Probing the nucleon and nuclei at small x

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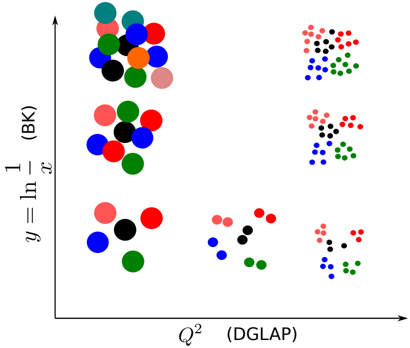
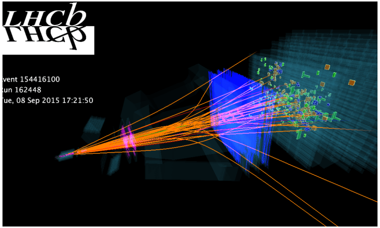
October 17, 2019 / Implications of LHCb measurements and future prospects



Non-linear QCD matter at $x \ll 1$
Density$\sim A^{1/3}$
Color Glass Condensate effective theory of QCD

LHCb is a fantastic detector

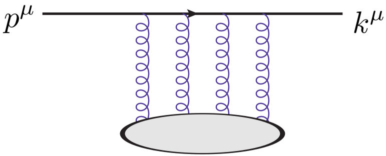


- Large parton densities at small $x \sim e^{-y}/\sqrt{s}$
- LHCb has good capabilities at forward rapidities
- Non-linear saturation effects $\Rightarrow$ e.g. nuclear suppression

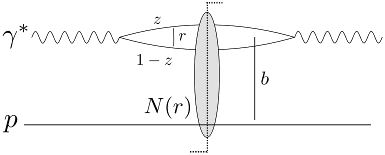
This talk: inclusive spectra, correlations, photoproduction, exclusive processes (my wish list!)

Probing protons and nuclei at high energy

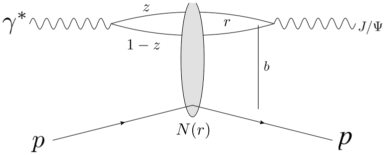
CGC: unified framework to describe inclusive and exclusive scattering



Inclusive $q + A \to q + X$
$\sigma \sim$ dipole amplitude $\sim$ gluon
(q in $\mathcal{A}$ and $\mathcal{A}^*$)



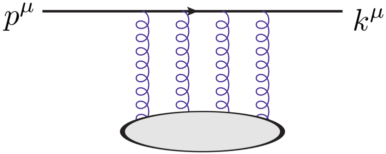
Deep inelastic scattering
$\sigma \sim$ dipole amplitude $\sim$ gluon
(optical theorem)



Exclusive processes
$\sigma \sim$ dipole amplitude^2

Probing protons and nuclei at high energy

CGC: unified framework to describe inclusive and exclusive scattering



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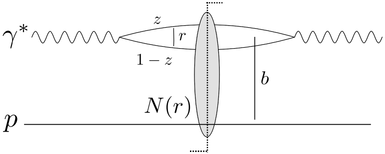

Deep inelastic scattering

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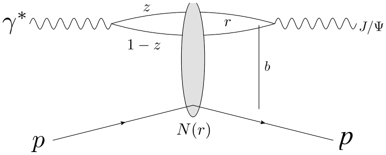
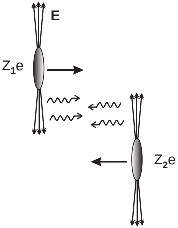


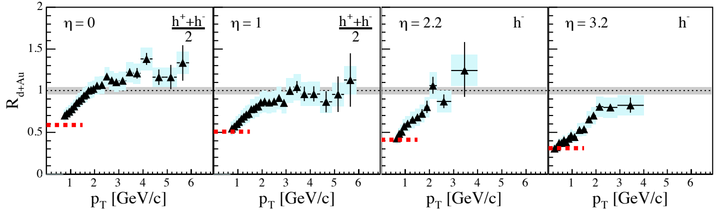
Exclusive processes

$\sigma \sim$ dipole amplitude^2

- Cross section written in terms of universal dipole amplitude (same in inclusive and exclusive!)
- CGC: perturbative evolution of dipole, predict x dependence
- Recall: You are doing $\gamma - p$ and $\gamma - Pb$ also (large b)!

