Testing Lorentz and CPT violation in the quark sector at colliders

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CEA Paris-Saclay

Based on:

A. Kostelecky, E.L. and A. Vieira, **1610.08755**, Phys.Lett.B. 769 (2017) 272
E.L. and N. Sherrill, **1805.11684**, Phys.Rev.D 98 (2018) 11
A. Kostelecky, E.L., N. Sherrill and A. Vieira, **1911.04002**, JHEP 04 (2020) 143
E.L., N. Sherrill, A. Szczepaniak and A. Vieira, **2011.02632**, JHEP 04 (2021) 228
A. Belyaev, L. Cerrito, E.L., S. Moretti and N. Sherrill, **2405.12162**

theory

ZEUS Collaboration, **2212.12750**, Phys.Rev.D 107 (2023) 9, 092008

experiment

Special thanks to Nathan Sherrill and to several members of the ZEUS collaboration (Devan Gangadharan, Achim Geiser, Matthew Wing, Katarzyna Wichmann, Iris Abt, Peter Bussey)

Outline

- Standard Model Extension (SME):
  an effective field theory which allows the incorporation of Lorentz and CPT violation
- Why looking for Lorentz and CPT violation?
- Lorentz Violation in the quark sector: Deep Inelastic Scattering and Drell-Yan
- Expected sensitivity at electron-proton and proton-proton colliders:
  - DIS at HERA (ZEUS, H1) and EIC
  - DY at LHC (Atlas, CMS)
- Results of DIS analysis using ZEUS entire dataset
- Constraints on top quark properties at LHC

The problem with interpreting Lorentz and CPT tests

- A consequence of CPT invariance is the equality of particle and antiparticle masses

t $\quad I(J^P) = 0(1/2^+)$

Charge = $\frac{2}{3}$ e Top = +1

See related review:

Top Quark

t-QUARK MASS	
t-Quark Mass (Direct Measurements)	172.57 ± 0.29 GeV (S = 1.5)
t-Quark Mass from Cross-Section Measurements	$162.5^{+2.1}_{-1.5}$ GeV
t-Quark Pole Mass from Cross-Section Measurements	172.4 ± 0.7 GeV
$m_t - m_{\bar{t}}$	-0.15 ± 0.20 GeV (S = 1.1)
t-quark DECAY WIDTH	$1.42^{+0.19}_{-0.15}$ GeV (S = 1.4)

  - Is there some parameter that the $\delta m_t = -0.15 \pm 0.20$ GeV measurement constrains?
  - Conventional Lorentz invariant QFTs preserve CPT: it is not possible to write different mass terms for particles and antiparticles
  - The Standard Model Extension (SME) is the only framework (as far as I know) in which these kind of measurements can be interpreted

- A similar problem appeared in studies of anomalous triple and quartic gauge boson interactions
  - Early studies focused on simply modifying the vertices ($\mathscr{L}_{\text{eff}} \in g_{WWV}\, \kappa_V\, W^\dagger_\mu W_\nu V^{\mu\nu} + \cdots$) which had issues with Gauge invariance and unitarity (requiring form factors and other ad-hoc solutions)
  - Modern approach uses the SM Effective Theory (SMEFT) in which $SU(2) \times U(1)$ invariant higher dimensional operators are introduced, thus bypassing entirely issues with gauge invariance and unitarity

Building the Standard Model Extension: basic idea

- The SME was originally formulated in the context of Spontaneous Lorentz Symmetry Breaking
- In presence of tensor fields with non-vanishing vacuum expectation values we get interactions like:

neglecting the fluctuating part of the tensor field

$$\frac{C^{\mu\nu}(x)}{M}\,\bar{\psi}(x)\gamma_\mu\partial_\nu\psi(x) = \Big(\underbrace{\langle C^{\mu\nu}(x)/M\rangle}_{c^{\mu\nu}\ \text{[coefficient for Lorentz Violation]}} + \delta C^{\mu\nu}(x)\Big)\,\bar{\psi}(x)\gamma_\mu\partial_\nu\psi(x) \Longrightarrow \boxed{c^{\mu\nu}\,\bar{\psi}(x)\gamma_\mu\partial_\nu\psi(x)}$$

- In 4-dimensional QFTs it is difficult to construct models in which tensor fields acquire dynamically a non-zero vacuum expectation value (vev), with some exceptions if gravity is included in the picture
- In the original papers of Kostelecky & Samuel these tensor vev's have been shown to appear quite naturally in String Theories.

[Kostelecky, Samuel, hep-ph/8806276]
[Kostelecky, Samuel, hep-ph/8909364]

- In this context the "natural" order of magnitude of these coefficients is connected to the ratio of the tensor vev's to typical String scales:

$$\frac{\langle T\rangle}{M} \sim \frac{M_{\rm EW}}{M_{\rm Planck}} \sim \frac{10^2\ \text{GeV}}{10^{19}\ \text{GeV}} \sim 10^{-17}$$

The renormalizable $SU(3) \times U(1)$ sector of the SME

- The modern approach is to focus on the low-energy effective theory and not to give too much weight to the Spontaneous Symmetry Breaking picture

  [Kostelecky, Potting, hep-ph/9501341]
  [Colladay, Kostelecky, hep-ph/9703464]
  [Colladay, Kostelecky, hep-ph/9809521]

- If we consider only renormalizable operators, the *SU(3)×U(1)* gauge, lepton and quark sectors are ($\psi = u, d, e$):

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} + \bar\psi(\gamma^\mu i D_\mu - m_\psi)\psi$$

$$\delta\mathcal{L}_{\rm SME} = -\frac{1}{4}\kappa_F^{\kappa\lambda\mu\nu}F_{\kappa\lambda}F_{\mu\nu} - \frac{1}{4}\kappa_G^{\kappa\lambda\mu\nu}G^a_{\kappa\lambda}G^a_{\mu\nu} + \bar\psi(\Gamma^\mu i D_\mu - M)\psi$$

where $\Gamma^\mu = c^{\mu\nu}\gamma_\nu + d^{\mu\nu}\gamma_5\gamma_\nu + e^\mu + if^\mu\gamma_5 + \frac{1}{2}g^{\alpha\beta\mu}\sigma_{\alpha\beta}$

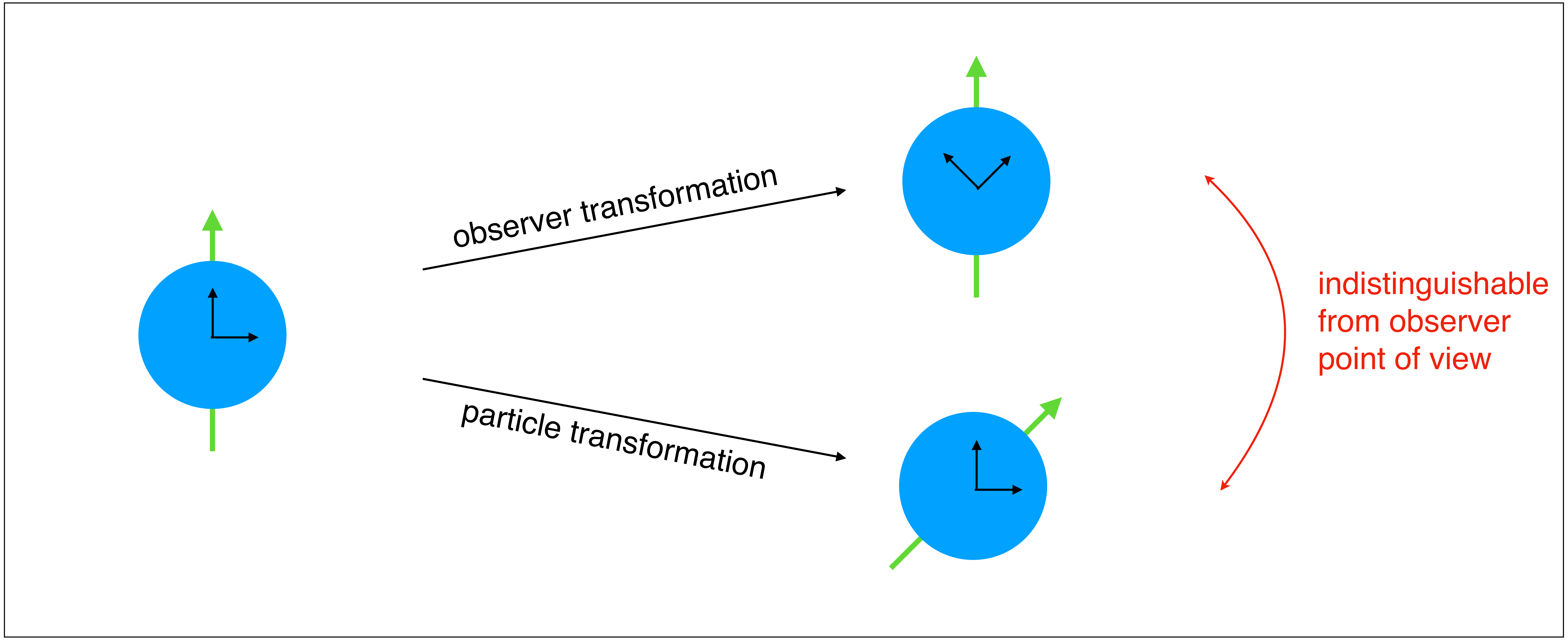
$M = a_\mu\gamma^\mu + b_\mu\gamma_5\gamma^\mu + \frac{1}{2}H^{\alpha\beta}\sigma_{\alpha\beta}$

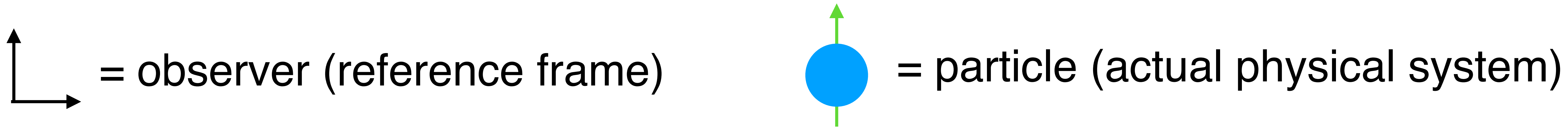
D_μ is the standard QCD & QED covariant derivative

- We need two consider two distinct types of Lorentz transformations:
  - Under observer transformations the SME Lagrangian is a scalar: for example $\bar\psi\gamma^\mu\psi$ and a_μ are both 4-vectors
  - Under particle transformations $\bar\psi\gamma^\mu\psi$ is a 4-vector and a_μ do not transform

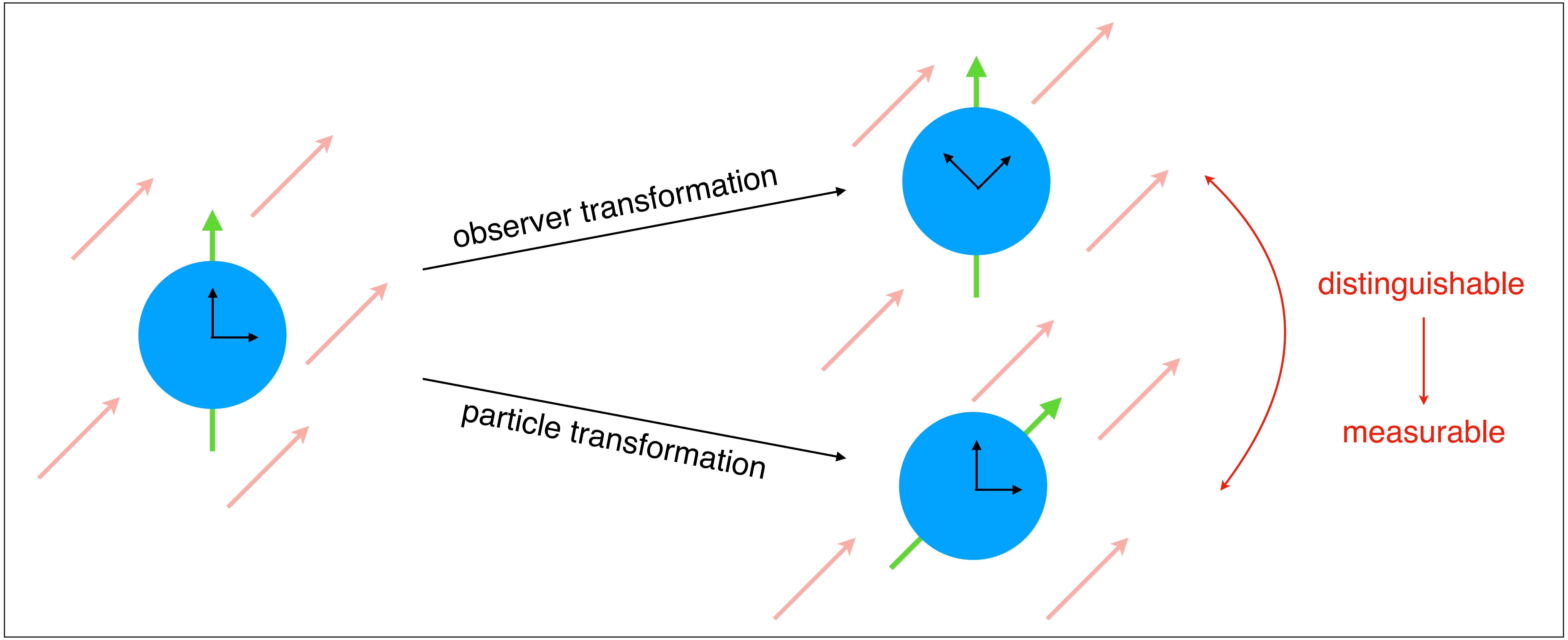
Observer vs Particle transformations

- A rotation of the observer cannot be distinguished from an opposite rotation of the system





- In presence of a directional background, the two rotations are inequivalent



= observer (reference frame) = particle (actual physical system) = Lorentz-violating background field

Observer vs Particle transformations

- **Observer transformations** are just a change of coordinates and **observer invariance is simply the statement that the physics is independent of the choice of coordinates**
- For instance, lets consider the action for the massless QED section of the SME on a curved manifold:

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{4}(D_\mu A_\nu - D_\nu A_\mu)(D_\alpha A_\beta - D_\beta A_\alpha)\left(g^{\mu\alpha}g^{\nu\beta}+\kappa^{\mu\alpha\nu\beta}\right) + i\frac{1}{2}\,\bar{\psi}\,\gamma_a e^a_\mu\,(\overleftrightarrow{D}_\nu - ieA_\nu)(g^{\mu\nu}+c^{\mu\nu})\psi\right]$$

Christoffel connection

Vierbein (tetrad)

Spinor connection

- The requirement that S is a scalar under change of coordinates (physics depends on $e^{iS/\hbar}$) requires that e, $c^{\mu\nu}$ **and** $\kappa^{\mu\alpha\nu\beta}$ **are rank 0, 2 and 4 tensors under general change of coordinates**
- If we limit to **flat space time** (connections $\to 0$, $e^\mu_a \to \delta^\mu_a$) the theory is only invariant under observer Lorentz transformations and e, $c^{\mu\nu}$ **and** $\kappa^{\mu\alpha\nu\beta}$ **are Lorentz tensors of rank 0, 2 and 4**
- **Particle transformations** act only on the system (and not on the reference frame nor the background fields). For instance, they connect a muon produced at rest with a muon produced with a boost γ in some direction.
- One of the consequences of this fact is that, in presence of coefficients for Lorentz Violation, the lifetime of a boosted muon and of a muon at rest seen by a boosted observer are different

Physical coefficients

- Not all coefficients introduced above are physical
- Some coefficients can be eliminated via a field redefinitions like:

$$\psi(x) \to e^{if(x)}\psi(x)$$

$$\psi(x) \to [1 + v(x)\cdot\Gamma]\psi(x) \quad \text{with} \quad \Gamma = \gamma^\alpha,\ \gamma_5\gamma^\alpha,\ \sigma^{\alpha\beta}$$

  ⇒ in this way a_μ and the antisymmetric part of $c_{\mu\nu}$ can be eliminated

- Some parts of the coefficients are not LV. For instance, even after removing its antisymmetric part we have: $c_{\mu\nu} = [c_{\mu\nu}]_{\text{traceless \& symmetric}} + \alpha\,\eta_{\mu\nu}$

  Lorentz Violating Lorentz Conserving

- Some coefficients can be eliminated via a choice of coordinates:

$$\mathcal{L} = -\frac{1}{4}\left(\kappa^{\kappa\lambda\mu\nu} + \eta^{\kappa\mu}\eta^{\lambda\nu}\right)F_{\kappa\lambda}F_{\mu\nu} + \left(\eta^{\mu\nu} + c^{\mu\nu}\right)\bar{\psi}\gamma_\mu i D_\nu \psi$$

$$\Big\downarrow \; x^\mu \to x^\mu - \frac{1}{2}\kappa^{\alpha\mu}{}_{\alpha\nu}x^\nu$$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \left(\eta^{\mu\nu} + c^{\mu\nu} + \frac{1}{2}\kappa^{\alpha}{}_{\mu\alpha\nu}\right)\bar{\psi}\gamma_\mu i D_\nu \psi$$

We can choose one sector of the SME to define the scales of the four coordinates

The Standard Model Extension (SME)

- ***Standard Model Extension***: *an <u>effective</u> field theory which has exact observer Lorentz covariance and that contains explicit preferred directions*

[Colladay, Kostelecky, hep-ph/9703464]
[Colladay, Kostelecky, hep-ph/980952]
[Kostelecky, hep-th/0312310]

- If we restrict to renormalizable interactions: this theory is called the ***minimal SME***

- The advantages of this approach include preservation of:
  - Standard Quantization
  - Microcausality
  - Spin-Statistic Theorem
  - Observer Lorentz covariance
  - Hermiticity
  - Positivity of the Energy
  - Power counting renormalizability
  - Conservation of Energy-Momentum for constant Lorentz Violating vacuum expectations values

- Note: the minimal SME is a renormalizable theory with the same particle content as the SM!

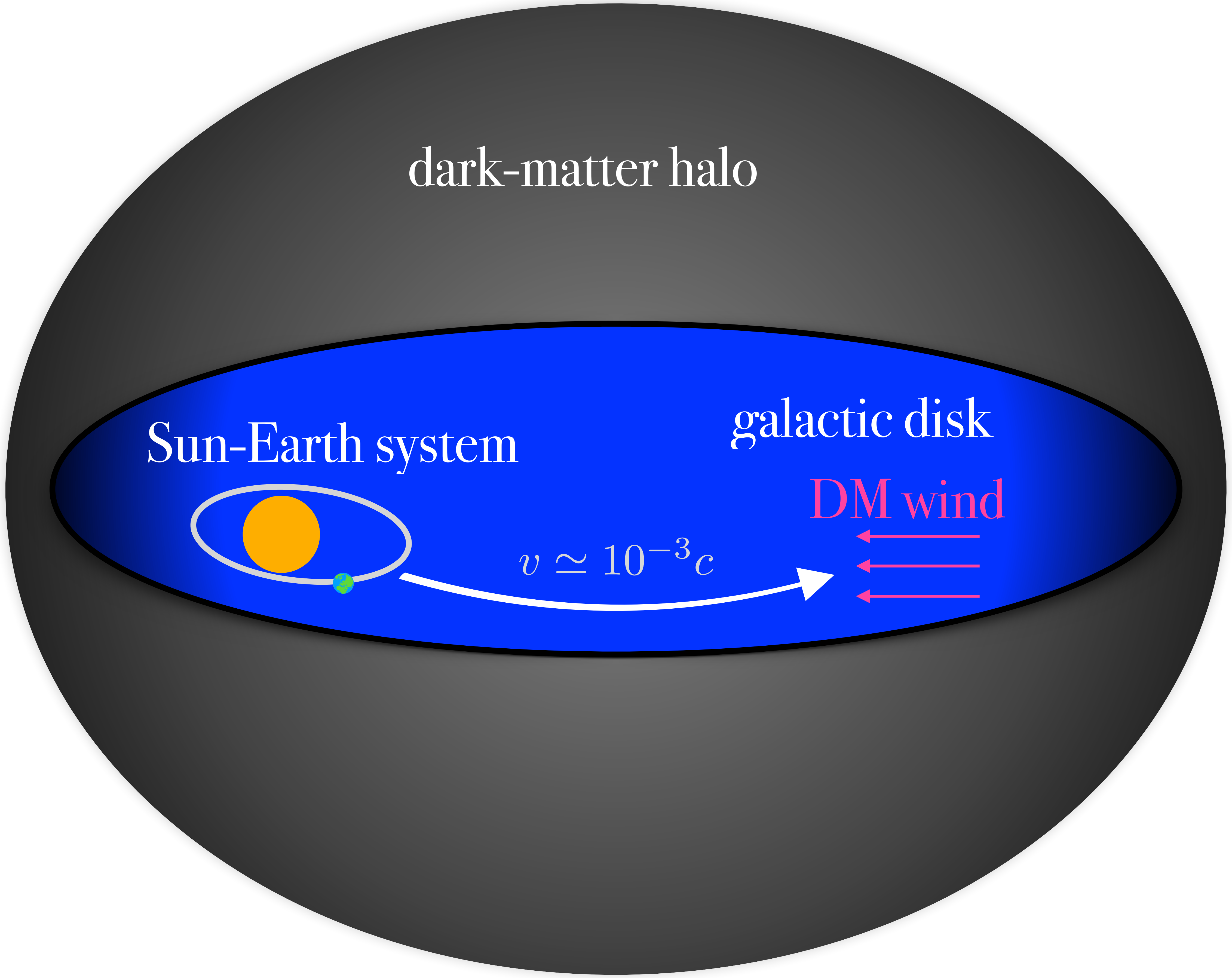
Motivations

Strategies used to explore physics Beyond the Standard Model in the last many decades:

- **New UV complete theories**
  - Introduce new particles and symmetries
  - Write down the most general Lorentz invariant renormalizable Lagrangian
  - E.g.: extra Higgs bosons, Supersymmetry, Little Higgs models, Vectorlike fermions, …
- **Effective theories**
  - New particles are too heavy to be directly detected
  - Their effects appear via modification of the coefficients of non-renormalizable operators
  - E.g.: Standard Model Effective Theory, Weak effective Hamiltonian (flavor physics), …
- **Backgrounds**
  - The discovery of the Higgs boson very strongly suggests the existence of fundamental backgrounds
  - Most studies focus on “Higgs-like” backgrounds: isotropic, homogenous and charged under some symmetry
  - The SME can be considered as a theory of “generalized backgrounds”

Motivations

The SME is also the effective theory that describes all kind of physical backgrounds

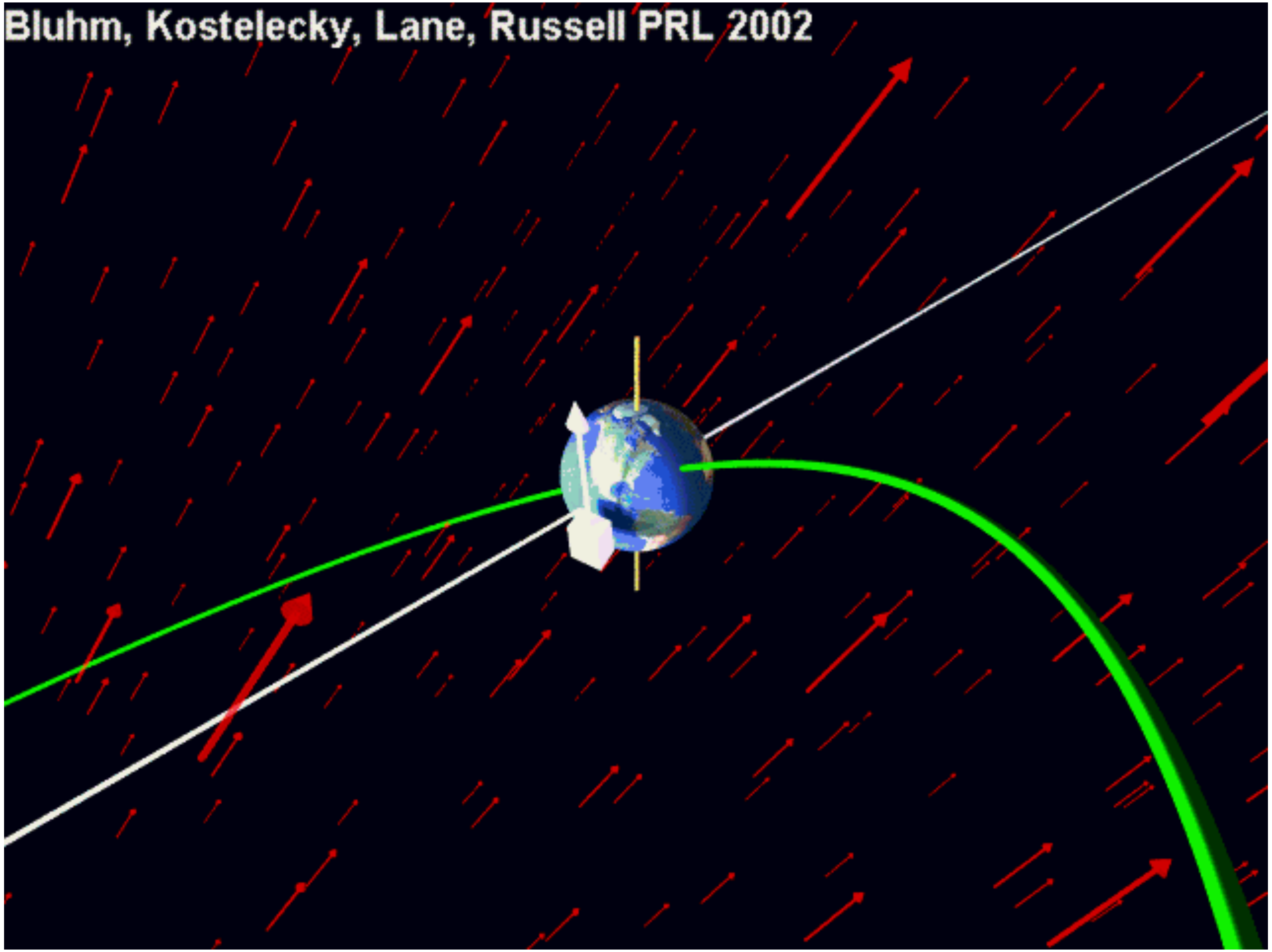


- In Sun-Earth system frame, a velocity-dependent dark matter "wind" is observed
- Produces daily variations ("rotation violation")
- Produces annual variations ("boost violation")
- In this example, dark matter interactions are Lorentz invariant, but lead to apparent Lorentz violation!

- Explicit implementation in the context of ultralight dark matter [Jiang, Pecjak, Perez, Sankaranarayanan; 2404.17636]
  - If the DM mass is $\ll$ 1 eV, the DM field ϕ is essentially a classical background
  - ϕ and SM particles interacts via dim=8 operators suppressed by powers of some heavy mediator scale M
  - The resulting effective interactions are SME interactions with

$$c_{\mu\nu} \sim \frac{m_\phi^2 \phi^2}{M^4} (v_\mu v_\nu - \eta_{\mu\nu}/4) \sim \frac{\rho_{\rm DM}}{M^4} (v_\mu v_\nu - \eta_{\mu\nu}/4)$$

Search strategy: sidereal oscillations and Sun Centered Frame



- The rotation of Earth through a constant directional background generates a time dependence with period equal to the sidereal day: $T_{\text{sid}} \simeq 23\text{h}56\text{m}$

- All coefficients are constrained in the **Sun Centered Frame** defined with respect to the 2000 spring equinox: **March 20 2000 at 7:35 am UTC**

Existing Constraints

- Experiments that focus on the properties of stable particles (electrons, muons, protons, neutrons, photons) yield very strong constraints:

$$\kappa_F^{\alpha\beta\mu\nu} < \left[10^{-14} - 10^{-32}\right] \qquad c^{\mu\nu}_{\mathrm{proton}} < \left[10^{-20} - 10^{-28}\right] \qquad c^{\mu\nu}_{\mathrm{muon}} < 10^{-11}$$

$$c^{\mu\nu}_{\mathrm{electron}} < \left[10^{-17} - 10^{-21}\right] \qquad c^{\mu\nu}_{\mathrm{neutron}} < \left[10^{-13} - 10^{-29}\right]$$

- Complete list of existing constraints is kept updated in:
  Data Tables for Lorentz and CPT Violation
  Kostelecky, Russell; *Rev.Mod.Phys.* 83 (2011) 11-31, 0801.0287v**17**

- Coefficients in the quark sectors are almost completely unconstrained due to the difficulty of accessing quark level transitions directly.

The QCD sector of the SME: renormalizable vs non-renormalizable

- We focus on the following SME terms (with dimension d=3,4,5):

$$\delta\mathscr{L} = \frac{1}{2} i c_{Q_1}^{\mu\nu} \overline{Q}_{1L}\gamma_\mu \overleftrightarrow{D}_\nu Q_{1L} + \frac{1}{2} i c_U^{\mu\nu} \overline{U}_R \gamma_\mu \overleftrightarrow{D}_\nu U_R + \frac{1}{2} i c_D^{\mu\nu} \overline{D}_R \gamma_\mu \overleftrightarrow{D}_\nu D_R$$
$$- \frac{1}{2} i a_{Q_1}^{(5)\mu\alpha\beta} \overline{Q}_{1L}\gamma_\mu i D_{(\alpha} i \overleftrightarrow{D}_{\beta} Q_{1L} - \frac{1}{2} i a_U^{(5)\mu\alpha\beta} \overline{U}_R \gamma_\mu i D_{(\alpha} i \overleftrightarrow{D}_{\beta} U_R - \frac{1}{2} i a_D^{(5)\mu\alpha\beta} \overline{D}_R \gamma_\mu i D_{(\alpha} i \overleftrightarrow{D}_{\beta} D_R$$
$$- a_{Q_3}^\mu \overline{Q}_{3L}\gamma_\mu Q_{3L} - a_T^\mu \overline{T}_R \gamma_\mu T_R - a_B^\mu \overline{B}_R \gamma_\mu B_R$$

$$= \sum_{q=u,d} \left[\frac{1}{2} \bar{q} \left(c_q^{\mu\nu} + \gamma_5\, d_q^{\mu\nu} \right) i\gamma_\mu \overleftrightarrow{D}_\nu q - \frac{1}{2} \left(a_q^{(5)\mu\alpha\beta} + \gamma_5\, b_f^{(5)\mu\alpha\beta} \right) \bar{q}\gamma_\mu i D_{(\alpha} i \overleftrightarrow{D}_{\beta} q \right]$$
$$- \sum_{q=t,b} \bar{q} \left(a_f^\mu + \gamma_5\, b_f^\mu \right) \gamma_\mu q$$

The SME coefficients originate at scales higher than the EW breaking one and need to be introduced in terms of $SU(2) \times U(1)$ fields: Q_{iL} are doublets and (U_R, D_R, T_R, B_R) are singlets

Mass eigenstate basis

	P	CPT
a^μ	+	−
b^μ	−	−
$c^{\mu\nu}$	+	+
$d^{\mu\nu}$	−	+
$a^{(5)\mu\alpha\beta}$	+	−
$b^{(5)\mu\alpha\beta}$	−	−

- Note that only three of the four mass eigenstate coefficients are independent.

For instance:

$$c_u^{\mu\nu} = (c_Q^{\mu\nu} + c_U^{\mu\nu})/2 \qquad d_u^{\mu\nu} = (c_Q^{\mu\nu} - c_U^{\mu\nu})/2$$
$$c_d^{\mu\nu} = (c_Q^{\mu\nu} + c_D^{\mu\nu})/2 \qquad d_d^{\mu\nu} = (c_Q^{\mu\nu} - c_D^{\mu\nu})/2$$

Lorentz Violation in the quark sector

- Several strategies have been proposed to study LV coefficients in the quark and gluon sectors:
  - Using Chiral Perturbation Theory to connect quark/gluon and hadron coefficients
    [Kamand, Altschul, Schindler, 1608.06503 and 1712.00838]
    [Altschul, Schindler, 1907.02490]
  - Study of hadronic properties sensitive to short distance physics (e.g.: meson-antimeson mixing)
    [Kostelecky, hep-ph/9809572]
    [D0 collaboration, 1506.04123 and 1608.06935]
  - Study of Lorentz violation in top decays and top hadrons
    [D0 collaboration, 1203.6106]
    [Berger, Kostelecky, 1509.08929]
    [Altschul, 2005.14099]
    [Belyaev, Cerrito, E.L., Moretti, Sherrill, 2405.12162]
  - Constraints on quark coefficients from their impact on photon propagation (i.e. finite loop effects and mixing).
    [Satunin, 1705.07796]
  - Exploit asymptotic freedom at large energies to express electron-hadron and hadron-hadron cross sections in terms of calculable Hard Scattering Kernels (which depend on the LV coefficients) and universal Parton Distribution Functions

$\Longleftarrow$ This talk

Using χ_{PT} to connect LV in quarks and hadrons

SKIP

- In order to connect quark and nucleon coefficients one can attempt a spurion analysis in which the coefficients for Lorentz violation are assigned chiral transformation properties
- Focusing on the $c_{\mu\nu}$ coefficients, one can write:

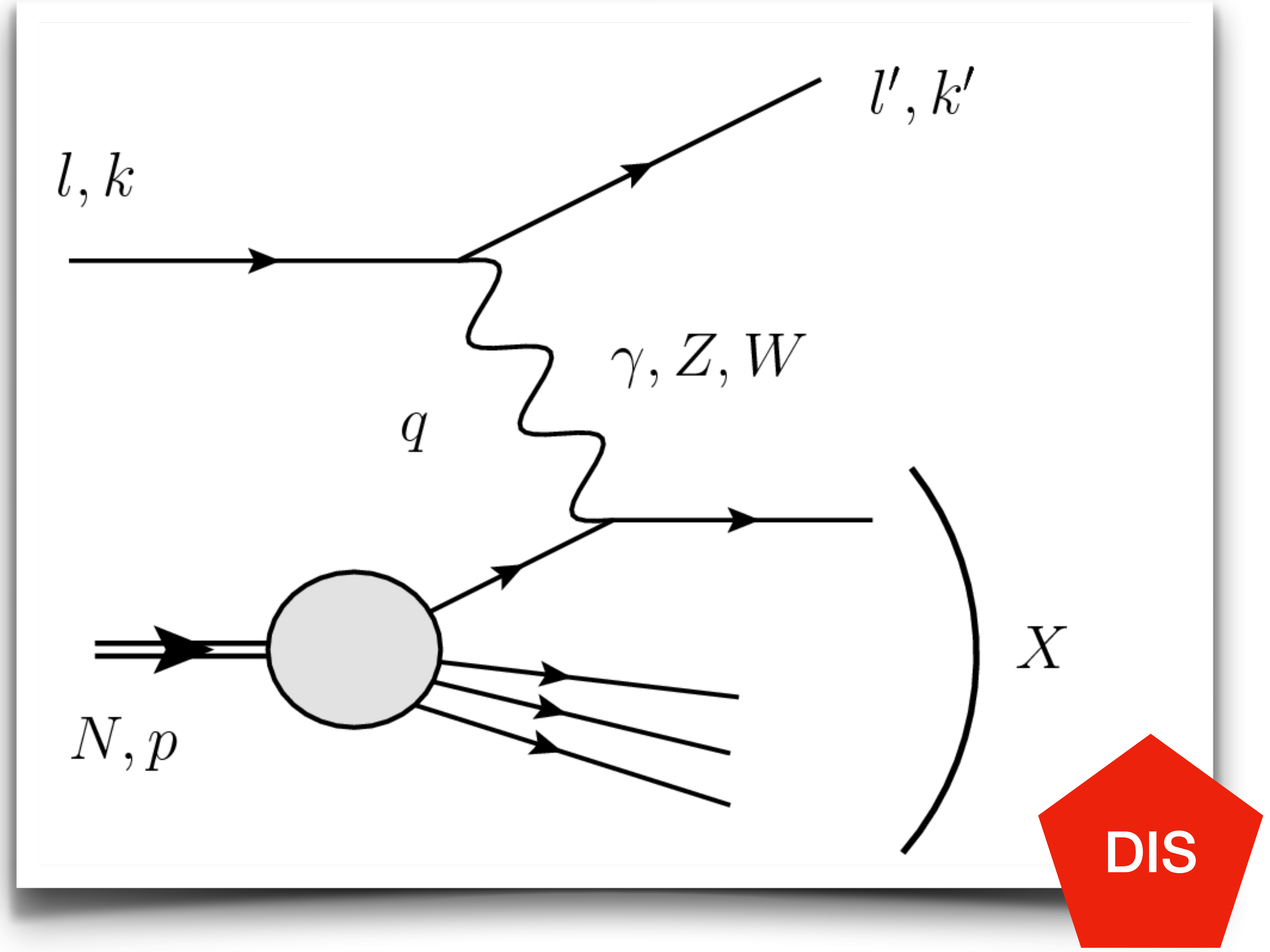
$$\delta\mathcal{L}_{\rm SME} = i\bar{Q}_L C_L^{\mu\nu}\gamma_\mu D_\nu Q_L + i\bar{Q}_R C_R^{\mu\nu}\gamma_\mu D_\nu Q_R$$

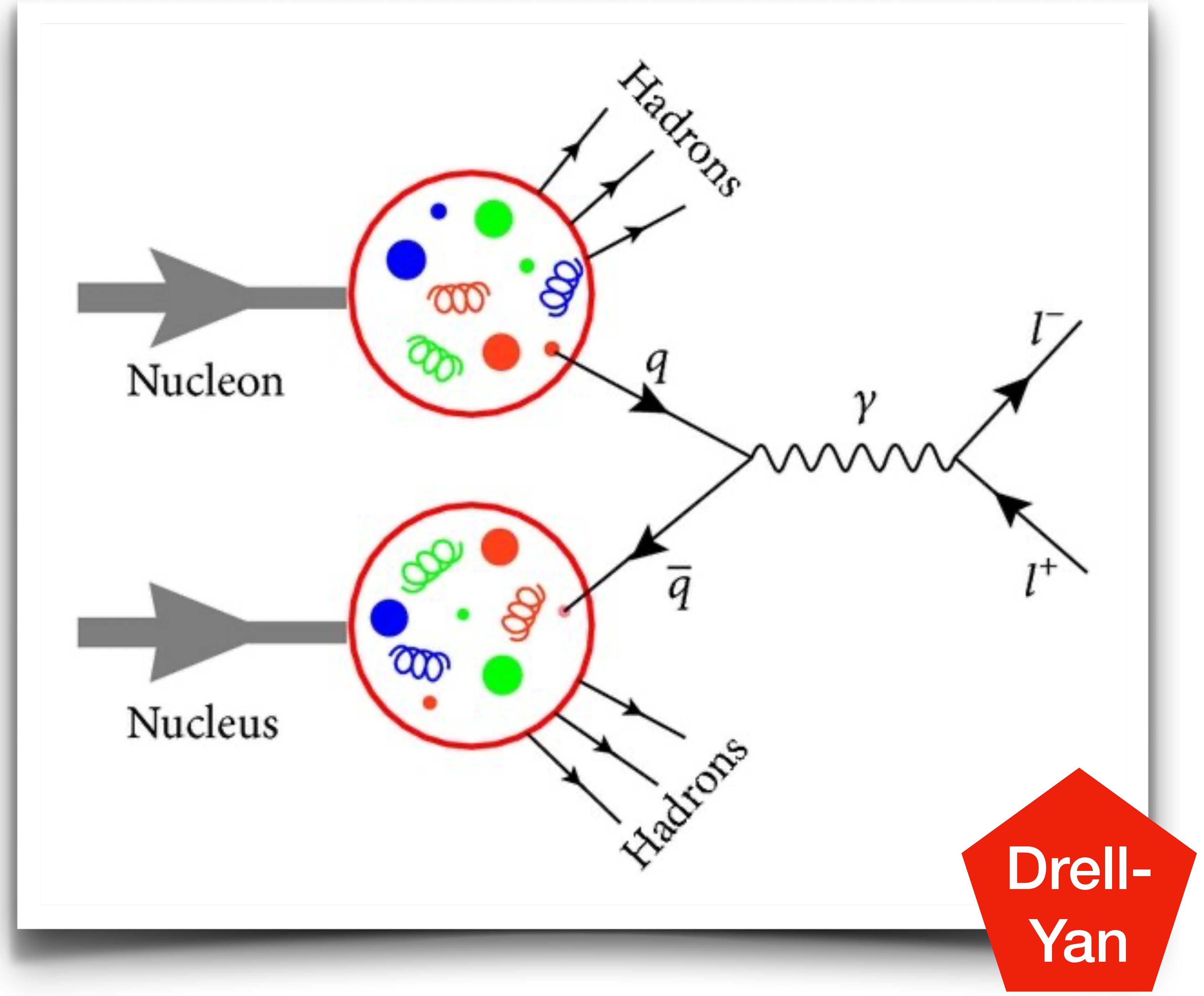
- Crucial observation: $C^{\mu\nu}_{L,R}$ **explicitly break** $SU(2)_L \times SU(2)_R$
- Strong Isospin invariance can be **formally restored** by assigning: $C_L^{\mu\nu} \to U_L C_L^{\mu\nu} U_L^\dagger$ and $C_R^{\mu\nu} \to U_R C_R^{\mu\nu} U_R^\dagger$
- The idea is to "upgrade" the coefficients $C^{\mu\nu}_{L,R}$ to non-dynamical fields (called **spurions**) and assume that they are the **only source of explicit** $SU(2)_L \times SU(2)_R$ **breaking**
- In this framework the quark $c^{\mu\nu}$ coefficients induce corresponding coefficients for the proton:

$$c_p^{\mu\nu} = \left[\frac{1}{2}\alpha^{(1)} + \alpha^{(2)}\right](c_{u_L}^{\mu\nu} + c_{u_R}^{\mu\nu}) + \left[-\frac{1}{2}\alpha^{(1)} + \alpha^{(2)}\right](c_{d_L}^{\mu\nu} + c_{d_R}^{\mu\nu})$$

where the $\alpha^{(1,2)}$ coefficients are non-perturbative and expected to be *O(1)*

Light Quark Sector





Lorentz Violation in the quark sector: high energy interactions

- Lorentz and CPT violating terms we consider:

$$\delta\mathscr{L} = \sum_{f=u,d,s}\left[\frac{1}{2}\bar{\psi}_f\left(c_f^{\mu\nu}+\gamma_5\, d_f^{\mu\nu}\right) i\gamma_\mu \overset{\leftrightarrow}{D}_\nu\psi_f - \frac{1}{2}\left(a_f^{(5)\mu\alpha\beta}+\gamma_5\, b_f^{(5)\mu\alpha\beta}\right)\bar{\psi}_f\gamma_\mu iD_{(\alpha}i\overset{\leftrightarrow}{D}_{\beta}\psi_f\right]$$

- We will discuss:
  - Constraints on $c_f^{\mu\nu}$ and $a_f^{(5)\mu\alpha\beta}$ $(f = u, d, s)$ from Deep Inelastic Scattering (DIS) measurements at ZEUS (Neutral current DIS is controlled by photon exchange) and expectations for the Electron Ion Collider (EIC)
    [Kostelecky, E.L.,Vieira, 1610.08755]
    [E.L., Sherrill, 1805.11684]
    [Kostelecky, E.L., Sherrill, Vieira, 1911.04002]
    [ZEUS collaboration (including E.L. and N. Sherrill), 2309.02889]
  - Prospects for constraining $c_f^{\mu\nu}$, $d_f^{\mu\nu}$, $a_f^{(5)\mu\alpha\beta}$ and $b_f^{(5)\mu\alpha\beta}$ $(f = u, d, s)$ coefficients using the Drell-Yan process $pp \to Z \to \mu\mu$ at ATLAS.
    [Kostelecky, E.L., Sherrill, Vieira, 1911.04002]
    [E.L., Sherrill, Szczepaniak, Vieira, 2011.02632]
    [E.L., Sherrill, to appear]
    [ATLAS collaboration + E.L. and N. Sherrill, in progress]

Lorentz Violation in the quark sector: high energy interactions

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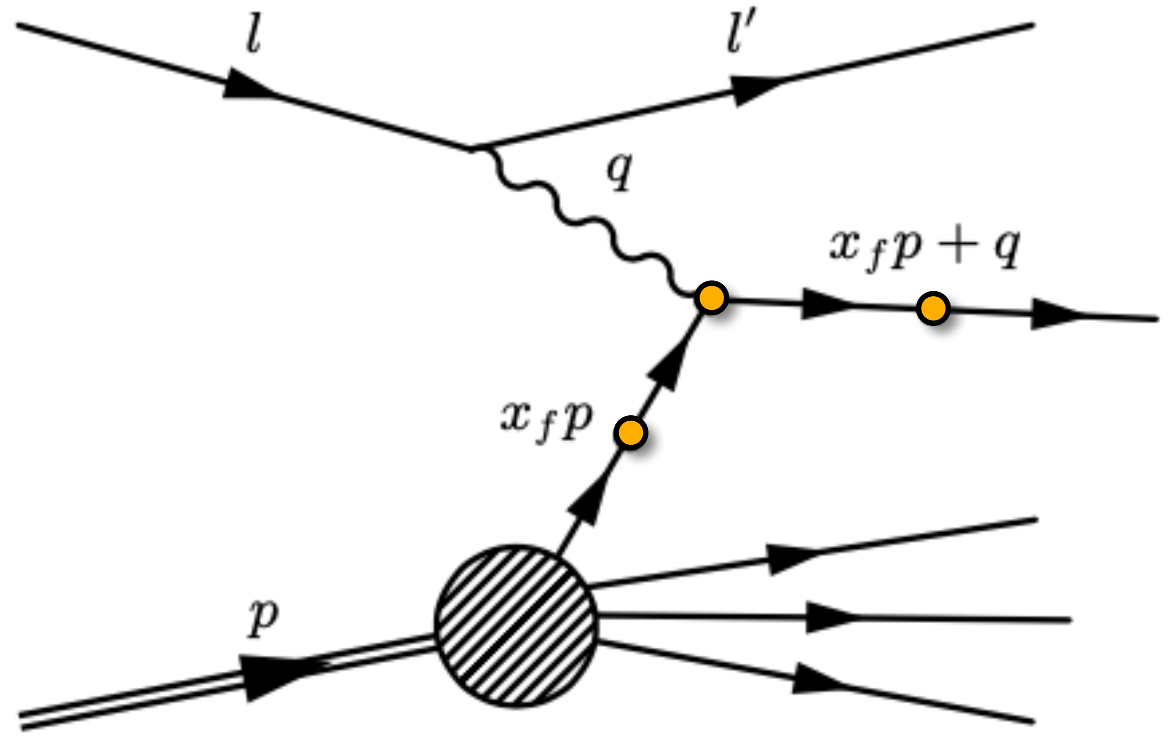
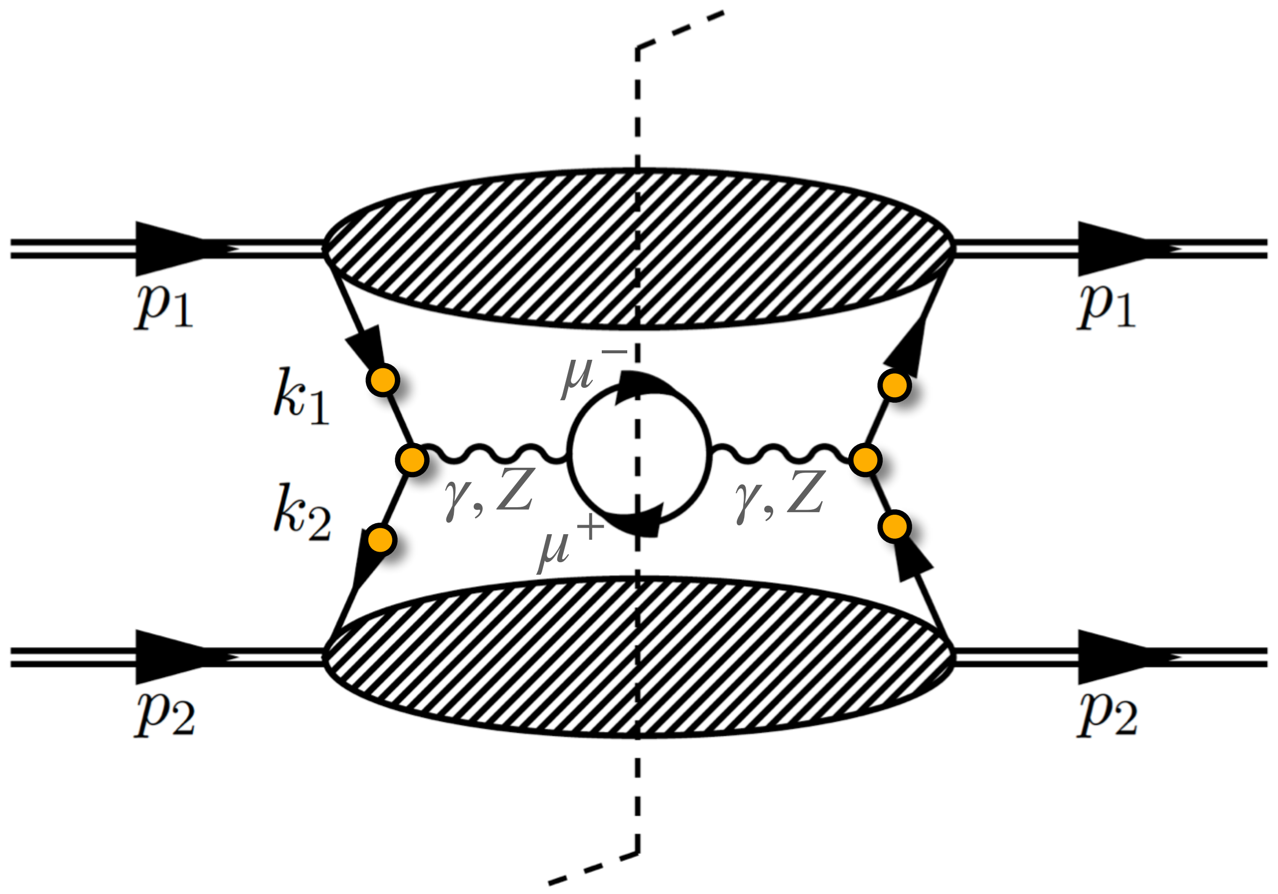
- Deep Inelastic Scattering and Drell-Yan (both γ and Z) cross sections:

$$\sigma_{\text{DIS}} \approx \sum_q \int d\xi\; \sigma^{\text{SME}}_{eq\to eX}(\xi)\, f_q(\xi)$$

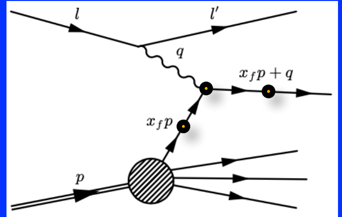
$$\sigma_{\text{DY}} \approx \sum_{q_1,q_2} \int d\xi_1 d\xi_2\; \sigma^{\text{SME}}_{q_1q_2\to\mu^+\mu^-X}(\xi_1,\xi_2)\, f_{q_1}(\xi_1) f_{q_2}(\xi_2)$$

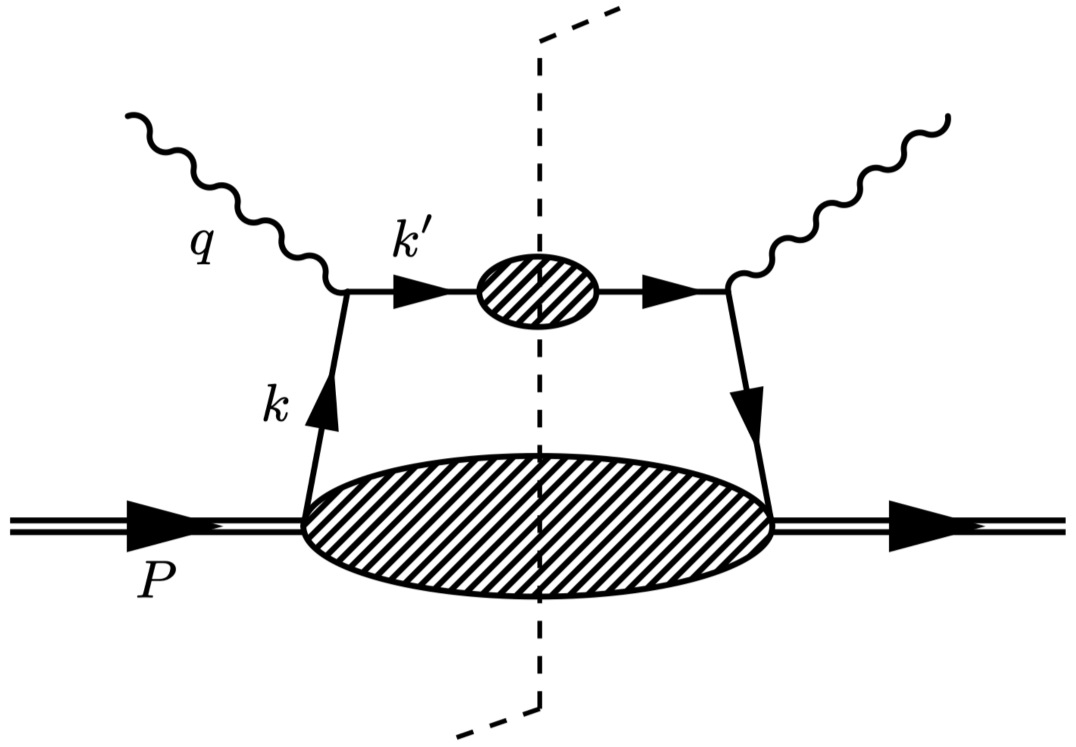
Unexplored issue: we could not exclude the possibility that the PDFs, $f_q(x)$, depend on certain light-cone projections of the coefficients.





