Exclusive dijet production

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Mäntysaari, Mueller, Schenke, PRD 99, 074004 (2019), 1902.05087 [hep-ph]
Salazar, Schenke, PRD 100 034007 (2019), 1905.03763 [hep-ph]

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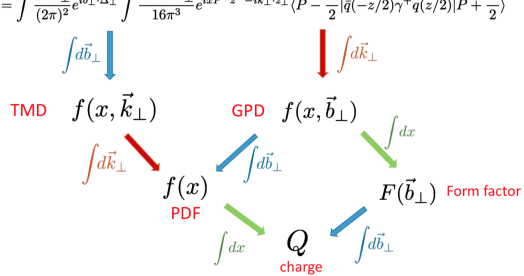
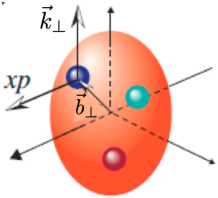
EIC Yellow Report Temple meeting, March 20, 2020

Motivation: multi dimensional pictures of nuclei

The most complete description of the partonic structure

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





Graphics from Y. Hatta

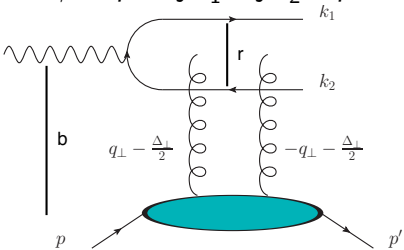
This talk

Theoretical analyses of exclusive dijet production, without feasibility studies.

MC generator also in progress? E. Aschenauer, yesterday

Access to Wigner distribution: diffractive dijet production

$\gamma^* + p \to \text{jet}_1 + \text{jet}_2 + p$



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

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

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

Hatta, Xiao, Yuan, 1601.01585

Hagiwara *et al*, 1706.01765

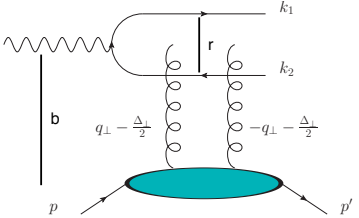
v_2 connected to elliptic part of gluon Wigner distribution xW_2:

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

Direct connection in the "correlation limit" ($|\mathbf{P}| \gg |\mathbf{\Delta}|$) at $Q^2 \to 0$

CGC calculation for dijet production

$$\gamma^* + p \to \text{jet}_1 + \text{jet}_2 + p$$



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

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2\mathbf{P}\mathrm{d}^2\mathbf{\Delta}} \sim \int_{\mathbf{b}\,\mathbf{b}'\,\mathbf{r}\,\mathbf{r}'} e^{-i(\mathbf{b}-\mathbf{b}')\cdot\mathbf{\Delta}} e^{-i(\mathbf{r}-\mathbf{r}')\cdot\mathbf{P}} N(\mathbf{r},\mathbf{b}) N(\mathbf{r}',\mathbf{b}') \otimes \cdots$$

$\mathbf{P}$ and $\mathbf{\Delta}$ 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 $\theta(\mathbf{k},\mathbf{b})$

Dijet production probes how dipole-target interaction depends on the dipole orientation

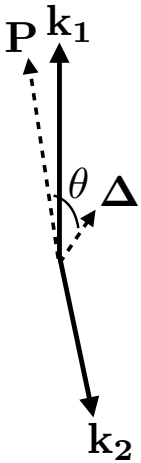
Kinematics

EIC kinematics used here

- $Q^2 = 1\text{GeV}^2$
- $W = 100\text{GeV}$
- $|\mathbf{P}|$: "mean jet p_T"
- $|\mathbf{\Delta}|$: recoil
- Longitudinal momentum fraction $z \in [0.1, 0.9]$

I mostly consider charm jets here (small $p_T \approx$ charmed mesons), to avoid contribution from large dipoles

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



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

Baseline study

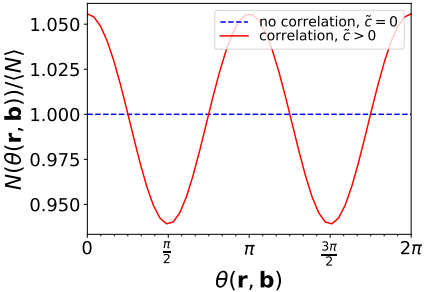
Dipole-proton scattering N: IPsat parametrization (dependence on $T(\mathbf{b})$ and saturation)

