Phenomenological analysis of the scalar PDF

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Higher-twist parton distribution functions

Gluon at low energy, “the glue that binds us all”?

- What are higher-twist distribution functions?
- What information do they encapsulate?
- From low-energy experiments to higher Q^2.

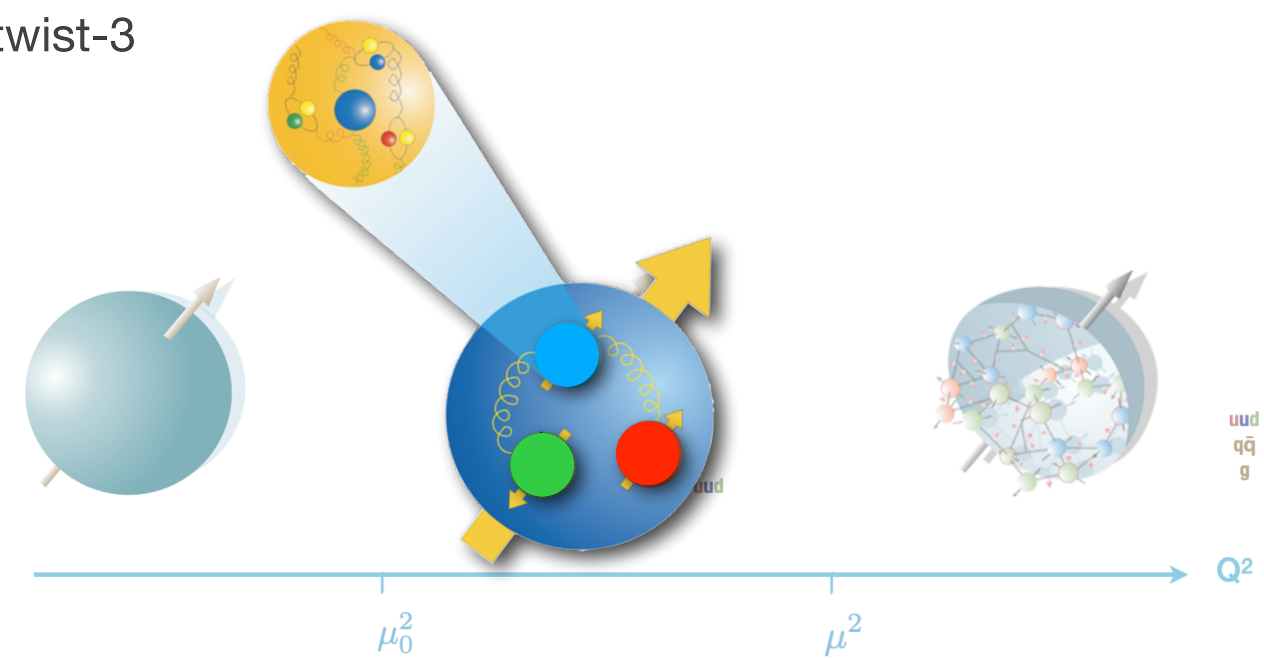
One possible definition for higher-twist contributions: terms effectively suppressed like $(M/Q)^{t-2}$

Fixed Target DIS & SIDIS: M/Q is not so small

- <u>either</u> spurious contaminations
- <u>or</u> spin asymmetries can be defined to be sensitive to twist-3

↓

This talk: extraction of the twist-3 PDF $e(x)$
[2203.14975]



Scalar PDF

The composition of the scalar PDF is worked out through the EoM of QCD:

$$e^q(x) = e^q_{\rm loc}(x) + e^q_{\rm gen}(x) + e^q_{\rm mass}(x)$$

"local" term — originates from singularity

genuine qgq correlation — originates from covariant derivative

quark mass term — originates from kinetic+mass

$$e^q_{\rm loc}(x) = \frac{1}{2M}\int \frac{d\lambda}{2\pi}\, e^{i\lambda x}\langle P|\bar{\psi}_q(0)\psi_q(0)|P\rangle = \frac{\delta(x)}{2M}\langle P|\bar{\psi}_q(0)\psi_q(0)|P\rangle$$

Only observable-related contribution to the proton mass:

the singularity of e(x) is proportional to the pion-nucleon sigma term through sum rules [e.g. Kodaira & Tanaka, PTP, Vol. 101].

[Schweitzer and Efremov, JHEP08006]
[Burkardt & Koike, NPB632]
[Ji, NPB960]
[Lorcé, Pasquini, Schweitzer, JHEP01 (2015)]
[Pasquini & Rodini, PLB788]
[Hatta & Zhao, PRD102]
[Bhattacharya et al., PRD102]

Scalar PDF and the proton mass

QCD mass decomposition

$$M_P = M_m + M_a + M_q + M_g$$

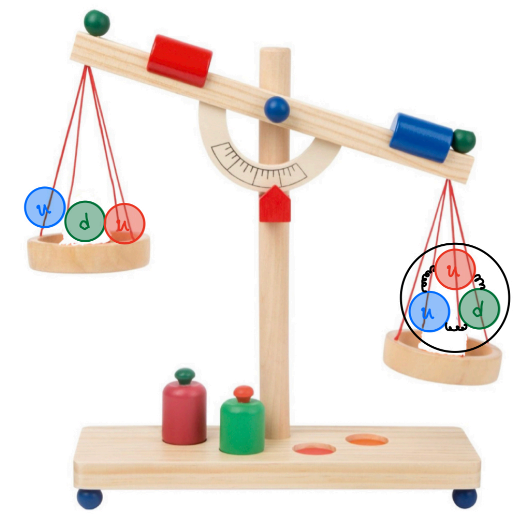
quark mass $M_m = \sum_q \sigma_q$

trace anomaly

quark and gluon energy $\propto < x >_{q,g}$

[Ji, PRL 74; Ji, PRD 52]
[Lorcé, EPJC78; Lorcé et al, 2109.11785]

see talk by Andreas Metz (WG5)

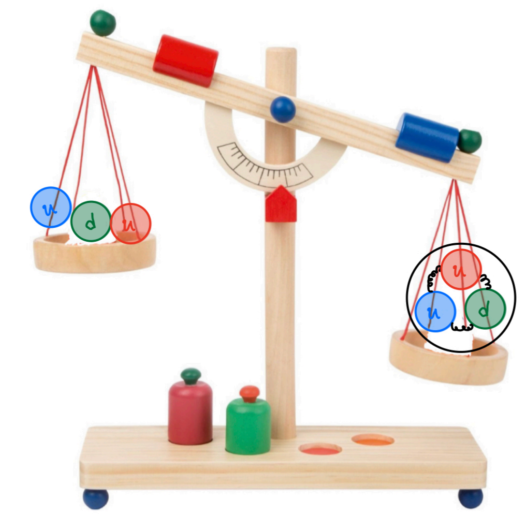


Sigma terms

$$\langle P | m_u \bar{u} u + m_d \bar{d} d | P \rangle = \sigma_{\pi N}$$

- have been determined from theoretical analysis of πN data [Meissner et al.]
- have been evaluated on the lattice [Constantinou et al.]
- pheno analysis of $e(x)$ could pave the way towards another possible determination

Scalar PDF and the proton mass



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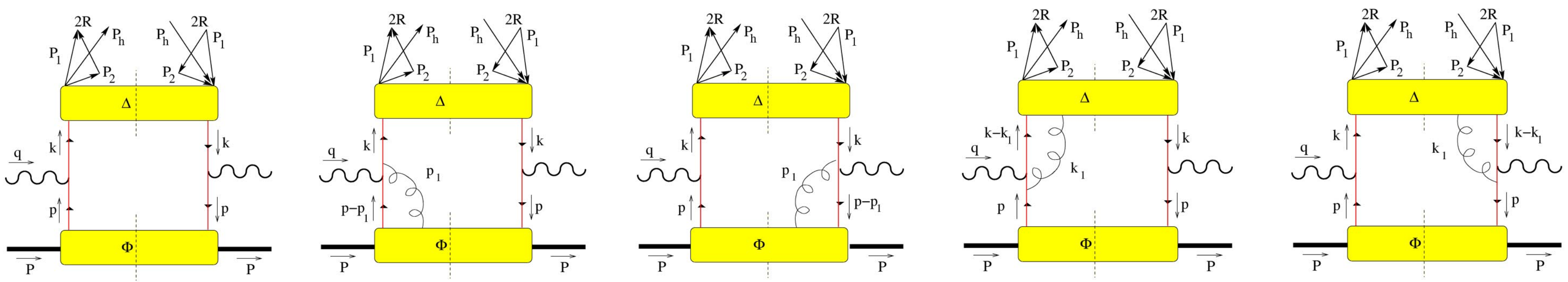
- have been evaluated on the lattice [Constantinou et al.]
- pheno analysis of $e(x)$ could pave the way towards another possible determination
  - can be accessed through single-hadron SIDIS [Efremov et al, PRD67]
  - can be accessed through dihadron SIDIS: **this talk**

Twist-3 in SIDIS dihadron production

[Bacchetta & Radici, PRD69]



- collinear framework — led to collinear transversity extraction [Radici, Jakob & Bianconi, PRD65].

