Azimuthal particle correlations as a probe of collectivity in deep inelastic electron-proton collisions at HERA

Silvia Masciocchi[1,2], Jacobus Onderwaater[1,2], Ilya Selyuzhenkov[2]
on behalf of the ZEUS Collaboration

[1]Universität Heidelberg
[2]GSI

Quark Matter 2018, 15 May 2018

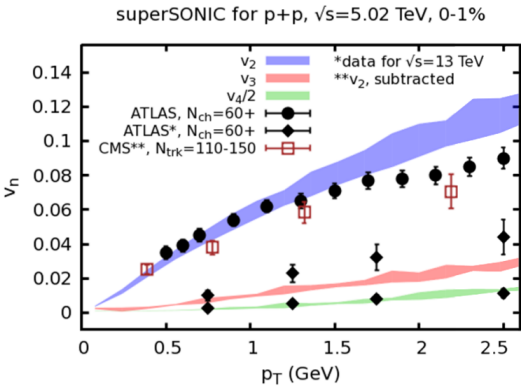
UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

ISOQUANT SFB1225

GSI

ZEUS

Searching for collectivity in small systems



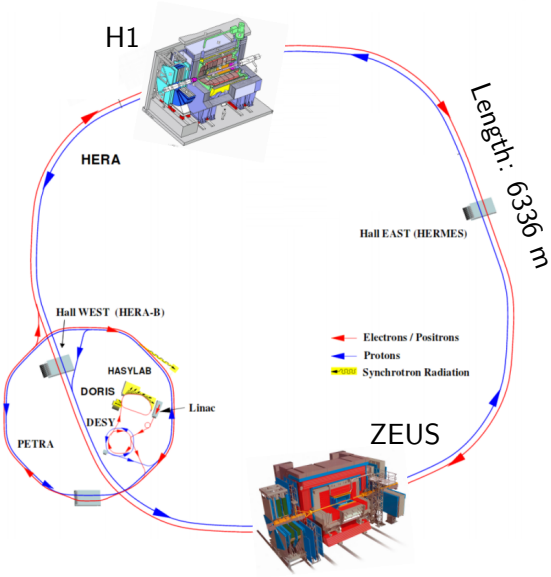
Azimuthal particle correlations are used to measure collectivity in large collision systems.

Correlations in pp collisions reveal features similar to larger systems like pA and AA.

Measurements in even smaller systems such as *ee* and **electron-proton** can test the onset of collectivity.

Weller & Romatschke Phys.Lett. B774 (2017) 351-356

The HERA collider and experiments



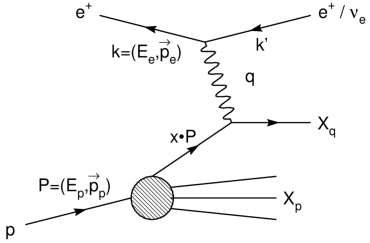
- Location: DESY, Hamburg, Germany
- Data taking: 1992 - 2007
- 27.6 GeV electrons/positrons
  920 GeV protons
  $\rightarrow \sqrt{s} = 318$ GeV
- H1 & ZEUS - 4π detectors
- HERA I+II:
  500 pb^{-1} per experiment

Deep inelastic scattering in electron-proton collisions

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

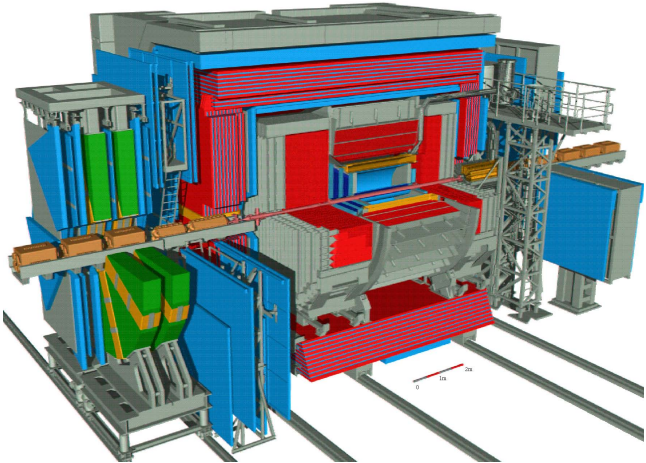
$$x_{Bj} = \frac{Q^2}{2\,P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$



- Inclusive electron-proton collisions:
  - neutral current (NC)
  - charged current
- ZEUS triggers for specific physics processes
- We investigate Deep Inelastic Scattering (DIS) NC events (high photon virtuality, $Q^2 > 1\text{GeV}^2$)

ZEUS detector



- Tracking:
  Central tracking detector (CTD) and micro vertex detector (MVD) in a 1.43 T magnetic field.
- Trigger for DIS NC:
  Identification of the scattered electron from the pattern of energy deposits in the CAL.

