Diffractive Vector Meson and Dijet production from CGC at EIC

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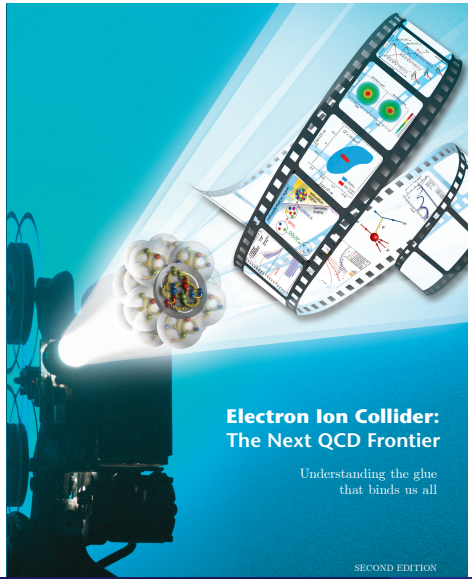
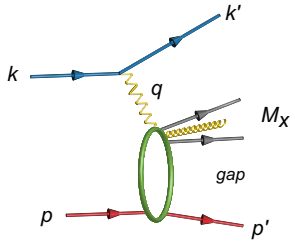
Diffraction and the EIC microscope



Production of meson / dijet with a rapidity gap

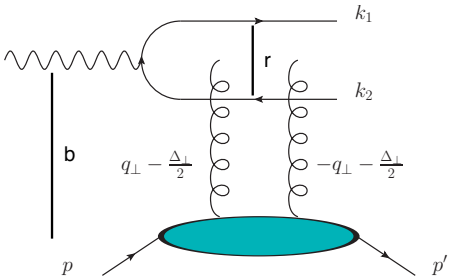


Advantages of diffraction

- (At least) 2-gluon exchange $\Rightarrow$ sensitivity
- Measure t $\Rightarrow$ access to geometry

This talk: physics at small x (and small[ish] $|t|$)

Diffraction at high energy



$$\mathcal{A}^{\gamma^* p \to J/\Psi p} \sim \int \mathrm{d}^2 r \mathrm{d}^2 b e^{ib\cdot\Delta} \Psi^* \Psi(r) N(r, b, x_p)$$

High energy factorization

1. $\gamma \to q + \bar{q}$ (photon wave function Ψ)
2. Dipole-target interaction (dipole amplitude N)
3. $q + \bar{q} \to J/\Psi, \rho, \ldots$ (J/Ψ wave function) or $q + \bar{q} \to$ dijet

Target remains intact (Good-Walker picture)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} \sim |\langle \mathcal{A} \rangle|^2$$

Note: $N \sim xg$, so $\sigma \sim$ gluon^2
+ access to geometry: $t \leftrightarrow b$ Fourier transform

Advantage of CGC: unified framework to describe inclusive and diffractive scattering

Incoherent diffraction = target dissociation

Incoherent cross section

- Target final state $|f\rangle \neq$ initial state $|i\rangle$
- Rapidity gap between J/Ψ and target remnants

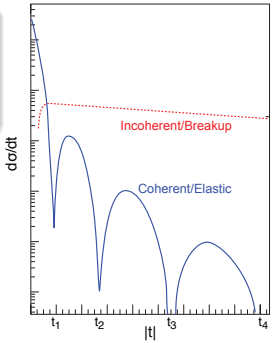
$$\sigma_{\text{incoherent}} \sim \sum_{f \neq i} |\langle f|\mathcal{A}|i\rangle|^2$$
$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$$

Average over initial states:

$$\sigma_{\text{incoherent}} \sim \langle|\mathcal{A}|^2\rangle_\Omega - |\langle\mathcal{A}\rangle_\Omega|^2$$

Incoherent cross section = variance of $\mathcal{A}^{\gamma^* A \to VA}$

- Measures the amount of event-by-event fluctuations in target configurations Ω



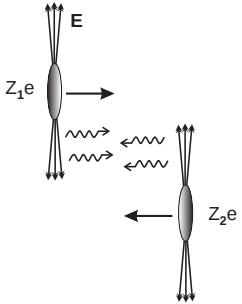
Miettinen, Pumplin, PRD 18, 1978, Caldwell, Kowalski, Phys.Rev. C81 (2010) 025203

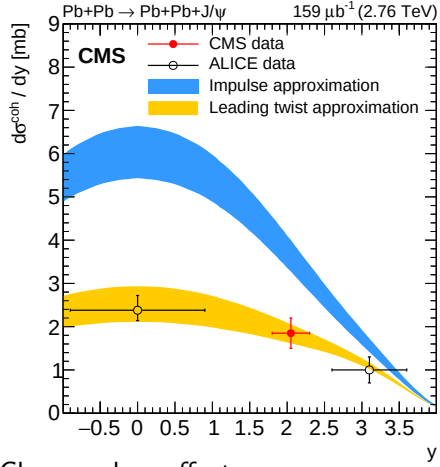
Experimental separation: intact/dissociated proton/nucleus?

