Explore Nucleon/nucleus Tomography through Correlation Measurements

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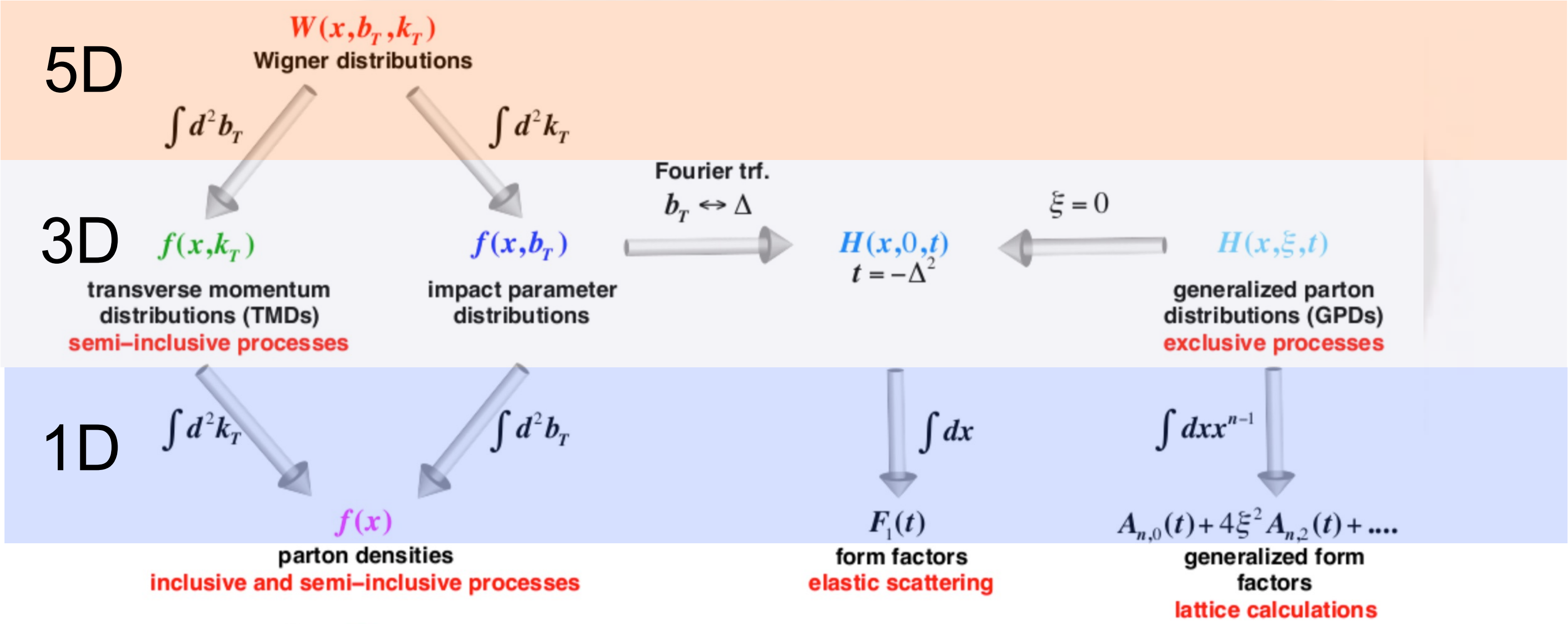
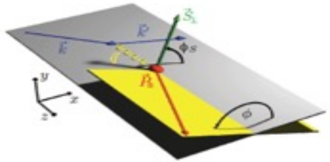
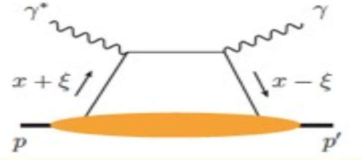
Lawrence Berkeley National Laboratory

Why Correlation Measurements?

- **Wigner distributions (Belitsky, Ji, Yuan)**

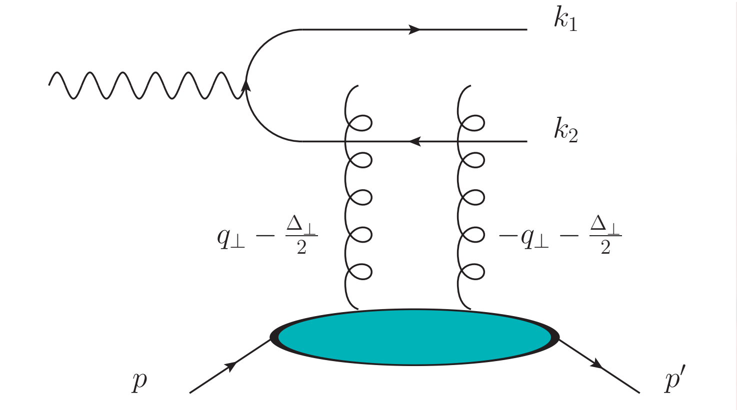


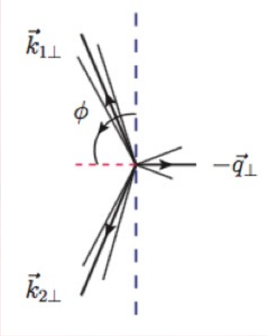




Directly measure the gluon Wigner distribution?

Hatta-Xiao-Yuan,1601.01585





cos(2ϕ) anisotropy

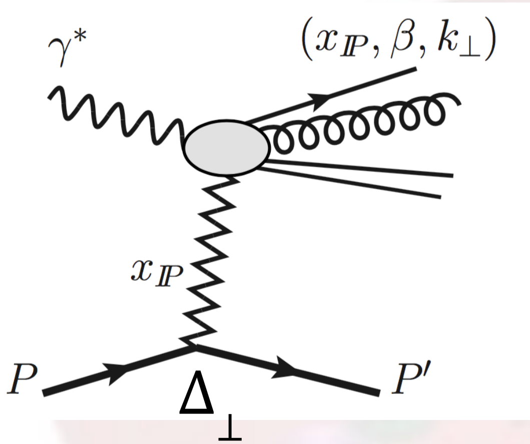
- In the Breit frame, by measuring the recoil of final state proton, one can access Δ_T. By measuring jets momenta, one can approximately access q_T.
- The diffractive dijet cross section is proportional to the square of the Wigner distribution → nucleon/nucleus tomography

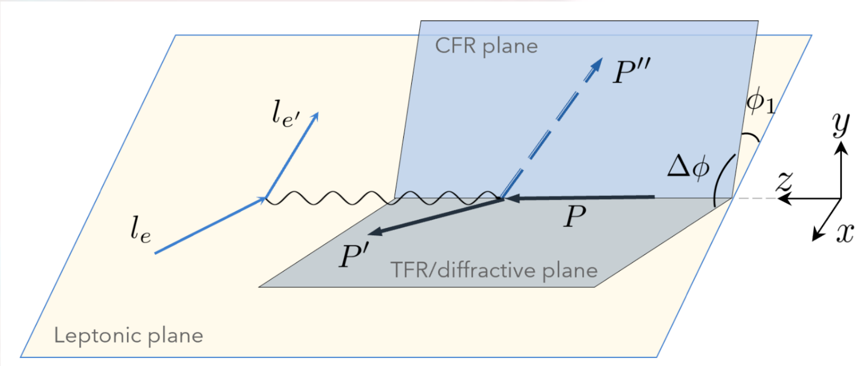
$$x\mathcal{W}_g^T(x, |\vec{q}_\perp|, |\vec{b}_\perp|) + 2\cos(2\phi) x\mathcal{W}_g^\epsilon(x, |\vec{q}_\perp|, |\vec{b}_\perp|)$$

