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

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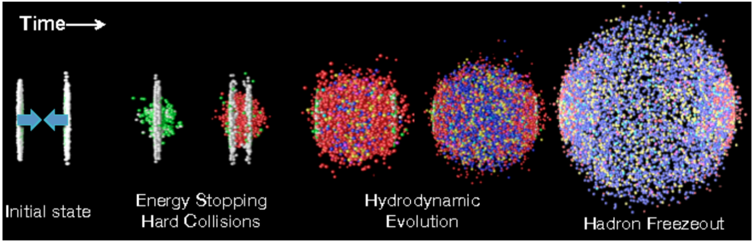
Subject of this analysis

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

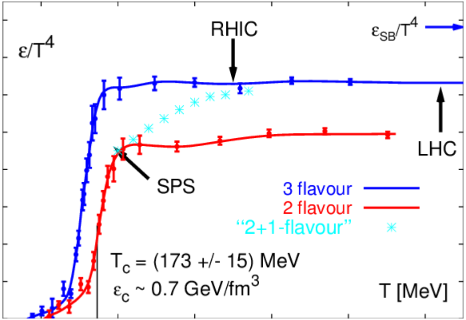


Central Question:
Is a similar kind of multibody environment created in much smaller ***ep*** systems produced at HERA?

Outline

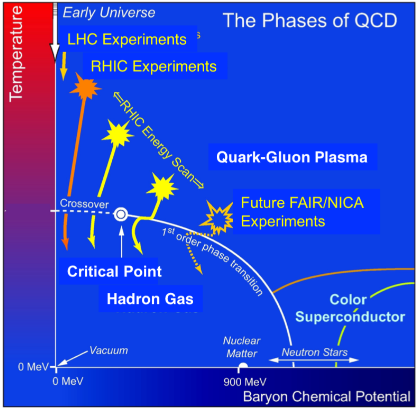
- Introduction to heavy-ion ($\boldsymbol{A} + \boldsymbol{A}$) collisions
    - A new form of matter expected
    - Pillars of heavy-ion measurements
- Surprising observation in $\boldsymbol{p} + \boldsymbol{p}$ collisions at the LHC
- ZEUS analysis in $\boldsymbol{ep}$

A new form of matter expected



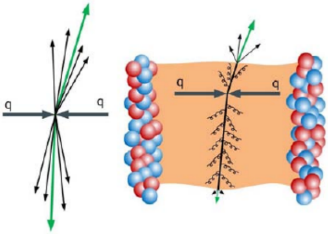
Lattice QCD predicts a sharp rise of the energy density of matter around T=170 GeV.
The transition is caused by an increase in the number of degrees of freedom.
Hadrons → deconfined quarks and gluons (**Quark-Gluon Plasma**.)

A new form of matter expected



- The shear magnitude of current accelerator beam energies and the miniscule size of a nucleus creates enormous energy densities and temperatures.
- Both the LHC and RHIC reach temperatures expected in the early Universe about 1 microsecond after the Big Bang.
- Observations in heavy-ion collisions can tell us about the early Universe.

Pillars of heavy-ion measurements: **Jet Quenching**



- Most of the time, the hardest scatter will occur off center.
- This means that one parton will traverse a greater path length through the collision zone.

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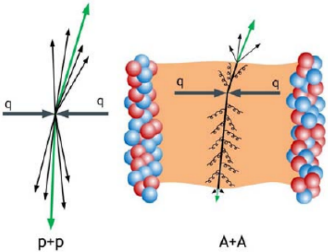

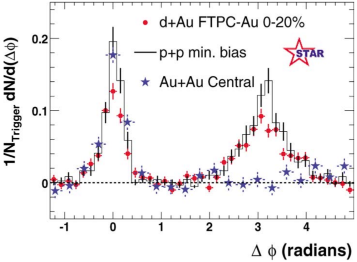

- Most of the time, the hardest scatter will occur off center.
- This means that one parton will traverse a greater path length through the collision zone.
- A dramatic suppression of back-to-back jets was found at RHIC (Jet Quenching).
- Interpreted as an indication of substantial final-state **rescattering**.

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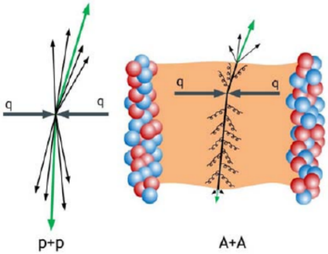

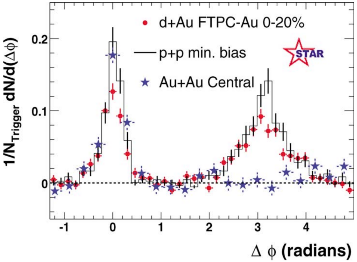

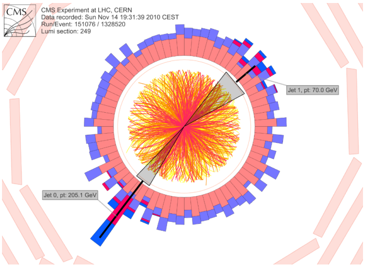

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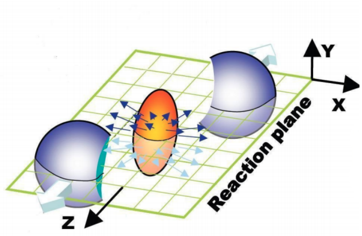
- This means that one parton will traverse a greater path length through the collision zone.
- A dramatic suppression of back-to-back jets was found at RHIC (Jet Quenching).
- Interpreted as an indication of substantial final-state **rescattering**.
- Jet Quenching was confirmed at the LHC.