- modulations of spin asymmetries single out:

$$\frac{\left[\text{twist-3 PDF} \times \text{twist-2 FF}\right] + \left[\text{twist-2 PDF} \times \text{twist-3 FF}\right]}{\text{unpolarized}}$$

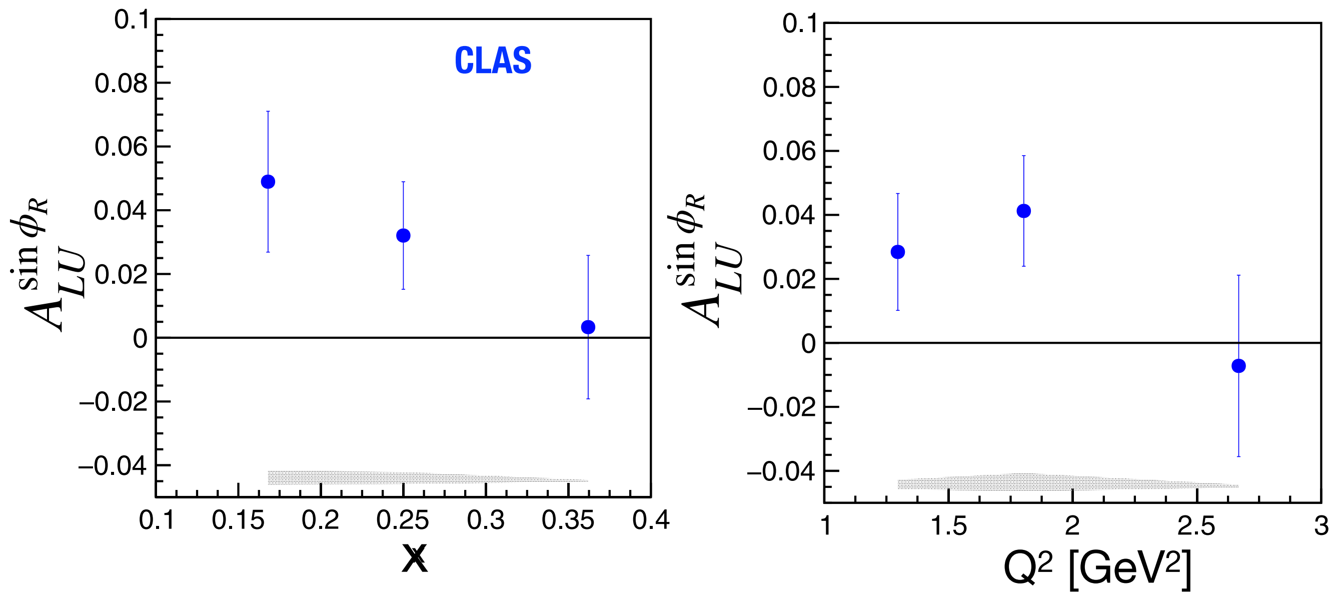
- Scalar PDF from the beam spin asymmetry

$$A_{LU}^{\sin\phi_R}(x, z, m_{\pi\pi}) \propto \frac{M}{Q} \frac{\sum_q e_q^2 \left[x e^q(x)\, H_{1,sp}^{\sphericalangle,q}(z, m_{\pi\pi}) + \frac{m_{\pi\pi}}{zM} f_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z, m_{\pi\pi}) \right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z, m_{\pi\pi})}$$

Beam spin asymmetry at CLAS and CLAS12

- dihadron SIDIS on proton target is sensitive to $e^P \equiv \frac{1}{9}(4\, e^{u_V} - e^{d_V})$;

[Bacchetta & Radici, *PRD*69 (2004)]
[Courtoy, 1405.7659]



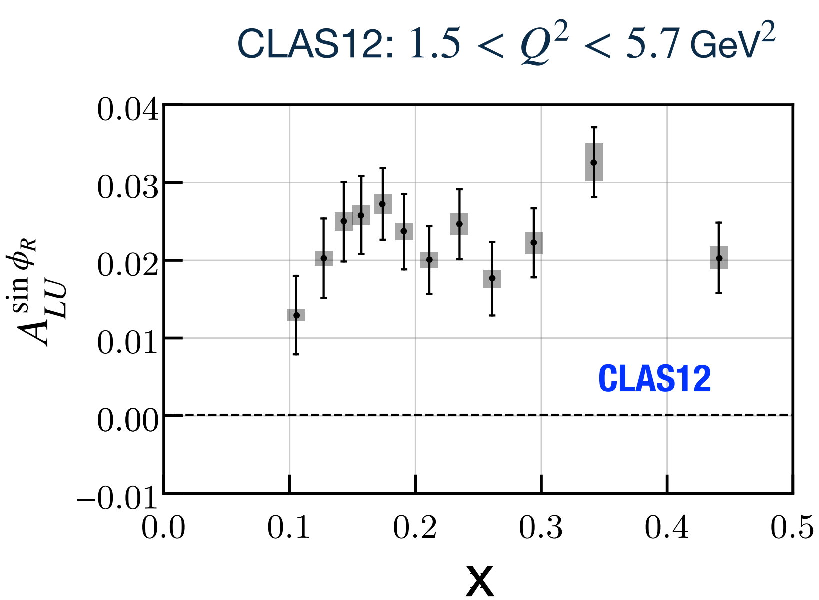
[CLAS Collaboration, PRL126 (2021) 6, 062002]

- non-vanishing twist-3 effects at CLAS12;

- projections of beam spin asymmetries on $(x, z, M_h; Q^2, y)$

  (x, z, M_h)-triptychs from the parton distribution and fragmentation function.

Road map for e(x) extraction and (global) analysis.



[CLAS Collaboration, PRL126 (2021) 152501]

Extraction of $e(x)$ from CLAS data

$$A_{LU}^{\sin\phi_R}(x,z,m_{\pi\pi}) \propto \frac{M}{Q}\frac{\sum_q e_q^2\left[x e^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi}) + \frac{m_{\pi\pi}}{zM}\, f_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi})\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,m_{\pi\pi})}$$

leading-twist DiFFs

Twist-2 Dihadron Fragmentation Functions

- Phenomenologically tested for the twist-2 transversity PDF [Bacchetta, Courtoy & Radici, PRL107 and follow-ups]
- extracted in e^+e^- at Belle here: [Radici, Courtoy, Bacchetta, JHEP 05 (2015)]
- we get the ratio R that is believed to be universal (portable) *up to evolution effects*

$$R(z,M_h) = \frac{|\boldsymbol{R}|}{M_h}\,\frac{H_1^{\sphericalangle\, u}(z,M_h;Q_0^2)}{D_1^u(z,M_h;Q_0^2)}$$

chiral-odd DiFF

unpolarized DiFF

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$\tilde{G}^{\sphericalangle}$ = genuine twist-3

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chiral-odd DiFF

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How to treat twist-3 Dihadron Fragmentation Functions?

Extraction of $e(x)$ from CLAS data

$$A_{LU}^{\sin\phi_R}(x,z,m_{\pi\pi}) \propto \frac{M}{Q}\frac{\sum_q e_q^2\left[xe^q(x)\,H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi}) + \frac{m_{\pi\pi}}{zM}\,f_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi})\right]}{\sum_q e_q^2\,f_1^q(x)\,D_{1,ss+pp}^q(z,m_{\pi\pi})}$$

leading-twist DiFFs

$\tilde{G}^{\sphericalangle} = \text{genuine twist-3}$

Twist-3 Dihadron Fragmentation Functions

- Unknown phenomenologically;
- Model evaluations for genuine twist-3 DiFF: $\tilde{D}^{\sphericalangle}$ [Luo et al.,PRD100], $\tilde{G}^{\sphericalangle}$ [Yang et al., PRD99]
- Estimate of Interference FF through the asymmetries on longitudinally-polarized target at COMPASS

[Sirtl, PhD thesis, 2017]

$$A_{UL}^{\sin(\phi_R)} = -\frac{M}{Q}\frac{|\boldsymbol{R}|}{M_h}\frac{\sum_q e_q^2\left[xh_L^q(x)H_1^{\angle q,sp}(z,M_h^2) + \frac{M_h}{Mz}g_1^q(x)\tilde{G}^{\angle q,sp}(z,M_h^2)\right]}{\sum_q e_q^2 f_1^q(x)D_1^{q,ss+pp}(z,M_h^2)}$$

$$A_{LL}^{\cos(\phi_R)} = \frac{M}{Q}\frac{|\boldsymbol{R}|}{M_h}\frac{\sum_q e_q^2\left[xe_L^q(x)H_1^{\angle q,sp}(z,M_h^2) - \frac{M_h}{Mz}g_1^q(x)\tilde{D}^{\angle q,sp}(z,M_h^2)\right]}{\sum_q e_q^2 f_1^q(x)D_1^{q,ss+pp}(z,M_h^2)}.$$

$$A_{UL}^{\sin(\phi_R)} = 0.0050 \pm 0.0010(\text{stat}) \pm 0.0007(\text{sys}).$$

$$A_{LL}^{\cos(\phi_R)} = -0.0135 \pm 0.0064(\text{stat}) \pm 0.0046(\text{sys}).$$

$\Rightarrow |A_{LL}^{\cos\phi_R}| >> A_{UL}^{\sin\phi_R}$

Twist-3 dihadron fragmentation functions: COMPASS

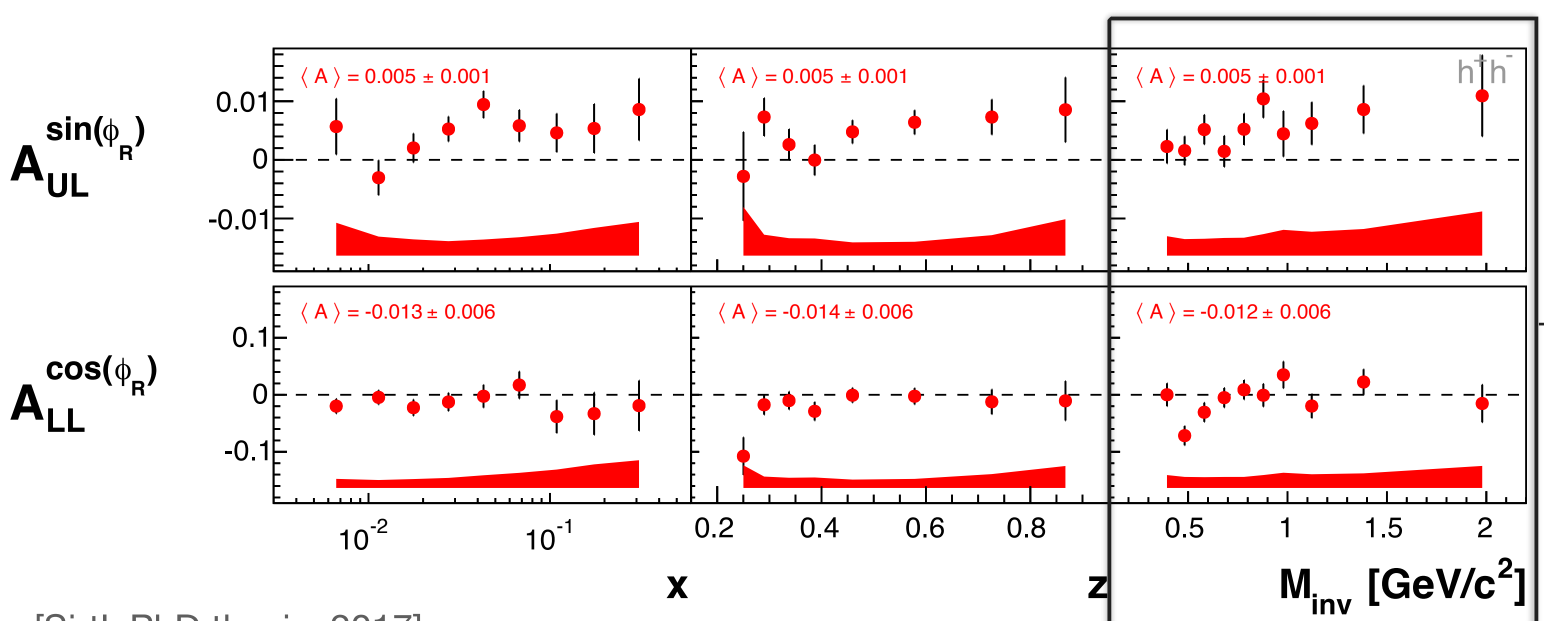
Can we understand $|A_{LL}^{\cos\phi_R}| >> A_{UL}^{\sin\phi_R}$ in the usual approximations?

