Two-particle azimuthal correlations as a probe of collective behaviour in deep inelastic *ep* scattering at HERA

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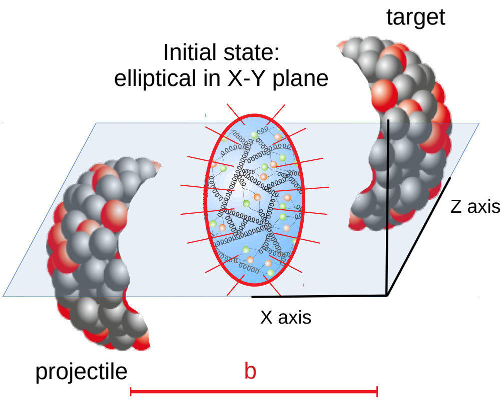
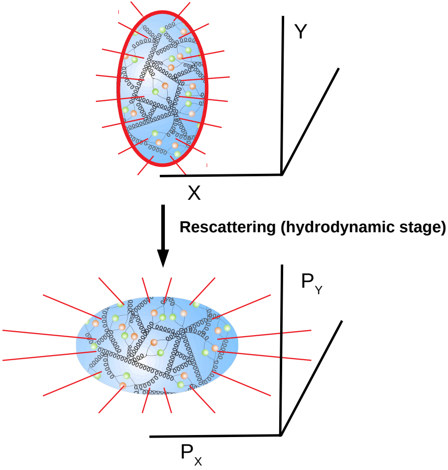
ZEUS

High-energy heavy-ion collisions: initial state



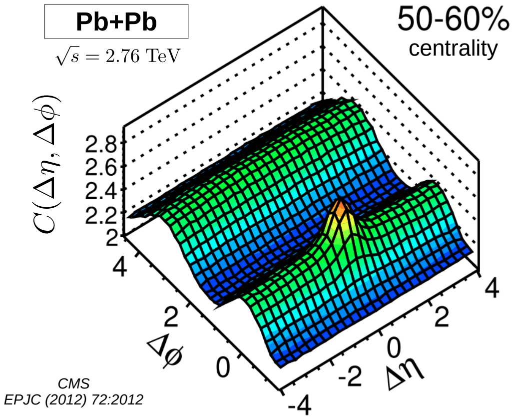
- Most spatial configurations in the initial state correspond to partially overlapping nuclei.
- Consequently, the initial scattering leaves behind an elliptically eccentric zone in the transverse plane.

High-energy heavy-ion collisions: final state



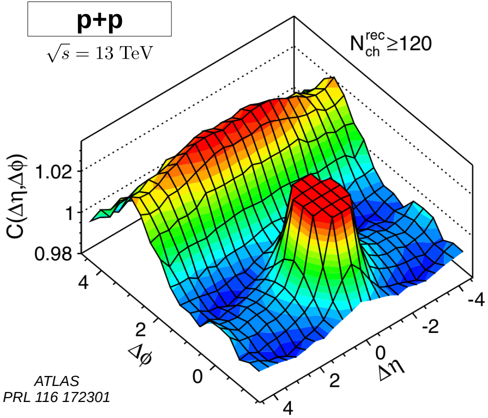
- Subsequently, a prominent stage of **rescattering** is expected that rapidly leads to a local thermal equilibrium.
- **Hydrodynamics of a QCD fluid** is used to describe the evolution of this matter.
- This is a non-perturbative process that converts the initial-state spatial eccentricity into a final-state momentum anisotropy.