= insertion of a SME coefficient

Lorentz Violation in the quark sector: DIS 

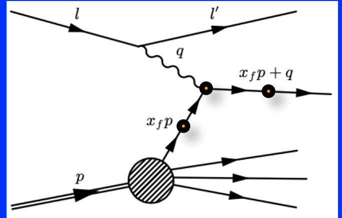


- $\mathscr{L} = \frac{1}{2}\bar{q}\gamma_\mu(g^{\mu\nu} + c^{\mu\nu})i\gamma_\mu \overleftrightarrow{D}_\nu q$
- The **quark dispersion relation is modified**:

  $k_\mu(\eta^{\mu\nu} + c^{\mu\nu})(\eta_{\nu\lambda} + c_{\nu\lambda})k^\lambda = \tilde{k}^\mu \tilde{k}_\mu = 0$
- In the proof of factorization we need to take k such that $\tilde{k}^2 \sim \Lambda^2$
- **Covariance forces the choice:** $\tilde{k}^\mu = \xi P^\mu$
- Taking the **imaginary part of the internal propagator** $(k'^\mu = k + q)$ forces $\tilde{k}'^2 = (\tilde{k} + \tilde{q})^2 \sim \Lambda^2$
- The proof of factorization is almost identical to the SM case after transforming to a modified Breit frame defined as the $P - \tilde{q}$ center of mass frame
- The parton distribution functions become:

$$\underbrace{f(n \cdot \tilde{k}, P^\mu, c^{\mu\nu})}_{\left(\frac{n \cdot \tilde{k}}{n \cdot P}, \frac{c_{\mu\nu}n^\mu P^\nu}{n \cdot P}, \frac{c_{\mu\nu}P^\mu P^\nu}{\Lambda^2}\right) = \left(\xi, c_{\mu\nu}n^\mu \bar{n}^\nu, c_{\mu\nu}\bar{n}^\mu \bar{n}^\mu \frac{(n \cdot P)^2}{\Lambda^2}\right)} = \int \frac{d\lambda}{2\pi} e^{-i(n\cdot\tilde{k})\lambda} \langle P | \bar{\psi}(\lambda\tilde{n}) \frac{\not{n}}{2} \psi(0) | P \rangle$$

- light-cone projections of the coefficients
- potential non-perturbative enhancement

Lorentz Violation in the quark sector: DIS 

- The DIS cross section is $d\sigma = L_{\mu\nu} W^{\mu\nu}$, where $L^{\mu\nu}$ and $W^{\mu\nu}$ are the leptonic and hadronic tensors (the latter is expressed in terms of W_1 and W_2)
- In the SM: $T^{\mu\nu} \sim \int_0^1 \frac{f_i(\xi)}{\xi} Q_i^2 \xi P_\alpha (\xi P_\beta + q_\beta) \frac{\mathrm{Tr}[\gamma^\alpha \gamma^\mu \gamma^\beta \gamma^\nu]}{(\xi P + q)^2 + i\varepsilon} + (\mu \leftrightarrow \nu, q \leftrightarrow -q)$
- In the SME: $T^{\mu\nu} \sim \int_0^1 \frac{f_i(\xi, \cdots)}{\xi} Q_i^2 \xi P_\alpha (\xi P_\beta + q_\beta) \frac{\mathrm{Tr}[\Gamma^\alpha \Gamma^\mu \Gamma^\beta \Gamma^\nu]}{(\xi P + \tilde{q})^2 + i\varepsilon} + (\mu \leftrightarrow \nu, q \leftrightarrow -q)$

  where $\Gamma^\mu = \gamma^\mu + c^{\mu\nu}\gamma_\nu$ and $W^{\mu\nu} = \mathrm{Im}[T^{\mu\nu}]$

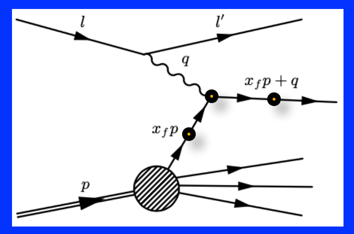
  - The trace in the numerator is simply expanded keeping only linear terms in $c^{\mu\nu}$
  - We need the imaginary part of the denominator:

$$\frac{1}{\pi}\mathrm{Im}\frac{1}{(\xi P + \tilde{q})^2 + i\varepsilon} = \delta(\tilde{q}^2 + 2\xi P \cdot \tilde{q}) = \frac{1}{2P \cdot q}\left[\delta(\xi - x) + \delta'(\xi - x) c^{\mu\nu} H_{\mu\nu}\right]$$

Yields terms proportional to the derivative of the PDFs

$x = \frac{-2P \cdot q}{q^2}$ is Bjorken-x

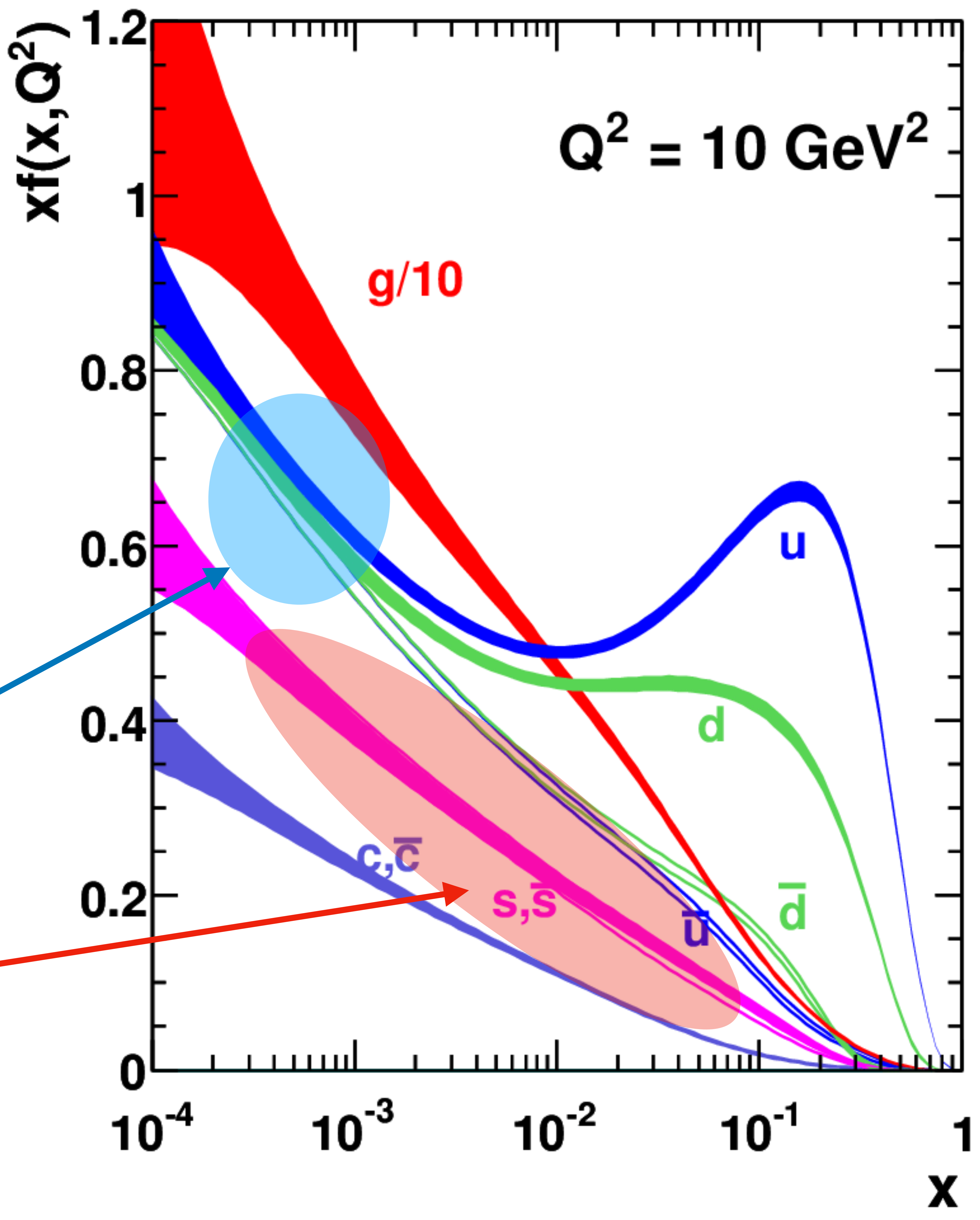
Lorentz Violation in the quark sector: DIS

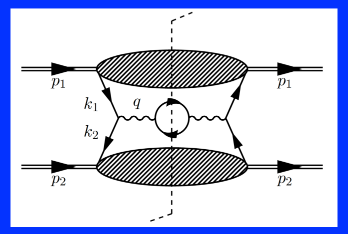


- **Deep Inelastic Scattering ($a_f^{(5)\mu\nu\alpha}$)**
  [A. Kostelecky, Z. Li; 1812.11672]
  [Kostelecky, E.L., N. Sherrill and A. Vieira, 1911.04002]

  - These coefficients have dimension $(\text{Mass})^{-1}$ and they appear multiplied by the typical energy scale of the process: on general grounds we find **enhanced sensitivity in higher-energy experiments** (LHC > HERA > EIC)

  - These coefficients are CPT-violating, implying that the cross section depends on the difference $q(x) - \bar{q}(x)$:
    - no sensitivity at low x where sea quarks dominate and $q(x) \sim \bar{q}(x)$
    - no sensitivity to strange quarks for which $f_s(x) \sim f_{\bar{s}}(x)$ for all x.



Lorentz Violation in the quark sector: Drell-Yan 

[Kostelecky, E.L., Sherrill, Vieira, 1911.04002]
[E.L., Sherrill, Szczepaniak, Vieira, 2011.02632]

- **Drell-Yan ($c_f^{\mu\nu}$ and $d_f^{\mu\nu}$)**

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3N_c}\sum_f \left[\frac{e_f^2}{2Q^4} + \frac{1 - m_Z^2/Q^2}{(Q^2 - m_Z^2)^2 + m_Z^2\Gamma_Z^2}\frac{1 - 4\sin^2\theta_W}{4\sin^2\theta_W\cos^2\theta_W}e_f g_{fL} + \frac{1}{(Q^2 - m_Z^2)^2 + m_Z^2\Gamma_Z^2}\frac{1 + (1 - 4\sin^2\theta_W)^2}{32\sin^4\theta_W\cos^4\theta_W}g_{fL}^2\right]\int_\tau^1 dx\frac{\tau}{x}\hat{\sigma}_f + (L \to R)$$

$$\hat{\sigma}_f = \left(1 + \frac{2}{s}c_{fL}^{\mu\nu}(1 + x^2/\tau)(p_{1\mu}p_{1\nu} + p_{1\mu}p_{2\nu} + (p_1 \leftrightarrow p_2))\right)\left[f_f(x)f_{\bar{f}}(\tau/x) + f_f(\tau/x)f_{\bar{f}}(x)\right]$$
$$+\frac{2}{s}c_{fL}^{\mu\nu}\left(xp_{1\mu}p_{1\nu} + \frac{\tau}{x}p_{1\mu}p_{2\nu} + (p_1 \leftrightarrow p_2)\right)\left[f_f(x)f'_{\bar{f}}(\tau/x) + f'_f(\tau/x)f_{\bar{f}}(x)\right]$$

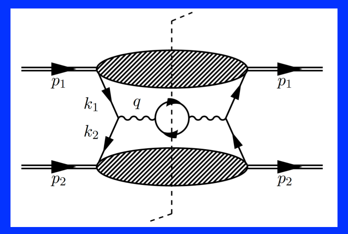
$$c_Q = c_{uL} = c_{dL}$$
$$c_U = c_{uR}$$
$$c_D = c_{dR}$$

- Focus on the Z pole where cross section is resonant and is sensitive to both $c_f^{\mu\nu}$ and $d_f^{\mu\nu}$ coefficients

  The QED part is L-R symmetric implying that only $\frac{1}{2}(c_{uL}^{\mu\nu} + c_{uR}^{\mu\nu}) = c_u^{\mu\nu}$ and $\frac{1}{2}(c_{dL}^{\mu\nu} + c_{dR}^{\mu\nu}) = c_d^{\mu\nu}$ appear

  The Z contribution is L-R asymmetric implying sensitivity to $\frac{1}{2}(c_{uL}^{\mu\nu} - c_{uR}^{\mu\nu}) = d_u^{\mu\nu}$ and $\frac{1}{2}(c_{dL}^{\mu\nu} - c_{dR}^{\mu\nu}) = d_d^{\mu\nu}$

- In the lab frame cross section depends only on the c_f^{33} and c_f^{00} coefficients

Lorentz Violation in the quark sector: Drell-Yan 

~SKIP

- Interactions involving the $c^{\mu\nu}$ and $d^{\mu\nu}$ coefficients are:

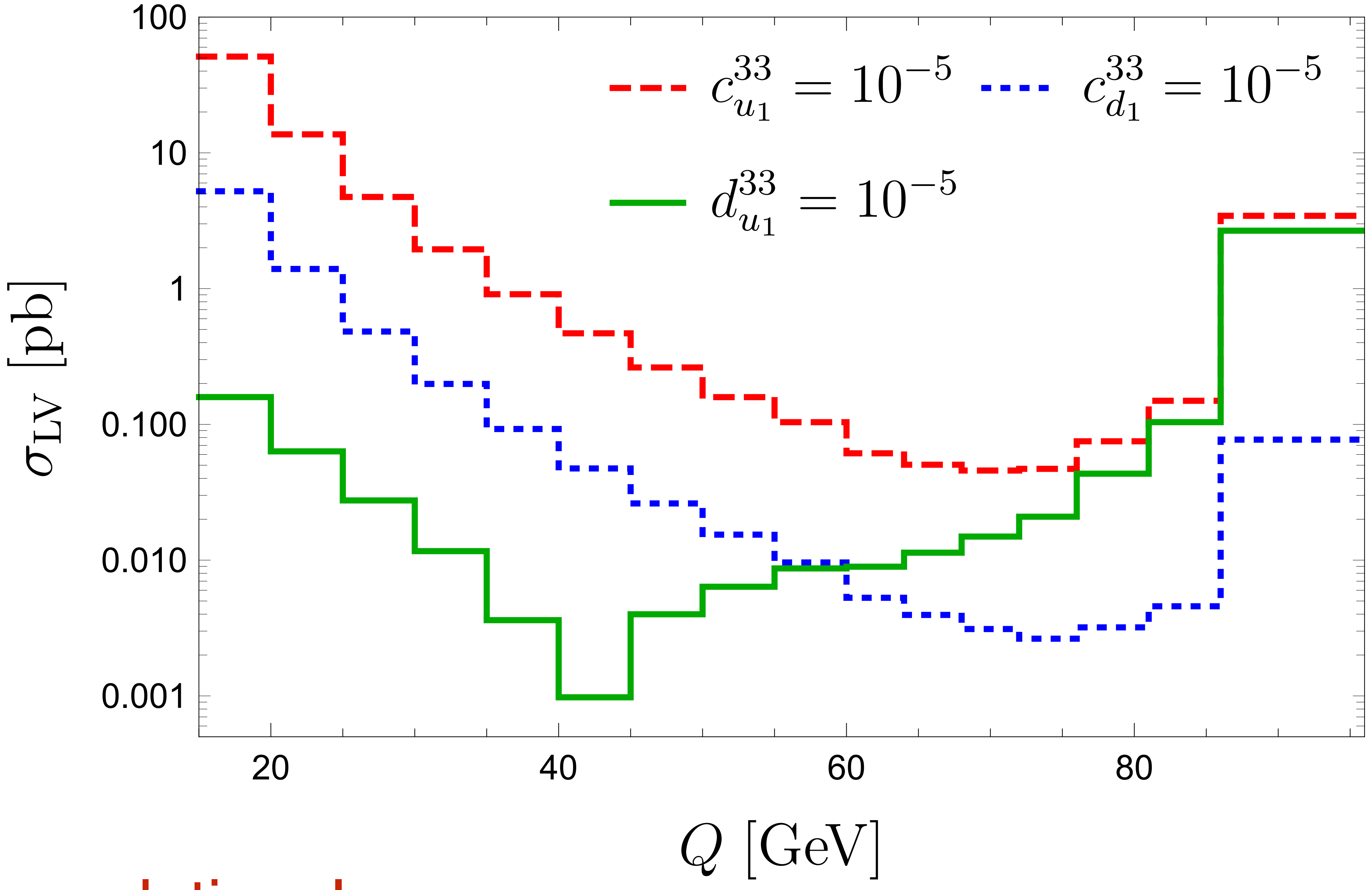
$$\frac{1}{2} i\bar{\psi}(\eta^{\mu\nu} + c^{\mu\nu} + d^{\mu\nu}\gamma_5)\gamma_\mu \overleftrightarrow{\partial}_\nu \psi$$

- The fermion propagator can be written as:

 $$= P_L \frac{i\tilde{k}_L}{\tilde{k}_L^2} + P_R \frac{i\tilde{k}_R}{\tilde{k}_R^2}$$

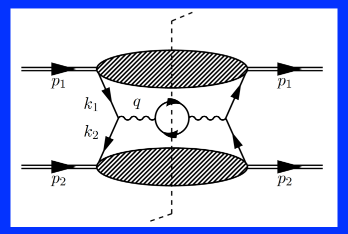
where $\tilde{k}^\mu_{L,R} = (\eta^{\mu\nu} + c^{\mu\nu} \pm d^{\mu\nu})k_\nu$

$\Rightarrow$ Left and Right chiral components obey different dispersion relations!



- In parity conserving theories like QED and QCD all $d^{\mu\nu}$ effects vanish for unpolarized initial state (because of cancellation between left and right contributions).
  This is the case for electron-proton DIS and low-q^2 Drell-Yan.

- **Drell-Yan on the Z-pole offers a unique opportunity to constraints quark $d^{\mu\nu}$ coefficients**

Lorentz Violation in the quark sector: Drell-Yan 

~SKIP

[A. Kostelecky, E.L., N. Sherrill and A. Vieira, 1911.04002]
[E.L., Sherrill, Szczepaniak, Vieira, 2011.02632]
[E.L., Sherrill, to appear]

- **Drell-Yan ($a_f^{(5)\mu\nu\alpha}$ and $b_f^{(5)\mu\nu\alpha}$)**

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3N_c}\sum_f \left[\frac{e_f^2}{2Q^4} + \frac{1-m_Z^2/Q^2}{(Q^2-m_Z^2)^2+m_Z^2\Gamma_Z^2}\frac{1-4\sin^2\theta_W}{4\sin^2\theta_W\cos^2\theta_W}e_f g_{fL} + \frac{1}{(Q^2-m_Z^2)^2+m_Z^2\Gamma_Z^2}\frac{1+(1-4\sin^2\theta_W)^2}{32\sin^4\theta_W\cos^4\theta_W}g_{fL}^2\right]\int_\tau^1 dx\frac{\tau}{x}\hat{\sigma}_f + (L\to R)$$

$$\hat{\sigma}_f = \left[1 + A_S(x,\tau/x)\right]f_{Sf}(x,\tau/x) - \frac{1}{sx}\left[A_A'(x,\tau/x)f_{Af}(x,\tau/x) + A_A(x,\tau/x)f_{Af}'(x,\tau/x)\right]$$

$$A_S(x,\tau/x) = E_p(x+\tau/x)\left(a_{Sf_L}^{(5)110} + a_{Sf_L}^{(5)220}\right)$$

$$A_A(x,\tau/x) = sE_p\left[\frac{1}{2}(x-\tau/x)(x+\tau/x)^2\left(a_{Sf_L}^{(5)000} + a_{Sf_L}^{(5)033}\right) + a_{Sf_L}^{(5)330}(x-\tau/x)(x^2+(\tau/x)^2)\right]$$

$$A_A'(x,\tau/x) = -\frac{s}{2x^2}E_p\left[2(x^4-2\tau x^2+3\tau^2)a_{Sf_L}^{(5)330} - (x^2-3\tau)(x^2+\tau)(a_{Sf_L}^{(5)000} + a_{sf_L}^{(5)033})\right]$$

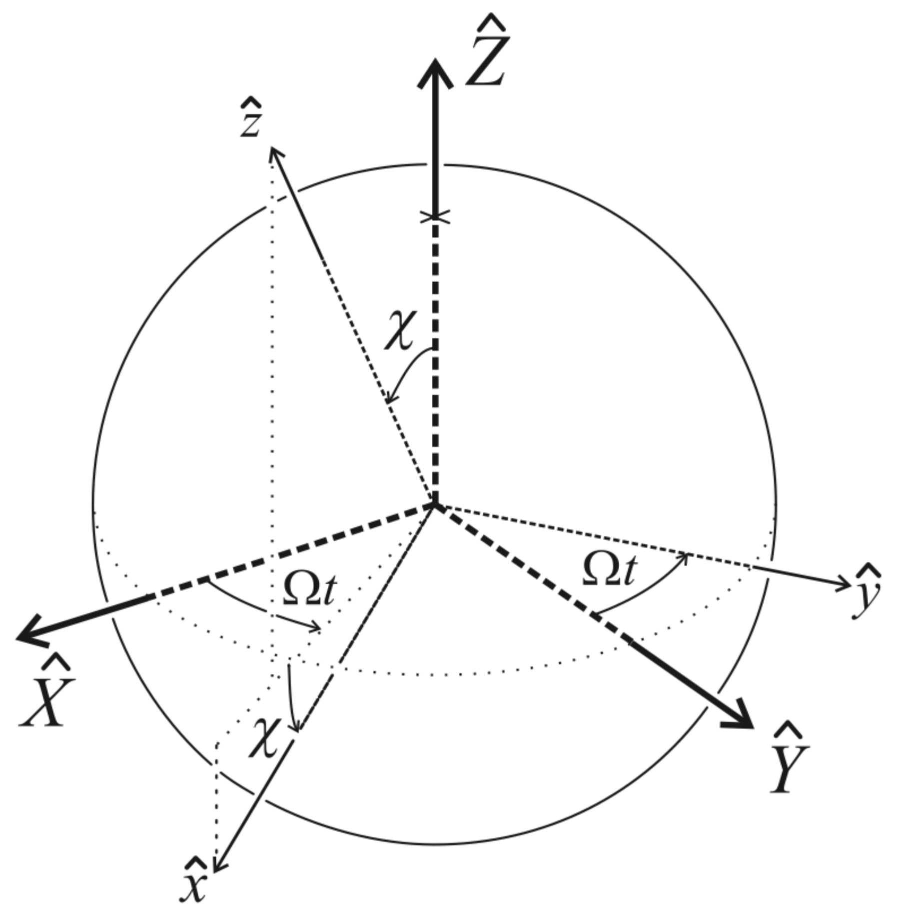
- As expected the $a^{(5)}$ and $b^{(5)}$ coefficients appear multiplied by the proton energy E_P
- Both symmetric (f_S) and antisymmetric (f_A) combinations of parton distribution functions appear: residual dependence on strange quarks (albeit not as $1/x$ enhanced as the up and down one)

Sun-centered vs lab frames

SKIP

- The tensor $c_{\mu\nu}$ as it appears in our equations is related to the corresponding tensor in the non-rotating inertial frame by a spatial rotation:

$$\mathcal{R} = \begin{pmatrix} \pm 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & \mp 1 & 0 \end{pmatrix} \begin{pmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \cos\chi\cos\omega_\oplus T_\oplus & \cos\chi\sin\omega_\oplus T_\oplus & -\sin\chi \\ -\sin\omega_\oplus & \cos\omega_\oplus & 0 \\ \sin\chi\cos\omega_\oplus T_\oplus & \sin\chi\sin\omega_\oplus T_\oplus & \cos\chi \end{pmatrix}$$



where χ is the colatitude of the experiment, $\omega_\oplus = 2\pi/(23\text{h}56\text{m})$ is the sidereal frequency, $T_\oplus$ is the local sidereal time, φ is the orientation of the experiments (for symmetric pp colliders) only the direction of the beams matters

- The c_f^{ij} and c_f^{0i} components of the $c_f^{\mu\nu}$ tensor are given by $c_f^{KL}\mathcal{R}_{Ki}\mathcal{R}_{Lj}$ and $c_f^{TK}\mathcal{R}_{iK}$, where c_f^{AB} $(A, B = T, X, Y, Z)$ is the tensor in the Sun-centered frame

Sun-centered vs lab frames

- The tensor $c_{\mu\nu}$ in the **lab frame** (that appears in our equations) is related to the corresponding tensor in the **Sun Centered Frame** by a spatial rotation. For instance:

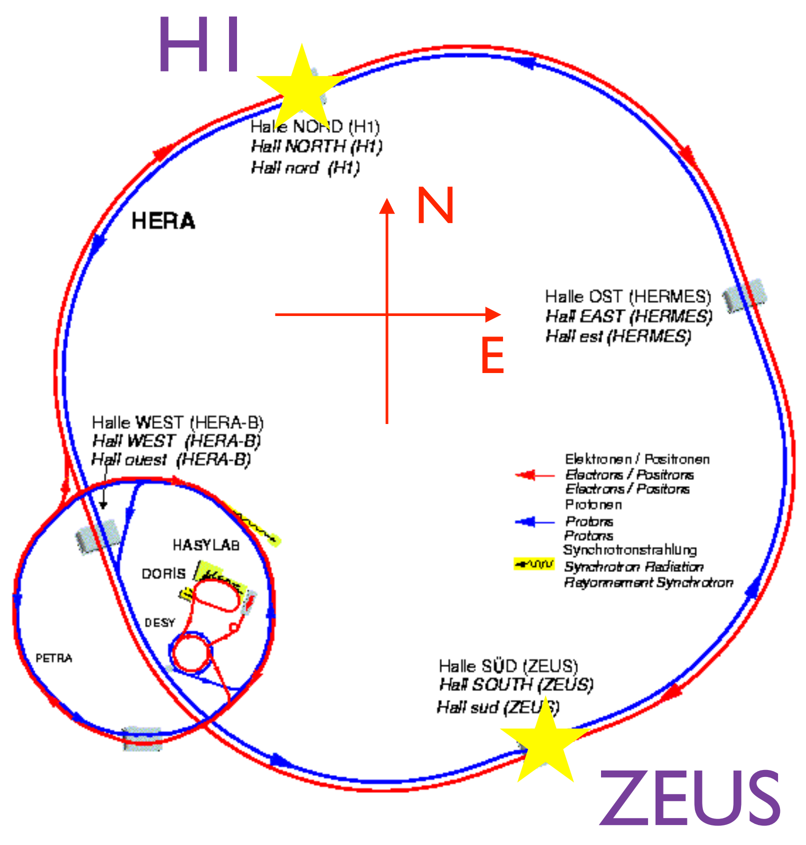
$$c^{00}_{fL,R} = c^{TT}_{fL,R}$$

$$\begin{aligned}
c^{33}_{fL,R} = & \frac{1}{2}(c^{XX}_{fL,R} + c^{YY}_{fL,R})\left(\cos^2\chi\sin^2\psi + \cos^2\psi\right) + c^{ZZ}_{fL,R}\sin^2\chi\sin^2\psi \\
& -2\, c^{XZ}_{fL,R}\sin\chi\sin\psi\left[\cos\chi\sin\psi\cos(\Omega_\oplus T_\oplus) + \cos\psi\sin(\Omega_\oplus T_\oplus)\right] \\
& -2\, c^{YZ}_{fL,R}\sin\chi\sin\psi\left[\cos\chi\sin\psi\sin(\Omega_\oplus T_\oplus) - \cos\psi\cos(\Omega_\oplus T_\oplus)\right] \\
& + c^{XY}_{fL,R}\left[(\cos^2\chi\sin^2\psi - \cos^2\psi)\sin(2\Omega_\oplus T_\oplus) - \cos\chi\sin(2\psi)\cos(2\Omega_\oplus T_\oplus)\right] \\
& + \frac{1}{2}(c^{XX}_{fL,R} - c^{YY}_{fL,R})\left[(\cos^2\chi\sin^2\psi - \cos^2\psi)\cos(2\Omega_\oplus T_\oplus) \right. \\
& \left. + \cos\chi\sin(2\psi)\sin(2\Omega_\oplus T_\oplus)\right] .
\end{aligned}$$

- The TT, $XX + YY$ and ZZ components are time independent and can be constrained by existing analyses without need for a dedicated sidereal time studies

Sun-centered vs lab frames

HERA

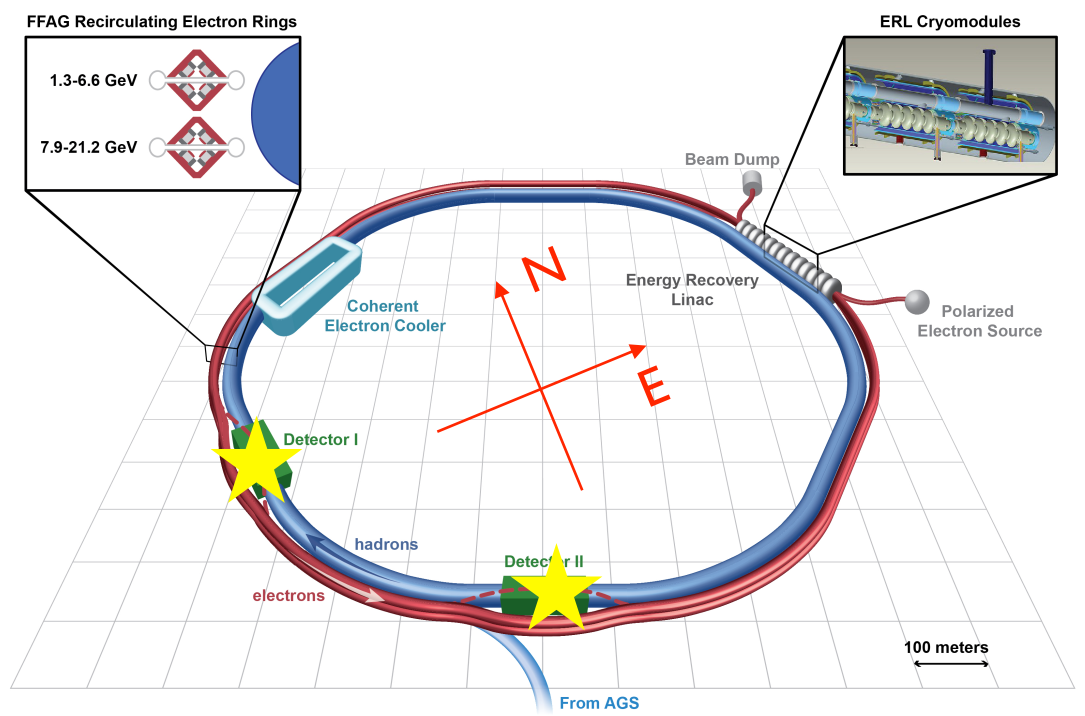


$\chi=36.4^o$

$\varphi_{ZEUS}=20^o$ NoE

$\varphi_{H1}=-20^o$ NoE

eRHIC (EIC)

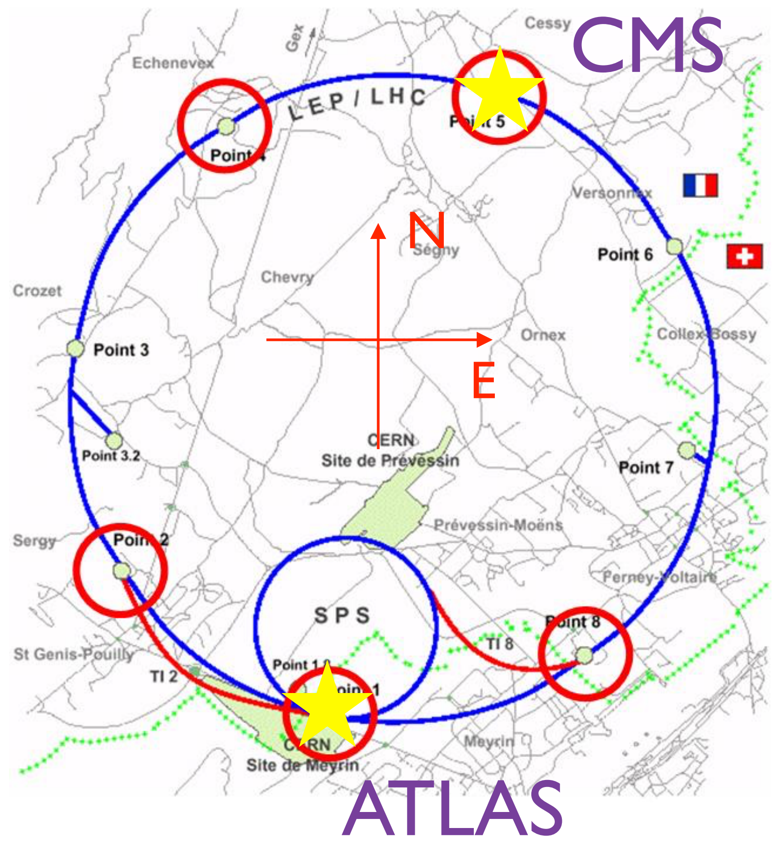


$\chi=49.1^o$

$\varphi_{eRHIC1}=-78.5^o$ NoE

$\varphi_{eRHIC2}=-16.8^o$ NoE

LHC



$\chi=46^o$

$\varphi_{ATLAS}=-14^o$ NoE

$\varphi_{CMS}=-14^o$ NoE

Sun-centered vs lab frames

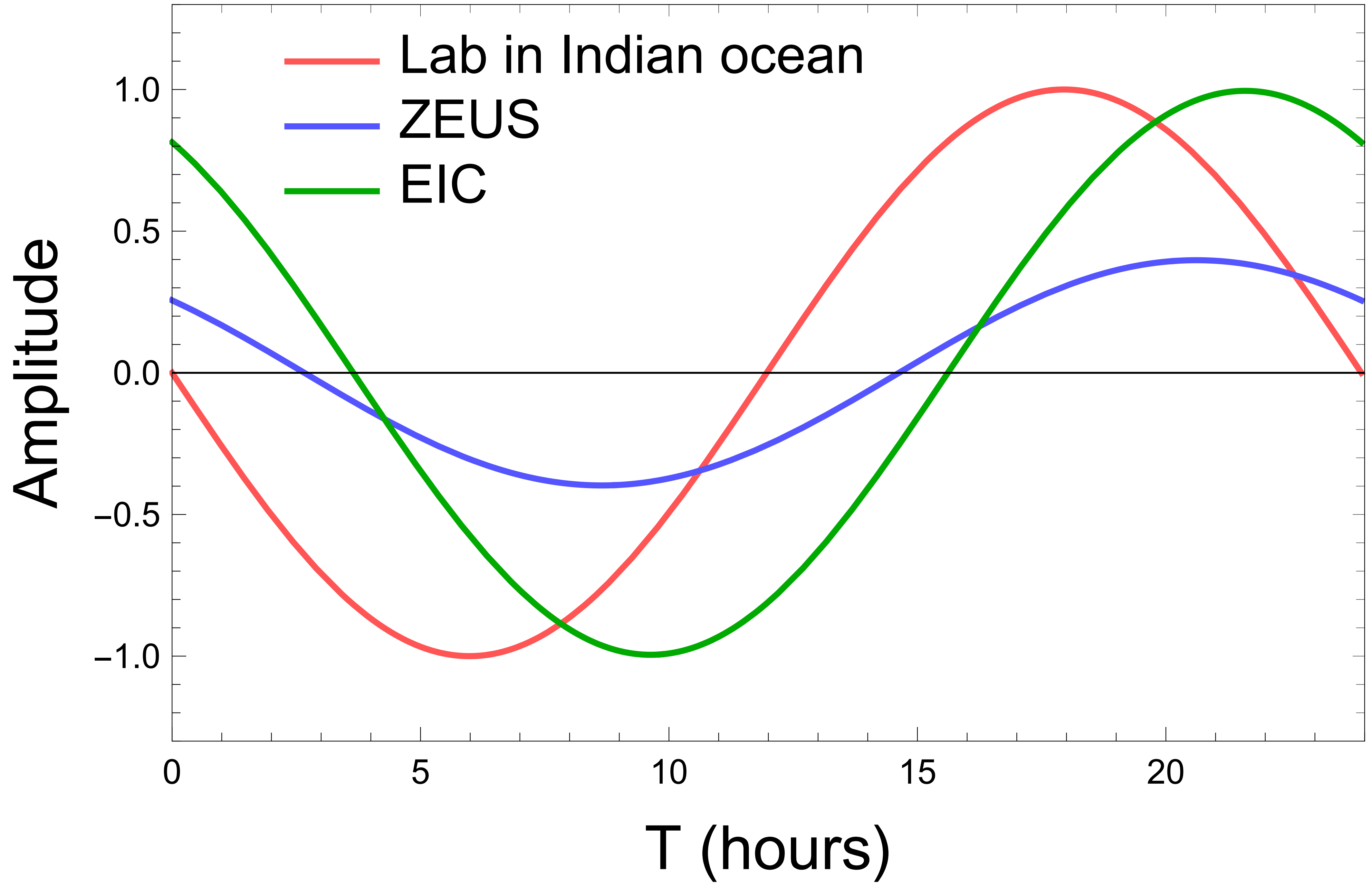
- **All laboratories have unique amplitude and phase modulations**

Independent of laboratory orientation

Ex. $$\left(\frac{\sigma_{\mathrm{SME}}(x,Q^2)}{\sigma_{\mathrm{SM}}(x,Q^2)}-1\right)\Bigg|_{c_u^{33}\,\mathrm{component}} \propto (\text{universal prefactor})\cdot c_u^{33}$$

laboratory coefficient

c_u^{XZ} time dependence at different labs



$$c_u^{33} = -2\, c_u^{XZ} \sin\chi \sin\psi \left[\cos\chi \sin\psi \cos(\omega_\oplus T_\oplus) + \cos\psi \sin(\omega_\oplus T_\oplus)\right]$$
+ other coefficients

$c_u^{XZ} = \text{SCF (1,3) component of } c_u^{\mu\nu}$

$\chi = \text{colatitude}$

$\psi = \text{beam NoE direction}$

$\omega_\oplus = \text{sidereal frequency}$

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

Expected constraints: HERA, EIC and LHC

- Estimated sensitivity of **DIS at HERA/EIC** and **Drell-Yan at LHC ($q^2 < (60\ \mathrm{GeV})^2$)**

	HERA	EIC	LHC
$\lvert a_{Su}^{(5)TXX} - a_{Su}^{(5)TYY}\rvert$	7.0×10^{-6}	2.3×10^{-6}	1.5×10^{-8}
$\lvert a_{Su}^{(5)XXZ} - a_{Su}^{(5)YYZ}\rvert$	1.8×10^{-5}	5.2×10^{-6}	-
$\lvert a_{Su}^{(5)TXY}\rvert$	2.3×10^{-6}	3.4×10^{-7}	2.7×10^{-9}
$\lvert a_{Su}^{(5)TXZ}\rvert$	4.7×10^{-6}	1.3×10^{-7}	7.2×10^{-9}
$\lvert a_{Su}^{(5)TYZ}\rvert$	4.6×10^{-6}	1.3×10^{-7}	7.0×10^{-9}
$\lvert a_{Su}^{(5)XXX}\rvert$	1.7×10^{-6}	1.4×10^{-7}	-
$\lvert a_{Su}^{(5)XXY}\rvert$	1.6×10^{-6}	1.4×10^{-7}	-
$\lvert a_{Su}^{(5)XYY}\rvert$	1.6×10^{-6}	1.4×10^{-7}	-
$\lvert a_{Su}^{(5)XYZ}\rvert$	1.0×10^{-5}	4.3×10^{-7}	-
$\lvert a_{Su}^{(5)XZZ}\rvert$	2.1×10^{-6}	1.2×10^{-7}	-
$\lvert a_{Su}^{(5)YYY}\rvert$	1.7×10^{-6}	1.4×10^{-7}	-
$\lvert a_{Su}^{(5)YZZ}\rvert$	2.1×10^{-6}	1.2×10^{-7}	-

[units of GeV^{-1}]

	HERA	EIC	LHC
$\lvert c_u^{TX}\rvert$	6.4×10^{-5}	5.8×10^{-7}	-
$\lvert c_u^{TY}\rvert$	6.4×10^{-5}	5.8×10^{-7}	-
$\lvert c_u^{XZ}\rvert$	3.2×10^{-4}	1.1×10^{-6}	7.3×10^{-5}
$\lvert c_u^{YZ}\rvert$	3.2×10^{-4}	1.2×10^{-6}	7.1×10^{-5}
$\lvert c_u^{XY}\rvert$	1.6×10^{-4}	1.3×10^{-6}	2.7×10^{-5}
$\lvert c_u^{XX} - c_u^{YY}\rvert$	5.0×10^{-4}	3.7×10^{-6}	1.5×10^{-4}

- EIC improvements over HERA are due to much larger expected luminosity
- $a^{(5)}$ coefficients produce enhanced effects at larger energies: DY at LHC dominates the potential constraints
- Drell-Yan on the Z-pole (LHC) is sensitive to an additional class of parity violating coefficients ($d_q^{\mu\nu}$) for which there is no sensitivity in unpolarized γ^* mediated DIS.

ATLAS search for sidereal signals of Z-pole quark Lorentz violation is underway - stay tuned!

Expected constraints: Drell-Yan at LHC on the Z-pole

- Constraints which we expect from sidereal time studies of **Drell-Yan at $Q^2 = m_Z^2$**

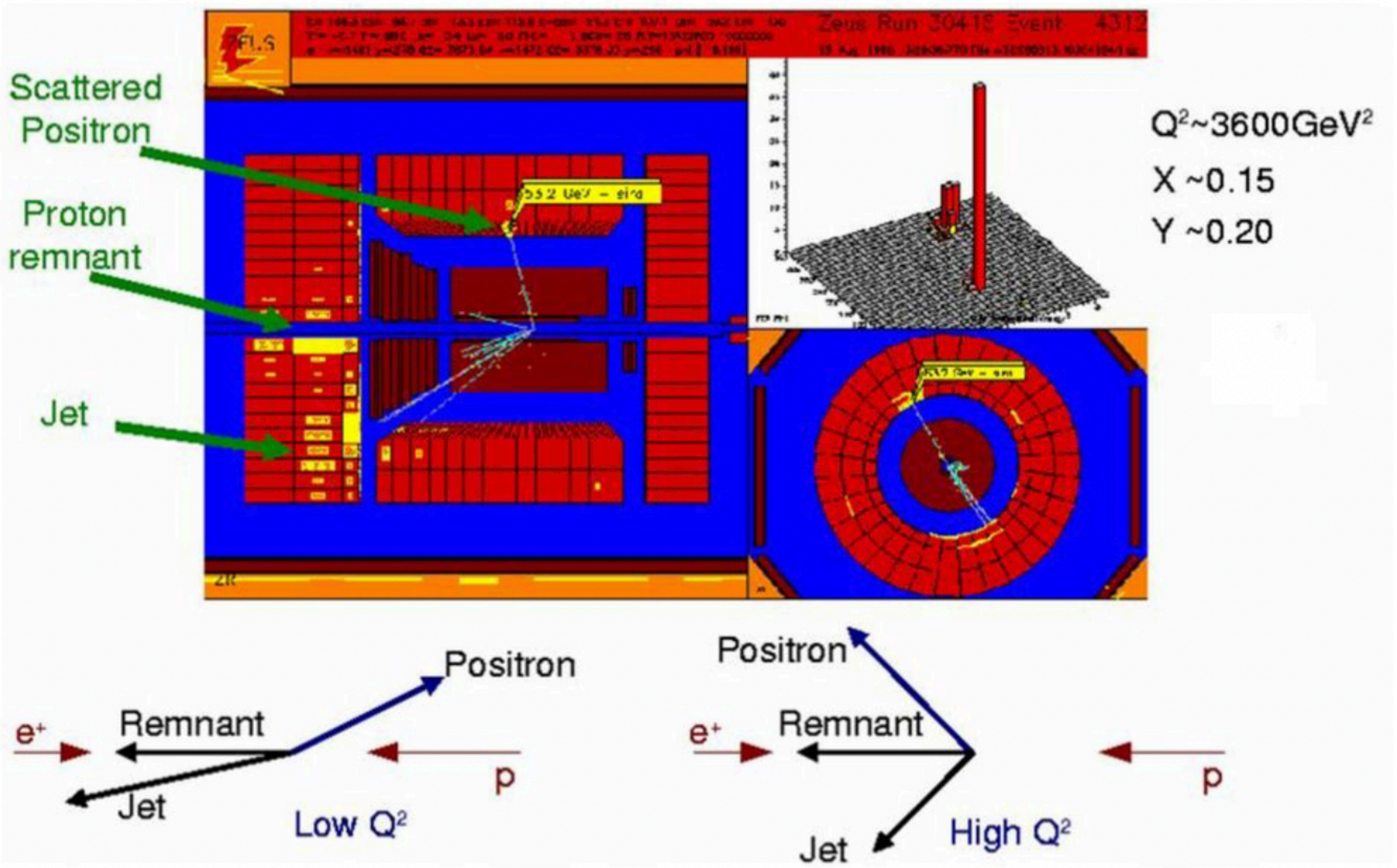
coefficient	$[\frac{d\sigma}{dQ}]_{Q=m_Z}$		
	nothing	δ_{lumi}	$\delta_{\text{lumi}},\ \delta_{\text{sel}}$
$\lvert c_{u_1}^{XY}\rvert$	8.4×10^{-4}	2.4×10^{-4}	1.1×10^{-4}
$\lvert c_{u_1}^{XZ}\rvert$	2.3×10^{-3}	6.3×10^{-4}	3.1×10^{-4}
$\lvert c_{u_1}^{YZ}\rvert$	2.3×10^{-3}	6.3×10^{-4}	3.1×10^{-4}
$\lvert c_{u_1}^{XX} - c_{u_1}^{YY}\rvert$	4.7×10^{-3}	1.3×10^{-3}	6.4×10^{-4}
$\lvert c_{d_1}^{XY}\rvert$	4.3×10^{-4}	1.2×10^{-4}	5.9×10^{-5}
$\lvert c_{d_1}^{XZ}\rvert$	1.2×10^{-3}	3.2×10^{-4}	1.6×10^{-4}
$\lvert c_{d_1}^{YZ}\rvert$	1.2×10^{-3}	3.2×10^{-4}	1.6×10^{-4}
$\lvert c_{d_1}^{XX} - c_{d_1}^{YY}\rvert$	2.4×10^{-3}	6.9×10^{-4}	3.3×10^{-4}
$\lvert d_{u_1}^{XY}\rvert$	3.7×10^{-4}	1.1×10^{-4}	5.1×10^{-5}
$\lvert d_{u_1}^{XZ}\rvert$	1.0×10^{-3}	2.8×10^{-4}	1.4×10^{-4}
$\lvert d_{u_1}^{YZ}\rvert$	1.0×10^{-3}	2.8×10^{-4}	1.4×10^{-4}
$\lvert d_{u_1}^{XX} - d_{u_1}^{YY}\rvert$	2.1×10^{-3}	6.0×10^{-4}	2.9×10^{-4}

[E.L., Sherrill, Szczepaniak, Vieira, 2011.02632]

coefficient $[\text{GeV}^{-1}]$	$[\frac{d\sigma}{dQ}]_{Q=m_Z}$		
	δ_{th}	$\delta_{\text{th}},\ \delta_{\text{lumi}}$	$\delta_{\text{th}},\ \delta_{\text{lumi}},\ \delta_{\text{sel}}$
$\lvert a_{Su}^{(5)TXY}\rvert$	4.3×10^{-8}	1.2×10^{-8}	6.0×10^{-9}
$\lvert a_{Su}^{(5)TXZ}\rvert$	1.8×10^{-6}	5.0×10^{-7}	2.4×10^{-7}
$\lvert a_{Su}^{(5)TYZ}\rvert$	1.8×10^{-6}	5.0×10^{-7}	2.4×10^{-7}
$\lvert a_{Su}^{(5)TXX} - a_{Su}^{(5)TYY}\rvert$	1.2×10^{-5}	3.4×10^{-6}	1.7×10^{-6}
$\lvert b_{Su}^{(5)TXY}\rvert$	5.7×10^{-8}	1.6×10^{-8}	7.9×10^{-9}
$\lvert b_{Su}^{(5)TXZ}\rvert$	2.4×10^{-6}	6.6×10^{-7}	3.2×10^{-7}
$\lvert b_{Su}^{(5)TYZ}\rvert$	2.3×10^{-6}	6.6×10^{-7}	3.2×10^{-7}
$\lvert b_{Su}^{(5)TXX} - b_{Su}^{(5)TYY}\rvert$	1.6×10^{-5}	4.5×10^{-6}	2.2×10^{-6}
$\lvert a_{Sd}^{(5)TXY}\rvert$	2.3×10^{-6}	6.5×10^{-7}	3.2×10^{-7}
$\lvert a_{Sd}^{(5)TXZ}\rvert$	9.4×10^{-5}	2.7×10^{-5}	1.3×10^{-5}
$\lvert a_{Sd}^{(5)TYZ}\rvert$	9.4×10^{-5}	2.6×10^{-5}	1.3×10^{-5}
$\lvert a_{Sd}^{(5)TXX} - a_{Sd}^{(5)TYY}\rvert$	6.4×10^{-4}	1.8×10^{-4}	8.7×10^{-5}

[E.L., Sherrill, to appear]

Deep Inelastic Scattering: ZEUS



ZEUS analysis: datasets and event selection

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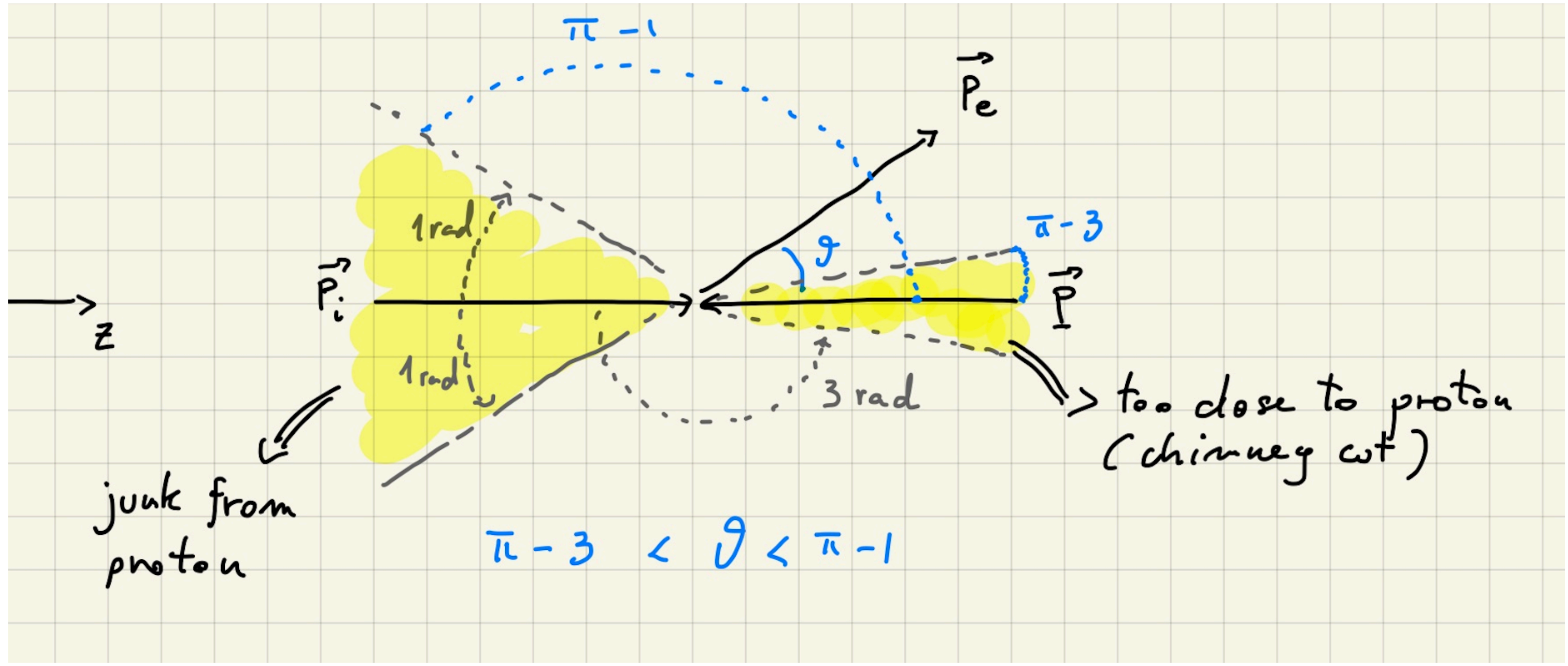
- We examined all (5 years) of HERA II data ($E_p = 920$ GeV, $E_e = 27$ GeV, $\mathscr{L}_{\rm tot} = 372\ {\rm pb}^{-1}$)

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	?

