Extraction of e(x), other higher twist topics

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"FORDECYT-PRONACES"

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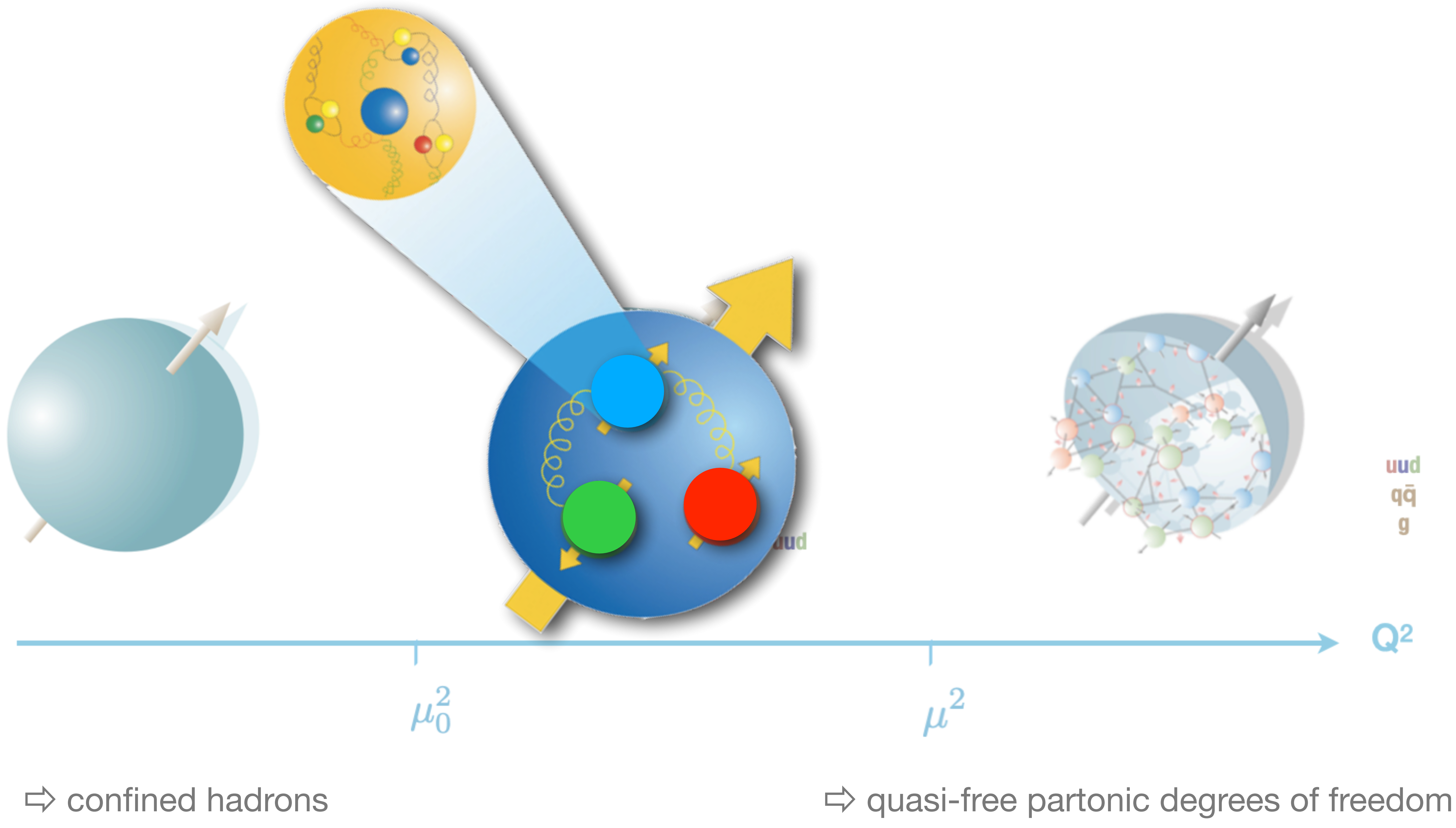
dgapa

Dirección General de Asuntos del Personal Académico

Higher-twist parton distribution functions

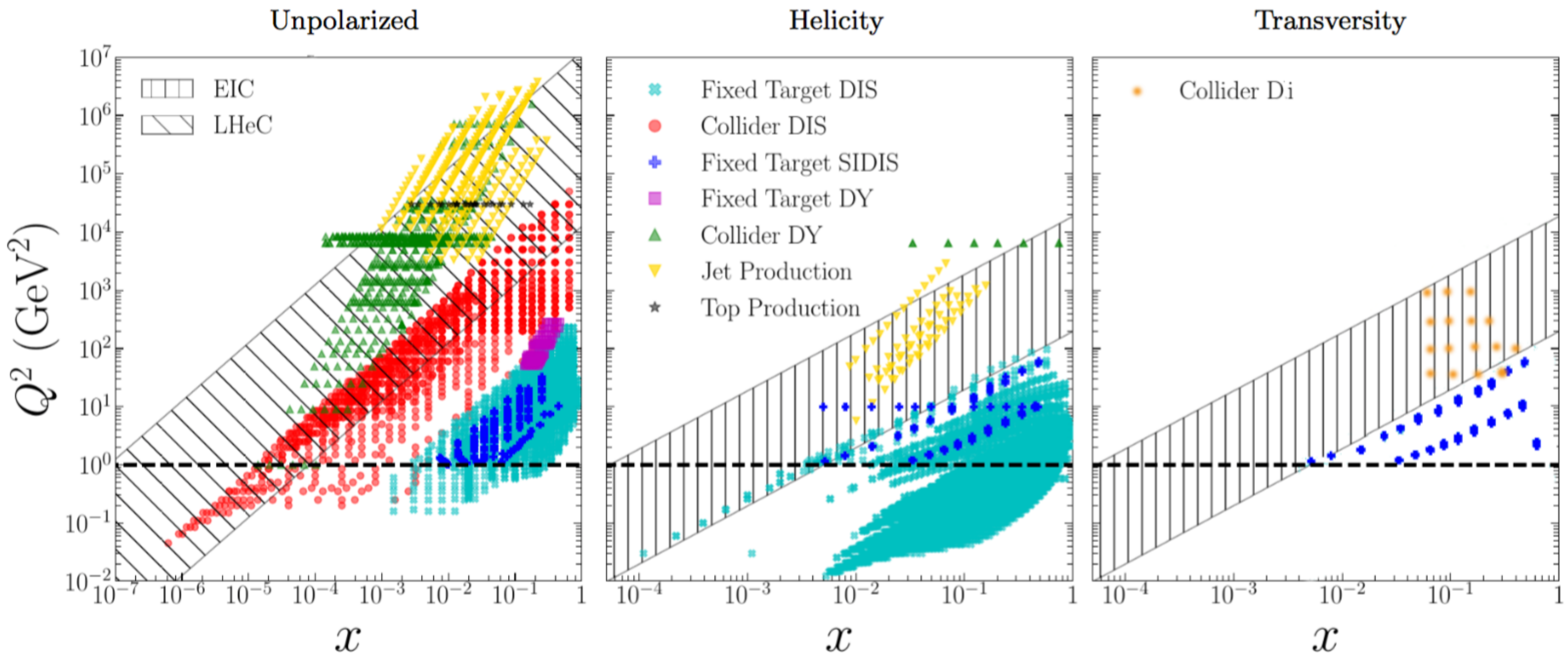
Gluon at low energy, “the glue that binds us all”?

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



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.

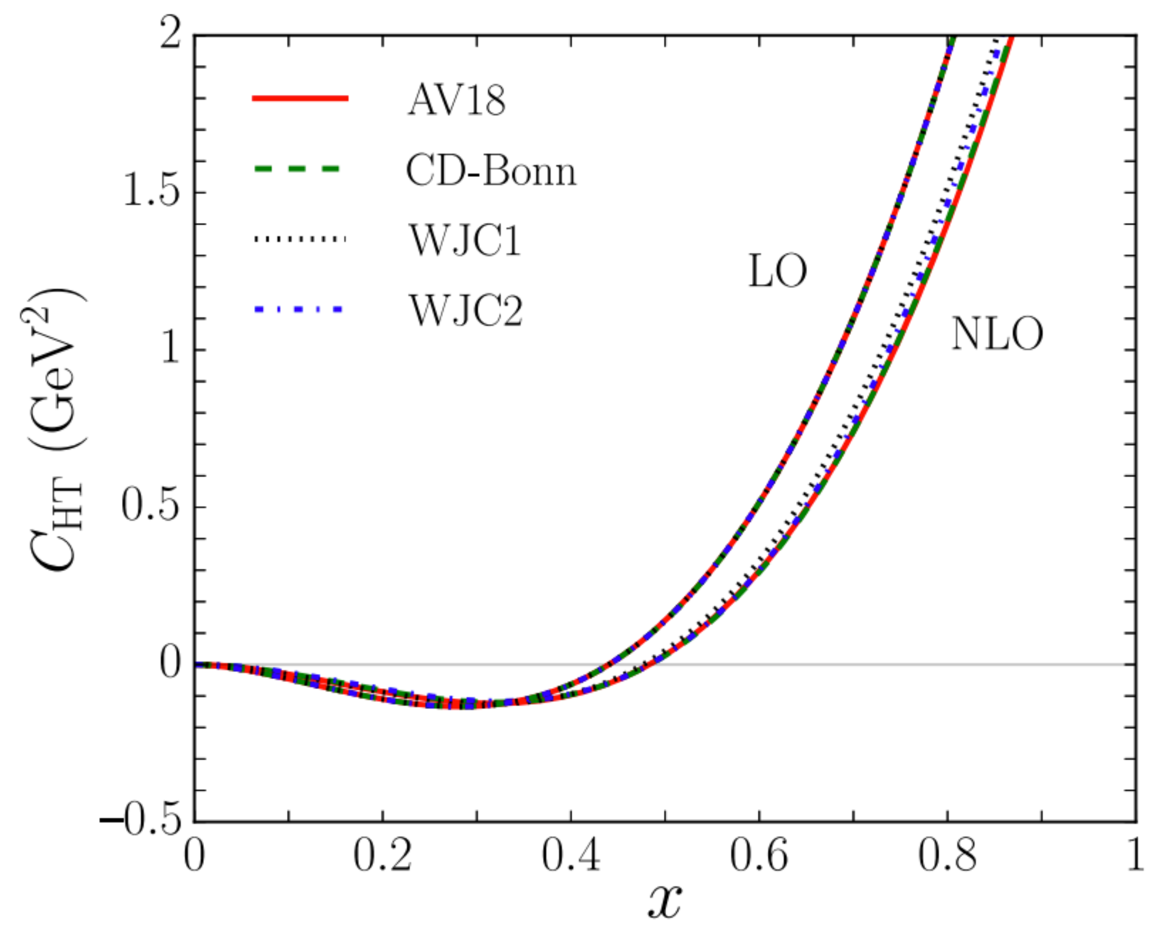
Higher-twist in observables

- **From spurious contaminations…**

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

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

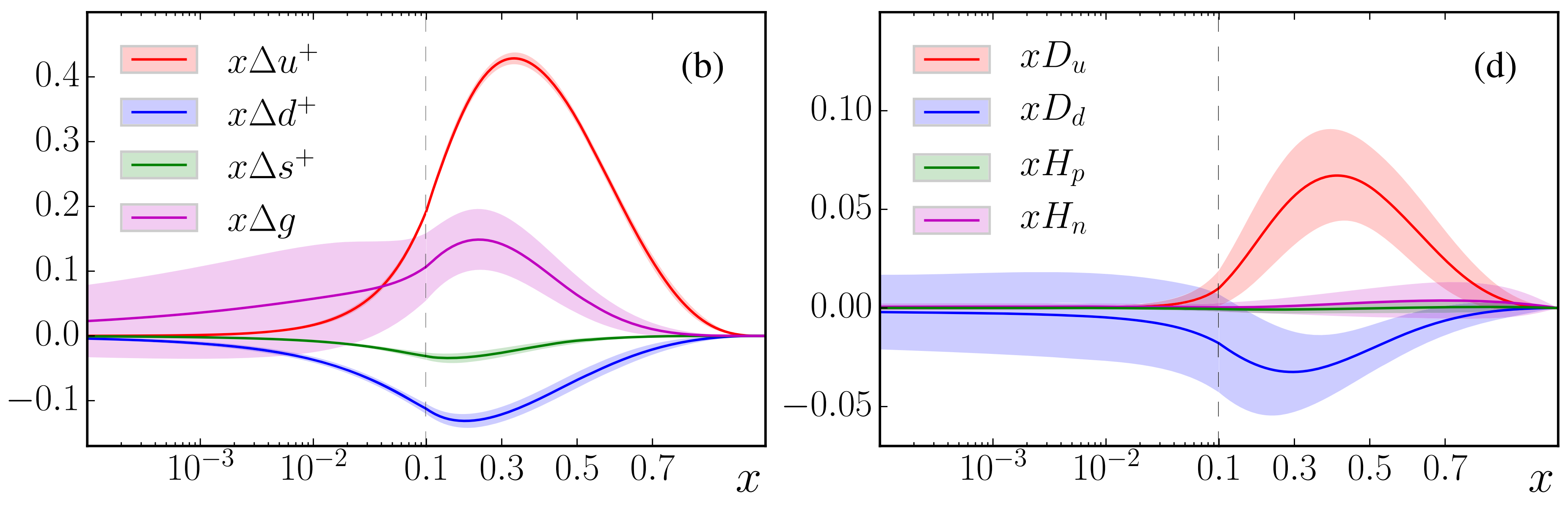
$$F_2(x,Q^2) = F_2^{\rm LT}(x,Q^2)\left(1+\frac{C_{\rm HT}(x)}{Q^2}\right)$$