Observations in heavy-ion collisions



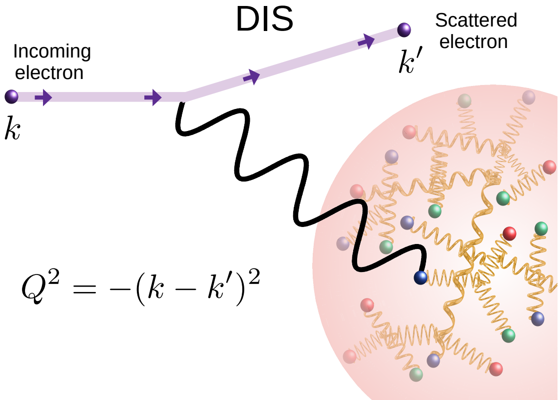
- Two particle correlations show a clear **double ridge**, which is interpretated as a sign of fluid-like behaviour.
- The fluid of QCD matter is referred to as a **Quark–gluon plasma (QGP)**.

Observations in high-multiplicity $p + p$ collisions



- The LHC revealed a similar double-ridge in high multiplicity $p + p$ collisions.
- The finding came as a **surprise** since a $p + p$ collision was thought to be too small to produce a thermally equilibrated QGP.
- **This motivated the search for similar effects in even smaller *ep* DIS at HERA.**

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:

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

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

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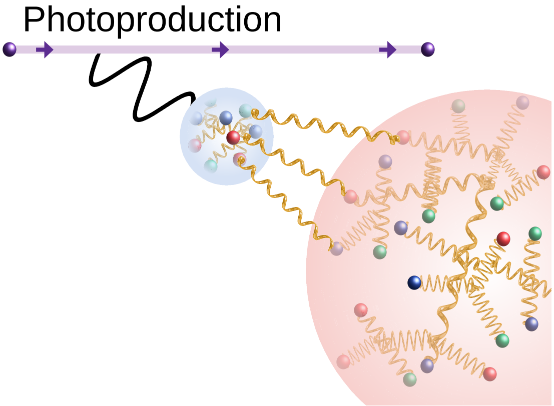
- Neutral current (NC) DIS involves exchange of photon or Z boson.

Photoproduction (PhP)



- PhP is defined by small virtualities: $Q^2 \ll \Lambda^2_{\mathrm{QCD}}$.
- Exchange photon may fluctuate into quarks and gluons.
- Larger interaction regions are probed.
- Scattering is hadron-like.
- **PhP is not presented here. A complementary ZEUS analysis in photoproduction on this subject will be published soon.**

Two-particle correlation function $c_n\{2\}$

Two-particle azimuthal correlations are measured:

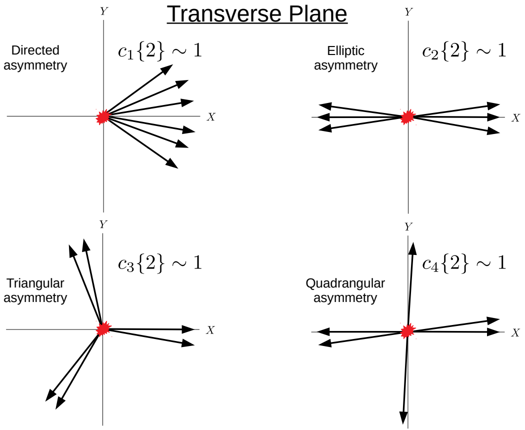
$$c_n\{2\} = \langle\langle \cos n(\phi_i - \phi_j)\rangle\rangle.$$

φ_i is the azimuthal angle of particle i.

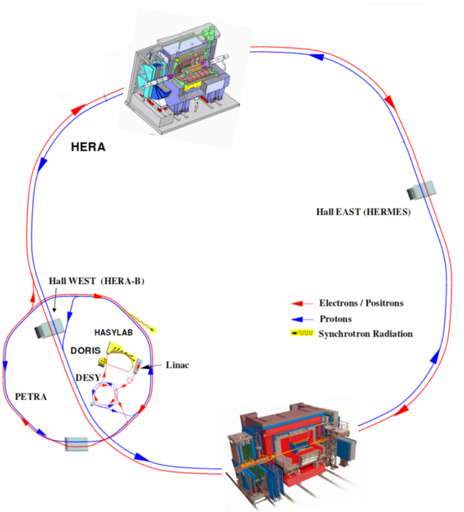
n is the harmonic.

