Testing Lorentz and CPT invariance with ZEUS data

Nathaniel Sherrill

University of Sussex

MPI, Munich 28/11/2023

1. Introduction

- Lorentz invariance and violation
- Effective description

2. Hadronic processes

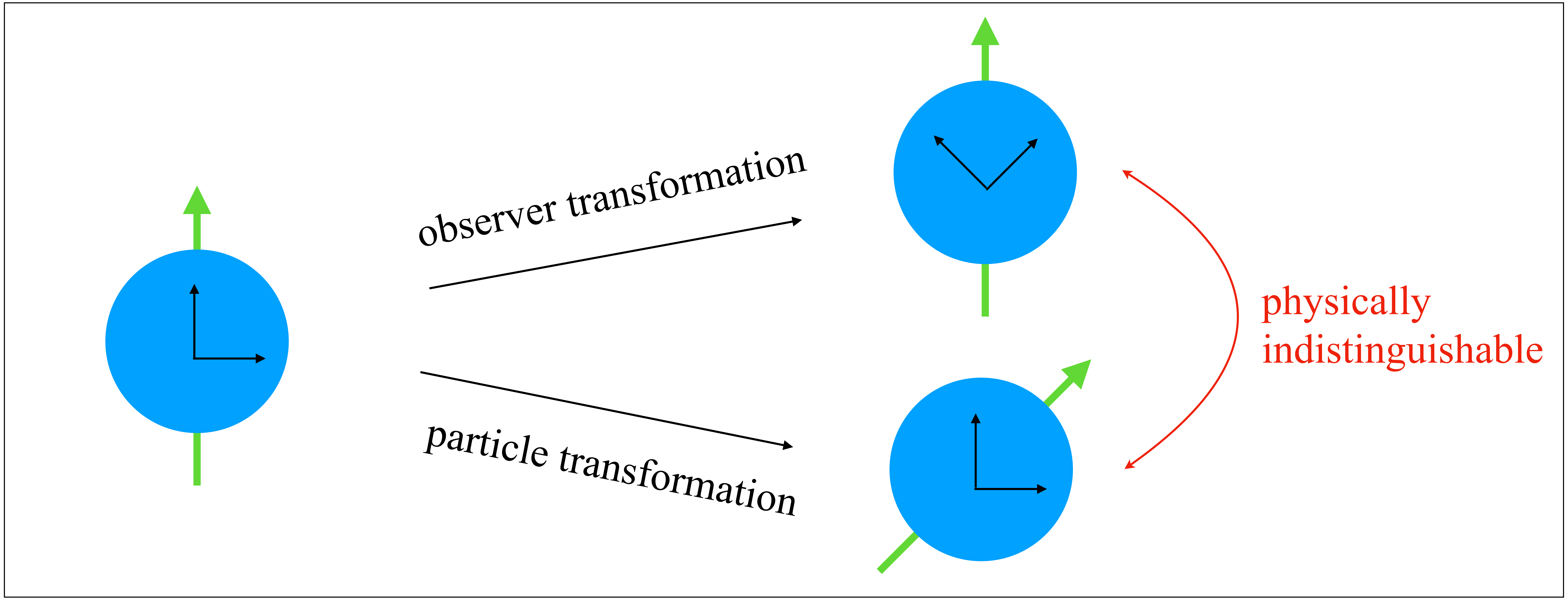
- Quark-sector effects
- Sidereal oscillations
- Lorentz-violating parton model

