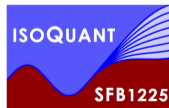# Azimuthal correlations in photoproduction and deep inelastic *ep* scattering at HERA

Dhevan Gangadharan

University of Houston

HERA 4 EIC, 9 June 2022
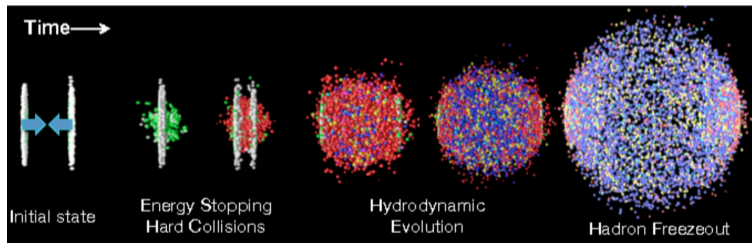
Subject of this analysis

The study of multibody QCD interactions under extreme conditions

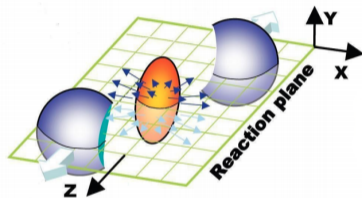Confinement in QCD "hides" the details of such interactions
We can collide **heavy nuclei** to open them up in the laboratory
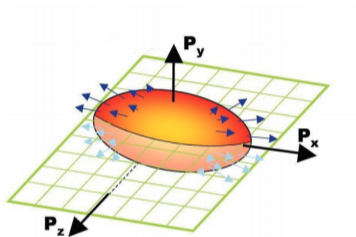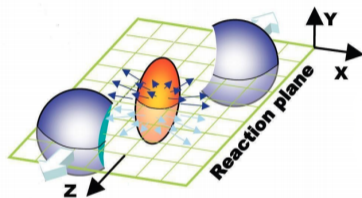

Central Question:
Is a similar kind of multibody environment created in much smaller **ep** systems produced at HERA?

A pillar of heavy-ion measurements: **Elliptic Anisotropy**
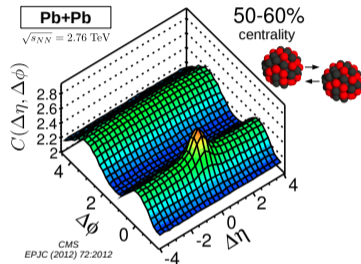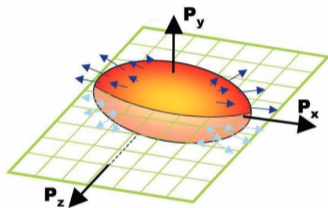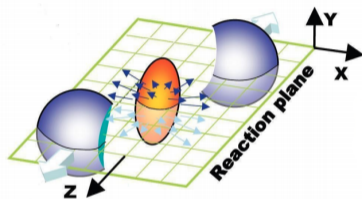

- The spatial configuration of the **initial scattering** typically has a large elliptic component.

A pillar of heavy-ion measurements: **Elliptic Anisotropy**

- The spatial configuration of the **initial scattering** typically has a large elliptic component.
- **Rescattering** between the produced partons converts this spatial eccentricity into an asymmetry in momentum space.

# A pillar of heavy-ion measurements: **Elliptic Anisotropy**

- The spatial configuration of the **initial scattering** typically has a large elliptic component.
- **Rescattering** between the produced partons converts this spatial eccentricity into an asymmetry in momentum space.
- The elliptic asymmetry is clearly evident in two-particle correlations: **collectivity**.

Double ridge in two-particle correlations
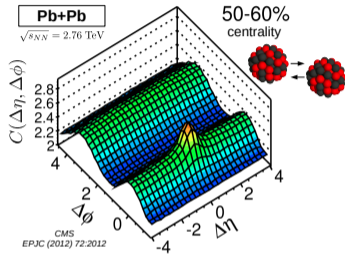
- Two particle correlations in heavy-ion collisions show a clear **double ridge**, which is interpreted as a sign of fluid-like behaviour in QCD—The QGP.
- $C(\Delta\eta, \Delta\varphi) = S(\Delta\eta, \Delta\varphi)/B(\Delta\eta, \Delta\varphi)$,
  S and B are formed from pairs from the same- and mixed-events, respectively.

Double ridge in two-particle correlations
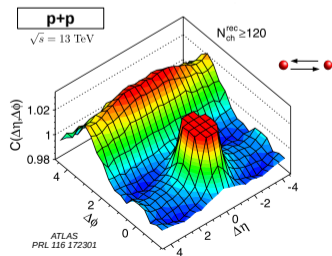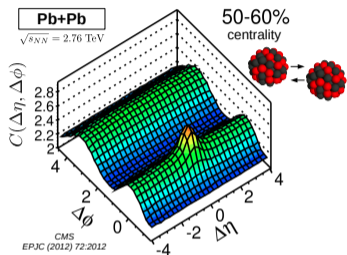
Pb+Pb
$\sqrt{s_{NN}} = 2.76$ TeV

50-60% centrality

$C(\Delta\eta, \Delta\varphi)$

CMS
EPJC (2012) 72:2012

p+p
$\sqrt{s} = 13$ TeV

$N_{ch}^{rec} \geq 120$

$C(\Delta\eta, \Delta\varphi)$

ATLAS
PRL 116 172301

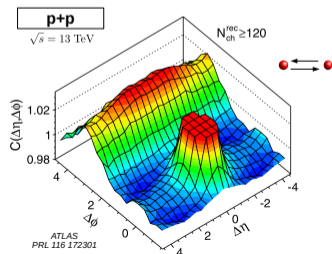- Two particle correlations in heavy-ion collisions show a clear **double ridge**, which is interpreted as a sign of fluid-like behaviour (QGP).
- $C(\Delta\eta, \Delta\varphi) = S(\Delta\eta, \Delta\varphi)/B(\Delta\eta, \Delta\varphi)$, S and B are formed from pairs from the same- and mixed-events, respectively.
- The start of the LHC revealed that high-multiplicity $p + p$ collisions also have a double-ridge!
- Such collisions were thought to be too small to produce a thermally equilibrated QGP.

