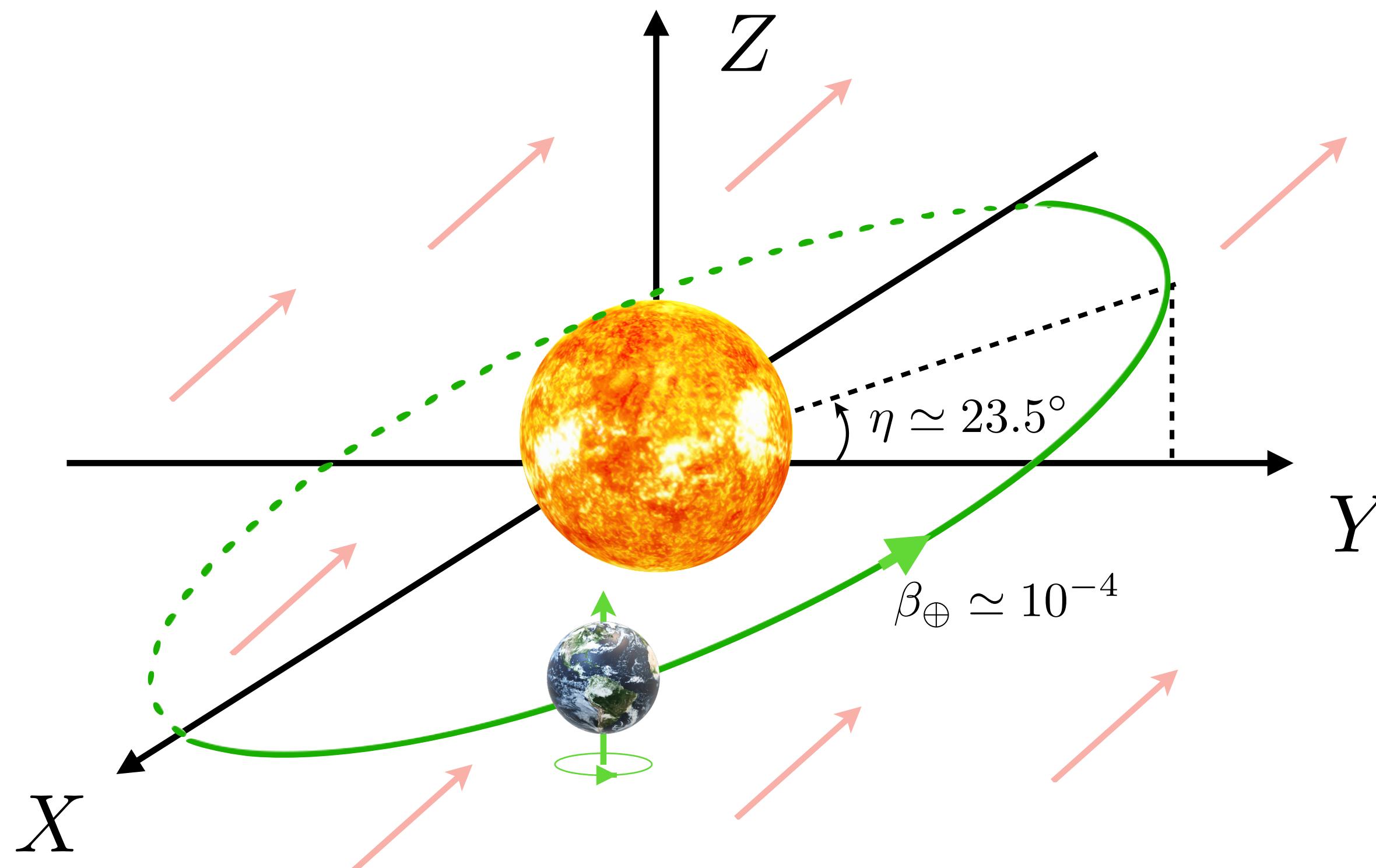
Sun-centered frame



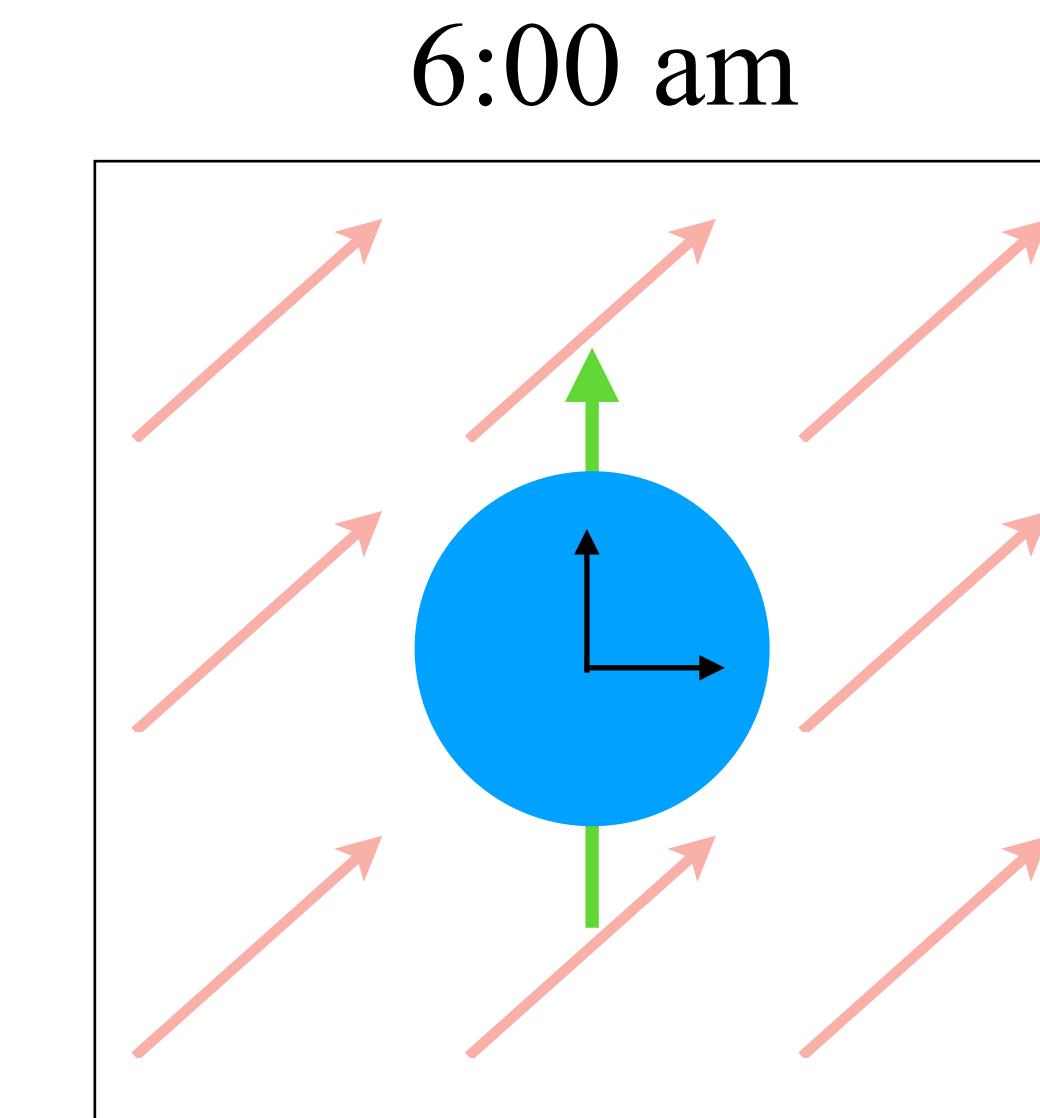
Lab-frame perspective



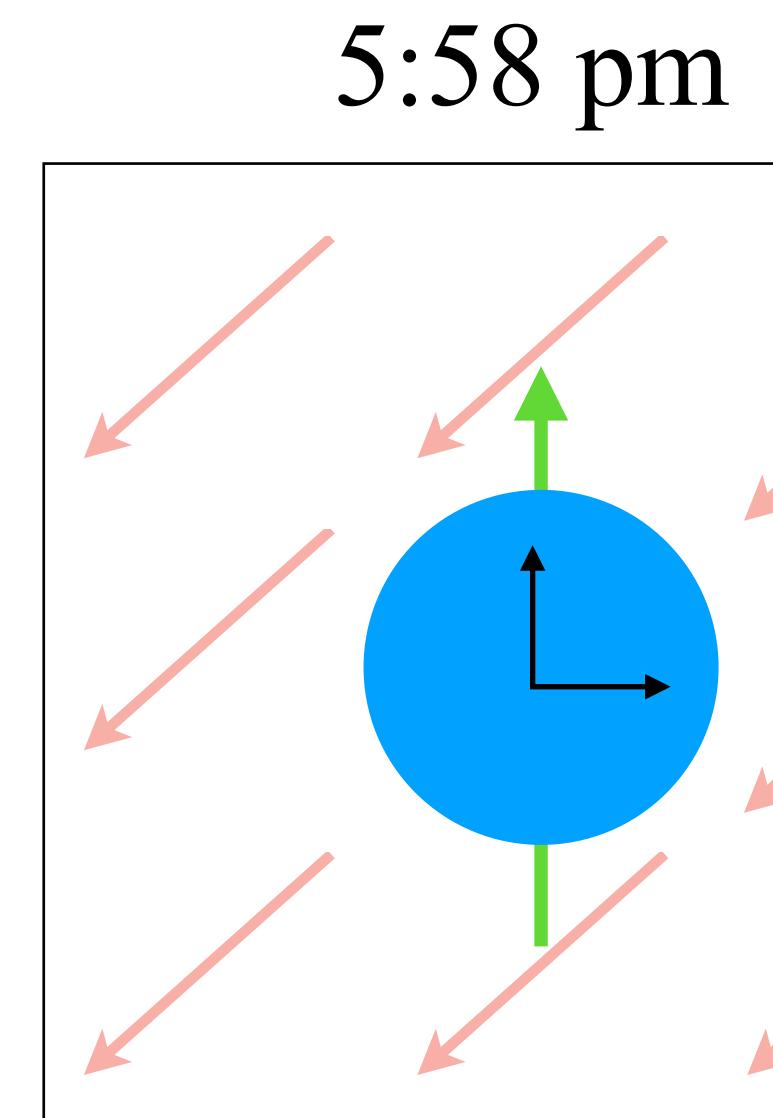
Sun-centered frame



Lab-frame perspective



6:00 am

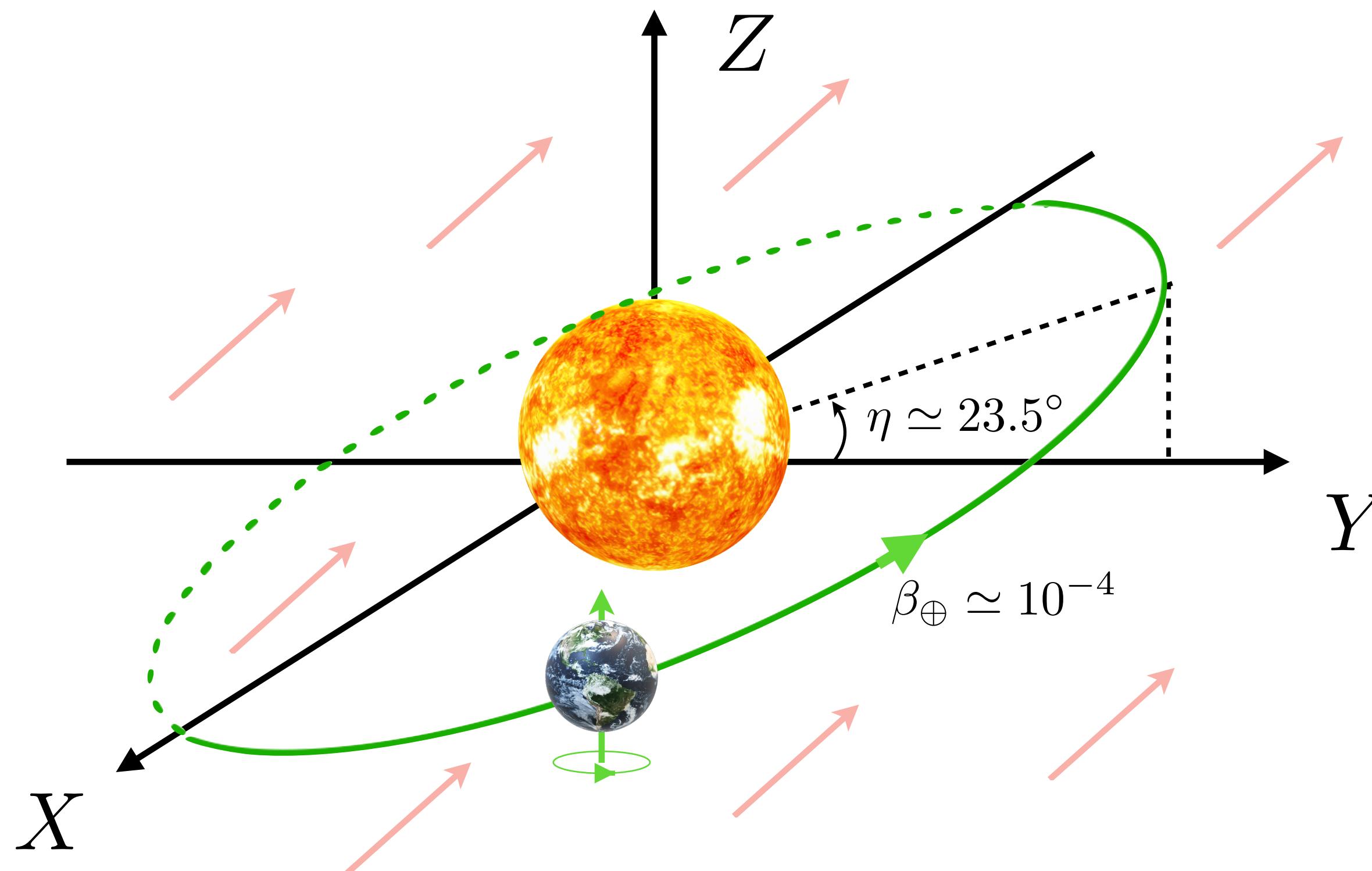


