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

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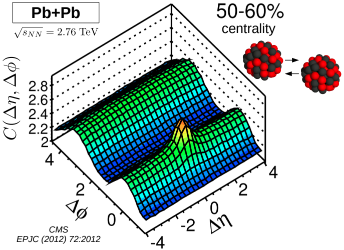
Motivating questions

1. How small can a colliding system be while still exhibiting the collective features typically associated with the quark–gluon plasma in heavy-ion collisions?
2. How many Multiparton Interactions are needed to set the stage for a collective environment?

Recent measurements using the ZEUS detector will be presented in neutral current DIS and photoproduction.

New ZEUS publication: JHEP 12 (2021) 102

Motivation for the analysis



- 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.

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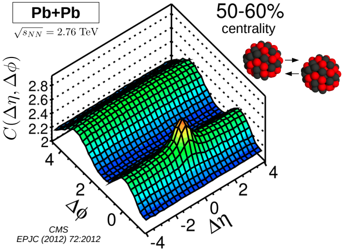

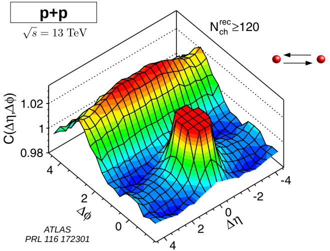

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- The start of the LHC revealed that high-multiplicity $p + p$ collisions also have a double-ridge!
- Such collisions were thought to be too small to produce a thermally equilibrated QGP.

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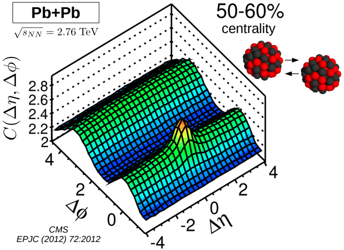

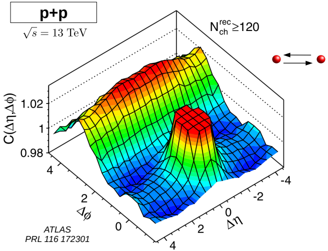

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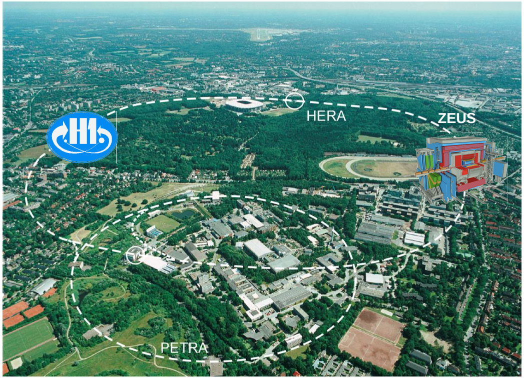
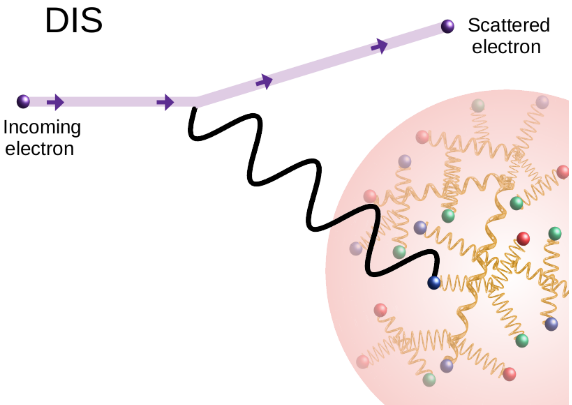
- **What about even more fundamental *ep* scattering at HERA??**

The HERA collider and main experiments



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

Deep inelastic scattering (DIS)



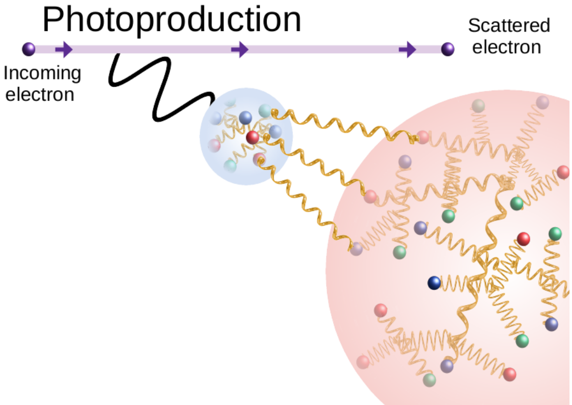
- DIS is defined by large virtualities: $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$.
- Transverse radius (R_t) and longitudinal length (L) of the probed region are given by:

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

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

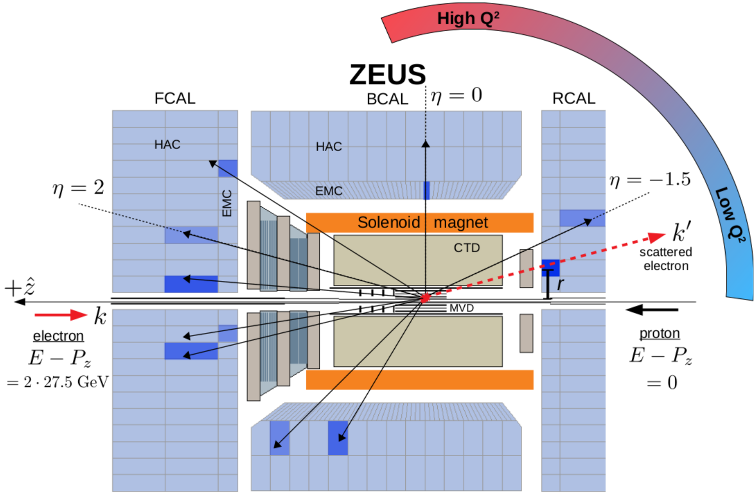
- Neutral current (NC) DIS involves the exchange of photon or Z boson.

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.

ZEUS detector and data selection (main cuts only)



Track selection for correlation analysis

- Reject scattered electron
- $-1.5 < \eta < 2.0$
- $0.1 < p_T < 5.0$ GeV
- $DCA_{XY,Z} < 2$ cm

DIS Event selection (0.2 M)

- $N_{\mathrm{ch}} \geq 20$
- DIS triggers
- electron probability > 90%
- $Q^2 = -(k - k')^2 > 5\ \mathrm{GeV}^2$
- $47 < \sum(E_i - P_{z,i}) < 69$ GeV

Photoproduction event selection (5 M)

- $N_{\mathrm{ch}} \geq 20$
- PhP oriented triggers
- electron probability < 90%
- $\sum(E_i - P_{z,i}) < 55$ GeV

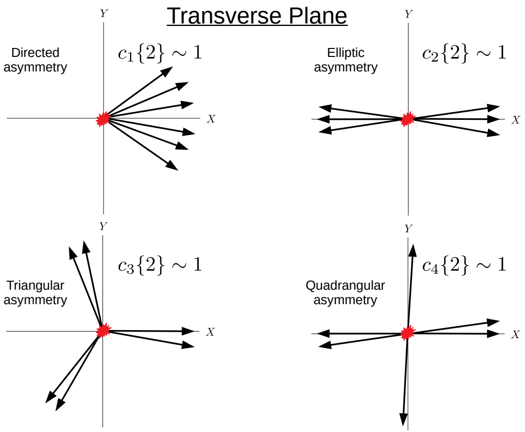
Two-particle correlation functions

Two-particle azimuthal correlations are measured:

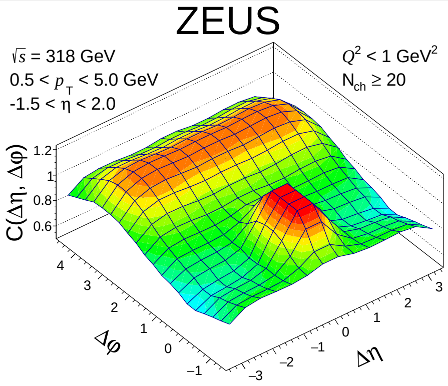
$c_n\{2\} = \langle\langle \cos n(\phi_i - \phi_j) \rangle\rangle$.

