Connecting Observables with High-density / Saturation Phenomena

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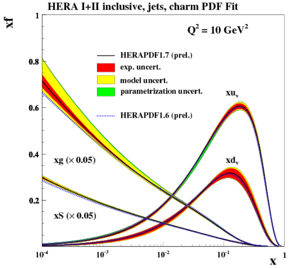
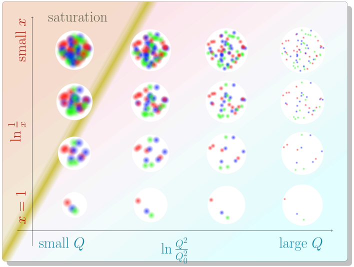
Saturation Physics (Color Glass Condensate)

QCD matter at extremely high gluon density





- Follow Larry's insights (Monday) on overview of high density gluons.
- Gluon density grows rapidly as x gets small.
- Many gluons with fixed size packed in a confined hadron, gluons overlap and recombine ⇒ Non-linear QCD dynamics (BK/JIMWLK) ⇒ saturation in gluon distributions (ultra-dense gluonic matter).
- Multiple Scattering (MV model) + Small-x (high energy) evolution

A Tale of Two Gluon Distributions

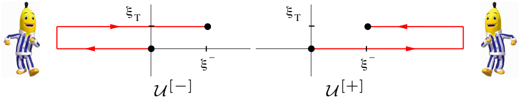
Two gauge invariant TMD operator def. [Bomhof, Mulders and Pijlman, 06] ▸ Link [Dominguez, Marquet, Xiao and Yuan, 11] ▸ Link

I. Weizsäcker Williams distribution: conventional density

$$xG_{\rm WW}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} {\rm Tr}\langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[+]\dagger}F^{+i}(0)\mathcal{U}^{[+]}|P\rangle.$$

II. Color Dipole gluon distributions:

$$xG_{\rm DP}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} {\rm Tr}\langle P|F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[-]\dagger}F^{+i}(0)\mathcal{U}^{[+]}|P\rangle.$$



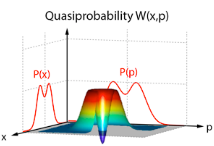
- Modified Universality for Gluon Distributions:

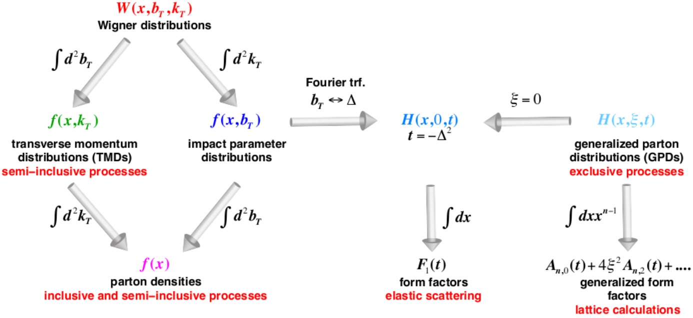
	Inclusive	Single Inc	DIS dijet	γ +jet	dijet in pA
$xG_{\rm WW}$	×	×	✓	×	✓
$xG_{\rm DP}$	✓	✓	×	✓	✓

✓ ⇒ Apppear. × ⇒ Do Not Appear.

Embedding small-x gluon in 3D Tomography

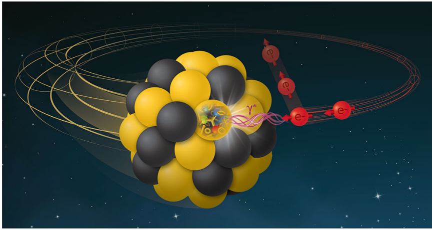
Wigner distributions [Belitsky, Ji, Yuan, 04] ingeniously encode all quantum information of how partons are distributed inside hadrons.





List of observables at EIC

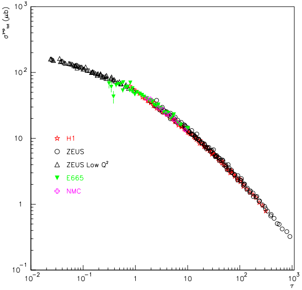
- CGC is elusive.
- Hunt it down via a set of observables
- List it from Inclusive $\rightarrow$ Exclusive.



1. Inclusive cross-section: Geometrical scaling in eA and Q_{sA}
2. Single-inclusive $\gamma + p/A \rightarrow h(\text{Jet}) + X$: Quark TMD
3. Inclusive dijet or dihadron: WW gluon TMD.
4. Long range correlation: Origin of collectivity
5. Diffractive vector meson production: gluon GPD.
6. Diffractive dijet production: gluon Wigner distribution.