Data sample, event and particle selection

Data sample:
ZEUS data preservation efforts enable new analysis of HERA data.
HERA II : 355 M events, 46M after DIS selection

Event selection:
$Q^2 > 5$ GeV^2
$E_e > 10$ GeV
$\theta_e > 1.0$
Consistency with DIS:
$47 < E - p_z < 69$ GeV$/c$

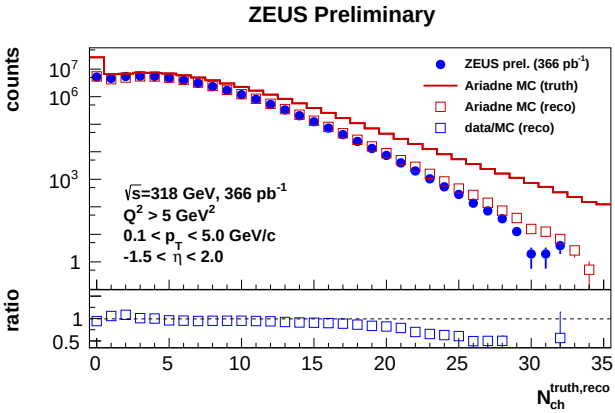
Track selection:
$0.1 < p_T < 5.0$ GeV$/c$
$-1.5 < \eta < 2.0$

Simulations (for comparison and corrections):
ARIADNE[1] (dipole cascade model)
LEPTO[2] (Lund string model)

True level particle selection:
Charged hadrons with lifetime $\tau > 1$ cm$/c$
- produced directly in the interaction
- decays of particles with $\tau < 1$ cm$/c$

[1] L. Lönnblad, Comp. Phys. Comm. 71 (1992) 15
[1] L. Lönnblad, Z. Phys. C 65 (1995) 285.
[2] G. Ingelman, A. Edin and J. Rathsman, Comp. Phys. Comm. 101 (1997) 108

Multiplicity distribution for DIS events



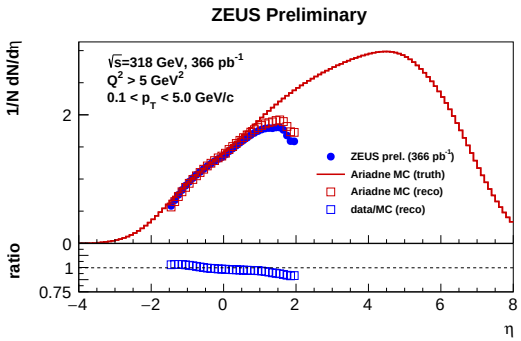
N_{ch} distributions:

- True N_{ch} distribution (line)
- Uncorrected N_{ch} distribution for data and simulation (open squares).

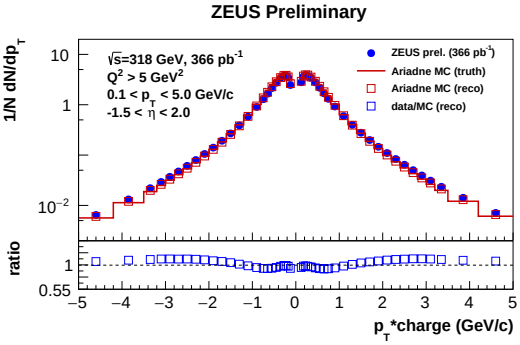
Uncorrected multiplicity N_{ch} up to ~ 30 tracks per event with a mean of $\langle N_{ch} \rangle \approx 4.5$

Track distributions

pseudorapidity



transverse momentum



- Large parts of the 'proton fragments' move out of the tracking acceptance.
- Monte Carlo describes data within $\sim 15\%$.

Azimuthal correlations

We measure 2-particle correlations:

$$c_n\{2\} = \langle\langle 2 \rangle\rangle = \langle\langle e^{in(\phi_\alpha - \phi_\beta)} \rangle\rangle$$

The inner brackets denote the average in a single event.
The outer brackets the average over all events.