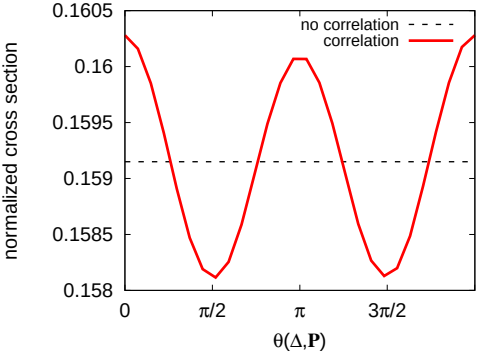
Introduce $\theta(\mathbf{r},\mathbf{b})$ dependence Altinoluk, Armesto, Beuf, Rezaeian, 1511.07452

Calculate two quark production (quark $\approx$ jet) $\mathbf{\Delta} = \mathbf{k}_1 + \mathbf{k}_2, \mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$

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

$$C_\theta(\mathbf{r},\mathbf{b}) = 1 - \tilde{c}\left[\frac{1}{2} - \cos^2\theta(\mathbf{r},\mathbf{b})\right]$$





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

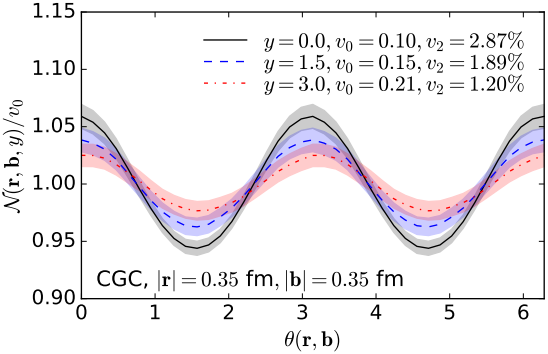
Realistic setup: angular correlations from CGC

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



H.M, N. Mueller, B. Schenke, 1902.05087

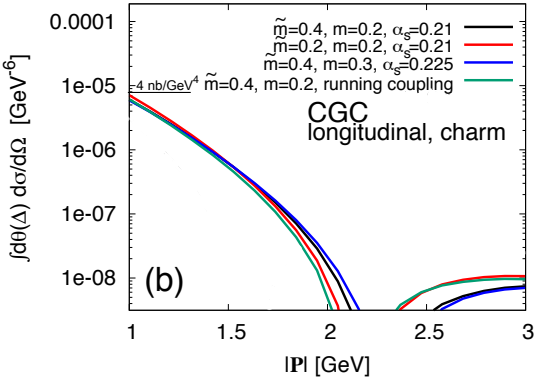
$$\mathcal{N}(\mathbf{r}, \mathbf{b}) = v_0(1 + 2v_2 \cos[2\theta(\mathbf{r}, \mathbf{b})])$$

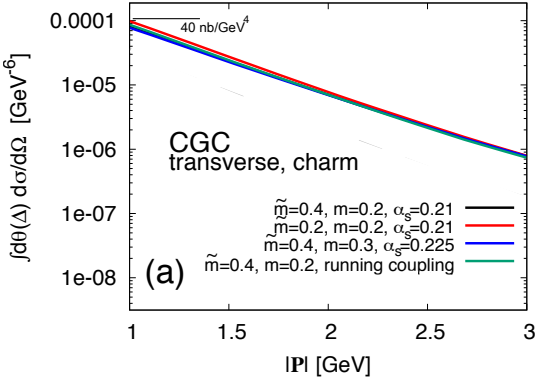
Evolution suppresses elliptic modulation

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 $|\mathbf{P}|$ $(\gamma^* + p \to \text{jet} + \text{jet} + p)$