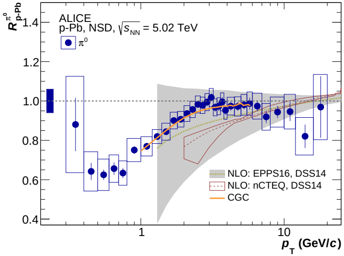


$$R_{pA} = \frac{\mathrm{d}N^{p/dA}}{N_{\mathrm{bin}}\mathrm{d}N^{pp}}$$



BRAHMS, nucl-ex/0403005

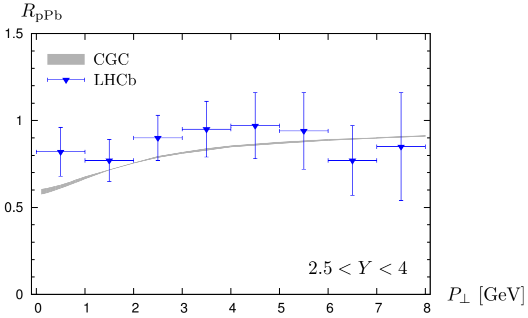
- Large nuclear suppression: forward RHIC, midrapidity LHC
- Some forward data from RHIC, tension between experiments
- LHC midrapidity: probe structure complicated $(x_1, x_2 \ll 1)$
- My wish: forward spectra in $p + p$ and $p + Pb$, and R_{pA}!
- Important when determining how saturation effects modify the nuclear structure at small x



ALICE, 1801.07051

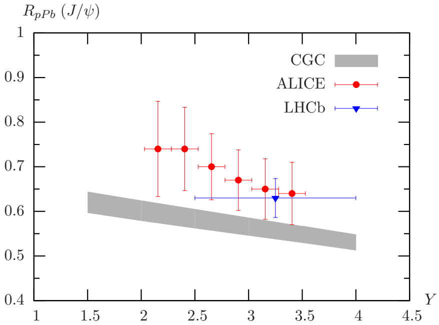
Forward spectra – thank you!

D mesons



B. Ducloué, T. Lappi, H.M, 1612.04585

J/Ψ mesons

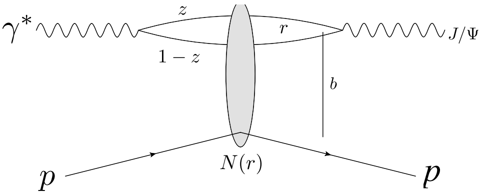


B. Ducloué, T. Lappi, H.M, 1503.02789

- Nice and useful data (both R_{pA} and spectra)
- CGC calculations compatible with data, but J/Ψ and D formation is complicated
- More inclusive (e.g. charged hadron, or π) measurements would have more impact

High energy factorization:

1. $\gamma^* \to q\bar{q}$ splitting, wave function $\Psi^\gamma(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically
3. $q\bar{q} \to J/\Psi$, wave function $\Psi^V(r, Q^2, z)$



Diffractive scattering amplitude

$$\mathcal{A}^{\gamma^* p \to Vp} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^{\gamma^*} \Psi^V(r, z, Q^2) e^{-i\mathbf{b}\cdot\boldsymbol{\Delta}} N(r, x, b)$$

- Impact parameter is the Fourier conjugate to the momentum transfer $\to$ Access to the spatial structure
- Recall: $N \sim$ gluon, so $\sigma \sim \text{gluon}^2$