Pillars of heavy-ion measurements: **Elliptic Anisotropy**



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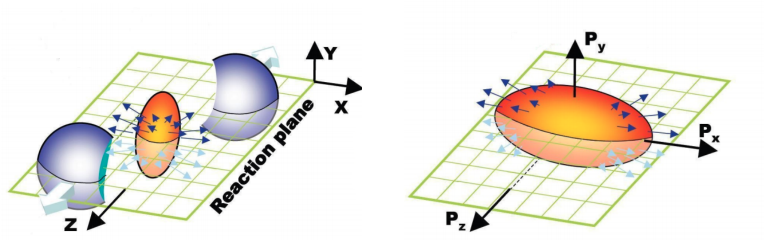
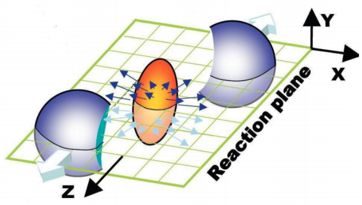
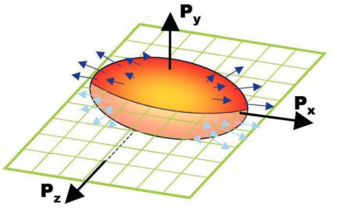
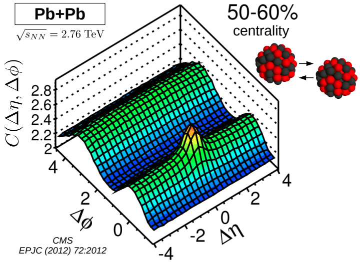


- The spatial configuration of the **initial scattering** typically has a large elliptic component.
- **Rescattering** between the produced partons converts this spatial eccentricity into an asymmetry in momentum space.

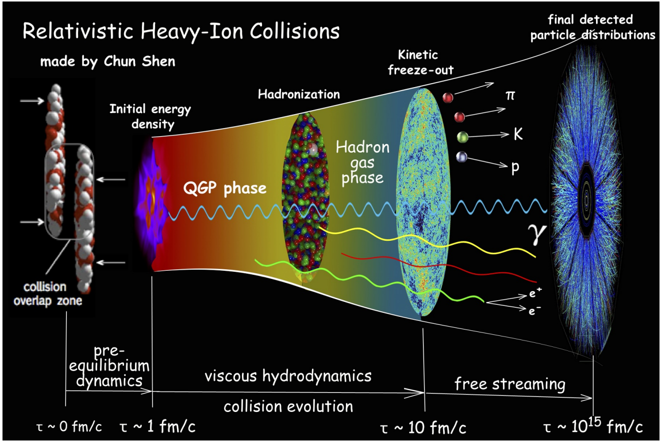






- The spatial configuration of the **initial scattering** typically has a large elliptic component.
- **Rescattering** between the produced partons converts this spatial eccentricity into an asymmetry in momentum space.
- The elliptic asymmetry is clearly evident in two-particle correlations: **collectivity**.

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.

QED fluid and QCD fluid

QED fluid

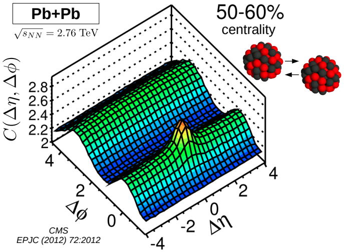
QCD fluid

Girolamo Sferrazaa Papa

QGP in heavy-ion collisions lives only a few yoctoseconds (10^{-24})

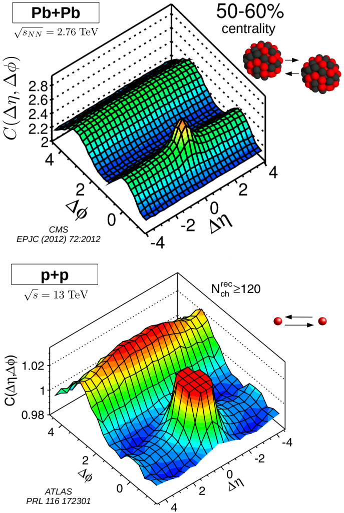
Surprising observation in $p+p$ collisions at the LHC

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



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- $C(\Delta\eta, \Delta\varphi) = S(\Delta\eta, \Delta\varphi)/B(\Delta\eta, \Delta\varphi)$,
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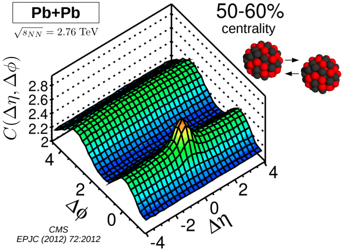
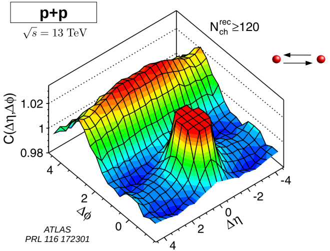
- The start of the LHC revealed that high-multiplicity $p + p$ collisions also have a double-ridge!
- Such collisions were thought to be too small to produce a thermally equilibrated QGP.