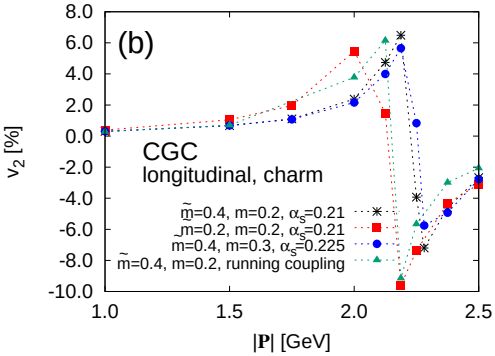
Close to correlation limit $|\mathbf{\Delta}| = 0.1\text{GeV}$ (higher momenta later), $Q^2 = 1\text{GeV}^2$ here

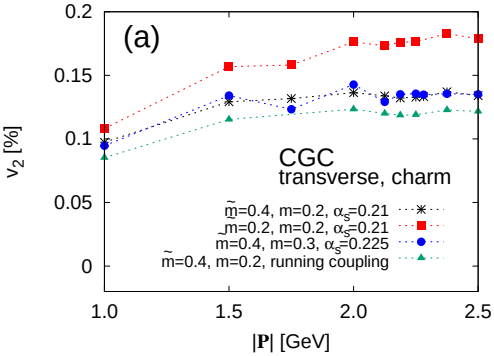
Is it experimentally possible to separate the two polarizations?

Diffractive dips in $\mathbf{\Delta}$ and (longitudinal) $\mathbf{P}$ spectra ($\mathbf{\Delta}$ not shown)

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

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

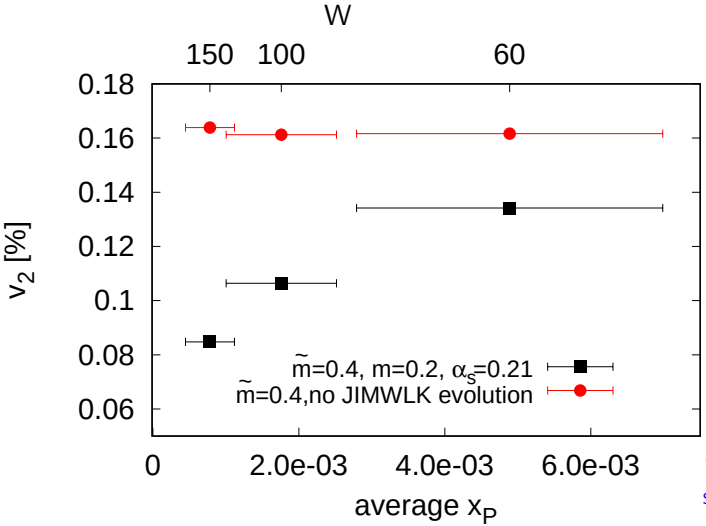




- Close to correlation limit ($|\mathbf{\Delta}| = 0.1\text{GeV}$), where direct connection to Wigner: very small modulation $\sim$ few% (L) or $\sim 0.1\%$ (T, dominates)
- Small sensitivy on IR regulators $m, \tilde{m}$ and fixed/running α_s (different lines)

$$\mathrm{d}\sigma \sim v_0(1 + 2v_2 \cos[2\theta(\mathbf{P}, \mathbf{\Delta})])$$ H.M, N. Mueller, B. Schenke, 1902.05087

Energy dependence of total v_2 (transverse + longitudinal)



With JIMWLK

- v_2 decreases by factor ~ 2 in the EIC energy range
- Similar effect in elliptic modulation of the Wigner (backup)
- Dominant reason: proton grows $\Rightarrow$ Smaller density gradients

No JIMWLK:

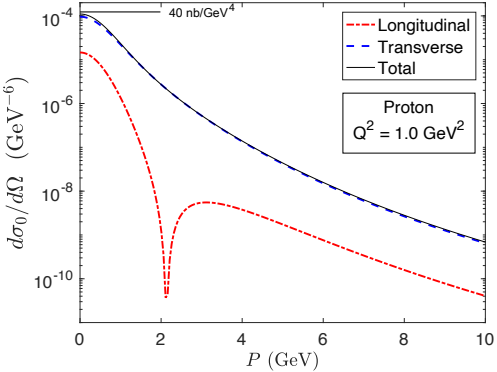
- No energy dependence

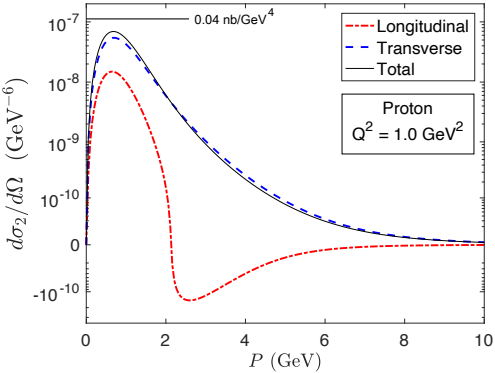
Q^2 dependence: backup H.M, N. Mueller, B. Schenke, 1902.05087