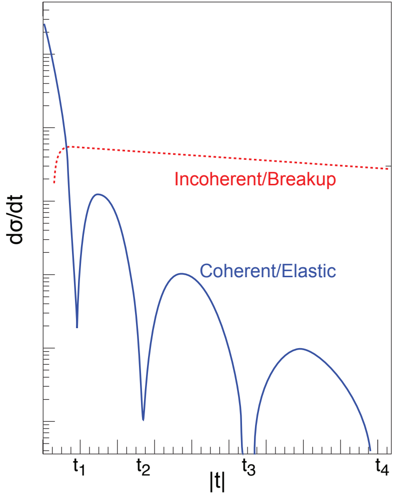
Two classes of diffractive events

Coherent diffraction:

Target proton/nucleus remains in the same quantum state

Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$



Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999

Two classes of diffractive events

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Probes average density

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

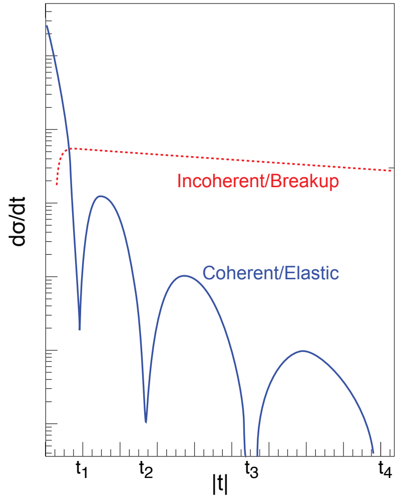
Incoherent/target dissociation:

Total diffractive $-$ coherent cross section

Target breaks up

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}^{\gamma^* p \to Vp}|^2 \rangle - |\langle \mathcal{A}^{\gamma^* p \to Vp} \rangle|^2$$

Variance, measures the amount of fluctuations!



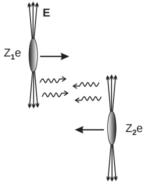
Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999

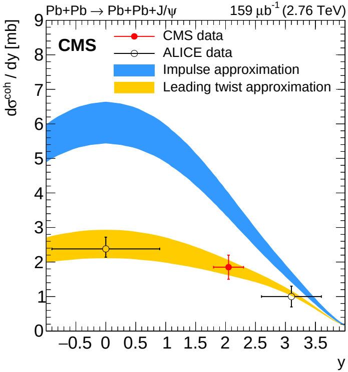
Vector meson production in ultraperipheral heavy ion collisions

Probing nuclear effects

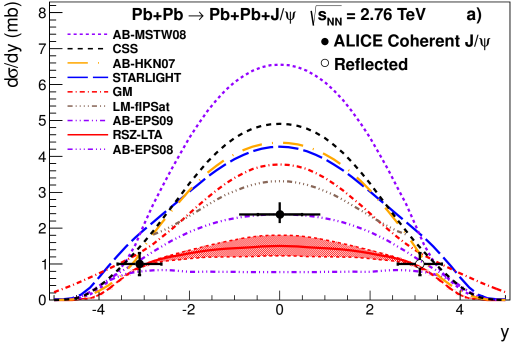
- Sensitivity on gluons ($\sigma \sim \text{gluon}^2$)

- $x \sim e^{-y}/\sqrt{s}$
- CGC calculations compatible
- pp, pA and AA data already from ALICE, CMS and LHCb
- My wish list: coherent and incoherent, A/p ratios and t spectra!
- Coherent-incoherent separation?