Motivation for the analysis

Pb+Pb
$\sqrt{s_{NN}} = 2.76$ TeV

50-60% centrality

$C(\Delta\eta, \Delta\varphi)$

CMS
EPJC (2012) 72:2012

p+p
$\sqrt{s} = 13$ TeV

$N_{ch}^{rec} \geq 120$

$C(\Delta\eta, \Delta\varphi)$

ATLAS
PRL 116 172301
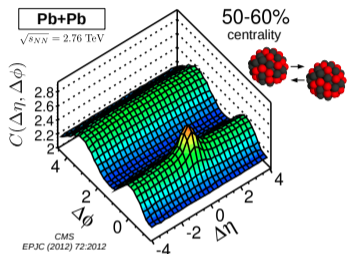
- Two particle correlations in heavy-ion collisions show a clear **double ridge**, which is interpreted as a sign of fluid-like behaviour (QGP).
- $C(\Delta\eta, \Delta\varphi) = S(\Delta\eta, \Delta\varphi)/B(\Delta\eta, \Delta\varphi)$, S and B are formed from pairs from the same- and mixed-events, respectively.
- The start of the LHC revealed that high-multiplicity $p + p$ collisions also have a double-ridge!
- Such collisions were thought to be too small to produce a thermally equilibrated QGP.
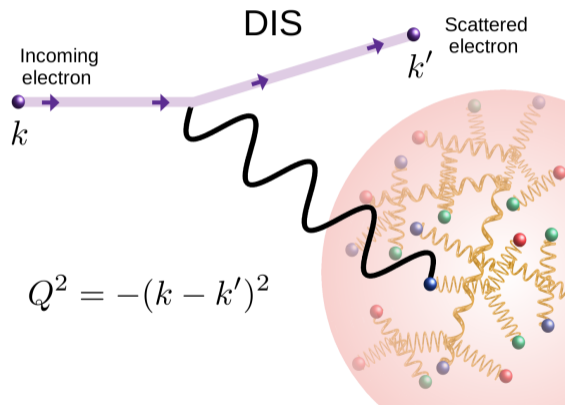- **What about even more fundamental *ep* scattering at HERA??**

The HERA collider and experiments
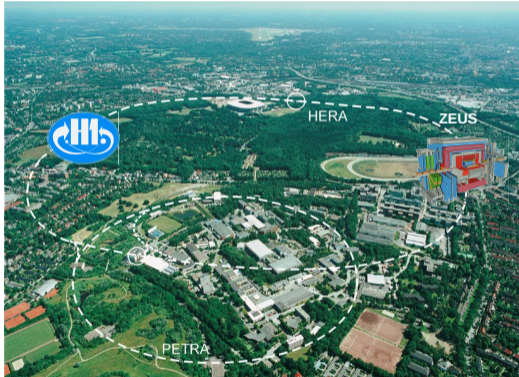
- Location: DESY, Hamburg, Germany
- Data taking: 1992 - 2007
- 27.5 GeV electrons/positrons
  920 GeV protons
  $\rightarrow \sqrt{s} = 318$ GeV
- HERA I+II:
    500 pb^{-1} per experiment

Deep inelastic scattering (DIS)

- DIS is defined by large virtualities: $Q^2 \gg \Lambda^2_{\text{QCD}}$.

- Transverse radius (R_t) and longitudinal length (L) of the probed region are given by:

  $R_t \sim \frac{1}{Q}$

  $L \sim \frac{1}{m_{proton}\, x}$ PRD 95 114008

- Neutral current (NC) DIS involves the exchange of photon or Z boson.

In the figure:

DIS

Incoming electron
k

Scattered electron
k'

$Q^2 = -(k-k')^2$

# Photoproduction (PhP)
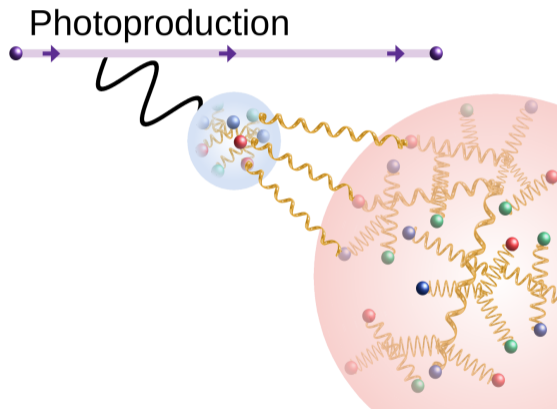
Photoproduction

- Photoproduction (γp) is defined by small virtualities: $Q^2 \ll \Lambda_{\mathrm{QCD}}^2$.
- Exchanged photon may fluctuate into quarks and gluons.
- Larger interaction regions are probed.
- **Multiparton Interactions are possible.**
- Scattering is hadron-like.

ep photoproduction: subsequent rescattering phase possible

Final-state particles

Rescattering

Initial-state surface with a dominant elliptical eccentricity
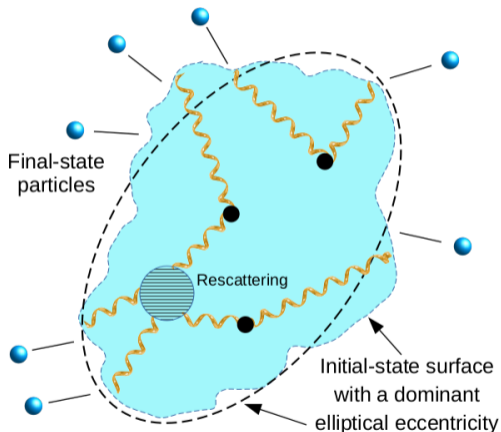
- The initial scattering is shown here with 3 MPIs (black dots)
- Unlike in DIS, the spatial extent of this "initial state" is finite with an irregular shape, in general.
- Subsequently, a phase of **rescattering may occur**, whereby a local thermal equilibrium might form.