5:58 pm

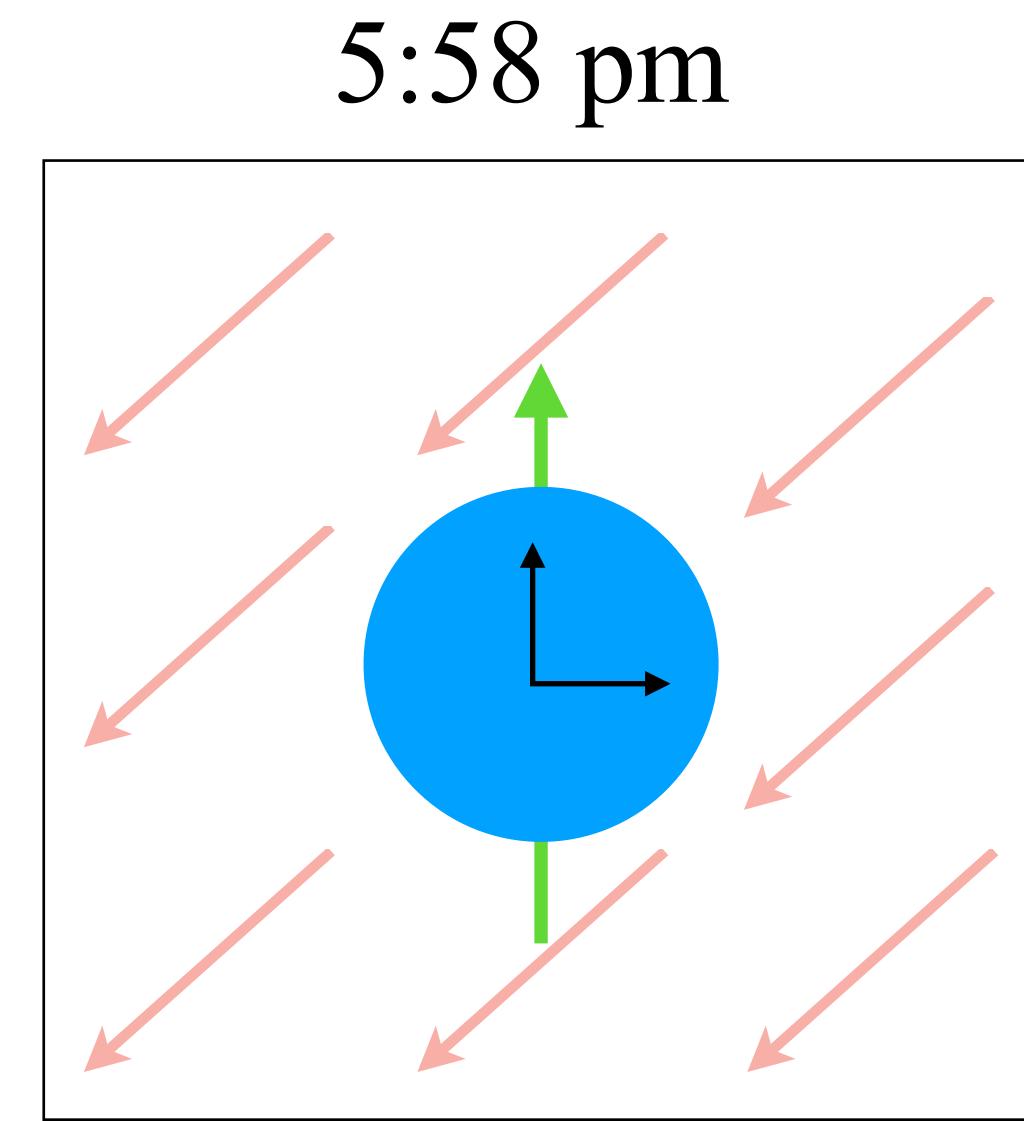
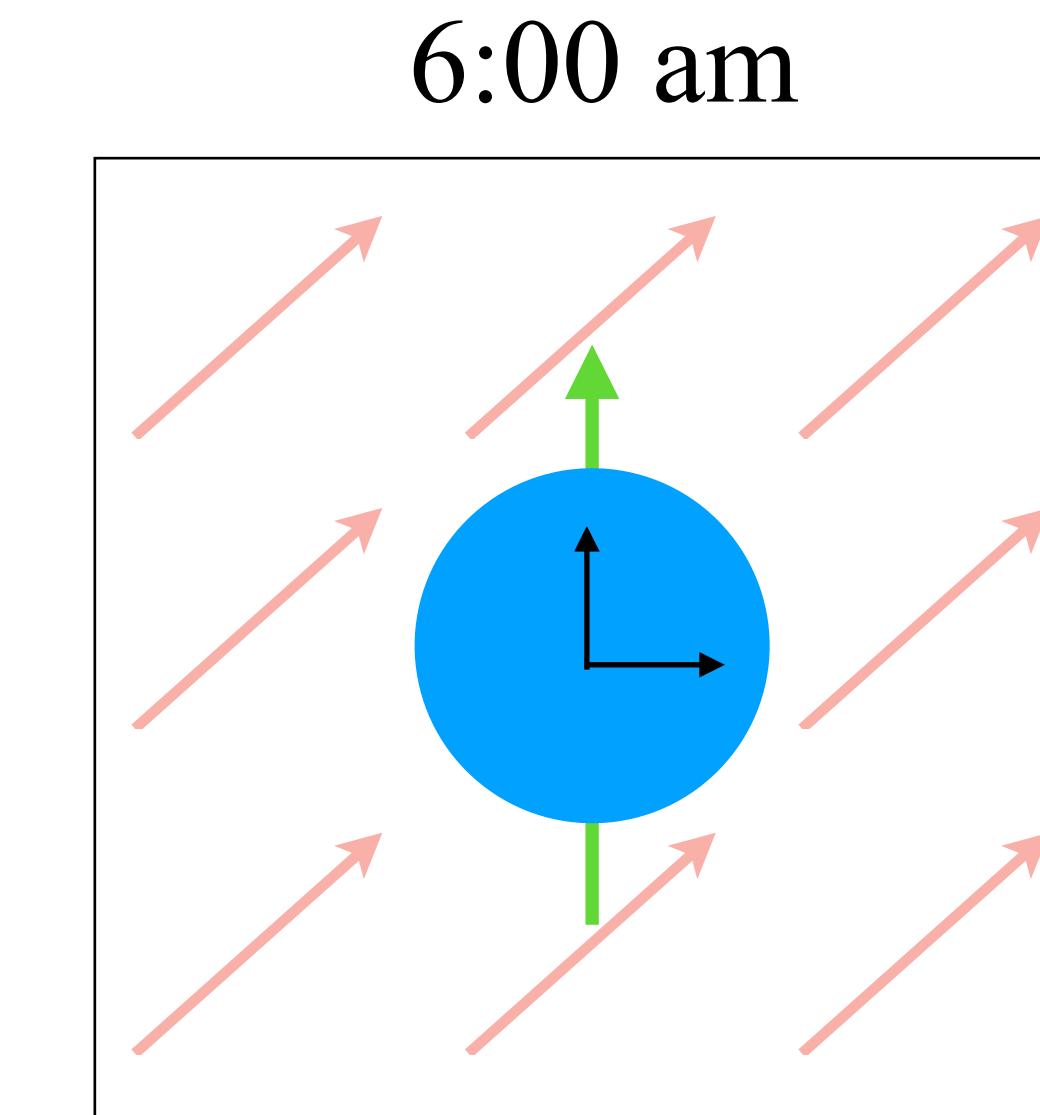
Express **laboratory coeffs.** in terms of **fixed SCF coeffs.**

$$c_{\text{lab}}^{\mu\nu} \approx R^{\mu}_{\alpha}(t)R^{\nu}_{\beta}(t)c_{\text{SCF}}^{\alpha\beta}$$

