preliminary request:
Search for collective effects in electron-proton collisions with ZEUS

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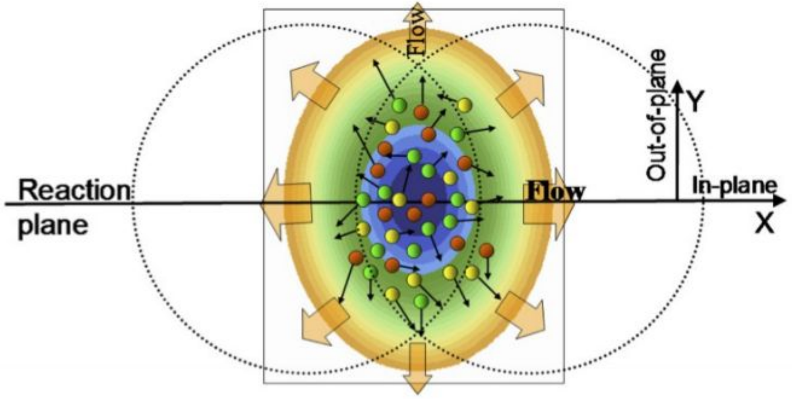
Collectivity and related anisotropy in heavy-ion collisions

Response of matter produced in the heavy-ion collision to the geometry of the initial state.

Produced particles receive a stronger boost along the short axis of the geometry wrt to the long axis (see ellipse on the right)

The amplitude (v_n) of the resulting anisotropy is quantified with a Fourier decomposition:

$$\frac{dN}{d(\varphi - \Psi_R)} = \frac{N_0}{2\pi}(1 + 2\sum_n v_n \cos[n(\varphi - \Psi_R)])$$



Analysis techniques

We report a measurement of 2-particle correlations:

$$c_n\{2\} = \langle\langle 2 \rangle\rangle \equiv \left\langle \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle \right\rangle \qquad v_n\{2\} = \sqrt{c_n\{2\}}$$

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

The correlation are studied as a function of

- event multiplicity
- separation of particles in pseudorapidity
- particle's transverse momentum

Different mechanisms resulting in 2-particle correlations

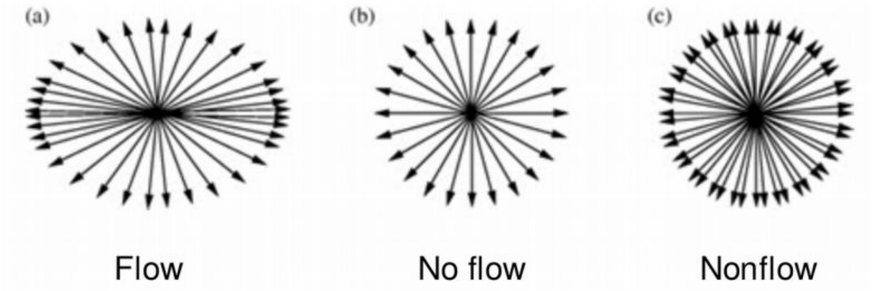
Multiple mechanisms contribute to (multi)particle correlations, from the initial state to response to the initial geometry.

Correlations contain flow, flow fluctuations and nonflow.

$$\langle\langle e^{in(\phi_a-\phi_b)}\rangle\rangle = \langle v_n^2\rangle + \delta_n$$

Flow fluctuations: $\sigma_{vn}^2 = \langle v_n^2\rangle - \langle v_n\rangle^2$

Nonflow: δ_n : resonances, jets, decays, momentum conservation



Suppression of δ_n (suppression of few particle correlated clusters):

- High multiplicity $\delta_2 \sim 1/M$
- Pseudo-rapidity gap (particles from jets and decays are mostly closeby in η)

Analyzed data sets (common ntuples)

	Trigger events (x10^6)	
Period	**All events in tree**	**DIS**
03p	3.7	0.24
04p	47	4.6
05e	132	17
06e	44	7.0
06p	87	12
07p	41	5.4
All	355	45.8

DIS: Sinistra electron, $Q^2 > 5$ GeV, $E_e > 10$ GeV, $47 < E-p_z < 69$ GeV, $\theta_e > 1$, $e_p > 0.9$, exclusion of some problematic detector areas

DIS selection

Sinistra electron:

- $Q^2 > 5$ GeV
- $E_e > 10$ GeV
- $\theta_e > 1$
- Sinistra probability: $e_p > 0.9$
- $47 < E-p_z < 69$ GeV