Observables for this analysis

To search for collective behaviour and MPI in *ep* scattering, we measured the following:

- Charged hadron multiplicity distribution: dN/dN_{ch}
- Transverse momentum distribution: dN/dp_{T}
- Pseudorapidity distribution: $dN/d\eta$
- Two-particle azimuthal correlation functions: $c_n\{2\}$ and $C(\Delta\eta, \Delta\varphi)$
- Four-particle cumulant azimuthal correlations: $c_n\{4\}$

I'll present recently published measurements of azimuthal correlations
in neutral current DIS and photoproduction with the ZEUS detector: JHEP 102 2021

Additional detailed measurements in DIS alone can be found in our previous paper
JHEP 04 (2020) 070.

Two- and four-particle correlation functions

Two-particle azimuthal correlations are measured:

$$c_n\{2\} = \langle\langle \cos n(\phi_i - \phi_j) \rangle\rangle$$

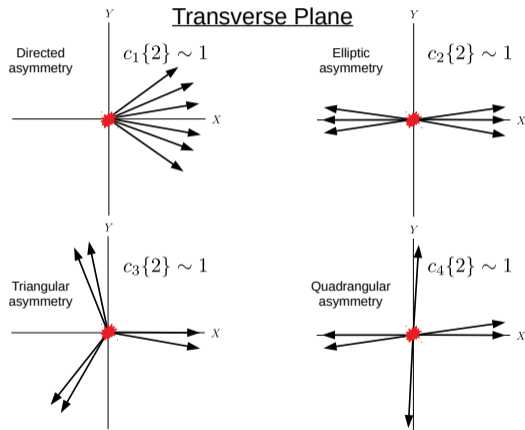φ_i is the azimuthal angle of particle i

n is the harmonic ($n=1, 2$ studied here)
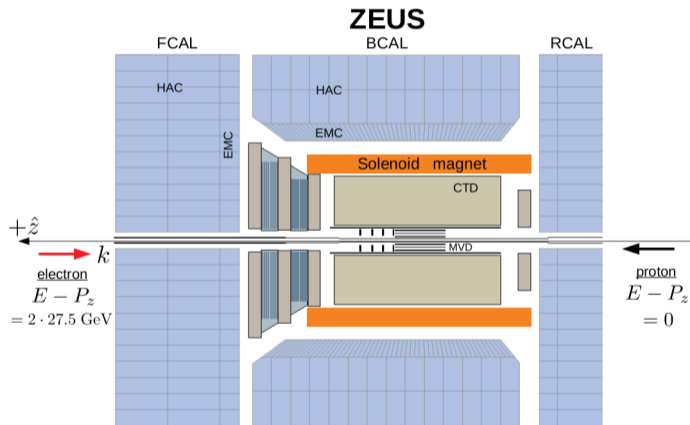
Four-particle cumulant correlations are also measured:

$$
\begin{aligned}
C_n\{4\} &= \langle\langle \cos n(\phi_i + \phi_j - \phi_k - \phi_l) \rangle\rangle \\
c_n\{4\}(p_{\mathrm{T},1}) &= C_n\{4\}(p_{\mathrm{T},1}) - 2\,c_n\{2\}(p_{\mathrm{T},1})\,c_n\{2\}
\end{aligned}
$$

Not shown here, see our JHEP publication.

Transverse Plane

Directed asymmetry $\quad c_1\{2\} \sim 1$

Elliptic asymmetry $\quad c_2\{2\} \sim 1$

Triangular asymmetry $\quad c_3\{2\} \sim 1$

Quadrangular asymmetry $\quad c_4\{2\} \sim 1$

ZEUS detector

ZEUS

FCAL · BCAL · RCAL

HAC · HAC · EMC

EMC

Solenoid magnet

CTD

MVD

$+\hat{z}$

k

electron
$E - P_z$
$= 2 \cdot 27.5$ GeV

proton
$E - P_z$
$= 0$

Charged particles are tracked in the central tracking detector (CTD) and micro vertex detector (MVD) in a 1.43 T magnetic field.

Depleted uranium calorimeters.
The barrel and rear ones are used to help identify the scattered electron.

A fully contained event is characterized by
$\sum_i (E_i - P_{z,i}) = 55$ GeV
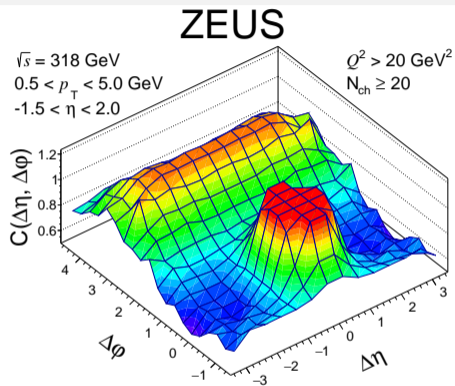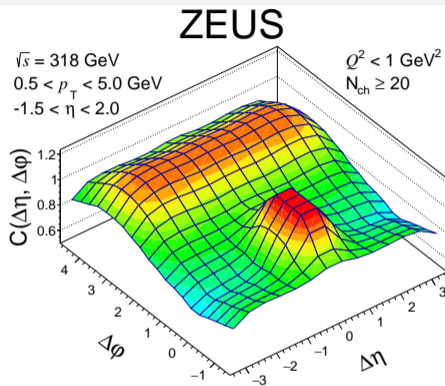due to energy and momentum conservation.