More correlations to study OAM, Spin-Orbital Correlations, …

See also, Bhattacharya's talk

New avenue: semi-inclusive diffractive DIS





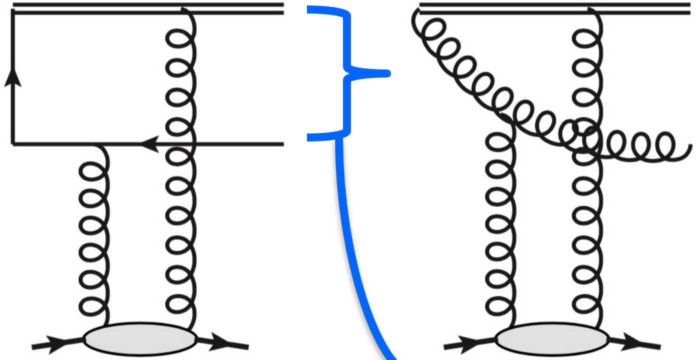
Iancu-Mueller-Triantafyllopoulos, 2112.06353;
Hatta-Xiao-Yuan, 2205.08060, Hatta-Yuan, 2403.19609;
Fucilla, Grabovsky, Li, Szymanowski, Wallon, 2310.11066 (NLO);
Guo, Yuan, 2312.01008

- Flavor dependence in the diffractive PDFs
- TMD dependence can be measured and so as the correlation between $k_\perp$ and $\Delta_\perp$

See also, Fucilla's talk

Compute the diffractive PDFs at small-x

- Definition is similar to TMDs for inclusive processes
- Requires large rapidity gap/color-singlet exchange

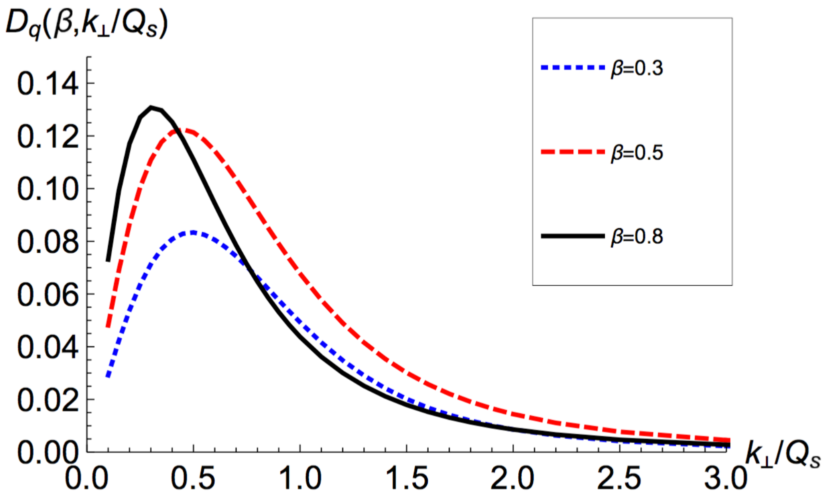


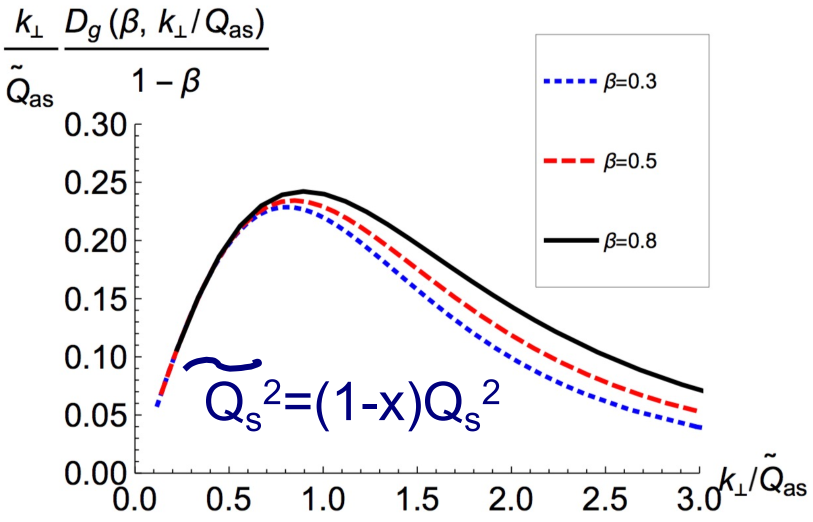
$$x\frac{d\, f_q^D(\beta,k_\perp;x_{I\!P})}{dY_{I\!P}\,dt\,d\phi_\Delta} = \int d^2k_{1\perp} d^2k_{2\perp} \mathcal{F}_{x_{I\!P}}(k_{1\perp},\Delta_\perp)$$

$$\times \mathcal{F}_{x_{I\!P}}(k_{2\perp},\Delta_\perp)\frac{N_c\beta}{(2\pi)^2}\mathcal{T}_q(k_\perp,k_{1\perp},k_{2\perp})$$

Transverse momentum dependence

Iancu, Mueller, Triantafyllopoulos, 2112.06353
Hatta, Xiao, Yuan, 2205.08060





Large kt: $$\frac{d\left[xf^D_{q,g}(\beta, k_\perp; x_{I\!P})\right]}{dY_{I\!P}dt}\Big|_{k_\perp \gg Q_s} = \frac{\alpha_s^2}{2\pi}\frac{\mathcal{C}_{q,g}}{k_\perp^4}\left(H_g(x_{I\!P})\right)^2$$

Elliptic Diffractive TMDs

- Elliptic correlation in the gluon Winger distribution will induce the elliptic correlation in the diffractive TMDs

$$\mathcal{F}_x = \mathcal{F}_0(|q_\perp|, |\Delta_\perp|) + 2\cos(2\phi_q - 2\phi_\Delta)\mathcal{F}_\epsilon(|q_\perp|, |\Delta_\perp|)$$

⇩

$$x\frac{d\, f_{q\epsilon}^{D}(\beta, k_\perp; x_{I\!P})}{dY_{I\!P}\, dt\, d\phi_\Delta} = 2\int d^2k_{1\perp} d^2k_{2\perp} \mathcal{F}_\epsilon(k_{1\perp}, \Delta_\perp) \quad (11)$$

$$\times \mathcal{F}_0(k_{2\perp}, \Delta_\perp) \frac{N_c \beta}{(2\pi)^2} \mathcal{T}_q(k_\perp, k_{1\perp}, k_{2\perp}) 2\cos(2\phi_{k_1} - 2\phi_\Delta) \; .$$