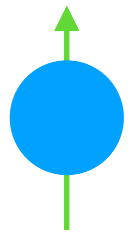
3. ZEUS search

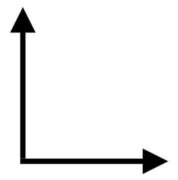
- Data
- Strategy
- Results

Observer vs. particle transformations

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

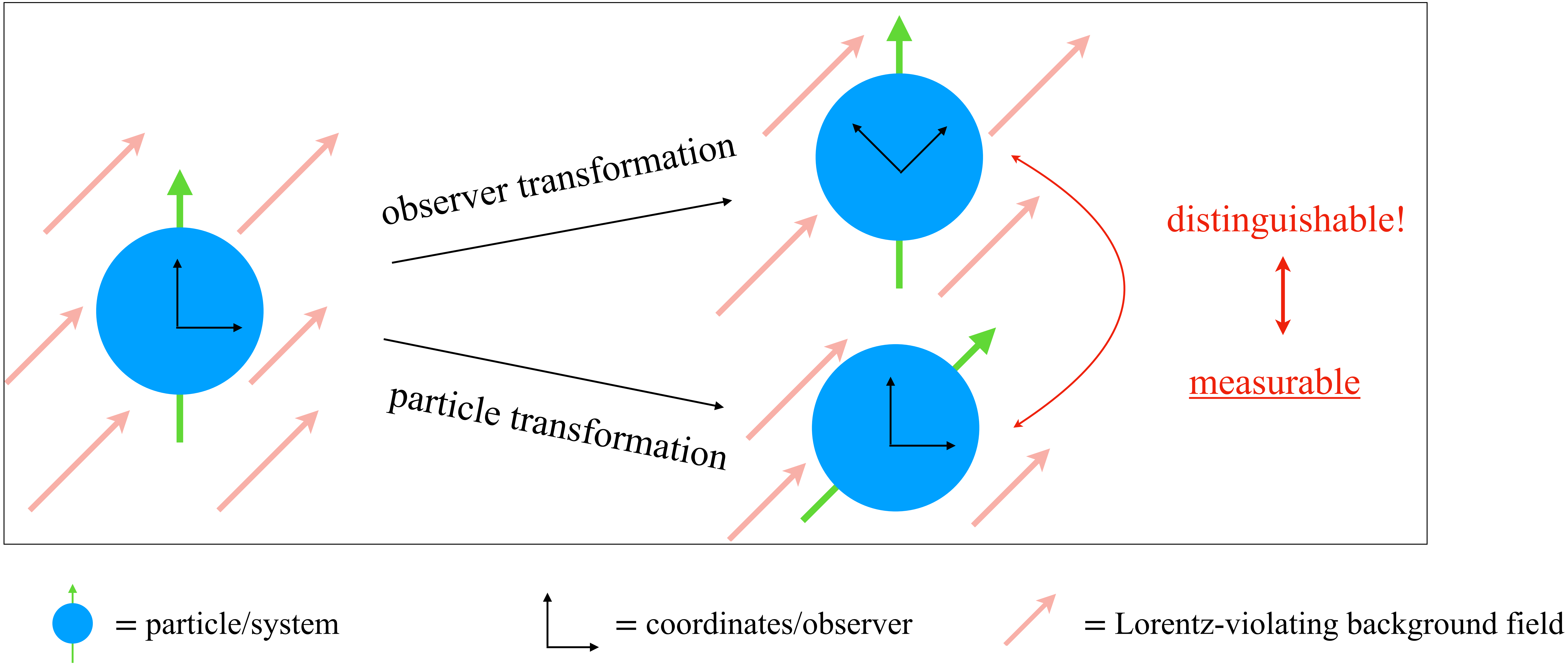


 = particle/system

 = coordinates/observer

Observer vs. particle transformations

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

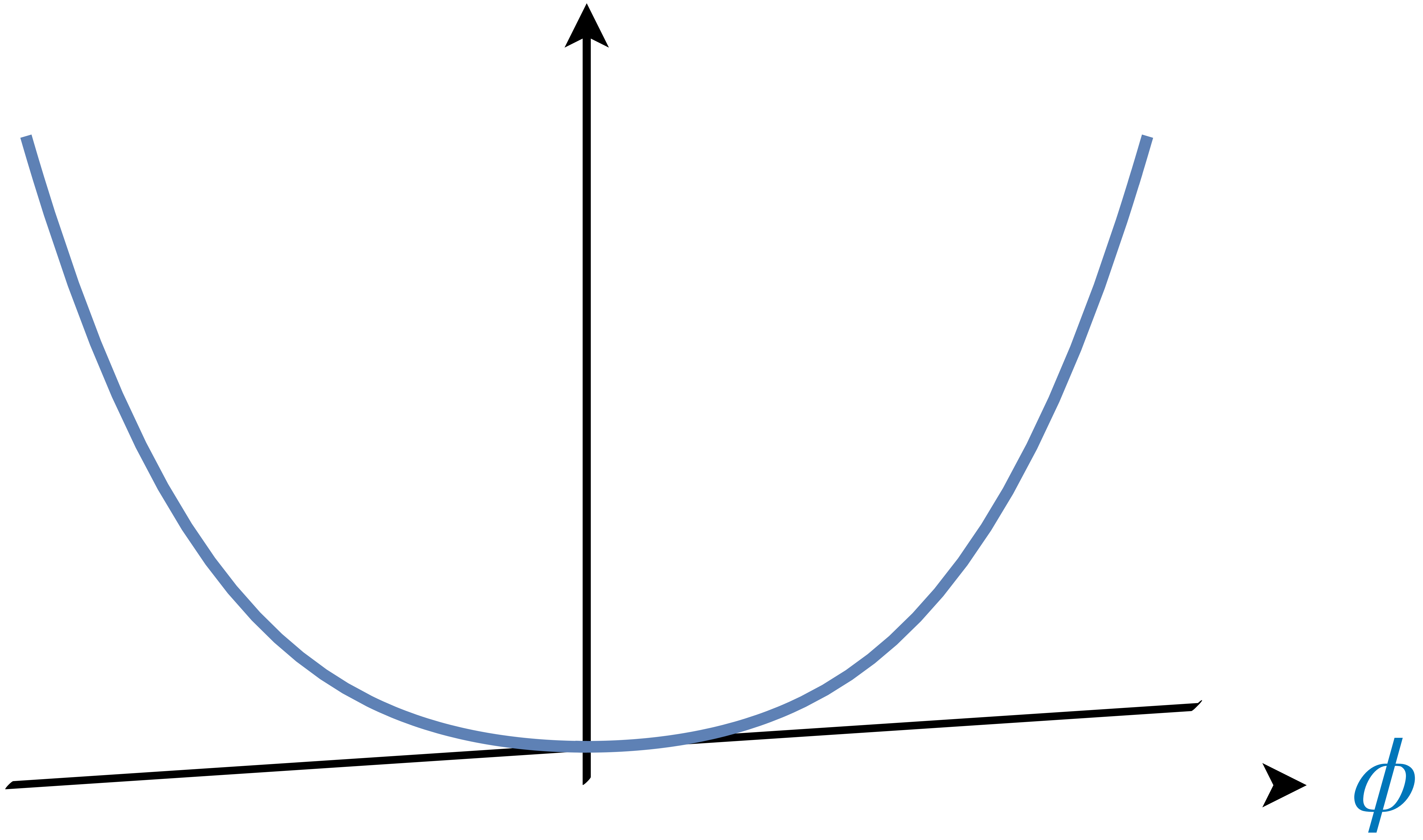


Higgs analogy

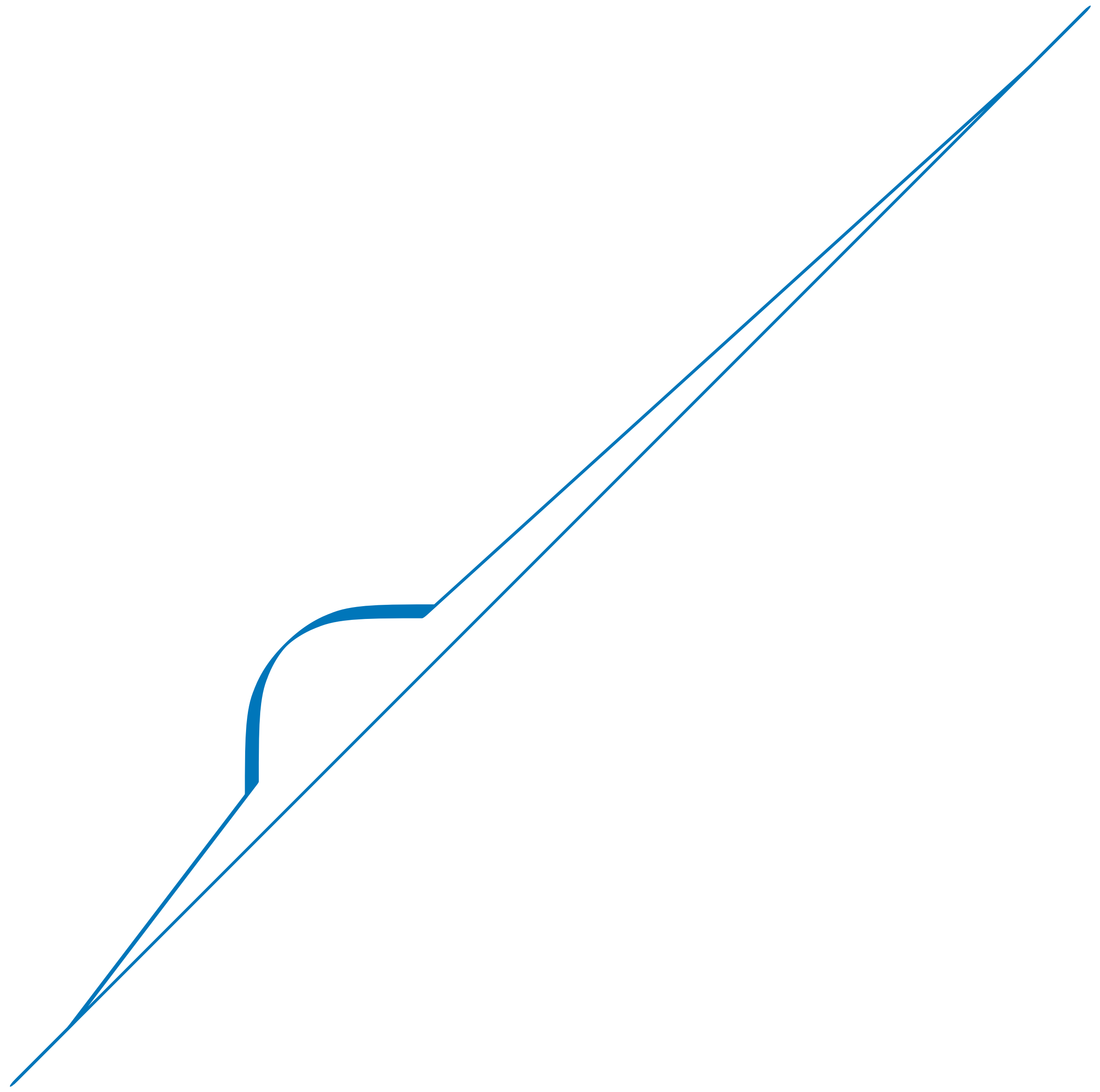
$$V(\phi) = (\phi^2 \pm \lambda^2)^2$$

Higgs analogy

$$V(\phi) = (\phi^2 + \lambda^2)^2$$



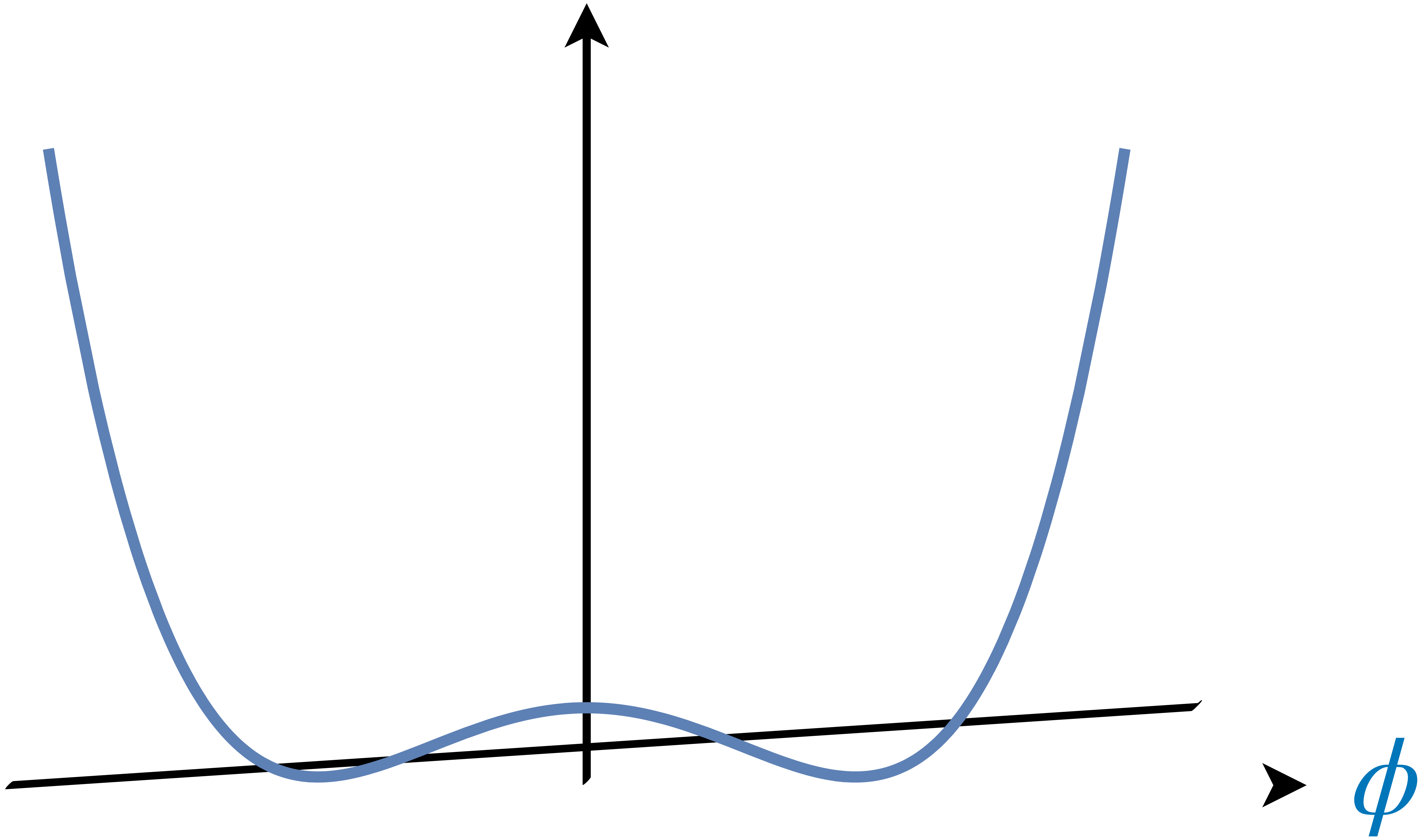
$$\langle \phi \rangle = 0$$

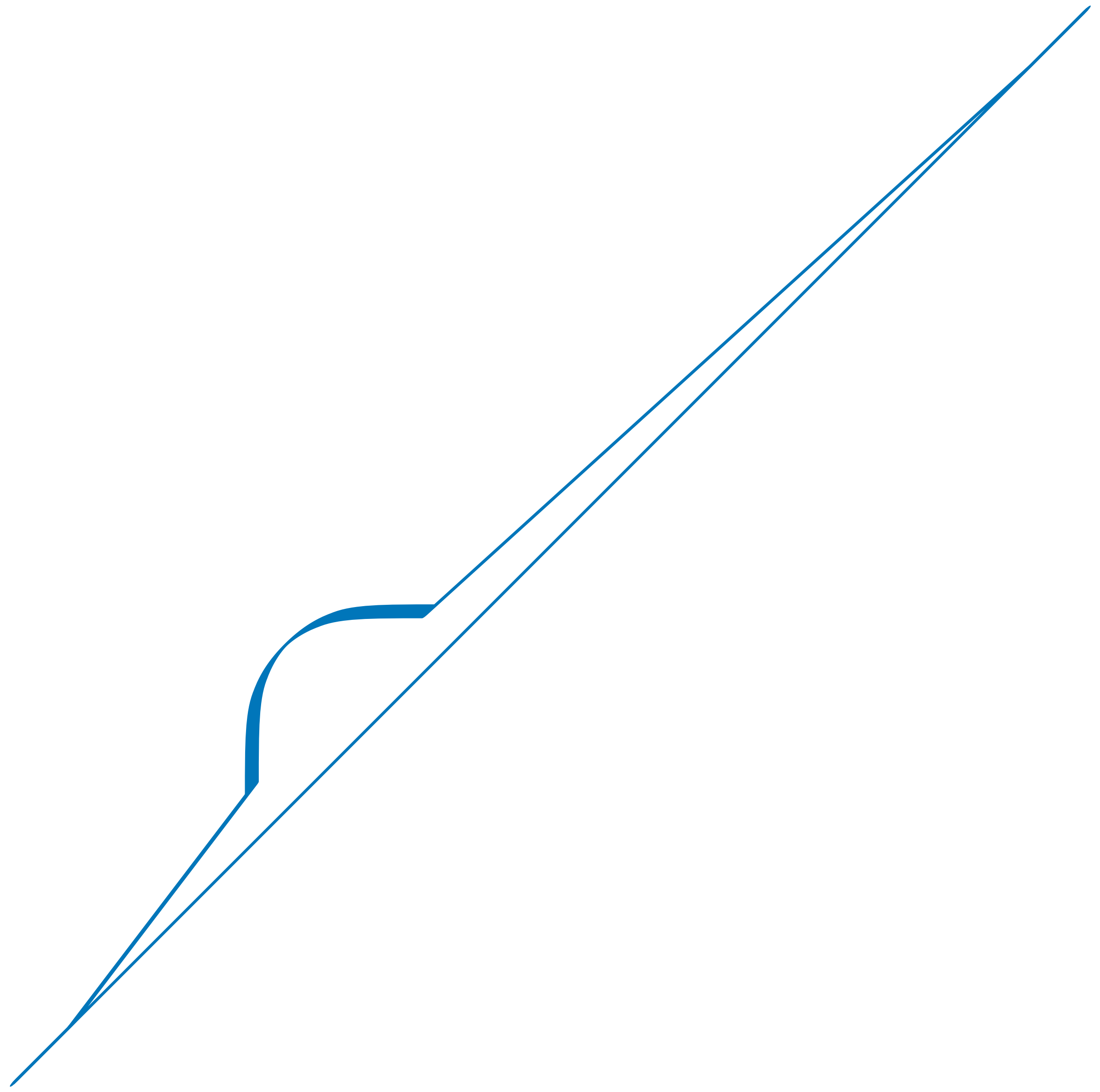


Vacuum

Higgs analogy

$$V(\phi) = (\phi^2 - \lambda^2)^2$$

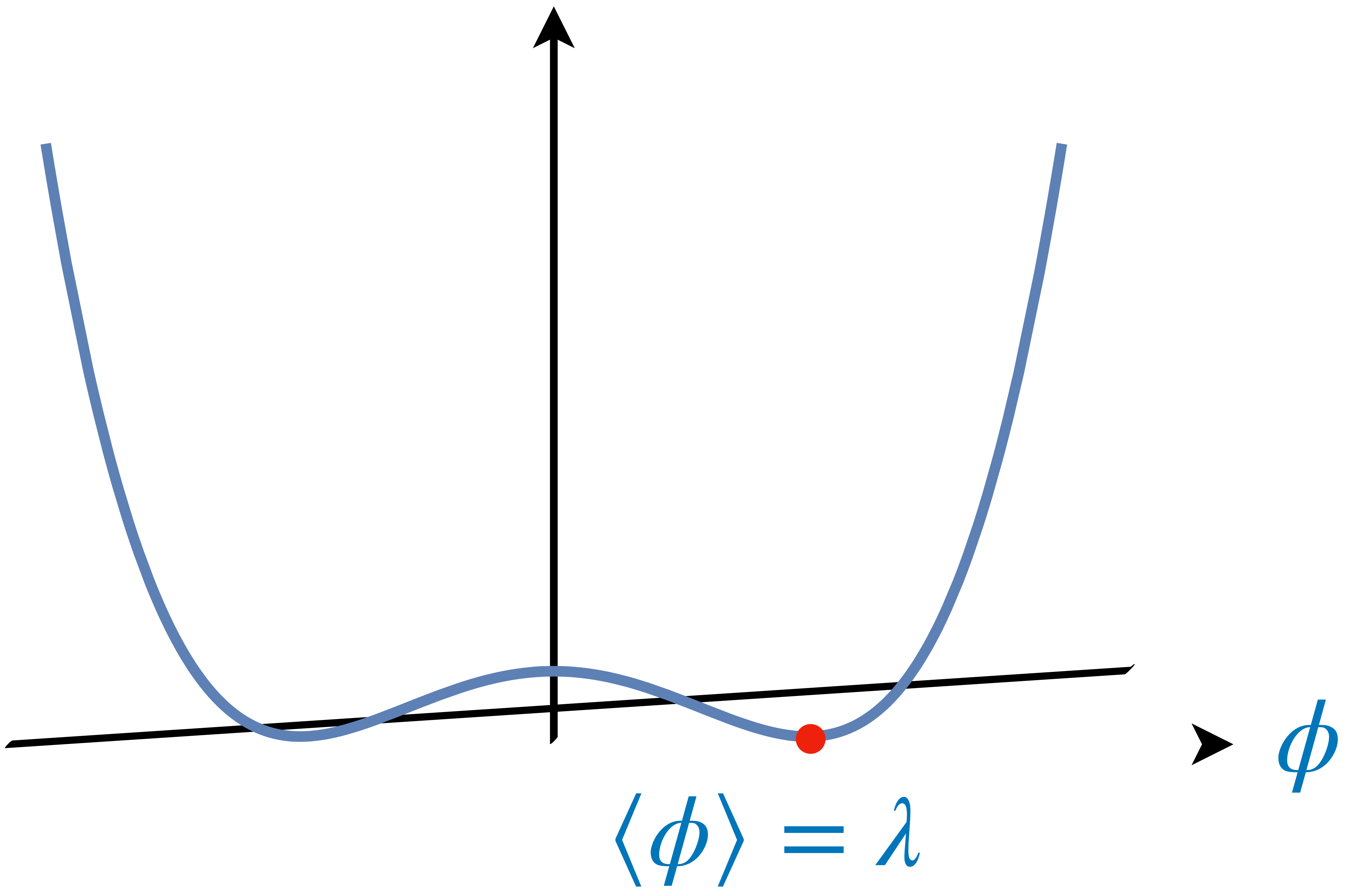


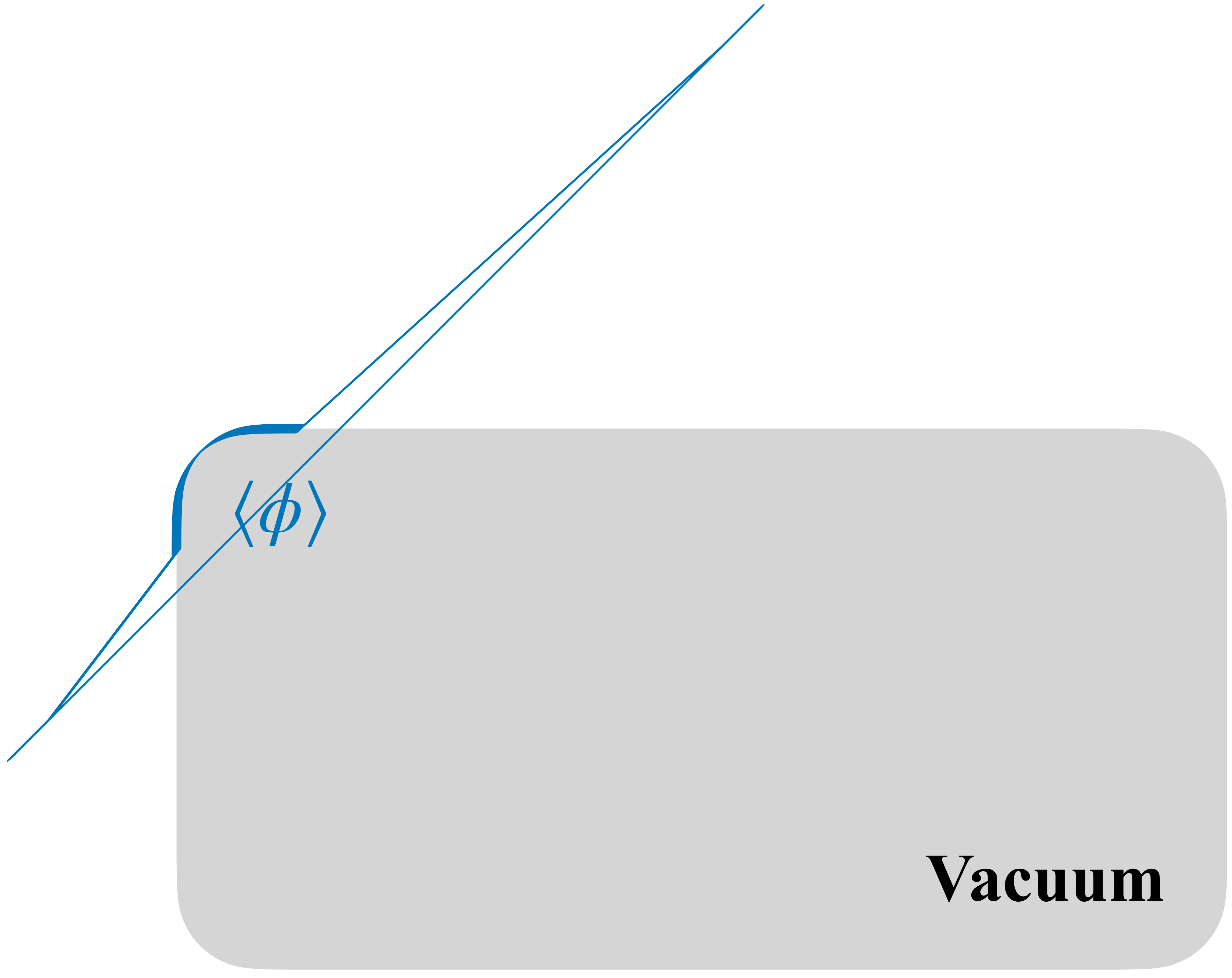


Vacuum

Higgs analogy

$$V(\phi) = (\phi^2 - \lambda^2)^2$$





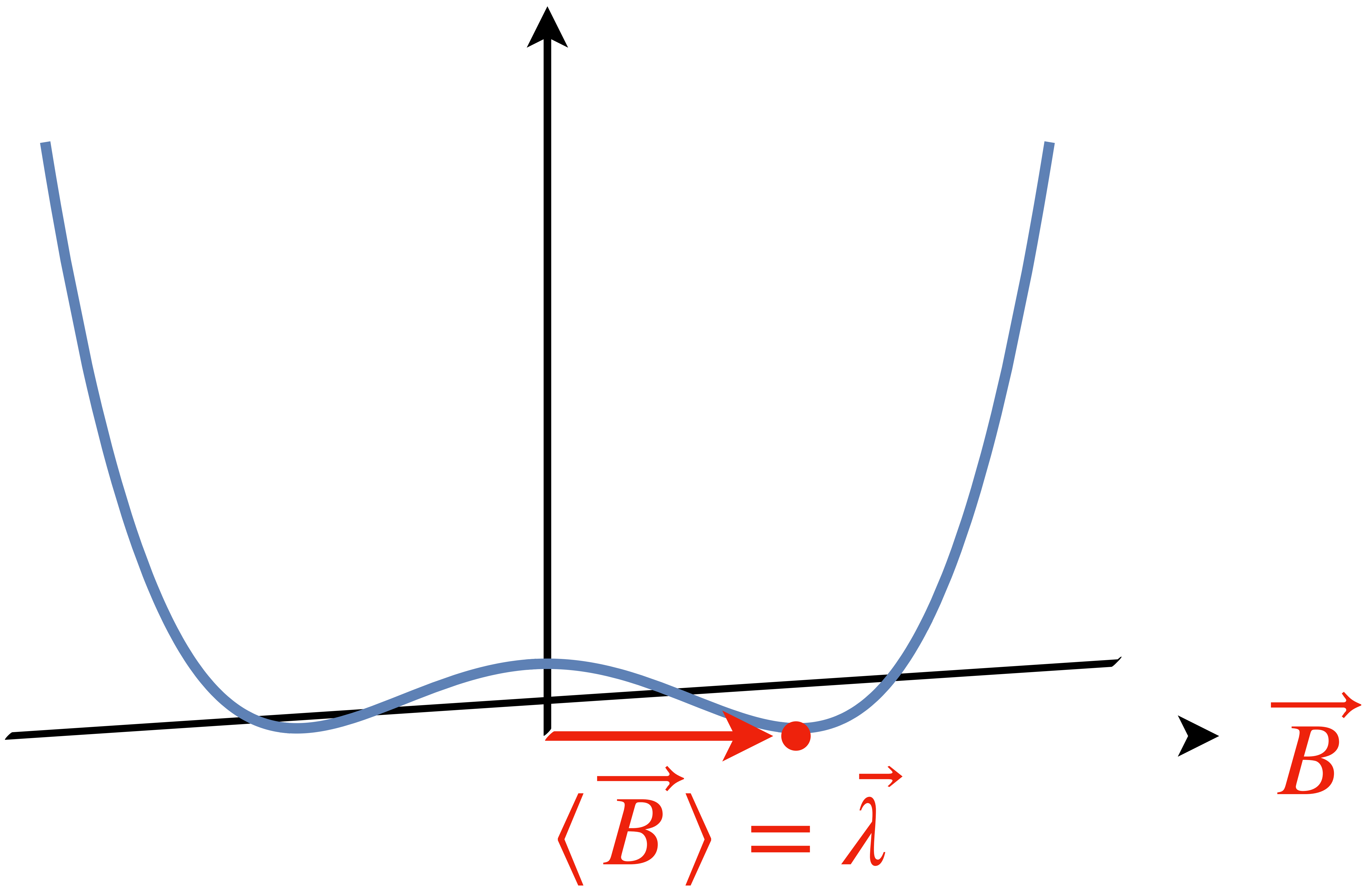
"Isotropic" vev

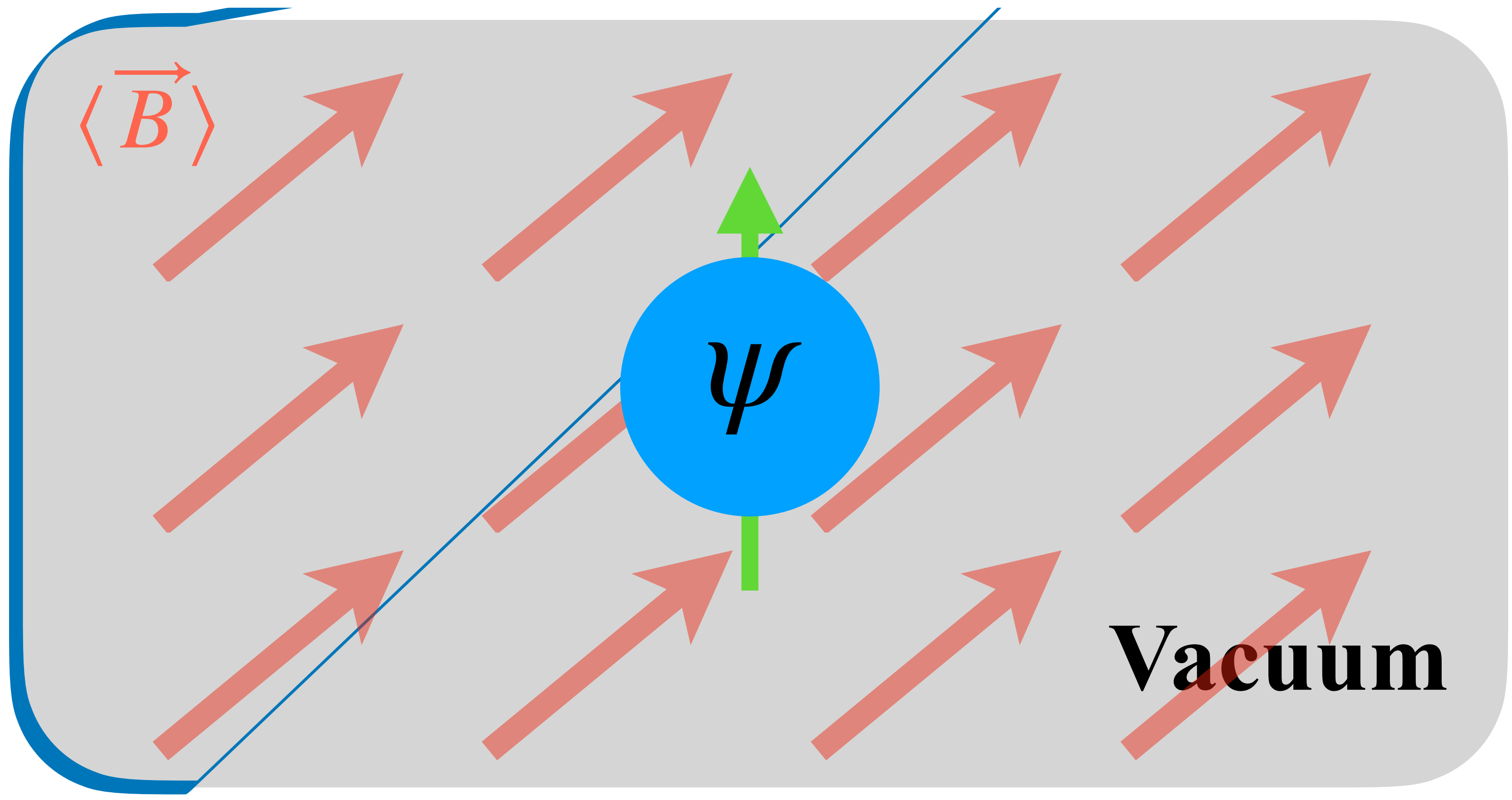
Higgs analogy

$$V(\overrightarrow{B}) = (\overrightarrow{B}^2 - \vec{\lambda}^2)^2$$

Higgs analogy

$$V(\vec{B}) = (\vec{B}^2 - \vec{\lambda}^2)^2$$





"*An*isotropic" vev ⇒Lorentz violation

$\langle B^\mu \rangle \equiv b^\mu$ matter can couple to background

$$\mathscr{L}'_{\mathrm{int}} \supset -b_\mu \underbrace{\bar{\psi}\gamma_5\gamma^\mu\psi}_{CPT\text{-odd operator}}$$

Lorentz- *and* CPT-violating effect!