- **…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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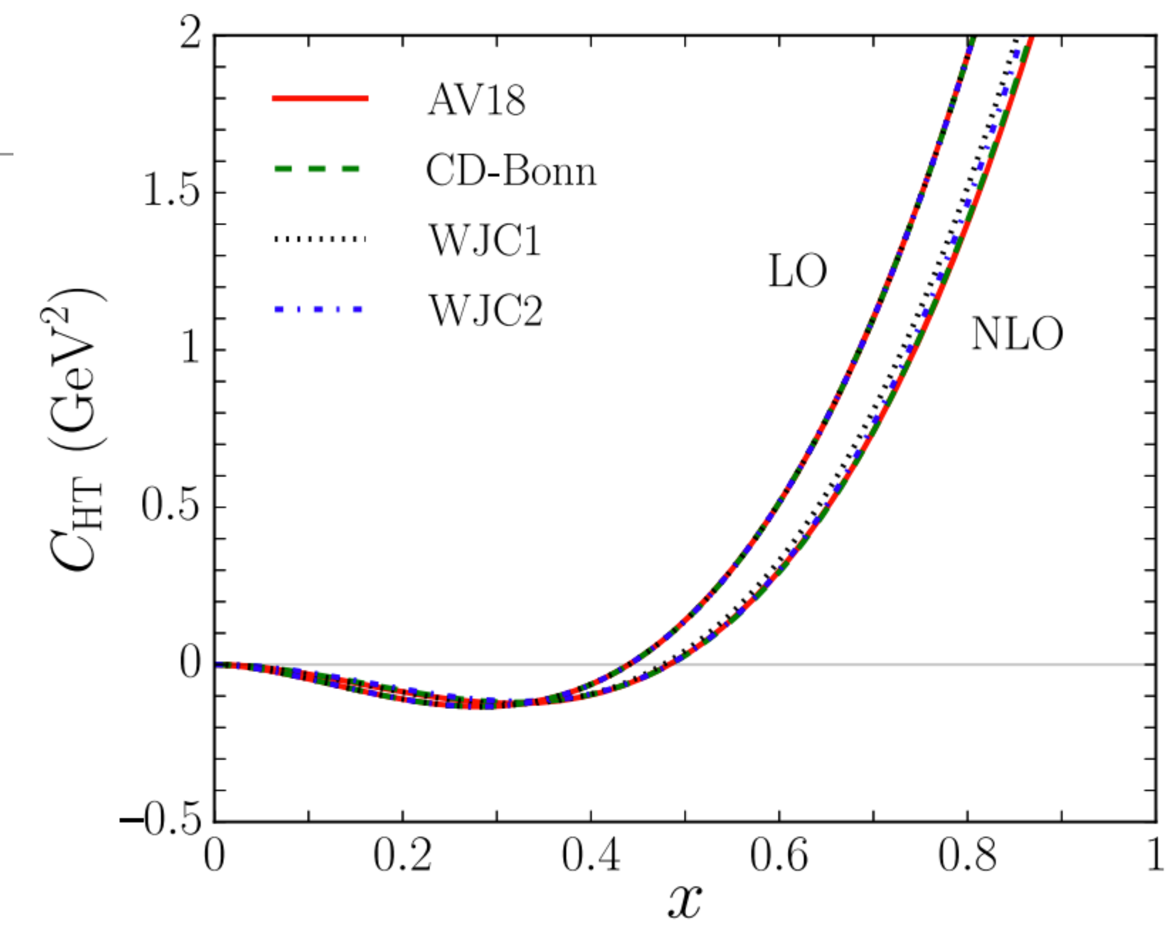

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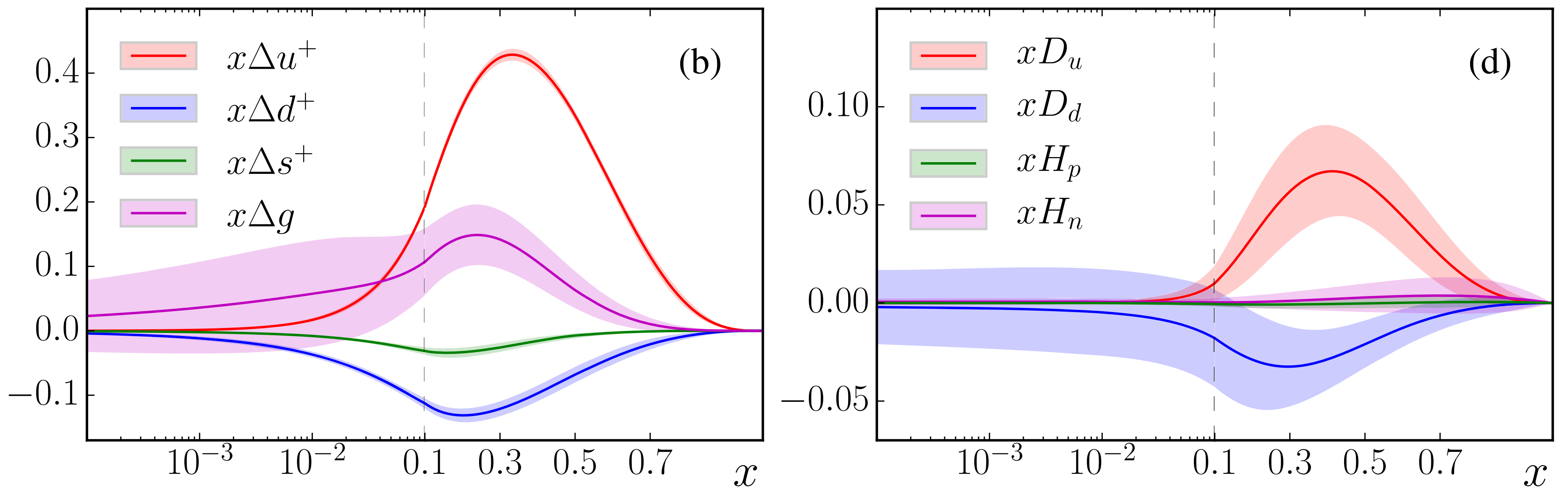
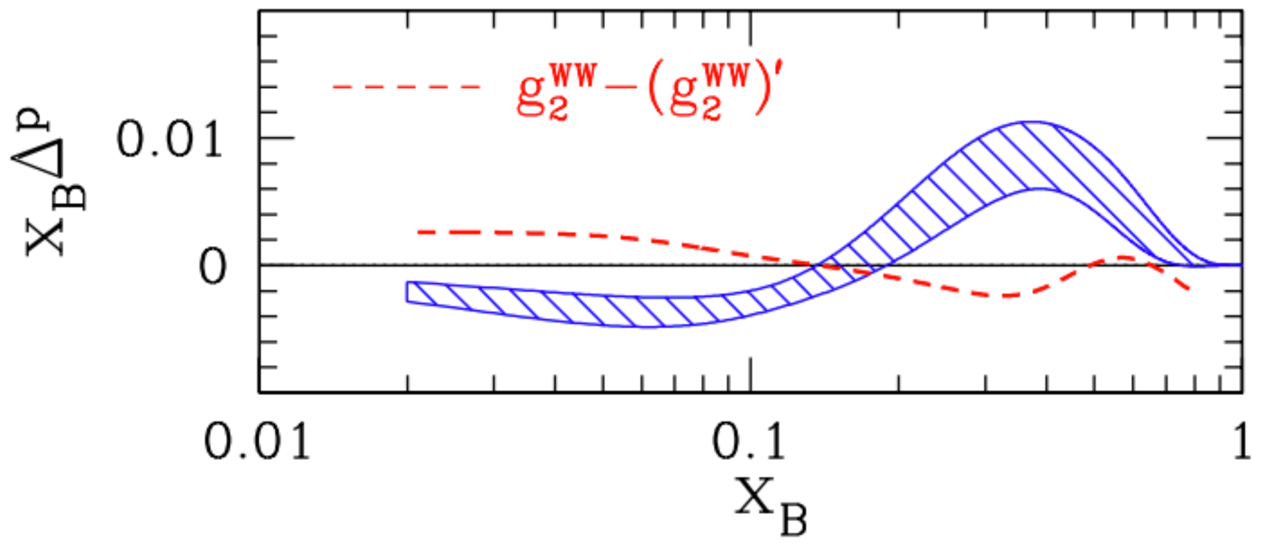


g_T is the only twist-3 PDF accessible through inclusive DIS

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

[Accardi et al, JHEP11 (2009)]

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



Dichotomy of twist-3

see talks by Shohini Bhattacharya (TMDs), Simonetta Liuti (GPDs)

1. Parametrizing the proton matrix element, relations between scalars and moments can be found: **Wandzura-Wilczek relation**.

$$g_2(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y) + \tilde{g}_2(x)$$

[e.g. Jaffe, eprint/9602236]

twist-2 PDF

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related to genuine qgq correlation through the equations of motion

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2. Light-cone dynamics imply the existence of singularities: $\delta(x)$.

$$g_2(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y) + \tilde{g}_2(x) \boxed{+ g_{2,\delta}(x)|_{\text{model}}}$$

[Jaffe & Ji, PRD43]
[Burkardt & Koike, NPB632]
[Aslan & Burkardt, PRD101]
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3. Mass terms:

$$g_2(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y) + \tilde{g}_2(x) + g_{2,\delta}(x)|_{\text{model}} \boxed{+ \frac{m_q}{M} F[f_{\text{twist-2}}(x)]}$$

Scalar PDF

Lots of interests for that function in the past years

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

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

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

"local" term

originates from singularity

genuine qgq correlation

originates from covariant derivative

quark mass term

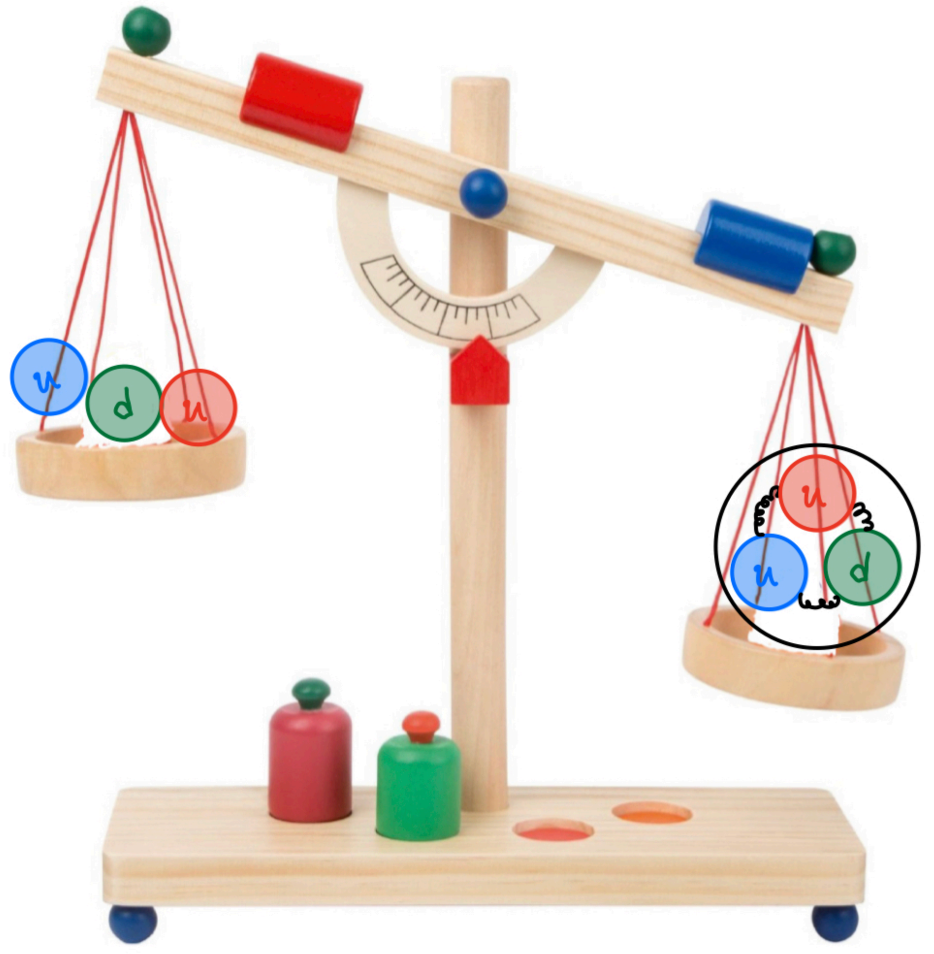
originates from kinetic+mass

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

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]

Scalar PDF and the proton mass



QCD mass decomposition

$$\boxed{M_P = M_m + M_a + M_q + M_g}$$

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]

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

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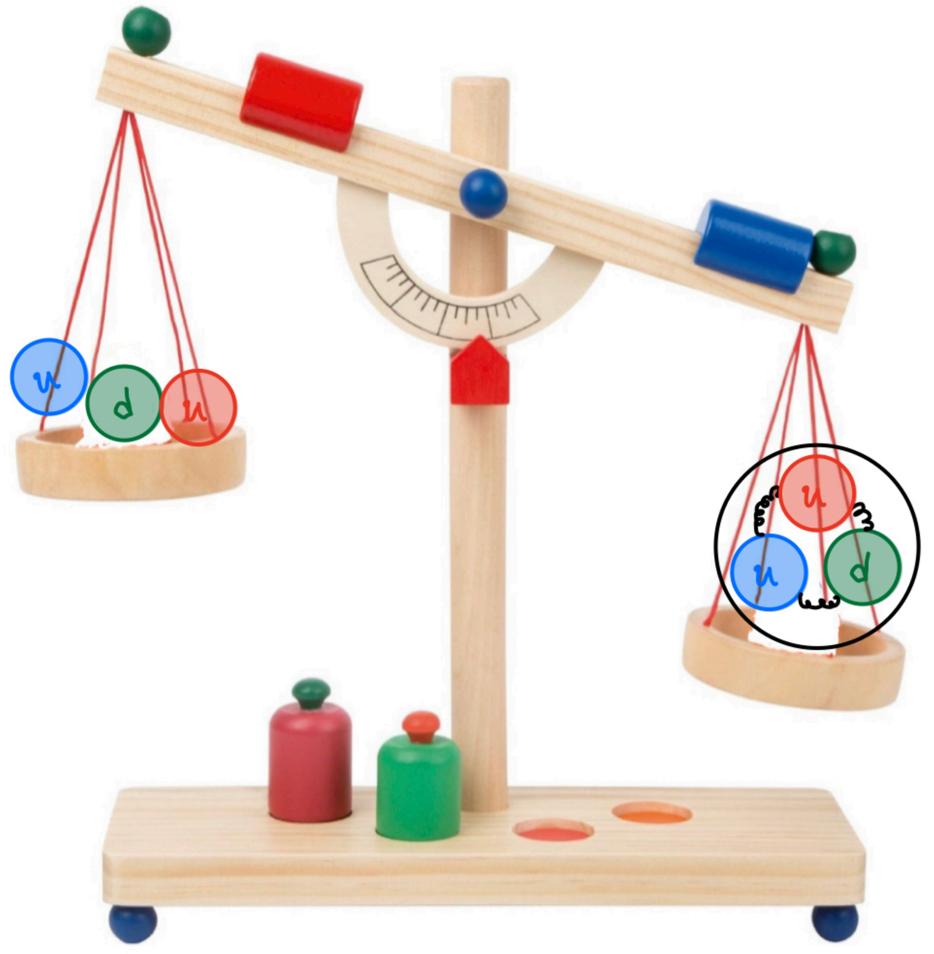

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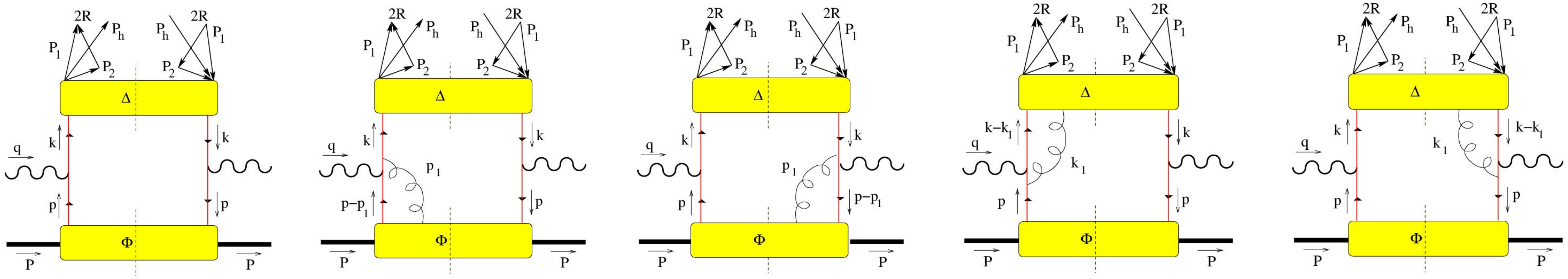
- can be accessed through single-hadron SIDIS
  —see talk by Timothy Hayward
  & [Efremov et al, PRD67]
- can be accessed through dihadron SIDIS
  this talk