Comparable $\cos(2\phi)$ asymmetry between $k_\perp$ and $\Delta_\perp$

Sivers-type Diffractive TMDs

- Spin-dependent odderon in the gluon Wigner distribution

$$\mathcal{F}_x^{+-}(q_\perp, \Delta_\perp) = (-i)\frac{q_\perp^x + iq_\perp^y}{M} O_{1T}^\perp(|q_\perp|, |\Delta_\perp|)$$

Boer, Echevarria, Mulders, Zhou, PRL 16

$$x\frac{d\, f_{1Tq}^{D\perp}(\beta, k_\perp; x_{I\!P})}{dY_{I\!P} dt} = 2\int d^2k_{1\perp} d^2k_{2\perp} O_{1T}^\perp(k_{1\perp}, \Delta_\perp)$$
$$\times \mathcal{F}_0(k_{2\perp}, \Delta_\perp)\frac{N_c\beta}{2\pi}\mathcal{T}_q(k_\perp, k_{1\perp}, k_{2\perp})\sin(\phi_{k_1} - \phi_S) \ .$$

Summarize the leading TMD DPDFs

Elliptic:

$$x\frac{df_{q\epsilon}^{D}(\beta,k_\perp;x_{I\!P})}{dY_{I\!P}\,dt\,d\phi_\Delta}=\frac{N_c\beta\Delta_\perp^2}{16(1-\beta)^2}\Gamma^q\Gamma_\epsilon^q\cos(2\phi_k-2\phi_\Delta)$$

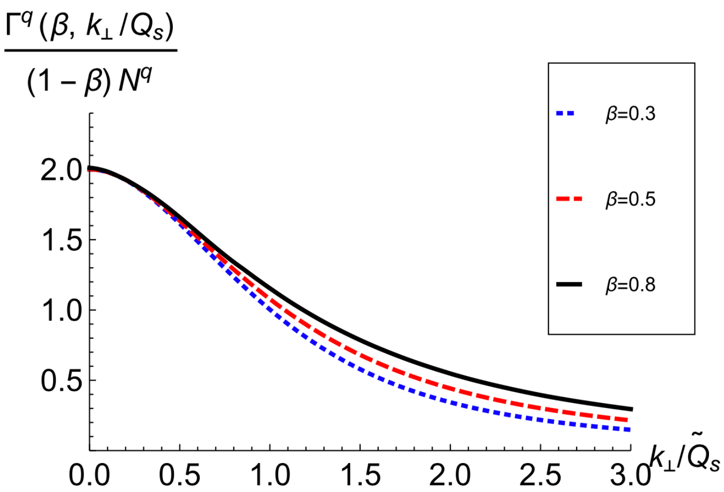
Sivers:

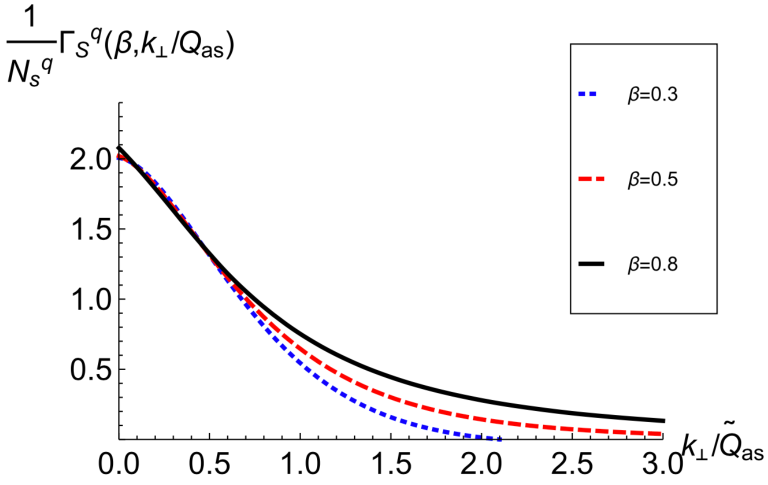
$$x\frac{df_{1Tq}^{D\perp}(\beta,k_\perp;x_{I\!P})}{dY_{I\!P}\,dt}=\frac{\pi N_c\beta}{8(1-\beta)^2}\Gamma^q\Gamma_{S_\perp}^q$$

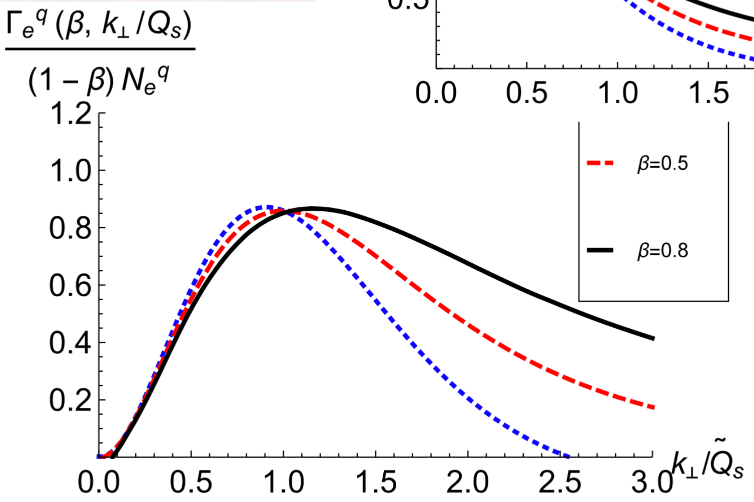
No linearly polarized gluon TMD DPDF!!

contrast to the non-diffractive case (Metz-Zhou 2011)

Transverse momentum dependence





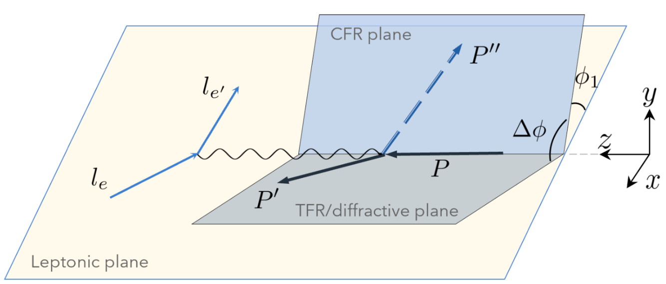


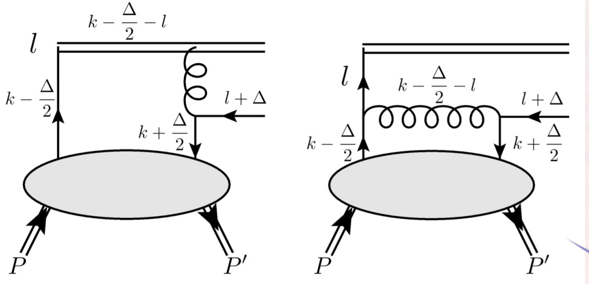
Modified geometric scaling is broken for the Sivers and Elliptic DPDFs

