Giornate Nazionali EIC_NET 2024 — Bologna

27-28 June 2024

Precision studies of QCD in the low energy domain of the EIC: a personal view

INFN
Istituto Nazionale di Fisica Nucleare
Sezione Pavia

Marco Radici

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ePIC

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The reference paper

Precision Studies of QCD in the Low Energy Domain of the EIC

V.D. Burkert,[1] L. Elouadrhiri,[1] A. Afanasev,[2] J. Arrington,[3] M. Contalbrigo,[4] W. Cosyn,[5,6] A. Deshpande,[7] D.I. Glazier,[8] X. Ji,[9,10] S. Liuti,[11] Y. Oh,[12,13] D. Richards,[1] T. Satogata,[1] A. Vossen,[14,1] H. Abdolmaleki,[15] A. Albataineh,[16] C.A. Aidala,[17] C. Alexandrou,[18] H. Avagyan,[1] A. Bacchetta,[19] M. Baker,[1] F. Benmokhtar,[20] J.C. Bernauer,[7,21] C. Bissolotti,[19] W. Briscoe,[2] D.Byers,[14] Xu Cao,[22] C.E. Carlson,[23] K. Cichy,[24] I.C. Cloet,[25] C. Cocuzza,[26] P.L. Cole,[27] M. Constantinou,[26] A. Courtoy,[28] H. Dahiyah,[29] K. Dehmelt,[7] S. Diehl,[30,31] C. Dilks,[14] C. Djalali,[32] R. Dupré,[33] S.C. Dusa,[1] B. El-Bennich,[34] L. El Fassi,[35] T. Frederico,[36] A. Freese,[37] B.R. Gamage,[1] L. Gamberg,[38] R.R. Ghoshal,[1] F.X. Girod,[1] V.P. Goncalves,[39,22,40] Y. Gotra,[1] F.K. Guo,[41,42] X. Guo,[9] M. Hattawy,[43] Y. Hatta,[44] T. Hayward,[30] O. Hen,[45] G. M. Huber,[46] C. Hyde,[43] E.L. Isupov,[47] B. Jacak,[3] W. Jacobs,[48] A. Jentsch,[44] C.R Ji,[49] S. Joosten,[25] N. Kalantarians,[50] Z. Kang,[51,52,53] A. Kim,[30,1] S. Klein,[3] B. Kriesten,[10] S. Kumano,[54] A. Kumar,[55] K. Kumericki,[56] M. Kuchera,[57] W.K. Lai,[58,59,51] Jin Li,[60] Shujie Li,[3] W. Li,[61] X. Li,[62] H.-W. Lin,[63] K.F. Liu,[64] Xiaohui Liu,[65,66] P. Markowitz,[5] V. Mathieu,[67,68] M. McEneaney,[14] A. Mekki,[69] J.P. B. C. de Melo,[70] Z.E. Meziani,[25] R. Milner,[45] H. Mkrtchyan,[71] V. Mochalov,[72,73] V. Mokeev,[1] V. Morozov,[74] H. Moutarde,[75] M. Murray,[76] S. Mtingwa,[77] P. Nadel-Turonski,[53] V.A. Okorokov,[73] E. Onyie,[1] L.L.Pappalardo,[4,78] Z. Papandreou,[79] C. Pecar,[14] A. Pilloni,[80,81] B. Pire,[82] N. Polys,[83] A. Prokudin,[84,1] M. Przybycien,[85] J-W. Qiu,[1] M. Radici,[86] R. Reed,[87] F. Ringer,[1,43] B.J. Roy,[88] N. Sato,[1] A. Schäfer,[89] B. Schmookler,[90] G. Schnell,[91] P. Schweitzer,[30] R. Seidl,[92,21] K.M. Semenov-Tian-Shansky,[12,93,94] F. Serna,[95,96] F. Shaban,[97] M.H. Shabestari,[98] K. Shiells,[10] A. Signori,[99,100] H. Spiesberger,[101] I. Strakovsky,[2] R.S. Sufian,[23,1] A. Szczepaniak,[102,1] L. Teodorescu,[103] J. Terry,[51,52] O. Teryaev,[104] F. Tessarotto,[105] C. Timmer,[1] Abdel Nasser Tawfik,[106] L. Valenzuela Cazares,[107] A. Vladimirov,[89,108] E. Voutier,[33] D. Watts,[109] D. Wilson,[110] D. Winney,[111,112] B. Xiao,[113] Z. Ye,[114] Zh. Ye,[115] F. Yuan,[3] N. Zachariou,[109] I. Zahed,[7] J.L. Zhang,[60] Y. Zhang,[1] and J. Zhou[116]

Prog. Part. Nucl. Phys. **131** (2023) 104032, arXiv:2211.15746

Motivation

from the FOREWORD:

... The goal of the initiative leading to this white paper was to take a fresh look at the changing landscape of the science underlying the need of a complementary approach towards the overall optimization and the execution of the EIC science program, and include, where appropriate, recent scientific advancements and challenges that go beyond the original motivation for the EIC. ...

- kickoff meeting (hybrid), MIT Dec. 15-16 2020 https://indico.bnl.gov/event/9794
- 1st workshop (online), ANL+CFNS Mar. 17-19 2021 https://indico.bnl.gov/event/10677
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... It identifies part of the science program in the precision studies of QCD that require or greatly benefit from the high luminosity and low to medium center-of-mass energies, and it documents the scientific underpinnings in support of such a program. The objective of this document is to help define the path towards the realization of the second interaction region.

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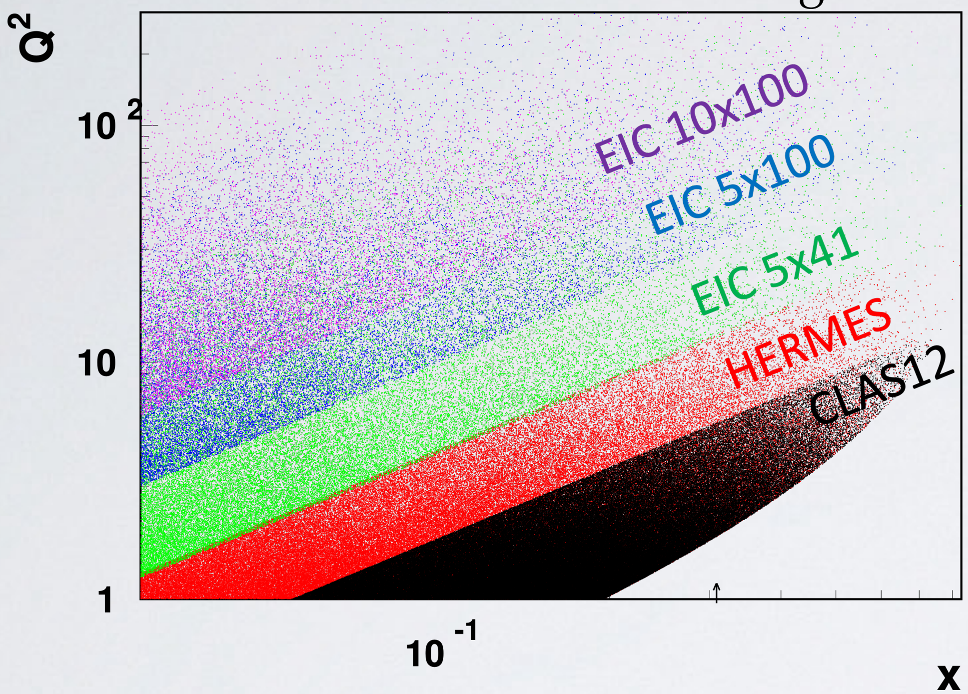
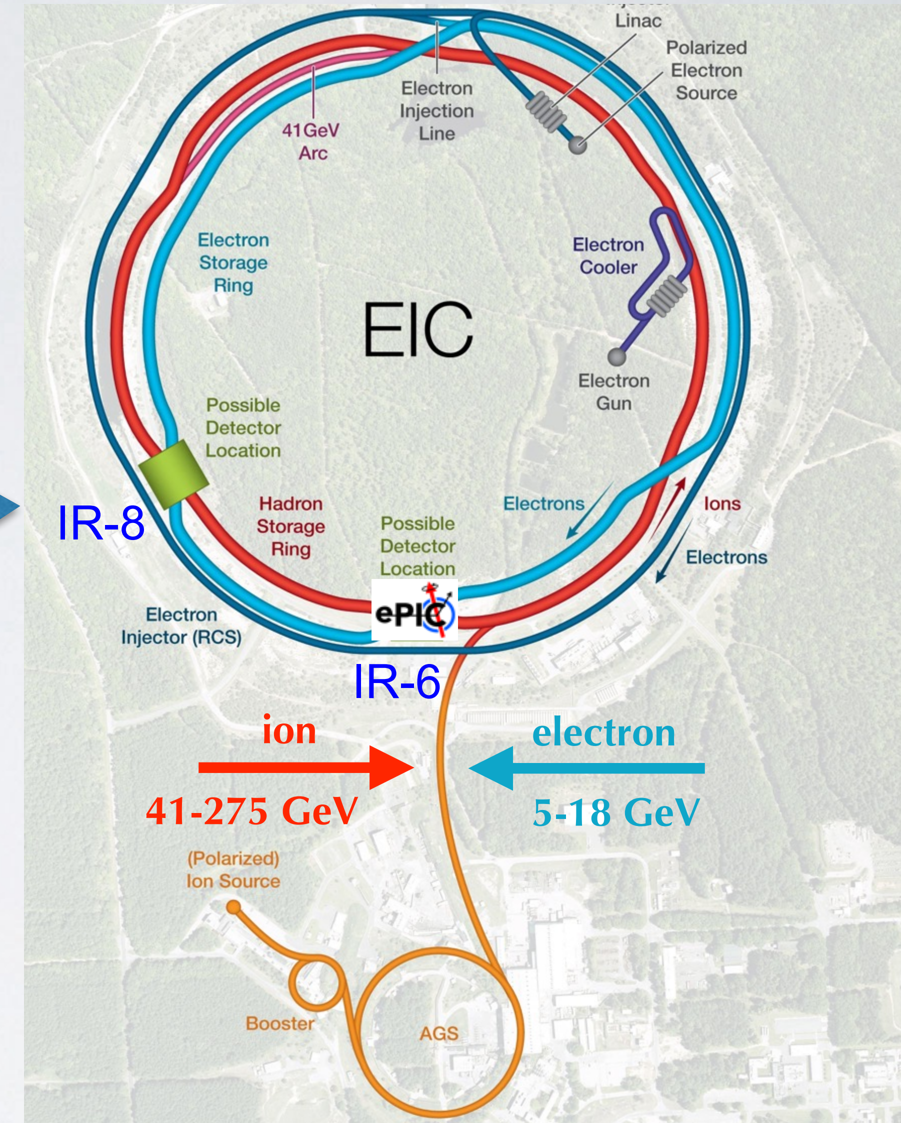
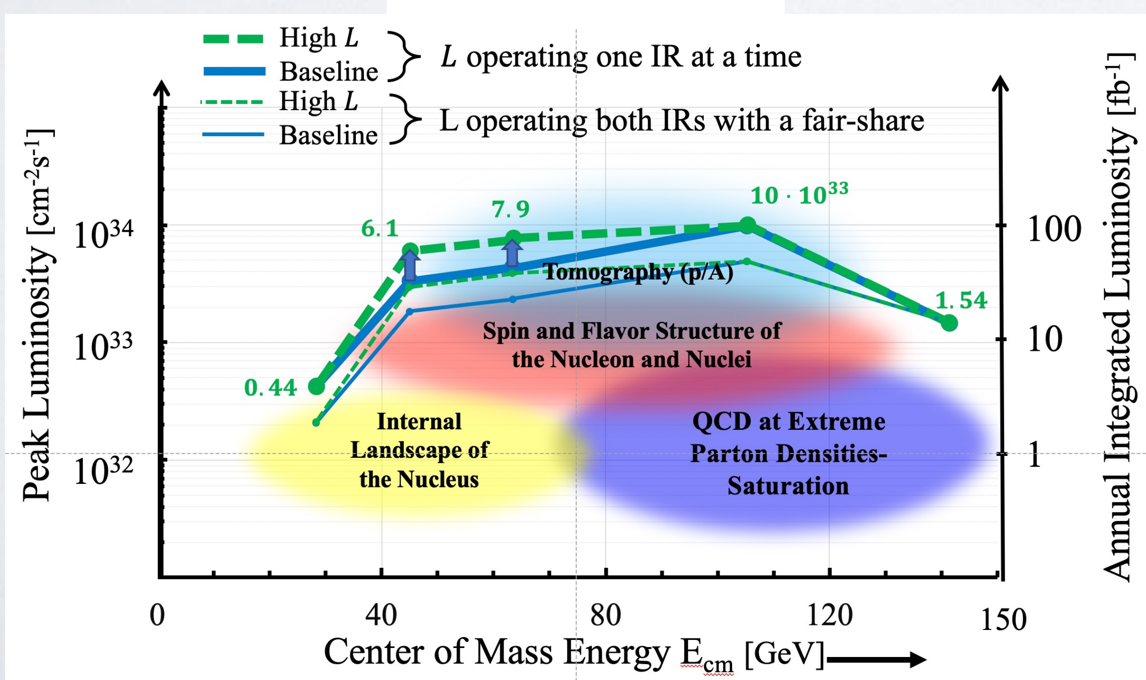
Motivation

Fig.19 of paper

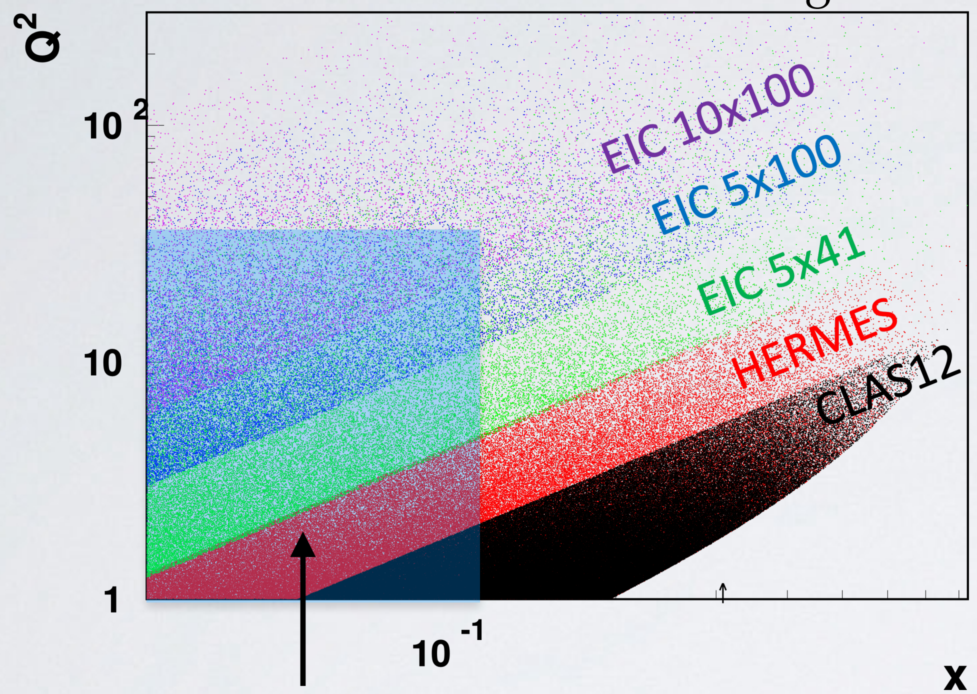


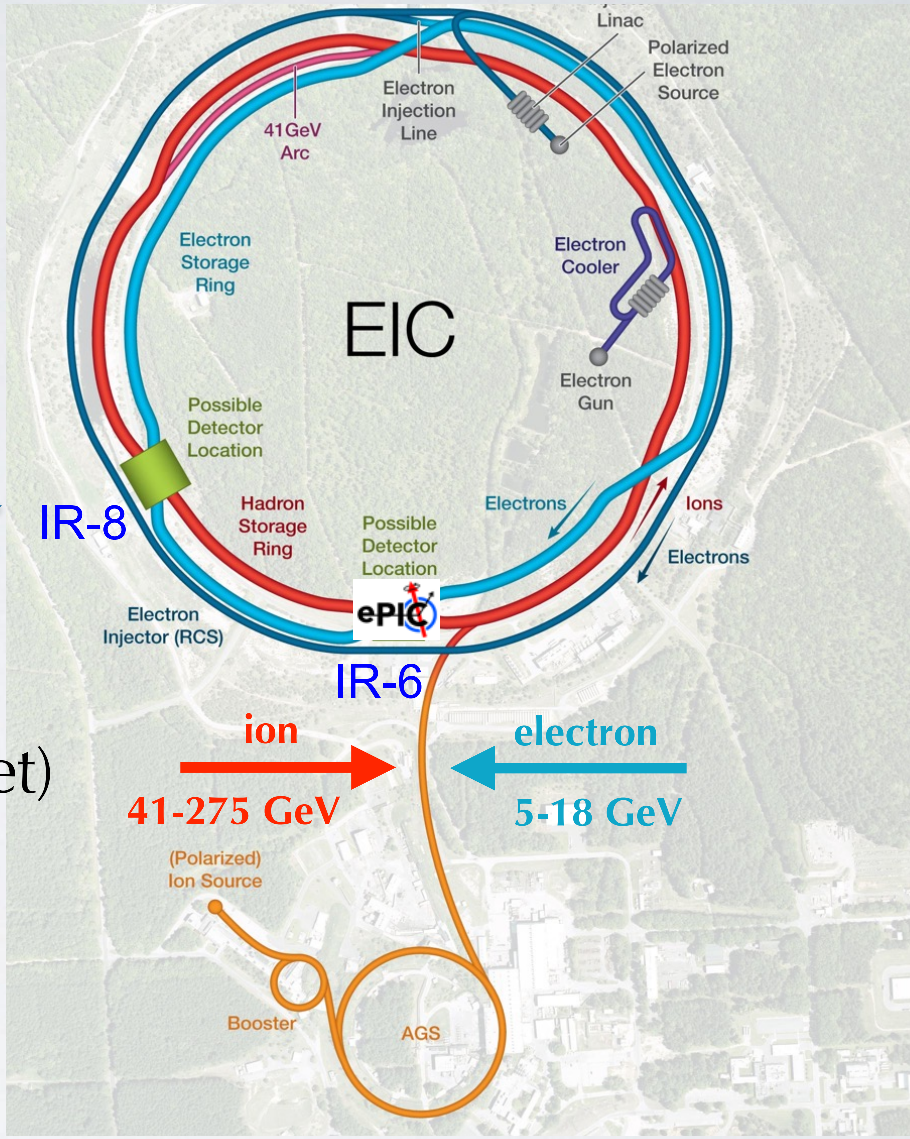




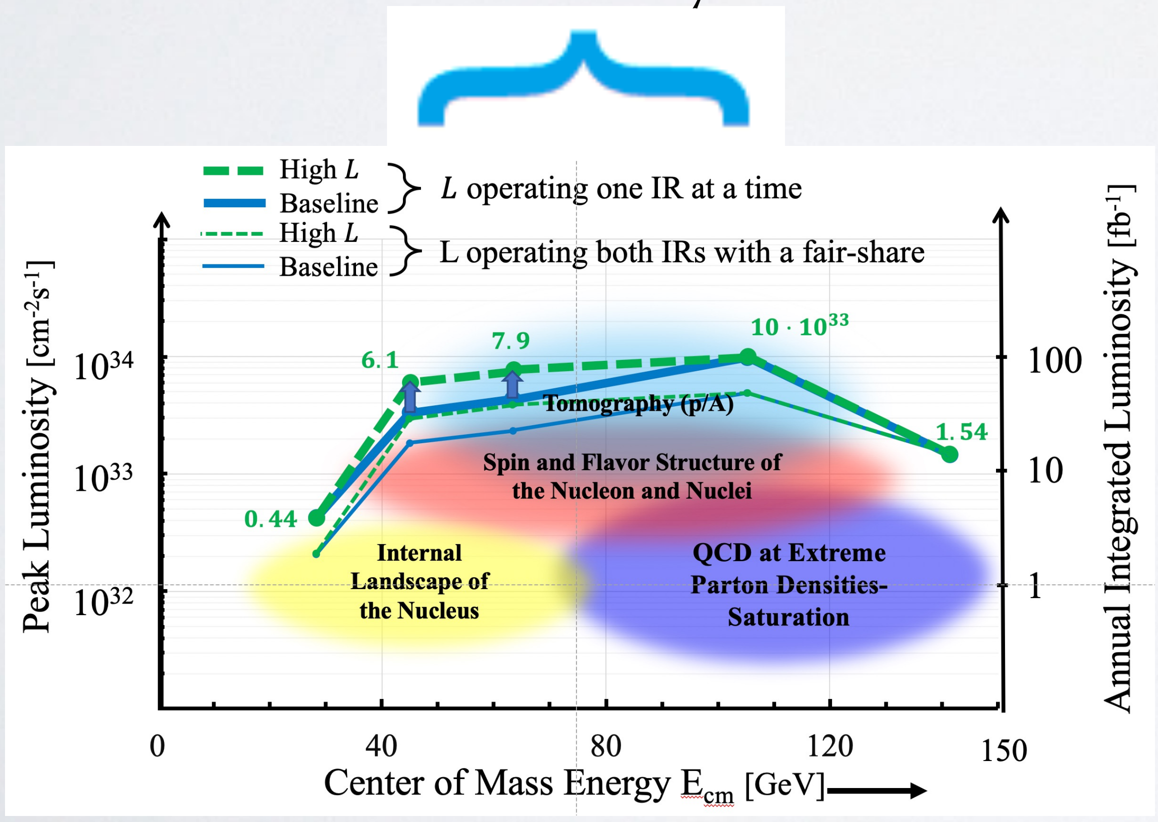
Motivation

Fig.19 of paper





area complementary to valence-like regime (fixed target) and with maximum luminosity



Outline of paper

I. Executive Summary

II. GPDs - 3D Imaging and mechanical properties of the nucleon

III. Mass and spin of the nucleon

IV. Accessing the Momentum Dependent Structure of the nucleon in Semi-Inclusive Deep Inelastic Scattering

V. Exotic meson spectroscopy

VI. Science highlights of light and heavy nuclei

VII. Precision studies of Lattice QCD in the EIC era

VIII. Science of far forward particle detection

IX. Radiative effects and corrections

X. Artificial Intelligence applications

XI. The EIC interaction regions for a high impact science program with discovery potential

too many topics for a thorough overview in 30 min.

