What will the EIC program teach us about heavy ion physics? What will the EIC program learn from heavy ion physics?

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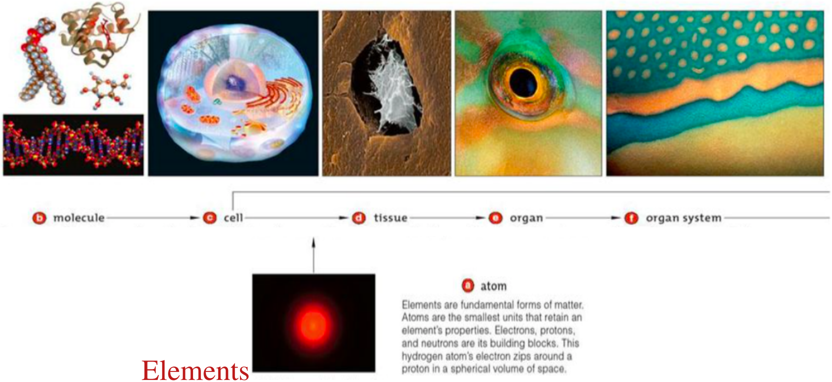
Life is an Emergent Property

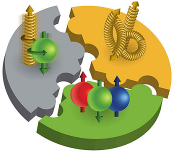
The philosophical concept of “emergent properties": Understanding the individual parts alone is insufficient to understand or predict system behavior. Thus, emergent properties necessarily come from the interactions of the parts of the larger system.

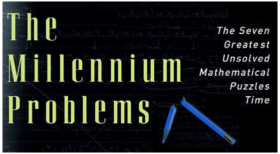
Systems

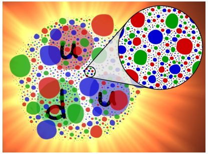


Elements

Emergent Phenomena in QCD







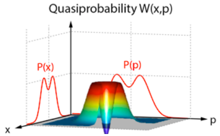
- How does the spin of proton arise from quarks and gluons? (Spin puzzle)
- What are the emergent properties of dense gluon system?
- How does proton mass arise? Mass gap: million dollar question.
- How does gluon bind quarks and gluons inside proton?
- We need the 3D information of the quark and gluon inside the proton!

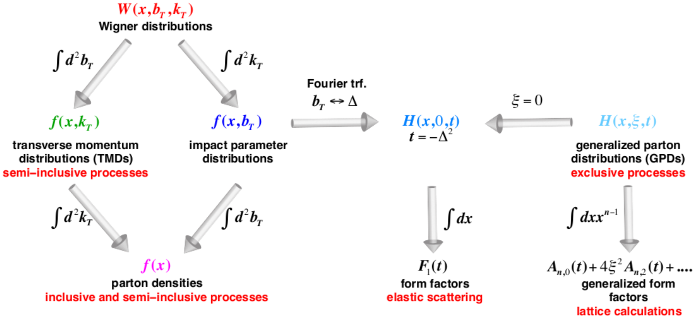
EIC: keys to unlocking these mysteries! Many opportunities are in front of us!

3D Tomography of Proton

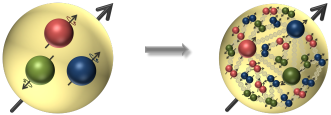
[Marquet, IS2023]

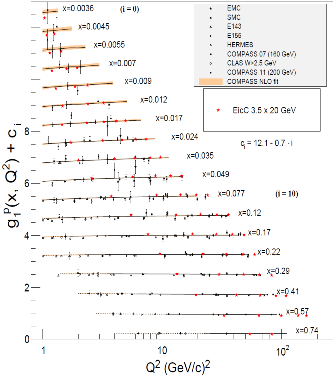
Wigner distributions [Belitsky, Ji, Yuan, 04] ingeniously encode all quantum information of how partons are distributed inside hadrons.





Understanding Nucleon Spin





Jaffe-Manohar decomposition

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{\text{Quark}} + \underbrace{\Delta G + L_g}_{\text{Gluon}}$$

- Quark spin $\Delta\Sigma$ is only 30% of proton spin.
- $g_1(x, Q^2) = \frac{1}{2}\sum e_q^2 \left[\Delta q + \Delta\bar{q}\right]$
- The rest of the proton spin must come from the gluon spin ΔG, quark and gluon OAM $L_{q,g}$.
- Orbital motions of quark and gluon are essential. Need $b_\perp \times k_\perp$!