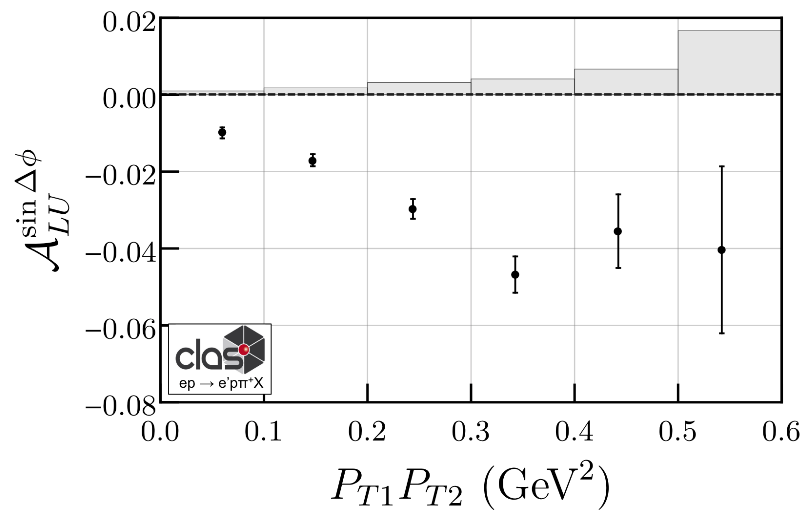
Complementary probes to small-x Sivers

- Semi-inclusive DIS, TMD Sivers function
  - Spin-dependent odderon, Boer, Echevarria, Mulders, Zhou, 1511.03485
- Exclusive meson production in ep collisions
  - Connection to the QCD odderon, Boussarie, Hatta, Szymanowski, Wallon, 1912.08182
- Semi-inclusive Diffractive DIS, Sivers diffractive TMDs
  - Comparable asymmetries, Hatta, Yuan, 2403.19609

Compute the Diffractive PDFs at moderate-x and the spin asymmetries in semi-inclusive diffractive DIS



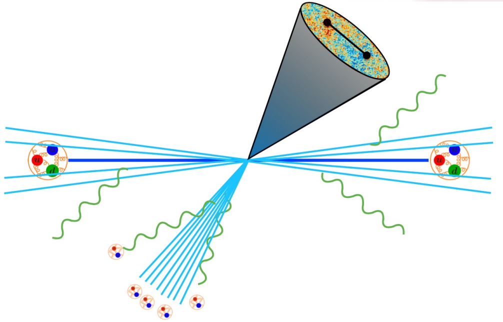


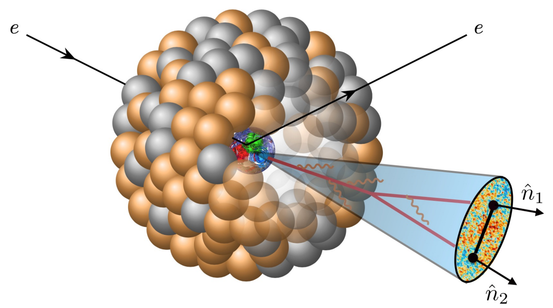


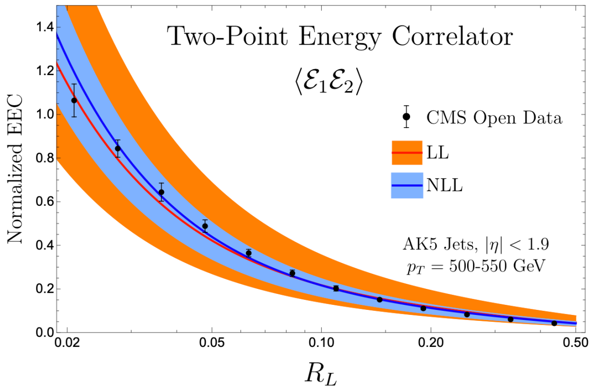
CLAS Coll., 2208.05508

Guo, Yuan, 2312.01008;
Bhattacharya, Guo, Lin, Yuan, Zhou, work in progress

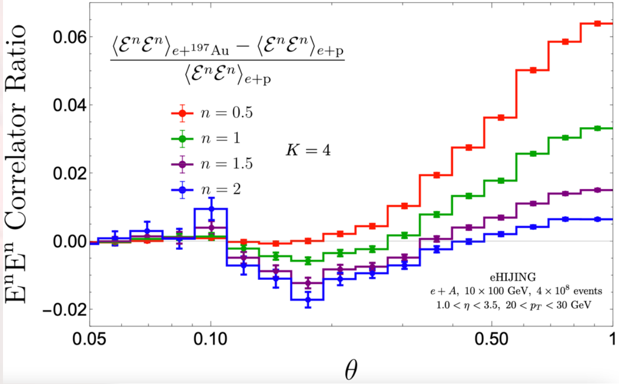
Energy-Energy Correlator to study the Jet-substructure in pp/AA/EIC







Lee, Mecaj, Moult, 2205.03414



Devereaux, Fan, Ke, Lee, Moult, 2303.08143

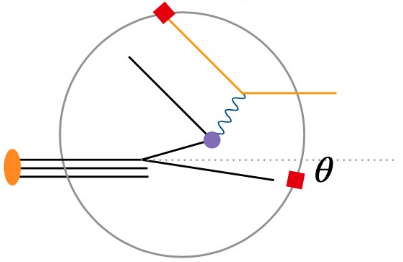
Looking at the other side, Hadron structure: nucleon EEC

$$f_{q,EEC}(x,\theta) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi E_P} e^{ixp^+y^-} \frac{\gamma^+}{2} \langle p\,|\,\bar{\psi}(0)\mathscr{E}(\theta)\mathscr{L}\psi(y^-)\,|\,p\rangle$$

$$= \sum_X \sum_{i\in X} \frac{E_i}{E_P} \delta(\theta_i^2 - \theta^2)\delta((1-x)p^+ - p_X^+) \frac{\gamma^+}{2} \langle p\,|\,\bar{\psi}(0)\,|\,X\rangle\langle X\,|\,\mathscr{L}\psi(0)\,|\,p\rangle$$

Liu, Zhu, 2209.02080
Cao, Liu, Zhu, 2303.01530

$$x_B = \frac{Q^2}{2P\cdot q}$$



$$\Lambda_{QCD} \ll Q\theta \ll Q$$

$$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma}\left(\frac{x_B}{z}, Q^2, \mu\right) f_{\rm EEC}(z,\theta,\mu)$$

$$\propto \int \frac{dz}{z} \hat{\sigma}\left(\frac{x_B}{z}\right) \frac{1}{\theta^2} \int \frac{d\xi}{\xi}(1 - \frac{z}{\xi})P(\frac{z}{\xi})[\xi f(\xi)]$$