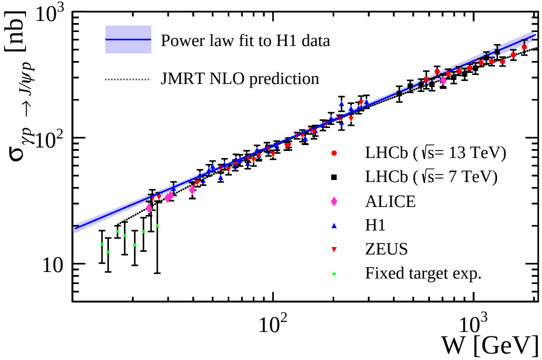




Clear nuclear effects (coherent): impulse approximation = scaled $\gamma + p$



ALICE, 1305.1467

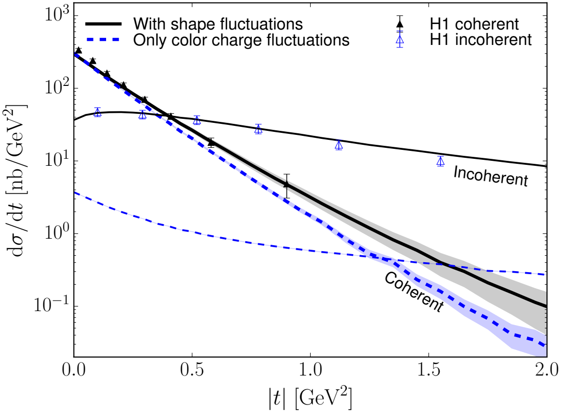


LHCb, 1806.04079

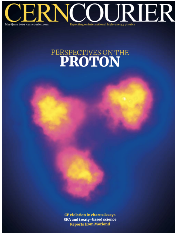
- γA: nPDFs and CGC calculations compatible
- pp: HERA measurements extended to large W, deviation from the power law?

Constraining proton fluctuations: $\gamma + p \to J/\Psi + p$ ($W = 75\,\mathrm{GeV}$)

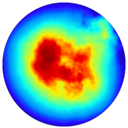
Proton geometry from HERA J/Ψ data
(Coherent $\sim$ average, incoherent $\sim$ fluctuations



Fluctuations



Round

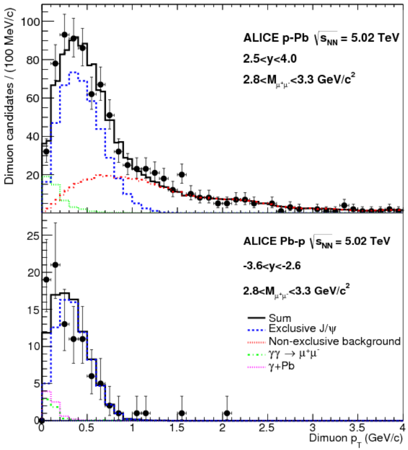


H1: 1304.5162

HERA data requires large event-by-event fluctuations
CGC calculation H.M, B. Schenke, 1607.01711

Energy dependence – LHC advantage

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

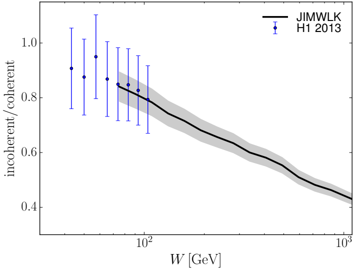


ALICE arXiv:1406.7819, 1809.03235

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

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

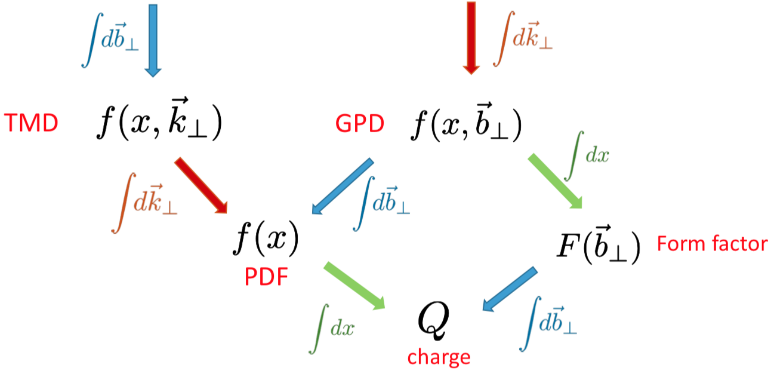
(Qualitatively) compatible with CGC evolution

