

# Constraints on Lorentz and CPT violation in the quark sector using ZEUS data

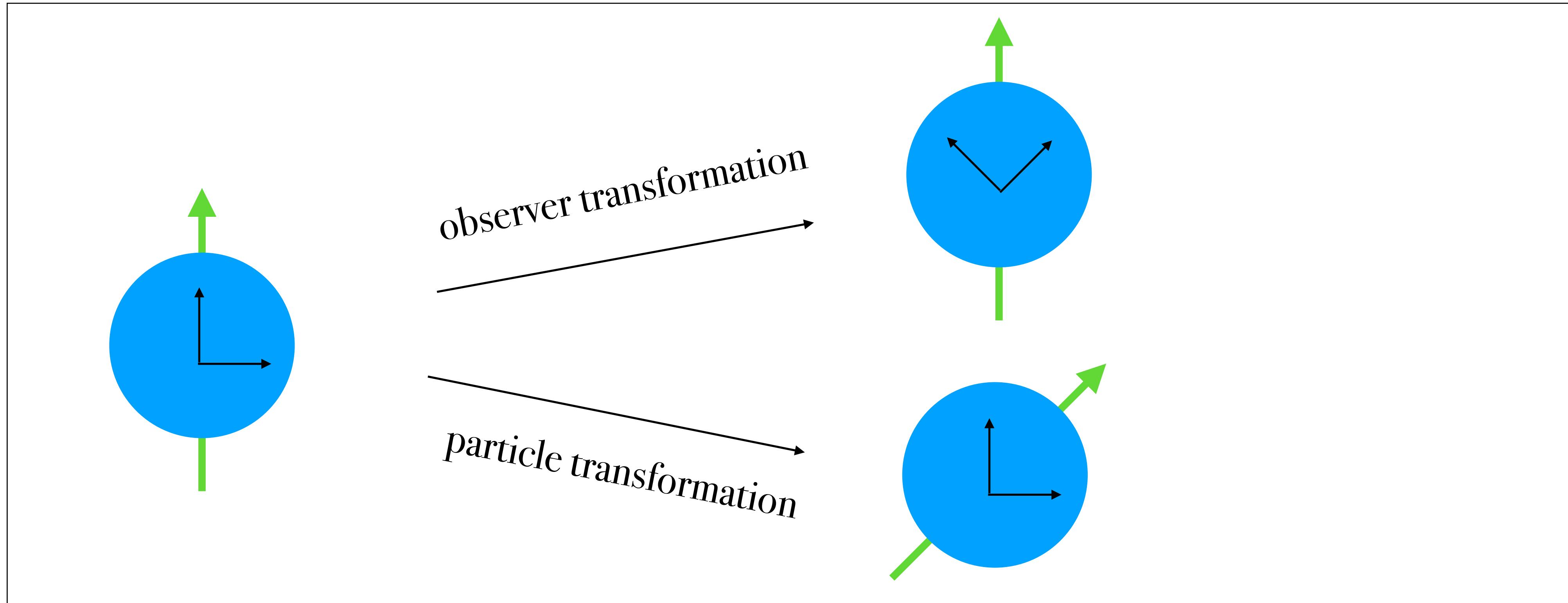
Nathaniel Sherrill  
University of Sussex

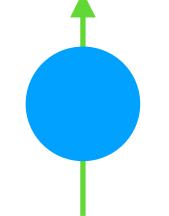
On behalf of the ZEUS Collaboration

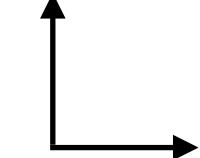
ICHEP 2022 Bologna

# Basic concepts

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

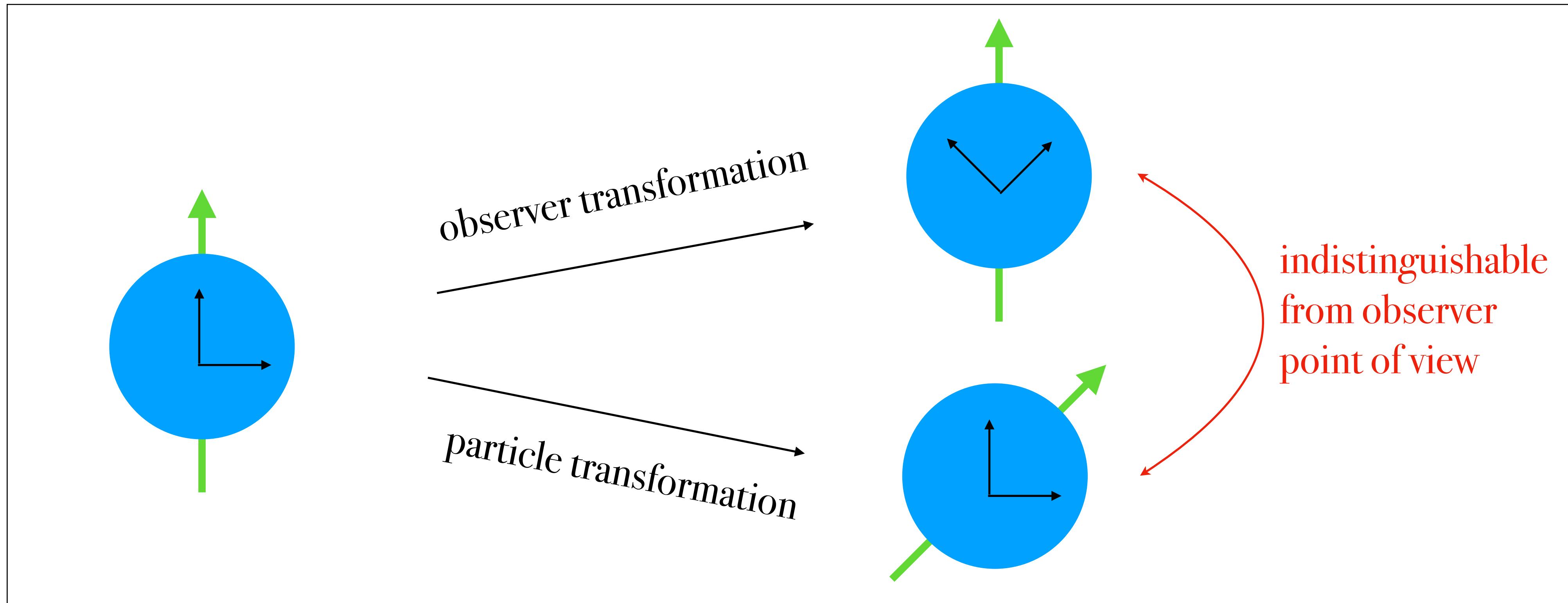


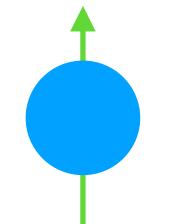
 = particle/system

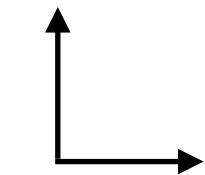
 = coordinates/observer

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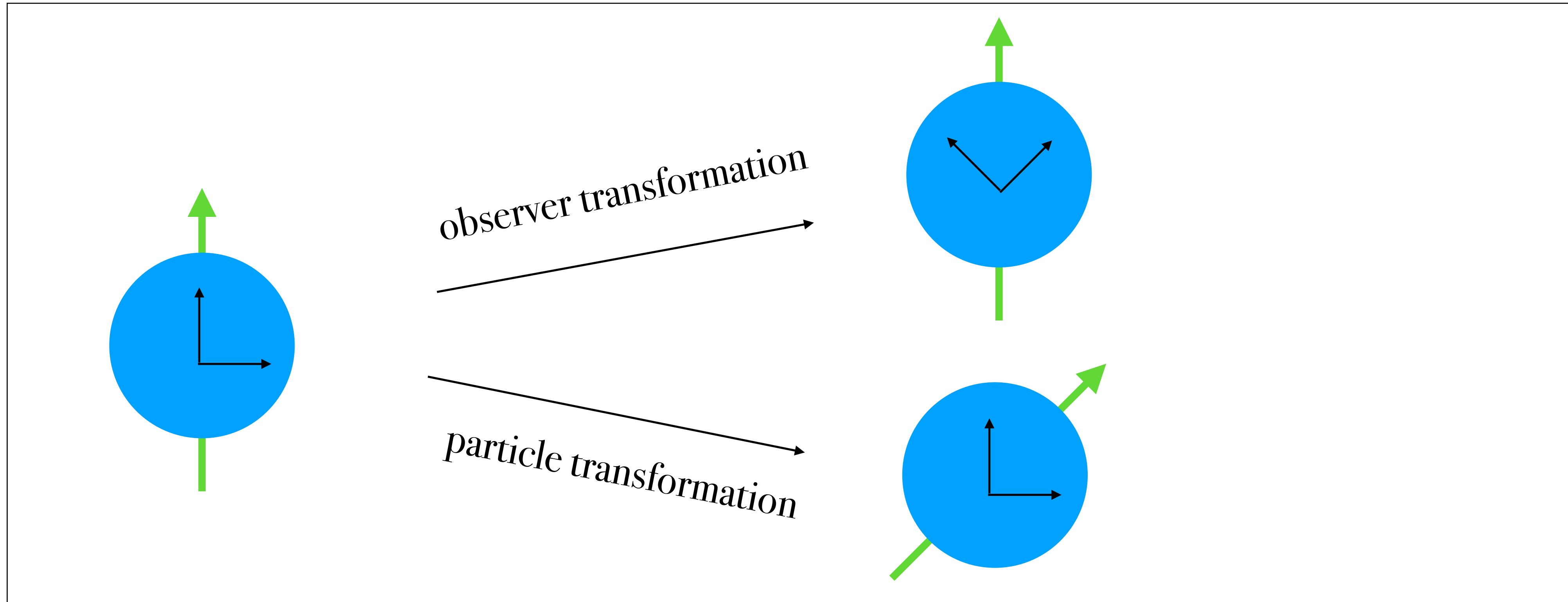


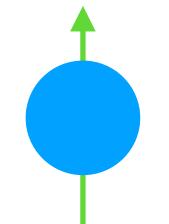
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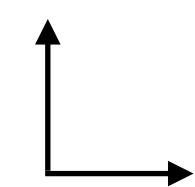
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# Basic concepts

