Two-particle azimuthal correlations as a probe of collectivity in deep inelastic $ep$ scattering at HERA

1$^{\text{st}}$ paper presentation
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Outline

**Paper draft and analysis note:** [http://www.desy.de/~phch/ZEUS/zep.html](http://www.desy.de/~phch/ZEUS/zep.html)

1) Collectivity and the motivation for the analysis
2) Two-particle correlation function
3) Event and track selection
4) Single particle efficiency corrections
5) Systematic uncertainties
6) Abstract and final figures for publication
7) Monte Carlo closure test problem
   1) List of considered variations
   2) Changes wrt preliminary analysis
8) Sample event display (as per Mariusz’ question)
Collectivity in heavy-ion collisions

- **Collectivity**: Correlated multiparticle emission generated by a common physical mechanism.

Non-central collision

Expansion wrt to this common symmetry plane

Correlated multiparticle emission
Motivation for the analysis

- It has long been observed that relativistic heavy-ion collisions are capable of generating a many body system in a local thermal equilibrium. Correlated multiparticle emission occurs in the final-state in response to initial anisotropies.
- Recent measurements (since 2010) in smaller systems have revealed a strikingly similar behavior.

![Snapshots of typical energy density profiles](image)

*Fig. 1.* Snapshots of typical energy density profiles in the transverse plane for Pb+Pb (left panel), p+Pb (center panel) and p+p collisions (right panel, including zoom-in to enlarge system) at $\sqrt{s} = 5.02$ TeV. The actual box sizes used in simulations were adapted to individual systems. Note that for a typical p+p collision, initial conditions from the OSU model are very close to (but nevertheless slightly different from) those obtained from spherical nucleons, cf. Ref. [42].
Recent studies from LHC

- Azimuthal two-particle correlation functions, $c_n \{2 \} \sim v_n^2$, are sensitive to the collective response of the system to asymmetries in the initial-state energy-density.

**Observation:** Similar values of $v_n$ at similar multiplicity are seen in wide variety of collisions from heavy-ions down to pp.

**Conclusion:** A collective response to the initial-state emerges even in small systems.

- **Natural question:** How small is too small to depart from collectivity?
Search for collectivity in $ep$ collisions at HERA

**Deep inelastic scattering (DIS)**

$\text{lepton} \rightarrow k'
\text{proton} \rightarrow p,
\gamma^* \rightarrow g = k - k'$

**Photoproduction (PHP)**

**Direct**

$e^- \rightarrow p$

**Resolved**

$e^- \rightarrow p$

DIS provides a substantially different system than those produced in hadronic collisions (RHIC and the LHC) because the initial hard scattering is non-hadronic.

The paper presents results in neutral current DIS only.

Resolved PHP may also provide an interesting future study. The initial hard scattering is hadronic and is therefore more similar to collisions at RHIC and the LHC

To be studied in a future analysis.
Collective azimuthal correlations described with $v_n$ and measured with $c_n$

Azimuthal part of momentum spectrum with respect to common symmetry planes ($\Psi_m$)

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi p_T} \frac{d^2 N}{dp_T dy} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \{m\} \cos [n(\varphi - \Psi_m)] \right].$$

Fourier coefficients related to each symmetry plane by

$$v_n \{m\} = \langle \cos [n(\varphi - \Psi_m)] \rangle,$$

For the case $n=m$, one can extract $v_n \{n\}$ through two-particle correlations

$$c_n \{2\} = \langle \cos [n(\varphi_1 - \varphi_2)] \rangle,$$

In the case of correlated particle production only through the symmetry planes

$$v_n^2 \{n\} \approx c_n \{2\}.$$
Explicit form of correlation function used in this analysis

\[ c_n\{2\} = \sum_e N \left[ \sum_{i,j>i} M w_i w_j \cos[n(\varphi_i - \varphi_j)] \right] / \sum_e [N_{ch}(N_{ch} - 1)]_e \]

- \( N \): total number of events.
- \( n \): harmonic.
- \( M \): uncorrected charged particle multiplicity.
- \( N_{ch} \): corrected charged particle multiplicity. \( N_{ch} = \sum_i w_i \)
- \( \varphi \): azimuthal angle of track
- \( w \): track weight = \( w_p \times w_\varphi \).
- \( w_p \): inverse of reconstruction efficiency as a function of \( p_T \) and \( \eta \). Determined from MC.
- \( w_\varphi \): inverse of azimuthally dependent reconstruction efficiency. Determined from real data after the application of \( w_p \) in the 1\textsuperscript{st} pass over real data. \( c_n\{2\} \) measured in 2\textsuperscript{nd} and final pass over the data.