The inner and outer brackets denote an average within an event and over all events, respectively.

Detector acceptance corrections described in the backup.



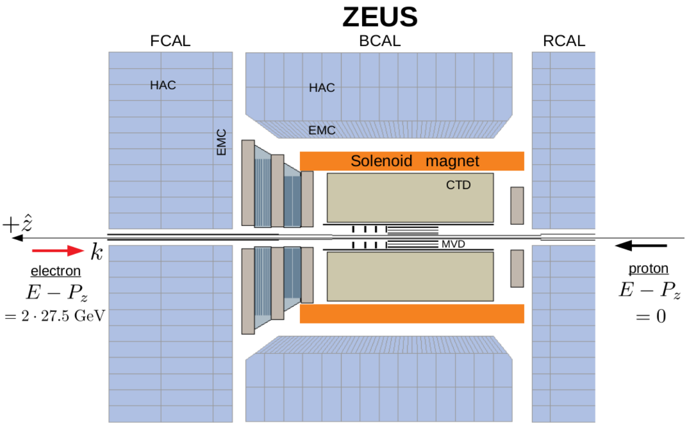
The HERA collider and experiments



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

We present recently published measurements of two-particle correlations in NC DIS with ZEUS: **JHEP 04 (2020) 070.**

DIS event and track selection

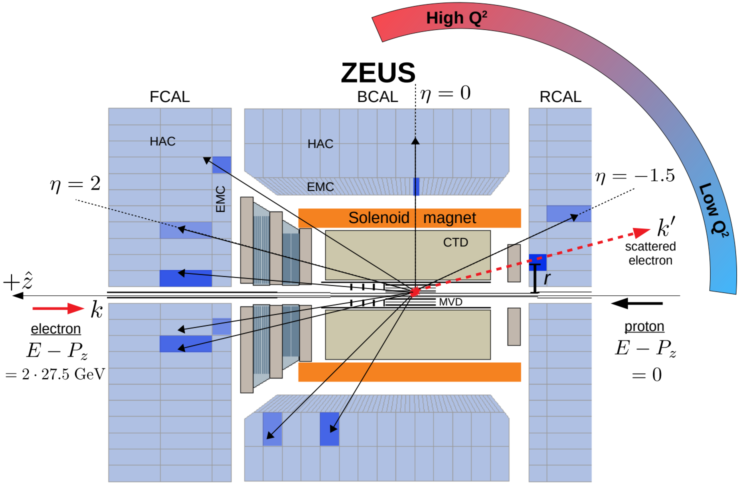


Charged particles are tracked in the central tracking detector (CTD) and micro vertex detector (MVD) in a 1.43 T magnetic field.

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.

DIS event and track selection



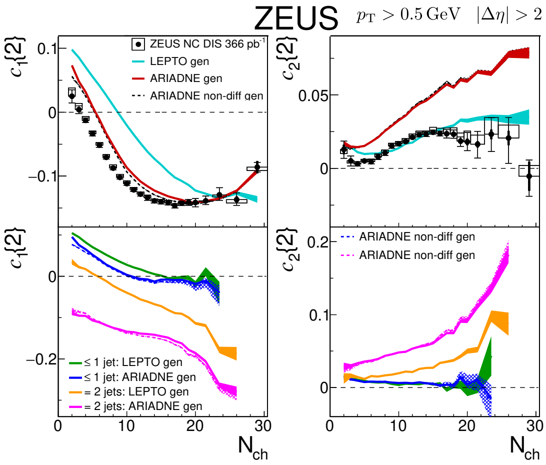
Event selection (46 M)