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

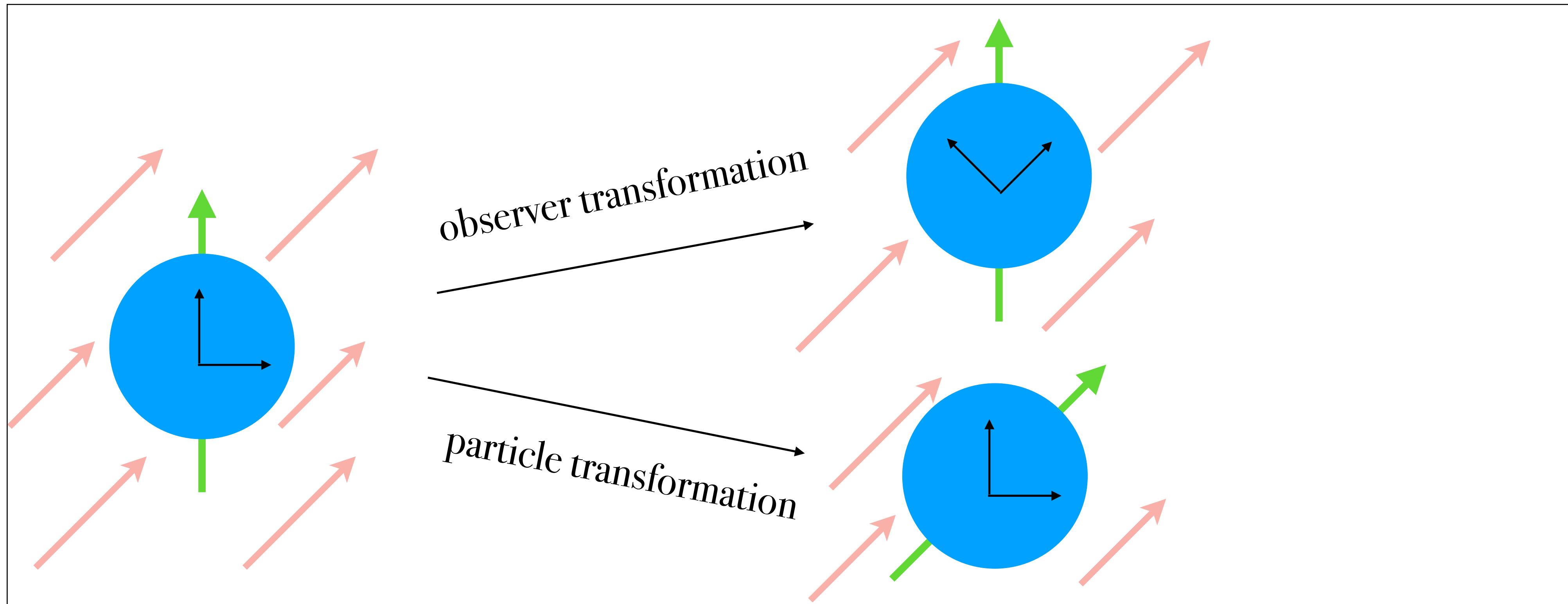


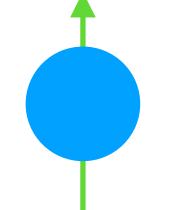
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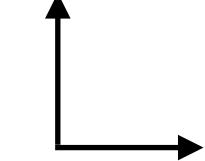
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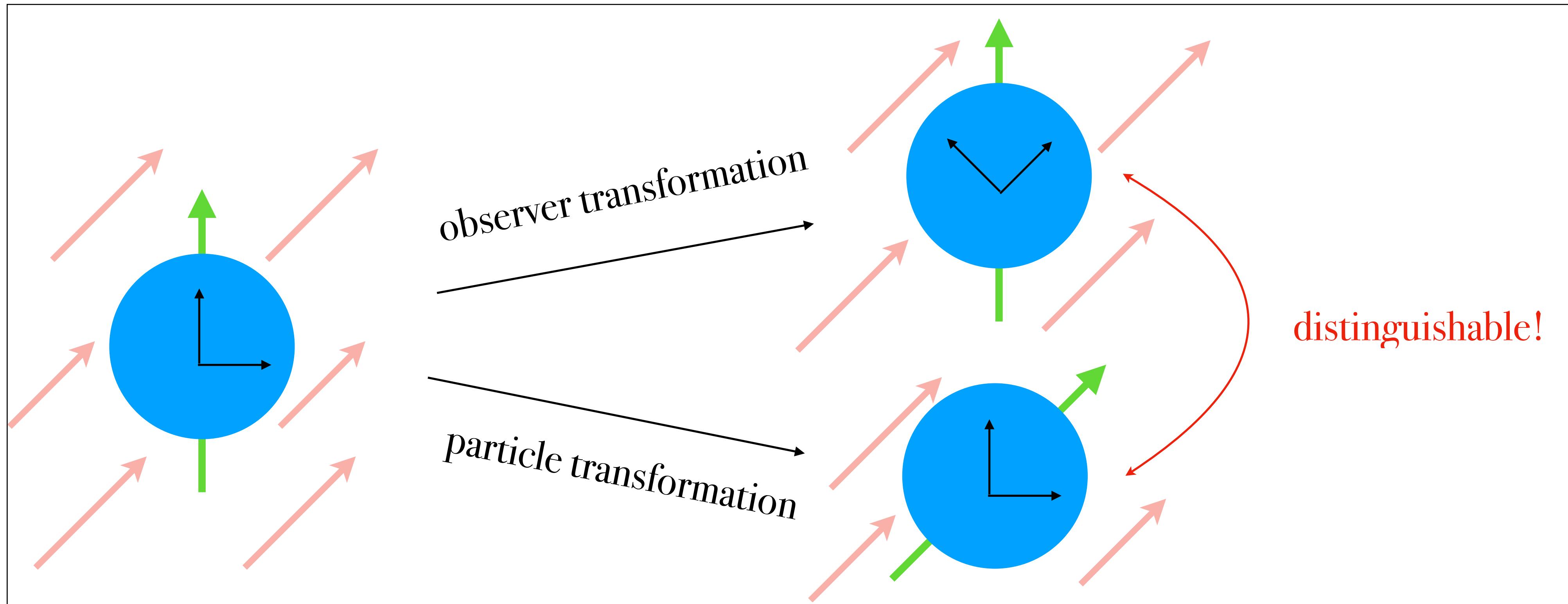
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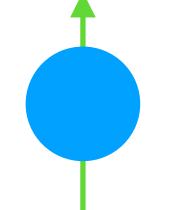
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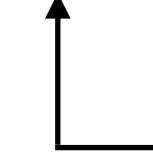
 = Lorentz-violating background fields

# Basic concepts

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



 = particle/system

 = coordinates/observer

 = Lorentz-violating background fields

# Quark-sector effects in DIS

- ◆ Lorentz- and CPT-violating effects are generically parametrized in a framework known as the Standard-Model Extension (SME)
- ◆ Quark-sector effects are largely unstudied

D. Colladay, V. A. Kostelecký, PRD **55**, 6760 (1997); PRD **58**, 116002 (1998)

V. A. Kostelecký, E. Lunghi, A. Vieira, PLB **769**, 272 (2017)

E. Lunghi, NS, PRD **98**, 115018 (2018)

V. A. Kostelecký, E. Lunghi, NS, A. Vieira, JHEP **04** (2020) 143

$$\delta\mathcal{L}_{\text{LV}} \supset \sum_{f=u,d,\dots} \bar{\psi}_f (\eta^{\mu\nu} + \color{red}c_f^{\mu\nu}) i\gamma_\mu \overset{\leftrightarrow}{D}_\nu \psi_f - \frac{1}{2} \color{red}a_f^{(5)\mu\alpha\beta} \bar{\psi}_f \gamma_\mu iD_{(\alpha} iD_{\beta)} \psi_f$$

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CPT even, 6 time-dependent observable combinations per flavor