Standard-Model Extension (SME)

SME = Lorentz- and CPT-violating effective field theory

D. Colladay, V. A. Kostelecky, PRD **55**, 6760 (1997);
PRD **58**, 116002 (1998);
V. A. Kostelecky, PRD **69**, 105009 (2004);
V. A. Kostelecky, Z. Li, PRD **103**, 024059 (2021)

SME = SM+LV

Contains all possible terms that break Lorentz *and* CPT symmetry in **EFT**

$$\mathscr{L}_{\mathrm{LV}} \supset k^{\mu\cdots}{}_{\nu\cdots}{}^{a\cdots}(x)\,\mathcal{O}_{\mu\cdots}{}^{\nu\cdots}{}_{a\cdots}(x)$$

- All violate Lorentz, ~1/2 violate CPT as well
- Typically organized by mass dimension

$d \leq 4$ "Minimal SME" e.g. $-a_\mu \bar{\psi}\gamma^\mu\psi$ $\quad [a_\mu] = \mathrm{GeV}$

$d > 4$ "Nonminimal SME" e.g. $-\frac{1}{4}k^{\alpha\kappa\lambda\mu\nu}F_{\kappa\lambda}\partial_\alpha F_{\mu\nu}$

Minimal SME properties

$SU(3)\times SU(2)\times U(1)$ structure	✓
$SU(2)\times U(1)$ breaking	✓
Renormalizability	✓
Spin statistics	✓
Observer Lorentz invariance	✓
Energy-momentum conservation	✓
Quantization	✓
Microcausality	✓
Particle Lorentz invariance	✗
CPT invariance	✗

Constraints

Some effects have been strongly constrained

Data Tables for Lorentz and CPT Violation,
V. A. Kostelecký, N. Russell, arXiv:0801.0287v16 (2023 version)

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

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

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

$$\longleftrightarrow$$

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

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

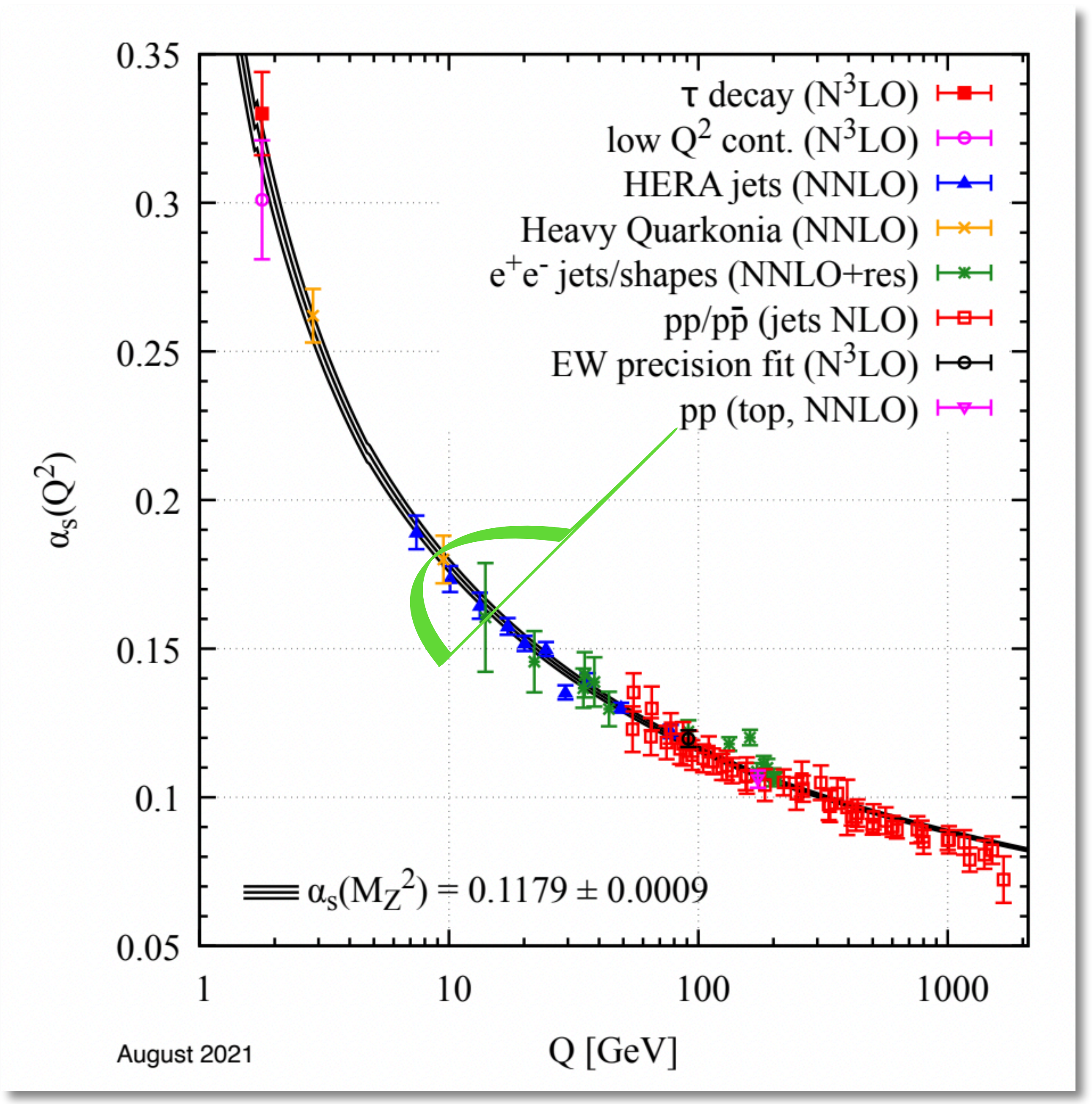
$$|(a_L)_{\beta\mu\tau}| \lesssim 10^{-23}\ \text{GeV}$$

Others, not so much

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

Unstable, QCD, and EW sectors are comparatively unexplored!

Quarks



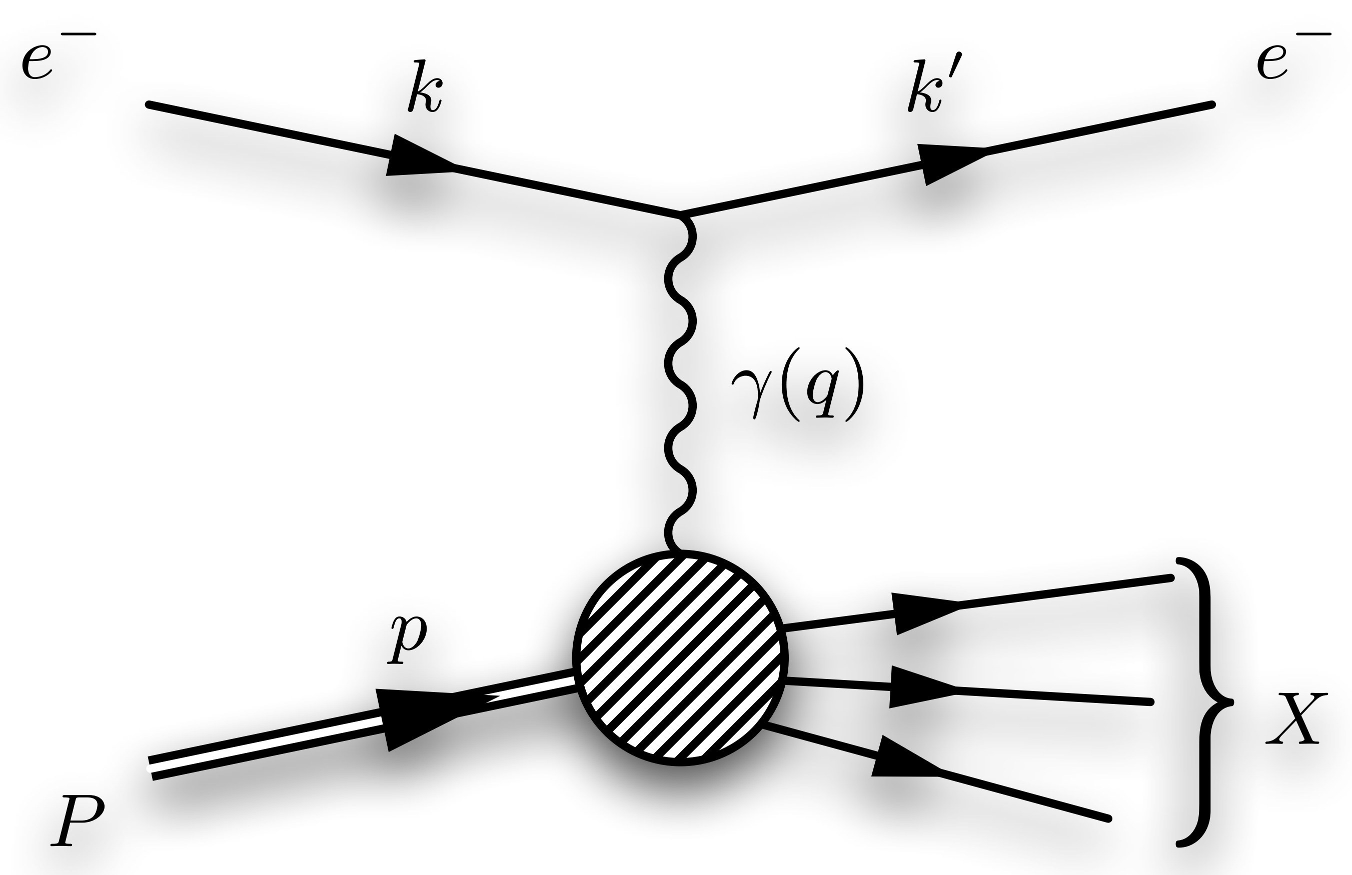
https://pdg.lbl.gov/2021

Direct access to Lorentz properties of quarks is challenging

@ large momentum transfer

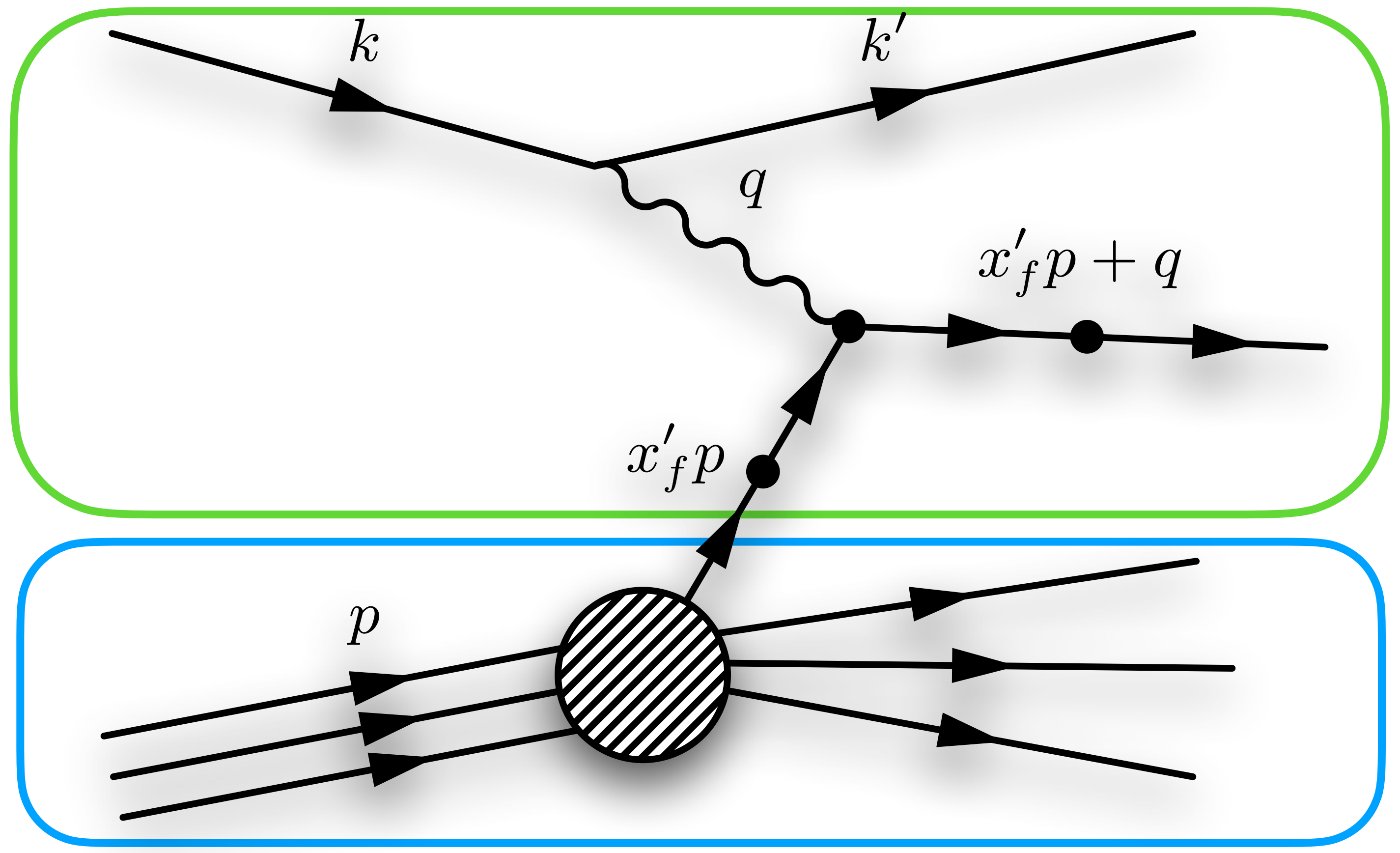
- asymptotic freedom
- perturbative QCD
- factorization

Example: deep inelastic scattering (DIS)



$$-q^2 \gg M^2_{\text{proton}}$$

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



factorization (LO)

$\Rightarrow$ **provides direct access to parton couplings**

Lorentz-violating quarks

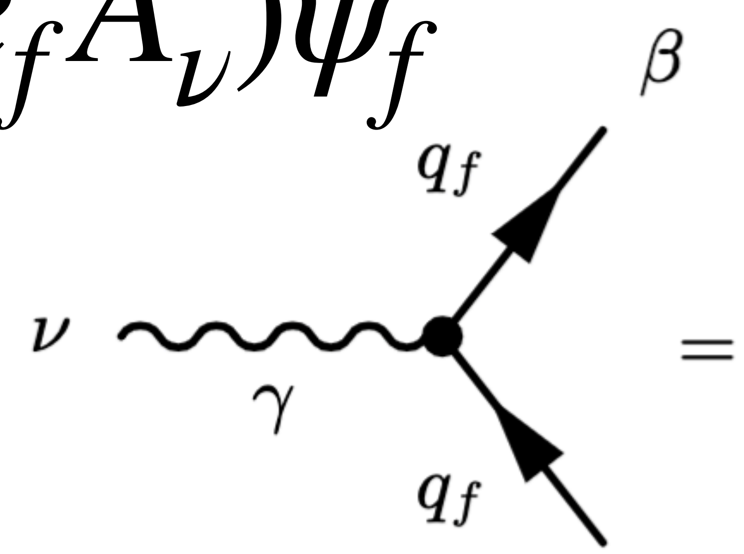
Can perturbative calculations still reliably be performed?