Applications of J/Ψ production 1: saturation (coherent photoproduction)

- Enhance saturation effects:
  $Q^2_{s,A} \sim A^{1/3} x^{-\lambda}$
  (increasing A cheaper than decreasing x)
- Varying A at the EIC $\Rightarrow$ different Q^2_s

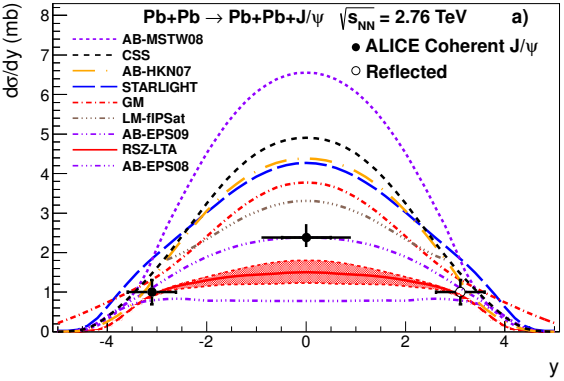
Already data from UPCs ($x \sim e^{-} y/\sqrt{s}$)





Clear nuclear effects:
impulse approximation = scaled $\gamma + p$

Coherent diffraction, model comparison

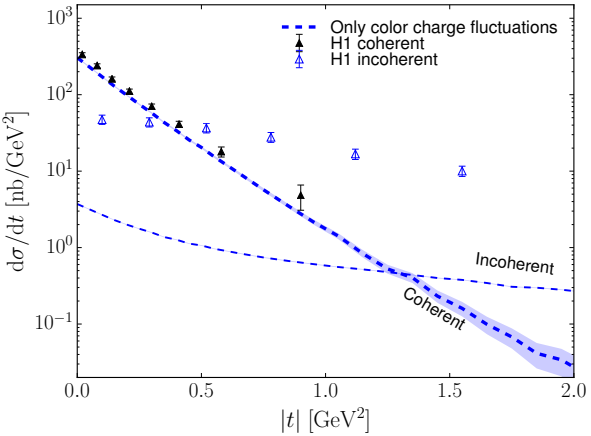


ALICE, 1305.1467

- nPDF (e.g. AB-EPS09) and saturation (LM-fIPsat) compatible
- Trivial $\gamma p \to \gamma A$ scaling clearly ruled out (AB-MSTW08)
- LHC UPC:
  - Limited to $Q^2 = 0$
  - No t spectra available (yet?)
  - Coherent-incoherent separation difficult

Applications of J/Ψ production 2: proton shape

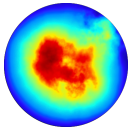
HERA data with only color charge fluctuations ($x \sim 10^{-3}$)



Recall

- Coherent $\sim$ average
- Incoherent $\sim$ fluct (variance)

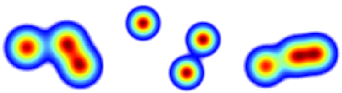
Round CGC proton:
Color charges +Yang-Mills



H.M, B. Schenke, 1607.01711, H1: 1304.5162

Constraining proton fluctuations

Simple constituent quark inspired picture:



- Sample quark positions from a Gaussian distribution (width B_{qc})
- Small-x gluons are located around the valence quarks (width B_q).
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations

Proton = 3 overalpping hot spots

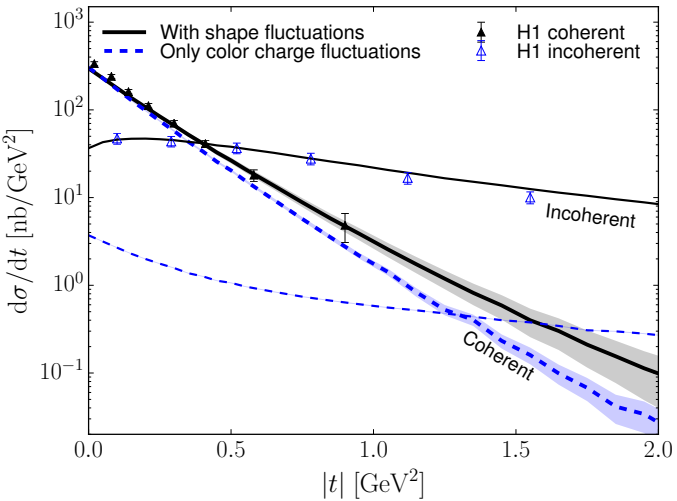
$$T_{\text{proton}}(b) = \sum_{i=1}^{3} T_q(b - b_i) \qquad T_q(b) \sim e^{-b^2/(2B_q)}$$

+ density fluctuations for each hot spot

H.M, Schenke, 1607.01711, 1603.04349, also more complicated geometries

Similar setup e.g. in Bendova, Cepila, Contreras; Cepila, Contreras, Krelina, Takaki; Traini, Blaizot