Can we single out twist-3 DiFFs through this approximation?

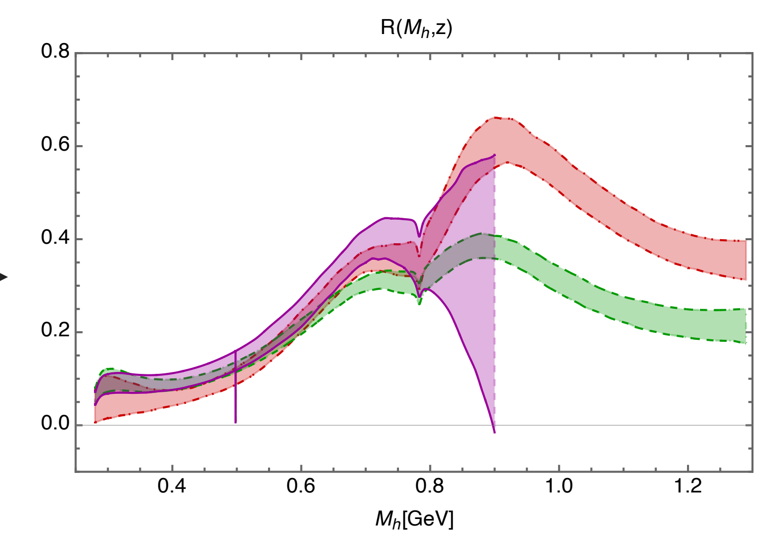
$$A_{LL}^{\cos\phi_R} \stackrel{?}{=} -\frac{M}{Q}\frac{|\mathbf{R}|}{M}\frac{\sum_q e_q^2 g_1(x)/z\,\tilde{D}^{\sphericalangle}}{\sum_q e_q^2 f_1(x) D_1}$$

Our goal here is to find a proportionality factor κ such that

$$\max\left\{\int \tilde{G}^{\sphericalangle}\right\} \equiv \int \tilde{D}^{\sphericalangle} = \kappa \int \tilde{H}_1^{\sphericalangle}$$



[Sirtl, PhD thesis, 2017]



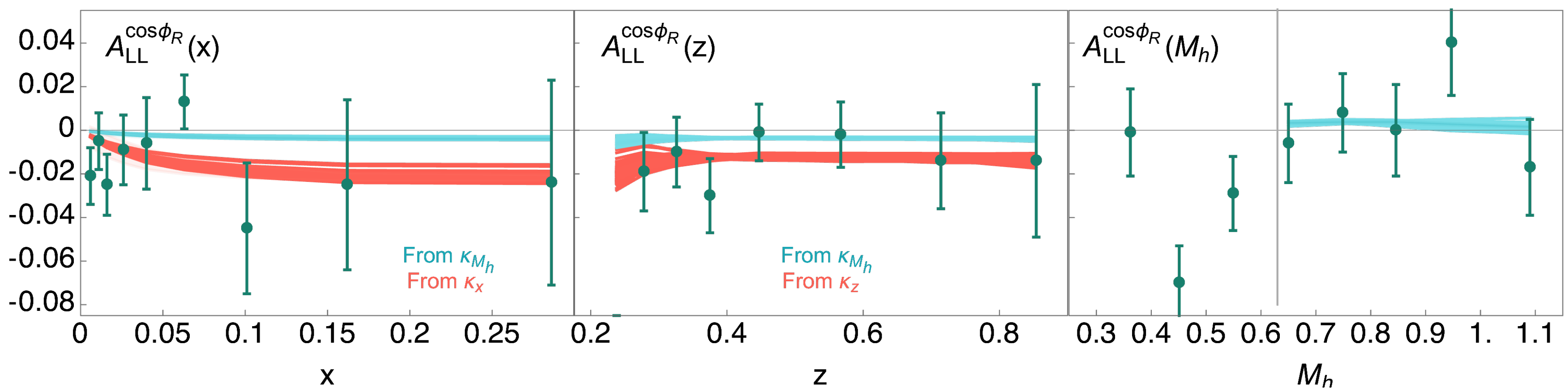
[Radici, AC, Bacchetta, *JHEP* 05 (2015)]

Our ansatz for the twist-3 DiFF contribution

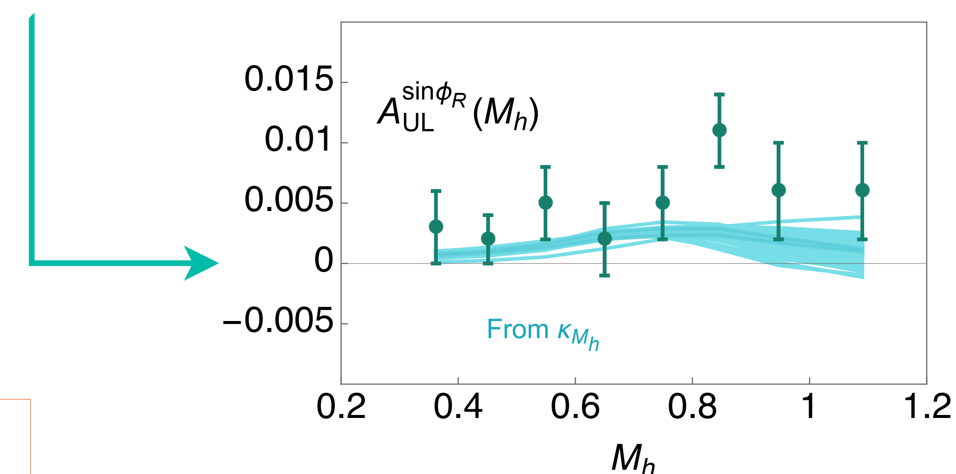
- CLAS12: split invariant-mass regions $M_h >$ or < 0.63 GeV to pinpoint vector meson contributions
- We assume the trend of all interference DiFFs in the invariant mass is similar for $M_h > 0.63$ GeV (up to overall sign)

  $\Rightarrow$ supported by model evaluation of $\tilde{D}^{\sphericalangle}$ and $\tilde{G}^{\sphericalangle}$

- Reproducing $A_{LL}^{\cos\phi_R}$ in that range sets our upper bound to $\kappa \Rightarrow \kappa_{M_h}$



- κ_{M_h} reproduces the order of magnitude for $A_{UL}^{\sin\phi_R}$ adequately



Invariant-mass behavior is key, twist-2 DiFFs alone not enough to interpret all M_h -projected twist-3 asymmetries.

Point-by-point e(x) from CLAS data

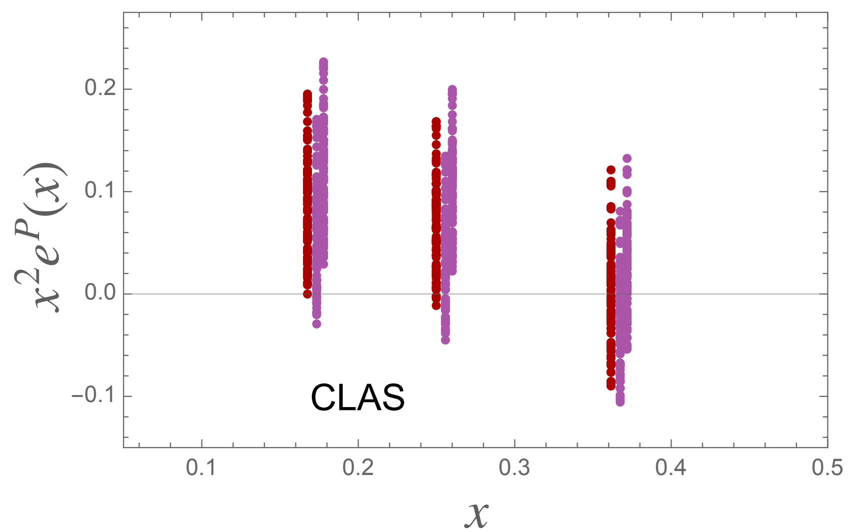
[Courtoy, 1405.7659]
[Courtoy, Miramontes, Avakian, Mirazita, Pisano, 2203.14975]