Sun-centered frame



Lab-frame perspective

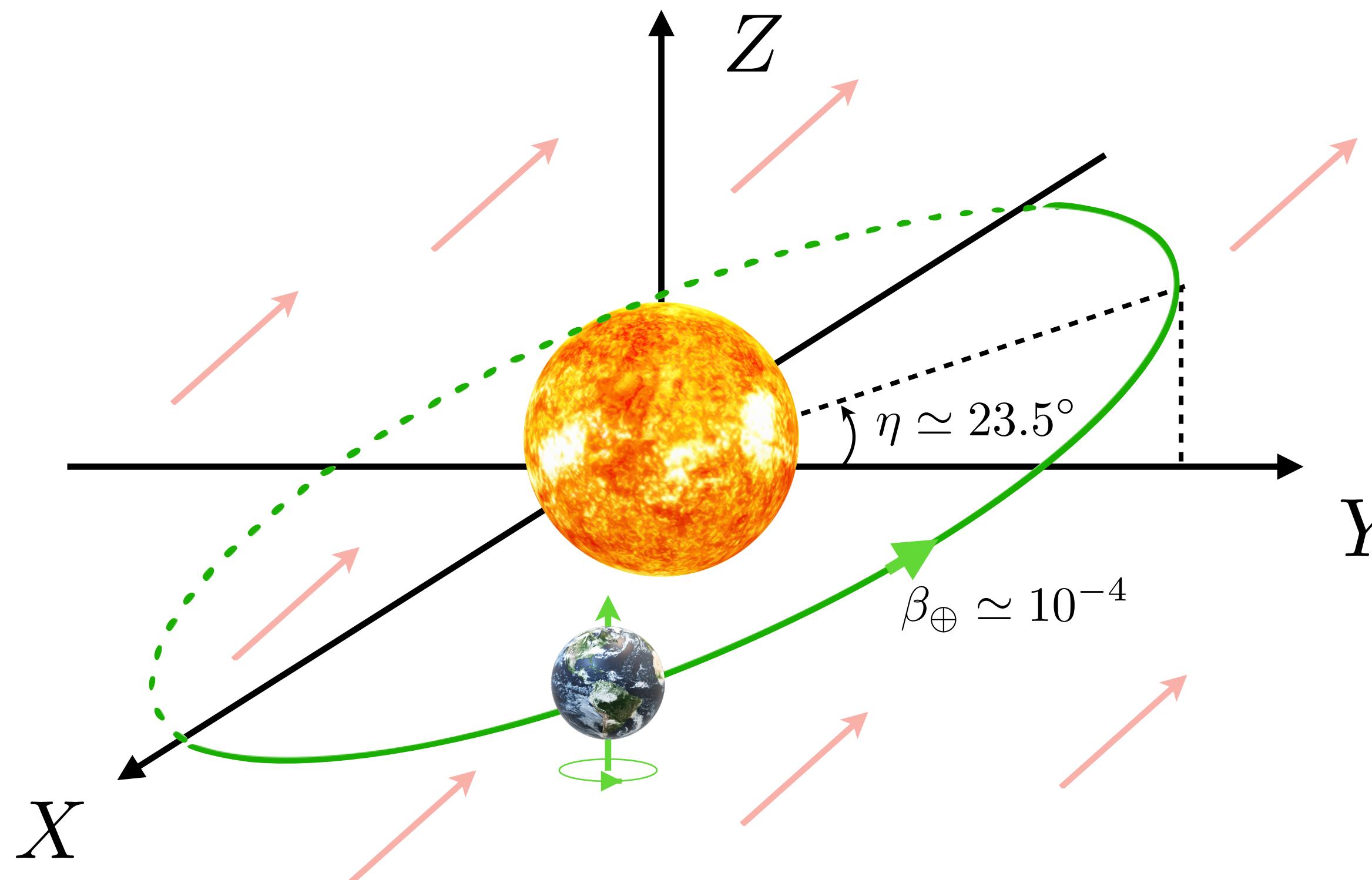


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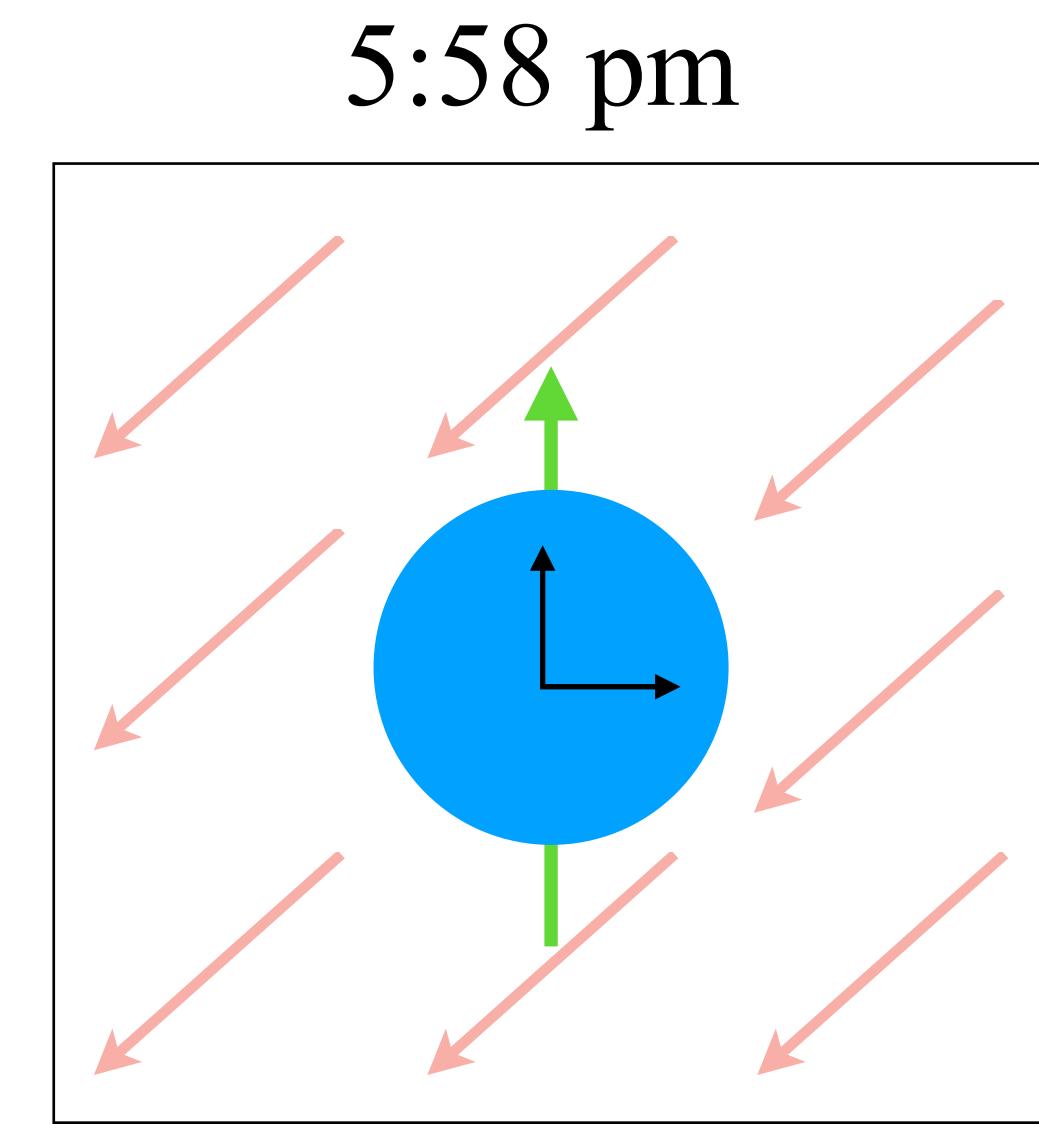
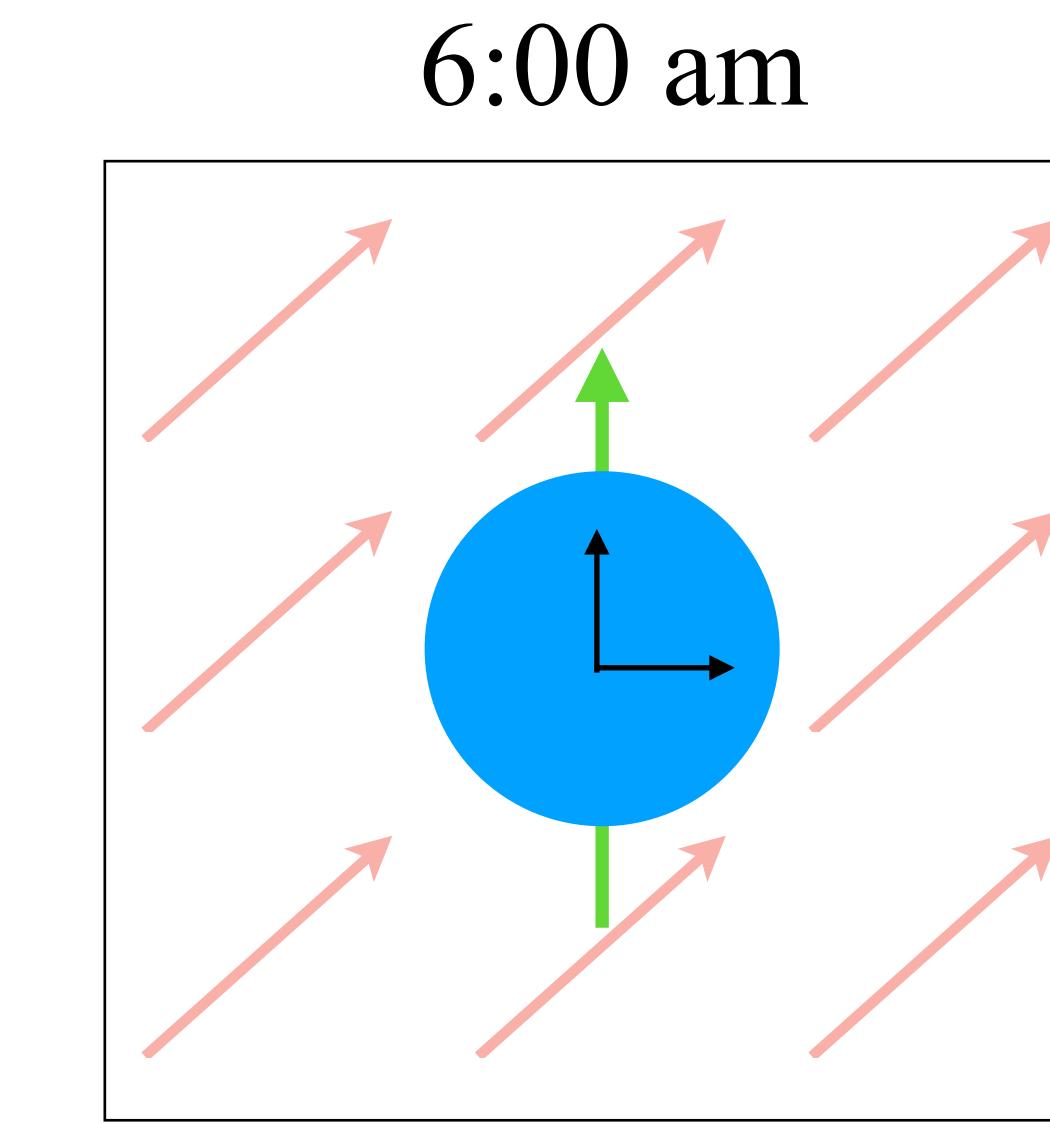
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$\mu, \nu \in 0, 1, 2, 3$ $\alpha, \beta \in T, X, Y, Z$

Sun-centered frame



Lab-frame perspective



Express **laboratory coeffs.** in terms of **fixed SCF coeffs.**

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$$\sigma = \sigma_{\text{SM}}(1 + A c_{\text{SCF}}^{TX} \cos(\omega_{\oplus} T_{\oplus}) + \dots) \quad \alpha, \beta \in T, X, Y, Z$$

Observables

We considered luminosity-*insensitive* ratios

$$r(\text{PS}_1, \text{PS}_2) = \frac{\int_{\text{PS}_1} dx dQ^2 \frac{d\sigma}{dx dQ^2 d\phi_T} / \int_{\text{PS}_1} dx dQ^2 d\phi_T \frac{d\sigma}{dx dQ^2 d\phi_T}}{\int_{\text{PS}_2} dx dQ^2 \frac{d\sigma}{dx dQ^2 d\phi_T} / \int_{\text{PS}_2} dx dQ^2 d\phi_T \frac{d\sigma}{dx dQ^2 d\phi_T}}$$

(r_{SM} = 1)

E.g. PS₁ = Q² > Q_{cut}² and PS₂ = Q² < Q_{cut}²

Event timestamp
 $\phi_T = \text{Mod}(T_\oplus, T_p)/T_p \in [0,1] = \text{event phase}$
Signal period: $T_p = T_{\text{sid.}} \approx 23 \text{ h } 56 \text{ min}$
 $< T_{\text{solar}} = 24 \text{ h}$

Observables

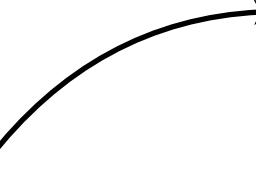
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Calculated r with several choices: $\begin{cases} T_p = T_{\text{solar}}, \textcolor{red}{T}_{\text{sid.}}, T_{\text{test}} = [1 \text{ h}, 24 \text{ h} + 4 \text{ min}] \\ N_{\text{bins}} = 4, 8, 12, 16, 25, 50, 75, 100 \end{cases}$