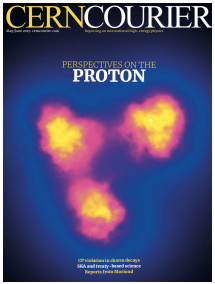
Constraining proton fluctuations: $\gamma + p \to J/\Psi + p$



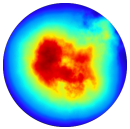
HERA data requires large event-by-event fluctuations

H.M, B. Schenke, 1607.01711

Fluctuations



Round



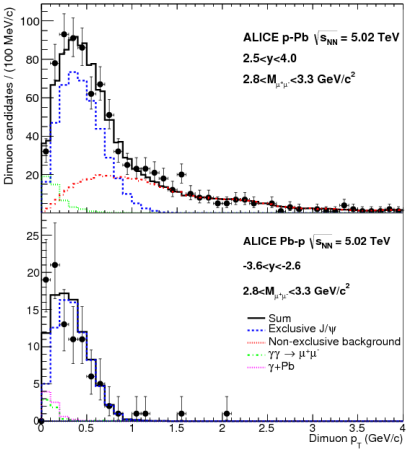
Energy dependence

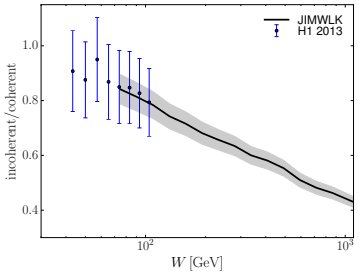
ALICE measurement in $\gamma + p \to J/\Psi + p(p^*)$ collisions (p+Pb UPC)

$x \sim 10^{-2} \to 2 \cdot 10^{-5}$

- Incoherent cross section ≈ 0 at small x
- Smoother proton (black disk) at small x?

(Qualitatively) compatible with CGC evolution



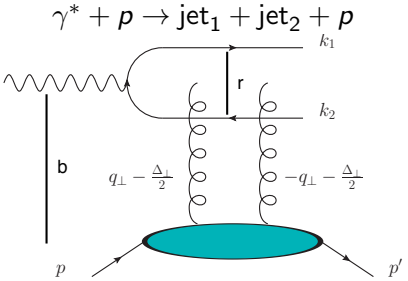


ALICE arXiv:1406.7819, 1809.03235

H. M, B: Schenke, 1806.06783, also Cepila et al, 1608.07559

Diffractive dijets: more differential imaging

Two momenta, extra handle



Y. Hatta, B-W. Xiao, F. Yuan, 1601.01585

$\mathrm{d}\sigma \sim v_0(1 + 2v_2 \cos[2\theta(\mathbf{P}, \mathbf{\Delta})])$

- $\mathbf{\Delta} = \mathbf{k}_1 + \mathbf{k}_2$ recoil momentum
- $\mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$ dijet momentum
- Nearly back-to-back jets, $|\mathbf{P}| > |\mathbf{\Delta}|$

Hatta, Xiao, Yuan, 1601.01585
Hagiwara *et al*, 1706.01765
v_2 in principle connected to elliptic part of gluon Wigner distribution in certain limit ($Q^2 \to 0$, $|\mathbf{P}| \gg |\mathbf{\Delta}|$), in practice complicated

H. M, N. Mueller, B. Schenke, 1902.05087:
CGC calculation of dijet cross section and Wigner

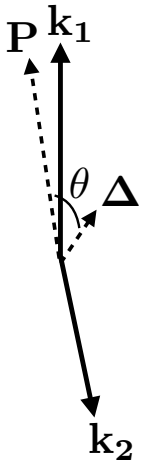
Kinematics

EIC kinematics used here

- $Q^2 = 1\text{GeV}^2$
- $W = 100\text{GeV}$
- $|\mathbf{P}| = 1 \ldots 3\text{GeV}$ ("mean jet p_T")
- $|\mathbf{\Delta}| = 0.1\text{GeV}$ (recoil)
- $m_c = 1.4\text{GeV}$ (charm jets, avoid large dipoles)
- Longitudinal momentum fraction $z \in [0.1, 0.9]$

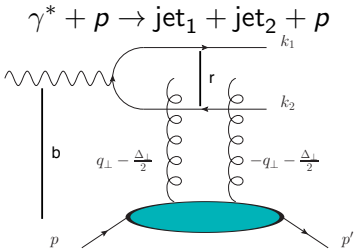
Fourier expansion in terms of $\theta(\mathbf{P}, \mathbf{\Delta})$:

Note: one may have $v_1 \neq 0$, depending on kinematics (backup!)



$$\mathbf{\Delta} = \mathbf{k}_1 + \mathbf{k}_2, \mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$$

CGC calculation for dijet production



Y. Hatta, B-W. Xiao, F. Yuan, 1601.01585

$$\mathrm{d}\sigma \sim v_0(1 + 2v_2 \cos[2\theta(\mathbf{P}, \mathbf{\Delta})])$$