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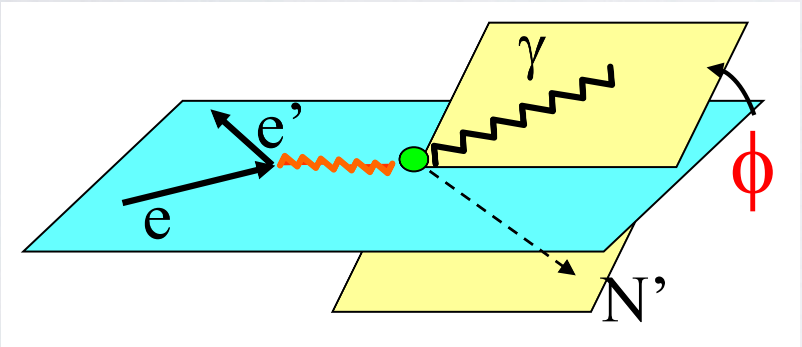
personal list of some top measurements

Exclusive processes

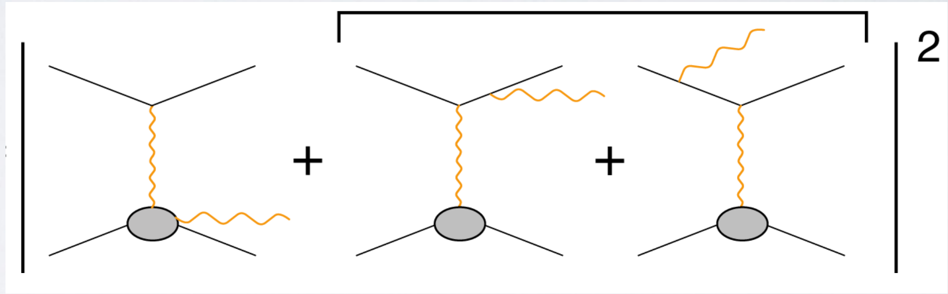
II. GPDs - 3D Imaging and mechanical properties of the nucleon

III. Mass and spin of the nucleon

Deeply Virtual Compton Scattering (DVCS)



DVCS Bethe-Heitler

$d\sigma \sim$ 

interference
of BH-DVCS
amplitudes

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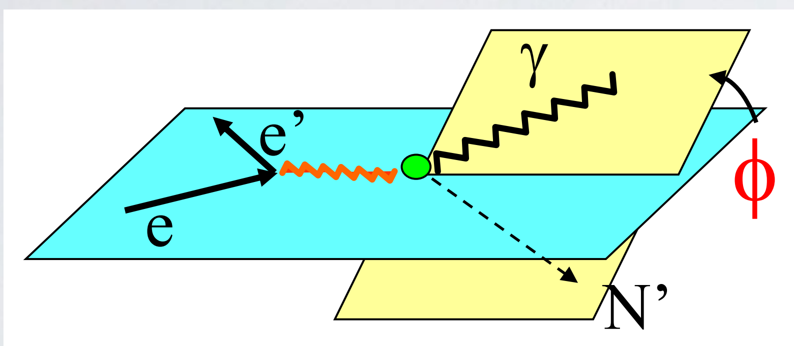
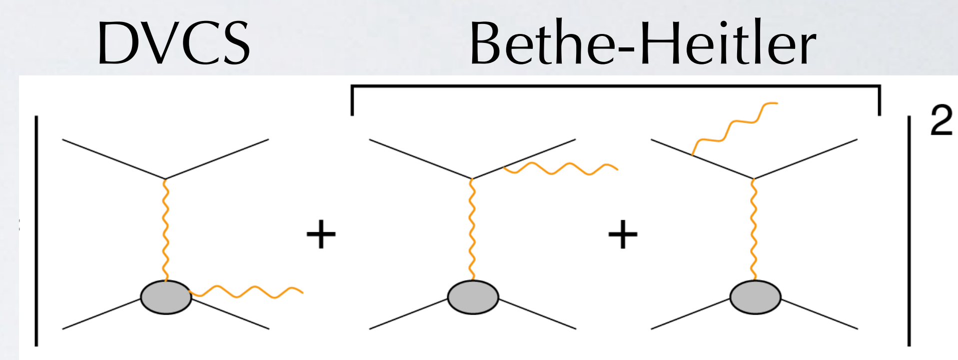
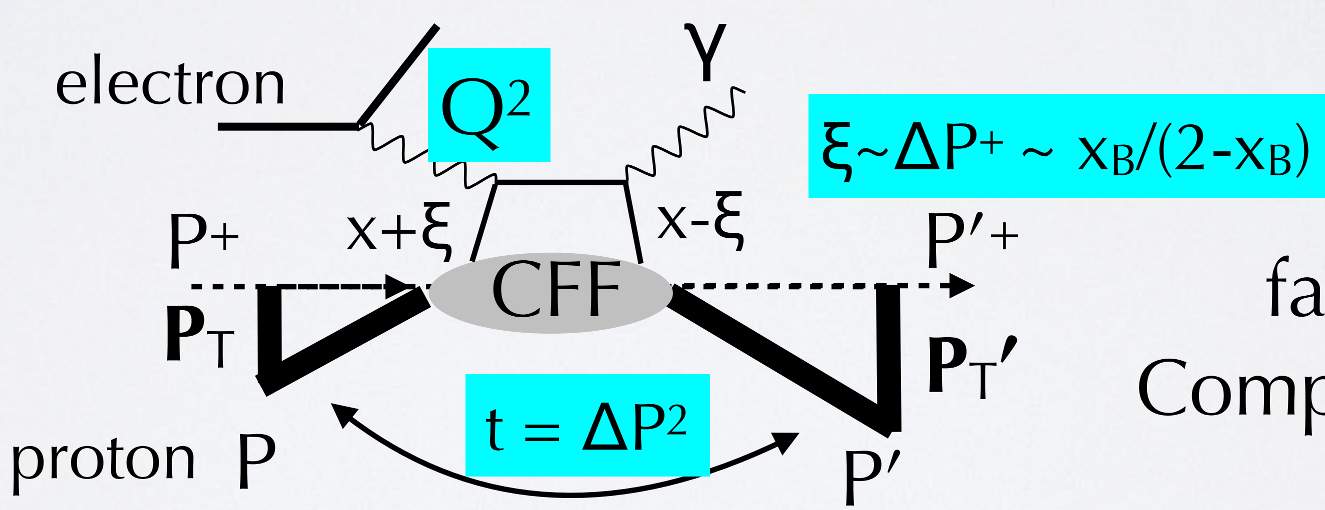


$d\sigma \sim$



interference of BH-DVCS amplitudes



$t \ll Q^2$

factorization of Compton Form Factors (CFF)

Exclusive processes

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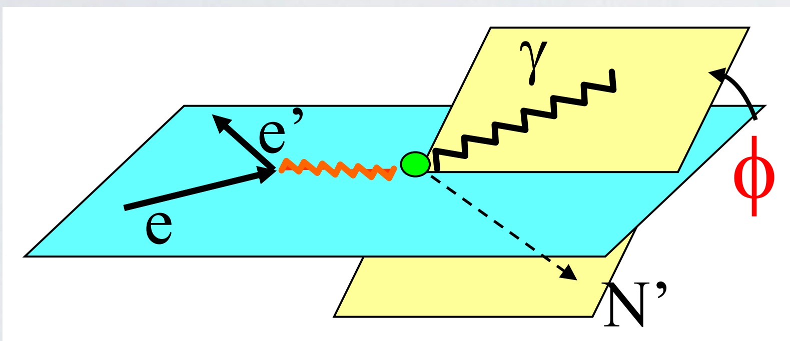

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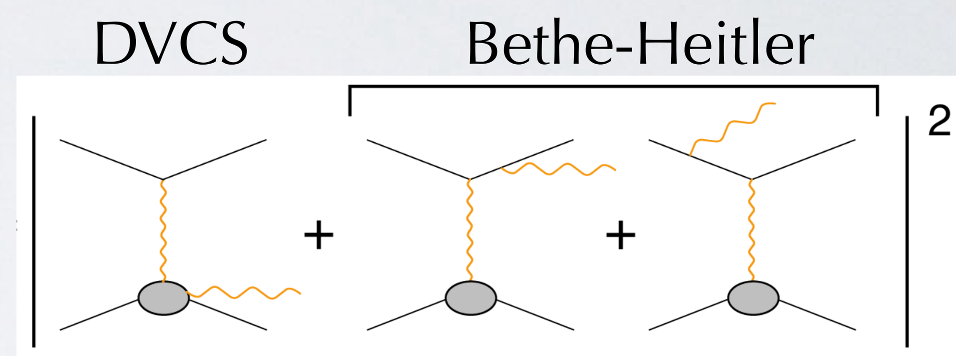
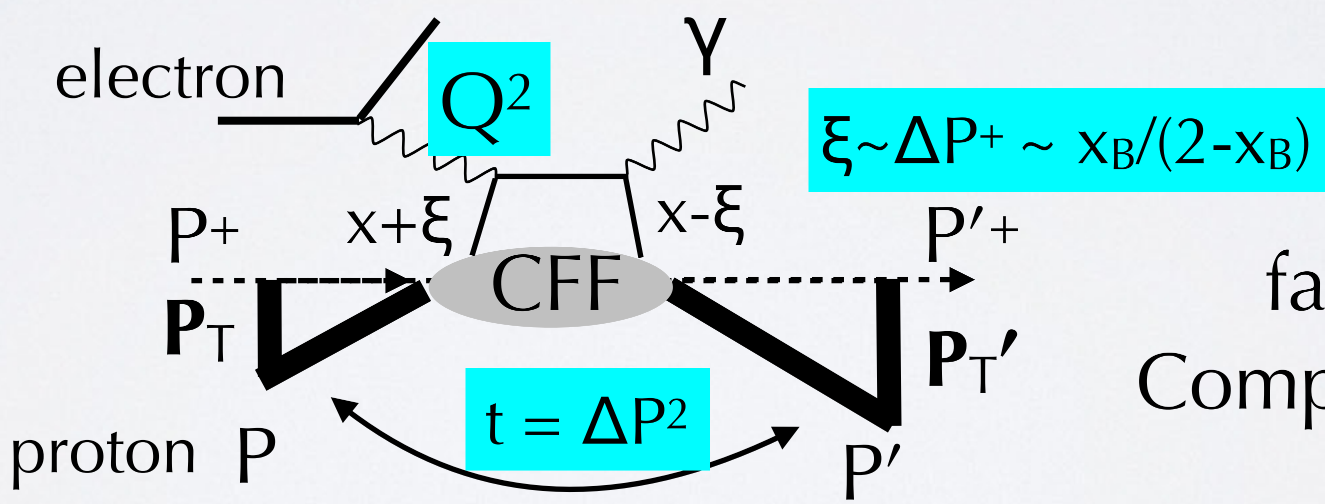


interference of BH-DVCS amplitudes



$t \ll Q^2$

factorization of Compton Form Factors (CFF)

$$\mathrm{CFF}(\xi, t) = \mathrm{PV}\int_{-1}^{1} dx\, \frac{\mathrm{GPD}(x,\xi,t)}{x-\xi} - i\pi\, \mathrm{GPD}(x = \pm\,\xi, \xi, t) + o\left(\frac{1}{Q^2}\right)$$

leading-twist GPDs

GPD are Fourier Transform of matrix elements of bilocal operators

4 structures accessible in DVCS

	operator	GPD	CFF	FF
unpol. quark	**vector** $\bar{\psi}\gamma^\mu\psi$	H	$\mathscr{H}$	F_1
	tensor $\bar{\psi}\sigma^{\mu\nu}\Delta_\nu\psi$	E	$\mathscr{E}$	F_2
L-pol. quark	**axial vector** $\bar{\psi}\gamma^\mu\gamma_5\psi$	$\tilde{H}$	$\tilde{\mathscr{H}}$	G_A
	pseudo-scalar $\bar{\psi}\gamma_5\psi$	$\tilde{E}$	$\tilde{\mathscr{E}}$	G_P

flip N spin

4 additional chiral-odd structures (T-pol. quark)
accessible only in DVMP

Properties of GPDs

Polynomiality (Lorentz covariance)

$$\int_{-1}^{1} dx\, x^m\, \mathrm{GPD}(x,\xi,t) = \sum_{j=0}^{\left[\frac{m}{2}\right]} \xi^{2j}\, C_{2j}(t) + \mathrm{mod}(m,2)\, \xi^{m+1}\, C_{m+1}(t)$$

Ji, J.Phys.G **24** (98) 1181
Radyushkin, P.L. **B449** (99) 81

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<u>special cases:</u>

m=0 → connection to form factors FF(t) Ex.

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t)$$

$$\int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t)$$

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m=1 → generalized form factors → extrapolation ($t \to 0$) → mass and spin

Ex.

$$\int_{-1}^{1} dx\, x\, H^q(x,\xi,t) = M^q(t) + D^q(t)\,\xi^2$$

$$\int_{-1}^{1} dx\, x\, E^q(x,\xi,t) = 2J^q(t) - M^q(t) - D^q(t)\,\xi^2$$

$M(0)$ mass and momentum

$J(0)$ angular momentum

$D(0)$ "D-term" related to mechanical properties

Polyakov, P.L. **B555** (03) 57

byproduct: N spin sum rule

$$\frac{1}{2}\int_{-1}^{1} dx\, x\, \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right] = J^q$$

Ji, P.R.L. **78** (97) 610

Properties of GPDs

QCD Energy-Momentum Tensor (EMT) $T^{\mu\nu} = \bar{\psi}\gamma^{\mu}\frac{i}{2}\overleftrightarrow{D}^{\nu}\psi - F^{a\mu\lambda}F^{a\nu}{}_{\lambda} + \frac{1}{4}g^{\mu\nu}F^2$

$$\langle P'|\,T^{q,g}_{\mu\nu}\,|P\rangle = \bar{u}(P')\,\left[M^{q,g}(t)\,\frac{P_\mu P_\nu}{M_N} + J^{q,g}(t)\,\frac{i(P_\mu\sigma_{\nu\rho} + P_\nu\sigma_{\mu\rho})\,\Delta^\rho}{2M_N} + D^{q,g}(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\,\Delta^2}{5M_N} + \bar{c}_{q,g}(t)\,g_{\mu\nu}\right]\,u(P)$$

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connection to generalized form factors

"trace anomaly"

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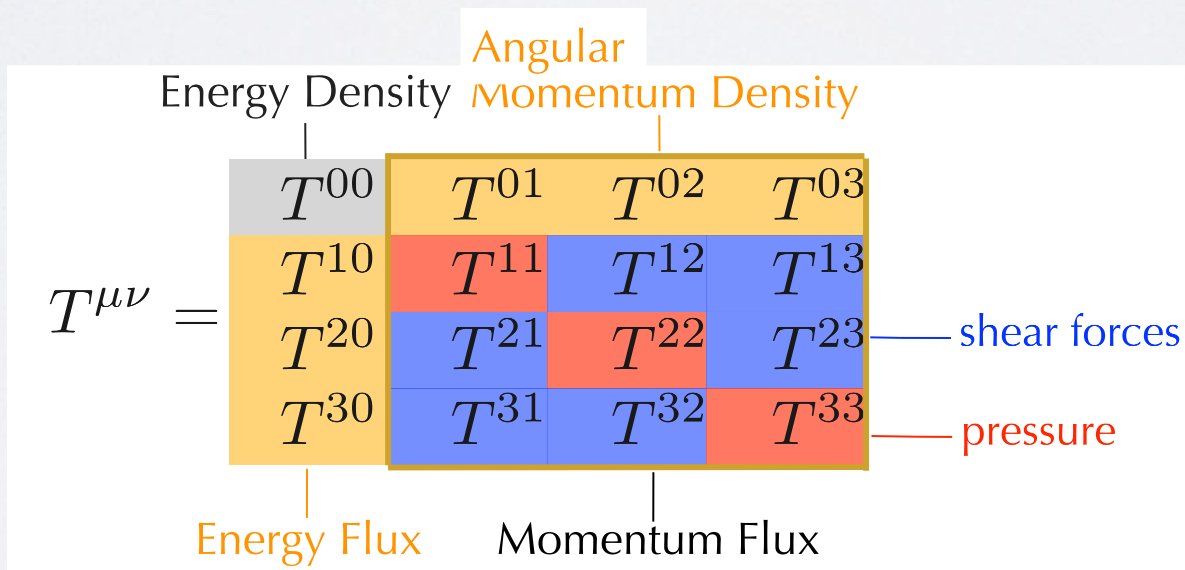
in Breit frame (**Δ**=**P**′-**P**), static EMT $T_{\mu\nu}(\mathbf{r}) = \int \frac{d\boldsymbol{\Delta}}{2E(2\pi)^3}\, e^{-i\boldsymbol{\Delta}\cdot\mathbf{r}}\,\langle P'|T_{\mu\nu}|P\rangle$ → probability density interpretation



Lorcé et al, P.L. **B776** (18) 38
Lorcé et al., E.P.J. **C79** (19) 1
Polyakov, P.L. **B555** (03) 57

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$\int d\mathbf{r}\, T_{00}(\mathbf{r}) = M_N$

Energy Density

Angular Momentum Density

$$T^{\mu\nu} = \begin{matrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{matrix}$$

shear forces

pressure

Energy Flux

Momentum Flux

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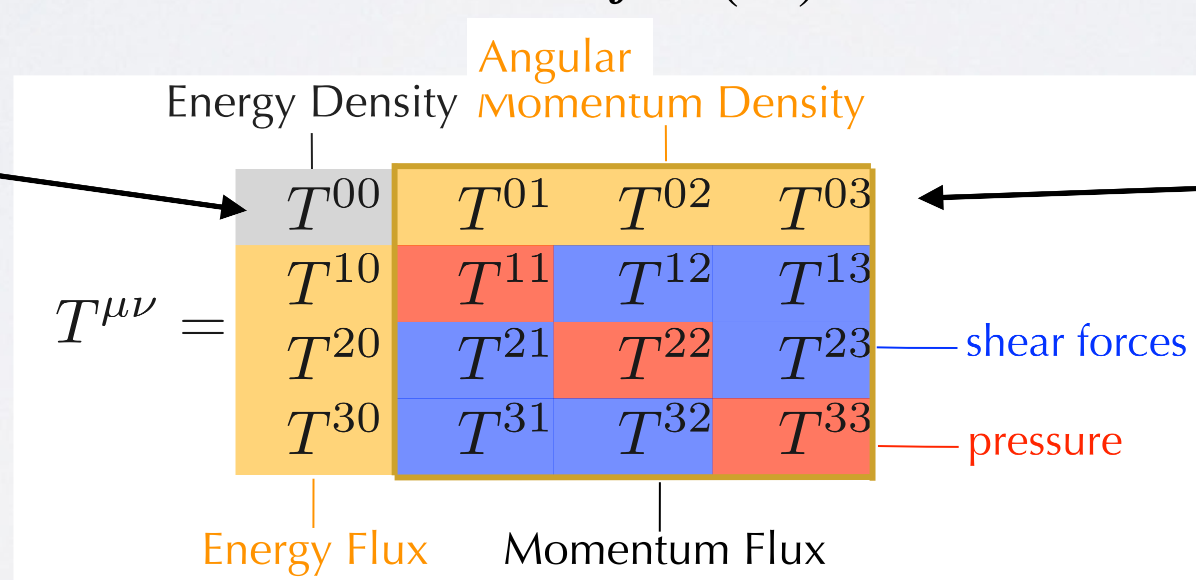

$\int d\mathbf{r}\,(\mathbf{S}\times\mathbf{r})_k\,T_{0k}(\mathbf{r}) = 1/2$

Lorcé et al, P.L. **B776** (18) 38
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shear forces

pressure

Energy Flux — Momentum Flux

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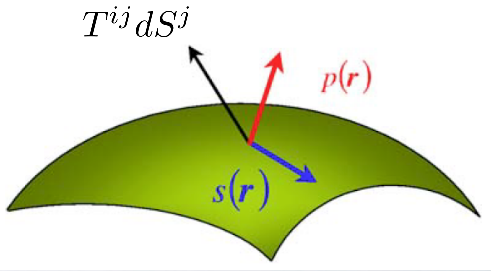
$$T_{ij}(\mathbf{r}) = s(r)\left(\frac{r_i r_j}{r^2} - \frac{1}{3}\delta_{ij}\right) p(r)\,\delta_{ij}$$



$$D(0) = -\frac{16\pi}{15}M_N\int_0^\infty dr\, r^4\, s(r) = 4\pi M_N\int_0^\infty dr\, r^4\, p(r)$$

D-term related to internal forces

Attempts of Femtography

Probability density distribution in impact parameter space

$$q(x, \mathbf{b}_\perp) = \int \frac{d\mathbf{\Delta}_\perp}{(2\pi)^2} e^{i\mathbf{\Delta}_\perp \cdot \mathbf{b}_\perp} H^q(x, 0, -\mathbf{\Delta}_\perp^2)$$

Burkardt, P.R. D**62** (00) 071503

extrapolation of data to ξ ~ ΔP+ = 0

$$\langle \mathbf{b}_\perp^2(x) \rangle = \frac{\int d\mathbf{b}_\perp \, \mathbf{b}_\perp^2 \, q(x, \mathbf{b}_\perp)}{\int d\mathbf{b}_\perp \, q(x, \mathbf{b}_\perp)}$$

Attempts of Femtography

Probability density distribution in impact parameter space

$$q(x,\mathbf{b}_\perp) = \int \frac{d\mathbf{\Delta}_\perp}{(2\pi)^2}\, e^{i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp} H^q(x,0,-\mathbf{\Delta}_\perp^2)$$

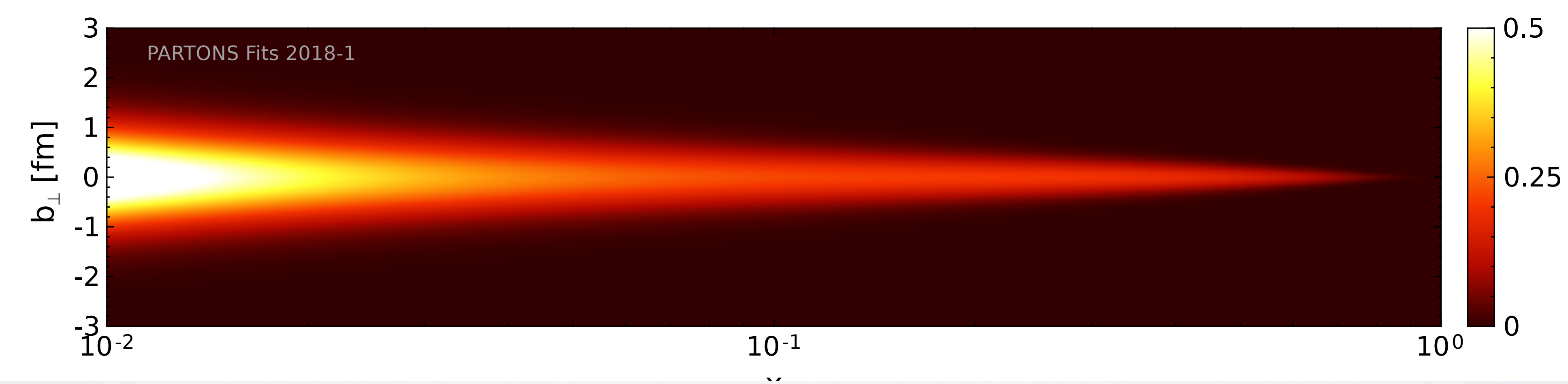
Burkardt, P.R. D**62** (00) 071503

extrapolation of data to ξ ~ $\Delta P^+ = 0$

fitting H^q to CLAS6 and HERMES data

$$\langle \mathbf{b}_\perp^2(x)\rangle = \frac{\int d\mathbf{b}_\perp\, \mathbf{b}_\perp^2\, q(x,\mathbf{b}_\perp)}{\int d\mathbf{b}_\perp\, q(x,\mathbf{b}_\perp)}$$