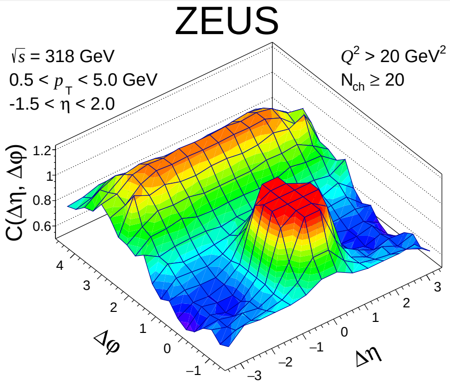
φ_i is the azimuthal angle of particle i.

n is the harmonic.



Results: Ridge plots



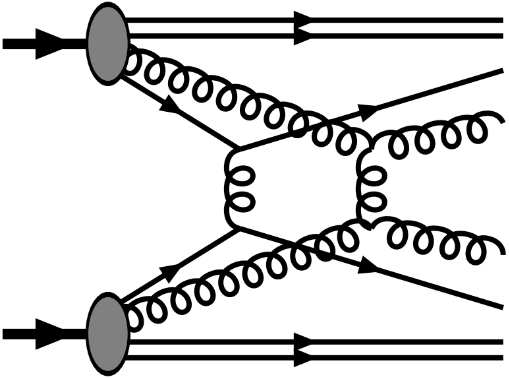


A near-side peak and away-side ridge are clearly visible.

Photoproduction correlations are dimished wrt those in DIS.

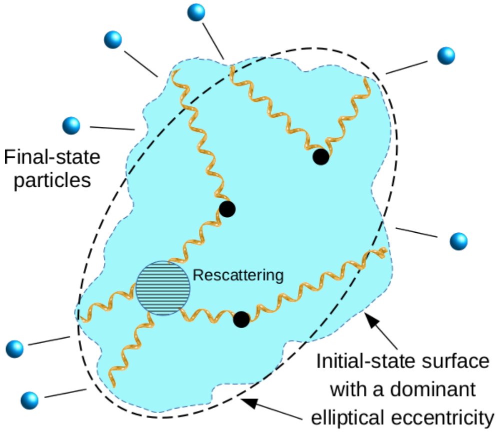
No visible double-ridge.

Multiparton Interactions (MPI)



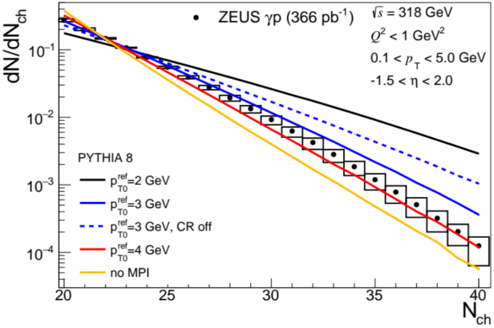
- MPI occur when there's more than one $2 \to 2$ partonic scattering between the beam particles in a given event.
- If the scatterings are sufficiently hard ($p_T \gtrsim 1$ GeV), they can be modeled in an event generator like PYTHIA.
- **Established feature in high-multiplicity hadronic collisions.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

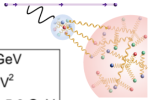
A subsequent rescattering phase is possible



- 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.

Results: dN/dN_{ch}





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

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

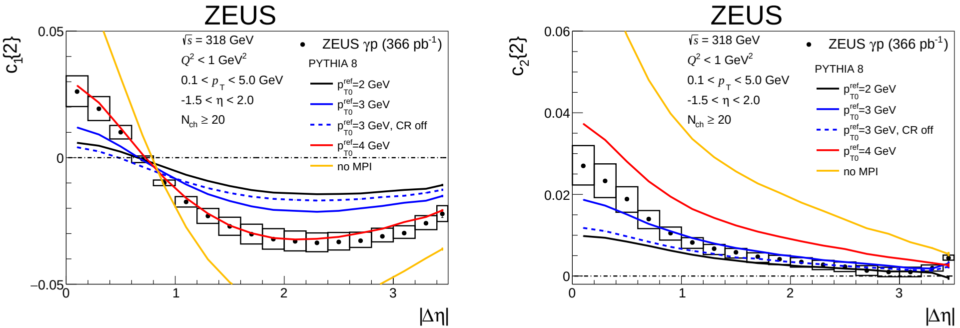
$$\frac{d\sigma}{dp_{\mathrm{T}}^2} \propto \frac{\alpha_s^2(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)}{(p_{\mathrm{T0}}^2 + p_{\mathrm{T}}^2)^2}$$

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

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

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

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.
- Red and blue lines favored: $2 \lesssim \langle nMPI \rangle \lesssim 4$.

