Probing the nucleon and nuclei at small $x$

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October 17, 2019 / Implications of LHCb measurements and future prospects
Exploring the QCD phase diagram: the LHCb potential

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 $q + A \rightarrow q + X$

$\sigma \sim \text{dipole amplitude} \sim \text{gluon}$

$q$ in $A$ and $A^*$

Deep inelastic scattering

$\sigma \sim \text{dipole amplitude} \sim \text{gluon}$

(optical theorem)

Exclusive processes

$\sigma \sim \text{dipole amplitude}^2$
Probing protons and nuclei at high energy

**CGC**: unified framework to describe inclusive and exclusive scattering

\[ q + A \rightarrow q + X \]
\[ \sigma \sim \text{dipole amplitude} \sim \text{gluon} \]
\( q \) in \( A \) and \( A^* \)

**Deep inelastic scattering**
\[ \sigma \sim \text{dipole amplitude} \sim \text{gluon} \]
(optical theorem)

- 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 \( b \)!

\[ \sigma \sim \text{dipole amplitude}^2 \]
1. Inclusive particle production $p + Pb$

$$R_{pA} = \frac{dN^p/dA}{N_{bin}dN^{pp}}$$

- 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 $x$
Forward spectra – thank you!

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

B. Ducloué, T. Lappi, H.M, 1612.04585

B. Ducloué, T. Lappi, H.M, 1503.02789
2. Diffraction, vector meson photoproduction

High energy factorization:

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

Diffractive scattering amplitude

$$ A_{\gamma^* p \rightarrow Vp} \sim \int d^2b dz d^2r \psi^\gamma \psi^V(r, z, Q^2) e^{-ib \cdot \Delta} N(r, x, b) $$

- Impact parameter is the Fourier conjugate to the momentum transfer
  → Access to the spatial structure
- Recall: $N \sim$ gluon, so $\sigma \sim$ gluon$^2$
Two classes of diffractive events

Coherent diffraction:
Target proton/nucleus remains in the same quantum state
Probes average density

\[
\frac{d\sigma}{dt} \sim |\langle A^{\gamma^* p \rightarrow Vp} \rangle|^2
\]

Incoherent/target dissociation:
Total diffractive − coherent cross section
Target breaks up

\[
d\sigma_{\gamma^* p \rightarrow Vp} \sim \langle|A^{\gamma^* p \rightarrow Vp}|^2\rangle - |\langle A^{\gamma^* p \rightarrow Vp} \rangle|^2
\]

Variance, measures the amount of fluctuations!

\[
\frac{d\sigma}{dt} |t|
\]

Coherent/Elastic
Incoherent/Breakup

t_1 t_2 t_3 t_4

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001
Two classes of diffractive events

Coherent diffraction:
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\frac{d\sigma^{\gamma^* p \rightarrow Vp^*}}{dt} \sim \langle |A^{\gamma^* p \rightarrow Vp}|^2 \rangle − |\langle A^{\gamma^* p \rightarrow Vp} \rangle|^2
\]

Variance, measures the amount of fluctuations!
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 $\gamma + p$
Coherent diffraction

\[ \frac{d\sigma}{dy} (\text{mb}) \]

\( y \)-distribution of the cross-section for the reaction \( \text{Pb+Pb} \rightarrow \text{Pb+Pb} + J/\psi \) at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \).

- ALICE Coherent \( J/\psi \)
- Reflected

\( \gamma A \): nPDFs and CGC calculations compatible

\( pp \): HERA measurements extended to large \( W \), deviation from the power law?

\( \sigma_{\gamma p} \rightarrow J/\psi p \) [nb]

- Power law fit to H1 data
- JMRT NLO prediction

\( W \) [GeV]

- LHCb (\( \sqrt{s} = 13 \text{ TeV} \))
- LHCb (\( \sqrt{s} = 7 \text{ TeV} \))
- ALICE
- H1
- ZEUS
- Fixed target exp.
Constraining proton fluctuations: $\gamma + p \rightarrow J/\Psi + p \ (W = 75 \text{ GeV})$

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

HERA data requires large event-by-event fluctuations

**CGC calculation H.M, B. Schenke, 1607.01711**
Energy dependence – LHC advantage

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

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

- Incoherent cross section $\approx 0$ 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

\[ W(x, \vec{k}_{\perp}, \vec{b}_{\perp}) = \int \frac{d^2 \Delta_{\perp}}{(2\pi)^2} e^{i\vec{b}_{\perp} \cdot \vec{\Delta}_{\perp}} \int \frac{dz^- d^2 z_{\perp}}{16\pi^3} e^{ixP^+ z^- - i\vec{k}_{\perp} \cdot \vec{z}_{\perp}} \langle P - \frac{\Delta}{2} | q(-z/2) \gamma^+ q(z/2) | P + \frac{\Delta}{2} \rangle \]
Diffractive dijets and the Wigner distribution: more differential imaging

Two momenta, extra handle

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

\[ \Delta = k_1 + k_2 \text{ recoil momentum} \]
\[ P = \frac{1}{2}(k_1 - k_2) \text{ dijet momentum} \]
\[ \text{Nearly back-to-back jets, } |P| > |\Delta| \]

\[ d\sigma \sim \nu_0(1 + 2\nu_2 \cos[2\theta(P, \Delta)]) \]

