Hadron shape fluctuations and its relation to DIS

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Heavy ion collisions: Initial spatial anisotropy $\Rightarrow$ momentum anisotropy. Pb + Pb data well described by relativistic hydrodynamics (collectivity)

Fourier harmonics $v_n$

$$\frac{dN}{d\phi} \sim N_0(1 + 2v_2 \cos(2\phi) + \ldots)$$
LHC surprise

Large elliptic flow $v_2$ seen in proton-lead collisions!
Something causes collectivity, again hydrodynamically evolving QGP?

Same hydro framework fails with the LHC $p+Pb$ data:

![Graph showing CMS $p+Pb$ $v_2$ and $p+Pb$ $v_2$](Schenke, Venugopalan, 1405.3605)
Proton geometry from heavy ion physics point of view

LHC surprise

Large elliptic flow $v_2$ seen in proton-lead collisions!

Something causes collectivity, again hydrodynamically evolving QGP?

Same hydro framework fails with the LHC $p+Pb$ data:

But a round proton was assumed!

And nature is quantum mechanical (more complicated)

Schenke, Venugopalan, 1405.3605
Going beyond round proton

A fundamental question
How are quarks and gluons distributed spatially inside the proton?
How do the positions fluctuate?

Practical applications to for example
Collective phenomena in $p + A$ and $p + p$
Mäntysaari, Schenke, Shen, Tribedy, Heinz,
Singer, Welsh, Moreland, Bernhard, Ke, Bass, Albacete, Petersen, Soto-Ontoso

Exclusive scattering processes
Mäntysaari, Schenke, Cepila, Contreras, Takaki, Krelina

Elastic $p + p$ and hollowness effect
Albacete, Soto-Ontoso

This talk: use exclusive scattering in $e + p$ to constrain the fluctuations
Applications to heavy ion phenomenology

Also other approaches
Deep Inelastic Scattering as a probe of the proton structure

DIS at high energy: dipole picture

Optical theorem:
\[ \sigma \gamma^* p \sim \text{dipole amplitude} \]

\[ \sigma \gamma^* p \rightarrow Vp \sim |\text{dipole amplitude}|^2 \]

Universal dipole amplitude

QCD dynamics is included in the dipole amplitude \( N \)

- Total cross section \( \sim N \sim \text{gluon density} \)
- Diffraction \( \sim N^2 \sim \text{gluon density}^2 \)
  + access to spatial structure
Diffractive vector meson production

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

\[ \mathcal{A}_{\gamma^* p \rightarrow V p} \sim \int d^2 b d z d^2 r \Psi_{\gamma^*} \Psi^V(r, z, Q^2) e^{-ib \cdot \Delta} N(r, x, b) \]

- Impact parameter is the Fourier conjugate of the momentum transfer
- Access to the spatial structure
Average over configurations

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

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

\[ \langle \rangle \text{: average over target configurations} \left[ N(r, b) \right] \]

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

\[ d\sigma_{\gamma^* p \rightarrow \gamma p} \]
Coherent/Elastic
Incoherent/Breakup
t1 t2 t3 t4

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001
Average over configurations

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

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

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

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

Variance, measures the amount of fluctuations!

\langle \rangle: average over target configurations \([N(r, b)]\)
Constraining proton fluctuations: $\gamma + p \rightarrow J/\Psi + p$

HERA data with only color charge fluctuations

Round proton IP-Glasma proton: Color charges + Yang-Mills

Problem with the incoherent cross section

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

Now proton = 3 overlapping hot spots.

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

H.M, Schenke, 1607.01711, 1603.04349, also more complicated geometries
Constraining proton fluctuations: $\gamma + p \rightarrow J/\psi + p$

$|t| \ [\text{GeV}^2]$

$|t| \ [\text{GeV}^2]$ with fluctuations
Round proton
H1 coherent
H1 incoherent

$W = 75 \text{ GeV}$

H.M, B. Schenke, 1607.01711

Large event-by-event fluctuations are needed
Implications on heavy ion phenomenology: p+A

Round protons: hydro simulations failed to describe $v_2$ in $p + Pb$ collisions

\[
\left\langle v_2^2 \right\rangle^{1/2}
\]

Schenke, Venugopalan, 1405.3605
Hydro + fluctuations from HERA $J/\Psi$ data: success

H.M, Schenke, Shen, Tribedy, 1705.03177
Implications on heavy ion phenomenology: \( p + A \)

Hydro + fluctuations from HERA \( J/\Psi \) data: success

\[ v_{2}(2) \text{ IP-Plasma+fluc. proton+MUSIC+UrQMD } \tau_{0}=0.4 \text{ fm} \]

\[ v_{3}(2) \text{ IP-Plasma+fluc. proton+MUSIC+UrQMD } \tau_{0}=0.4 \text{ fm} \]

\[ v_{2}(2) \text{ CMS peripheral subtracted} \]

\[ v_{3}(2) \text{ CMS peripheral subtracted} \]

\[ 0-20\% \text{ pPb @ 5.02 TeV} \]

\[ R_{\text{long}} \text{ (fm)} \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \]

\[ k_{T} \text{ (GeV)} \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.1 \]

\[ \frac{R_{\text{out}}}{R_{\text{side}}} \text{ (fm)} \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.1 \]

\[ \text{decays only} \]

\[ \text{full UrQMD} \]