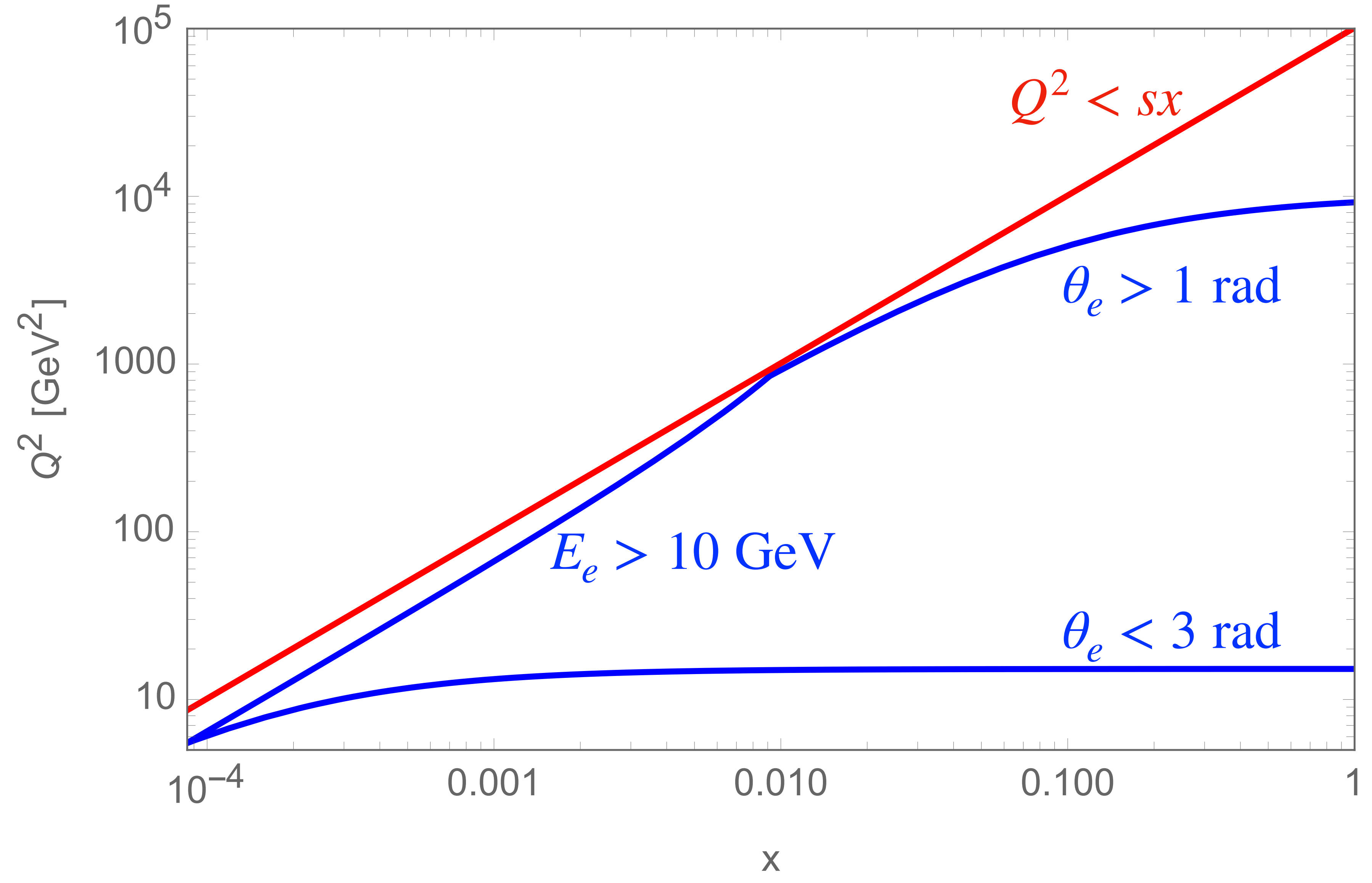


- We focused on a clean DIS selection:

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

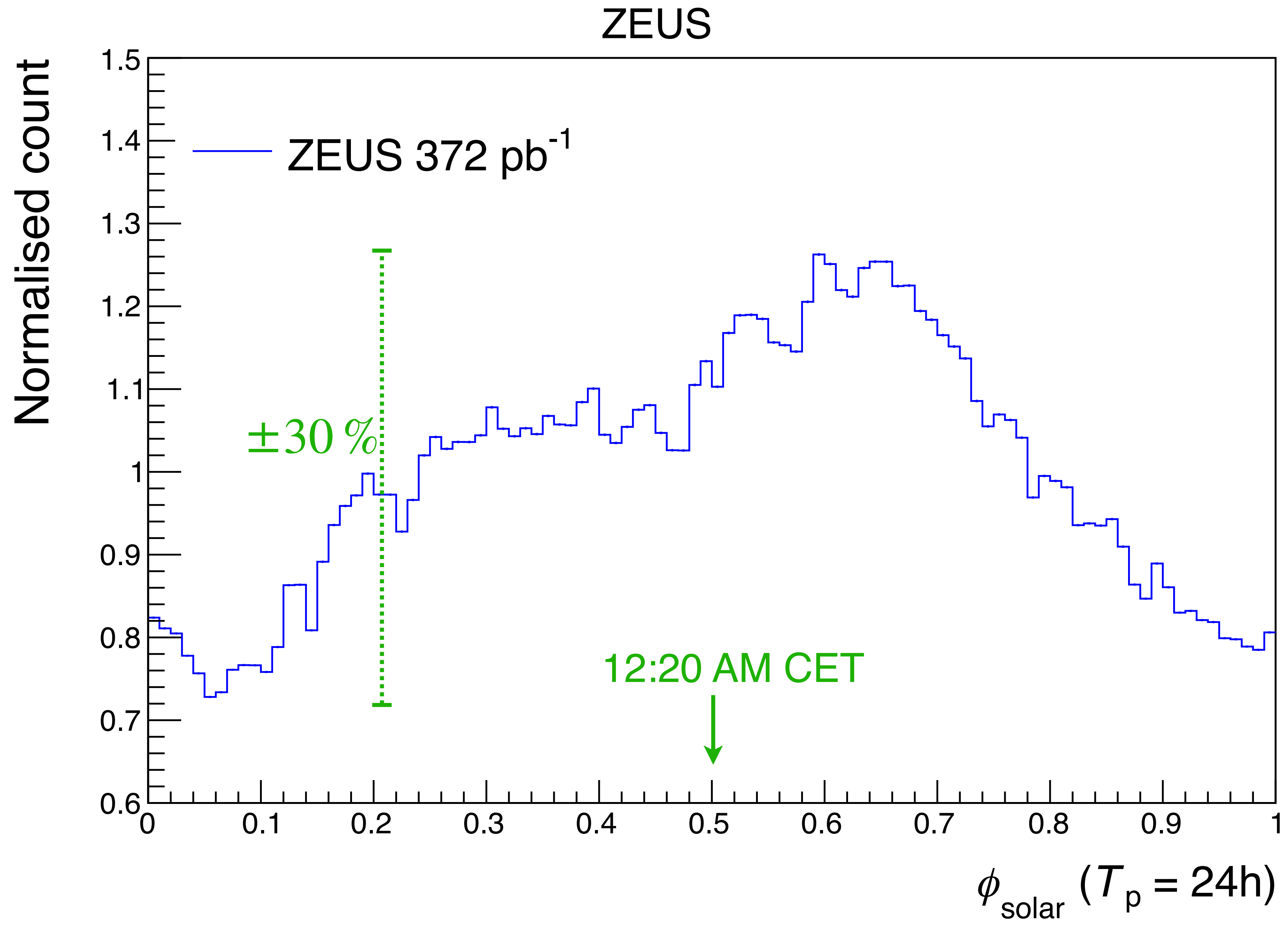
45M events with:

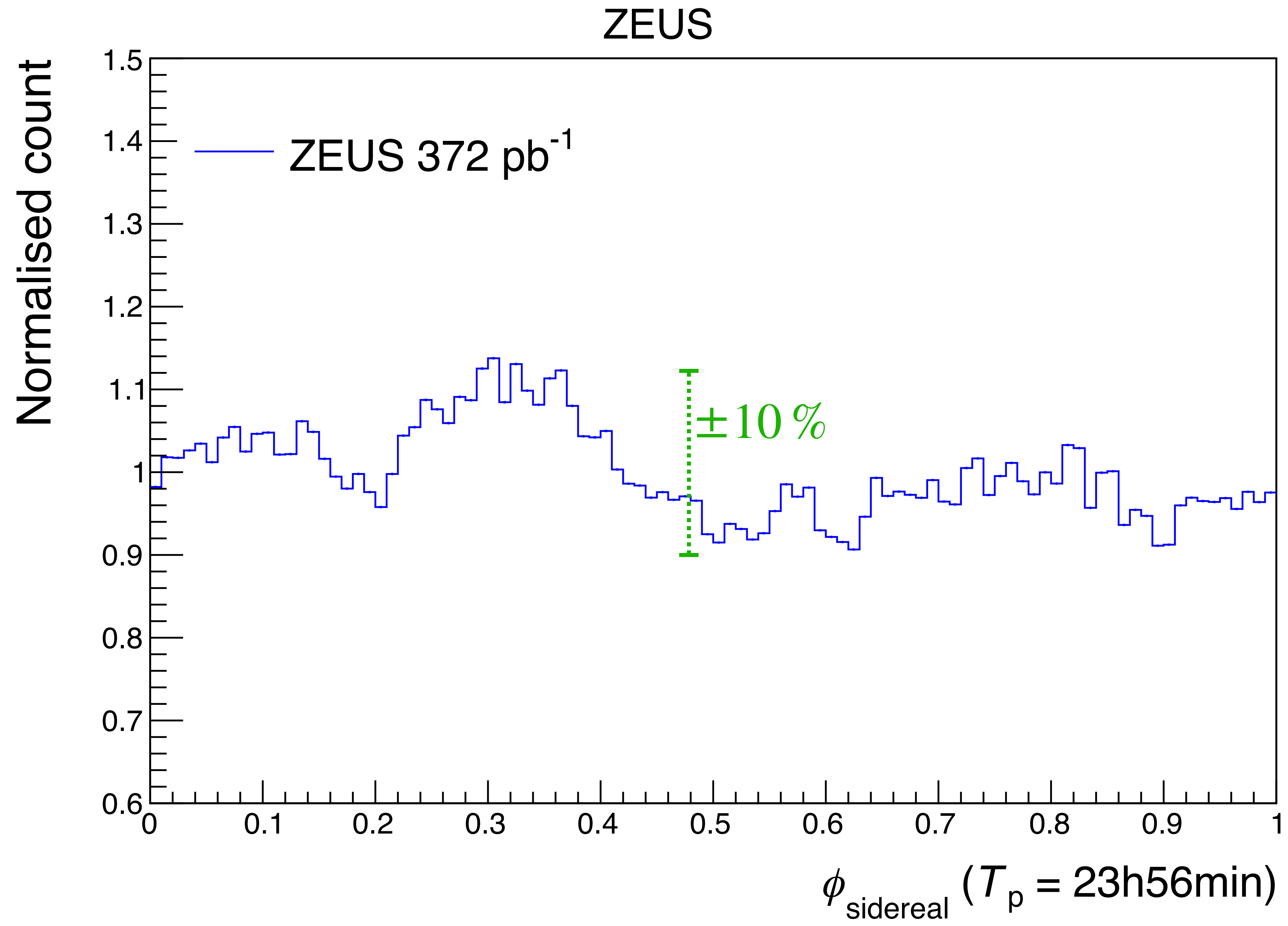
$$\begin{cases} x \in [7.7\times 10^{-5}, 1] \\ Q \in [2.2, 94]\ {\rm GeV} \end{cases}$$



ZEUS analysis: strategy

- The dependence of the luminosity on the time of the day is too large to be sufficiently diluted by the difference between the solar (24h) and sidereal (23h56m) periods:





- We bypass this problem by relying on the phase space dependence of the SME calculation
- Different regions in the (x, Q^2) plane have different dependence on the SME coefficients and allow the construction or ratios sensitive to the coefficients but independent of the luminosity

ZEUS analysis: strategy

- Given two regions in x and Q^2 $(\mathrm{PS}_{1,2})$ we build the following double ratios:

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

where $\phi_T = \mathrm{Mod}(T_\oplus, T)/T$ is the time phase built from the event time stamp $T_\oplus$ and the testing period T (we expect a possible signal for $T = T_{\mathrm{sidereal}}$ and a null result for all other periods)

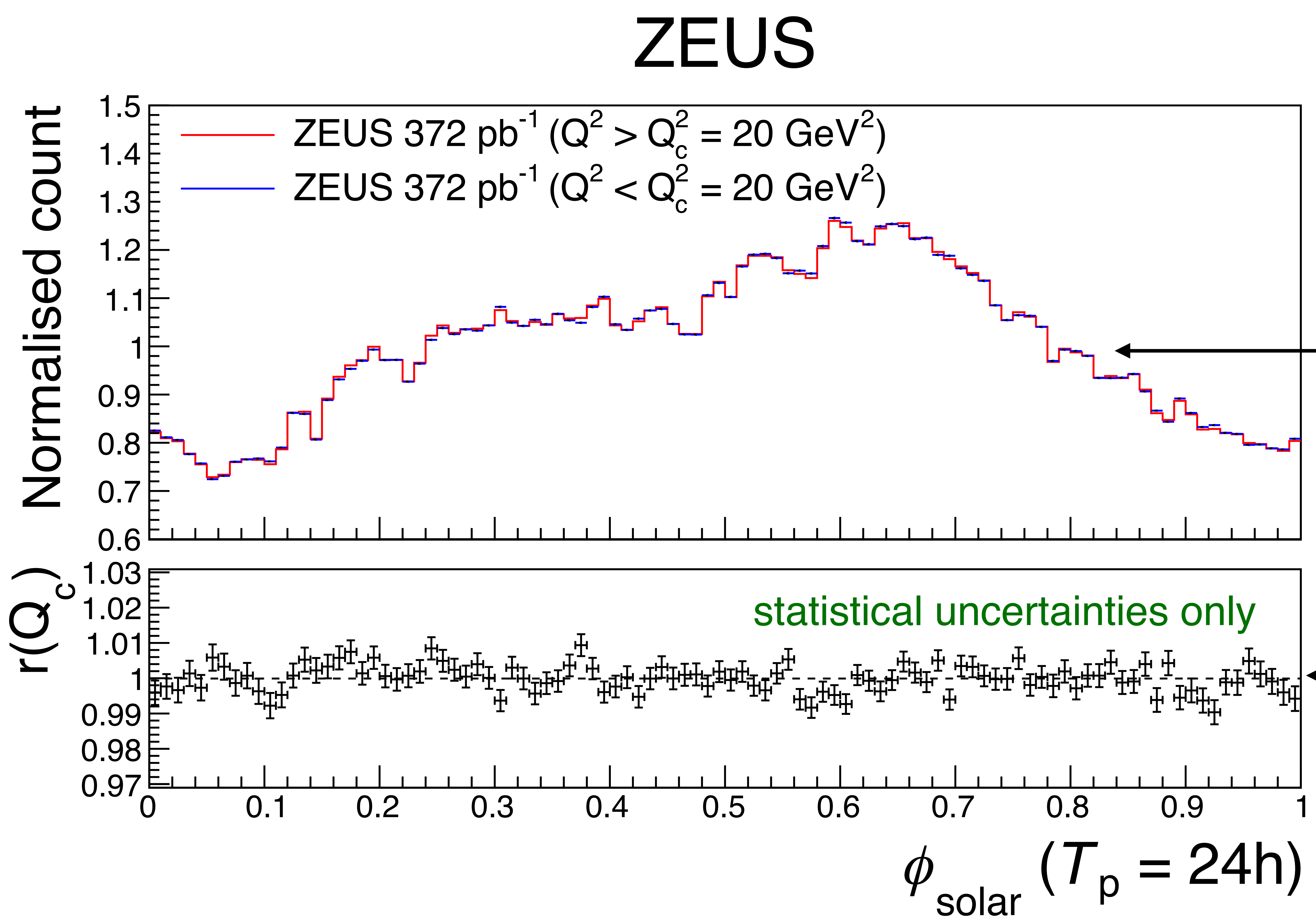
- We consider two different ratios and three testing periods

	T=1h	T=23h56m	T=24h
$Q^2_{\mathrm{cut}} = 20\ \mathrm{GeV}^2$	✘	✘	✘
$x_{\mathrm{cut}} = 10^{-3}$	✘	✓	✘

null tests | signal | null test but cross-contamination with signal is possible

- Slicing the phase space in Q^2 yields a ratio which is almost insensitive to the SME coefficients
- The cut $x_{\mathrm{cut}} = 10^{-3}$ is optimal: roughly halves the whole phase space thus minimizing stat uncertainties, while retaining a strong sensitivity to the SME coefficients

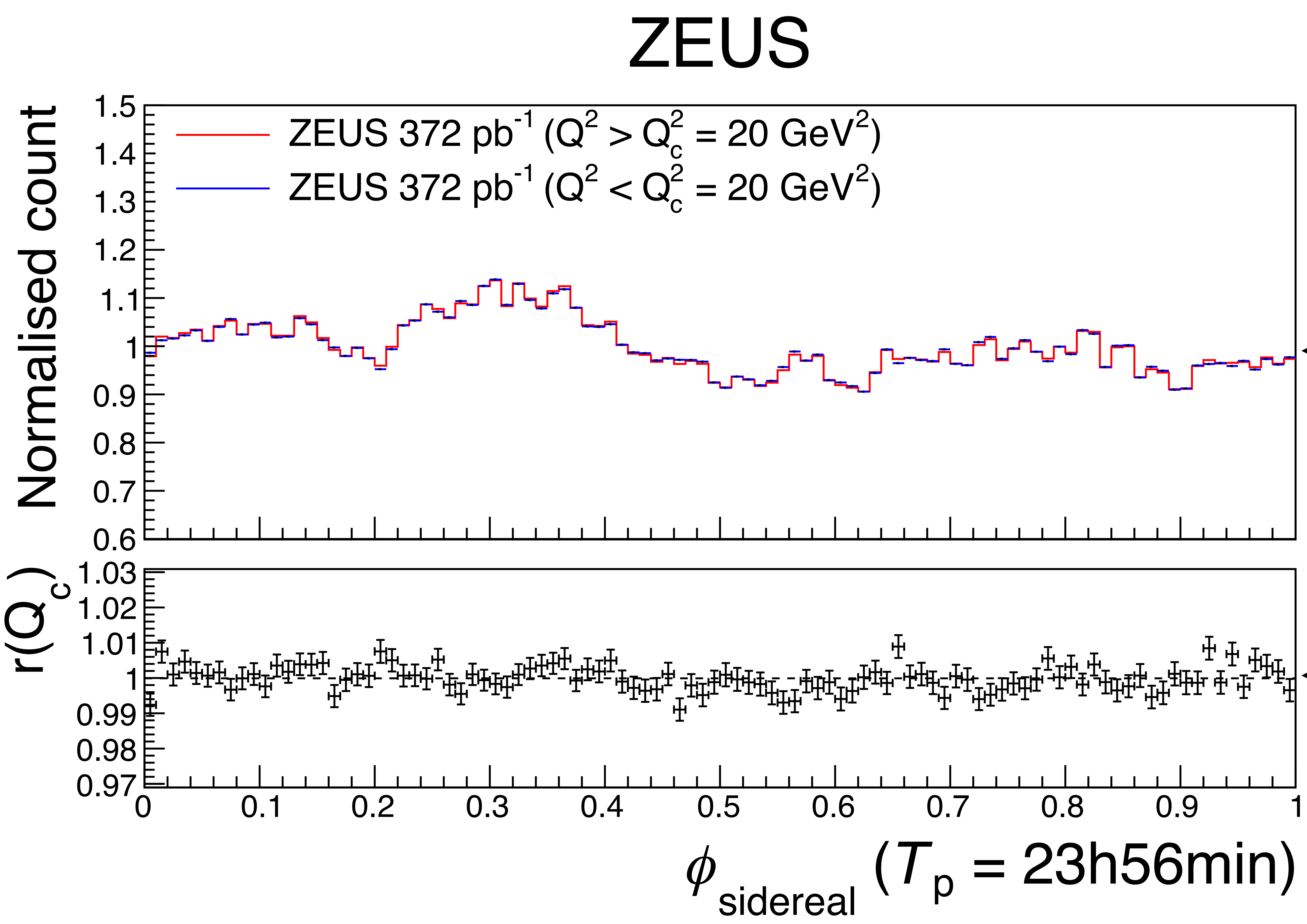
ZEUS analysis: control region (Q^2_{cut}, T_{solar})



Both distributions follow the luminosity profile

Dependence on luminosity drops out!

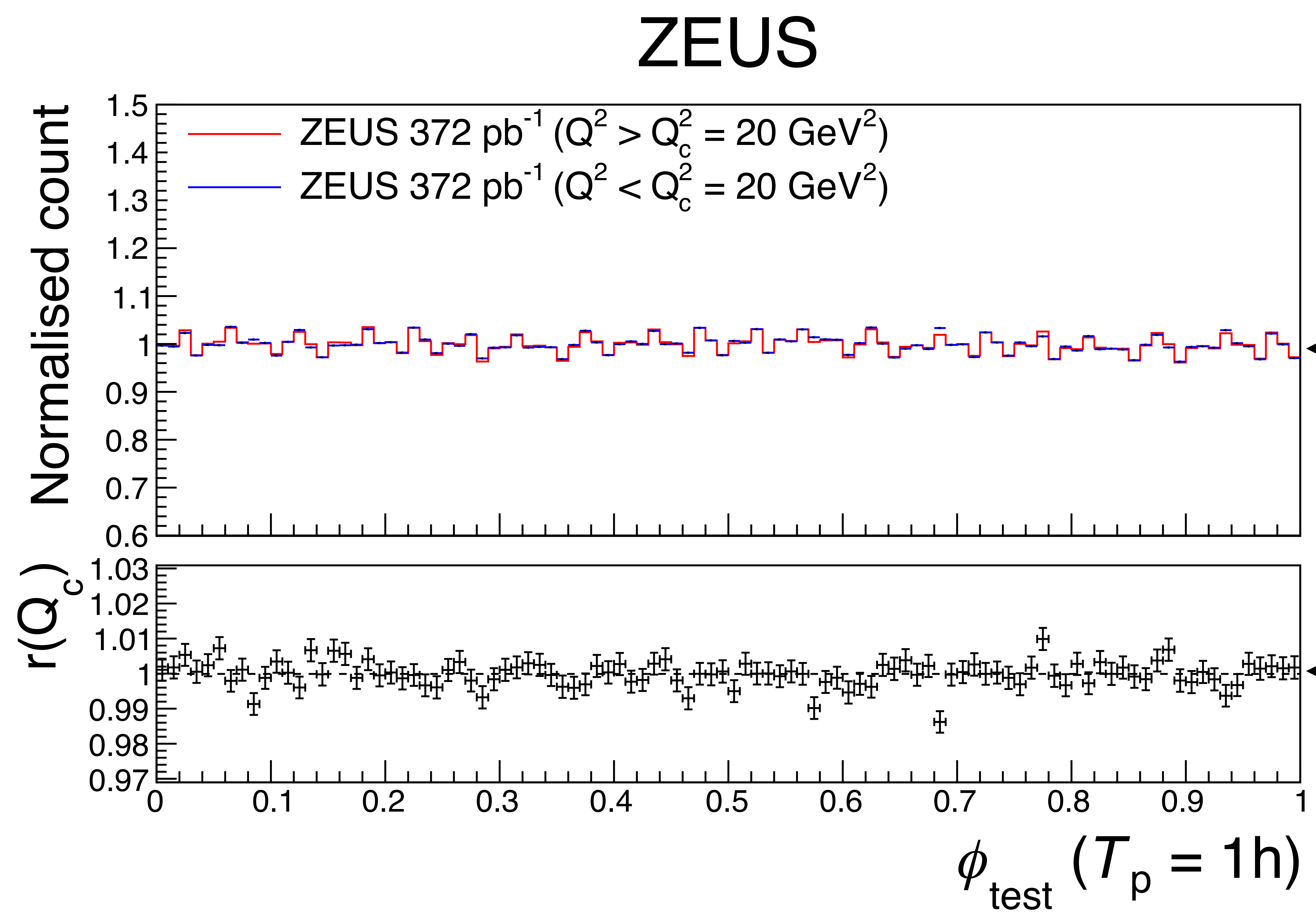
ZEUS analysis: control region (Q^2_{cut}, T_{sidereal})



Day/night effect partially diluted

Dependence on luminosity drops out!

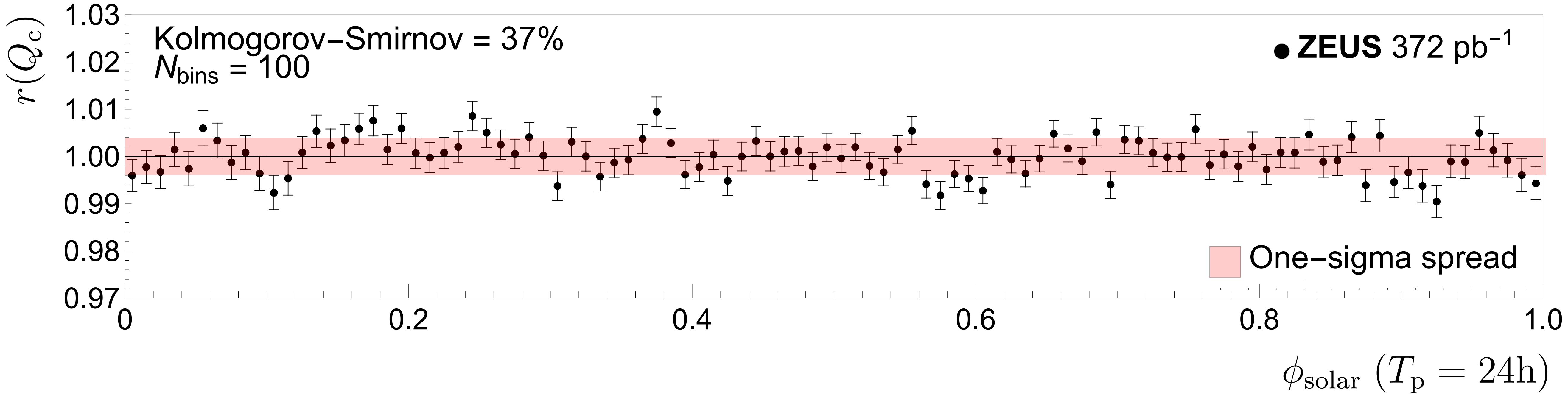
ZEUS analysis: control region (Q^2_{cut}, $T = 1\mathrm{h}$)

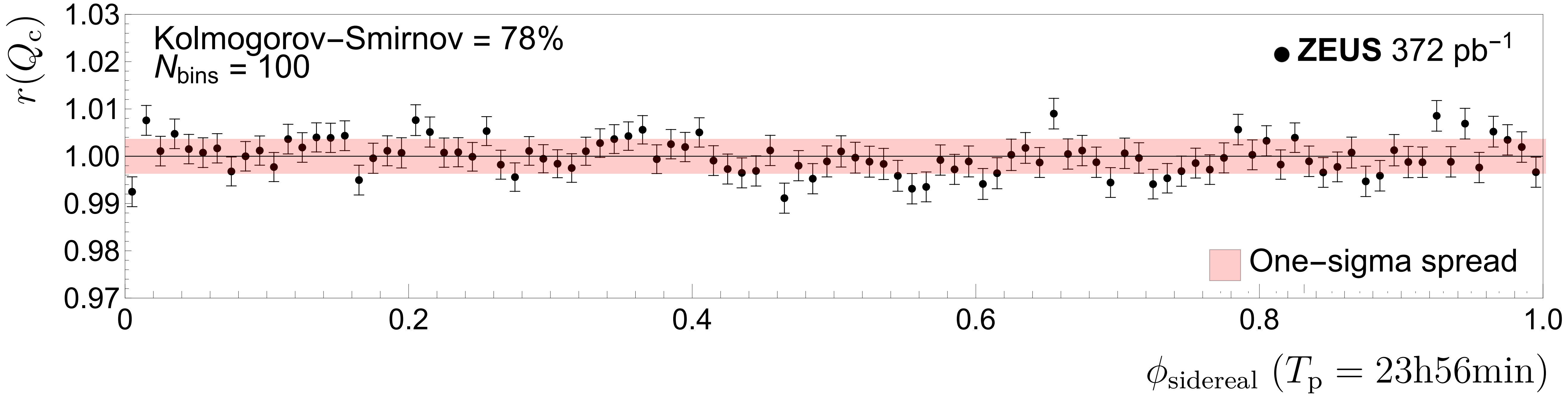


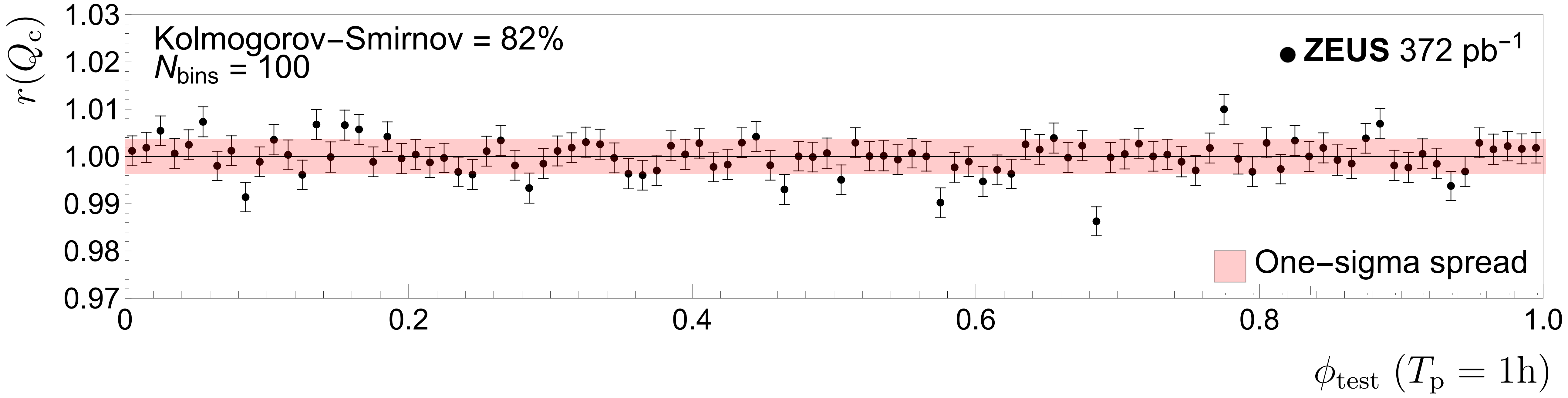
← Day/night effects completely eliminated

← Dependence on luminosity drops out!

ZEUS analysis: control region (Q^2_{cut}) summary



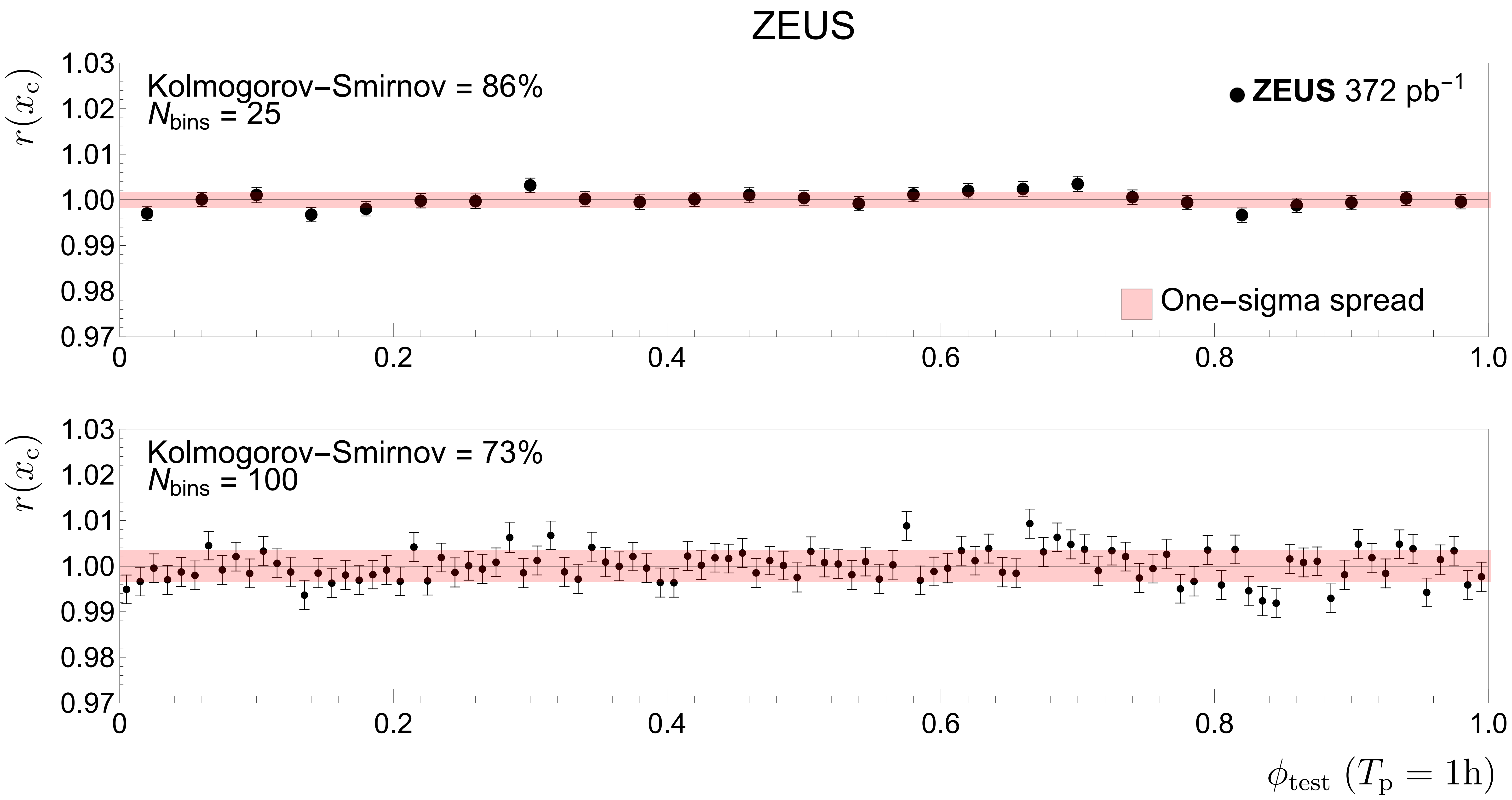




- Small KS probabilities($< 5\,\%$) would signal the presence of unaccounted-for systematic uncertainties
- All binned distribution show no strong evidence of this
- The one-sigma spread is simply the standard deviation of the central values: **the difference between this spread and the statistical uncertainty can be considered a determination of systematic uncertainties**

ZEUS analysis: control region (x_{cut}, $T = 1\mathrm{h}$)

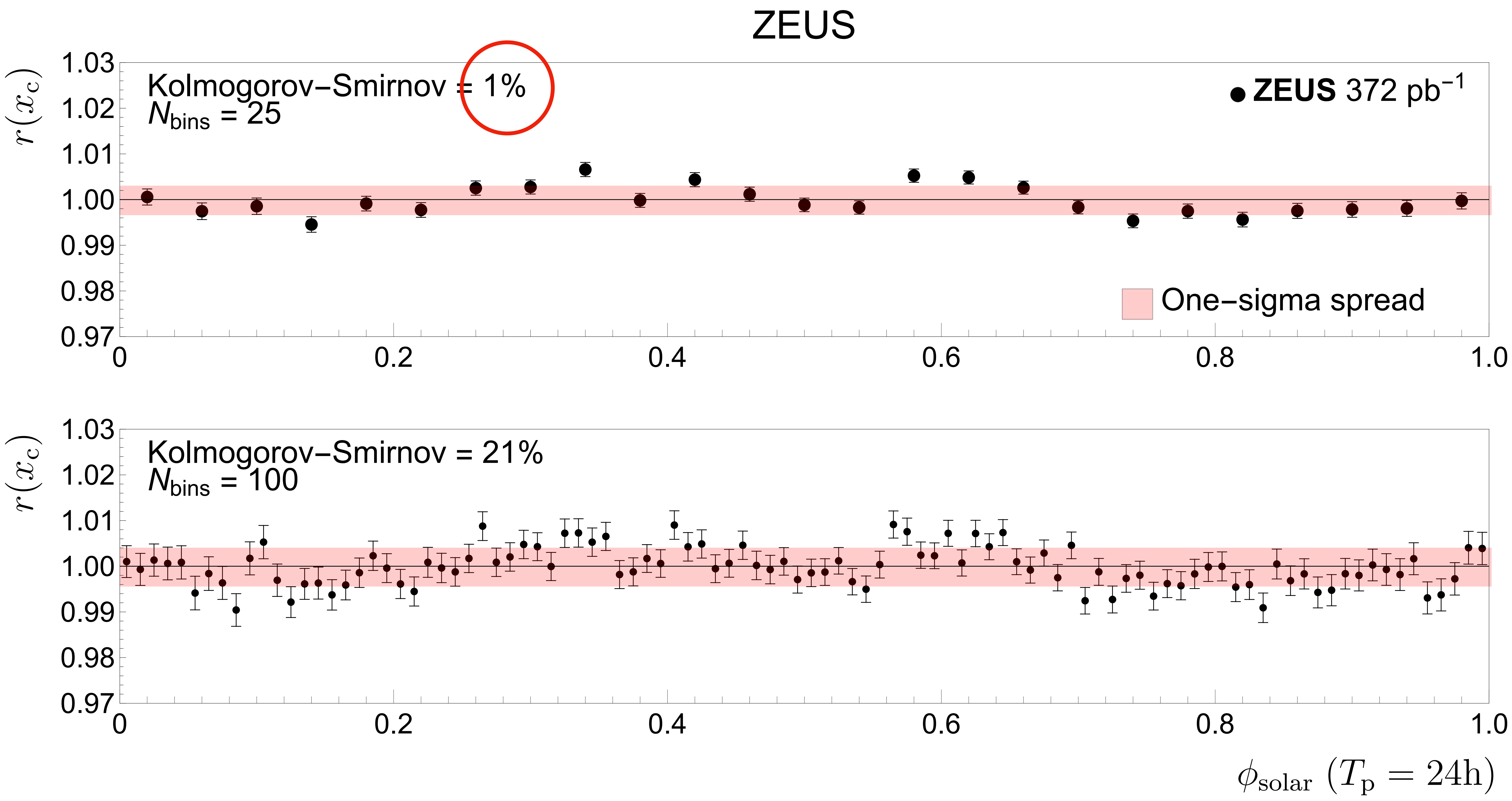
- This observable is sensitive to SME coefficients but not when binned using a test phase $T = 1\mathrm{h} \ll T_{\mathrm{sidereal}}$



- **No evidence of large unaccounted systematic uncertainties**

ZEUS analysis: control region (x_{cut}, T_{solar})

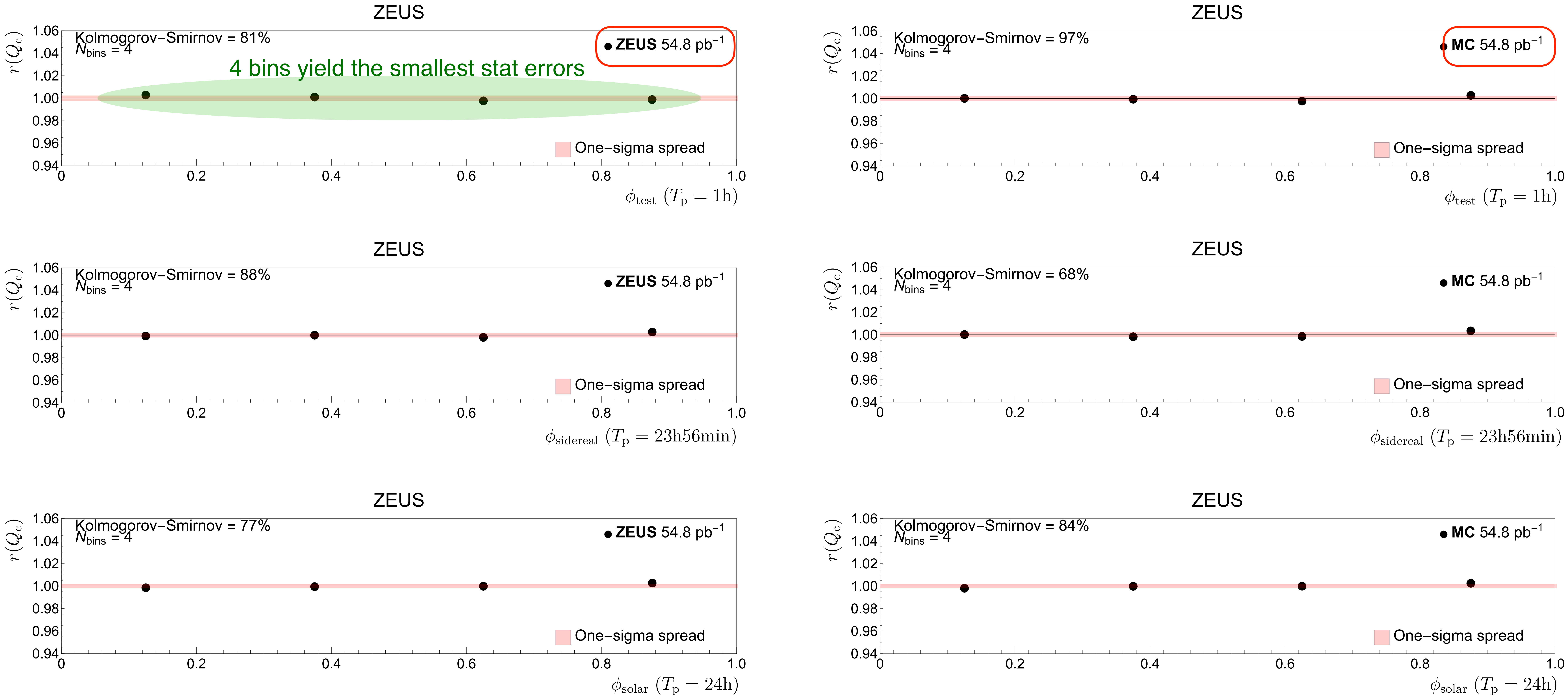
- This observable is sensitive to SME coefficients **but the small difference $T_{\text{solar}} - T_{\text{sidereal}} = 4\text{m}$ could lead to cross contamination with the signal region**: an observable day/night effect might not be completely washed out when binning using the sidereal phase (or vice versa!)



- Small KS probabilities for some binnings suggests that presence of unaccounted for systematics

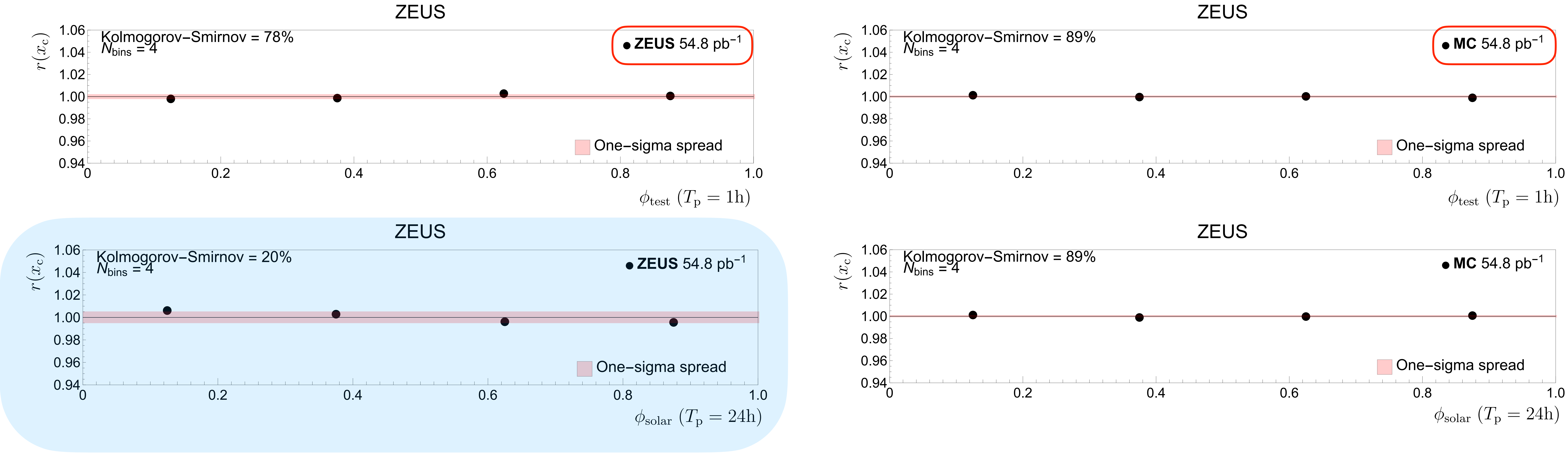
ZEUS analysis: systematic uncertainties from Monte Carlo?

- The control ratio $r(Q_c)$ does not show any evidence of systematic effects



ZEUS analysis: systematic uncertainties from Monte Carlo?

- Monte Carlo studies of the ratio $r(x_c)$ yield results that are fully compatible with statistical uncertainties alone:



(1) Systematics beyond Monte Carlo?

(2) Genuine day/night effect?

(3) Remnant of a genuine sidereal signal?