- DIS triggers
- $Q^2 = -(k - k')^2 > 5\ \mathrm{GeV}^2$
- $k'_0 > 10\ \mathrm{GeV}$
- $r > 15$ cm
- $\theta_e > 1$ rad
- $47 < \sum(E_i - P_{z,i}) < 69$ GeV
- $|V_z| < 30$ cm

Track selection for correlation analysis

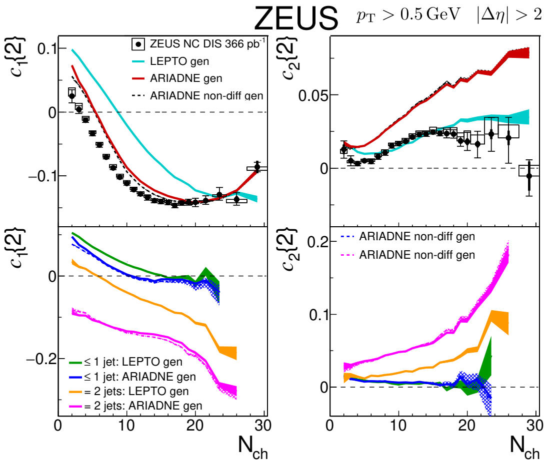
- Reject scattered electron
- $-1.5 < \eta < 2.0$
- $0.1 < p_T < 5.0$ GeV
- ≥ 1 MVD hit
- $\mathrm{DCA}_{XY,Z} < 2$ cm
- $\Delta R > 0.4$ (cone around scattered electron)

$c_1\{2\}$ & $c_2\{2\}$ versus charged particle multiplicity N_{ch}

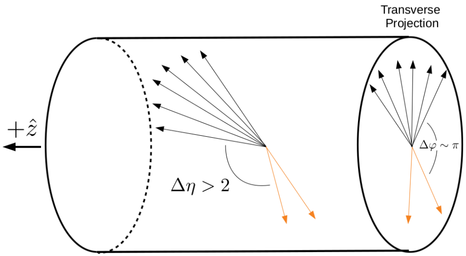


- $c_1\{2\}$ is better described by the ARIADNE generator.
- $c_2\{2\}$ is better described by the LEPTO generator.
- Neither model works well for both harmonics.
- The diffractive component in ARIADNE only slightly influences $c_2\{2\}$.
- Massless jets were reconstructed from the generated hadrons with the k_T algorithm and $E_t > 2$ GeV, $\Delta R = 1$.
- Jets can explain the observed correlations.

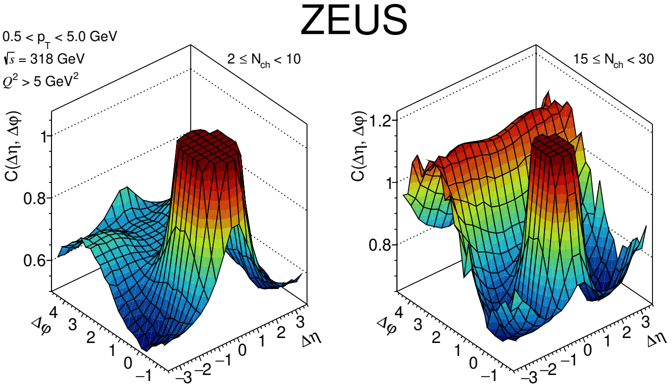
$c_1\{2\}$ & $c_2\{2\}$ versus charged particle multiplicity N_{ch}



- Short-range ($|\Delta\eta| \sim 0$) correlations are strongest at low N_{ch}
- Longe-range correlations ($|\Delta\eta| > 2$, orange-black pairs) of the first harmonic are negative and the largest in magnitude