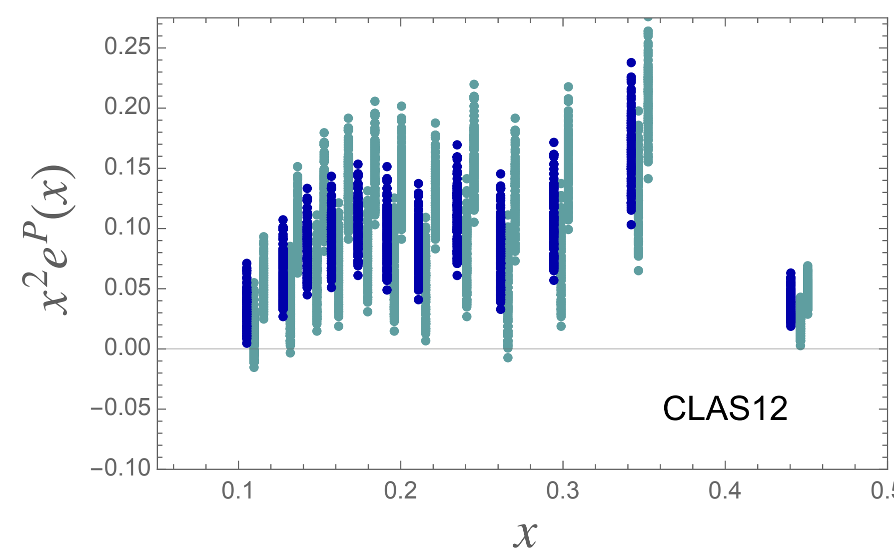
- <u>Scenario I:</u> Wandzura-Wilczek approximation

$$\frac{e^V(x)}{f_1^\Sigma(x)} \frac{\tilde{H}_1^\sphericalangle}{D_1} \propto \frac{Q}{M} A_{LU}^{\sin\phi_R}$$

- <u>Scenario II:</u> beyond WW approximation

$$\frac{e^V(x)}{f_1^\Sigma(x)} \frac{\tilde{H}_1^\sphericalangle}{D_1} \propto \frac{Q}{M} A_{LU}^{\sin\phi_R} \pm \kappa \frac{f_1^V(x)}{f_1^\Sigma(x)} \frac{\tilde{H}_1^\sphericalangle}{D_1}$$





Evolution omitted thanks to low-Q^2 values —Q=1GeV

Uncertainty on unpolarized PDF taken into account

Sign of twist-3 DiFFs undetermined

Point-by-point e(x) from CLAS data

[Courtoy, 1405.7659]
[Courtoy, Miramontes, Avakian, Mirazita, Pisano, 2203.14975]

- **Scenario I:** Wandzura-Wilczek approximation

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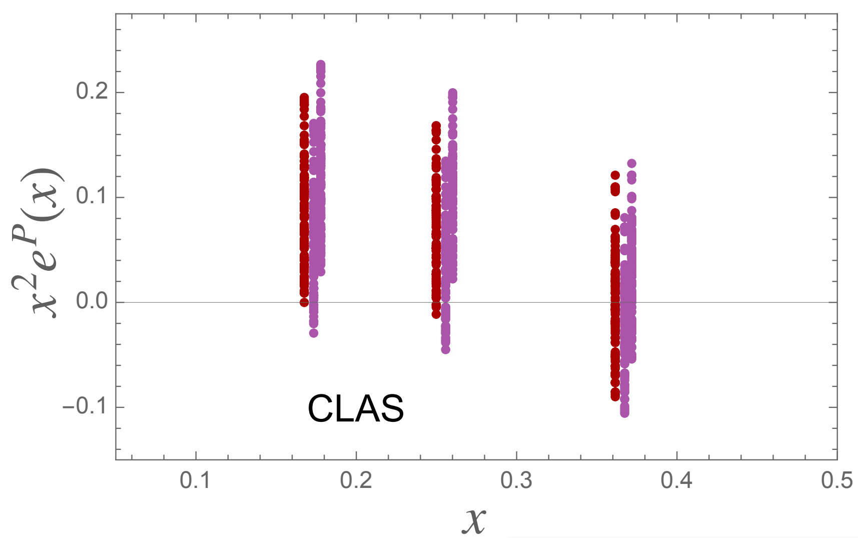
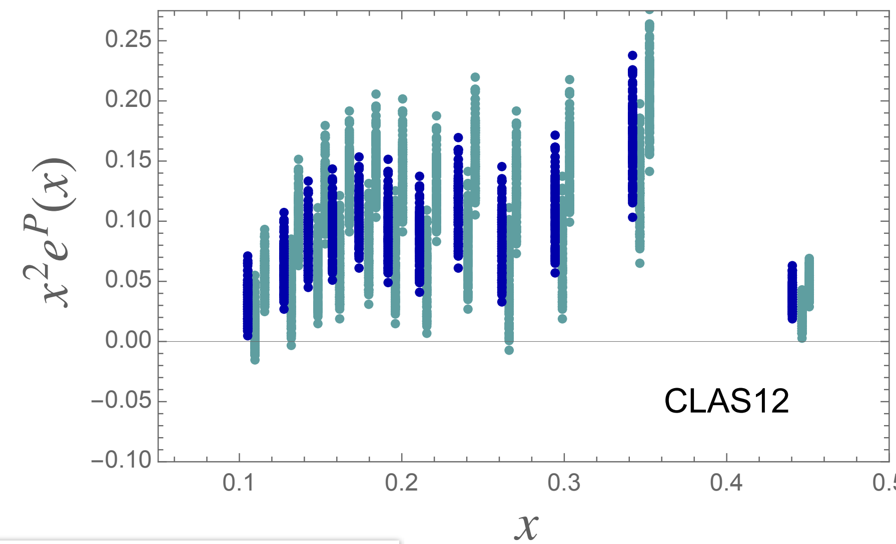
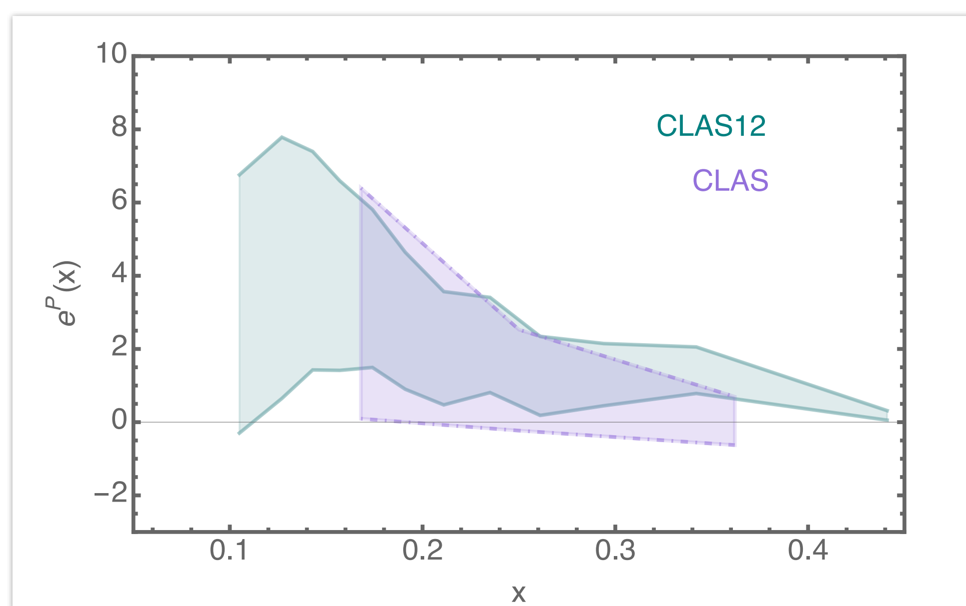