Track selection
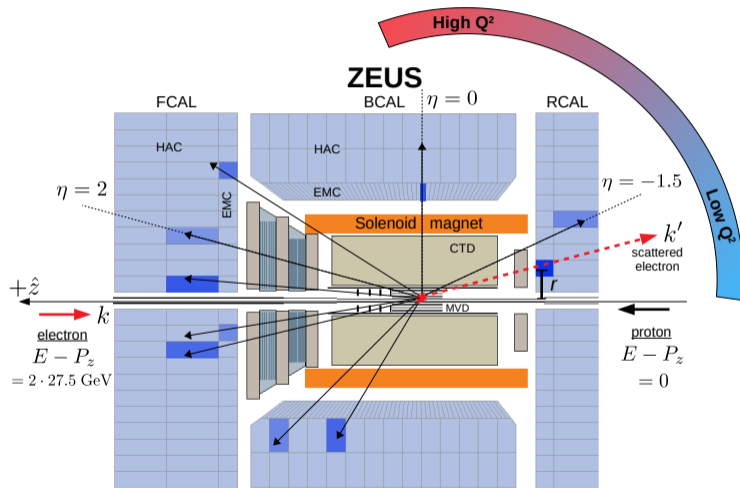
Track selection for correlation analysis

- Reject scattered electron (if detected)
- $-1.5 < \eta < 2.0$
- $0.1 < p_T < 5.0$ GeV
- ≥ 1 MVD hit
- $\text{DCA}_{XY,Z} < 2$ cm
- $\Delta R > 0.4$ (cone around electron)

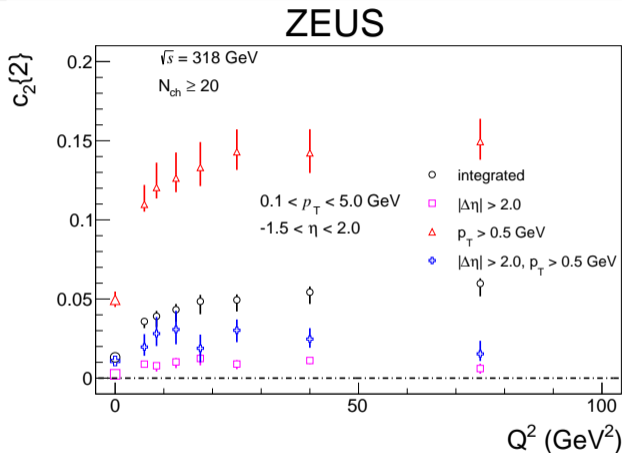$$N_{\text{ch}} = \sum_{i}^{N_{\text{rec}}} w_i^{(1)}$$

Results: Ridge plots

A near-side peak and away-side ridge are clearly visible.
Photoproduction correlations are dimished wrt those in DIS.
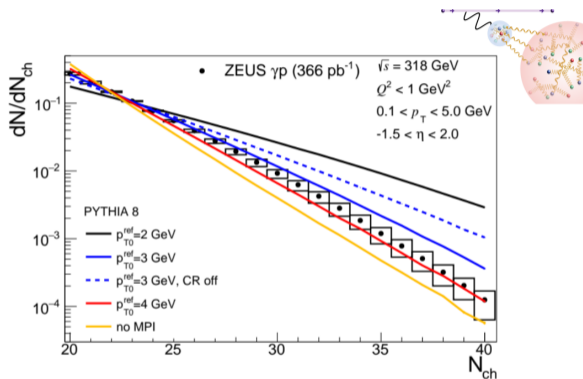**No visible double-ridge.**

Results: Q^2 evolution of $c_2\{2\}$

Photoproduction correlation strengths ($Q^2 = 0$) are clearly diminished wrt those in DIS.

Study of MPI in *ep* photoproduction

Results: dN/dN_{ch}

ZEUS γp (366 pb^{-1})

$\sqrt{s} = 318$ GeV
$Q^2 < 1$ GeV^2
$0.1 < p_T < 5.0$ GeV
$-1.5 < \eta < 2.0$

PYTHIA 8

- $p_{T0}^{ref} = 2$ GeV
- $p_{T0}^{ref} = 3$ GeV
- $p_{T0}^{ref} = 3$ GeV, CR off
- $p_{T0}^{ref} = 4$ GeV
- no MPI

	$p_{T0}^{ref} = 2$	$p_{T0}^{ref} = 3$	$p_{T0}^{ref} = 4$
$\langle nMPI \rangle$	8.3	3.8	2.2

The level of MPI and IR divergencies are controled by the p_{T0} parameter in PYTHIA 8.
It is used to regularize the interaction cross section in PYTHIA 8.

$$\frac{d\sigma}{dp_T^2} \propto \frac{\alpha_s^2(p_{T0}^2 + p_T^2)}{(p_{T0}^2 + p_T^2)^2}$$
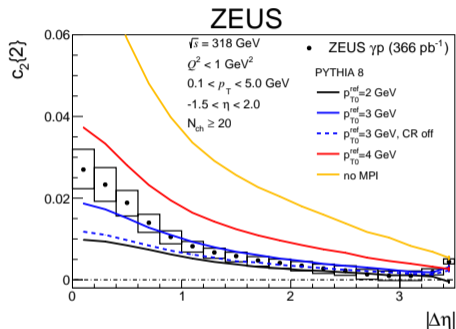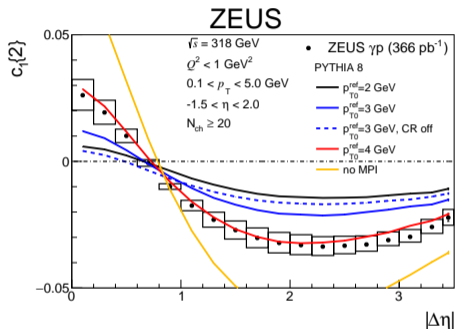
The energy dependence of this parameter is given by $p_{T0} = p_{T0}^{ref} (W/7\,\text{TeV})^{0.215}$, where W is the γp $\sqrt{s}$.