\( c_n\{2\} \) is measured as a function of \( N_{ch} \), \( |\eta_1 - \eta_2| \), and \( (p_{T1} + p_{T2}) / 2 \).
All are defined in the lab frame.
Neutral DIS event selection

- Check that at least one DIS trigger bit fired.

Properties of the identified sinistra are further used to select neutral DIS events
- Energy in CAL > 10 GeV.
- Probability > 0.9 as determined by the neural network algorithm.
- Polar angle > 1.0 rad.
- $Q^2 > 5$ GeV/c.
- Radial impact location in the CAL > 15 cm.
- Trajectory through CAL did not cross the chimney or HES fiducial/CAL crack.

Consistency check using hadronic part of event
- $47 < E - P_z < 69$ GeV.
Event vertex and track selection

Event vertex selection
- $-30 < V_z < 30$ cm.
- $| V_{xy} - \text{BeamSpot}_{xy} | < 0.5$ cm.
- $N_{\text{vertex}}$ tracks $> 0$.
- Fraction of tracks associated to event vertex $> 0.1$.
- Event vertex $\chi^2 / N_{\text{vertex}} < 50$.

Track selection
- ZTT (refitted) tracking type (ZEUS tracking).
- Reject sinistra candidate.
- Require at least 1 hit point in the MVD.
- Require $\text{DCA}_{xy} < 2$ cm, $\text{DCA}_z < 4$ cm.
- $0.1 < p_T < 5.0$ GeV/c.
- $-1.5 < \eta < 2.0$. 
# Data & MC samples

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Version</th>
<th>All events</th>
<th>After DIS trigger</th>
<th>After Vtx cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>03p</td>
<td>v08b</td>
<td>3.7 M</td>
<td>0.3 M</td>
<td>0.2 M</td>
</tr>
<tr>
<td>04p</td>
<td>v08b</td>
<td>47.5</td>
<td>6.2</td>
<td>4.7</td>
</tr>
<tr>
<td>05e</td>
<td>v08b</td>
<td>130.0</td>
<td>22.0</td>
<td>16.4</td>
</tr>
<tr>
<td>06e</td>
<td>v08b</td>
<td>44.2</td>
<td>8.5</td>
<td>7.0</td>
</tr>
<tr>
<td>06p</td>
<td>v08b</td>
<td>86.6</td>
<td>14.4</td>
<td>11.8</td>
</tr>
<tr>
<td>07p</td>
<td>v08b</td>
<td>41.2</td>
<td>6.7</td>
<td>5.4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>353.2 M</td>
<td>58.1 M</td>
<td>45.5</td>
</tr>
</tbody>
</table>

**Table 1:** The analyzed real data samples and number of events.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Version</th>
<th>All events</th>
<th>After DIS trigger</th>
<th>After Vtx cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariadne 0304p</td>
<td>v08b</td>
<td>18.2 M</td>
<td>12.3 M</td>
<td>10.0 M</td>
</tr>
<tr>
<td>Ariadne 05e</td>
<td>v08b</td>
<td>60.4</td>
<td>40.6</td>
<td>31.4</td>
</tr>
<tr>
<td>Ariadne 06e</td>
<td>v08b</td>
<td>23.9</td>
<td>15.9</td>
<td>13.0</td>
</tr>
<tr>
<td>Ariadne 0607p</td>
<td>v08b</td>
<td>62.0</td>
<td>41.4</td>
<td>33.7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>164.5 M</td>
<td>110.2 M</td>
<td>88.1 M</td>
</tr>
</tbody>
</table>

**Table 2:** The analyzed Ariadne MC data samples and number of events.

Statistics for LEPTO are very similar to ARIADNE.
Definition of “primary” particles

A particle is considered primary if it has a mean proper lifetime $\tau > 1$ cm/c and it was produced directly in the collision or from a decay of a particle with $\tau < 1$ cm/c, restricted to decay chains leading to the interaction of colliding particles.