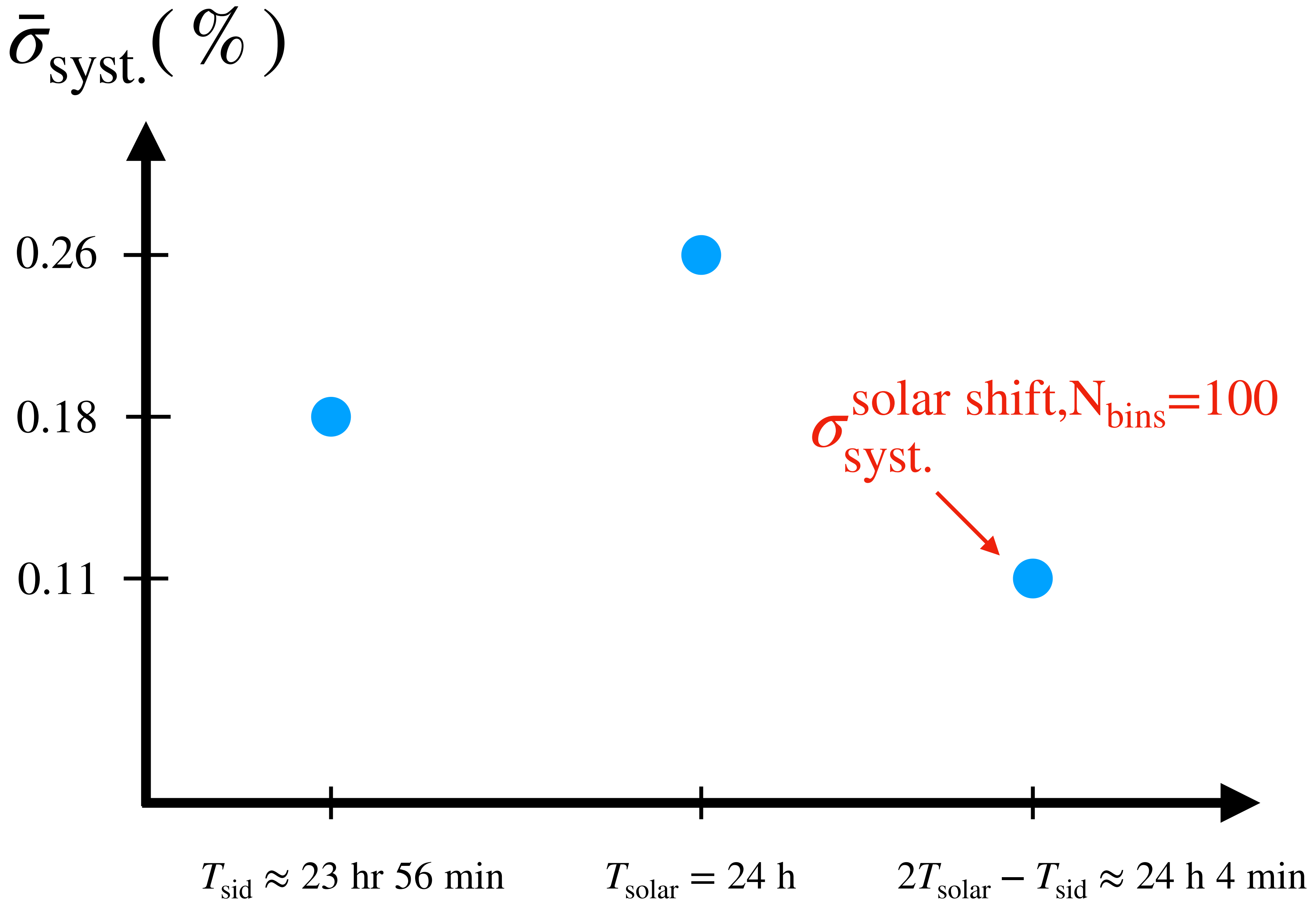
- $T_p = 1h$ with 4 bins: each bin is 15 min; $T_p = 24h$ with 4 bins: each bin is 6 hours.
- Strategy: use 100 solar/sidereal bins in such a way that each bin is about 15 min long.

ZEUS analysis: estimating systematic uncertainties

- We extract an estimate of the systematic uncertainty per bin using the difference between the observed one-sigma spread and the statistical uncertainties:

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

- Estimated systematics for $T_{\text{sidereal}} = 23\text{h}56\text{m}$, $T_{\text{solar}} = 24\text{h}$ and for the symmetric period $T = 24\text{h}4\text{m}$:

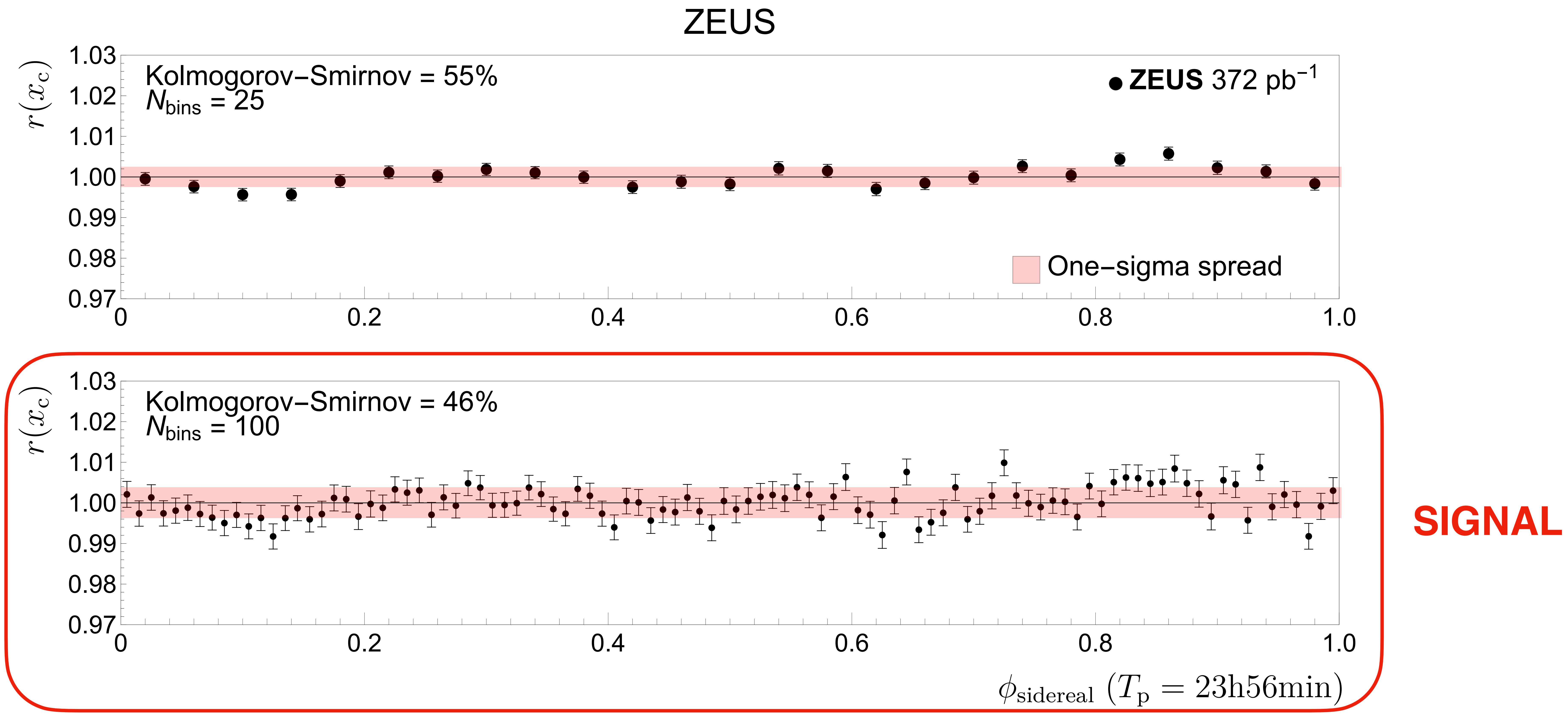


- We observe the largest systematics for T_{solar}
- The decrease in systematic uncertainties when shifting the period by $\pm 4\text{m}$ suggests that there might be a systematic effect associated with day/night effects
- We use systematic extracted from the $T = 24\text{h}4\text{m}$ study as an estimate of the missing systematic uncertainties in the signal distribution at $T = T_{\text{sidereal}}$:

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

ZEUS analysis: **signal region** $(x_{\rm cut}, T = T_{\rm sidereal})$

- The main results of the analysis is the following sidereal distribution:



- The KS probabilities are around 50% and are consistent with a normal distribution with mean unity and variance equal to the statistical uncertainty
- **The p-value of the SM hypothesis ($r(x_c) = 1$ in each bin) is 0.16 indicating a reasonable description of data**

ZEUS analysis: theory predictions

SKIP

- In order to place constraints on the coefficients we need the theory predictions for the ratios we consider
- In terms of lab frame coefficients we get:

$$
\begin{aligned}
r_c(x > x_c, x < x_c) = \; 1 & -12.8\, c_u^{03} - 13.9\, c_u^{33} + 0.9\, (c_u^{11} + c_u^{22}) - 4.2\, c_d^{03} - 2.9\, c_d^{33} + 0.1\, (c_d^{11} + c_d^{22}) \\
& -3.4\, c_s^{03} - 1.8\, c_s^{33} + 2.9 \times 10^{-2}\, (c_s^{11} + c_s^{22}) \\
r_{a^{(5)}}(x > x_c, x < x_c) = \; 1 & -6.1 \times 10^3\, a_u^{(5)003} + 6.8 \times 10^3\, a_u^{(5)033} - 2.5 \times 10^3\, a_u^{(5)333} \\
& +5.0 \times 10^2\, (a_u^{(5)113} + a_u^{(5)223} - a_u^{(5)011} - a_u^{(5)022}) \\
& -4.1 \times 10^2\, a_d^{(5)003} + 4.7 \times 10^2\, a_d^{(5)033} - 1.7 \times 10^2\, a_d^{(5)333} \\
& +40\, (a_d^{(5)113} + a_d^{(5)223} - a_d^{(5)011} - a_d^{(5)022})
\end{aligned}
$$

- Conversion to the Sun Centered Frame introduces time dependence. For instance:

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

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

- We get up terms with frequencies $\omega_\oplus$, $2\omega_\oplus$ and $3\omega_\oplus$

ZEUS analysis: constraints on the SME coefficients

- In order to place constraints we use the calculated theory predictions (on which most uncertainties cancel - e.g. PDF set dependence is at the % level) and the experimental results to build a chi-square:

$$\chi^2 = \frac{1}{(\sigma_{\text{tot}}^{\text{sid}})^2} \sum_{i=1}^{N_{\text{bins}}} \left(r_i^{\text{exp}} - r_i^{\text{theo}} \right)^2$$

- Given our less-than-optimal understanding of the small, yet non negligible, systematic uncertainties, we adopt a conservative approach and will simply **exclude values of the coefficients which yield a p-value smaller than 0.05:**

$$p(\chi^2, n_{\text{dof}}) < 0.05$$

- The **SM p-value is** $p_{\text{SM}} = 0.16$, implying that $c_q^{\mu\nu} = 0 = a_q^{(5)\mu\nu\alpha}$ is never rejected

- Therefore, the allowed regions which we obtain contain the null hypothesis (i.e. $c_q^{\mu\nu} = 0 = a_q^{(5)\mu\nu\alpha}$) by construction

ZEUS analysis: constraints on the SME coefficients

CONSTRAINTS ON $c_q^{\mu\nu}$ COEFFICIENTS

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
- $c_s^{\mu\nu}$ are first limits on strange quark coefficients

ZEUS analysis: constraints on the SME coefficients

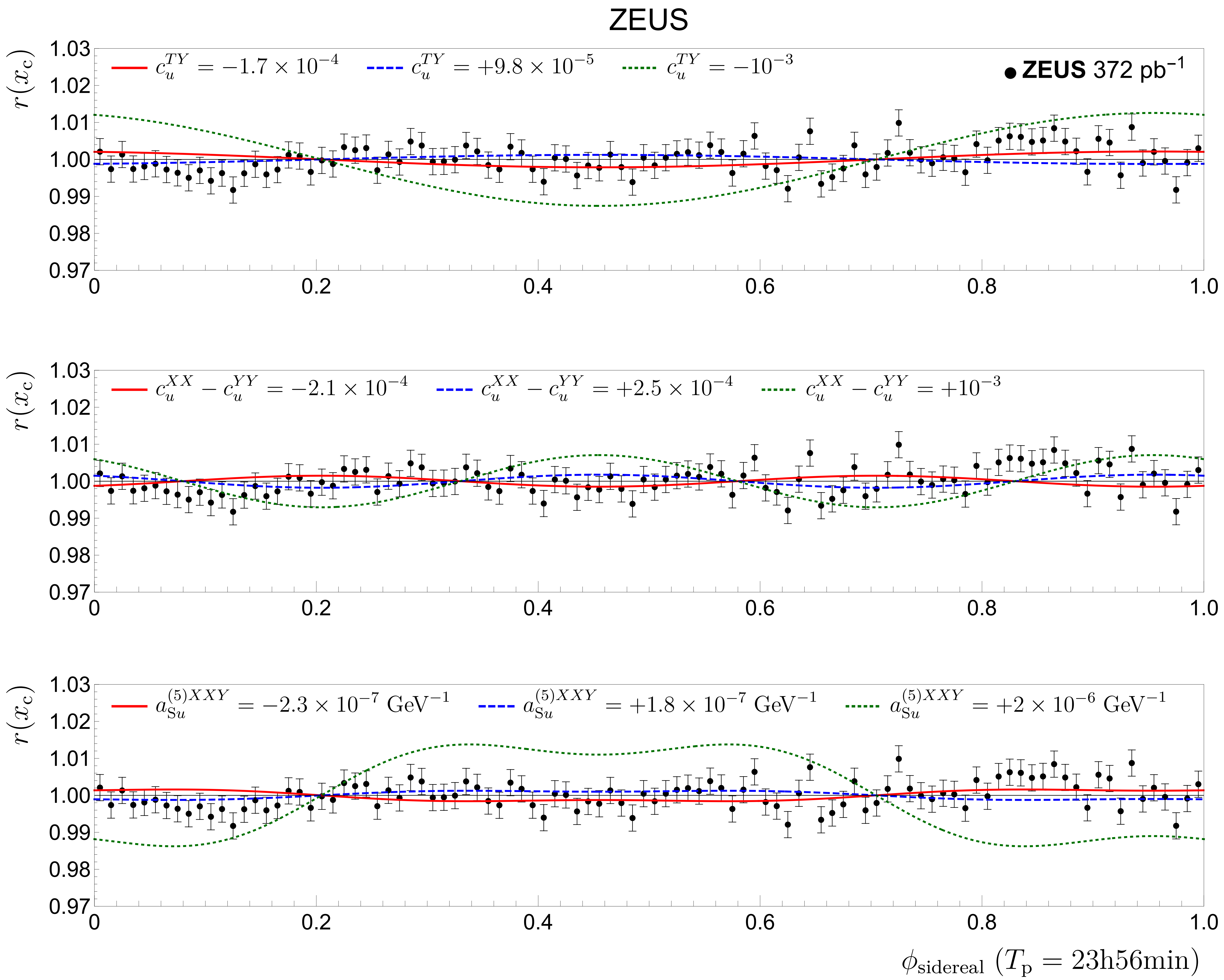
CONSTRAINTS ON $a_q^{(5)\mu\nu\alpha}$ COEFFICIENTS

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}

Coefficient	Lower (GeV^{-1})	Upper (GeV^{-1})
$a_{Sd}^{(5)TXX} - a_{Sd}^{(5)TYY}$	-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}
$a_{Sd}^{(5)YYY}$	-4.3×10^{-6}	2.3×10^{-6}
$a_{Sd}^{(5)YZZ}$	-5.4×10^{-6}	3.1×10^{-6}

- No previous constraints exist on any $a_q^{(5)\mu\nu\alpha}$ coefficient
- These coefficients are CPT violating: the near equality of s and $\bar{s}$ PDFs results in a near exact cancellation of $a_s^{(5)\mu\nu\alpha}$ effects on the DIS cross section: no bounds on $a_s^{(5)\mu\nu\alpha}$ can be extracted.

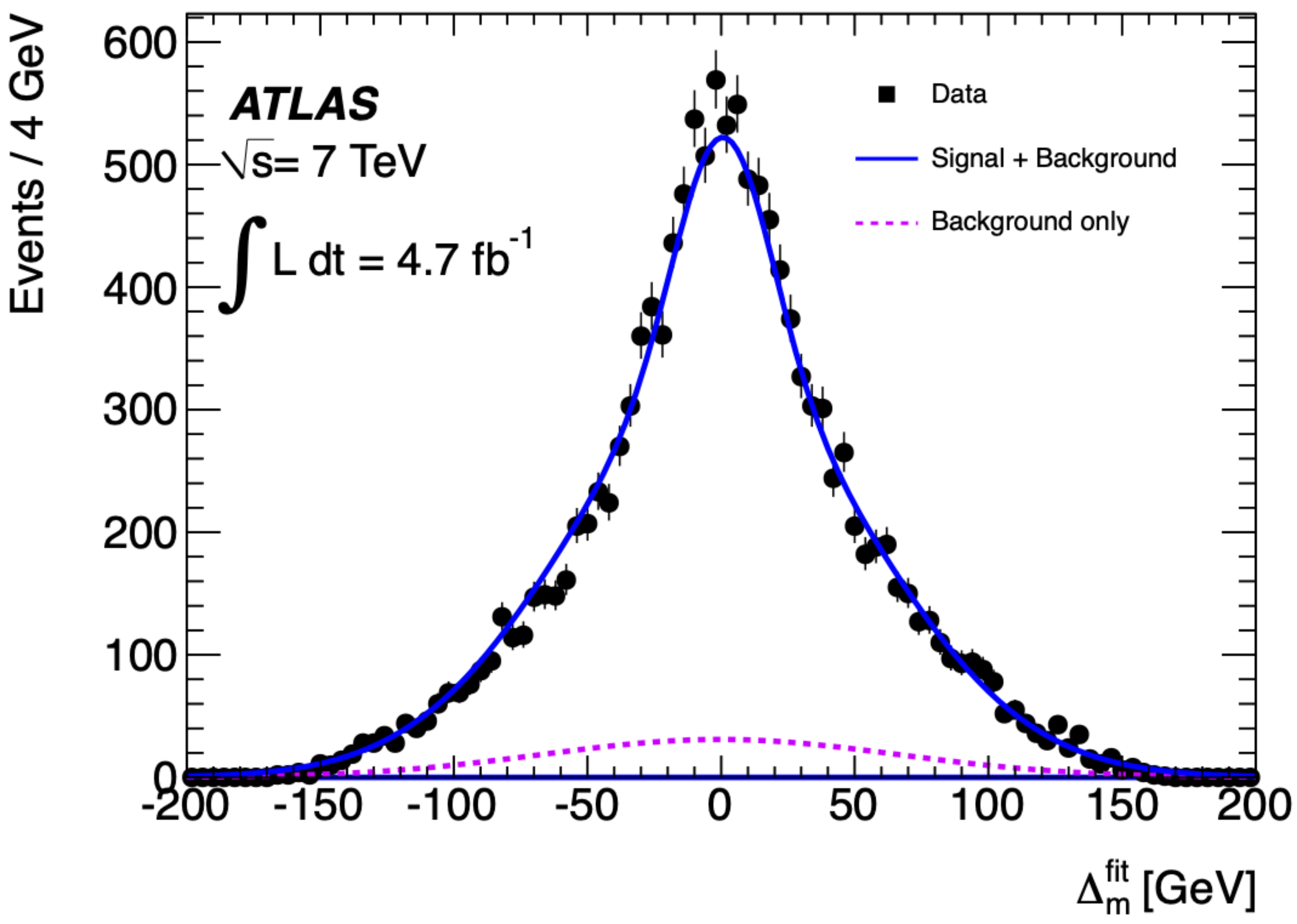
ZEUS analysis: example of excluded signals



= $p = 0.05$ "boundary values"

= excluded value

Top Quark Sector: theory and experiment



Top quark coefficients

- The Lagrangian terms we are interested in are: [Belyaev, Cerrito, E.L., Moretti, Sherrill, 2405.12162]

$$\mathscr{L}_{\rm CPT} = -\, a_Q^\mu\,(\bar t_L \gamma_\mu t_L + \bar b_L \gamma_\mu b_L) - a_T^\mu\, \bar t_R \gamma_\mu t_R - a_B^\mu\, \bar b_R \gamma_\mu b_R$$

- In the limit in which we set $m_b = 0$, appropriate field redefinitions show that the only surviving term is:

$$\mathscr{L}_{\rm CPT} = (a_Q^\mu - a_T^\mu)\, \bar t_R \gamma_\mu t_R = b^\mu\, \bar t_R \gamma_\mu t_R$$

- The dispersion relations for top and anti-tops reads:

$$p_t^2 = m_t^2 - p\cdot b \pm [(p\cdot b)^2 - m_t^2 b^2]^{1/2}$$
$$p_{\bar t} = m_t^2 + p\cdot b \pm [(p\cdot b)^2 - m_t^2 b^2]^{1/2}$$

where m_t is the top mass that appears in the Lagrangian and $\pm$ correspond to the two helicities.

- ATLAS and CMS extract a "kinematical" top mass which corresponds to $m^{\rm eff} = (p^2)^{1/2}$:

We can extract constraints on the b^μ coefficients from helicity averaged measurements of

$$\Delta m_{t\bar t} \equiv m_t^{\rm eff} - m_{\bar t}^{\rm eff} = -\,\frac{(p_t + p_{\bar t})\cdot b}{2m_t}$$

Top quark coefficients

- In pp collisions, after averaging over the events, we have $\langle E_t + E_{\bar t}\rangle \neq 0$ and $\langle \vec p_t + \vec p_{\bar t}\rangle = 0$, implying that only the coefficient $b_0 = b_T$ (in the SCF) can be actually constrained by existing measurements:

$$\Delta m_{t\bar t} = -\frac{1}{2}\frac{\langle E_t + E_{\bar t}\rangle}{m_t} b_T$$

- Both Atlas and CMS measured the $t\bar t$ mass difference:

$$\Delta m^{\rm exp}_{t\bar t} = \begin{cases} (+0.67 \pm 0.61 \pm 0.41)\ \text{GeV} & \text{Atlas, } E_{\rm CM} = 7\ \text{TeV},\ \mathscr{L} = 4.7\ \text{fb}^{-1} \\ (-0.15 \pm 0.19 \pm 0.09)\ \text{GeV} & \text{CMS, } E_{\rm CM} = 8\ \text{TeV},\ \mathscr{L} = 19.6\ \text{fb}^{-1} \end{cases}$$

- In order to extract a bound we need the average energy of the $t\bar t$ pair in the fiducial region:

	$t\bar t$	$t\bar t \to \ell\nu jjb\bar b$ tot	$t\bar t \to \ell\nu jjb\bar b$ fid [GeV]
$\langle E_t + E_{\bar t}\rangle_{@7\ TeV}$	706.3	708.9	658.4
$\langle E_t + E_{\bar t}\rangle_{@8\ TeV}$	738.9	742.2	674.4
$\langle E_t + E_{\bar t}\rangle_{@13\ TeV}$	878.8	883.7	725.2
$\langle E_t + E_{\bar t}\rangle_{@13.6\ TeV}$	892.5	898.7	729.1

$$b_T \in \begin{cases} [-1.1, 0.42]\ \text{GeV} & \text{ATLAS @ 7 TeV} \\ [-0.14, 0.29]\ \text{GeV} & \text{CMS @ 8 TeV} \end{cases}$$

[First bounds on b_T]

Top quark coefficients

- The contribution to the $t\bar{t}$ mass difference from $b^{X,Y,Z}$ are more complicated:

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} -b_Z \sin\chi\cos\psi + \cos(\omega_\oplus T_\oplus)(b_X\cos\chi\cos\psi + b_Y\sin\psi) + \sin(\omega_\oplus T_\oplus)(b_Y\cos\chi\cos\psi - b_X\sin\psi) \\ b_Z\cos\chi + \sin\chi[b_X\cos(\omega_\oplus T_\oplus) + b_Y\sin(\omega_\oplus T_\oplus)] \\ -b_Z\sin\chi\sin\psi + \cos(\omega_\oplus T_\oplus)(b_X\cos\chi\sin\psi - b_Y\cos\psi) + \sin(\omega_\oplus T_\oplus)(b_Y\cos\chi\sin\psi + b_X\cos\psi) \end{pmatrix}$$

$$\Delta m_{t\bar{t}}^{\text{eff}} = -\frac{1}{2m_t}\left[b_T\Delta_T + b_Z\Delta_Z + \sum_{A=X,Y} b_A\Big(C_A\cos(\omega_\oplus T_\oplus) + S_A\sin(\omega_\oplus T_\oplus)\Big)\right]$$

$$\begin{aligned}
\Delta_T &= E_t + E_{\bar{t}}\ , \\
\Delta_Z &= -\sin\chi\cos\psi(p_1+\bar{p}_1) + \cos\chi(p_2+\bar{p}_2) - \sin\chi\sin\psi(p_3+\bar{p}_3)\ , \\
C_X &= \cos\chi\cos\psi(p_1+\bar{p}_1) + \sin\chi(p_2+\bar{p}_2) + \cos\chi\sin\psi(p_3+\bar{p}_3)\ , \\
S_X &= -\sin\psi(p_1+\bar{p}_1) + \cos\psi(p_3+\bar{p}_3)\ , \\
C_Y &= -S_X\ , \\
S_Y &= C_X\ ,
\end{aligned}$$

$\chi = 43.7^{\text{o}}$ (colatitude of CERN)
$\psi = -11.3^{\text{o}}$ (orientation of Atlas and CMS)

- The terms proportional to $b^{X,Y,Z}$ average to zero when integrating over the whole phase space
- Additionally the $b^{X,Y}$ terms vanish also when averaging over the sidereal period
- This means that dedicated experimental analyses are required to extract bounds

Top quark coefficients

- A simple strategy to extract a bound on b^Z is to consider the observable:

$$\langle \Delta m_{t\bar{t}}^{\mathrm{eff}\,\prime} \rangle = \langle \Delta m_{t\bar{t}}^{\mathrm{eff}} \,\mathrm{sgn}[\Delta_Z] \rangle = -\frac{b_Z}{2m_t} \langle |\Delta_Z| \rangle$$

[$\langle\rangle$ indicates phase space average]

- For $b^{X,Y}$ a sidereal time analysis is unavoidable:

$$\Delta m_{t\bar{t}}^{\mathrm{eff}} = -\frac{b_X}{2m_t} \Delta_X^{(n)} \,,$$

$$\Delta_X^{(n)} = C_X \langle \cos(\omega_\oplus T_\oplus) \rangle_n + S_X \langle \sin(\omega_\oplus T_\oplus) \rangle_n$$

- Using Monte Carlo to calculate the relevant quantities we are able to calculate "projected" bounds by assuming that the final experimental uncertainties on the "new" $\Delta m_{t\bar{t}}^{\mathrm{eff}}$ will be similar to on the actual mass difference.

	7 TeV		8 TeV		13 TeV		13.6 TeV	
	tot	fid	tot	fid	tot	fid	tot	fid
$\langle \lvert\Delta_Z\rvert \rangle$	72	68	76	70	97	79	100	80
$\langle \lvert C_X\rvert \rangle$	74	69	79	70	103	84	103	81
$\langle \lvert S_X\rvert \rangle$	418	329	451	361	590	416	603	405

[units of GeV]

$$|b_Z|_{\mathrm{expected}} \lesssim 4.6 \text{ GeV}$$

$$|b_{X,Y}|_{\mathrm{expected}} \lesssim 0.8 \text{ GeV}$$

Conclusions

- Quark and gluon SME coefficients are extremely hard to constrain because of the non-perturbative QCD
- Two main approaches:
  - Connect quark/gluon and proton coefficients in Chiral Perturbation theory
  - Access quark/gluon coefficients directly using factorization in high-energy collisions (e-p and p-p)
- In high energy interactions SME effects induce sidereal time dependence on various cross sections and can be constrained by a “straightforward” sidereal binning analysis
- We performed detailed studies of sensitivity of neutral current DIS at the upcoming Electron-Ion Collider at Brookhaven and of Drell-Yan at LHC
- We used ZEUS data to constrain place constraints on $c^{\mu\nu}_{u,d}$ and $a^{(5)\alpha\beta\gamma}_{u,d}$, and Atlas/CMS data to constraint b_T (top)
- To appear:
  - Analysis of the Drell-Yan cross section at ATLAS


Backup

SME

Symmetry Transformations: Observer vs Particle

- In order to discuss Lorentz Violation it is important to separate ***observer*** and ***particle*** transformations
- ***Observer transformations***
  - Act on the observer reference frame while leaving the system unchanged
  - Only observable quantities transform
  - Might or might not have "physical meaning"
    - Parity: look at the system in a mirror
    - Lorentz: look at the system from a rotated/boosted reference frame
    - Cartesian to polar change of coordinates
- ***Particle transformations***
  - Act on the system while leaving the observer frame unchanged
  - All quantities the appear in a theory (fields, couplings, …) and have to be assigned transformation properties in order to achieve invariance

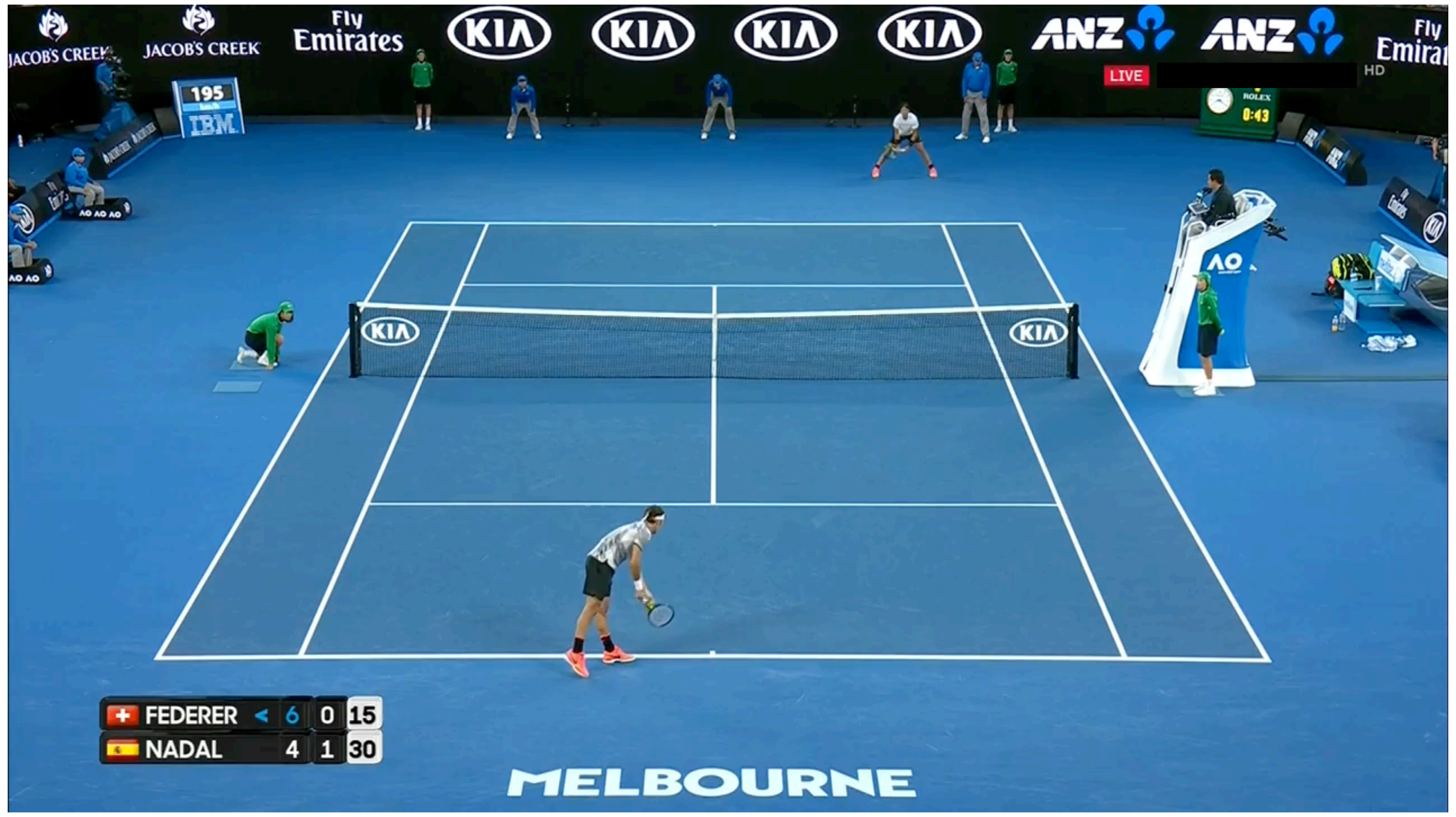
Symmetry Transformations: Observer vs Particle

- A muon decaying at rest has a certain lifetime that changes if the muon is observed in a frame boosted in some direction or if the muon itself is boosted in the opposite direction:
  if observer Lorentz transformations describe correctly the effect of boosting one reference frame and particle transformations are a symmetry of nature, these two lifetimes are identical (relativity principle)

- One could modify observer Lorentz transformations and construct a modified particle transformation that leaves the physics invariant.
  - This is what happened in the transition from Galilean to Lorentz invariance. Note that even though kinematical effects vanish for small velocities, the change in metric is dramatic (think: magnetism!)
  - We will not pursue this route

- ***We preserve observer Lorentz transformations but spontaneously break particle Lorentz invariance***

  - The muon lifetime of a boosted muon and of a muon at rest measured in a boosted frame differ (breakdown of the relativity principle)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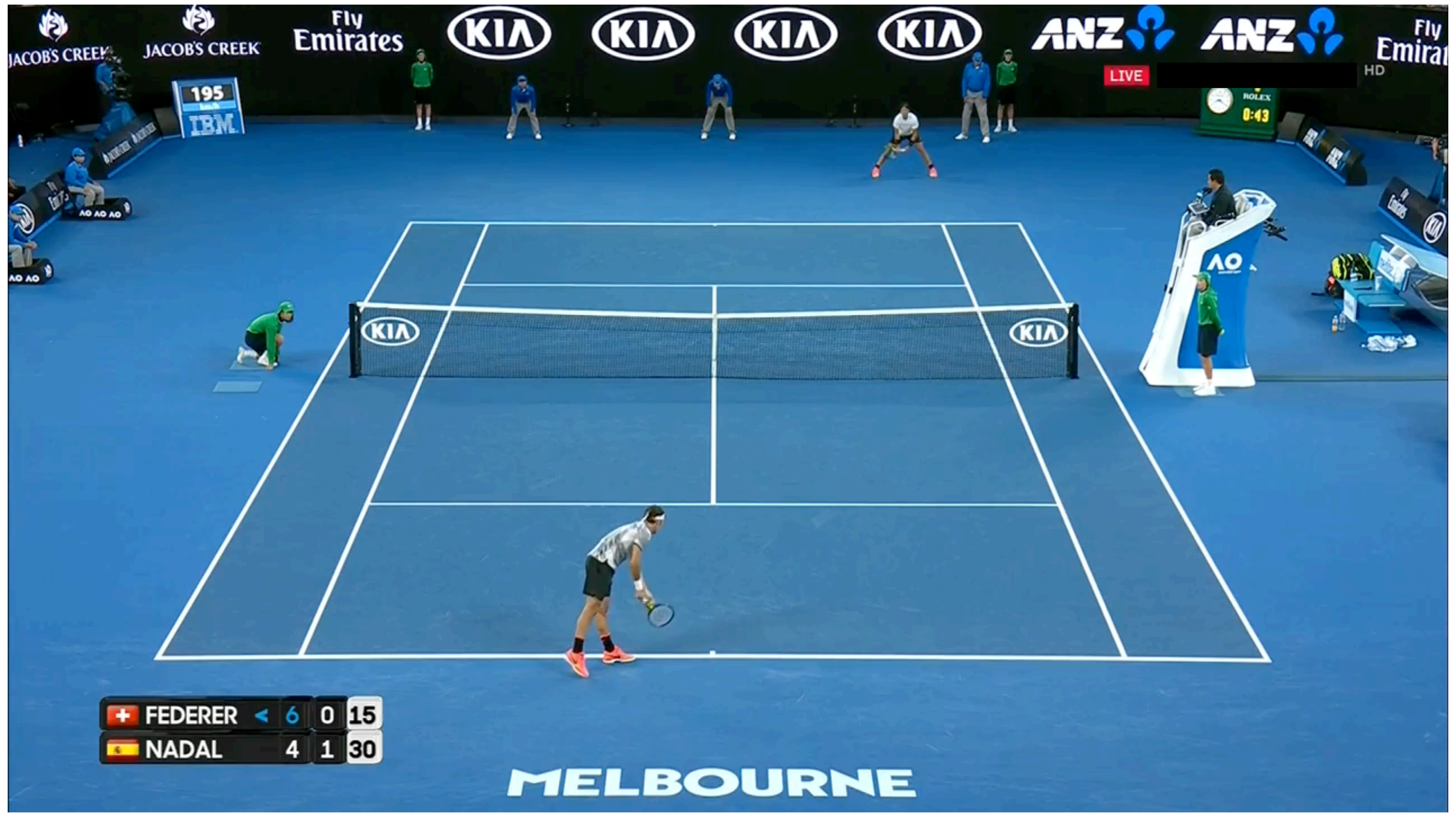
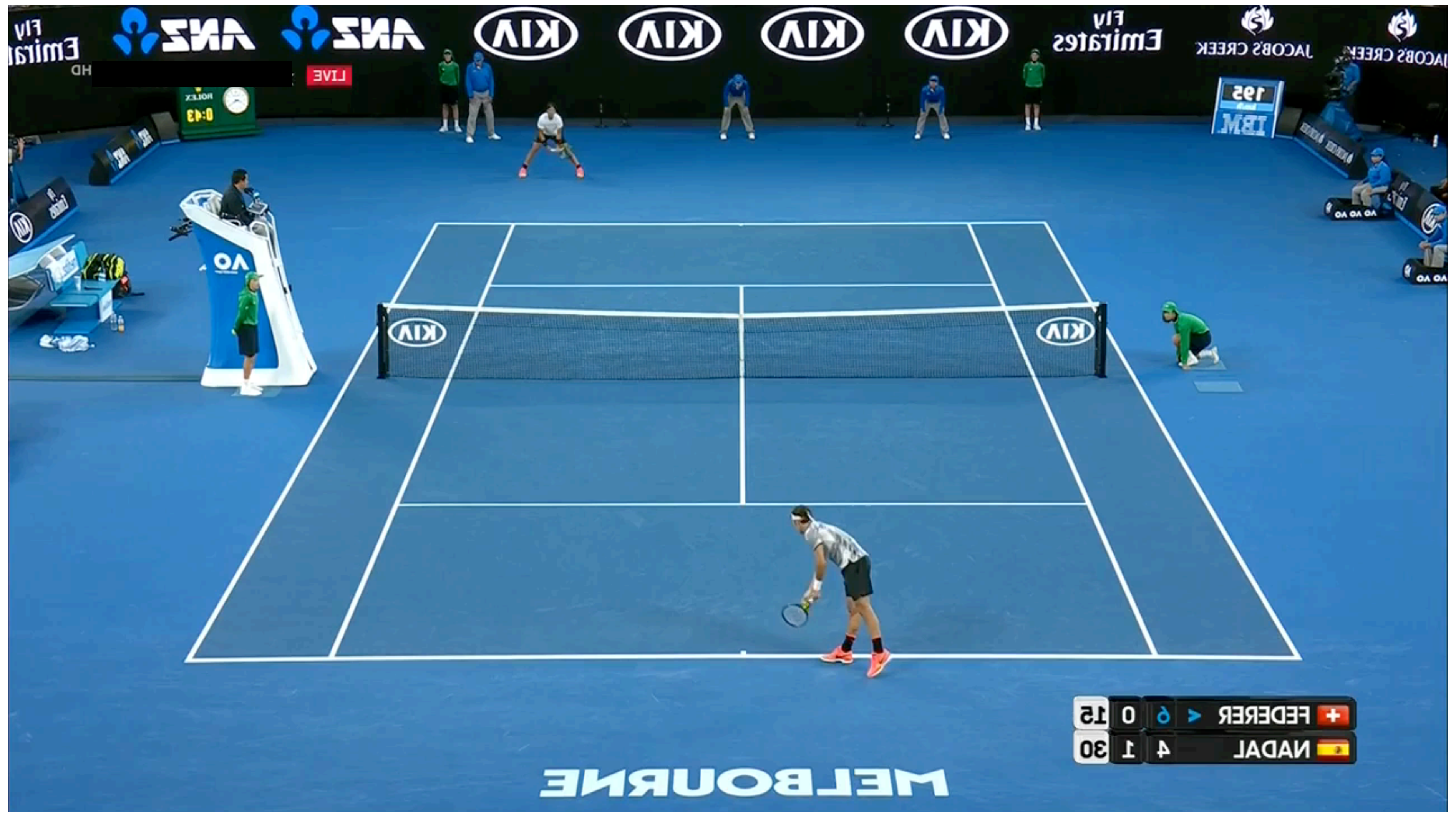
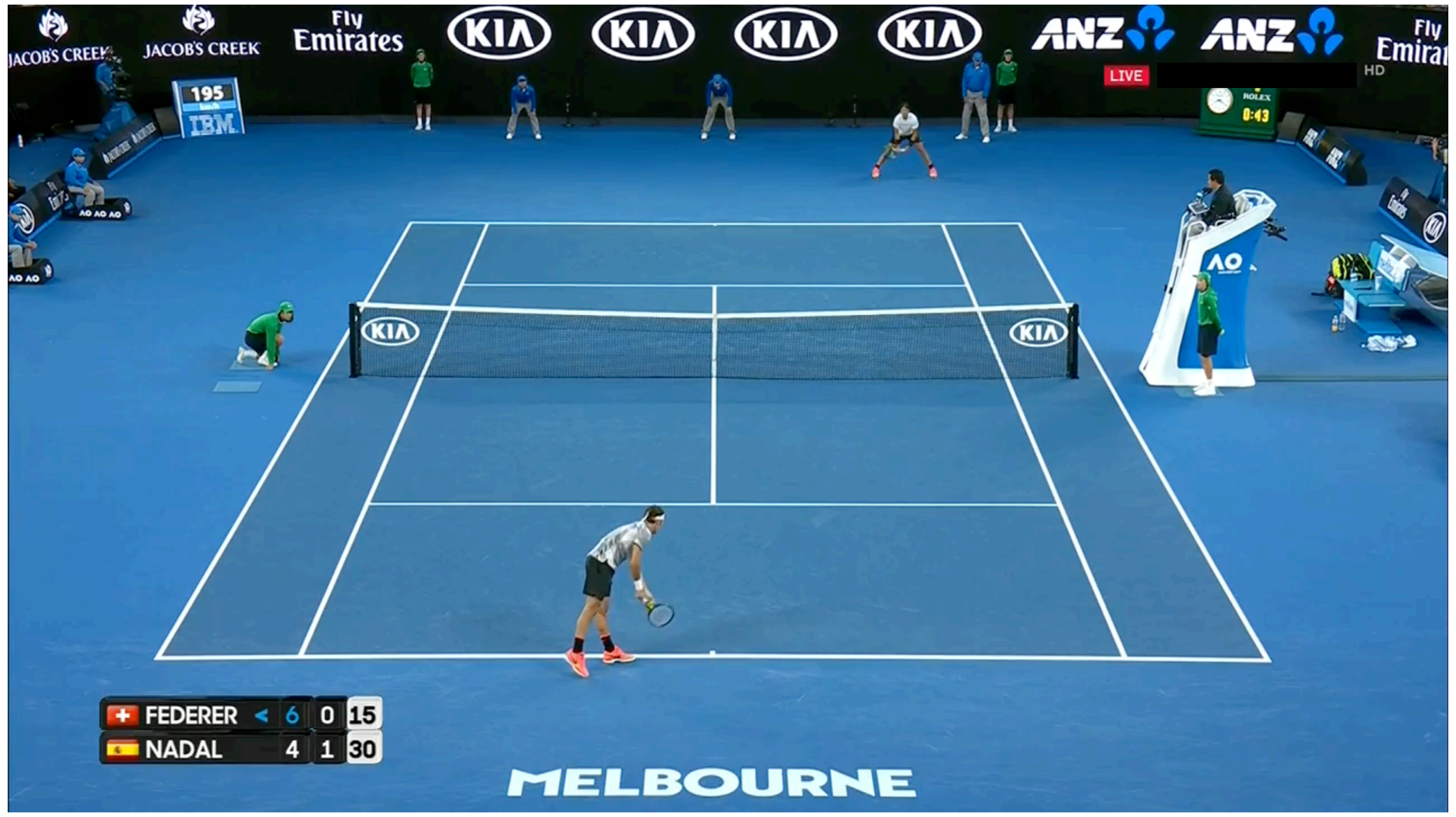
Observer transformation

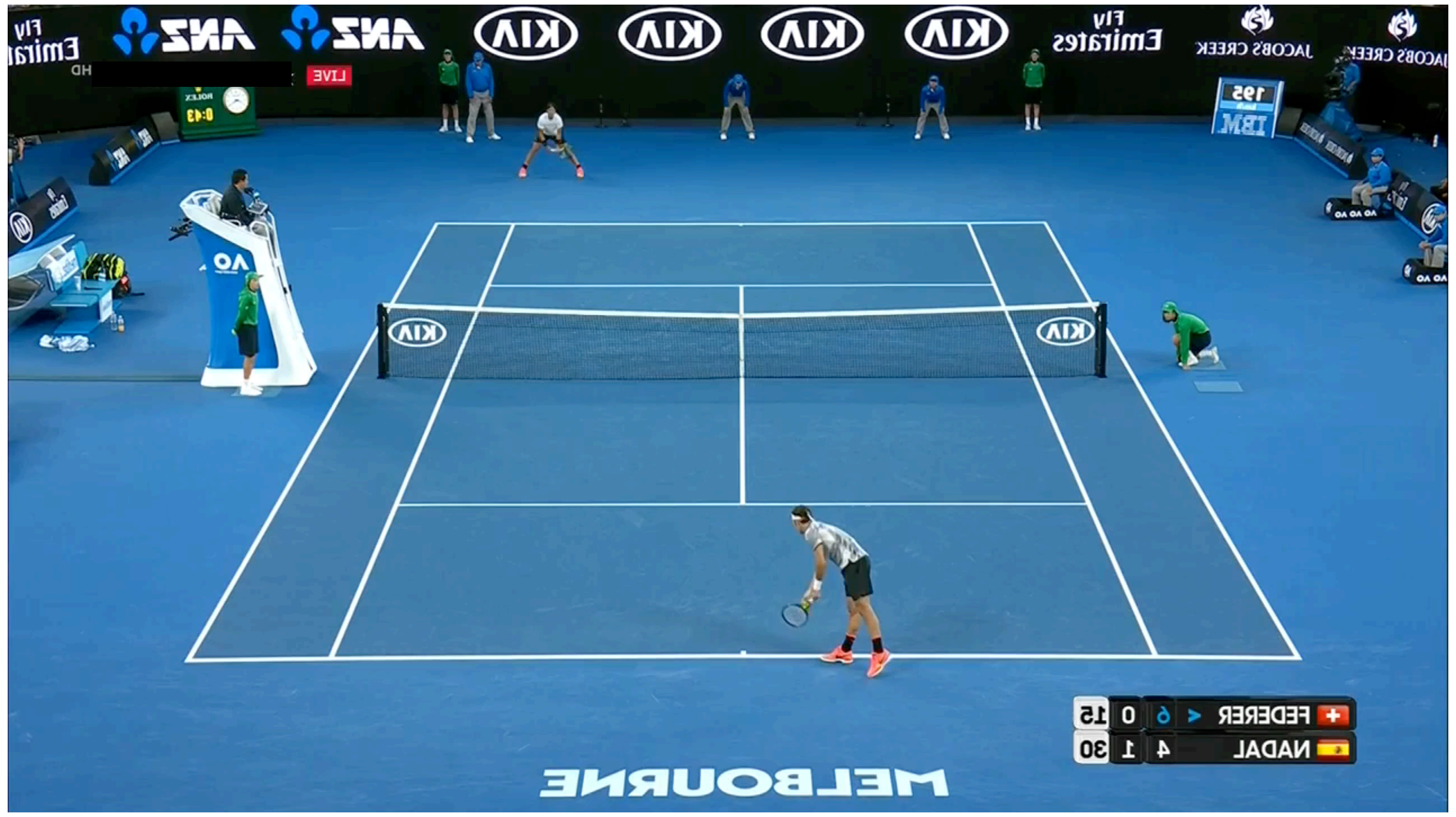




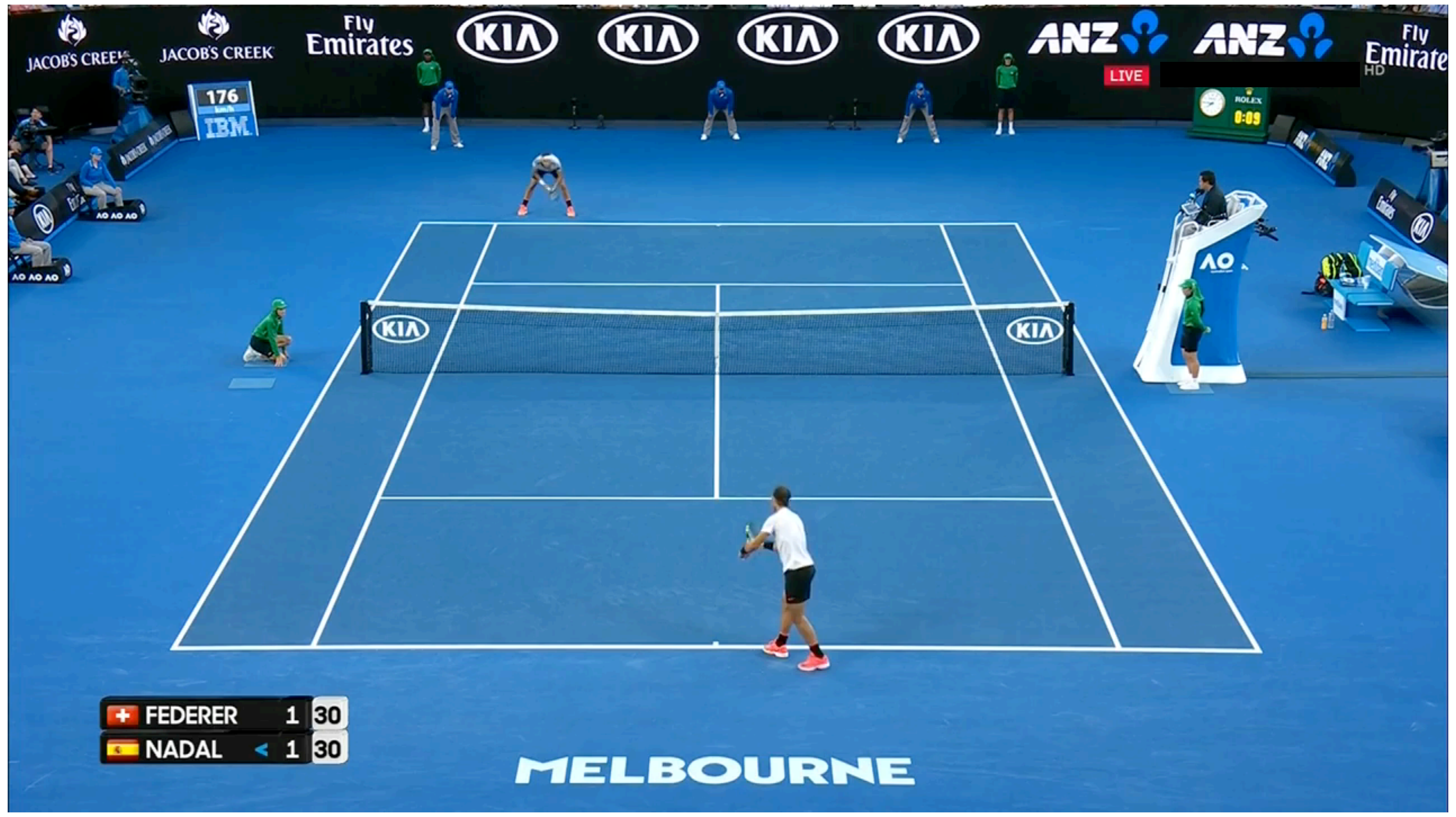
Symmetry Transformations: Observer vs Particle

Observer transformation



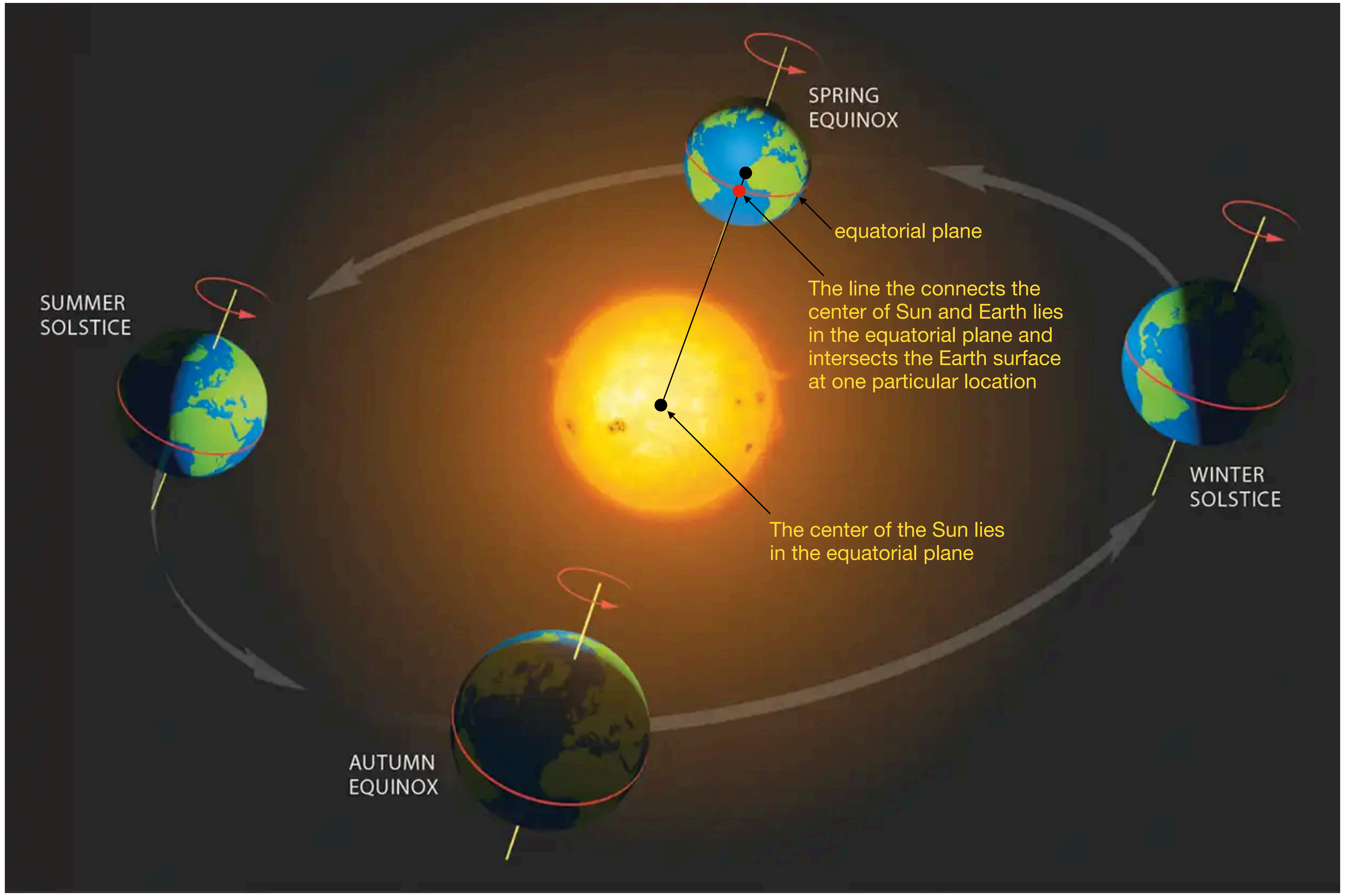


Particle transformation



Search strategy: Sun Centered Frame

- It is necessary to specify a reference frame where the coefficients are defined once and for all: the **Sun Centered Frame** (SCF)



- Conventional choice is to use the 2000 vernal (spring) equinox: March 20 2000 at 7:35 am UTC
- The equinox defines not only the orientation of the axis but also the beginning of time
- Times at locations which are not on the same meridian as the 2000 equinox need to be shifted accordingly:

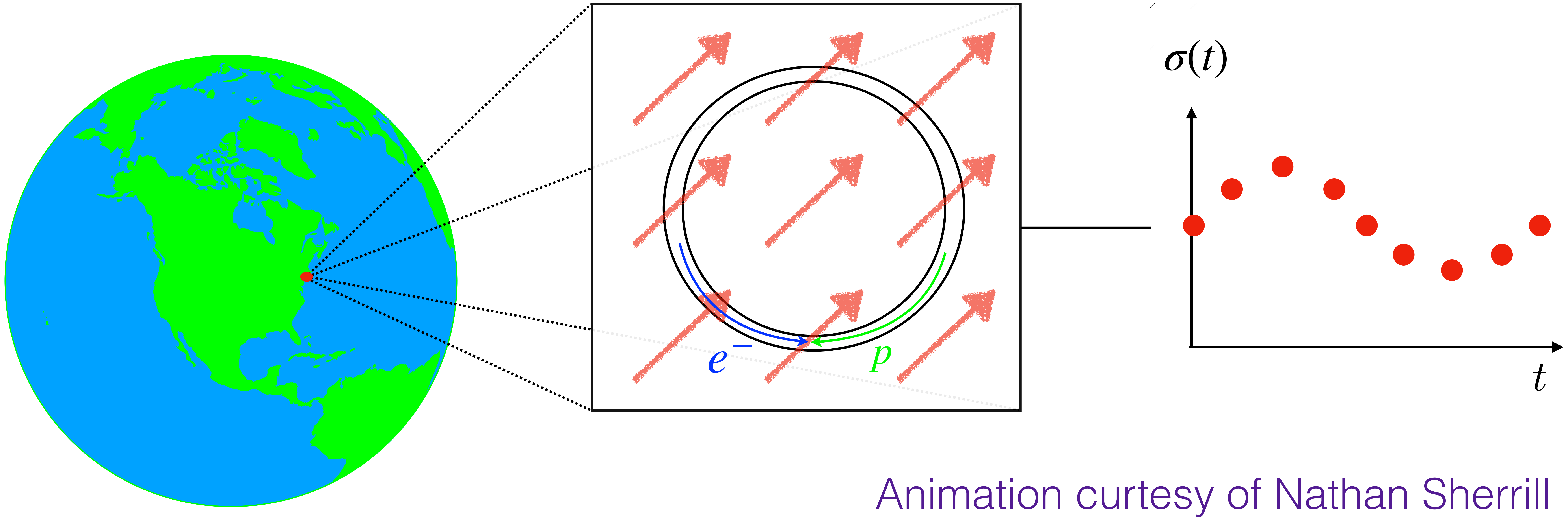
$$\Delta T = \frac{2\pi}{\omega_\oplus} \frac{\lambda_0 - \lambda}{360^o} \simeq 3.75 \text{ hrs}$$

where $\omega_\oplus$ is the sidereal frequency, $\lambda_0 = 66.25^o$ is the longitude of the 2000 equinox and $\lambda \simeq 9.9^o$ is the longitude of CERN/DESY.