More MPI $\rightarrow$ lower p_{T0}^{ref}

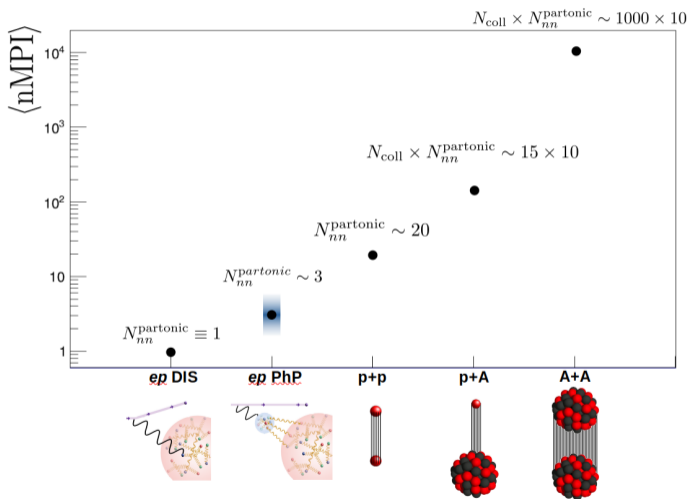Colour Reconnection (CR) is PYTHIA's modeling of rescattering between partons from different MPIs

Results: dN/dp_T and $dN/d\eta$

- The scenarios of no MPI and very many MPI are disfavored.

# Results: $c_1\{2\}$ and $c_2\{2\}$ versus $\Delta\eta$

- Correlation strengths are diluted by MPI.
- The scenarios of no MPI and very many MPI are disfavored.

Illustration of MPI growth

- Rough illustration of how nMPI grows from DIS to heavy-ions
- N_{coll}: number of binary nucleon-nucleon collisions
- $N_{nn}^{\mathrm{partonic}}$: number of parton scatterings per binary nucleon-nucleon collision
- Estimates for N_{coll} taken from
  - Ann. Rev. Nucl. Part. Sci. 57, 205 (2007)
  - PRC 97 024905 (2018).
- Estimates for $N_{nn}^{\mathrm{partonic}}$ taken from PYTHIA 8

Azimuthal correlations at the EIC
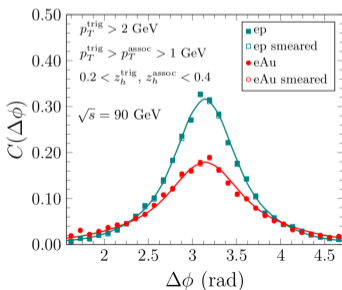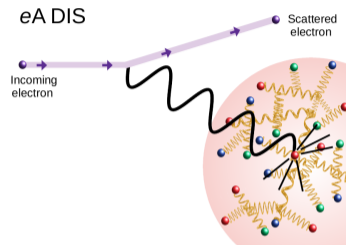
Collective behaviour in _eA_ collisions?

- At the EIC, collective behaviour may emerge in _eA_ nuclear DIS or photoproduction.
- The nucleus (e.g. Pb) is a much larger system than a proton and is a strongly correlated system.

Azimuthal correlations to search for gluon saturation

- Broadening or even a disapearance of away-side jets is expected from a quantum evolution inside a saturated system.
- To focus on low x, $1 < Q^2 < 2$ GeV^2 and $0.6 < y < 0.8$ are selected ($Q^2 = sxy$).
- Left figure taken from Fig. 7.63 of EIC Yellow Report

Summary of measurements

- Measurements of charged-particle azimuthal correlations at high multiplicity have been presented using ZEUS data in *ep* photoproduction (γp) and NC DIS at $\sqrt{s} = 318$ GeV.

- There is **no clear indication of a double ridge** from $C(\Delta\eta, \Delta\varphi)$ in either γp or DIS.

- Two-particle correlation strengths are markedly diminished in γp wrt DIS.

- The observations in both regimes **do not** reveal significant collective behaviour like that seen in heavy-ions or high-multiplicity hadronic collisions.

- While there is no consistent value of $p_{\mathrm{T0}}^{\mathrm{ref}}$ in PYTHIA 8 that describes all the γp data, **the "no MPI" scenario is strongly disfavored**.

Backup

Responses to the motivating questions

DIS probes very small length scales in the proton ($\ll 1$ fm). Photoproduction probes much larger scales, which can be as large as the proton itself.

The observations in both regimes **do not** reveal significant collective behaviour like that seen in heavy-ions or high-multiplicity hadronic collisions.

The concept of multiparton interactions provides a useful tool to help understand the emergence of collective behaviour.

It sets the stage for a potential rescattering phase.

|	nMPI	Collectivity
ep photoproduction	~ 3	No
pp high-multiplicity	~ 20	Yes

The initial states in both systems may be similar in spatial extent but completely different in the number of MPI.

