Early EIC Physics Discussion

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Topics

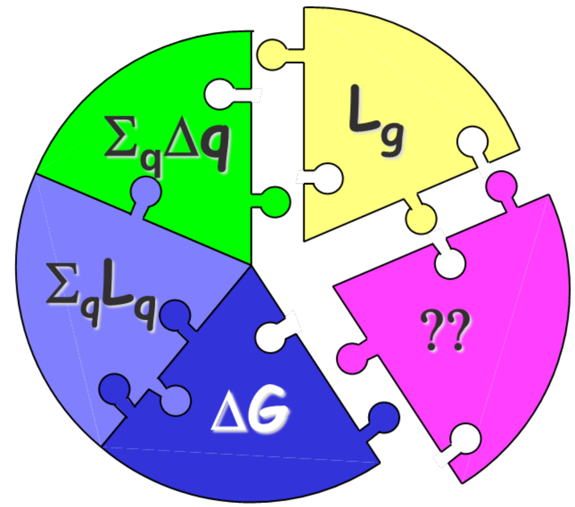
- 1D proton structure (F_2, F_L structure functions, unpolarized PDFs): too "bread and butter”, will not discuss today
- Longitudinal Spin (polarized DIS: g_1 structure function, parity violating structure functions (?); polarized SIDIS).
- Momentum-space structure: TMDs
- 3D proton structure: GPDs
- Origin of the proton mass
- e+A at small x: saturation signals
- e+A at large x: in-medium hadronization, nuclear PDFs and GPDs

Early EIC Matrix

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG
Note: the eA luminosity is per nucleon					

Longitudinal Spin

Proton Helicity Sum Rule



- Helicity sum rule (Jaffe&Manohar, 1989; cf. Ji, 1997):

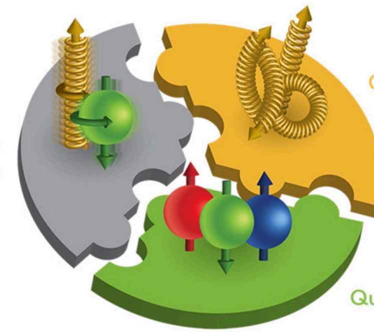
$$\frac{1}{2} = S_q + L_q + S_g + L_g$$

with the net quark and gluon spin

$$S_q(Q^2) = \frac{1}{2}\int_0^1 dx\, \Delta\Sigma(x,Q^2) \qquad S_g(Q^2) = \int_0^1 dx\, \Delta G(x,Q^2)$$

- L_q and L_g are the quark and gluon orbital angular momenta (OAM)

Proton Spin Puzzle



- The spin puzzle began when the EMC collaboration measured the proton g_1 structure function ca 1988. Their data resulted in

$$S_q \approx 0.03$$

- It appeared (constituent) quarks do not carry all of the proton spin (which would have naively corresponded to $S_q = 1/2$).

$$\frac{1}{2} = S_q + L_q + S_g + L_g$$

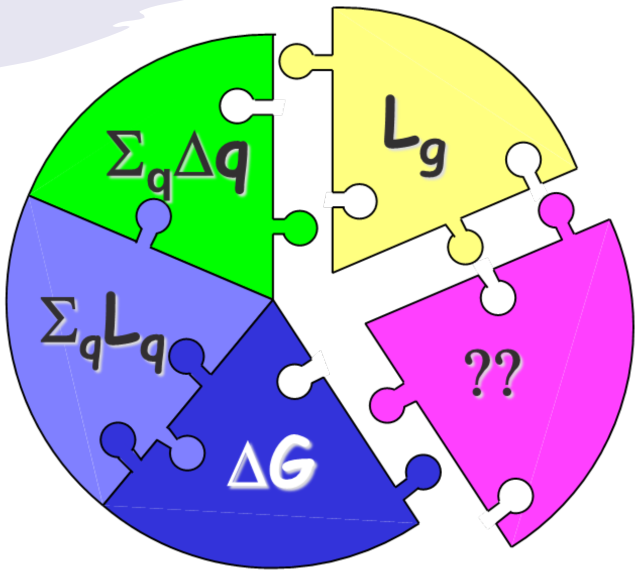
- Missing spin can be
  - Carried by gluons
  - In the orbital angular momenta of quarks and gluons
  - At small x:

$$S_q(Q^2) = \frac{1}{2} \int\limits_0^1 dx\, \Delta\Sigma(x, Q^2) \qquad S_g(Q^2) = \int\limits_0^1 dx\, \Delta G(x, Q^2)$$

Can't integrate down to zero, use x_{min} instead!

  - Or all of the above!

Current Knowledge of Proton Spin



- The proton spin carried by the quarks is estimated to be (for $0.001 < x < 1$)

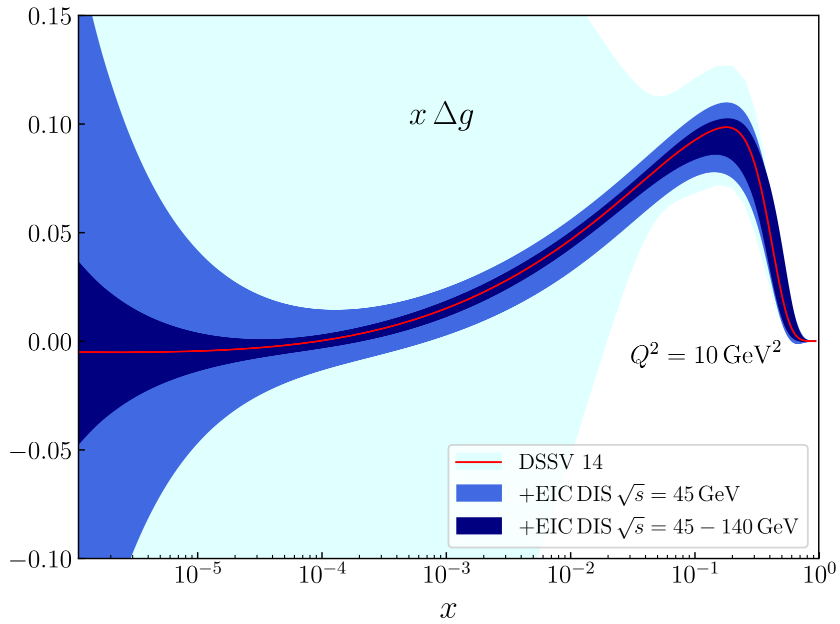
$$S_q(Q^2 = 10 \text{ GeV}^2) \in [0.15, 0.2]$$

- The proton spin carried by the gluons is (for $0.01 < x < 1$, STAR+PHENIX+COMPASS +HERMES+… , analyzed by DSSV, JAM, NNPDF…)

$$S_G(Q^2 = 10 \text{ GeV}^2) \in [0.13, 0.26]$$

- Unfortunately, the uncertainties are large. Note also that the x-ranges are limited, with more spin (positive or negative) possible at small x.

How much spin is there at small x?

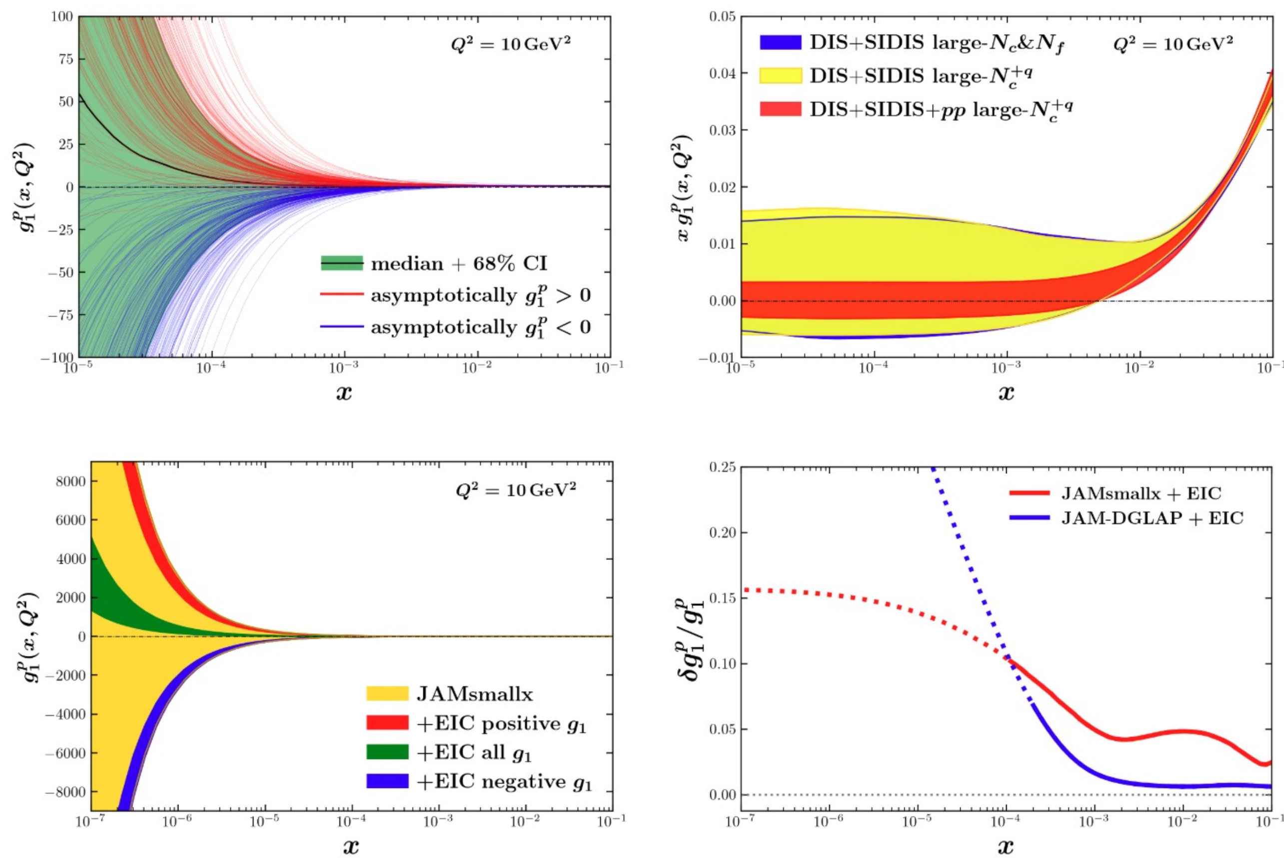


- E. Aschenauer et al, 2020 (DGLAP-based helicity PDF extraction from data)
- Uncertainties are very large at small x. Note that this is x∆G, the uncertainties for ∆G are 1/x = 100-10000 times larger! EIC will reduce them, but only where there will be data.

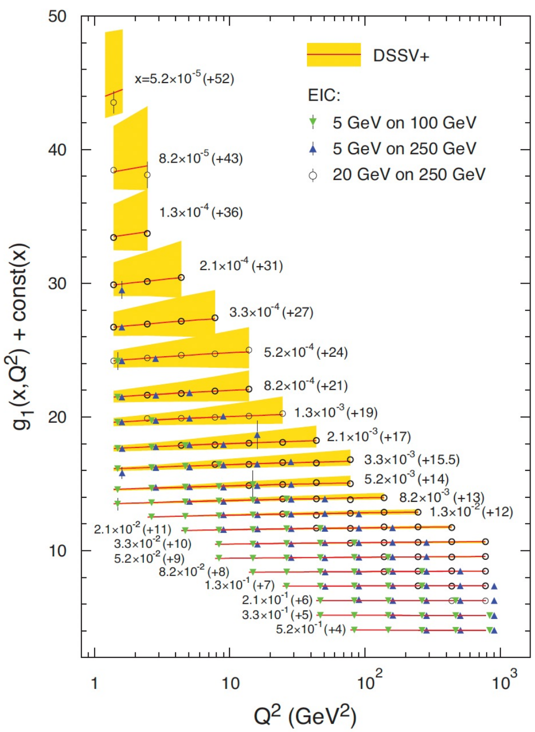
Longitudinal Spin: Small-*x* Evolution

- Small-x evolution can predict helicity distributions at small x.
- But: hard to fix initial conditions given the existing data (note: not all polarized p+p data has been analyzed yet).
- End result: also a spread of predictions for EIC.
- EIC will provide constraints:

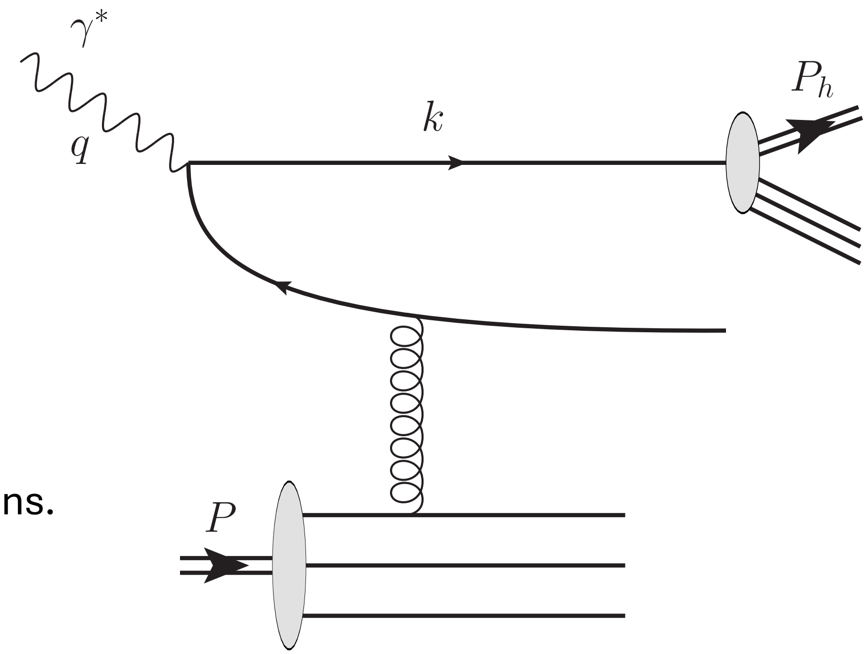
- Plots are from JAMsmallx, D. Adamiak et al, 2503.21006 [hep-ph]



Projected g_1 measurements at EIC



Polarized SIDIS



+ Also couples to helicity PDFs

- The coupling involves fragmentation functions.

$$g_1^h(x,z,Q^2) = \frac{1}{2}\sum_{q,\bar{q}} e_q^2\,\Delta q(x,Q^2)\,D_1^{h/q}(z,Q^2)$$

Parity-violating structure functions?

PV structure functions probe helicity PDFs too:

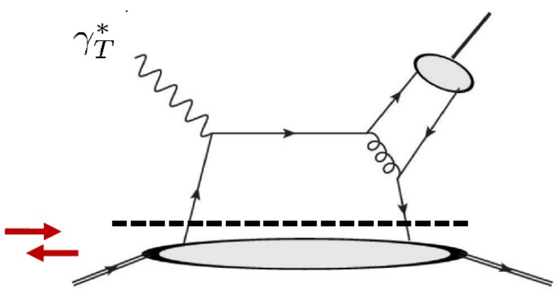
$$\left[g_5^{\gamma},\ g_5^{\gamma Z},\ g_5^{Z}\right] = \sum_q [0,\ e_q g_A^q,\ g_V^q g_A^q]\ (\Delta\overline{q} - \Delta q)$$

$$g_5^{W^-} = (-\Delta u + \Delta\overline{d} + \Delta\overline{s} - \Delta c \ldots)$$

Hard to measure? Especially the CC one.

Probing quark OAM through π^0 production in ep collisions

Scattering amplitude



Scattering amplitude:

$$A \propto \int dx \int d^2k_\perp \, H(x,\xi,z,k_\perp,\Delta_\perp)\, f^q(x,\xi,k_\perp,\Delta_\perp) \int dz \phi_\pi(z)$$

Collinear twist-expansion of hard part:

$$H(k_\perp,\Delta_\perp) = H(k_\perp=0,\Delta_\perp=0) + \frac{\partial H(k_\perp,\Delta_\perp=0)}{\partial k_\perp^\mu}\Big|_{k_\perp=0} k_\perp^\mu + \frac{\partial H(k_\perp=0,\Delta_\perp)}{\partial \Delta_\perp^\mu}\Big|_{\Delta_\perp=0} \Delta_\perp^\mu + \ldots$$

Twist 3 term

Shohini's talk

Probing quark OAM through π^0 production in ep collisions

Cross section

$$\frac{d\sigma}{dt dQ^2 dx_B d\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2 \xi^3 \Delta_\perp^2}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)}\left[1+(1-y)^2\right]$$

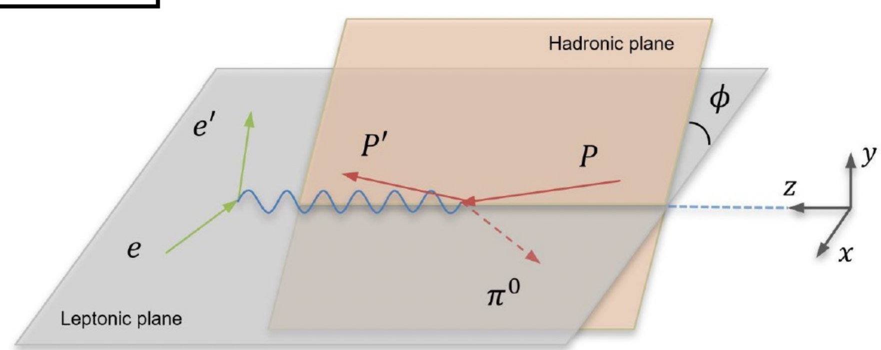
Shohini's talk

$$\times\left\{\left[|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2+2\frac{M^2}{\Delta_\perp^2}|\mathcal{F}_{1,2}+\mathcal{G}_{1,2}|^2\right]+\cos(2\phi)a\left[-|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2+|\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2\right]\right.$$

$$\left.+\lambda\sin(2\phi)\,2a\,\mathrm{Re}\left[(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4})\left(\mathcal{F}_{1,1}^*+\mathcal{G}_{1,1}^*\right)\right]\right\}$$

Distinguished experimental signature of quark OAM

$$\phi = \phi_{l_\perp} - \phi_{\Delta_\perp}$$



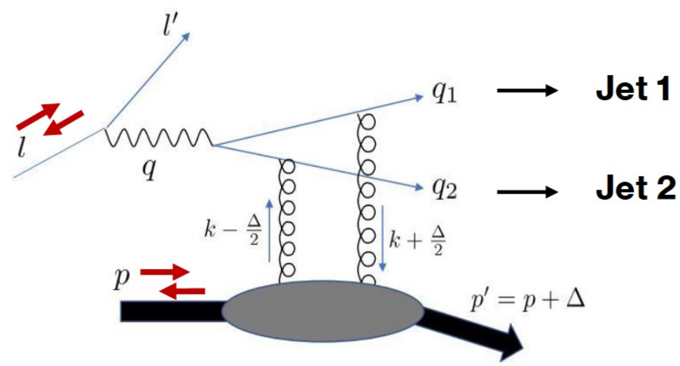
Selected works on gluon GTMDs

Probing gluon OAM through exclusive di-jet production

PHYSICAL REVIEW LETTERS **128**, 182002 (2022)

Signature of the Gluon Orbital Angular Momentum

Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[1,3,‡]



Main result (double spin asymmetry):