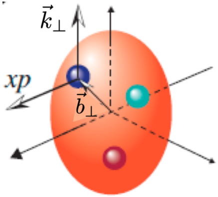


H. M, B: Schenke, 1806.06783, also Cepila et al, 1608.07559

The most complete description of the partonic structure

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



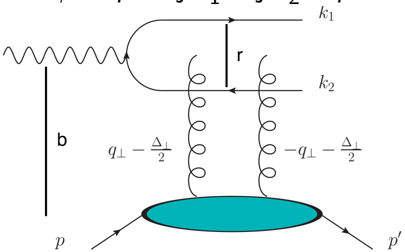


Graphics from Y. Hatta

Diffractive dijets and the Wigner distribution: more differential imaging

Two momenta, extra handle

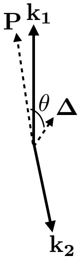
$\gamma^* + p \to \text{jet}_1 + \text{jet}_2 + p$



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

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

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

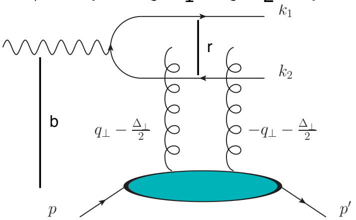


Hatta, Xiao, Yuan, 1601.01585
Hagiwara *et al*, 1706.01765
v_2 in principle connected to elliptic part of gluon Wigner distribution in certain limit ($Q^2 \to 0$ [=LHC], $|\mathbf{P}| \gg |\mathbf{\Delta}|$)

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

CGC calculation of dijet production

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



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

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

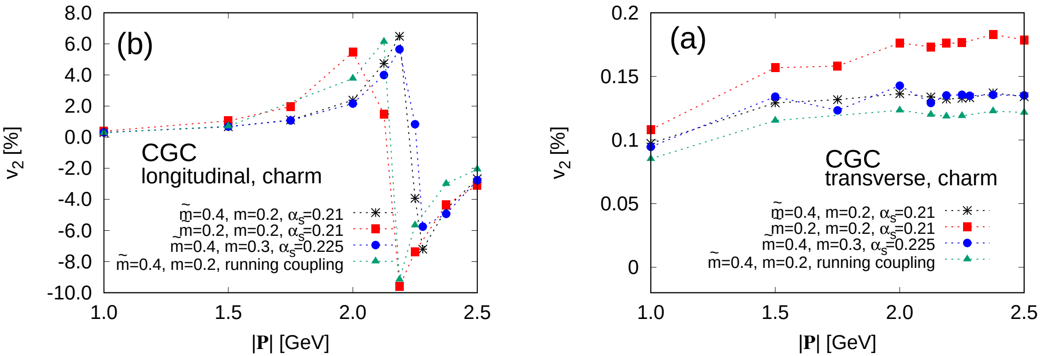
- $\mathbf{\Delta} = \mathbf{k}_1 + \mathbf{k}_2$
- $\mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$

Altinoluk, Armesto, Beuf, Rezaeian, 1511.07452

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

$\mathbf{P}$ and $\mathbf{\Delta}$ are conjugates to dipole size and impact parameter.

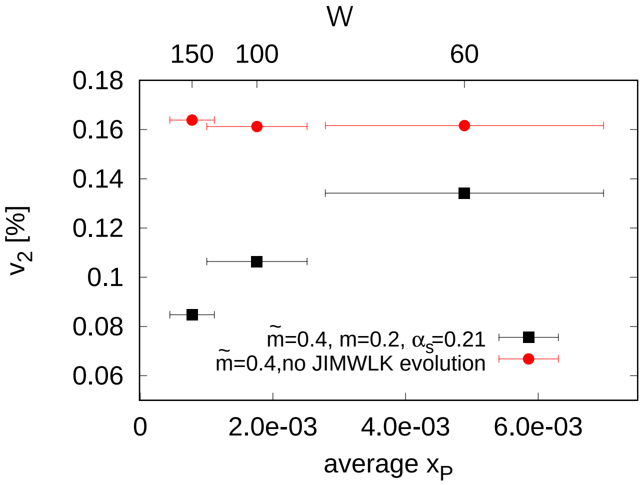
- Coordinate space:
  Dipole-target interaction $N(\mathbf{r}, \mathbf{b})$ depends on $\theta(\mathbf{r}, \mathbf{b})$
- Momentum space:
  Cross section depends on $\theta(\mathbf{P}, \mathbf{\Delta})$
- Mixed space:
  Wigner distribution $xW(\mathbf{k}, \mathbf{b})$ depends on $\theta(\mathbf{k}, \mathbf{b})$