- Notion of partons?
- Factorization, PDFs?
- Optical theorem, Ward identities?
- Gluons? NLO? …

First studies considered unpolarized electron-proton DIS

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

$$\mathscr{L} \supset \sum_{f=u,d} (\eta^{\mu\nu} + c_f^{\mu\nu} + \gamma_5 d_f^{\mu\nu}) \bar{\psi}_f \gamma_\mu (i \overleftrightarrow{\partial}_\nu - e e_f A_\nu) \psi_f$$



$$= -ie\,(2\pi)^4\,\delta^4\,(\Sigma p)\,\left[\gamma^\nu + c_f^{\mu\nu}\gamma_\mu + d_f^{\mu\nu}\gamma_5\gamma_\mu\right]_{\beta\alpha}$$

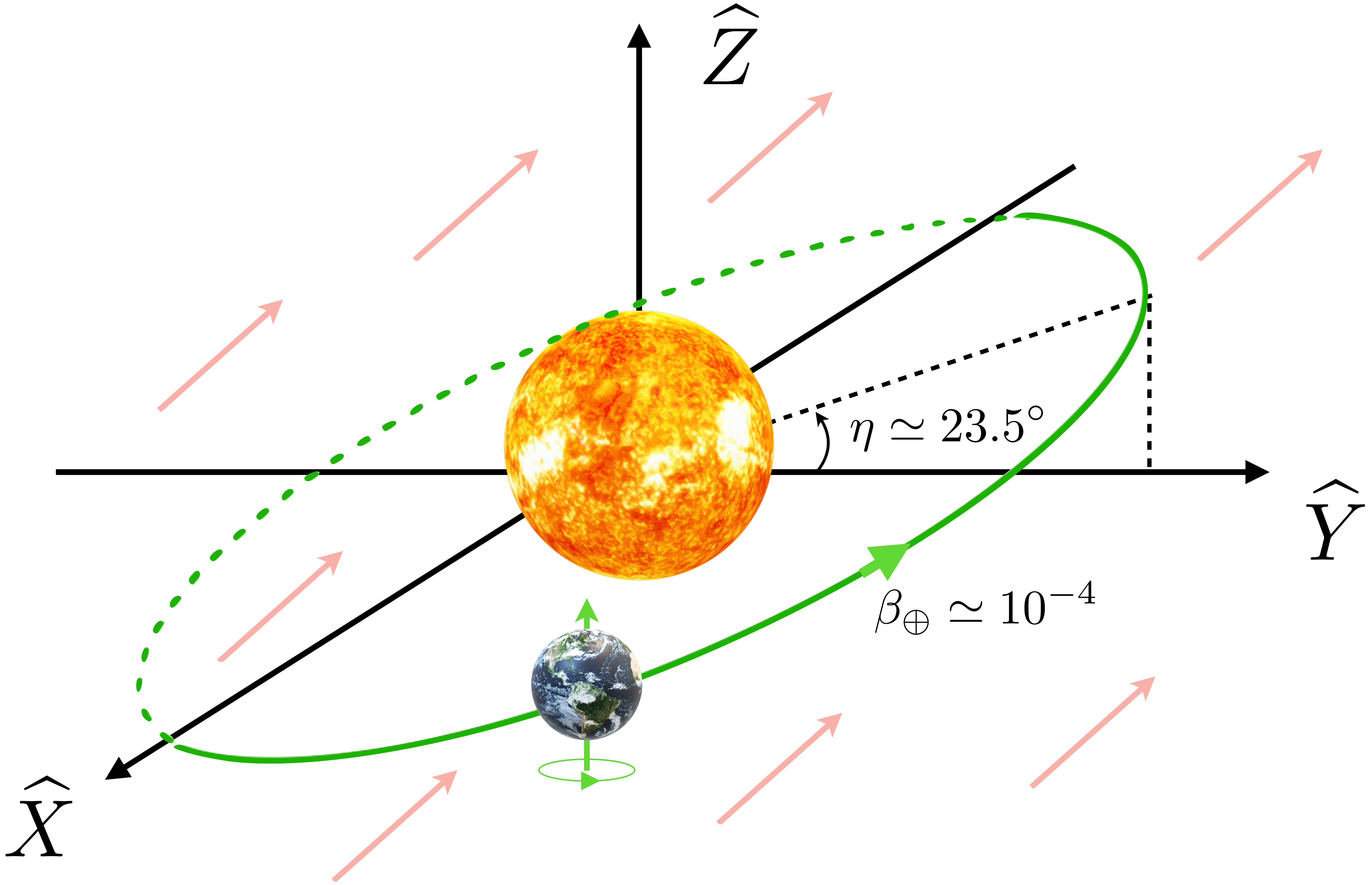
$$= \frac{i}{(\eta^{\mu\nu} + c_f^{\mu\nu} + \gamma_5 d_f^{\mu\nu})\gamma_\mu p_\nu}$$

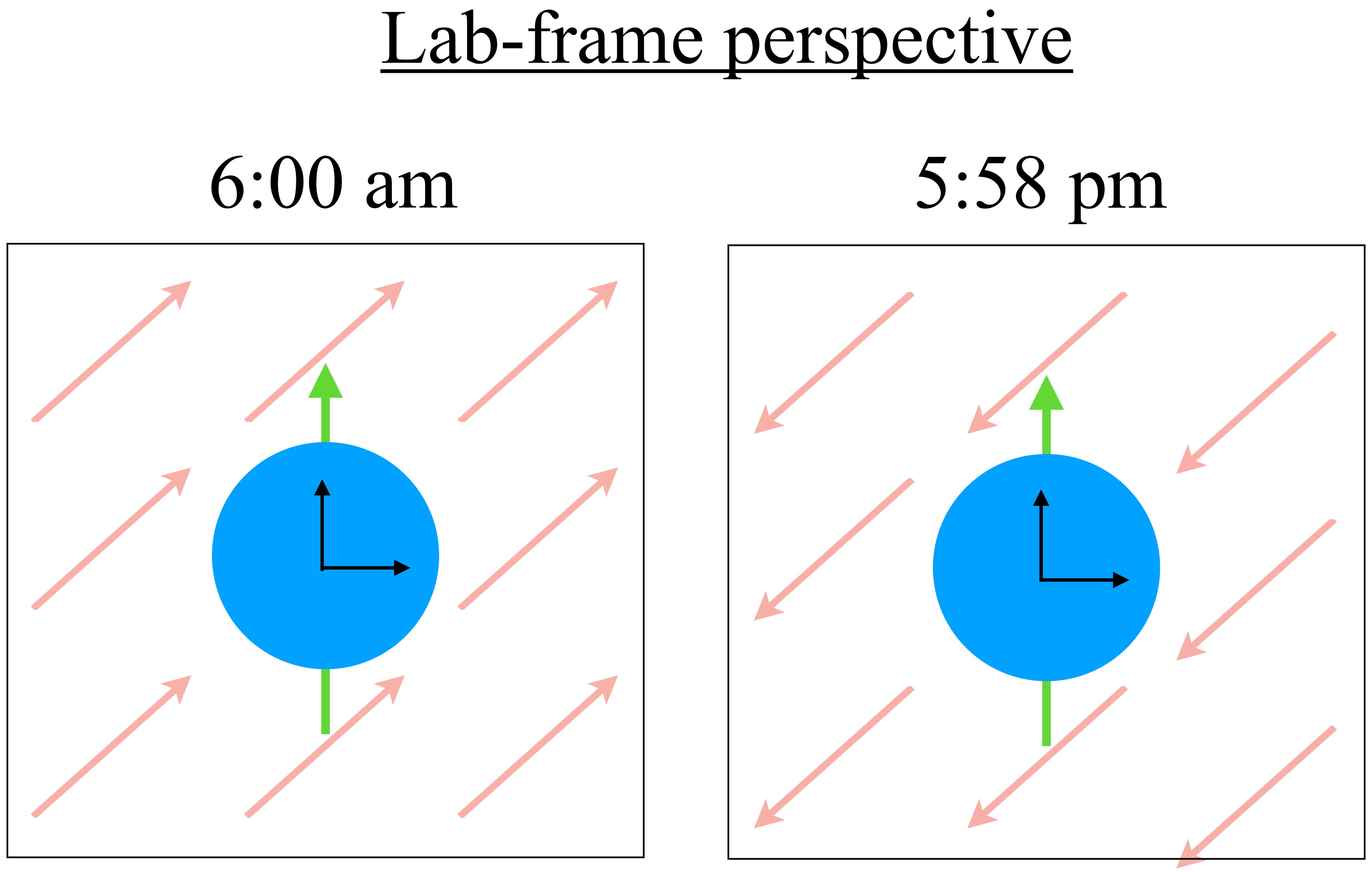
Calculate DIS cross section with perturbative insertions of (renormalizable) quark operators

Sidereal oscillations

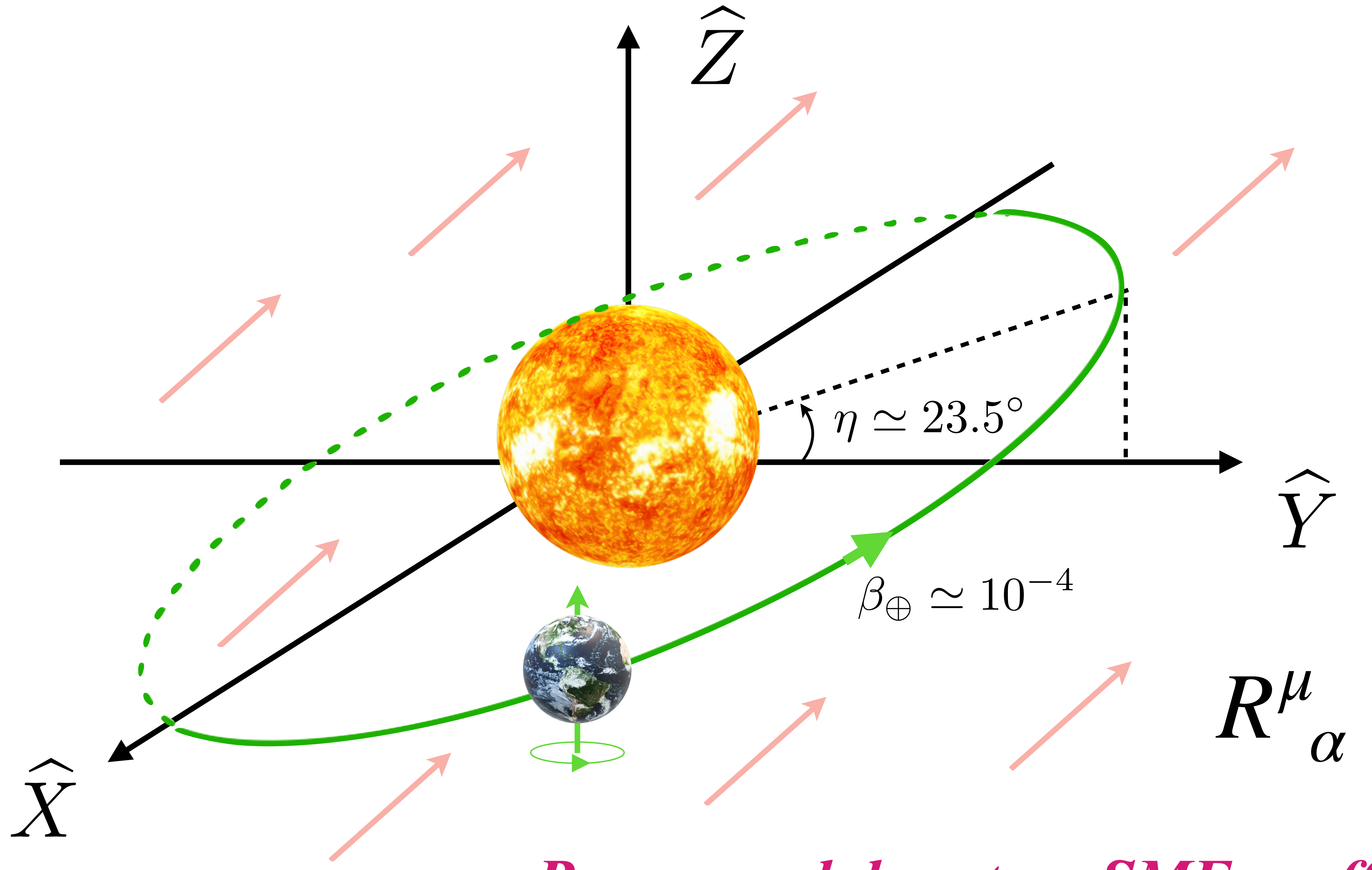
Laboratories on Earth's surface are noninertial ⇒ observables change with time

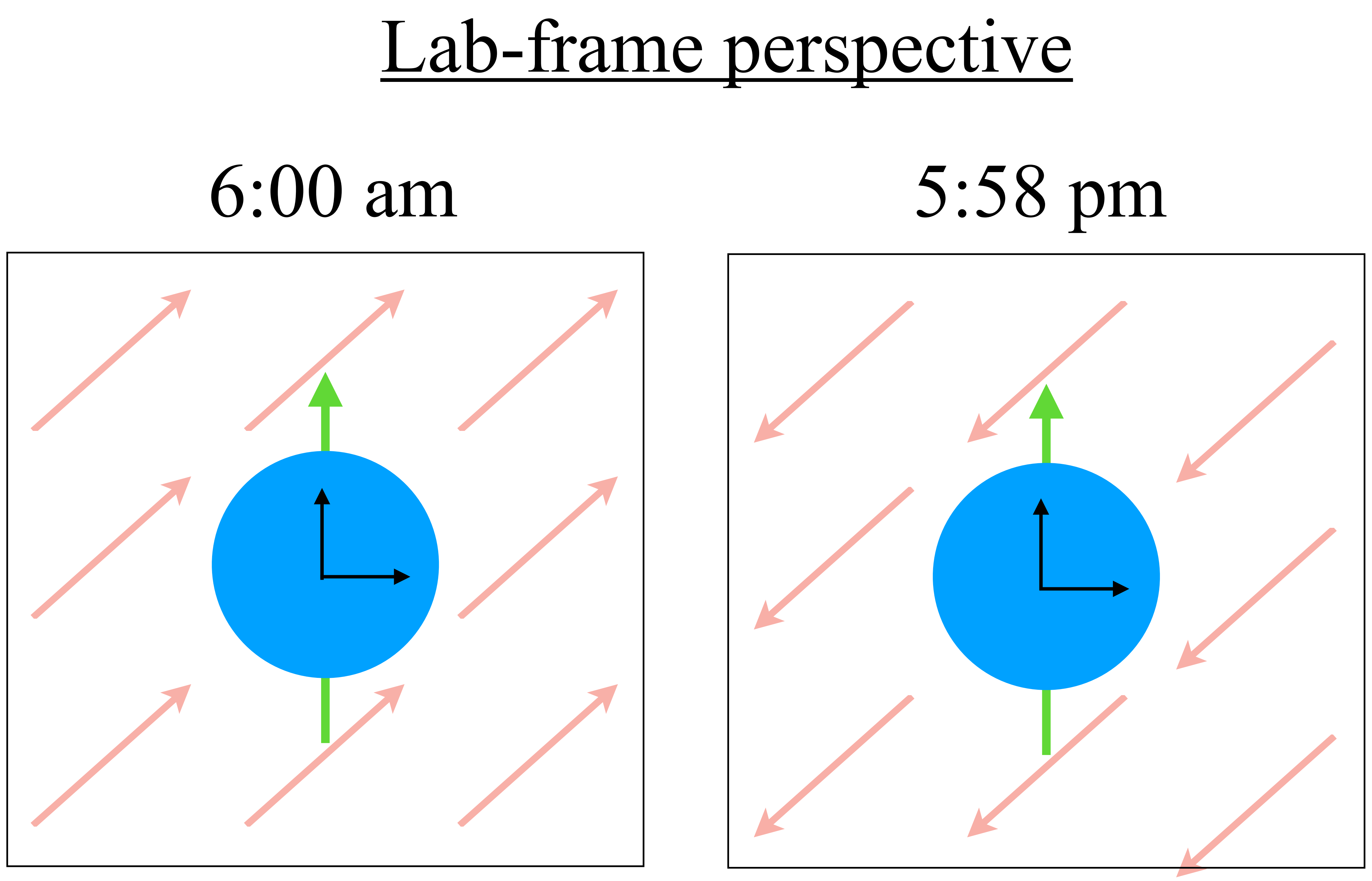
<u>Useful</u> to introduce ≈ inertial Sun-Centered Frame (SCF)





Sidereal oscillations





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

$$\overbrace{c_{\text{lab}}^{\mu\nu}}^{\mu,\nu\,=\,0,1,2,3} \approx R^\mu{}_\alpha R^\nu{}_\beta \overbrace{c_{\text{SCF}}^{\alpha\beta}}^{\alpha,\beta\,=\,T,X,Y,Z}$$

Lab coeffs. function of
$\cos(\omega_\oplus T_\oplus)$, $\sin(\omega_\oplus T_\oplus)$

$\omega_\oplus = 2\pi/T_{\text{sid.}} \approx 2\pi/(23\text{ h }56\text{ min})$
$T_\oplus =$ local sidereal time