Used only for estimation of efficiency corrections.

<table>
<thead>
<tr>
<th>Specie</th>
<th>Width $\Gamma$ (GeV)</th>
<th>Mean proper lifetime $\tau$ (ps)</th>
<th>$\tau$ (cm/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p^+$</td>
<td>0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$n$</td>
<td>$7.478 \times 10^{-28}$</td>
<td>$8.861 \times 10^{+14}$</td>
<td>$2.656 \times 10^{+13}$</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>$2.996 \times 10^{-19}$</td>
<td>$2.212 \times 10^{+06}$</td>
<td>$6.63 \times 10^{+04}$</td>
</tr>
<tr>
<td>$K_L$</td>
<td>$1.287 \times 10^{-17}$</td>
<td>$5.148 \times 10^{+04}$</td>
<td>1543</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$2.528 \times 10^{-17}$</td>
<td>$2.621 \times 10^{+04}$</td>
<td>785.7</td>
</tr>
<tr>
<td>$K^+$</td>
<td>$5.317 \times 10^{-17}$</td>
<td>$1.246 \times 10^{+04}$</td>
<td>373.6</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>$2.27 \times 10^{-15}$</td>
<td>291.9</td>
<td>8.751</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$2.501 \times 10^{-15}$</td>
<td>264.9</td>
<td>7.943</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>$4.02 \times 10^{-15}$</td>
<td>164.8</td>
<td>4.941</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>$4.45 \times 10^{-15}$</td>
<td>148.9</td>
<td>4.464</td>
</tr>
<tr>
<td>$K^0_S$</td>
<td>$7.351 \times 10^{-15}$</td>
<td>90.14</td>
<td>2.702</td>
</tr>
<tr>
<td>$\Omega^-$</td>
<td>$8.071 \times 10^{-15}$</td>
<td>82.1</td>
<td>2.461</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>$8.209 \times 10^{-15}$</td>
<td>80.72</td>
<td>2.42</td>
</tr>
</tbody>
</table>
Efficiency corrections

- Corrections for non-uniform efficiency are done by applying two types of weights to the correlation functions and $N_{ch}$ estimation.

1) $w_p$
2) $w_\phi$

- $w_p$ is determined from Monte Carlo simulations and is equal to the inverse of the tracking efficiency. It is calculated differentially wrt: $p_T$, $\eta$, charge, and data taking period.

- $w_\phi$ quantifies the azimuthal variation of the tracking efficiency and is extracted from the first pass over real data with $w_p$ weights applied. It is calculated differentially wrt: $\eta$, charge, and data taking period.
Tracking efficiency: $w_p$

Calculated differentially wrt: $p_T$, $\eta$, charge, and data taking period.
Considered systematic uncertainties