- Electron-ion collider kinematics: modulation $\sim$ few% (L) or $\sim$ 0.1% (T)
- UPC at LHC: only transverse real phototons
- CGC calculation H.M, N. Mueller, B. Schenke, 1902.05087 : Wigner distribution has similar features
- Larger modulation at larger $\mathbf{\Delta}$, but connection to Wigner more complicated

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

Energy dependence of total v_2 (transverse + longitudinal)



With JIMWLK (pert. x evolution)

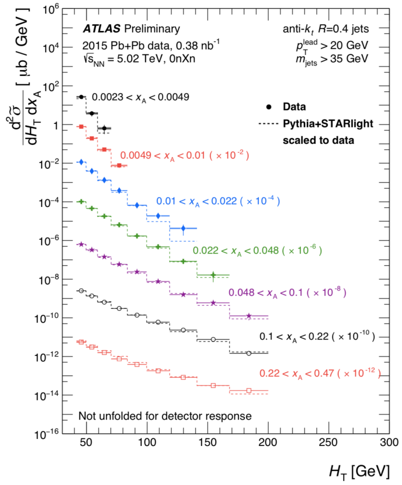
- v_2 decreases by factor ~ 2 in the EIC energy range
- Dominant reason: proton grows $\Rightarrow$ Smaller density gradients

No JIMWLK:

- No energy dependence

Analysis in EIC kinematics, much more evolution at the LHC energies

4. Inclusive photoproduction processes



ATLAS-CONF-2017-011

Inclusive $\gamma + p/A$ processes: just being started...

- ATLAS: first dijet measurements at large p_T
- Advantage: Also useful for nuclear PDF analyses

Guzey, Klasen, 1811.10236

- Many processes I would want to see ($p_T \sim$ a few GeV)
  - Inclusive hadron/jet spectra
  - Dijet azimuthal correlations
    Saturation: back-to-back correlation vanishes in $p \to A$
    H.M, Lappi, 1209.2853
  - Nuclear suppression factors
  - Rapidity (Bjorken-x) dependencies

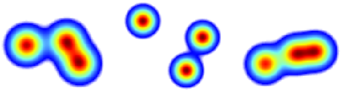
Conclusions

- LHCb has a unique kinematical coverage
- Access large parton densities and non-linear QCD at small x
- Inclusive forward spectra and nuclear modification factors
  - Very basic observable, would have high impact
- Coherent and incoherent vector meson production
  - Access non-linear effects, probe geometry and geometry fluctuations
- Diffractive dijet production
  - Potential to constrain the gluon Wigner distribution
- Inclusive photoproduction
  - Spectra, correlations,...
  - Useful for nuclear PDF studies also

BACKUPS

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

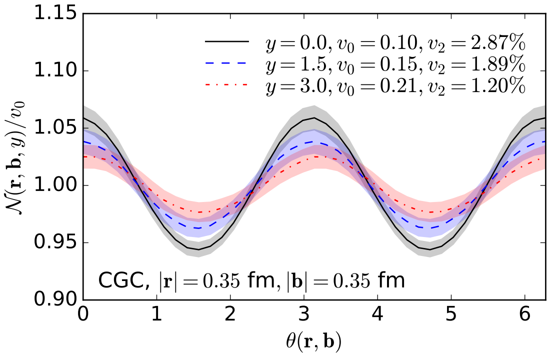
H.M, Schenke, 1607.01711, 1603.04349, also more complicated geometries

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

Realistic setup: angular correlations from CGC

CGC setup

- Proton local density $Q_s^2(\mathbf{b})$
- Random color charges, Yang-Mills equations
- Perturbative small-x evolution
- Dipole-proton scattering amplitude N
  Dipole size $\mathbf{r}$, impact parameter $\mathbf{b}$