Signature of gluon OAM is cosine angular modulation

$$d\sigma^{\mathbf{asym}} \sim -\Re e\left[\left\{\mathcal{H}_g^{(1)*}(\xi) + \frac{4q_\perp^2}{q_\perp^2+\mu^2}\mathcal{H}_g^{(2)*}(\xi)\right\}\mathcal{L}_g(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

$$+\Re e\left[\mathcal{H}_g^{(1)*}(\xi)\,\tilde{\mathcal{H}}_g^{(2)}(\xi)\right]\cos(\phi_{l_\perp} - \phi_{\Delta_\perp})$$

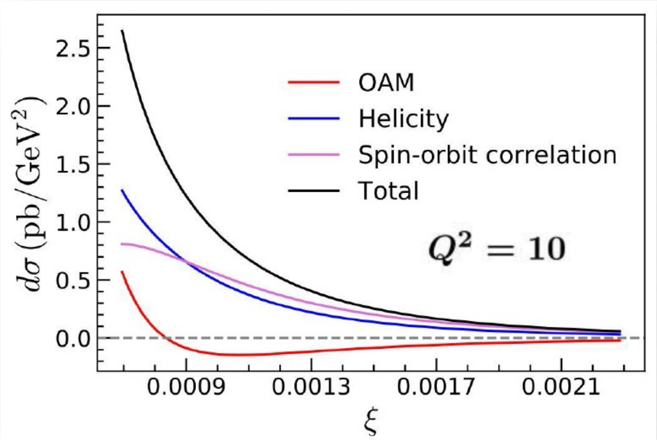
Shohini's talk

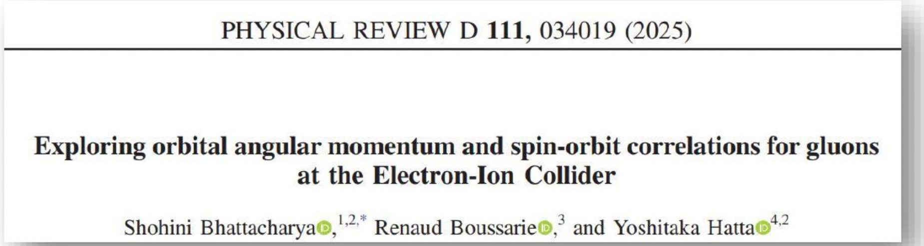
Selected works on gluon GTMDs

Probing gluon OAM & spin-orbit correlation at small x

Updated numerical results (SB, Boussarie, Hatta, 2404.04209)**:**

Shohini's talk




PHYSICAL REVIEW D **111,** 034019 (2025)

Exploring orbital angular momentum and spin-orbit correlations for gluons at the Electron-Ion Collider

Shohini Bhattacharya,[1,2,*] Renaud Boussarie,[3] and Yoshitaka Hatta[4,2]

Spin-orbit correlation is more accurately constrained than **OAM** because the latter necessitates the precise determination of both unpolarized and polarized gluon distributions

OAM Distributions

- Let us write the (Jaffe-Manohar) quark and gluon OAM in terms of the Wigner distribution as

$$L_z = \int \frac{d^2 b_\perp \, db^- \, d^2 k_\perp \, dk^+}{(2\pi)^3} \, (\underline{b} \times \underline{k})_z \, W(k,b)$$

- After much algebra, we arrive at the quark and gluon OAM distributions at small x :

$$L_{q+\bar{q}}(x,Q^2) = \frac{N_c N_f}{2\pi^3} \int\limits_{\Lambda^2/s}^{1} \frac{dz}{z} \int\limits_{\max\left\{\frac{1}{zs}, \frac{1}{Q^2}\right\}}^{\min\left\{\frac{1}{zQ^2}, \frac{1}{\Lambda^2}\right\}} \frac{dx_{10}^2}{x_{10}^2} \Big[Q(x_{10}^2, zs) - 3\, G_2(x_{10}^2, zs) - I_3(x_{10}^2, zs) - 2\, I_4(x_{10}^2, zs) + I_5(x_{10}^2, zs) + 3\, I_6(x_{10}^2, zs) \Big]$$

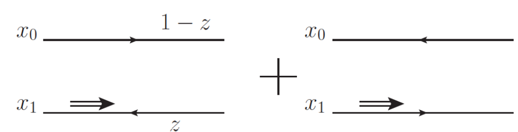
$$L_G(x,Q^2) = -\frac{2\, N_c}{\alpha_s \pi^2} \Bigg\{ \left[2 + 6\, x_{10}^2 \frac{\partial}{\partial x_{10}^2} + 2\, x_{10}^4 \frac{\partial^2}{\partial (x_{10}^2)^2} \right] \left[I_4(x_{10}^2, zs) + I_5(x_{10}^2, zs) \right] + \left[1 + x_{10}^2 \frac{\partial}{\partial x_{10}^2} \right] \left[I_5(x_{10}^2, zs) + I_6(x_{10}^2, zs) \right] \Bigg\}_{x_{10}^2 = 1/Q^2,\, zs = Q^2/x}$$

OAM Distributions and Moment Amplitudes

$$L_{q+\bar{q}}(x,Q^2) = \frac{N_c N_f}{2\pi^3} \int\limits_{\Lambda^2/s}^{1} \frac{dz}{z} \int\limits_{\max\left\{\frac{1}{zs},\frac{1}{Q^2}\right\}}^{\min\left\{\frac{1}{zQ^2},\frac{1}{\Lambda^2}\right\}} \frac{dx_{10}^2}{x_{10}^2} \Big[Q(x_{10}^2, zs) - 3\,G_2(x_{10}^2, zs) - I_3(x_{10}^2, zs) - 2\,I_4(x_{10}^2, zs) + I_5(x_{10}^2, zs) + 3\,I_6(x_{10}^2, zs)\Big]$$

$$L_G(x,Q^2) = -\frac{2\,N_c}{\alpha_s \pi^2} \left\{ \left[2 + 6\,x_{10}^2 \frac{\partial}{\partial x_{10}^2} + 2\,x_{10}^4 \frac{\partial^2}{\partial (x_{10}^2)^2}\right] \left[I_4(x_{10}^2, zs) + I_5(x_{10}^2, zs)\right] + \left[1 + x_{10}^2 \frac{\partial}{\partial x_{10}^2}\right] \left[I_5(x_{10}^2, zs) + I_6(x_{10}^2, zs)\right] \right\}_{x_{10}^2 = 1/Q^2,\; zs = Q^2/x}$$

- Q and G_2 are the same as above. However, we also now have the impact parameter **moments of dipole amplitudes**, labeled I_3, I_4, I_5 and I_6:



$$\int d^2x_1\, x_1^i\, Q_{10}(zs) = x_{10}^i\, I_3(x_{10}^2, zs) + \ldots,$$

$$\int d^2x_1\, x_1^i G_{10}^j(zs) = \epsilon^{ij}\, x_{10}^2\, I_4(x_{10}^2, zs) + \epsilon^{ik}\, x_{10}^k\, x_{10}^j\, I_5(x_{10}^2, zs) + \epsilon^{jk}\, x_{10}^k\, x_{10}^i\, I_6(x_{10}^2, zs) + \ldots$$

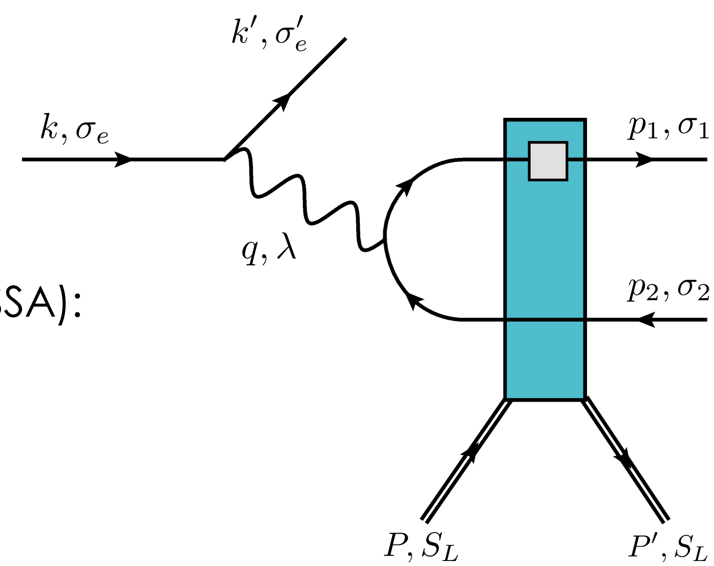
Elastic dijet production in e+p collisions

The process is similar to the one above, except now the proton remains intact.

One considers two observables, double spin asymmetry (DSA) and single spin asymmetry (SSA):

$$d\sigma^{DSA} = \frac{1}{4} \sum_{\sigma_e, S_L} \sigma_e \, S_L \, d\sigma(\sigma_e, S_L),$$

$$d\sigma^{SSA} = \frac{1}{4} \sum_{\sigma_e, S_L} S_L \, d\sigma(\sigma_e, S_L)$$



Hatta et al, 2016; S. Bhattacharya, R. Boussarie and Y. Hatta, 2022 & 2024; S. Bhattacharya, D. Zheng and J. Zhou, 2023; YK, B. Manley, 2410.21260 [hep-ph]

Measuring OAM distributions in elastic e+p collisions

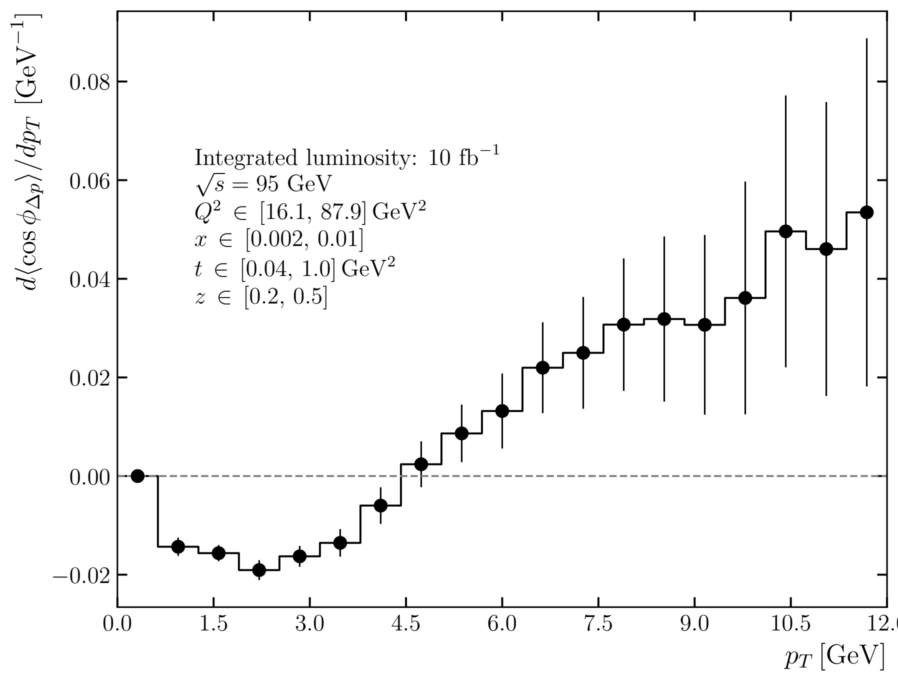
- In the small-t limit (pT , Q >> $\Lambda_{QCD} \gg \Delta_\perp$ with $t = -\Delta_\perp^2$) the elastic dijet DSA measures moments of dipole amplitudes, thus **allowing (in principle) to measure OAM distributions!**
- Cf. Hatta et al, 2016; S. Bhattacharya, R. Boussarie and Y. Hatta, 2022 & 2024; S. Bhattacharya, D. Zheng and J. Zhou, 2023.
- Feasibility study in progress (G.Z. Becker, J. Borden, B. Manley, YK).

$$
\begin{aligned}
& z(1-z)\,\frac{1}{2}\sum_{S_L,\lambda\pm1} S_L\,\lambda\,\frac{d\sigma^{\gamma^* p\to q\bar{q}p'}_{\text{symm. }\lambda\lambda}}{d^2p\,d^2\Delta\,dz} = -\frac{2}{(2\pi)^5 z(1-z)s}\int d^2x_{12}\,d^2x_{1'2'}\,e^{-i\underline{p}\cdot(\underline{x}_{12}-\underline{x}_{1'2'})}\,N(x^2_{1'2'},s) \qquad (107\text{a})\\
& \times\Bigg\{\Bigg[\bigg(1-2z+i\underline{\Delta}\cdot\underline{x}_{12}\,\left(z^2+(1-z)^2\right)-\frac{i}{2}\,\underline{\Delta}\cdot\underline{x}_{1'2'}\,(1-2z)^2\bigg)\,Q(x^2_{12},s)-i\underline{\Delta}\cdot\underline{x}_{12}\,I_3(x^2_{12},s)\\
& \qquad -i\underline{\Delta}\times\underline{x}_{12}\,J_3(x^2_{12},s)\Bigg]\,\Phi^{[1]}_{\text{TT}}(\underline{x}_{12},\underline{x}_{1'2'},z)\\
& \quad +\Bigg[i(1-2z)\Big(\Delta^j\epsilon^{ji}x^2_{12}I_4(x^2_{12},s)+\underline{\Delta}\times\underline{x}_{12}\,x^i_{12}I_5(x^2_{12},s)+\Delta^i\,x^2_{12}J_4(x^2_{12},s)+\underline{\Delta}\cdot\underline{x}_{12}\,x^i_{12}J_5(x^2_{12},s)\Big)\\
& \qquad -\left[1+i\,(1-2\,z)\,\underline{\Delta}\cdot\left(\underline{x}_{12}-\frac{\underline{x}_{1'2'}}{2}\right)\right]\,\left(\epsilon^{ik}x^k_{12}G_2(x^2_{12},s)+x^i_{12}G_1(x^2_{12},s)\right)\Bigg]\\
& \qquad \times\,\left(\partial^i_{\underline{1}}-ip^i\right)\,\Phi^{[2]}_{\text{TT}}(\underline{x}_{12},\underline{x}_{1'2'},z)\Bigg\}+\mathcal{O}(\Delta^2_\perp),\\
& z(1-z)\,\frac{1}{2}\sum_{S_L,\lambda=\pm1} S_L\,\left[e^{i\lambda\phi}\,\frac{d\sigma^{\gamma^* p\to q\bar{q}p'}_{\text{symm. }0\lambda}}{d^2p\,d^2\Delta\,dz}+\text{c.c.}\right] = -\frac{2i\sqrt{2}}{2(2\pi)^5 z(1-z)s}\int d^2x_{12}\,d^2x_{1'2'}\,e^{-i\underline{p}\cdot(\underline{x}_{12}-\underline{x}_{1'2'})} \qquad (107\text{b})\\
& \times N(x^2_{1'2'},s)\Bigg\{\Bigg[\bigg(1-2z+i\,\underline{\Delta}\cdot\underline{x}_{12}\,(z^2+(1-z)^2)-\frac{i}{2}\underline{\Delta}\cdot\underline{x}_{1'2'}\,(1-2z)^2\bigg)\,Q(x^2_{12},s)-i\underline{\Delta}\cdot\underline{x}_{12}\,I_3(x^2_{12},s)\\
& \qquad -i\underline{\Delta}\times\underline{x}_{12}\,J_3(x^2_{12},s)\Bigg]\,\left[\frac{\hat{k}\cdot\underline{x}_{12}}{x_{12}}\Phi^{[1]}_{\text{LT}}(\underline{x}_{12},\underline{x}_{1'2'},z)-\frac{\hat{k}\cdot\underline{x}_{1'2'}}{x_{1'2'}}\Phi^{[1]}_{\text{LT}}(\underline{x}_{1'2'},\underline{x}_{12},z)\right]\\
& \quad +\Bigg[i(1-2z)\Big(\Delta^j\epsilon^{ji}\,x^2_{12}\,I_4(x^2_{12},s)+\underline{\Delta}\times\underline{x}_{12}\,x^i_{12}\,I_5(x^2_{12},s)+\Delta^i\,x^2_{12}\,J_4(x^2_{12},s)+\underline{\Delta}\cdot\underline{x}_{12}\,x^i_{12}\,J_5(x^2_{12},s)\Big)\\
& \qquad -\left[1+i\,(1-2\,z)\,\underline{\Delta}\cdot\left(\underline{x}_{12}-\frac{\underline{x}_{1'2'}}{2}\right)\right]\,\left(\epsilon^{ik}x^k_{12}G_2(x^2_{12},s)+x^i_{12}G_1(x^2_{12},s)\right)\Bigg]\\
& \quad \times\left(\partial^i_{\underline{1}}-ip^i\right)\left[\frac{\hat{k}\times\underline{x}_{12}}{x_{12}}\Phi^{[2]}_{\text{LT}}(\underline{x}_{12},\underline{x}_{1'2'},z)+\frac{\hat{k}\times\underline{x}_{1'2'}}{x_{1'2'}}\Phi^{[2]}_{\text{LT}}(\underline{x}_{1'2'},\underline{x}_{12},z)\right]\Bigg\}+\mathcal{O}(\Delta^2_\perp),
\end{aligned}
$$

OAM measurement with elastic dijets: feasibility study (very preliminary!)

Vertical axis – cos $\phi_{\Delta pT}$ harmonic in elastic dijets A_{LL}.

pT = jets b2b momentum
Δ = momentum transfer
assumed int. luminosity = 10 fb^{-1}

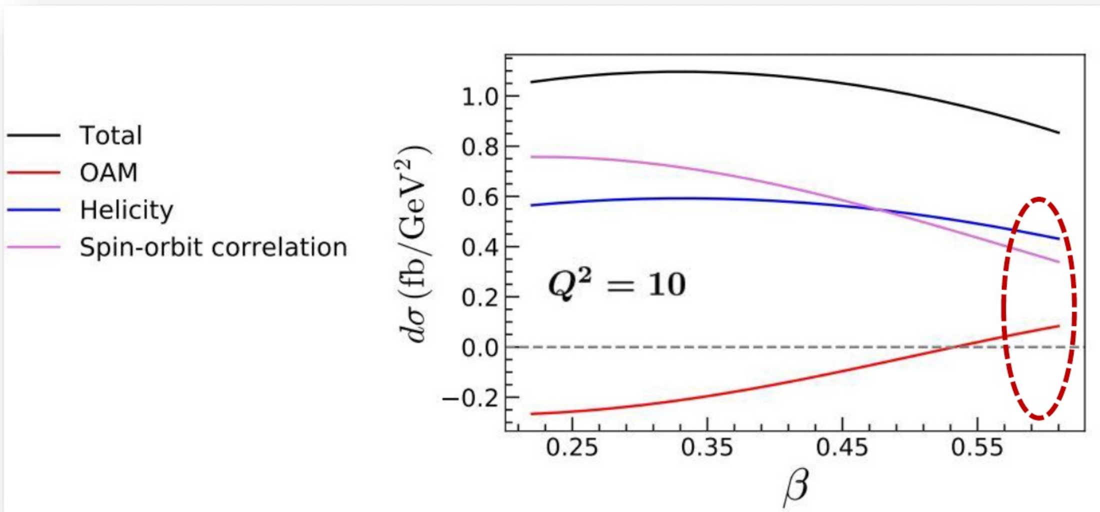


JAMsmallx (Brandon Manley) – preliminary!