Moutarde et al., E.P.J. **C78** (18) 890



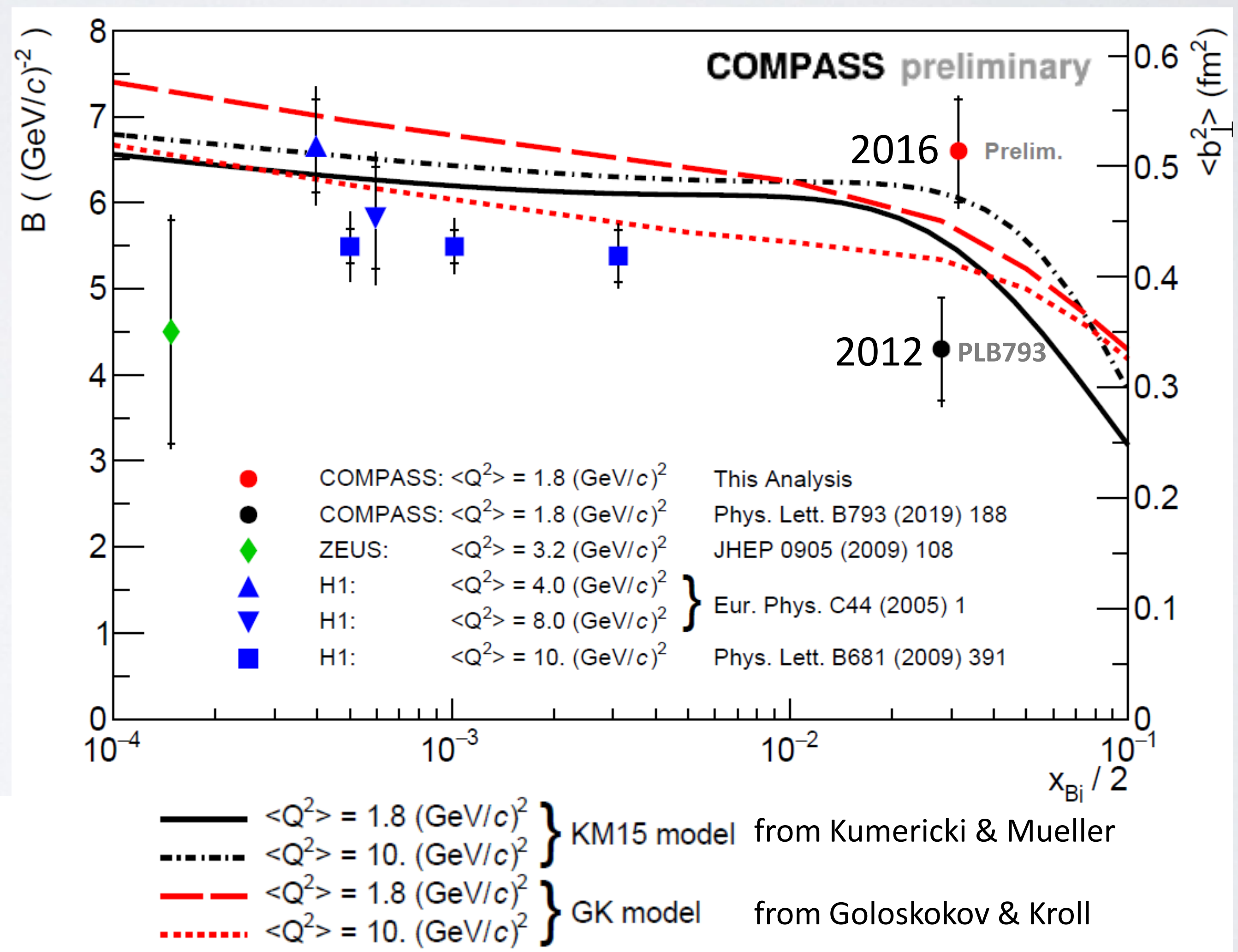
high-momentum (valence) quarks are at the core of the nucleon, low-momentum (sea) quarks spread to its periphery

Attempts of Femtography

latest from COMPASS: $\dfrac{d\sigma^{\mathrm{DVCS}}}{dt} \sim \left(\mathrm{Im}[\mathscr{H}(\xi,\xi,t)]\right)^2 \leftrightarrow e^{-B(\xi)\,|t|}$

$x = \xi \approx x_B/2$ small → "extrapolation" to $\xi = 0$

$\langle \mathbf{b}_\perp^2(x)\rangle \approx 2\,B(\xi)$



2012 statistics = Ref

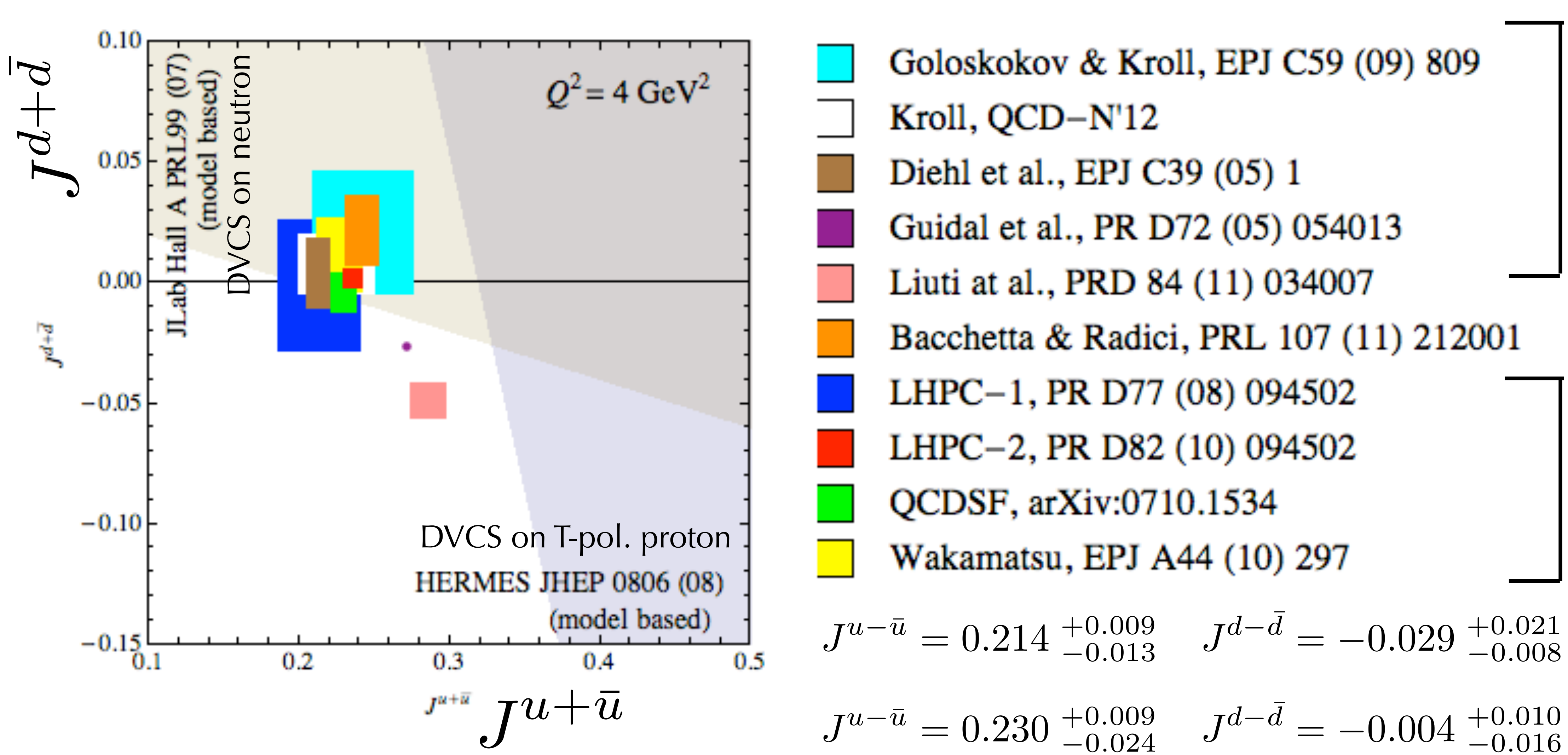
2016 analysed statistics = 2.3 × Ref

2016+2017 expected statistics = 10 × Ref

N. d'Hose at Trasnversity 2024

Angular momentum

$$J^q = \frac{1}{2}\int_{-1}^{1} dx\, x\, \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$



models of GPD

color lensing Sivers ↔ E

lattice

$J^{u-\bar{u}} = 0.214\,^{+0.009}_{-0.013}$ $\quad J^{d-\bar{d}} = -0.029\,^{+0.021}_{-0.008}$

$J^{u-\bar{u}} = 0.230\,^{+0.009}_{-0.024}$ $\quad J^{d-\bar{d}} = -0.004\,^{+0.010}_{-0.016}$

D-term and N internal forces

D-term from GPDs H and E

$$\int_{-1}^{1} dx\, x\, H^q(x,\xi,t) = M^q(t) + D^q(t)\,\xi^2$$

$$\int_{-1}^{1} dx\, x\, E^q(x,\xi,t) = 2J^q(t) - M^q(t) - D^q(t)\,\xi^2$$

but GPDs are “buried” inside CFF $\mathscr{H}$, $\mathscr{E}$

D-term and N internal forces

D-term from GPDs H and E

$$\int_{-1}^{1} dx\, x\, H^q(x,\xi,t) = M^q(t) + D^q(t)\,\xi^2$$

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but GPDs are "buried" inside CFF $\mathscr{H}$, $\mathscr{E}$

DVCS: BSA data → Im[$\mathscr{H}$], unpol. dσ^0 → Re[$\mathscr{H}$]

dispersion relations: $\mathrm{Re}[\mathscr{H}(\xi,t,Q^2)] = \frac{1}{\pi}\mathrm{PV}\int dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}[\mathscr{H}(x,t,Q^2)] - \Delta(t,Q^2)$

$$\Delta(t,Q^2) = 4\sum_q e_q^2 \left[d_1^q(t,Q^2) + d_3^q(t,Q^2) + d_5^q(t,Q^2) + \ldots\right] \approx \frac{25}{18}\sum_q D^q(t)$$

D-term and N internal forces

D-term from GPDs H and E

$$\int_{-1}^{1} dx\, x\, H^q(x,\xi,t) = M^q(t) + D^q(t)\,\xi^2$$

$$\int_{-1}^{1} dx\, x\, E^q(x,\xi,t) = 2J^q(t) - M^q(t) - D^q(t)\,\xi^2$$

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$$\Delta(t,Q^2) = 4\sum_q e_q^2 \left[d_1^q(t,Q^2) + \underbrace{d_3^q(t,Q^2)}_{\to 0} + \underbrace{d_5^q(t,Q^2)}_{\to 0} + \dots \right] \approx \frac{25}{18}\sum_q D^q(t)$$

$Q^2 \to \infty$

$$\frac{4}{5} d_1(t) = D(t)$$

Anikin & Teraev, P.R.D **76** (07) 056007

D-term and N internal forces

D-term from GPDs H and E

$$\int_{-1}^{1} dx\, x\, H^q(x,\xi,t) = M^q(t) + D^q(t)\,\xi^2$$

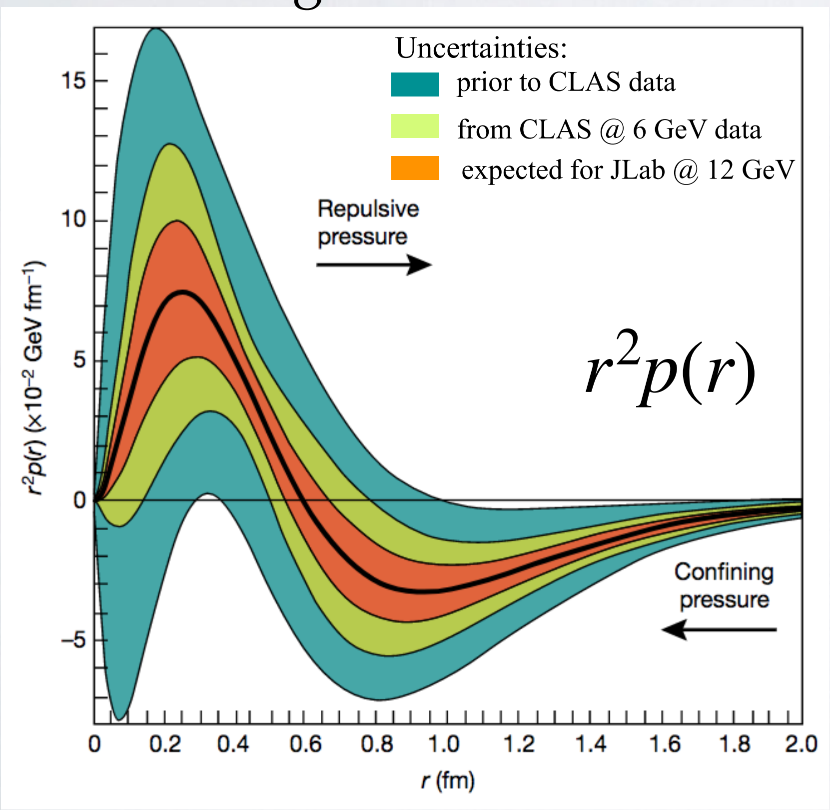
$$\int_{-1}^{1} dx\, x\, E^q(x,\xi,t) = 2J^q(t) - M^q(t) - D^q(t)\,\xi^2$$

but GPDs are "buried" inside CFF $\mathscr{H}$, $\mathscr{E}$

DVCS: BSA data → Im[$\mathscr{H}$], unpol. dσ^0 → Re[$\mathscr{H}$]

dispersion relations: $\mathrm{Re}[\mathscr{H}(\xi,t,Q^2)] = \frac{1}{\pi}\mathrm{PV}\int dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right)\mathrm{Im}[\mathscr{H}(x,t,Q^2)] - \Delta(t,Q^2)$

using CLAS6 data



Girod et al., Nature **557** (18) 7705

$$\Delta(t,Q^2) = 4\sum_q e_q^2\left[d_1^q(t,Q^2) + d_3^q(t,Q^2) + d_5^q(t,Q^2) + \ldots\right] \approx \frac{25}{18}\sum_q D^q(t)$$

$Q^2 \to \infty$: $d_3^q \to 0$, $d_5^q \to 0$, $\frac{4}{5}d_1(t) = D(t)$

Anikin & Teraev, P.R.D **76** (07) 056007

stability

$$\int_0^\infty dr\, r^2\, p(r) = 0$$

$$D(0) = 4\pi M_N \int_0^\infty dr\, r^4\, p(r) < 0$$

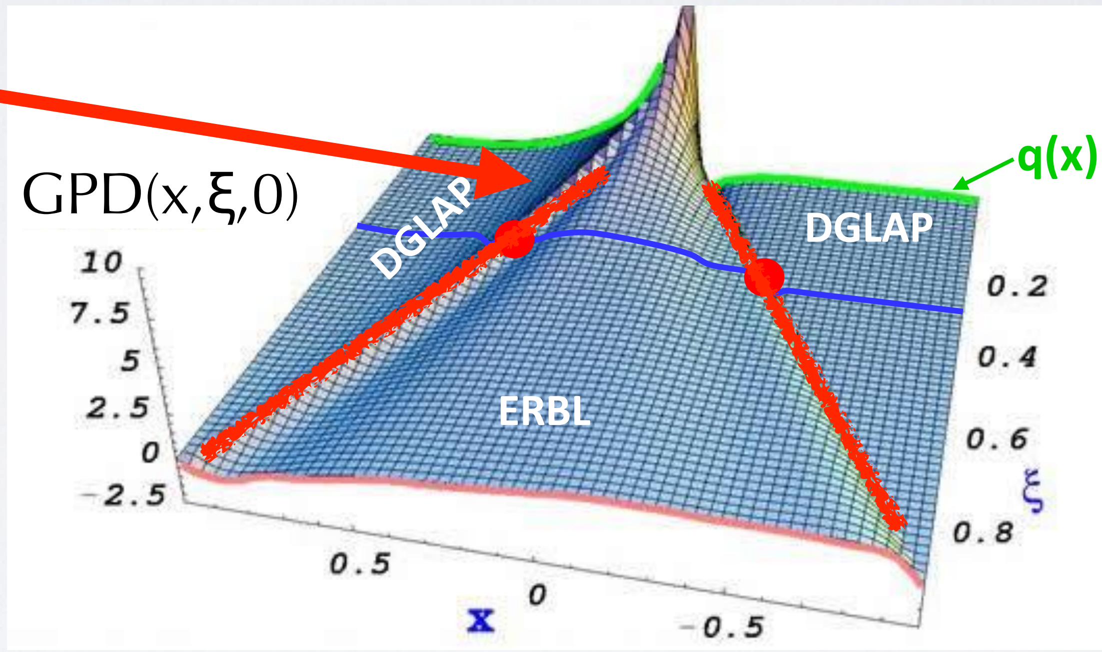
Perevalova et al., P.R.D **94** (16) 054024

consistent with data & models

Exclusive processes

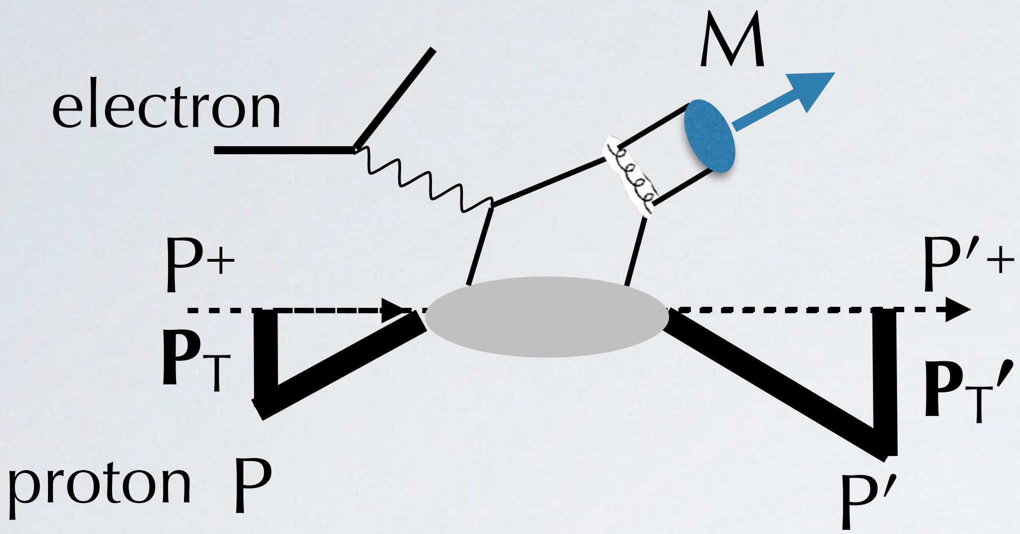
$$\mathrm{CFF}(\xi,t) = \underbrace{\mathrm{PV}\int_{-1}^{1} dx\, \frac{\mathrm{GPD}(x,\xi,t)}{x-\xi}}_{\mathrm{Re(CFF)}} - \underbrace{i\pi\,\mathrm{GPD}(x=\pm\,\xi,\xi,t)}_{\mathrm{Im(CFF)}} + o\left(\frac{1}{Q^2}\right)$$

Access only to the
$(x = \pm\,\xi, \xi, t)$ dependence

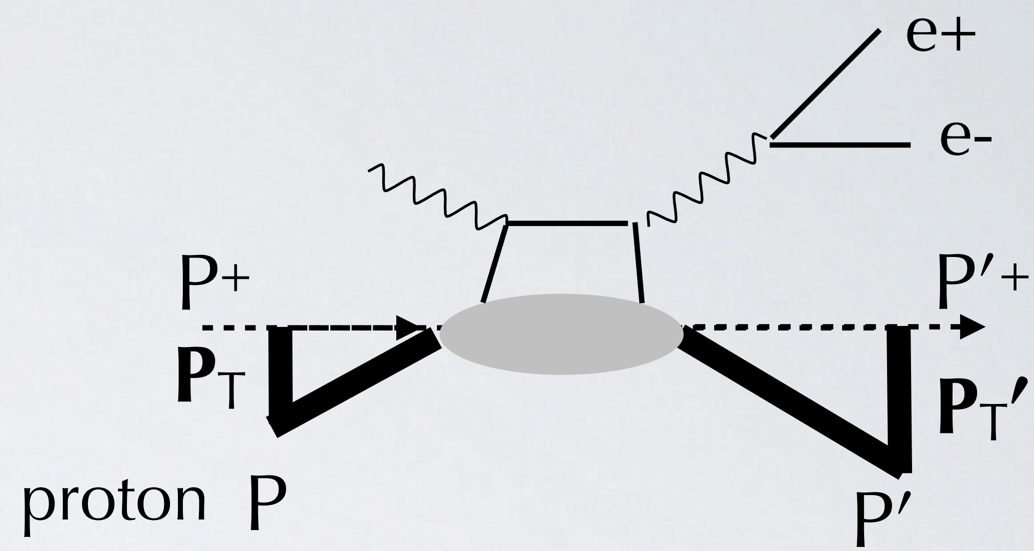


Need to combine information from
- different DVCS measurement
- different processes