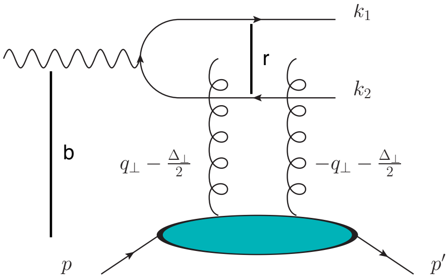
$$\mathcal{N}(\mathbf{r},\mathbf{b}) = v_0(1+2v_2\cos[2\theta(\mathbf{r},\mathbf{b})])$$

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

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

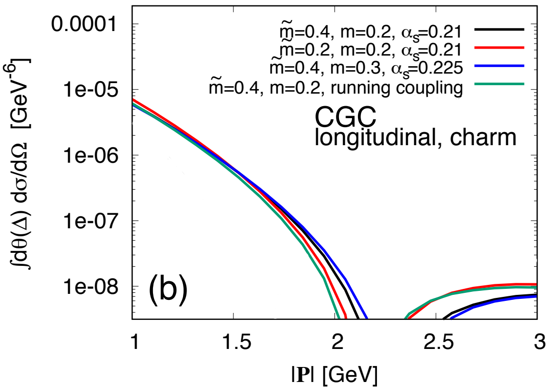
Target remains intact (Good-Walker picture)

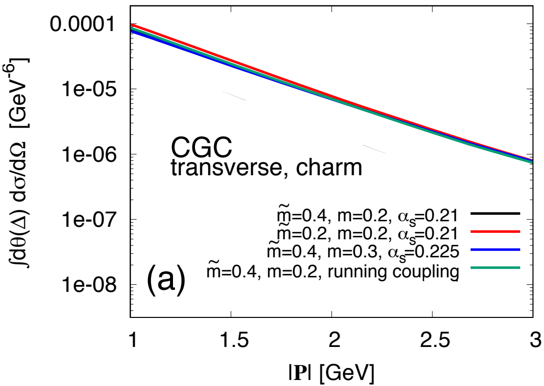
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} \sim |\langle \mathcal{A} \rangle|^2$$

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

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 $\mathbf{\Delta}$ spectra (not shown)

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

Baseline study

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

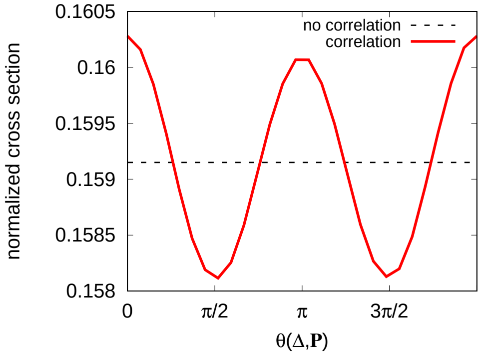
Calculate two quark production (quark $\approx$ jet) $\boldsymbol{\Delta} = \mathbf{k}_1 + \mathbf{k}_2, \mathbf{P} = \frac{1}{2}(\mathbf{k}_1 - \mathbf{k}_2)$

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

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

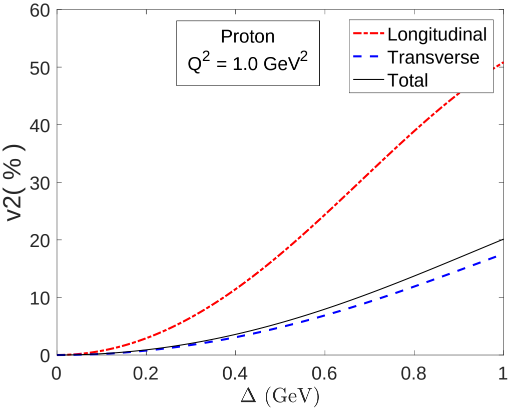
$T(\mathbf{b})$: proton density profile

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



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

Larger modulation away from correlation limit



Salazar, Schenke, 1905.03763

- Significant modulation at large $|\mathbf{\Delta}|$
- ... 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