- $\mathbf{\Delta} = \mathbf{k}_1 + \mathbf{k}_2$
- $\mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$

Altinoluk, Armesto, Beuf, Rezaeian, 1511.07452

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathbf{P}\mathrm{d}\mathbf{\Delta}} \sim \int_{\mathbf{b}\,\mathbf{b}'\,\mathbf{r}\,\mathbf{r}'} e^{-i(\mathbf{b}-\mathbf{b}')\cdot\mathbf{\Delta}} e^{-i(\mathbf{r}-\mathbf{r}')\cdot\mathbf{P}} N(\mathbf{r},\mathbf{b}) N(\mathbf{r}',\mathbf{b}') \otimes \cdots$$

P and **Δ** are conjugates to dipole size and impact parameter.

- Coordinate space:
  Dipole amplitude $N(\mathbf{r}, \mathbf{b})$ depends on $\theta(\mathbf{r}, \mathbf{b})$
- Momentum space:
  Cross section depends on $\theta(\mathbf{P}, \mathbf{\Delta})$
- Mixed space:
  Wigner distribution $xW(\mathbf{k}, \mathbf{b})$ depends on $\theta(\mathbf{k}, \mathbf{b})$

Baseline study

Introduce $\mathbf{r}, \mathbf{b}$ correlation to the IPsat Altinoluk, Armesto, Beuf, Rezaeian, 1511.07452

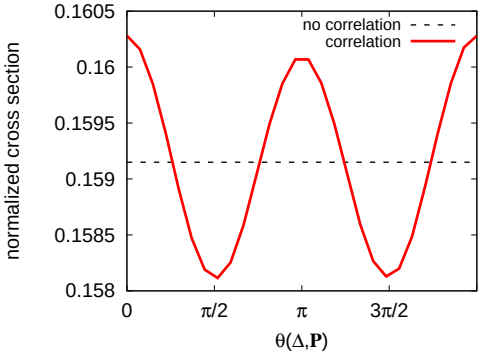
Calculate two quark production (quark $\approx$ jet)

$$\mathbf{\Delta} = \mathbf{k}_1 + \mathbf{k}_2, \mathbf{P} = \tfrac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$$

$$N(\mathbf{r}, \mathbf{b}, x) = 1 - \exp\left[-\mathbf{r}^2 F(x, \mathbf{r}) T_p(\mathbf{b}) C_\theta(\mathbf{r}, \mathbf{b})\right],$$
$$C_\theta(\mathbf{r}, \mathbf{b}) = 1 - \tilde{c}\left[\tfrac{1}{2} - \cos^2\theta(\mathbf{r}, \mathbf{b})\right]$$

$T(\mathbf{b})$: proton density profile

- $\tilde{c} = 0$: Standard IPsat (dashed)
- $\tilde{c} > 0$: Artificial dependence on $\mathbf{r} \cdot \mathbf{b}$ (solid line)



Dijet cross section has no dependence on $\theta(\mathbf{P}, \mathbf{\Delta})$ if $\tilde{c} = 0$ (dashed line)

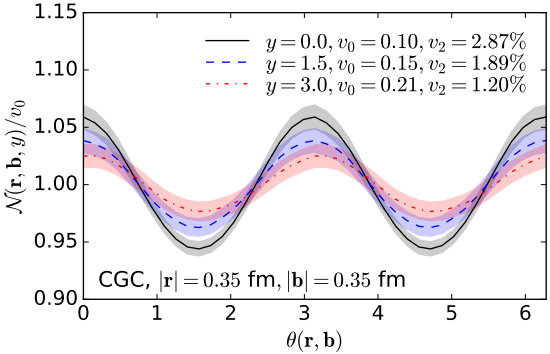
Realistic setup: angular correlations from CGC

Initial conditon $x = 0.01$

- IPsat $Q_s^2(\mathbf{b}) \Rightarrow$ color charge density ρ
- MV model, local Gaussian $\langle \rho\rho \rangle \sim Q_s^2$
- Yang-Mills Eqs $\Rightarrow$ Wilson lines $\Rightarrow \mathcal{N}$
- Infrared regulator: mass $\tilde{m}$

Small-x evolution

- JIMWLK equation
- Fixed and running coupling
- Infrared regulator: mass m



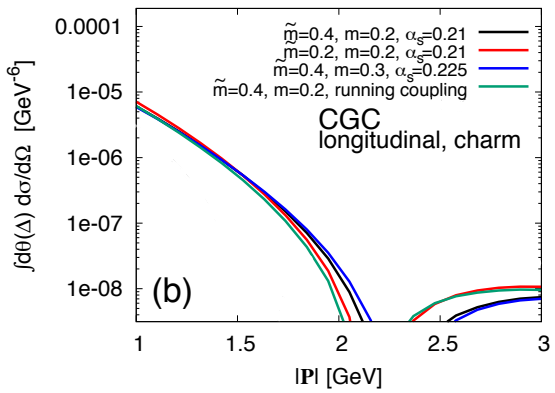
$$\mathcal{N}(\mathbf{r}, \mathbf{b}) = v_0(1 + 2v_2 \cos[2\theta(\mathbf{r}, \mathbf{b})])$$

