Glue Imaging in Production of Vector Mesons ($J/\Psi, \phi \cdots$)

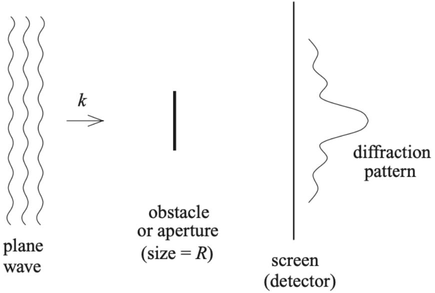
Bo-Wen Xiao

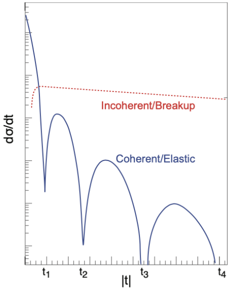
School of Science and Engineering,
The Chinese University of Hong Kong, Shenzhen

2nd Precision Studies on QCD at EIC

An analogy to Fraunhofer Diffraction in Optics

[QCD at high energy, Kovchegov and Levin, 12]

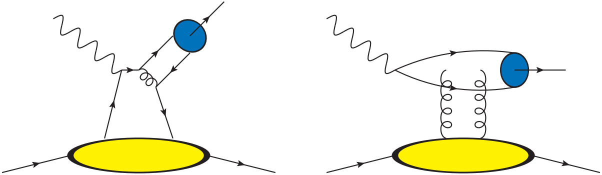




- Treat the hadron target in DIS as a black disk. [Joseph von Fraunhofer, 1821]
- Similar pattern in optics ($\theta_i^{\min} \sim 1/(kR)$) and high energy QCD $t_i \sim \frac{1}{R^2}$.
- Two difference: 1. σ sensitive to gluon distribution; 2. Breakup of the target.
- This motivates us to use diffractive scattering to study gluon spatial distribution.

Gluon GPDs and DVMP processes

For exclusive/diffractive processes with $V = J/\Psi, \phi \cdots$

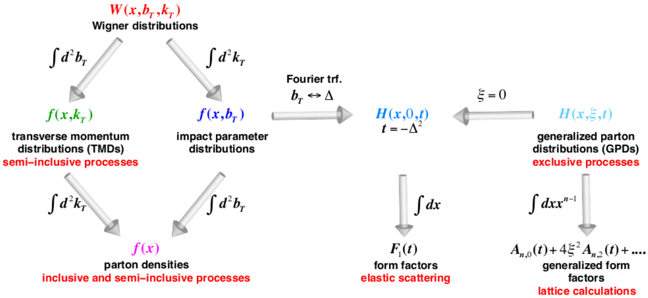


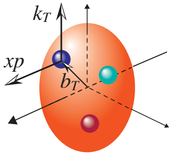
$$\gamma^*(q) + p/A(p) \to V(q - \Delta) + p/A(p + \Delta)$$

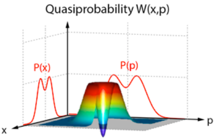
- The latter diagram is dominant at small-x (high energy) limit.
- Widely studied at small-x [Brodsky, Frankfurt, Gunion, Mueller, Strikman, 94; Kowalski, Teaney, 03; Kowalski, L. Motyka, Watt, 06, Watt, Kowalski, 08; Kowalski, Caldwell, 10; Berger, Stasto, 13; Rezaeian, Schmidt, 13]...
- Incoherent diffractive production for nucleon/nuclear targets [T. Lappi, H. Mantysaari, 11; Toll, Ullrich, 12; Lappi, Mantysaari, R. Venugopalan, 15; T. Lappi, Mantysaari, Schenke, 16]...; Review by [Mantysaari, 20]
- DVMP at NLO. [Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon, 16]

Wigner distribution

Wigner distributions [Ji, 03; Belitsky, Ji, Yuan, 2004] ingeniously encode all quantum information of how partons are distributed inside hadrons.







- Quasi-probability distribution; Not positive definite. [F. Yuan's talk]
- GPDs encode the parton spatial distributions.

The exact connection between dipole amplitude and Wigner distribution

[Hatta, Xiao, Yuan, 16] Def. of gluon Wigner distribution:

$$
\begin{aligned}
xW_g^T(x,\vec{q}_\perp;\vec{b}_\perp) &= \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ixP^+\xi^- - iq_\perp\cdot\xi_\perp} \\
&\times \left\langle P+\frac{\Delta_\perp}{2}\middle| F^{+i}\left(\vec{b}_\perp+\frac{\xi}{2}\right) F^{+i}\left(\vec{b}_\perp-\frac{\xi}{2}\right) \middle| P-\frac{\Delta_\perp}{2}\right\rangle ,
\end{aligned}
$$

Define GTMD [Meissner, A. Metz and M. Schlegel, 09]