Selected works on gluon GTMDs

Probing gluon OAM through Semi Inclusive Diffractive Deep Inelastic Scattering

Numerical results (SB, Boussarie, Hatta, 2404.04209)**:**



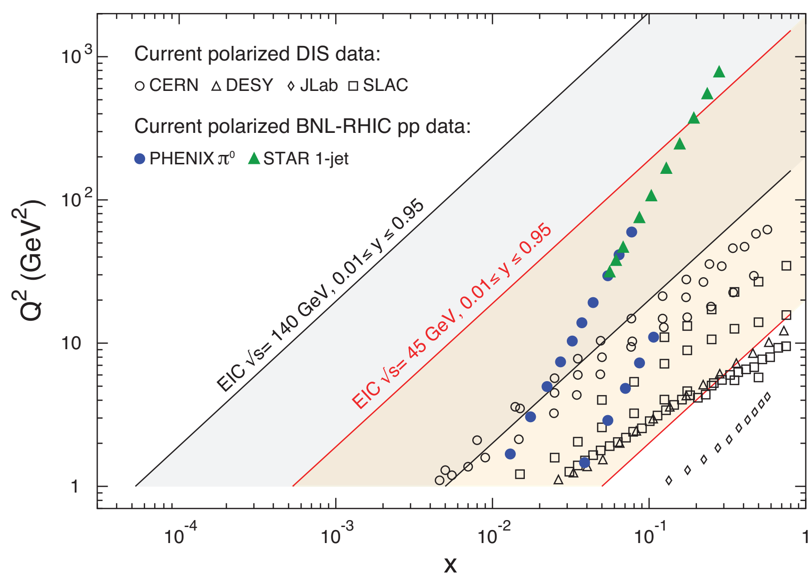
Shohini's talk

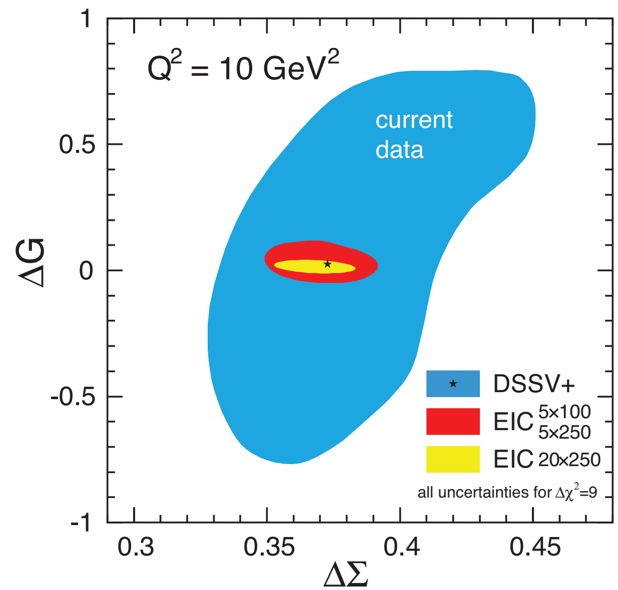
Challenging, yet there is no requirement to reconstruct jets & we still maintain sensitivity to OAM

EIC & Spin Puzzle

Still, even with the EIC data we need to extrapolate quark and gluon spin down to smaller x: small-x evolution can do that.

- Parton helicity distributions are sensitive to low-x physics.
- EIC would have an unprecedented low-x reach for a polarized DIS experiment, allowing to pinpoint the values of quark and gluon contributions to proton's spin:



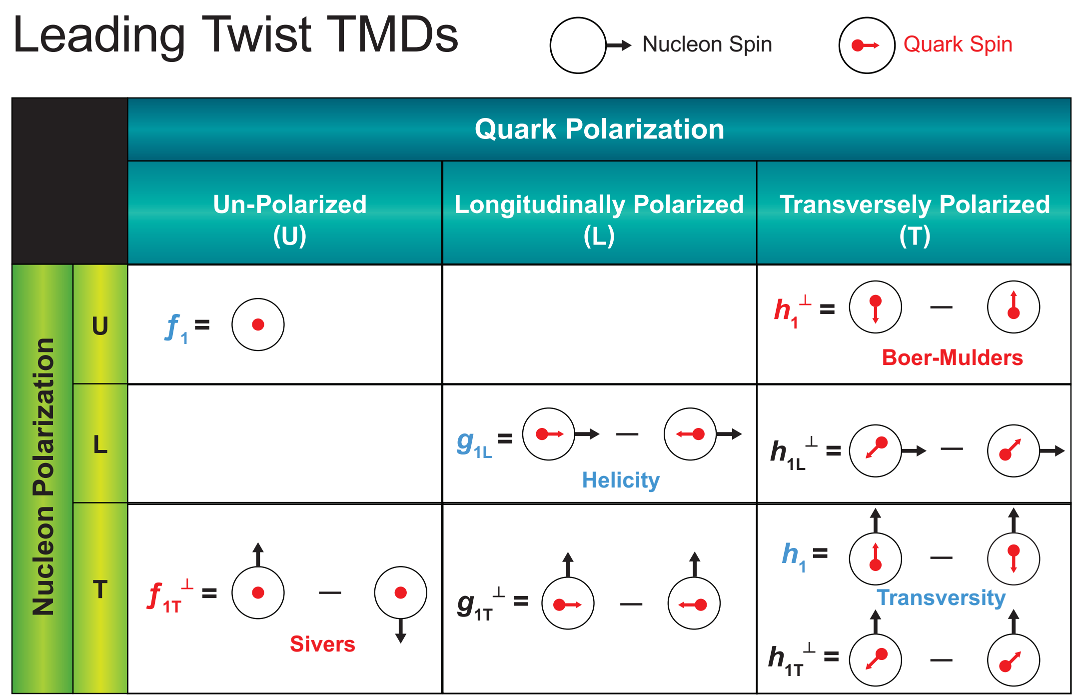


- ΔG and ΔΣ are integrated over x in the 0.001 < x < 1 interval.

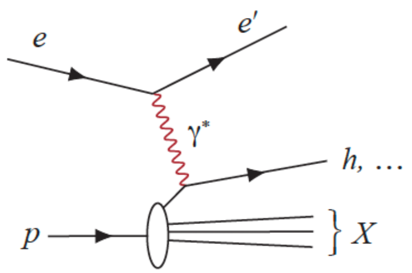
TMDs

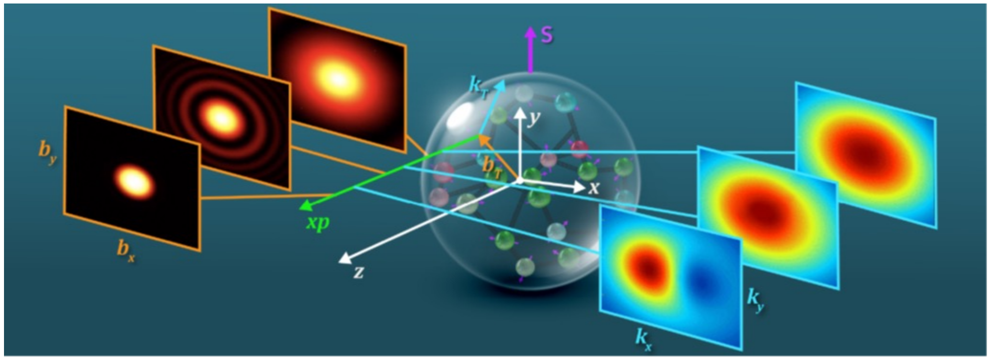
Quark TMDs

- Different TMDs probe different aspects of the proton structure.



TMDs are extracted from the SIDIS cross section





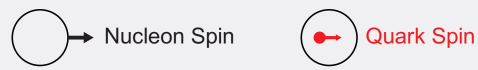
Unpolarized proton and electron (from A. Bacchetta's talk in January 2025):

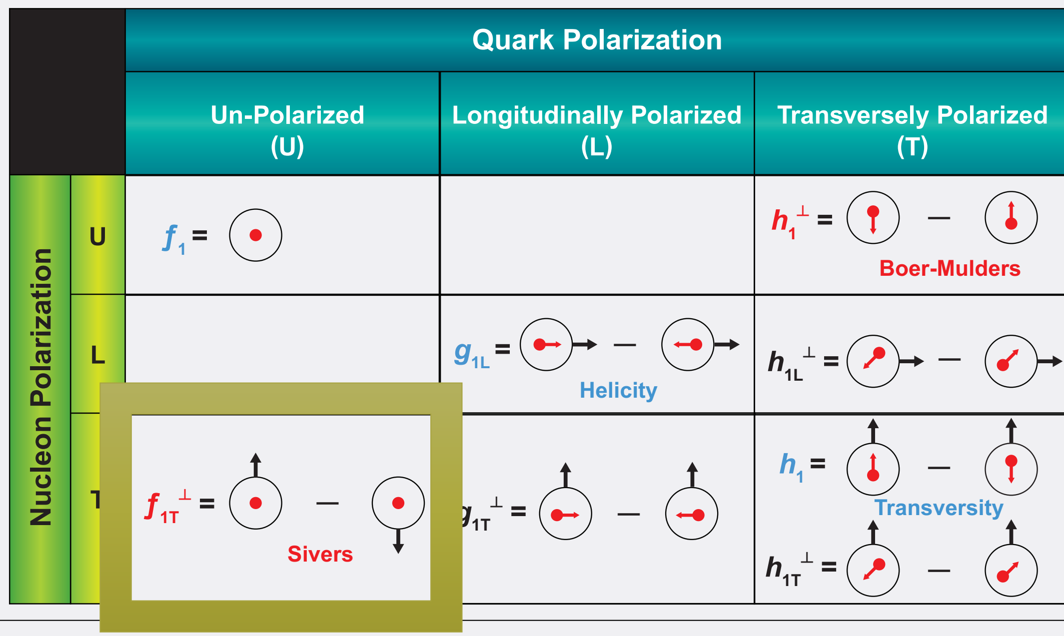
$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{2\pi\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\Big\}$$

TMD PFDs and FFs

Sivers function

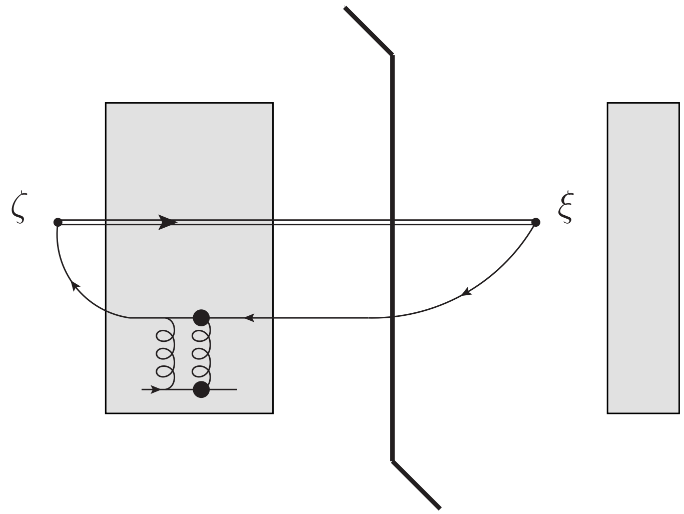
Leading Twist TMDs





Sivers function

The Siver function at small x is also related to the dipole amplitude from above – only to its C-odd component.



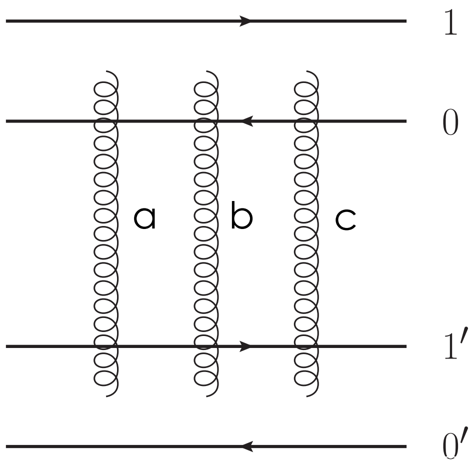
Its leading small-x asymptotics is given by **the spin-dependent odderon** (D. Boer, M. G. Echevarria, P. Mulders and J. Zhou '15):

$$f_{1T}^{\perp q}(x, k_T^2) \sim \text{Fourier} \quad \text{transform} \left\{ \mathcal{O}(x_\perp, b_\perp, Y) \right\}$$

The Sivers function also depends on the sub-eikonal dipole amplitude (YK, M. G. Santiago, 2209.03538 [hep-ph]; 2108.03667 [hep-ph]) – this generates a correction to the above odderon contribution.

Odderon as a 3-gluon exchange

- In perturbation theory, the *C*-odd exchange can be due to
  - 1-gluon exchange: yes, it is *C*-odd, but not color-singlet, cannot give an elastic amplitude.
  - 2-gluon exchange: can be color-singlet, but not *C*-odd. (Each gluon has *C*=-1.)
  - 3 gluon exchange: can be both color-singlet and *C*-odd! That's the Odderon at the lowest order.



Note that the gluons must be in a symmetric d^{abc} color state ($d^{abc} = 2\,\mathrm{tr}[t^a\,\{t^b, t^c\}]$). If the color group was SU(2), there would be no Odderon.

Disconnected gluon lines imply sum over all possible gluon connections to the quark and anti-quark lines.

TOTEM and D0 Collaborations announced the odderon discovery in pp vs. ppbar elastic scattering in late 2020. Results from other experiments are needed to seal the discovery.

Odderon high-energy asymptotics

$$\mathcal{O}_{10}(s) \sim s^{\alpha_{odd}-1}$$

- BLV solution: $\alpha_{odd} - 1 = \mathcal{O}(\alpha_s^2)$
- At NLO it turns out that the intercept is still zero (YK, 2012; C. Marquet): $\alpha_{odd} - 1 = \mathcal{O}(\alpha_s^3)$
- The intercept is shown to be zero at any order in the coupling at large N_C (S. Caron-Huot, 2013):

$$\alpha_{odd} - 1 = \mathcal{O}\left(\frac{1}{N_c}\right)$$

- In AdS/CFT, several intercepts were found, but zero was still the leading one (R. C. Brower, M. Djuric, and C.-I. Tan, 2009):

$$\alpha_{odd} - 1 = \mathcal{O}\left(\frac{1}{\lambda}\right), \quad \lambda = g^2 N_c$$

- It appears likely that the Odderon intercept is exactly zero in QCD and *N*=4 SYM. Not clear why. Is there a symmetry that protects it?

x-Dependence of A_N

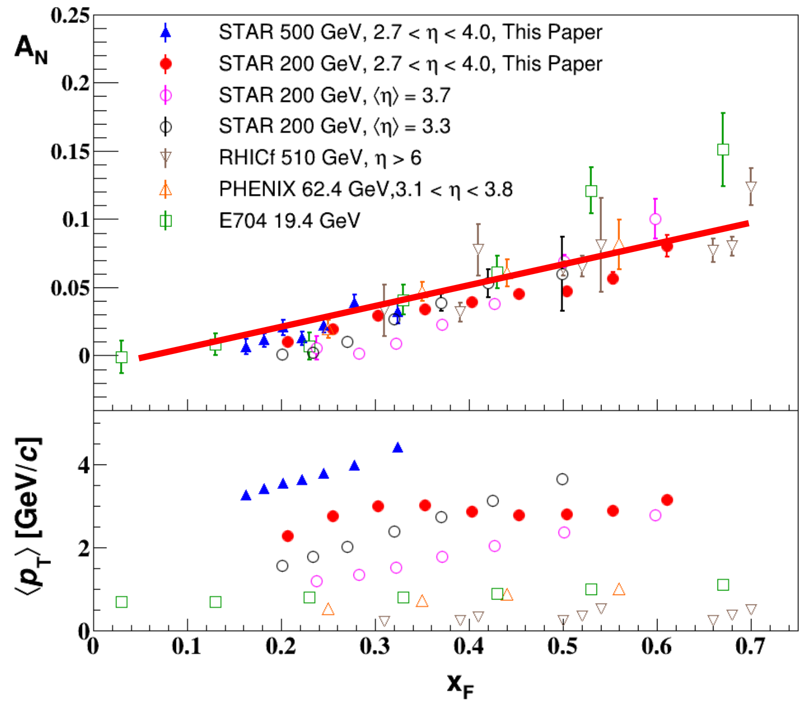
$$A_N \sim x\, f_{1T}^{\perp}$$

Sivers function at small x scales as

$$f_{1T}^{\perp\, NS}(x \ll 1, k_T^2) = C_O(x, k_T^2)\,\frac{1}{x} + C_1(x, k_T^2)\left(\frac{1}{x}\right)^{3.4\sqrt{\frac{\alpha_s N_c}{4\pi}}}$$

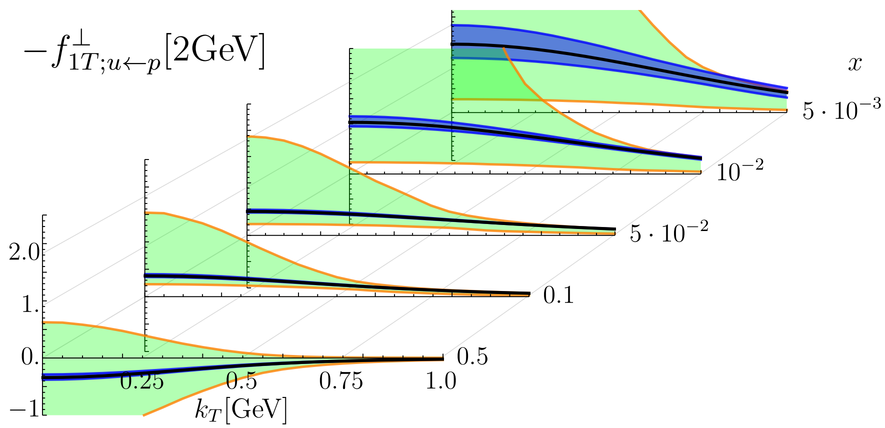
- The spin-dependent odderon (D. Boer, M. G. Echevarria, P. Mulders and J. Zhou '15) gives the first term above. It predicts **A_N=const(x).**
- The second term is due to sub-eikonal small-x evolution (YK, M.G. Santiago, '22), with the power of x also close to 1.
- The data indicates more like A_N~x, albeit at not very small x. **Can STAR measure A_N precisely at very low x_F? This may confirm the odderon discovery at the Tevatron+LHC.**
- **Can the EIC help find the spin-dependent odderon? test the sub-eikonal x-dependence?**

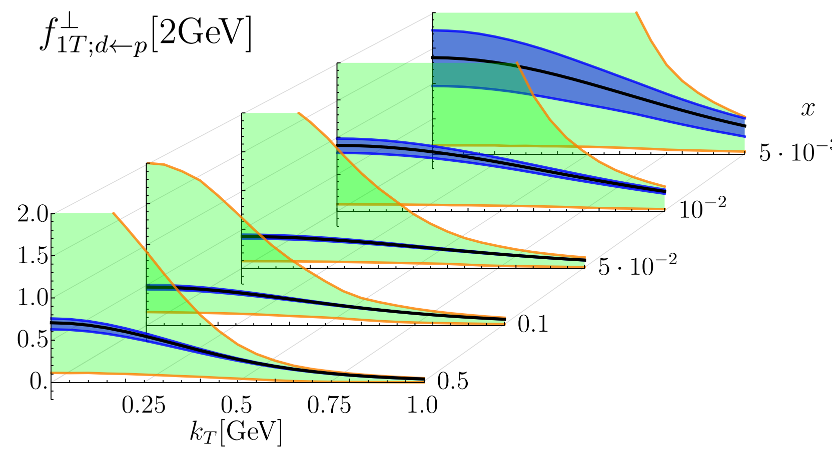
π^0's, STAR, arXiv:2012.11428 [hep-ex]



Sivers function at EIC

- The Sivers function can be measured at EIC in the SIDIS process (YR plots below by A. Vladimirov):

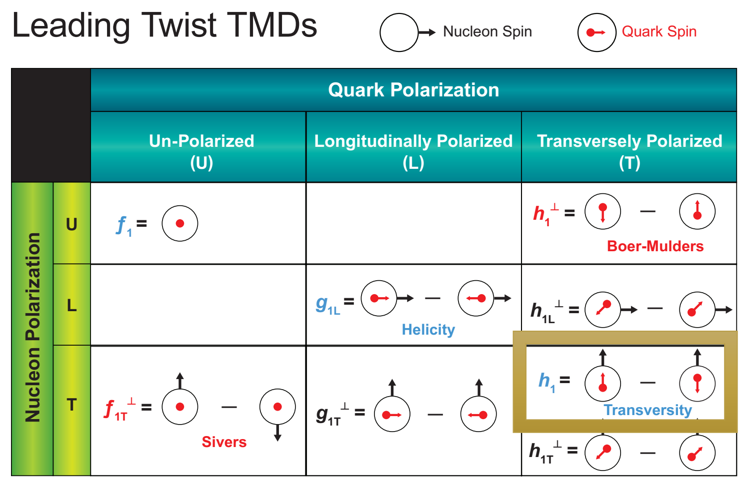




- It would help understand the small-x asymptotics of this function.
- Spin-dependent odderon search: a dedicated study is needed.