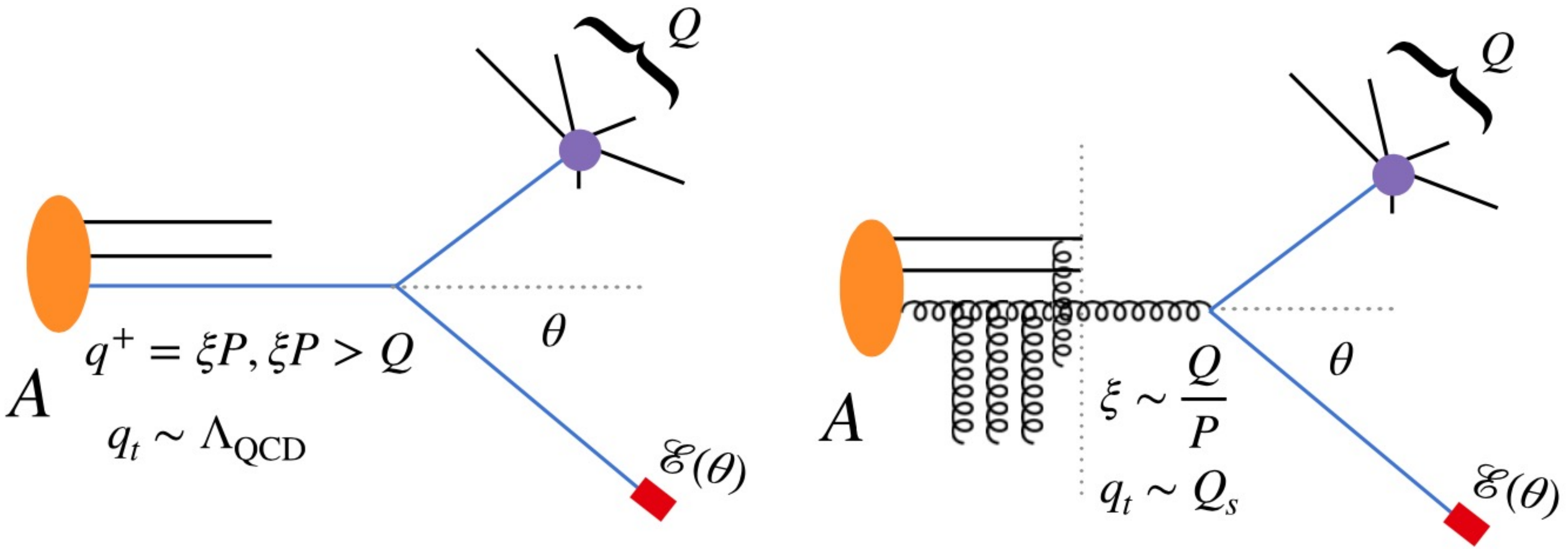
→ Perturbative scaling

- θ-distribution solely determined by $f_{\rm EEC}$
- In the collinear factorization:
  - $d\Sigma/d\ln\mu = P \otimes \Sigma$, solely determined by the vacuum splitting function
  - $\Sigma \sim \theta^{-2}$ at LO, $\Sigma \sim \theta^{-2+\gamma[\alpha_s]}$ to all orders

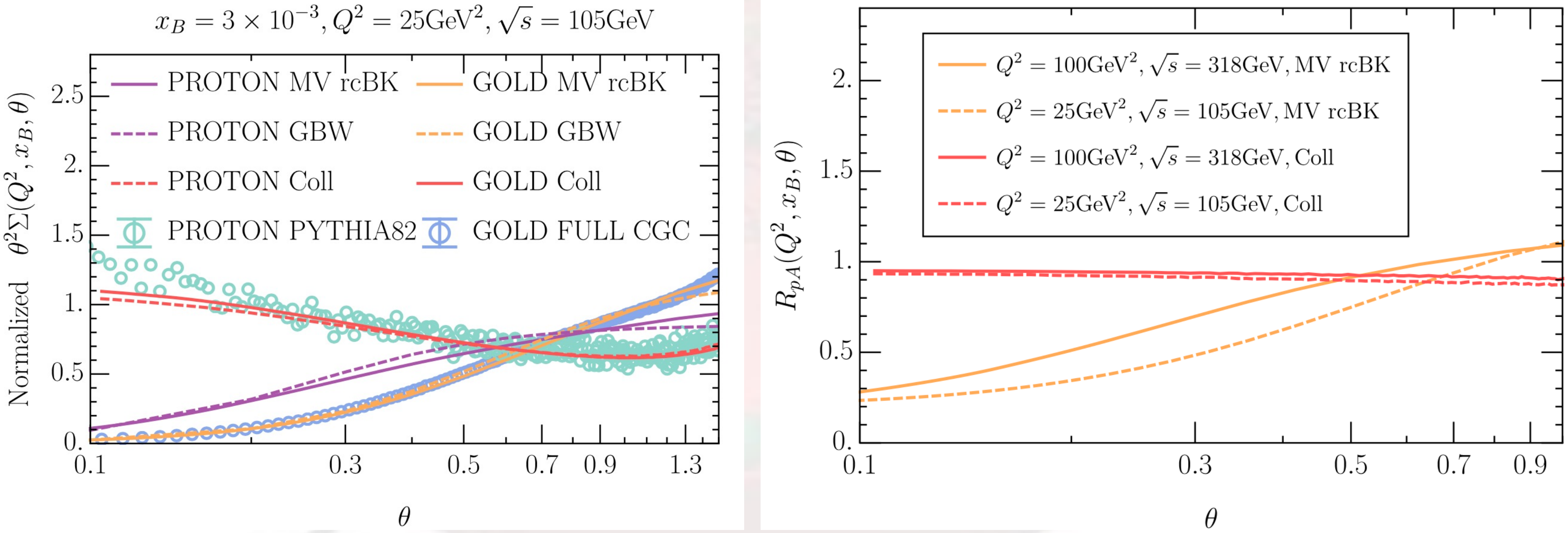
→ All order resummation

What happens at small-x

Liu, Liu, Pan, Yuan, Zhu, 2301.01788



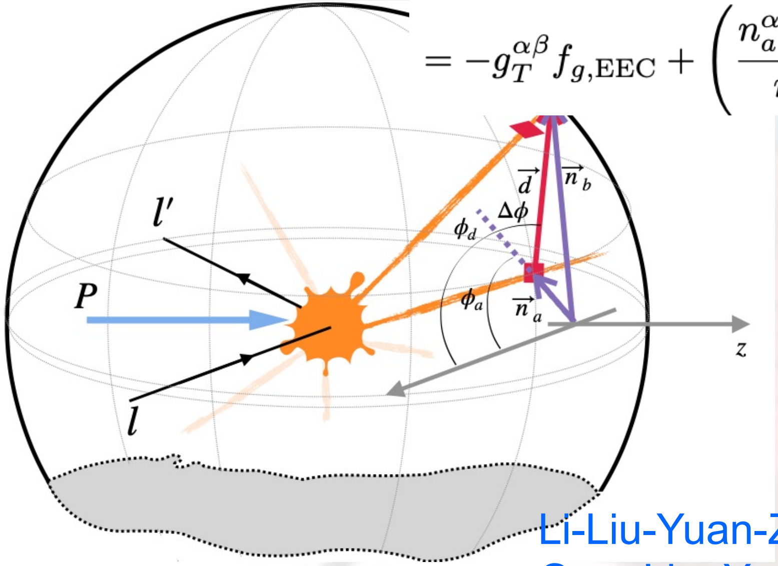
Gluon saturation modify small- θ behavior