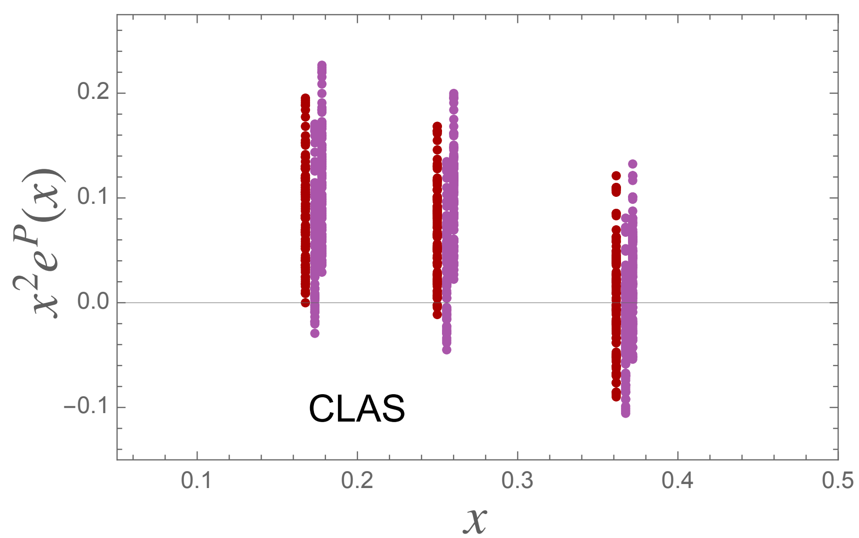


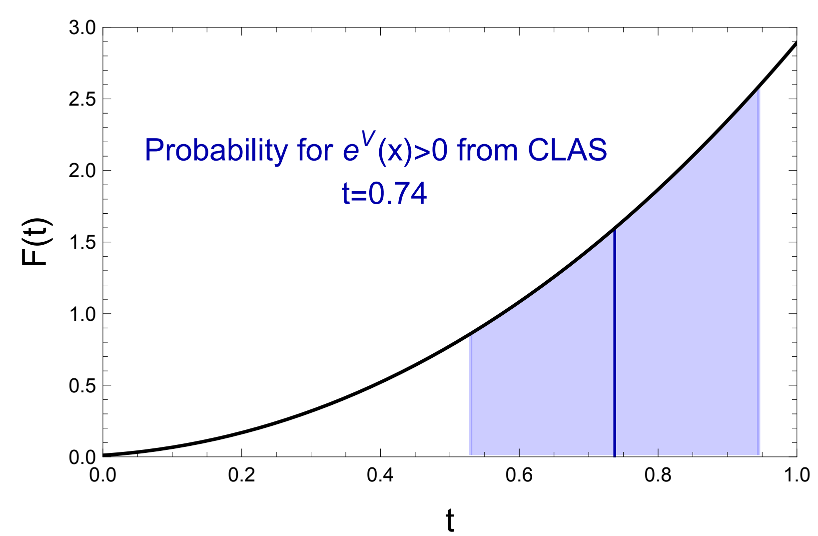
Combined uncertainty at 90% CL



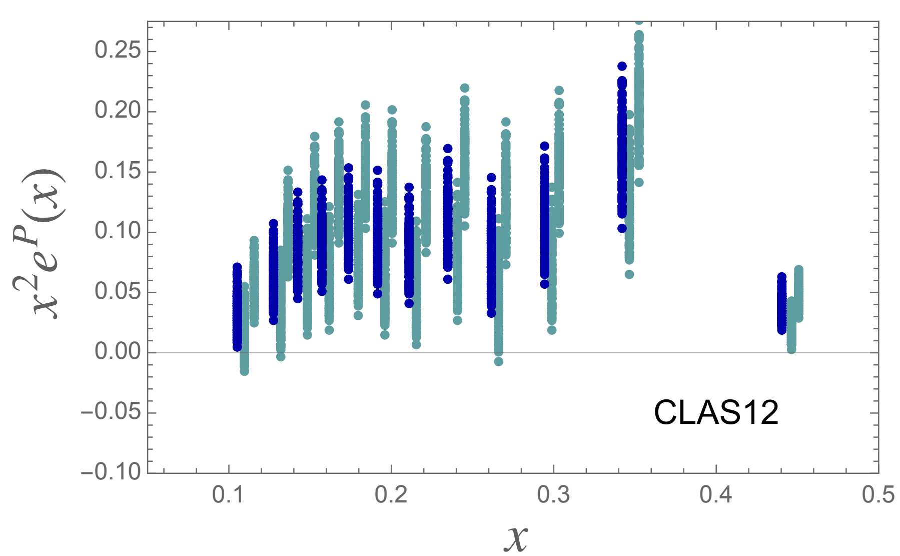
What is the probability for $e^P(x)$ to be non-zero?

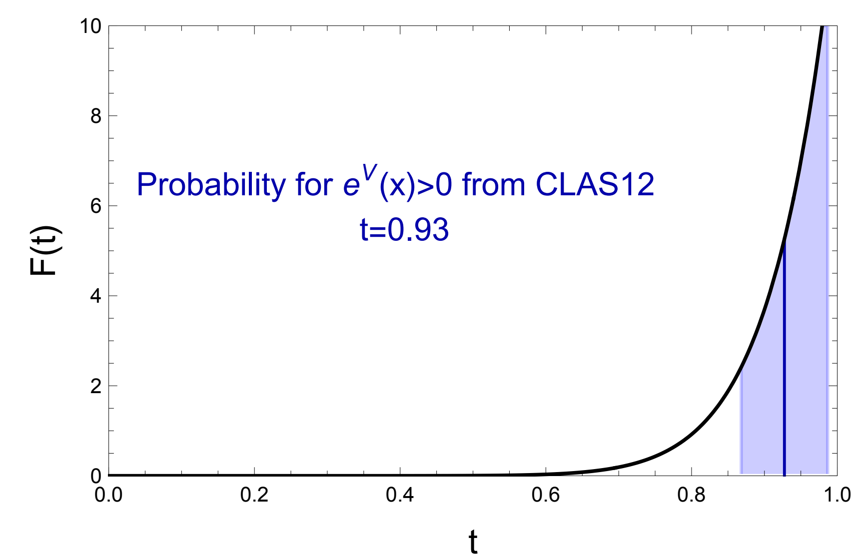
Probability that the proton combination is greater than zero —not exactly "how incompatible with zero is it?"— is a useful information from the point-by-point extraction of a collinear twist-3 PDF with a minimum set of approximations.





Mostly far from zero!





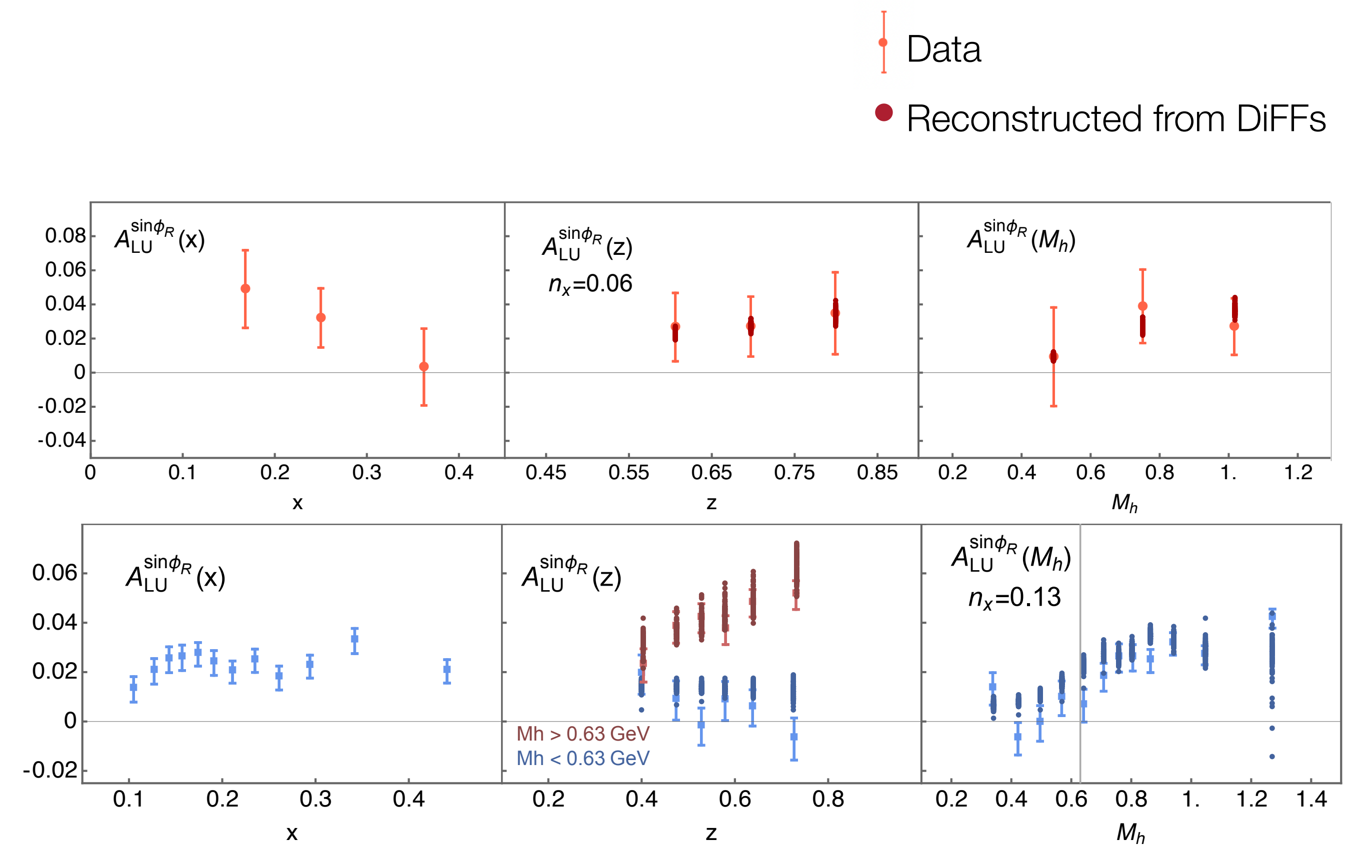
Universality of non-perturbative functions

- Dihadron fragmentation functions

DiFF extracted in e^+e^-, to be tested against SIDIS multiplicities

Consistency check on SIDIS (z, M_h) dependence at CLAS & CLAS12

Determination of the integral of $e^P(x)$ from reconstruction: n_x



- Twist-2 and -3 PDFs

➡ Universality of transversity in pp and SIDIS [Radici et al, PRD94]

➡ Global analysis of the transversity possible [Radici & Bacchetta, PRL120; JAM Coll., PRD102]

➡ Are twist-3 PDFs universal?

Yet to be answered.

Examples through TMD and dynamical twist-3 relations (e.g. Sivers and Qiu-Sterman)