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:

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

- 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

see talk by Christopher Dilks

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

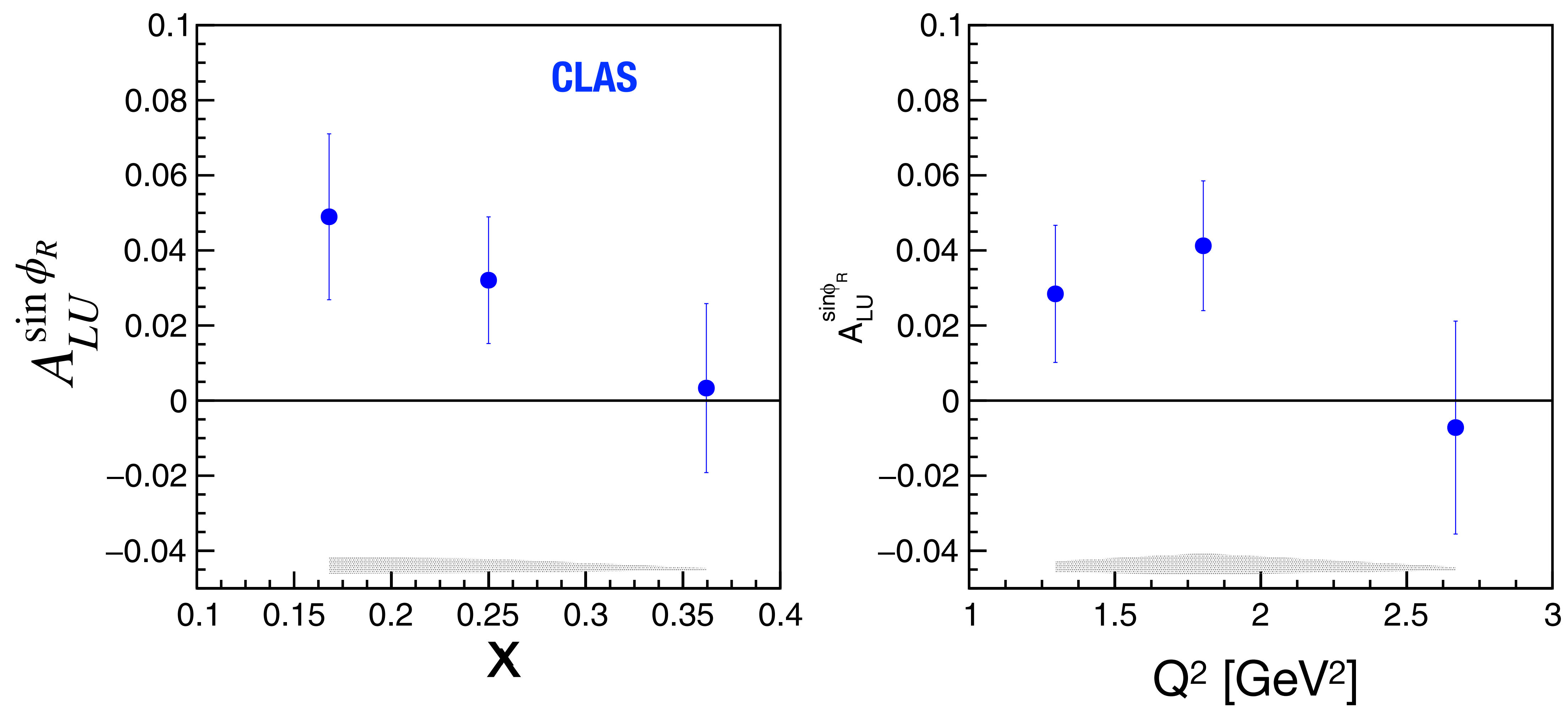
[Bacchetta & Radici, *PRD*69 (2004)]
[Courtoy, 1405.7659]

- non-vanishing twist-3 effects at CLAS12;

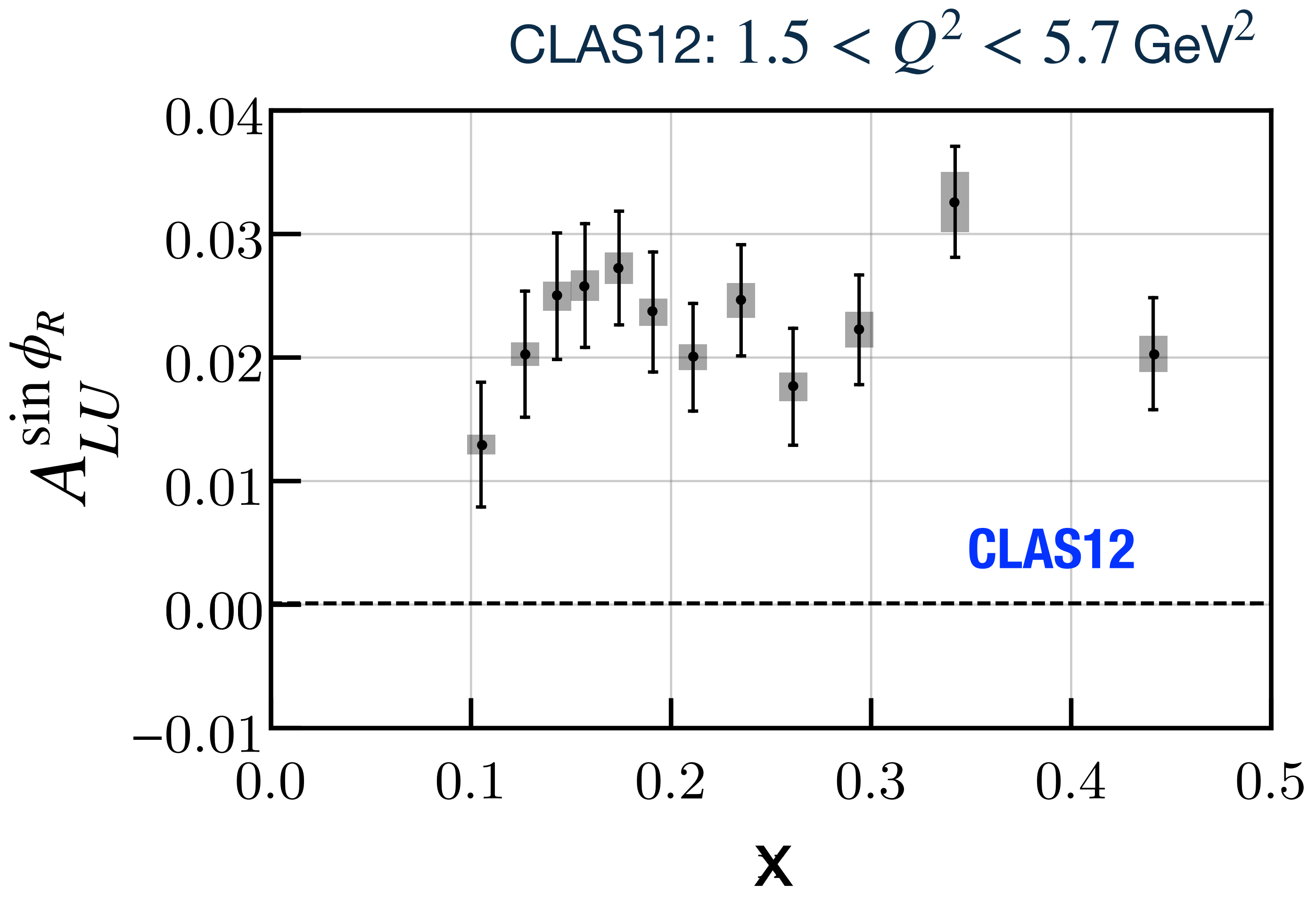
- projections of beam spin asymmetries on $(x, z, M_h; Q^2, y)$

➡ (x, z, M_h) triptych from the parton distribution and fragmentation function.

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



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



[CLAS Collaboration, PRL126 (2021) 152501]

Extraction of $e(x)$ from CLAS data

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$\Downarrow$

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*

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

chiral-odd DiFF

unpolarized DiFF

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leading-twist DiFFs

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

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How to treat twist-3 Dihadron Fragmentation Functions?

Extraction of e(x) from CLAS data

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

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]

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

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

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

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

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

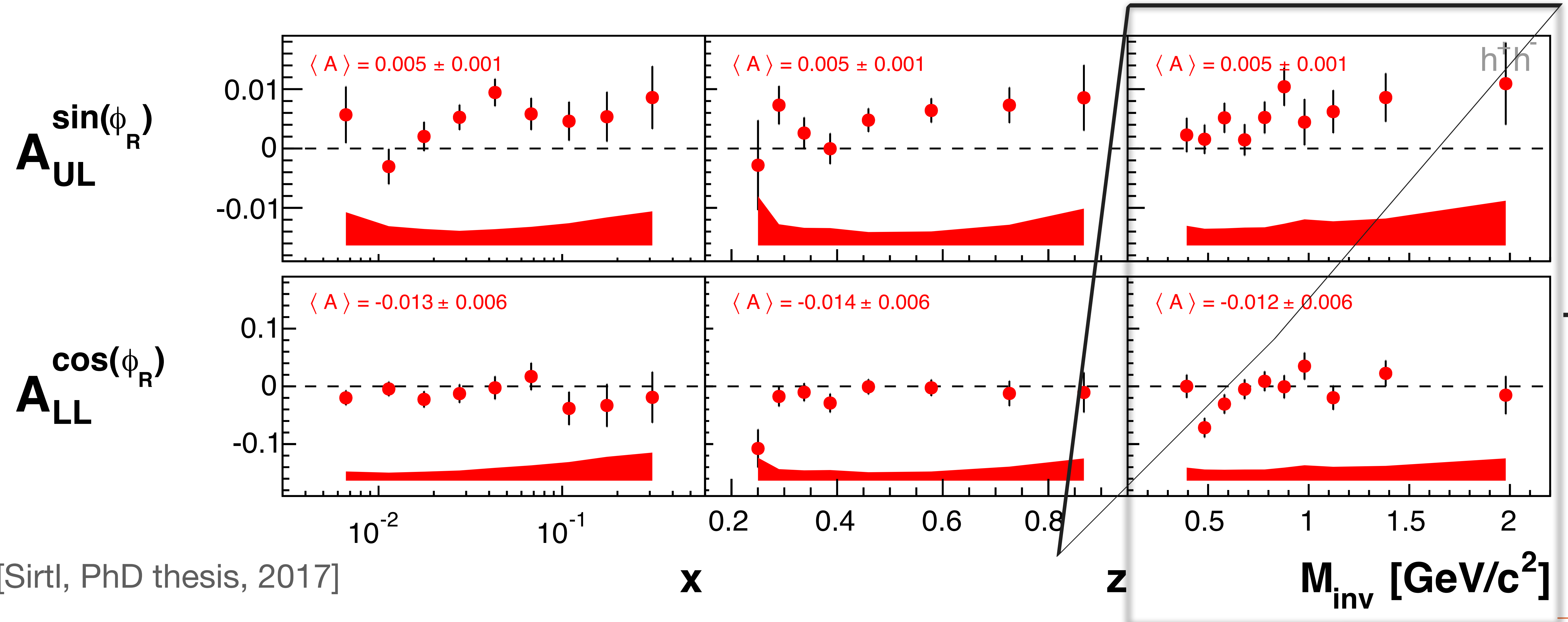
Twist-3 dihadron fragmentation functions: COMPASS

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

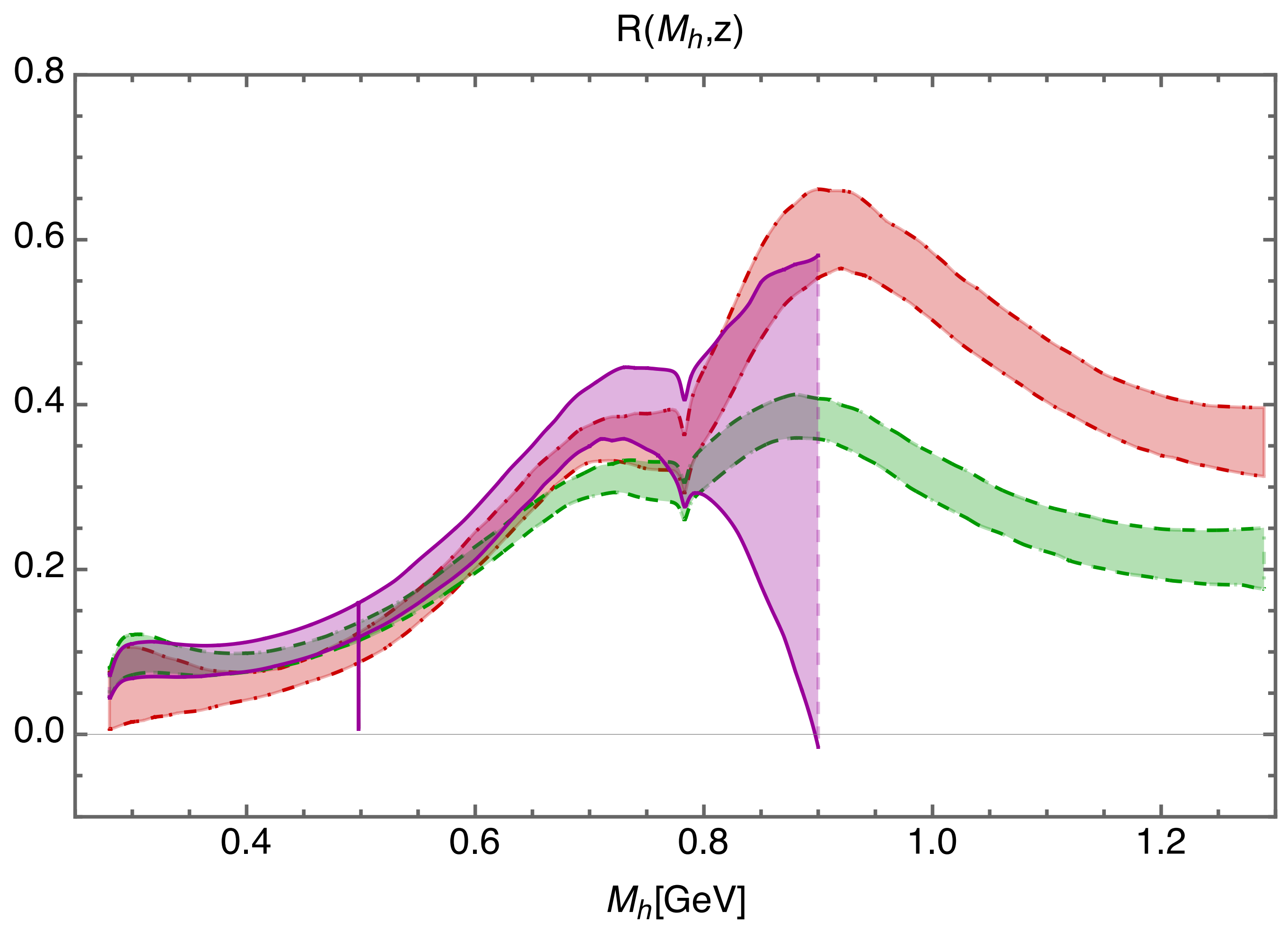
Can we single out twist-3 DiFFs through this approximation?