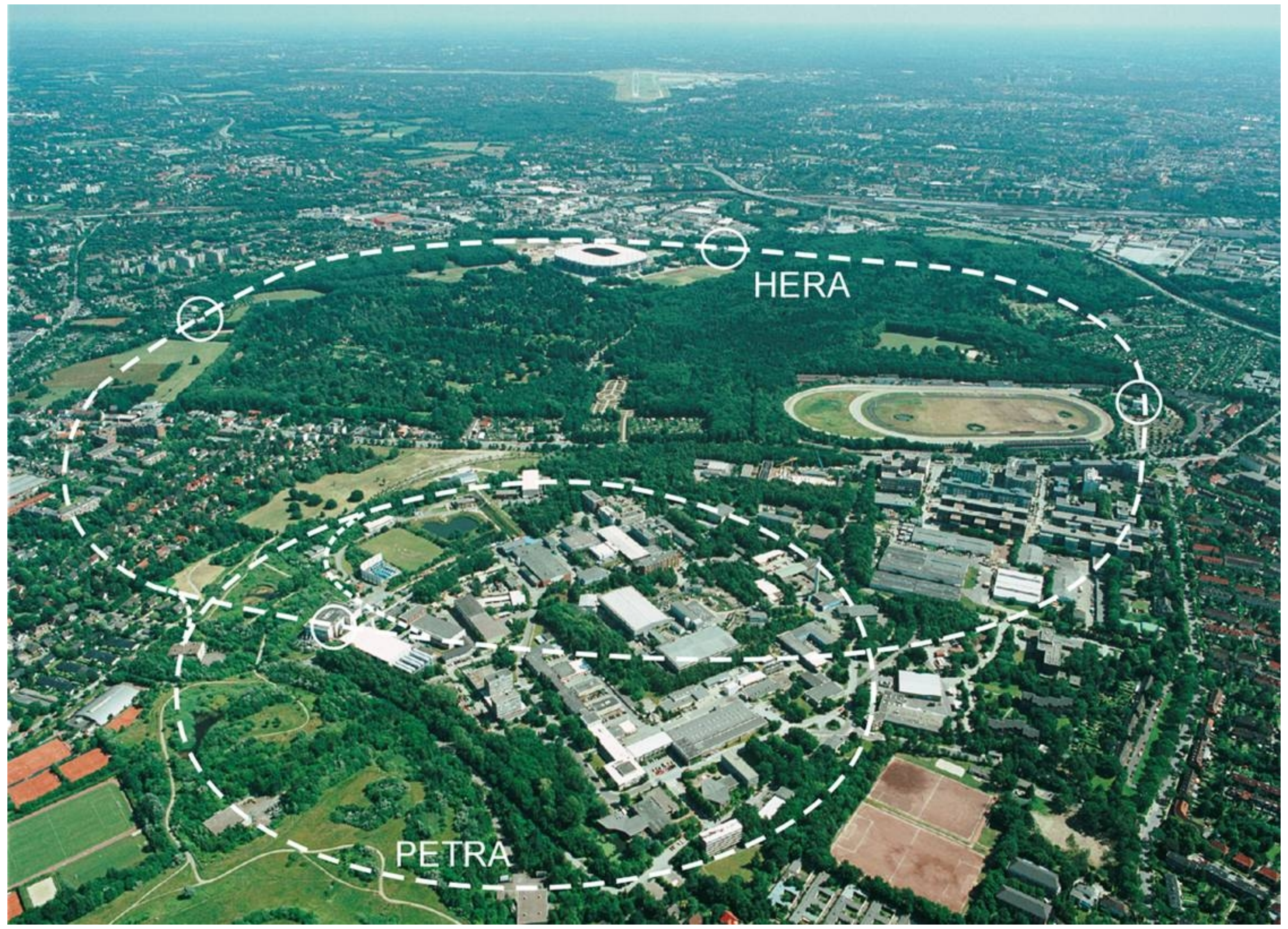
Sidereal oscillations

Six coefficient combinations induce oscillations

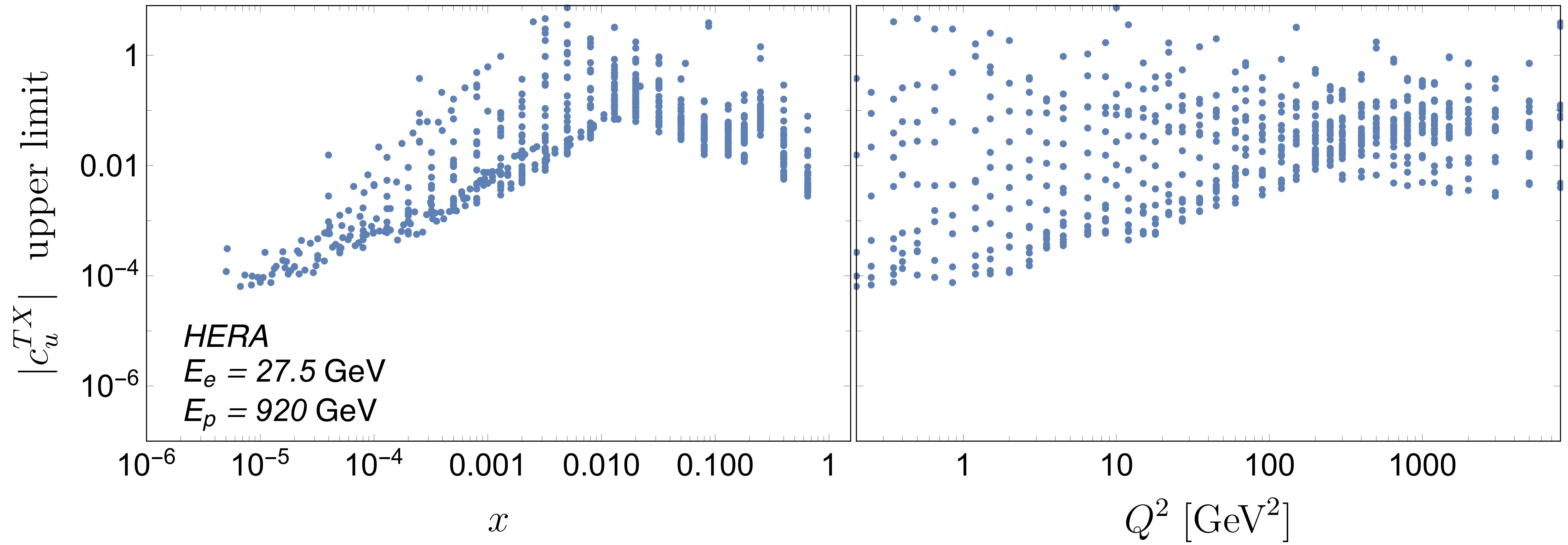
$$\sigma \approx \sigma_{\rm SM}[1 + c_f^{\alpha\beta} f_{\alpha\beta}(x, Q^2, T_\oplus)]$$

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

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



www.desy.de



- Larger collision energies favored
- Most sensitivity @ low x, Q^2
- Best limits $\sim \mathcal{O}(10^{-5})$

Lorentz- and CPT-violating parton model

Initial studies assumed LO parton model kinematics $k = \xi p$ (inconsistent here)

V. A. Kostelecký, E. Lunghi, NS, A. R. Vieira, JHEP **04**, 143 (2020)
E. Lunghi, NS, A. Szczepaniak, A. R. Vieira, JHEP **04**, 228 (2021)

Develop Lorentz-violating analog to parton model

$$\mathscr{L}_\psi = \frac{1}{2}\bar{\psi}\left(\gamma^\mu iD_\mu + \widehat{\mathcal{Q}}\right)\psi + \mathrm{h.c.}$$

$$\begin{aligned}\frac{1}{2}\bar{\psi}\,\widehat{\mathcal{Q}}\,\psi \supset & - a^\mu\bar{\psi}\gamma_\mu\psi - b^\mu\bar{\psi}\gamma_5\gamma_\mu\psi + \cdots \\ & + c^{\mu\nu}\bar{\psi}\gamma_\mu iD_\nu\psi + d^{\mu\nu}\bar{\psi}\gamma_5\gamma_\mu iD_\nu\psi + \cdots \\ & - a^{(5)\mu\alpha\beta}\bar{\psi}\gamma_\mu iD_{(\alpha}iD_{\beta)}\psi + \cdots \\ & + \cdots\end{aligned}$$

CPT odd, renormalizable

CPT even, renormalizable

CPT odd, nonrenormalizable

Example: $c_f^{\mu\nu}$ and $a_f^{(5)\mu\alpha\beta}$

Modified Dirac equation

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

$$\Downarrow$$

$$\tilde{k}^2 \equiv E^2 - \vec{k}^2 + \mathcal{O}(c_f^{kk}, \pm a_f^{kkk}) = 0 \qquad (k \not\approx \xi p)!$$

$$k_f^\mu = \xi(p^\mu - c_f^{\mu p}) \pm \xi^2 a_f^{\mu pp}$$

- Standard parton-model relation no longer holds!
- Consistency with factorization, covariance, and Ward identities *requires*

$$\boxed{\tilde{k}^\mu = \xi p^\mu}$$

- Holds @ tree-level for electroweak interactions
- "Physical" quark momentum flavor, particle/antiparticle, and spin dependent in general!

ZEUS data

ZEUS Collaboration,
PRD **107**, 092008 (2023)

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

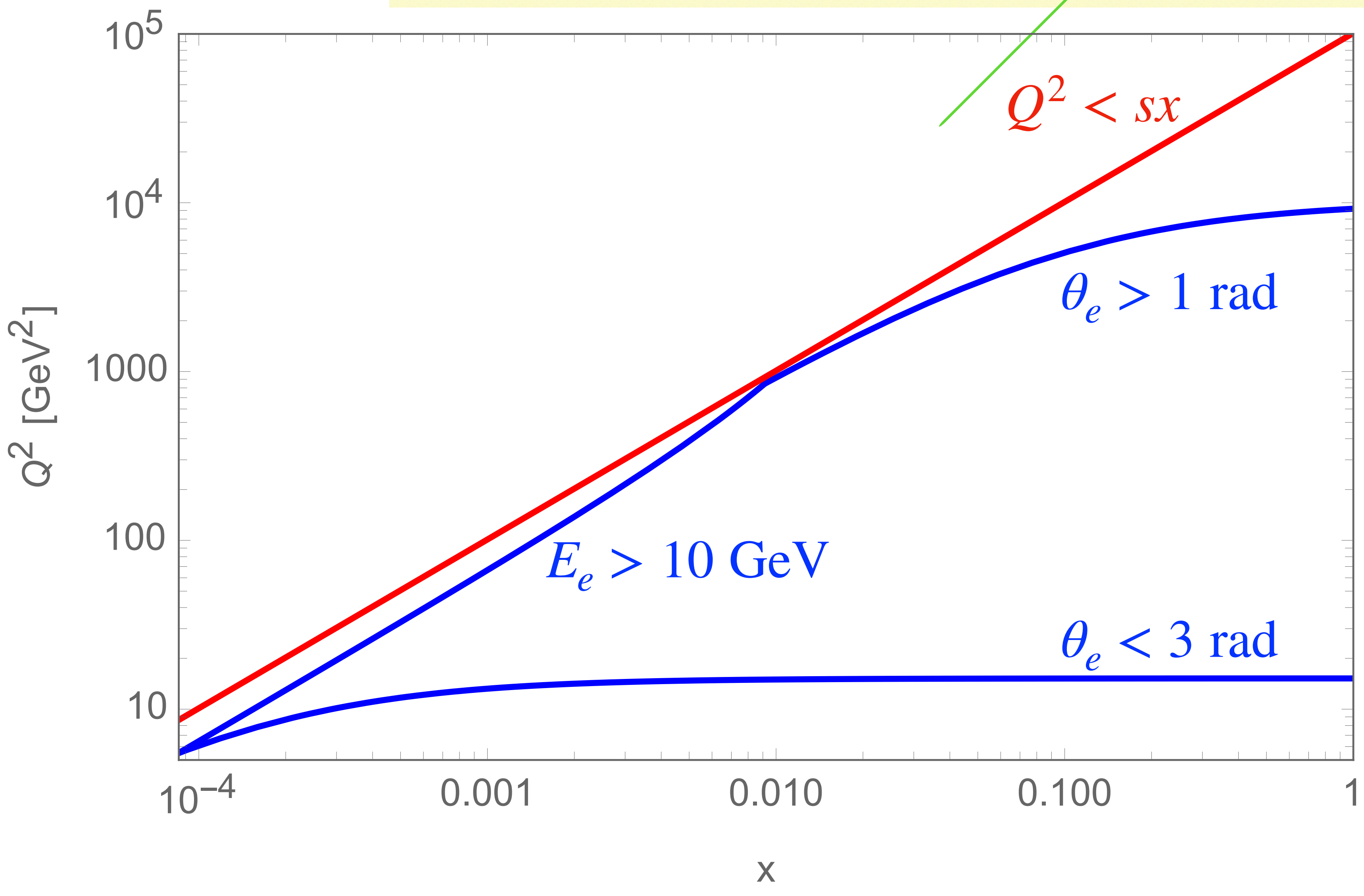
$$E_p = 920 \text{ GeV} \qquad E_{e^\pm} = 27.5 \text{ GeV}$$

$$\int \mathscr{L}_{\text{lumi}}(t)dt = 372 \text{ pb}^{-1}$$

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	?

DIS event selection

- $Q^2 > 5 \text{ GeV}^2$
- $E_{e^\pm}^{\text{scattered}} > 10 \text{ GeV}$
- $47 \text{ GeV} < E - p_z < 69 \text{ GeV}$
- $e^\pm$ detection probability > 0.9
- $1 \text{ rad} < \theta(\text{e}^\pm)_{\text{min}} < 3 \text{ rad}$



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

Cross sections

$$\frac{d\sigma}{dx\, dQ^2\, d\phi_{T_\mathrm{p}}}$$

timestamp of DIS event

$$\phi_{T_\mathrm{p}} = \mathrm{Mod}(T_\oplus, T_\mathrm{p})/T_\mathrm{p} \in [0,1] = \text{event phase}$$

Lorentz-violating signal $\Rightarrow T_\mathrm{p} = T_{\mathrm{sid.}} = 23.9345$ h

Instantaneous luminosity $\mathscr{L}_{\mathrm{lumi}}(t)$ (and thus # events/sec $\propto d\sigma$) decays over ~ several hours for each fill — must account for/subtract away

Problem: $\mathscr{L}_{\mathrm{lumi}}(t)$ not available!

Cross-section ratios

Instead consider *luminosity-insensitive* double ratios of cross sections $r(\mathrm{P}S_1, \mathrm{P}S_2)$

$\mathrm{PS}_{1,2}$ are chosen cuts of phase space, e.g. $\mathrm{P}S_1 = Q^2 > Q^2_{\mathrm{cut}}$ and $\mathrm{P}S_2 = Q^2 < Q^2_{\mathrm{cut}}$

$$r(\mathrm{P}S_1, \mathrm{P}S_2) = \frac{\int_{\mathrm{PS}_1} dxdQ \frac{d\sigma}{dQ\, dx\, d\phi_T} / \int_{\mathrm{PS}_1} dxdQd\phi_T \frac{d\sigma}{dQ\, dx\, d\phi_T}}{\int_{\mathrm{PS}_2} dxdQ \frac{d\sigma}{dQ\, dx\, d\phi_T} / \int_{\mathrm{PS}_2} dxdQd\phi_T \frac{d\sigma}{dQ\, dx\, d\phi_T}}$$

- ☑ Equal to 1 in absence of LV
- ☑ Can focus on PS regions of interest
- ☑ (Partial) cancellation of systematics

Chosen cuts:

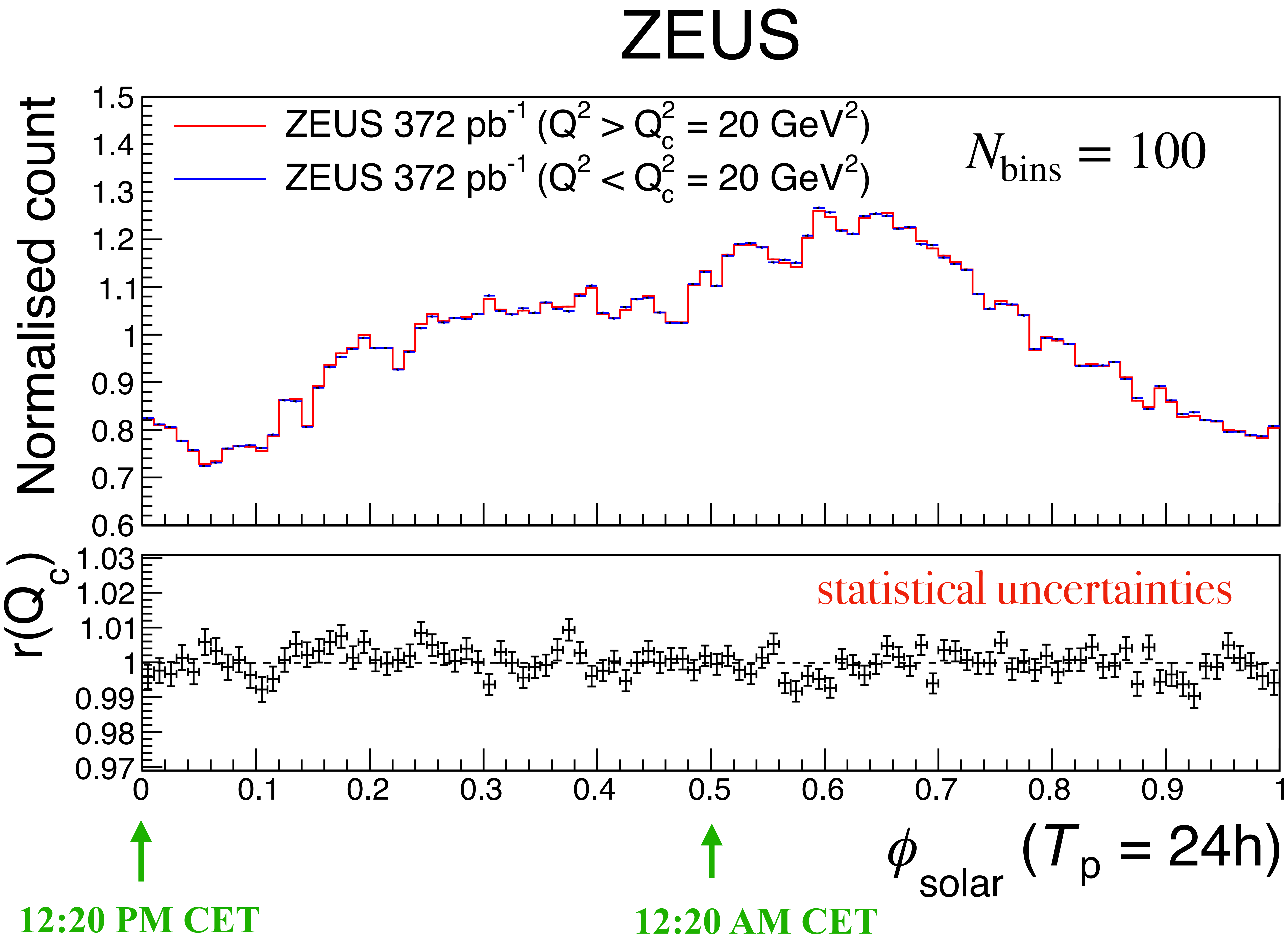
$Q^2_{\mathrm{cut}} = 20\ \mathrm{GeV}^2$ → *negligible* sensitivity to LV $\Rightarrow$ *control studies*

$x_{\mathrm{cut}} = 10^{-3}$ → sensitive to LV $\Rightarrow$ *search*

➤ no time dependence expected

Four test periods considered: $T_{\mathrm{p}} = (T_{\mathrm{solar}}, T_{\mathrm{sid.}}, [1\ \mathrm{h}, 24\ \mathrm{h}\ 4\ \mathrm{min})] = T_{\mathrm{test}})$