Ridge figures in DIS

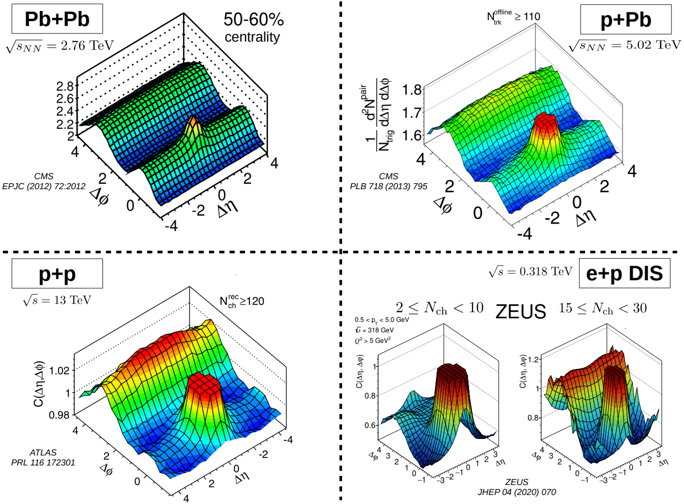


Jet peak centered at $\Delta\varphi \sim \Delta\eta \sim 0$.

Away-side ridge at high N_{ch} is expected from tilted dijets.

No double ridge visible at high N_{ch}

Ridge comparisons between the LHC and HERA DIS



Summary and outlook

- Two-particle azimuthal correlations have been measured in *ep* neutral current deep inelastic scattering with ZEUS.
- Comparisons of the observed correlations with available models of DIS suggest that the measured correlations are dominated by contributions from jets.
- The correlations do not indicate the kind of collective behaviour recently observed in high-multiplicity hadronic collisions at the highest RHIC and LHC energies.
- **Soon to be published results in photoproduction will shed more light on multi-particle production mechanisms and how they evolve from DIS to hadronic collisions.**

Backup

Correcting for detector effects

Applied weights from Monte Carlo simulations:

- w_i: Single-particle weights (1/efficiency) as a function of charge, p_T, φ, and η.
- $w_{\Delta\varphi}$: Two-particle weights formed from the ratio of the number of generated to reconstructed pairs as a function of $\Delta\varphi$, $|\Delta\eta|$, N_{ch}, and relative charge.

Corrected event multiplicity is a weighted sum over all reconstructed tracks N_{rec}:

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

Measured two-particle correlation function:

$$c_n\{2\} = \sum_{e}^{N_{events}} \left[\sum_{i \neq j}^{N_{\mathrm{rec}}} w_i w_j w_{\Delta\varphi} \cos n(\varphi_i - \varphi_j) \right]_e \Bigg/ \sum_{e}^{N_{events}} \left[\sum_{i \neq j}^{N_{\mathrm{rec}}} w_i w_j w_{\Delta\varphi} \right]_e$$

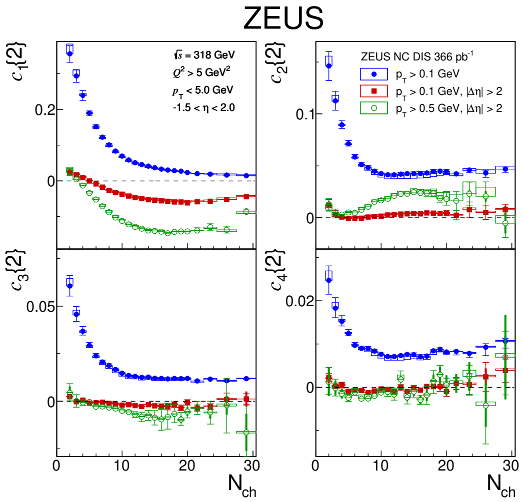
Systematic uncertainties

Considered sources of systematic uncertainties:

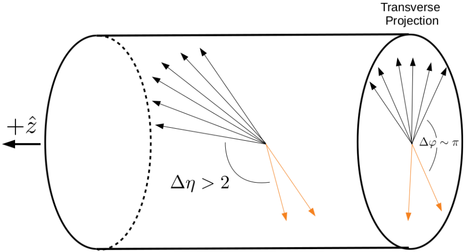
- Monte Carlo closure test (dominant source)
- Secondary contamination
- DIS event selection
- Efficiency corrections

Monte Carlo test uncertainty shown with boxes.
The other systematic uncertainties are added bin-by-bin in quadrature and shown with thin capped lines.