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

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]



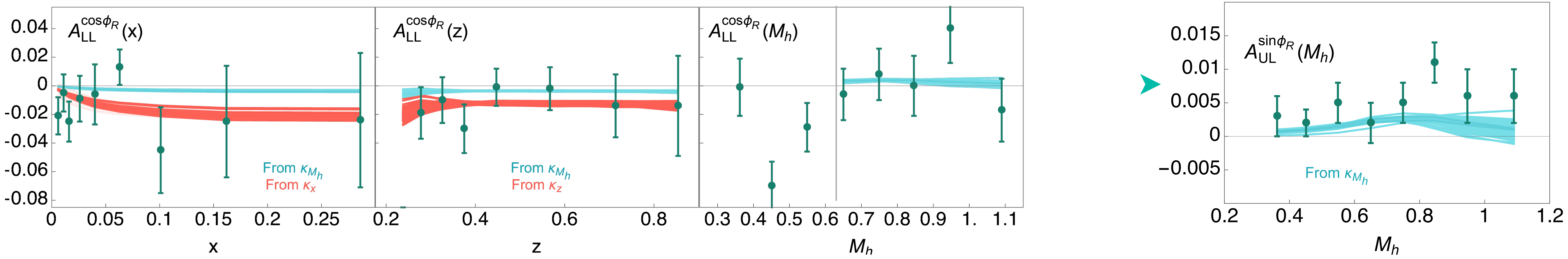
[Radici, AC, Bacchetta, *JHEP* 05 (2015)]

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



$\Rightarrow$ invariant-mass behavior is key, twist-2 DiFF alone not enough to interpret all M_h -projected twist-3 asymmetries.

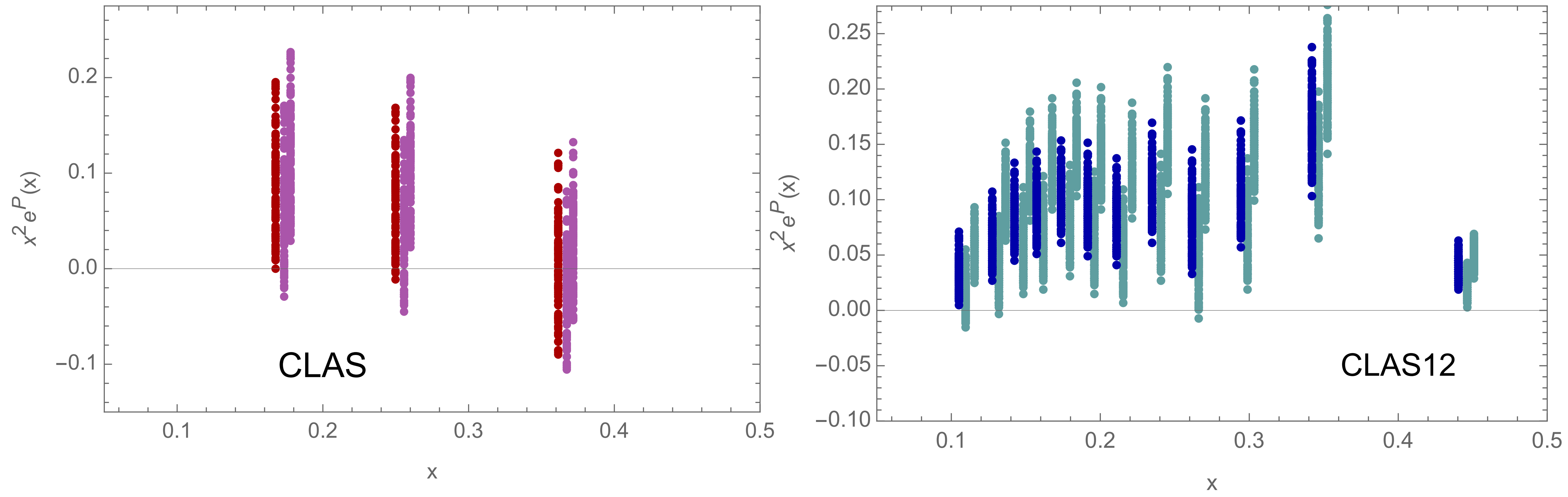
Point-by-point e(x) from CLAS data

- <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

[Courtoy, 1405.7659]
[Courtoy, Miramontes, Avakian, Mirazita, in progress]

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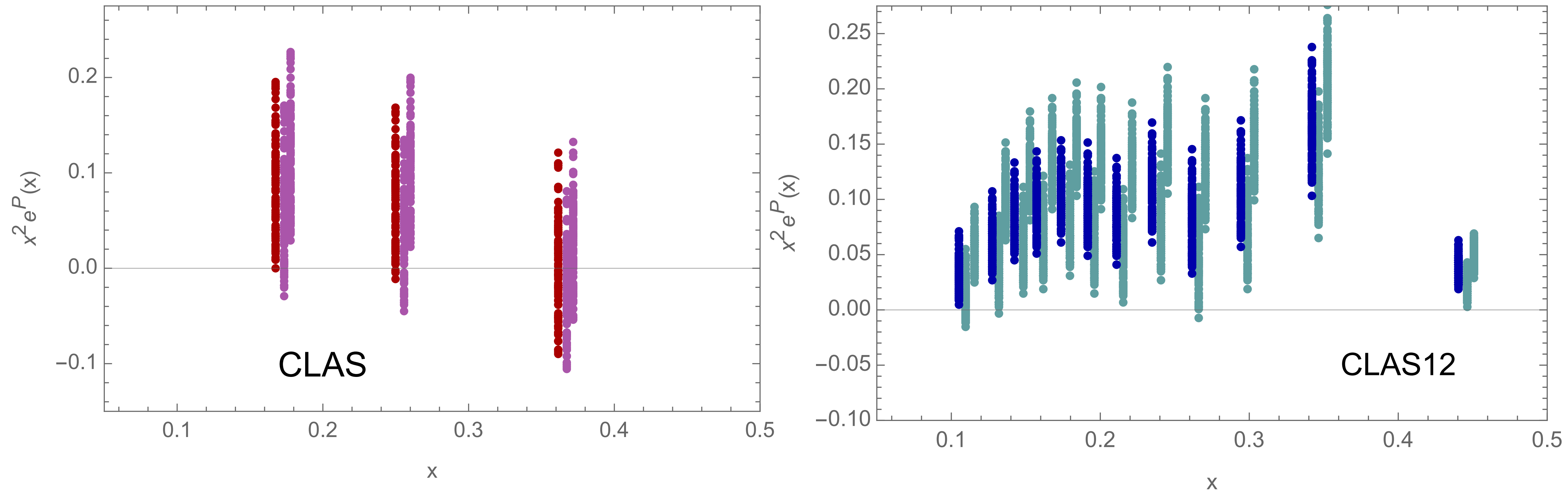

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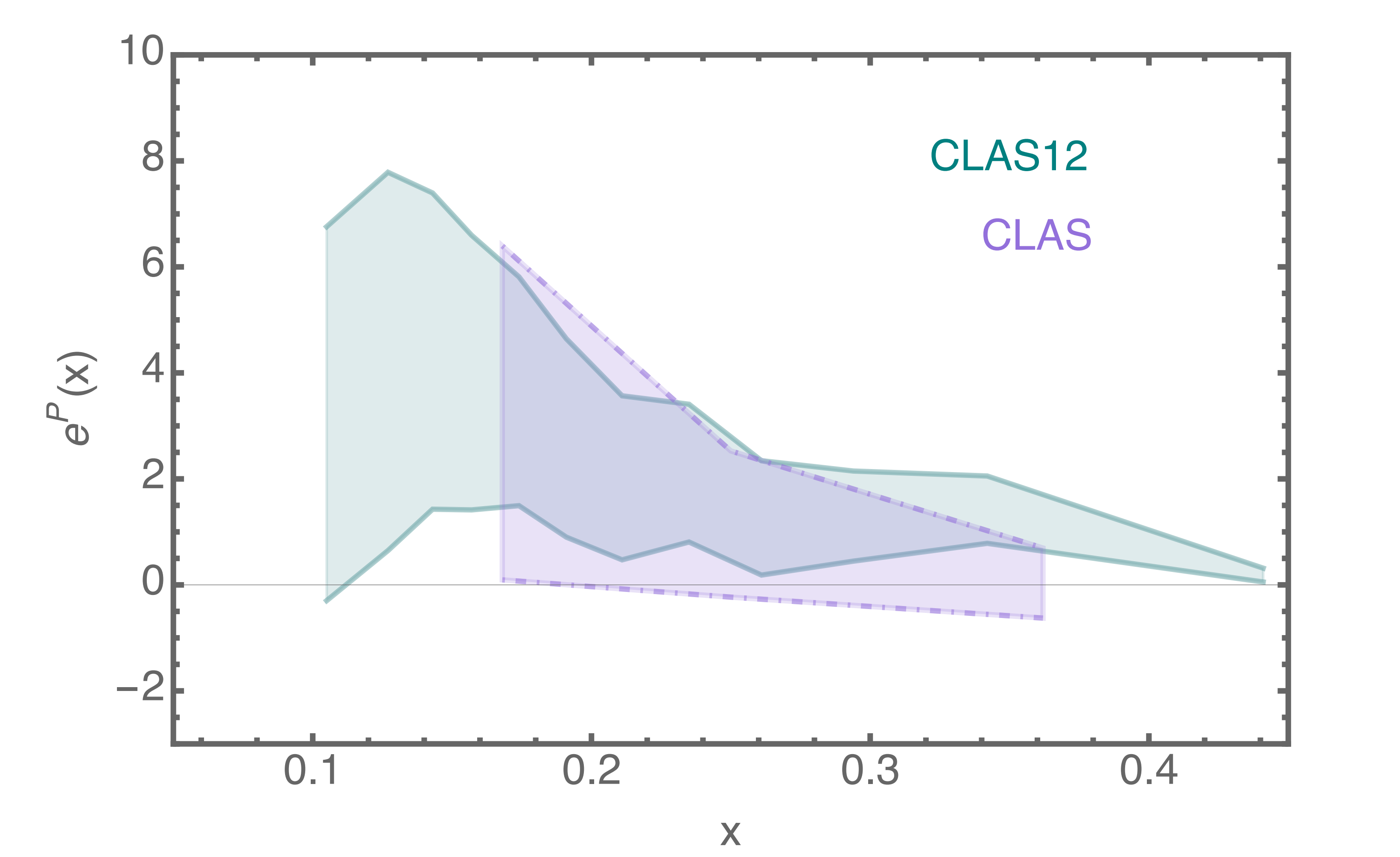
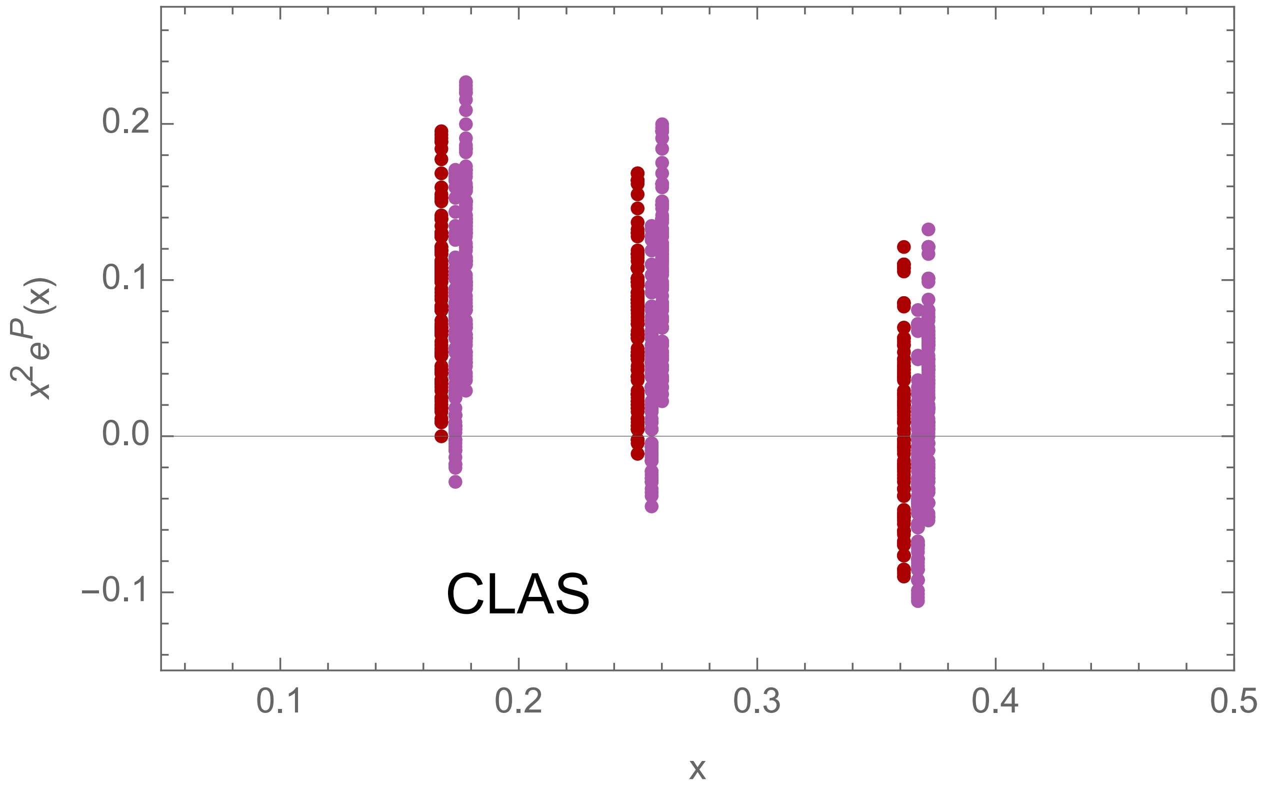
Combining the uncertainty at 90% CL⇒