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

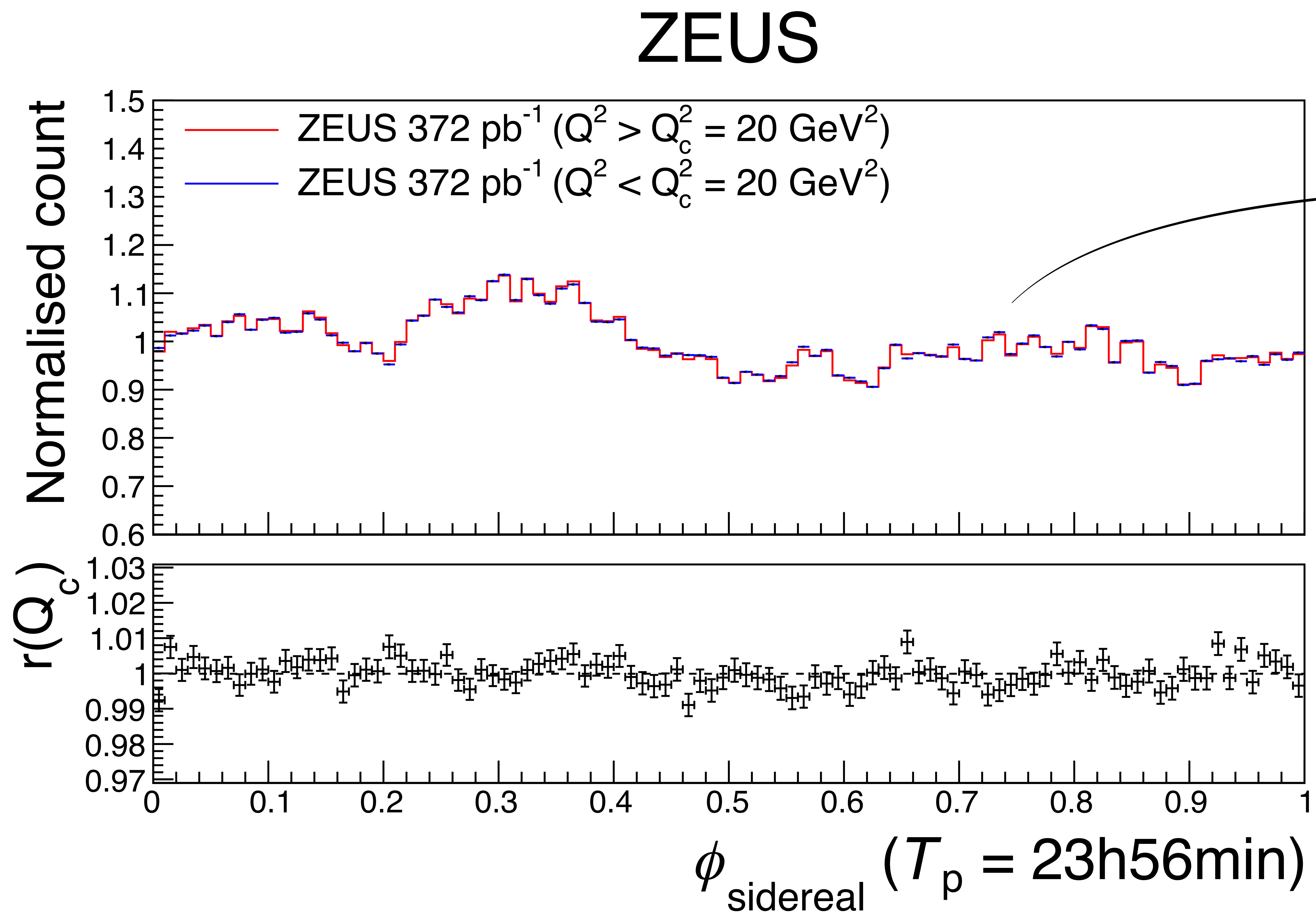


$$\text{Norm. count} = \frac{\#\text{ events per bin}}{(\text{total \# events}) \times (\text{bin width})}$$

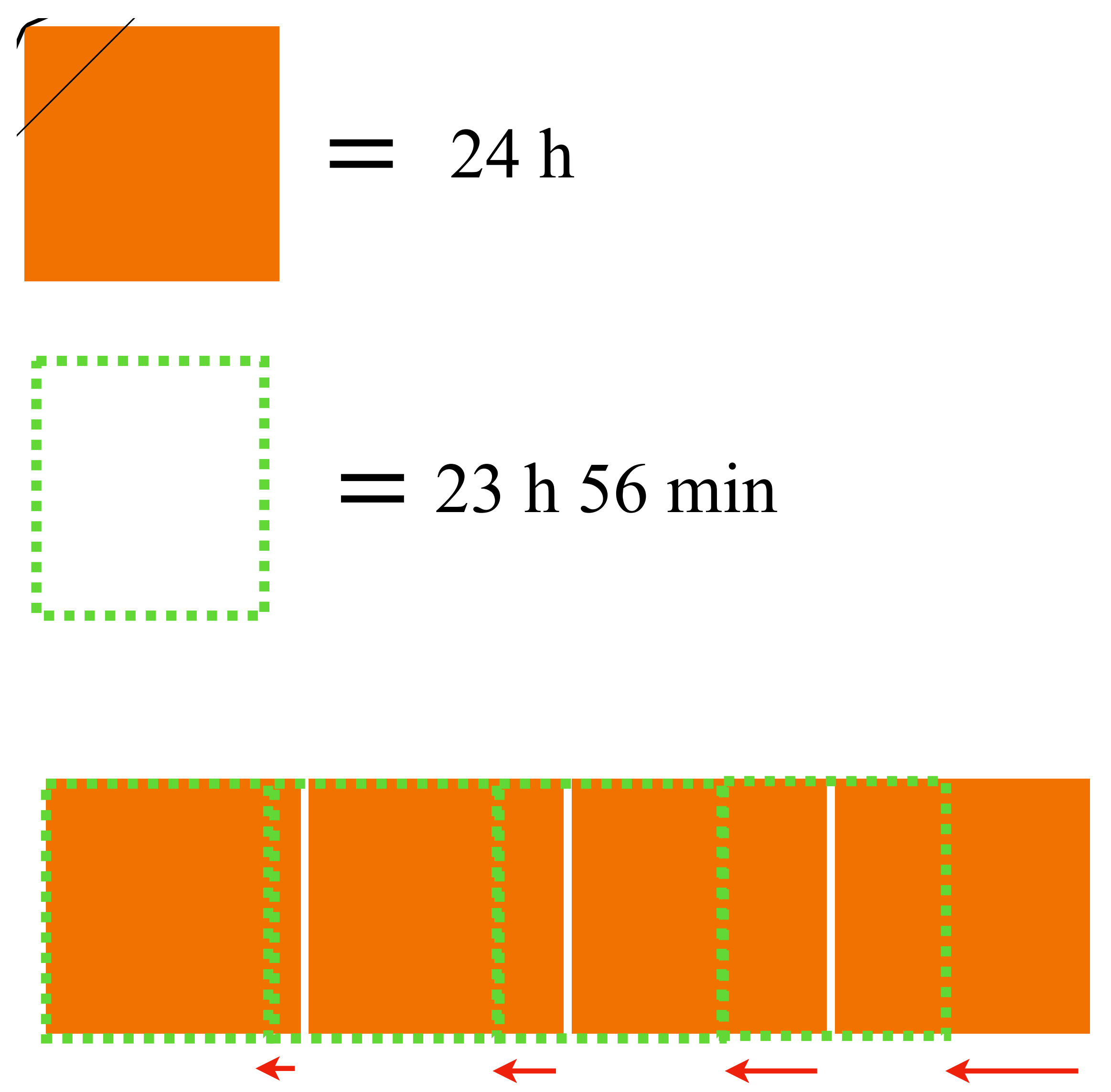
Distributions follow luminosity profile

Luminosity drops out!

Control studies: $(Q^2_{cut}, T_{sidereal})$

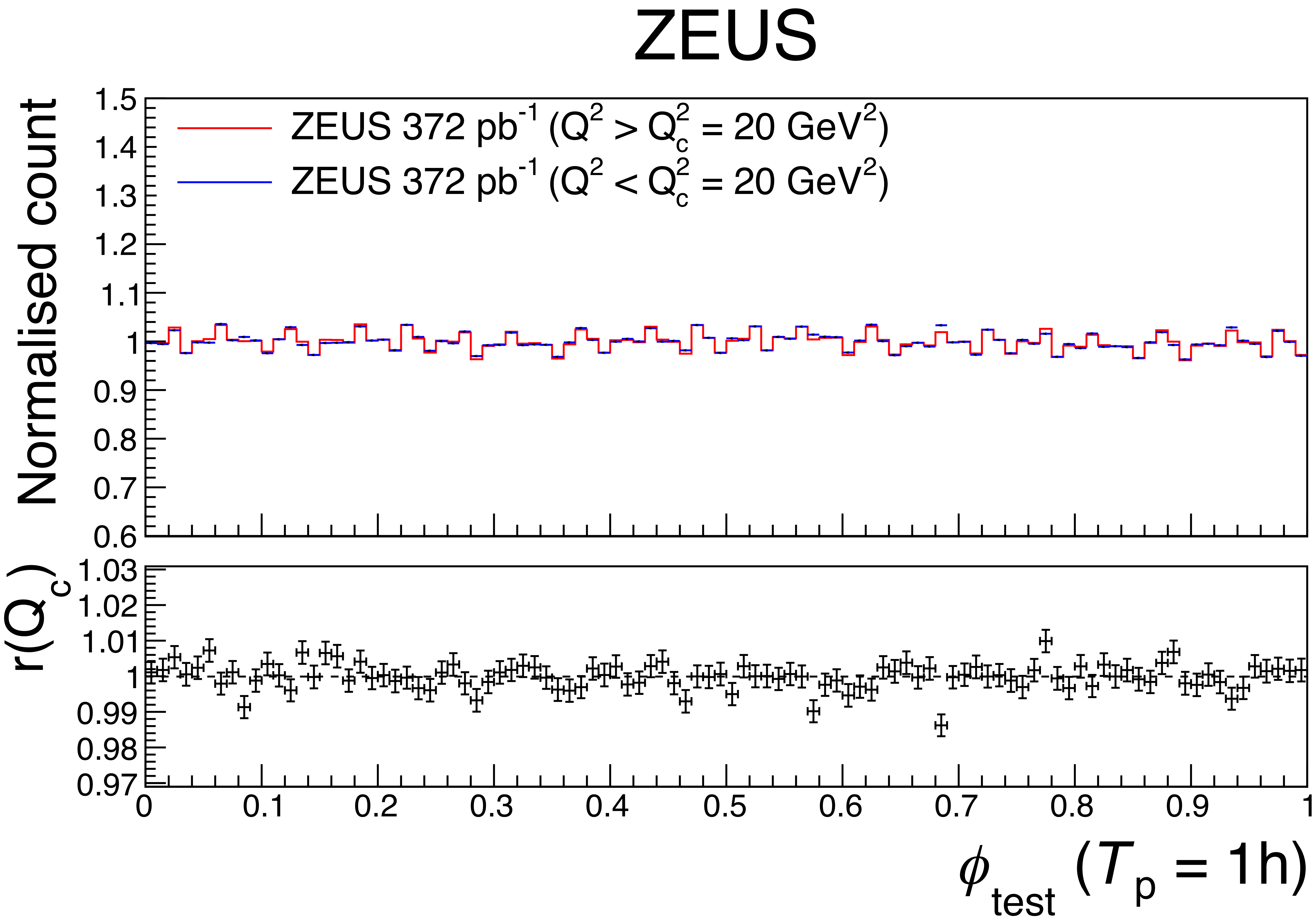


Partial dilution of solar period



Sidereal period collect events from different days — becomes pronounced over long periods of data-taking

Control studies: (Q^2_{cut}, $T_{\mathrm{test}} = 1$ h)

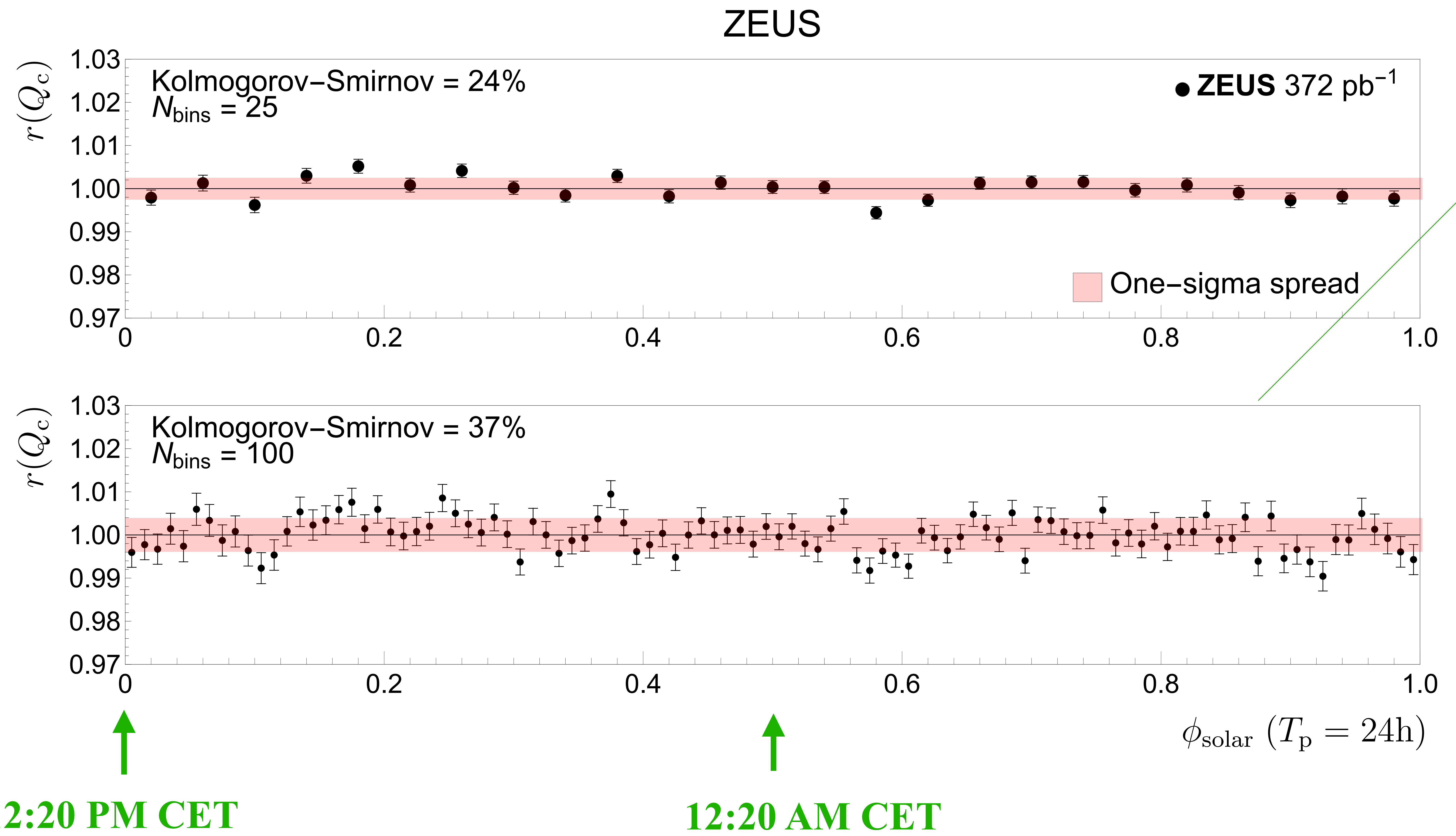


1 hour period mixes everything

All bins expected to have similar # events (is observed)

$(Q^2_{\rm cut}$, solar): systematics

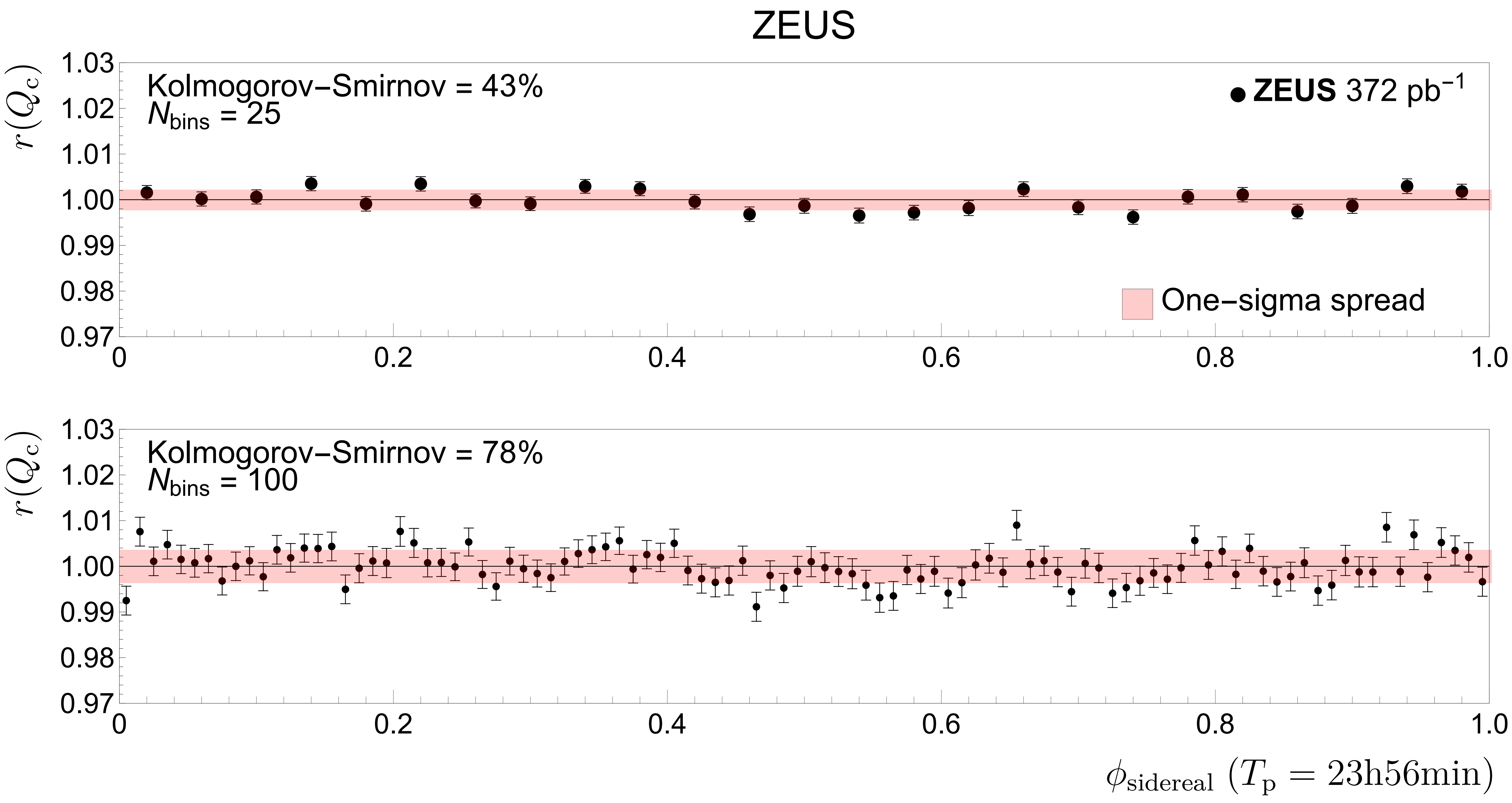
To what extent do systematic uncertainties affect distributions?