The correlations are studied as a function of

- event multiplicity
- separation of particles in pseudorapidity
- relative/mean pair transverse momentum

Correcting for detector effects

Applied particle weights:

- w_{eff}: Monte Carlo based efficiency weights as a function of charge, p_T and η (on average $\sim 90\%$).
- w_φ: Data-driven φ-weights as a function of charge, η and event multiplicity (correction ranges between $10^{-3} - 10^{-4}$).

Corrected event multiplicity:

$$N_{ch} = \sum w_{eff} \; w_\varphi$$

Two-particle correlation:

$$c_n\{2\} = \langle w_{eff}^{\alpha} \; w_\varphi^{\alpha} \; w_{eff}^{\beta} \; w_\varphi^{\beta} \; \cos(\varphi_\alpha - \varphi_\beta) \rangle$$

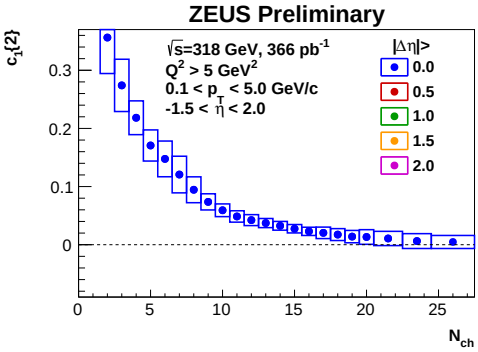
Systematic uncertainties

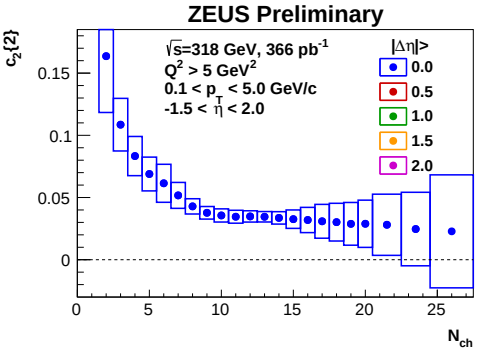
Considered sources of systematic uncertainties:

- event selection
- trigger
- tracking efficiency
- Monte Carlo closure test (dominant source)

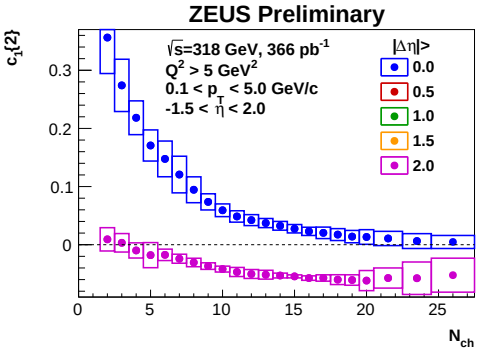
Variations are added bin-by-bin in quadrature to the total systematic uncertainty.

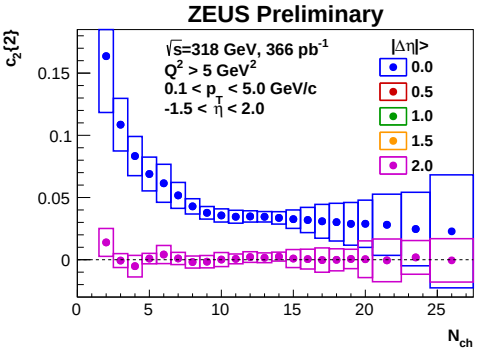
Multiplicity-dependent $c_1\{2\}$ and $c_2\{2\}$ with increasing η-separation