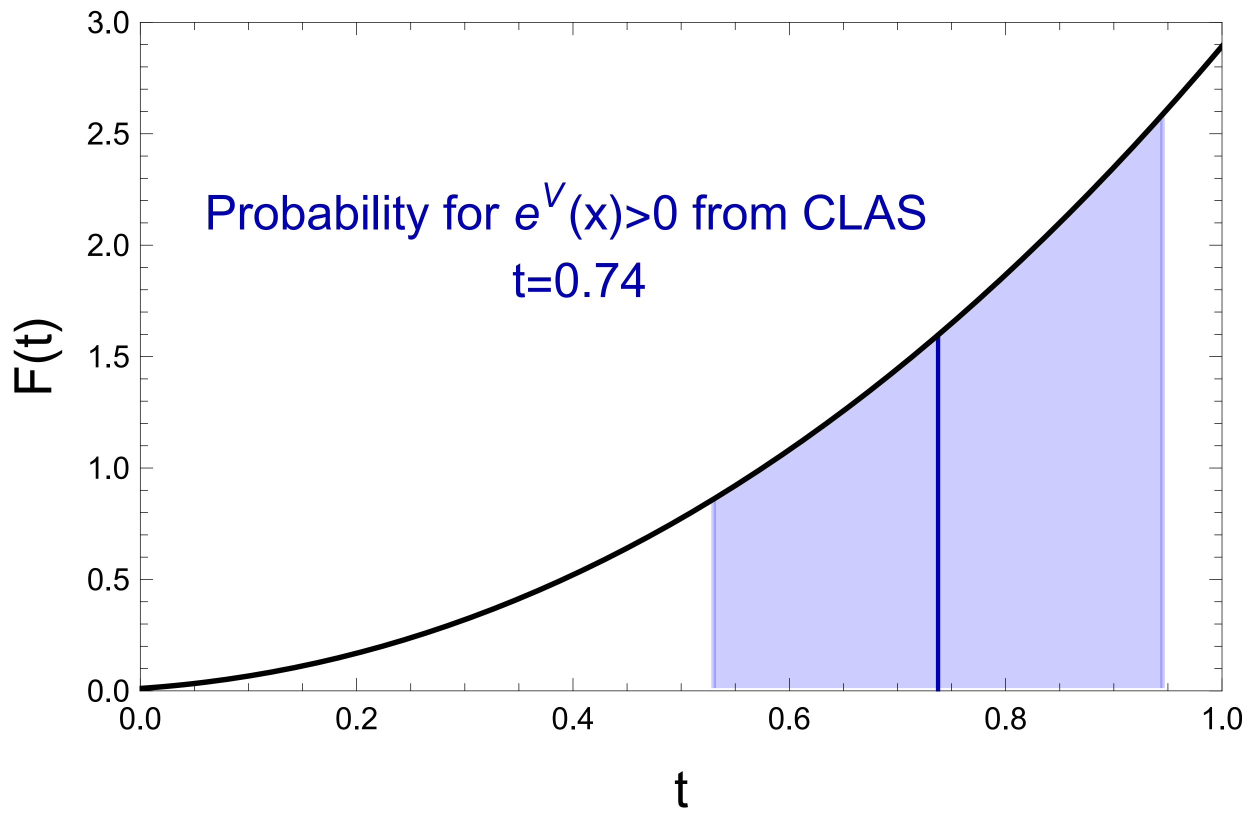


[Courtoy, 1405.7659]
[Courtoy, Miramontes, Avakian, Mirazita, in progress]

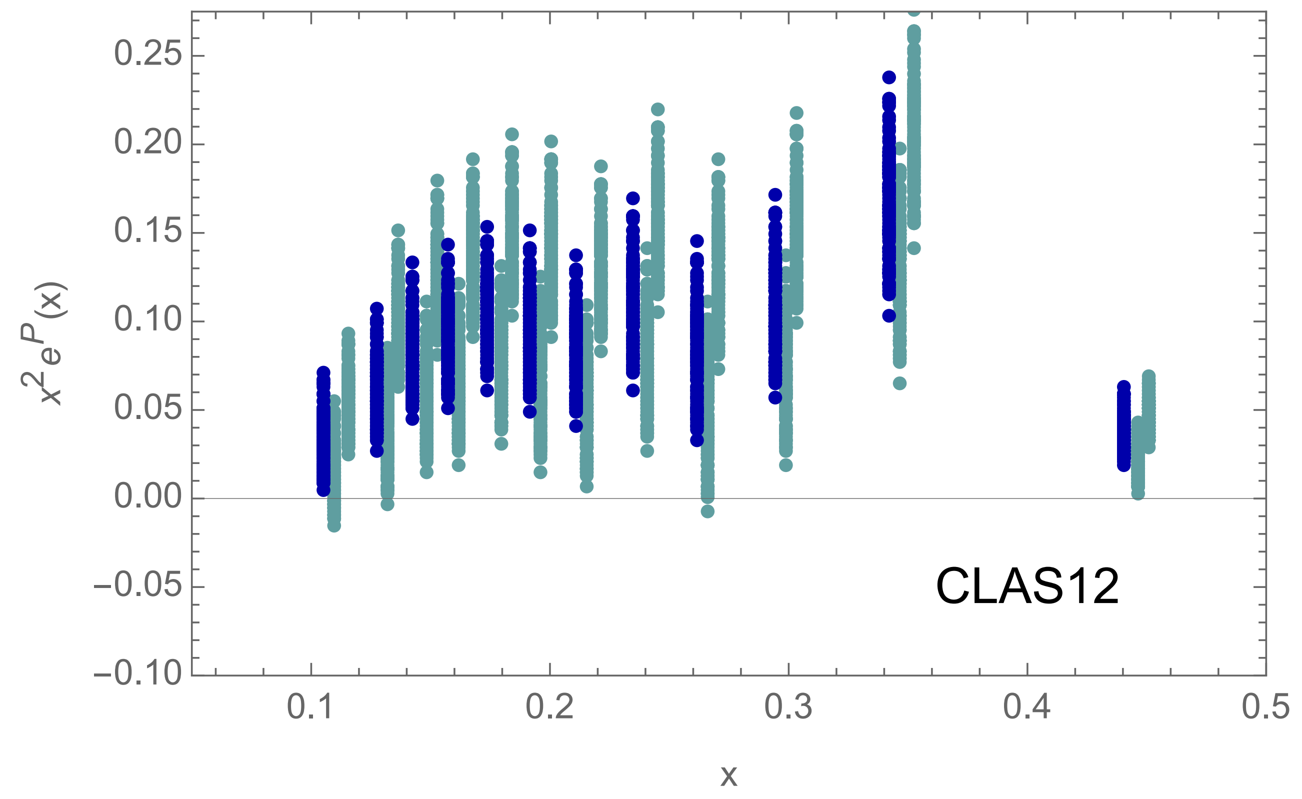
What is the probability for $e^P(x)$ to be non-zero?

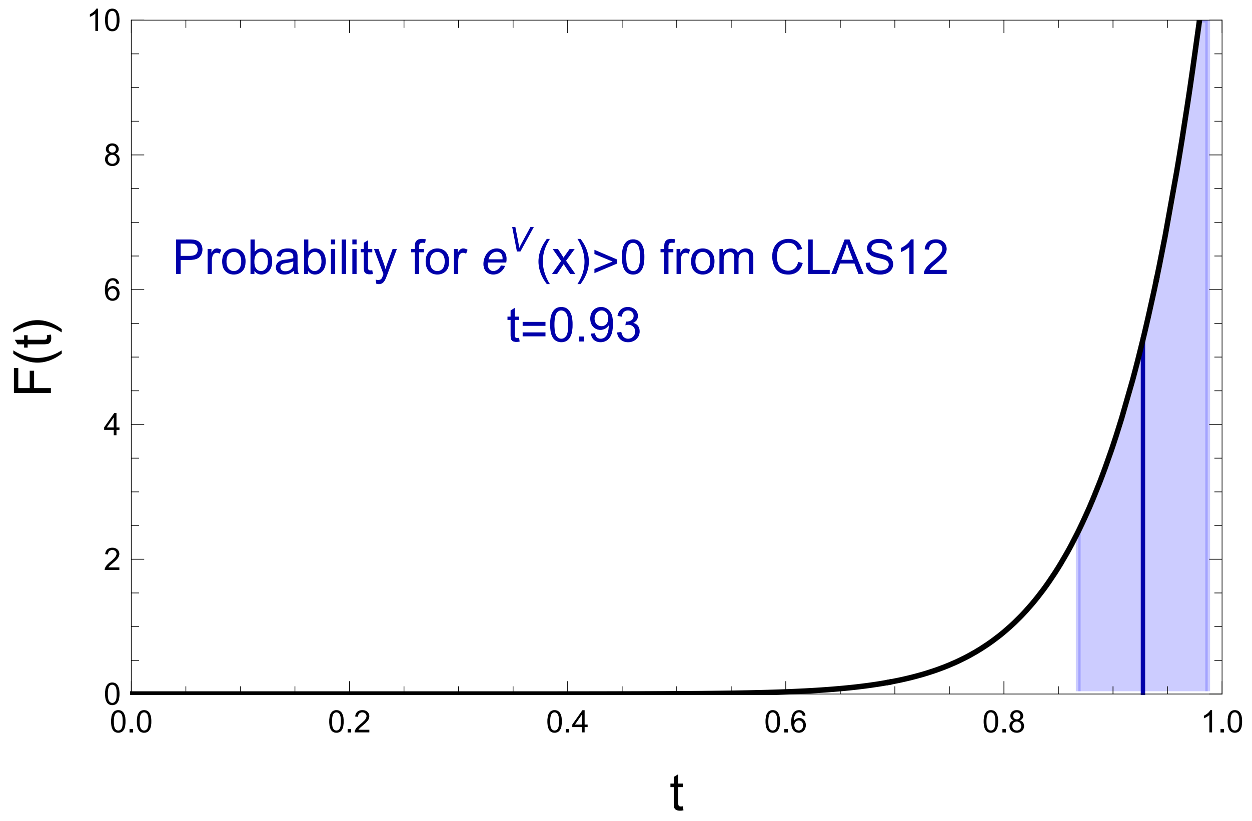
Probability that the proton combination is <u>greater</u> than zero —not exactly “how incompatible with zero is it?”— is a useful information from the point-by-point extraction of a collinear twist-3 PDF with a minimum set of approximations.



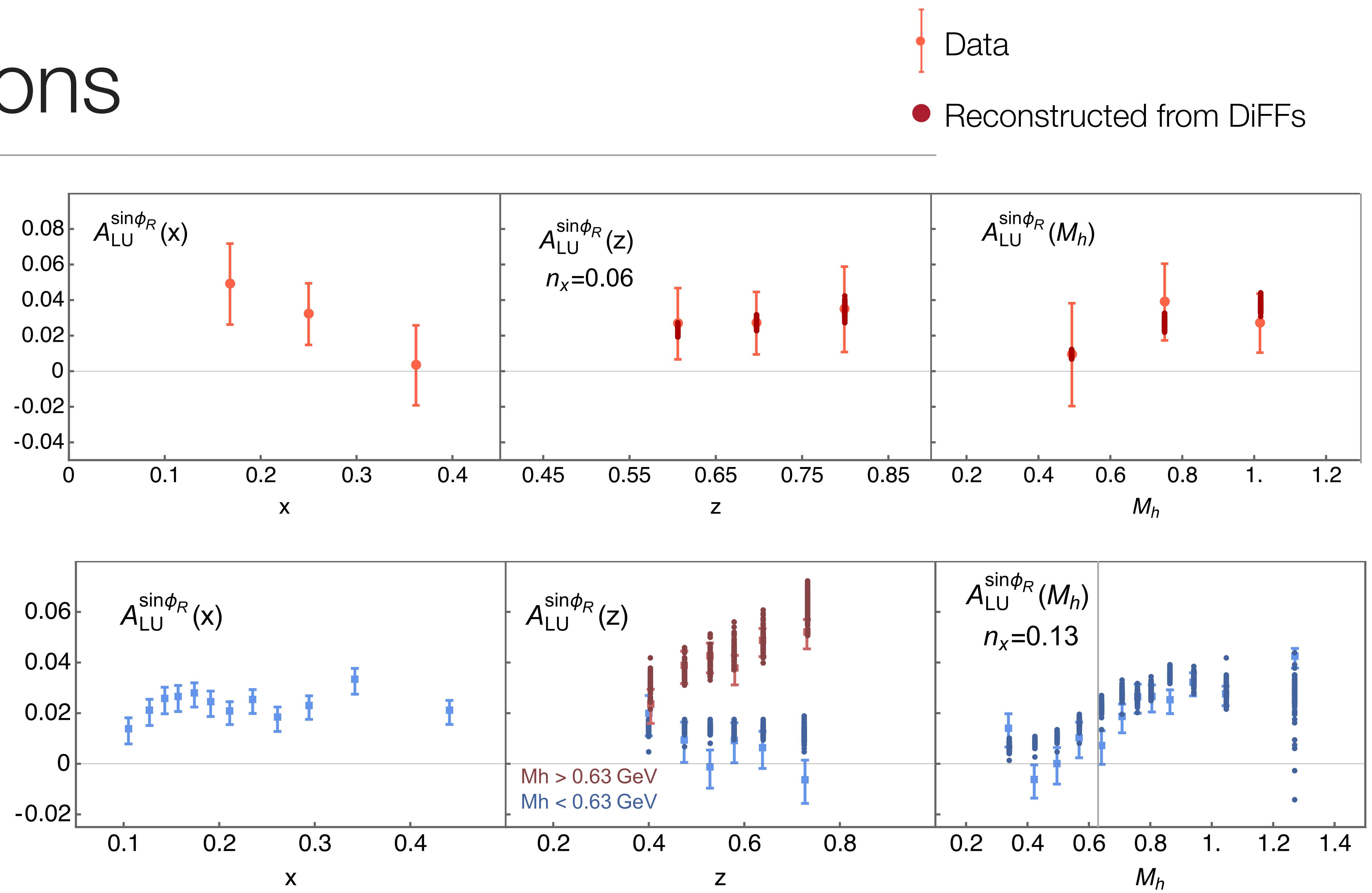


Mostly far from zero!





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] — see talk by Alexei Prokudin
  - ➡ Are twist-3 PDFs universal?

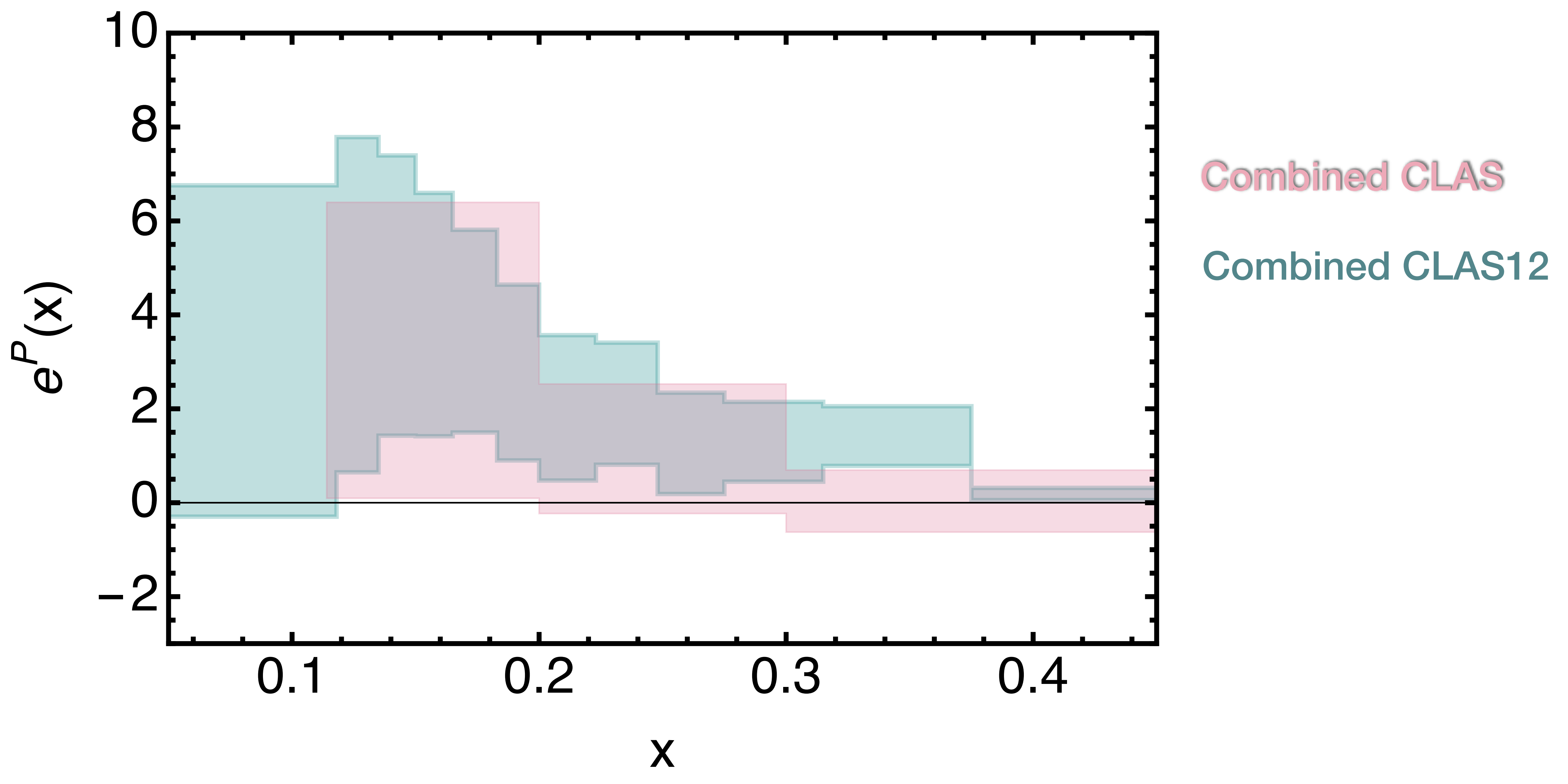
  Yet to be answered.