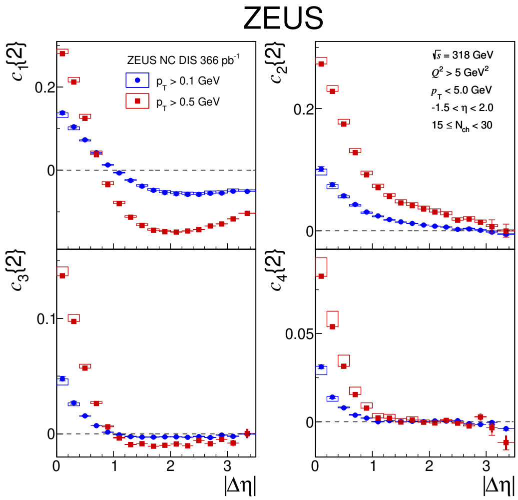
$c_n\{2\}$ versus charged particle multiplicity N_{ch}



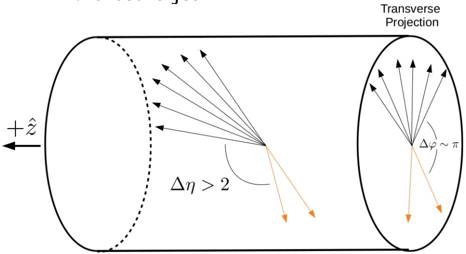
- Short-range ($|\Delta\eta| \sim 0$) correlations are strongest at low N_{ch}
- Longe-range correlations ($|\Delta\eta| > 2$, orange-black pairs) of the first harmonic are negative and the largest in magnitude



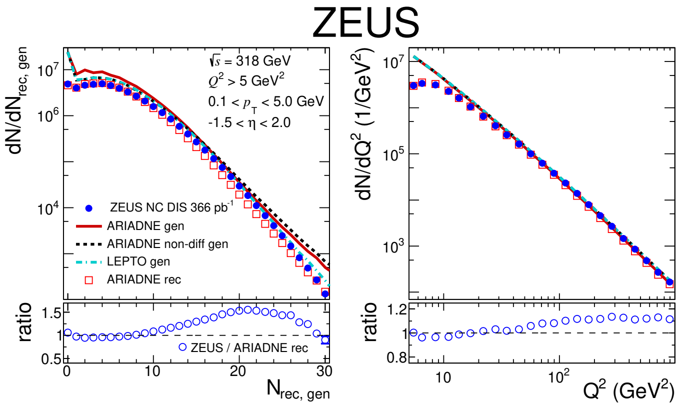
$c_n\{2\}$ versus $|\Delta\eta|$



- The correlations with $p_T > 0.5$ GeV (red) are more pronounced than those at low p_T (blue) as expected from particles in jet-like structures
- Negative (positive) $c_1\{2\}$ ($c_2\{2\}$) for $p_T > 0.5$ GeV extend out to $|\Delta\eta| \sim 3$
- Large directed and elliptic anisotropy $\rightarrow$ tilted dijet