Multiplicity-dependent $c_1\{2\}$ and $c_2\{2\}$ with increasing η-separation

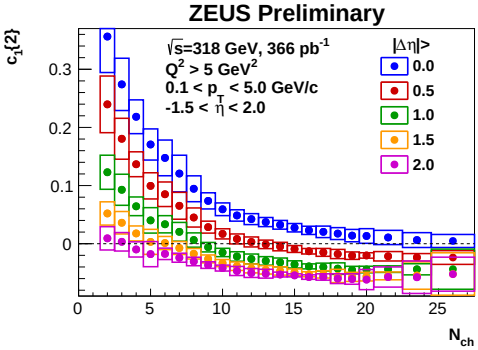


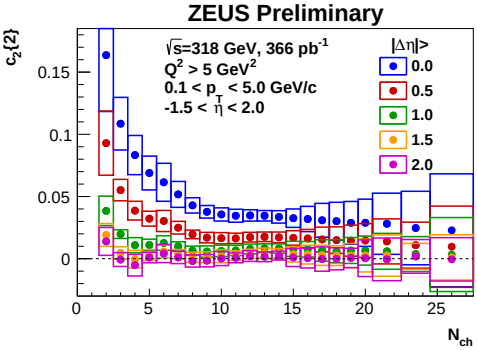


$|\Delta\eta| > 2.0$: $c_1\{2\}$ changes sign $\rightarrow$ consistent with momentum conservation.

$|\Delta\eta| > 2.0$: $c_2\{2\}$ consistent with zero.

Multiplicity-dependent $c_1\{2\}$ and $c_2\{2\}$ with increasing η-separation

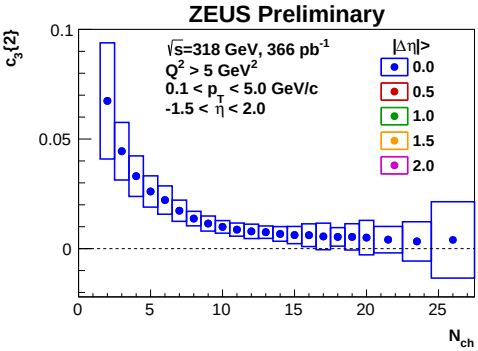


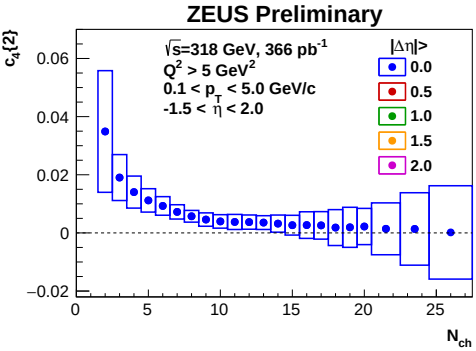


$|\Delta\eta| > 2.0$: $c_1\{2\}$ changes sign $\rightarrow$ consistent with momentum conservation.

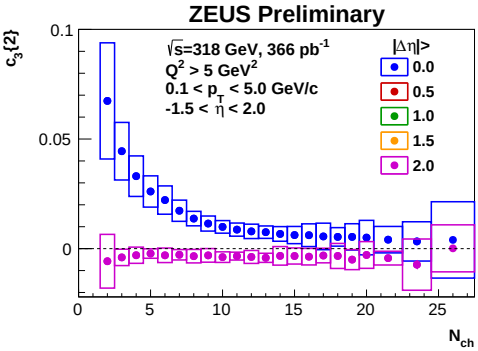
$|\Delta\eta| > 2.0$: $c_2\{2\}$ consistent with zero.

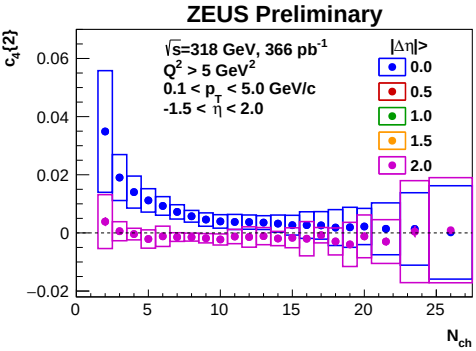
Multiplicity-dependent $c_3\{2\}$ and $c_4\{2\}$ with increasing η-separation





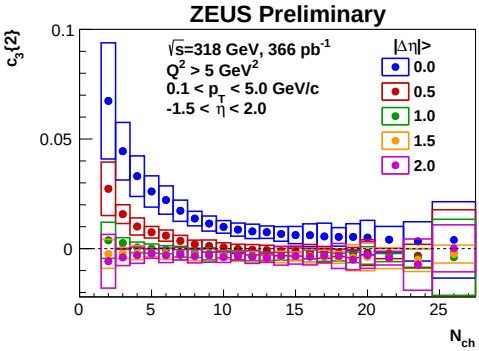
Multiplicity-dependent $c_3\{2\}$ and $c_4\{2\}$ with increasing η-separation

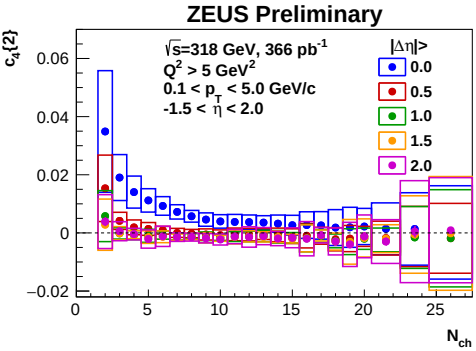




$|\Delta\eta| > 2.0$: $c_3\{2\}$ and $c_4\{2\}$ are consistent with zero.