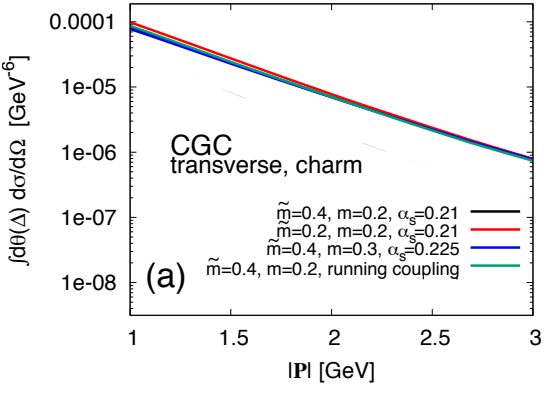
Evolution suppresses elliptic modulation

Expect to see that also in dijet production

Parameters constrained by HERA F_2 and J/Ψ data H.M, B. Schenke 1607.01711, 1806.06783

Charm dijets, dependence on dijet momentum $|\mathbf{P}|$ $(\gamma^* + p \to \text{jet} + \text{jet} + p)$



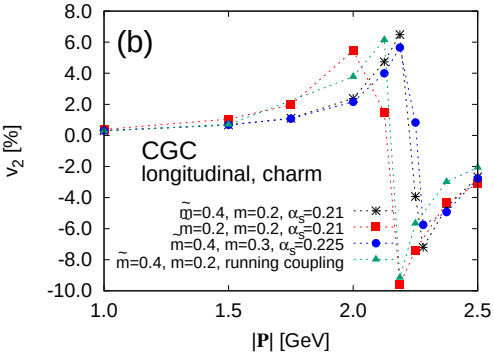


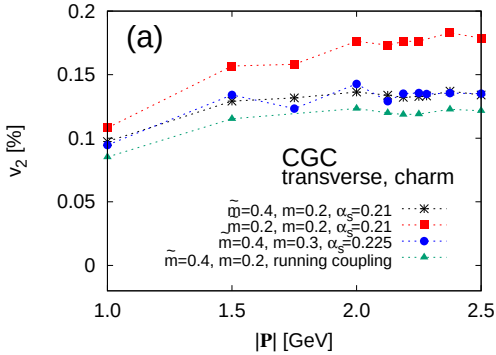
Transverse component dominates at $Q^2 = 1\text{GeV}^2$

Diffractive dips also in $\boldsymbol{\Delta}$ spectra (not shown)

$\mathbf{P}$ conjugate to dipole size $\mathbf{r}$, dip $\sim$ size of the projectile $\sim 1/\sqrt{m_c^2 + z(1-z)Q^2}$

Charm dijets, extracted v_2 ($\gamma^* + p \to \text{jet} + \text{jet} + p$)

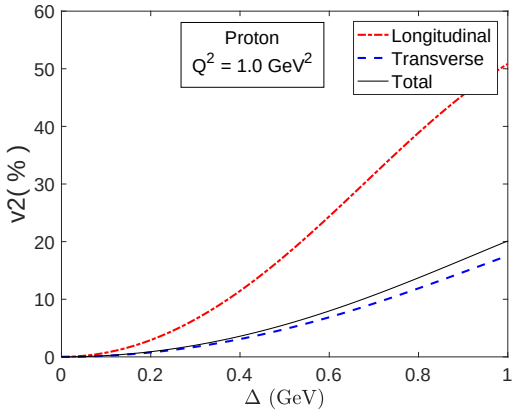




- Small sensitivy on IR regulators $m, \tilde{m}$ and fixed/running α_s
- In this kinematics small modulation $\sim$ few% (L) or $\sim 0.1\%$ (T, dominates)

$$\mathrm{d}\sigma \sim v_0(1 + 2v_2 \cos[2\theta(\mathbf{P}, \mathbf{\Delta})])$$