<table>
<thead>
<tr>
<th>Type of Systematic</th>
<th>Reference</th>
<th>Variation(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC closure</td>
<td>generator correlations</td>
<td>reconstructed correlations</td>
</tr>
<tr>
<td>$Z$-vertex interval</td>
<td>$-30 &lt; V_z &lt; -8$ cm</td>
<td>$8 &lt; V_z &lt; 30$</td>
</tr>
<tr>
<td>Vertex total $\chi^2/N_{vtx_tracks}$</td>
<td>$&lt; 50$</td>
<td>$&lt; 10$</td>
</tr>
<tr>
<td>Data taking period</td>
<td>All</td>
<td>individual periods 04p to 07p</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>Ariadne 06e</td>
<td>Lepto 06e</td>
</tr>
<tr>
<td>DCA cuts</td>
<td>DCA$<em>{xy} &lt; 2.0$ cm, DCA$</em>{z} &lt; 4.0$</td>
<td>DCA$<em>{xy} &lt; 1.0$ cm, DCA$</em>{z} &lt; 2.0$</td>
</tr>
<tr>
<td>DIS trigger consistency check</td>
<td>$47 &lt; E - P_z &lt; 69$ GeV</td>
<td>$45 &lt; E - P_z &lt; 71$</td>
</tr>
<tr>
<td>Sinistra probability and polar angle</td>
<td>$P_e &gt; 0.9, \theta_e &gt; 1$ rad</td>
<td>$P_e &gt; 0.8, \theta_e &gt; 0.5$</td>
</tr>
<tr>
<td>Radius cut for the Sinistra's entrance location around $(x,y) = (-1,0)$</td>
<td>15 cm</td>
<td>17 cm</td>
</tr>
<tr>
<td>Sinistra chimney cut</td>
<td>Reject $(-10 &lt; x &lt; 10 &amp;&amp; 110 &lt; y &lt; -141)$</td>
<td>Reject $(-12 &lt; x &lt; 12 &amp;&amp; 113 &lt; y &lt; -143)$</td>
</tr>
<tr>
<td>HES fiducial/CAL crack cut in RCAL</td>
<td>Reject $( (5 &lt; x &lt; 11 &amp;&amp; y &gt; 0) | (-15 &lt; x &lt; -9 &amp;&amp; y &lt; 0) &amp;&amp; z &lt; 0141 )$</td>
<td>Reject $( (4 &lt; x &lt; 12 &amp;&amp; y &gt; 0) | (-16 &lt; x &lt; -10 &amp;&amp; y &lt; 0) &amp;&amp; z &lt; -143 )$</td>
</tr>
</tbody>
</table>
Decomposition of systematics for $c_2\{2\}$ vs Nch

- Dominant source of systematics discussed later.
- Points corresponding to different sources of systematics are shifted horizontally with an Nch bin.
- Total systematic uncertainty is the sum quadrature of all sources.
Decomposition of systematics for $c_2\{2\}$ vs $< p_T >$

- Dominant source of systematics discussed later.
- Points corresponding to different sources of systematics are shifted horizontally with an Nch bin.
- Total systematic uncertainty is the sum quadrature of all sources.
Measurements of two-particle azimuthal correlations, $c_n\{n\}$, are presented in neutral current deep inelastic $ep$ scattering with virtuality $Q^2 > 5$ GeV$^2$ at $\sqrt{s}=318$ GeV recorded with the ZEUS detector at HERA.

The $c_n\{n\}$ of charged hadrons are measured in the range of lab pseudo-rapidity $-1.5 < \eta < 2$ and transverse momentum $0.1 < p_T < 5$ GeV/c for harmonics $n=1-4$ and event multiplicities up to six times larger than the average $<N_{ch}>$=5.

No significant long-range correlations for the second harmonic $c_n\{2\}$ are observed at high multiplicities for $p_T > 0.1$ GeV/c, while a positive $c_n\{2\}$ is found for $p_T > 0.5$ GeV/c. The simultaneous increase with $p_T$ of negative $c_n\{1\}$ indicates that the nonzero $c_n\{2\}$ at high $p_T$ is likely due to hard processes and not collectivity.

The available Monte Carlo models of deep inelastic scattering, tuned to reproduce the inclusive particle production, fail to quantitatively describe $c_n\{n\}$.

The measurements provide new insights about the origin of collective effects recently observed at the top RHIC and the LHC energies in high multiplicity collisions of small systems such as $pp$. 
Message:

- The reconstructed single particle distributions in Ariadne with the ZEUS detector response are compatible with data to within 10%.
- ZEUS acceptance far from proton fragmentation peak. This is the main reason why a direct comparison to LHC results is not straightforward.
Paper Figure 2 (main result)

Message:

- Peaks at low $N_{ch}$ are short-range in nature since they are largely removed with a rapidity separation.
- $c_1{\{2\}}$ and $c_3{\{2\}}$ become negative with a rapidity separation, which is expected from the effects of momentum conservation, e.g. when back-to-back di-jet processes dominate particle production.
- No significant long-range correlations with the 3$^{rd}$ and 4$^{th}$ harmonic.