CPT odd, 12 time-dependent observable combinations per flavor

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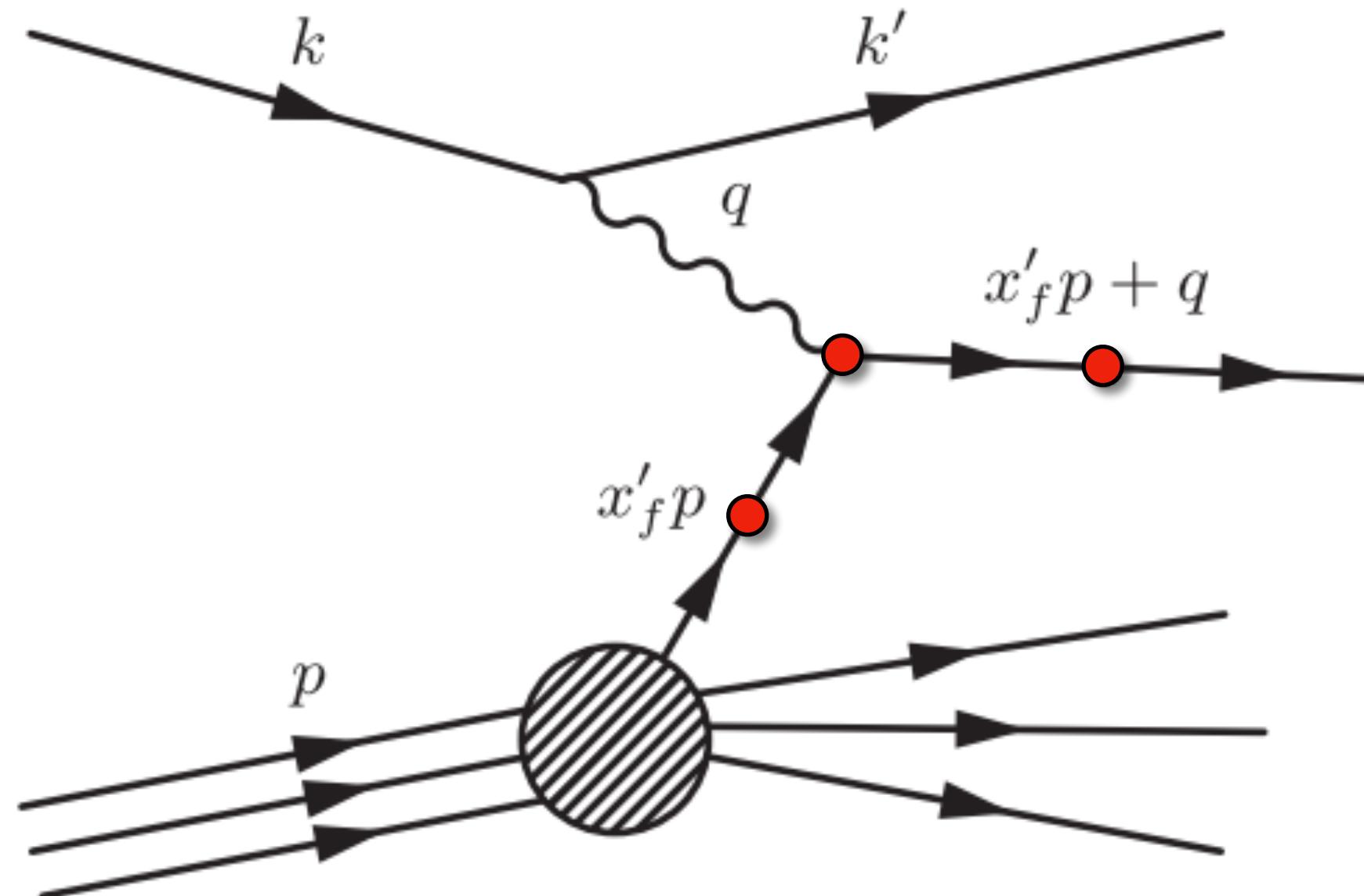
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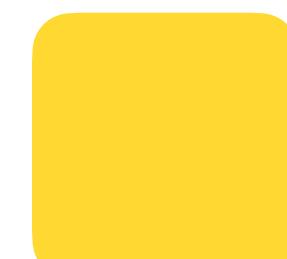
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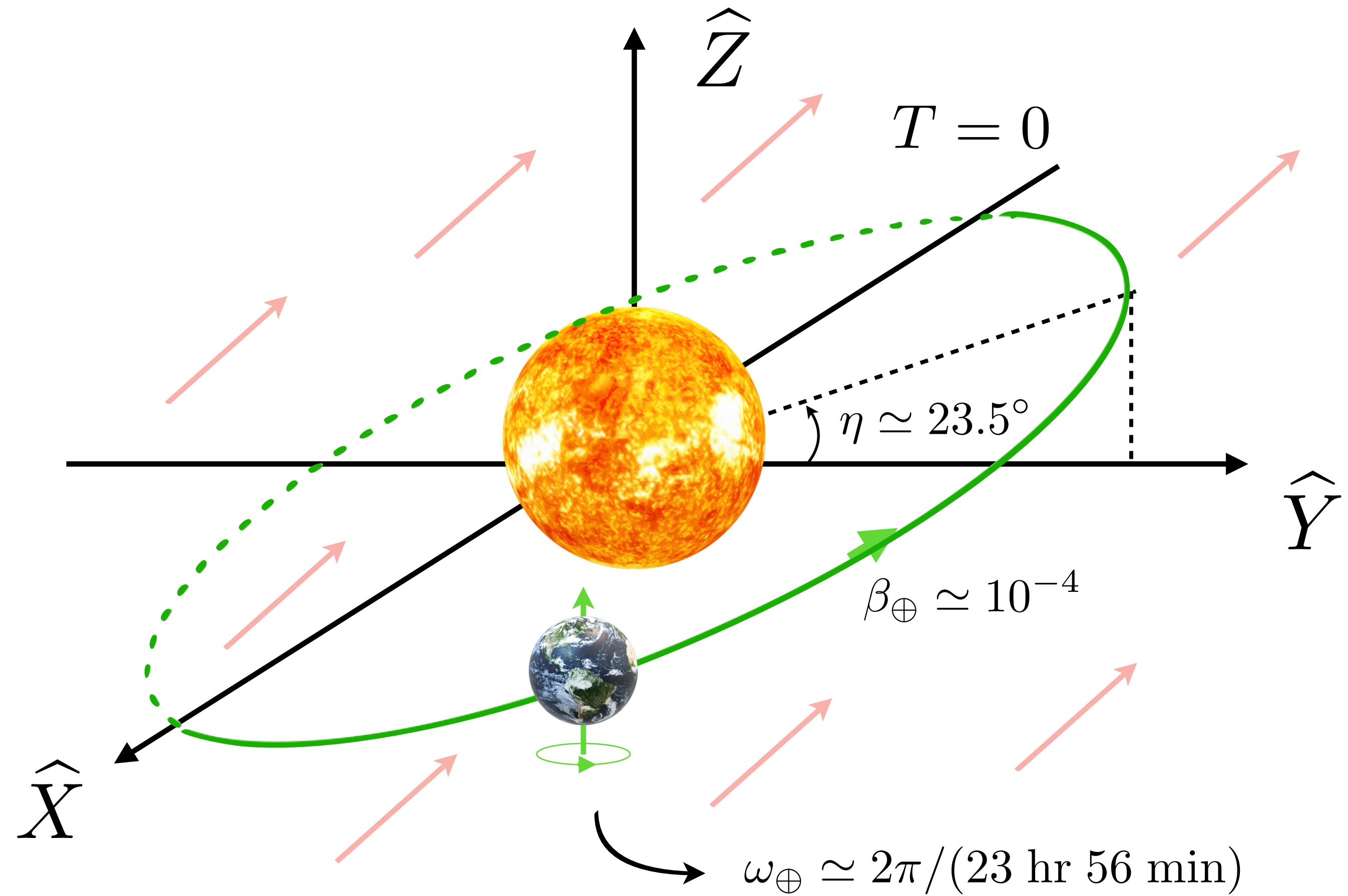
- Modified quark propagation and interaction

- Cross sections for DIS calculated at LO in LV

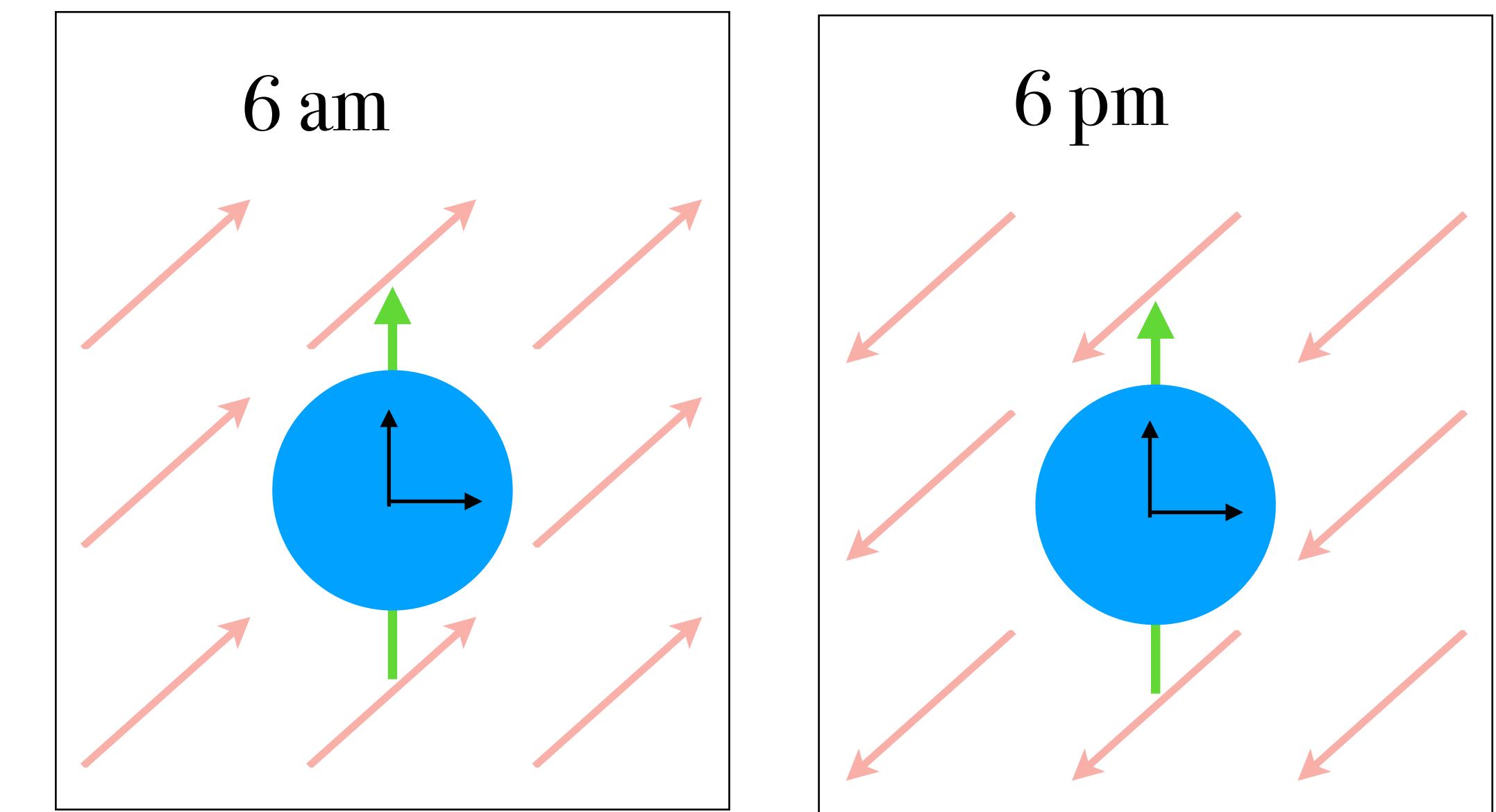
# Sidereal oscillations

- Inertial Sun-centered frame (SCF) introduced to place constraints

R. Bluhm, V. A. Kostelecký, C. D. Lane, N. Russell, PRD **68**, 125008 (2003); PRL **88**, 090801 (2002);  
V. A. Kostelecký and M. Mewes, PRD **66**, 056005 (2002)