Larger modulation away from correlation limit

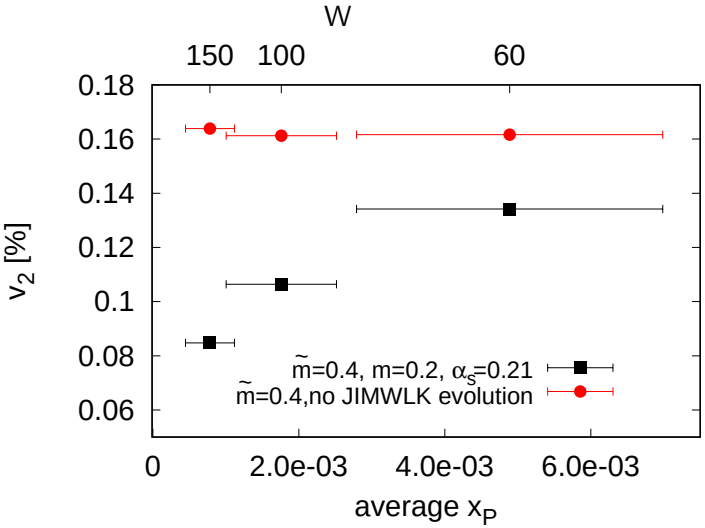


Salazar, Schenke, 1905.03763

- Significant modulation at large $|\boldsymbol{\Delta}|$
- ... where connection to Wigner is less clear
- But can calculate σ and Wigner from CGC H. M, N. Mueller, B. Schenke, 1902.05087
- Similar result in calculation including soft gluon radiation in the final state

  Hatta, Mueller, Ueda, Yuan,1907.09491

Energy dependence of total v_2 (transverse + longitudinal)



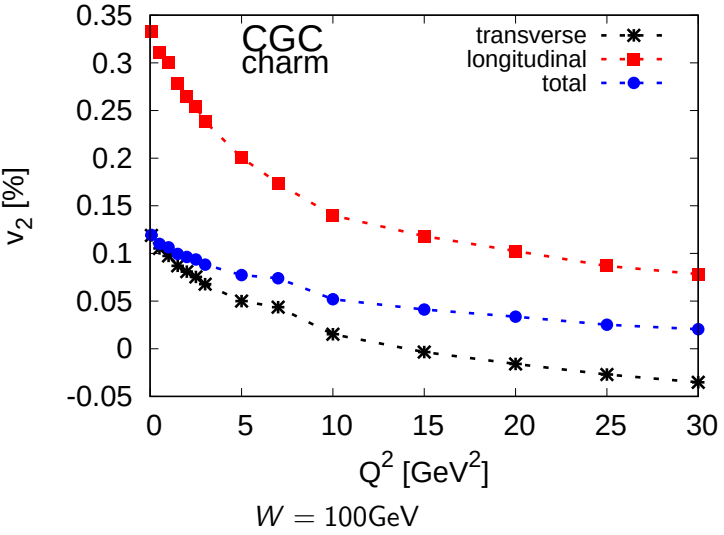
With JIMWLK

- v_2 decreases by factor ~ 2 in the EIC energy range
- Dominant reason: proton grows $\Rightarrow$ Smaller density gradients
- Similar growth seen in J/Ψ spectra at HERA

No JIMWLK:

- No energy dependence

Q^2 dependence



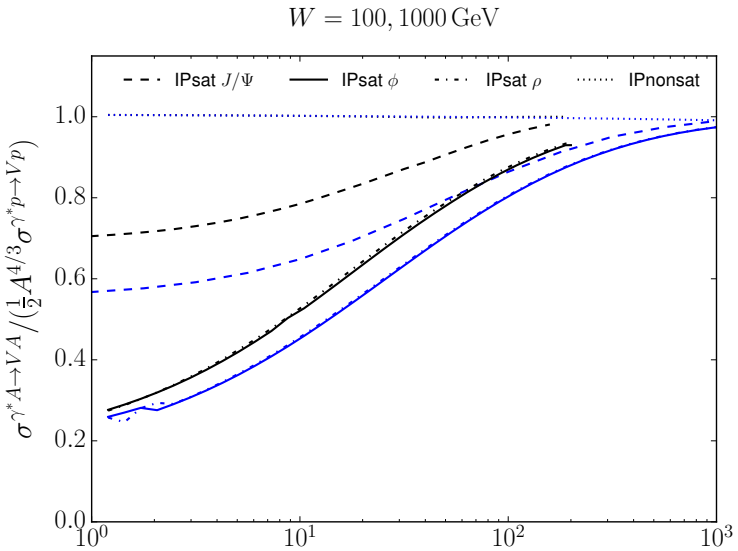
- Large $Q^2 \Rightarrow$ smaller dipoles sensitive to smaller density gradients
- Transverse v_2 can become negative at large Q^2

Conclusions

- Exclusive vector meson production is powerful
  - Sensitivity on small-x gluons
  - Access to geometry
  - Access to fluctuations
  - Need coherent – incoherent separation
- Dijet production: extra handle more detailed iimaging
- Angular modulation in the cross section:
  Intrinsic impact parameter-transverse momentum correlations in the gluon distribution
- Predict angular modulation at the EIC for charm dijets from CGC
  - And energy and Q^2 dependence
  - Small modulation $\sim 0.1 \ldots 1\%$ close to correlation limit
  - Larger away from the correlation limit
- Also in 1902.05087 and backup: Calculated Wigner and Husimi distributions describing small-x gluons from CGC
  - Elliptic modulation of these distributions $\sim$ dijet v_2
- Work in progress: incoherent dijet production