Figure 2: $c_n{\{2\}}$ as a function of $N_{ch}$ for $n = 1 - 4$ with and without a rapidity separation, and for $p_T > 0.5$ GeV/c. The statistical uncertainties are shown as vertical lines although they are typically smaller than the marker size. Systematic uncertainties are shown with boxes.
The $c_1^2$ and $c_3^2$ dependence on $\Delta \eta$ is qualitatively similar but with different magnitude modulations. Both change sign near $\Delta \eta \approx 1$, which shows that the short-range correlations extends up to about one unit of rapidity separation after which the long range effects, such as momentum conservation, become dominant contributions to $c_1^2$ and $c_3^2$.

- Integrated over the full $p_T$ range, $c_2^2$ and $c_4^2$ vanish for $\Delta \eta > 2$.
- Long-range correlations are stronger at high $p_T$ for which $c_2^2$ extends out to 3 units of $\Delta \eta$.

**Figure 3:** $c_n^2$ for $10 \leq N_{ch} < 25$ as a function of $\Delta \eta$ and different selection for pair transverse momentum $\langle p_T \rangle > 0.1$ GeV/c and $\langle p_T \rangle > 0.5$ GeV/c. The statistical uncertainties are shown as vertical lines although they are typically smaller than the marker size. Systematic uncertainties are shown with boxes.
For both $c_1^2$ and $c_2^2$, the correlation strength grows with increasing $p_T$ up to a few GeV/c, which is universally observed in all collision systems.

The extracted value of $v_2$ at RHIC and the LHC ranges between $0.05 - 0.1$ at $p_T \approx 1$ GeV/c.

At a similar $p_T$ value, the corresponding difference between the central values of $c_2^2$ at low and high multiplicity yields an estimate of $v2 \approx 0.07$ but with systematic uncertainties of a similar magnitude.

**Figure 4:** $c_1^2$ and $c_2^2$ as a function of $\langle p_T \rangle$ for low and high $N_{ch}$. Low $N_{ch}$ correlations are down-scaled by a factor of $\sqrt{\langle N_{ch} \rangle_{low} / \langle N_{ch} \rangle_{high}}$ as explained in the text. The statistical uncertainties are shown as vertical lines although they are typically smaller than the marker size. Systematic uncertainties are shown with boxes.
The models are able to reproduce the qualitative features of the data but fail quantitatively.

Both LEPTO and ARIADNE predict an increase in $c_2\{2\}$ with $N_{ch}$, which the data does not support.

Figure 5: $c_1\{2\}$ and $c_2\{2\}$ with and without a rapidity separation as a function of $N_{ch}$ compared to the expectations from Monte Carlo event generators. The statistical uncertainties are shown as vertical lines although they are typically smaller than the marker size. Systematic uncertainties are shown with boxes.
It is clear that short-range correlations ($\Delta \eta < 1$) are underestimated in LEPTO while long-range correlations are overestimated in ARIADNE.

The growth of correlations with $<p_T>$ is also overestimated in ARIADNE.

Figure 6: $c_2\{2\}$ as a function of $\Delta \eta$ and $<p_T>$ for $10 \leq N_{ch} < 25$ compared to the expectations from Monte Carlo event generators. The statistical uncertainties are shown as vertical lines although they are typically smaller than the marker size. Systematic uncertainties are shown with boxes.
Conclusions for the paper

- For $p_T > 0.1$ GeV/c, no significant long-range correlations are observed with $c_2\{2\}$, $c_3\{2\}$, and $c_4\{2\}$.
- Strong long-range anti-correlations are observed with $c_1\{2\}$ as expected due to momentum conservation.
- At high $p_T$, large long-range (anti-)correlations extending past $\Delta\eta = 2$ with both $c_1\{2\}$ and $c_2\{2\}$ are observed.
- Models of deep inelastic scattering which are able to reproduce single-particle spectra and the event multiplicity distribution, fail to quantitatively describe two-particle correlations. The LEPTO and ARIADNE event generators both predict a strong increase in $c_2\{2\}$ at high Nch, which the data does not support.
- The measurements provide new constraints for models of deep inelastic scattering and add important information on the origin of collective effects recently observed at RHIC and the LHC. Future studies with existing photoproduction data at HERA, in which the initial scattering is similarly partonic as in hadron-hadron interactions, will provide a bridge between the presented DIS results and studies at RHIC and the LHC.