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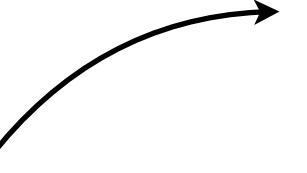
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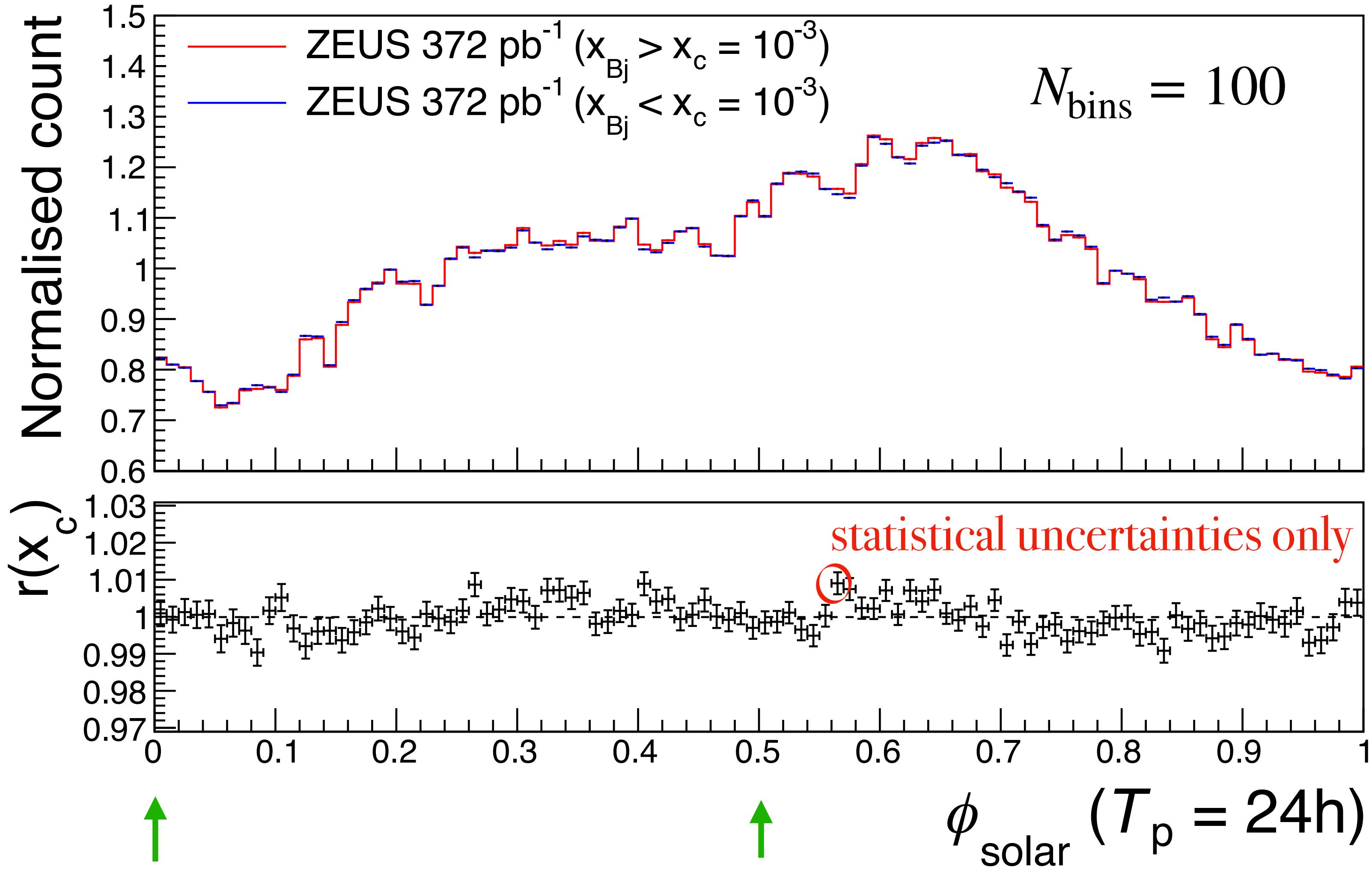
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Cross sections and systematics sensitive to $x \Rightarrow$ performed search with $x_{\text{cut}} = 10^{-3}$

 Event timestamp
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$(x_{\text{cut}}, T_{\text{solar}})$

ZEUS



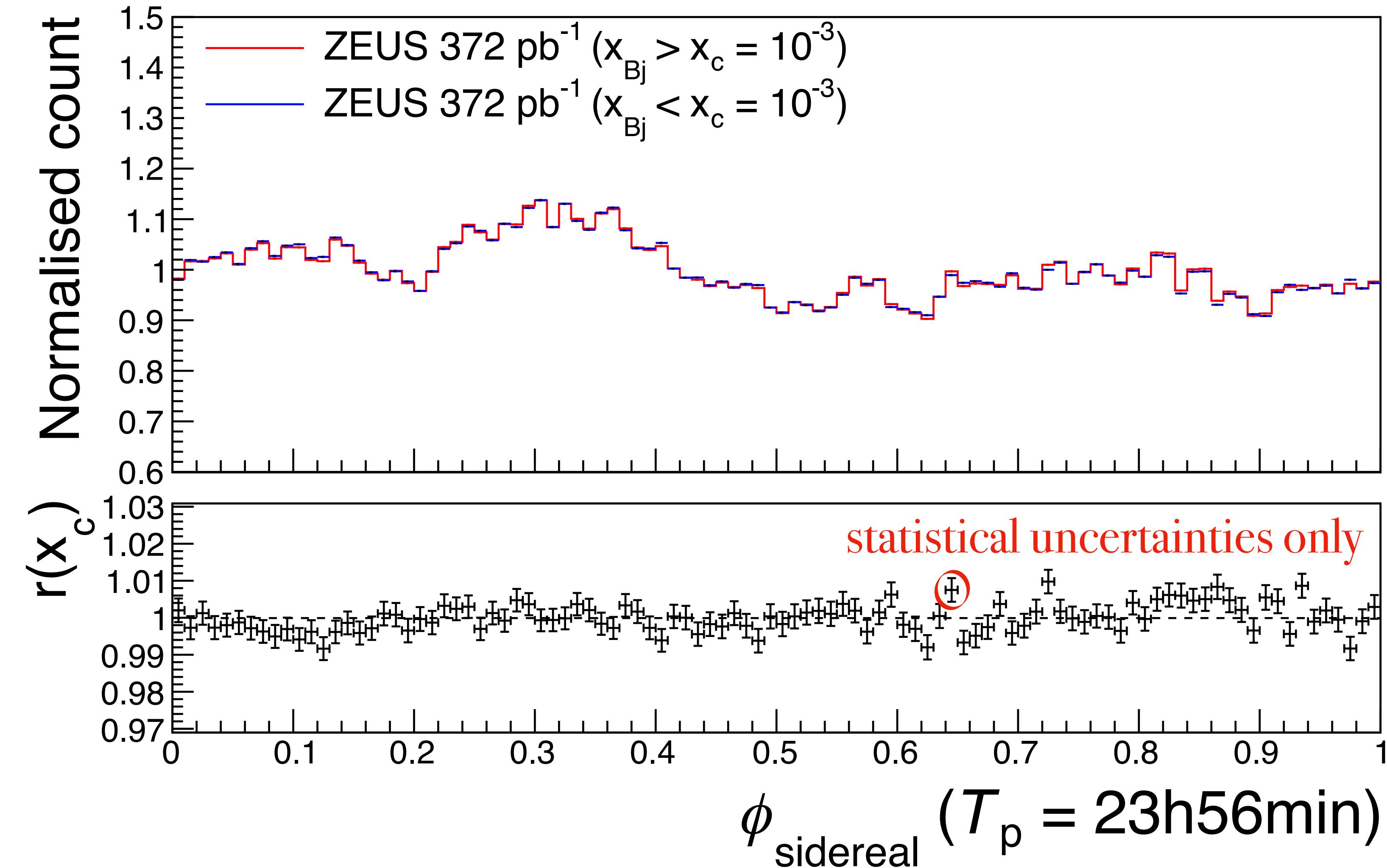
$$\text{curves} = \frac{\# \text{ events per bin}}{(\text{total } \# \text{ events}) \times (\text{bin width})}$$

Distributions follow
luminosity profile

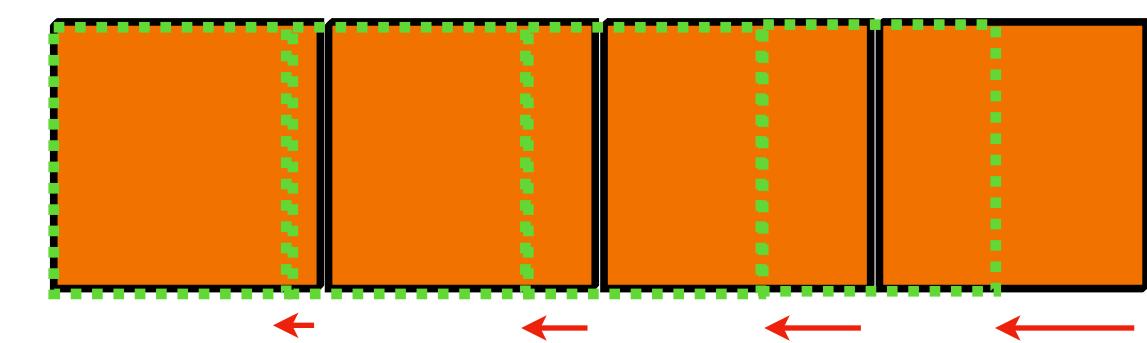
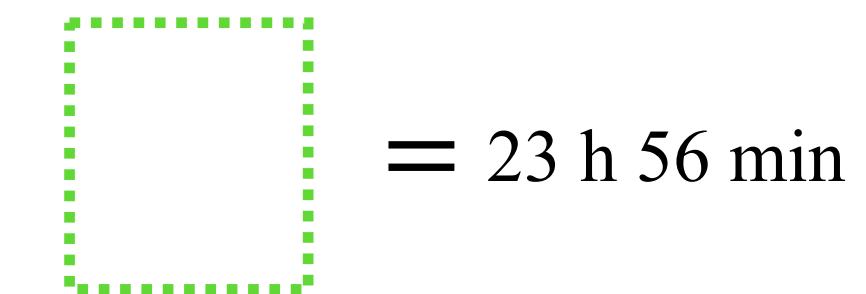
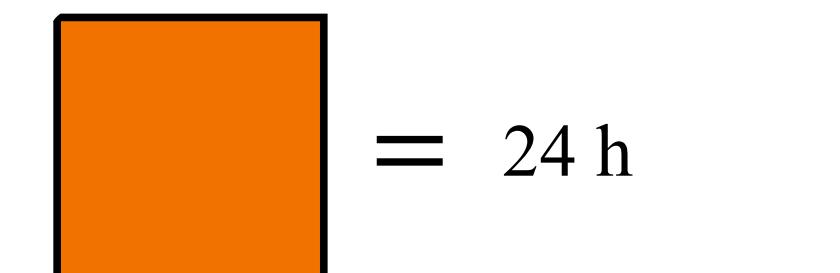
Luminosity drops out!