$= \sigma_{\text{central values}}$

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

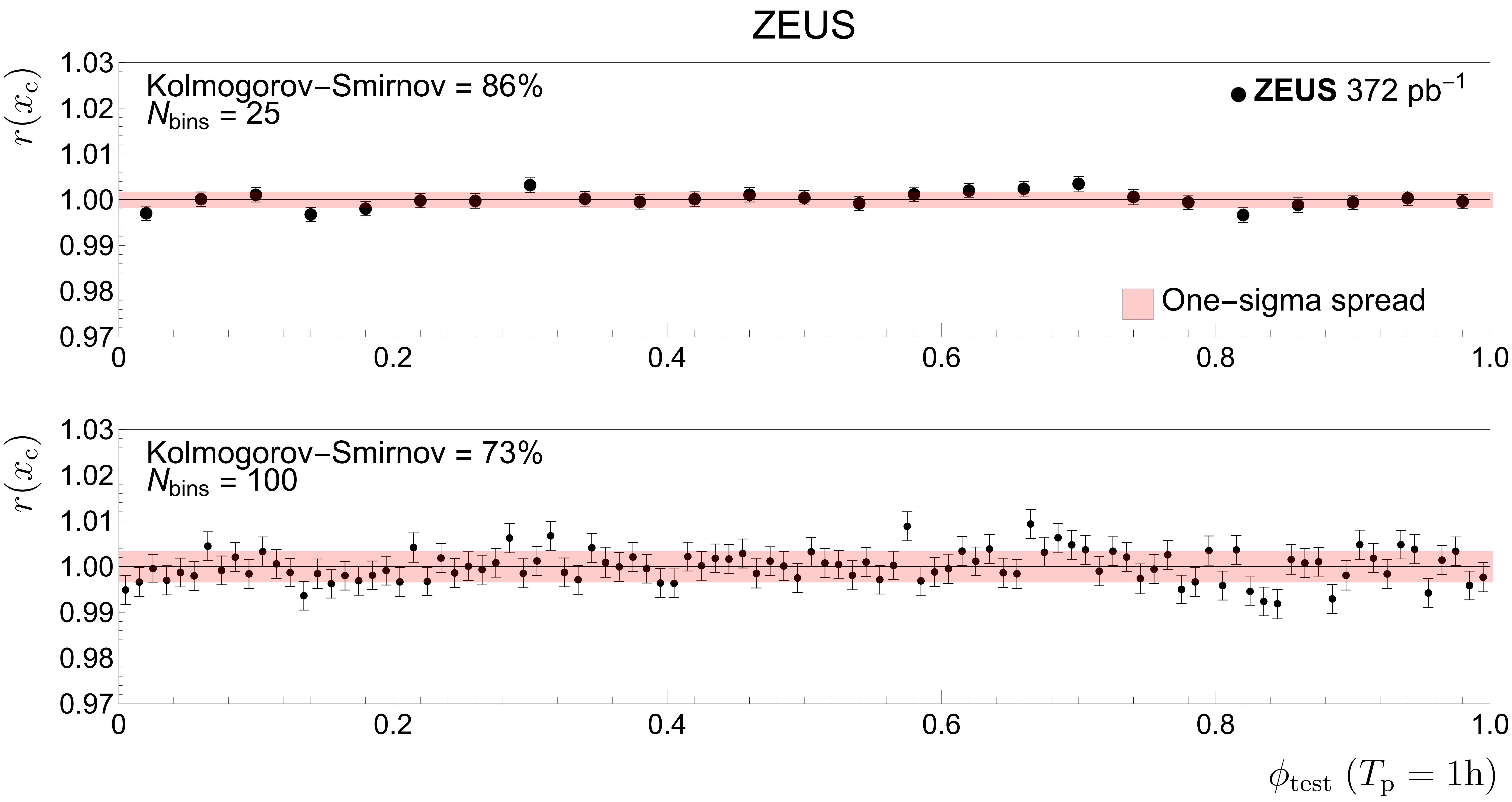
(Q^2_{cut}, sidereal): systematics



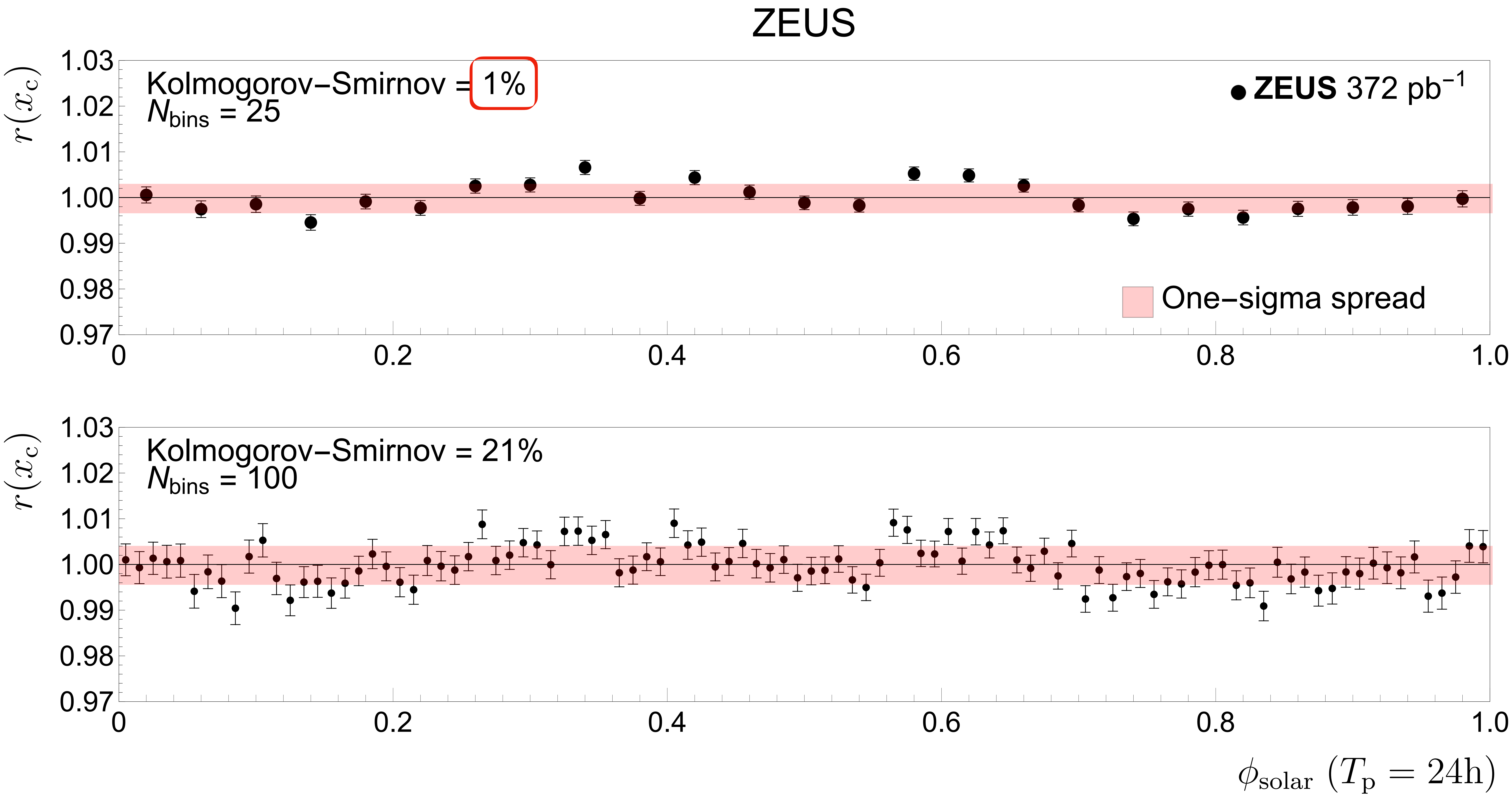
Control studies: summary

- No evidence for impact of systematic uncertainties in all cases ✓
- *Cannot* conclude the same for x_{cut} distributions since efficiencies more sensitive to x (e.g. high/low trigger efficiencies)
- $d\sigma$ is also sensitive to LV effects from different x regions
- $\Rightarrow$ perform x_{cut} analyses

$(x_{\mathrm{cut}} = 10^{-3}, T_{\mathrm{test}} = 1\ \mathrm{h})$



$(x_{\mathrm{cut}}, T_{\mathrm{solar}})$



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

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

Monte Carlo/trigger studies

$$\sigma_{\text{syst}} \sim \begin{cases} 0.1\,\%\,, & 1\text{ h} \\ 0.3\,\%\,, & 24\text{ h} \end{cases}$$

(not observed in any prior ZEUS studies)

Not due to known sources! $\Rightarrow$ Check with MC events and “High”/“Low” triggers

MC events

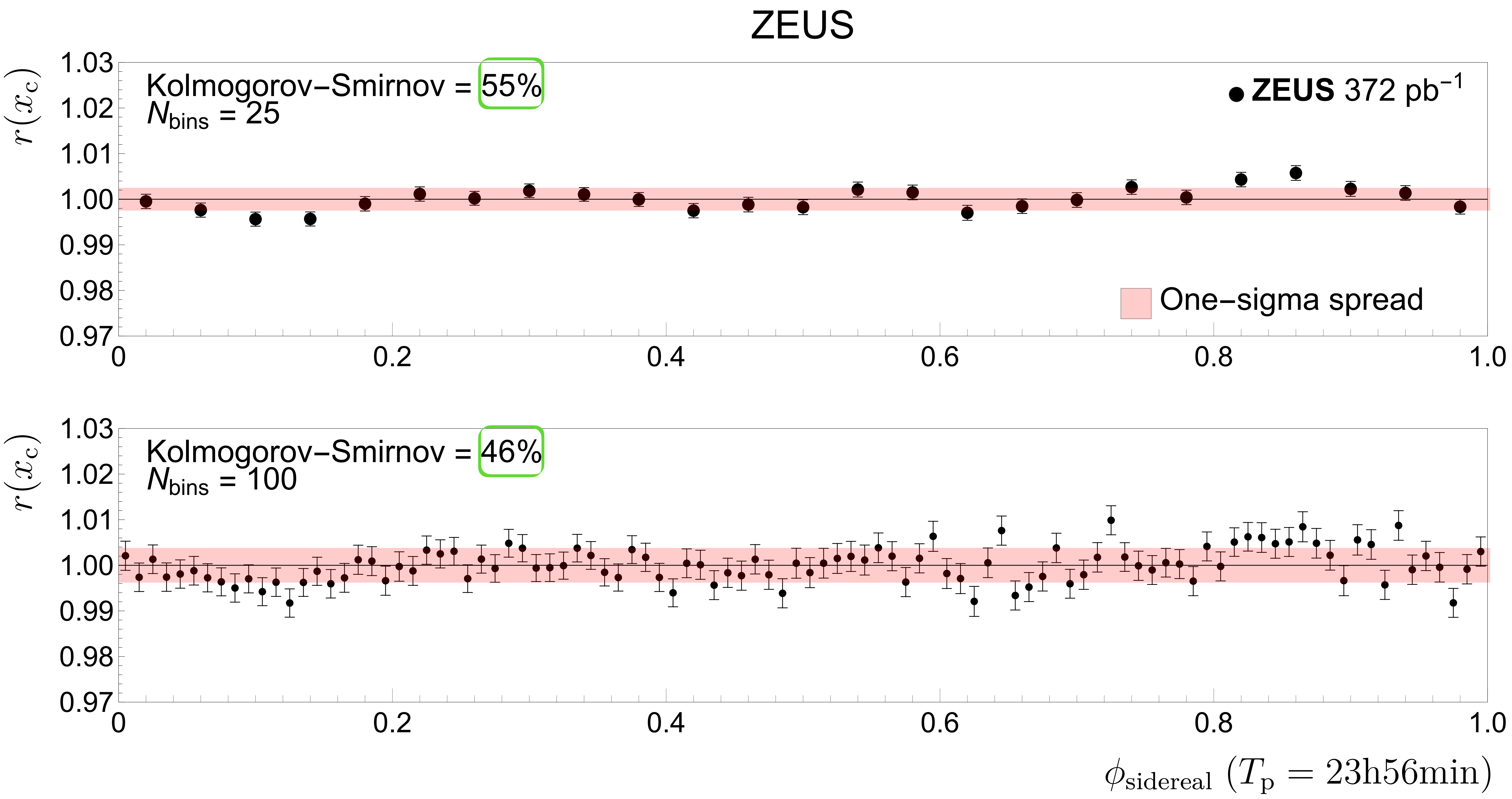
- MC events are generated based on the state of detector/luminosity tied to real data “run number”
- Used this to created MC “timestamps” and analogous distributions
- Distributions consistent with statistics alone

High/Low trigger distributions

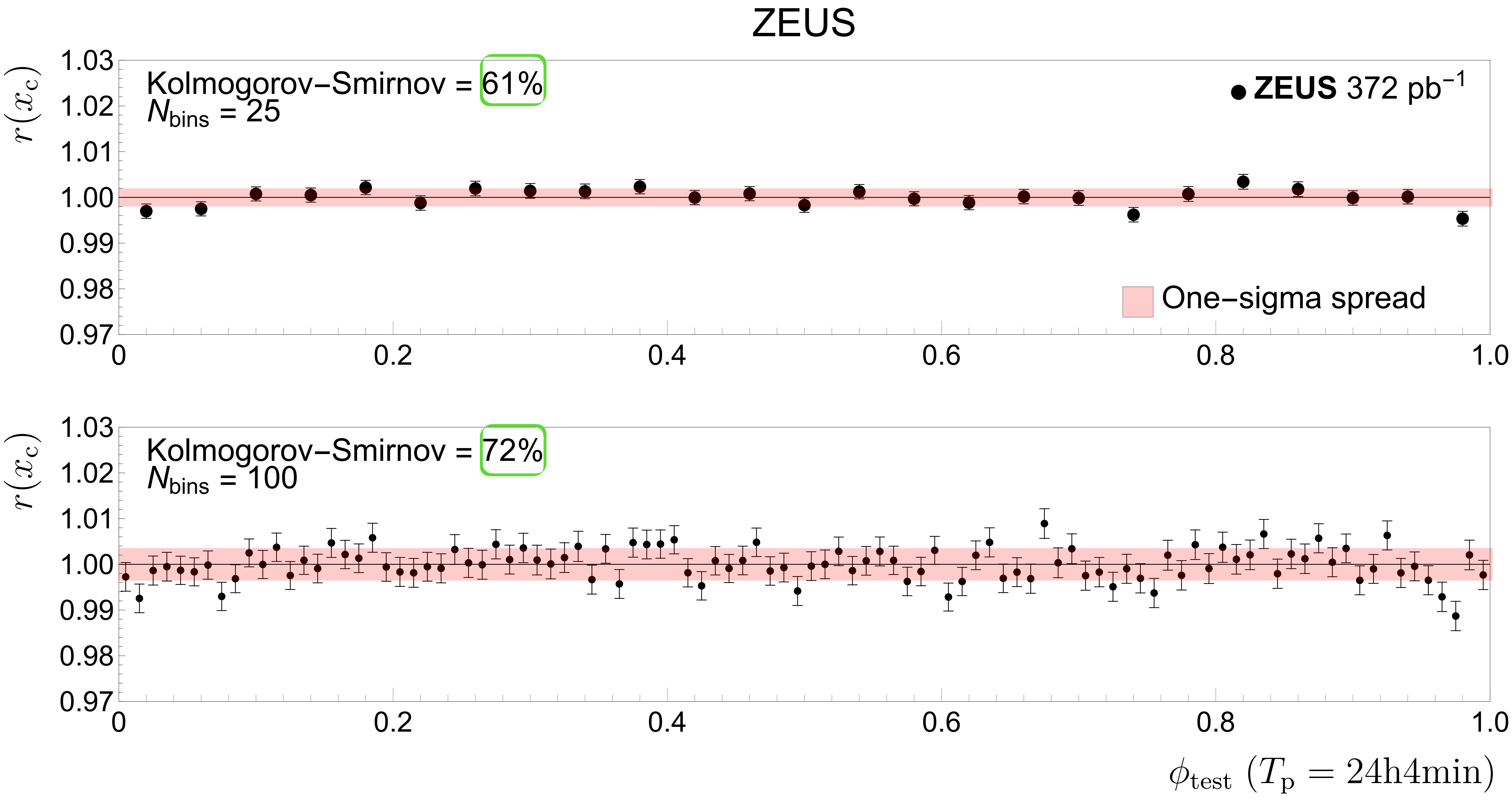
- Detector operates in different trigger configurations if # events is large (“High”) vs small (“Low”)
- Studied High and Low events separately
- Distributions consistent with statistics alone

Conclusions: extracted systematics are not accounted for by known detector effects

$(x_{\mathrm{cut}}, T_{\mathrm{sidereal}})$



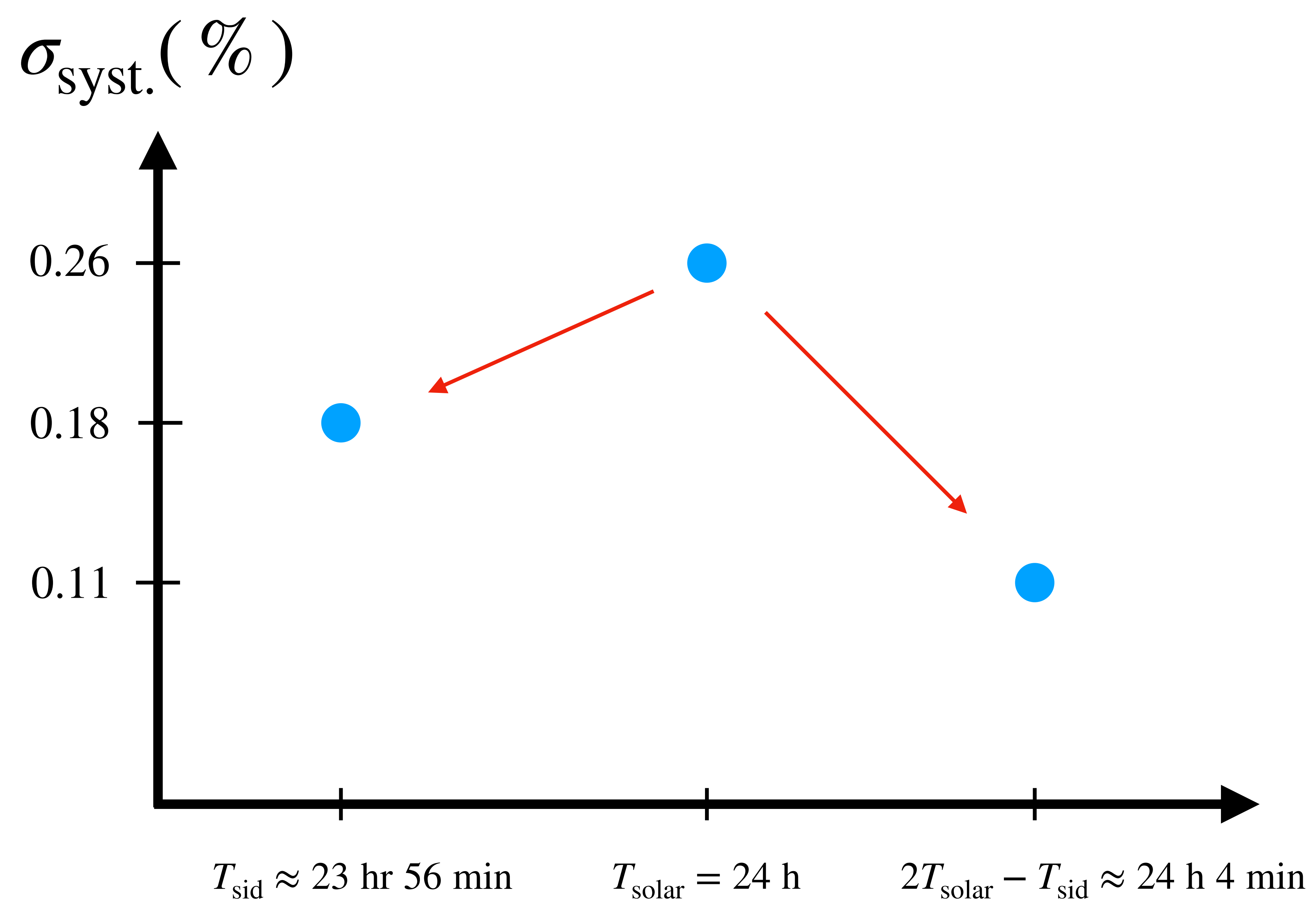
$(x_{\text{cut}}, T_{\text{test}} = 24\ \text{h}\ +\ 4\ \text{min})$



x_{cut} analyses: summary

Pervasive $\sigma_{\text{syst.}}$, largest for solar distributions, many of which have low KS probabilities, *could indicate* a "solar-periodic" effect:

- Smaller $\sigma_{\text{syst.}}$ from sidereal distributions compatible with genuine 24 h effect diluted by $\approx \pm 4$ min (?)
- Cannot verify this conjecture — choose to *conservatively* adopt $\sigma_{\text{syst.}}$ as extracted by $2T_{\text{solar}} - T_{\text{sid}}$ = "solar shifted" phase
- Choice avoids "washing out" possible genuine sidereal effect
- Chose $N_{\text{bins}} = 100$ for analysis



$$\boxed{\sigma_{\text{sid}}^{\text{tot}} \approx \sqrt{\left(\bar{\sigma}_{\text{stat}}^{\text{sid}}\right)^2 + \left(\sigma_{\text{syst.}}^{\text{solar shift}}\right)^2} = 0.35\,\%}$$

Constraints

The theoretical ratios are calculated in each bin:

$$r_i^{\text{theo}} = \frac{N_{\text{bins}}}{2\pi} \int_{\frac{2\pi(i-1)}{N_{\text{bins}}}}^{\frac{2\pi i}{N_{\text{bins}}}} r(x > x_c, x < x_c; \theta_\oplus) d\theta_\oplus \quad (\theta_\oplus = \omega_\oplus T_\oplus)$$

$$r_c(x > x_c, x < x_c) = 1 - 12.8\, c_u^{03} - 13.9\, c_u^{33} + 0.9\, (c_u^{11} + c_u^{22})$$
$$- 4.2\, c_d^{03} - 2.9\, c_d^{33} + 0.1\, (c_d^{11} + c_d^{22})$$
$$- 3.4\, c_s^{03} - 1.8\, c_s^{33} + 2.9 \times 10^{-2}\, (c_s^{11} + c_s^{22})$$

$$r_{a^{(5)}}(x > x_c, x < x_c) = 1 - 6.1 \times 10^3\, a_u^{(5)003} + 6.8 \times 10^3\, a_u^{(5)033} - 2.5 \times 10^3\, a_u^{(5)333}$$
$$+ 5.0 \times 10^2\, (a_u^{(5)113} + a_u^{(5)223} - a_u^{(5)011} - a_u^{(5)022})$$
$$- 4.1 \times 10^2\, a_d^{(5)003} + 4.7 \times 10^2\, a_d^{(5)033} - 1.7 \times 10^2\, a_d^{(5)333}$$
$$+ 40\, (a_d^{(5)113} + a_d^{(5)223} - a_d^{(5)011} - a_d^{(5)022})$$

Express lab ↔ SCF coefficients, e.g.

$$c_f^{03} = \underbrace{- c_f^{TZ} \sin(\chi)\sin(\psi)}_{} + c_f^{TX} \left[\cos(\psi)\sin(\omega_\oplus T_\oplus) + \cos(\chi)\cos(\omega_\oplus T_\oplus)\sin(\psi)\right]$$
$$+ c_f^{TY} \left[\cos(\chi)\sin(\psi)\sin(\omega_\oplus T_\oplus) - \cos(\psi)\cos(\omega_\oplus T_\oplus)\right]$$

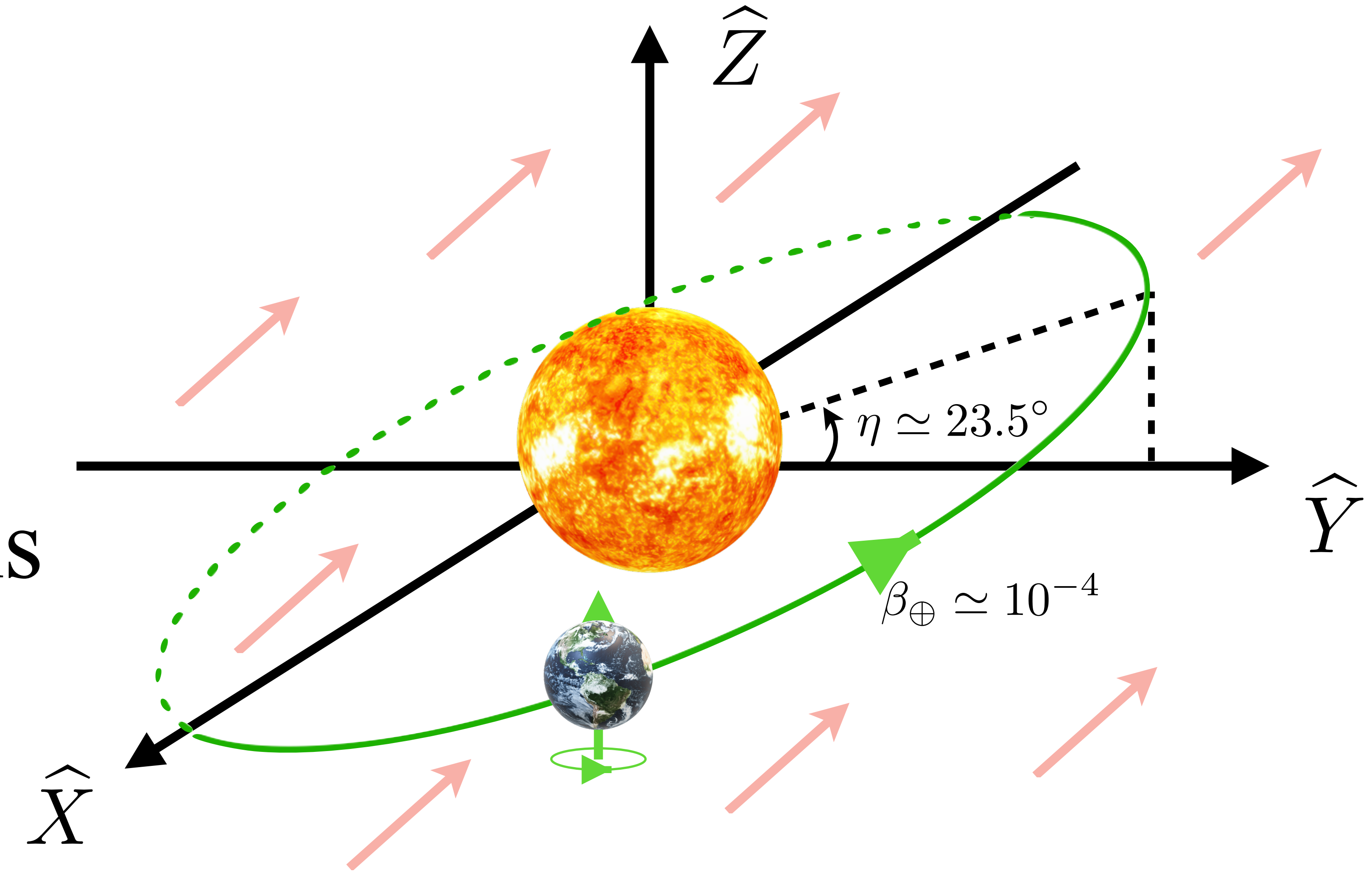
χ = colatitude lab $\quad \psi$ = beam orientation NoE

Time-independent part

Time-dependent part

Coefficients

A subset of $c_f^{\mu\nu}, a_f^{(5)\mu\alpha\beta}$ coefficients contribute to sidereal oscillations



- Those that violate ***rotation invariance***
- Can be determined from direct calculation, symmetry considerations

Observable coefficients defined in the SCF with indices T, X, Y, Z

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

rotation violating

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

rotation and CPT violating

For u, d, and s quarks and antiquarks: 42 coefficients contribute to signal

Constraints

The theoretical ratios are calculated in each bin:

$$r_i^{\text{theo}} = \frac{N_{\text{bins}}}{2\pi} \int_{\frac{2\pi(i-1)}{N_{\text{bins}}}}^{\frac{2\pi i}{N_{\text{bins}}}} r(x > x_c, x < x_c; \theta_\oplus) d\theta_\oplus \quad (\theta_\oplus = \omega_\oplus T_\oplus)$$

For each of the 42 coefficients for LV construct $\boxed{\chi^2 = \frac{1}{(\sigma_{\text{tot}}^{\text{sid}})^2} \sum_{i=1}^{N_{\text{bins}}} \left(r_i^{\text{exp}} - r_i^{\text{theo}} \right)^2}$

Data reasonably described by Standard Model $\begin{cases} \chi^2_{\text{SM}} & = 113.8 \\ p_{\text{SM}} & = 0.16 \end{cases}$

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}

- ☑ First direct *experimental* constraints on all coefficients
- Theory estimates from cosmic rays $|c_{u,d}^{\mu\nu}| \sim 10^{-21}$ (!)
- M. Schreck, PRD **96**, 095026 (2016)
  - Estimate involves significant model dependence
- ☑ $c_s^{\mu\nu}$ limits derived here are first limits on sea quarks

Constraints

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

These coefficients are *not* sensitive to *s* (or any sea) quarks!

$$f_s(x) \approx f_{\bar{s}}(x)$$

$$a^{(5)}_{\bar{s}} = -\, a^{(5)}_{s}$$

$$\Rightarrow d\sigma_s \sim a^{(5)}_s f_s(x) + a^{(5)}_{\bar{s}} f_{\bar{s}}(x) \approx 0$$

- No previous constraints exist on $a^{(5)}_{\text{quark}}$ coefficients
- One possible point of comparison: effective *proton* coefficients $|a^{(5)}_{\text{proton}}| \sim 10^{-8} - 10^{-7}\ \text{GeV}^{-1}$ from hydrogen transitions
  - V. A. Kostelecký, A. Vargas, PRD **92**, 056002 (2015)

ZEUS
$c_u^{TY} = -1.7 \times 10^{-4}$
$c_u^{TY} = +9.8 \times 10^{-5}$
$c_u^{TY} = -10^{-3}$
ZEUS 372 pb^{-1}
$c_u^{XX} - c_u^{YY} = -2.1 \times 10^{-4}$
$c_u^{XX} - c_u^{YY} = +2.5 \times 10^{-4}$
$c_u^{XX} - c_u^{YY} = +10^{-3}$
$a_{\mathrm{Su}}^{(5)XXY} = -2.3 \times 10^{-7}$ GeV^{-1}
$a_{\mathrm{Su}}^{(5)XXY} = +1.8 \times 10^{-7}$ GeV^{-1}
$a_{\mathrm{Su}}^{(5)XXY} = +2 \times 10^{-6}$ GeV^{-1}
$r(x_c)$
ϕ_{sidereal} (T_p = 23h56min)
= p = 0.05 "boundary values"
= excluded value

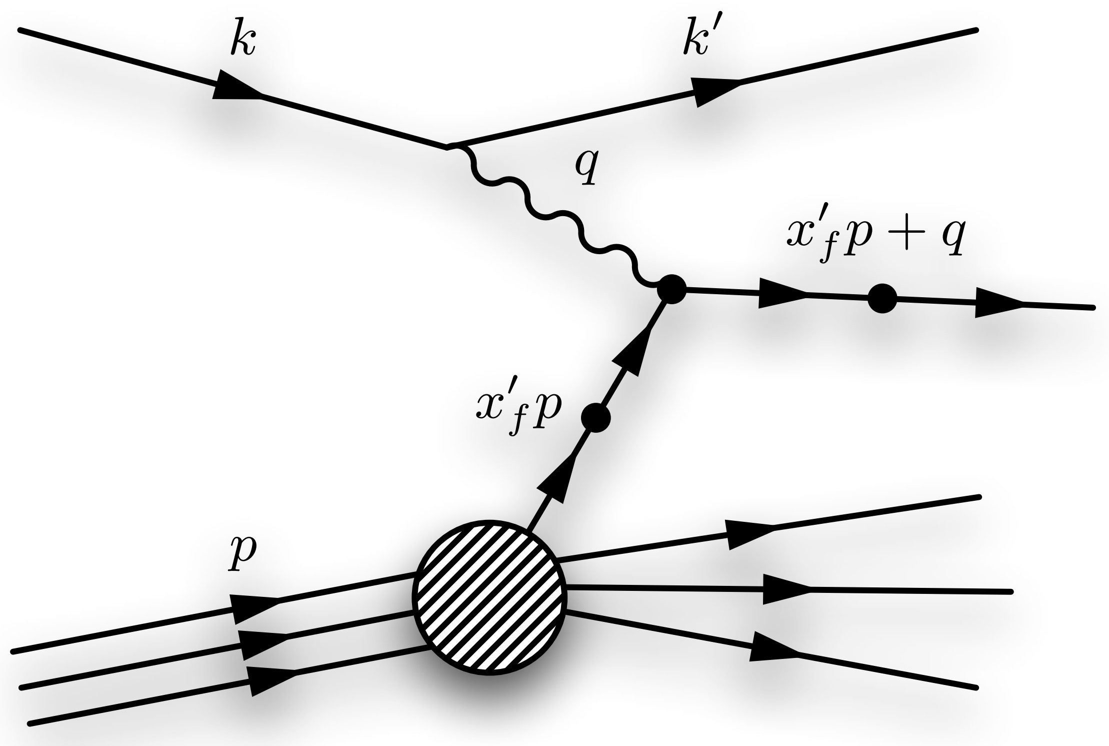
Take-home messages

1. Lorentz and CPT violation from EFT

- ☑ Minimal deviations from SM (and GR)
- ☑ Can reliably calculate perturbative corrections
- ☑ Can probe corrections with sensitive experiments

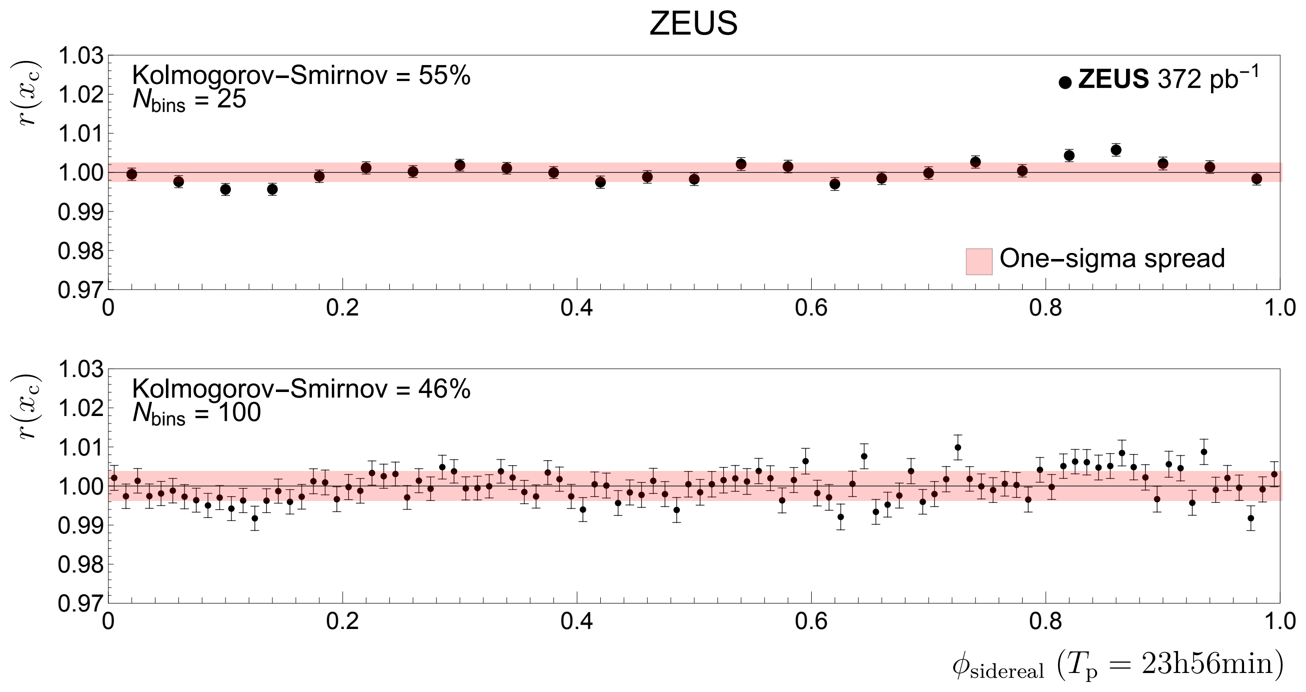
SME = SM+LV

2. Parton-model extension developed



- ☑ Path to access challenging parton-level signals
- ☑ Framework to build on/generalize (e.g. NLO effects)

3. ZEUS study first of its kind



- ☑ Direct test of anisotropic (light-)quark LV/CPTV
- ☑ Foundation for future studies

Stay tuned!