Elliptic part of the cross section

Modified MV model, $\theta(\mathbf{r},\mathbf{b})$ dependence from color charge density gradients Salazar, Schenke, 1905.03763

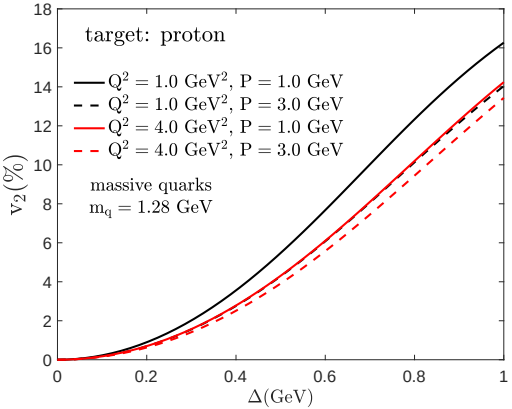
$$\frac{\mathrm{d}\sigma^{\gamma^* p\to q_1+q_2+p}}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_0}{\mathrm{d}\Omega} + 2\cos 2\theta(\mathbf{P},\mathbf{\Delta})\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega} \qquad (\mathrm{d}\Omega = \mathrm{d}q_1^-/q_1^-\,\mathrm{d}q_2^-/q_2^-\,\mathrm{d}^2\mathbf{P}\mathrm{d}^2\mathbf{\Delta})$$





Modulation maximal at $|\mathbf{P}| \approx 1$GeV. Here $|\mathbf{\Delta}| = 0.1$GeV, modulation again small $\sim 0.1\%$.

Larger modulation away from correlation limit

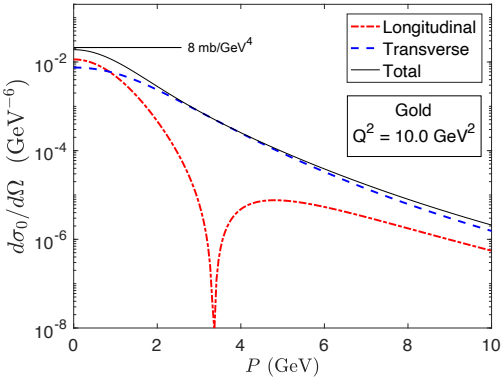


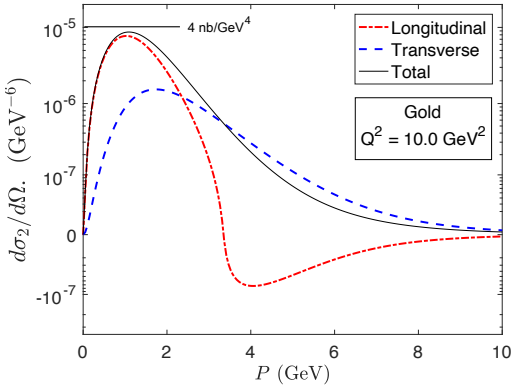
Salazar, Schenke, 1905.03763

- Modulation increases with $|\mathbf{\Delta}|$
- Larger Q^2, smaller modulation: smaller dipoles effectively see smaller density gradients
- Approximations of Salazar, Schenke, 1905.03763 are not reliable at large $|\mathbf{\Delta}|$, but a full calculation is possible
- Similar observation found in Hatta, Mueller, Ueda, Yuan, 1907.09491
- Recall: direct connection to the Wigner distribution in the correlation limit $|\mathbf{P}| \gg |\mathbf{\Delta}|$