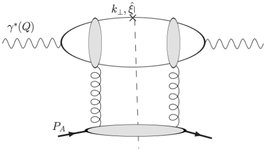
Inclusive Observables

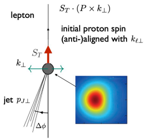
- Geometrical Scaling in DIS: All data of $\sigma_{tot}^{\gamma^* p}$ with $x \leq 0.01$ and $Q^2 \leq 450 GeV^2$ plotting as function of a single variable $\tau = Q^2/Q_s^2$ falls on a curve.
- What about eA collisions at EIC? $Q_{sA}^2(x)$



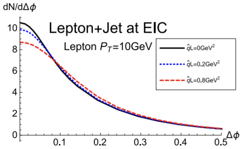
- [Golec-Biernat, Stasto, Kwiecinski,01]: $Q_s^2(x) = (x_0/x)^\lambda \mathrm{GeV}^2$ with $x_0 = 3.04 \times 10^{-3}$ and $\lambda = 0.288$.
- [Munier, Peschanski, 03; etc]: explained by small-x framework.
- [Kovchegov, Pitonyak, Sievert, 16, 17] Link Polarized case: g_1 structure function at small-x and $\Delta\Sigma$.

SIDIS and new progress





Electron-jet corretions



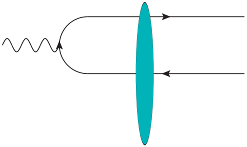
- [Mueller, 99; Marquet, Xiao, Yuan, 09] SIDIS in the Breit frame: Measure quark k_T distribution.
- [Liu, Ringer, Vogelsang, Yuan,19] Link Lepton + jet

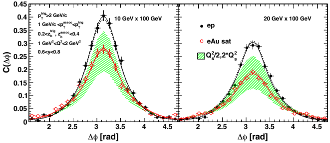
New hard probe in the Lab frame: $l + p/A \rightarrow l' + \text{Jet} + X$

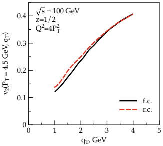
- Direct probe of quark TMDs. $\Delta\phi = \phi_J - \phi_l - \pi$
- Sivers: distortion due to proton's transverse spin S_T!
- Also sensitive to cold nuclear medium P_T broadening!

DIS dijet

Unique golden channel for the Weizsäcker Williams distribution.

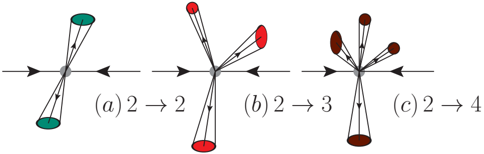






- Back-to-back correlation $C(\Delta\phi)$: [Dominguez, Marquet, Xiao and Yuan, 11] [Zheng, Aschenauer, Lee and BX, 14] ▸ Link
- Due to soft gluon radiations, Sudakov resummation needs to be implemented. [Mueller, Xiao, Yuan, 13] ▸ Link
- Due to linearly polarized gluon[Metz, Zhou, 11] ▸ Link: analog of elliptic flow v_2 in DIS. [Dumitru, Lappi, Skokov, 15] ▸ Link

Perturbative expansions in dijet productions



Correlations:

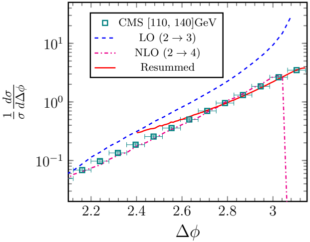
- 2 → 2: 0th order
- 2 → 3: leading order
- 2 → 4: next-to-leading order

$$\sigma_0 \sum_{i=0}^{\infty} \alpha_s^i \left(L^i + C^{(i)} \right)$$ ideal QCD expansion

$$\sigma_0 \sum_{i=0}^{n-1} \alpha_s^i L^i \quad \Big| \quad \sigma_0 \sum_{i=0}^{n-1} \alpha_s^i C^{(i)}$$ ⇐ pQCD

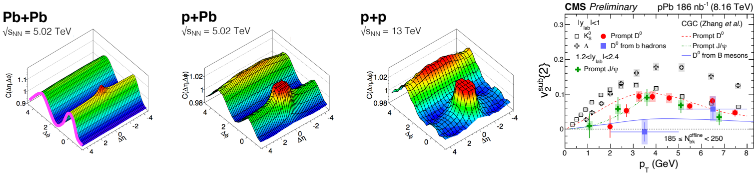
$$\sigma_0 \sum_{i=n}^{\infty} \alpha_s^i L^i \quad \Big| \quad \sigma_0 \sum_{i=n}^{\infty} \alpha_s^i C^{(i)}$$