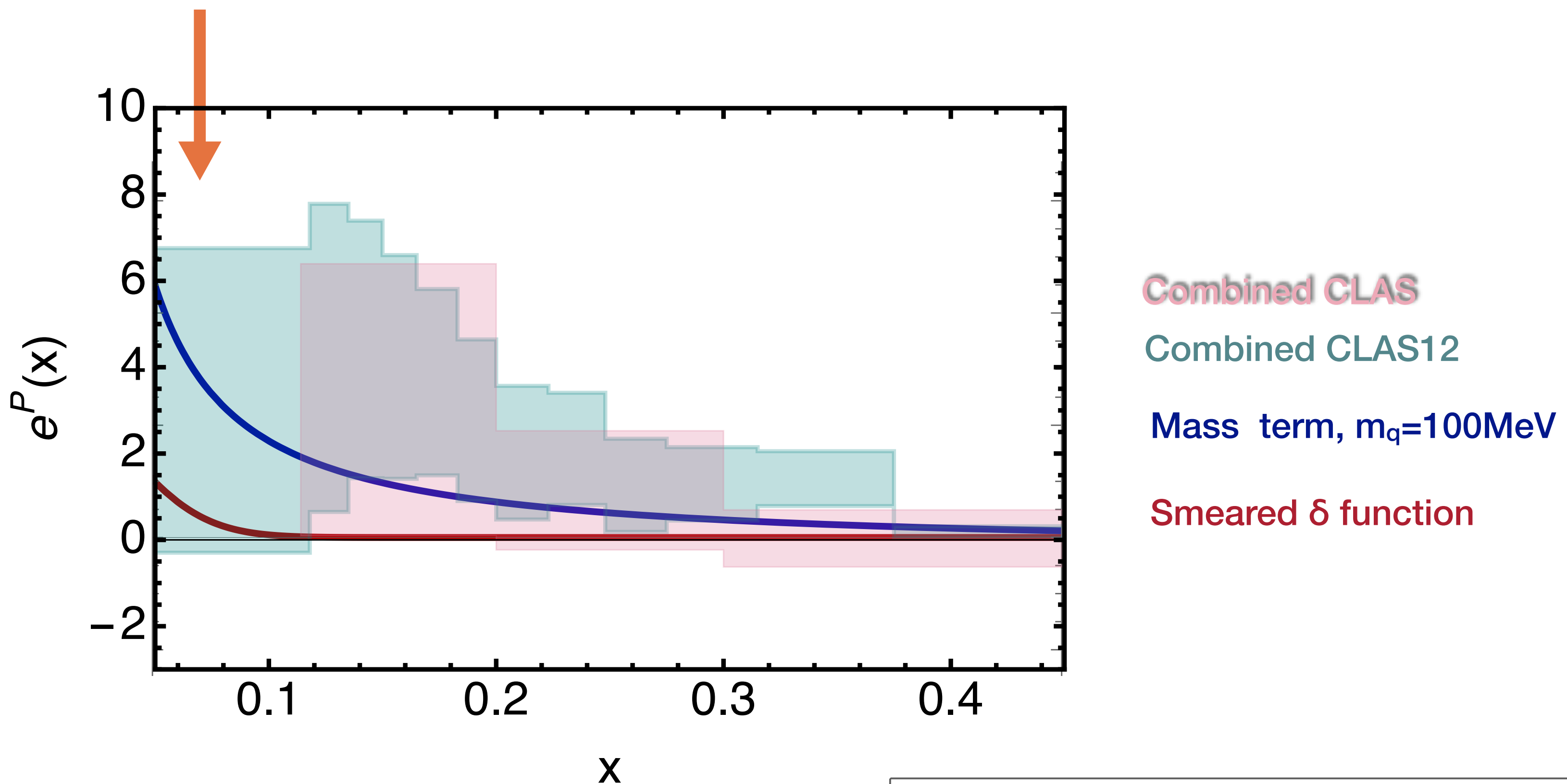
see talk by Shohini Bhattacharya (WG5)

Consequences of the extraction

1. Are twist-3 PDFs non-zero? Yes, to a certain CL.

2. Can we access qgq correlations and more non-perturbative information? Let's take the example of e(x).

Some nonperturbative effects expected in the small(ish)-x region, e.g. [Pasquini & Rodini, PLB 788]



Other nonperturbative effects at not so small x, e.g. in the MIT bag.

Schematic models for illustration purpose only!

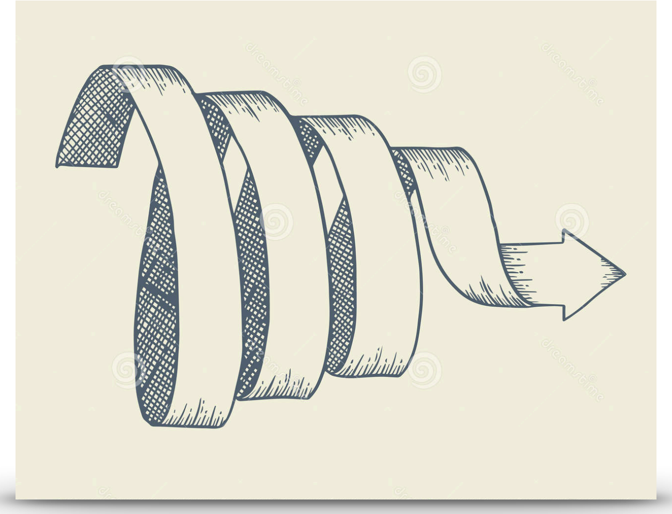
Moments will matter.

Conclusions

We have discussed the role of **higher-twist distributions** in the understanding of hadron structure. We have presented a **truly updated extraction of the scalar PDF, e(x)**. It is non-zero to more than 75% probability.

The study of higher-twist PDFs will contribute to, e.g.

- *Precision 3D imaging of nucleons.*
- *Emergence of hadronic mass —from the scalar PDF.*
- *Proton spin puzzle — from GPDs.*



Higher-twist distributions will unveil aspects of hadron dynamics.

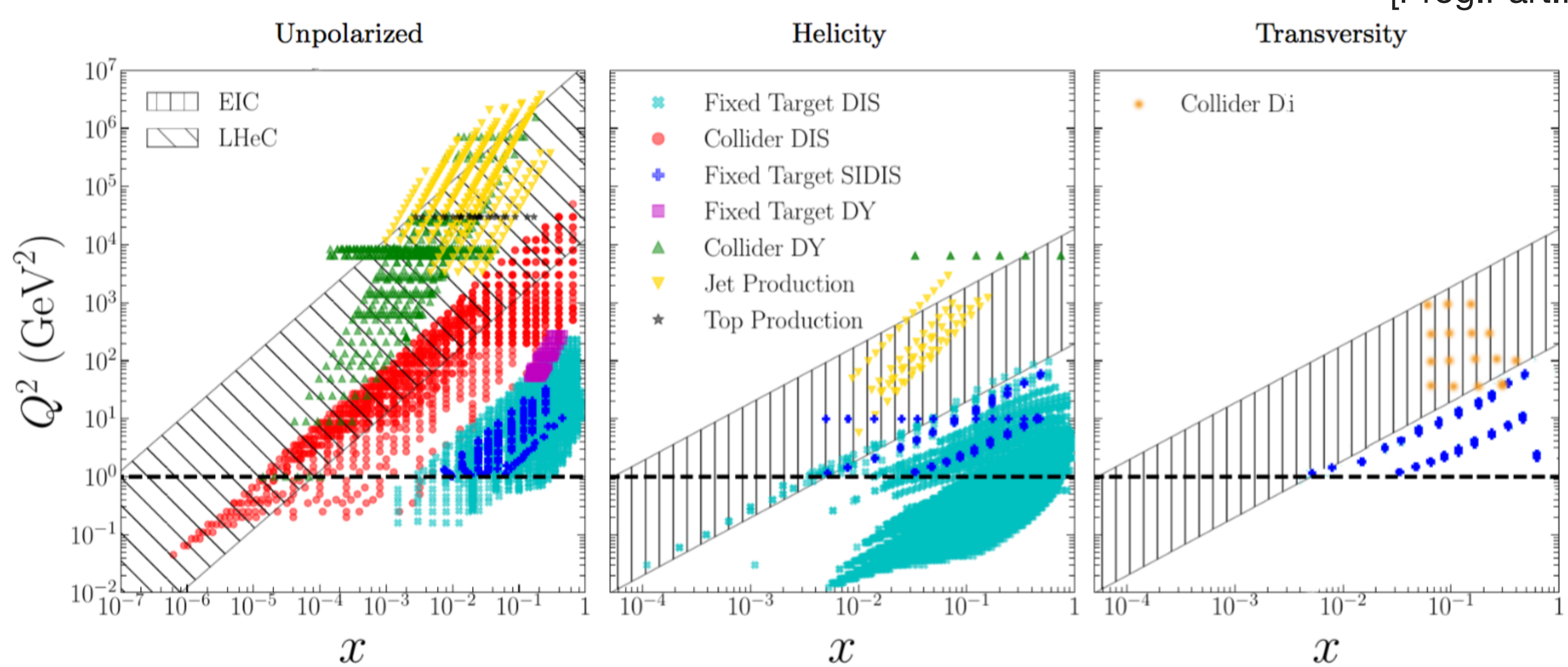
Higher-twist distributions are accessible but require more statistics, phenomenological and theoretical developments.

Combine efforts with the lattice QCD?
[e.g. Bhattacharya et al, PRD102; Braun & Vladimirov, JHEP10(2021)087]

Backup

PDF kinematics coverage: collinear PDFs

[Prog.Part.Nucl.Phys. 121 (2021) 103908]



One possible definition for higher-twist contributions: terms effectively suppressed like $(M/Q)^{t-2}$

Fixed Target DIS & SIDIS: M/Q is not so small

- Spurious contaminations
- Spin asymmetries can be defined to get sensitive to twist-3
- Present data: Hermes, COMPASS, JLab.

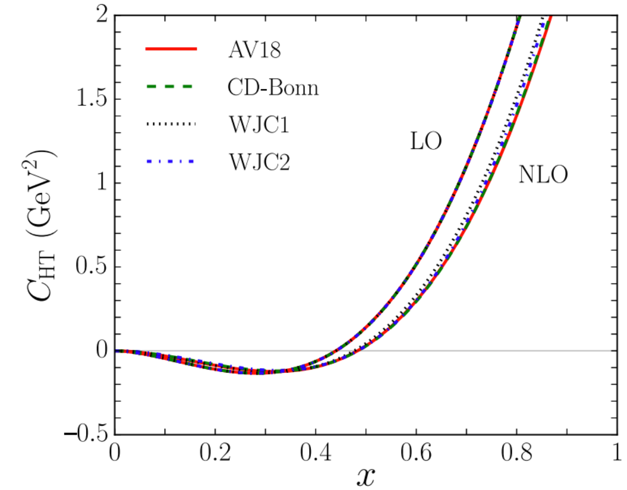
Higher-twist in observables

- **From spurious contaminations…**

CJ15 global analysis includes lower cuts on W^2. [Accardi et al., PRD93]

$$F_2(x, Q^2) = F_2^{\rm LT}(x, Q^2)\left(1 + \frac{C_{\rm HT}(x)}{Q^2}\right)$$

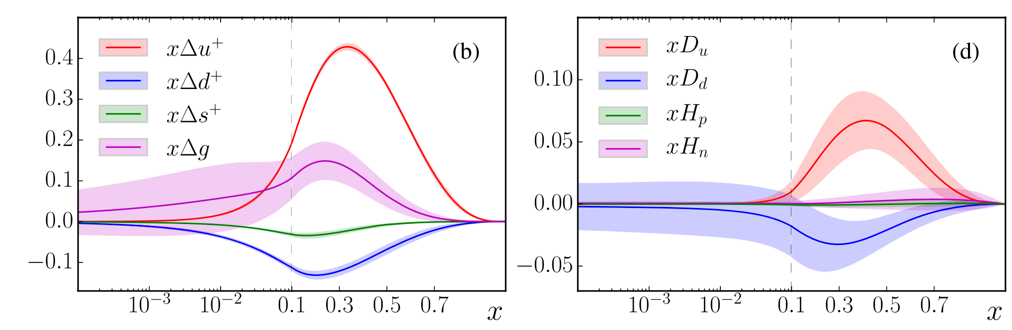
HT's role in fulfilling duality [e.g. Melnitchouk et al., Phys.Rept.406]