Lab-frame perspective



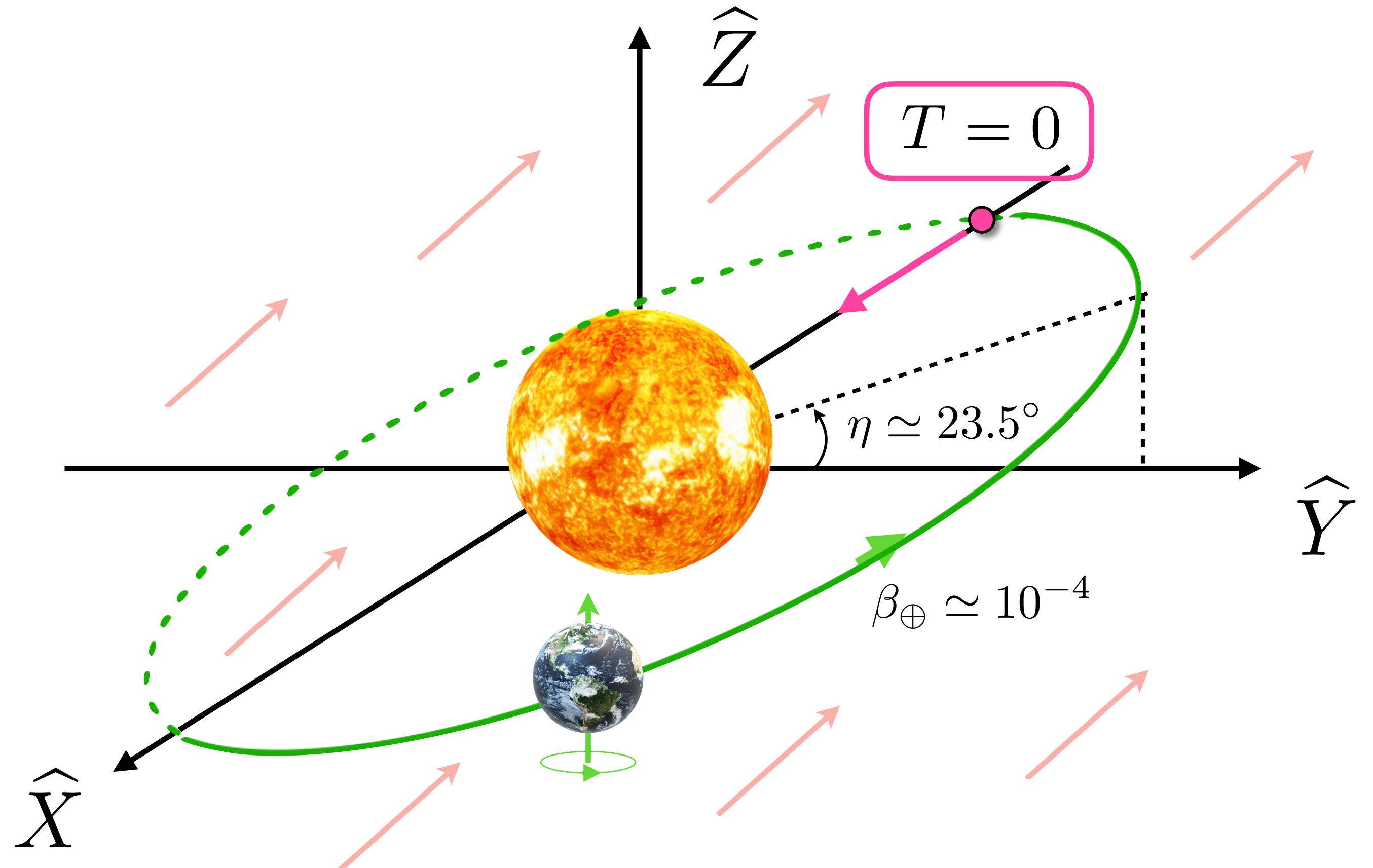
- Reexpress laboratory coeffs. in terms of fixed SCF coeffs.

$$\Rightarrow$$

$$c_{\text{lab}}^{\mu\nu} = \Lambda^\mu{}_\alpha \Lambda^\nu{}_\beta c_{\text{SCF}}^{\alpha\beta}$$

# Sidereal oscillations

- Time origin identified with 2000 vernal equinox: 7:35 am UTC 20/03/2000



V. A. Kostelecký, A. C. Melissinos, and M. Mewes, PLB 761, 1 (2016)  
Y. Ding, V. A. Kostelecký PRD **94**, 056008 (2016)

$$T - T_{\oplus} = \frac{2\pi}{\omega_{\oplus}} \frac{\lambda_0 - \lambda}{360^\circ} \simeq 3.75 \text{ hrs}$$

$T$  = SCF time coordinate

$T_{\oplus}$  = laboratory local sidereal time

$$\frac{2\pi}{\omega_{\oplus}} = 23 \text{ hrs } 56 \text{ mins } 4.091 \text{ secs}$$

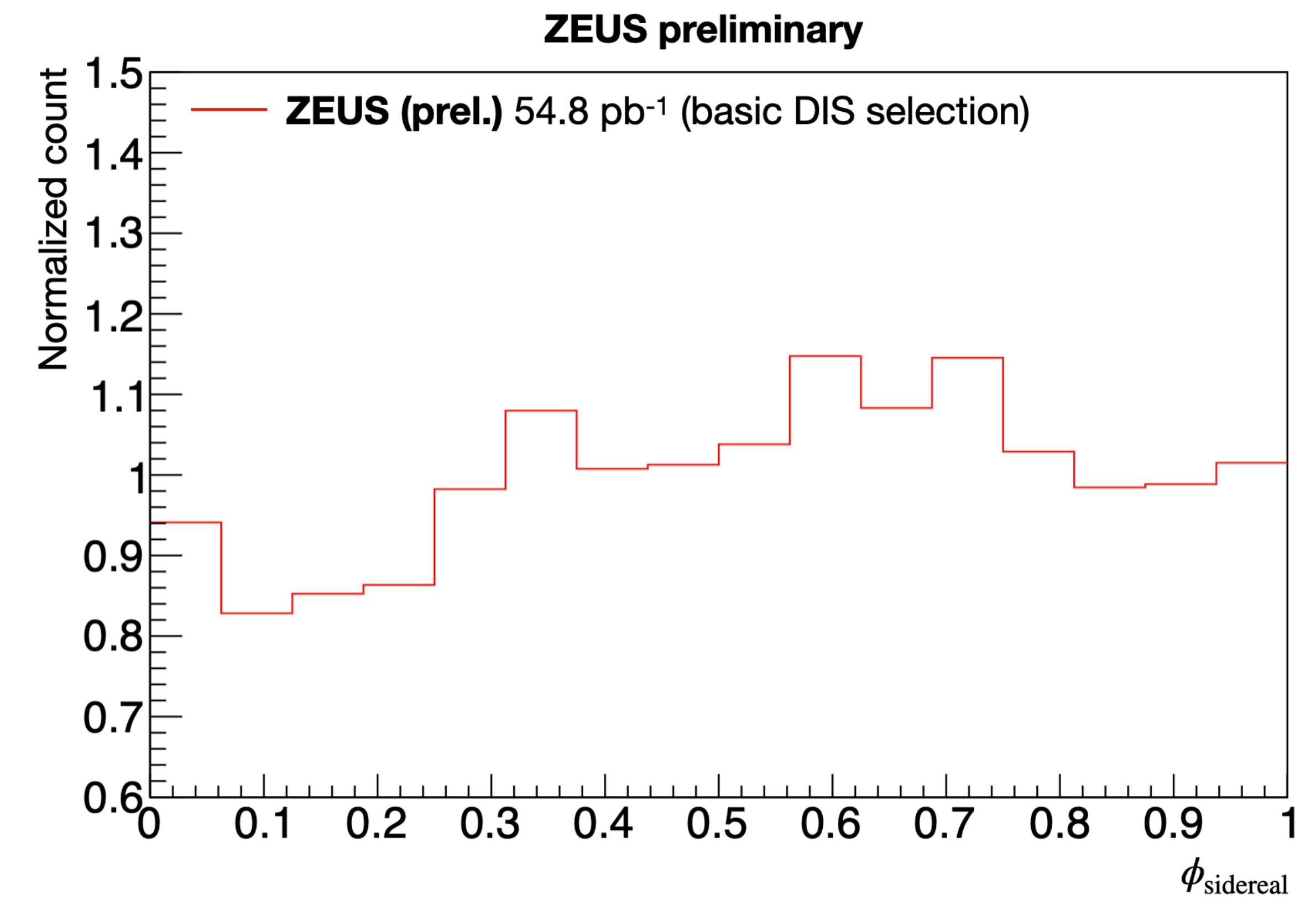
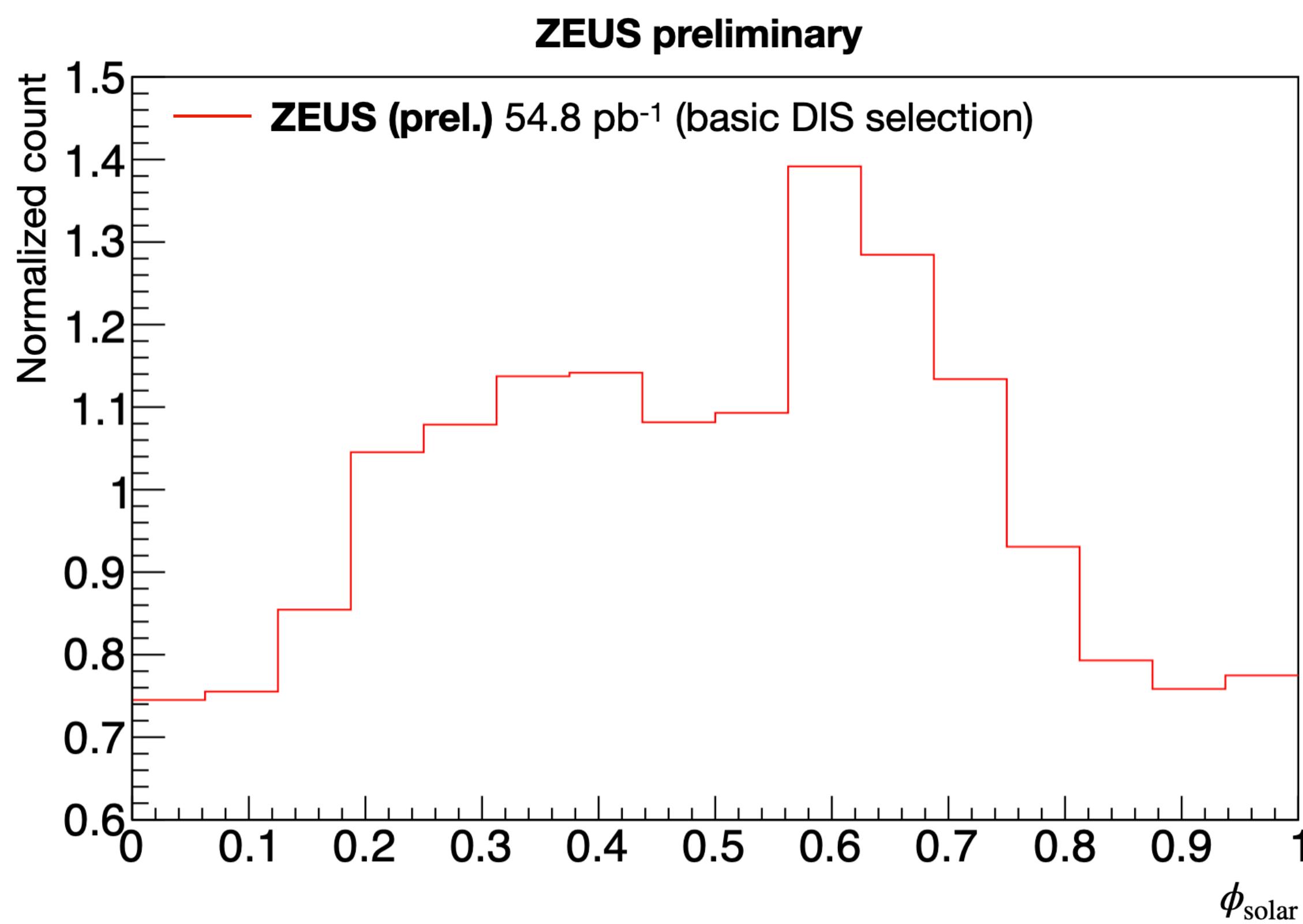
$$\lambda_0 = 66.25^\circ$$

$$\lambda = 9.88^\circ (\text{DESY})$$

$$\Rightarrow T_{\oplus}|_{\text{DESY}} = 0 = 11:20 \text{ am UTC} = 12:20 \text{ pm CET}$$