  Examples through TMD and dynamical twist-3 relations (e.g. Sivers and Qiu-Sterman) — see talk by Shohini Bhattacharya

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).



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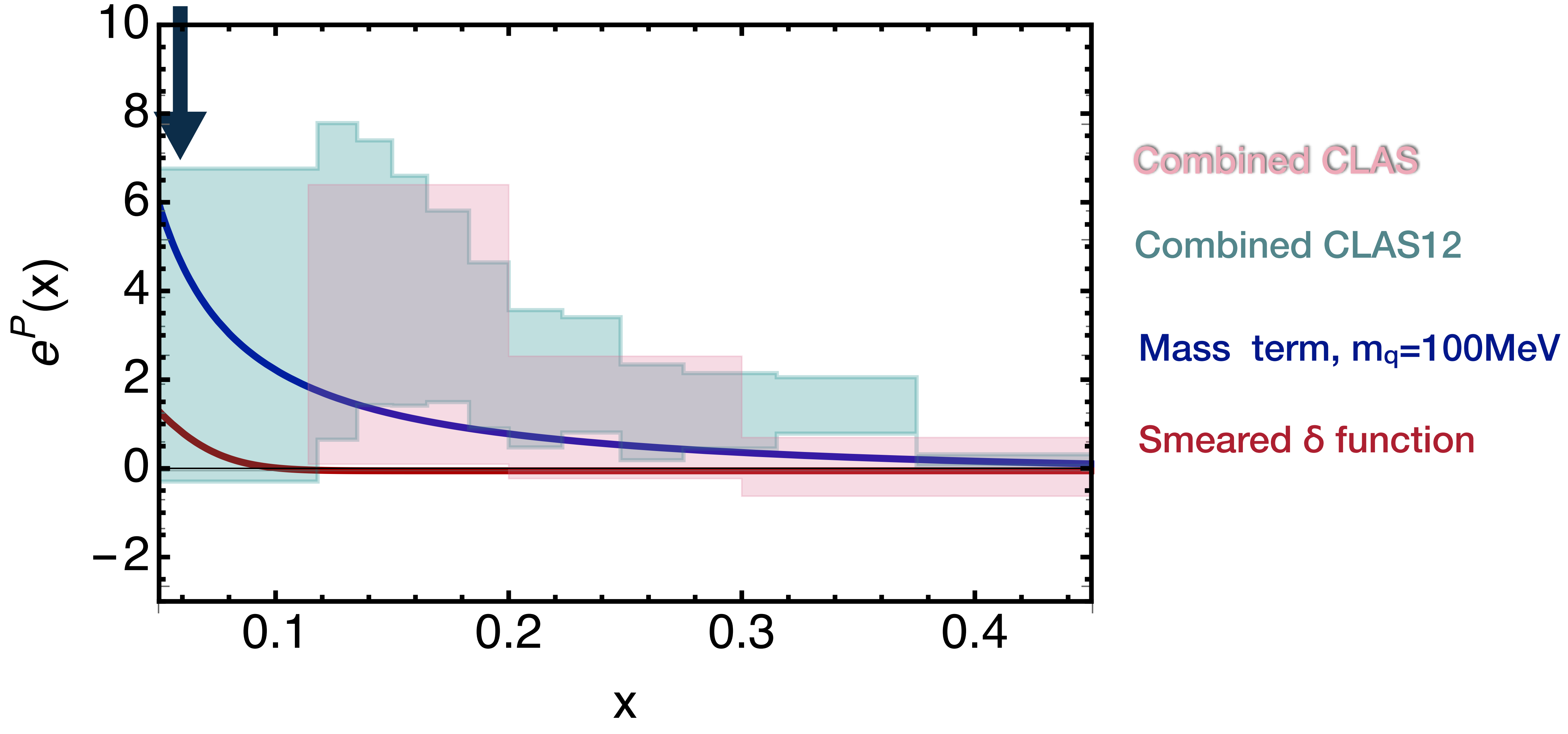
Some nonperturbative effects expected in the small(ish)-x region



Schematic models for illustration purpose only!

Moments will matter.

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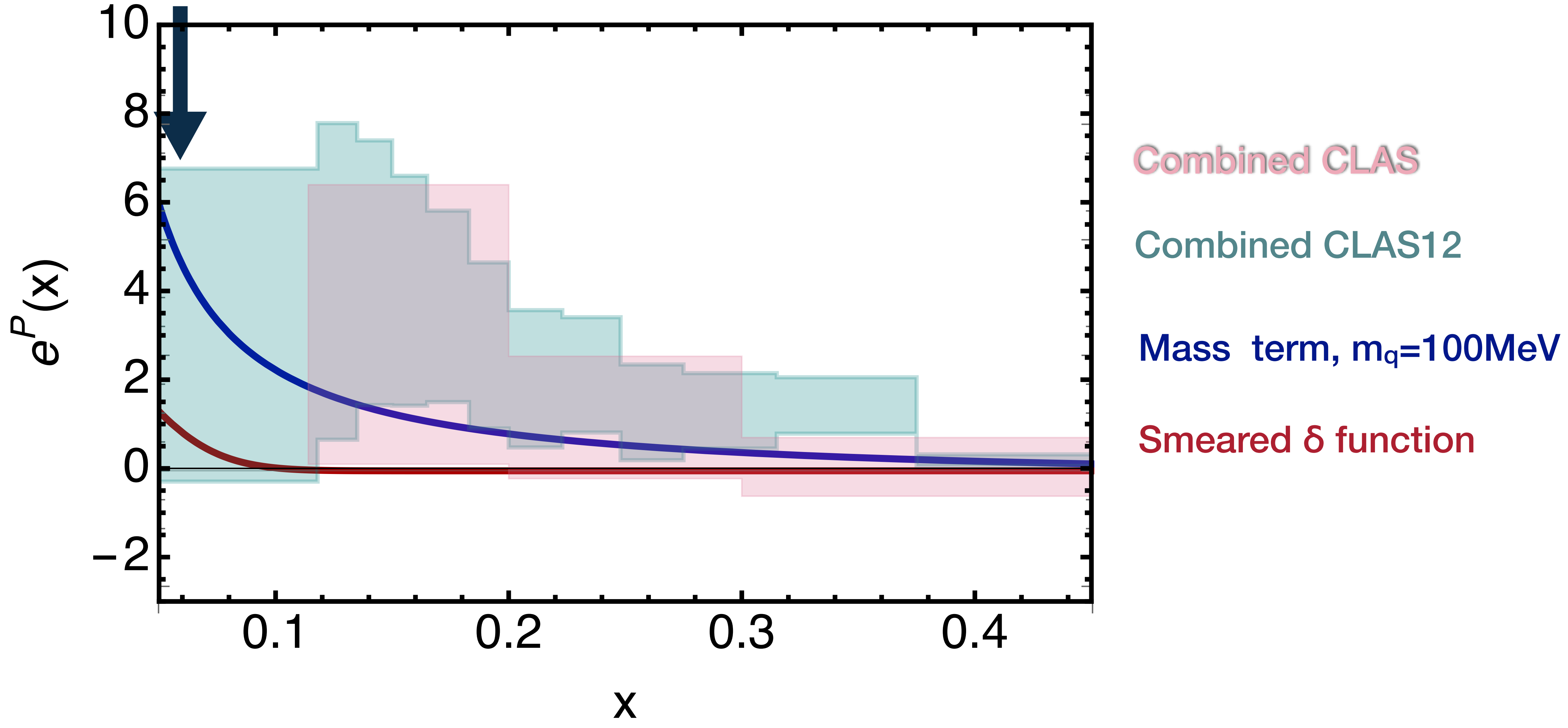
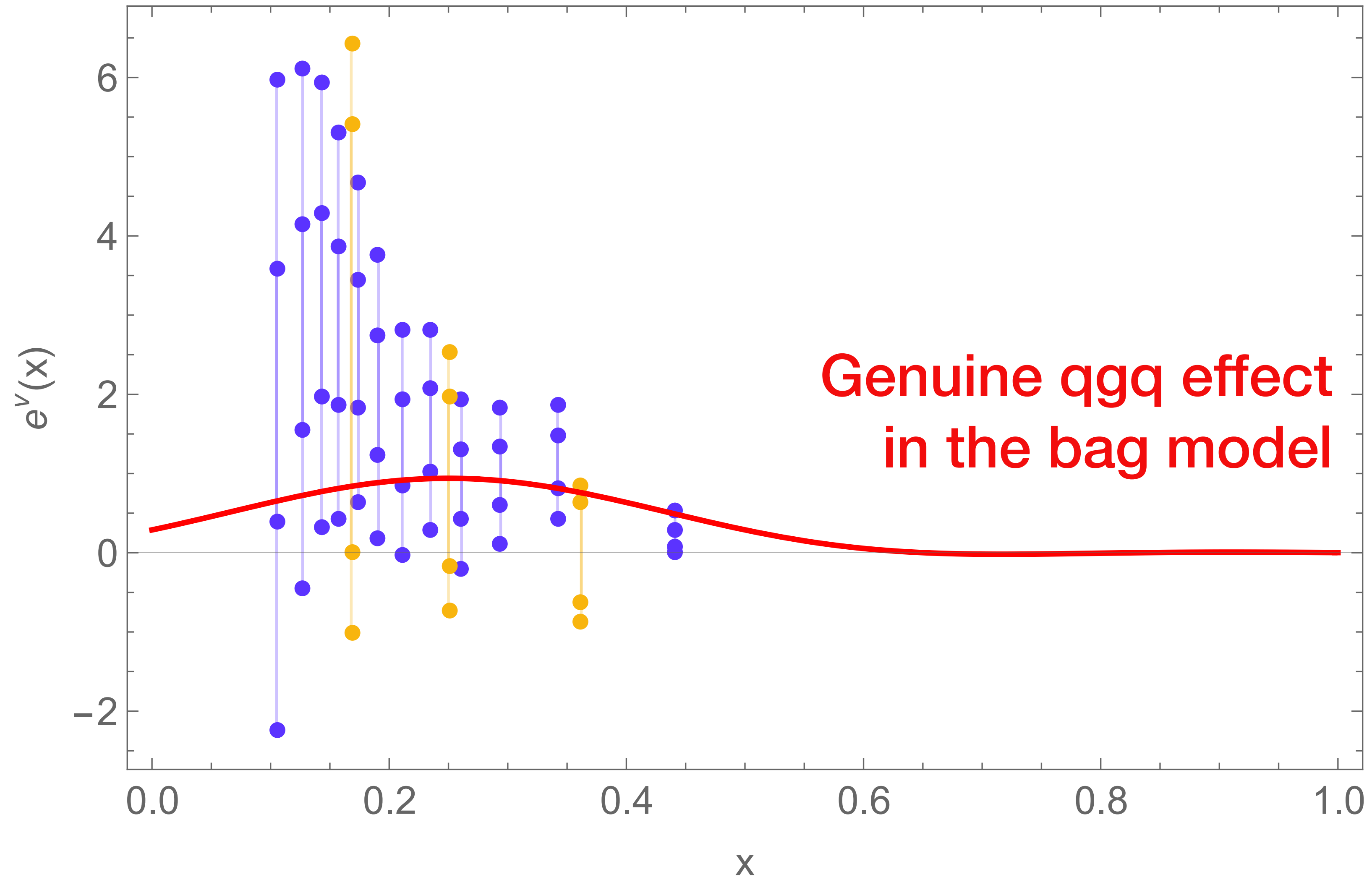


Other nonperturbative effects at not so small x



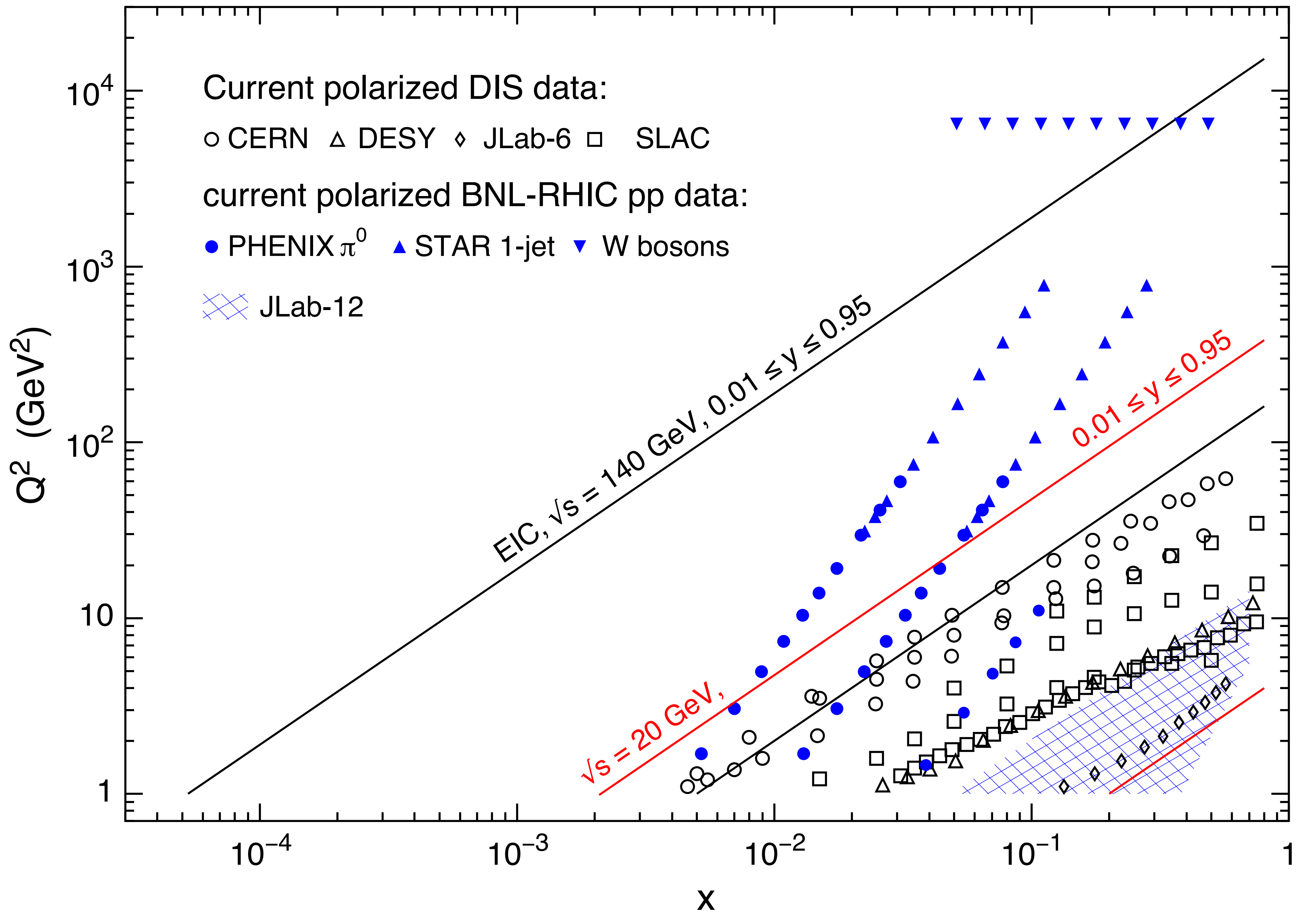
Courtesy of S. Calderón-Acosta
to be updated…