Transversity at small x

Transversity



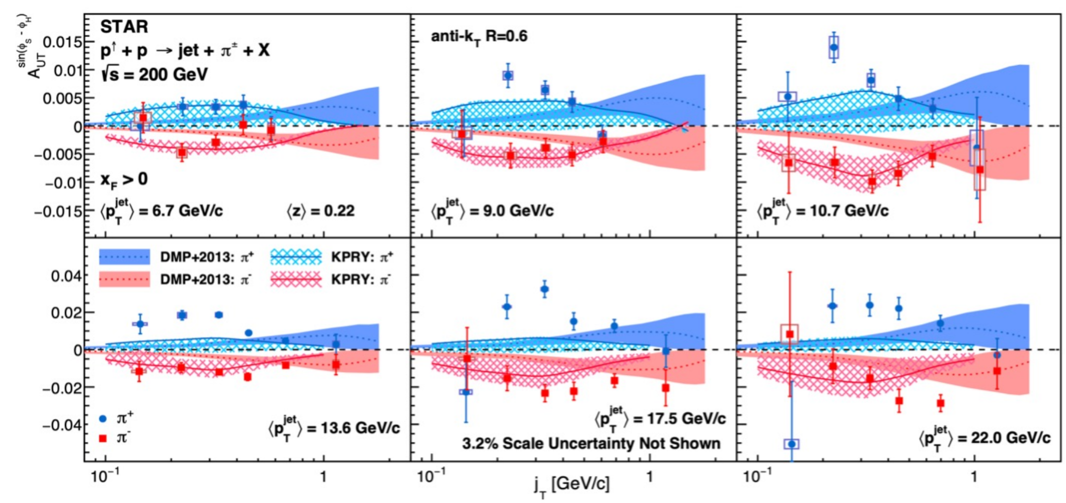
- Another fundamental object, but C-odd, hence hard to measure.

$$\delta q(Q^2) = \int_0^1 dx\, h_1(x, Q^2)$$

- Related to the proton's tensor charge.
- Transversity can be extracted from A_{UT} at RHIC due to the Collins effect,

  A_{UT}~ transversity X interference fragmentation function.

- See pioneering work by M. Radici and A. Bacchetta, '18.
- EIC would certainly help narrow down the error bars.



STAR, 2205.11800 [hep-ex]

Small-x Asymptotics of Quark Transversity

- The small-x asymptotics of transversity is given by (R. Kirschner et al, '96; YK, M. Sievert, '18)

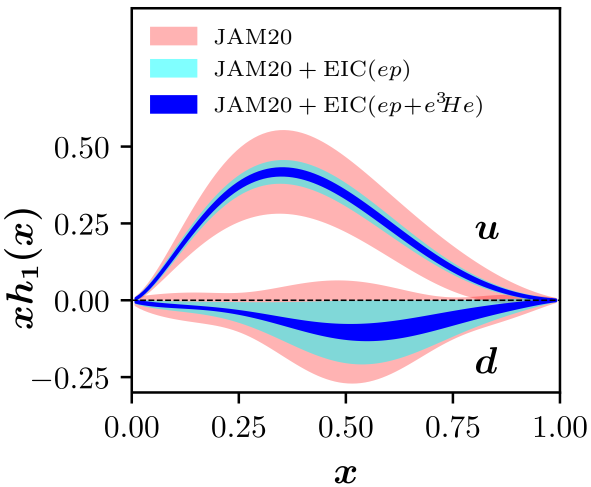
$$h_{1T}^{NS}(x, k_T^2) \sim h_{1T}^{\perp NS}(x, k_T^2) \sim \left(\frac{1}{x}\right)^{\alpha_t^q} \quad \text{with} \quad \alpha_t^q = -1 + 2\sqrt{\frac{\alpha_s C_F}{\pi}}$$

- For $\alpha_s = 0.3$ we get

$$h_{1T}^{NS}(x, k_T^2) \sim h_{1T}^{\perp NS}(x, k_T^2) \sim x^{0.243}$$

This result agrees with extractions from data (see J. Benel, A. Courtoy, and R. Ferro-Hernandez, '19).

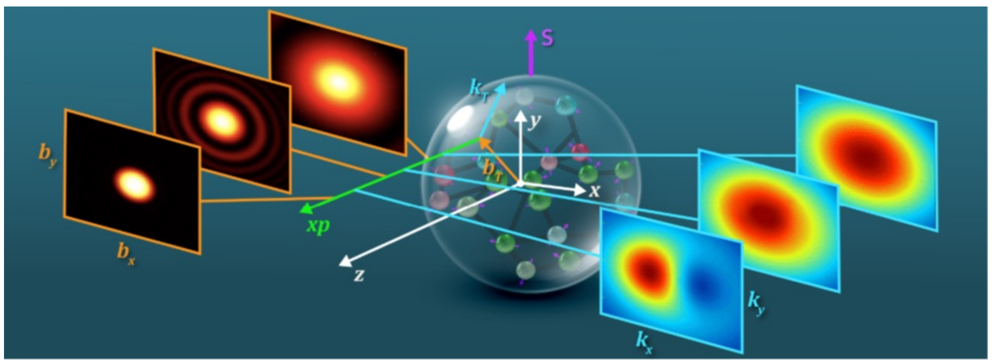
It can be further tested at EIC (YR plot by JAM Collaboration):

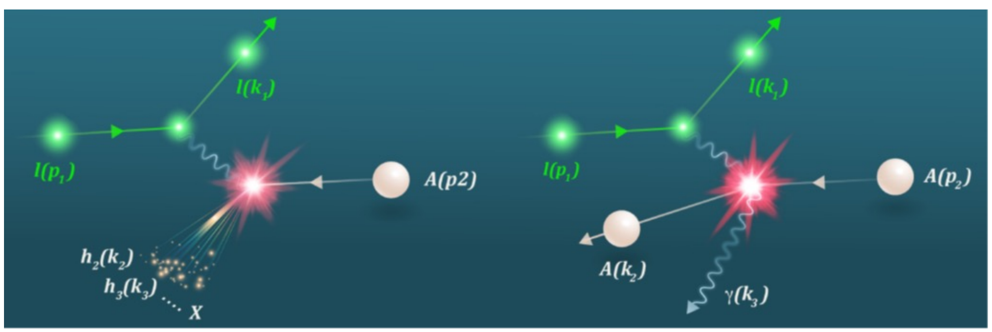


For the small-x asymptotics of various other TMDs, see M.G. Santiago, D. Adamiak, Y. Tawabutr, 2412.14154 [hep-ph]

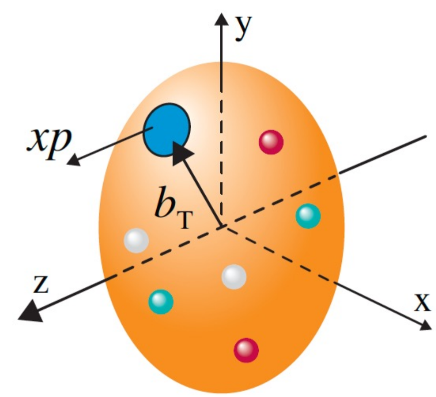
GPDs

Generalized Parton Distributions

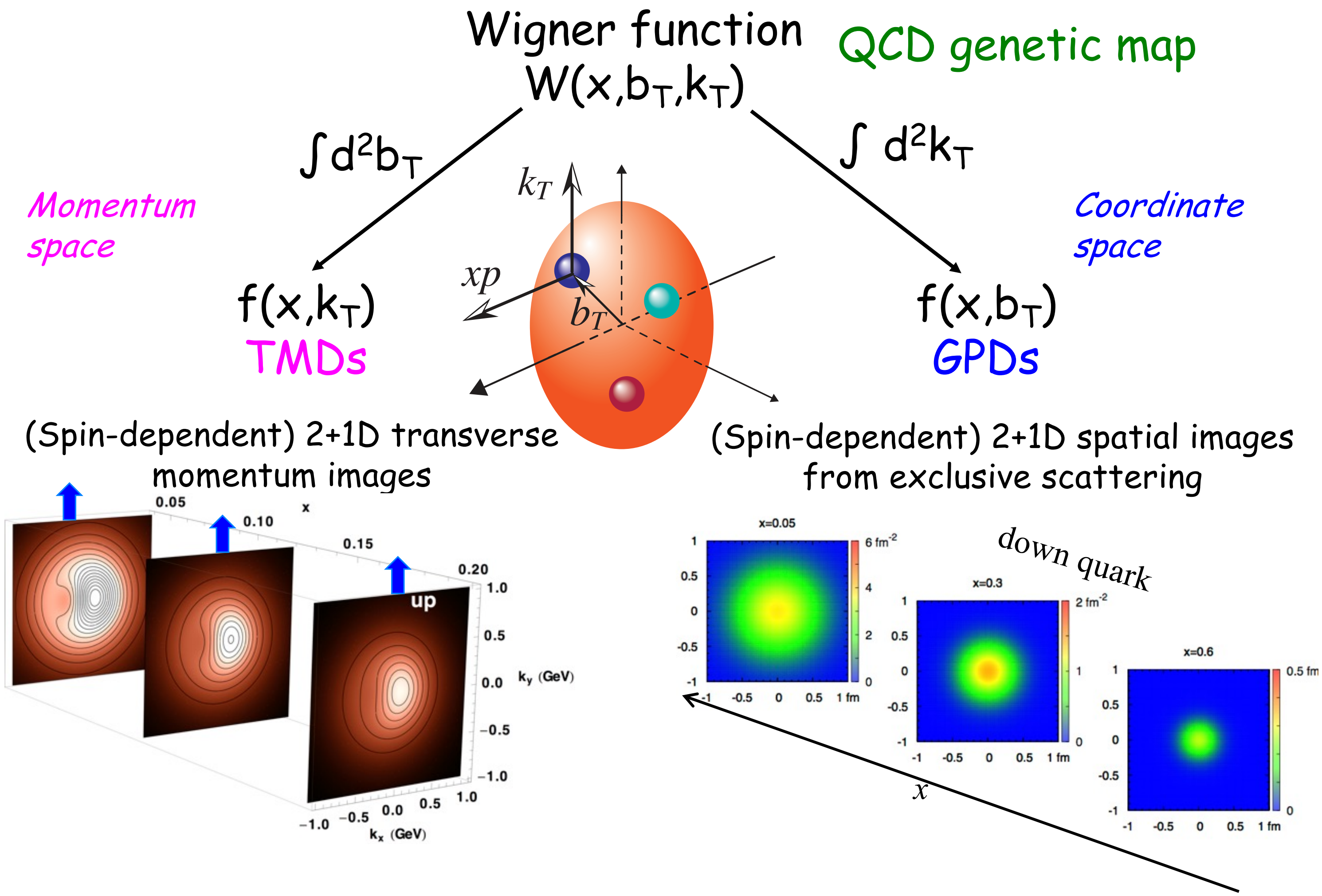




- GPDs probe the 3D spatial structure of the nucleon.
- They are challenging to extract from data.
- Usually, people consider DVCS and exclusive vector meson production.



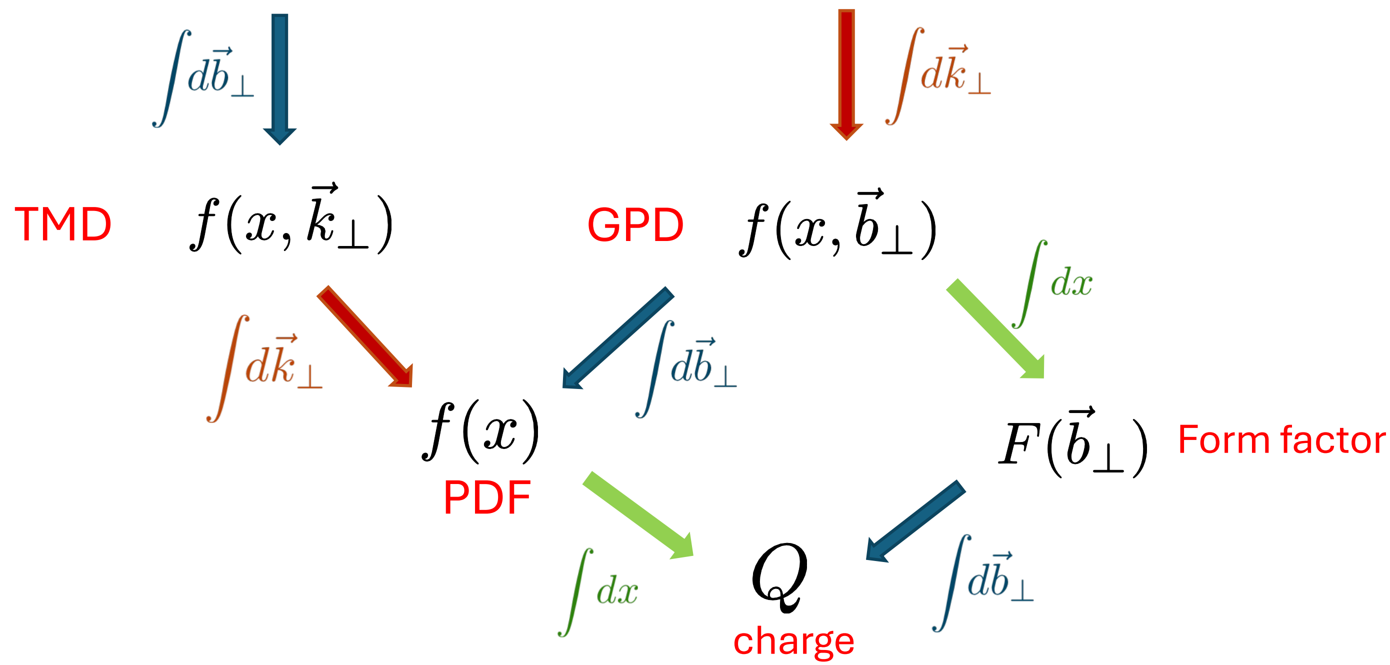
2+1 dimensional Imaging of Quarks & Gluons



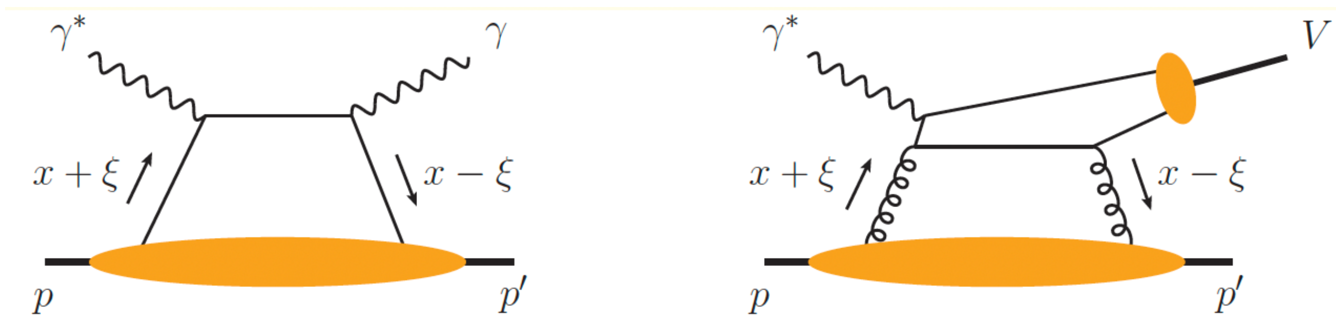
5D tomography:
Wigner distribution— the "mother distribution"

Belitsky, Ji, Yuan (2003);

$$W(x, \vec{k}_\perp, \vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \int \frac{dz^- d^2 z_\perp}{16\pi^3} e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp} \langle P - \frac{\Delta}{2} | \bar{q}(-z/2)\gamma^+ q(z/2) | P + \frac{\Delta}{2} \rangle$$



DVCS and exclusive vector meson production



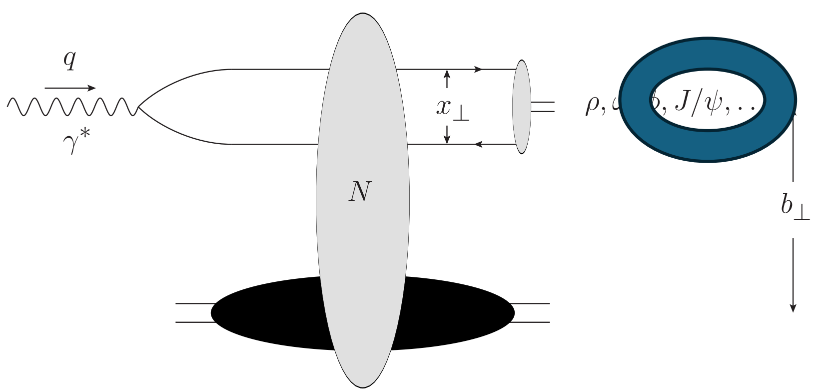
DVCS is a rare process (cross section ~α_{EM}^3), hard to measure – is this an early EIC observable?

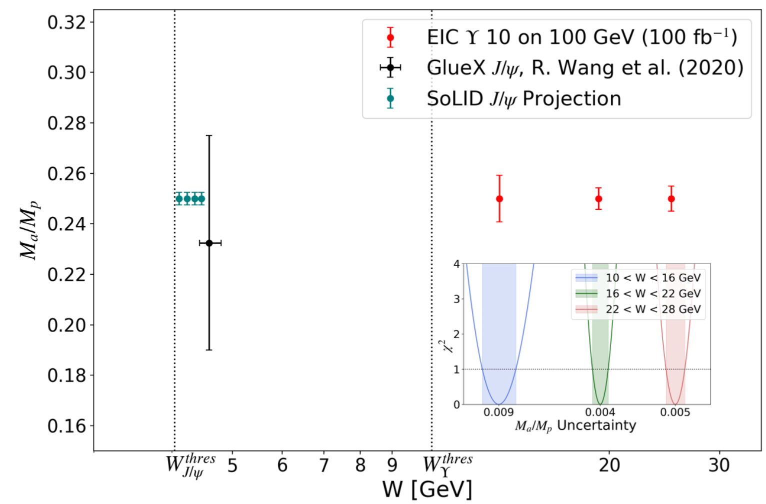
Exclusive vector meson production is not as suppressed: still large rapidity gaps are rare. Can this be an early EIC observable?