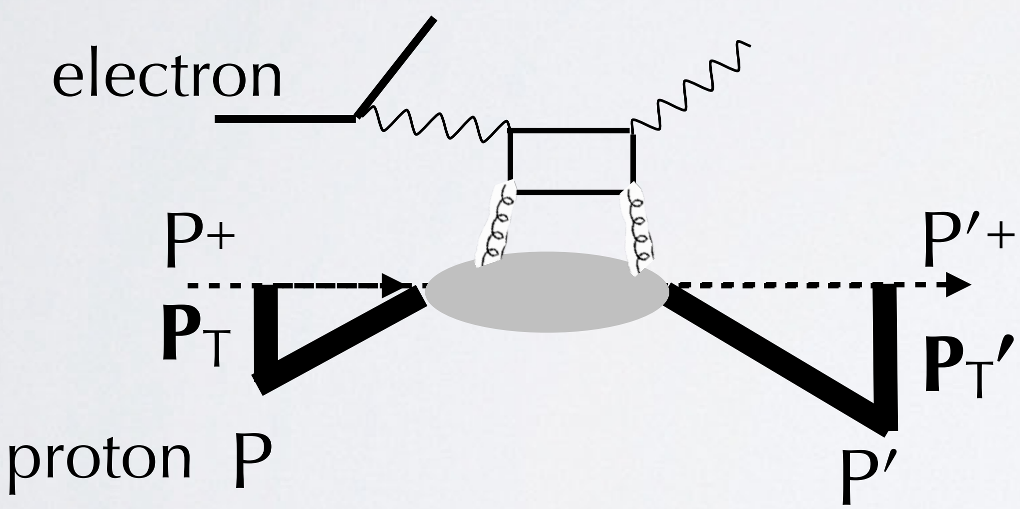
Exclusive processes



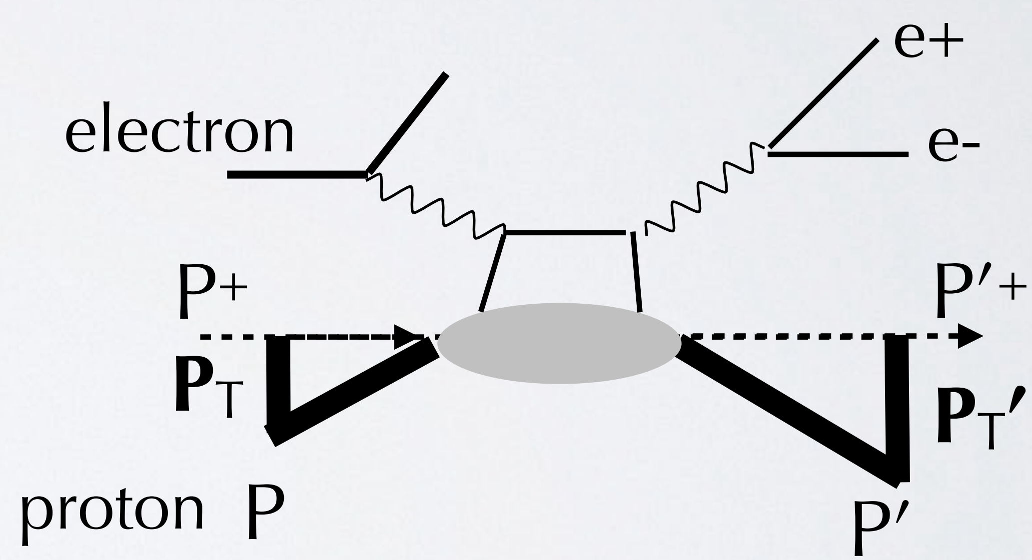
Deeply Virtual Meson Production (**DVMP**)
(access to transversity GPD)



Time-like Compton Scattering (**TCS**)
(sensitive to D-term via Re[$\mathscr{H}$])



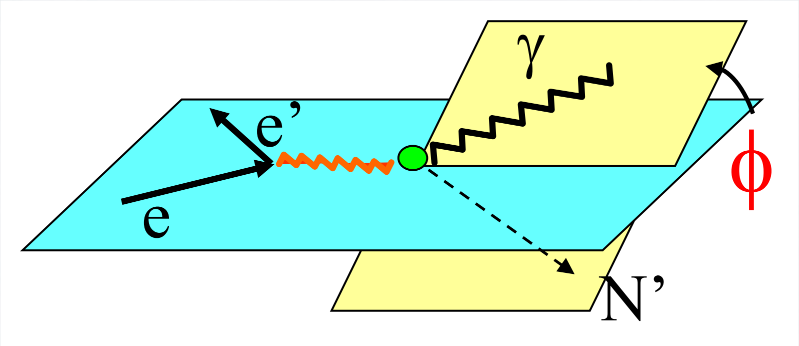
gluon channel of **DVCS**
($\rightarrow \mathcal{O}(\alpha_s)$ corrections)



Double DVCS (**DDVCS**)
(go beyond $x = \pm\,\xi$ limitation)

reactions (γ*N→N′M, γN→N′γ*) in backward kin. ($|u| \ll s, t$)
→ Transition Distribution Amplitudes (TDA)

CFF combinations in DVCS



polarized beam
unpol. target

BSA $\Delta\sigma_{LU} \sim \sin\phi\, f\left[\mathrm{Im}[\mathcal{H}], \mathrm{Im}[\tilde{\mathcal{H}}], \mathrm{Im}[\mathcal{E}]\right]$

unpol. beam
L-pol. target

ℓTSA $\Delta\sigma_{UL} \sim \sin\phi\, f\left[\mathrm{Im}[\mathcal{H}], \mathrm{Im}[\tilde{\mathcal{H}}], \mathrm{Im}[\mathcal{E}], \mathrm{Im}[\tilde{\mathcal{E}}]\right]$

polarized beam
L-pol. target

DSA $\Delta\sigma_{LL} \sim (A + B\cos\phi)\, f\left[\mathrm{Re}[\mathcal{H}], \mathrm{Re}[\tilde{\mathcal{H}}], \mathrm{Re}[\mathcal{E}]\right]$

unpol. beam
T-pol. target

tTSA $\Delta\sigma_{UT} \sim \cos\phi\, \sin(\phi_S - \phi)\, f\left[\mathrm{Im}[\mathcal{H}], \mathrm{Im}[\mathcal{E}]\right]$

unpol. beam
different charges
unpol. target

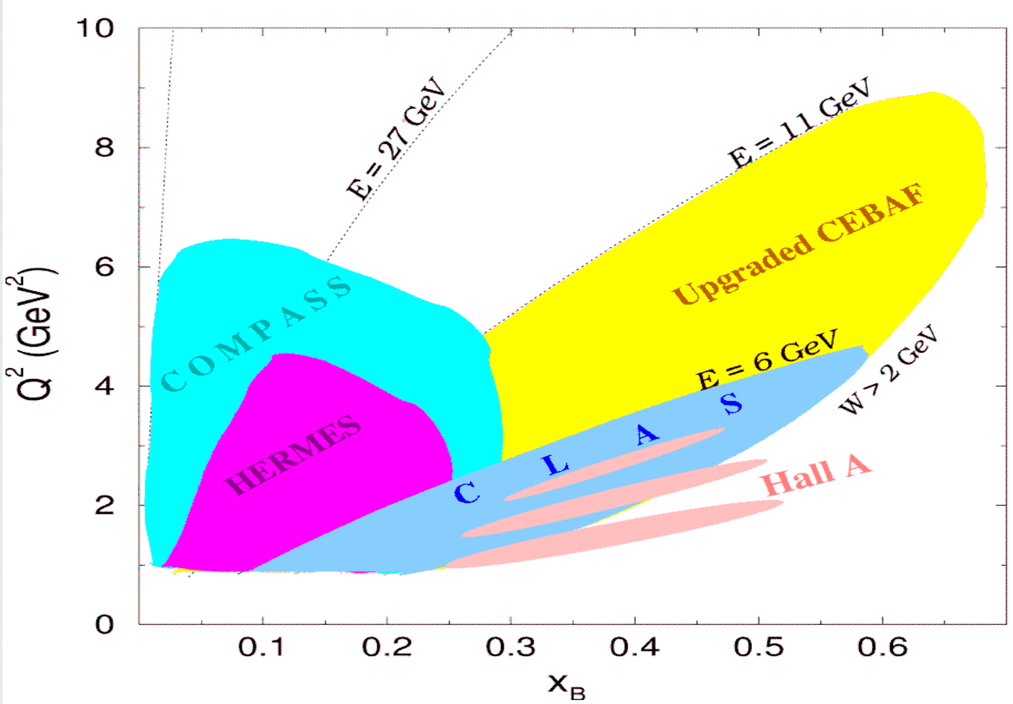
BCA $\Delta\sigma_{c} \sim \cos\phi\, f\left[\mathrm{Re}[\mathcal{H}], \mathrm{Re}[\tilde{\mathcal{H}}], \mathrm{Re}[\mathcal{E}]\right]$

History of DVCS exp.'s

JLAB	
Hall A	*CLAS (Hall B)*
p,n-DVCS, Beam-pol. CS	p-DVCS, BSA,lTSA,DSA,CS

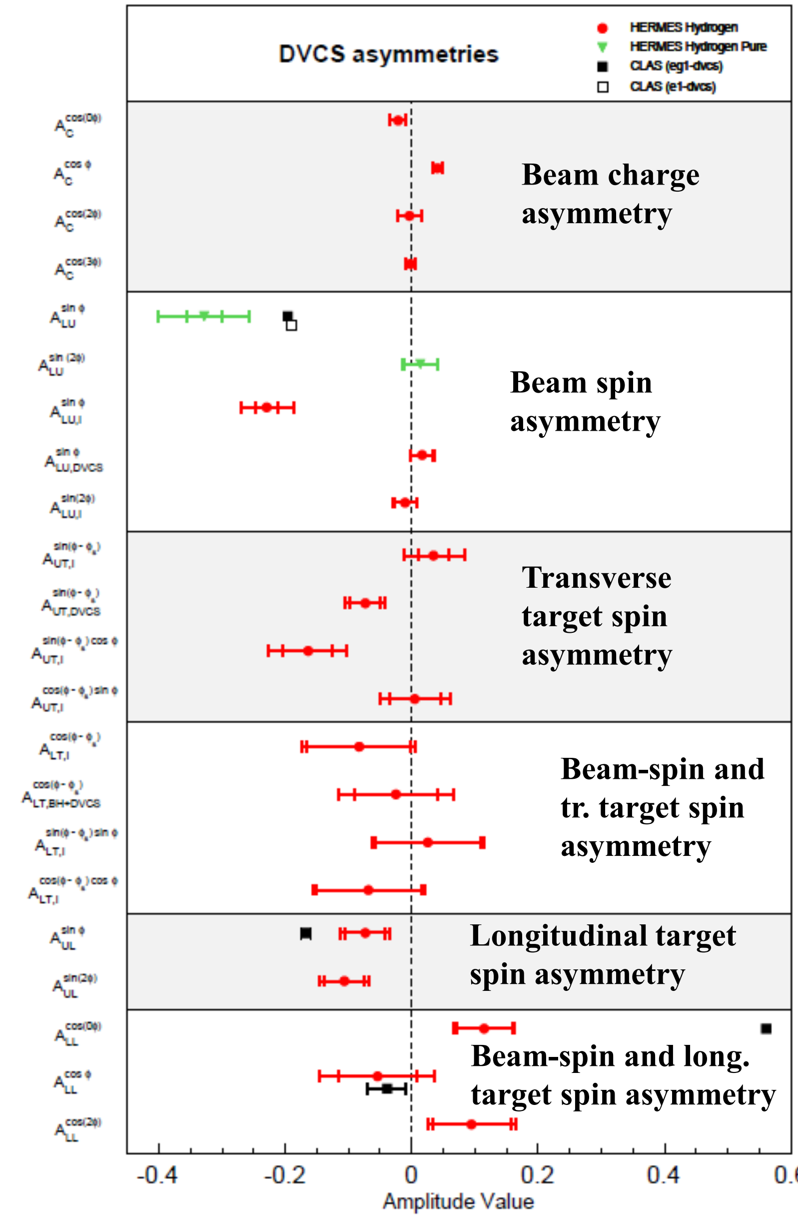
DESY	
HERMES	*H1/ZEUS*
p-DVCS,BSA,BCA, tTSA,lTSA,DSA	p-DVCS,CS,BCA

CERN
COMPASS
p-DVCS CS,BSA,BCA, tTSA,lTSA,DSA



CLAS, HERMES: first observation of DVCS-BH interference in the beam-spin asymmetry (2001)

Hall A: test of scaling for DVCS (2006)



Ongoing and future programs

S. Niccolai, Transversity 2024

JLab12 DVCS

Observable (target)	12-GeV experiments	CFF sensitivity	Status
σ, $\Delta\sigma_{beam}$(p)	Hall A CLAS12 Hall C	Re$\mathcal{H}$(p), Im$\mathcal{H}$(p)	Data taken in 2016; Phys. Rev. Lett. 128 (2022) Data taken in 2018-2019; CS analysis under review Experiment just finished
BSA(p) + **TCS**	CLAS12	Im$\mathcal{H}$(p)	Data taken in 2018-2019; Phys. Rev. Lett. 130 (2023) Phys. Rev. Lett. 127 (2021)
lTSA(p), lDSA(p)	CLAS12	Im$\tilde{\mathcal{H}}$(p), Im$\mathcal{H}$(p), Re$\tilde{\mathcal{H}}$(p), Re$\mathcal{H}$(p)	Experiment completed in March 2023
tTSA(p)	CLAS12	Im$\mathcal{H}$(p), Im$\mathcal{E}$(p)	Experiment foreseen for > 2027
BSA(n)	CLAS12	Im$\mathcal{E}$(n)	Data taken in 2019-2020; BSA paper ready for release
lTSA(n), lDSA(n)	CLAS12	Im$\mathcal{H}$(n), Re$\mathcal{H}$(n)	Experiment completed in March 2023

first ever **TCS**

flavor sep. of CFF
Ji's sum rule

combining Hermes & Hall A p DVCS + CLAS12 BSA on p,n DVCS → flavor separation of CFF

Kumericki et al., JHEP **07** (11) 073

+ plans for **DDVCS** and **positron DVCS**

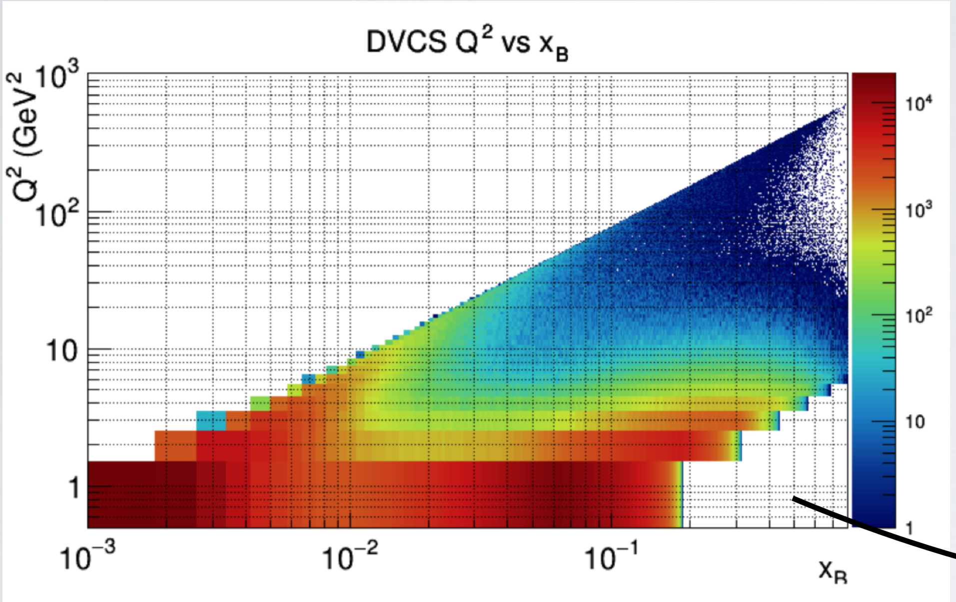
COMPASS DVCS

DVMP on π^0, ρ^0, ω, ϕ, J/ψ using 2016,17 data →

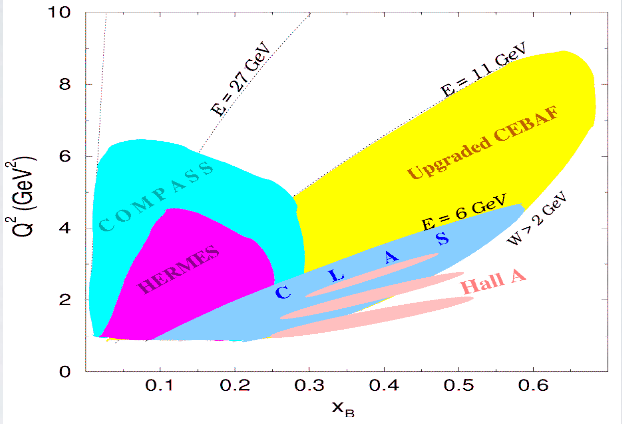
- transversity GPD
- gluon GPD
- flavor decomposition

see N. d'Hose, Transversity 2024

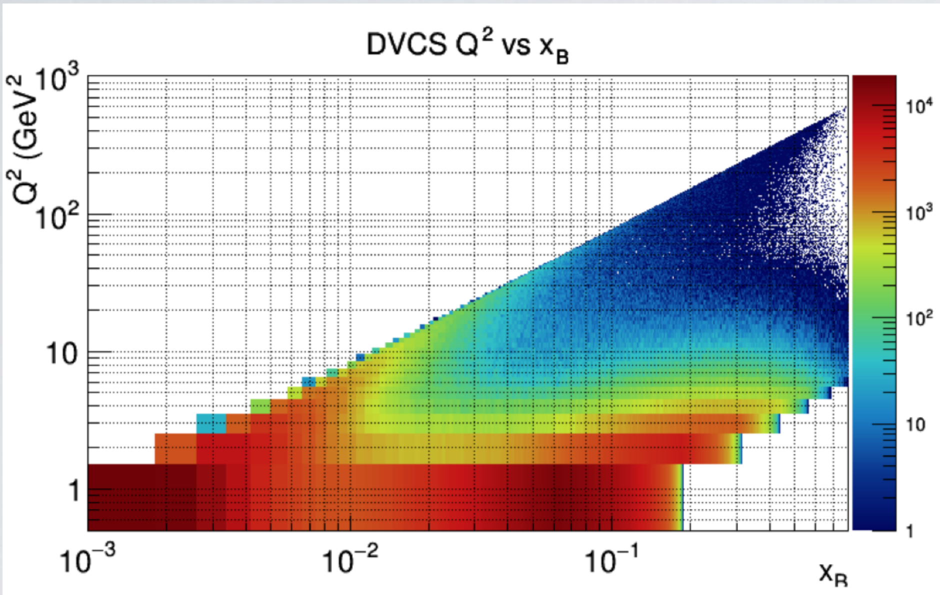
The EIC at low/medium energy: CFF



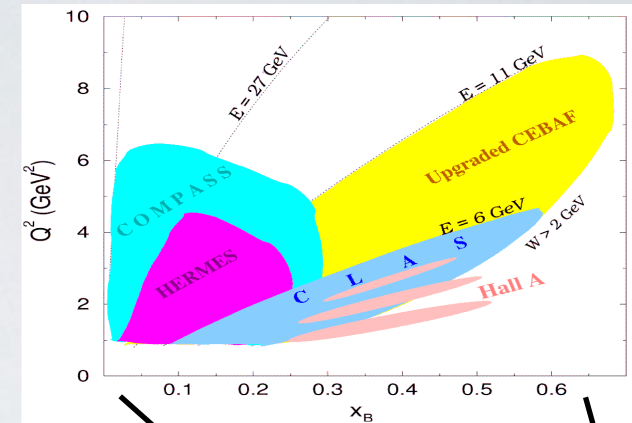
DVCS events / pixel
$\sqrt{s} = 31$ GeV
assumed integrated luminosity of 200 fb^{-1}
(Fig.8 paper)



The EIC at low/medium energy: CFF

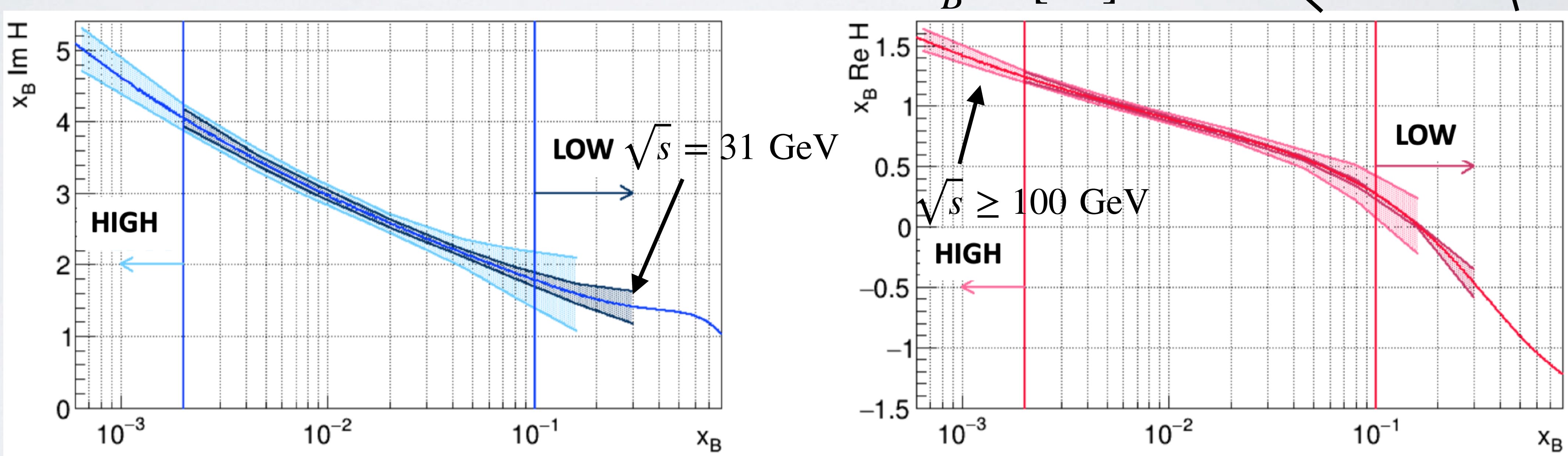


\# DVCS events / pixel
$\sqrt{s} = 31$ GeV
assumed integrated luminosity of 200 fb^{-1}
(Fig.8 paper)



$x_B\,\mathrm{Im}[\mathscr{H}]$

$x_B\,\mathrm{Re}[\mathscr{H}]$



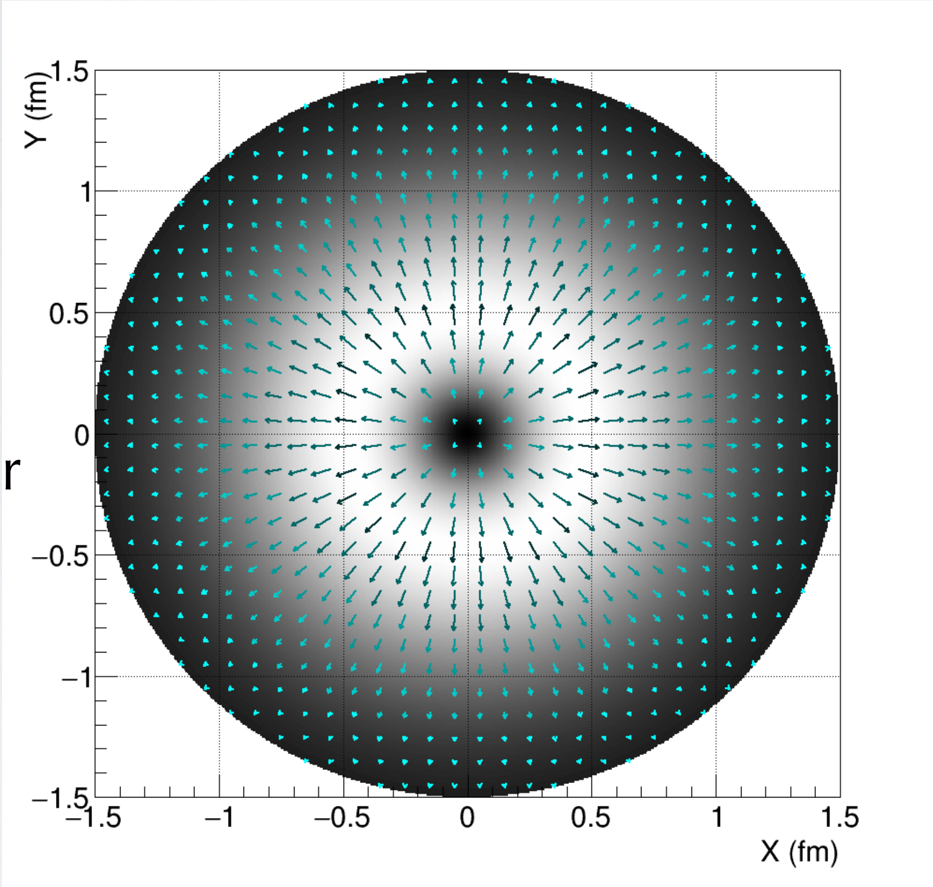
simulated DVCS events at the EIC (Fig.7 of paper)