Understanding Proton Mass

Mass decomposition [Ji, 95]

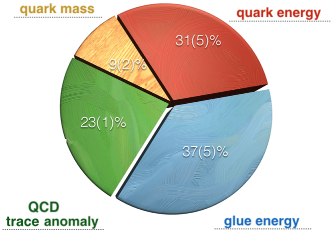
$$M = \underbrace{M_q + M_m}_{\text{Quark}} + \underbrace{M_g + M_a}_{\text{Gluon}}$$

M_q : quark energy

M_m : quark mass (condensate)

M_g : gluon energy

M_a : trace anomaly



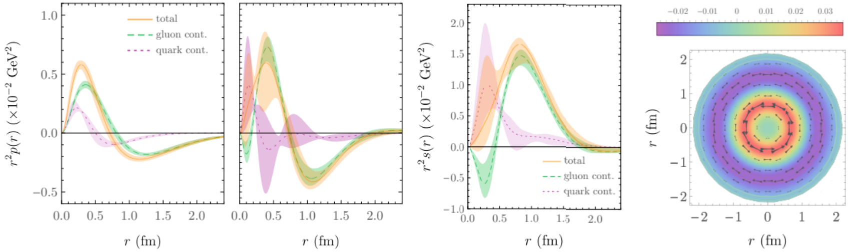
[χQCD, Yang, *et al*, 18]

- Understand and measure each contribution.
- Study the pressure and shear in the energy momentum tensor.

Pressure and Shear forces inside proton

[Shanahan, Delmold, 19] Link

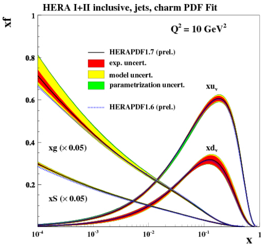
$$T^{ij}(r) = \left(\frac{r^i r^i}{r^2} - \frac{1}{3}\delta^{ij}\right) s(r) + \delta^{ij} p(r)$$

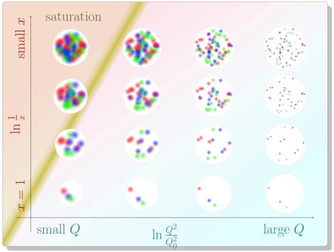


- The spatial of static EMT define the stress tensor. It can be decomposed in a traceless part associated with shear forces $s(r)$ and a trace associated with the pressure $p(r)$.
- $s(r)$ and $p(r)$ are computed in LQCD recently.

Saturation Physics (Color Glass Condensate)

Describe Emergent Phenomenon of the ultra-dense QCD cold matter.

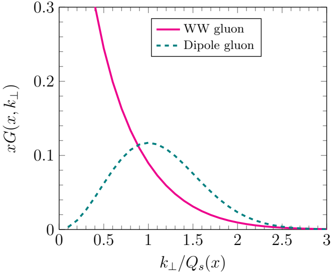




- Gluon density grows rapidly as x gets small. BFKL evolution!
- Resummation of the $\alpha_s \ln \frac{1}{x} \Rightarrow$ BFKL equation.
- Many gluons with fixed size packed in a confined hadron, gluons overlap and recombine $\Rightarrow$ Non-linear QCD dynamics (BK/JIMWLK) $\Rightarrow$ ultra-dense gluonic matter
- Saturation = Multiple Scattering (MV model) + Small-x (high energy) evolution

A Tale of Two Gluon Distributions[1]

In small-x physics, there are two gluon distributions:[Kharzeev, Kovchegov, Tuchin; 03]
I. Weizsäcker Williams gluon distribution([Kovchegov, Mueller, 98] and MV model)
II. Color Dipole gluon distributions: (known for many years)



- In MV model, these two gluon distributions are different.
- Same perturbative tail when $k_\perp \gg Q_s$.
  "A Tale of Two Gluon Distributions" $\Rightarrow$
  "A Tail of Two Gluon Distributions" [B. Zajc]
- Which gluon distribution to use in a given process?
- Why are there exactly two gluon distributions?
  Generalized Universality

[1] From Y. Kovchegov and C. Dickens.