⇑ resummation ↖ negligible



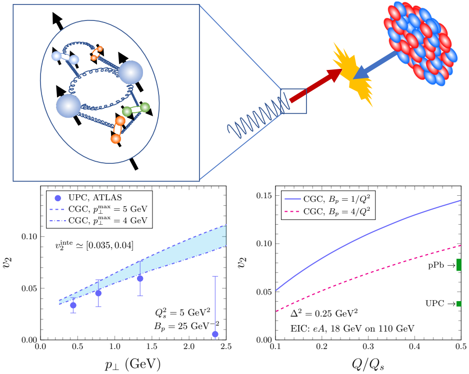
- pQCD expansion breaks down in the back-to-back region.
- Appearance of large logarithms $L \sim \ln^2 \frac{P_\perp^2}{q_\perp^2}$ with $P_\perp \gg q_\perp$.
- Imbalance $\vec{q}_\perp \equiv \vec{p}_{1\perp} + \vec{p}_{2\perp}$, jet $P_\perp \sim p_{1\perp} \sim p_{2\perp}$.

Collectivity at EIC?



- Collectivity is everywhere in systems small and large!
- Final state vs Initial state interpretation. Not clear yet!
- Anisotropy of heavy mesons favors IS effect.
  [Zhang, Marquet, Qin, Wei, Xiao, 19] Link
- New results from UPC in PbPb collisions at LHC. (Mini-EIC)
- What about the collectivity at the EIC on the horizon?

v_2 Predictions in γA collisions from CGC

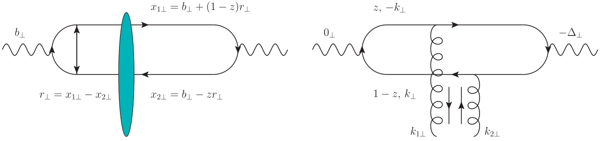


[Shi, Wang, Wei, Xiao, Zheng, 21] Link

- Photons can have a rich QCD structure due to fluctuation.
- Similarity between $\gamma^* A$ and pA collisions at high energy as far as high multiplicity events are concerned.

Explicit expressions for gluon GPDs

Small-x GPDs[Hatta, Xiao, Yuan, 17] Link $F = F_0 + 2\cos 2\Delta\phi\, F_\epsilon$

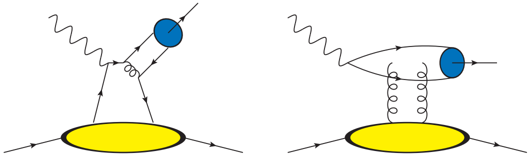


$$\frac{1}{P^+}\int \frac{d\zeta^-}{2\pi} e^{ixP^+\zeta^-}\langle p'|F^{+i}(-\zeta/2)F^{+j}(\zeta/2)|p\rangle$$
$$= \frac{\delta^{ij}}{2} xH_g(x,\Delta_\perp) + \frac{xE_{Tg}(x,\Delta_\perp)}{2M^2}\left(\Delta_\perp^i\Delta_\perp^j - \frac{\delta^{ij}\Delta_\perp^2}{2}\right) + \cdots,$$

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

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

Gluon GPDs and DVMP $V = J/\Psi, \phi \cdots$

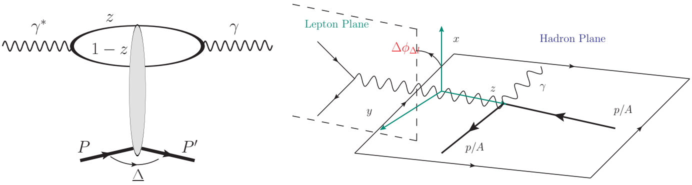


$$\gamma^*(q) + p/A(p) \to V(q - \Delta) + p/A(p + \Delta)$$

- The latter diagram is dominant at small-x (high energy) limit.
- Widely studied[Brodsky, Frankfurt, Gunion, Mueller, Strikman, 94; Kowalski, Teaney, 03; Kowalski, Motyka, Watt, 06; 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; Lappi, Mantysaari, Schenke, 16]...;
- NLO[Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon, 16] Link

Probing gluon GPD at small-x

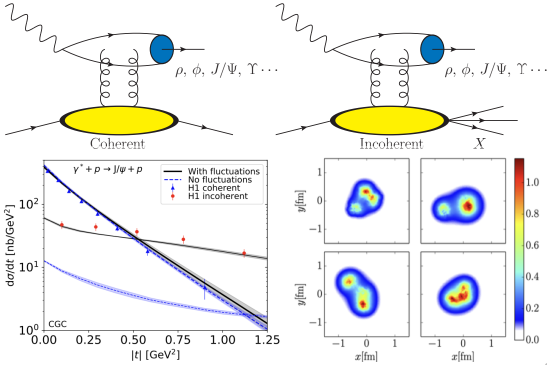
DVCS and DVMP [Mantysaari, Roy, Salazar, Schenke, 20] Link