Motivation for the analysis





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- Such collisions were thought to be too small to produce a thermally equilibrated QGP.
- **What about even more fundamental *ep* scattering at HERA??**

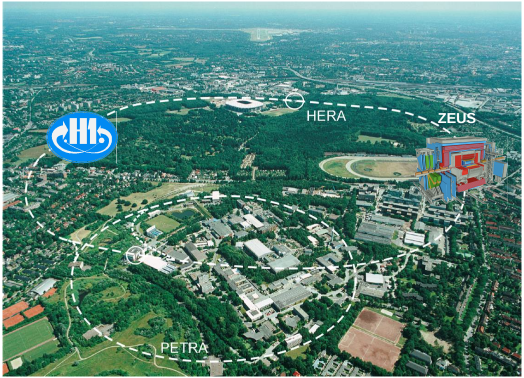
Motivating questions

How small can a colliding system be while still exhibiting the collective behaviour typically associated with the quark–gluon plasma observed in heavy-ion collisions?

What kind of environment could collectivity evolve from?

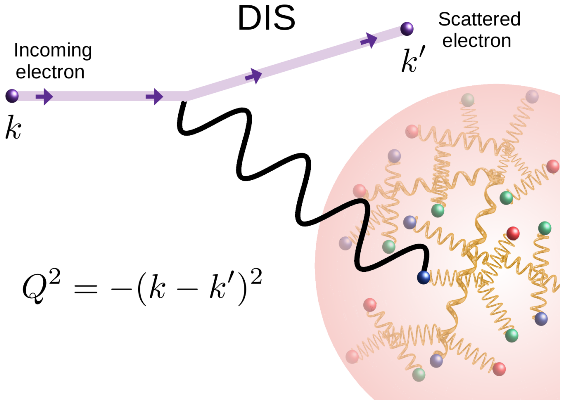
I'll present recently posted measurements of azimuthal correlations in neutral current DIS and photoproduction with the ZEUS detector: arXiv:2106.12377 (Submitted to JHEP)

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)

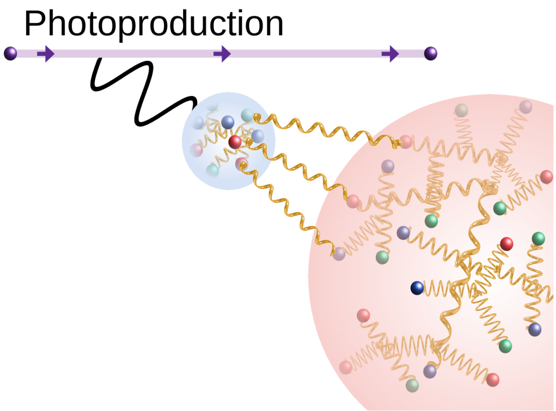


- DIS is defined by large virtualities: $Q^2 \gg \Lambda^2_{\text{QCD}}$.
- Transverse radius (R_t) and longitudinal length (L) of the probed region are given by:

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

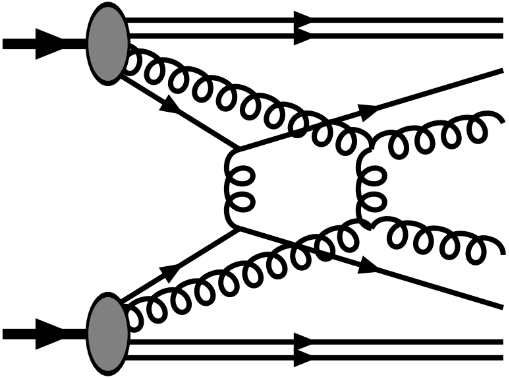
  $L \sim \frac{1}{m_{proton}\, x}$ PRD 95 114008
- Neutral current (NC) DIS involves the exchange of photon or Z boson.

Photoproduction (PhP)



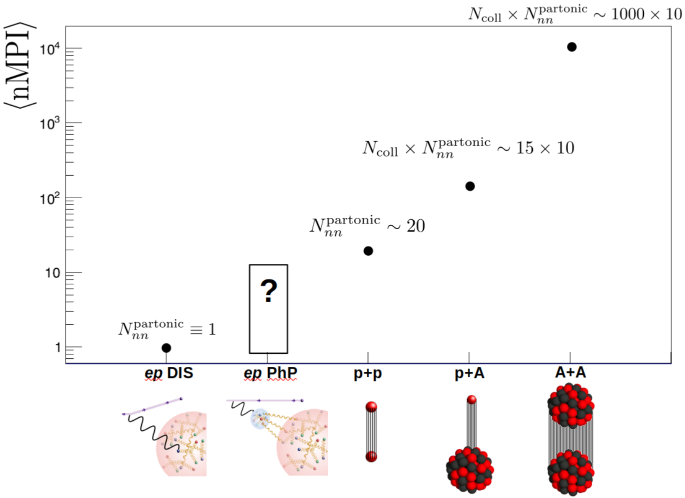
- Photoproduction (γp) is defined by small virtualities: $Q^2 \ll \Lambda^2_{\mathrm{QCD}}$.
- Exchanged photon may fluctuate into quarks and gluons.
- Larger interaction regions are probed.
- **Multiparton Interactions are possible.**
- Scattering is hadron-like.