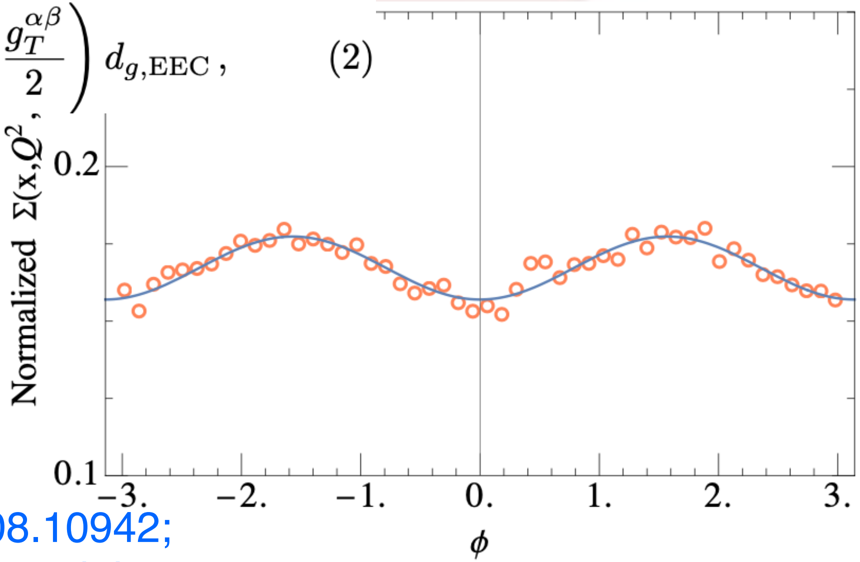


Liu, Liu, Pan, Yuan, Zhu, 2301.01788

Spinning gluon and long range correlations in DIS and proton-proton collisions

$$f_{g,\mathrm{EEC}}^{\alpha\beta}(x,\vec{n}_a) = \int \frac{dy^-}{4\pi x P^+} e^{-ixP^+\frac{y^-}{2}}$$
$$\times \langle P|\mathcal{F}^{+\alpha}(y^-)\,\mathcal{L}^\dagger[\infty,y^-]\hat{\mathcal{E}}(\vec{n}_a)\mathcal{L}[\infty,0]\mathcal{F}^{+\beta}(0)|P\rangle$$
$$= -g_T^{\alpha\beta} f_{g,\mathrm{EEC}} + \left(\frac{n_{a,T}^\alpha n_{a,T}^\beta}{n_{a,T}^2} - \frac{g_T^{\alpha\beta}}{2}\right) d_{g,\mathrm{EEC}}\,, \qquad (2)$$





Li-Liu-Yuan-Zhu, 2308.10942;
Guo, Liu, Yuan, Zhu, work in progress

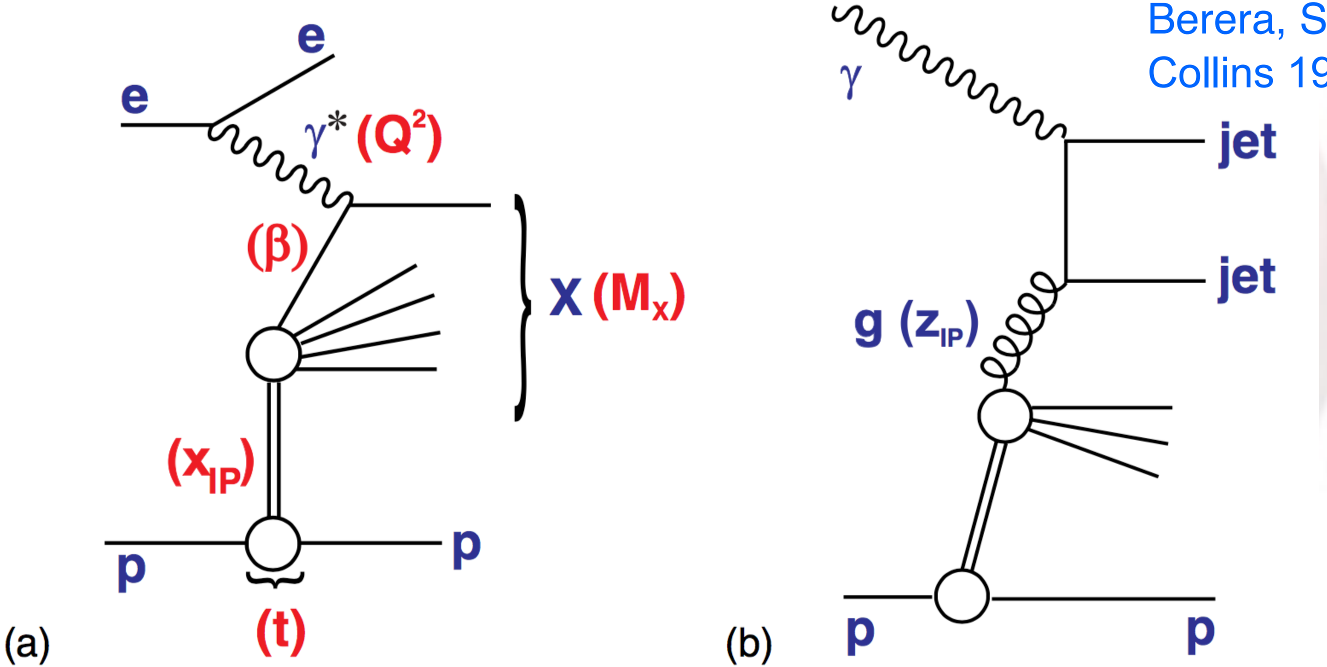
Conclusion

- Correlation measurements at current and future facilities offer unique opportunities to study nuclear tomography, answering the questions of nucleon spin (OAM), energy-mass decompositions (Gravitational Form Factors)
- Nucleon energy-energy correlators show promising features to probe the internal structure of hadrons
  - Need more theoretical studies, such as high order calculations, extension to small-x domain, etc.