BACKUPS

Large nuclear suppression in vector meson production



Diffractive dijets: more differential imaging

The most complete description of the partonic structure

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

$\int d\vec{b}_\perp$ $\int d\vec{k}_\perp$

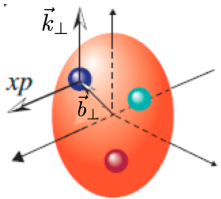
TMD $f(x,\vec{k}_\perp)$ GPD $f(x,\vec{b}_\perp)$

$\int d\vec{k}_\perp$ $\int d\vec{b}_\perp$ $\int dx$

$f(x)$ PDF $F(\vec{b}_\perp)$ Form factor

$\int dx$ $\int d\vec{b}_\perp$

Q charge



Graphics from Y. Hatta

Wigner and Husimi distributions – to the mixed space

Compare predicted dijet v_n to gluon Wigner and Husimi distributions Hagiwara, Hatta, Ueda, 1609.05773

Wigner distribution $xW(x, \mathbf{P}, \mathbf{b})$

- Most complete description
- No probabilistic interpretation (uncertainty principle)
- Not positive definite
- Large dipoles important

Husimi distribution $xH(x, \mathbf{P}, \mathbf{b})$

- Wigner + with Gaussian smearing
- Positive definite, probabilistic interpretation
- Dependence on the smearing parameter l
- Large dipoles suppressed by l

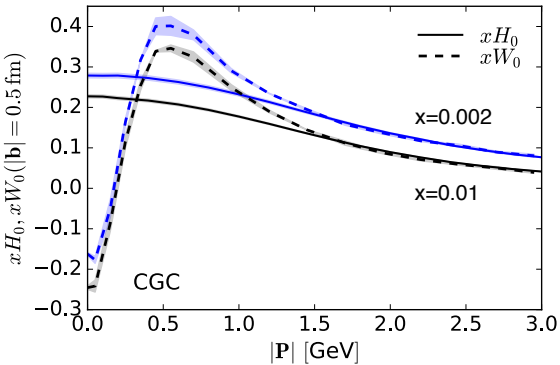
$$xW(x, \mathbf{P}, \mathbf{b}) = \frac{-2N_c}{(2\pi)^2 \alpha_s} \int_{\mathbf{r}} e^{i\mathbf{P}\cdot\mathbf{r}} \left(\frac{1}{4}\nabla^2_{\mathbf{b}} + \mathbf{P}^2 \right) \mathcal{N}(\mathbf{r}, \mathbf{b}, x) = xW_0 + 2xW_2 \cos[2\theta(\mathbf{P}, \mathbf{b})].$$

$$xH(x, \mathbf{P}, \mathbf{b}) = \frac{1}{\pi^2} \int_{\mathbf{b}'\,\mathbf{P}'} e^{-(\mathbf{b}-\mathbf{b}')^2/l^2 - l^2(\mathbf{P}-\mathbf{P}')^2} xW(x, \mathbf{P}', \mathbf{b}') = xH_0 + 2xH_2 \cos[2\theta(\mathbf{P}, \mathbf{b})]$$

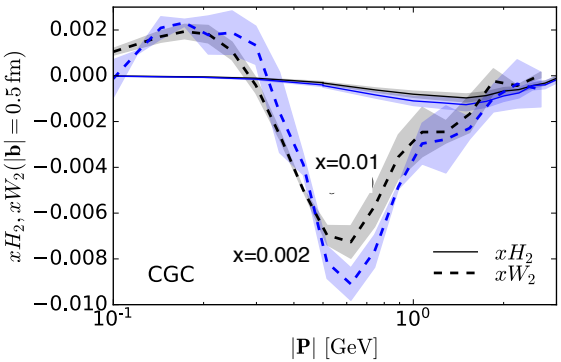
Here $l = 1\text{GeV}^{-1}$ corresponds to coordinate space smearing distance ~ 0.2 fm

Wigner and Husimi distributions - to the mixed space

$xH = xH_0 + 2xH_2 \cos 2\theta(\mathbf{P}, \mathbf{b}), xW = xW_0 + 2xW_2 \cos 2\theta(\mathbf{P}, \mathbf{b})$



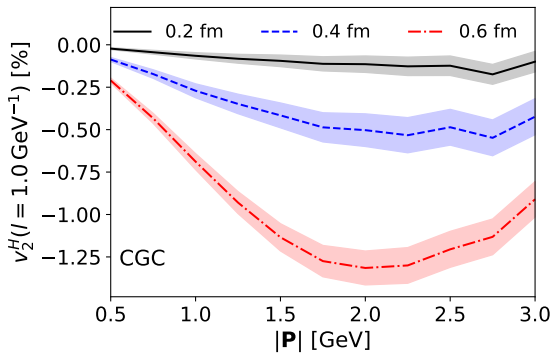
- Wigner distribution negative at small $|\mathbf{P}|$
- At $|\mathbf{P}| \gtrsim 1/l$ matches Husimi