Summary

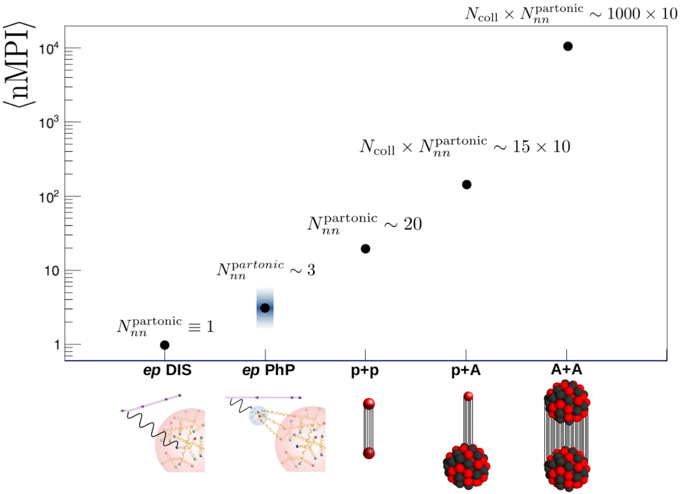
- Measurements of charged-particle azimuthal correlations have been presented ZEUS data in *ep* photoproduction (γp) and NC DIS.
- There is no clear indication of a double ridge in either γp or DIS. The observations **do not** reveal significant collective behaviour like that seen in heavy-ions or high-multiplicity 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 their spatial extent but completely different in the number of MPI.

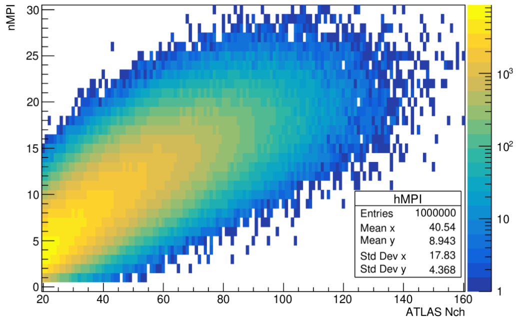
Backup

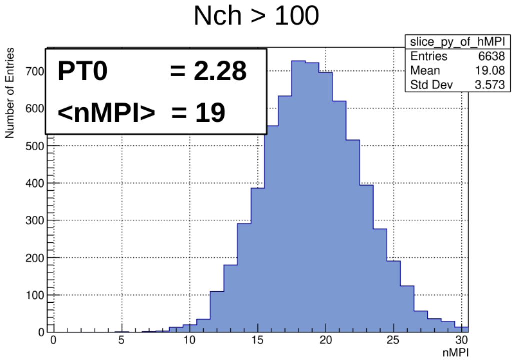
Illustration of MPI growth



- 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

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



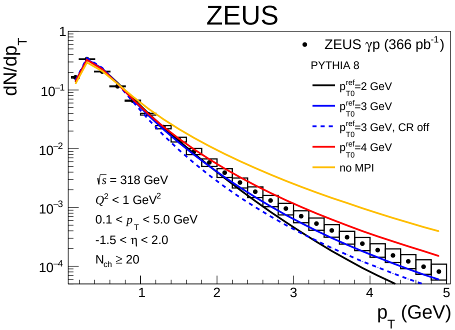


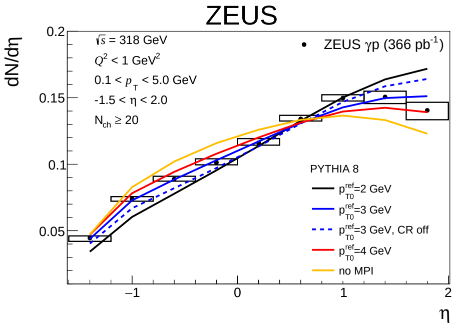
PYTHIA $p + p$ events at $\sqrt{s} = 13$ TeV were generated.