$(x_{\text{cut}}, T_{\text{sid.}})$

ZEUS

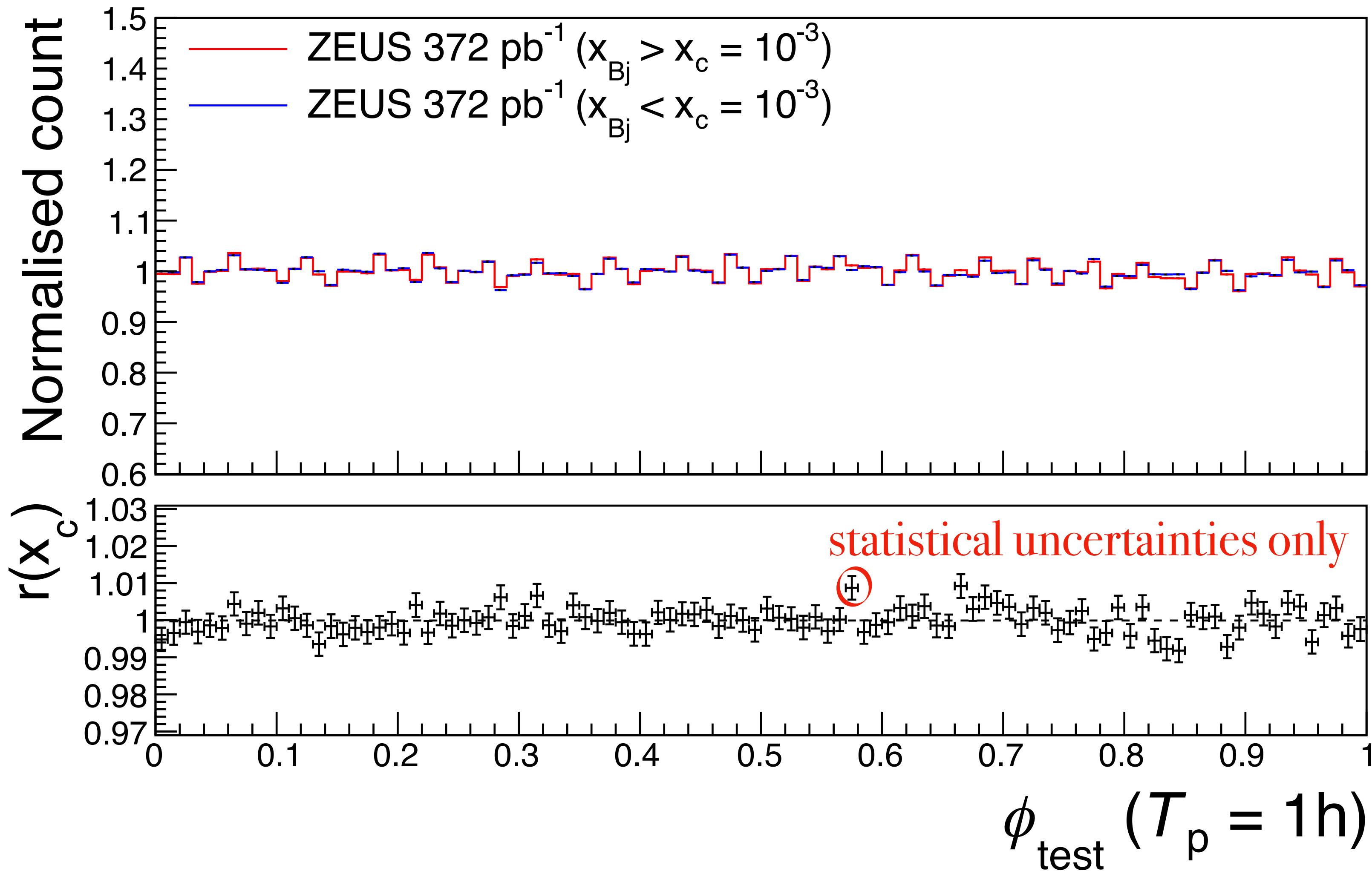


Partial dilution of solar binning



$(x_{\text{cut}}, T_{\text{test}} = 1 \text{ h})$

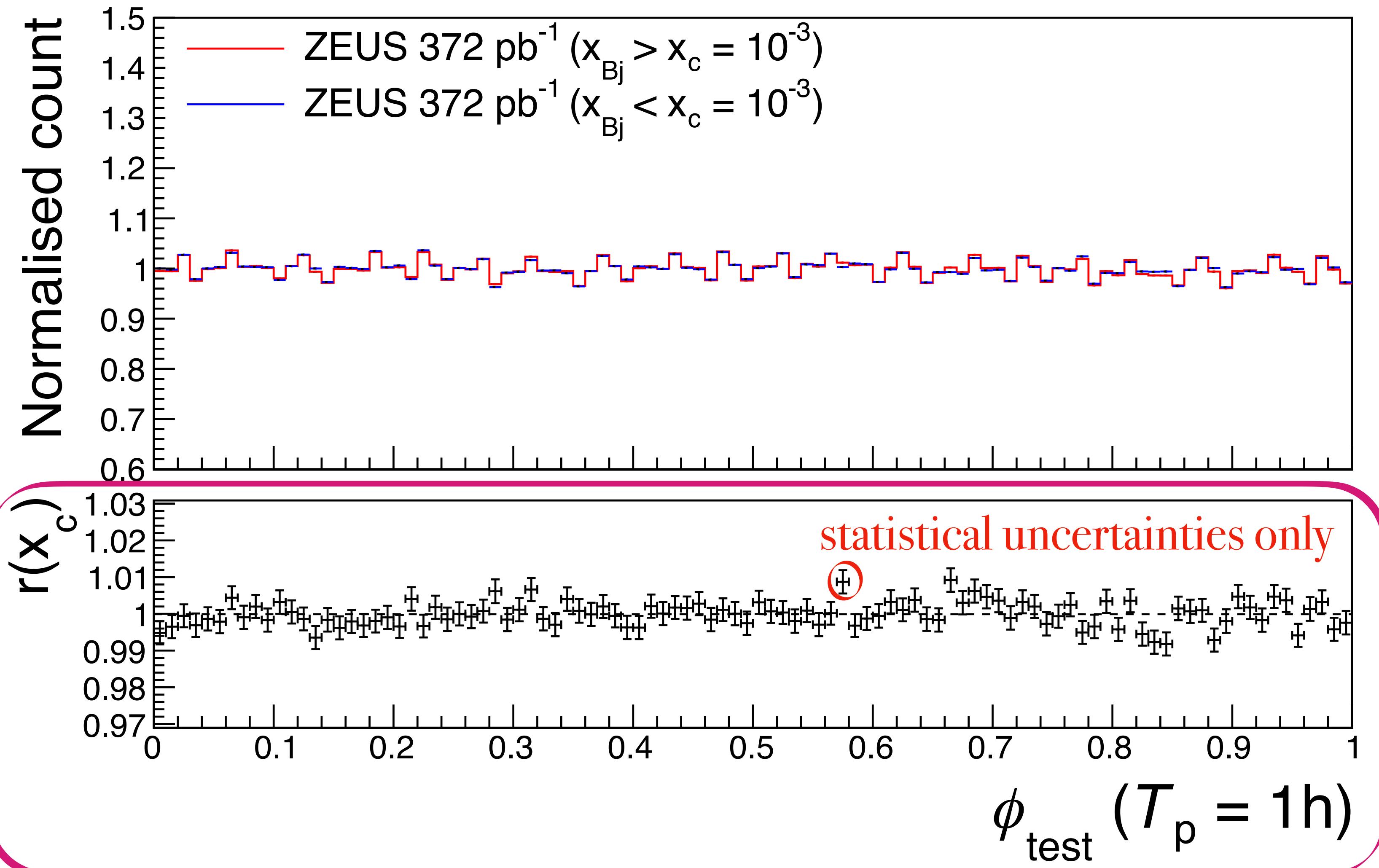
ZEUS



1 hour binning scrambles
everything — all bins expected to
have similar # events (observed)

$(x_{\text{cut}}, T_{\text{test}} = 1 \text{ h})$

ZEUS

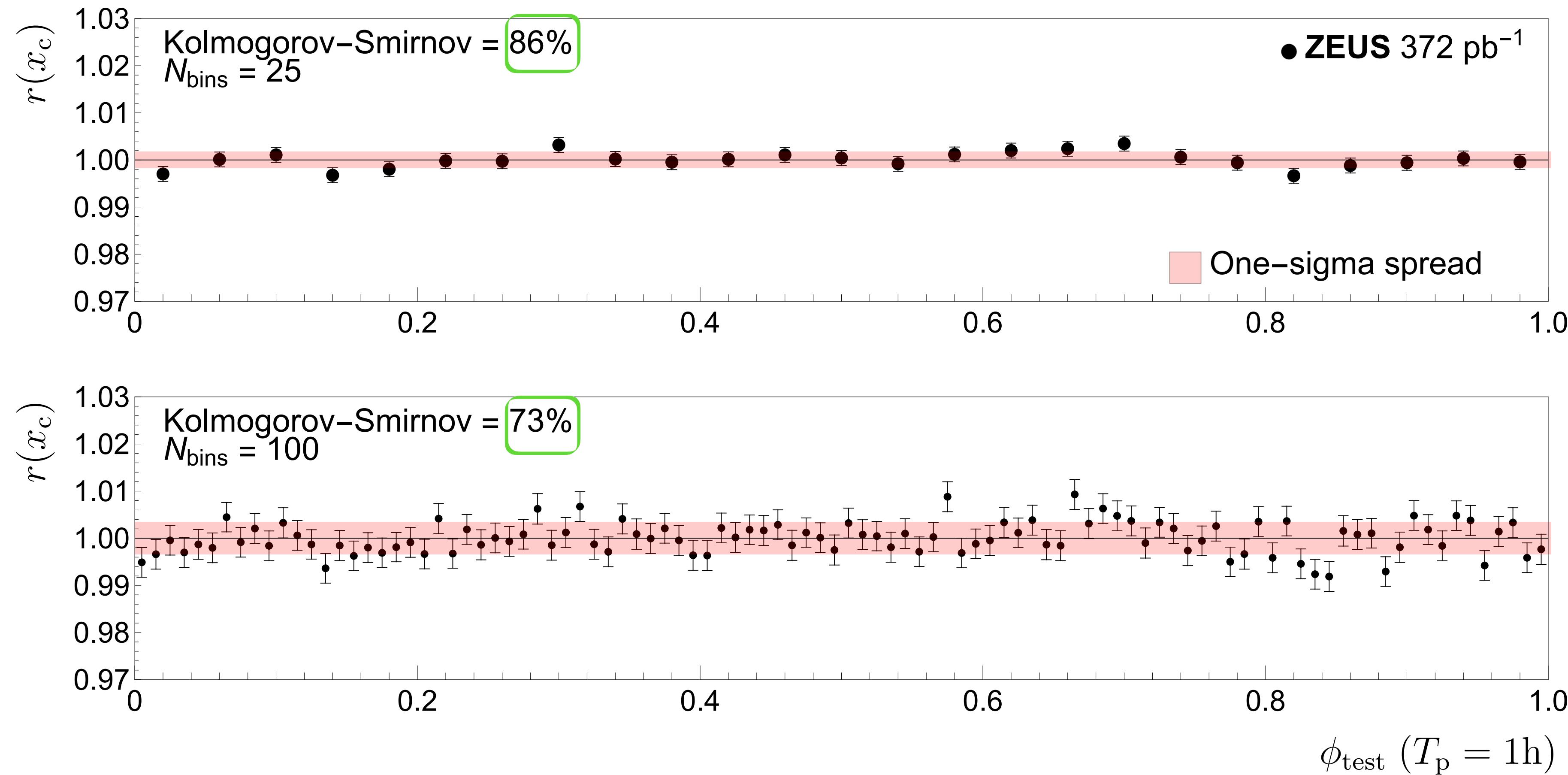


1 hour binning scrambles
everything — all bins expected to
have similar # events (observed)

Most systematics cancel in ratio,
but are any unaccounted for?