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

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

Diffractive vector meson production

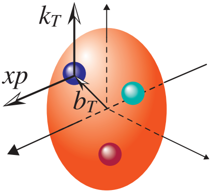


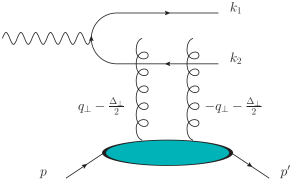
- Sensitive to proton fluctuating shape. (Variance) [Mantysaari, Schenke, 16; Mantysaari, Roy, Salazar, Schenke, 20]
- Good-Walker: measure of fluct. $\frac{d\sigma_{\text{incoh}}}{d\hat{t}} \sim \langle|\mathcal{A}|^2\rangle - |\langle\mathcal{A}\rangle|^2$

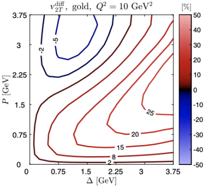
Can we measure Wigner distributions?

- Can we measure Wigner distribution/GTMD? Yes, we can!
- Diffractive back-to-back dijets in *ep*/*eA* collisions. [Hatta, Xiao, Yuan, 16] Link
- Further predictions of asymmetries due to correlations.

$$
\begin{aligned}
xW_g^T(x, \vec{q}_\perp; \vec{b}_\perp) &= x\mathcal{W}_g^T \quad \text{Symmetric part} \\
&+ 2\cos(2\phi)x\mathcal{W}_g^\epsilon + \cdots \quad \text{Anisotropies}
\end{aligned}
$$



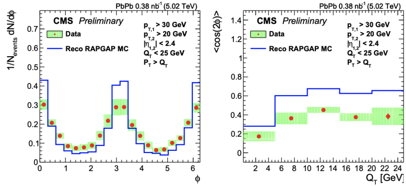


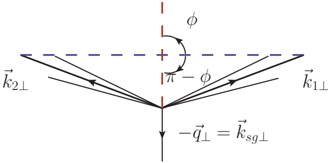


- Study of the elliptic anisotropy.[Mäntysaari, Mueller, Salazar and Schenke, 20] Link

CMS: Dijet photoproduction in UPC (PbPb)

$$\gamma + \text{Pb} \to \text{Jet} + \text{Jet} + \text{Pb}$$

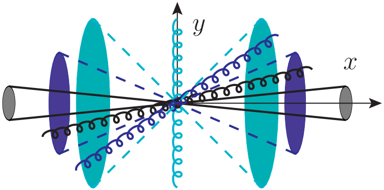


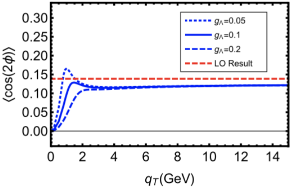


1. Preliminary analysis ▸ Link [CMS-PAS-HIN-18-011]
2. Large asymmetries observed!
3. Indicate additional sources ?

Asymmtries due to final state gluon radiations are important. [Hatta, Xiao, Yuan, Zhou, 21] ▸ Link

Contributions from final state gluon radiations



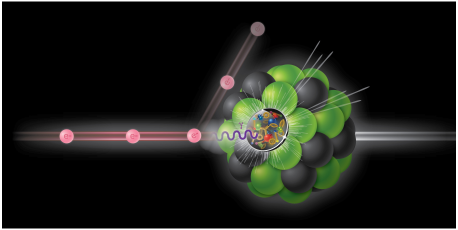


Consider soft gluon radiations near jet cone in $\gamma A/p \to q\bar{q} + A/p$

$$g^2 \int \frac{d^3 k_g}{(2\pi)^3 2E_{k_g}} \delta^{(2)}(q_\perp + k_{g\perp}) C_F \frac{2k_1 \cdot k_2}{k_1 \cdot k_g k_2 \cdot k_g}$$
$$= \frac{C_F \alpha_s}{\pi^2 q_\perp^2} \left[c_0^{\text{diff}} + 2\cos(2\phi)\, c_2^{\text{diff}} + \ldots \right].$$
$$c_0^{\text{diff}} = \ln \frac{a_0}{R^2}\,, \qquad\qquad c_2^{\text{diff}} = \ln \frac{a_2}{R^2}\,.$$

Observed asymmetry should includes initial and final state contributions!

Summary



- EIC will be the First eA collider.
- There is a wide range of observables at EIC for small-x physics.
- Inclusive process $\rightarrow$ Exclusive process: more information, however, more demanding and challenging in theory and exp.
- EIC will provide us data with unprecedented precision, and possibly compelling evidences for gluon saturation (CGC).