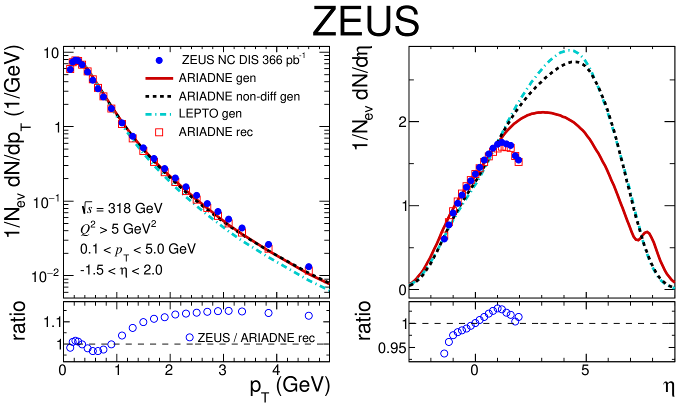


DIS event distributions



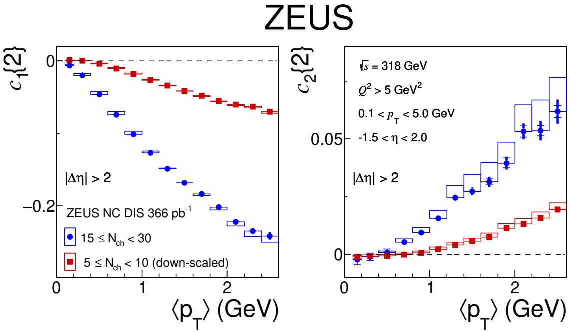
- Uncorrected multiplicity, $N_{\rm rec}$, and Q^2 distributions.
- ARIADNE MC simulations with ZEUS detector response gives a fair description of the measured ZEUS data.
- $\langle N_{\rm rec} \rangle = 5$
- $\langle Q^2 \rangle = 30 \ {\rm GeV}^2$

DIS track distributions



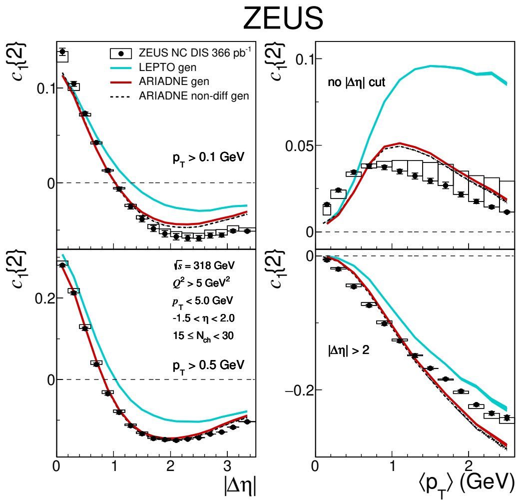
- Uncorrected p_T and η track distributions.
- Reconstructed ARIADNE is compatible with the data to within about 10%.
- Most of the proton fragments lie outside of the ZEUS acceptance near $\eta = 4$.
- The proton remains intact for the diffractive events as seen with the small peak in ARIADNE near $\eta = 8$.

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



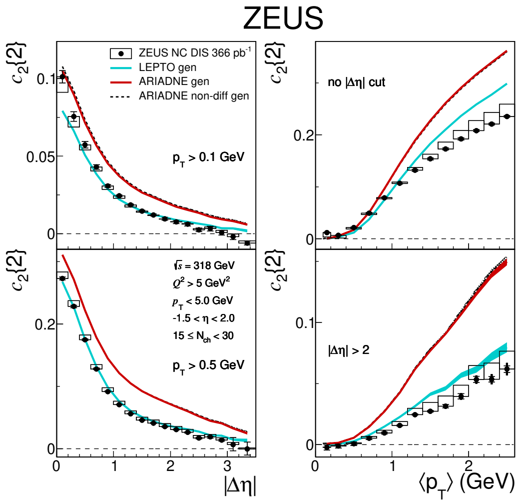
- Correlations at low N_{ch} were down-scaled by $\langle N_{ch} \rangle_{low} / \langle N_{ch} \rangle_{high}$.
- Scaling factor inspired by observations in heavy-ion collisions where non-collective behaviour contributes to $c_2\{2\}$ as $1/N_{ch}$.
- The observed excess correlation at N_{ch} wrt low N_{ch} is stronger for $c_1\{2\}$ and $c_2\{2\}$.
- Therefore, the $1/N_{ch}$ scaling of non-collective correlations may not be appropriate for *ep* scattering.