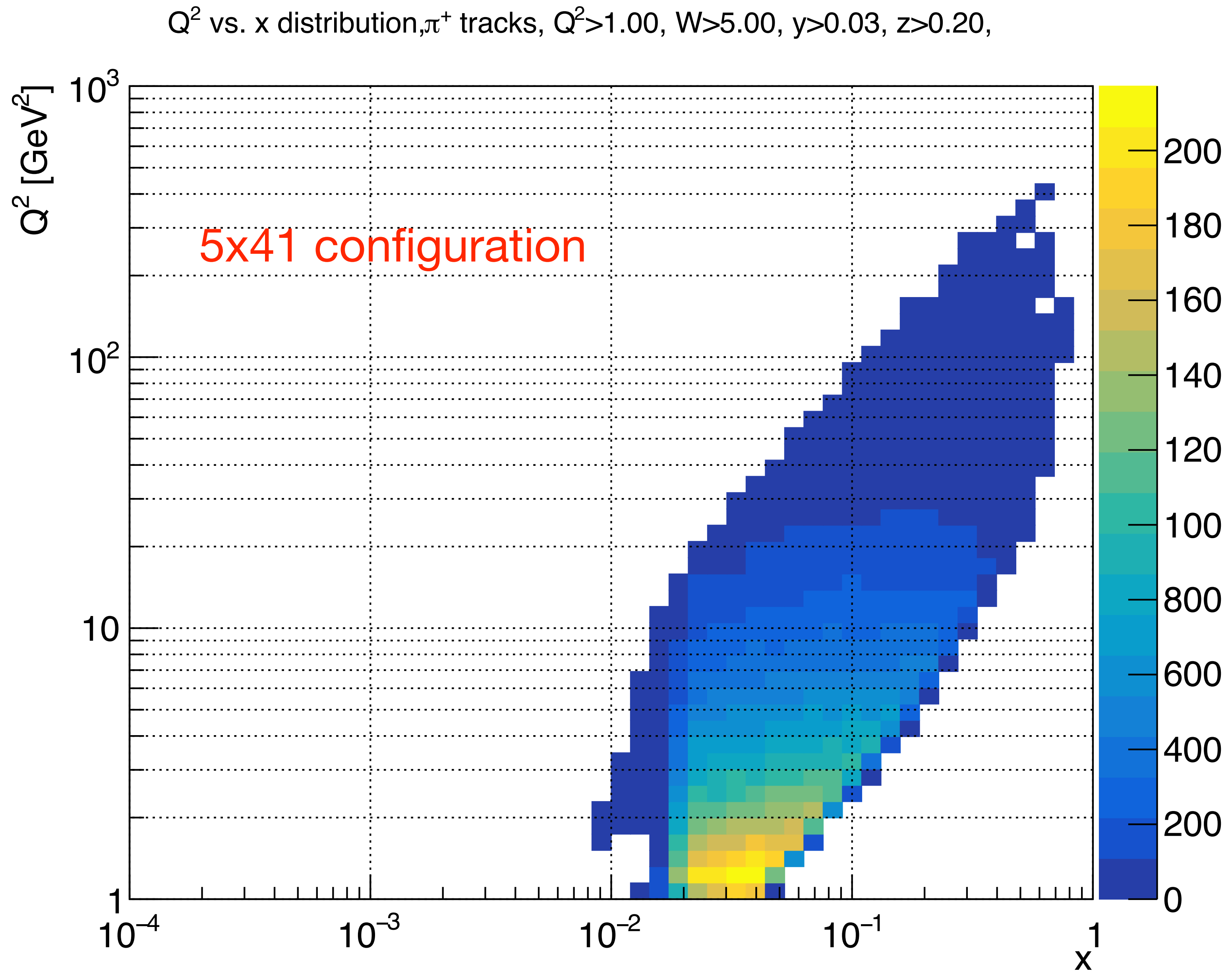
<u>Schematic models for illustration purpose only!</u>

<u>Moments will matter.</u>

Can we study qgq correlation at the EIC?

EIC Yellow Report [2103.05419]





Projections for IR2@EIC White Paper by A. Vossen

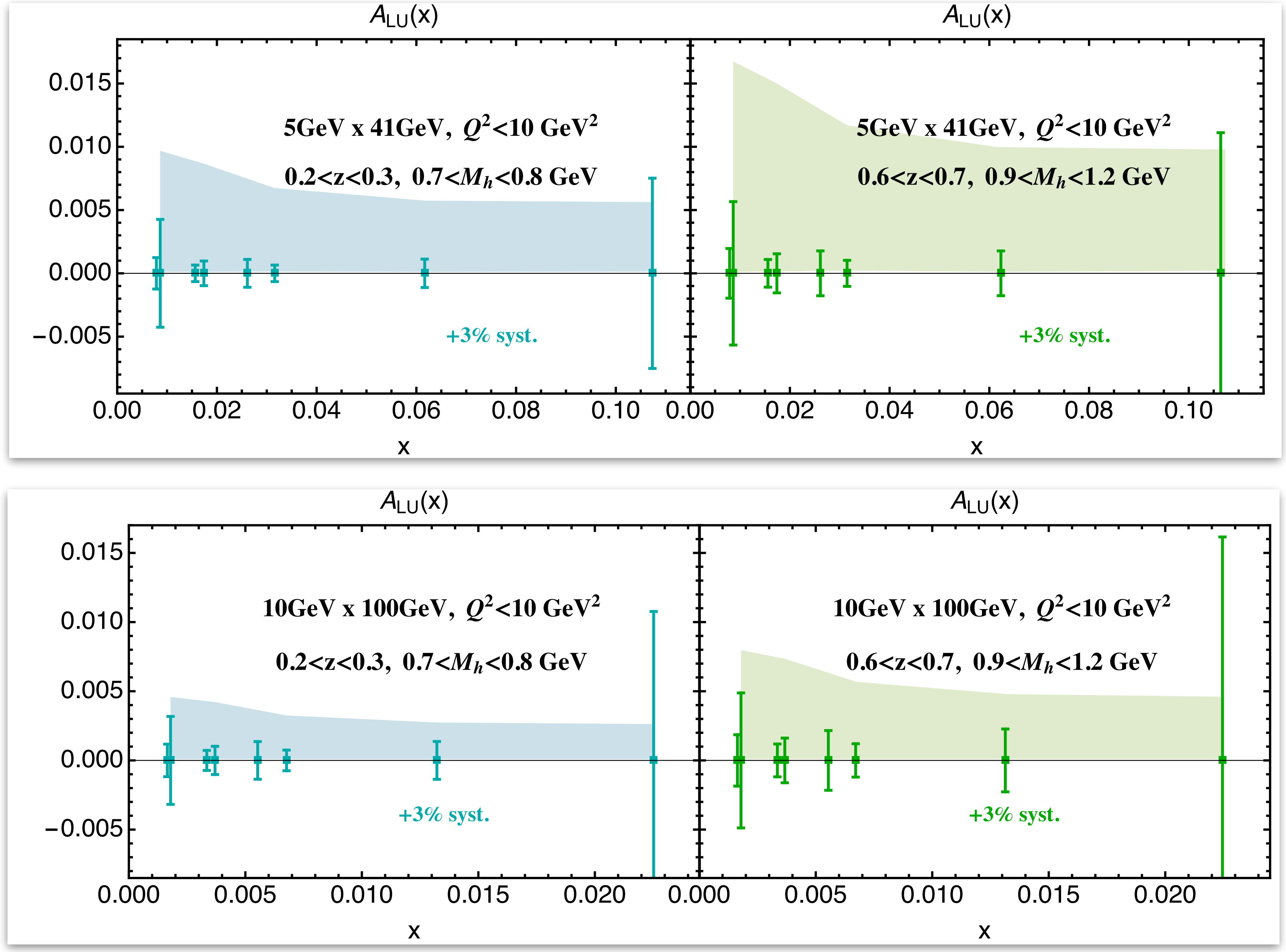
Future: EIC will cover low- to mid-Q^2 and smallish x values

- 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

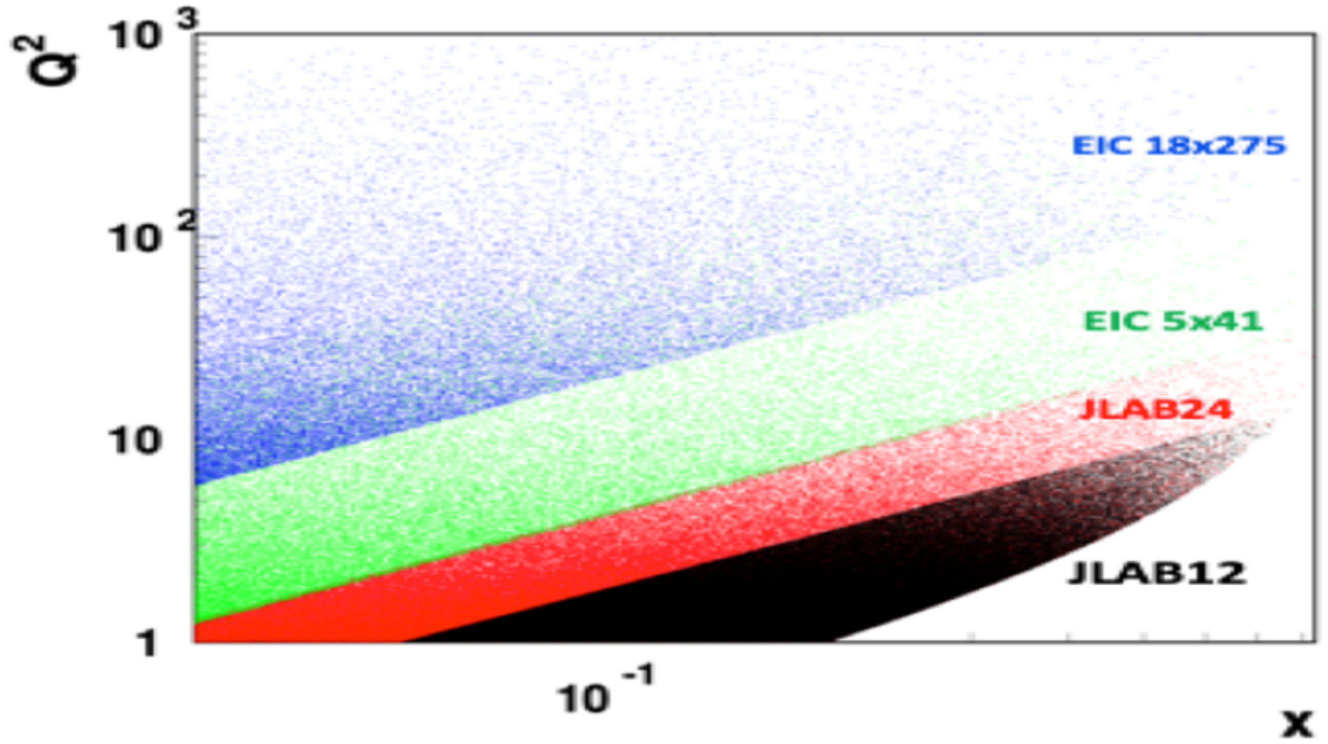


- Non-negligible for lowest beam configurations

↓

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 & White 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

Unpolarized PDFs at in the large x & low Q^2 regime

Denominator of asymmetries rely on first term in the expansion of their unpolarized structure function

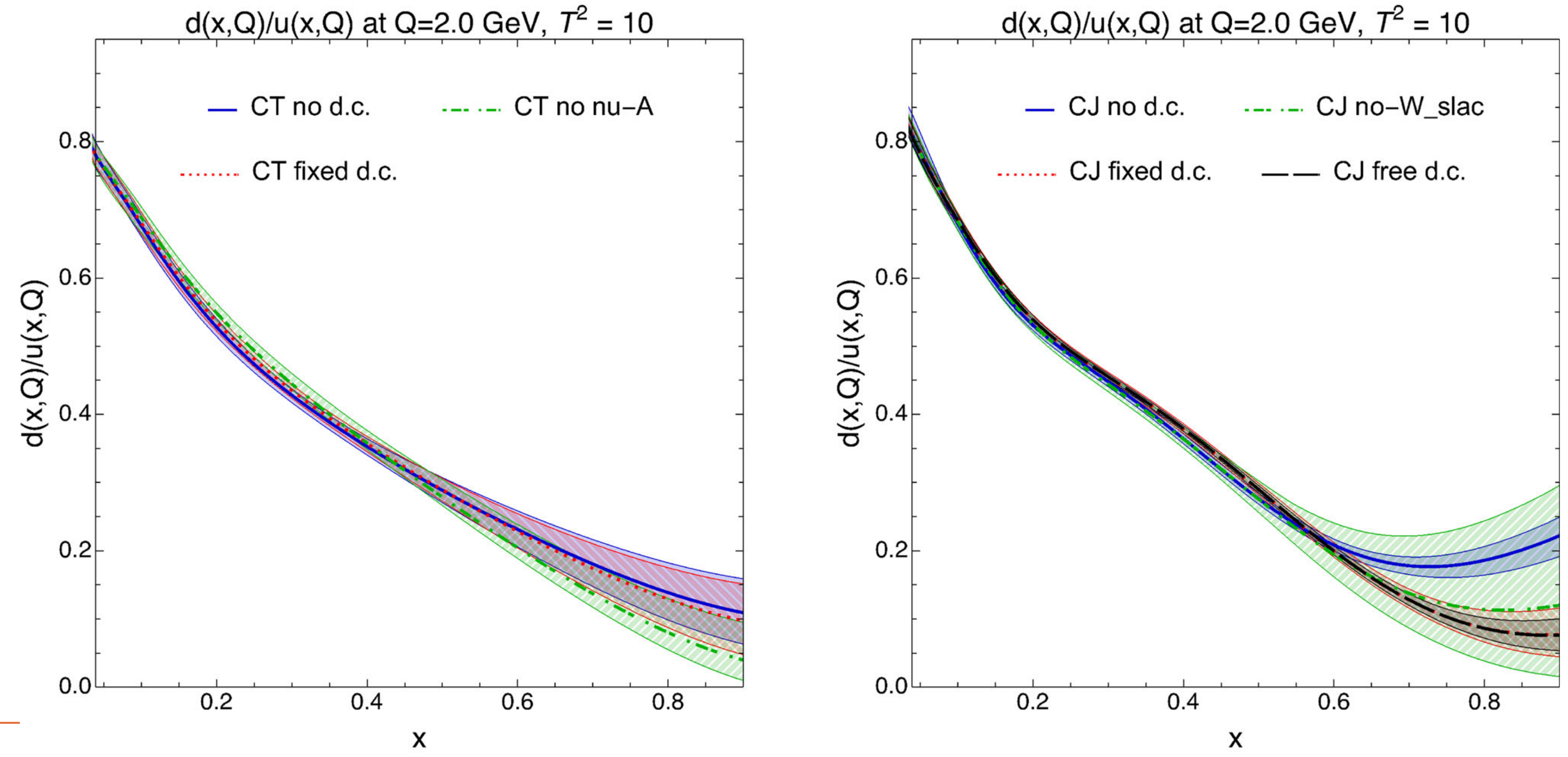
$$\frac{[\text{twist-3 PDF} \times \text{twist-2 FF}] + [\text{twist-2 PDF} \times \text{twist-3 FF}]}{\text{unpolarized}}$$

Unpolarized PDFs:
(large x, low Q^2) is either in the extrapolation region for high-energy global analyses —CT, MSHT, NNPDF
or requires non-perturbative corrections related to the resonance region, e.g. TMC, HT — CJ, JAM.