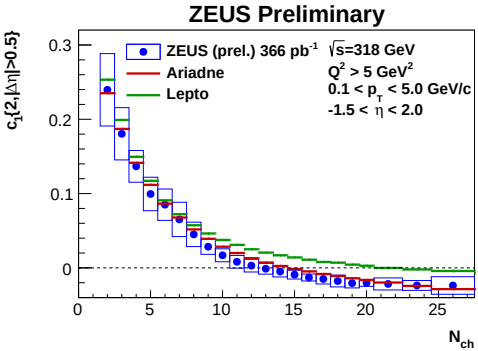
Multiplicity-dependent $c_3\{2\}$ and $c_4\{2\}$ with increasing η-separation

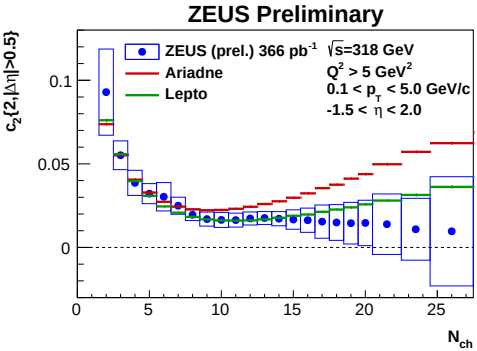




$|\Delta\eta| > 2.0$: $c_3\{2\}$ and $c_4\{2\}$ are consistent with zero.

Model comparison for $c_1\{2\}$ and $c_2\{2\}$ with $|\Delta\eta| > 0.5$

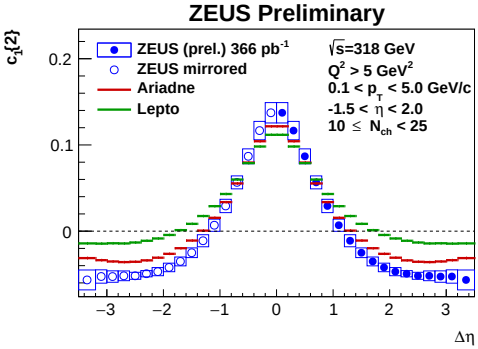


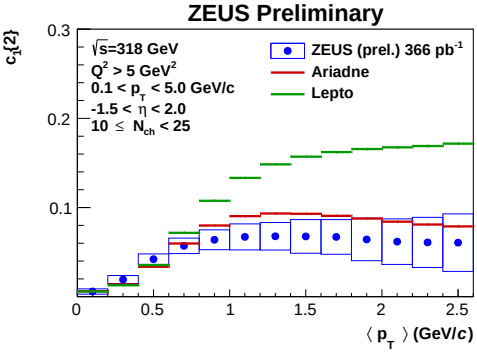


Ariadne in better agreement with data for $c_1\{2\}$

Lepto in better agreement with data for $c_2\{2\}$

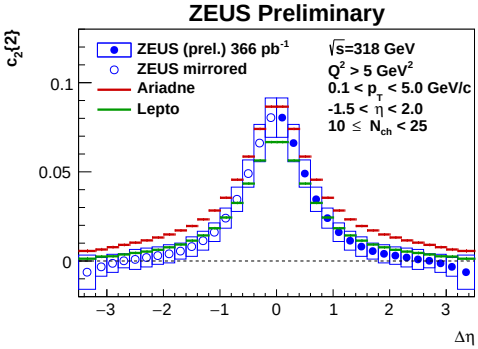
Differential 2-particle correlations ($n = 1$) for high multiplicity events

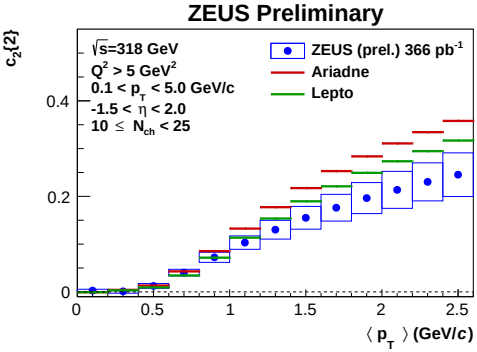




$c_1\{2\}$ vs $\Delta\eta$ and $\langle p_T \rangle$ (Δp_T in backup) at high multiplicity ($10 \leq N_{ch} < 25$).