Coherent dijet with gold targets

$$\frac{\mathrm{d}\sigma^{\gamma^* p\to q_1+q_2+p}}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_0}{\mathrm{d}\Omega} + 2\cos 2\theta(\mathbf{P},\mathbf{\Delta})\frac{\mathrm{d}\sigma_2}{\mathrm{d}\Omega} \qquad (\mathrm{d}\Omega = \mathrm{d}q_1^-/q_1^-\,\mathrm{d}q_2^-/q_2^-\,\mathrm{d}^2\mathbf{P}\mathrm{d}^2\mathbf{\Delta})$$

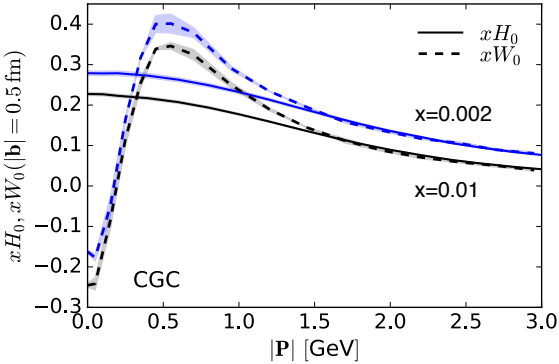


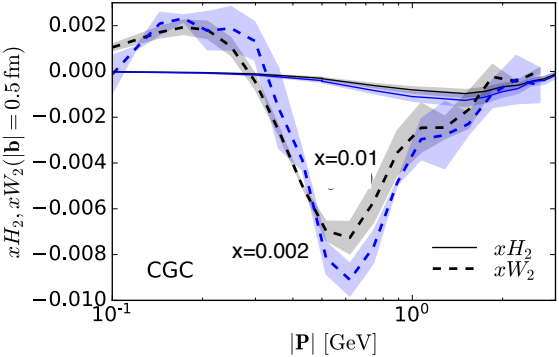


Salazar, Schenke, 1905.03763 Here $|\mathbf{\Delta}| = 0.1$GeV, resulting in small modulation (need again higher $|\mathbf{\Delta}|$)

Wigner and Husimi distributions - gluons in the mixed space

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





- Can compute these from the same CGC framework H.M, N. Mueller, B. Schenke, 1902.05087
- Or extract from xs Hagiwara et al, 1706.01765

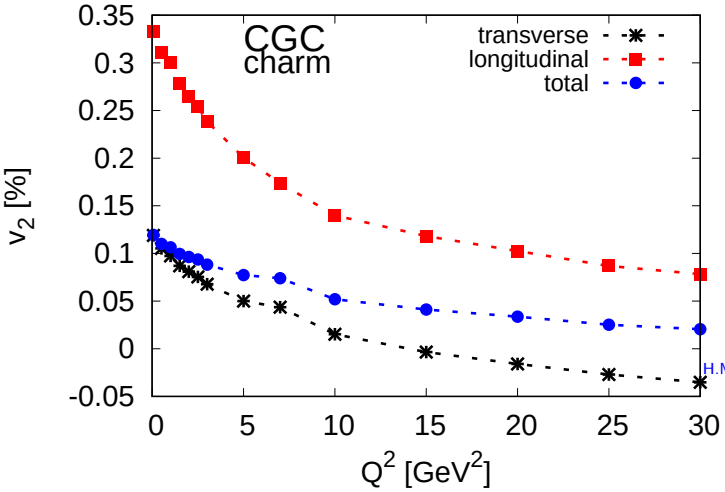
- Wigner distribution negative at small $|\mathbf{P}|$
- At $|\mathbf{P}| \gtrsim 1/l$ matches Husimi

Conclusions

- Coherent (charmed) dijet production calculable from the CGC framework
- Angular modulation in the cross section due to intrinsic impact parameter-transverse momentum correlations in the gluon distribution
- Elliptic modulation tiny in the correlation limit $|\mathbf{P}| \gg |\mathbf{\Delta}|$
- Interesting kinematical region $|\mathbf{P}| \sim$ a few GeV, $|\mathbf{\Delta}| \sim$ GeV
  Can we extract $\sim 10\%$ modulation?
- This region is also sensitive to multi gluon correlations in inclusive and incoherent diffractive dijet production H.M, N. Mueller, F. Salazar, B. Schenke, PRL124, 112301 (2020), 1912.05586
- Connection to Wigner direct in the correlation limit. Can also compute Wigner and Husimi gluon distributions (with x evolution!) from the same CGC framework