Evolution of a heavy-ion collision
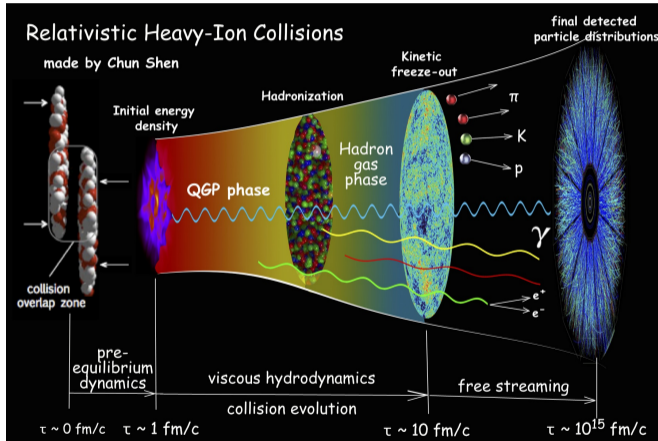
- The **initial scattering** takes place over an extended region.
- A subsequent stage of **rescattering** produces a thermally equilibrated system.
- This fluid of QCD matter is called the **quark-gluon plasma (QGP)**.
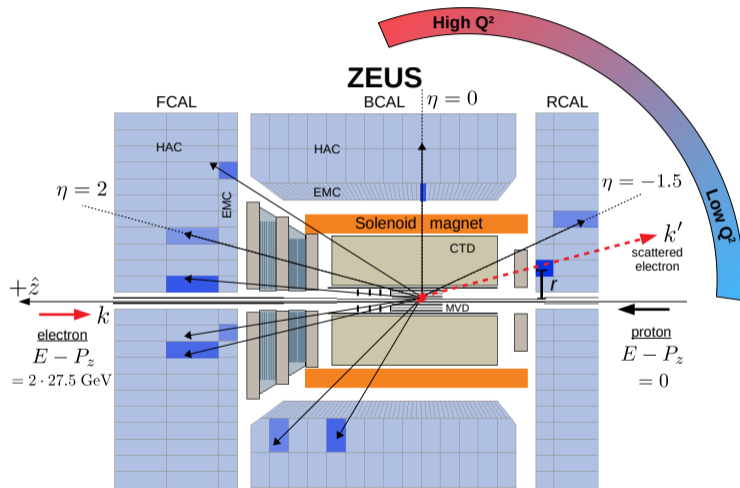- Relativistic **hydrodynamics** describes the evolution of the QGP.

DIS event selection
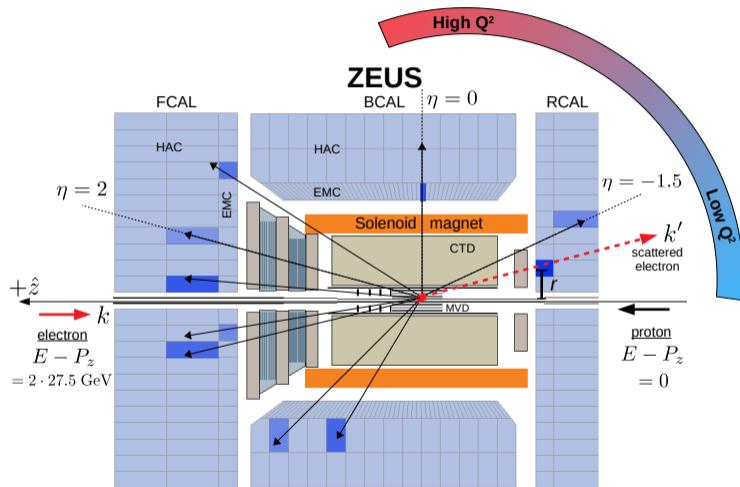
DIS Event selection (0.2 M)

- $N_{\mathrm{ch}} \geq 20$
- DIS triggers
- electron probability $> 90\%$
- $Q^2 = -(k - k')^2 > 5\ \mathrm{GeV}^2$
- $k_0' > 10\ \mathrm{GeV}$
- $r > 15$ cm
- $\theta_e > 1$ rad
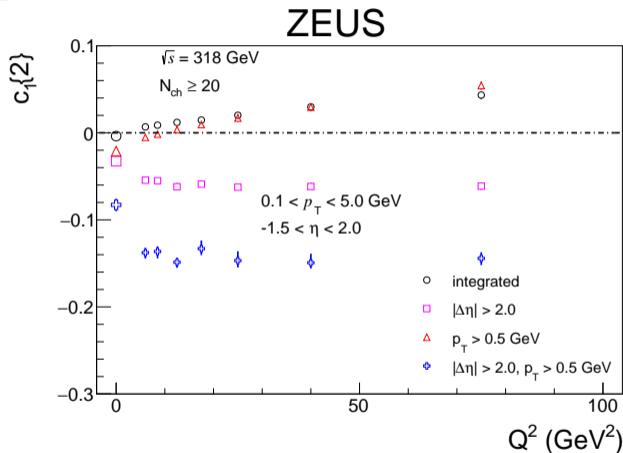- $47 < \sum(E_i - P_{z,i}) < 69$ GeV
- $|V_z| < 30$ cm