Change in degrees of freedom.
Increased complexity on which most SIDIS-based extractions at low Q^2 will rely.

“We can tackle higher twist parts”—see talk by Andrea Signori
Can we tackle the denominator?

Comparison of CTEQ-TEA (CT) and CTEQ-JLab (CJ) analyses [Accardi et al, EPJC81]



Towards a (global) analysis of the scalar PDF

Classes of *first principle* constraints for *x*-dependence of twist-3 PDFs

- support in $x \in [0,1]$
- end-point: $f(x = 1) = 0$
- sum rules as output: $< x >_n = \int_0^1 dx\, x^{n-1} f(x)$ — some moments evaluated on the lattice.
- no QCD evolution for now —DGLAP eqs known for twist-3 starting from n>2.

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Huge family of functions that might describe the data.

The role of parametrization is important — neural-network approaches treat the problem differently.

[Kovarik et al, Rev.Mod.Phys. 92 (2020)]

Consequently, the PDF uncertainty is comprised of four categories of contributions:

1. *Experimental uncertainties*, including statistical and correlated and uncorrelated systematic uncertainties of each experimental data set;
2. *Theoretical uncertainties*, including the absent higher-order and power-suppressed radiative contributions, as well as uncertainties in using parton showering programs to correct the data in order to compare to fixed-order perturbative cross sections;
3. *Parameterization uncertainties* associated with the choice of the PDF functional form;
4. *Methodological uncertainties*, such as those associated with the selection of experimental data sets, fitting procedures, and goodness-of-fit criteria.

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Systematize the study of the parametrization for a faithfull analysis.

$\Longrightarrow$ **Fantômas4QCD**

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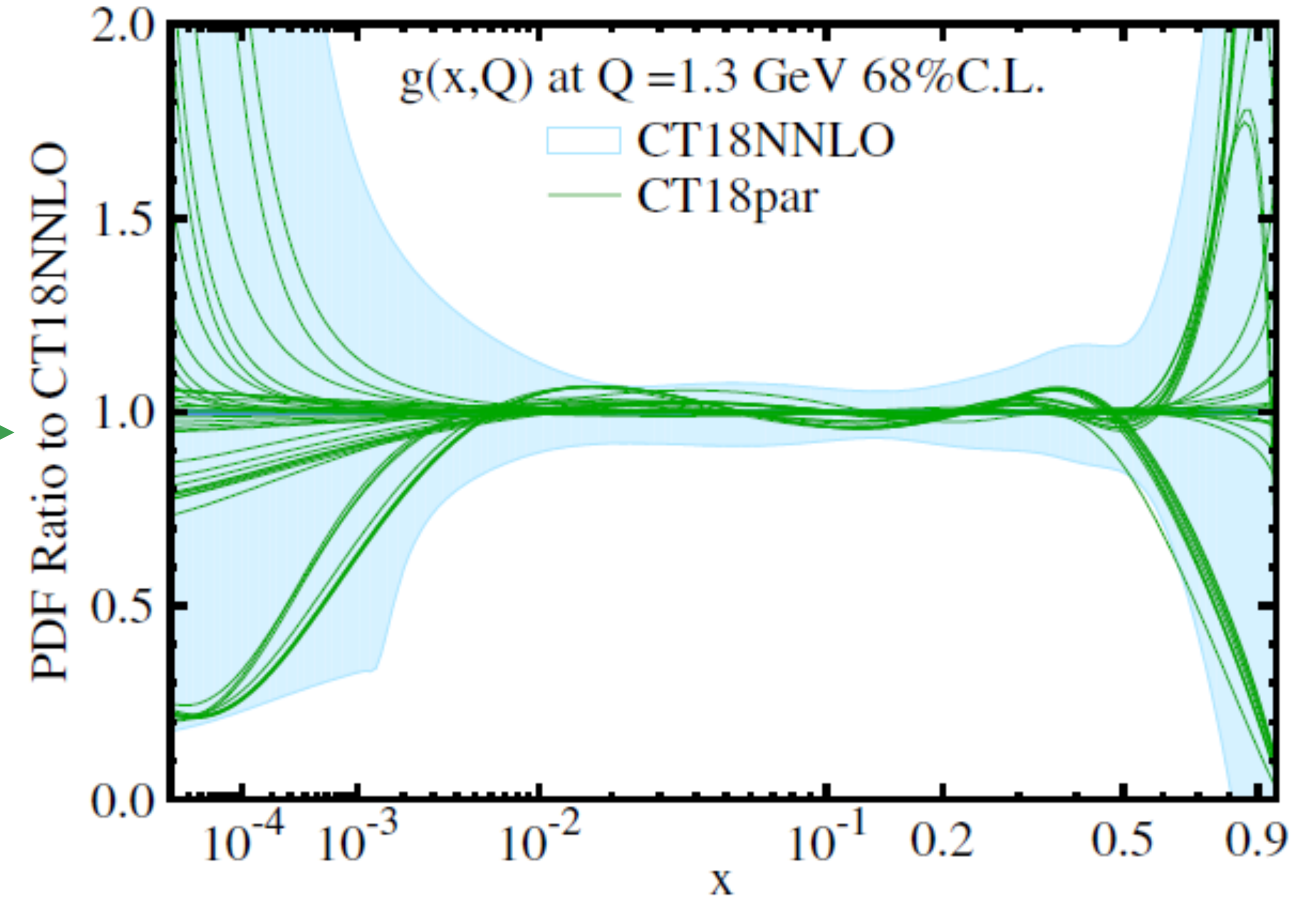
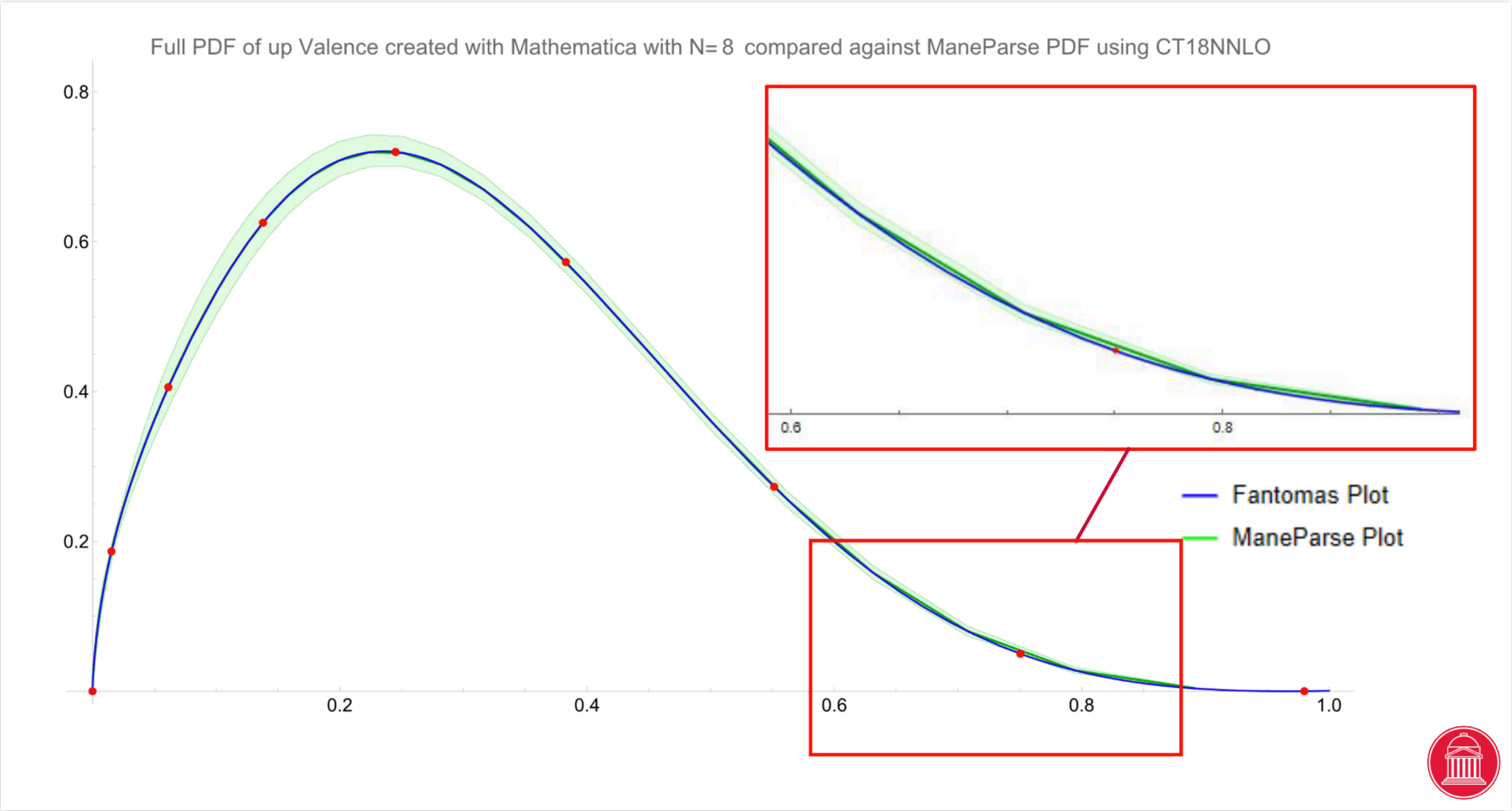
Fantômas4QCD

Uncertainty on the PDFs coming from the choice of functional form shown for the unpolarized PDFs of CT18.



[Hou et al, Phys.Rev.D 103 (2021)]

<u>Fantômas will propose an unbiased version of the analytic parametrizations for a variety of nonperturbative QCD functions.</u>



[Courtoy, Nadolsky & students, in progress]

Fantômas team

Ryan Guess (SMU)
Lucas Kotz (SMU)
Maximiliano Ponce Chávez (UNAM)
Varada Purohit (SMU)

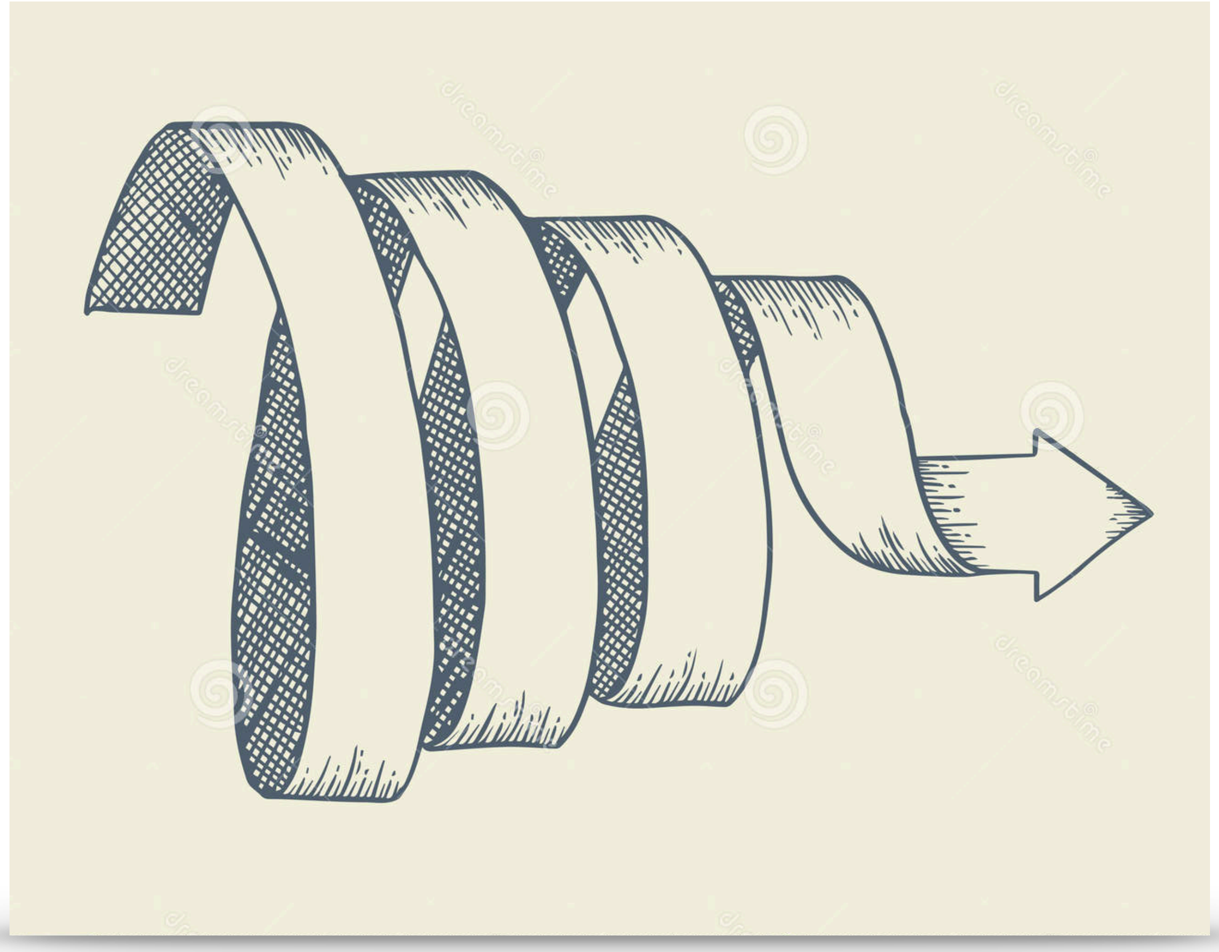
Pavel Nadolsky (SMU)
AC (UNAM)

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.

From the EIC wish list, higher twists 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]