Proton structure fluctuations: from HERA to the LHC

Heikki Mäntysaari

Brookhaven National Laboratory

DIS 2017

A fundamental question
How are the quarks and gluons distributed in space inside the nucleon?

Practical applications
Initial state geometry is a necessary input for hydrodynamical simulations

- Collective phenomena seen in pp&pA
- Initial state geometry \( \Rightarrow \) final state collectivity

Diffractive processes probe
- Spatial density profile
- **Density fluctuations**

ATLAS, arXiv:1409.1792
Diffractive vector meson production in dipole picture

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

Diffractive scattering amplitude

$$A \sim \int d^2b dzd^2r \Psi^\gamma \Psi^V(r, z, Q^2) e^{-ib \cdot \Delta} N(r, x, b)$$

- Fourier transfer from impact parameter to transverse momentum $\Delta$ → access to spatial structure
- $\Delta = \text{transverse momentum of the vector meson}$
- $N$ is universal dipole-proton scattering amplitude (here: IPsat/IP-Glasma)
Coherent diffraction = target remains intact

Target is at the same quantum state before and after the scattering:

\[ \langle \rangle = \text{target average} \quad \text{(Miettinen, Pumplin, PRD 18, 1978, ...)} \]

\[ \frac{d\sigma}{dt} \gamma^* p \rightarrow V p \sim |\langle A(x, Q^2, t)\rangle|^2 \]

with

\[ A \sim \int d^2 b dz d^2 r \psi^* \psi^v(r, z, Q^2) e^{-ib \cdot \Delta} N(r, x, b) \]

- Coherent \( t = -\Delta^2 \) spectra is Fourier transfer of the average density
Incoherent diffraction = target breaks up

Total diffractive cross section $\rightarrow$ coherent cross section $\rightarrow$ target breaks up

$$\frac{d\sigma_{\gamma^* p \rightarrow V p^*}}{dt} \sim \langle |A(x, Q^2, t)|^2 \rangle - \left| \langle A(x, Q^2, t) \rangle \right|^2$$

with

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

- Incoherent cross section is variance $\Leftrightarrow$ sensitive to fluctuations
Incoherent diffraction $= \text{target breaks up}$

Total diffractive cross section $- \text{coherent cross section} \rightarrow \text{target breaks up}$

$$\frac{d\sigma_{\gamma^* p \rightarrow V p^*}}{dt} \sim \langle |A(x, Q^2, t)|^2 \rangle - |\langle A(x, Q^2, t) \rangle|^2$$

with

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

- Incoherent cross section is variance $\Leftrightarrow$ sensitive to fluctuations

Constraints

Simultaneous description of coherent and incoherent data allows us to constrain the average shape and the amount of fluctuations
Constraining proton fluctuations

Start with a 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
Constraining proton fluctuations

Start with a 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.

Now proton = 3 overlapping hot spots.

\[ T_{\text{proton}}(b) = \sum_{i=1}^{3} T_q(b - b_i) \quad T_q(b) \sim e^{-b^2/(2B_q)} \]
Adding color charge fluctuations: IP-Glasma

- Use IPsat dipole model to obtain $Q_s(b_T)$ from $T_{\text{proton}}(b_T)$
- MV-model: Sample color charges, density $\sim Q_s(b_T)$
- Solve Yang-Mills equations to obtain the Wilson lines

$$V(b_T) = P \exp \left( -ig \int \frac{\rho(x^-, b_T)}{\nabla^2 + m^2} \right)$$

- Dipole amplitude: $N(x_T, y_T) = 1 - \text{Tr} V(x_T)V^\dagger(y_T)/N_c$
- Fix parameters $B_{qc}, B_q$ and $m$ with HERA data

Wilson lines will be input for hydrodynamical calculations later!
$\gamma p \rightarrow J/\psi p, W = 75 \text{ GeV}$

- Color charge fluctuations alone are not enough
IP-Glasma and HERA $\gamma p \rightarrow J/\Psi p$ data

- Large geometric fluctuations are needed
- Also included $Q_s$ fluctuations that improve the description at small $|t|$ ($\sim$ large distance)

Parameters fitted to H1 data

H.M., B. Schenke, PRD94 (2016), 034042
Application I: collectivity in pA collisions

Large elliptic flow ($v_2$) seen in pA collisions

IP-Glasma with hydro works will with the AA data, apply to pA
Does it work?

First approach: round proton with only color charge fluctuations

B. Schenke, R. Venugopalan,
PRL113 (2014) 102301

Color charge and $Q_s$ fluctuations in the initial state do not create large enough flow harmonics to the final state
Hydro calculations with proton fluctuations from HERA

Hydro numbers

- $\tau_0 = 0.4$ fm
- $T_{fo} = 155$ MeV
- Shear and bulk viscosity
- Initial $\pi^{\mu\nu}$
- $\eta/s = 0.2$

Good description of $v_n$ at high multiplicities.