- **…to genuine effects**

JAM analysis of the helicity PDF g_1 extends to g_T, with $g_T=g_1+g_2$. [Sato et al., PRD93]

$$g_2^{(\tau 3)}(x, Q^2) = D(x, Q^2) - \int_x^1 \frac{dz}{z} D(z, Q^2)$$



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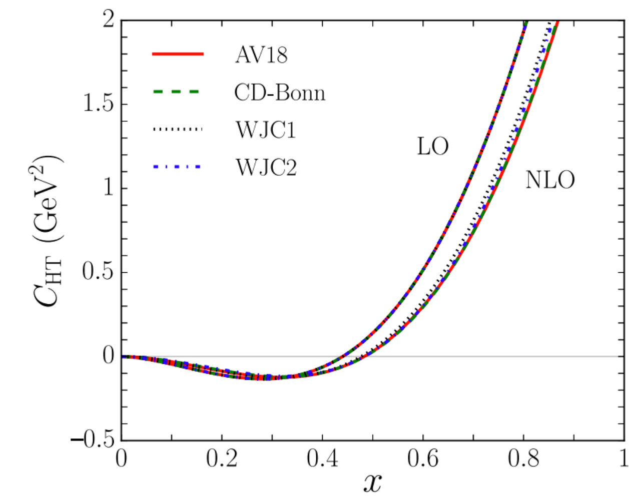

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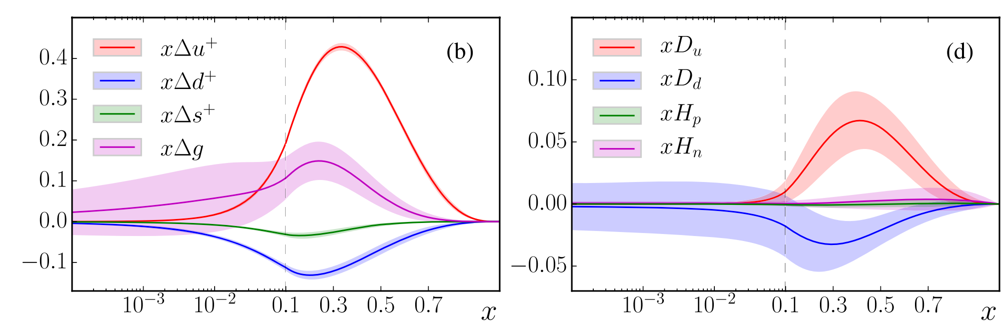
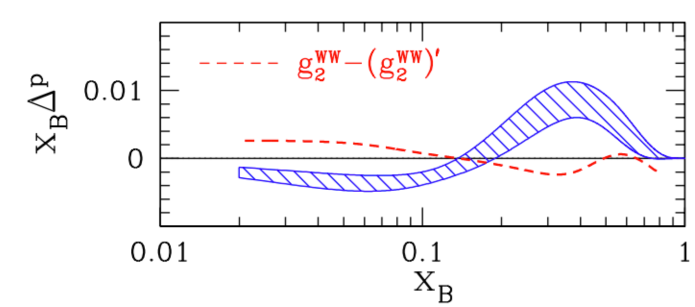


g_T is the only twist-3 PDF accessible through inclusive DIS

Exploratory studies suggest that quark-gluon-quark correlations are non-zero.

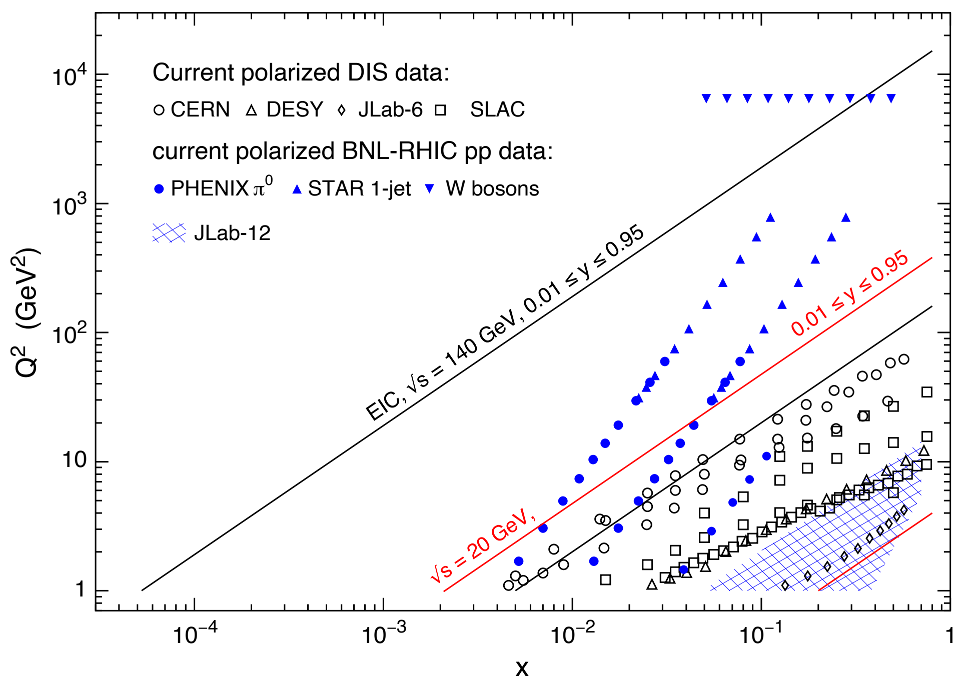
[Accardi et al, JHEP11 (2009)]

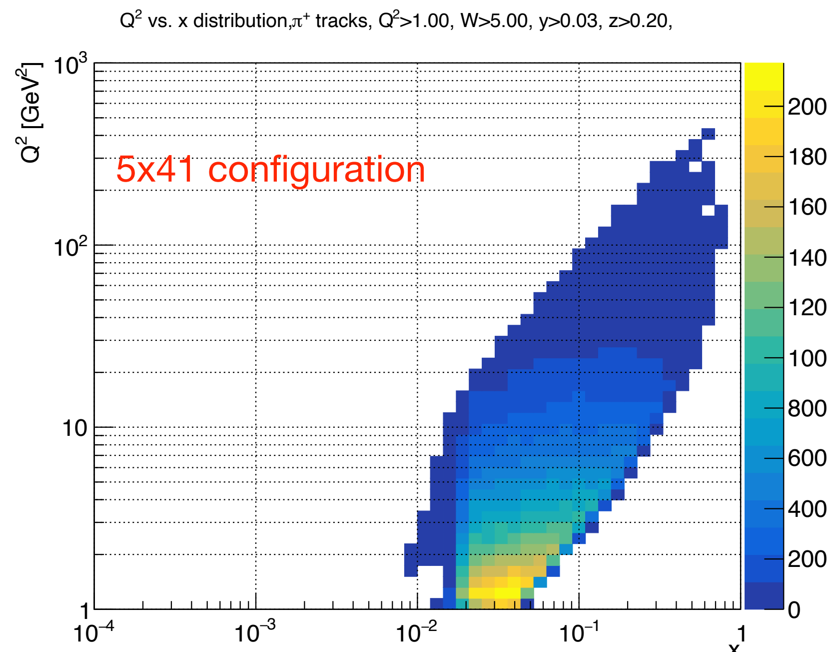
$$\Delta_{\rm ex}(x_B,Q^2) = g_2^{\rm ex}(x_B,Q^2) - g_2^{\rm WW}(x_B,Q^2)$$



Can we study qgq correlation at the EIC?

EIC Yellow Report [2103.05419]





Projections for IR2@EIC White Paper by A. Vossen

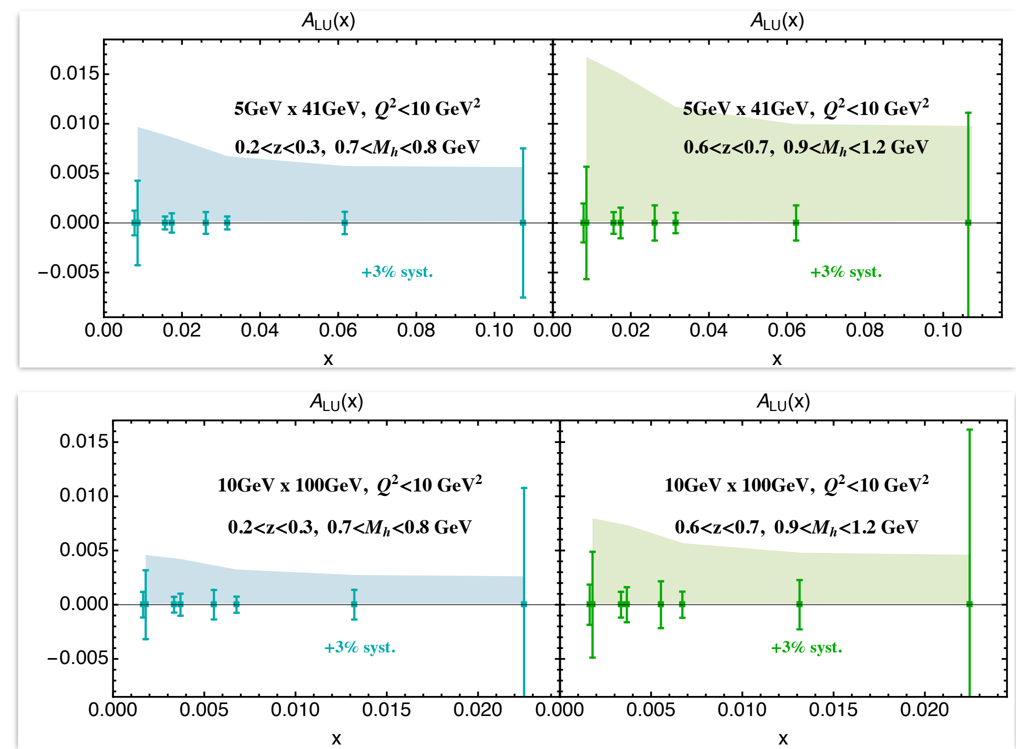
Future: EIC will cover low- to mid-Q^2 and smallish x values

- Yellow Report: access to multiparton correlations.
- Proposal for a 2nd interaction region — IR2@EIC.
- Complementarity with present data.