Hatta, Xiao, Yuan, 1601.01585
Hagiwara et al, 1706.01765

\( \nu_2 \) in principle connected to elliptic part of gluon Wigner distribution in certain limit \((Q^2 \to 0 [=\text{LHC}], |P| \gg |\Delta|)\)

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

\[ \gamma^* + p \rightarrow \text{jet}_1 + \text{jet}_2 + p \]

\[ q^\perp - \Delta^\perp \]

Altinoluk, Armesto, Beuf, Rezaeian, 1511.07452

\[ \frac{d\sigma}{dP d\Delta} \sim \int_{bb'} e^{-i(b-b')\cdot \Delta} e^{-i(r-r')\cdot P} N(r, b) N(r', b') \otimes \cdots \]

- \( P \) and \( \Delta \) are conjugates to dipole size and impact parameter.
  - Coordinate space: Dipole-target interaction \( N(r, b) \) depends on \( \theta(r, b) \)
  - Momentum space: Cross section depends on \( \theta(P, \Delta) \)
  - Mixed space: Wigner distribution \( xW(k, b) \) depends on \( \theta(k, b) \)

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

- \( \Delta = k_1 + k_2 \)
- \( P = \frac{1}{2}(k_1 - k_2) \)

Y. Hatta, B-W. Xiao, F. Yuan, 1601.01585
Charm dijets, extracted $v_2 \left( \gamma^* + p \rightarrow \text{jet} + \text{jet} + p \right)$

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 $\Delta$, but connection to Wigner more complicated

$$d\sigma \sim v_0 \left( 1 + 2v_2 \cos[2\theta(P, \Delta)] \right)$$
Energy dependence of total $v_2$ (transverse + longitudinal)

With JIMWLK (pert. $x$ evolution)
- $v_2$ decreases by factor $\sim 2$ 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

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

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

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 $p \rightarrow A$

H.M, Lappi, 1209.2853

- Nuclear suppression factors
- Rapidity (Bjorken-$x$) dependencies

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ATLAS-CONF-2017-011

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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 overlapping hot spots

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

+ 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 $Q_s^2(b)$
- Random color charges, Yang-Mills equations
- Perturbative small-$x$ evolution
- Dipole-proton scattering amplitude $N$
  
  Dipole size $r$, impact parameter $b$

\[ N(r, b, y) = v_0(1 + 2v_2 \cos[2\theta(r, b)]) \]

Evolution suppresses elliptic modulation

Expect to see that also in dijet production

Parameters constrained by HERA $F_2$ and $J/\Psi$ data

H. M., B. Schenke 1607.01711, 1806.06783
Diffraction at high energy

High energy factorization

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

Target remains intact (Good-Walker picture)

\[
\frac{d\sigma}{dt} \sim |\langle A \rangle|^2
\]

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

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

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

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

Introduce $r, b$ correlation to the IPsat

Calculate two quark production ($\text{quark} \approx \text{jet}$)

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

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

$T(b)$: proton density profile

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

Dijet cross section has no dependence on $\theta(P, \Delta)$ if $\tilde{c} = 0$ (dashed line)
Larger modulation away from correlation limit

- Significant modulation at large $|\Delta|$
- ... where connection to Wigner is less clear
- But can calculate $\sigma$ 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)

Salazar, Schenke, 1905.03763
Wigner and Husimi distributions – to the mixed space

Compare predicted dijet $v_n$ to gluon Wigner and Husimi distributions

<table>
<thead>
<tr>
<th>Wigner distribution $xW(x, P, b)$</th>
<th>Husimi distribution $xH(x, P, b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most complete description</td>
<td>Wigner + with Gaussian smearing</td>
</tr>
<tr>
<td>No probabilistic interpretation (uncertainty principle)</td>
<td>Positive definite, probabilistic interpretation</td>
</tr>
<tr>
<td>Not positive definite</td>
<td>Dependence on the smearing parameter $l$</td>
</tr>
<tr>
<td>Large dipoles important</td>
<td>Large dipoles suppressed by $l$</td>
</tr>
</tbody>
</table>

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

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

Here $l = 1\text{GeV}^{-1}$ corresponds to coordinate space smearing distance $\sim 0.2 \text{ fm}$.
Wigner and Husimi distributions - to the mixed space

\[ xH = xH_0 + 2xH_2 \cos 2\theta(P, b), \quad xW = xW_0 + 2xW_2 \cos 2\theta(P, b) \]

- Wigner distribution negative at small \( |P| \)
- At \( |P| \gtrsim 1/l \) matches Husimi
- Elliptic parts negative, match at \( |P| \gtrsim 1/l \)
- \( |xW_2| \gg xH_2 \) at small \( |P| \)
Husimi distribution, closer look

Study Husimi distribution and define $v^H_2 = xH_2/xH_0$, find $v^H_2 \sim 0.1 \ldots 1\% \sim$ dijet $v_2$

- Large ellipticity at large impact parameters
- $v^H_2 \rightarrow 0$ at large $P$: target smooth at small distance scales

- Generally $v^H_2 \rightarrow 0$ due to evolution
- Increasing $|v^H_2|$ at small $|P|$: proton grows, and gradients at scale $\sim l$ start to contribute