Differential 2-particle correlations ($n = 2$) for high multiplicity events





$c_2\{2\}$ vs $\Delta\eta$ and $\langle p_T \rangle$ (Δp_T in backup) at high multiplicity ($10 \leq N_{ch} < 25$).

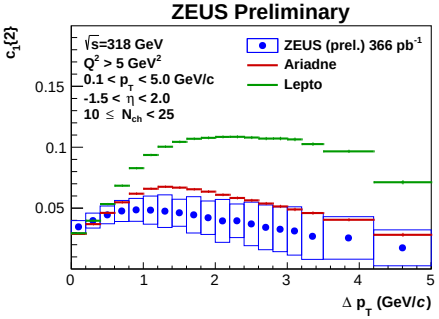
Summary

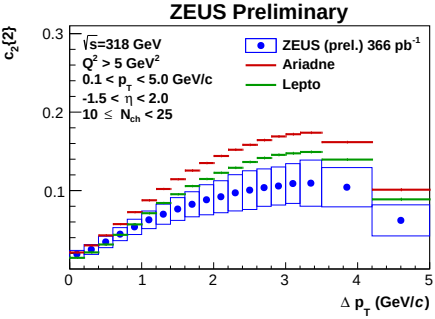
- Reported new preliminary results (ZEUS-prel-18-01) for 2-particle correlations in electron-proton collisions measured for harmonics $n = 1 - 4$ vs:
  - N_{ch}, $\Delta\eta$, $\langle p_T \rangle$, Δp_T
- $c_n\{2\}$ is consistent with 0 for larger N_{ch} and $\Delta\eta$ for n=2,3,4
- $c_1\{2\}$ changes sign for large $\Delta\eta$, a signature of momentum conservation.
- Comparisons to different Monte Carlo generators tuned to HERA data are able to reproduce overall features of the multiplicity dependence of the correlations.

- New analysis of ZEUS data adds new information to the ongoing efforts in the search for collective effects in high multiplicity collisions of small systems at LHC and RHIC.

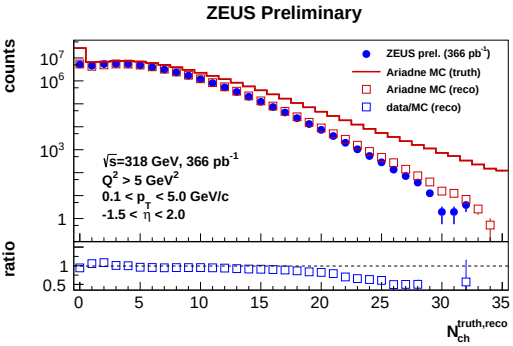
Backup

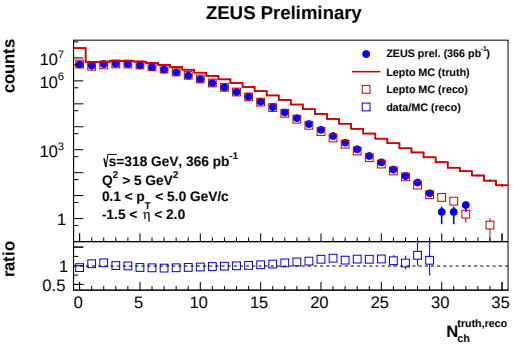
$c_n\{2\}$ vs Δp_T for first and second harmonic