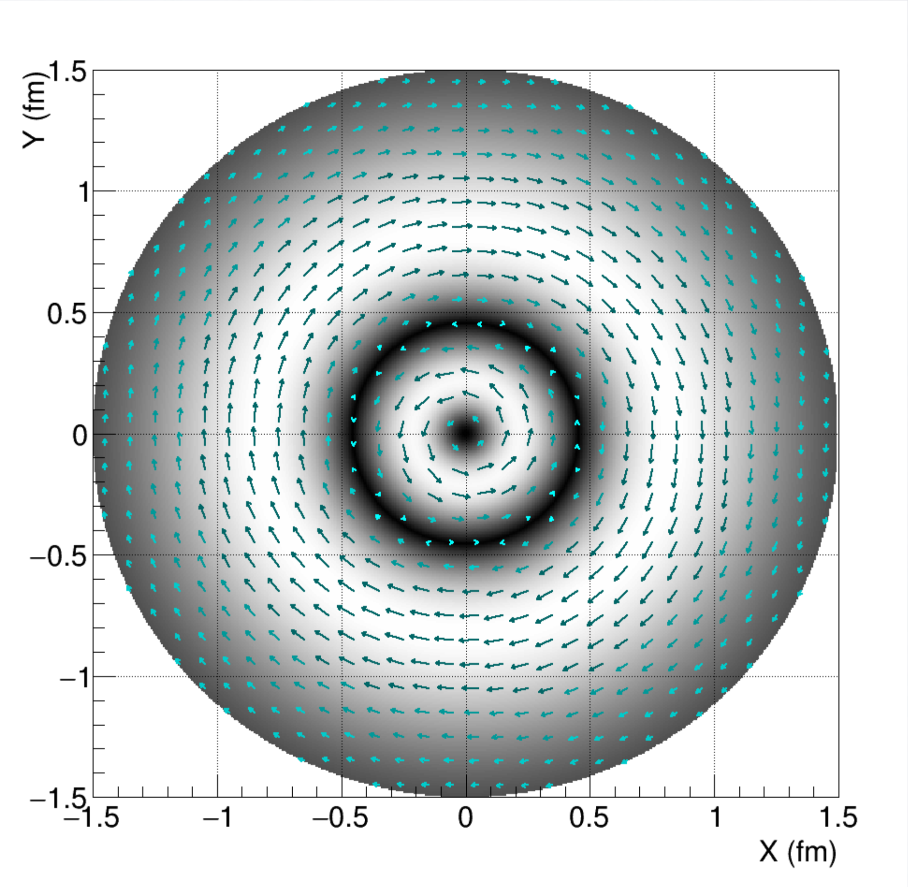
the EIC at low energy can complement fixed-target data with higher precision

The EIC at low/medium energy: D-term

radial force

tangential force



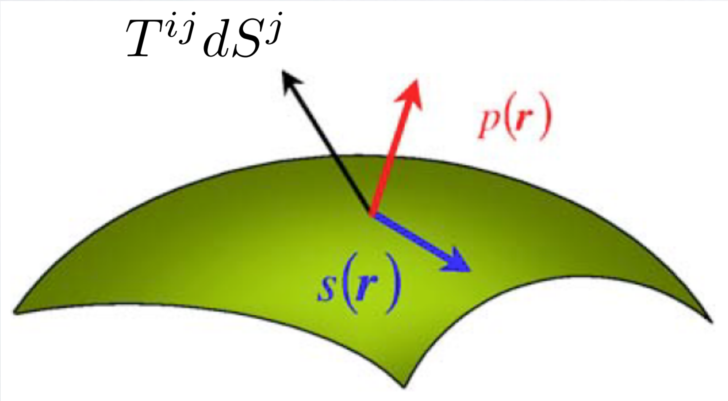


always positive
fades away with r

node at
r~0.45 fm
then
changes sign

(Fig.13 paper)

stress tensor



The EIC at low/medium energy: N mass

QCD EMT

$$\langle P' | T^{q,g}_{\mu\nu} | P \rangle = \bar{u}(P') \left[M^{q,g}(t) \frac{P_\mu P_\nu}{M_N} + J^{q,g}(t) \frac{i(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho})\, \Delta^\rho}{2M_N} + D^{q,g}(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\, \Delta^2}{5M_N} + \bar{c}_{q,g}(t)\, g_{\mu\nu} \right] u(P)$$

N mass

$$M_N \to \langle P | T^q_{00} + T^g_{00} | P \rangle =$$

The EIC at low/medium energy: N mass

QCD EMT

$$\langle P' | T^{q,g}_{\mu\nu} | P \rangle = \bar{u}(P') \left[M^{q,g}(t) \frac{P_\mu P_\nu}{M_N} + J^{q,g}(t) \cancel{\frac{i(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho})\, \Delta^\rho}{2M_N}} + D^{q,g}(t) \cancel{\frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\, \Delta^2}{5M_N}} + \bar{c}_{q,g}(t)\, g_{\mu\nu} \right] u(P)$$

N mass

$$M_N \to \langle P | T^q_{00} + T^g_{00} | P \rangle = \mathbf{E_q} + \mathbf{E_g}$$

relativistic motion
of quarks and gluons
(~70% ?)

The EIC at low/medium energy: N mass

QCD EMT

$$\langle P'|T^{q,g}_{\mu\nu}|P\rangle = \bar{u}(P')\left[M^{q,g}(t)\frac{P_\mu P_\nu}{M_N} + J^{q,g}(t)\cancel{\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N}} + D^{q,g}(t)\cancel{\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N}} + \bar{c}_{q,g}(t)\,g_{\mu\nu}\right]u(P)$$

N mass

$$M_N \to \langle P|T^q_{00}+T^g_{00}|P\rangle = \quad E_q + E_g \qquad + \bar{c}_q(0)\left(=\langle\bar{\psi}m\psi\rangle\right) \qquad + \bar{c}_g(0)\left(=\langle\frac{\beta(g)}{2g}F^{\mu\nu}F_{\mu\nu}+\gamma_m\bar{\psi}m\psi\rangle\right)$$

relativistic motion of quarks and gluons (~70% ?)

quark condensate σ-term from πN scatt. (~9%?)

trace anomaly M_a ?

The EIC at low/medium energy: N mass

QCD EMT

$$\langle P'|T^{q,g}_{\mu\nu}|P\rangle = \bar{u}(P')\left[M^{q,g}(t)\frac{P_\mu P_\nu}{M_N} + J^{q,g}(t)\frac{\cancel{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}}{\cancel{2M_N}} + D^{q,g}(t)\frac{\cancel{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}}{\cancel{5M_N}} + \bar{c}_{q,g}(t)\,g_{\mu\nu}\right]u(P)$$

N mass

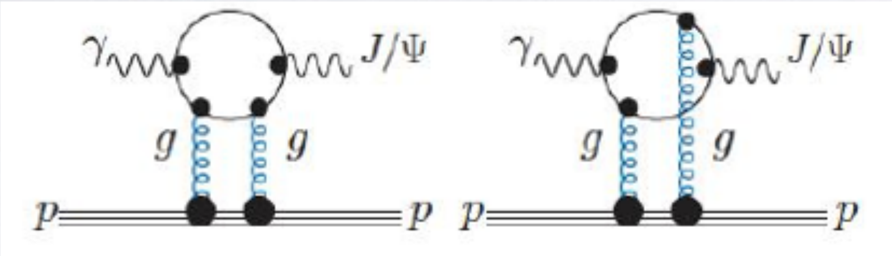
$$M_N \to \langle P|T^q_{00}+T^g_{00}|P\rangle = \quad E_q + E_g \qquad + \bar{c}_q(0)\left(=\langle\bar{\psi}m\psi\rangle\right) \qquad + \bar{c}_g(0)\left(=\langle\frac{\beta(g)}{2g}F^{\mu\nu}F_{\mu\nu}+\gamma_m\bar{\psi}m\psi\rangle\right)$$

relativistic motion
of quarks and gluons
(~70% ?)

quark condensate
σ-term from πN scatt.
(~9%?)

trace anomaly M_a
?

threshold γ- and e-production of J/ψ or Υ



$$\frac{d\sigma}{dt} \sim |\mathscr{M}_{\gamma p\to J/\psi}(t)|^2 \sim |\langle P'|T^{\mu\,g}_{\mu}|P\rangle|^2 \xrightarrow{t\to 0} M_a$$

The EIC at low/medium energy: N mass

QCD EMT

$$\langle P'|T^{q,g}_{\mu\nu}|P\rangle = \bar{u}(P')\left[M^{q,g}(t)\frac{P_\mu P_\nu}{M_N} + J^{q,g}(t)\cancel{\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N}} + D^{q,g}(t)\cancel{\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N}} + \bar{c}_{q,g}(t)\, g_{\mu\nu}\right]u(P)$$

N mass

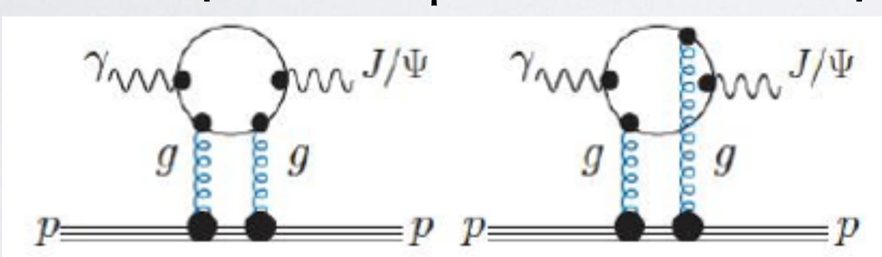
$$M_N \to \langle P|T^q_{00} + T^g_{00}|P\rangle = \quad E_q + E_g \qquad + \bar{c}_q(0)\left(= \langle\bar{\psi} m \psi\rangle\right) \qquad + \bar{c}_g(0)\left(= \langle\frac{\beta(g)}{2g}F^{\mu\nu}F_{\mu\nu} + \gamma_m \bar{\psi} m \psi\rangle\right)$$

relativistic motion
of quarks and gluons
(~70% ?)

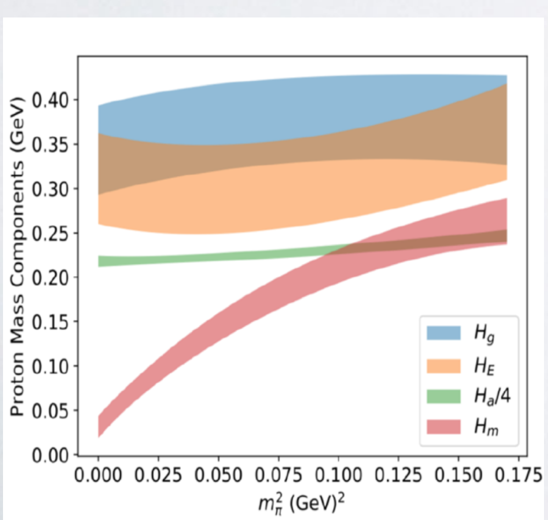
quark condensate
σ-term from πN scatt.
(~9%?)

trace anomaly M_a
?

threshold γ- and e-production of J/ψ or Υ



$$\frac{d\sigma}{dt} \sim |\mathscr{M}_{\gamma p\to J/\psi}(t)|^2 \sim |\langle P'|T^{\mu\, g}_{\mu}|P\rangle|^2 \xrightarrow{t\to 0} M_a$$



Alexandrou et al.,
P.R.L. **119** (17) 142002

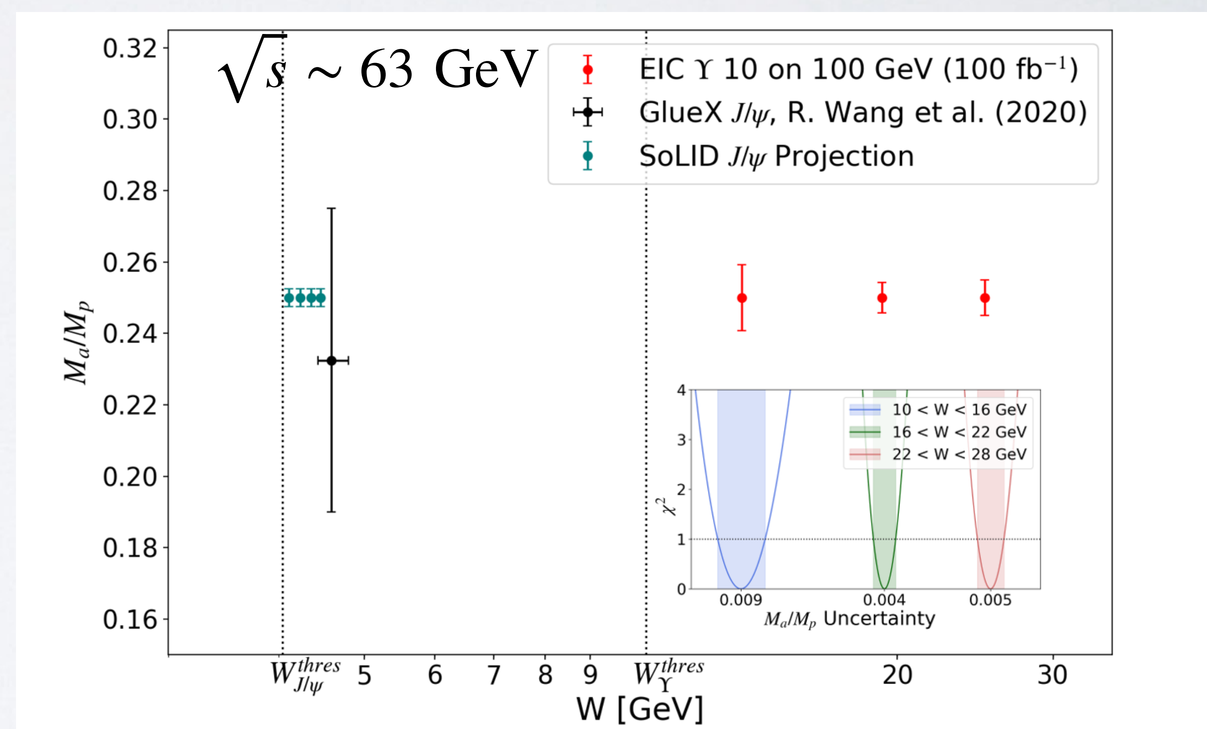
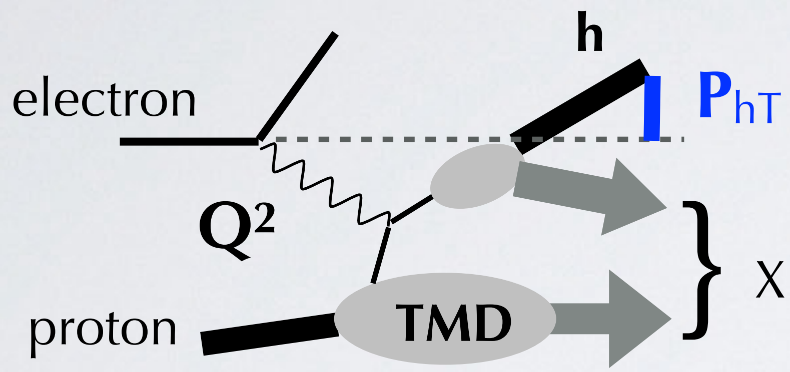


Figure 7.26: Projection of the trace anomaly contribution to the proton mass (M_a/M_p) with Υ photoproduction on the proton at the EIC in 10 × 100 GeV electron/proton beam-energy

EIC Yellow Report, N.P.. **A1026** (22) 122447

Semi-inclusive processes

IV. Accessing the Momentum Dependent Structure of the nucleon in Semi-Inclusive Deep Inelastic Scattering



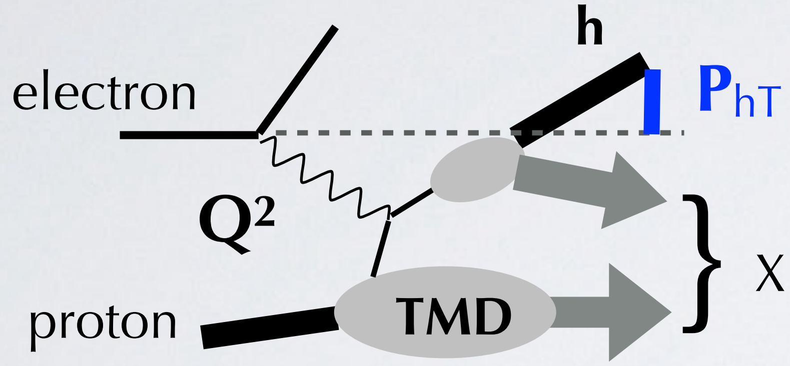
factorization if $\mathbf{q}_T = \mathbf{P}_{hT}/z \ll \mathbf{Q}$

$\mathbf{P}_{hT}$ "feels" intrinsic $\mathbf{k}_T$ of confined motion

Ji, Yuan, Ma, P.R. D**71** (05)
Rogers & Aybat, P.R. D**83** (11)
Collins, "Foundations of Perturbative QCD" (11)
Echevarria, Idilbi, Scimemi, JHEP **1207** (12)

Semi-inclusive processes

IV. Accessing the Momentum Dependent Structure of the nucleon in Semi-Inclusive Deep Inelastic Scattering



factorization if $\mathbf{q}_T = P_{hT}/z \ll \mathbf{Q}$

P_{hT} "feels" intrinsic $\mathbf{k}_T$ of confined motion

Ji, Yuan, Ma, P.R. D**71** (05)
Rogers & Aybat, P.R. D**83** (11)
Collins, "Foundations of Perturbative QCD" (11)
Echevarria, Idilbi, Scimemi, JHEP **1207** (12)

affinity = probability to fulfill fact. th.

Boglione et al., JHEP **04** (22) 084

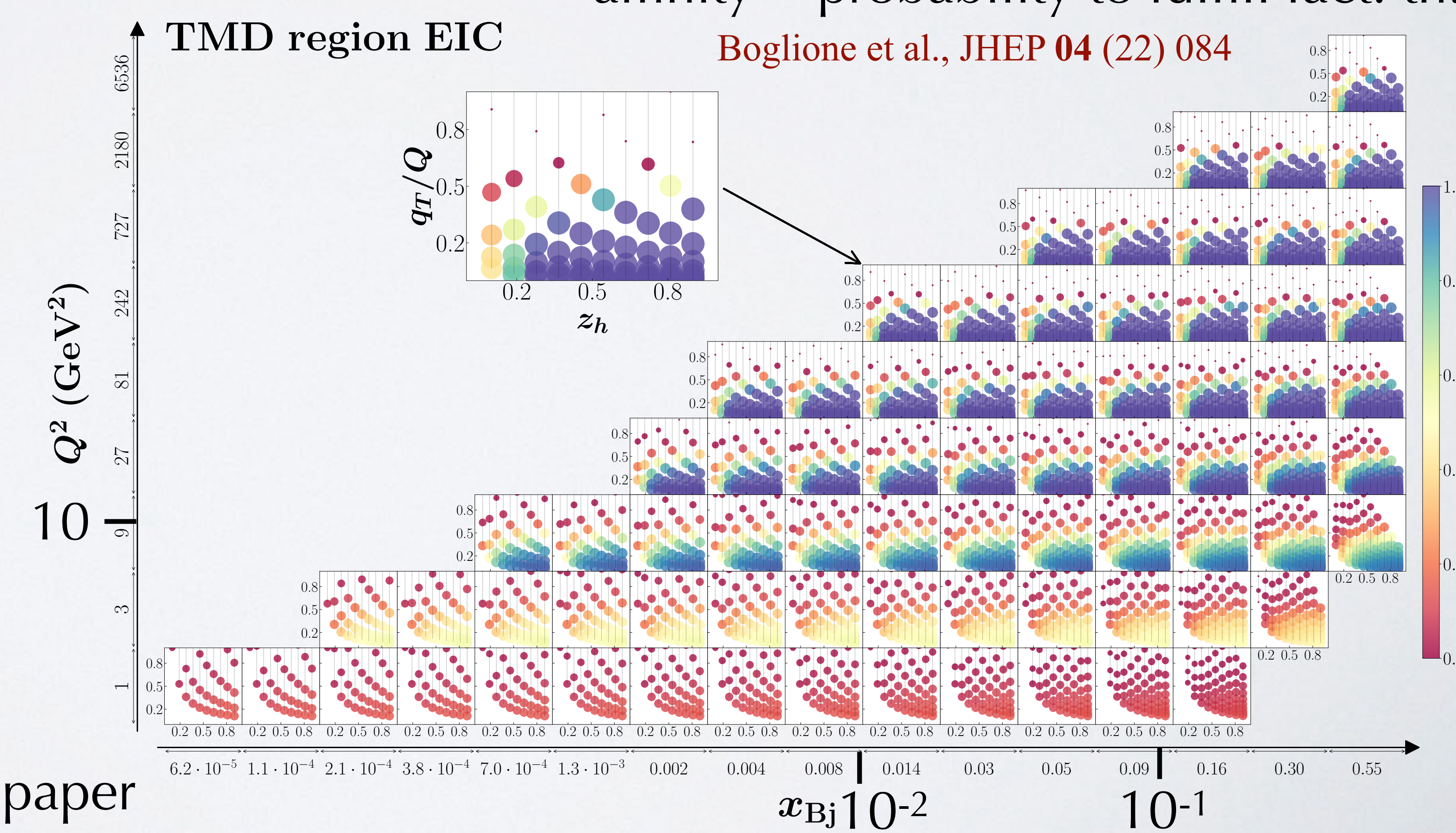
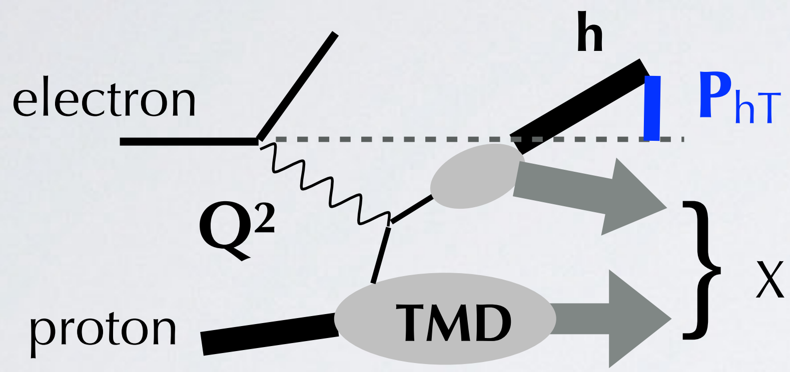


Fig.23 of paper

Semi-inclusive processes

IV. Accessing the Momentum Dependent Structure of the nucleon in Semi-Inclusive Deep Inelastic Scattering



factorization if $\mathbf{q}_T = \mathbf{P}_{hT}/z \ll \mathbf{Q}$

$\mathbf{P}_{hT}$ "feels" intrinsic $\mathbf{k}_T$ of confined motion

Ji, Yuan, Ma, P.R. D**71** (05)
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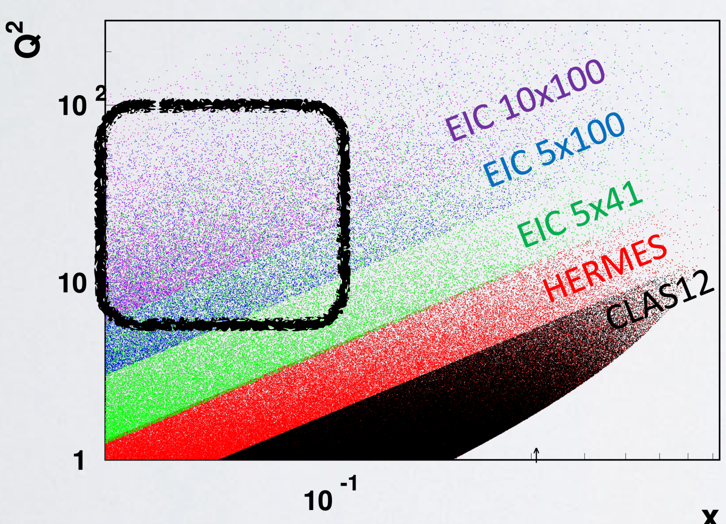
Echevarria, Idilbi, Scimemi, JHEP **1207** (12)

affinity = probability of fulfill fact. th.