A Tale of Two Gluon Distributions

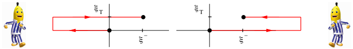
Two gauge invariant gluon definitions: [Dominguez, Marquet, Xiao and Yuan, 11]

I. Weizsäcker Williams gluon distribution: conventional gluon distributions

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

II. Color Dipole gluon distributions: not probability density

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



$\mathcal{U}^{[-]}$ $\mathcal{U}^{[+]}$

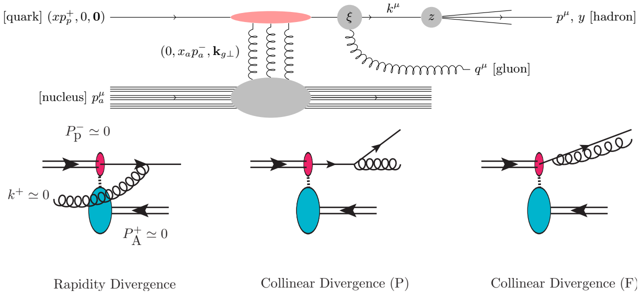
Generalized Universality for Gluon Distributions: $\times \Rightarrow$ Do Not Appear. $\surd \Rightarrow$ Apppear.

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

Form CGC perspective, Complementary physics missions in pA and eA collisions.

Single inclusive hadron productions in pA collisions

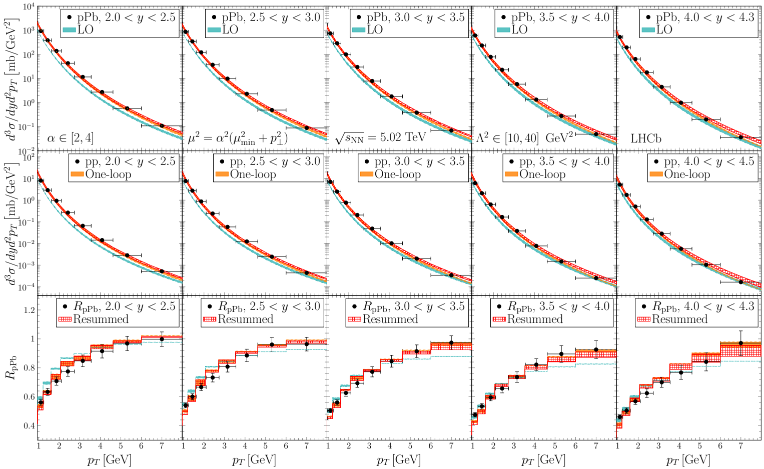
$p + A \to H + X$ [Chirilli, BX and Yuan, 12] (Ten-year effort) [Altinoluk, IS2023]



- Factorization: 1. collinear to target nucleus; rapidity divergence $\Rightarrow$ BK evolution for UGD $\mathcal{F}(k_\perp)$;2. collinear to the initial quark; $\Rightarrow$ DGLAP evolution for PDF; 3. collinear to the final quark. $\Rightarrow$ DGLAP evolution for FFs.
- Kinematic constraint: Subtraction proper amount of logarithms before taking $s \to \infty$.
- Resummation of additional threshold/Sudakov logarithms.

NLO Single Hadron Productions in pA collisions

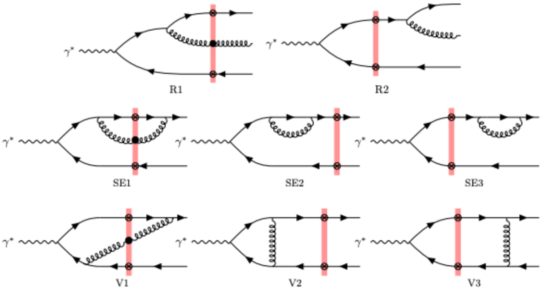
[Shi, Wang, Wei, Xiao, 21] ‣ 2112.06975 [hep-ph] [LHCb: 2108.13115]



- Sudakov/Threshold resummation help stabilize NLO.
- Precision test needs reliable NLO calculation from CGC.
- Proof of concept for NLO predictive power.
- Agreement with forward LHCb data.
- Rapidity evolution of R_{pPb}.

NLO DIS dijets

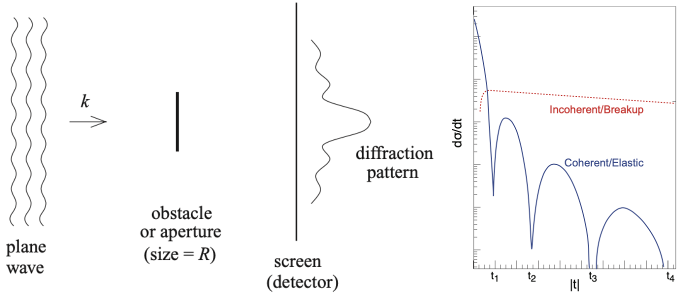
[Caucal, Salazar, Schenke, Stebel and Venugopalan, 2304.03304]
see also [Taels, Altinoluk, Beuf and Marquet, 2204.11650]



- Proved factorization at one-loop.
- Resummation of small-x and Sudakov logarithms.
- Provide more reliable predictions for measurements at future EIC.