Photoproduction event selection
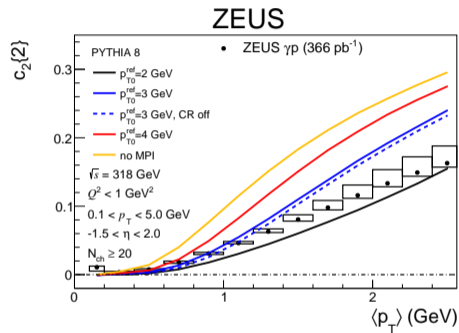

Photoproduction event selection (5 M)
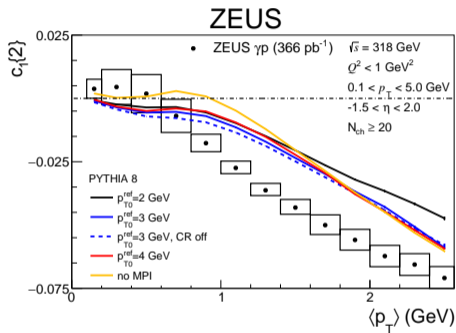
- $N_{\text{ch}} \geq 20$
- PhP oriented triggers
- electron probability $< 90\%$
- $k'_0 < 15 \text{ GeV}$
- $\sum(E_i - P_{z,i}) < 55$ GeV
- $|V_z| < 30$ cm
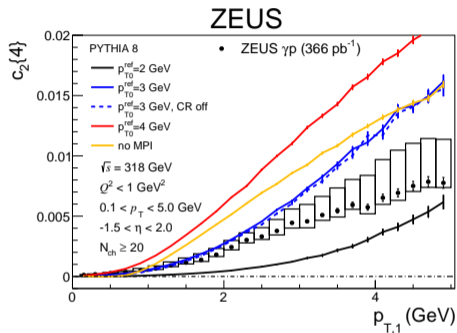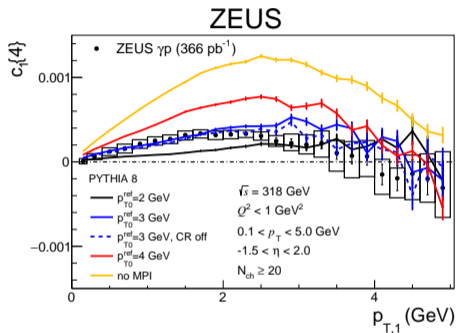
Results: Q^2 evolution of $c_1\{2\}$

Photoproduction correlation strengths ($Q^2 = 0$) are clearly diminished wrt those in DIS.

# Results: $c_1\{2\}$ and $c_2\{2\}$ versus $\langle p_T \rangle$

- $c_1\{2\}$ versus $\langle p_T \rangle$ not sensitive to MPI and not described well by PYTHIA 8.
- More extreme levels of MPI are favored by $c_2\{2\}$ versus $\langle p_T \rangle$.

Results: $c_1\{4\}$ and $c_2\{4\}$ versus $p_{T,1}$

- Four-particle cumulant is positive, which is in contrast to the negative values seen in non-central heavy-ion collisions.
- The scenarios of no MPI and very many MPI are disfavored.

Multiparton Interactions (MPI)
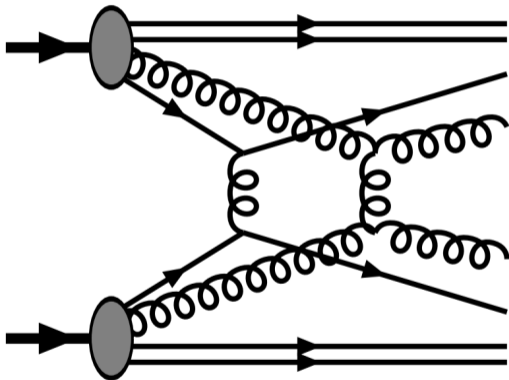
- MPI occur when there's more than one $2 \to 2$ partonic scattering between the beam particles in a given event.
- If the scatterings are sufficiently hard ($p_T \gtrsim 1$ GeV), they can be modeled in an event generator like PYTHIA 8.
- Established feature in high-multiplicity hadronic collisions. Not conclusively observed in *ep* scattering so far.
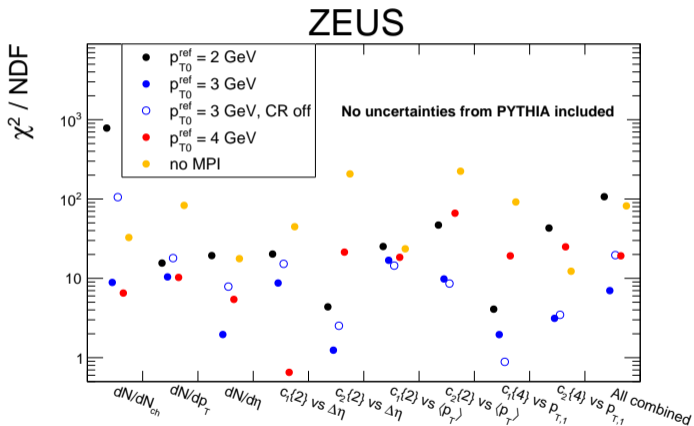
Tracking efficiency corrections

The efficiency correction weights for 1-, 2-, and 4-particle distributions are defined as:

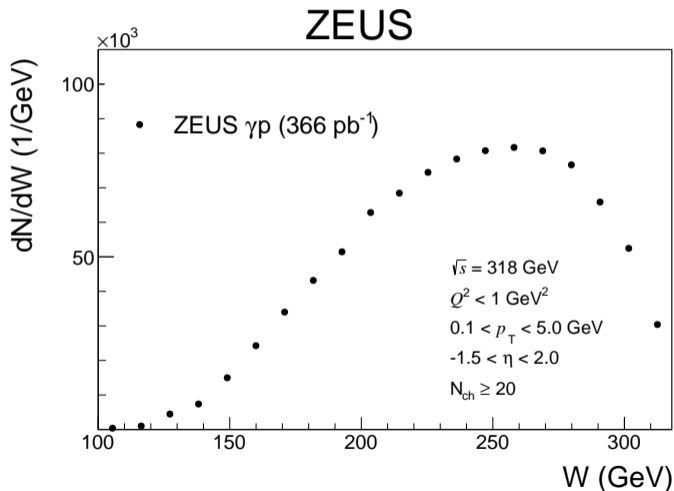$$w^{(n)} = \frac{N_{gen}^n(\vec{x})}{N_{rec}^n(\vec{x})}$$

They are computed differentially in Monte Carlo simulations of the ZEUS detector:

dimension of $\vec{x}$	One-particle (n=1)	Two-particle (n=2)	Four-particle (n=4)
x_1	φ	$\varphi_1 - \varphi_2$	$\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4$
x_2	η	$\langle \eta_i - \langle \eta \rangle \rangle$	$\langle \eta_i - \langle \eta \rangle \rangle$
x_3	p_T	$\langle p_{T,i} - \langle p_T \rangle \rangle$	$\langle p_{T,i} - \langle p_T \rangle \rangle$
x_4 (charge)	q	$|q_1 + q_2|$	$|q_1 + q_2 + q_3 + q_4|/2$
x_5	-	N_{rec}	N_{rec}