# ZEUS DIS events

- Roughly 7 million DIS selected events from ZEUS 2006 data analyzed  $E_e = 27.5 \text{ GeV}, E_p = 920 \text{ GeV}$

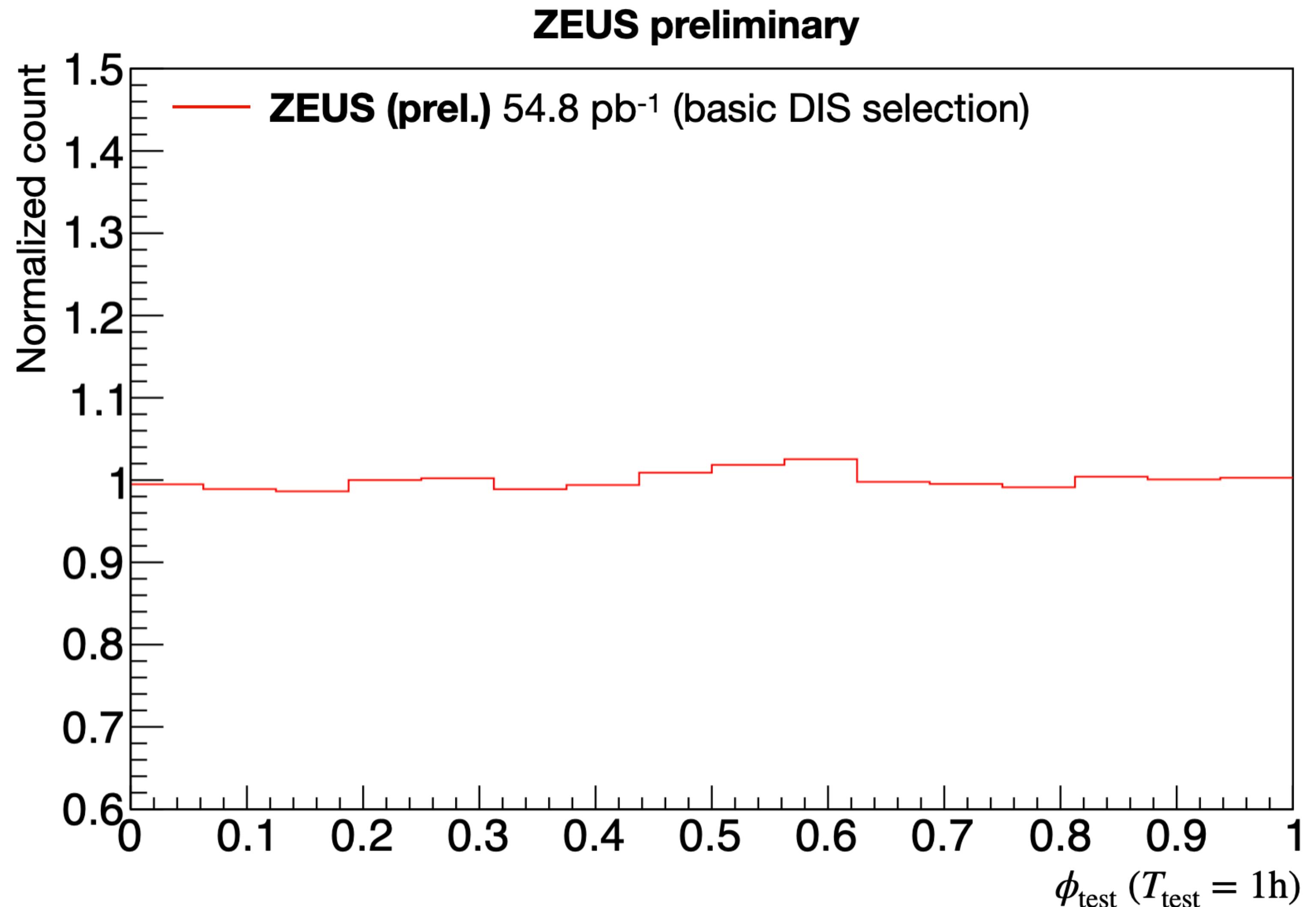


- Strong solar variation due to beam luminosity not completely eliminated with sidereal binning

$$\phi_T = \text{Mod}(T_\oplus, T)/T$$

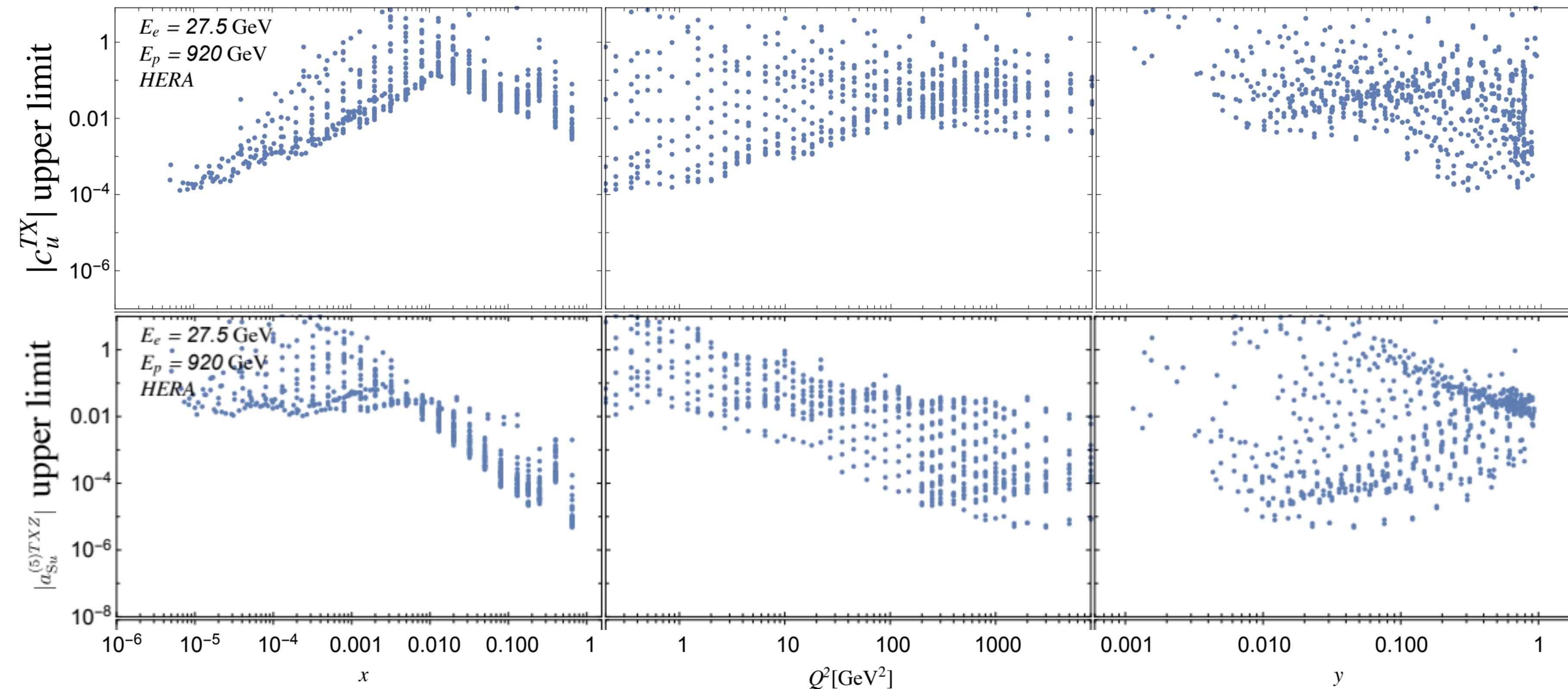
# ZEUS DIS events

- ◆ Several years of data not available to observe expected flattening of distribution from homogeneous sampling of luminosity
- ◆ Instead, can *test* this expectation by shrinking the binning interval
- ◆ A one-hour test interval, which contains no physical significance, produces a nearly flat distribution



# Bypassing the luminosity

- ◆ Instantaneous luminosity info. could be used to eliminate this source of time dependence (not available!); instead note LV effects sensitive to DIS kinematics



- ◆ Consider *ratio* of sidereal distributions at different  $(x, Q^2)$

◆ Loss of statistics  
◆ Luminosity uncertainties cancel

# Bypassing the luminosity

- In the analysis we consider the ratios with

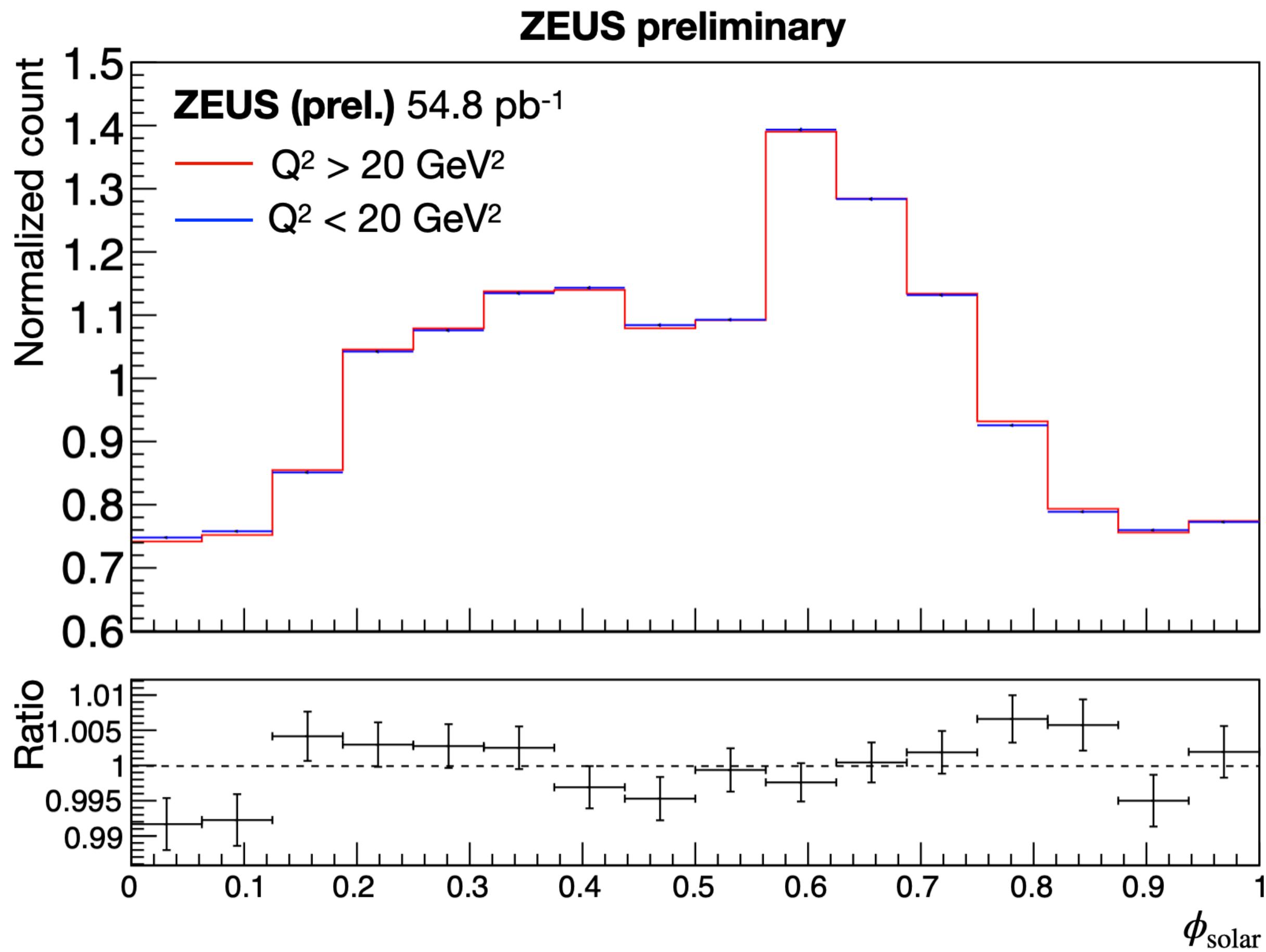
$$r(\text{PS}_1, \text{PS}_2) = \frac{\int_{\text{PS}_1} dx dQ \frac{d\sigma(e^- p \rightarrow e^- X)}{dQ dx d\phi_T}}{\int_{\text{PS}_1} dx dQ d\phi_T \frac{d\sigma(e^- p \rightarrow e^- X)}{dQ dx d\phi_T}} / \frac{\int_{\text{PS}_2} dx dQ \frac{d\sigma(e^- p \rightarrow e^- X)}{dQ dx d\phi_T}}{\int_{\text{PS}_2} dx dQ d\phi_T \frac{d\sigma(e^- p \rightarrow e^- X)}{dQ dx d\phi_T}}$$