Sun-centered vs lab frames

- The structure of the time dependent DIS and DY cross sections is:

$$\sigma(T_\oplus) = \sigma_{\rm SM}\Big[1 + (c_f^{TT},\ c_f^{TZ},\ c_f^{ZZ}) + (c_f^{TX},\ c_f^{TY},\ c_f^{YZ},\ c_f^{XZ})(\cos\omega_\oplus T_\oplus,\ \sin\omega_\oplus T_\oplus)$$
$$+ (c_f^{XY},\ c_f^{XX} - c_f^{YY})(\cos 2\omega_\oplus T_\oplus,\ \sin 2\omega_\oplus T_\oplus)\Big]$$



Animation curtesy of Nathan Sherrill

$$\chi_{PT}$$

Using χ_{PT} to connect LV in quarks and hadrons

- In absence of quark masses, the two-flavor QCD Lagrangian has an exact $SU(2)_L \times SU(2)_R$ chiral symmetry:

$$\mathscr{L}_{\rm QCD} = \overline{Q}\, i\not{D}\, Q = \overline{Q}_L\, i\not{D}\, Q_L + \overline{Q}_R\, i\not{D}\, Q_R$$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \to U_L\, Q_L \quad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \to U_R\, Q_R$$

$$\overline{Q}_L U_L^\dagger\, i\not{D}\, U_L Q_L + \overline{Q}_R U_R^\dagger\, i\not{D}\, U_R Q_R = \overline{Q}_L\, i\not{D}\, Q_L + \overline{Q}_R\, i\not{D}\, Q_R = \mathscr{L}_{\rm QCD}$$

- The chiral symmetry is spontaneously broken by non-perturbative QCD:

$$SU(2)_L \times SU(2)_R \to SU(2)_{\rm Isospin}$$

$SU(2)_{\rm Isospin}$ is the diagonal subgroup of $SU(2)_L \times SU(2)_R$ $(U_L = U_R = U_I)$:

$$Q_L \to U_I\, Q_L\,,\; Q_R \to U_I\, Q_R \quad \Rightarrow \quad Q \to U_I\, Q$$

- This happens because $\overline{Q}Q = \bar{u}u + \bar{d}d$ acquires a vacuum expectation value

- For each broken symmetry generator a Goldstone boson appears $(\pi^\pm, \pi^0)$

Using χ_{PT} to connect LV in quarks and hadrons

- At low energies we can write an effective theory of QCD which describes the interactions amongst the three resulting Goldstone bosons $(\pi^\pm, \pi^0)$:

$$\mathcal{L}_{\chi\mathrm{PT}} = \frac{F^2}{4}\mathrm{tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] + \cdots \qquad U = \exp\left[\frac{i}{F}\begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}\right] \qquad F \simeq 93\ \mathrm{MeV}$$

  While QCD has only one parameter (α_s), the chiral Lagrangian has infinitely many. As long as we remain at very low energies only a handful is relevant.

- Note that $U \to U_L\, U\, U_R^\dagger$ imply that the chiral Lagrangian is exactly invariant under $SU(2)_L \times SU(2)_R$

- A common quark mass term explicitly breaks the chiral symmetry:

$$\mathcal{L}_m = m_u \bar{u}u + m_d \bar{d}d = \bar{Q}\begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} Q = \bar{Q}MQ.$$

- How can we include quark mass terms in the meson Lagrangian?

Using χ_{PT} to connect LV in quarks and hadrons

- We can perform a spurion analysis
- The idea is to "upgrade" the mass matrix M to a constant field (spurion) and assign to it transformation properties which preserve the chiral symmetry.
- Assigning $M \to U_R M U_L^\dagger$ we have $\overline{Q}_R M Q_L + \text{h.c.} \to \overline{Q}_R U_R^\dagger \left(U_R M U_L^\dagger\right) U_L Q_L + \text{h.c.} = \overline{Q}_R M Q_L + \text{h.c.}$
- Assuming that all quark mass effects appear through the spurion M we can write:
  $\delta\mathscr{L}_{\chi PT} = \frac{V^3}{2}\text{tr}\left[MU + U^\dagger M^\dagger\right] + \cdots$
  where V is the quark condensate.
- The pions acquire a mass proportional to $(m_u + m_d)/2$.
- At the cost of introducing extra couplings it is possible to include the nucleon doublet (p, n) in the theory

Using χ_{PT} to connect LV in quarks and hadrons

- In order to connect quark and nucleon coefficients one can attempt a spurion analysis in which the coefficients for Lorentz violation are assigned chiral transformation properties

[Kamand, Altschul, Schindler; 1608.06503]

[Kamand, Altschul, Schindler; 1712.00838]

[Altschul, Schindler; 1907.02490]

- Focusing on the $c_{\mu\nu}$ coefficients, we can write:

$$\delta\mathcal{L}_{\text{SME}} = i\bar{Q}_L C_L^{\mu\nu}\gamma_\mu D_\nu Q_L + i\bar{Q}_R C_R^{\mu\nu}\gamma_\mu D_\nu Q_R$$

where $C^{\mu\nu}_{L/R} = \begin{bmatrix} c^{\mu\nu}_{u_{L/R}} & 0 \\ 0 & c^{\mu\nu}_{d_{L/R}} \end{bmatrix}$ and $c^{\mu\nu}_q = (c^{\mu\nu}_{q_L} + c^{\mu\nu}_{q_R})/2$

- Strong Isospin invariance can be restored by assigning:
$C_L^{\mu\nu} \to U_L C_L^{\mu\nu} U_L^\dagger$ and $C_R^{\mu\nu} \to U_R C_R^{\mu\nu} U_R^\dagger$

- Lorentz violating effects appear in the Chiral Lagrangian as additional $SU(2)\times SU(2)$ symmetric terms involving the pion triplet, the nucleon doublet and the spurions $C^{\mu\nu}_{L,R}$

Using χ_{PT} to connect LV in quarks and hadrons

- The leading terms are:

$$\mathcal{L}_{\pi}^{\text{LO}} = \beta^{(1)}\frac{F^2}{4}\left({}^1C_{R\mu\nu} + {}^1C_{L\mu\nu}\right)\text{Tr}[(\partial^\mu U)^\dagger \partial^\nu U]$$

pion triplet

$$\begin{aligned}
\mathcal{L}_{\pi N}^{\text{LO}} = & \Big\{\alpha^{(1)}\bar{\Psi}[(u^\dagger\, {}^3C_R^{\mu\nu} u + u\, {}^3C_L^{\mu\nu} u^\dagger)(\gamma_\nu iD_\mu + \gamma_\mu iD_\nu)]\Psi \\
& + \alpha^{(2)}\left({}^1C_R^{\mu\nu} + {}^1C_L^{\mu\nu}\right)\bar{\Psi}(\gamma_\nu iD_\mu + \gamma_\mu iD_\nu)]\Psi \\
& + \alpha^{(3)}\bar{\Psi}[(u^\dagger\, {}^3C_R^{\mu\nu} u - u\, {}^3C_L^{\mu\nu} u^\dagger)(\gamma_\nu\gamma^5 iD_\mu + \gamma_\mu\gamma^5 iD_\nu)]\Psi \\
& + \alpha^{(4)}\left({}^1C_R^{\mu\nu} - {}^1C_L^{\mu\nu}\right)\bar{\Psi}(\gamma_\nu\gamma^5 iD_\mu + \gamma_\mu\gamma^5 iD_\nu)\Psi\Big\},
\end{aligned}$$

nucleon doublet

where $u^2 = U$

- ${}^1C_{L,R}^{\mu\nu}$ and ${}^3C_{L,R}^{\mu\nu}$ are the trace and traceless parts of $C_{L,R}^{\mu\nu}$ and transform as

$${}^1C_L^{\mu\nu} \to {}^1C_L^{\mu\nu} \qquad {}^3C_L^{\mu\nu} \to U_L\, {}^3C_L^{\mu\nu} U_L^\dagger$$

$${}^1C_R^{\mu\nu} \to {}^1C_R^{\mu\nu} \qquad {}^3C_R^{\mu\nu} \to U_R\, {}^3C_R^{\mu\nu} U_R^\dagger$$

Using χ_{PT} to connect LV in quarks and hadrons

- Relevant two and four pion interactions ($U = \exp\left[i\phi_a\tau_a/F\right]$):

$$\mathcal{L}_\pi^{\mathrm{LO},2\phi} = \frac{\beta^{(1)}}{2}(c_{u_L}^{\mu\nu} + c_{d_L}^{\mu\nu} + c_{u_R}^{\mu\nu} + c_{d_L}^{\mu\nu})\partial_\mu\phi_a\partial_\nu\phi_a$$

$$\mathcal{L}_\pi^{\mathrm{LO},4\phi} = \frac{\beta^{(1)}}{6F^2}(c_{u_L}^{\mu\nu} + c_{d_L}^{\mu\nu} + c_{u_R}^{\mu\nu} + c_{d_L}^{\mu\nu})(\phi_a\phi_b\partial_\mu\phi_a\partial_\nu\phi_b - \phi_b\phi_b\partial_\mu\phi_a\partial_\nu\phi_a)$$

- The proton kinetic Lagrangian becomes

$$\delta L_{\mathrm{SME}} = \bar{\psi}_p\left[(\eta^{\mu\nu} + c_p^{\mu\nu})\gamma_\nu iD_\mu - m_p\right]\psi_p$$

with

$$\boxed{c_p^{\mu\nu} = \left[\frac{1}{2}\alpha^{(1)} + \alpha^{(2)}\right](c_{u_L}^{\mu\nu} + c_{u_R}^{\mu\nu}) + \left[-\frac{1}{2}\alpha^{(1)} + \alpha^{(2)}\right](c_{d_L}^{\mu\nu} + c_{d_R}^{\mu\nu})}$$

- The $\alpha^{(1,2)}$ and $\beta^{(1)}$ coefficients are non-perturbative and expected to be $O(1)$

Using χ_{PT} to connect LV in quarks and hadrons

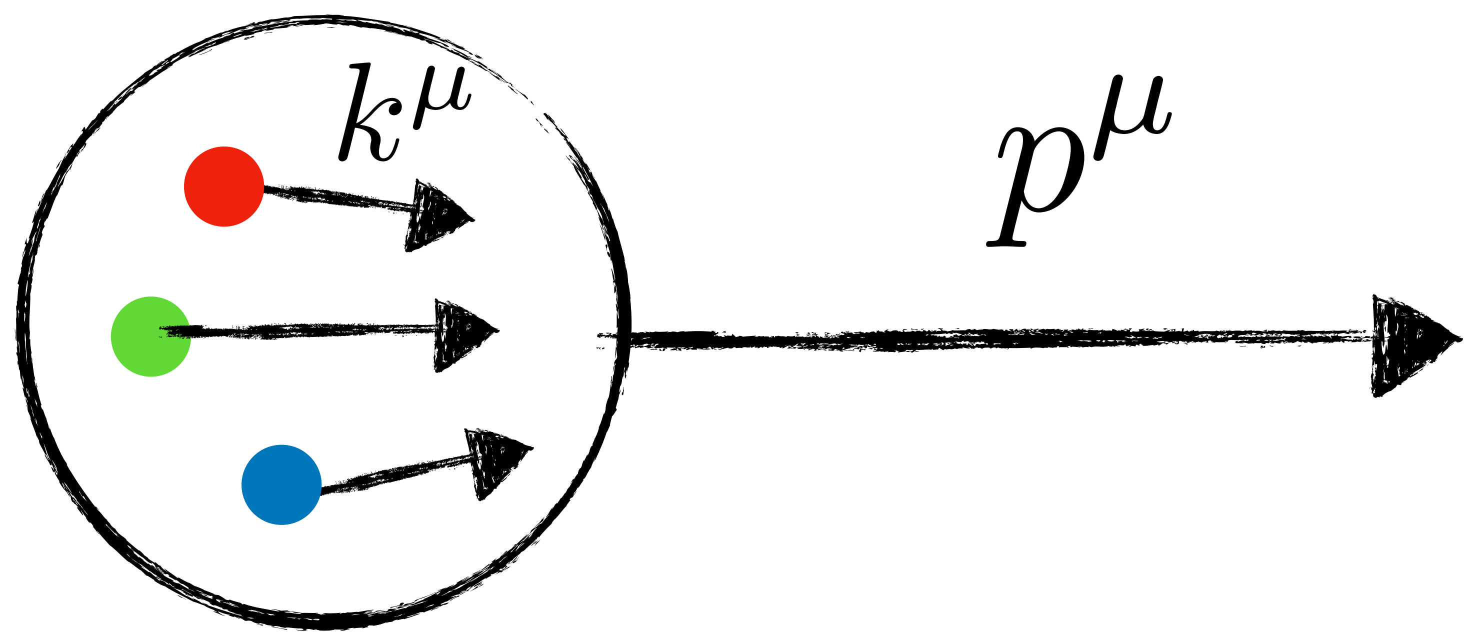
- If this is accurate the bounds on these coefficients are of order $10^{-25} \div 10^{-20}$

- Some open questions remain.
  - The role of LV in the gluon sector: it is possible to move $c_q^{\mu\nu}$ (q=u or d) into a $\kappa^{\alpha}{}_{\mu\alpha\nu}$ and it is not clear how to assign spurion transformation properties to the latter.
  - Quark and Hadron coefficients mix: a given type of nucleon coefficients can receive contributions from multiple types of quark level coefficients. Disentangling can be difficult
  - It is unclear how to connect these results to constraints obtained from studying the propagation of ultra-high energy protons

DIS and Drell-Yan

QCD factorization in presence of Lorentz Violation

- Standard partonic picture at large energies:



$$k^\mu \simeq \xi p^\mu$$

Do Lorentz-violating effects change this picture?

- Lorentz and CPT violating terms we consider:

$$\mathscr{L} = \sum_{f=u,d} \frac{1}{2}\bar{\psi}_f i\gamma^\mu \overleftrightarrow{D}_\mu \psi_f + \frac{1}{2}\bar{\psi}_f \left(c_f^{\mu\nu} + \gamma_5 d_f^{\mu\nu} \right) i\gamma_\mu \overleftrightarrow{D}_\nu \psi_f - \frac{1}{2} a_f^{(5)\mu\alpha\beta} \bar{\psi}_f \gamma_\mu i D_{(\alpha} i \overleftrightarrow{D}_{\beta} \psi_f$$

- The coefficients $a_f^{(5)}$ are non-renormalizable (mass dimension -1) and tend to appear multiplied by the largest scale in the system: their effects are larger at very high energies

- Factorization holds: cross sections are given by convolutions of time-dependent hard scattering kernels and parton distribution functions

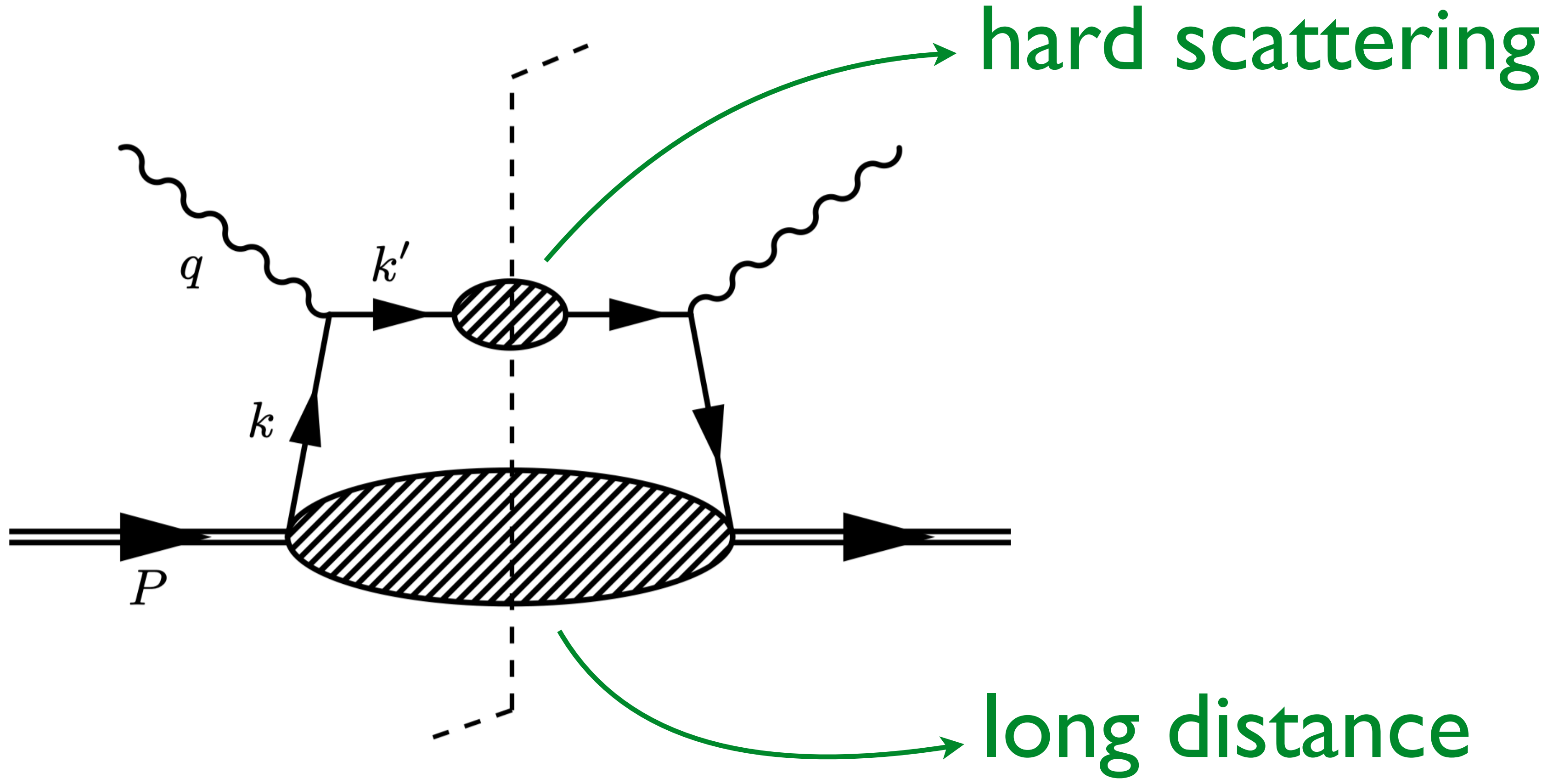
Kostelecky, E.L., Sherrill, Vieira; 1911.04002

Deep Inelastic Scattering: Factorization in the SM

- The parton model picture emerges from an all-orders proof of factorization:

Kostelecky, Lunghi, Vieira; 1610.08755

Kostelecky, Lunghi, Sherrill, Vieira; 1911.04002



- In the Breit frame it can be shown that only one component of k enters the hard scattering: $k^\mu \to \xi P^\mu$
- The amplitude becomes a one dimensional convolution of parton distribution functions and hard scatterings
- The parton distribution functions admit a covariant expression:

$$f(n\cdot k, P^\mu) = \int \frac{d\lambda}{2\pi} e^{-i(n\cdot k)\lambda} \langle P\,|\,\bar\psi(\lambda n)\frac{\not n}{2}\psi(0)\,|\,P\rangle$$

[n is a light-cone vector proportional to P]

- Reparameterization invariance (rescaling of n) and covariance imply that the PDF can only depend on $\xi \equiv n\cdot k / n\cdot P$. We can replace $f(n\cdot k, P^\mu) \to f(\xi)$

- The final expression for the double differential decay rate (γ exchange only) is:

$$\frac{d\sigma}{dx\,dy\,d\phi} = \frac{\alpha^2}{q^4}\sum_f Q_f^2\, x'_f\, f_f(x'_f)\Bigg[\frac{ys^2}{\pi}(1+(1-y)^2)\delta_f + \frac{y^2 s}{x}x_f - \frac{4M^2}{s}(c_f^{kk'}+c_f^{k'k}) + 4(c_f^{k'P}+c_f^{Pk'}) + \frac{4}{x}(1-y)c_f^{kk} - 4xyc_f^{PP} - \frac{4}{x}c_f^{k'k'} + 4(1-y)(c_f^{kP}+c_f^{Pk})\Bigg]$$

large effects at low x

where

- $P^\mu = E_p(1,-\hat{k})$, $k^\mu = E(1,\hat{k})$ and $k'^\mu = E'(1,\hat{k}')$ are the proton, incoming and outgoing electron momenta in the **lab frame** (e.g. for HERA E = *27.5 GeV* and E_p = *920 GeV*). s is the center-of-mass energy of the collision.

- $y = \dfrac{P\cdot q}{P\cdot k} = \dfrac{Q^2}{4E_pE\,x}$
- $\delta_f = \dfrac{\pi}{ys}\left(1 - \dfrac{2}{ys}(c_f^{Pq}+c_f^{qP}+2xc_f^{PP})\right)$

$$x'_f = x - x_f = x - \frac{2}{ys}(c_f^{qq}+xc_f^{qP}+xc_f^{Pq}+x^2c_f^{PP})$$

- $c_f^{pq} \equiv p_\mu c_f^{\mu\nu} q_\nu$
- In our numerical results we include also Z boson exchange diagrams

Deep Inelastic electron-proton Scattering

- In the case of e-p DIS this discussion can be formalized in the language of an Operator Product Expansion:

$$d\sigma \sim |M(ep \to eX)|^2 \sim \mathrm{Im}[M(ep \to ep)] \sim \mathrm{Im}\langle p|TJ_\mu(z)J_\nu(0)|p\rangle \sim C^{\mu\nu\mu_1\cdots\mu_n}(z)\,\langle p|O_{\mu_1\cdots\mu_n}(0)|p\rangle$$

optical theorem — em current — OPE — Wilson Coefficients — local operators

- The operators that appear for DIS are:

$$O_{\mu_1\cdots\mu_n} = \bar{q}\gamma_{\mu_1} iD_{\mu_2}\cdots iD_{\mu_n} q + \text{symmetrizations} - \text{traces}$$

$$\langle p|O_{\mu_1\cdots\mu_n}|p\rangle = \mathscr{A}_n\, p_{\mu_1}\cdots p_{\mu_n}$$

[The proton momentum p is the only vector the matrix elements depend on]

- The Fourier transforms of the Wilson coefficients are:

$$\int dz\, e^{iz\cdot q}\, C^{\mu\nu\mu_1\cdots\mu_n}(z) \sim \frac{q^{\mu_1}\cdots q^{\mu_n}}{Q^{2n}}\left(\frac{q^\mu q^\nu}{Q^2} - g^{\mu\nu}\right) + \cdots$$

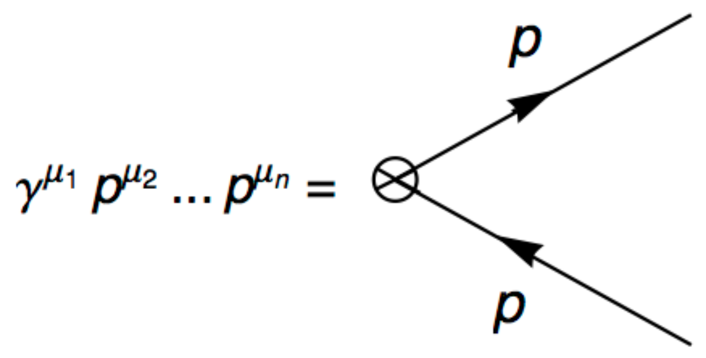
Deep Inelastic electron-proton Scattering

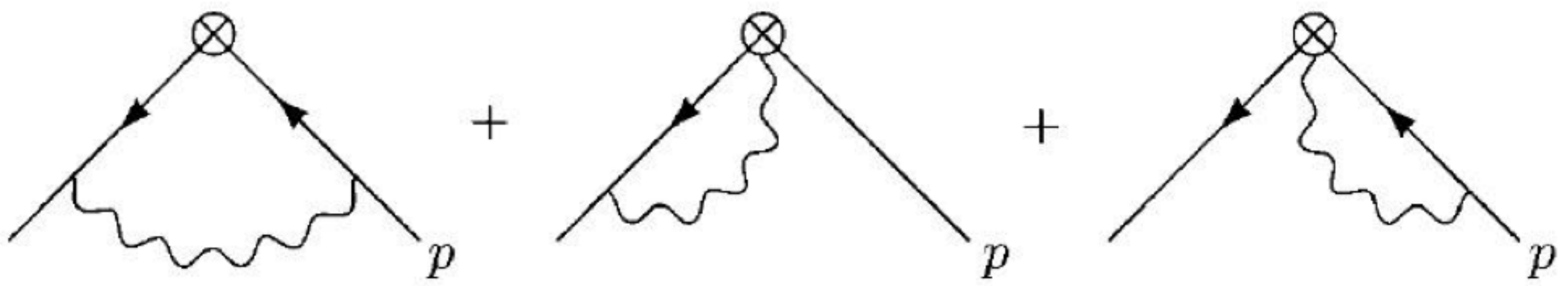
- The product of matrix elements and Wilson coefficients contains powers of $\frac{2p \cdot q}{-q^2} = \frac{1}{x} > 1$: all operators contribute at the same order!

- It is not too difficult to show that the cross section that emerges from the OPE is identical to the parton model one if we identify the PDF with:

$$f(x) = \frac{1}{\pi} \sum_n \frac{\mathscr{A}_n}{x^n}$$

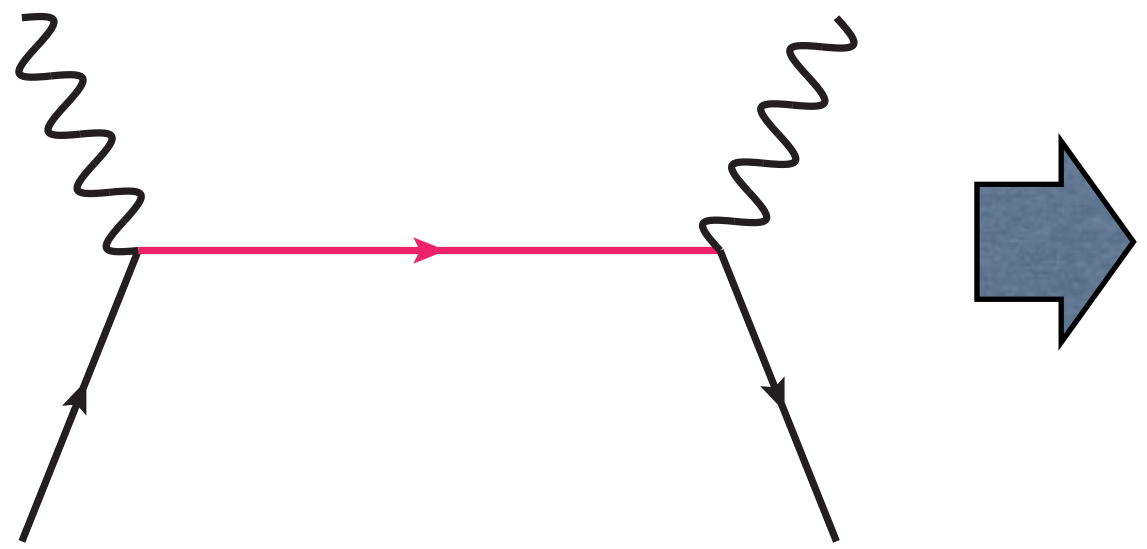
- The DGLAP evolution is reproduced by the standard RGE's for the the operators:





Deep Inelastic Scattering: SME (OPE)

- We seek the OPE for the product of two electromagnetic currents:



$$\bar{\psi}_f(x)\Gamma_f^\mu \frac{i(i\tilde{\not\partial}+\tilde{\not q})}{(i\tilde{\partial}+\tilde{q})^2}\Gamma_f^\nu \psi_f(0)$$

$$\boxed{\begin{aligned}\tilde{q}^\mu &= (g^{\mu\nu}+c^{\mu\nu})q_\nu \\ \tilde{\gamma}^\mu &= (g^{\mu\nu}+c^{\mu\nu})\gamma_\nu\end{aligned}}$$

- Expand: $\dfrac{1}{(i\tilde{\partial}+\tilde{q})^2} = \dfrac{1}{\tilde{q}^2}\sum_{n=0}^{\infty}\left(-\dfrac{2i\tilde{q}\cdot\tilde{\partial}}{\tilde{q}^2}\right)^n + O(\tilde{\partial}^2/\tilde{q}^2)$

- Operator basis: $\hat{O}_{\mu_1\cdots\mu_n} = \bar{q}\gamma_{\mu_1}i\tilde{D}_{\mu_2}\cdots i\tilde{D}_{\mu_n}q$ + symmetrizations – traces
  - ∗ Why symmetric?
  - ∗ Why are traces suppressed?

  In the SM this follows directly from the fact that the matrix elements of the operators are functions of the sole proton momentum:
  only matrix elements of symmetric operator are non-vanishing and traces are proportional to $P^2 = m_p^2 \ll Q^2$

Deep Inelastic Scattering: SME (OPE)

- The perturbative evaluation of the matrix elements of the SME operators between on-shell SME quark states with momentum k ($\tilde{k}^2 = 0$) yields:

  $\langle k | \bar{q}\gamma^{\mu_1} i\tilde{\partial}^{\mu_2} \cdots i\tilde{\partial}^{\mu_n} q | k \rangle \propto \tilde{k}^{\mu_1} \cdots \tilde{k}^{\mu_n}$ $\Rightarrow$ totally symmetric and traceless

- For n=2: $\hat{O}^{\mu_1\mu_2} = \bar{q}\gamma_\alpha i\tilde{D}_\beta q \ \left(g^{\alpha\mu_1}g^{\beta\mu_2} + g^{\alpha\mu_2}g^{\beta\mu_1} - 2g^{\alpha\beta}g^{\mu_1\mu_2}\right)$

$$= \underbrace{\boxed{\bar{q}\tilde{\gamma}_\alpha iD_\beta q}}_{= T_{\alpha\beta}} \left(g^{\alpha\mu_1}g^{\beta\mu_2} + g^{\alpha\mu_2}g^{\beta\mu_1} - 2g^{\alpha\beta}g^{\mu_1\mu_2} + \text{antisymm in } \alpha, \beta\right)$$

$= T_{\alpha\beta}$ the SME energy-momentum tensor $\Rightarrow$ $\langle P | T_{\alpha\beta} | P \rangle \propto P_\alpha P_\beta$

$$\langle P | \hat{O}^{\mu_1\mu_2} | P \rangle = \langle P | T_{\alpha\beta} | P \rangle \left(g^{\alpha\mu_1}g^{\beta\mu_2} + g^{\alpha\mu_2}g^{\beta\mu_1} - 2g^{\alpha\beta}g^{\mu_1\mu_2} + \text{antisymm in } \alpha, \beta\right)$$
$$\propto P^{\mu_1}P^{\mu_2}$$

- All of this strongly suggests: $\langle P | \hat{O}^{\mu_1\cdots\mu_n} | P \rangle = 2A_n P^{\mu_1}\cdots P^{\mu_n}$

- The matrix elements A_n are the moments of the quarks PDFs and can depend on scalar quantities like $c_{\mu\nu}P^\mu P^\nu/\Lambda^2$

- Putting everything together reproduces exactly the factorization result

Drell-Yan

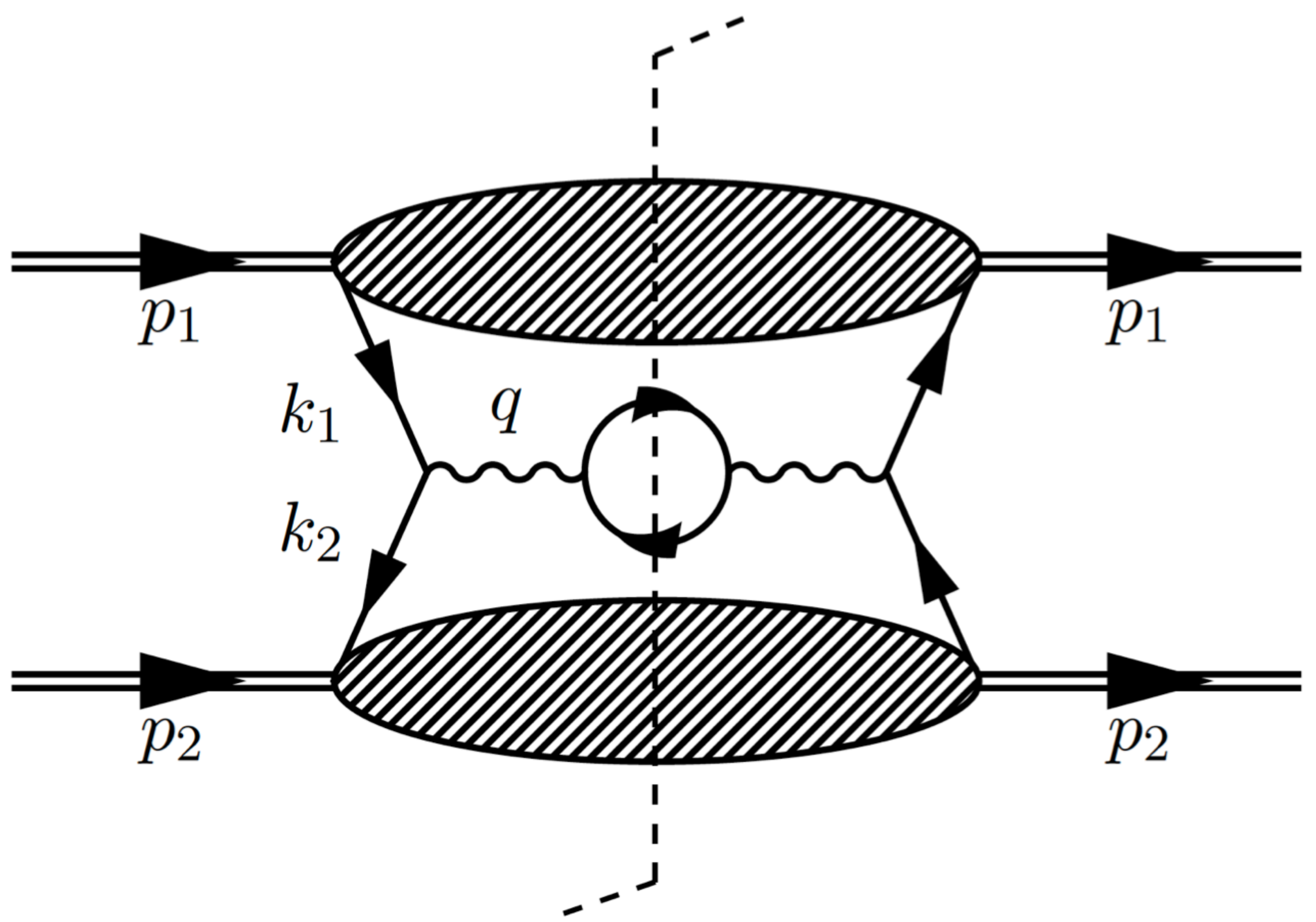
- Factorization for Drell-Yan in the SME is achieved following (mostly) the same steps as in the DIS case

[Kostelecky, Lunghi, Sherrill, Vieira; 1911.04002]

[Lunghi, Sherrill, Szczepaniak, Vieira; 2011.02632]

- The cross section can be written as convolution between hard scattering which depend explicitly on SME coefficients and universal PDFs which are the same that appear in DIS:

$$\sigma \sim \sum_f \int d\xi \, d\xi' \, \hat{\sigma}_f(\xi, \xi') \, f_f(\xi) \, f_{\bar{f}}(\xi')$$



For $c^{\mu\nu}$ coefficients:
$\tilde{k}_1 = \xi p_1$ and $\tilde{k}_2 = \xi' p_2$

Expected constraints

Expected constraints: general considerations

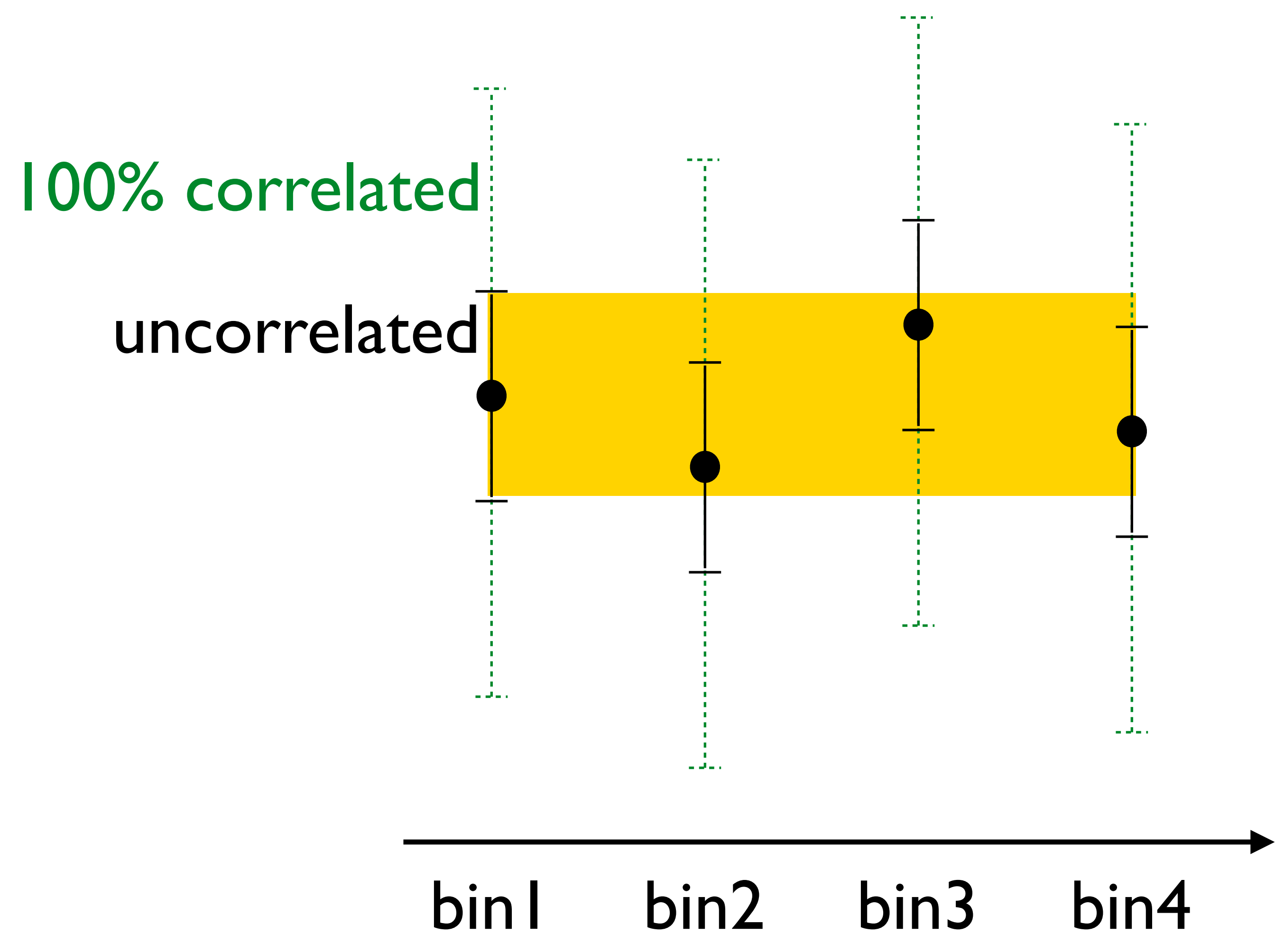
- Terms that contribute to the time averaged cross section ($c_f^{TT}, c_f^{TZ}, c_f^{ZZ}$) are hard to constrain because DIS measurements are used to define the PDFs
  - Nevertheless LV corrections introduce a novel Q^2 dependence into the cross section that leads to a tree-level violation of Bjorken scaling
  - It might be possible to constrain these coefficients by disentangling the weak logarithmic Q^2 dependence introduced by the DGLAP equations and the strong power Q^2 dependence of the LV terms.

- On the other hand, terms that do not contribute to the time averaged cross section (c_f^{TX}, c_f^{TY}, c_f^{YZ}, c_f^{XZ}, c_f^{XY}, $c_f^{XX} - c_f^{YY}$) can be constrained in a straightforward way by employing a sidereal time analysis of the cross section.

- We calculated the expected constraints that can be obtained from a 4-bin sidereal time analysis of the whole *ZEUS+H1* DIS combined results [arXiv:1506.06042].