Boglione et al., JHEP **04** (22) 084



EIC low/medium energy well into TMD factorization region

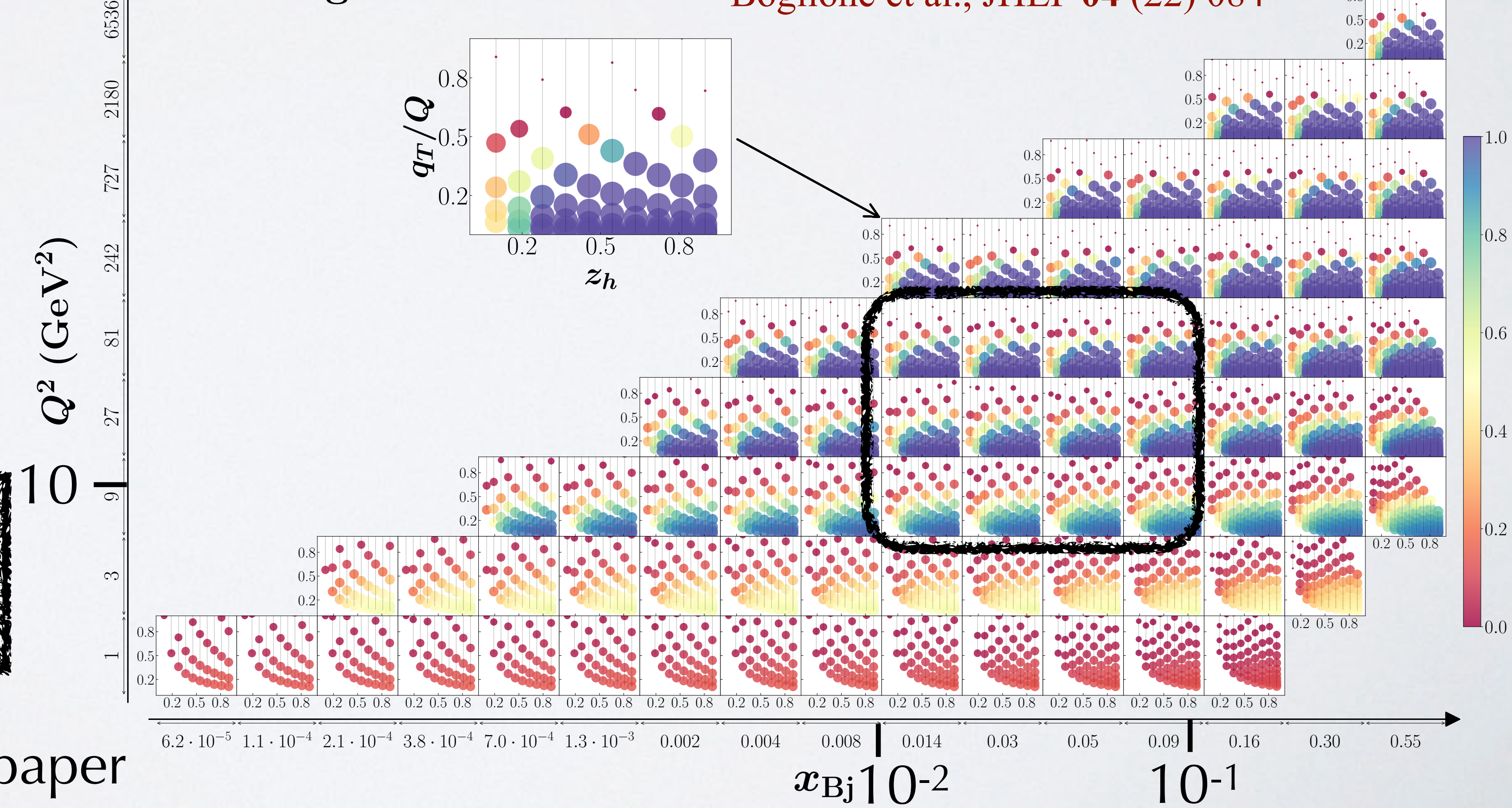


Fig.23 of paper

SIDIS cross section

twist-2 Axx

twist-3 Axx

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

target pol.

$$\times\left\{\begin{array}{ll}
1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h & \\
+\ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h & \mathbf{U}\\
+\ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] & \mathbf{L}\\
+\ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] & \\
+\ S_T\left[\begin{array}{l}
A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)\\
+\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\\
+\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\\
+\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S\\
+\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)
\end{array}\right] & \mathbf{T}\\
+\ S_T\lambda\left[\begin{array}{l}
\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\\
+\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S\\
+\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)
\end{array}\right] &
\end{array}\right\}$$

SIDIS cross section

twist-2 Axx

twist-3 Axx

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

target pol.

$$\times \left\{ \begin{array}{ll}
1+\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h & \\
+\lambda\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LU}^{\sin\phi_h}\sin\phi_h & \mathbf{U} \\
+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] & \mathbf{L} \\
+S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LL}^{\cos\phi_h}\cos\phi_h\right] & \\
+S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array}\right] & \mathbf{T} \\
+S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right] &
\end{array} \right\}$$

relative statistical uncertainty

$$\frac{\text{depolar. fact. }(y,\varepsilon)}{[\text{N. counts }(x,Q^2)]^{1/2}} \qquad \sqrt{s}\sim 30\text{ GeV}$$

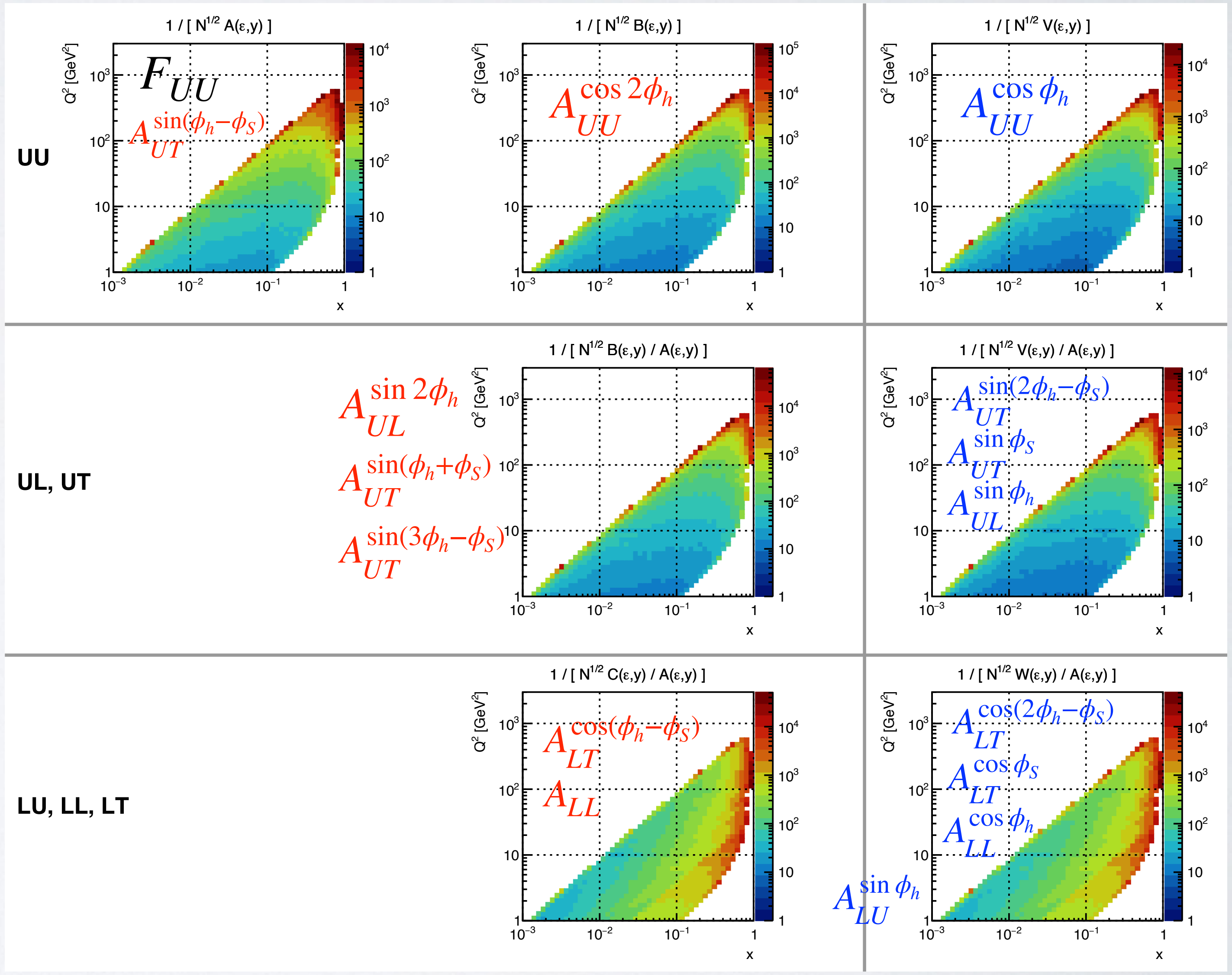


Fig.16 of the paper

SIDIS cross section

twist-2 Axx

twist-3 Axx

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

target pol.

$$\times \Big\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LU}^{\sin\phi_h}\sin\phi_h$$

U

$$+ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h}\sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

L

$$+ S_T\left[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\right]$$

$$+ S_T\lambda\left[\sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) + \sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos\phi_S}\cos\phi_S \ldots\right]$$

T

relative statistical uncertainty

$$\frac{\text{depolar. fact. } (y,\varepsilon)}{[\text{N. counts } (x,Q^2)]^{1/2}} \qquad \sqrt{s} \sim 30 \text{ GeV}$$

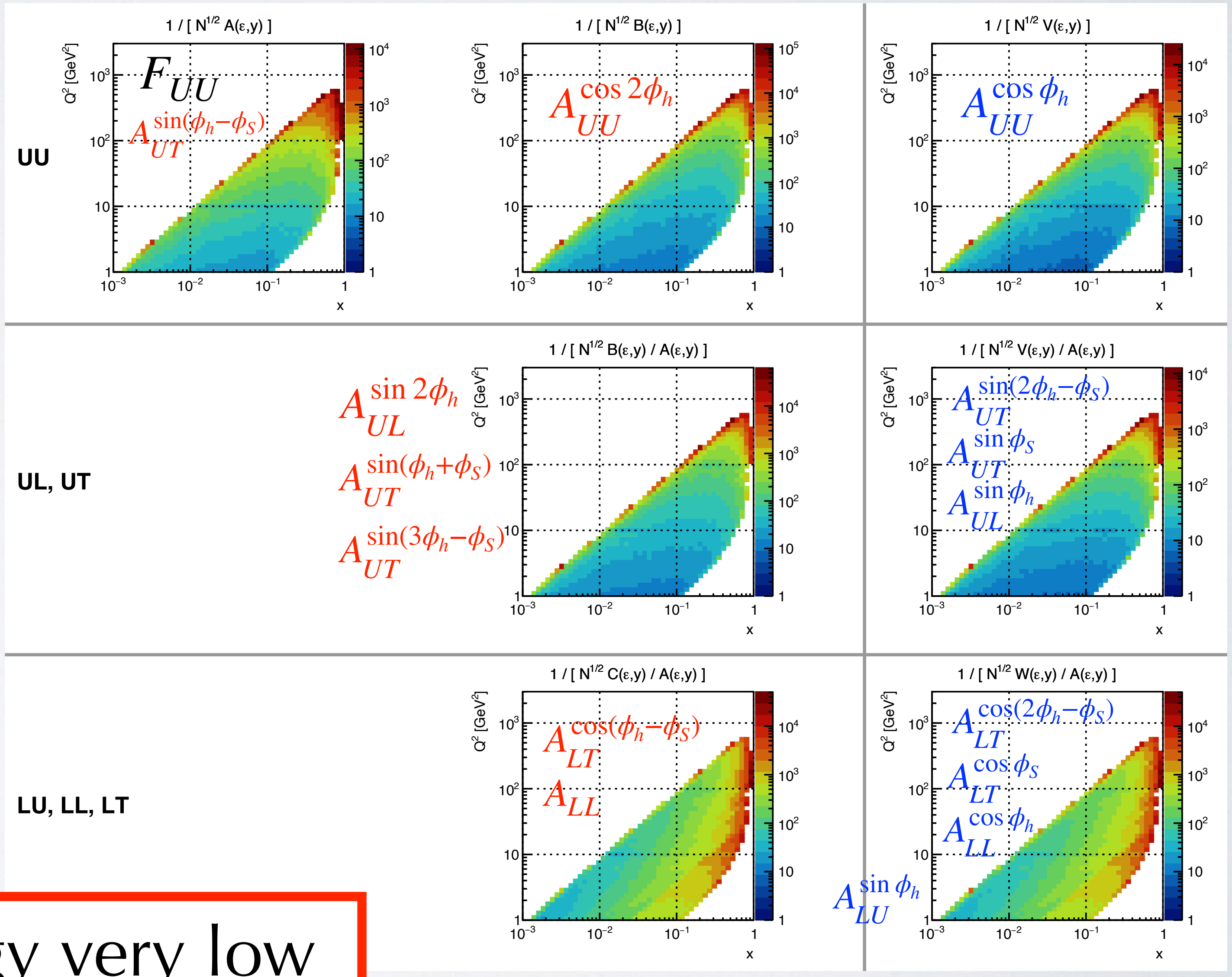


Fig.16 of the paper

For EIC at low/medium energy very low statistical uncertainties for UU, UL, UT

EIC impact on unpol. TMD

unpolarized cross section $e\, p \to e' + \pi^+ + X$

Adam et al. (ATHENA Coll.), JINST **17** (22) P10019

- th. uncertainty from PV17 fit (global fit of SIDIS + Drell-Yan)

  Bacchetta et al., JHEP **06** (17) 081

- ATHENA projected errors (2% pt-to-pt + 3% scale systematic error)

In each (x,Q^2), kinematics with largest impact is shown

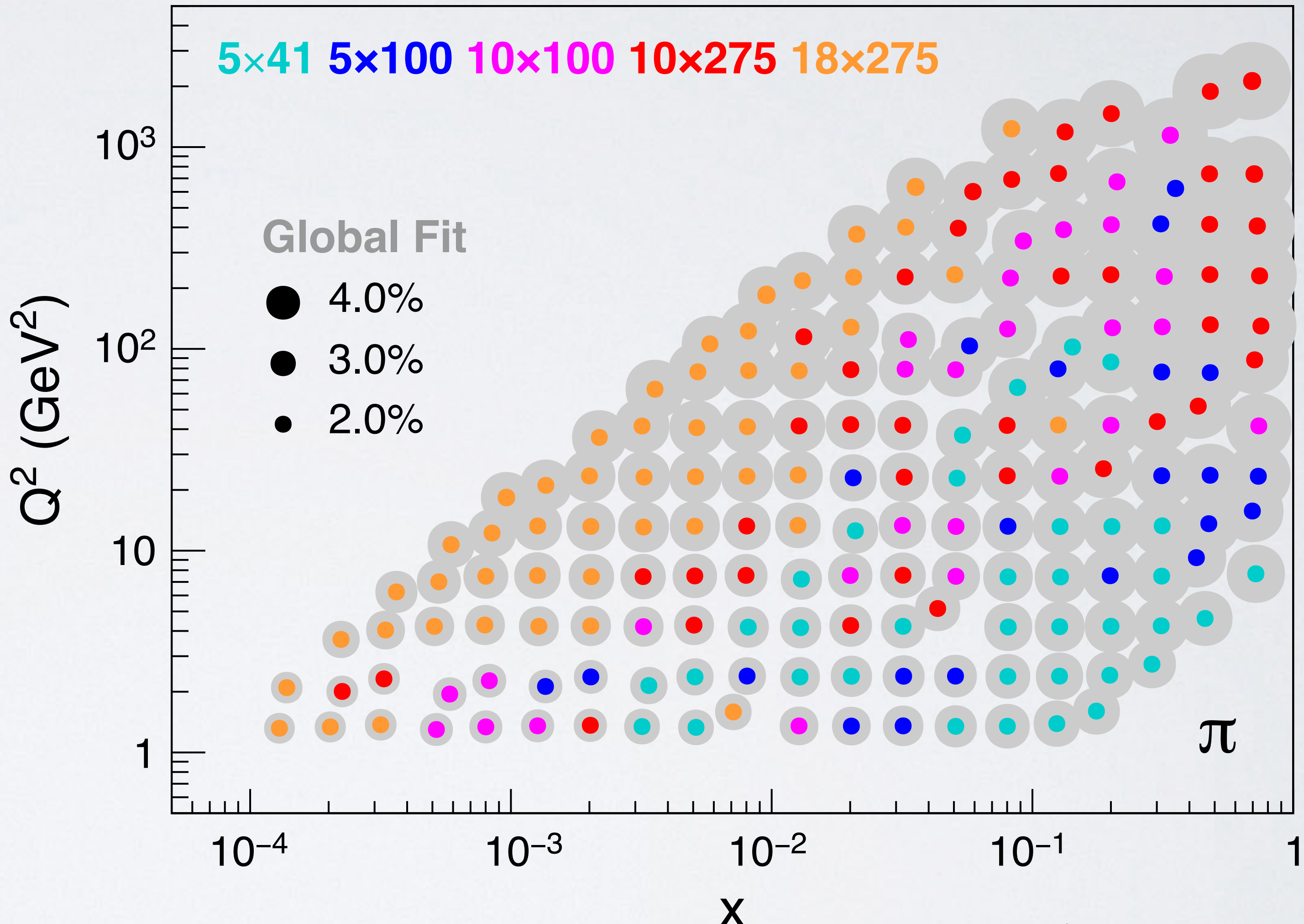


Fig.24 of the paper

EIC impact on unpol. TMD

unpolarized cross section $\quad e\, p \rightarrow e' + \pi^{+} + X$

Adam et al. (ATHENA Coll.), JINST **17** (22) P10019

th. uncertainty from PV17 fit (global fit of SIDIS + Drell-Yan)

Bacchetta et al., JHEP **06** (17) 081

ATHENA projected errors
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In each (x,Q^2), kinematics with largest impact is shown