Back-up

New Avenue: Diffractive DIS

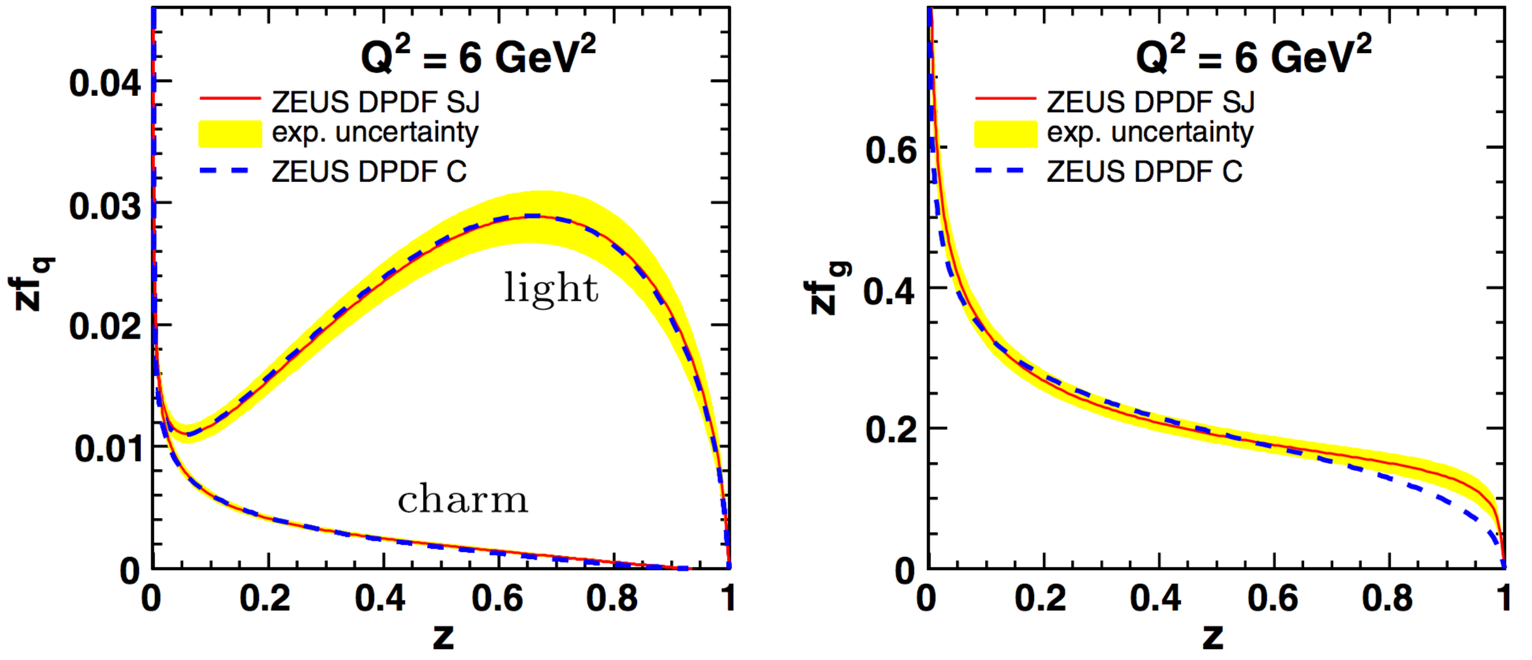
Trentadue, Veneziano, 1994
Berera, Soper, 1996
Collins 1998



HERA Legacy: Newman-Wing, Rev. Mod. Phys. 86, 1037(2014)

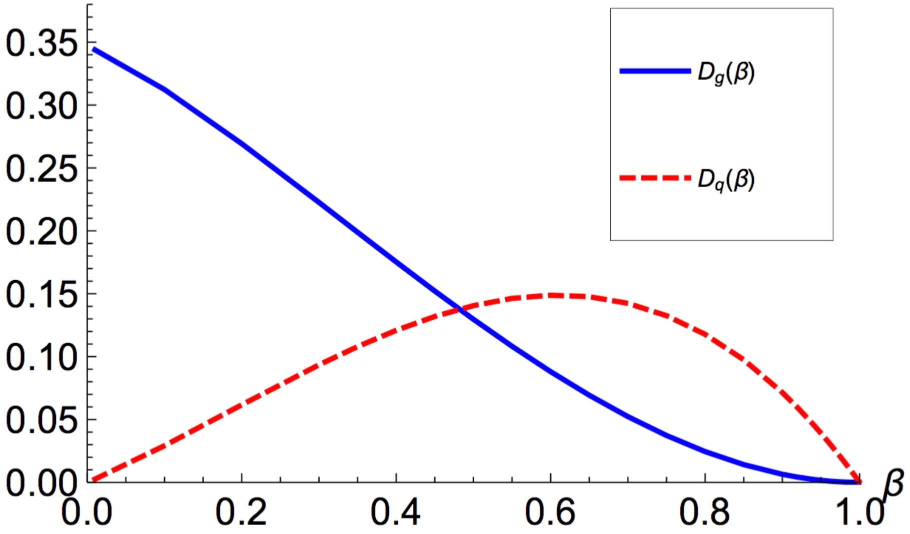
Compare to the HERA measurements

ZEUS, NPB831, 1 (2010)



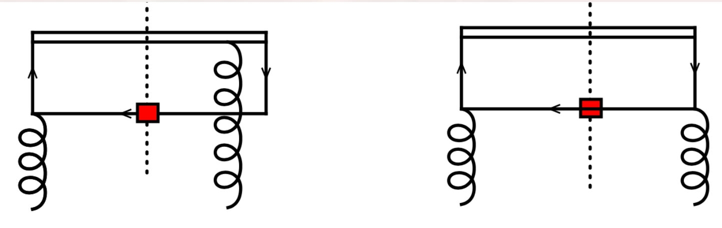
Integrate over transverse momentum

$$\mathcal{D}_q(\beta) = \beta\left(b_1(1-\beta) + b_2(1-\beta)^2\right) \quad \mathcal{D}_g(\beta) = (a_0 + a_1\beta)(1-\beta)^2$$



- Different power behaviors for the quark and gluons
- Inputs for the diffractive PDFs at the initial scale

Compute the EEC distribution Collinear vs CGC



Collinear:

$$f_{q,\mathrm{EEC}}(x,\theta)=\frac{\alpha_s T_R}{2\pi\theta^2}\int_x^1\frac{d\xi}{\xi}(1-\xi)(\xi^2+(1-\xi)^2)\left[\frac{x}{\xi}f_g\left(\frac{x}{\xi}\right)\right]$$

CGC:

$$f_{q,\mathrm{EEC}}(x_B,\theta)=\frac{N_C S_\perp}{8\pi^4}\int d^2\vec{g}_t\int_{\xi_{\mathrm{cut}}}^1\frac{d\xi}{\xi}\mathcal{A}_{qg}(\xi,\theta,\vec{g}_t)F_{g,x_B}(\vec{g}_t)$$

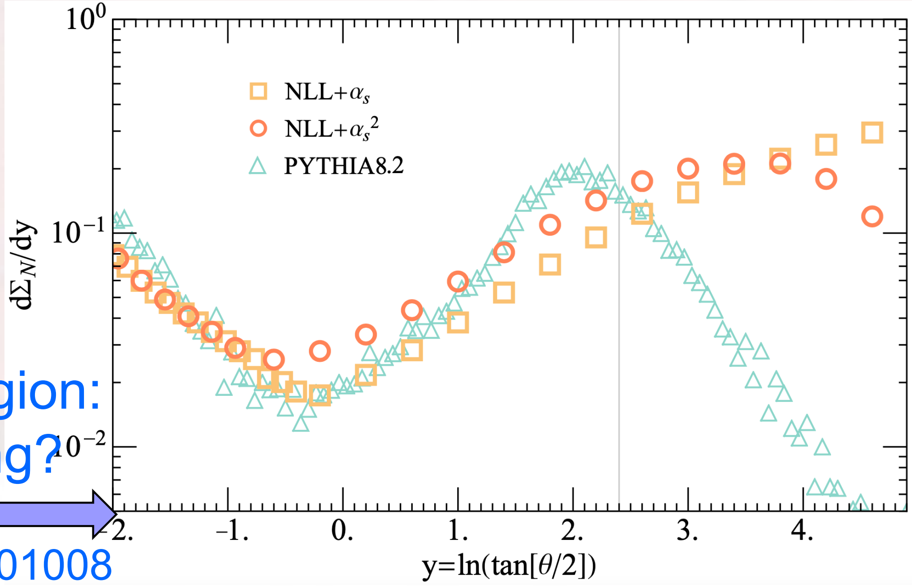
$$\mathcal{A}_{qg}(\xi,\theta,\vec{g}_t)=\frac{1}{\theta^2}(1-\xi)\vec{k}_t^2(\vec{k}_t-\vec{g}_t)^2\left|\frac{\vec{k}_t}{\xi\vec{k}_t^2+(1-\xi)(\vec{k}_t-\vec{g}_t)^2}-\frac{\vec{k}_t-\vec{g}_t}{(\vec{k}_t-\vec{g}_t)^2}\right|^2$$

$$k_t=[(1-\xi)/2](Q/2)\theta,$$

Resummation of collinear logs will modify the power behavior

$$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma}\left(\frac{x_B}{z}, Q^2, \mu\right) f_{\rm EEC}(z, \theta, \mu) \qquad \Sigma(x_B, Q^2, \theta) \sim \theta^{-2+\gamma}$$