Multiparton Interactions (MPI)



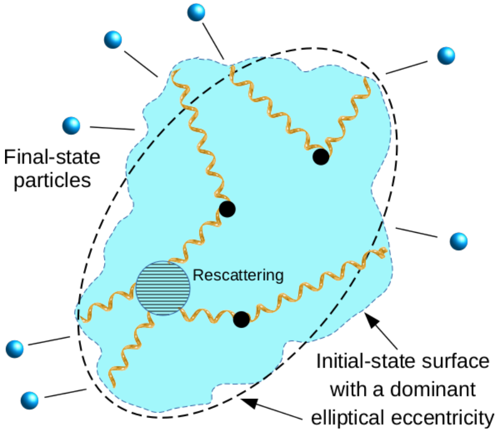
- MPI occur when there's more than one $2 \to 2$ partonic scattering between the beam particles in a given event.
- If the scatterings are sufficiently hard ($p_T \gtrsim 1$ GeV), they can be modeled in an event generator like PYTHIA 8.
- Established feature in high-multiplicity hadronic collisions.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

Illustration of MPI growth



- Rough illustration of how nMPI grows from DIS to heavy-ions
- N_{coll}: number of binary nucleon-nucleon collsions
- N_{nn}^{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}^{partonic} taken from PYTHIA 8

ep photoproduction: subsequent rescattering phase possible



- 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 behavoiur 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: $c_n\{4\}$

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:

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

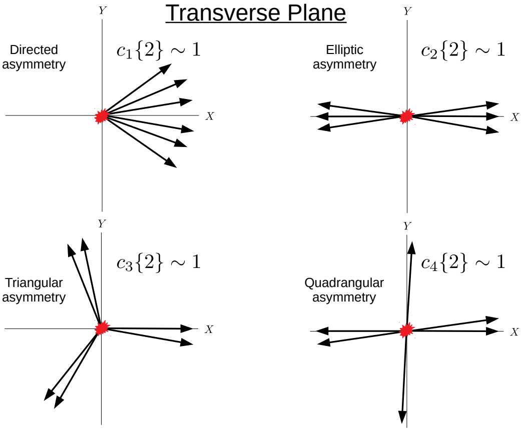
φ_i is the azimuthal angle of particle i

n is the harmonic (n=1, 2 studied here)

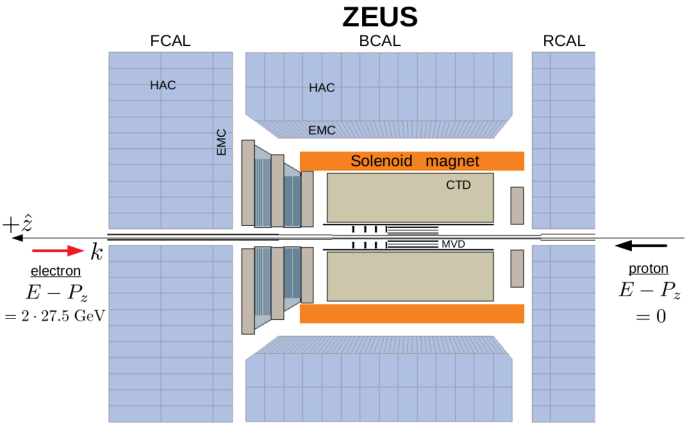
Four-particle cumulant correlations are also measured:

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

where $p_{\mathrm{T},1}$ is the transverse momentum of particle i



ZEUS detector

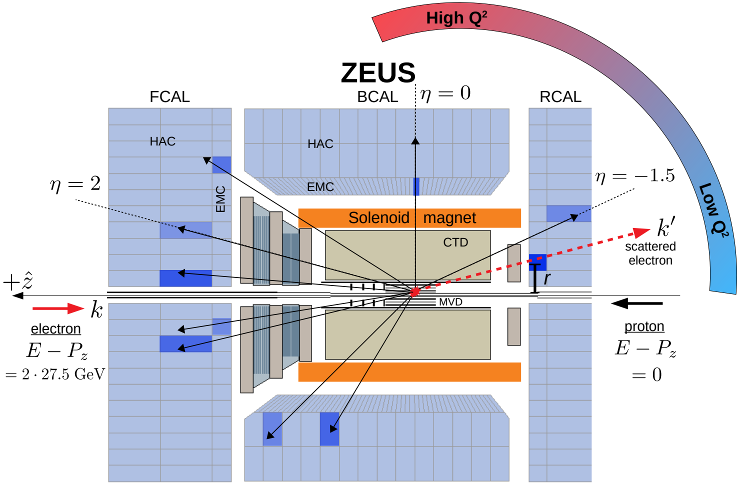


Charged particles are tracked in the central tracking detector (CTD) and micro vertex detector (MVD) in a 1.43 T magnetic field.