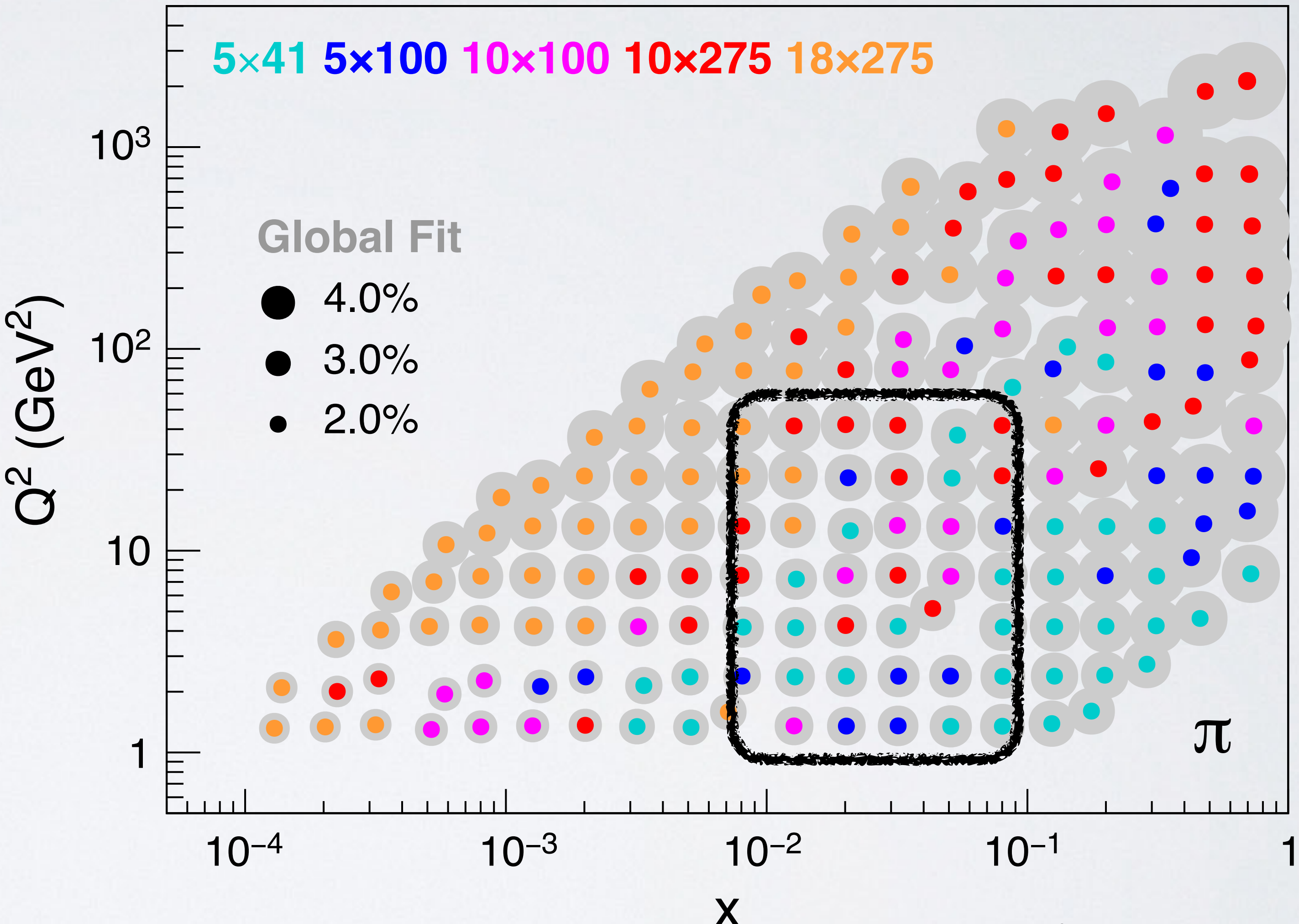
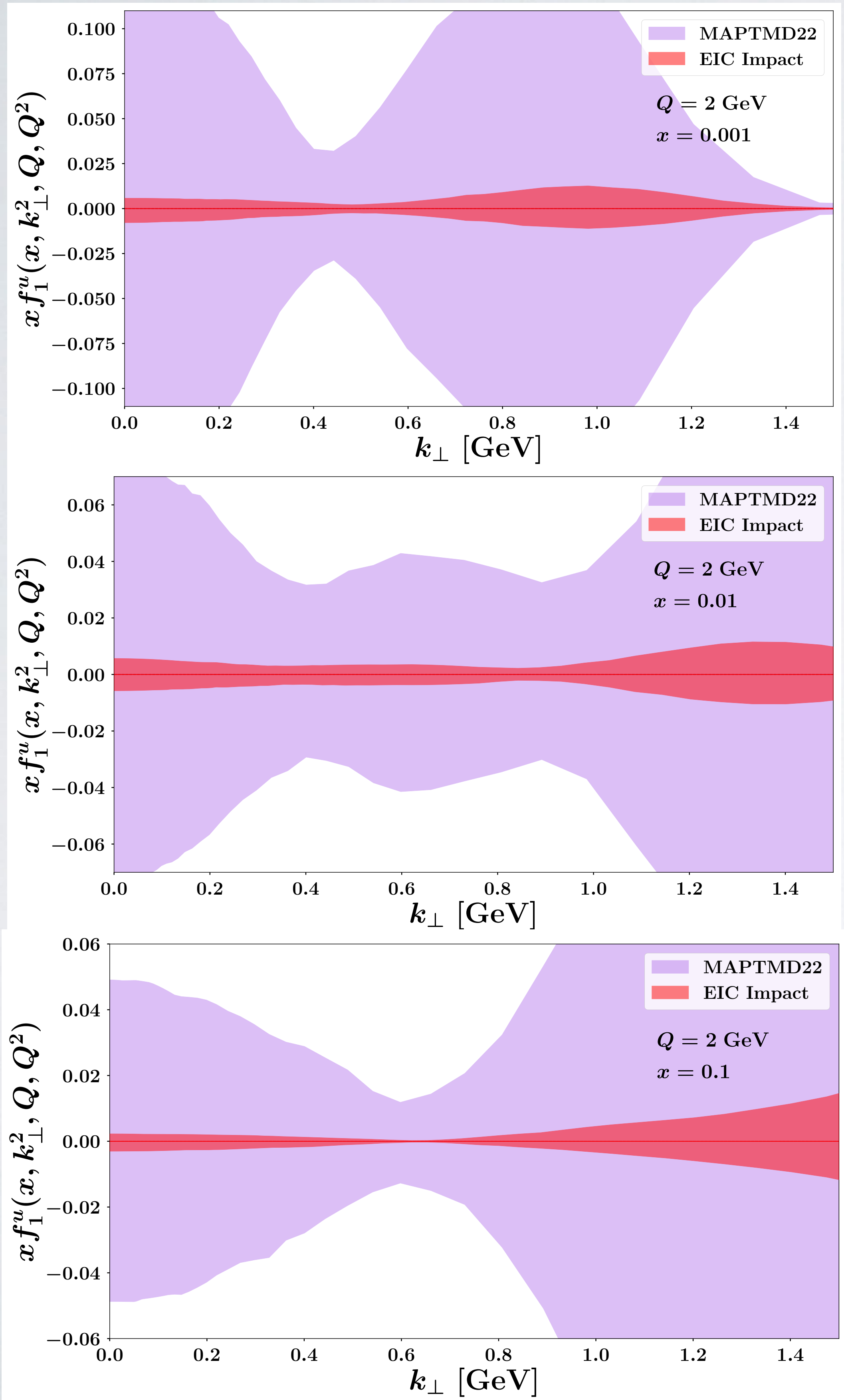


Fig.24 of the paper

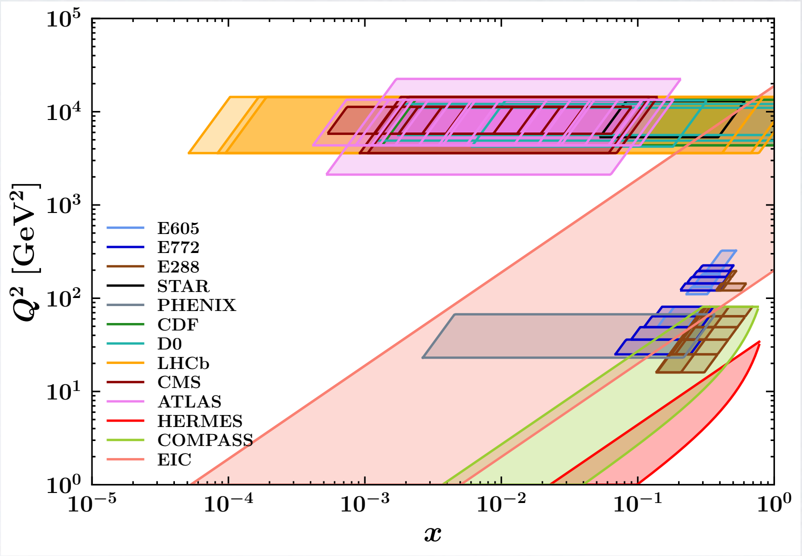
major impact from low/medium energy configurations

EIC impact on unpol. TMD



MAPTMD22 global fit of
2031 SIDIS + Drell-Yan data

Bacchetta et al. (MAP Coll.), JHEP **10** (22) 127

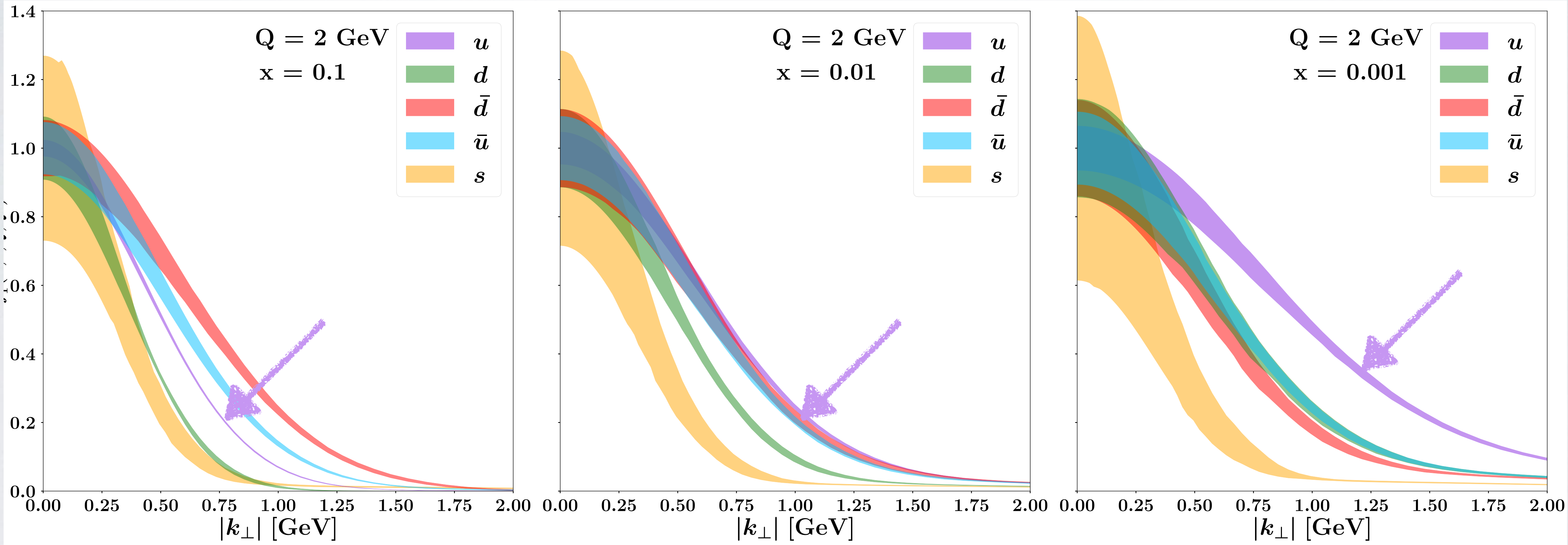


EIC impact at $\sqrt{s} \sim 63$ GeV
already important at x=0.1

EIC impact on unpol. TMD

MAPTMD24 global fit of 2031 SIDIS + Drell-Yan data
including flavor dependence of k_T-distribution
Bacchetta et al. (MAP Coll.), arXiv:2405.13833

$$\frac{f_1(x,k_T;Q)}{f_1(x,0;Q)}$$



- very different k_T behavior
- it changes with x

th. error band =
68% of all replicas

EIC impact on Sivers TMD

TSSA e p↑ → e′ + π+ + X

Adam et al. (ATHENA Coll.), JINST **17** (22) P10019

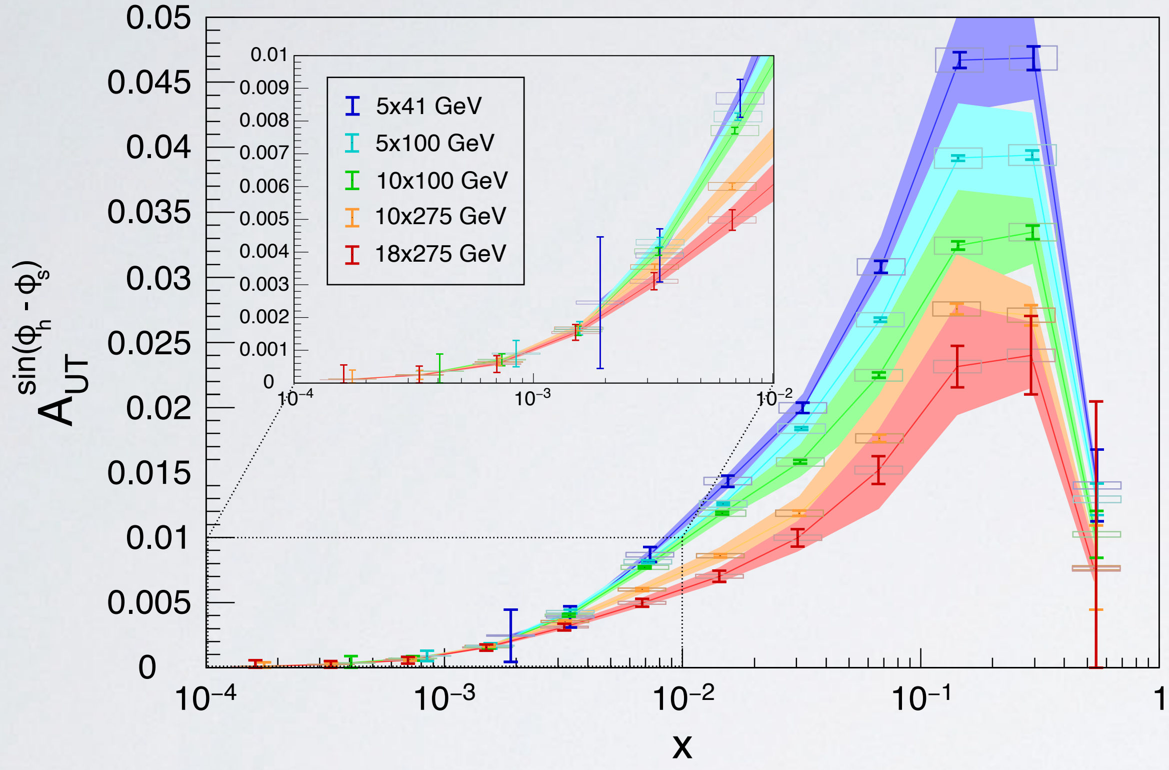


Fig.18 of the paper

Sivers TMD from

Bacchetta et al., P.L. **B827** (22) 136961

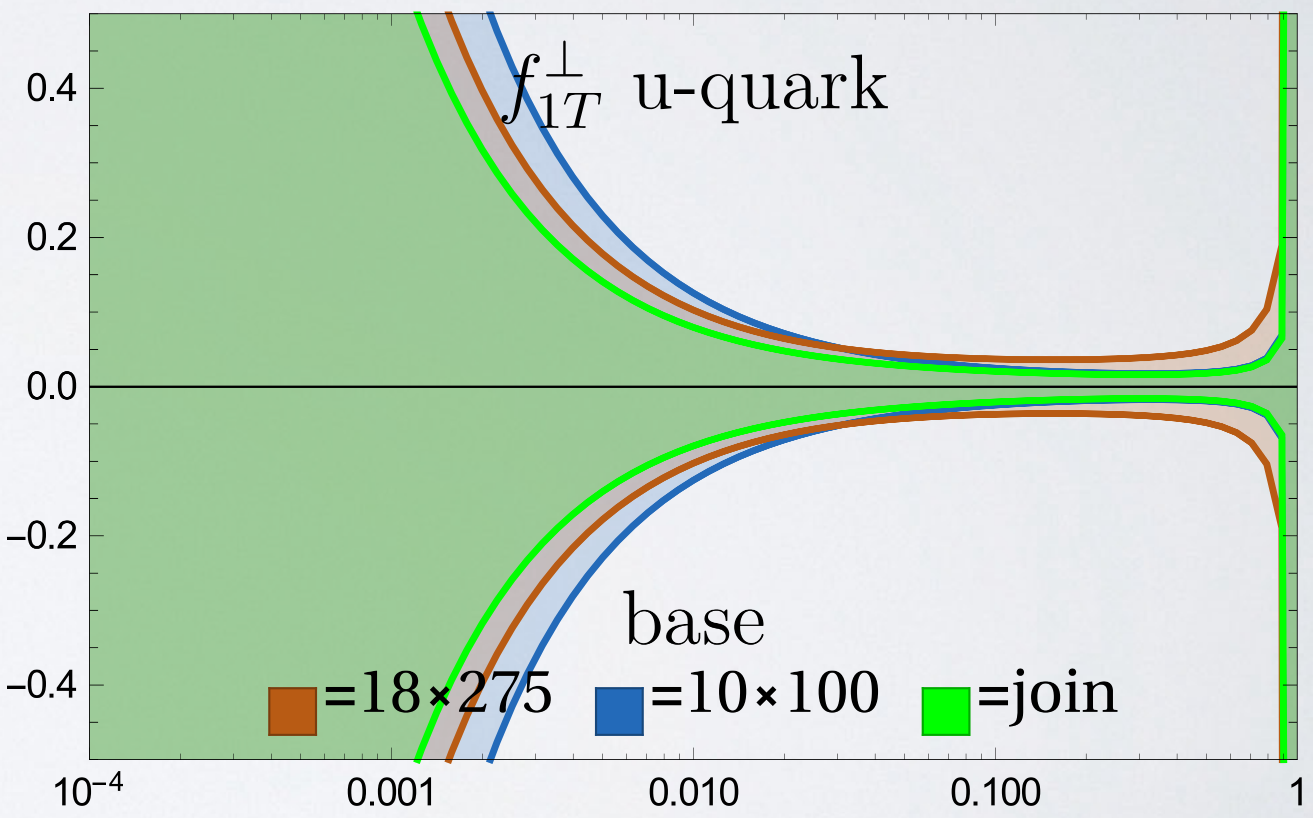


Fig.26 of the paper x

EIC impact on Sivers TMD

TSSA e p↑ → e′ + π⁺ + X

Adam et al. (ATHENA Coll.), JINST **17** (22) P10019

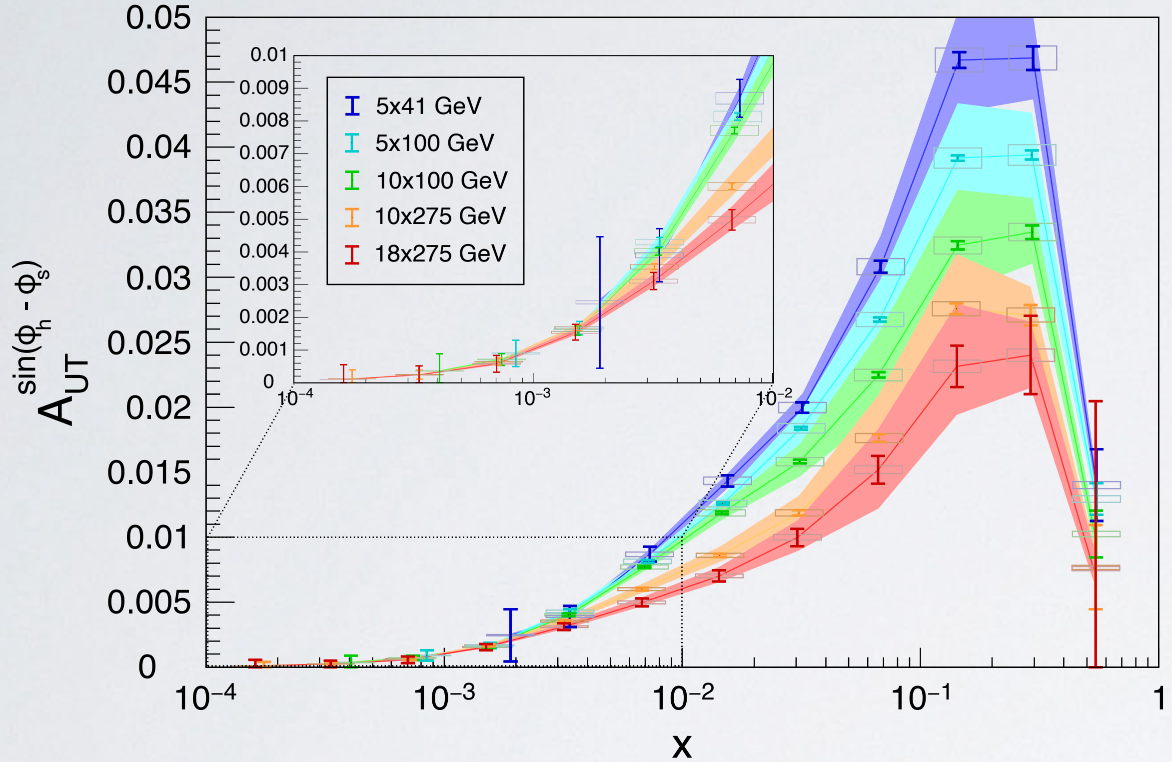


Fig.18 of the paper

Sivers TMD from

Bacchetta et al., P.L. **B827** (22) 136961

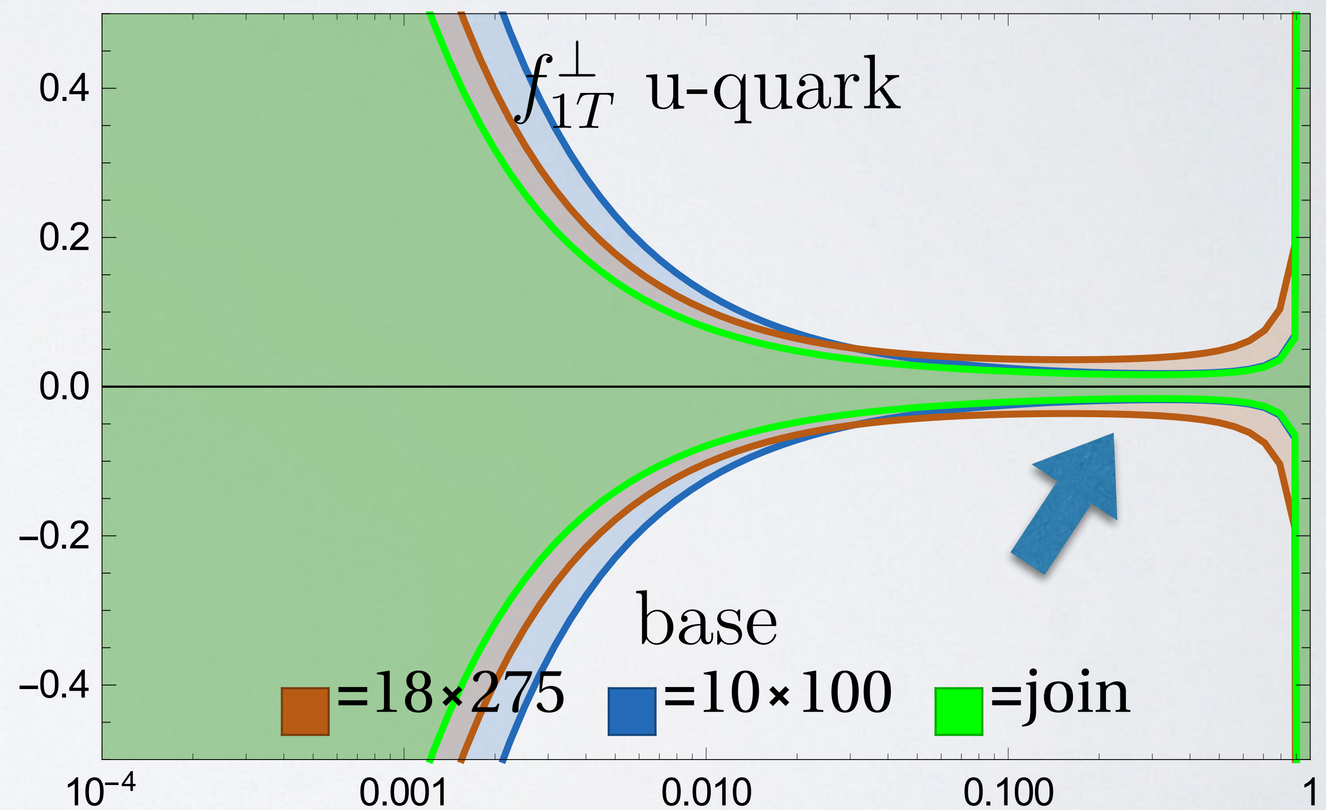
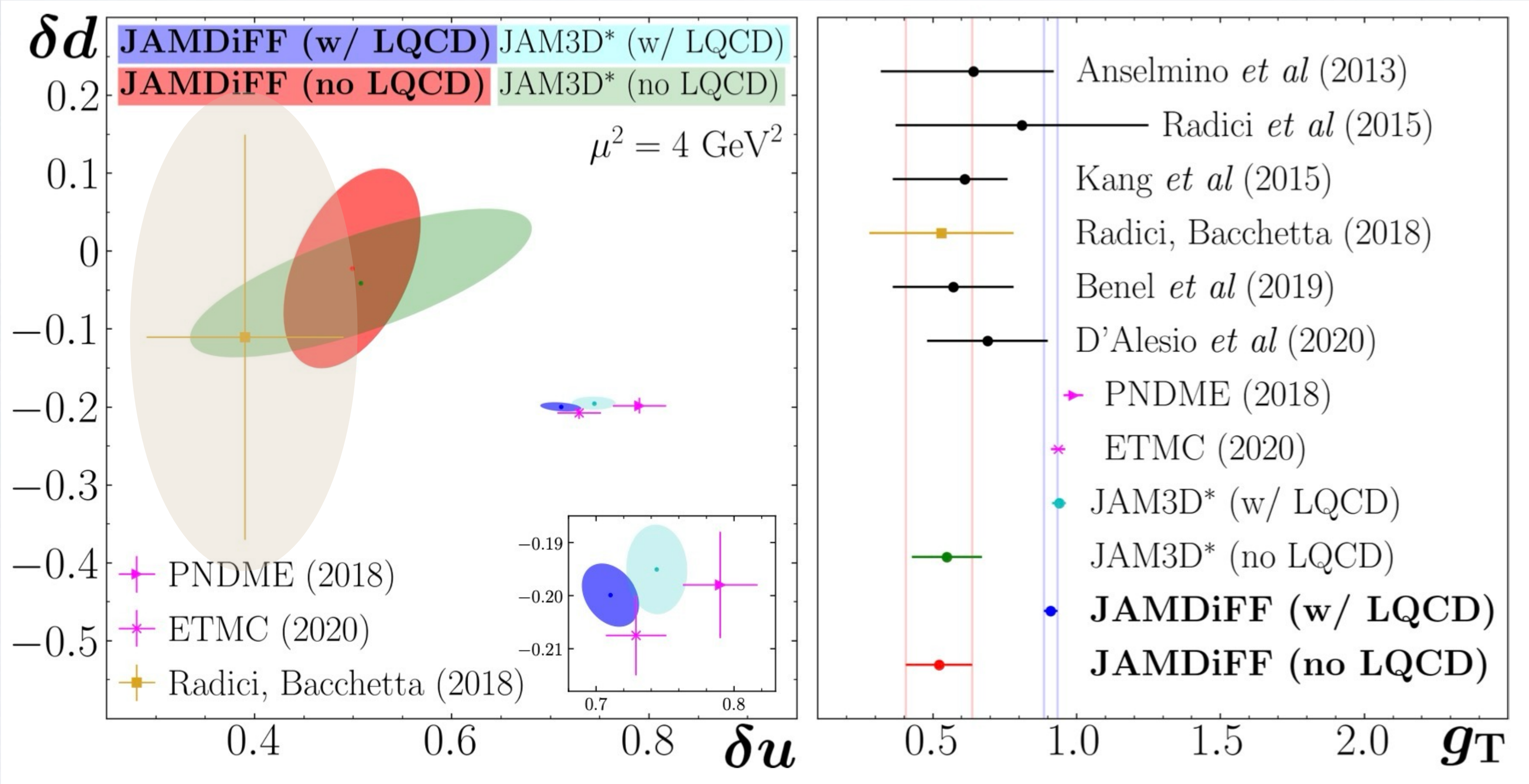