- PS<sub>1,2</sub> are particular slices of phase space, e.g. PS<sub>1</sub> = Q<sup>2</sup> > Q<sub>cut</sub><sup>2</sup> and PS<sub>2</sub> = Q<sup>2</sup> < Q<sub>cut</sub><sup>2</sup>

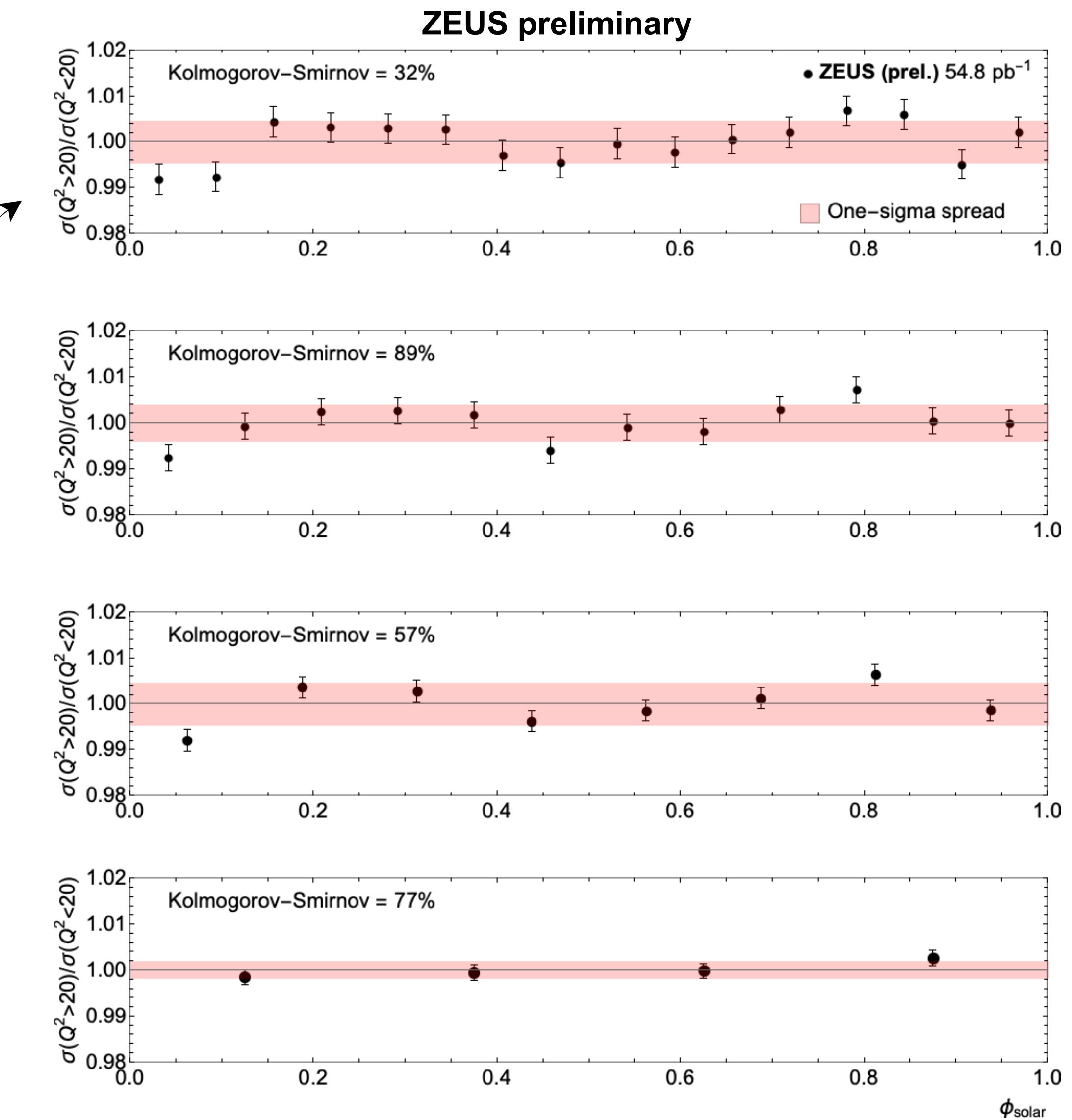
- Choice cuts:  
 $Q_{\text{cut}}^2 = 20 \text{ GeV}^2 \xrightarrow{\text{negligible sensitivity to LV}} \Rightarrow \text{control study}$   
 $x_{\text{cut}} = (5 \times 10^{-4}, 10^{-3}) \xrightarrow{\text{strong sensitivity for}} (c_{u,d}^{\mu\nu}, a_{u,d}^{(5)\lambda\mu\nu})$

- Three binning scenarios:  $T = (T_{\text{solar}}, T_{\text{sidereal}}, T_{\text{test}} = 1 \text{ hr})$  no time dependence expected

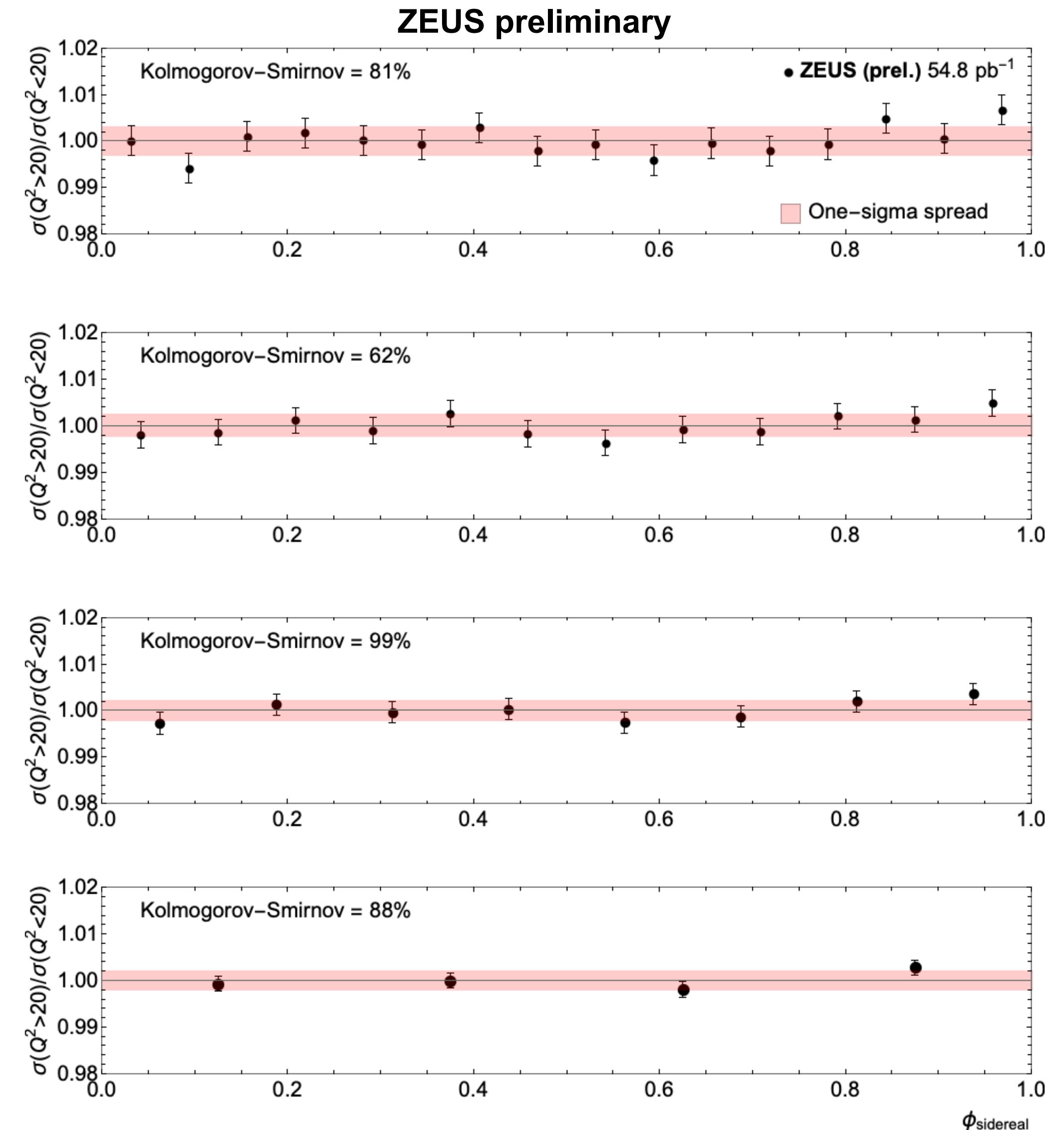
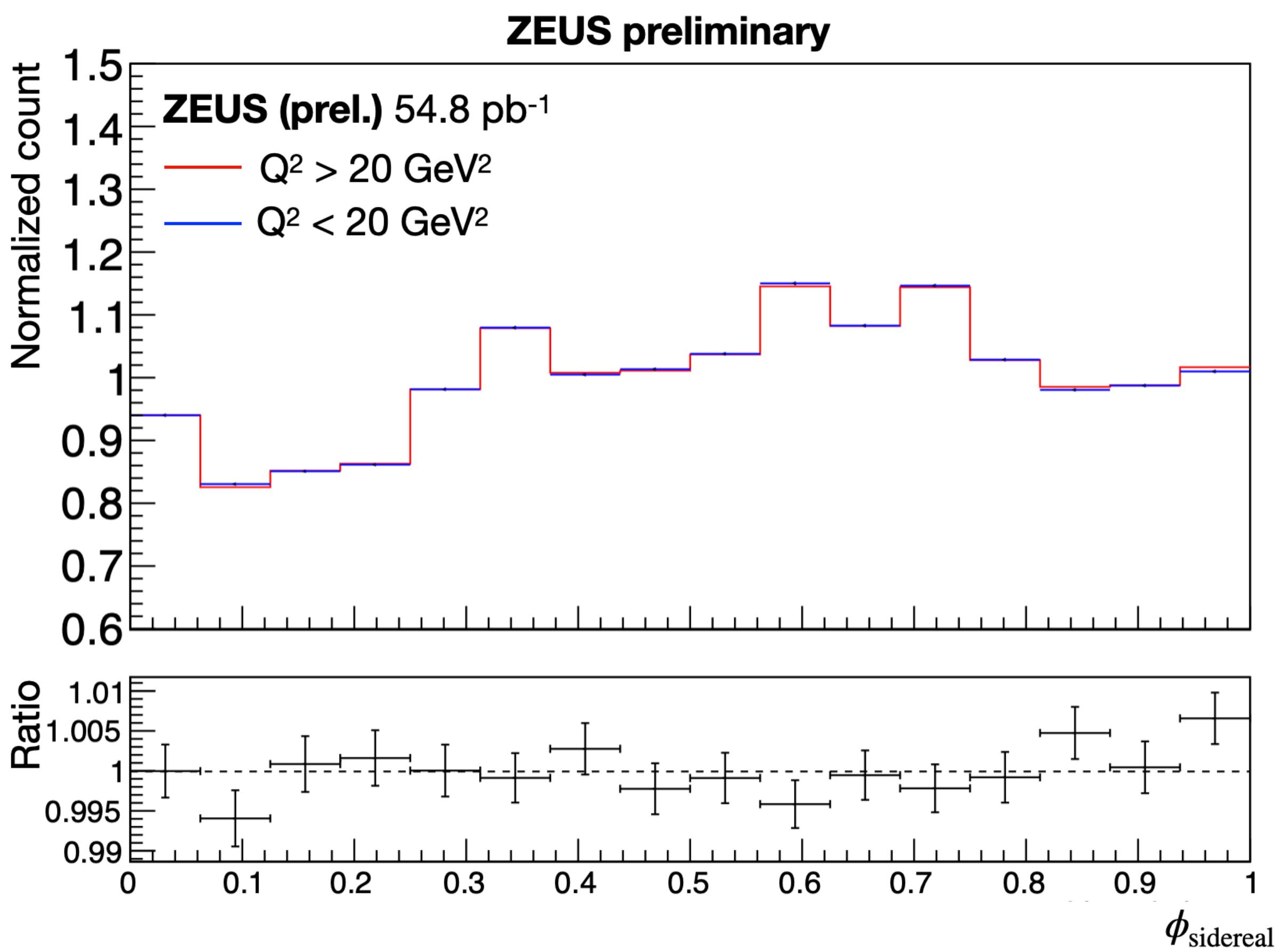
# Control study: ( $Q^2_{\text{cut}}, T_{\text{solar}})$ )