\( \text{ALICE } \pi^{+} + \pi^{-} \quad K^{+} + K^{-} \quad p + \bar{p} \quad \Lambda + \bar{\Lambda} \)

\[ \pi^{+} (\eta/s)(T) \quad K^{+} (\eta/s)(T) \quad p (\eta/s)(T) \quad \Lambda (\eta/s)(T) \]

\[ \eta/s=0.2 \]

\[ 0-20\% \text{ pPb @ 5.02 TeV} \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.1 \]

\[ R_{\text{side}} \text{ (fm)} \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.1 \]

\[ R_{\text{out}} (\text{fm}) \]

\[ 0.0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.1 \]

H. M. Schenke, Shen, Tribedy, 1705.03177
Alternative approach: fluctuations from $p + A$ data

Extract proton shape parameters from hydro simulations of $p + Pb$ data by applying Bayesian methodology, similar results

Proton thickness function

Moreland, Bernhard, Ke, Bass, QM2017 and 1704.04486
Alternative approach 2: symmetric cumulants in $p + p$

CMS: in central $p + p$ correlation between $v_2$ and $v_3$ becomes negative
Explained: fluctuating hot spots + short range repulsive correlations

CMS: $SC(2, 3) < 0$ in central $p + p$

Sign change with 3 hot spots + nonzero repulsive distance $r_c$

CMS-PAS-HIN-16-022

Albacete, Petersen, Soto-Ontoso, 1707.05592
**Beyond HERA**

A and $x$ dependence from the LHC

Ultra Peripheral heavy ion Collisions (UPC):
access to photonuclear reactions

- At $|b_T| > 2R_A$ one nucleus acts as a photon source

Two sources of fluctuations:

- Nucleon positions from Woods-Saxon
- Constituent quark structure for each nucleon

Exclusive $J/\Psi$ production: probe both components
Accessing fluctuations at different scales

LHC: Access nuclear gluon at very small $x$, midrapidity $x_p \approx 6 \cdot 10^{-4}$

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

| $|t|$ | $\mathrm{d} \sigma / \mathrm{d} t / \mathrm{d} y$ [mb/GeV$^2$] |
|---|---|
| $0.0$ | $10^3$ |
| $0.1$ | $10^2$ |
| $0.2$ | $10^1$ |
| $0.3$ | $10^0$ |
| $0.4$ | $10^1$ |
| $0.5$ | $10^2$ |
| $0.6$ | $10^3$ |
| $0.7$ | $10^4$ |

Geometric and $Q_s$ fluctuations in the nucleons
No subnucleon fluctuations

Generically
- $\sqrt{|t|}$ is conjugate to $b_T$
- Small $|t|$: fluctuations at nucleon scale
- Large $|t|$: fluctuations at subnucleon scale

LHC: see nucleon scale fluctuations in Pb

H.M. Schenke, 1703.09256; Cepila, Contreras, Krelina, 1711.01855:

ALICE UPC data \textsuperscript{(1406.7819)} seems to prefer subnucleon fluctuations
Bjorken-$x$ dependence

Approach 1: parametrize number of hot spots

Small-$x$ gluon emissions increase the number of hot spots

\[ N_{hs}(x) \sim x^{p_1}(1 + p_2 \sqrt{x}) \]

Cepila, Contreras, Tapia Takaki, 1608.07559

Approach 2: Solve small-$x$ evolution equations

Evolve proton structure by solving
- BK evolution with impact parameter \( \text{Berger, Stasto, 1106.5740} \)
- JIMWLK evolution \( \text{Schlichting, Schenke, 1407.8458, H.M., Schenke, 18xx.xxxx} \)

Fit HERA $F_2$ and exclusive data.
Difficulty: regulating confinement effects
Towards small $x$: $\gamma + p \rightarrow J/\Psi + p^*$

Increasing # of hot spots w energy: Smoother proton, less fluctuations

JIMWLK evolution event-by-event

Cepila, Contreras, Tapia Takaki, 1608.07559

H.M, Schenke, in progress
Ultraperipheral $p + A$ at the LHC:
Photon flux $\sim Z^2 \Rightarrow \gamma + p$ dominates

Forward/backward rapidity $J/\Psi$
High/low $W$

- No incoherent at high $W$
  $\Rightarrow$ smoother proton(?)

ALICE: 1406.7819
Conclusions

Multi dimensional event-by-event picture of the proton
- Input from (diffractive) DIS, applications on heavy ion phenomenology
- Or vice versa... 

Strong hints from HERA and LHC data that
- Proton geometry has large event-by-event fluctuations
- Fluctuations evolve in $x$

New interesting data coming
- Ultraperipheral collisions at the LHC
- Electron Ion Collider
BACKUPS
Lumpiness matters, not details of the density profile

Example: 3 valence quarks that are connected by "color flux tubes": Also a good description of the data with large fluctuations

H.M, B. Schenke, PRD94 034042
Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911