Fig.26 of the paper

At x~0.1 larger impact from medium energy configuration

Tensor charge: tension pheno-lattice

$$\delta q(Q^2) = \int_0^1 dx\, h_1^{q-\bar{q}}(x, Q^2) \qquad\qquad g_T = \delta u - \delta d$$



adapted from D. Pitonyak, QCD Evolution 24

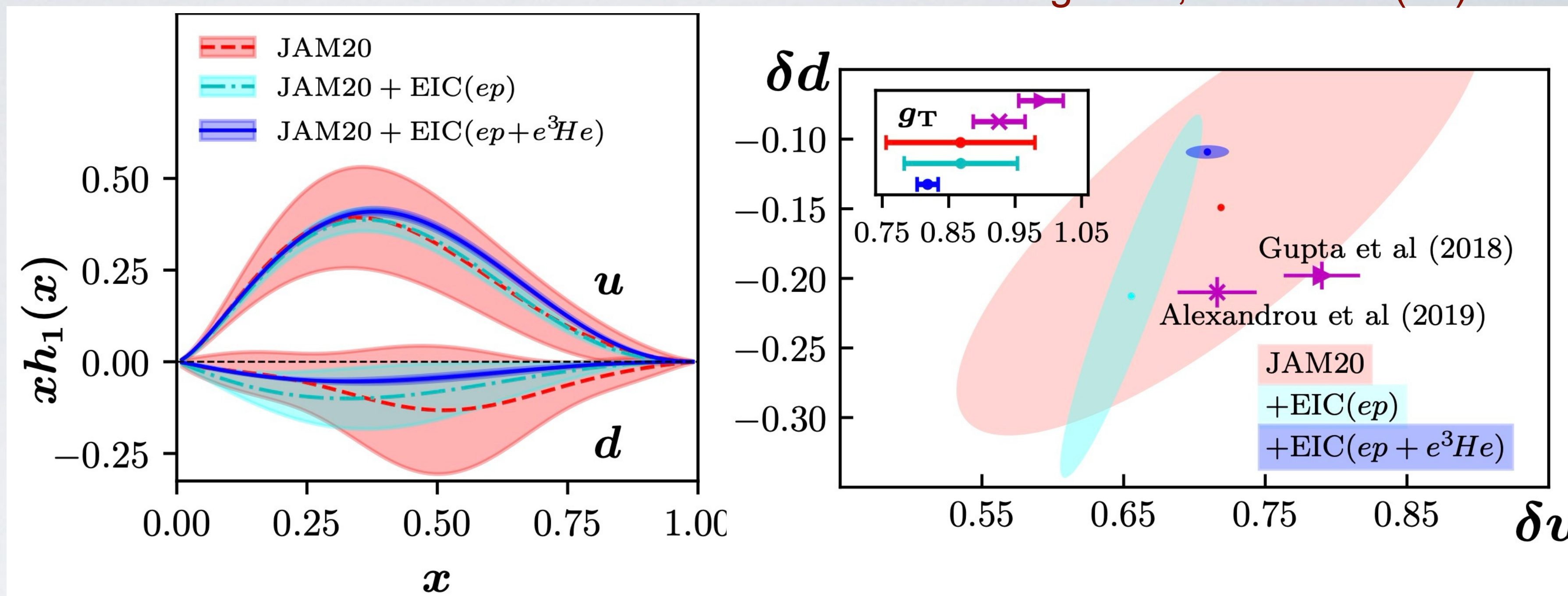
- **approximate compatibility of JAM with other phenomenology** when using both Collins effect and di-hadron mechanism but **not including lattice** results in the fit
- **including lattice as prior**, JAM still compatible with exp. data with both Collins effect and di-hadron mechanism but **deviates from other phenomenology**

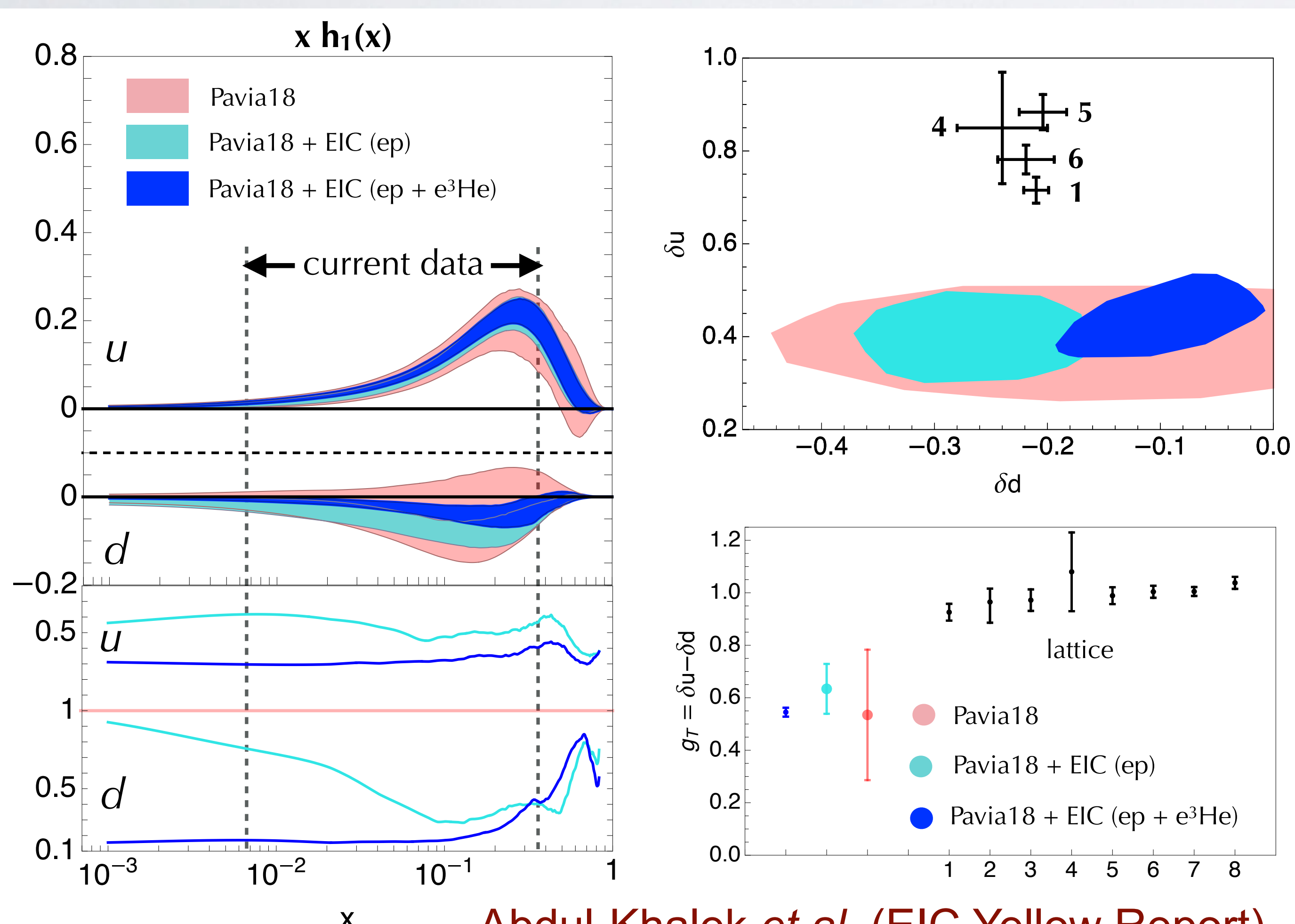
EIC impact on tensor charge

Gamberg *et al.*, P.L. **B816** (21)

Collins effect

$\mathcal{L}$=10 fb^{-1} , 8223 data pts.
proton [GeV]:
5x41, 5x100, 10x100, 18x275
^{3}He [GeV]:
5x41, 5x100, 18x100





Abdul-Khalek *et al.* (EIC Yellow Report),
N.P. **A1026** (22) 122447

di-hadron mechanism

$\mathcal{L}$=10 fb^{-1} , 3852 data pts
proton&^{3}He [GeV]: 10x100

Lattice results

1) **ETMC '19** Alexandrou et al., arXiv:1909.00485
2) **Mainz '19** Harris et al., P.R. D**100** (19) 034513
3) **LHPC '19** Hasan et al., P.R. D**99** (19) 114505
4) **JLQCD '18** Yamanaka et al., P.R. D**98** (18) 054516
5) **PNDME '18** Gupta et al., P.R. D**98** (18) 034503
6) **ETMC '17** Alexandrou et al., P.R. D**95** (17) 114514; (E) P.R. D**96** (17) 099906
7) **RQCD '14** Bali et al., P.R. D**91** (15) 054501
8) **LHPC '12** Green et al., P.R. D**86** (12) 114509

EIC impact on tensor charge

Gamberg *et al.*, P.L. **B816** (21)

Collins effect

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proton [GeV]:
5x41, 5x100, 10x100, 18x275
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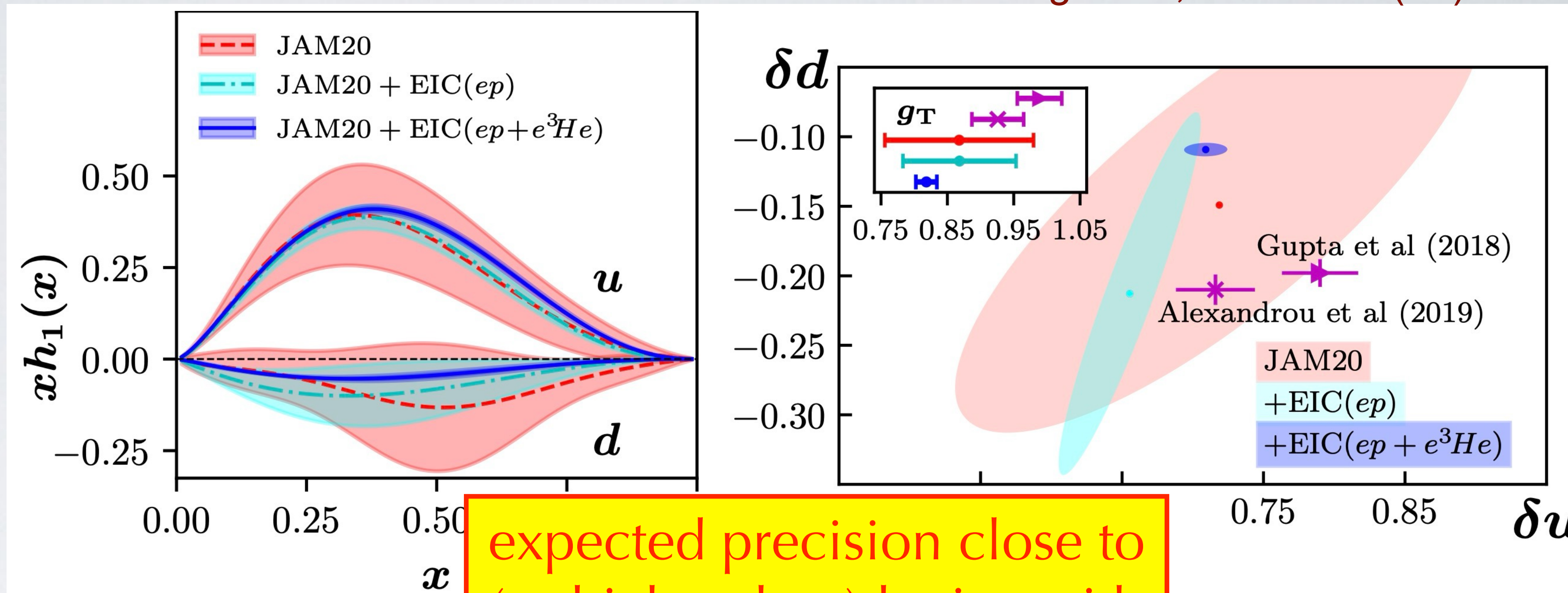
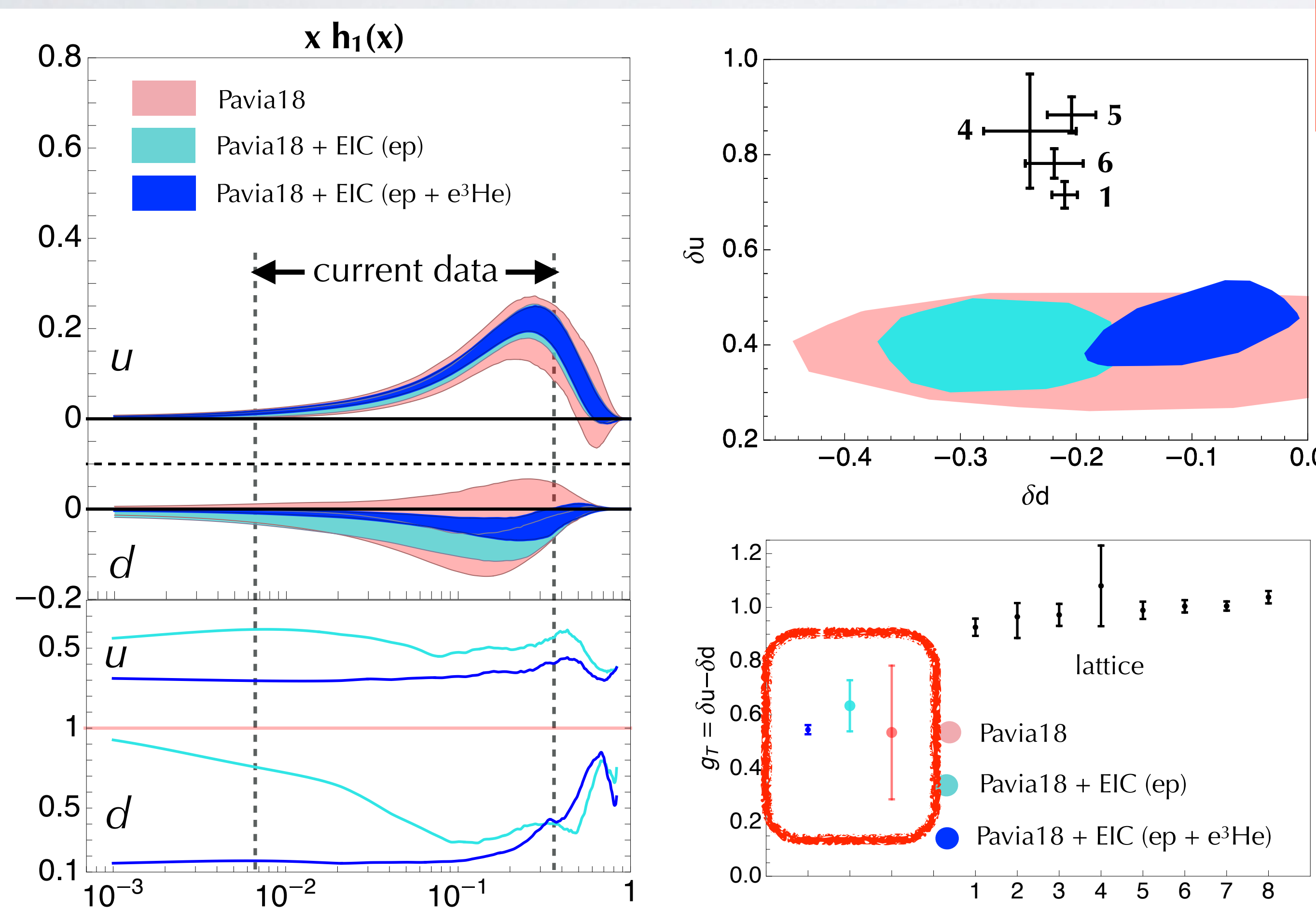


expected precision close to (or higher than) lattice with just $\sqrt{s} \sim 63$ GeV



Abdul-Khalek *et al.* (EIC Yellow Report), N.P. **A1026** (22) 122447

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7) **RQCD ’14** Bali et al., P.R. D**91** (15) 054501
8) **LHPC ‘12** Green et al., P.R. D**86** (12) 114509

The reference paper

Precision Studies of QCD in the Low Energy Domain of the EIC

V.D. Burkert,[1] L. Elouadrhiri,[1] A. Afanasev,[2] J. Arrington,[3] M. Contalbrigo,[4] W. Cosyn,[5,6] A. Deshpande,[7] D.I. Glazier,[8] X. Ji,[9,10] S. Liuti,[11] Y. Oh,[12,13] D. Richards,[1] T. Satogata,[1] A. Vossen,[14,1] H. Abdolmaleki,[15] A. Albataineh,[16] C.A. Aidala,[17] C. Alexandrou,[18] H. Avagyan,[1] A. Bacchetta,[19] M. Baker,[1] F. Benmokhtar,[20] J.C. Bernauer,[7,21] C. Bissolotti,[19] W. Briscoe,[2] D.Byers,[14] Xu Cao,[22] C.E. Carlson,[23] K. Cichy,[24] I.C. Cloet,[25] C. Cocuzza,[26] P.L. Cole,[27] M. Constantinou,[26] A. Courtoy,[28] H. Dahiyah,[29] K. Dehmelt,[7] S. Diehl,[30,31] C. Dilks,[14] C. Djalali,[32] R. Dupré,[33] S.C. Dusa,[1] B. El-Bennich,[34] L. El Fassi,[35] T. Frederico,[36] A. Freese,[37] B.R. Gamage,[1] L. Gamberg,[38] R.R. Ghoshal,[1] F.X. Girod,[1] V.P. Goncalves,[39,22,40] Y. Gotra,[1] F.K. Guo,[41,42] X. Guo,[9] M. Hattawy,[43] Y. Hatta,[44] T. Hayward,[30] O. Hen,[45] G. M. Huber,[46] C. Hyde,[43] E.L. Isupov,[47] B. Jacak,[3] W. Jacobs,[48] A. Jentsch,[44] C.R Ji,[49] S. Joosten,[25] N. Kalantarians,[50] Z. Kang,[51,52,53] A. Kim,[30,1] S. Klein,[3] B. Kriesten,[10] S. Kumano,[54] A. Kumar,[55] K. Kumericki,[56] M. Kuchera,[57] W.K. Lai,[58,59,51] Jin Li,[60] Shujie Li,[3] W. Li,[61] X. Li,[62] H.-W. Lin,[63] K.F. Liu,[64] Xiaohui Liu,[65,66] P. Markowitz,[5] V. Mathieu,[67,68] M. McEneaney,[14] A. Mekki,[69] J.P. B. C. de Melo,[70] Z.E. Meziani,[25] R. Milner,[45] H. Mkrtchyan,[71] V. Mochalov,[72,73] V. Mokeev,[1] V. Morozov,[74] H. Moutarde,[75] M. Murray,[76] S. Mtingwa,[77] P. Nadel-Turonski,[53] V.A. Okorokov,[73] E. Onyie,[1] L.L.Pappalardo,[4,78] Z. Papandreou,[79] C. Pecar,[14] A. Pilloni,[80,81] B. Pire,[82] N. Polys,[83] A. Prokudin,[84,1] M. Przybycien,[85] J-W. Qiu,[1] M. Radici,[86] R. Reed,[87] F. Ringer,[1,43] B.J. Roy,[88] N. Sato,[1] A. Schäfer,[89] B. Schmookler,[90] G. Schnell,[91] P. Schweitzer,[30] R. Seidl,[92,21] K.M. Semenov-Tian-Shansky,[12,93,94] F. Serna,[95,96] F. Shaban,[97] M.H. Shabestari,[98] K. Shiells,[10] A. Signori,[99,100] H. Spiesberger,[101] I. Strakovsky,[2] R.S. Sufian,[23,1] A. Szczepaniak,[102,1] L. Teodorescu,[103] J. Terry,[51,52] O. Teryaev,[104] F. Tessarotto,[105] C. Timmer,[1] Abdel Nasser Tawfik,[106] L. Valenzuela Cazares,[107] A. Vladimirov,[89,108] E. Voutier,[33] D. Watts,[109] D. Wilson,[110] D. Winney,[111,112] B. Xiao,[113] Z. Ye,[114] Zh. Ye,[115] F. Yuan,[3] N. Zachariou,[109] I. Zahed,[7] J.L. Zhang,[60] Y. Zhang,[1] and J. Zhou[116]

Prog. Part. Nucl. Phys. **131** (2023) 104032, arXiv:2211.15746

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