Main Conclusion:
The origin of two-particle correlations in $ep$ is likely from hard processes and not collectivity.
Three more topics to discuss

1) Analysis differences between preliminary and final results

2) The Monte Carlo closure test: a large source of systematic uncertainty.

3) Sample event displays as requested by Mariusz.
### Analysis differences between preliminary and final results

<table>
<thead>
<tr>
<th>Type</th>
<th>Preliminary</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) orange.Trk_prim_vtx flag</td>
<td>1</td>
<td>both 0 and 1 allowed</td>
</tr>
<tr>
<td>2) dca cuts</td>
<td>dca_xy &lt; 0.5 cm</td>
<td>dca_xy &lt; 2.0 cm and dca_z &lt; 4.0 cm</td>
</tr>
<tr>
<td>3) pair cuts</td>
<td>none</td>
<td>$\Delta\eta &gt; 0.05$</td>
</tr>
<tr>
<td>4) numerator of $p_T, \eta$ efficiency correction</td>
<td>all reconstructed particles</td>
<td>only primary reconstructed particles</td>
</tr>
<tr>
<td>5) $p_T, \eta$ efficiency binning</td>
<td>0.2 in $\eta$, 0.1 in $p_T$ for $p_T &lt; 0.3$</td>
<td>0.25 in $\eta$, 0.05 in $p_T$ for $p_T &lt; 0.3$.</td>
</tr>
<tr>
<td>6) phi correction multiplicity binning</td>
<td>differential</td>
<td>integrated</td>
</tr>
<tr>
<td>7) efficiency and phi correction charge binning</td>
<td>integrated</td>
<td>differential</td>
</tr>
</tbody>
</table>

Discussed in next slides
Prelim vs Final $c_2\{2\}$ vs $N_{ch}$

- Reduced systematic uncertainties wrt preliminary results.
- Change in central points are within previous systematics.
- Other comparisons in the form of absolute differences (Prelim – Final) shown in analysis note.
MC closure: list of considered variations

Track selection variation

- Raise $p_T$ min from 0.1 to 0.25 GeV/c.
- $-1.5 < \eta < 2.0 \Rightarrow -1.5 < \eta < 1.5$.
- Positive pairs versus negative pairs versus opposite-charge pairs.
- Apply a minimum number of CTD + MVD hit points based on $\eta$ (Fig 57 in note).
- HERA I vs HERA II (check of possible MVD induced bias).
- Remove Trk_prim_vtx=1 (track constrained to primary vertex) and apply wider dca cuts. This reduced the discrepancy somewhat (explained more later).
- Z-vertex position fluctuates within $-30 < V_z < +30$ cm. For that reason, very forward tracks might be often lost when $V_z$ is near +30 cm. We tried rejecting very forward generated tracks based on the Z-vertex (in backup slides).

Variations of tracking efficiency calculation

- Finer multiplicity binning of efficiency corrections.
- Matching algorithm used in tracking efficiency calculation.
  - Min match quality = +1 instead of -1 (default)
  - Our own matching algorithm based on track kinematics ($p_T$, $\eta$)
- Narrowed the kinematic interval to lie in the “comfortable” region of ZEUS where efficiencies are mostly constant: $0 < \eta < 1 \&\& 0.5 < p_T < 1.5$.
  In this interval out pair weights should not matter.
Improved MC closure tests for $c_2\{2\}$
Correlated pair loss from Trk_prim_vtx selection

- Trk_prim_vtx = 1 (primary vertex used in the refitting process)
- Trk_prim_vtx = 0 (primary vertex NOT used in the refitting process)

To remove influence of secondaries, reco tracks were required to have a matching primary gen particle.