Application II: Ultraperipheral AA collisions

UltraPeripheral heavy ion Collisions (UPC):
access to nuclear DIS before EIC

- At $|b_T| > 2R_A$ one nucleus acts as a photon source
- Write dipole-nucleus amplitude $N_A$ as

$$
1 - N_A(r_T, b_T, x) = 1 - \prod_{i=1}^{A} \left[ 1 - N(r_T, b_T - b_T,i, x) \right]
$$

Two sources of fluctuations:
- Sample nucleon positions from Woods-Saxon
- Sample constituent quark structure for each nucleon

Currently: no IP-Glasma description of the nucleus, use IPsat to describe dipole-nucleon scattering
Accessing fluctuations at different scales

\[ \text{Pb} + \text{Pb} \rightarrow J/\Psi + \text{Pb} + \text{Pb}, \sqrt{s} = 5.02 \text{ TeV}, y = 0 \]

- $\sqrt{|t|}$ is conjugate to $b_T$
- Small $|t|$: fluctuations of nucleon positions
- Large $|t|$: fluctuations at subnucleon scale
- Incoherent slope changes at $|t| \approx 0.25 \text{GeV}^2 \sim 0.4 \text{ fm}$

which is size of hot spots

Coherent: thick lines
Incoherent: thin lines

H. M., B. Schenke, arXiv:1703.09256
Comparison to LHC data, no subnucleonic fluctuations

Pb + Pb → $J/\Psi + Pb + Pb$ (coherent), $\sqrt{s_{NN}} = 2760$ GeV

Pb + Pb → $J/\Psi + Pb + Pb^*$ (incoherent), $\sqrt{s_{NN}} = 2760$ GeV

- Only fluctuations of nucleon positions from Woods-Saxon
  Coherent cross section overestimated and incoherent underestimated
- $\sim 20 \ldots 30\%$ normalization uncertainty from the $J/\Psi$ wave function

H.M, B. Schenke, arXiv:1703.09256
Comparison to LHC data, with subnucleon fluctuations

\[ \text{Pb} + \text{Pb} \rightarrow J/\Psi + \text{Pb} + \text{Pb} \text{ (coherent)}, \quad \sqrt{s_{NN}} = 2760 \text{ GeV} \]

- Consistently slightly above the data, incoherent/coherent ratio compatible
- \( \sim 20 \ldots 30\% \) normalization uncertainty from the \( J/\Psi \) wave function
Conclusions

- Constrain (amount of) proton structure fluctuations using HERA diffractive data
- Applications to LHC
  - pA hydro calculations compatible with LHC $\nu_n$ data
  - Required for good description of the LHC ultraperipheral AA data
  - $t$ spectra from UPC sensitive to scale at which fluctuations take place
- Next step: include small-$x$ evolution in terms of JIMWLK equation
Saturation scale fluctuations

Saturation scale fluctuations ($p + p$ multiplicity distributions: $\sigma \sim 0.5$)

$$P(\ln \frac{Q_s^2}{\langle Q_s^2 \rangle}) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left[ -\frac{\ln^2 \frac{Q_s^2}{\langle Q_s^2 \rangle}}{2\sigma^2} \right]$$

McLerran, Tribedy, arXiv:1508.03292: $p + p$ multiplicity distributions: $\sigma \sim 0.5$

- Shifted to keep average $Q_s$ unchanged
- Allow $Q_s^2$ of each constituent quark to fluctuate
- If no geometric fluctuations, divide transverse space to $\sim 1/Q_s^2$ cells where $Q_s^2$ fluctuates
Impact Parameter dependent saturation model for the dipole amplitude

\[
N = 1 - \exp\left[-\frac{\pi^2}{2N_c} \alpha_s x g(x, \mu^2) T_p(b) r^2\right]
\]

- \( T_p(b) \) is transverse proton density function (Gaussian)
- \( x g \) is DGLAP evolved gluon density
- Free parameters fitted to HERA \( F_2 \) data
  (Kowalski, Teaney 2003; Rezaeian et al, 2013)
Lumpiness matters, not details of the density profile

3 valence quarks that are connected by "color flux tubes":
Gaussian tubes connecting quarks. Also good description of the data

H.M, B. Schenke, PRD94 034042
Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911
Dependence on $\tau_0$
Insensitivity on infrared cutoff

IP-Glasma: IR cutoff $m \sim \Lambda_{\text{QCD}}$ to regulates long distance coulomb tails
- Proton size depends on $m$
- No sensitivity at large $|t|$
Saturation scale fluctuations w/o geometric fluctuations

Allow $Q_s^2$ to fluctuate, $P(\ln Q_s^2/\langle Q_s^2 \rangle) \sim \exp(-[\ln^2 Q_s^2/\langle Q_s^2 \rangle]/2\sigma)$

Constrained by $pp$ multiplicity fluctuations (McLerran, Tribedy, arXiv:1508.03292)

- $Q_s$ fluctuations alone are not enough
Saturation scale fluctuations + geometric fluctuations

Allow $Q_s$ of each constituent quark to fluctuate separately (IPsat):

- $Q_s$ fluctuations dominate incoherent cross section at small $|t|$ ($\sim$ large distance)
Allow $Q_s$ of each constituent quark to fluctuate

Constrained by $pp$ multiplicity data \cite{McLerran}

$Q_s$ fluctuations improve description at small $|t|$ $\sim$ large distance