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

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

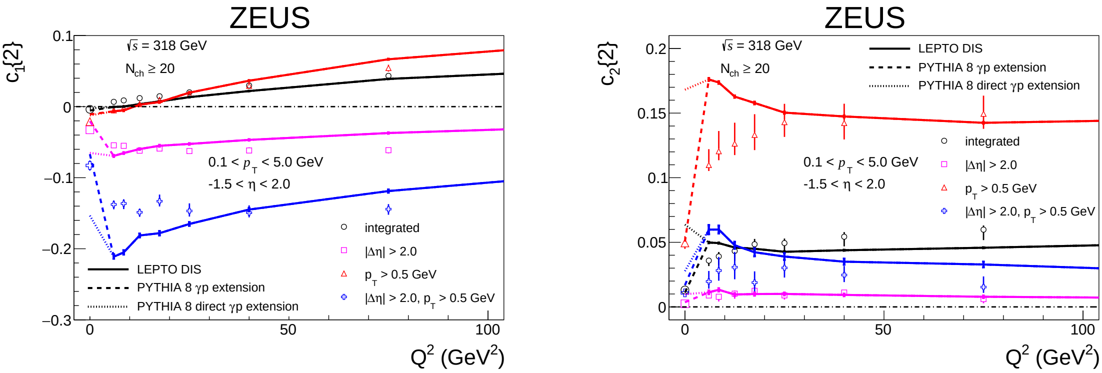
Results: dN/dp_{T} and $dN/d\eta$





- The scenarios of no MPI and very many MPI are disfavored.
- Red and blue lines favored: $2 \lesssim \langle nMPI \rangle \lesssim 4$.

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

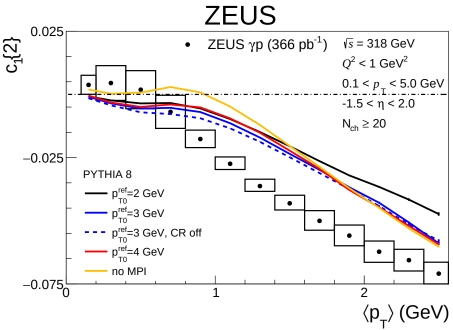


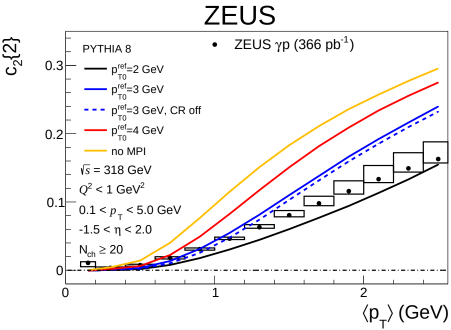
Photoproduction correlation strengths ($Q^2 = 0$) are clearly diminished wrt those in DIS.

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: $c_1\{2\}$ and $c_2\{2\}$ versus $\langle p_\mathrm{T}\rangle$





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

Two- and four-particle correlation functions

Two-particle azimuthal correlations are measured:

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

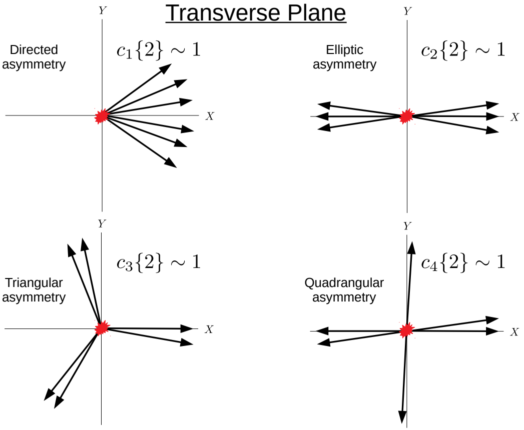
φ_i is the azimuthal angle of particle i.

n is the harmonic.

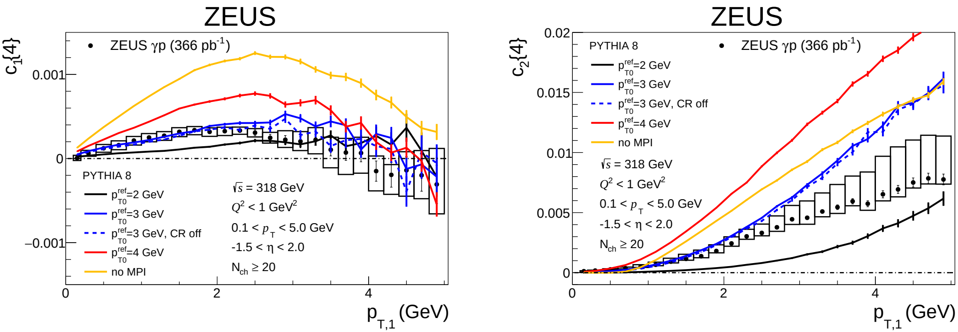
Four-particle cumulant correlations are also measured:

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

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

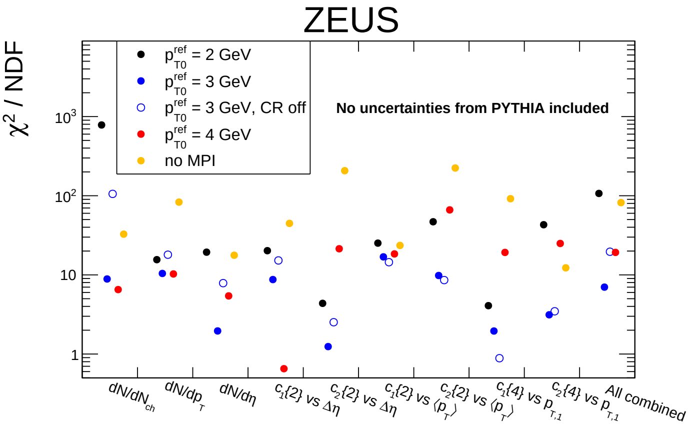


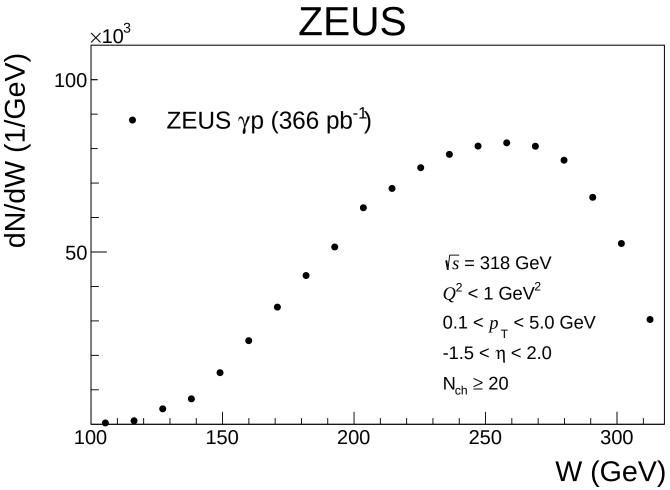
Results: Four-particle cumulants in photoproduction



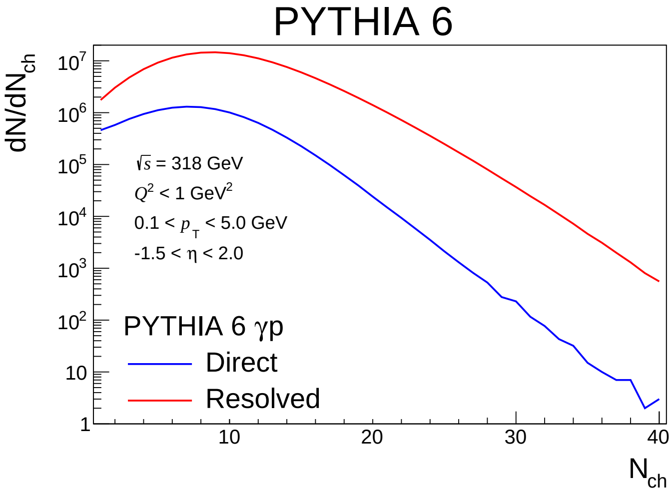
- Four-particle cumulant is positive, which is in contrast to the negative values seen in non-central heavy-ion collisions.
- The scenarios of no MPI and very many MPI are disfavored.

Condensed view of PYTHIA 8 comparisons




ZEUS
×10^3
dN/dW (1/GeV)
100
50
ZEUS γp (366 pb^-1)
√s = 318 GeV
Q^2 < 1 GeV^2
0.1 < p_T < 5.0 GeV
-1.5 < η < 2.0
N_ch ≥ 20
100
150
200
250
300
W (GeV)

Direct and Resolved event distributions



Tracking efficiency corrections

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

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

The 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}