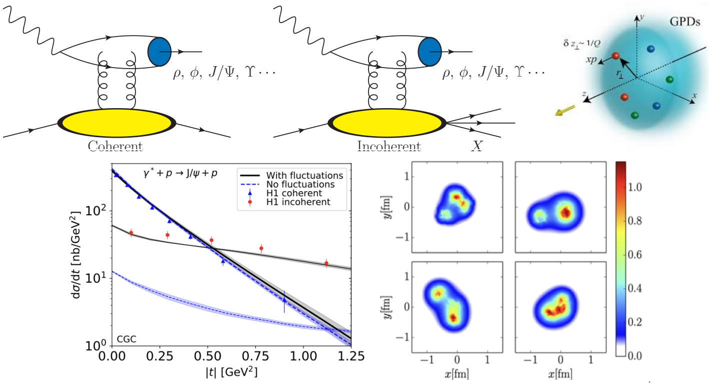
An analogy to Fraunhofer Diffraction in Optics

[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.
- Use diffractive scattering to study gluon spatial distribution.

Diffractive vector meson production

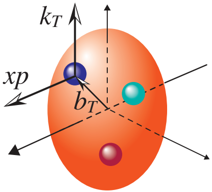


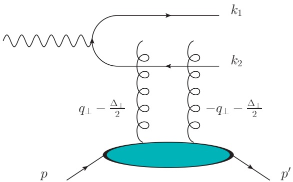
- Incoherent DVMP is sensitive to the proton fluctuating shape. (Vital for understanding flow)[Mantysaari, Schenke, 16; Mantysaari, Roy, Salazar, Schenke, 20]

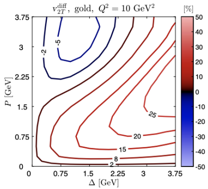
Can we measure Wigner distributions?

- 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.

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



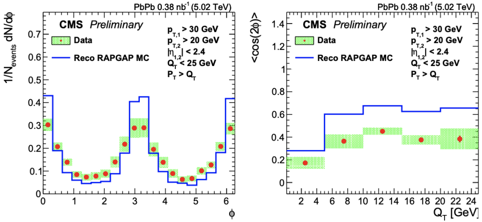


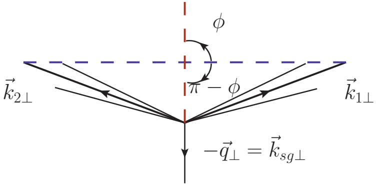


- Study of the elliptic anisotropy.[Mäntysaari, Mueller, Salazar and Schenke, 20] Link

CMS: Dijet photoproduction in UPC (PbPb)

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



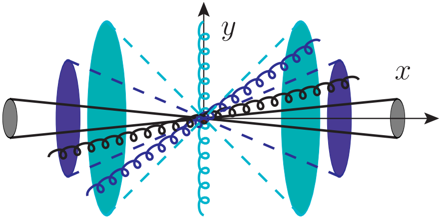


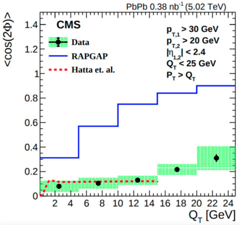
1. Preliminary analysis ▸ Link [CMS-PAS-HIN-18-011]
2. Large asymmetries between momentum sum $q_\perp = \vec{k}_{1\perp} + \vec{k}_{2\perp}$ and difference $\vec{k}_{1\perp} - \vec{k}_{2\perp}$ observed!
3. Indication of additional sources ?

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

Contributions from final state gluon radiations

[Hatta, Xiao, Yuan, Zhou, 21] ▸ Link





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

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

$$c_0^{\rm diff} = \ln \frac{a_0}{R^2}\,, \qquad c_2^{\rm diff} = \ln \frac{a_2}{R^2}\,.$$

Harmonics of Parton Saturation in Lepton-Jet Correlations at EIC

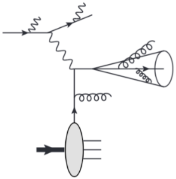
[Tong, Xiao, Zhang, 23] ‣ Link

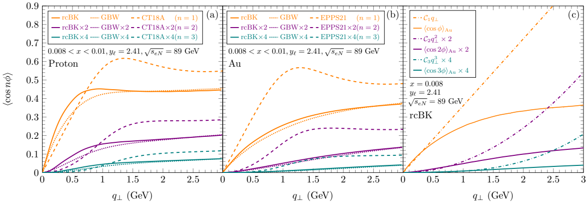
Use Fouier Harmonics to analyze and probe saturation effects.