Expectations for the EIC

EIC Yellow Report [2103.05419]

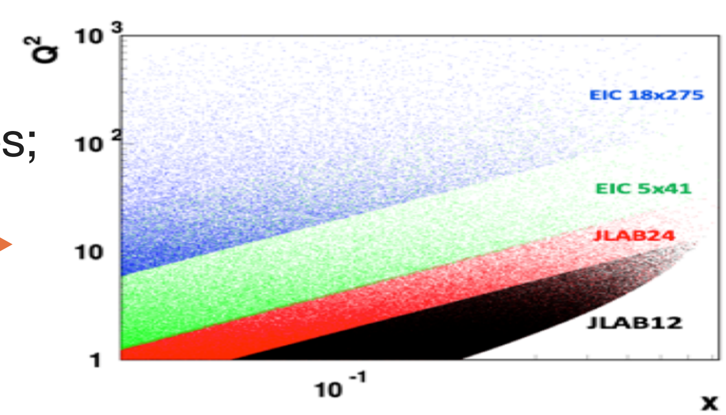
- EIC error projections (from transversity studies)
- Proton target shown, but need for neutron
- Models × DiFFs predictions
  - ➡ LC model [Pasquini & Rodini, PLB 788]
  - ➡ made-up mass-term contribution with mq=300MeV



- Non-negligible for lowest beam configurations

Archetype of observables for IR2@EIC

- Evolution equations for genuine qgq twist-3 known in most cases;
- Understanding of the various contributions to twist-3 PDFs;
- Especially “hot” for TMD studies.
- Require a second interaction region @EIC.



from H. Avakian
:e Paper for IR2@EIC.

Multi-parton distributions at the EIC

Large range of Q^2 values, includes smallish x regions

Sandbox for factorization and evolution studies

Complementary to fixed-target experiments (HERMES, CLAS,…)

Golden channel

fully inclusive DIS, access to g_T

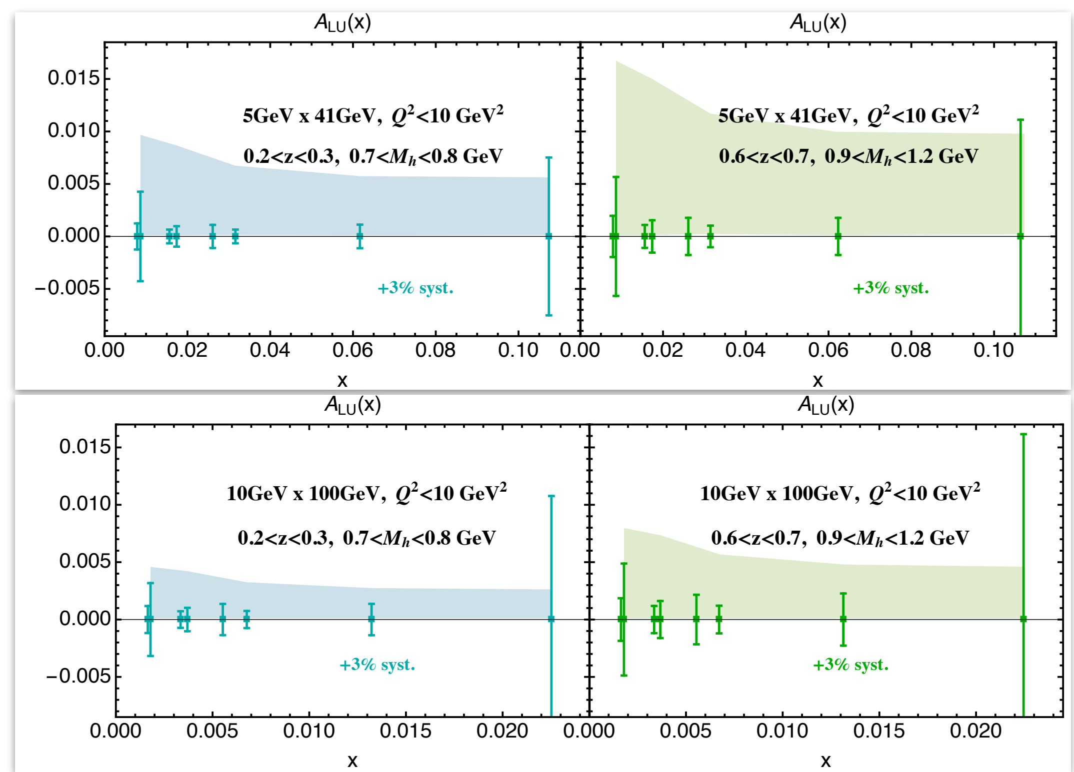
Silver channel

semi-inclusive DIS, access to e(x)

- **Collinear observables.**
- Plethora of interesting TMD, GPD higher-twist observables to be considered too
- subWG: Avakian, Burkardt, AC, Gamberg, Pitonyak, Sato, Schweitzer, Vossen

EIC coverage

EIC Yellow Report [2103.05419]



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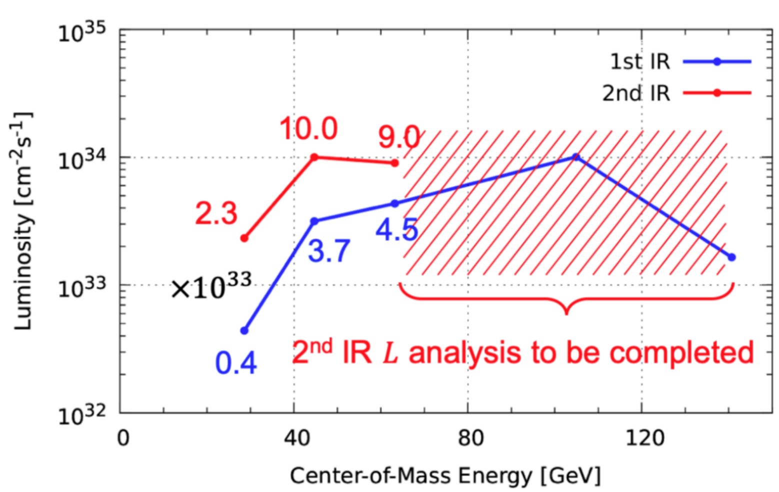
↓

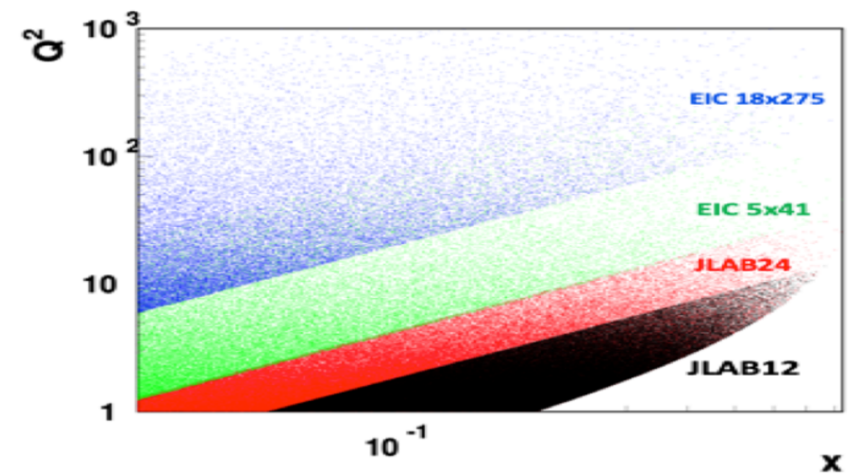
Archetype of observables for IR2@EIC

QCD and twist-3 PDFs

Underlying and omitted in all this presentation: Q^2-evolution!

from H. Avakian
& White Paper for IR2@EIC.





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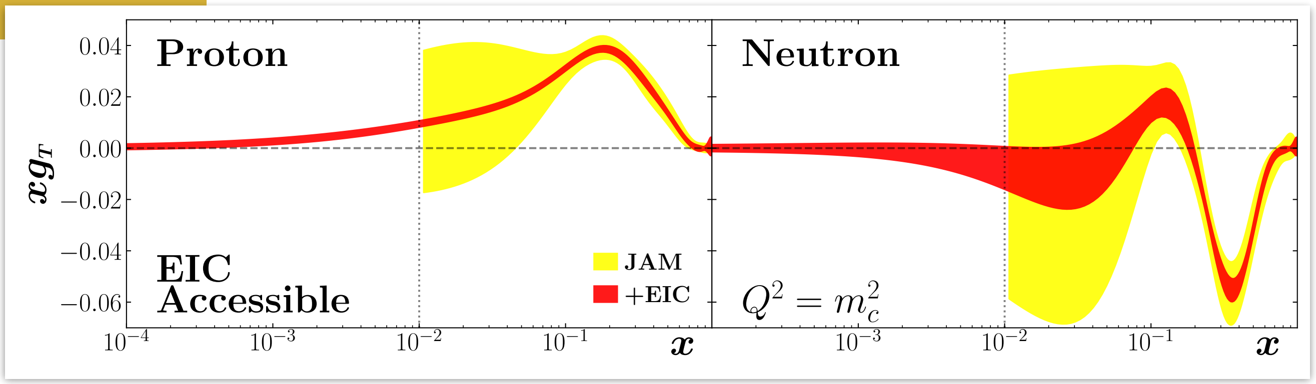

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