Proton Mass

EIC may shed light on the origin of the proton mass

J/psi or upsilon elastic production near threshold may probe an operator related to the QCD trace anomaly evaluated in the proton state. May measure the trace anomaly contribution to the proton mass.
(D. Kharzeev, 1990s; Y. Hatta, more recently).





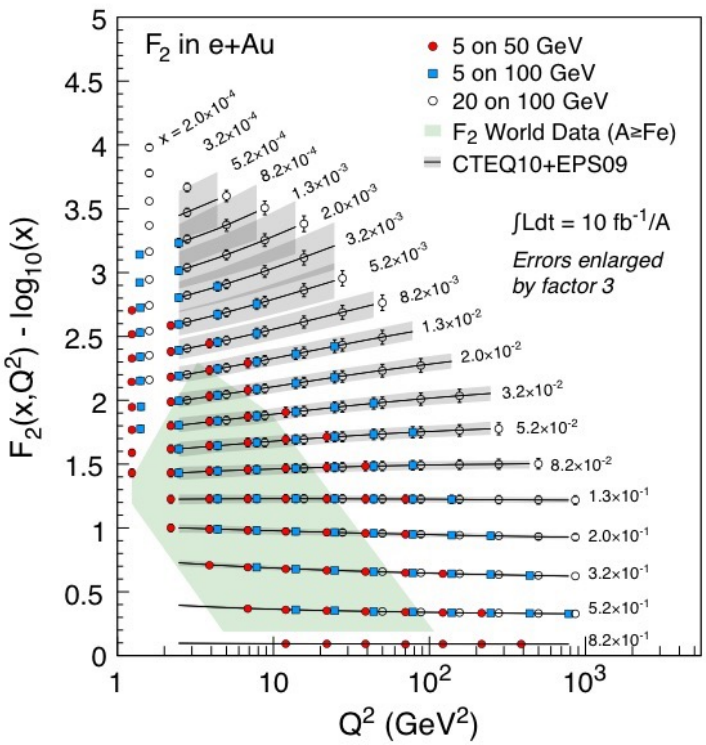
However, this appears to be a luminosity-hungry measurement. Is it for the early EIC?

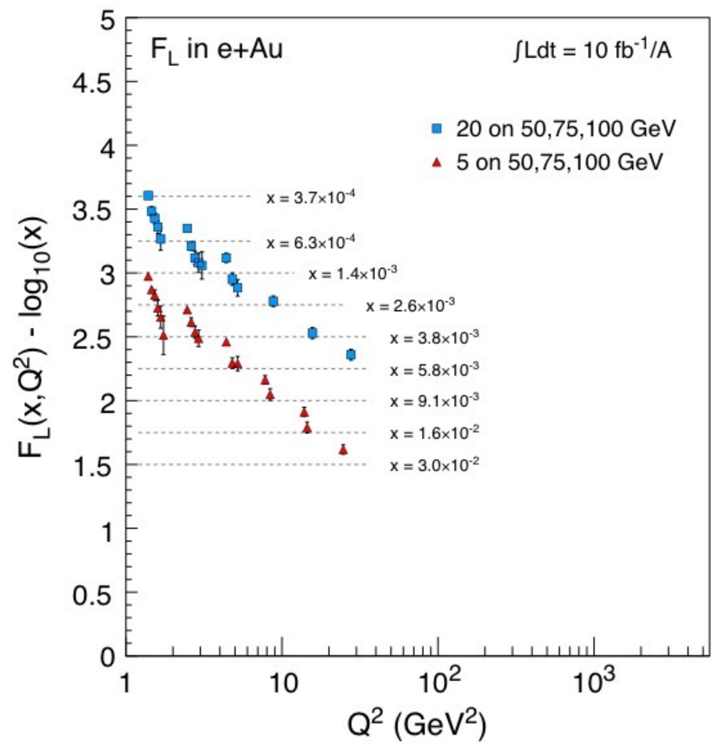
Saturation

(i) Nuclear Structure Functions

Structure Functions at EIC

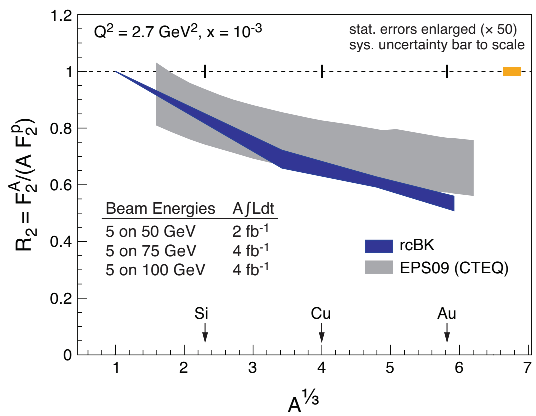
Nuclear structure functions F_2 and F_L (parts of σ^{e+A} cross section) which will be measured at EIC (values = EPS09+PYTHIA). Shaded area = (x, Q^2) range of the world e+A data.

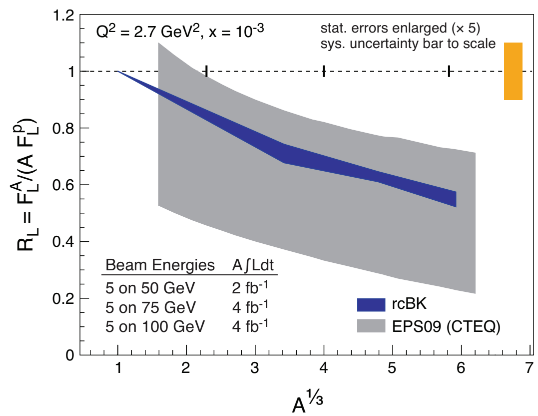


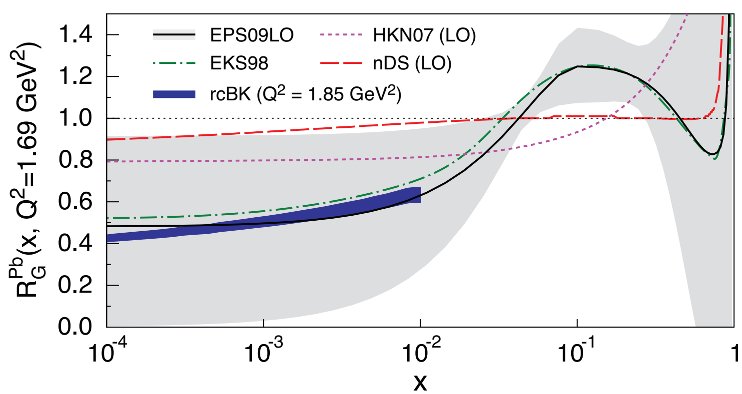


Nuclear Shadowing

- Saturation effects may explain nuclear shadowing: reduction of the number of gluons per nucleon with decreasing x and/or increasing A:



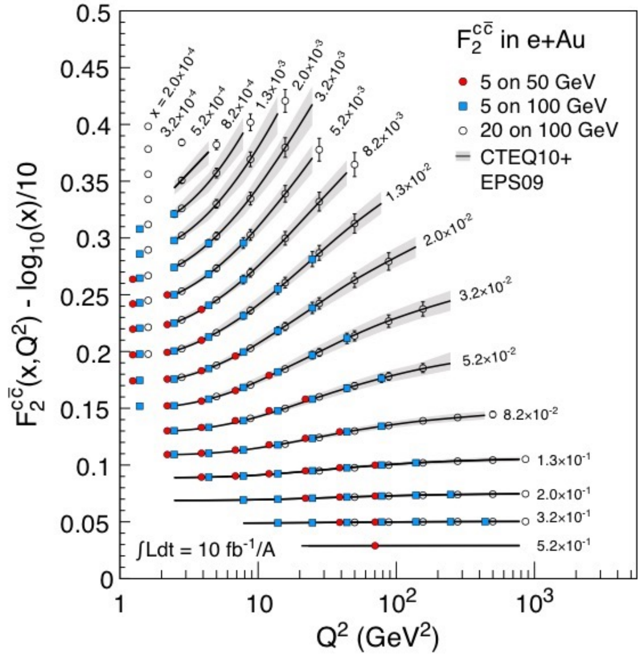


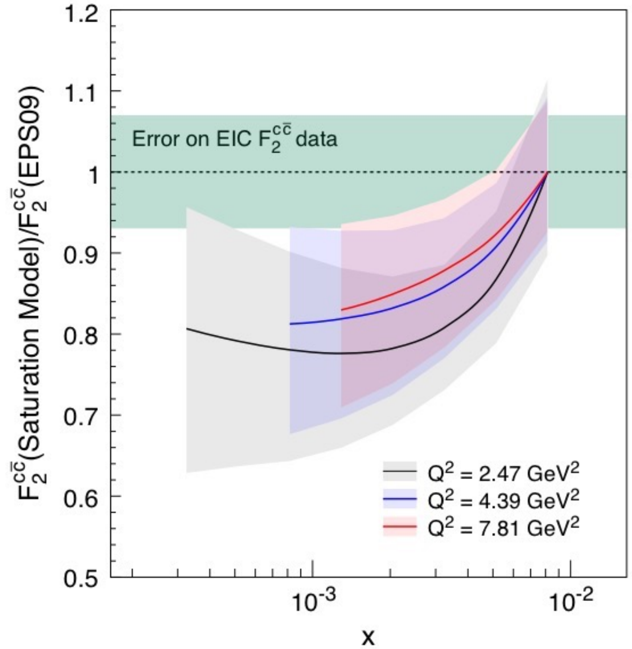


But: as DGLAP does not predict the x- and A-dependences, it needs to be constrained by the data.

Note that including heavy flavors (charm) for F_2 and F_L should help distinguish between the saturation versus non-saturation predictions.

Nuclear Shadowing for Charm

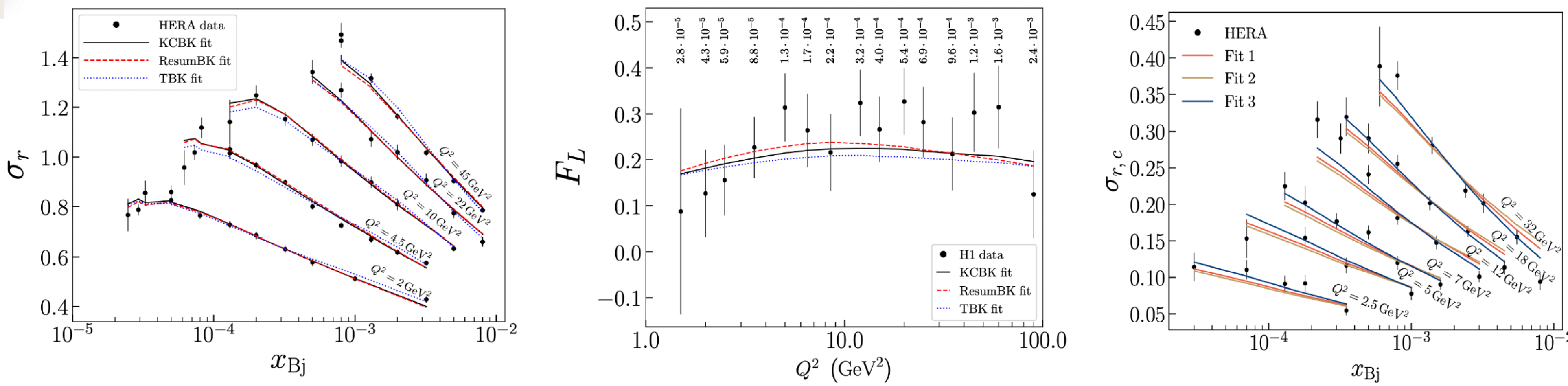




may help distinguish saturation vs DGLAP-based prediction

Structure functions: F_2 and F_L

- CGC at NLO provides a good simultaneous description of structure functions including charm



Beuf, Lappi, Hänninen, Mäntysaari (2020)

- However, F_2 has large non-perturbative contributions. It would be best to focus on F_L or $F_{2,c}$

- Confront CGC to nuclear structrure functions at the EIC

from Farid's talk

Structure functions: linear vs non-linear evolution

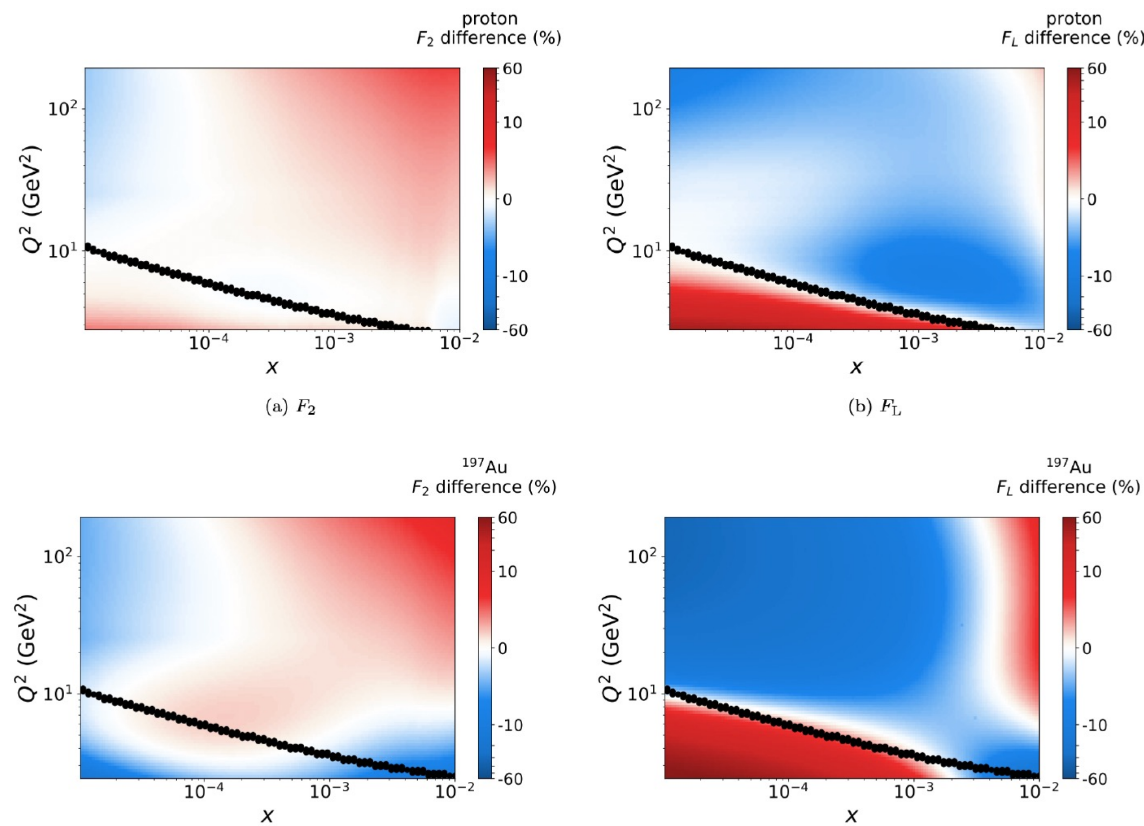
- Difference in predictions for $F_{2,L}$:
  linear (collinear/DGLAP)
  non-linear (dipole/Balitsky-Kovchegov)

$$(F_{2/L}^{\mathrm{BK}} - F_{2/L}^{\mathrm{DGLAP,Rew}})/F_{2/L}^{\mathrm{BK}}$$

- Stronger effects for F_L than F_2

- Stronger effects for γAu than γp

- It would be interesting to incorporate small-x evolution into DGLAP via BFKL (à la) and compare with non-linear BK



(a) F_2 (b) F_L

(a) F_2 (b) F_L

from Farid's talk

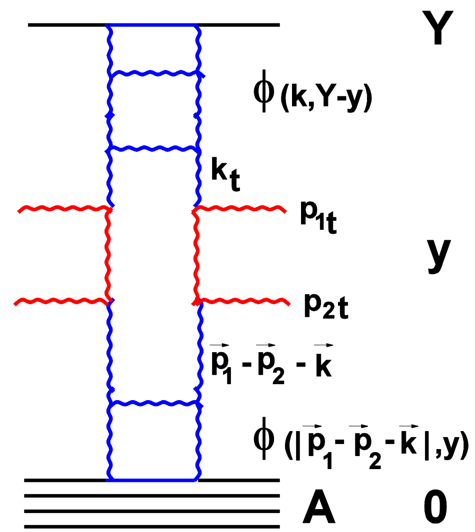
Armesto, Lappi, Mäntysaari, Paukkunen, Tevio (2022)

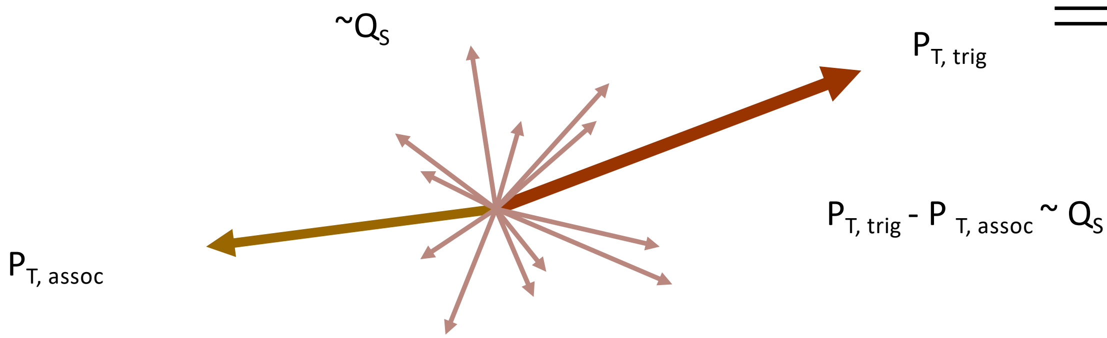
See also Marquet, Moldes, Zurita (2017)

(ii) Di-Hadron Correlations

De-correlation

- Small-x evolution ↔ multiple emissions
- Multiple emissions → de-correlation.