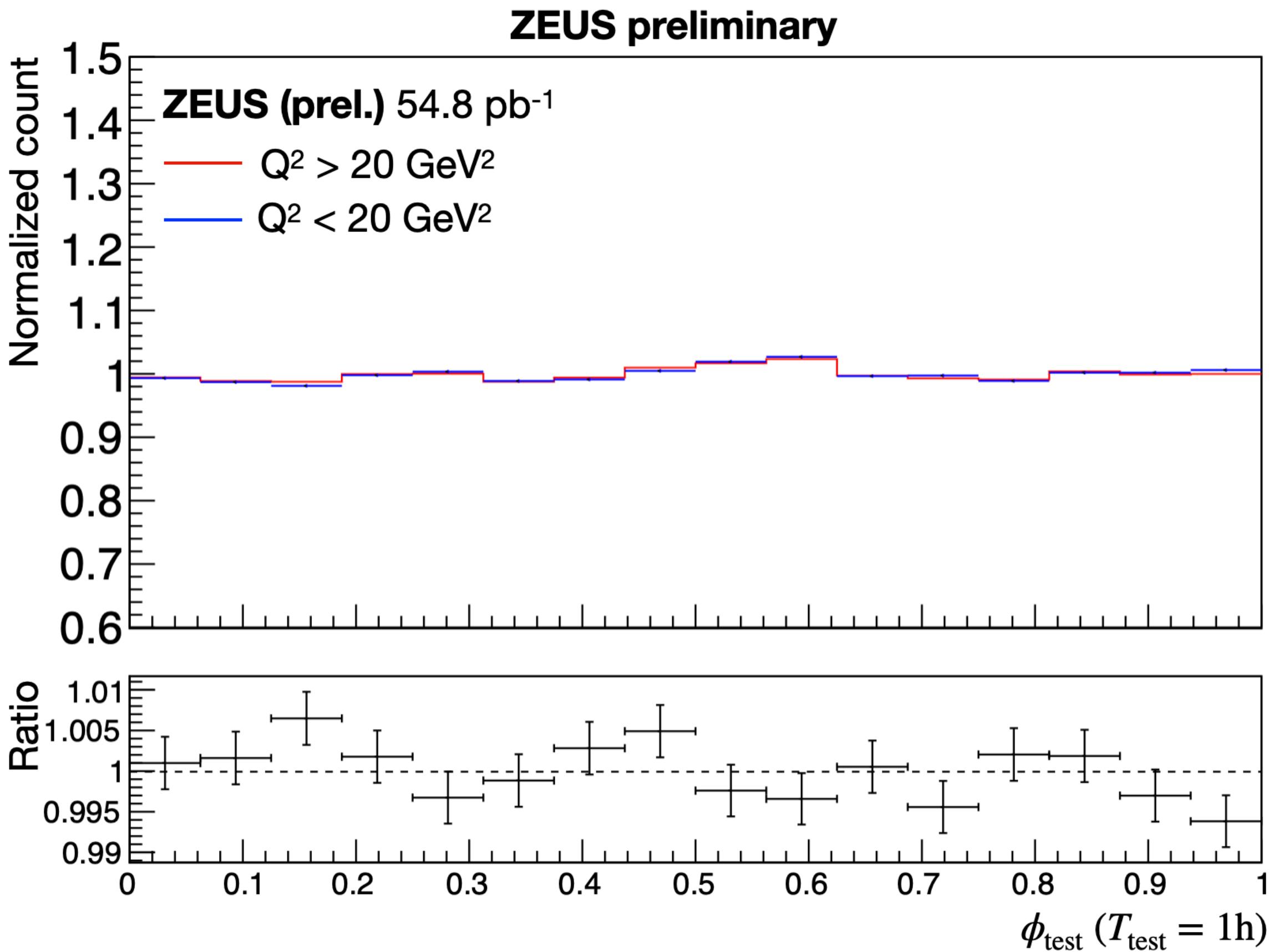
◆ 16, 12, 8, and 4 bins from top-to-bottom (right)



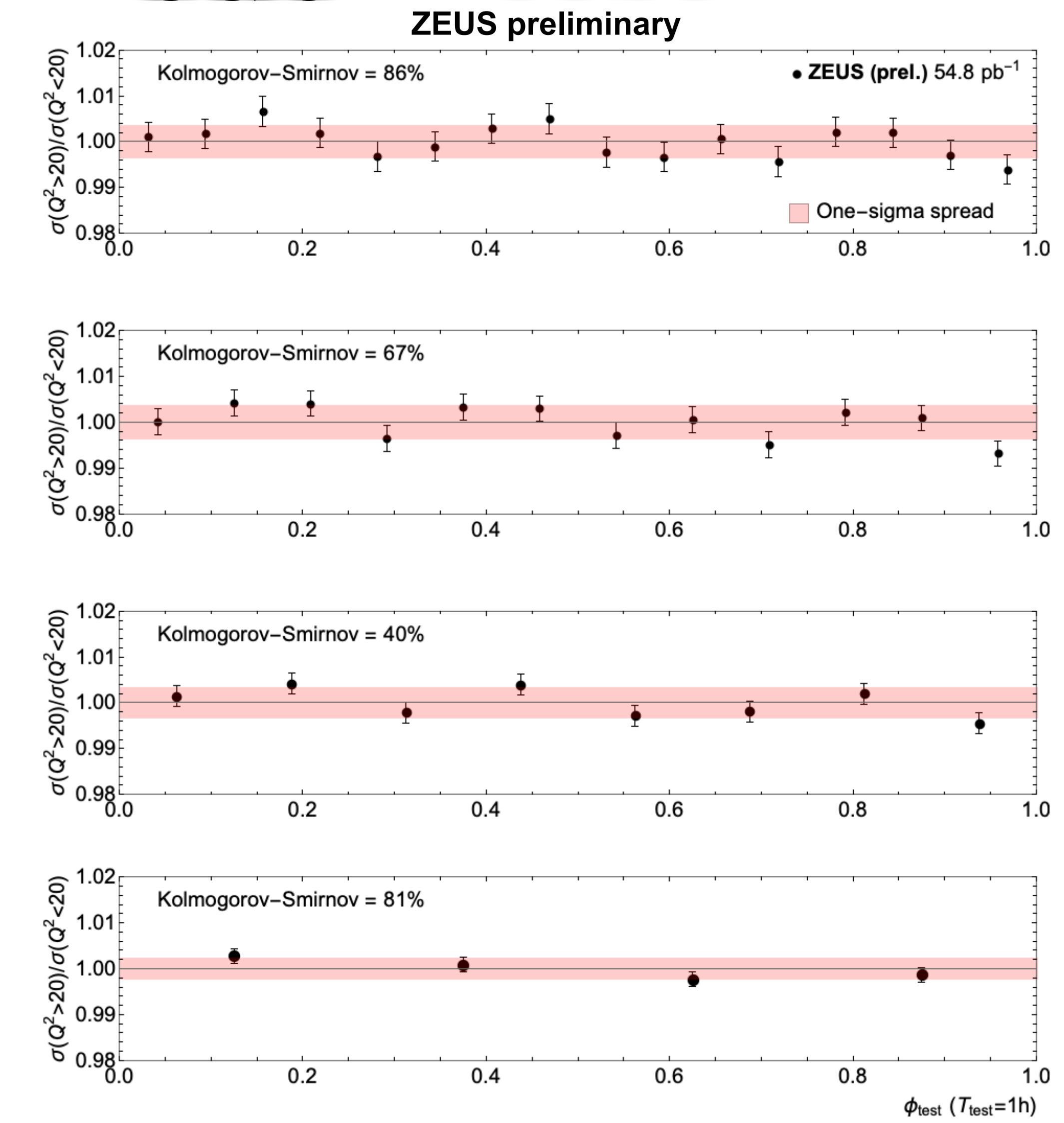
# Control study: ( $Q^2_{\text{cut}}$ , $T_{\text{sidereal}}$ )