Expected constraints: general considerations

- The constraints on coefficients which induce sidereal time variation are sensitive only to uncorrelated uncertainties:



Note that each sidereal time bin collects several months worth of data

- If experimental uncertainties are dominated by systematics (luminosity, efficiencies, …), it is important to understand their bin-to-bin correlation:
  this can be achieved by multiple random binning of data and Monte Carlo samples

- Note that day/nights effects are diluted by the sidereal time binning if data are taken over a long enough period

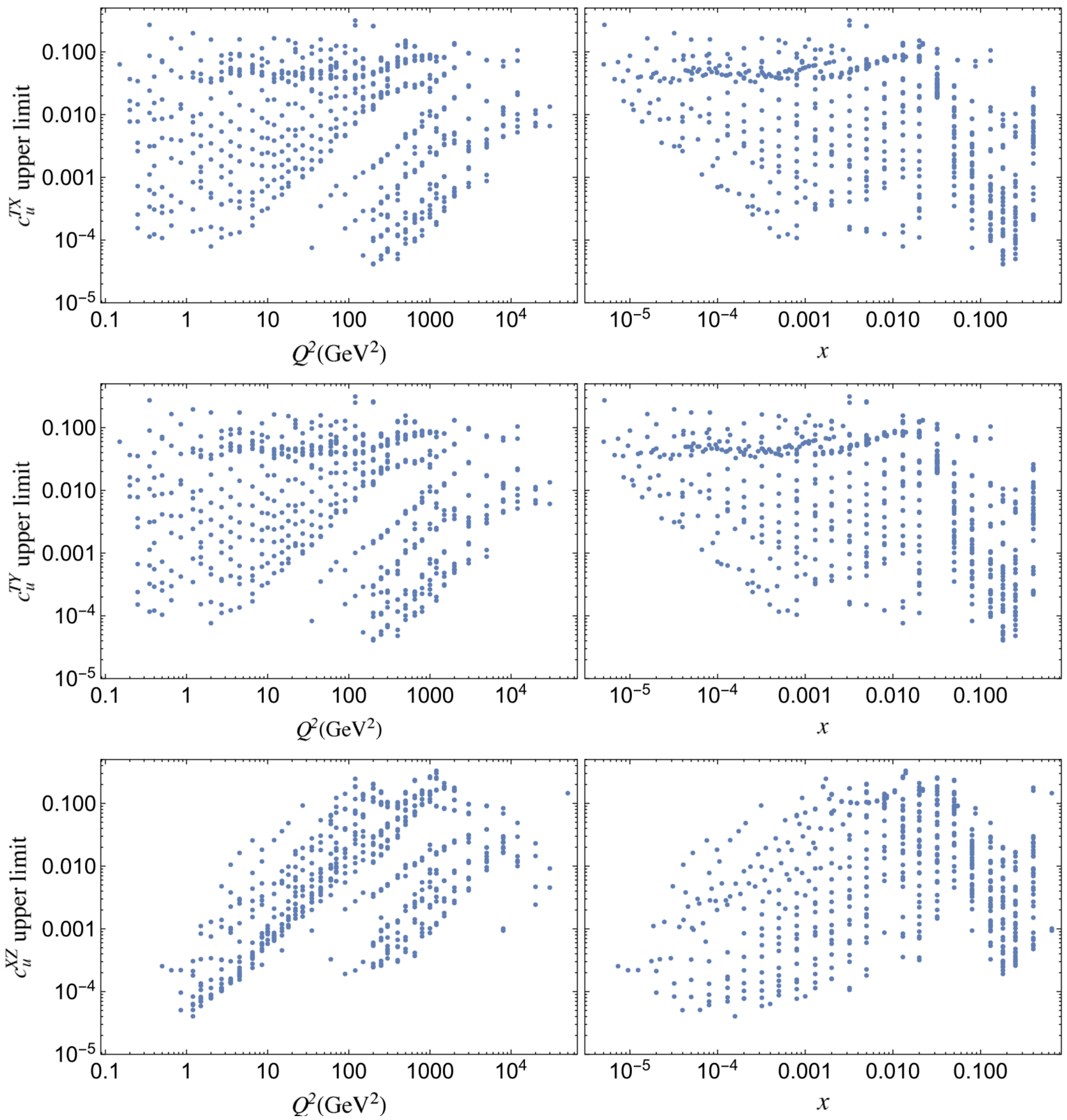
DIS - HERA - expected constraints on $c^{\mu\nu}$ coefficients

- We consider all neutral current measurements performed by *ZEUS* and *H1* [arXiv:1506.06042]
- ***For each measurement (i.e. each value/bin of x and Q^2):***
  - We estimate how the uncertainty increases due to a sidereal binning (4 bins)
  - The functional form that we assume for the binned theoretical cross section is $\sigma_i^{\text{th}}(x,Q) = \sigma^{\text{SM}}(x,Q) + \sigma_i^{\text{SME}}(x,Q)$ where i indexes the sidereal bin
  - We generate a set of 10^3 possible experimental results assuming a normal distribution and the absence of LV effects
  - For each set we extract the frequentist 95% C.L. upper limit using a standard chi-squared (4 measurements and 2 fit variables)
  - The expected upper limit is the median of the upper limits over the set

DIS - HERA - expected constraints on $c^{\mu\nu}$ coefficients

- Expected constraints as a function of Q^2 and x
- Best expected limits:

$$|c^u_{TX}| \lesssim 4\times 10^{-5}$$
$$|c^u_{TY}| \lesssim 4\times 10^{-5}$$
$$|c^u_{XZ}| \lesssim 4\times 10^{-5}$$
$$|c^u_{YZ}| \lesssim 4\times 10^{-5}$$
$$|c^u_{XY}| \lesssim 4\times 10^{-5}$$
$$|c^u_{XX} - c^u_{YY}| \lesssim 1\times 10^{-5}$$



DIS - HERA - expected constraints on $c^{\mu\nu}$ coefficients

- Best expected constraints:

$$|c^u_{TX}| \lesssim 4 \times 10^{-5}$$
$$|c^u_{TY}| \lesssim 4 \times 10^{-5}$$
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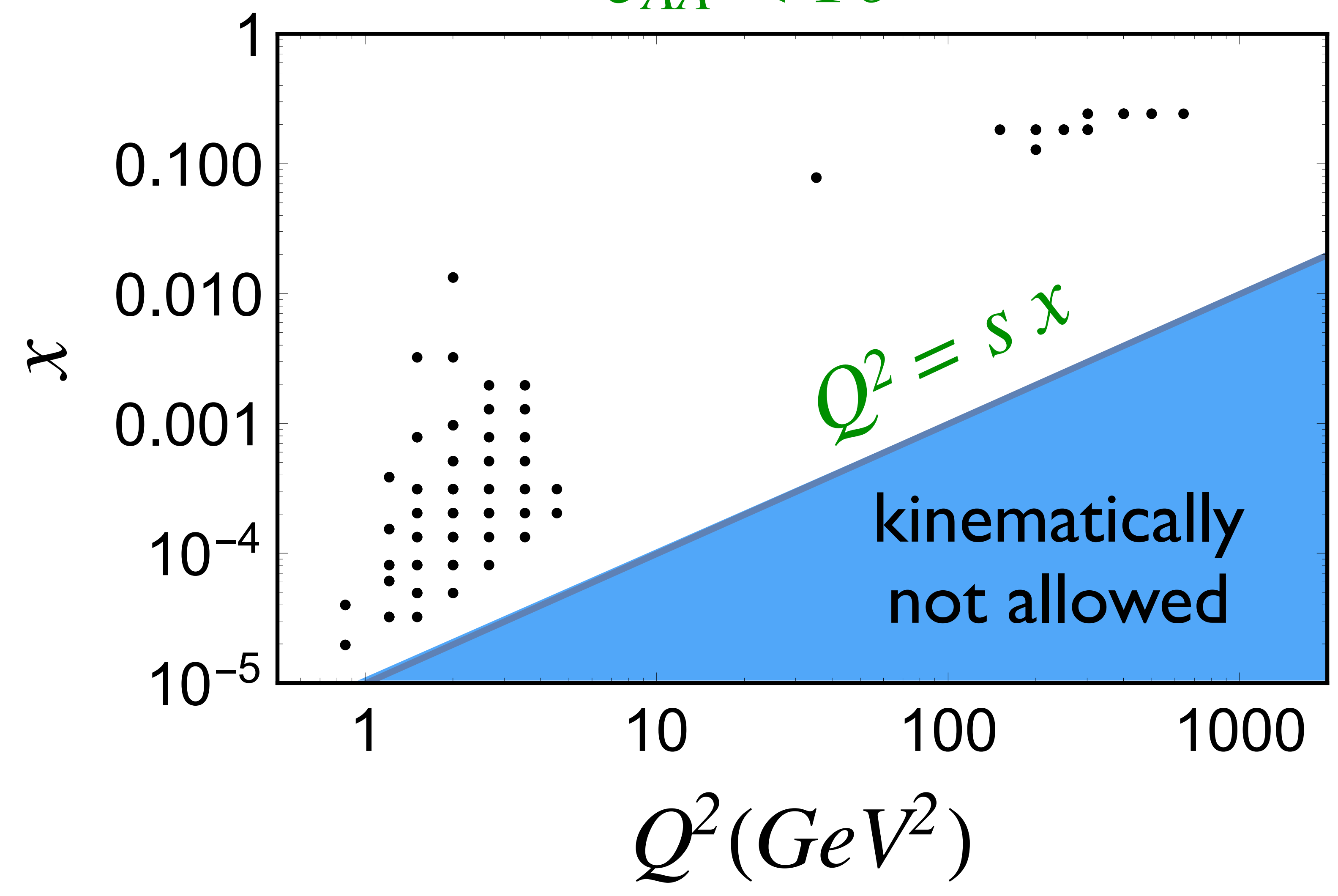
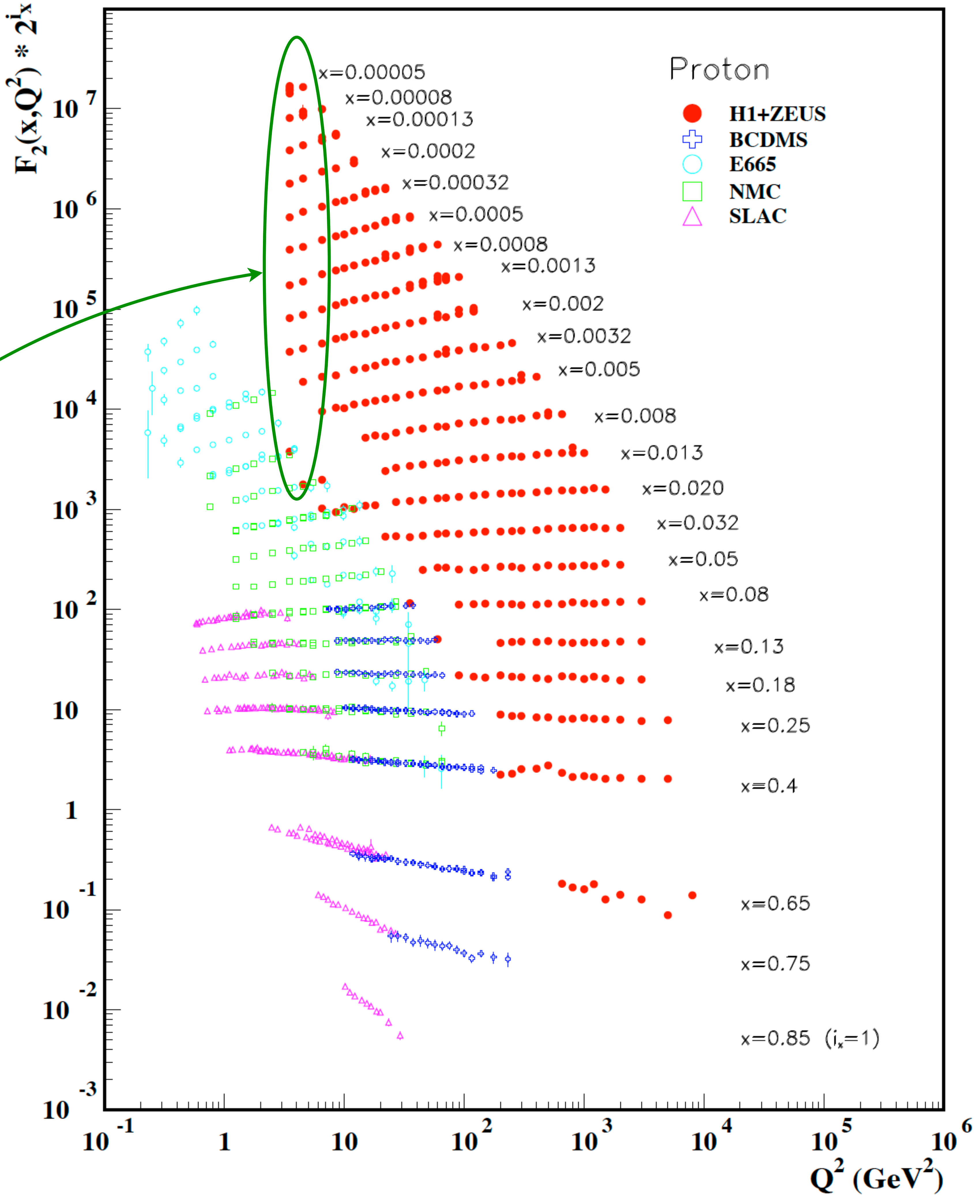
$$|c^u_{YZ}| \lesssim 4 \times 10^{-5}$$
$$|c^u_{XY}| \lesssim 4 \times 10^{-5}$$
$$|c^u_{XX} - c^u_{YY}| \lesssim 1 \times 10^{-5}$$

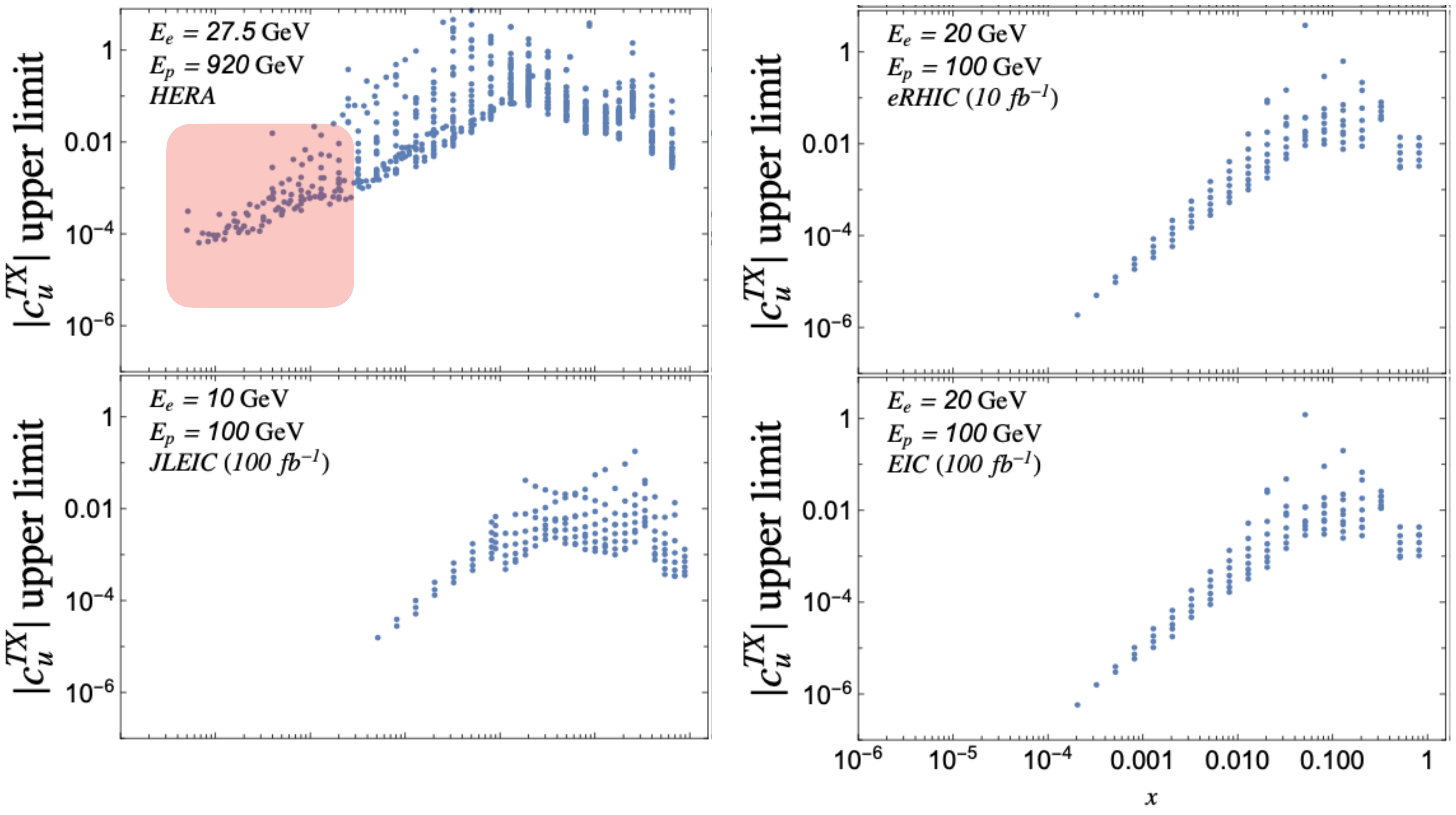
$c_{AA} < 10^{-4}$

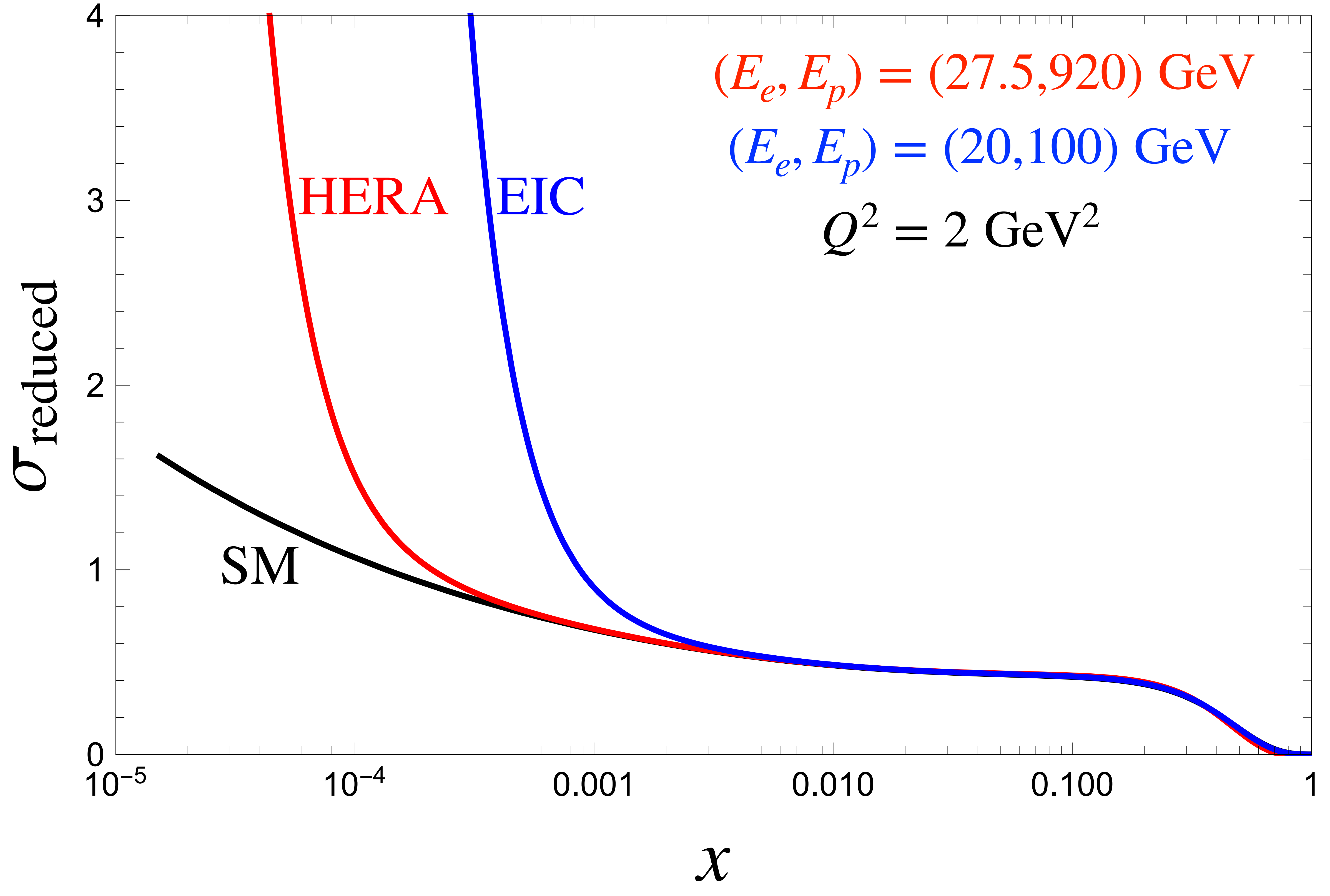




DIS - HERA/EIC - expected constraints on $c^{\mu\nu}$ coefficients

- For purely kinematical reasons HERA can reach very low x values





DIS - HERA/EIC - expected constraints on $c^{\mu\nu}$ coefficients

- The EIC main advantage over HERA data is the large target integrated luminosity

	JLEIC	eRHIC	HERA
Location	Jefferson Lab	BNL	DESY
Lumi (cm^{-2} s^{-1})	10^{34}	10^{33}	4×10^{31}
E_e (GeV)	[3,12]	[5,20]	27.5
E_p (GeV)	[20,100]	[50,250]	920

eRHIC will start with a yearly integrated luminosity of about 10 fb^{-1} and then upgrade it to 100 fb^{-1}

	HERA	JLEIC one year	eRHIC one year	JLEIC ten years	eRHIC ten years
$\|c_u^{TX}\|$	6.4 [6.7]	1.1 [11.]	0.26 [11.]	0.072 [9.3]	0.084 [11.]
	6.4 [6.7]	1.0 [10.]	0.19 [7.7]	0.062 [8.5]	0.058 [7.9]
$\|c_u^{TY}\|$	6.4 [6.7]	1.1 [11.]	0.27 [11.]	0.069 [9.4]	0.085 [11.]
	6.4 [6.7]	1.0 [10.]	0.18 [7.8]	0.065 [8.5]	0.058 [7.8]
$\|c_u^{XZ}\|$	32. [33.]	1.9 [16.]	0.36 [15.]	0.12 [16.]	0.11 [15.]
	32. [33.]	2.2 [19.]	0.85 [35.]	0.14 [19.]	0.26 [36.]
$\|c_u^{YZ}\|$	32. [33.]	1.8 [16.]	0.37 [15.]	0.12 [16.]	0.12 [15.]
	32. [33.]	2.2 [19.]	0.84 [35.]	0.14 [19.]	0.26 [36.]
$\|c_u^{XY}\|$	16. [16.]	7.0 [60.]	0.96 [40.]	0.44 [58.]	0.31 [40.]
	16. [16.]	3.3 [28.]	0.40 [17.]	0.20 [27.]	0.13 [17.]
$\|c_u^{XX} - c_u^{YY}\|$	50. [50.]	6.0 [51.]	2.8 [120.]	0.37 [50.]	0.89 [120.]
	50. [50.]	6.4 [54.]	2.0 [82.]	0.40 [53.]	0.63 [82.]

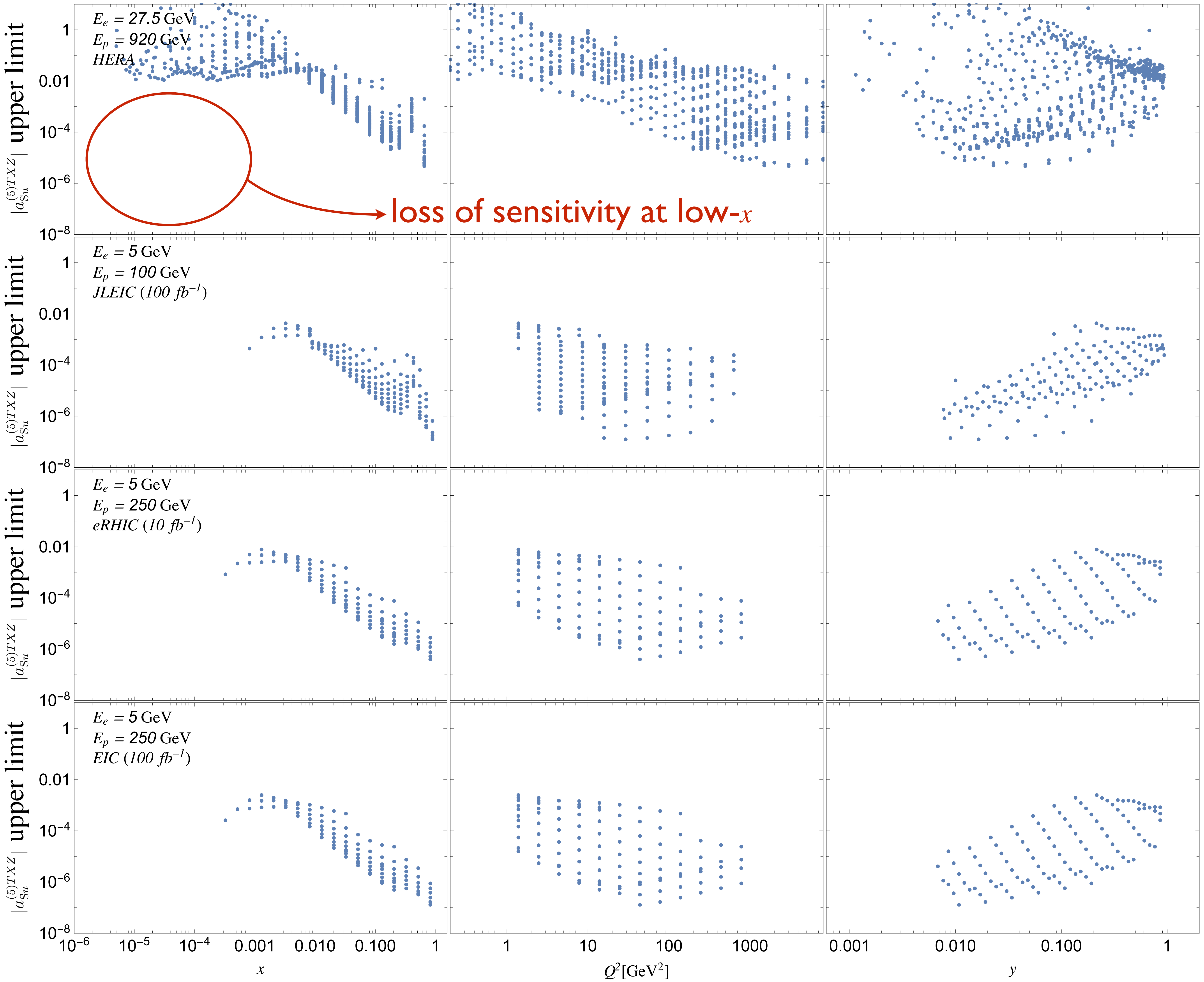
DIS - HERA/EIC - expected constraints on $a^{(5)\mu\alpha\beta}$ coefficients

- Expected bounds in units of $10^{-5}\ GeV^{-1}$

	HERA	JLEIC (one year)	eRHIC (one year)	JLEIC (ten years)	eRHIC (ten years)
$\lvert a^{(5)TXX}_{\mathrm{Su}} - a^{(5)TYY}_{\mathrm{Su}}\rvert$	7.0 [6.9]	4.3 [20.]	18. [20.]	2.3 [16.]	7.8 [20.]
$\lvert a^{(5)XXZ}_{\mathrm{Su}} - a^{(5)YYZ}_{\mathrm{Su}}\rvert$	18. [18.]	9.7 [17.]	12. [12.]	5.2 [14.]	9.7 [12.]
$\lvert a^{(5)TXY}_{\mathrm{Su}}\rvert$	2.3 [2.5]	0.46 [1.3]	1.1 [1.6]	0.50 [2.0]	0.34 [1.3]
$\lvert a^{(5)TXZ}_{\mathrm{Su}}\rvert$	4.7 [4.8]	0.13 [0.36]	0.40 [0.61]	0.13 [0.50]	0.13 [0.49]
$\lvert a^{(5)TYZ}_{\mathrm{Su}}\rvert$	4.6 [4.8]	0.12 [0.37]	0.40 [0.61]	0.13 [0.50]	0.13 [0.48]
$\lvert a^{(5)XXX}_{\mathrm{Su}}\rvert$	1.7 [1.8]	0.14 [0.40]	0.56 [0.86]	0.14 [0.53]	0.18 [0.70]
$\lvert a^{(5)XXY}_{\mathrm{Su}}\rvert$	1.6 [1.7]	0.15 [0.43]	0.55 [0.85]	0.14 [0.56]	0.18 [0.67]
$\lvert a^{(5)XYY}_{\mathrm{Su}}\rvert$	1.6 [1.7]	0.15 [0.42]	0.55 [0.85]	0.14 [0.56]	0.18 [0.68]
$\lvert a^{(5)XYZ}_{\mathrm{Su}}\rvert$	10. [11.]	0.68 [1.9]	1.4 [2.1]	0.79 [3.1]	0.43 [1.6]
$\lvert a^{(5)XZZ}_{\mathrm{Su}}\rvert$	2.1 [2.2]	0.12 [0.34]	0.39 [0.60]	0.12 [0.45]	0.13 [0.48]
$\lvert a^{(5)YYY}_{\mathrm{Su}}\rvert$	1.7 [1.7]	0.14 [0.41]	0.56 [0.87]	0.14 [0.53]	0.18 [0.68]
$\lvert a^{(5)YZZ}_{\mathrm{Su}}\rvert$	2.1 [2.1]	0.12 [0.35]	0.39 [0.60]	0.12 [0.46]	0.12 [0.47]

- The largest energies available at HERA allow to partially compensate for the lower luminosity

DIS - HERA/EIC - expected constraints on $a^{(5)\mu\alpha\beta}$ coefficients



- The $a^{(5)}$ coefficients are CPT violating
- The dispersion relation ($\tilde{k}^2 = 0$) in presence of these coefficients involves
  $\tilde{k}^\mu = k^\mu \mp a_f^{(5)\mu\alpha\beta} k_\alpha k_\beta$
  where the two signs correspond to particle and antiparticle
- The cross section depend on the difference $q(x) - \bar{q}(x)$ of the sea quark PDFs, implying a loss of sensitivity at low x where sea quarks dominate and $q(x) \sim \bar{q}(x)$

DY - LHC - expected constraints on $c^{\mu\nu}$ coefficients

- Constraints which we expect from sidereal time studies of Drell-Yan at various Q^2

coefficient	$[\frac{d\sigma}{dQ}]_{Q=17.5\text{ GeV}}$			$[\frac{d\sigma}{dQ}]_{Q=m_Z}$			$[\frac{d\sigma}{dQ}]_{Q=m_Z}/[\frac{d\sigma}{dQ}]_{Q=17.5\text{ GeV}}$	
	δ_{th}	δ_{th}, δ_{lumi}	δ_{th}, δ_{lumi}, δ_{sel}	nothing	δ_{lumi}	δ_{lumi}, δ_{sel}	δ_{th}, δ_{lumi}	δ_{th}, δ_{lumi}, δ_{sel}
$\lvert c_{u_1}^{XY}\rvert$	2.6×10^{-5}	2.3×10^{-5}	1.1×10^{-5}	8.4×10^{-4}	2.4×10^{-4}	1.1×10^{-4}	2.2×10^{-5}	1.0×10^{-5}
$\lvert c_{u_1}^{XZ}\rvert$	7.0×10^{-5}	6.2×10^{-5}	2.9×10^{-5}	2.3×10^{-3}	6.3×10^{-4}	3.1×10^{-4}	5.9×10^{-5}	2.7×10^{-5}
$\lvert c_{u_1}^{YZ}\rvert$	7.0×10^{-5}	6.1×10^{-5}	2.8×10^{-5}	2.3×10^{-3}	6.3×10^{-4}	3.1×10^{-4}	6.0×10^{-5}	2.7×10^{-5}
$\lvert c_{u_1}^{XX}-c_{u_1}^{YY}\rvert$	1.4×10^{-4}	1.3×10^{-4}	5.9×10^{-5}	4.7×10^{-3}	1.3×10^{-3}	6.4×10^{-4}	1.2×10^{-4}	5.7×10^{-5}
$\lvert c_{d_1}^{XY}\rvert$	2.3×10^{-4}	2.1×10^{-4}	9.6×10^{-5}	4.3×10^{-4}	1.2×10^{-4}	5.9×10^{-5}	2.7×10^{-4}	1.2×10^{-4}
$\lvert c_{d_1}^{XZ}\rvert$	6.3×10^{-4}	5.6×10^{-4}	2.6×10^{-4}	1.2×10^{-3}	3.2×10^{-4}	1.6×10^{-4}	7.2×10^{-4}	3.3×10^{-4}
$\lvert c_{d_1}^{YZ}\rvert$	6.3×10^{-4}	5.6×10^{-4}	2.5×10^{-4}	1.2×10^{-3}	3.2×10^{-4}	1.6×10^{-4}	7.3×10^{-4}	3.3×10^{-4}
$\lvert c_{d_1}^{XX}-c_{d_1}^{YY}\rvert$	1.3×10^{-3}	1.2×10^{-3}	5.4×10^{-4}	2.4×10^{-3}	6.9×10^{-4}	3.3×10^{-4}	1.5×10^{-3}	6.9×10^{-4}
$\lvert d_{u_1}^{XY}\rvert$	8.2×10^{-4}	7.3×10^{-4}	3.3×10^{-4}	3.7×10^{-4}	1.1×10^{-4}	5.1×10^{-5}	8.6×10^{-3}	4.0×10^{-3}
$\lvert d_{u_1}^{XZ}\rvert$	2.2×10^{-3}	2.0×10^{-3}	9.1×10^{-4}	1.0×10^{-3}	2.8×10^{-4}	1.4×10^{-4}	2.3×10^{-2}	1.0×10^{-2}
$\lvert d_{u_1}^{YZ}\rvert$	2.2×10^{-3}	2.0×10^{-3}	8.9×10^{-4}	1.0×10^{-3}	2.8×10^{-4}	1.4×10^{-4}	2.3×10^{-2}	1.0×10^{-2}
$\lvert d_{u_1}^{XX}-d_{u_1}^{YY}\rvert$	4.6×10^{-3}	4.1×10^{-3}	1.9×10^{-3}	2.1×10^{-3}	6.0×10^{-4}	2.9×10^{-4}	4.8×10^{-2}	2.2×10^{-2}

EIC vs LHC: comparative advantage

- EIC tends to deliver stronger bounds on renormalizable coefficients
- The large LHC energies increase enormously the sensitivity to non-minimal coefficients

	EIC (DIS)	**LHC**(DY)
$\lvert c_u^{XX} - c_u^{YY}\rvert$	0.37	5.7
$\lvert c_u^{XY}\rvert$	0.13	1.0
$\lvert c_u^{XZ}\rvert$	0.11	2.7
$\lvert c_u^{YZ}\rvert$	0.12	2.7

(in units of 10^{-5})

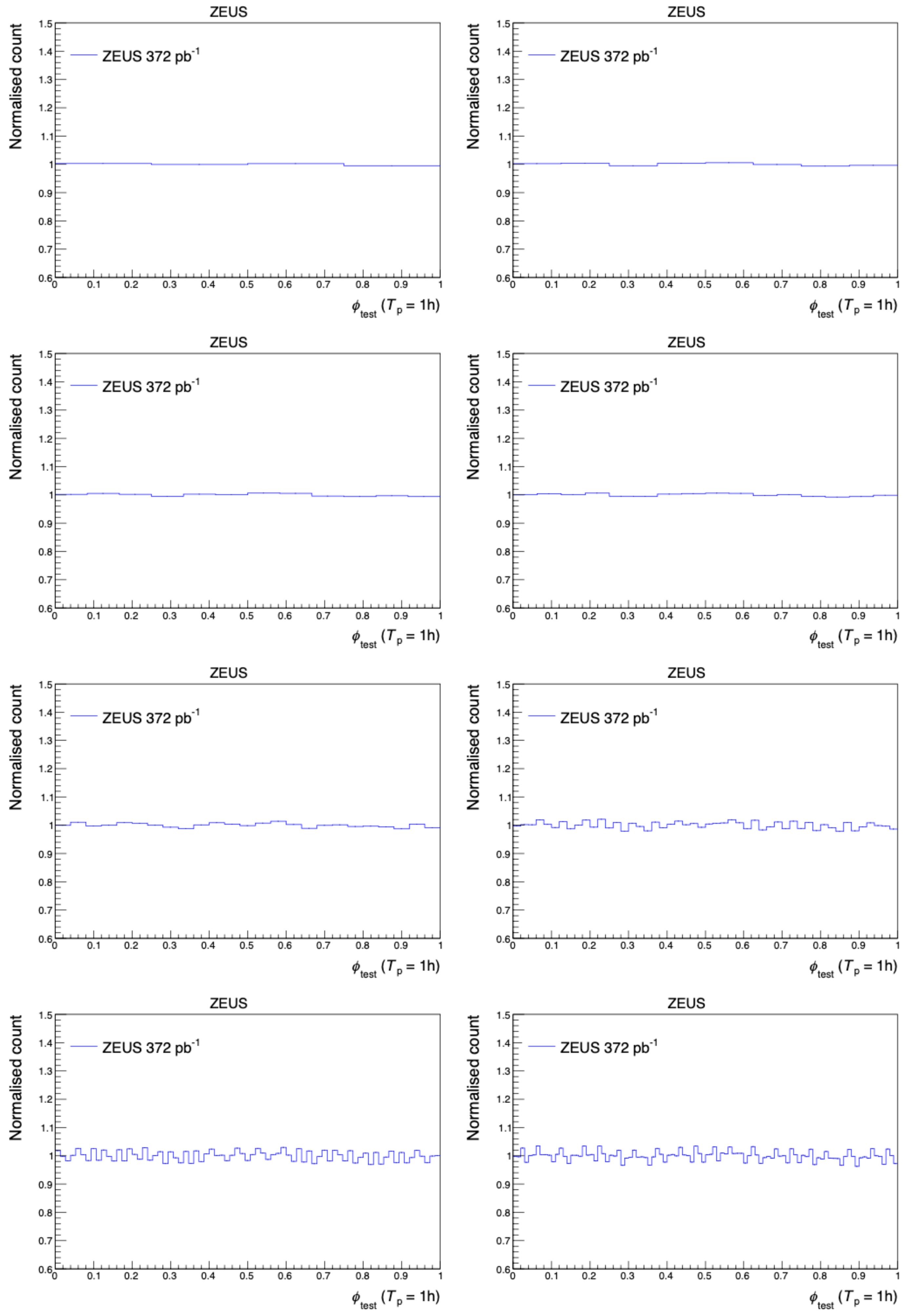
	EIC (DIS)	**LHC**(DY)
$\lvert a_{\mathrm{S}u}^{(5)TXX} - a_{\mathrm{S}u}^{(5)TYY}\rvert$	2.3	0.015
$\lvert a_{\mathrm{S}u}^{(5)TXY}\rvert$	0.34	0.0027
$\lvert a_{\mathrm{S}u}^{(5)TXZ}\rvert$	0.13	0.0072
$\lvert a_{\mathrm{S}u}^{(5)TYZ}\rvert$	0.12	0.0070

(in units of $10^{-6}\,GeV^{-1}$)