BACKUPS

Q^2 dependence



$W = 100\text{GeV}$

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

H.M, N. Mueller, B. Schenke, 1902.05087

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

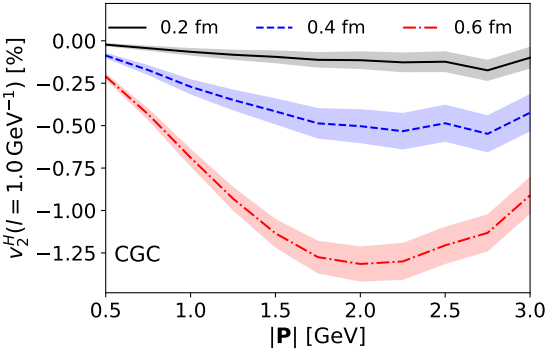
$$xW(x, \mathbf{P}, \mathbf{b}) = \frac{-2N_c}{(2\pi)^2 \alpha_s} \int_{\mathbf{r}} e^{i\mathbf{P}\cdot\mathbf{r}} \left(\frac{1}{4} \nabla_{\mathbf{b}}^2 + \mathbf{P}^2 \right) \mathcal{N}(\mathbf{r}, \mathbf{b}, x) = xW_0 + 2xW_2 \cos[2\theta(\mathbf{P}, \mathbf{b})].$$

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

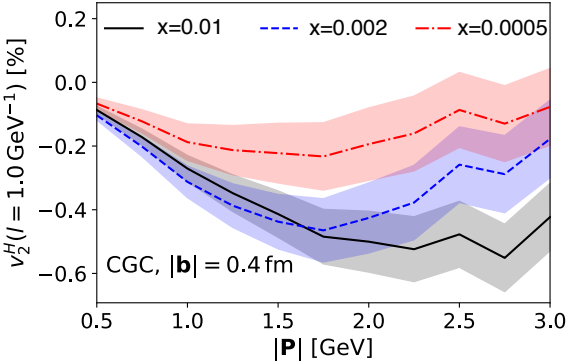
Here $l = 1\text{GeV}^{-1}$ corresponds to coordinate space smearing distance ~ 0.2 fm

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

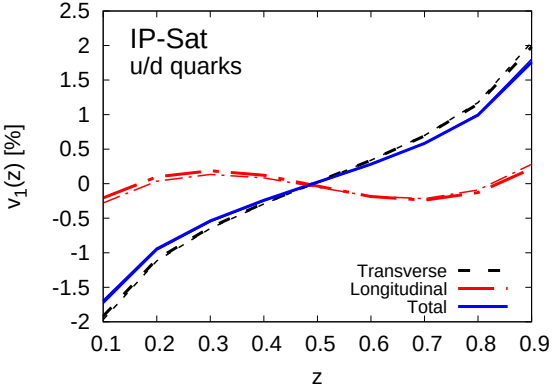


- Generally $v_2^H \to 0$ due to evolution
- Increasing $|v_2^H|$ at small $|\mathbf{P}|$: proton grows, and gradients at scale $\sim l$ start to contribute

Isolating kinematical effects effects

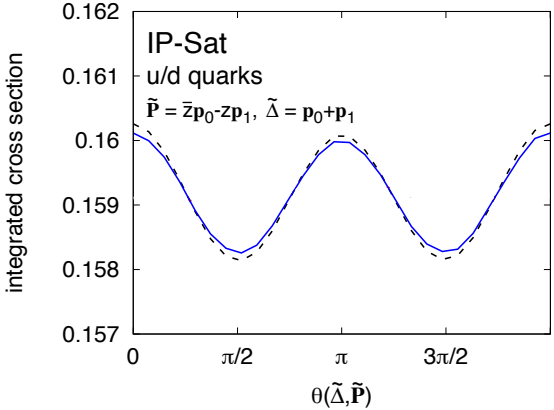
$\mathbf{\Delta} = \mathbf{k}_1 + \mathbf{k}_2, \mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$

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



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