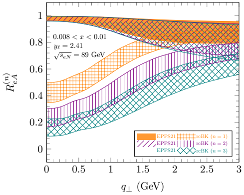
$$\frac{d^5\sigma(\ell P \to \ell' J)}{dy_\ell d^2P_\perp d^2q_\perp} = \sigma_0 \int \frac{b_\perp db_\perp}{2\pi} \sum_q e_q^2 x f_q(x, b_\perp) e^{-\mathrm{Sud}_P}$$

$$\left[J_0(q_\perp b_\perp) + \sum_{n=1}^{\infty} 2\cos(n\phi)\alpha_s \frac{C_F c_n(R)}{n\pi} J_n(q_\perp b_\perp)\right],$$

$$R_{eA}^{(n)} = \frac{\langle \cos n\phi \rangle_{eA}}{\langle \cos n\phi \rangle_{ep}}$$



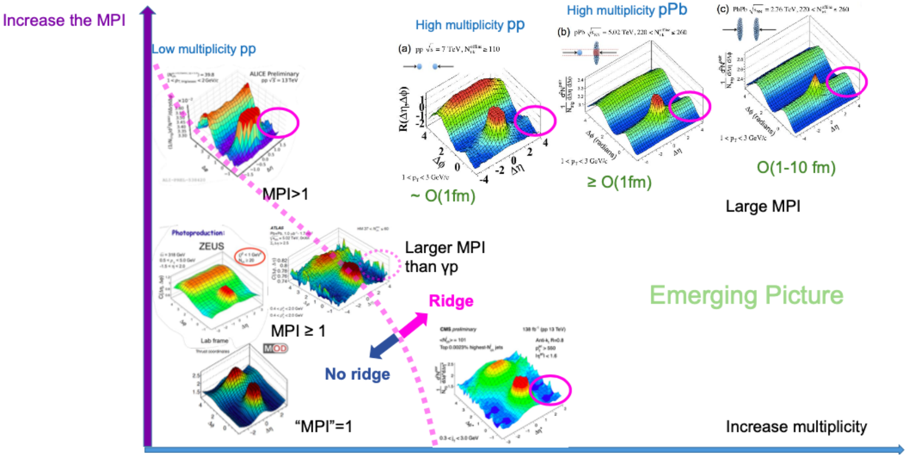




- Significant nuclear modification of the asymmetries ⇒ compelling evidence for saturation.

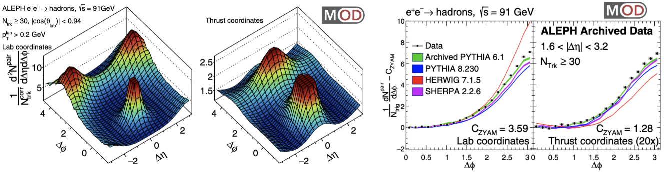
Origin of Collectivity

[Yen-Jie Lee, IS2023]: both MPI and High Multiplicity are needed



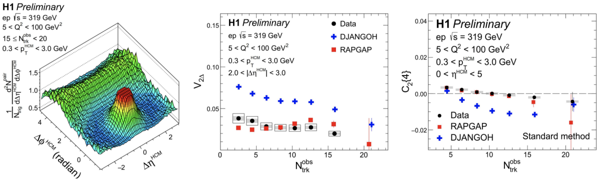
Search for collectivity in e^+e^- at LEP and in DIS at HERA

Two-Particle Correlations in e^+e^- with ALEPH data[Badea *et al*, 19] ▸ Link



- No significant long-range correlations is observed. ([ALEPH$e^+e^- \to W^+W^-$]?)