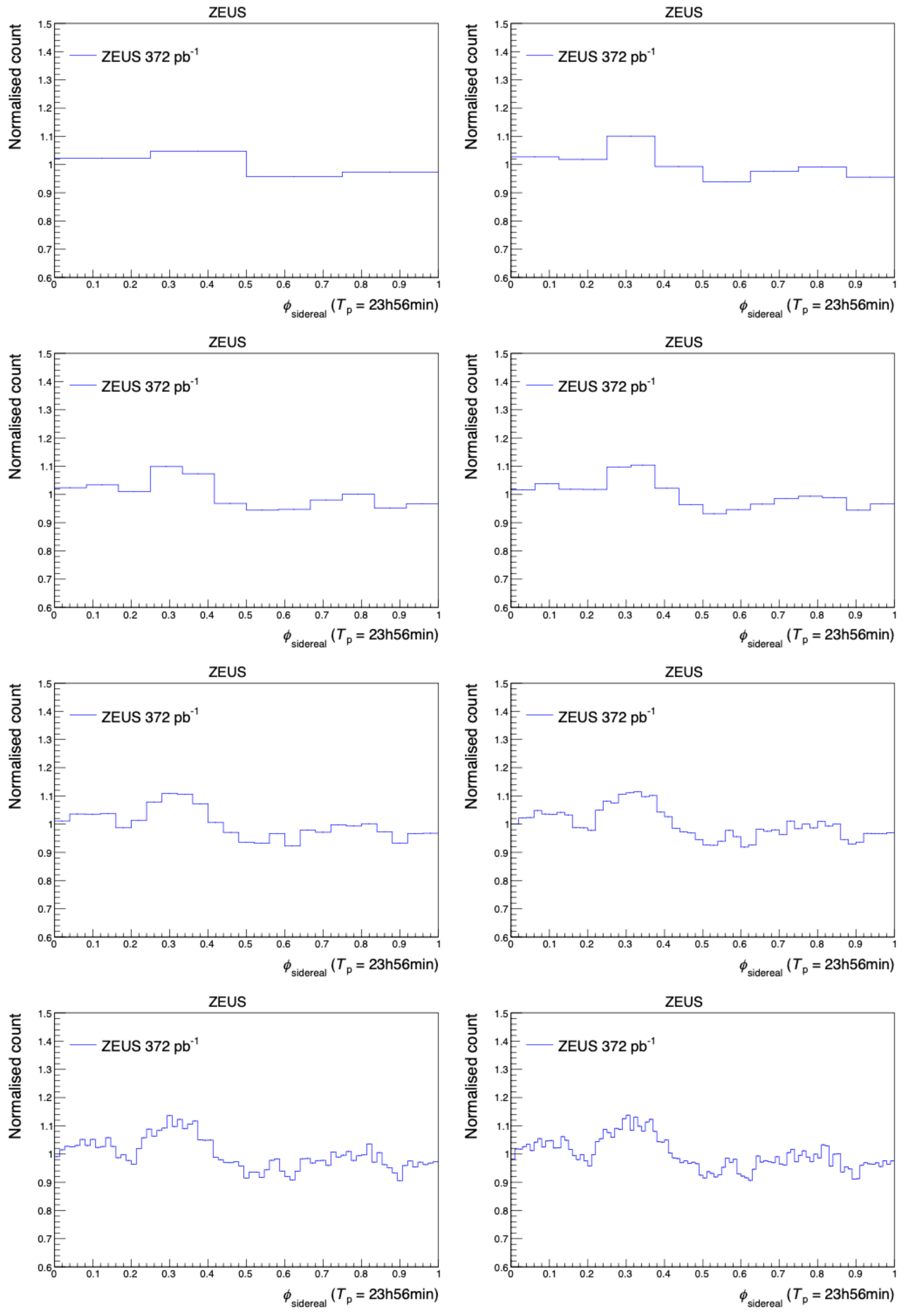
ZEUS analysis

Time dependence of all DIS events

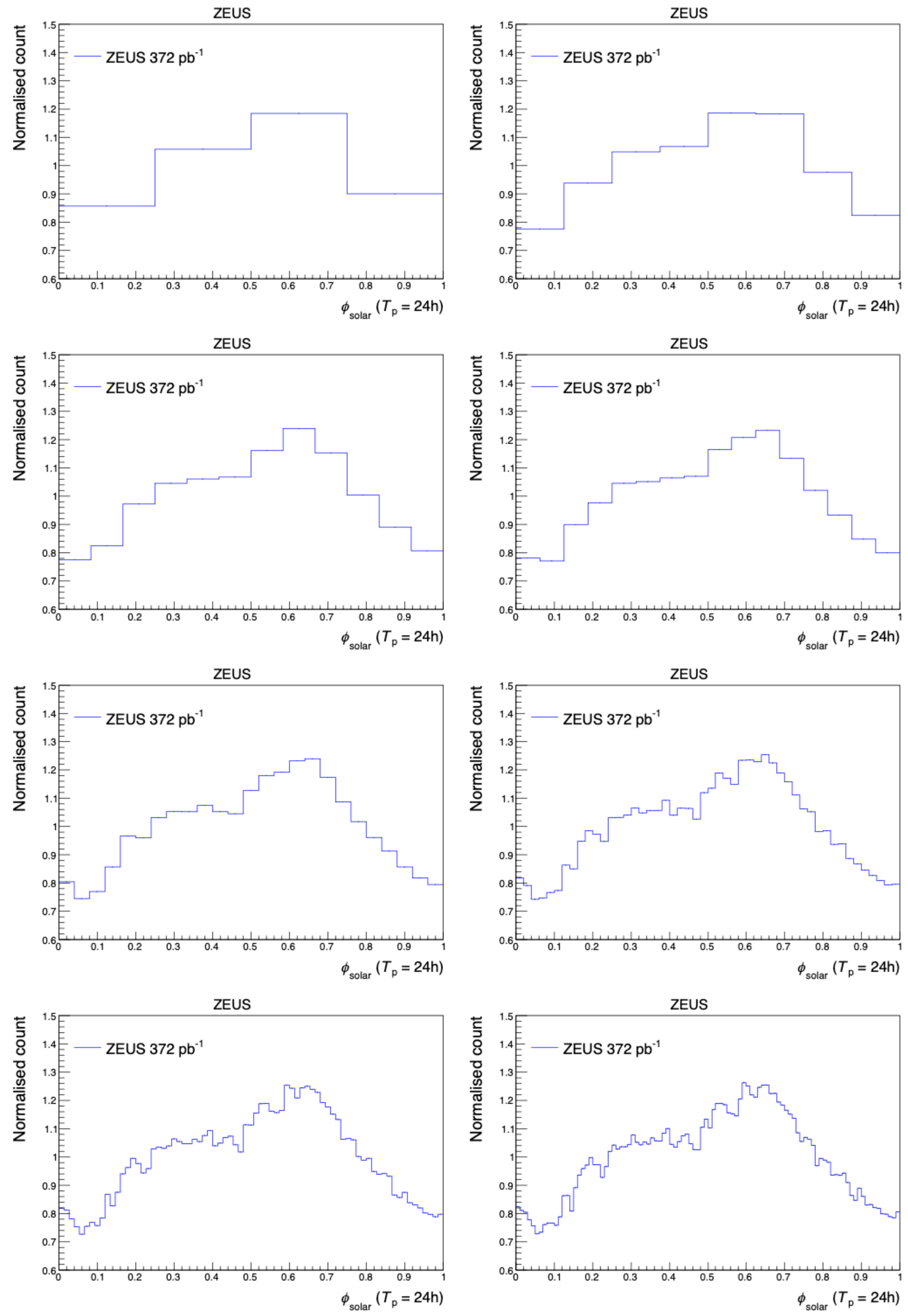
$T = 1\text{h}$



$T = T_{\text{sidereal}}$

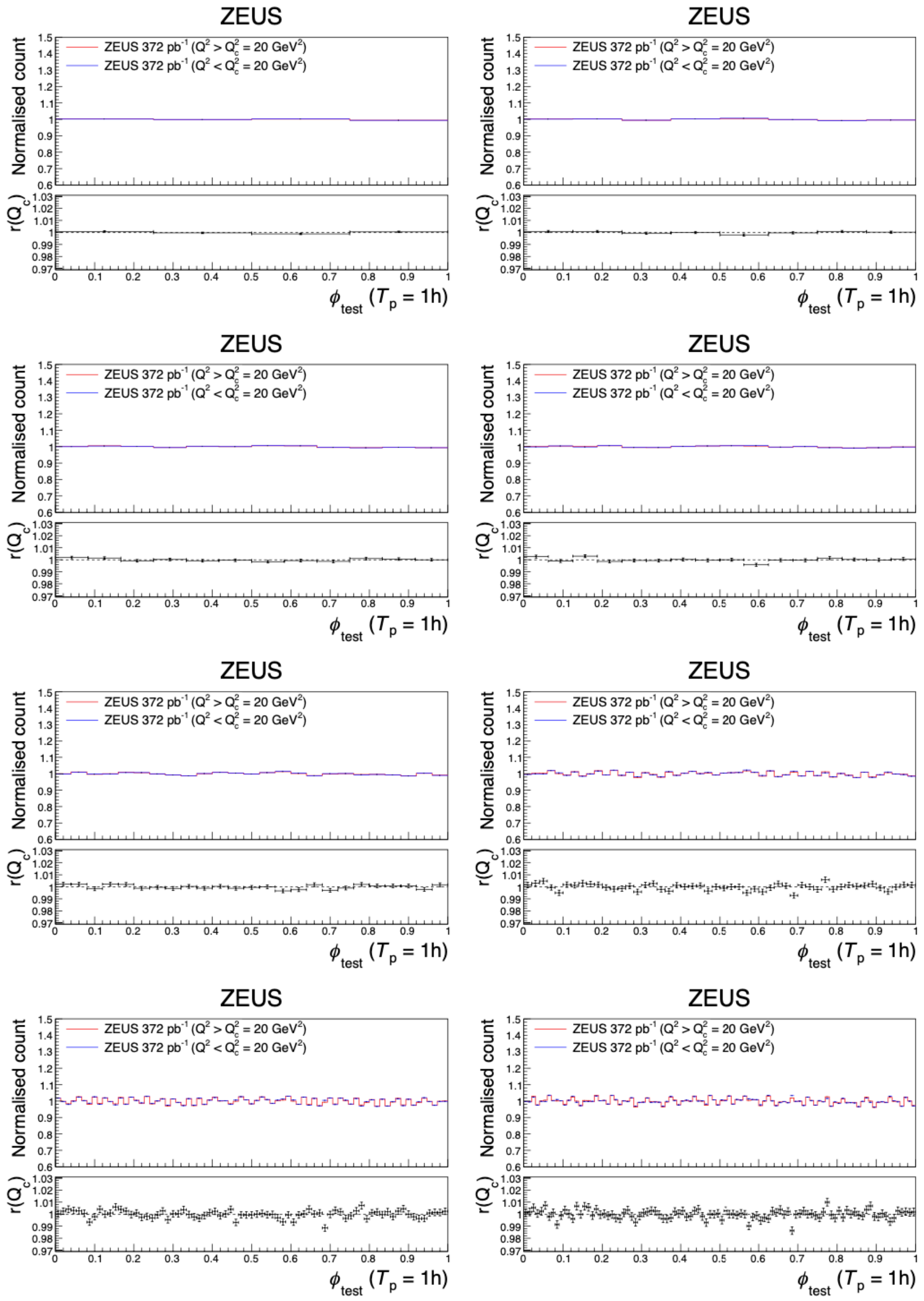


$T = T_{\text{solar}}$

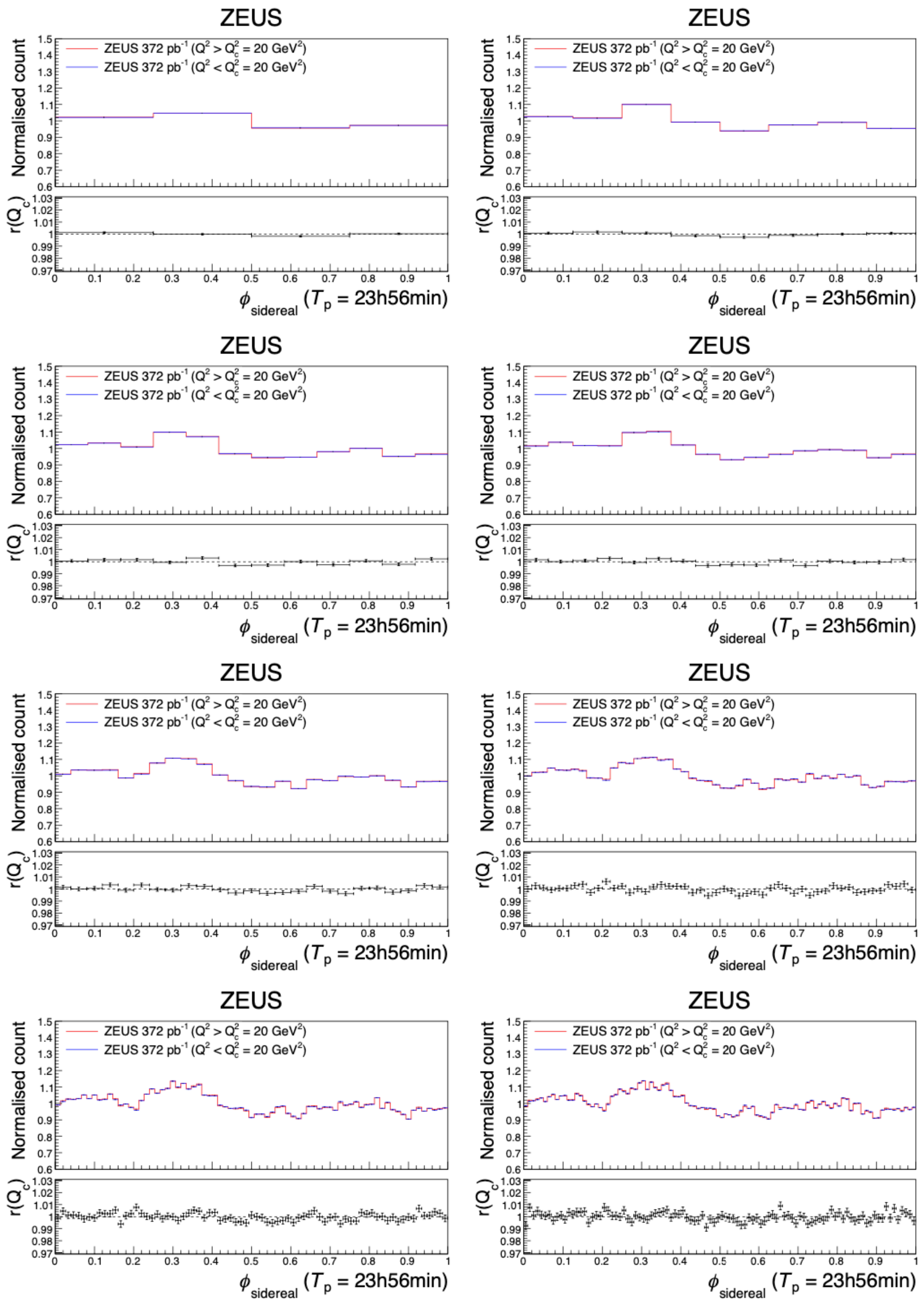


Time dependence of $r(Q_c)$

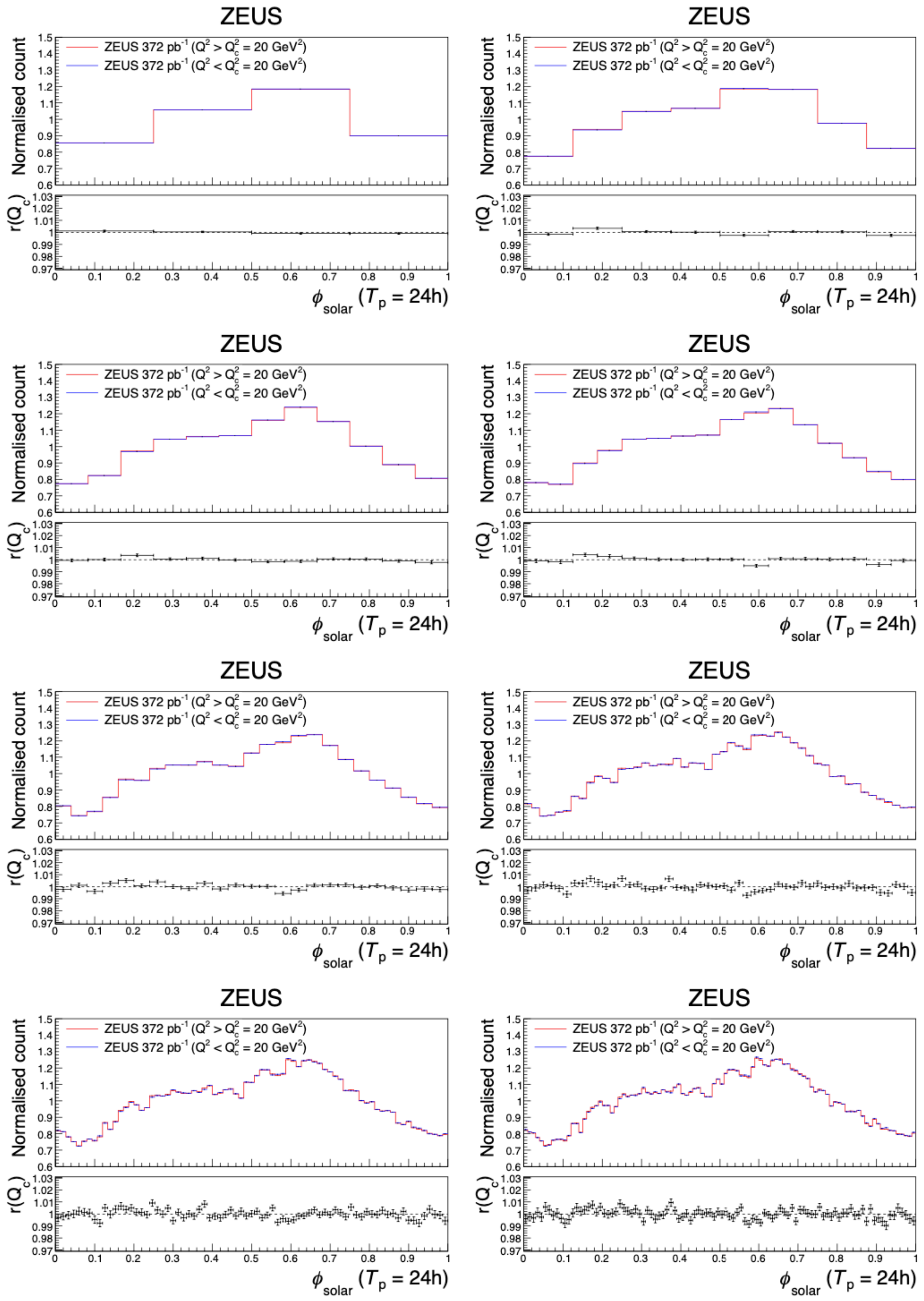
$T = 1\text{h}$



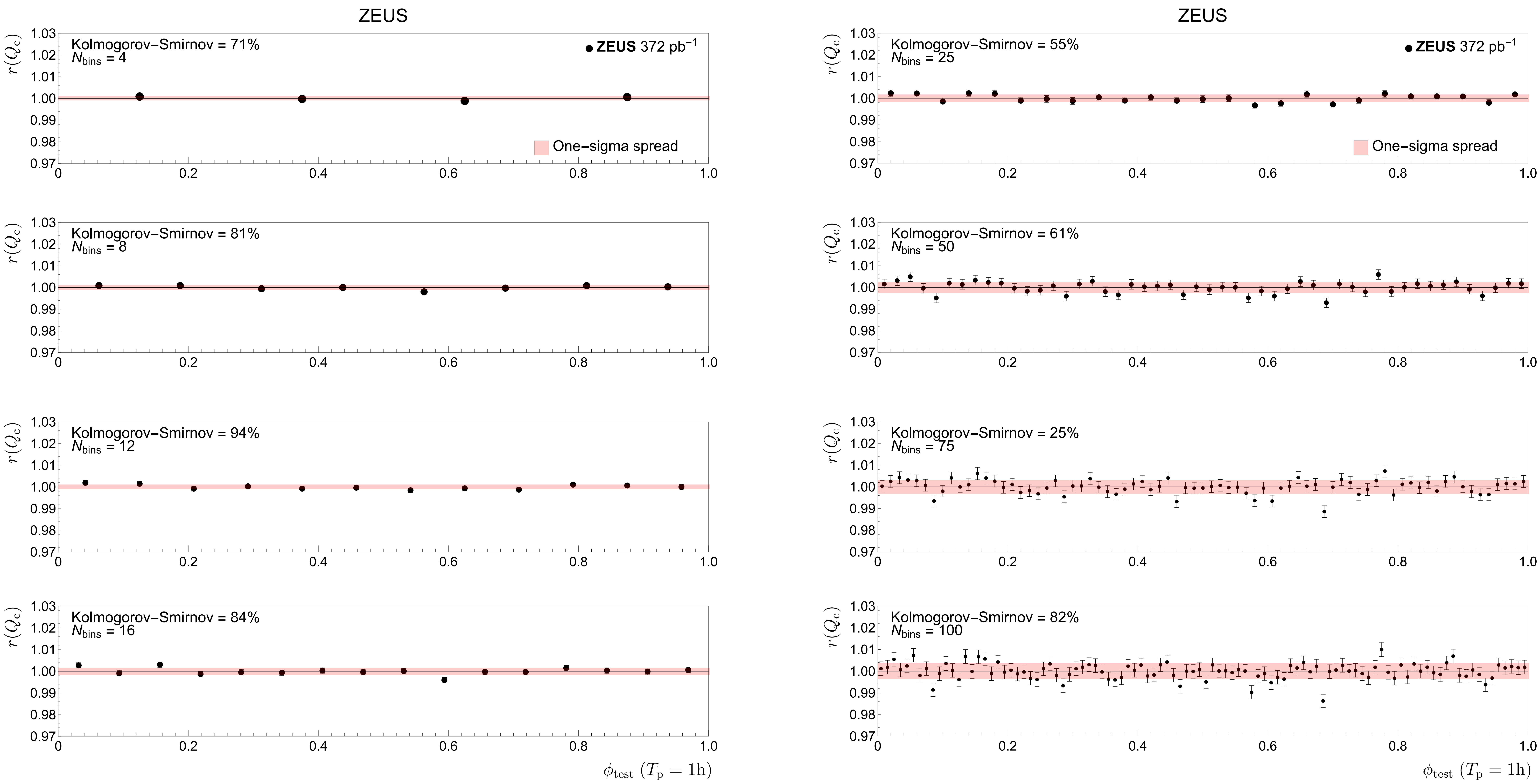
$T = T_{\text{sidereal}}$



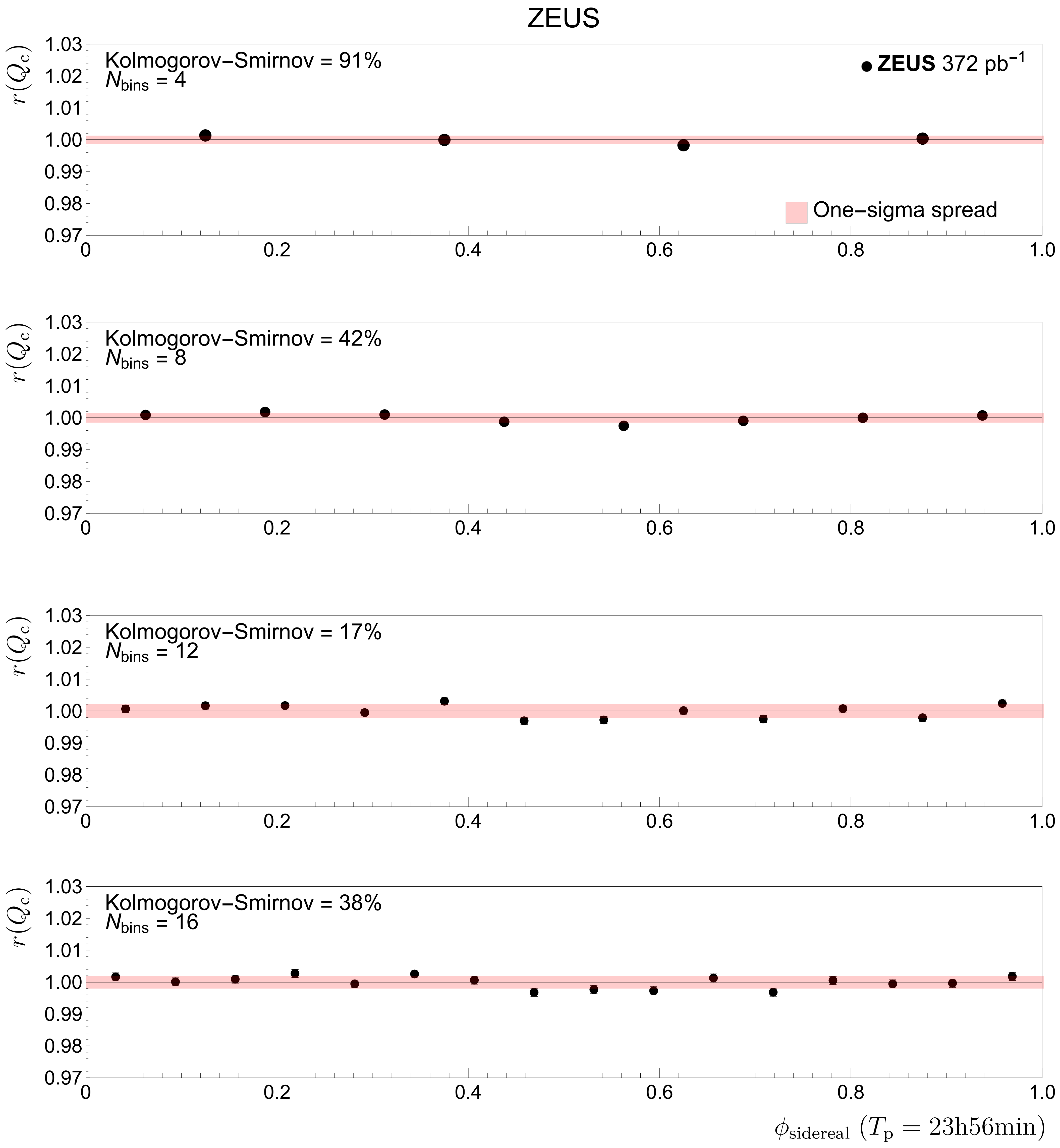
$T = T_{\text{solar}}$

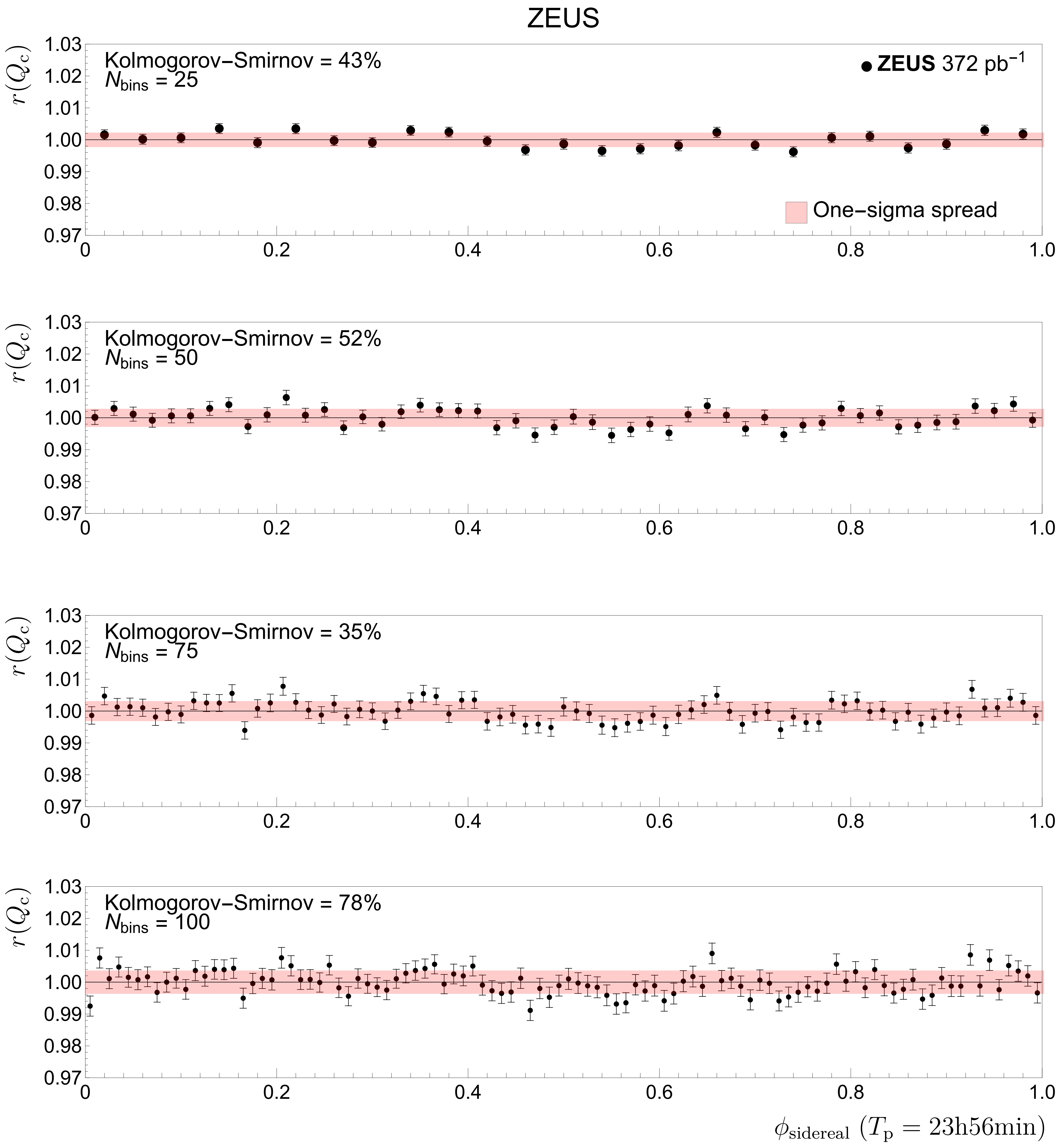


Time dependence of $r(Q_c)$: $T = 1\text{h}$

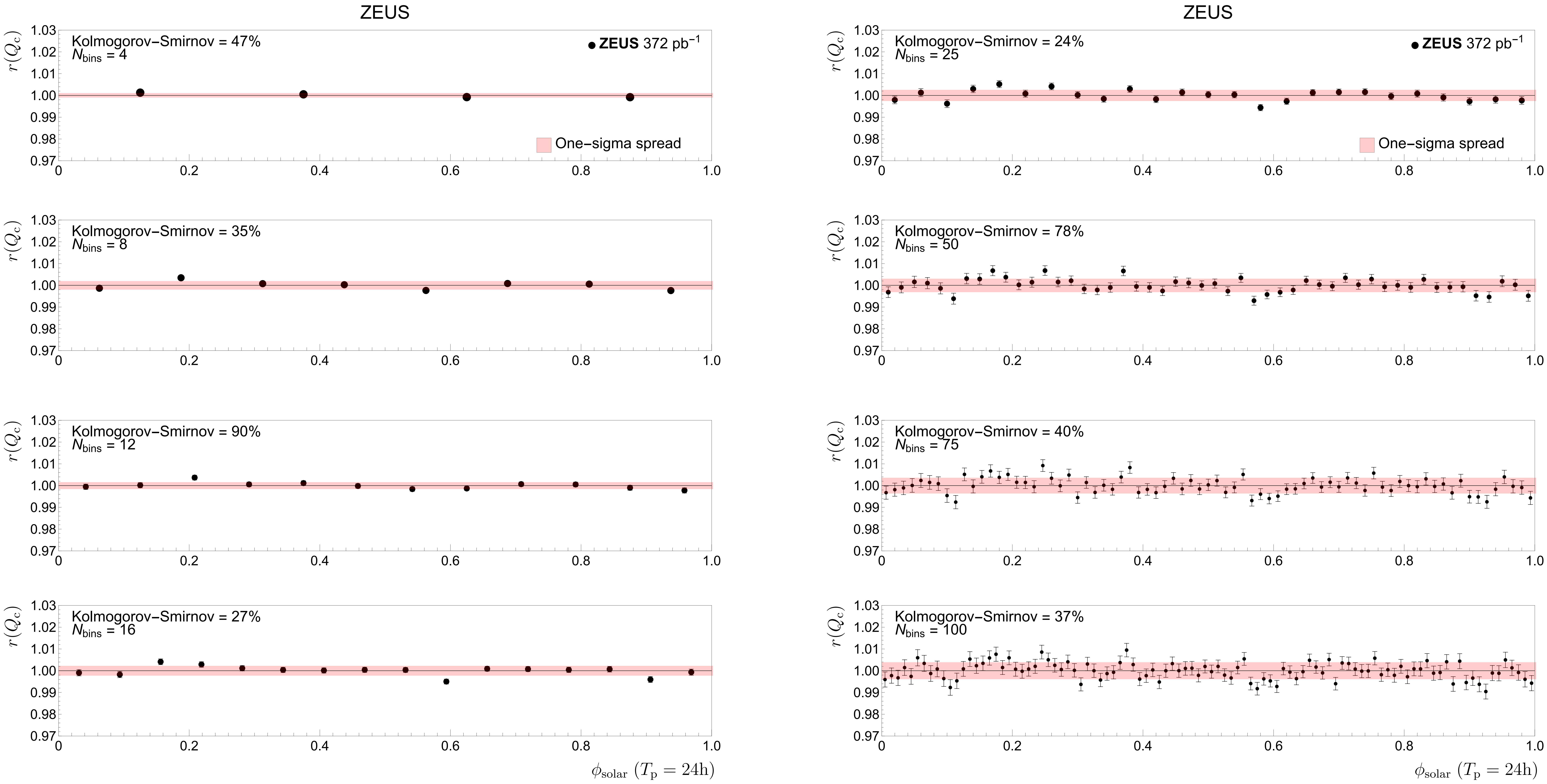


Time dependence of $r(Q_c)$: $T = T_{\text{sidereal}}$

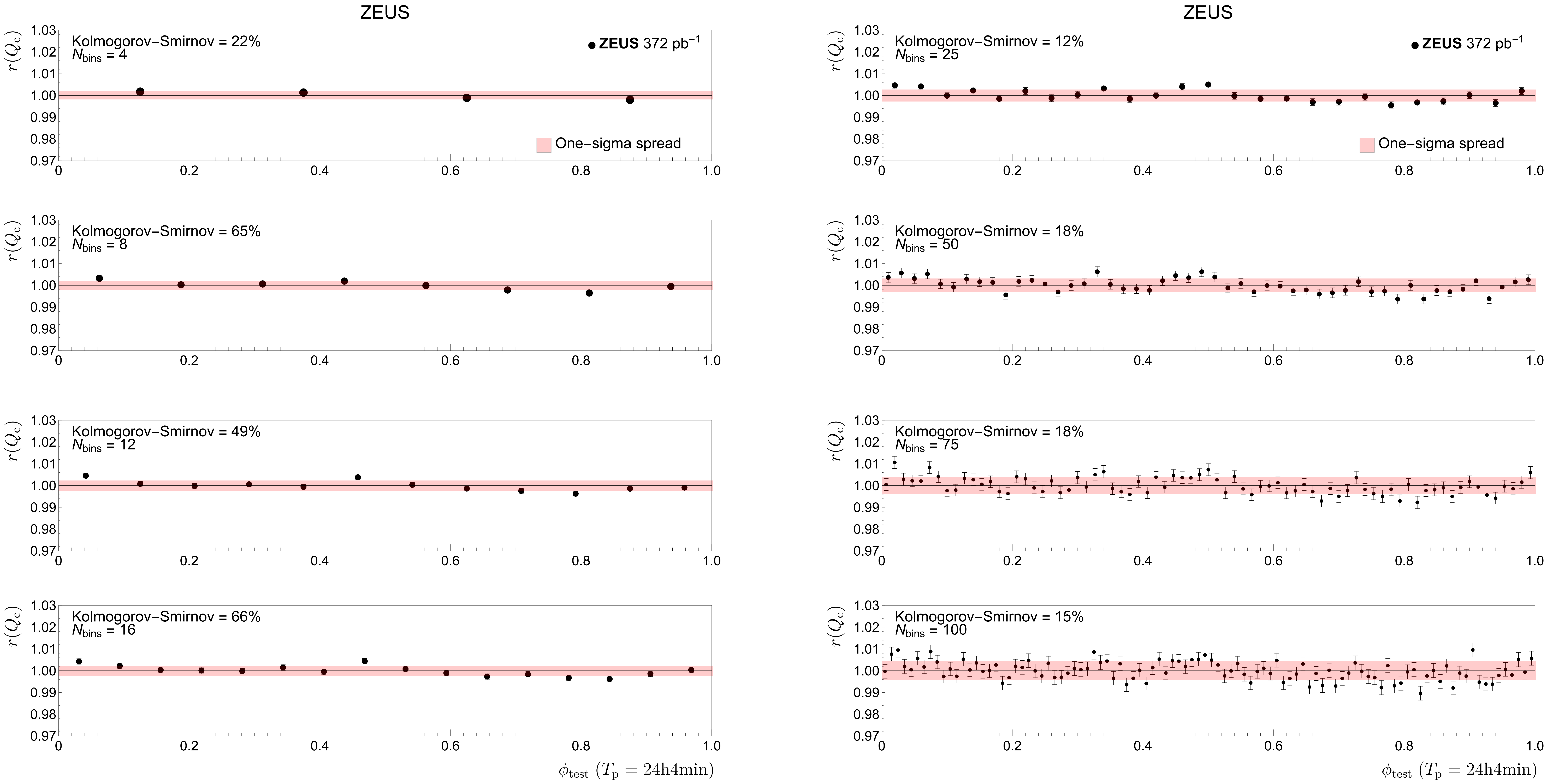




Time dependence of $r(Q_c)$: $T = T_{\text{solar}}$

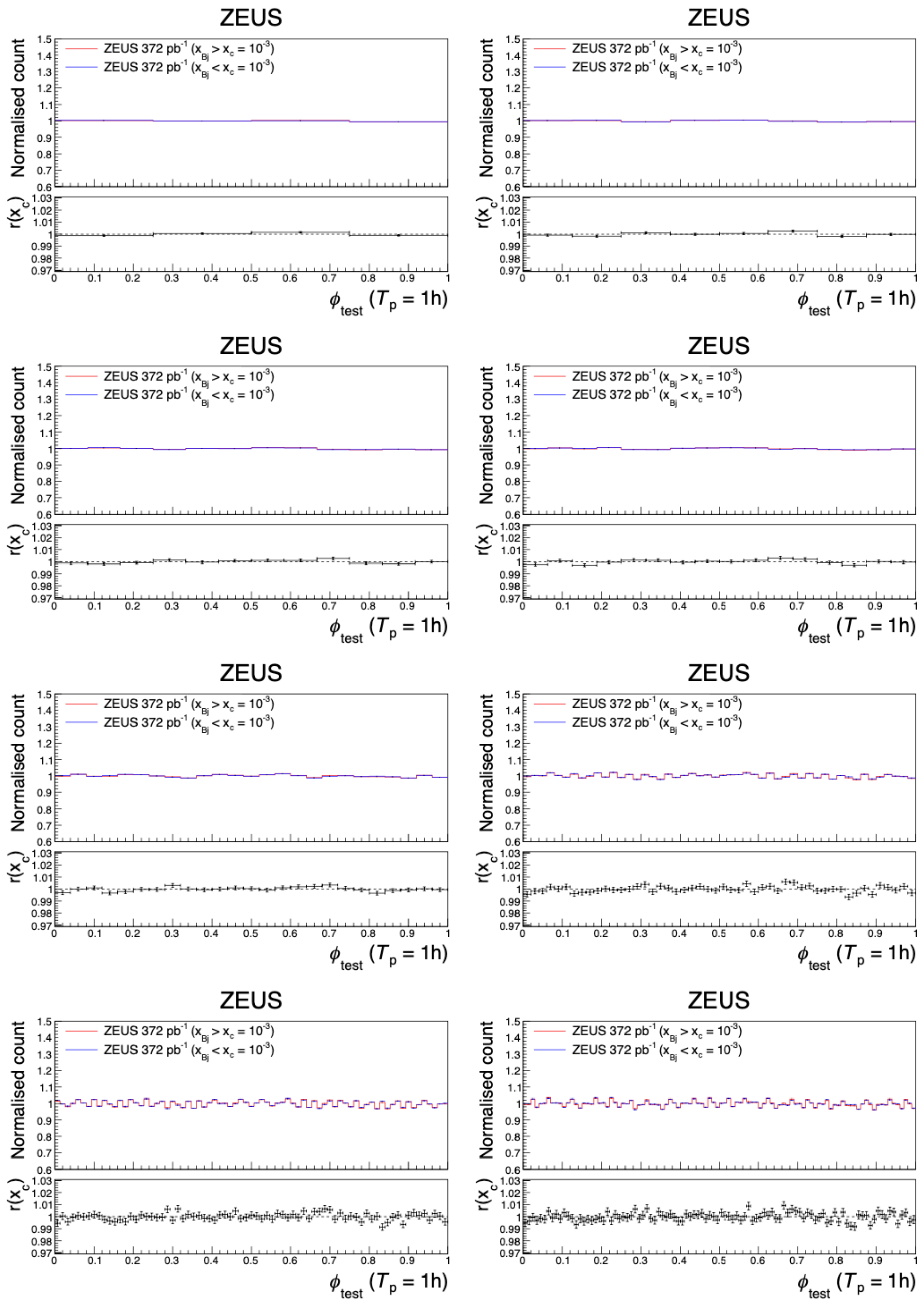


Time dependence of $r(Q_c)$: $T = T_{\text{solar}} + 4\text{m}$

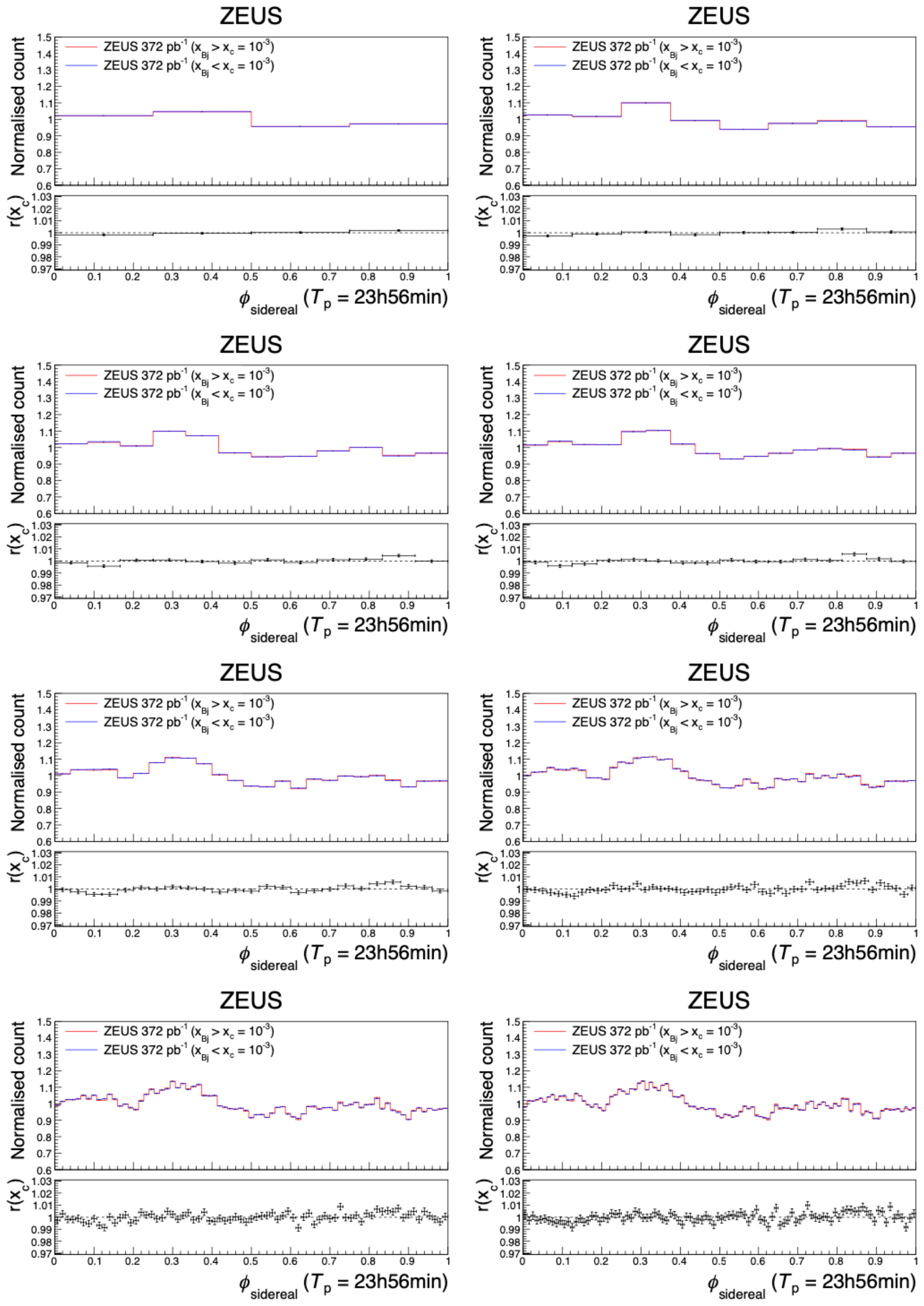


Time dependence of $r(x_c)$

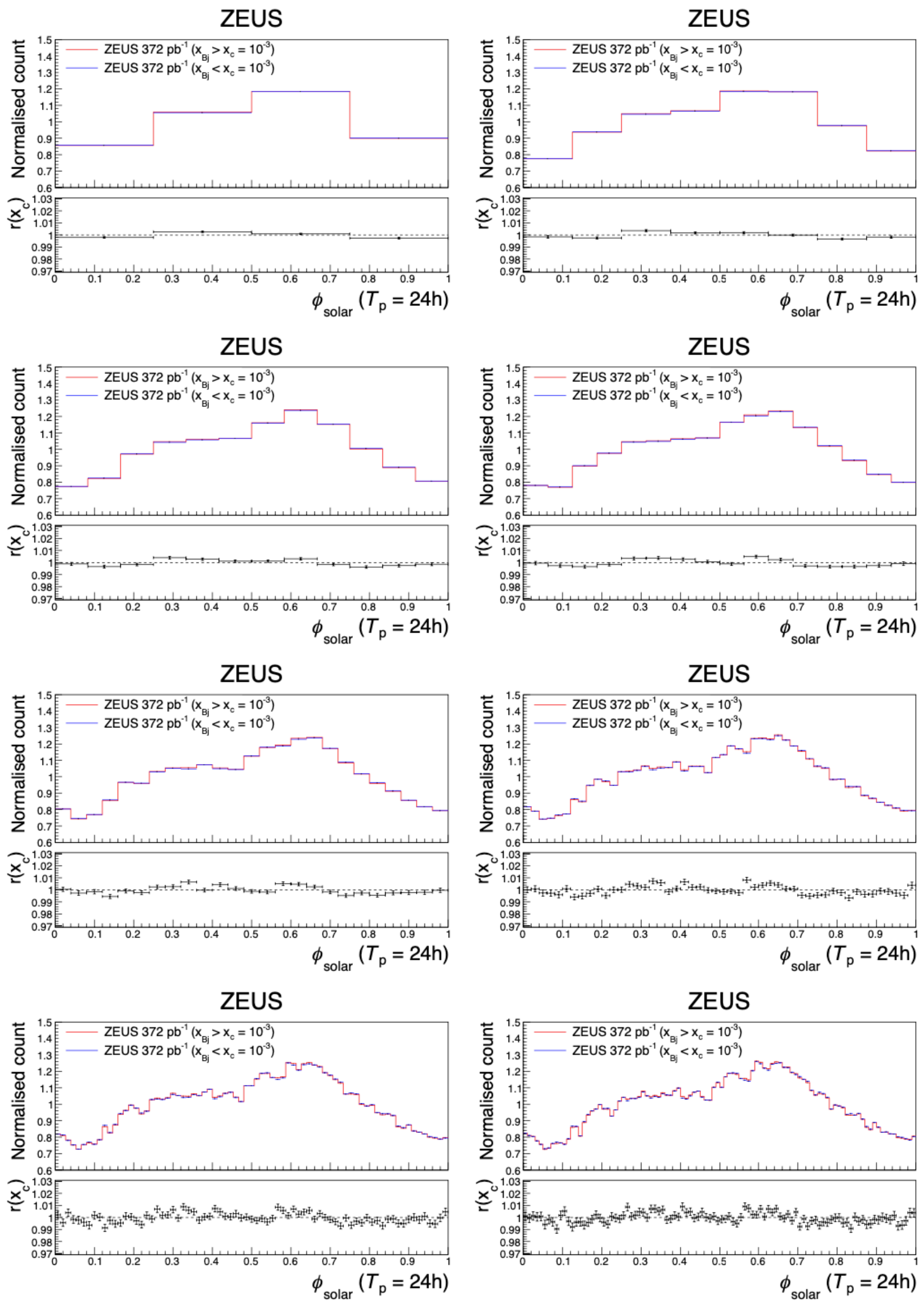
$T = 1\mathrm{h}$



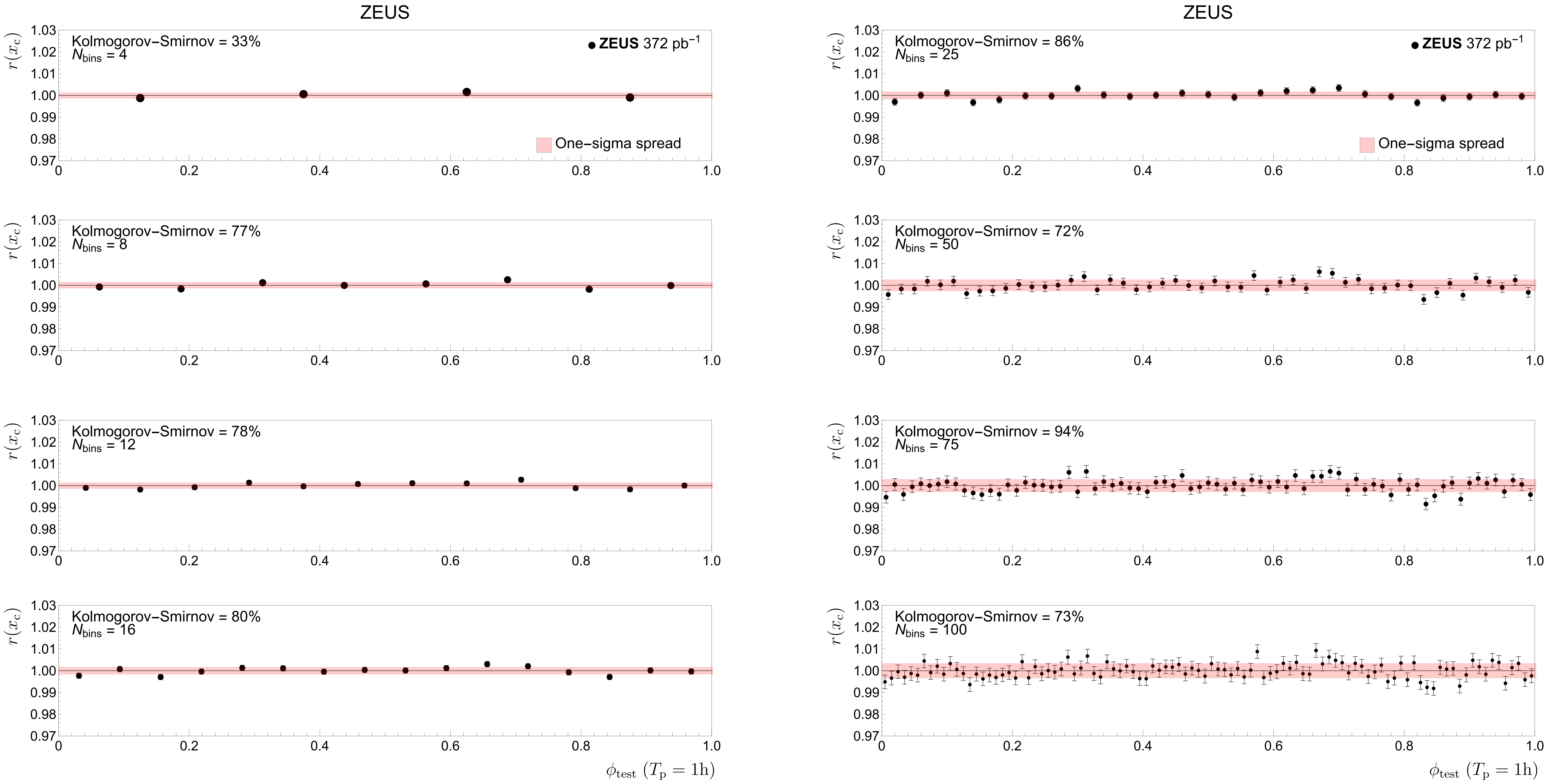
$T = T_{\mathrm{sidereal}}$



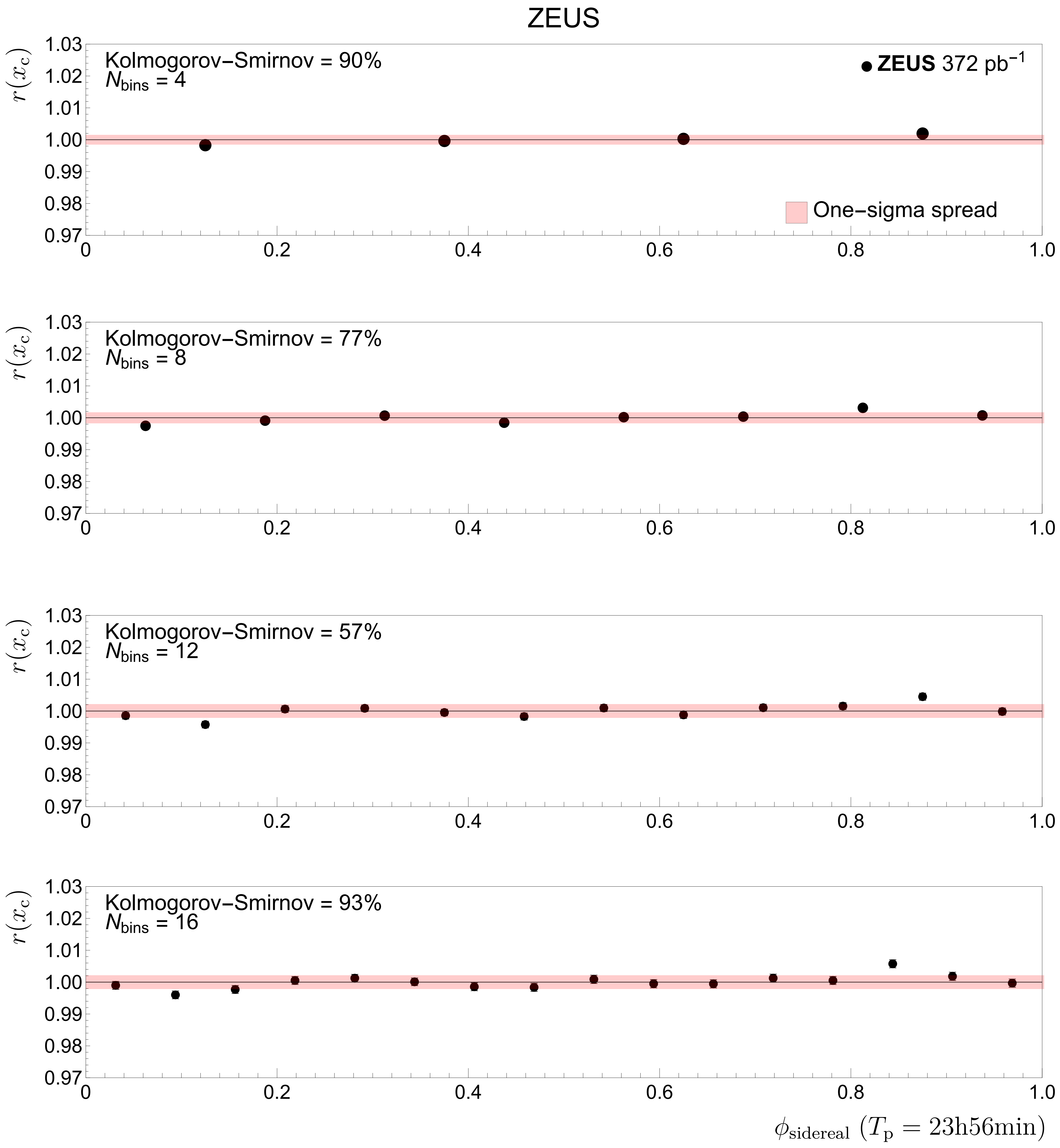
$T = T_{\mathrm{solar}}$

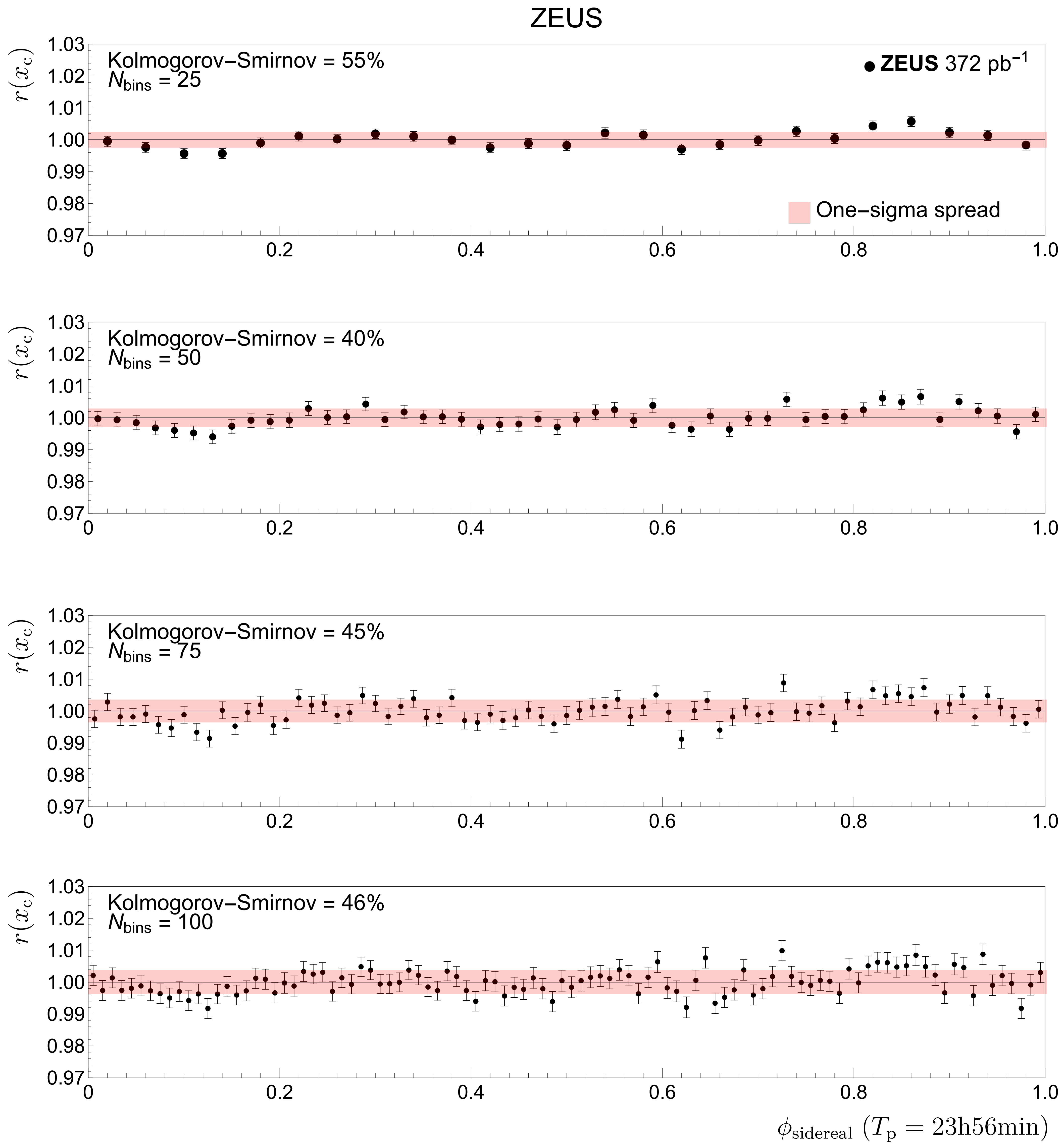


Time dependence of $r(x_c)$: $T = 1\mathrm{h}$

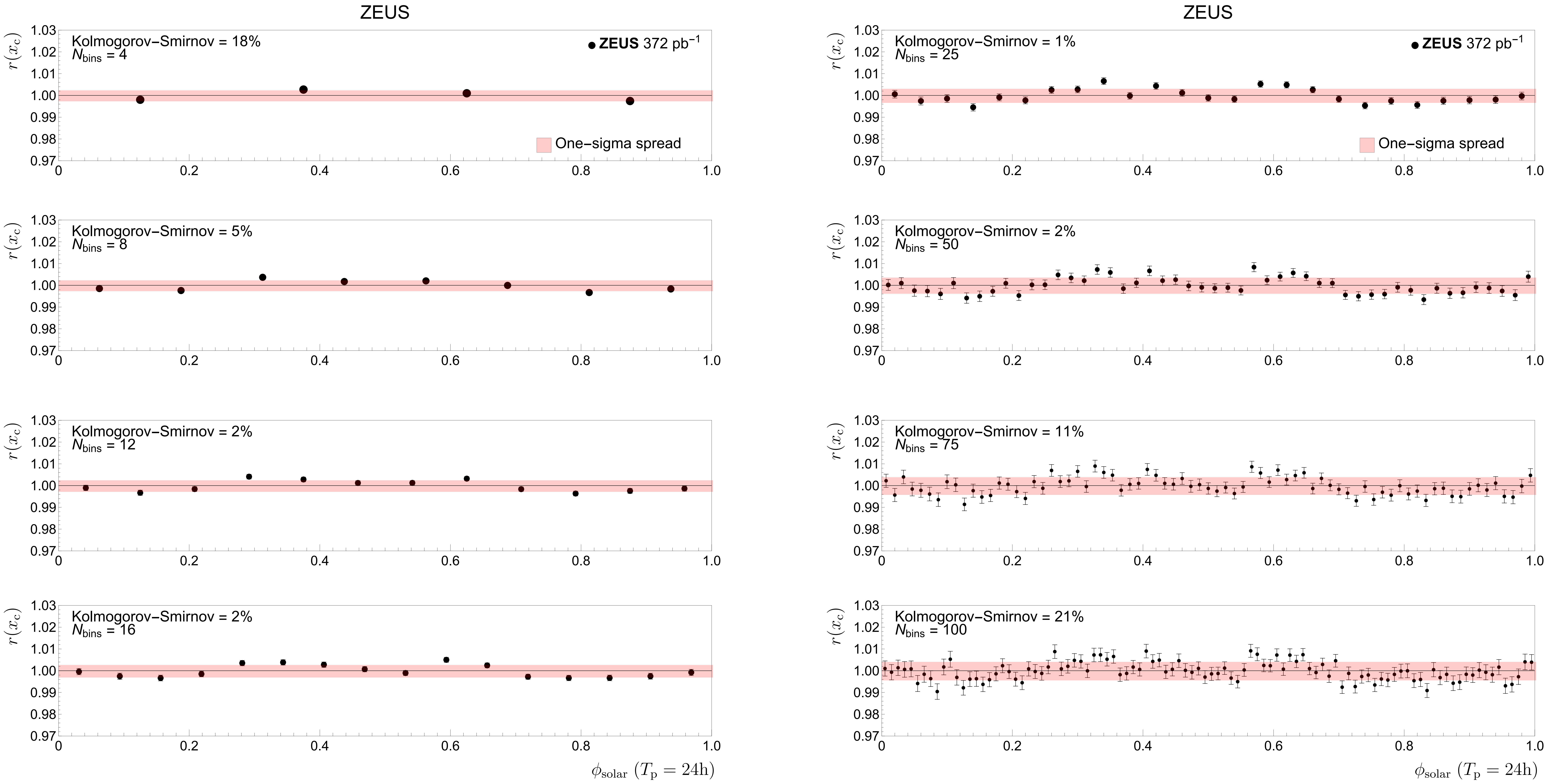


Time dependence of $r(x_c)$: $T = T_{\text{sidereal}}$

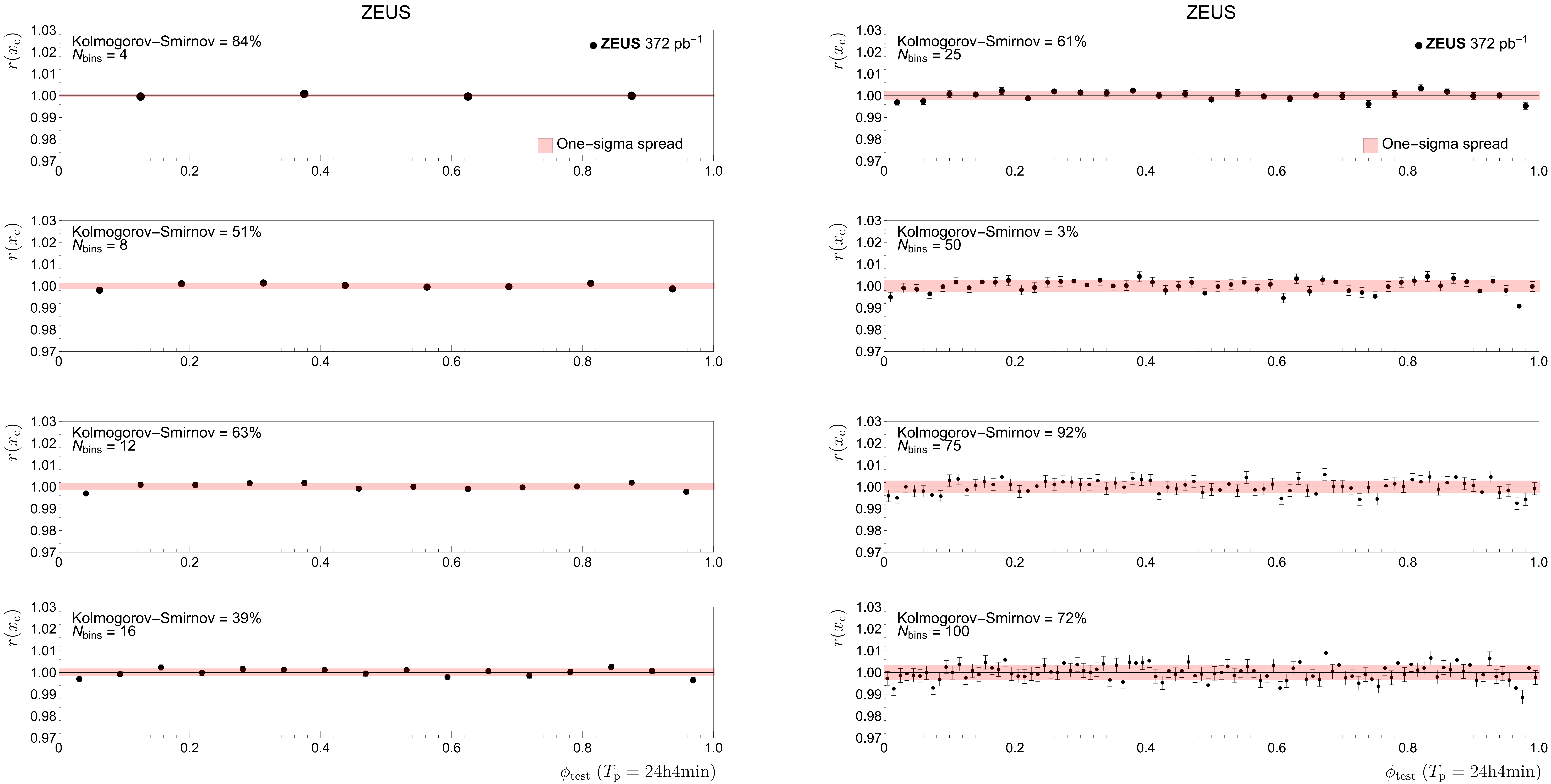




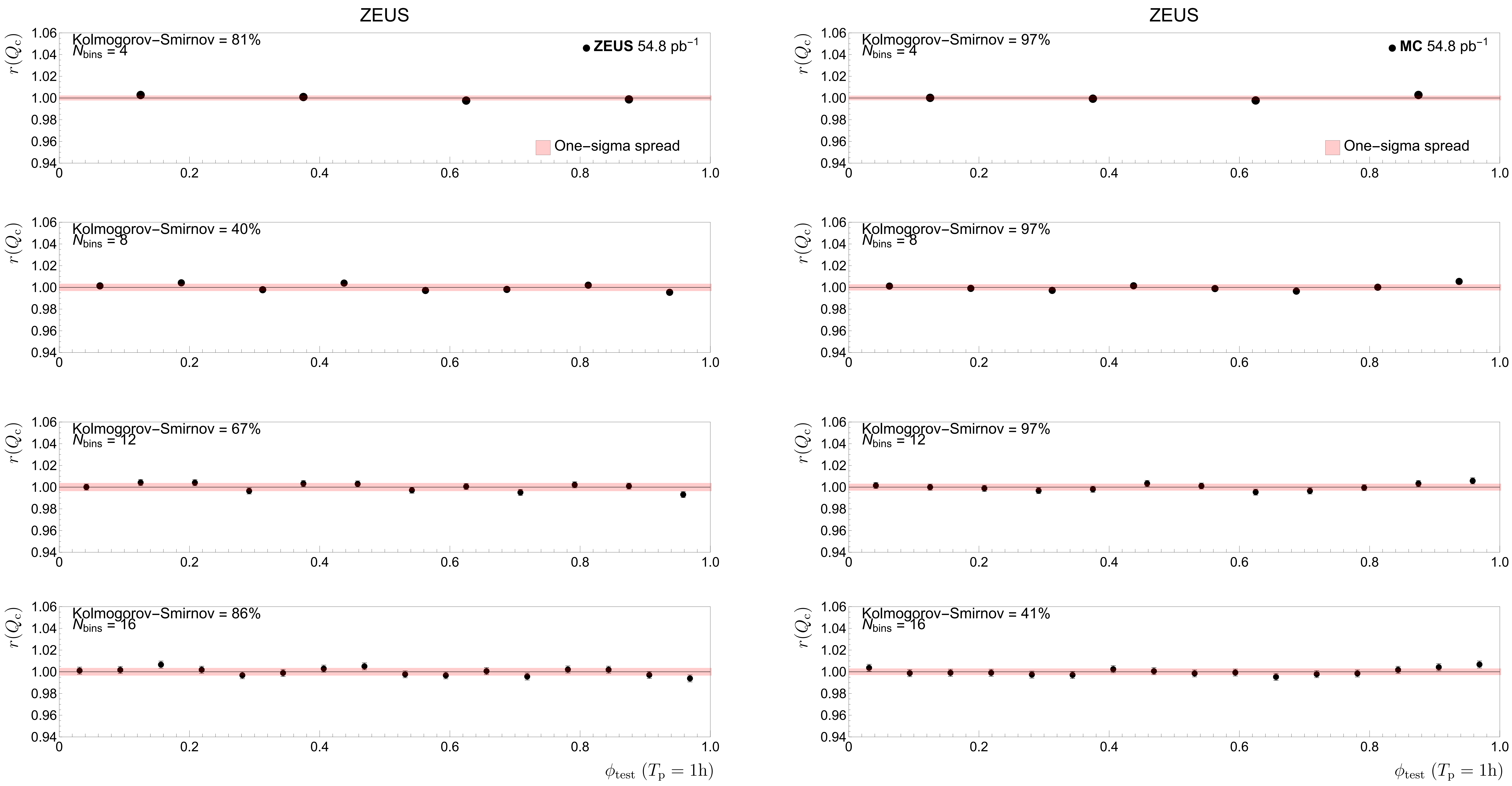
Time dependence of $r(x_c)$: $T = T_{\text{solar}}$