$(x_{\text{cut}}, T_{\text{test}} = 1 \text{ h})$: systematics

ZEUS

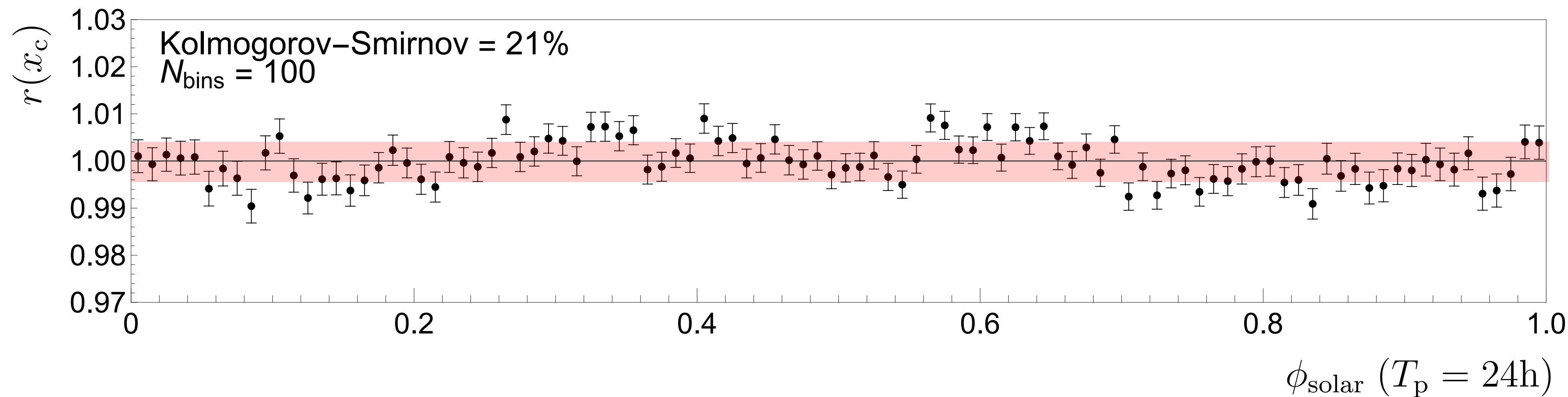
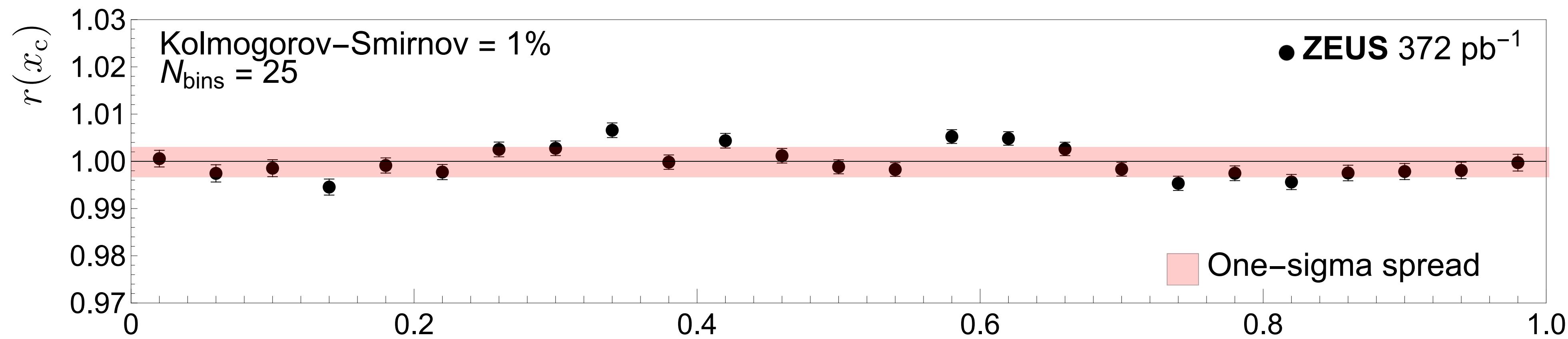


- Small ($\lesssim 5\%$) K-S % suggestive of unaccounted systematics
- Binned distributions show no strong evidence

$$\sigma_{\text{syst}} \approx \sqrt{\sigma^2 - \sigma_{\text{stat}}^2}$$

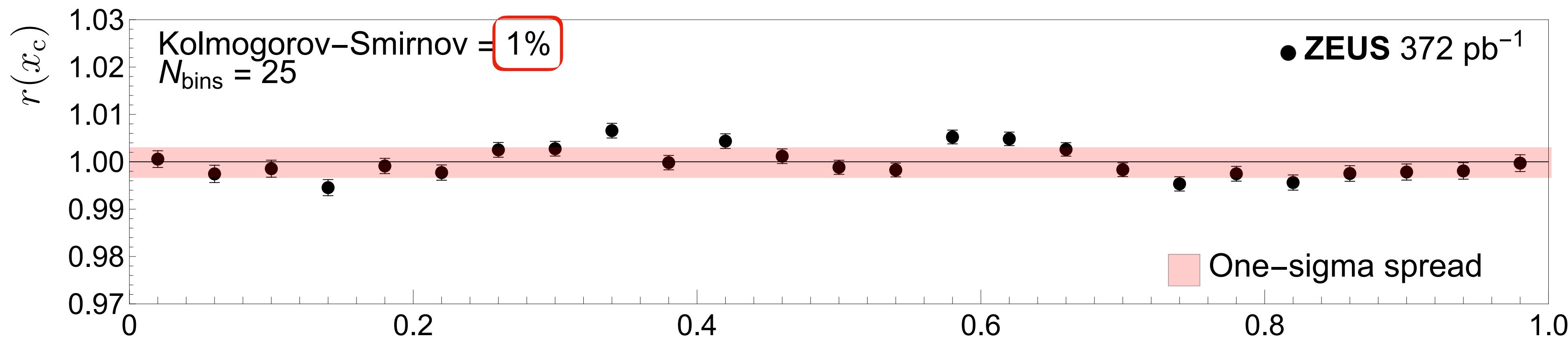
$(x_{\text{cut}}, T_{\text{solar}})$: systematics

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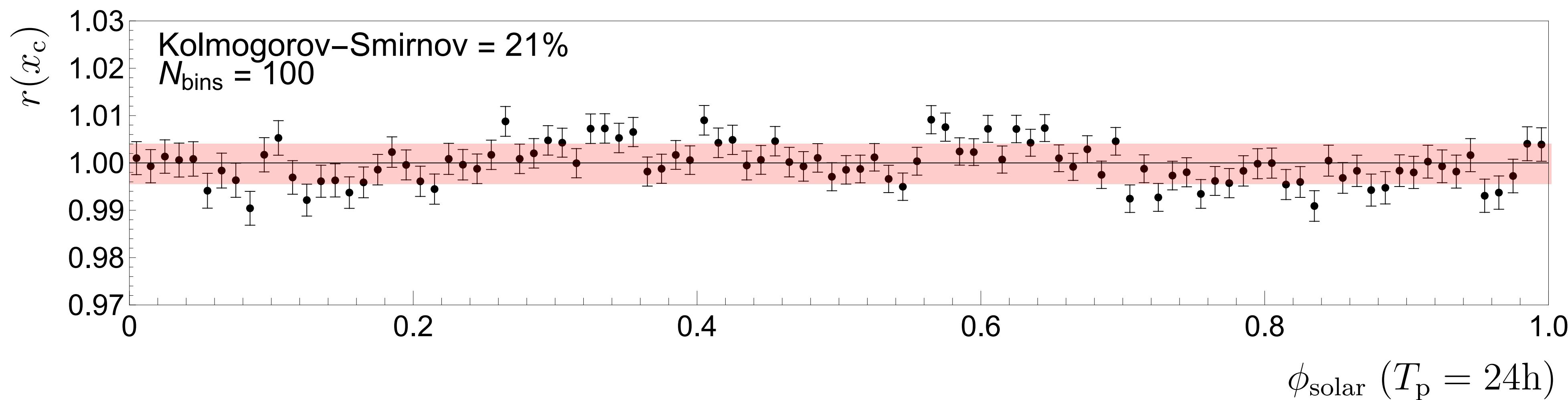