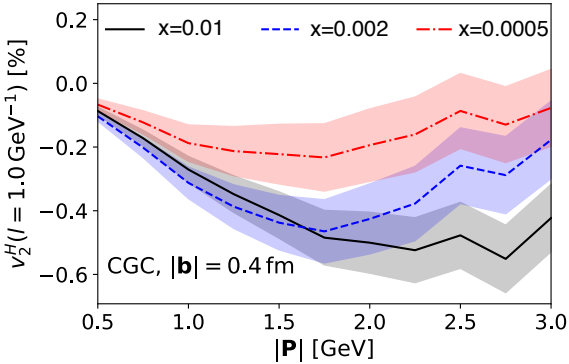
- Elliptic parts negative, match at $|\mathbf{P}| \gtrsim 1/l$
- $|xW_2| \gg xH_2$ at small $|\mathbf{P}|$

Husimi distribution, closer look

Study Husimi distribution and define $\mathbf{v_2^H} = \mathbf{xH_2}/\mathbf{xH_0}$, find $v_2^H \sim 0.1 \ldots 1\% \sim$ dijet v_2



- Large ellipticity at large impact parameters
- $v_2^H \to 0$ at large $\mathbf{P}$: target smooth at small distance scales

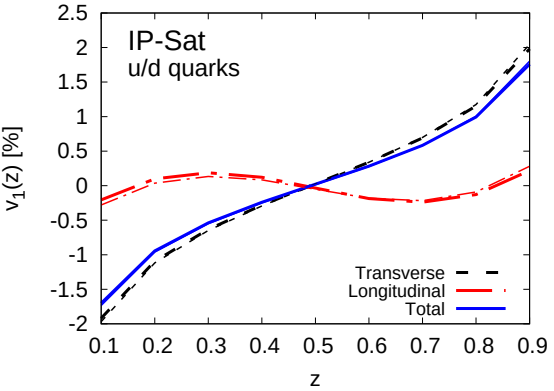


- Generally $v_2^H \to 0$ due to evolution
- Increasing $|v_2^H|$ at small $|\mathbf{P}|$: proton grows, and gradients at scale $\sim 1/$ start to contribute

Isolating kinematical effects effects

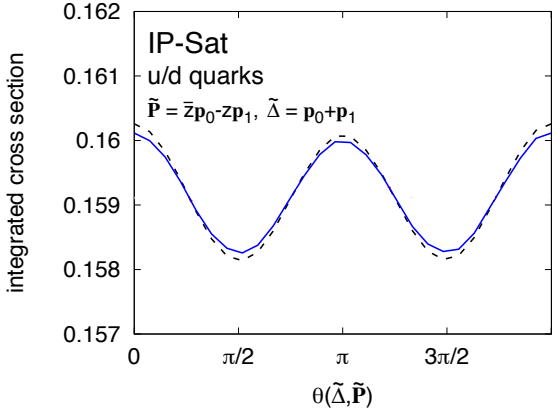
$\boldsymbol{\Delta} = \mathbf{k}_1 + \mathbf{k}_2, \mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$

- Probed $x_{\mathbb{P}}$ depends on $\theta(\mathbf{P}, \mathbf{b}) \Rightarrow v_1 \neq 0$
- Vanishes if $z_{\min} = 1 - z_{\max}$

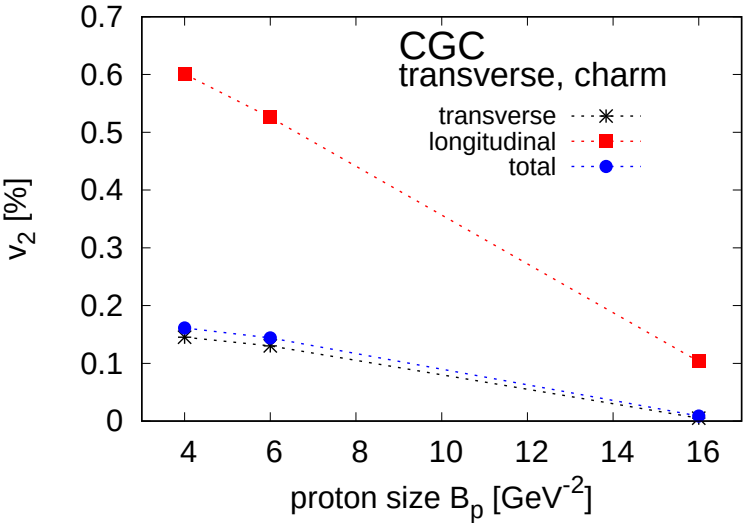


Alternative: $\tilde{\mathbf{P}} = (1 - z)\mathbf{k_1} - z\mathbf{k_2}$ Dumitru et al, 2018

- $x_{\mathbb{P}}$ independent of $\theta(\mathbf{P}, \mathbf{b})$, no v_1
- $v_2 \neq 0$ with no correlations in IPsat



Proton size dependence



Total cross section