Very large difference in reconstructed correlation strengths.

About 10% of our tracks have Trk_prim_vtx = 0.

For final results: accept Trk_prim_vtx=0 and open dca cuts.
Secondary and fake track pairs at small $\Delta \eta$

The ratio of the number of reco to gen pairs, after applying primary particle cuts.

To remove these pairs, we now apply a cut: $|\Delta \eta| > 0.05$
Correlated loss of primary track pairs

Subset 1: generated pairs which have a FULL match to pairs in our selected reco pool.
Subset 2: NO match
Subset 3: PARTIAL match

The ratio of different subsets of generated tracks

- $\Delta \phi$ distributions are clearly quite different for each subset. This is another way of viewing the closure test problem.
- The problem looks very similar in ARIADNE and LEPTO despite large differences in correlation strengths: $c_n^2$. 

MC closure conclusions and outlook

- Accepting tracks with Trk_prim_vtx = 0 reduces the closure test problem.
- No variation of our single-particle efficiency correction factors resolved the problem.
- We conclude that the bulk of this discrepancy is due to a correlated loss of track pairs.
- The absolute difference between generated and reconstructed correlations in MC is assigned as an additional systematic uncertainty.

Outlook for future studies
- The $\Delta \varphi$ ratios on the previous slide may potentially be used as an additional pair correction factor for future studies in PHP collisions.
- Additional studies are needed to determine whether this introduces a strong model dependence to our results.
Sample event display
pre-vertex tracks (No analysis cuts)

Pre-vertex tracks include those with VERY large dca.
Vertex tracks only include those with small dca.
Not shown here are the additional tracks accepted in this analysis with larger dca (up to 2 cm in xy, and 4 cm in z) but with an MVD hit point.
This is a sample high $N_{\text{ch}}$ event (~25 tracks).
Executive summary

- Two-particle correlations in DIS measured with ZEUS do NOT reveal significant collective effects.
- The measurements provide new constraints for models of deep inelastic scattering and add important information on the origin of collective effects recently observed at RHIC and the LHC.

Outlook

- Future studies in PHP, in particular resolved PHP, present an interesting opportunity to study “hadron-like” ep collisions similar to RHIC and the LHC. Perhaps collectivity turns on there…
- However, first the additional pair correction factor to remove the MC closure uncertainty needs a thorough validation.

EPS 2019 and new ALEPH publication

- We would like to present the final figures from the paper at EPS on July 13th.
- 2 weeks ago ALEPH has posted their results on the arXiv. ALEPH concludes that no collective effects are observed in e⁺e⁻ collisions.
Backup
Z-vertex distribution

ProjectionY of binx=[1,20] [x=0.00..1.00]

Number of Entries

\times 10^3

\begin{tabular}{|l|}
\hline
slice_py_ofEvt_vtxR_vtxZ \\
Entries & 6979396 \\
Mean & -0.4841 \\
Std Dev & 10.08 \\
\hline
\end{tabular}

DATA: 06e

Vz (cm)
Symmetry plane analysis from ATLAS

arXiv:1403.0489
Prelim vs Final $c_1\{2\}$ vs Nch

ZEUS Preliminary

$\sqrt{s}=318$ GeV, 366 pb$^{-1}$

$Q^2 > 5$ GeV$^2$

$0.1 < p_T < 5.0$ GeV/c

$-1.5 < \eta < 2.0$

Final results

$|\Delta \eta|$

- $0.0$
- $2.0$

Final - Prelim: $c_1$

Final - Prelim: $c_1\{|\Delta \eta|>2.0\}$
Prelim vs Final $c_2 \{2\}$ vs Nch

ZEUS Preliminary

$\sqrt{s} = 318$ GeV, 366 pb$^{-1}$

- $Q^2 > 5$ GeV$^2$
- $0.1 < p_T < 5.0$ GeV/c
- $-1.5 < \eta < 2.0$

Final results

$|\Delta \eta|$
- $0.0$
- $2.0$

Final - Prelim: $c_2$

$N_{ch}$
Tracking efficiency: $w_p$

With final analysis cuts

With preliminary analysis cuts

Note: the efficiency corrections for the prelim results were not really a primary particle reconstruction efficiency. The numerator included all reconstructed particles, not only those which were truly primary particles. The effect of this can be seen by the spike at very low $p_T$. 
Improved MC closure tests for $c_2\{2\}$

Preliminary analysis

Final analysis

Preliminary analysis

Final analysis
The MC closure problem was somewhat reduced by allowing some non-vertex tracks with larger DCAs.