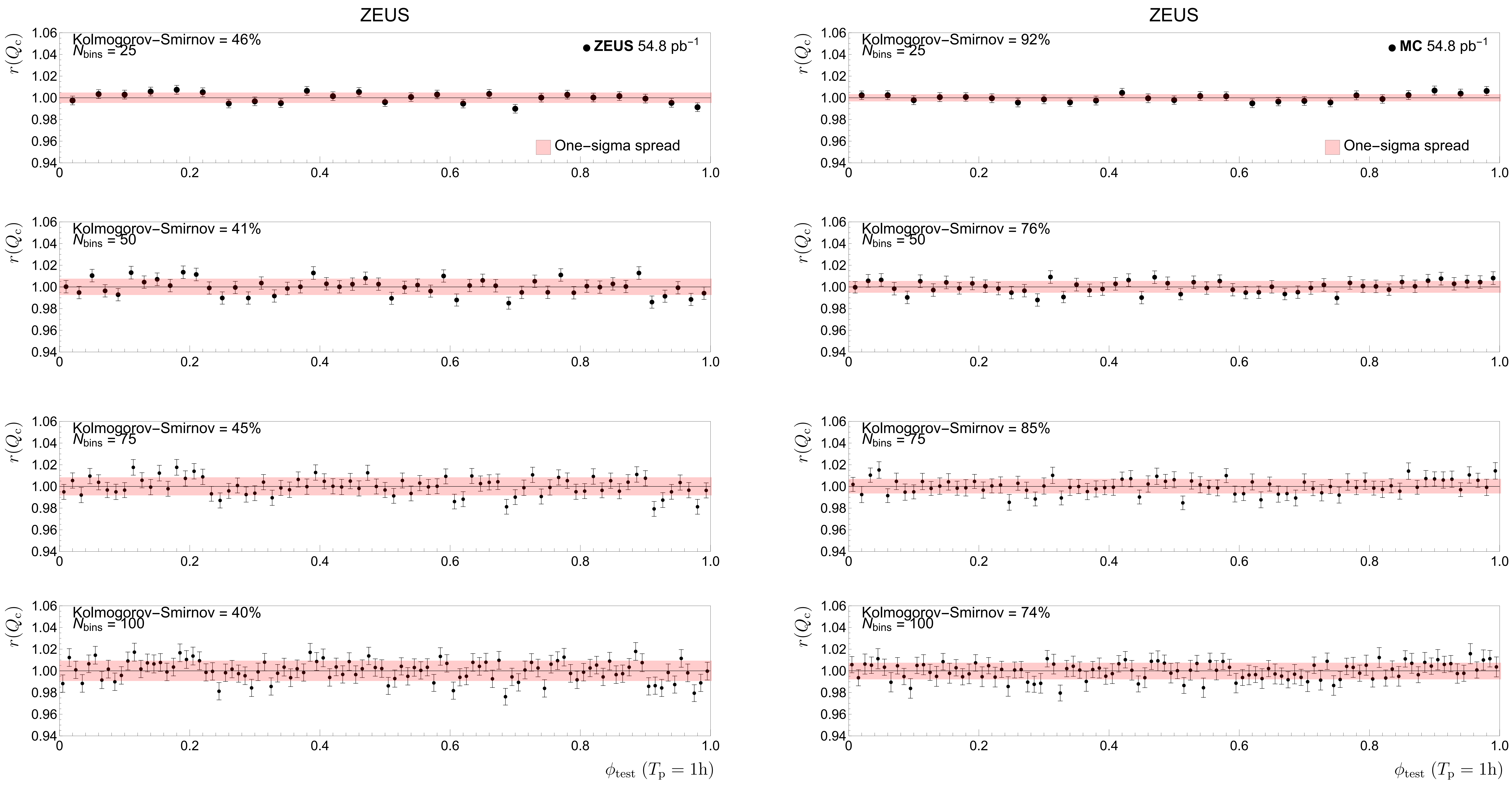
Time dependence of $r(x_c)$: $T = T_{\text{solar}} + 4\text{m}$



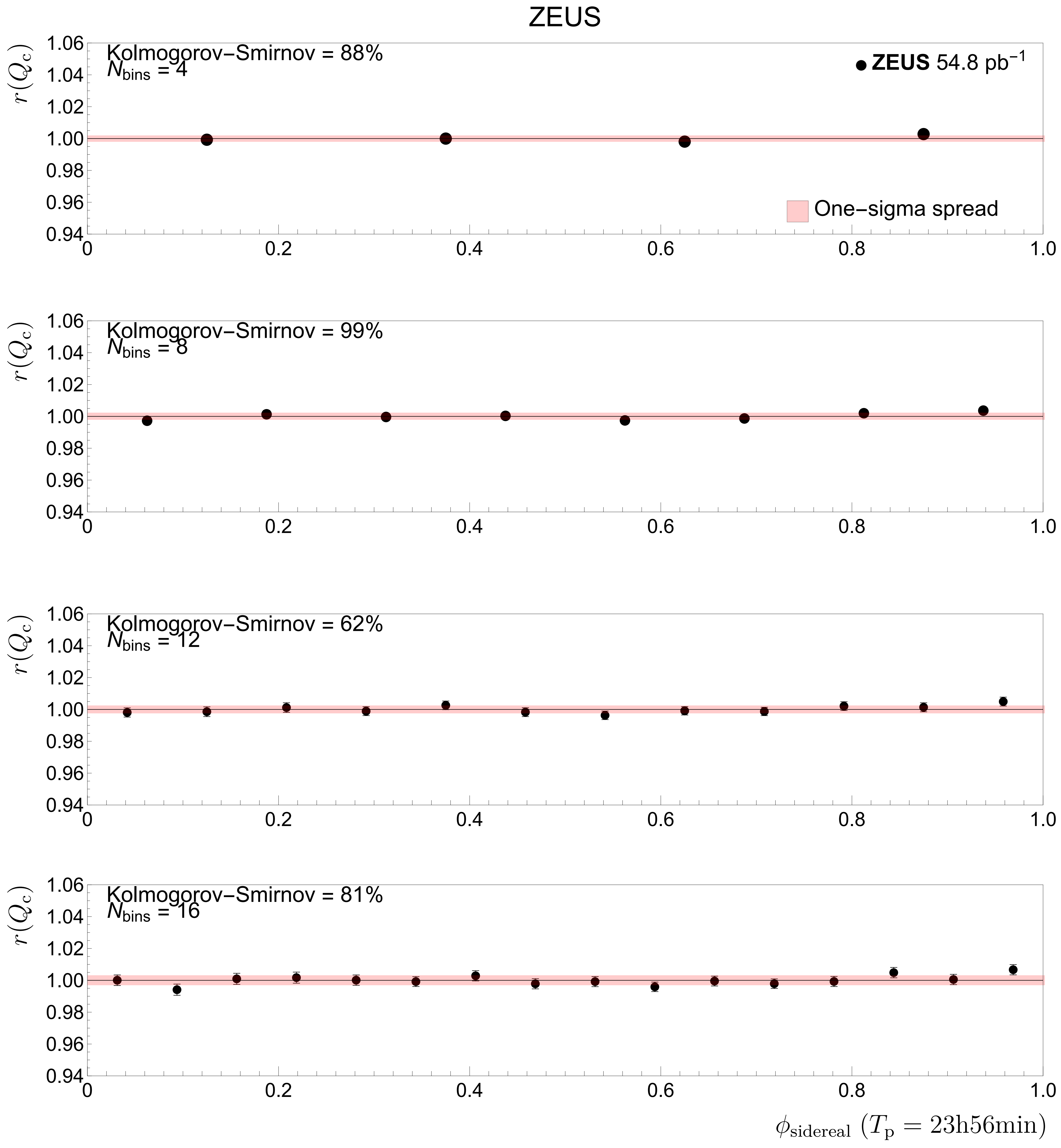
Monte Carlo study for $r(Q_c)$: $T = 1\mathrm{h}$

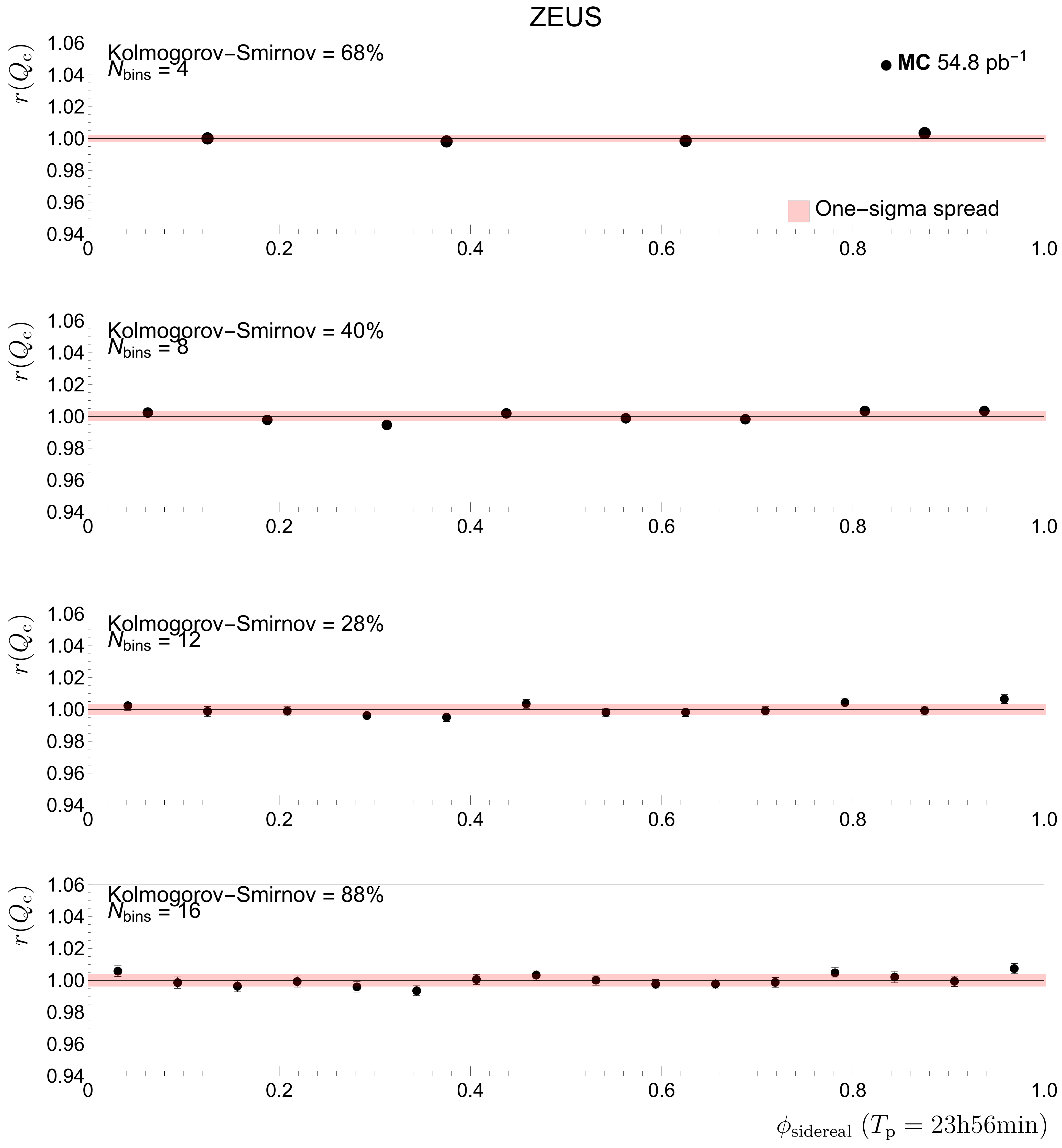


Monte Carlo study for $r(Q_c)$: $T = 1\mathrm{h}$

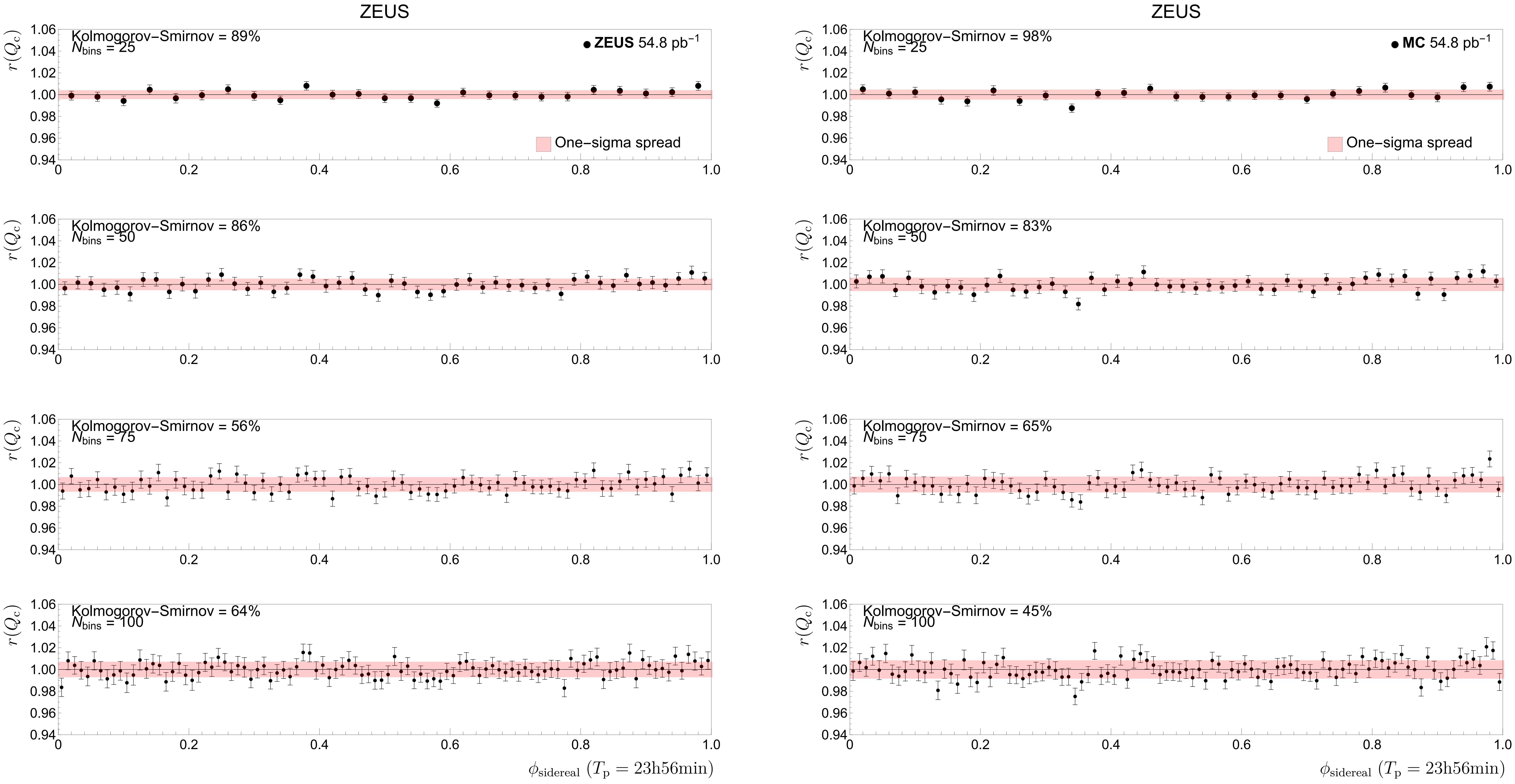


Monte Carlo study for $r(Q_c)$: $T = T_{\text{sidereal}}$

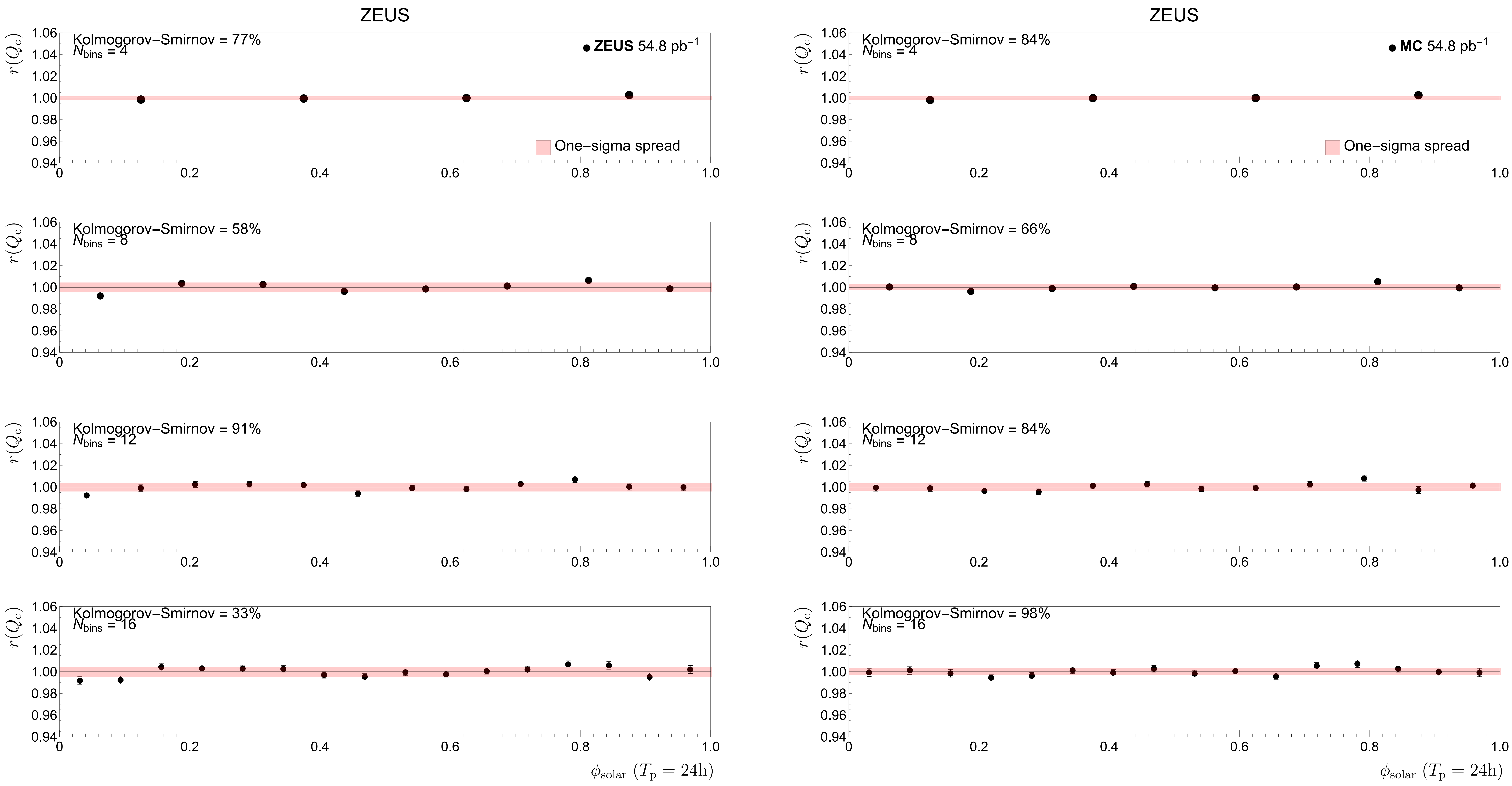




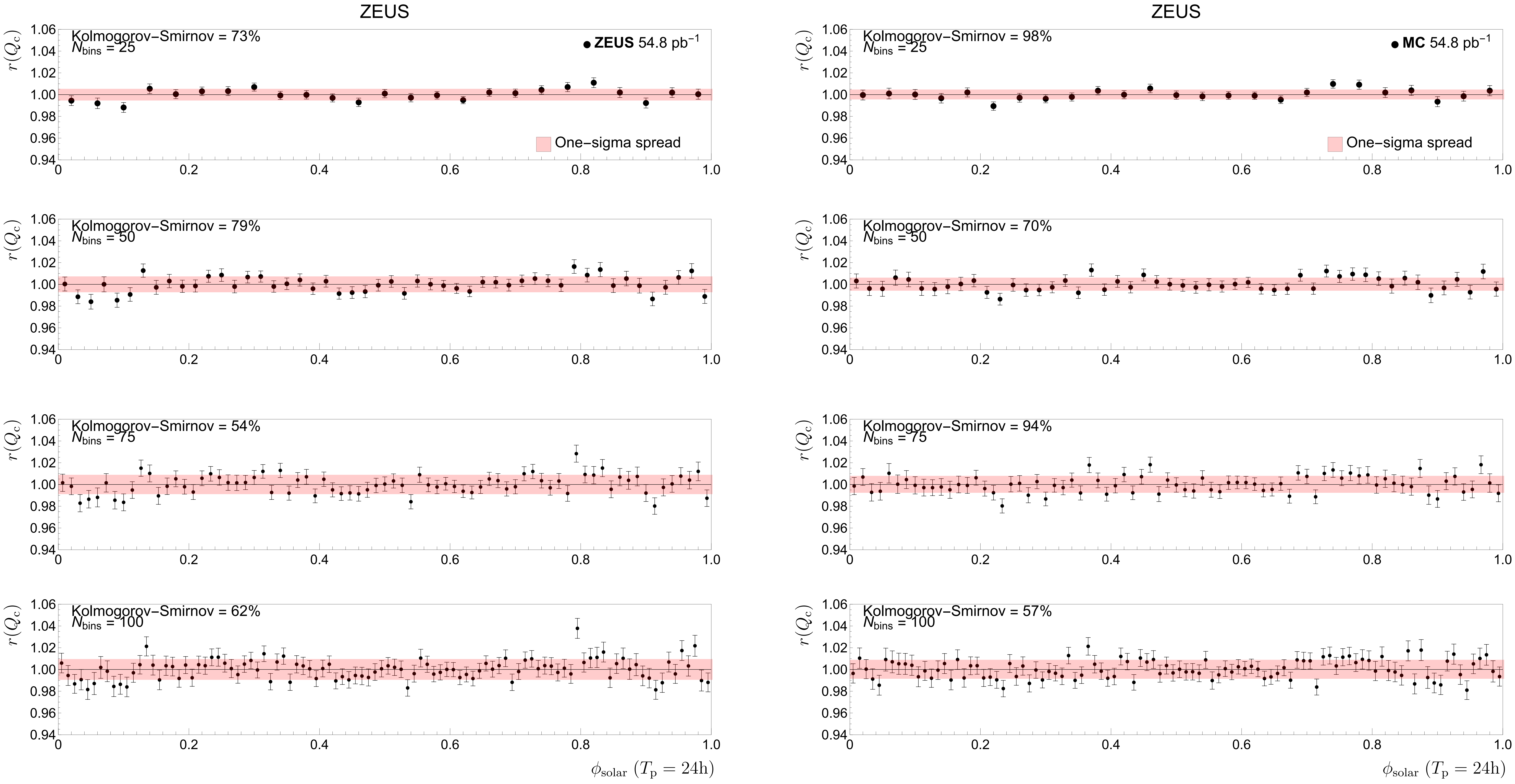
Monte Carlo study for $r(Q_c)$: $T = T_{\mathrm{sidereal}}$



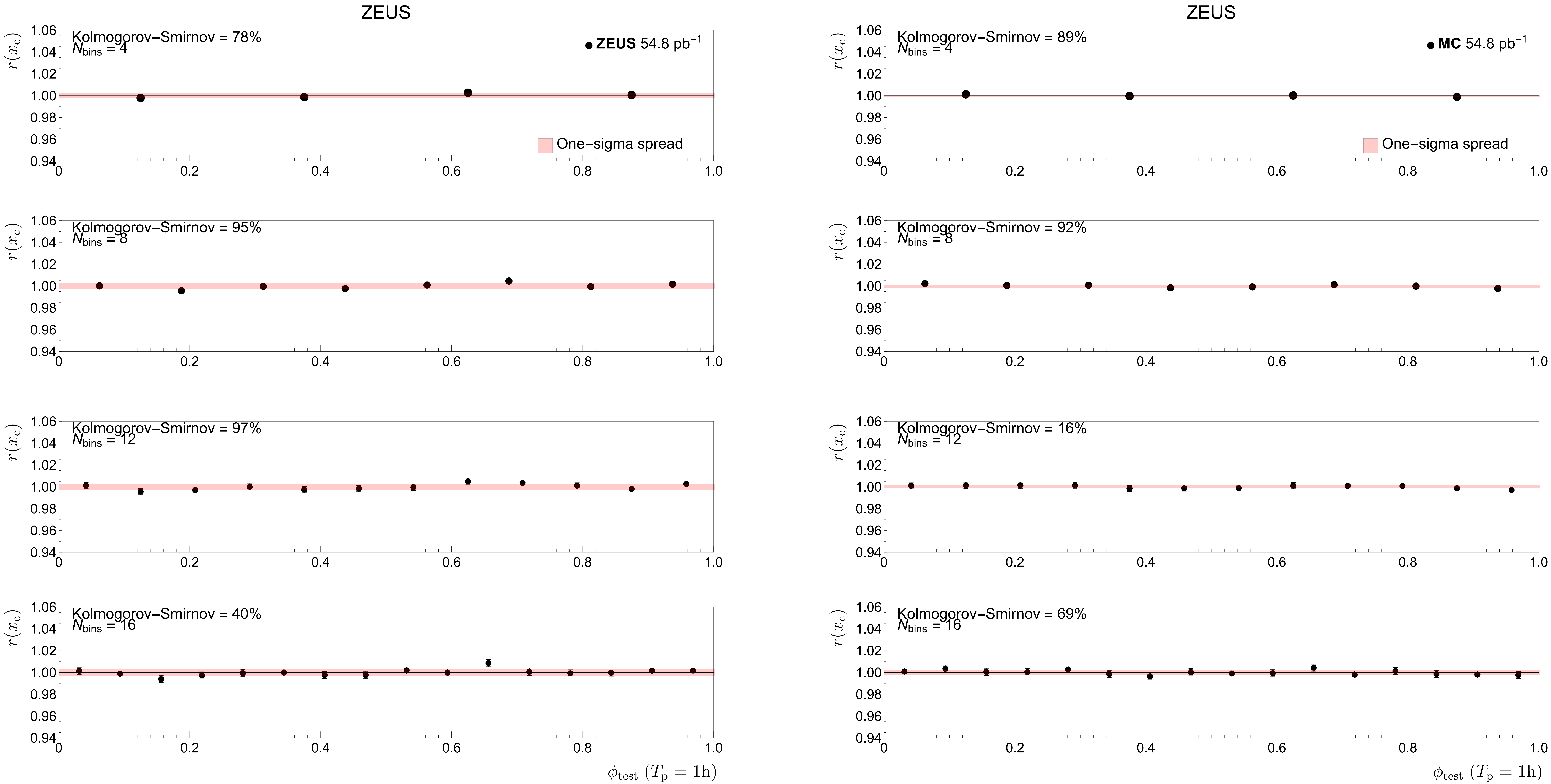
Monte Carlo study for $r(Q_c)$: $T = T_{\text{solar}}$



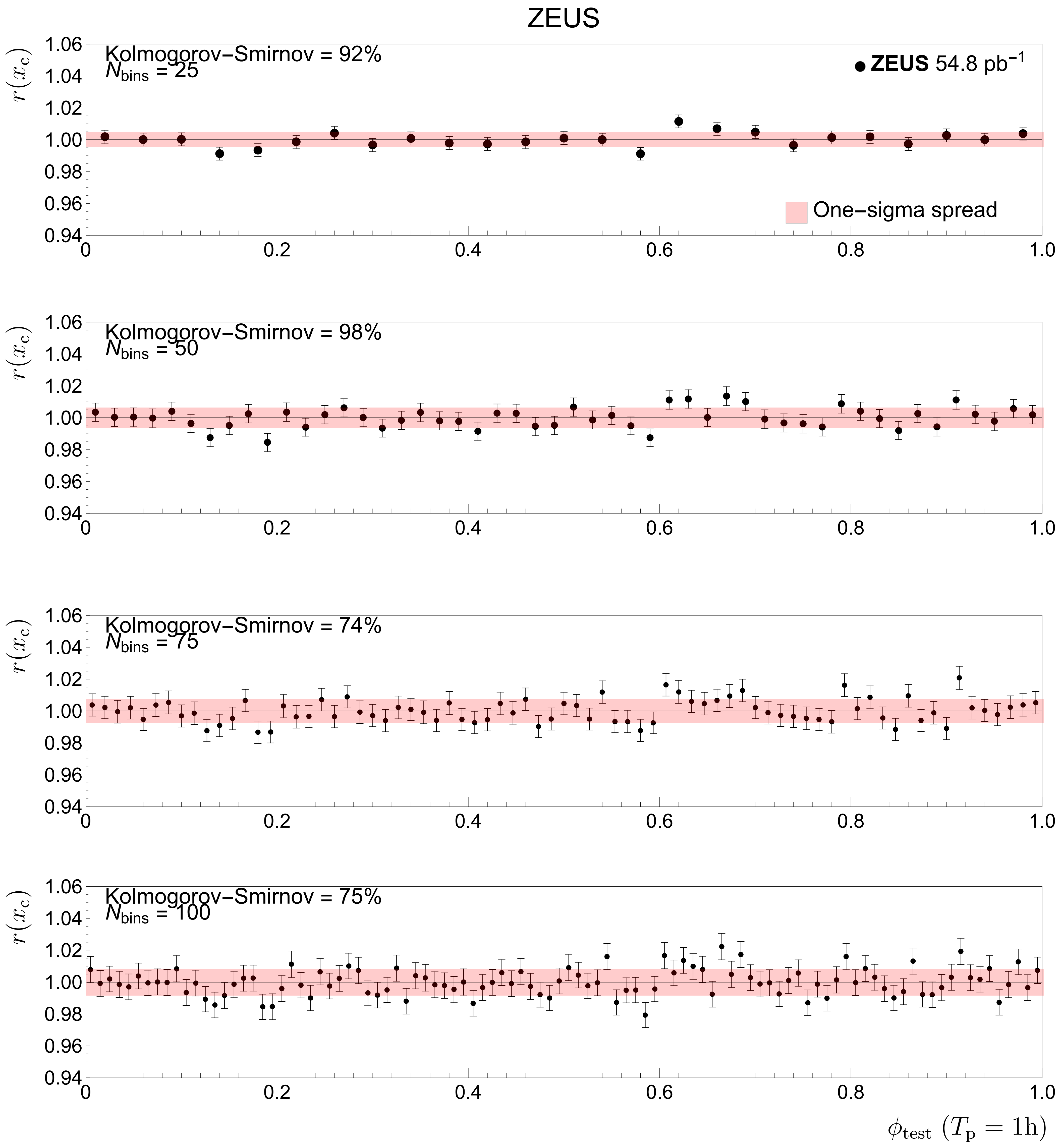
Monte Carlo study for $r(Q_c)$: $T = T_{\text{solar}}$

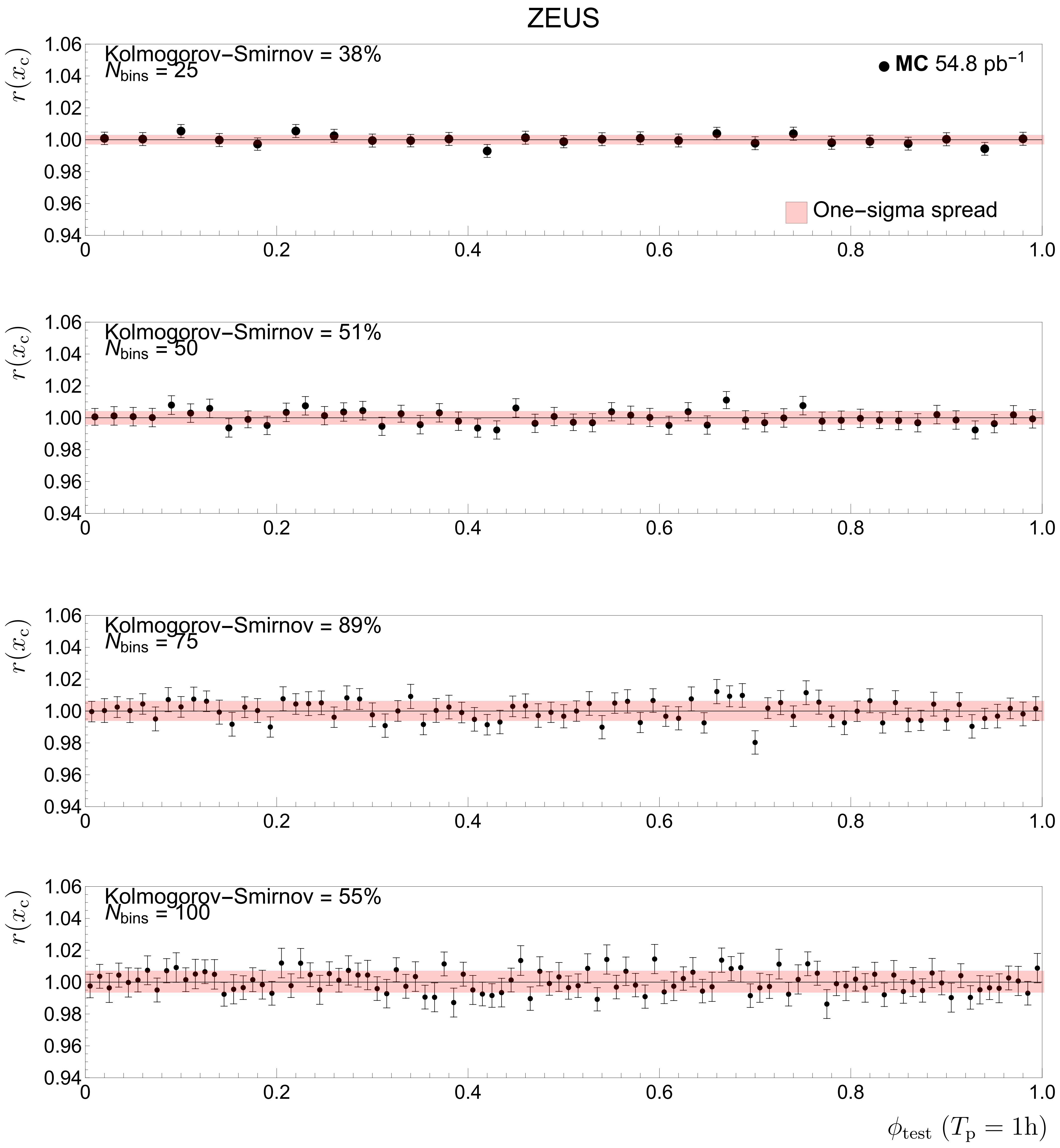


Monte Carlo study for $r(x_c)$: $T = 1\mathrm{h}$

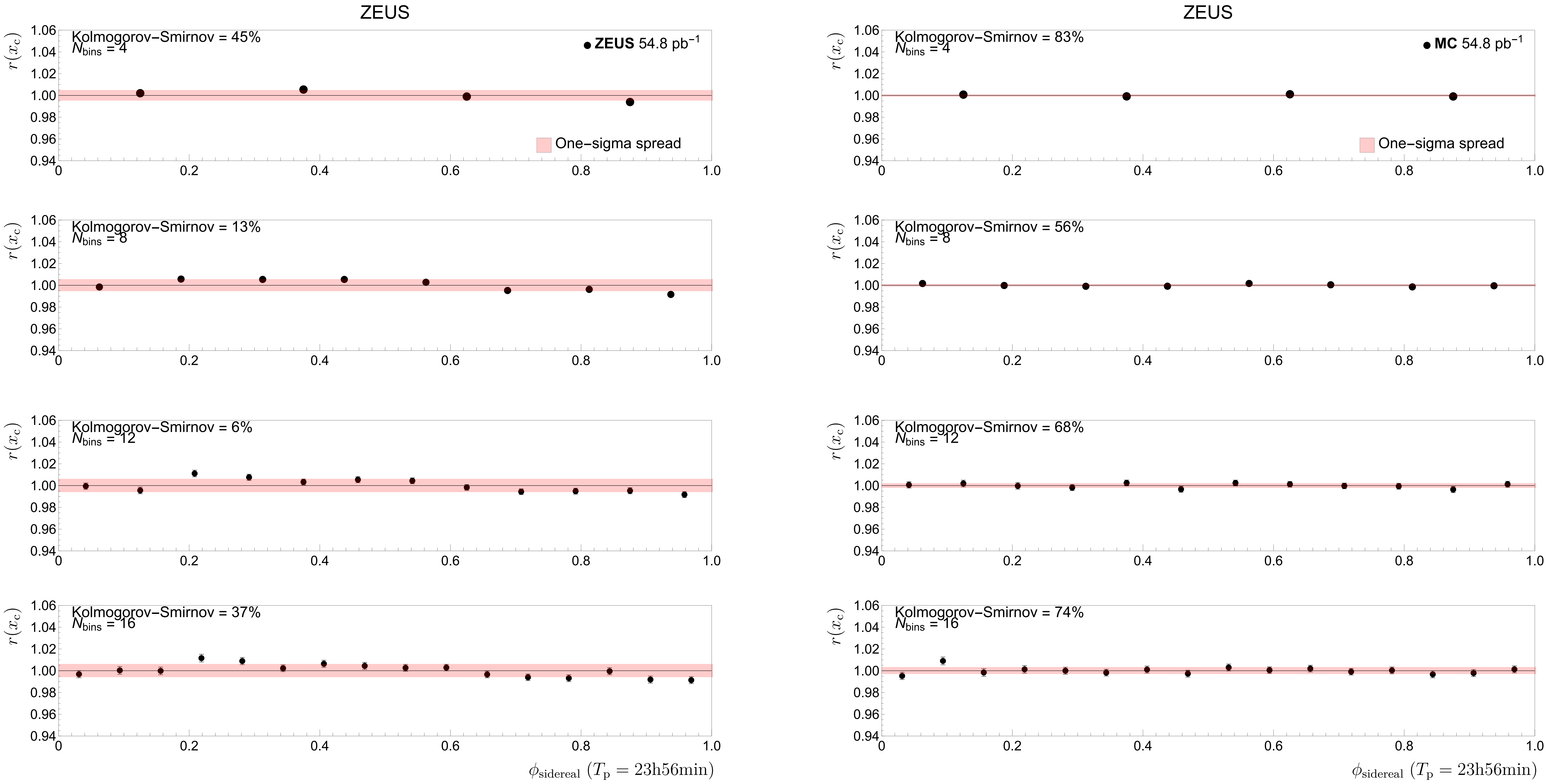


Monte Carlo study for $r(x_c)$: $T = 1\mathrm{h}$

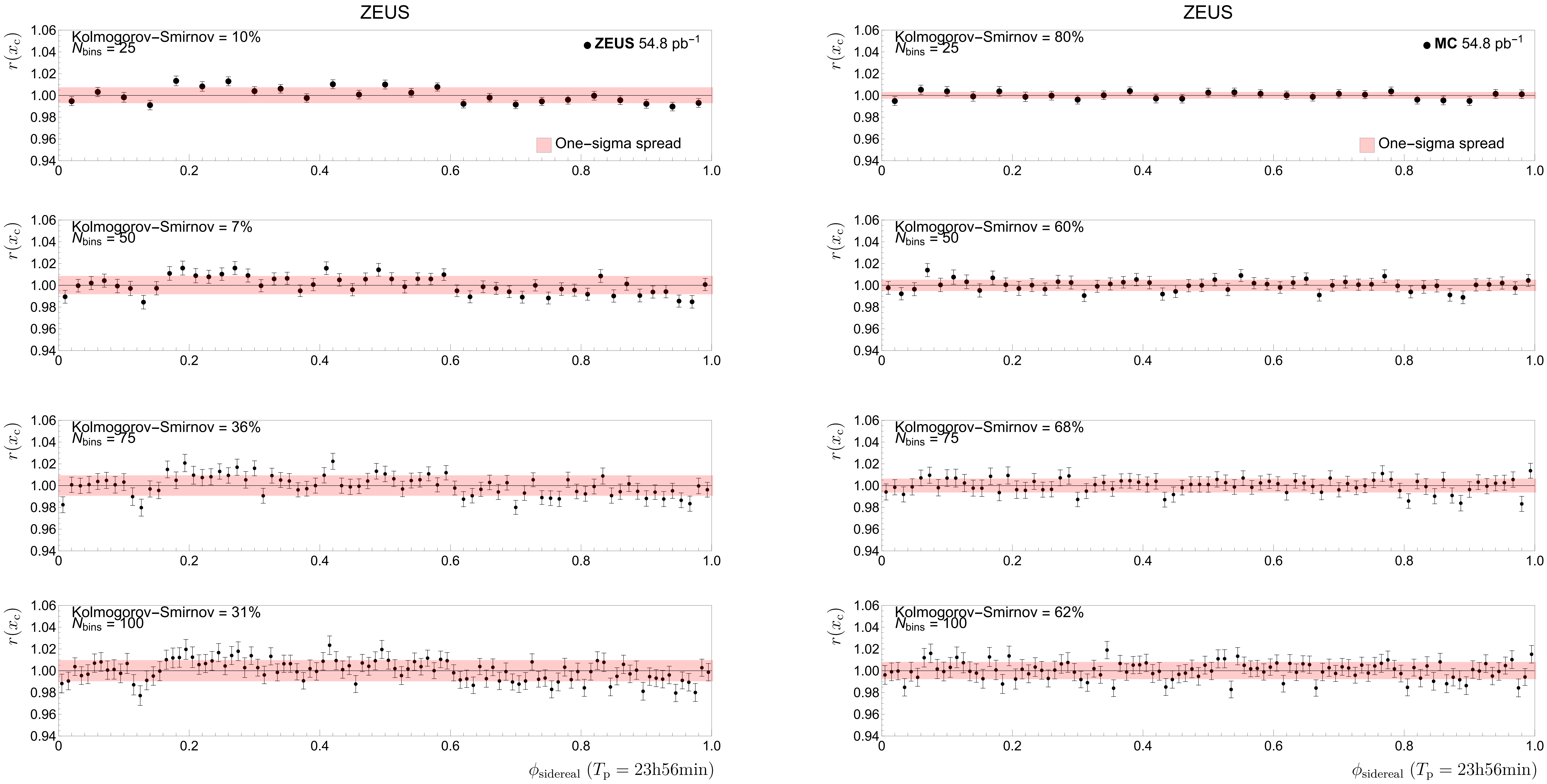




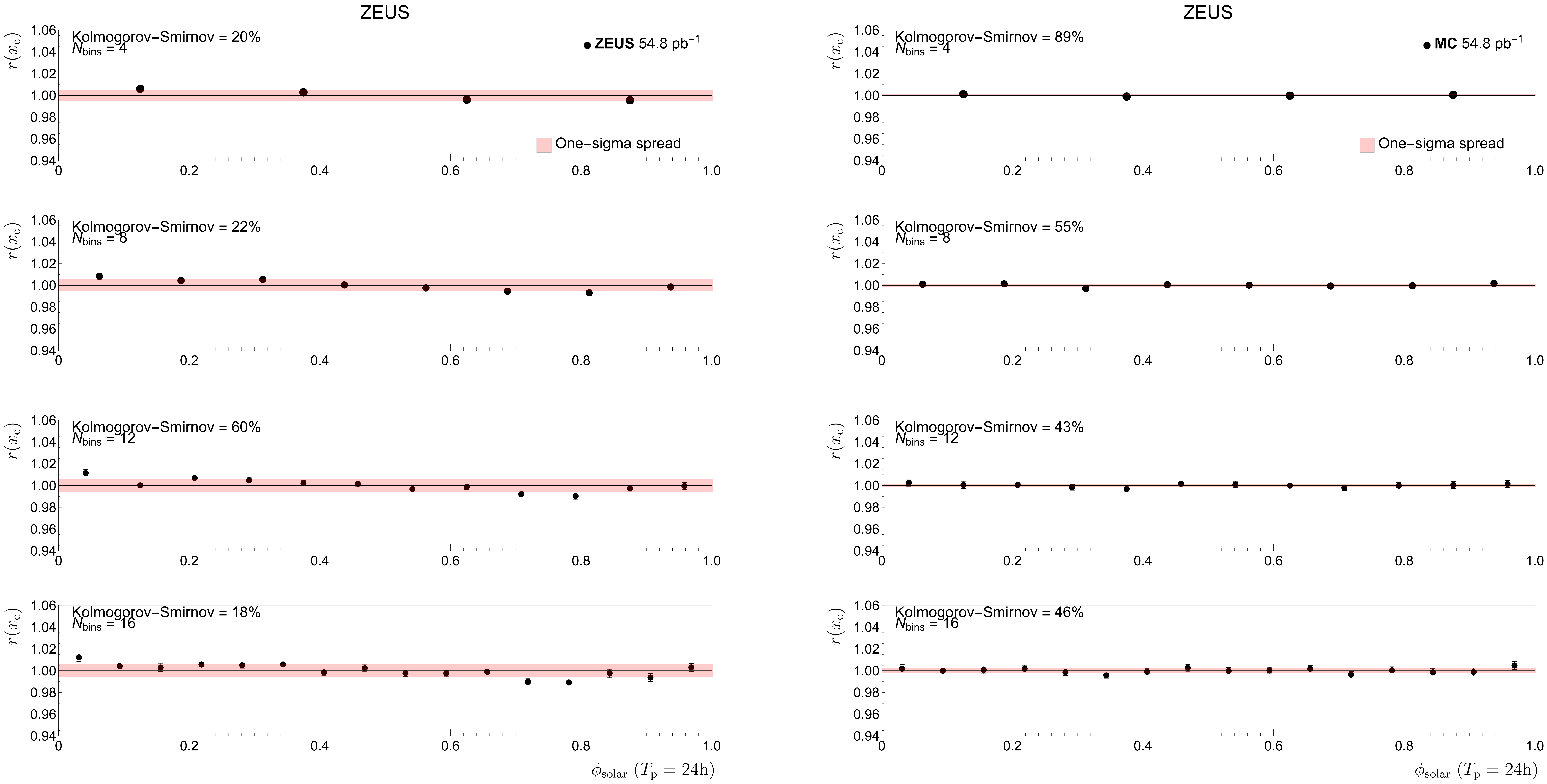
Monte Carlo study for $r(x_c)$: $T = T_{\mathrm{sidereal}}$



Monte Carlo study for $r(x_c)$: $T = T_{\mathrm{sidereal}}$



Monte Carlo study for $r(x_c)$: $T = T_{\text{solar}}$



Monte Carlo study for $r(x_c)$: $T = T_{\rm solar}$