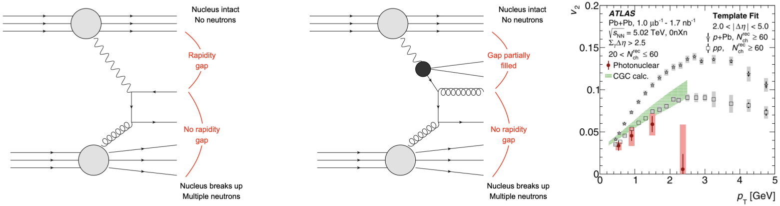
Search for collectivity at HERA [H1 Collaboration, IS2021] ▸ Link



- No collectivity observed at HERA. Data agree with RAPGAP. $Q^2 > 5\mathrm{GeV}^2$

Collectivity at EIC?

Two-particle correlations in photonuclear (Pb+Pb) UPC by ATLAS ▸ Link

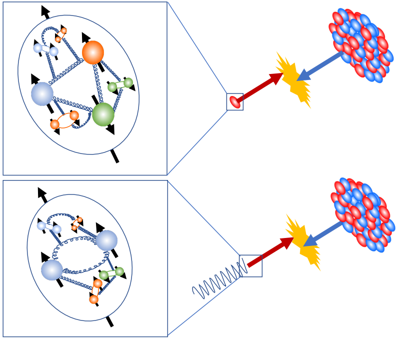


- Results for UPC in PbPb collisions. (Mini-EIC)
- WW equivalent photon approximation: Small virtuality, like a plane wave.
- Photons with energy up to 80 GeV at the LHC + the high-energy nuclei.
- What about predictions for the collectivity at the EIC on the horizon?

The Structure of Photons

Photons can have a very rich QCD structure

$$|\gamma\rangle = |\gamma_0\rangle + \sum_{m,n} |m\, q\bar{q} + n\, g\rangle + \sum_{\rho,\omega,\cdots} |V\rangle + \cdots ,$$



- Point like (high Q^2)
- Partonic
- VMD [Sakurai, 60]

Strong similarity between $\gamma^* A$ and pA collisions when γ^* has a long lifetime.

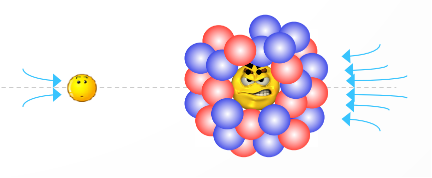
$$t_{\text{lifetime}} \sim \frac{1}{q^-} = \frac{q^+}{Q^2} \gg \frac{m_p}{P^-} R \quad \Rightarrow \quad x_B \ll \frac{1}{m_p R}$$

Comment: Collectivity in $\gamma^* A$ collisions regardless the underlying interpretation.

Collectivity in high multiplicity events in pA ($\gamma^* A$) collisions

Qualitative understanding of high multiplicity events and correlation.

- Fluctuation in parton density
- Many active partons
- Correlated multiple scatterings

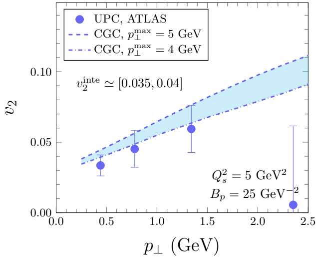


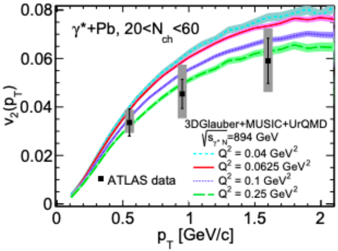
A CGC model for correlation based on the above three assumptions

- Let us pick two initially uncorrelated collinear partons (say $q + q$) from proton, and consider their interactions with the target nucleus.
- Correlation can be generated between them due to multiple interaction.
- Due to Unitarity, the un-observed partons do not affect the correlation of the system.

v_2 results in $\gamma^* A$ collisions from CGC and Hydro

[Shi, Wang, Wei, Xiao, Zheng, 21] ▸ Link [Zhao, Shen, Schenke, 22] ▸ Link





- Both agree with ATLAS UPC data ▸ Link
- Partonic structure VS vector meson.
- The future EIC may help to unravel the origin of the collectivity in general!
- Selecting different Q^2 and y bins $\Rightarrow$ handles to change system size and energy.
- High multiplicity events in ep collisions at HERA vs eA at EIC.

Summary

- Yet, many questions remained unanswered in QCD!
- Spin, Mass, Dense gluonic matter and 3D imaging, origin of collectivity, etc.
- Cutting-edge EIC will provide us 3D image of protons and heavy nuclei with unprecedented precision, and bring us new insights.
- Synergy of EIC and Heavy Ion Physics is important for us to find answers to these questions.