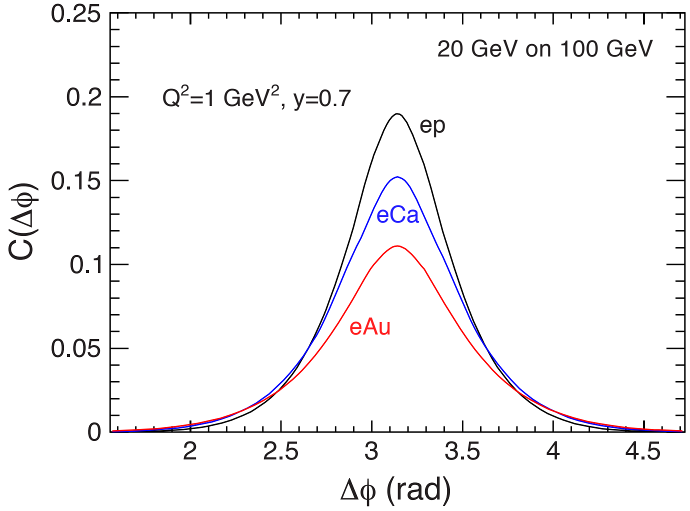


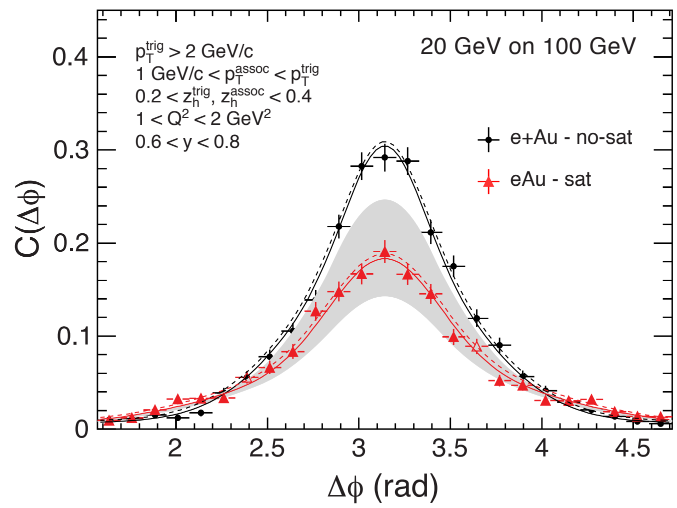


- B2B jets may get de-correlated in p_T with the spread of the order of Q_S

Di-hadron Correlations

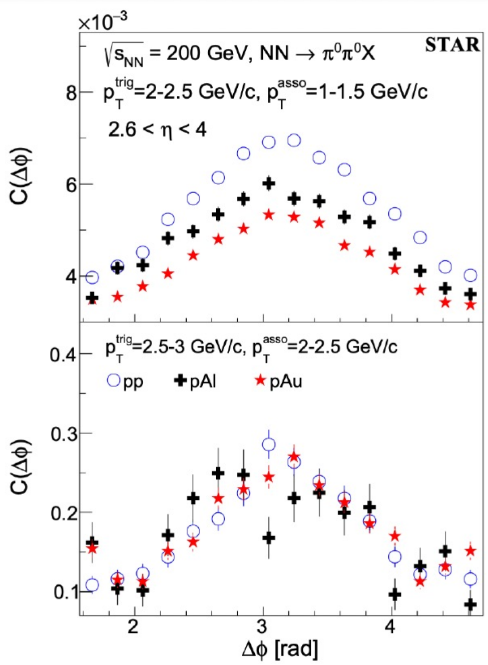
Depletion of di-hadron correlations is predicted for e+A as compared to e+p. (Dominguez et al ‘11; Zheng et al ‘14). This is a signal of saturation.



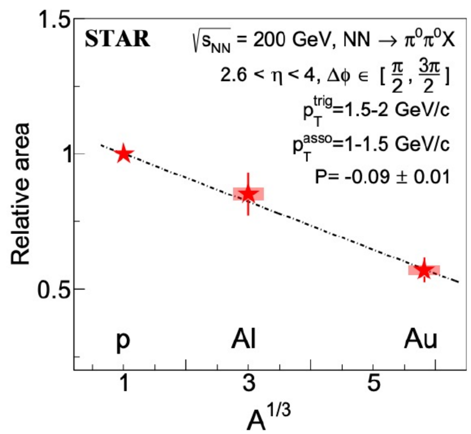


Two particle correlations at RHIC

Evidence for Nonlinear Gluon Effects in QCD and Their Mass Number Dependence at STAR

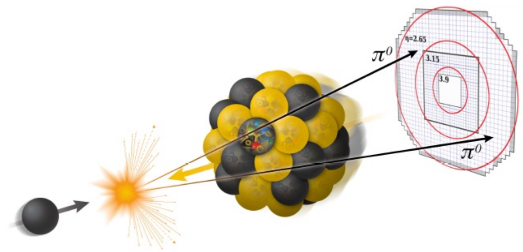


STAR Collaboration
Phys. Rev. Lett. 129, 092501 (2022)



Suppression characteristic of saturation

$$Q_s^2 \propto A^{1/3}$$

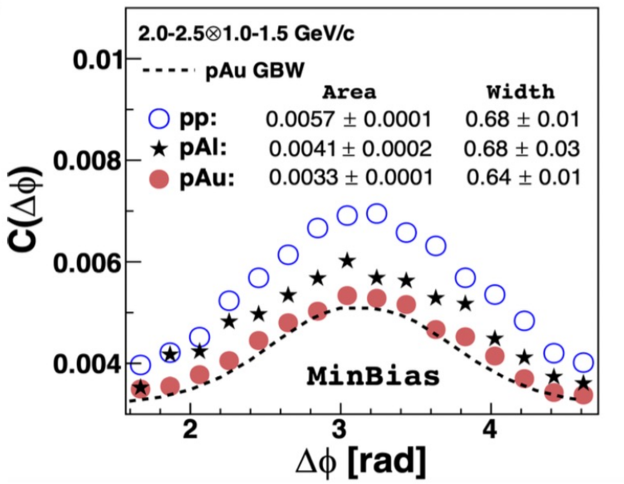


Xiaoxuan Chu and Elke Aschenauer

Two particle correlations at RHIC

Farid's talk

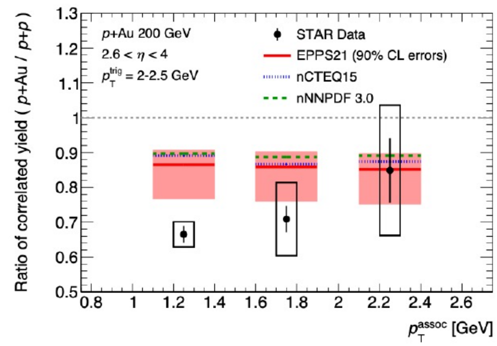
nPDF or saturation?

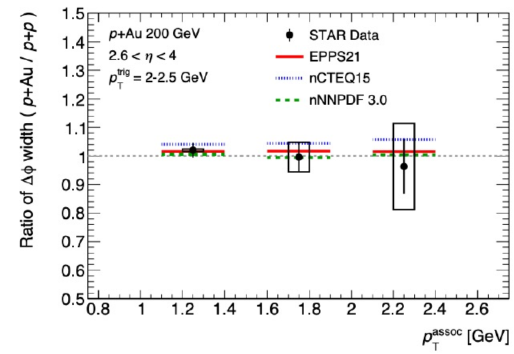


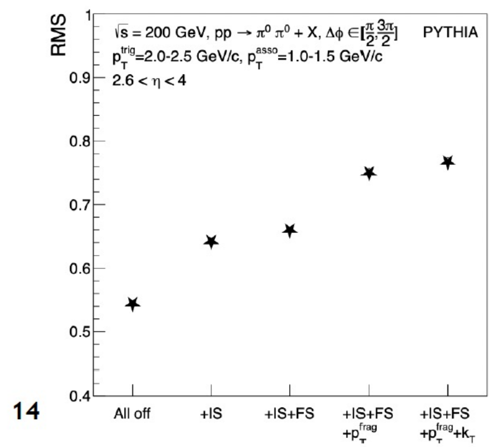
STAR (2021)

- CGC approach (work in progress Zhao et al)
  -Small-x evolution -> $p_\perp$-**dependent suppression** (more suppression for $p_\perp \lesssim Q_s(x)$)
  -Soft gluon radiation -> **similar width of correlation in pp and pA** (i.e. not much broadening) hints of this in full NLO calculation in DIS Caucal, Salazar, Schenke, Stebel, Venugopalan (2024)

- nPDFs approach: Perepelitsa (2025)
  di-hadron RHIC data shows **nuclear size dependent suppression** but **no significant broadening**







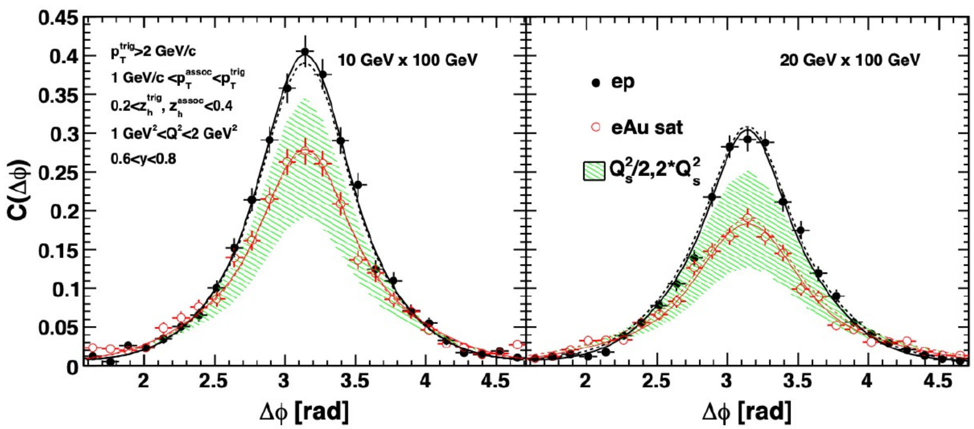
- Cassar, Wang, Chu, Aschenauer (2025)
  Parton shower + hadron fragmentation control width of correlation

  Absence of broadening is not necessarily challenge to the saturation paradigm

Two particle correlations at EIC

Farid's talk

Dihadron suppression
back-to-back peak at EIC

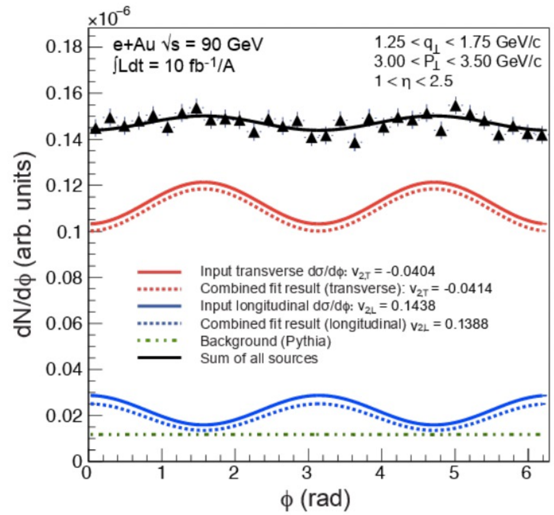


Zheng, Aschenauer, Lee, Xiao (2014)

Typical momentum transfer from proton/ nucleus to dihadron pair is $\sim Q_s$

Momentum imbalance → $k_\perp \sim Q_s$ ← Saturation scale

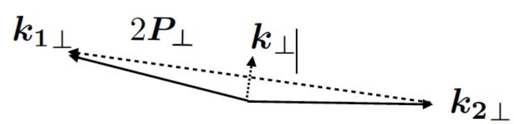
Dijet momentum imbalance
azimuthal correlations



Dumitru, Skokov, Ullrich (2018)

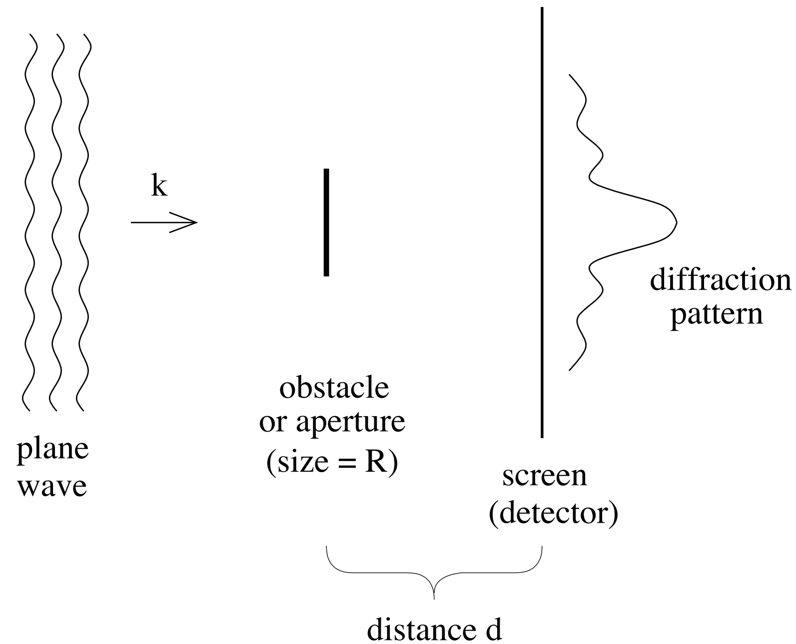
Sensitivity to linearly polarized gluons

ϕ angle between $P_\perp$ and $k_\perp$



(iii) Diffraction

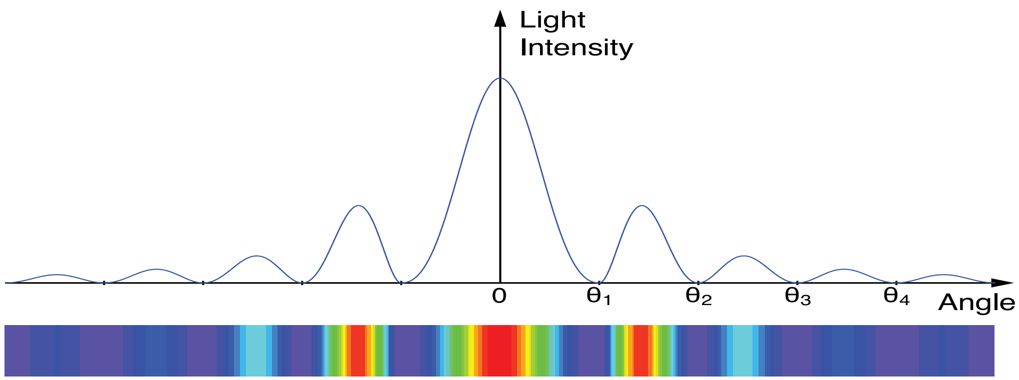
Diffraction in optics

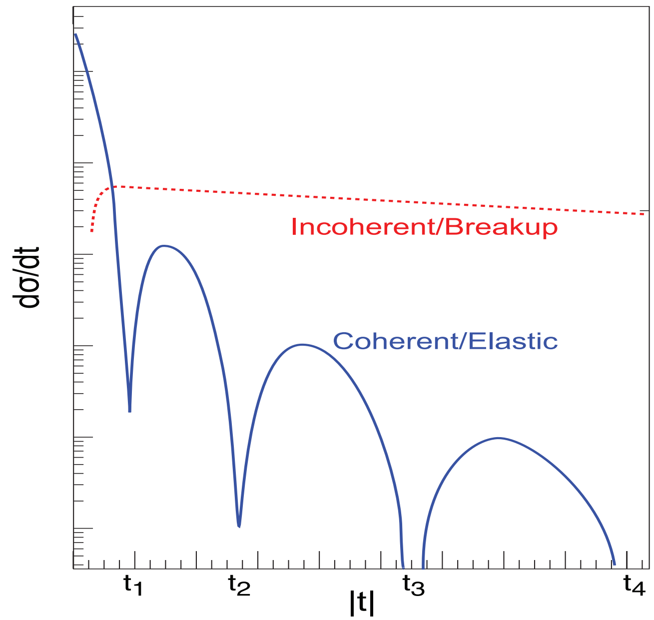


Diffraction pattern contains information about the size *R* of the obstacle and about the optical “blackness” of the obstacle.
In optics, diffraction pattern is studied as a function of the angle θ. In high energy scattering the diffractive cross sections are plotted as a function of the Mandelstam variable *t* with $\sqrt{|t|} = k \sin \theta$.

Optical Analogy

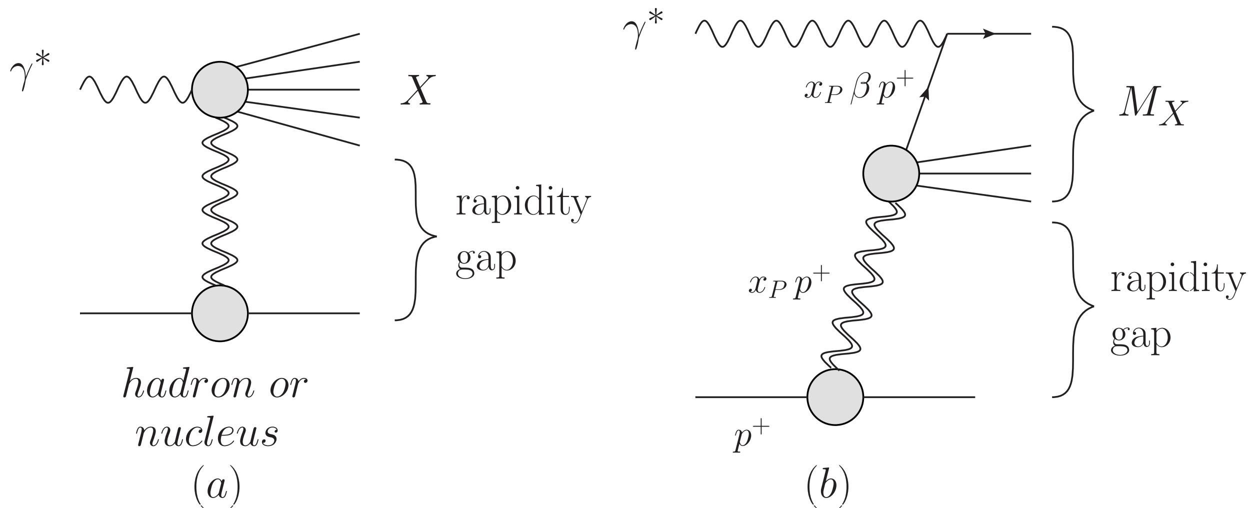
Diffraction in high energy scattering is not very different from diffraction in optics: both have diffractive maxima and minima:





Coherent: target stays intact;
Incoherent: target nucleus breaks up, but nucleons are intact.