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

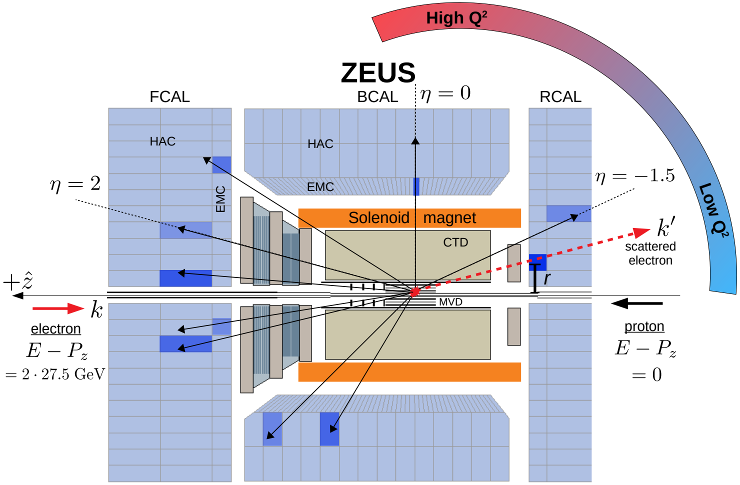


Track selection for correlation analysis

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

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

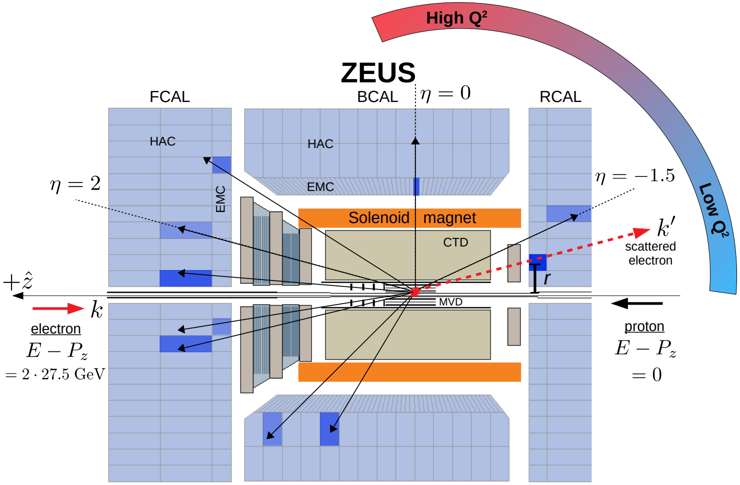
DIS event selection



DIS Event selection (0.2 M)

- $N_{ch} \geq 20$
- DIS triggers
- electron probability $> 90\%$
- $Q^2 = -(k - k')^2 > 5\ \text{GeV}^2$
- $k'_0 > 10\ \text{GeV}$
- $r > 15$ cm
- $\theta_e > 1$ rad
- $47 < \sum(E_i - P_{z,i}) < 69$ GeV
- $|V_z| < 30$ cm

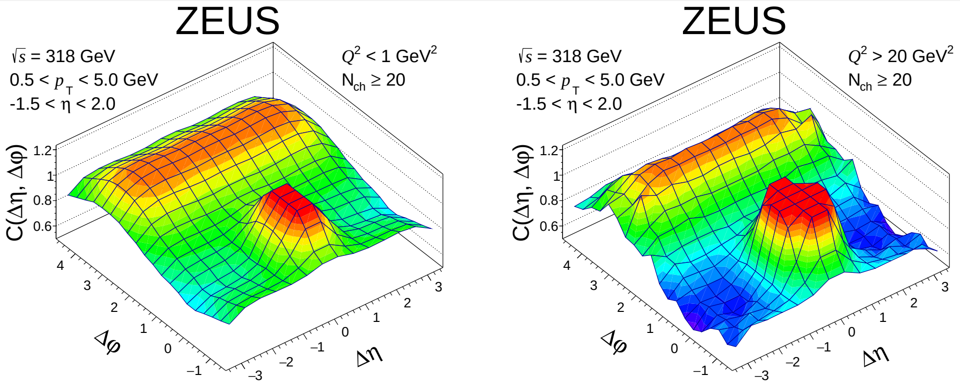
Photoproduction event selection



Photoproduction event selection (5 M)

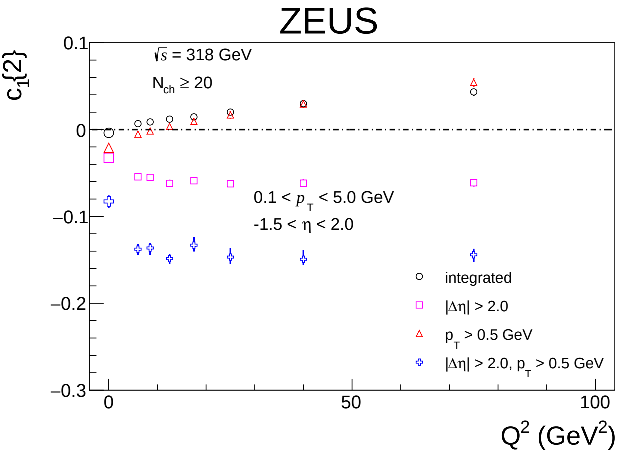
- $N_{ch} \geq 20$
- PhP oriented triggers
- electron probability $< 90\%$
- $k'_0 < 15$ GeV
- $\sum(E_i - P_{z,i}) < 55$ GeV
- $|V_z| < 30$ cm