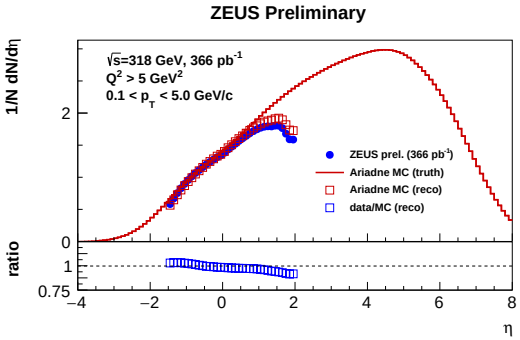


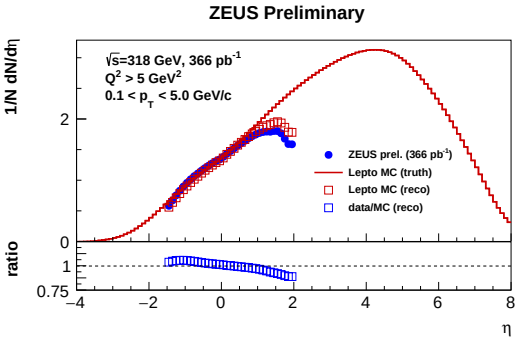
Models N_{ch}


ZEUS Preliminary
counts
ratio
ZEUS prel. (366 pb^{-1})
Ariadne MC (truth)
Ariadne MC (reco)
data/MC (reco)
$\sqrt{s}$=318 GeV, 366 pb^{-1}
Q^2 > 5 GeV^2
0.1 < p_T < 5.0 GeV/c
-1.5 < η < 2.0
$N_{ch}^{truth,reco}$

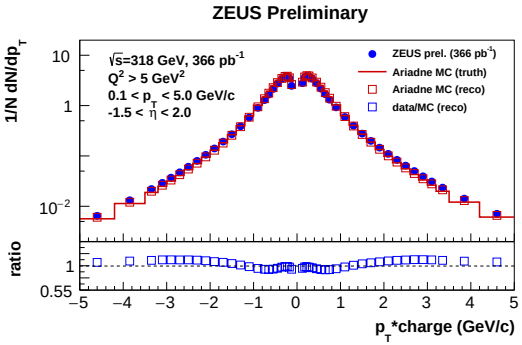

ZEUS Preliminary
counts
ratio
ZEUS prel. (366 pb^{-1})
Lepto MC (truth)
Lepto MC (reco)
data/MC (reco)
$\sqrt{s}$=318 GeV, 366 pb^{-1}
Q^2 > 5 GeV^2
0.1 < p_T < 5.0 GeV/c
-1.5 < η < 2.0
$N_{ch}^{truth,reco}$

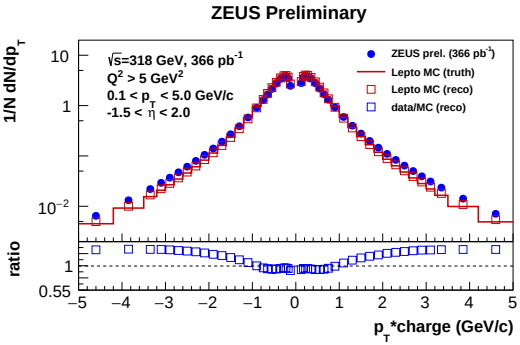
Models η


ZEUS Preliminary
√s=318 GeV, 366 pb-1
Q2 > 5 GeV2
0.1 < pT < 5.0 GeV/c
ZEUS prel. (366 pb-1)
Ariadne MC (truth)
Ariadne MC (reco)
data/MC (reco)
1/N dN/dη
ratio
η


ZEUS Preliminary
√s=318 GeV, 366 pb-1
Q2 > 5 GeV2
0.1 < pT < 5.0 GeV/c
ZEUS prel. (366 pb-1)
Lepto MC (truth)
Lepto MC (reco)
data/MC (reco)
1/N dN/dη
ratio
η

Models p_T


ZEUS Preliminary
√s=318 GeV, 366 pb-1
Q2 > 5 GeV2
0.1 < pT < 5.0 GeV/c
-1.5 < η < 2.0
ZEUS prel. (366 pb-1)
Ariadne MC (truth)
Ariadne MC (reco)
data/MC (reco)
1/N dN/dpT
ratio
pT*charge (GeV/c)


ZEUS Preliminary
√s=318 GeV, 366 pb-1
Q2 > 5 GeV2
0.1 < pT < 5.0 GeV/c
-1.5 < η < 2.0
ZEUS prel. (366 pb-1)
Lepto MC (truth)
Lepto MC (reco)
data/MC (reco)
1/N dN/dpT
ratio
pT*charge (GeV/c)