Diffraction terminology

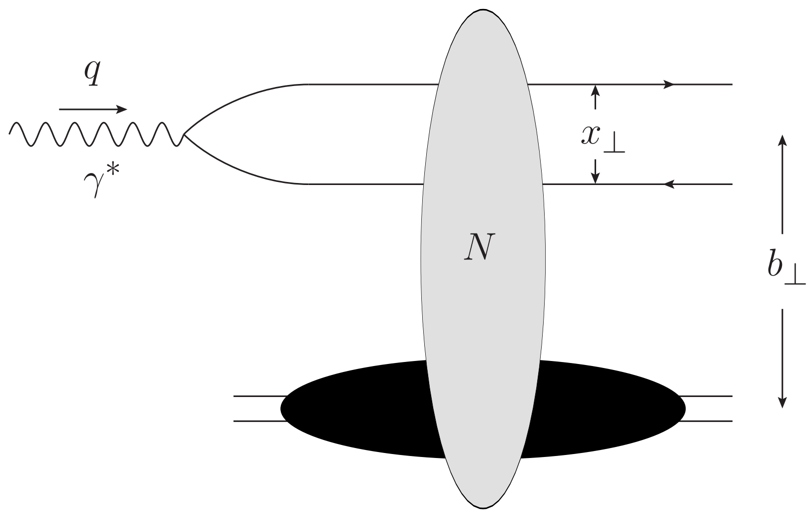


W^2 = cms energy squared for the photon+proton/nucleus system

$$x_P = \frac{Q^2 + M_X^2}{Q^2 + W^2} \approx \frac{M_X^2}{W^2} \qquad \beta = \frac{x_{Bj}}{x_P} = \frac{Q^2}{Q^2 + M_X^2} \approx \frac{Q^2}{M_X^2}$$

Quasi-elastic DIS

Consider the case when nothing but the quark-antiquark pair, i.e., two jets, are produced:



The quasi-elastic cross section is then proportional to the square of the dipole amplitude N:

$$\sigma_{el}^{\gamma^* A} = \int \frac{d^2 x_\perp}{4\pi} \, d^2 b_\perp \int_0^1 \frac{dz}{z\,(1-z)} \, |\Psi^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)|^2 \; N^2(\vec{x}_\perp, \vec{b}_\perp, Y)$$

Buchmuller et al '97, McLerran and Yu.K. '99

Diffraction on a black disk

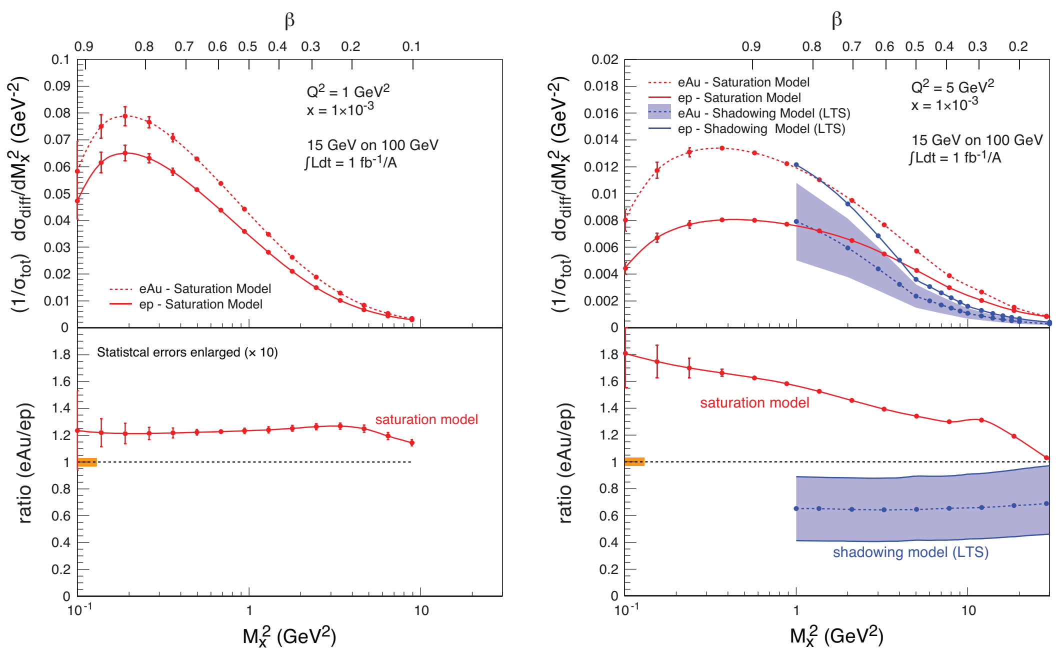
- For low Q^2 (large dipole sizes) the black disk limit is reached with N=1
- Diffraction (elastic scattering) becomes a half of the total cross section

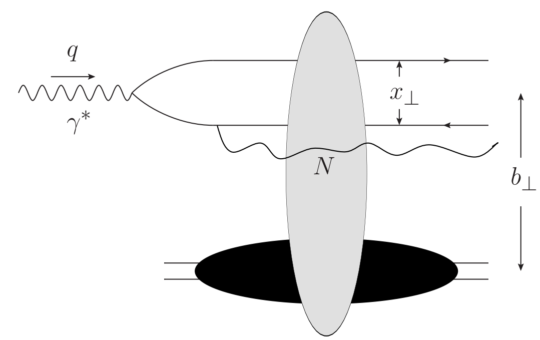
$$\frac{\sigma_{el}^{q\bar{q}A}}{\sigma_{tot}^{q\bar{q}A}} = \frac{\int d^2b\, N^2}{2\int d^2b\, N} \longrightarrow \frac{1}{2}$$

- Large fraction of diffractive events in DIS is a signature of reaching the black disk limit!
- HERA: ~15% (unexpected!) ; EIC: ~25% expected from saturation

Diffractive over total cross sections

- Here's an EIC measurement which may distinguish saturation from non-saturation approaches (from the 2012 EIC White Paper), using **diffractive to total double ratio**:



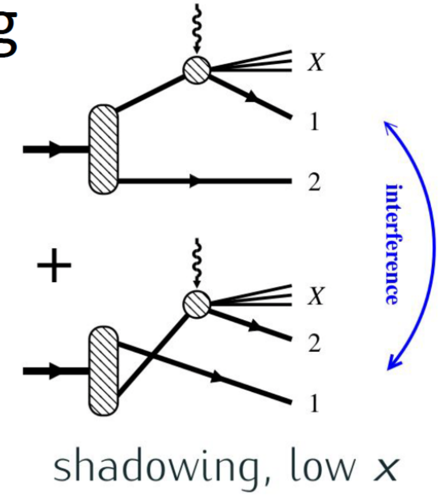


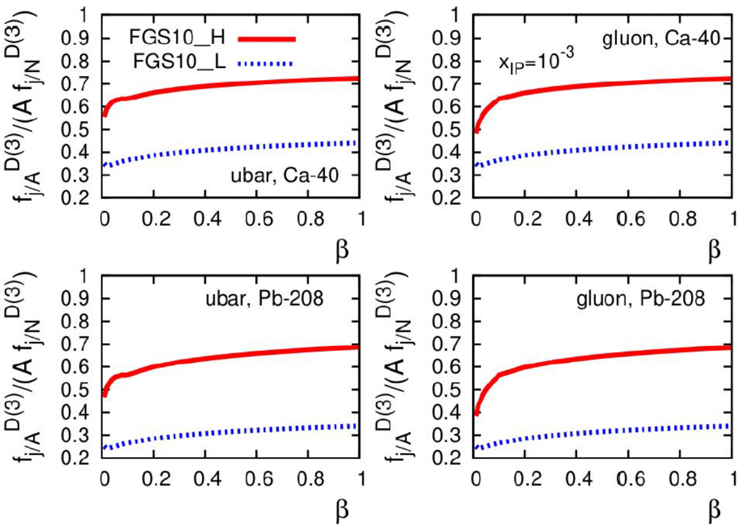
sat = Kowalski et al '08, plots generated by Marquet

no-sat = Leading Twist Shadowing (LTS), Kopeliovich, Tarasov, '02; Frankfurt, Guzey, Strikman '04, plots by Guzey

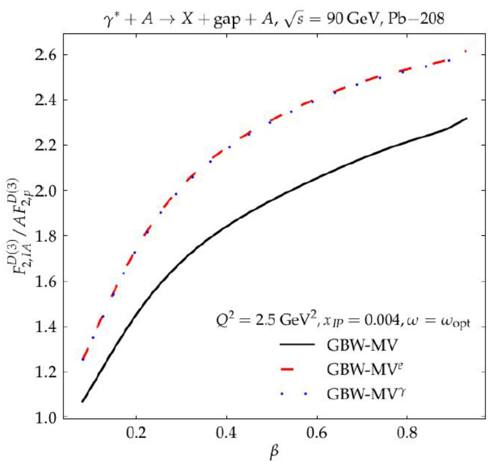
Nuclear diffractive pdfs: saturation vs LT shadowing

- LT nuclear shadowing predicts **reduction** of A/p ratio (interference)
- Gluon Saturation predices **enhancement**
- Measurement will discriminate





[Frankfurt, Guzey, Strikman, PhysRep 2012]

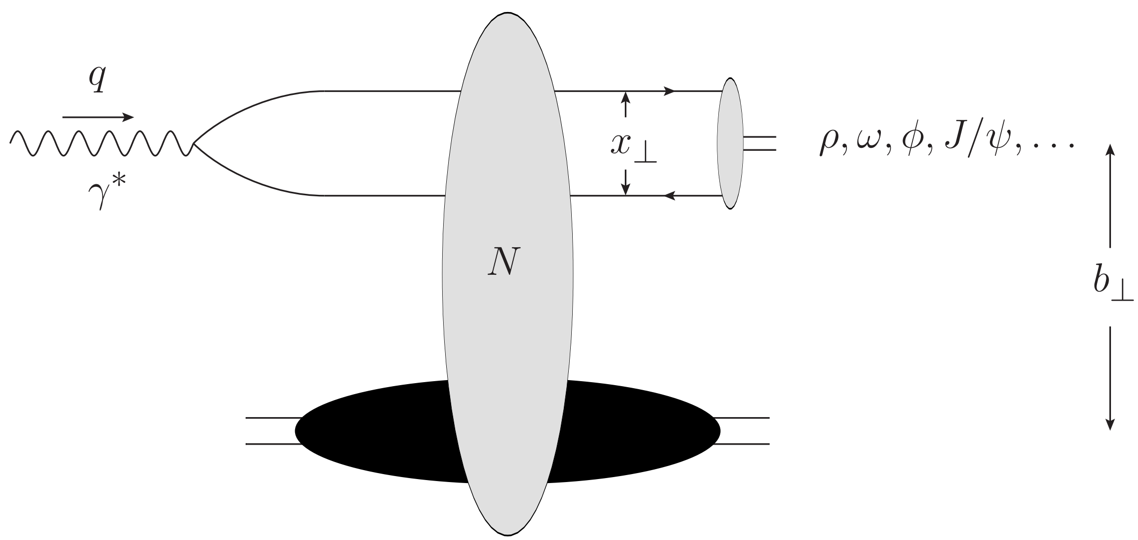


[Lappy, Le, Mantysaari, 2307.16486]

Wim's talk

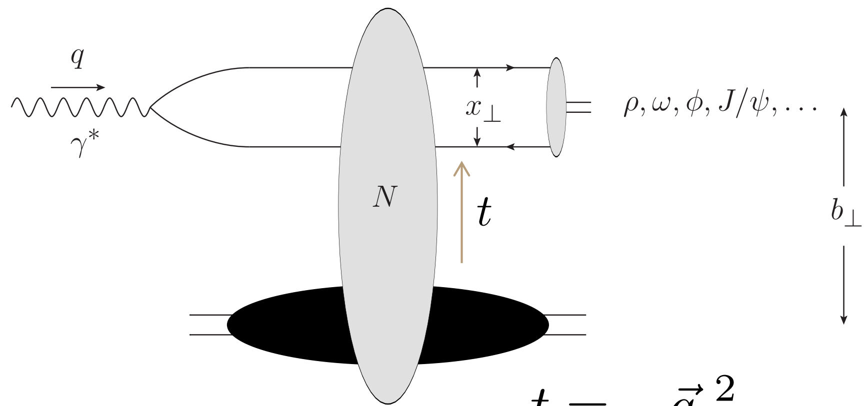
Exclusive Vector Meson Production

- An important diffractive process which can be measured at EIC is exclusive vector meson production (cf. UPCs):



Exclusive VM Production: Probe of Spatial Gluon Distribution

- Differential exclusive VM production cross section is



$$\frac{d\sigma^{\gamma^*+A\to V+A}}{dt} = \frac{1}{4\pi}\left|\int d^2b\, e^{-i\,\vec{q}_\perp\cdot\vec{b}_\perp}\, T^{q\bar{q}A}(\hat{s},\vec{b}_\perp)\right|^2$$

$$t = -\vec{q}_\perp^{\,2}$$

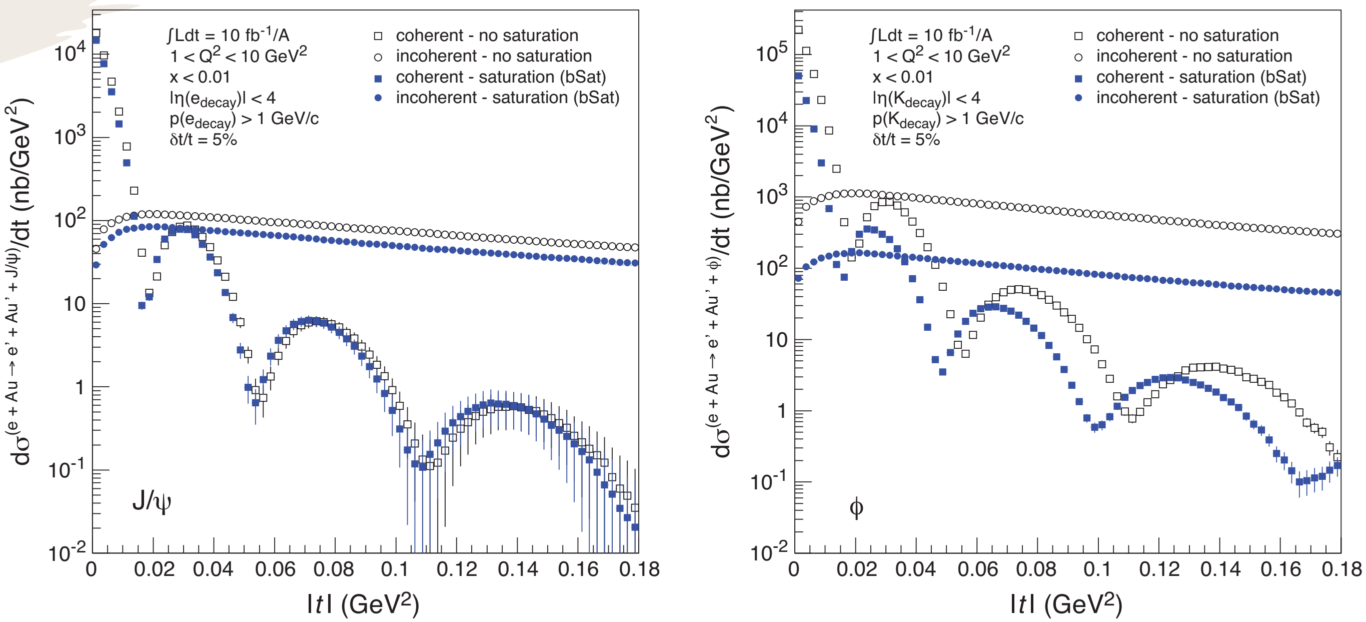
- the T-matrix is related to the dipole amplitude N:

$$T^{q\bar{q}A}(\hat{s},\vec{b}_\perp) = i\int \frac{d^2x_\perp}{4\,\pi}\int_0^1 \frac{dz}{z\,(1-z)}\;\Psi^{\gamma^*\to q\bar{q}}(\vec{x}_\perp,z)\;N(\vec{x}_\perp,\vec{b}_\perp,Y)\,\Psi^V(\vec{x}_\perp,z)^*$$

Brodsky et al ‘94, Ryskin ‘93

- Can study *t*-dependence of the *dσ/dt* and look at different mesons to find the dipole amplitude *N(x,b,Y)* (Munier, Stasto, Mueller ’01).
- Learn about the gluon distribution in space. This is similar to GPDs.

Exclusive VM Production as a Probe of Saturation



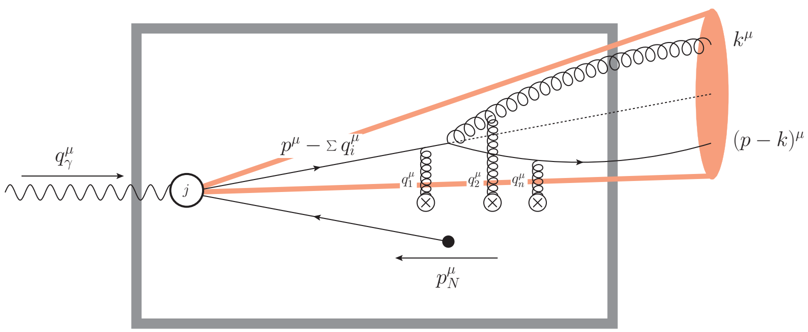
Plots by T. Toll and T. Ullrich using the Sartre event generator (b-Sat (=GBW+b-dep+DGLAP) + WS + MC, from the 2012 EIC White Paper).

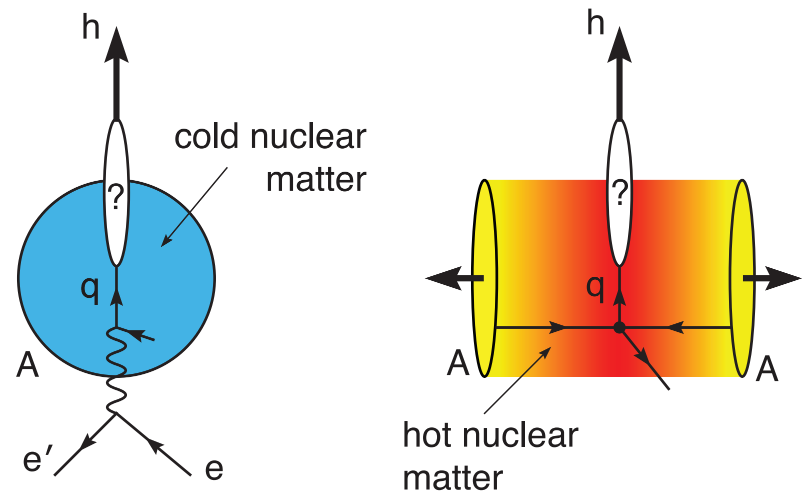
- J/psi is smaller, less sensitive to saturation effects
- Phi meson is larger, more sensitive to saturation effects

Large-x physics in e+A collisions

Energy Loss in Cold Nuclear Matter

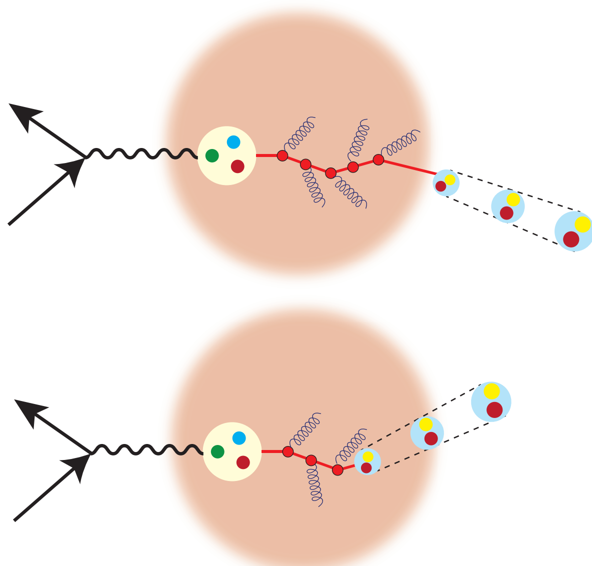
- EIC would be able to measure the energy loss of quarks in a cold nuclear matter (qhat), complementing the RHIC and LHC measurements of energy loss in hot QCD plasma:



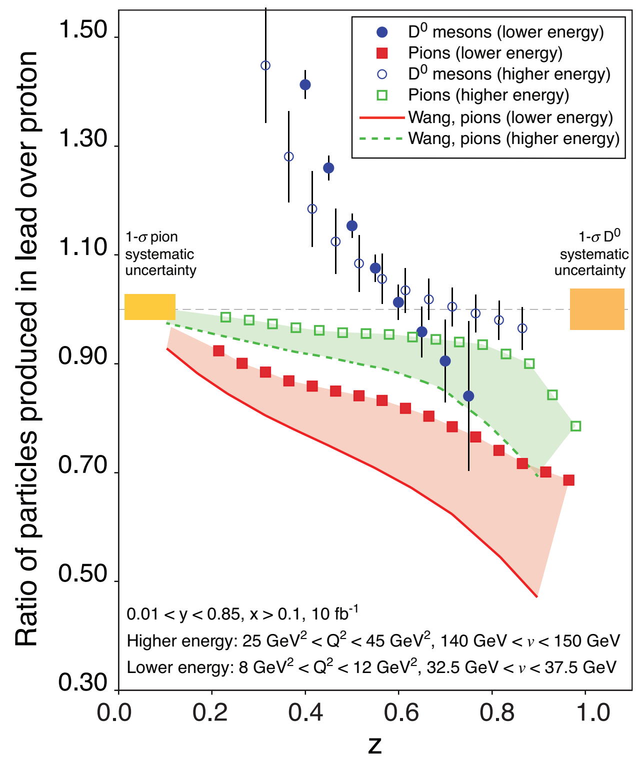


Energy Loss in Cold Nuclear Matter

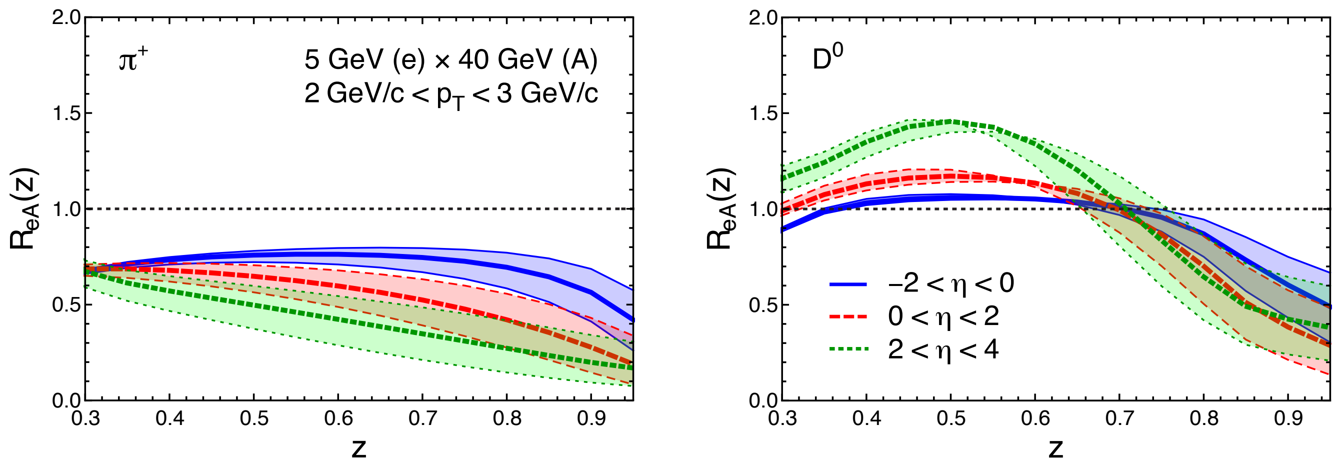
- By studying quark propagation in cold nuclear matter we can learn important information about hadronization and may even measure qhat in the cold nuclear medium:



$$z = \frac{E_h}{\nu}$$



In-medium fragmentation



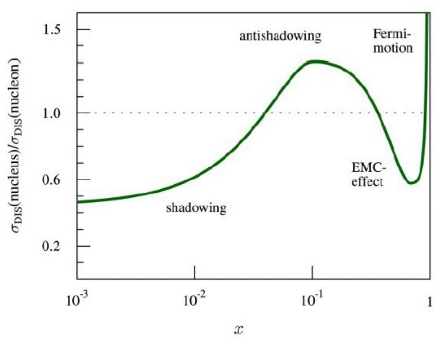
Modifications of the fragmentation functions by the cold nuclear medium.