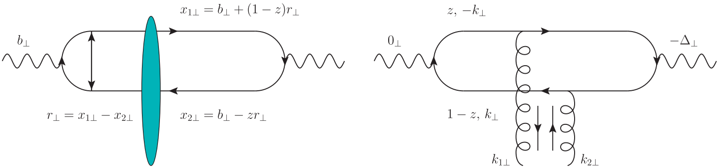
$$
xG(x,q_\perp,\Delta_\perp) \equiv \int d^2 b_\perp e^{-i\Delta\cdot b_\perp} xW_g^T(x,\vec{q}_\perp;\vec{b}_\perp).
$$

- With dipole-like gauge link, one finds

$$
\begin{aligned}
xG_{\mathrm{DP}}(x,q_\perp,\Delta_\perp) &= \frac{2N_c}{\alpha_s} \int \frac{d^2R_\perp d^2R'_\perp}{(2\pi)^4} e^{iq_\perp\cdot(R_\perp - R'_\perp) + i\frac{\Delta_\perp}{2}\cdot(R_\perp+R'_\perp)} \\
&\times \left(\nabla_{R_\perp}\cdot\nabla_{R'_\perp}\right) \frac{1}{N_c} \left\langle \mathrm{Tr}\left[U(R_\perp)\, U^\dagger(R'_\perp)\right]\right\rangle_x .
\end{aligned}
$$

- Relation to TMDs and GPDs. Small-x tells us more information about them.

Scattering amplitude

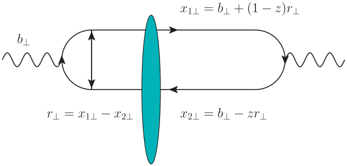


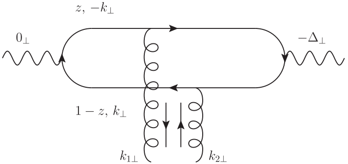
- At small-x, the lifetime of $q\bar{q}$ fluctuation $\tau_f \sim \frac{q^+}{Q^2} + \frac{q^+}{M_V^2} \gg \tau_{int}$ with $\tau_{int} \sim R/\gamma$.
- Factorize the amplitude into three pieces in coordinate space:

$$\mathcal{A}(\Delta_\perp) \sim \int d^2r_\perp d^2b_\perp e^{ib_\perp\cdot\Delta_\perp} \int_0^1 dz \Psi_{\gamma^*}(z, r_\perp)\Psi_V^*(z, r_\perp) \times \left\{1 - \frac{1}{N_c}\mathrm{Tr}\left[U(b_\perp + zr_\perp)U^\dagger(b_\perp - (1-z)r_\perp)\right]\right\}.$$

- I: $\gamma^* \to q\bar{q}$ splitting; II: $q\bar{q}$ scattering; III: CC of $V \to q\bar{q}$ splitting.

Relation between gluon GPDs and dipole scattering amplitude





[Hatta, Xiao, Yuan, 17] gluon GPDs with asymmetric dipole for arbitrary z

- Dipole scattering amplitude $S_x = \left\langle \frac{1}{N_c} \mathrm{Tr}\left[U(x_{1\perp})U^\dagger(x_{2\perp})\right] \right\rangle_x$ defines GTMD:

$$\mathcal{F}_x(\tilde{q}_\perp, \Delta_\perp) = \frac{1}{(2\pi)^4} \int d^2x_{1\perp} d^2x_{2\perp} e^{ik_{1\perp}\cdot x_{1\perp} - ik_{2\perp}\cdot x_{2\perp}} S_x(x_{1\perp}, x_{2\perp})$$

  with $k_{1\perp} \equiv \tilde{q}_\perp + z\Delta_\perp$ and $k_{2\perp} \equiv \tilde{q}_\perp - (1-z)\Delta_\perp$.

- Symmetric dipole definition with shifts of coordinate and momentum

$$F_x(q_\perp, \Delta_\perp) = \int \frac{d^2r_\perp d^2b_\perp}{(2\pi)^4} e^{ib_\perp\cdot\Delta_\perp + ir_\perp\cdot q_\perp} S_x\left(b_\perp + \frac{r_\perp}{2}, b_\perp - \frac{r_\perp}{2}\right)$$

Dipole scattering amplitude

Several properties of the scattering amplitude:

- $S_x = \left\langle \frac{1}{N_c} \mathrm{Tr}\left[U(b_\perp + \frac{r_\perp}{2}) U^\dagger (b_\perp - \frac{r_\perp}{2}) \right] \right\rangle_x$
- Due to the Pomeron exchange, S_x is predominantly real in small-x.
- $S_x = S_x^* \quad \Rightarrow \quad S_x$ can only depend on $b_\perp^2$, $r_\perp^2$ and $(r_\perp \cdot b_\perp)^{2n}$.
- Double Fourier transform:

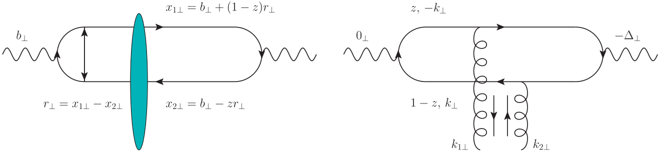
$$F_x(q_\perp, \Delta_\perp) = \int \frac{d^2 r_\perp d^2 b_\perp}{(2\pi)^4} e^{ib_\perp \cdot \Delta_\perp + ir_\perp \cdot q_\perp} S_x \left(b_\perp + \frac{r_\perp}{2}, b_\perp - \frac{r_\perp}{2} \right)$$

- Angular dependence after double Fourier transform

$$F_x(q_\perp, \Delta_\perp) = F_0(|q_\perp|, |\Delta_\perp|) + 2\cos 2(\phi_{q_\perp} - \phi_{\Delta_\perp}) F_\epsilon(|q_\perp|, |\Delta_\perp|) + \cdots .$$

- Non-trivial angular correlation between $\Delta_\perp$ and $q_\perp$ due to small-x dynamics.

Explicit expressions for gluon GPDs



$$
\begin{aligned}
&\frac{1}{P^+}\int \frac{d\zeta^-}{2\pi} e^{ixP^+\zeta^-} \langle p'|F^{+i}(-\zeta/2)F^{+j}(\zeta/2)|p\rangle \\
&= \frac{\delta^{ij}}{2} xH_g(x,\Delta_\perp) + \frac{xE_{Tg}(x,\Delta_\perp)}{2M^2}\left(\Delta_\perp^i\Delta_\perp^j - \frac{\delta^{ij}\Delta_\perp^2}{2}\right) + \cdots, \\
&\approx \frac{2N_c}{\alpha_s}\int d^2q_\perp \left(q_\perp^i - \frac{\Delta_\perp^i}{2}\right)\left(q_\perp^j + \frac{\Delta_\perp^j}{2}\right) F(q_\perp, \Delta_\perp)
\end{aligned}
$$

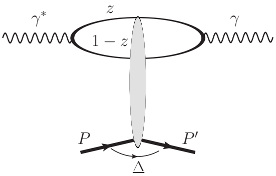
Comparing coefficients gives [Hatta, Xiao, Yuan, 17]

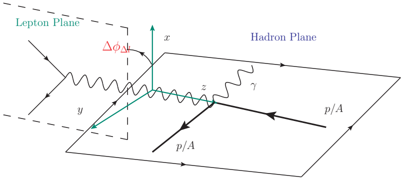
Helicity conserved: $xH_g(x,\Delta_\perp) = \dfrac{2N_c}{\alpha_s}\displaystyle\int d^2q_\perp q_\perp^2 F_0$

Helicity flipping: $xE_{Tg}(x,\Delta_\perp) = \dfrac{4N_cM^2}{\alpha_s\Delta_\perp^2}\displaystyle\int d^2q_\perp q_\perp^2 F_\epsilon$

Probing gluon GPD at small-x

DVCS[Hatta, Xiao, Yuan, 17] and DVMP [Mantysaari, Roy, Salazar, Schenke, 20]





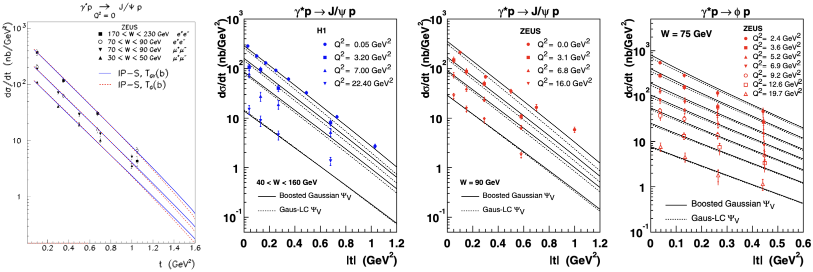
$$\frac{d\sigma_{TT}}{dx_B dQ^2 d^2\Delta_\perp} = \frac{\alpha_{em}^3}{\pi x_{Bj} Q^2}\left\{\left(1-y+\frac{y^2}{2}\right)(\mathcal{A}_0^2+\mathcal{A}_2^2)+(1-y)2\mathcal{A}_0\mathcal{A}_2\cos(2\phi_{\Delta l})\right\}$$

- $\mathcal{A}_0$: helicity conserved amplitude; $\mathcal{A}_2$: helicity-flip amplitude
- Use the lepton plane as a reference, one can measure angular correlations.
- $\cos 2\phi_{\Delta l}$ correlation is sensitive to the helicity-flip gluon GPD xE_{Tg}.