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

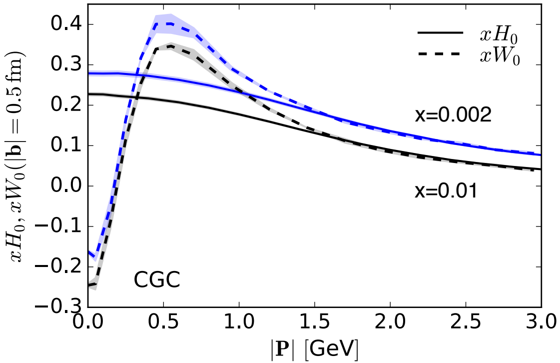
$$xW(x, \mathbf{P}, \mathbf{b}) = \frac{-2N_c}{(2\pi)^2 \alpha_s} \int_{\mathbf{r}} e^{i\mathbf{P}\cdot\mathbf{r}} \left(\frac{1}{4} \nabla_{\mathbf{b}}^2 + \mathbf{P}^2 \right) \mathcal{N}(\mathbf{r}, \mathbf{b}, x) = xW_0 + 2xW_2 \cos[2\theta(\mathbf{P}, \mathbf{b})].$$

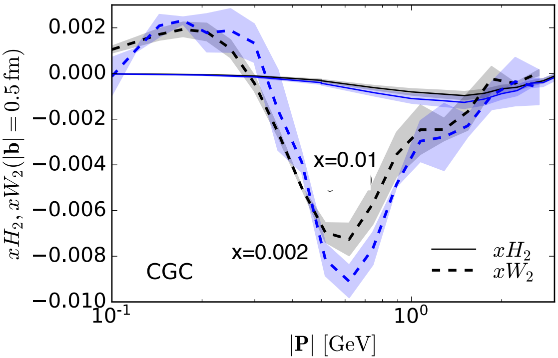
$$xH(x, \mathbf{P}, \mathbf{b}) = \frac{1}{\pi^2} \int_{\mathbf{b}' \, \mathbf{P}'} e^{-(\mathbf{b}-\mathbf{b}')^2/l^2 - l^2(\mathbf{P}-\mathbf{P}')^2} xW(x, \mathbf{P}', \mathbf{b}') = xH_0 + 2xH_2 \cos[2\theta(\mathbf{P}, \mathbf{b})]$$

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

Wigner and Husimi distributions - to the mixed space

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

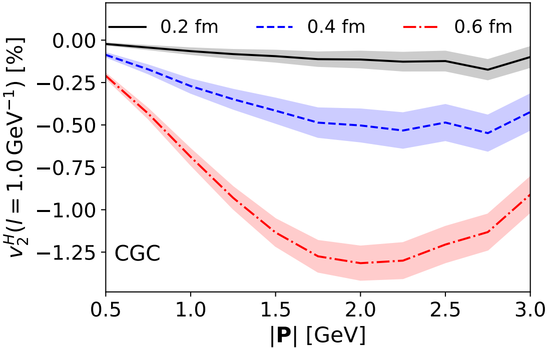


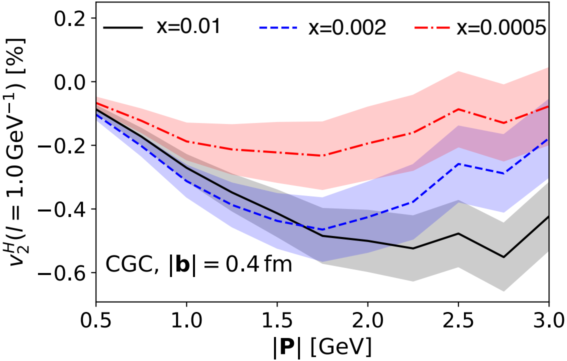


- Wigner distribution negative at small $|\mathbf{P}|$
- At $|\mathbf{P}| \gtrsim 1/l$ matches Husimi
- Elliptic parts negative, match at $|\mathbf{P}| \gtrsim 1/l$
- $|xW_2| \gg xH_2$ at small $|\mathbf{P}|$

Husimi distribution, closer look

Study Husimi distribution and define $\mathbf{v_2^H} = \mathbf{xH_2/xH_0}$, 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