$(x_{\text{cut}}, T_{\text{solar}})$: systematics

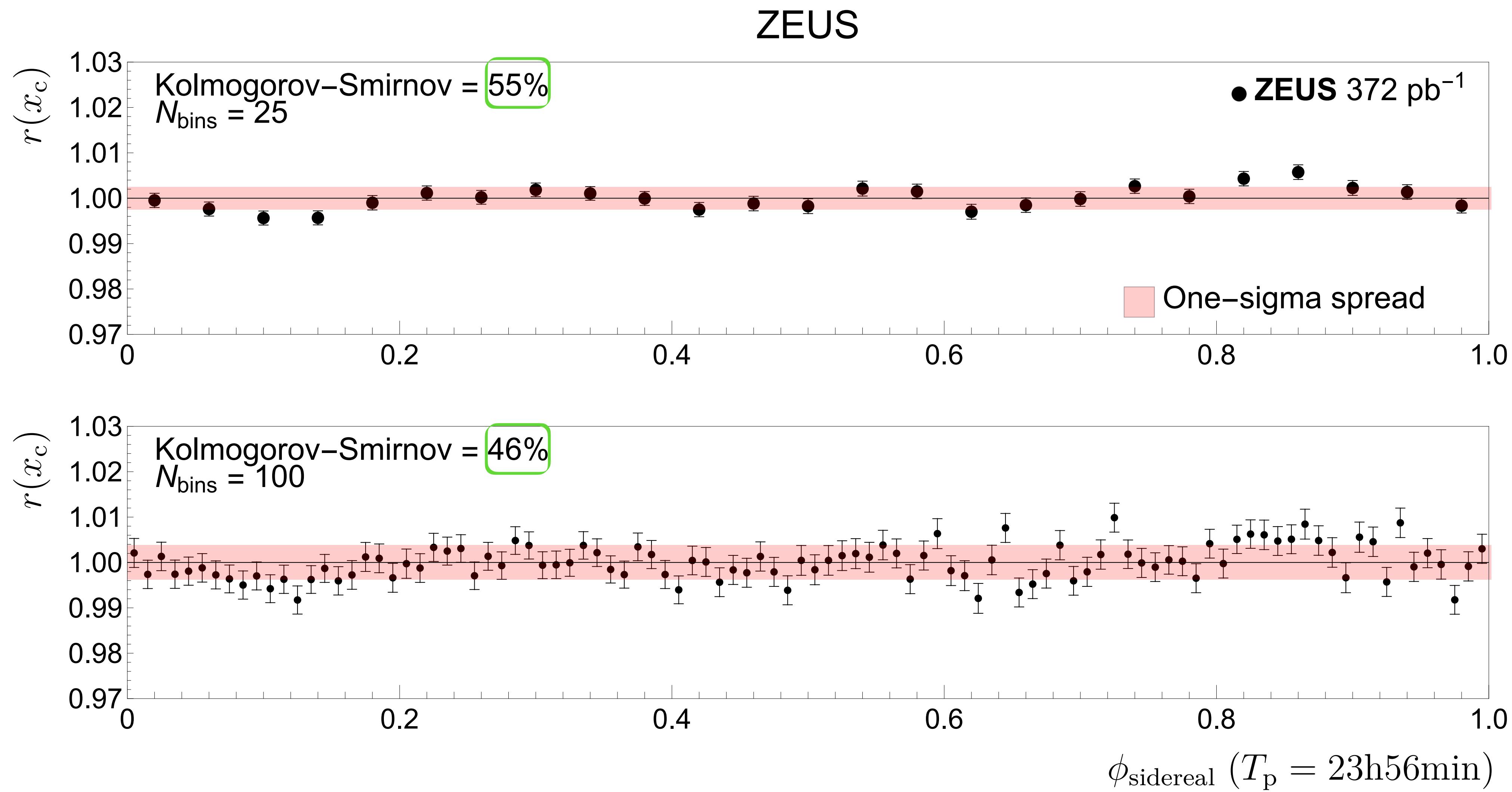
ZEUS



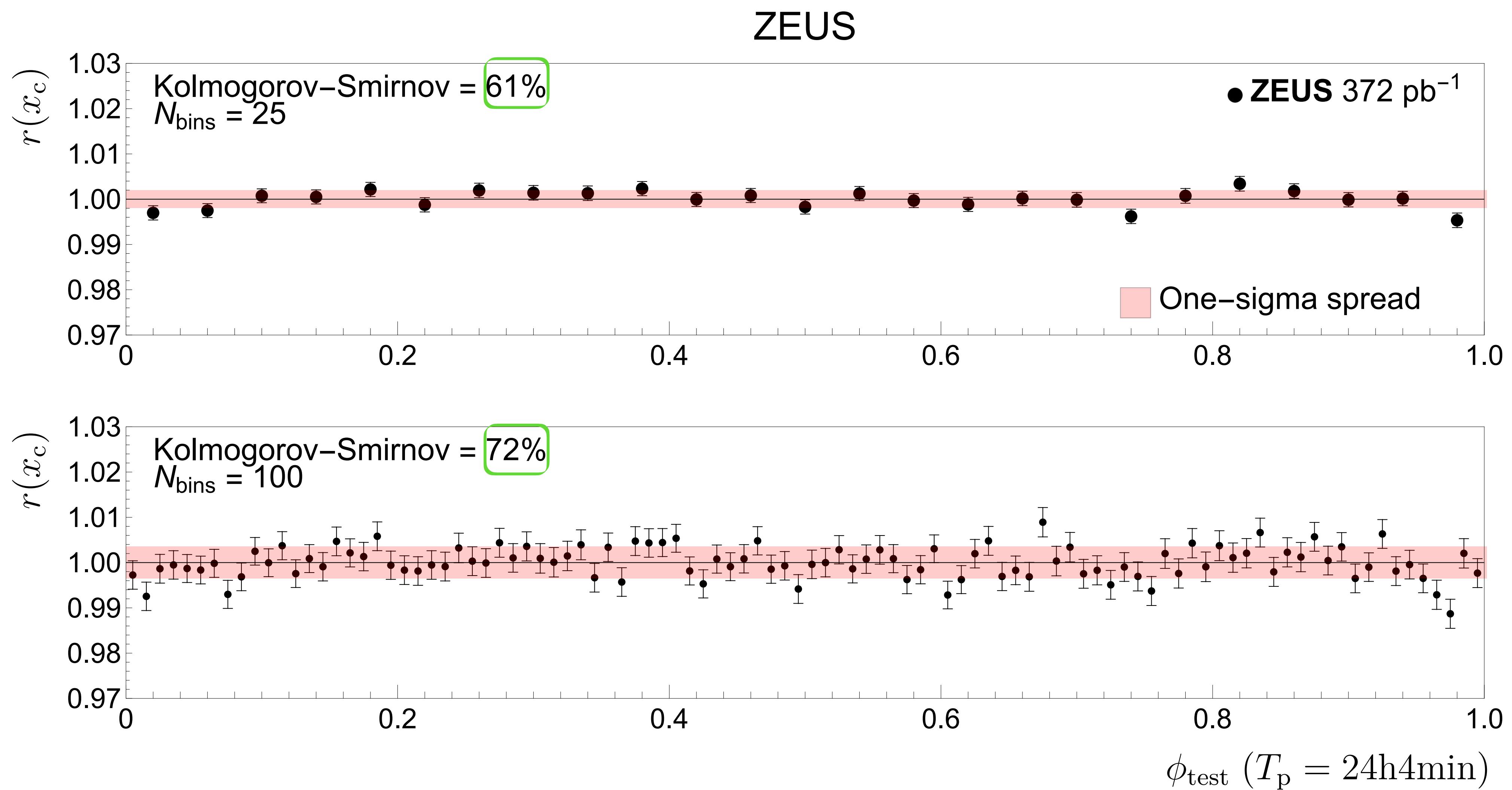
- Also find low K-S % for other bin configurations
 $N_{\text{bins}} = 8, 12, 16, 50$
- Indicates unaccounted for systematics



$(x_{\text{cut}}, T_{\text{sidereal}})$: systematics



$(x_{\text{cut}}, T_{\text{test}} = 24 \text{ h} + 4 \text{ min})$: systematics



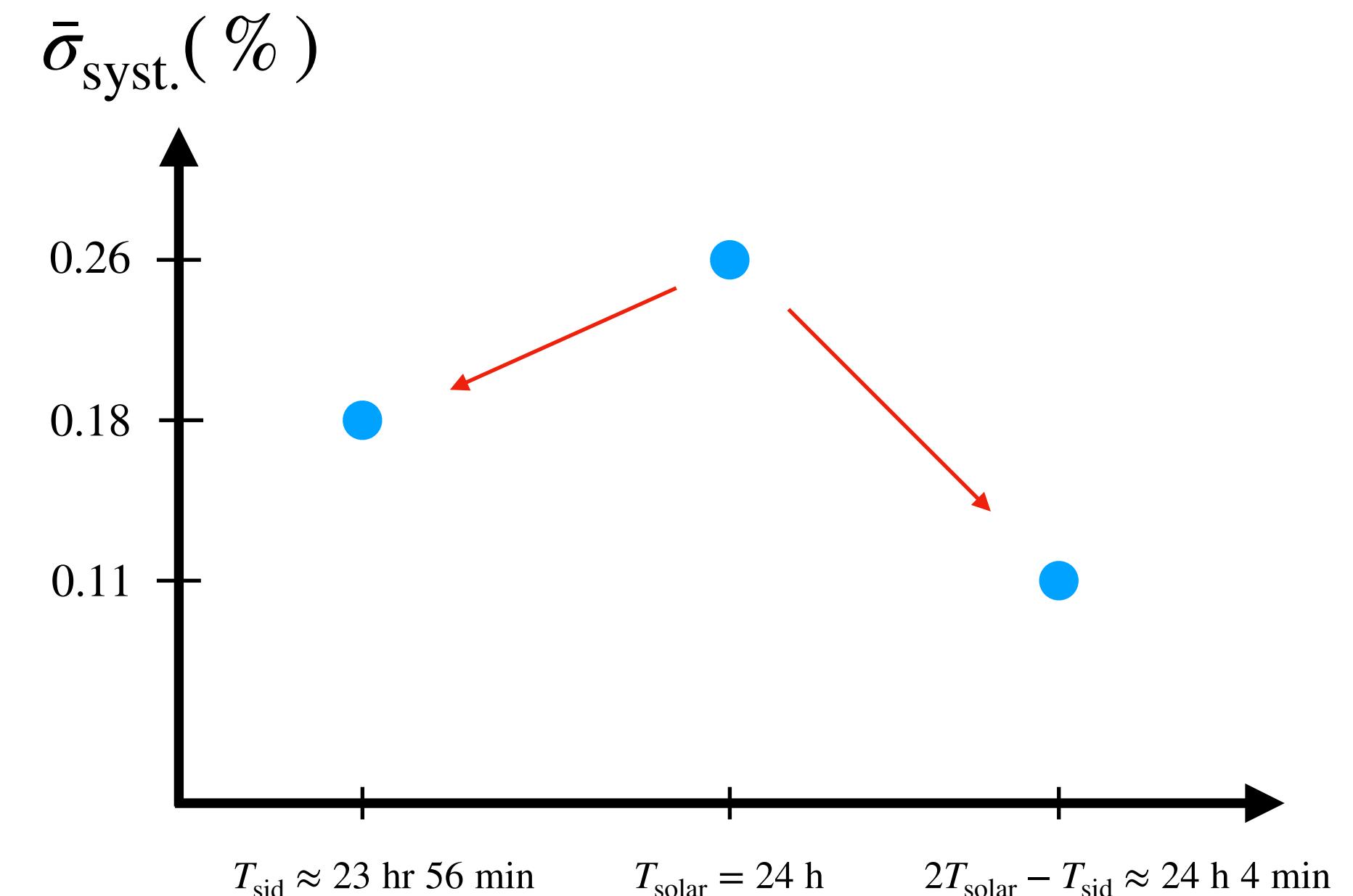
Systematics: summary

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- Unable to verify this conjecture — choose to *conservatively* adopt $\sigma_{\text{syst.}}$ as extracted by $2T_{\text{solar}} - T_{\text{sid}}$ = “solar shifted” phase



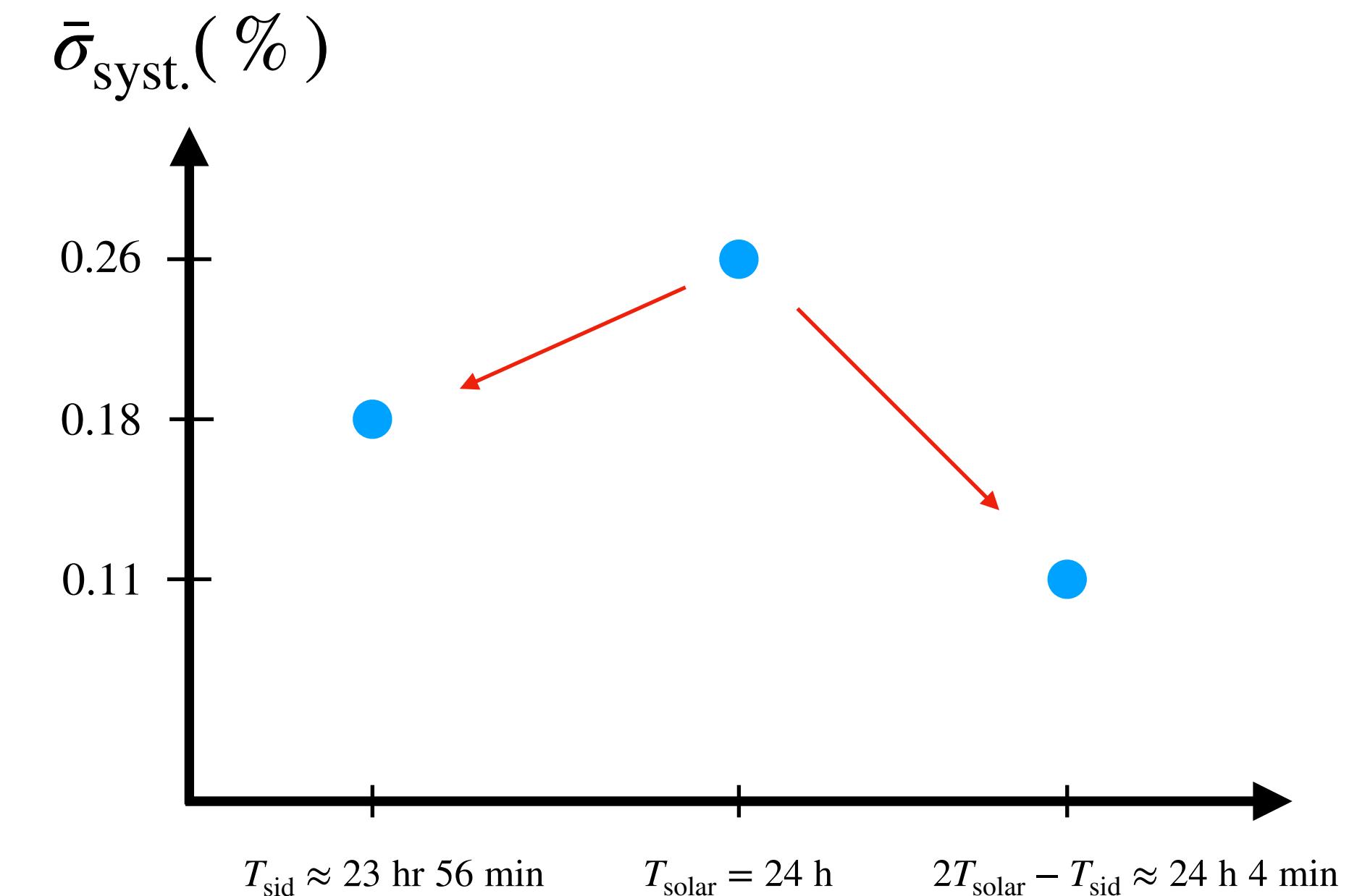
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$$\sigma_{\text{sid}}^{\text{tot}} \approx \sqrt{\bar{\sigma}_{\text{stat}}^{\text{sid}} + \sigma_{\text{syst.}}^{\text{solar shift, } N_{\text{bins}}=100}} = 0.35 \%$$

$$\chi^2 = \frac{1}{(\sigma_{\text{tot}}^{\text{sid}})^2} \sum_{i=1}^{N_{\text{bins}}} \left(r_i^{\text{exp}} - r_i^{\text{theo}} \right)^2 \quad (\chi^2_{\text{SM}} = 113.8, p_{\text{SM}} = 0.16)$$