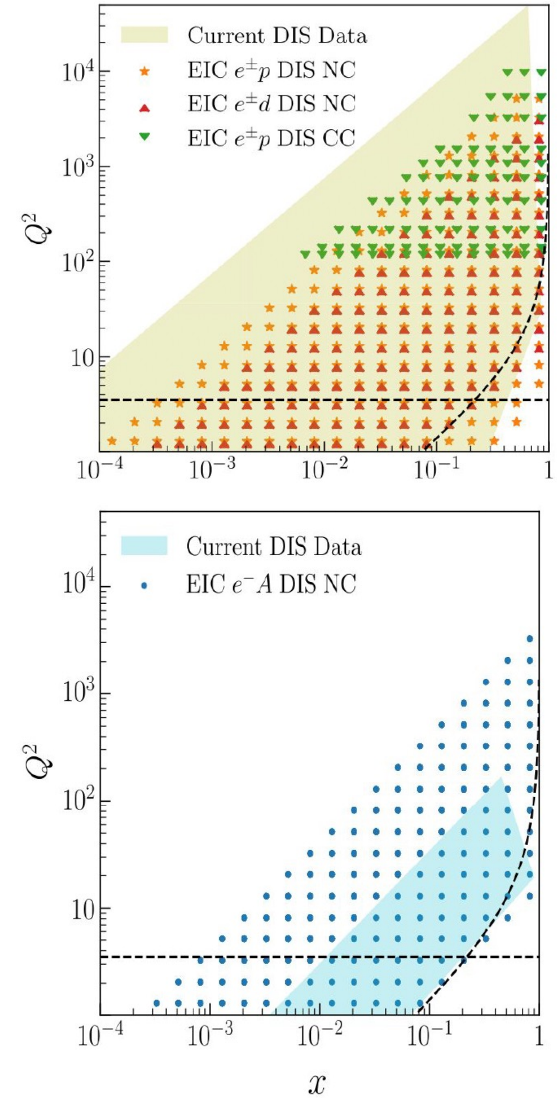
Nuclear pdfs

Wim's talk

- First collider with ep, ed, eA
  - Global analysis (biases)
  - Day 1 measurements (high precision, new x & Q^2 regions)
  - Fits without assumed A-dependence

- Medium modifications
  - (anti)shadowing, EMC
  - First for gluons
  - Q^2, A dependence



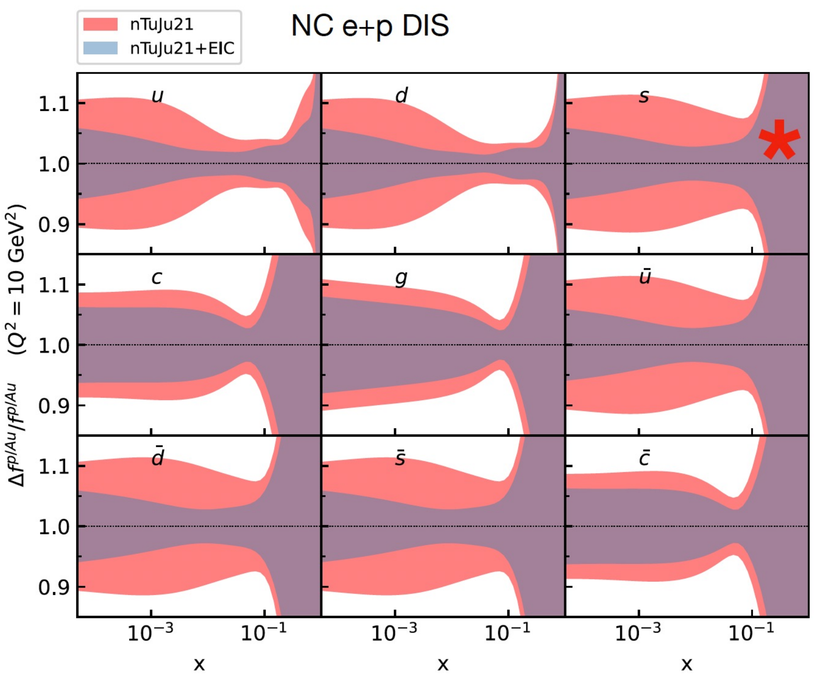


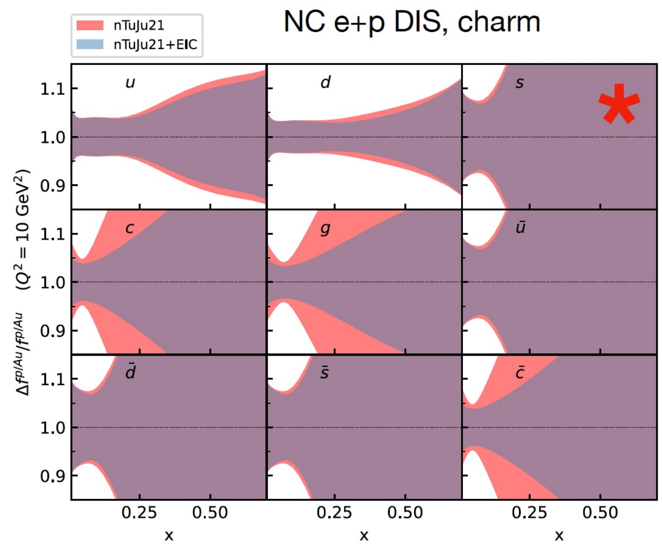
[Abdul Khalek et al, PRD2021]

e+A NC DIS for nuclear PDFs

simulated in YR: $\mathscr{L}_{int} \sim 10\, fb^{-1}$

expected : $\mathscr{L}_{int} \sim 1\, fb^{-1}$





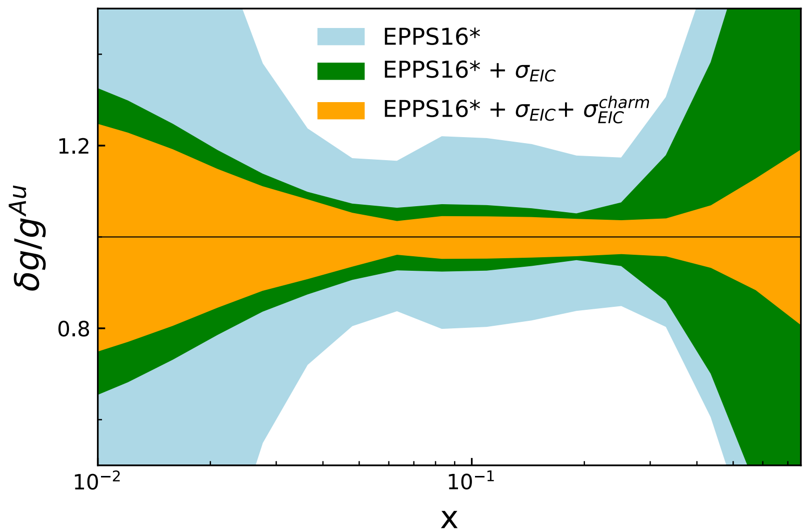
from P. Zurita's talk in January 2025

- ⚔️ light nuclei
- ⚔️ N3LO (approx.) available
- ⚔️ bottom possible?

🙁 A-dependence not possible

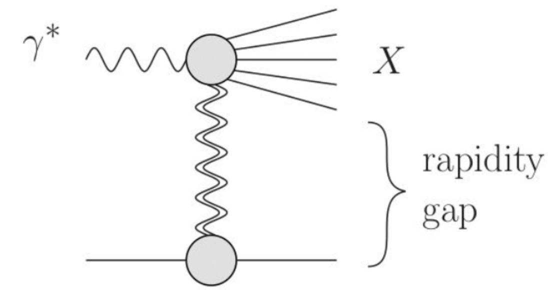
EIC impact on nPDFs

Significant improvement of our nPDFs' knowledge:



Nuclear diffractive pdfs

Wim's talk



- Diffraction
  - large rapidity gap between target/current fragmentation regions
  - Colorless exchange in *t*-channel (Pomeron, Reggeon, etc.)

- Observed at HERA → ~15% at low *x*
  - More (25%) expected at EIC (saturation)

- **Never** measured for eA

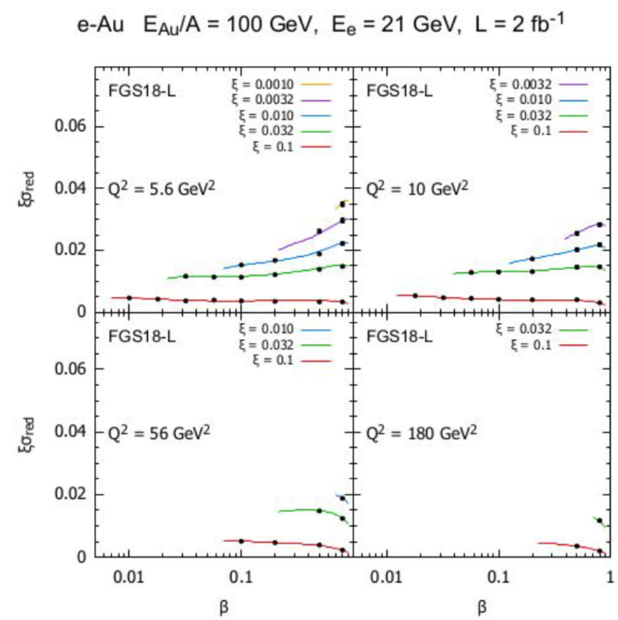
- Coherent/incoherent diffraction

  ↳ nuclear radius, global structure

  → nucleon/subnucleon fluctuations

  → can ePIC discriminate?

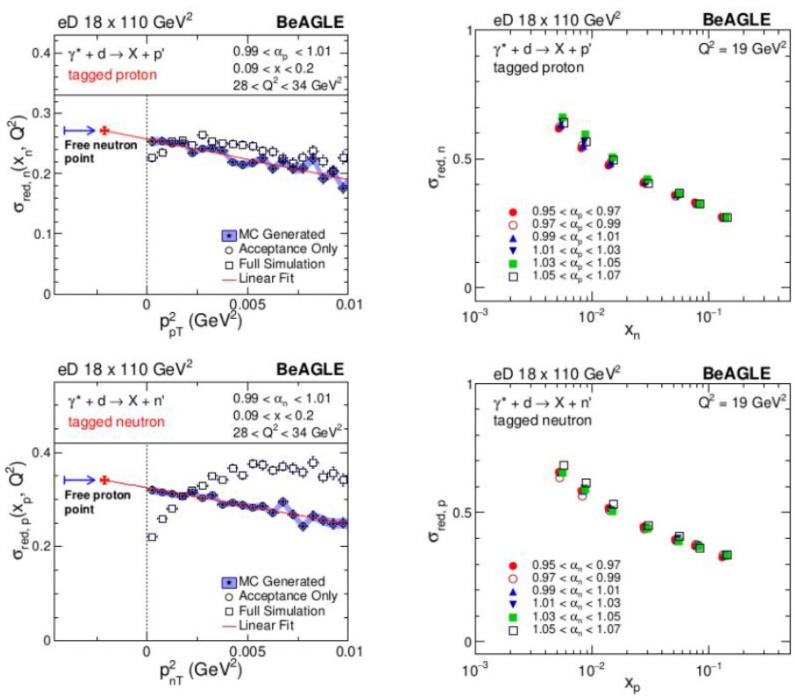
- Sensitive probe to gluon saturation
  - $g^2(x,Q^2)$



[Armesto, Newman, Slominski, Stasto, PRD19]

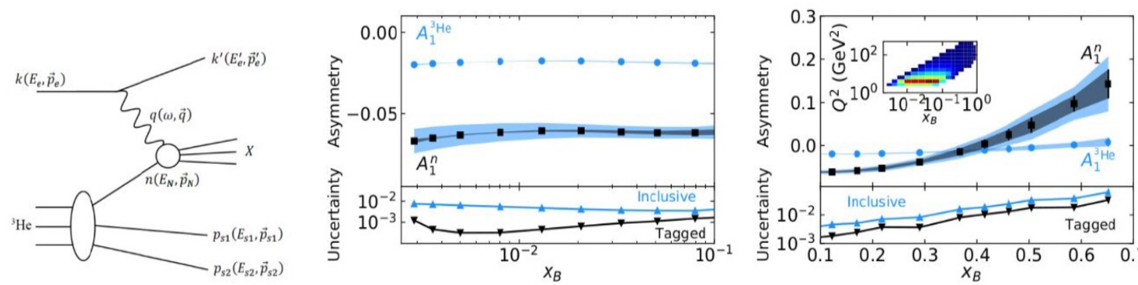
Neutron structure extraction: on-shell extrapolation

$$F_{2d} = [2(2\pi)^3]\, S_d(\alpha_p, \boldsymbol{p}_{pT})[\text{unpol}]\, F_{2n}(\tilde{x}, Q^2)$$



[Jentsch, Tu, Weiss, PRC21]

pol ^{3}He with double tagging for A1n **(g_{1n})**



I. Friscic et al., PLB'21

→ Final state (interactions) more complicated

Wim's talk

Neutron structure: tagging on steroids

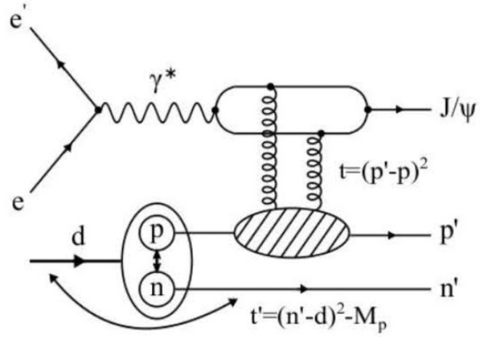
- Same procedure but more complicated hard process or tagging than tagged DIS
  - ↪ rates sufficient?

Wim's talk

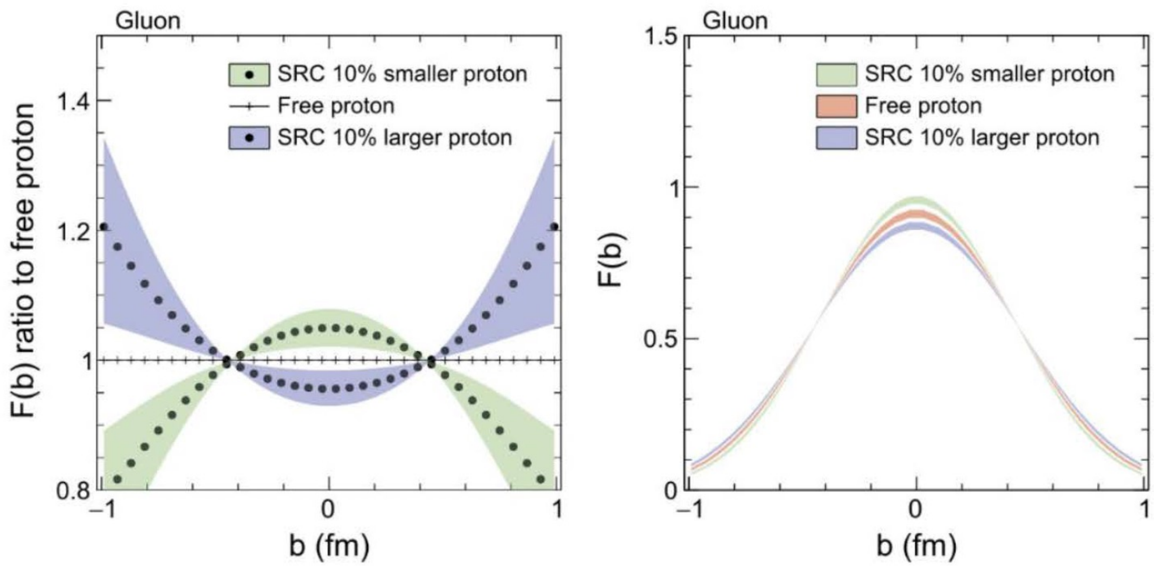
- Tagged SIDIS for neutron TMDs
  - ↪ $e + d \longrightarrow \pi + (X) + p$
  - ↪ $e + {}^{3}He(pol) \longrightarrow$ transverse n SSA?
- Tagged diffractive
  - ↪ differential study of nuclear shadowing
- Tagged exclusive
  - ↪ incoherent DVMP?
  - ↪ ~~coherent~~ (unpolarized?)
- Tag non-nucleonic components of nuclear wave function
  - ↪ Δ tagging for ed
  - ↪ short-range nature of NN-force (link with QCD dof)

Smaller cross section ↓

Diffractive deuteron break up: gluon density modification



- Double spectator tagging
- Study gluon densities as a function of nucleon momenta
- YR: ed 18x110 10fb^{-1} [Z. Tu et al. PLB'20]



Wim's talk

Z. Tu et al, PLB'21