Condensed view of PYTHIA 8 comparisons

W distribution

Direct and Resolved event distributions

PYTHIA 6

$\sqrt{s}$ = 318 GeV
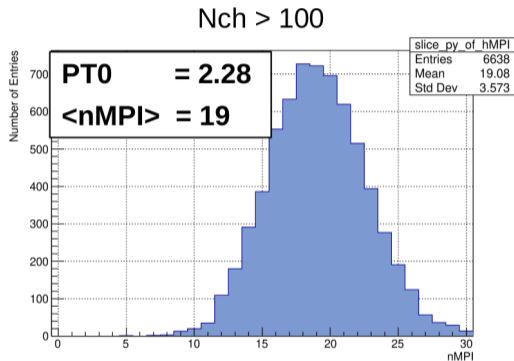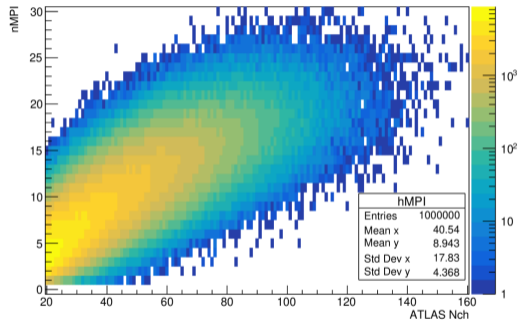
$Q^2 < 1$ GeV^2

$0.1 < p_T < 5.0$ GeV

$-1.5 < \eta < 2.0$

PYTHIA 6 γp

Direct

Resolved
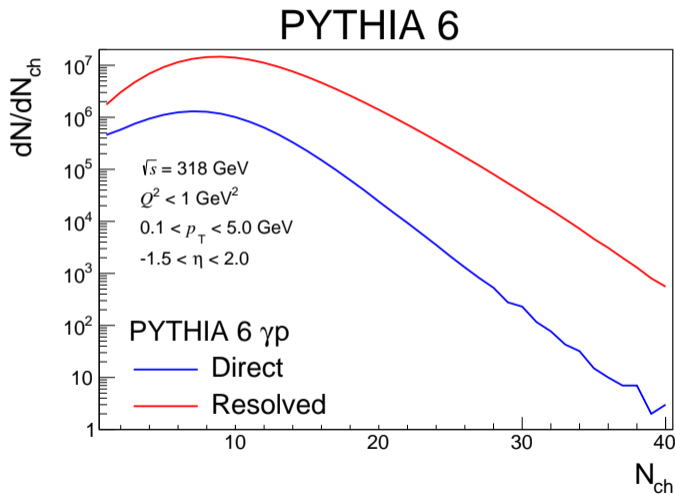
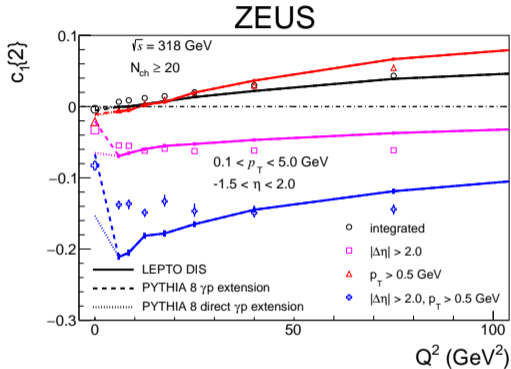# nMPI in high-multiplicity $p + p$ PYTHIA 8 at LHC energies

PYTHIA 8 $p + p$ events at $\sqrt{s} = 13$ TeV were generated.

N_{ch} was counted according to the ATLAS acceptance used in PRL 116 172301.

$-2.5 < \eta < 2.5$, $0.4 < p_{\mathrm{T}} < 50$ GeV

Results: Q^2 evolution of $c_1\{2\}$

$\gamma\boldsymbol{p}$ direct: photon couples directly to a quark in the proton.
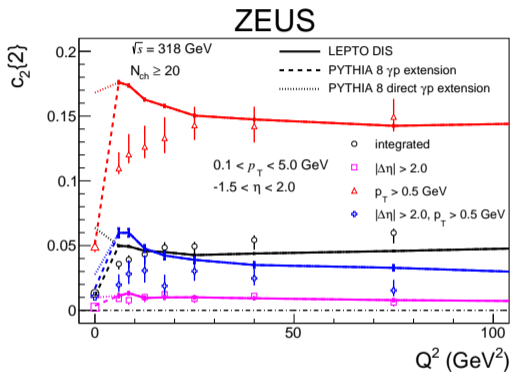
$\gamma\boldsymbol{p}$ resolved: photon splits into quarks and gluons which then scatter with the proton (MPI possible).

Photoproduction correlation strengths ($Q^2 = 0$) are clearly diminished wrt those in DIS.

The LEPTO model of DIS gives a rough qualitative description of the data.

PYTHIA 8 with only the direct component of γp predicts much stronger correlations

than the full calculation (direct + resolved).

Results: Q^2 evolution of $c_2\{2\}$

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γp **direct**: photon couples directly to a quark in the proton.

γp **resolved**: photon splits into quarks and gluons which then scatter with the proton (MPI possible).

Photoproduction correlation strengths ($Q^2 = 0$) are clearly diminished wrt those in DIS.

The LEPTO model of DIS gives a rough qualitative description of the data.

PYTHIA 8 with only the direct component of γp predicts much stronger correlations than the full calculation (direct + resolved).