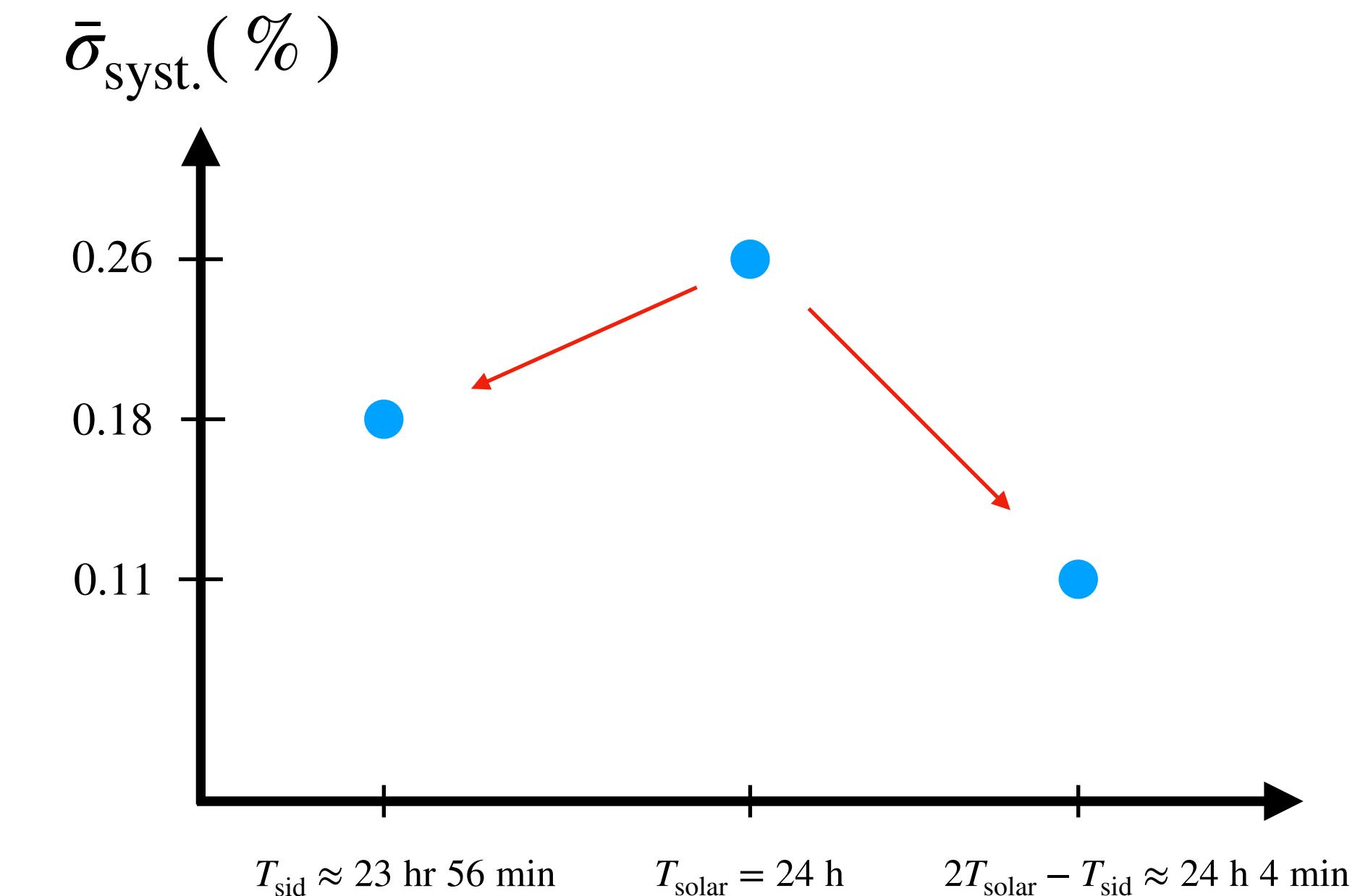
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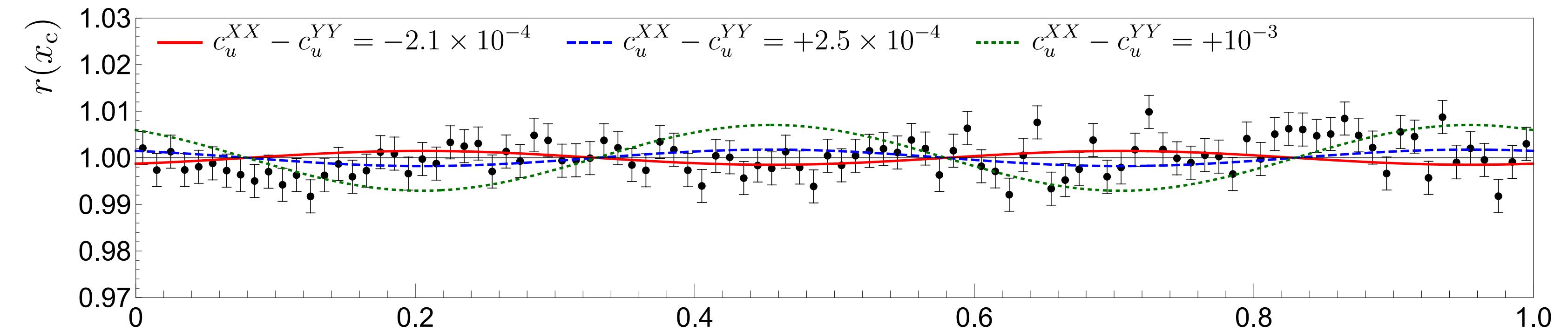
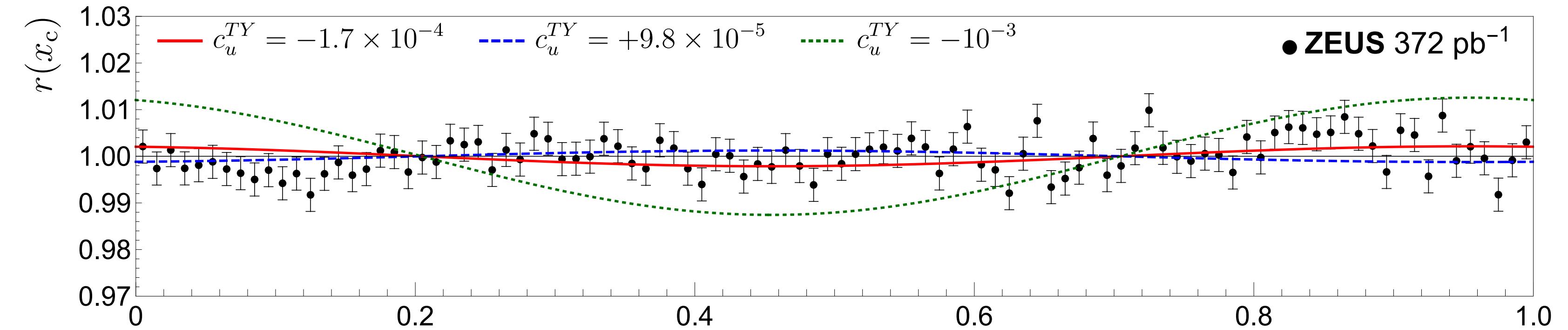
Conservative approach: exclude lower and upper values of LV coefficients that yield $p < 0.05$

Constraints

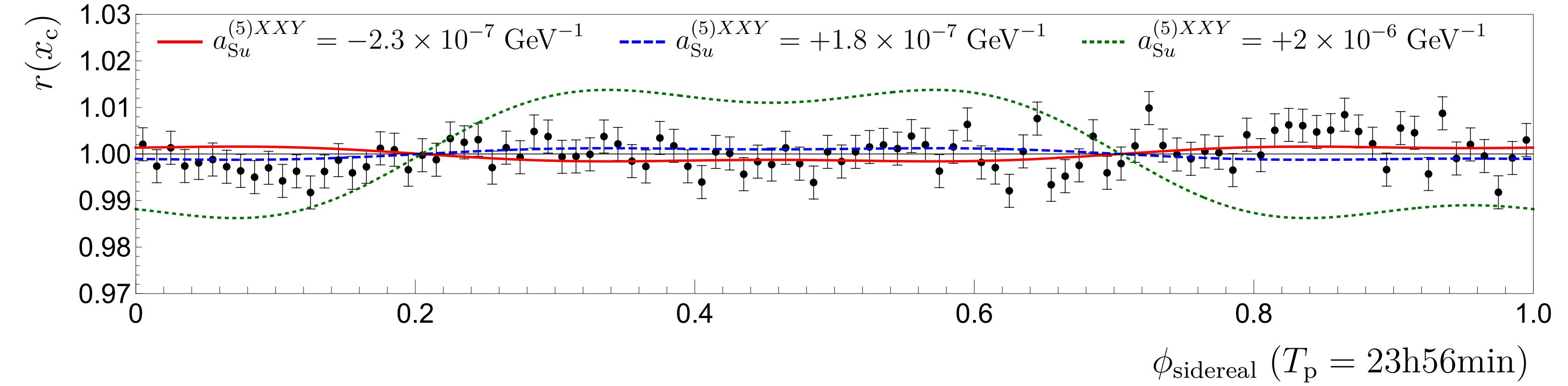
| Coefficient | Lower | Upper |
|-----------------------|-----------------------|----------------------|
| c_u^{TX} | -2.5×10^{-4} | 6.6×10^{-5} |
| c_u^{TY} | -1.7×10^{-4} | 9.8×10^{-5} |
| c_u^{XY} | -3.2×10^{-4} | 4.1×10^{-5} |
| c_u^{XZ} | -5.4×10^{-4} | 1.4×10^{-4} |
| c_u^{YZ} | -3.7×10^{-4} | 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} |

| Coefficient | Lower (GeV^{-1}) | Upper (GeV^{-1}) |
|-------------------------------------|-----------------------------|-----------------------------|
| $a_{Su}^{(5)TXX} - a_{Su}^{(5)TYY}$ | -5.1×10^{-7} | 4.3×10^{-7} |
| $a_{Su}^{(5)XXZ} - a_{Su}^{(5)YYZ}$ | -1.7×10^{-6} | 2.0×10^{-6} |
| $a_{Su}^{(5)TXY}$ | -8.3×10^{-8} | 6.5×10^{-7} |
| $a_{Su}^{(5)TXZ}$ | -2.9×10^{-7} | 1.1×10^{-6} |
| $a_{Su}^{(5)TYZ}$ | -4.3×10^{-7} | 7.4×10^{-7} |
| $a_{Su}^{(5)XXX}$ | -3.9×10^{-7} | 1.2×10^{-7} |
| $a_{Su}^{(5)XXY}$ | -2.3×10^{-7} | 1.8×10^{-7} |
| $a_{Su}^{(5)XYY}$ | -4.6×10^{-7} | 9.2×10^{-8} |
| $a_{Su}^{(5)XYZ}$ | -2.6×10^{-6} | 3.3×10^{-7} |
| $a_{Su}^{(5)XZZ}$ | -5.4×10^{-7} | 1.4×10^{-7} |
| $a_{Su}^{(5)YYY}$ | -2.9×10^{-7} | 1.5×10^{-7} |
| $a_{Su}^{(5)YZZ}$ | -3.6×10^{-7} | 2.1×10^{-7} |
| $a_{Sd}^{(5)TXX} - a_{Sd}^{(5)TYY}$ | -7.3×10^{-6} | 6.1×10^{-6} |
| $a_{Sd}^{(5)XXZ} - a_{Sd}^{(5)YYZ}$ | -2.4×10^{-5} | 2.8×10^{-5} |
| $a_{Sd}^{(5)TXY}$ | -1.2×10^{-6} | 9.4×10^{-6} |
| $a_{Sd}^{(5)TXZ}$ | -4.1×10^{-6} | 1.6×10^{-5} |
| $a_{Sd}^{(5)TYZ}$ | -6.1×10^{-6} | 1.1×10^{-5} |
| $a_{Sd}^{(5)XXX}$ | -5.7×10^{-6} | 1.7×10^{-6} |
| $a_{Sd}^{(5)XXY}$ | -3.4×10^{-6} | 2.7×10^{-6} |
| $a_{Sd}^{(5)XYY}$ | -6.8×10^{-6} | 1.3×10^{-6} |
| $a_{Sd}^{(5)XYZ}$ | -3.7×10^{-5} | 4.6×10^{-6} |
| $a_{Sd}^{(5)XZZ}$ | -8.1×10^{-6} | 2.1×10^{-6} |
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| $a_{Sd}^{(5)YZZ}$ | -5.4×10^{-6} | 3.1×10^{-6} |

ZEUS



$= p = 0.05$ “boundary values”
 $=$
 $=$ excluded value



Take-home messages

ZEUS analysis (quark sector) couplings

- 5 years of DIS data binned, no evidence of significant sidereal effect
- First constraints on several light-quark coefficients

Excellent future prospects

- ZEUS II?
- ATLAS: Run-II, spin-dependent constraints from Drell-Yan