Helicity conserved: $xH_g(x,\Delta_\perp) = \dfrac{2N_c}{\alpha_s}\int d^2q_\perp q_\perp^2 F_0$

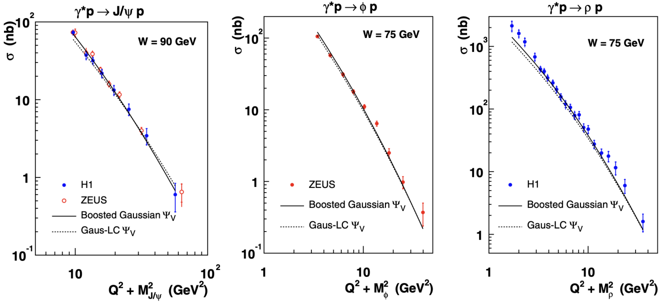
Helicity flipping: $xE_{Tg}(x,\Delta_\perp) = \dfrac{4N_c M^2}{\alpha_s \Delta_\perp^2}\int d^2q_\perp q_\perp^2 F_\epsilon$

Dipole model and HERA data



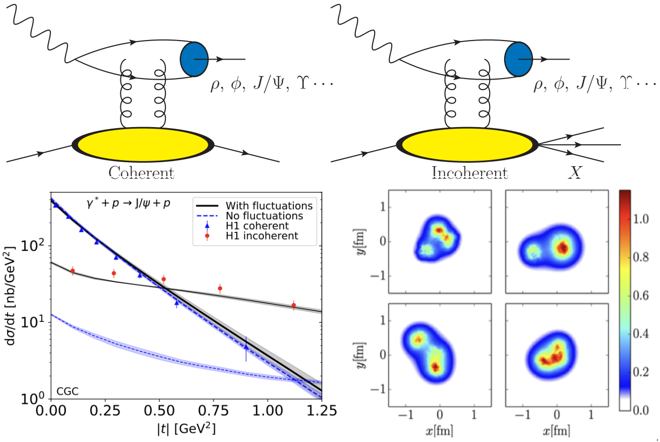
- [Kowalski, Teaney, 03; Kowalski, Motyka, Watt, 06]

Dipole model and HERA data



- [Kowalski, Motyka, Watt, 06]

Diffractive vector meson production

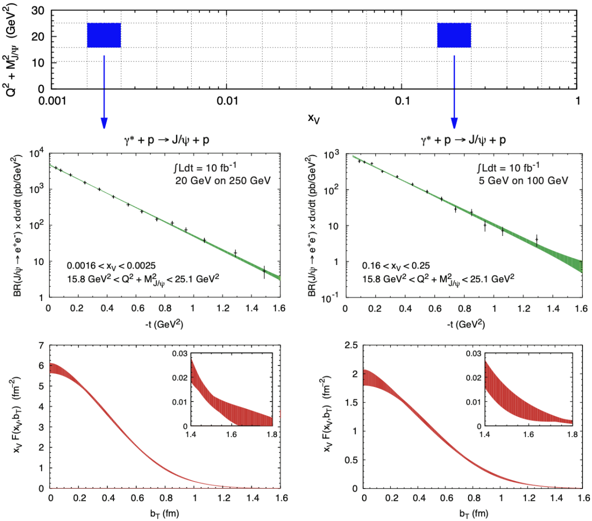


- Incoherent DVMP is sensitive to the proton fluctuating shape. (Variance) [Mantysaari, Schenke, 16; Mantysaari, Roy, Salazar, Schenke, 20]

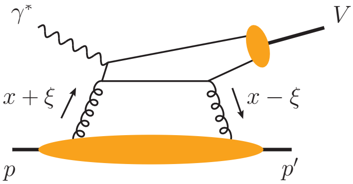
Good-Walker: measure of fluctuation $\frac{d\sigma_{\text{incoh}}}{d\hat{t}} \sim \langle|\mathcal{A}|^2\rangle - |\langle\mathcal{A}\rangle|^2$

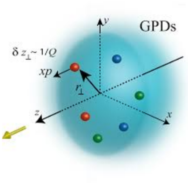
Spatial Imaging at EIC

- Ultimate goal: spatial distributions (via FT). [EIC white paper, 1212.1701]



Summary





- Gluon spatial imaging through DVMP.
- Probing non-trivial angular correlation and helicity-flip GPD.
- Study of fluctuations via incoherent diffractive productions.
- Another interesting topic: Heavy quarkonium near threshold and proton mass. [D. Kharzeev, 96; ...; Hatta, Yang, 18; Kou, Wang, Chen, 21; Guo, Ji, Liu, 21; Sun, Tong, Yuan, 21;...] Small-x picture no longer applies. Paradigm shift!