Results: Ridge plots



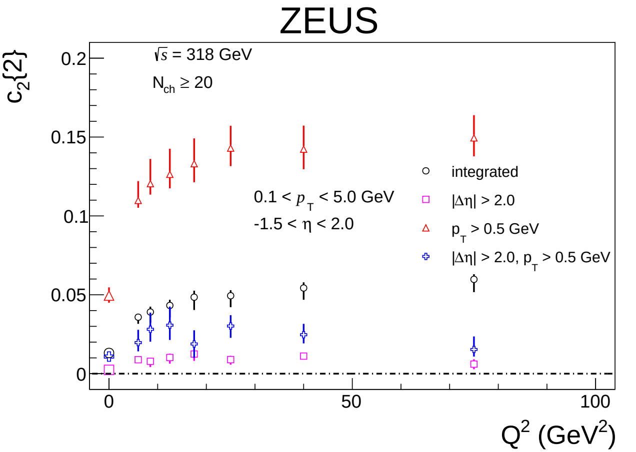
A near-side peak and away-side ridge are clearly visible.
Photoproduction correlations are dimished wrt those in DIS.
No visible double-ridge.

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



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

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



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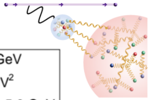
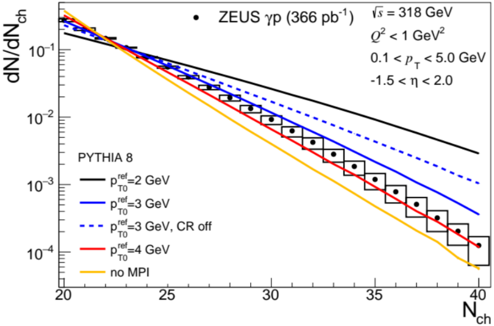
Study of MPI in *ep* photoproduction

Results: $dN/dN_{\rm ch}$





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

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

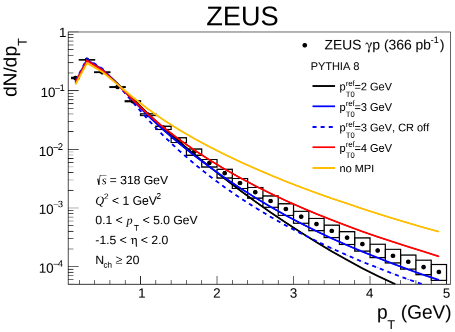
$$\frac{d\sigma}{dp_{\rm T}^2} \propto \frac{\alpha_s^2(p_{\rm T0}^2 + p_{\rm T}^2)}{(p_{\rm T0}^2 + p_{\rm T}^2)^2}$$

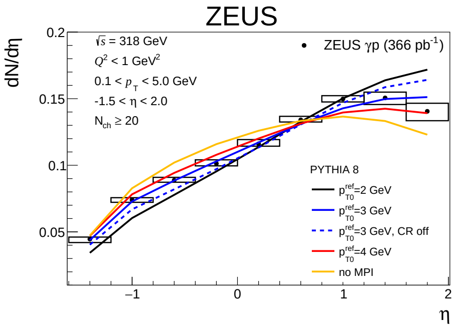
The energy dependence of this parameter is given by $p_{\rm T0} = p_{\rm T0}^{\rm ref}\,(W/7\,{\rm TeV})^{0.215}$, where W is the γp $\sqrt{s}$.

More MPI → lower $p_{\rm T0}^{\rm ref}$

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

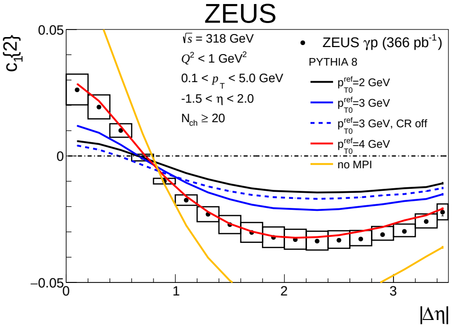
Results: dN/dp_{T} and $dN/d\eta$

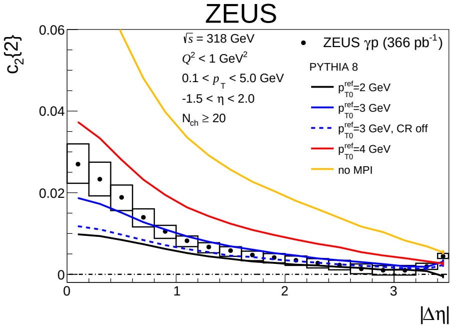




- The scenarios of no MPI and very many MPI are disfavored.