If the MC closure problem is instead treated with additional $\Delta \varphi$ weights, we could get an estimate of the “would be” systematics by removing the closure and DCA systematics.
The MC closure problem was somewhat reduced by allowing some non-vertex tracks with larger DCAs.

If the MC closure problem is instead treated with additional $\Delta \phi$ weights, we could get an estimate of the “would be” systematics by removing the closure and DCA systematics.

With MC closure and DCA systematics

Without MC closure and DCA systematics
A comparison of ZEUS preliminary to LHC results

Comparison is however not so straightforward because pseudorapidity coverage is very different. LHC results are from the region in between the proton fragmentation peaks. ZEUS results are 2-5 pseudorapidity units away from the proton fragmentation peak.
Previous MC closure test from Jaap’s study

- Generated correlations in MC are substantially larger than reconstructed correlations at high Nch.

- This issue substantially reduces the sensitivity to small signals at high Nch.
- Many variations in event and track selections were considered.
- Many variations in single-particle tracking efficiency corrections were considered.
- One variation was found which slightly reduces this bias (Trk_prim_vtx).
DCA distributions in 06e data

- Retained tracks: $dca_{xy} < 2.0$ cm
- Retained tracks: $dca_z < 4.0$ cm
DCA distributions in Ariadne

Retained tracks:
dca_xy < 2.0 cm

Retained tracks:
dca_z < 4.0 cm
Single particle purities
There is a depletion of pairs at low $\Delta \phi$ which is larger at high $N_{ch}$. This is another way of viewing MC closure problem.

The red line is a pol0 fit between 0.75 and 2.25.
$c_2\{2\}$ from generated $\Delta\phi$ subset distributions

- This figure was produced by computing $\langle \cos(2*\Delta\phi) \rangle$ convoluted with the generated $\Delta\phi$ distribution subsets from the previous slide.
- Closure test problem visible from this perspective using subsets of generator particles.
Closure test: Z-vertex fluctuations

The Z-vertex position fluctuates from event to event within \(-30 < V_z < 30 \text{ cm}\). Very forward tracks (\(\eta \sim 2.0\)) are more likely to be lost when \(V_z \sim 30 \text{ cm}\) because their path length in the CTD is shorter.

Accept generated tracks only if their polar angle is large enough such that their radial exit location is greater than \(R_{\text{min}} = 28 \text{ cm}\).

\[
\theta > \tan^{-1} \left( \frac{R_{\text{MIN}}}{L_{\text{CTD}}/2 - Z_{\text{vtx}}} \right)
\]
N_{ch} correction factors

- Ratio of the number of reconstructed particles passing the selection criteria to the number of true generated primaries. Values above unity indicate fake tracks and/or secondary contamination. 06e data.
Pre-vtx track event display; event 41328
Vertex track event display; event 41328
Pre-vtx track event display; event 6469
Vertex track event display; event 6469
Sinistra entrance location as seen by HES

(a) Before Event cuts

(b) After Event cuts

Figure 6: x vs y coordinate of the sinistra’s entrance location in the calorimeter. The HES fiducial cut is responsible for main difference between the two figures. 06e data.
Closure test: finer multiplicity bins for efficiency corrections

Modified bin edges: 0.5, 4.5, 9.5, 14.5, 19.5, 24.5, 29.5, 34.5, 39.5, 44.5, 49.5

Default bin edges: 0.5, 4.5, 9.5, 17.5, 49.5
Closure test: HERA I

No MVD in HERA I (fewer material interaction products)