# Control study: ( $Q^2_{\text{cut}}, T_{\text{test}}$ )



No evidence for impact of  
stochastic remnants of systematic  
uncertainties for all periods



# Control study: ( $x_{\text{cut}}, T_{\text{test}}$ )

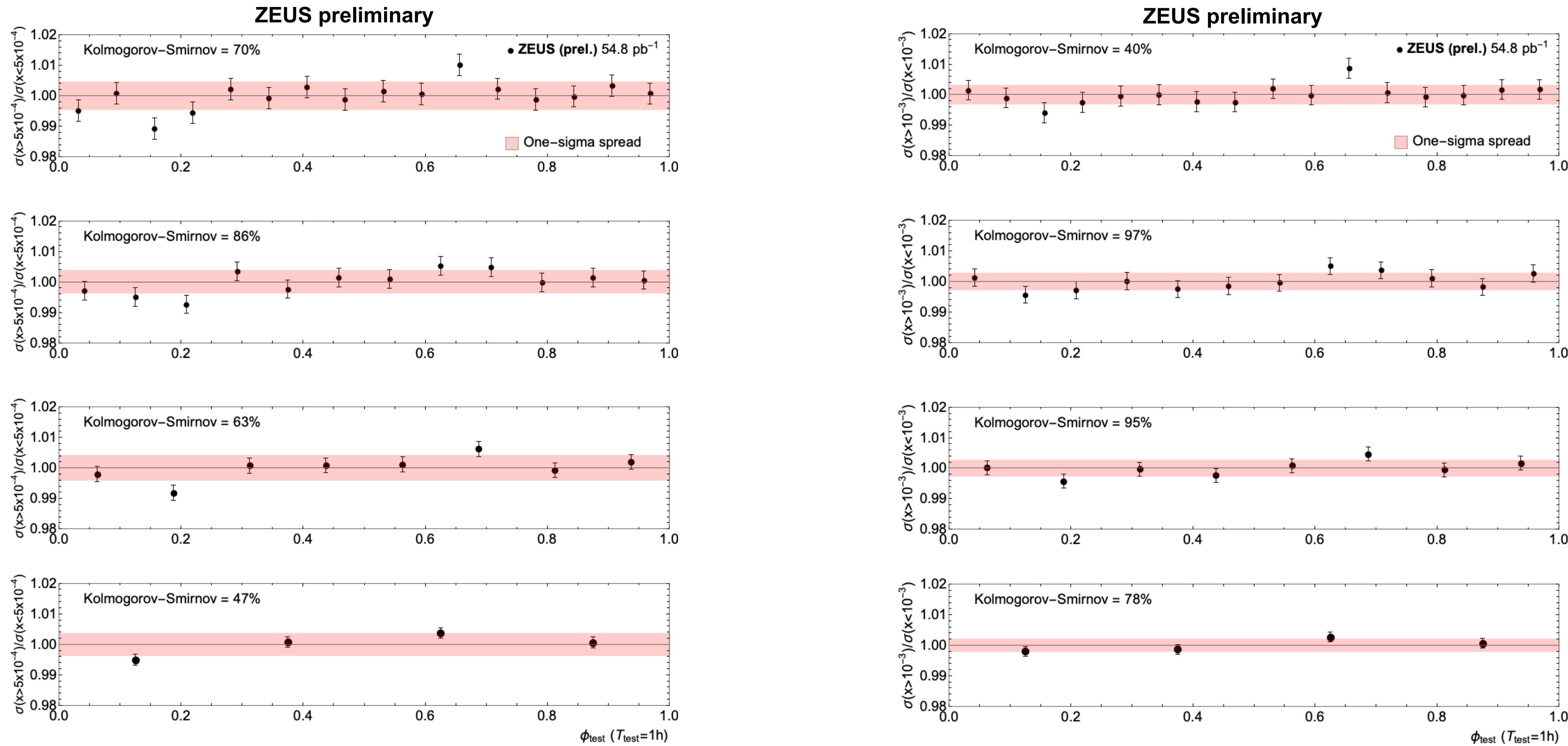
- ◆ Recall theory double ratios with  $x$  cuts exhibit strong sensitivity to LV effects
- ◆ Explicit theoretical double ratios:

$$r(x > x_c, x < x_c) = 1 - 30 c_u^{03} - 23 c_u^{33} + 0.86 (c_u^{11} + c_u^{22}) \quad (x_c = 5 \times 10^{-4})$$
$$- 8.5 c_d^{03} - 5.1 c_d^{33} + 0.13 (c_d^{11} + c_d^{22})$$

$$r(x > x_{a(5)}, x < x_{a(5)}) = 1 - 6.3 \times 10^3 a_u^{(5)003} + 7.0 \times 10^3 a_u^{(5)033} - 2.5 \times 10^3 a_u^{(5)333} \quad (x_{a(5)} = 10^{-3})$$
$$- 5.2 \times 10^2 (a_u^{(5)011} + a_u^{(5)022} + a_u^{(5)113} + a_u^{(5)223})$$
$$- 5.1 \times 10^2 a_d^{(5)003} + 5.7 \times 10^2 a_d^{(5)033} - 2.1 \times 10^2 a_d^{(5)333}$$
$$- 47 (a_d^{(5)011} + a_d^{(5)022} + a_d^{(5)113} + a_d^{(5)223})$$

- ◆ However, we *cannot* conclude that 1 year of data results in binned solar and sidereal distributions split by  $x_{\text{cut}}$  are consistent with statistical uncertainties alone  $\Rightarrow$  consider  $T_{\text{test}}$

# Control study: $(x_{\text{cut}}, T_{\text{test}})$



- ◆ Consistent with Gaussian distributions with central value = 1,  $\sigma = \sigma_{\text{stat}}$ .

# Potential bounds

- Assuming that sidereal distributions will look similar to the test ones, **potential bounds** are extracted by fitting theoretical expressions to the test distributions

$c_{u,d}^{\mu\nu}$

coefficient $\times 10^4$	16 bins	12 bins	8 bins	4 bins	
$ c_u^{YZ} $	4.0	3.9	3.7	5.5	
	$ c_u^{XX} - c_u^{YY} $	2.8	2.5	3.5	6.3
	$ c_u^{XZ} $	6.4	6.6	6.8	7.4
	$ c_u^{XY} $	1.4	1.4	1.4	2.0
	$ c_u^{TY} $	1.3	1.2	1.2	1.7
	$ c_u^{TX} $	2.0	2.1	2.2	2.3
$ c_d^{YZ} $	18.0	18.0	17.0	25.0	
	$ c_d^{XX} - c_d^{YY} $	13.0	11.0	16.0	28.0
	$ c_d^{XZ} $	29.0	30.0	31.0	33.0
	$ c_d^{XY} $	6.1	6.3	6.5	9.1
	$ c_d^{TY} $	4.5	4.4	4.2	6.1
	$ c_d^{TX} $	7.1	7.4	7.7	8.3

# Potential bounds

$a_u^{(5)\lambda\mu\nu}$

coefficient $\times 10^6$ GeV	16 bins	12 bins	8 bins	4 bins
$ a_{Su}^{(5)TXX} - a_{Su}^{(5)TYY} $	0.42	0.45	0.43	0.52
$ a_{Su}^{(5)XXZ} - a_{Su}^{(5)YYZ} $	0.75	0.78	0.76	0.78
$ a_{Su}^{(5)TXY} $	0.41	0.42	0.43	0.51
$ a_{Su}^{(5)TXZ} $	1.54	1.61	1.60	1.79
$ a_{Su}^{(5)TYZ} $	0.87	0.90	0.99	0.95
$ a_{Su}^{(5)XXX} $	0.60	0.63	0.62	0.69
$ a_{Su}^{(5)XXY} $	0.31	0.30	0.32	0.37
$ a_{Su}^{(5)XYY} $	0.52	0.54	0.54	0.65
$ a_{Su}^{(5)XYZ} $	1.64	1.70	1.70	2.02
$ a_{Su}^{(5)XZZ} $	0.77	0.80	0.79	0.89
$ a_{Su}^{(5)YYY} $	0.36	0.36	0.39	0.36
$ a_{Su}^{(5)YZZ} $	0.43	0.45	0.49	0.47

$a_d^{(5)\lambda\mu\nu}$

$ a_{Sd}^{(5)TXX} - a_{Sd}^{(5)TYY} $	5.18	5.55	5.31	6.39
$ a_{Sd}^{(5)XXZ} - a_{Sd}^{(5)YYZ} $	9.22	9.49	9.24	9.59
$ a_{Sd}^{(5)TXY} $	4.98	5.15	5.18	6.14
$ a_{Sd}^{(5)TXZ} $	18.70	19.60	19.40	21.80
$ a_{Sd}^{(5)TYZ} $	10.60	10.90	12.00	11.50
$ a_{Sd}^{(5)XXX} $	7.39	7.76	7.70	8.58
$ a_{Sd}^{(5)XXY} $	3.89	3.68	3.86	4.63
$ a_{Sd}^{(5)XYY} $	6.44	6.69	6.65	8.04
$ a_{Sd}^{(5)XYZ} $	19.60	20.30	20.40	24.10
$ a_{Sd}^{(5)XZZ} $	9.54	9.98	9.88	11.10
$ a_{Sd}^{(5)YYY} $	4.41	4.50	4.85	4.38
$ a_{Sd}^{(5)YZZ} $	5.39	5.55	6.10	5.85

# Conclusions

- ◆ An analysis searching for Lorentz and CPT violation in the quark sector with ZEUS DIS data is presented:
  - Binned events indicate significant solar and residual sidereal dependence emanating from the beam luminosity
  - Double-ratio distributions from contrasting regions of phase space present the possibility to bypass instantaneous luminosity
  - Control studies were performed with  $x$ ,  $Q^2$  cuts and indicate binned double-ratio data is consistent with statistical uncertainties only
  - For the case of  $(x_{\text{cut}}, T_{\text{test}})$ , potential bounds on 36 coefficients for Lorentz violation were extracted

THANK YOU!