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





- Correlation strengths are diluted by MPI.
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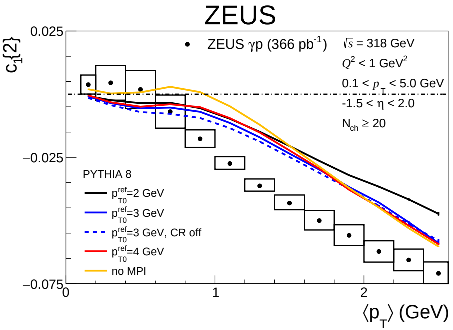
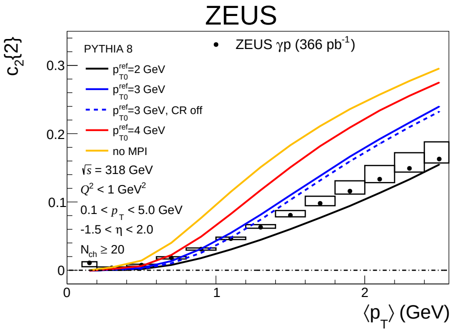
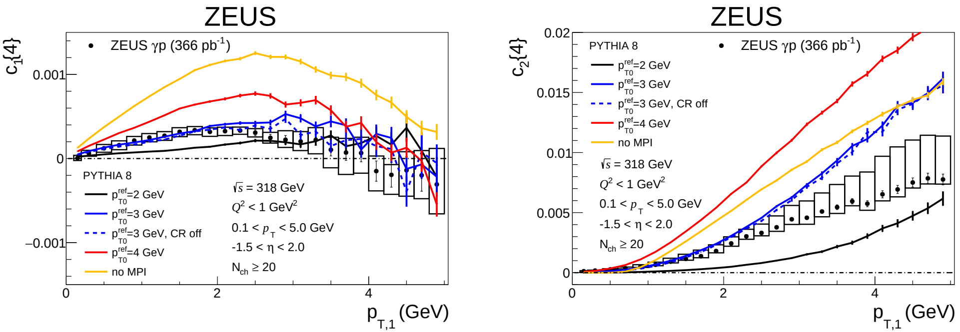
Results: $c_1\{2\}$ and $c_2\{2\}$ versus $\langle p_T \rangle$





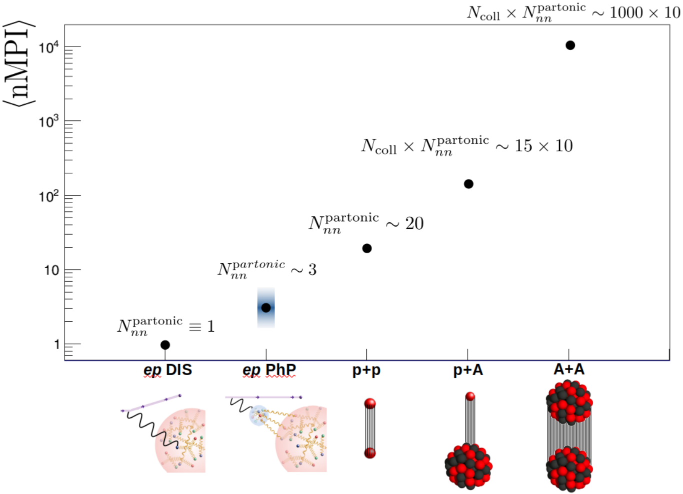
- $c_1\{2\}$ versus $\langle p_T \rangle$ not sensitive to MPI and not described well by PYTHIA 8.
- More extreme levels of MPI are favored by $c_2\{2\}$ versus $\langle p_T \rangle$.

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.

Illustration of MPI growth



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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.
- dN/dN_{ch} , dN/dp_{T}, and $dN/d\eta$ were measured in γp.
- 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.
- 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**.
- Other parameters in PYTHIA 8 such as those related parton showering should be investigated to improve the description of the data.

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.

Backup

Tracking efficiency corrections

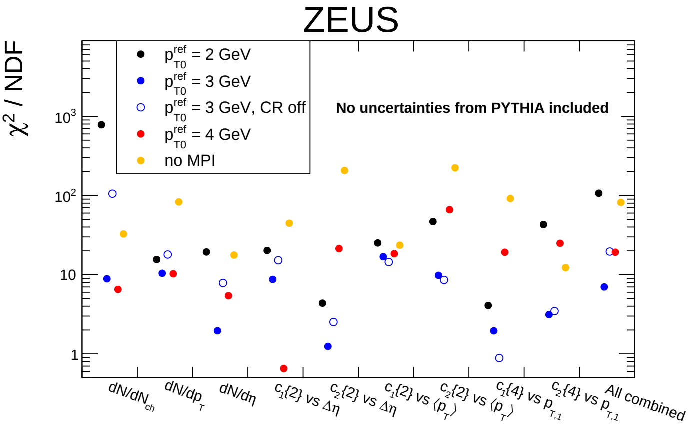
The efficiency correction weights for 1-, 2-, and 4-particle distributions are defined as:

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

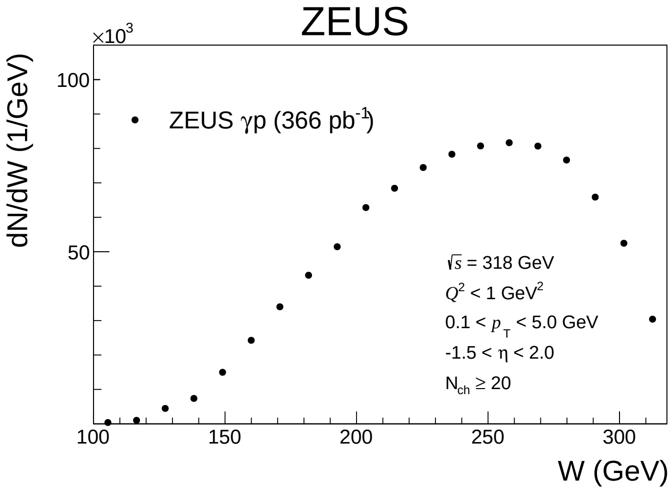
They are computed differentially in Monte Carlo simulations of the ZEUS detector:

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	$\lvert q_1 + q_2 \rvert$	$\lvert q_1 + q_2 + q_3 + q_4 \rvert / 2$
x_5	-	N_{rec}	N_{rec}

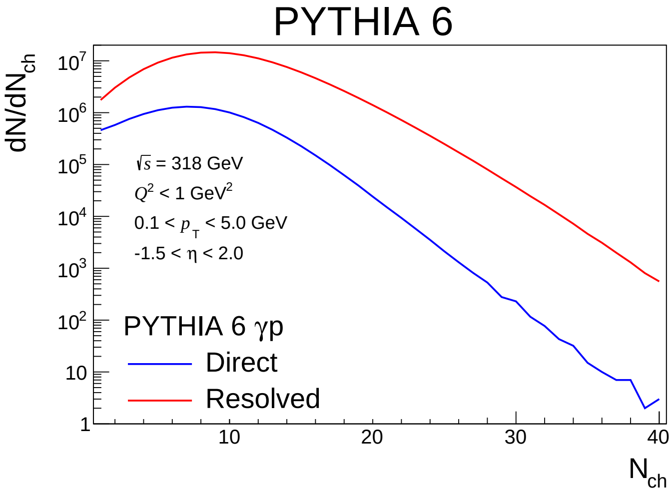
Condensed view of PYTHIA 8 comparisons



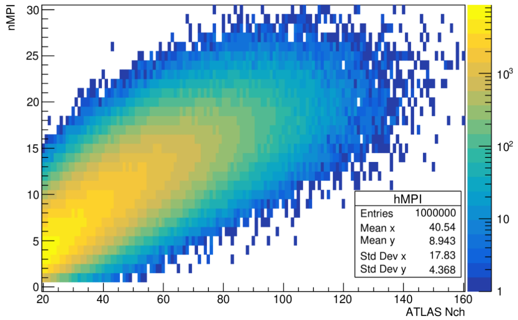
W distribution

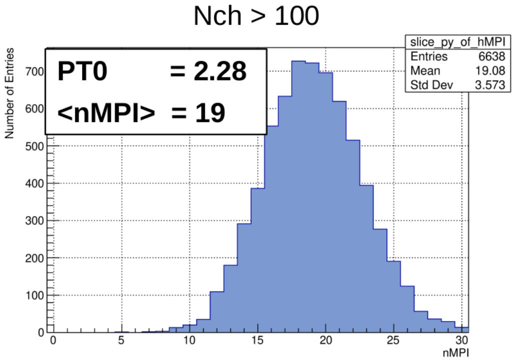


Direct and Resolved event distributions



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



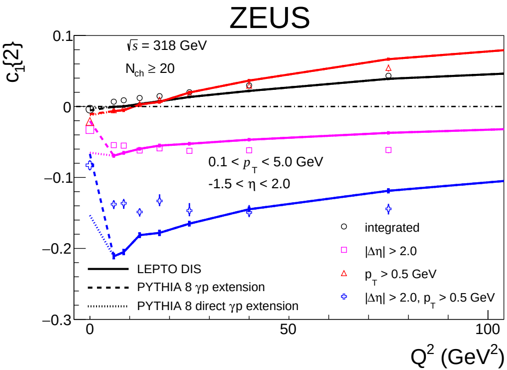


PYTHIA 8 $p + p$ events at $\sqrt{s} = 13$ TeV were generated.

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 $c_1\{2\}$



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

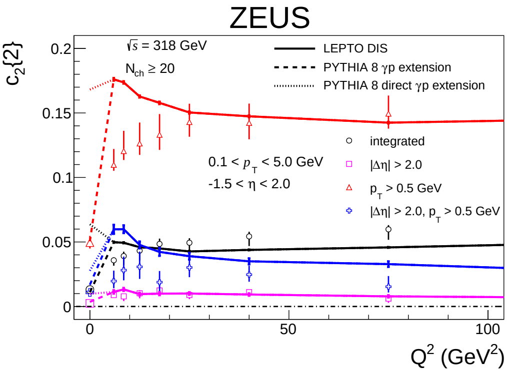
γp **resolved**: photon splits into quarks and gluons which then scatter with the proton (MPI possible).

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).

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



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