Cao, Liu, Zhu, 2303.01530

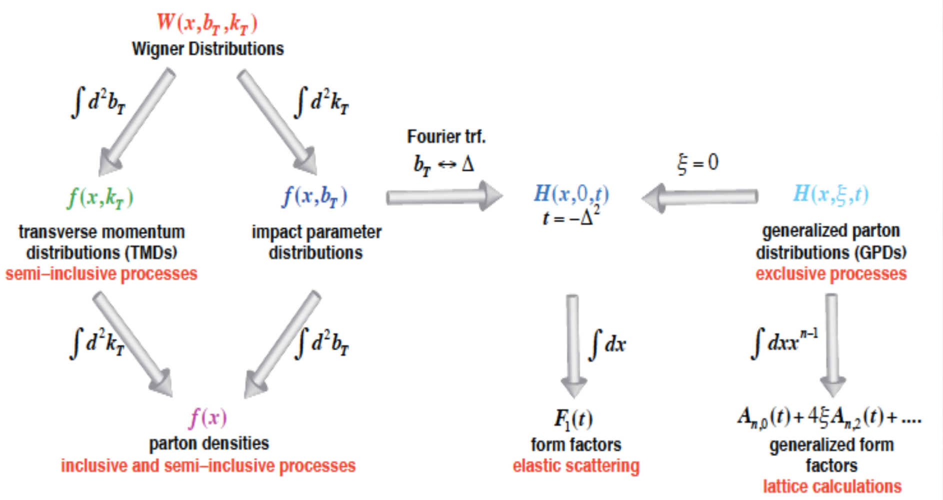


Non-perturbative region: free parton streaming?

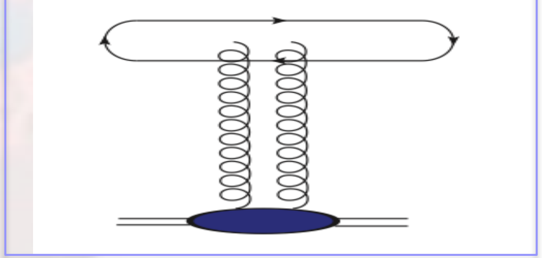
Guo-Yuan, 2312.01008

See also the transition from target fragmentation region to the current frag. region: Cao, Li, Mi, 2312.07655

Comprehensive program needed to explore the QCD landscape at small-x



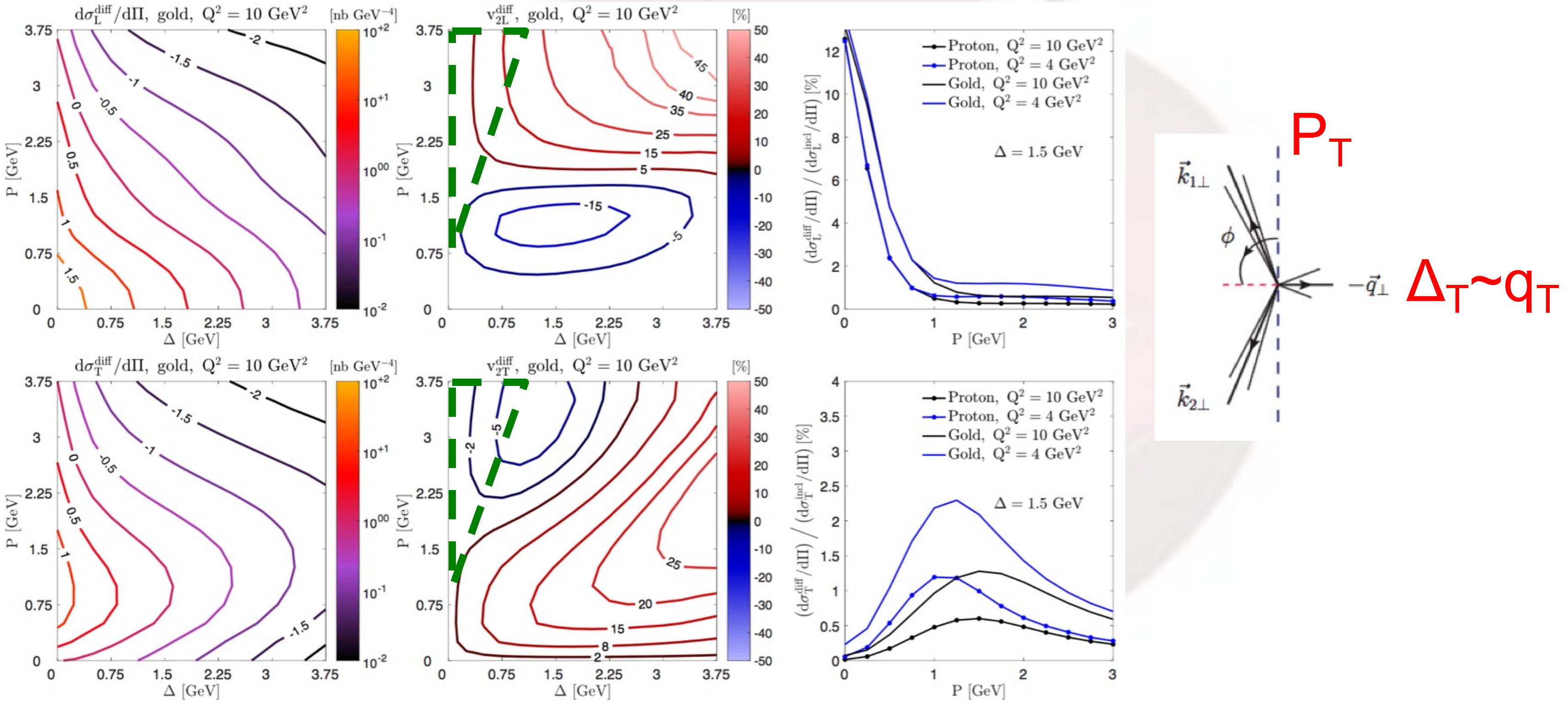
Small-x



$$\frac{1}{N_c}\left\langle \mathrm{Tr}\left[U\left(R_\perp\right)U^\dagger\left(R'_\perp\right)\right]\right\rangle_x$$

Hatta-Xiao-Yuan,1601.01585
earlier: Mueller, NPB 1999

This has generated a lot of interests…



CGC calculations: Mäntysaari-Mueller-Salazar-Schenke, 1912.05586, 1902.05087; Mäntysaari-Roy-Salazar-Schenke 2011.02464