Model comparisons of $c_1\{2\}$ versus $|\Delta\eta|$ and $\langle p_T \rangle$



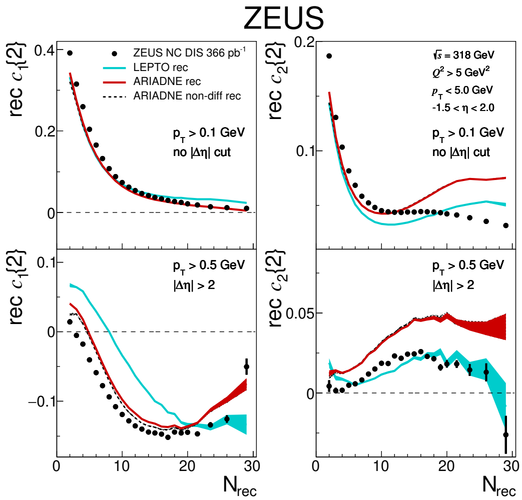
- ARIADNE predictions describe the data for the 1st harmonic reasonably well.

Model comparisons of $c_2\{2\}$ versus $|\Delta\eta|$ and $\langle p_T \rangle$



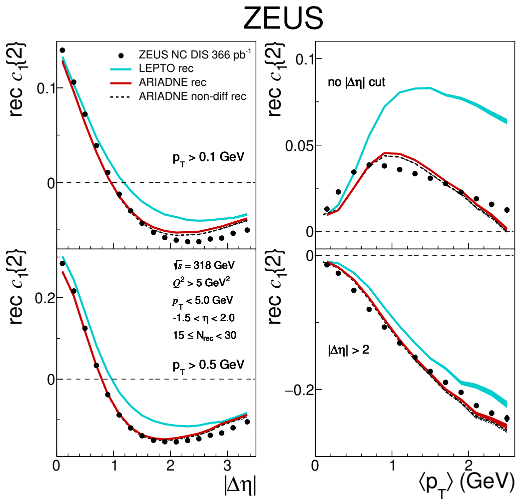
- LEPTO predictions describe the data for the 2nd harmonic reasonably well.

Raw $c_1\{2\}$ and $c_2\{2\}$ versus $N_{\rm rec}$ compared to models



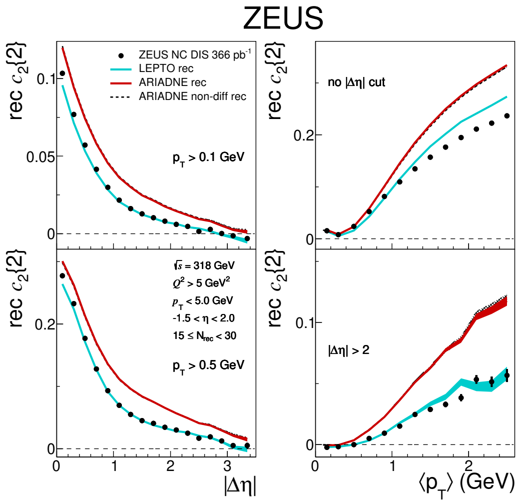
- LEPTO/ARIADNE provides a reasonable description of the reconstructed data.
- Utilization of tracking efficiency corrections from such Monte Carlo data is reasonably justified.

Raw $c_1\{2\}$ versus $|\Delta\eta|$ and $\langle p_T \rangle$ compared to models



- ARIADNE provides a reasonable description of the reconstructed data.
- Utilization of tracking efficiency corrections from such Monte Carlo data is reasonably justified.

Raw $c_2\{2\}$ versus $|\Delta\eta|$ and $\langle p_T \rangle$ compared to models



- LEPTO provides a reasonable description of the reconstructed data.
- Utilization of tracking efficiency corrections from such Monte Carlo data is reasonably justified.