Exclusion of some problematic detector areas

Radius cut :

```
if(sqrt( TMath::Power((Sipos[0][0] + 1),2.0) + TMath::Power(Sipos[0][1],2.0) )
< 15) isDIS = false;
```

Chimney cut (RCAL):

```
if ( (Sipos[0][0] > -10) && (Sipos[0][0] < 10   )  &&
   (Sipos[0][1] > 110) && (Sipos[0][2] < -141.)){
   isDIS = false;
}
            //HES fiducal/CAL crack cut (RCAL)
        if (     ( ( (Sipos[0][0] > 5) && (Sipos[0][0] < 11) && (Sipos[0][1] > 0.) )
              || ( (Sipos[0][0] > -15) && (Sipos[0][0] < -9) && (Sipos[0][1] < 0.) ) )
            && (Sipos[0][2] < -141.) ){
          isDIS = false;
                 if ( (Sinrsl[0] < 3) ||
              (Sitrkp[0] < 0.3 * Sicalene[0]) ||
              (run < 45000)){
            isDIS = false;
          }
```

DIS trigger bits

HPP20

```
 if (((ibits(Tltw[3],16+0,1) > 0) && (ibits(Sltw[5],7-1,1) > 0))
(ibits(Tltw[3],16+1,1) > 0)
((ibits(Tltw[3],16+2,1) > 0) && (ibits(Sltw[5],7-1,1) > 0))
((ibits(Tltw[3],16+3,1) > 0) && (ibits(Sltw[5],7-1,1) > 0))
((ibits(Tltw[3],16+4,1) > 0) && (ibits(Sltw[5],7-1,1) > 0))
(ibits(Tltw[3],16+5,1) > 0)
((ibits(Tltw[3],16+10,1) > 0) && (ibits(Sltw[5],7-1,1) > 0))
(ibits(Tltw[2],16+0,1) > 0)
(ibits(Tltw[2],16+1,1) > 0)
(ibits(Tltw[2],16+2,1) > 0)
(ibits(Tltw[2],16+8,1) > 0)
(ibits(Tltw[13],16+0,1) > 0)
(ibits(Tltw[11],16+14,1) > 0)
(ibits(Tltw[11],16+3,1) > 0))
```

TLT HFL2 (inclusive mesons in DIS) and HFL10 (e in DIS)

```
if ( (ibits(Tltw[9],16+1,1) > 0) || (ibits(Tltw[9],16+9,1) > 0) )
```

TLT HFL6 (dijets in DIS)

```
if (ibits(Tltw[9],16+5,1) > 0)
```

Event selection

- DIS selection
- $-30 <$ vertex $Z < 30$ cm
- Fraction of tracks associated to event vertex > 0.1
- N_{vtx} tracks > 0
- Event vertex from beam spot (R_{xy}) < 0.5

Track selection

- $0.1 < p_T < 5$ GeV/c
- $-1.5 < \eta < 2.0$
- Tracks constrained to the vertex (orange.Trk_prim_vtx = true)
- Exclude scattered electron (orange.Trk_id[itrack] != orange.Sitrknr[0])
- Trk_Imppar < 0.5 cm
- MVD hits > 0 (MVD hits = orange.Trk_nbr[itrack] + orange.Trk_nbz[itrack] + orange.Trk_nwu[itrack] + orange.Trk_nwv[itrack];)

Simulation selection

Event level

- $Q^2 > 5\ GeV^2$, in code : orange.Mc_q2 > 5
- 47<E-Pz<69 GeV, in code : 47<(orange.Mc_esum-orange.Mc_ez)<69
- Final state lepton energy E > 10 GeV, in code: orange.Mc_pfsl[3] > 10
- Final state lepton theta > 1

Track level

- $0.1 < p_T < 5$ GeV/*c*
- $-1.5 < \eta < 2.0$

For calculation of tracking efficiency, the same selection is applied on data and MC on the reconstruction level.

Correcting for track reconstruction effects

Particles reconstruction efficiency as a function of p_T, η, φ, *charge* and *event multiplicity* is considered.

Particle weights are extracted in two steps:

1. p_T-η-*charge* efficiency is calculated by comparing generated and reconstructed yields in simulation
2. φ weights are extracted from data, after filling φ-η-*charge*-*event multiplicity* maps with the weights from step 1

The product of 1. and 2. gives the track weight. Weights are calculated separately for each dataset.

The 2-particle correlation is modified to include weights:

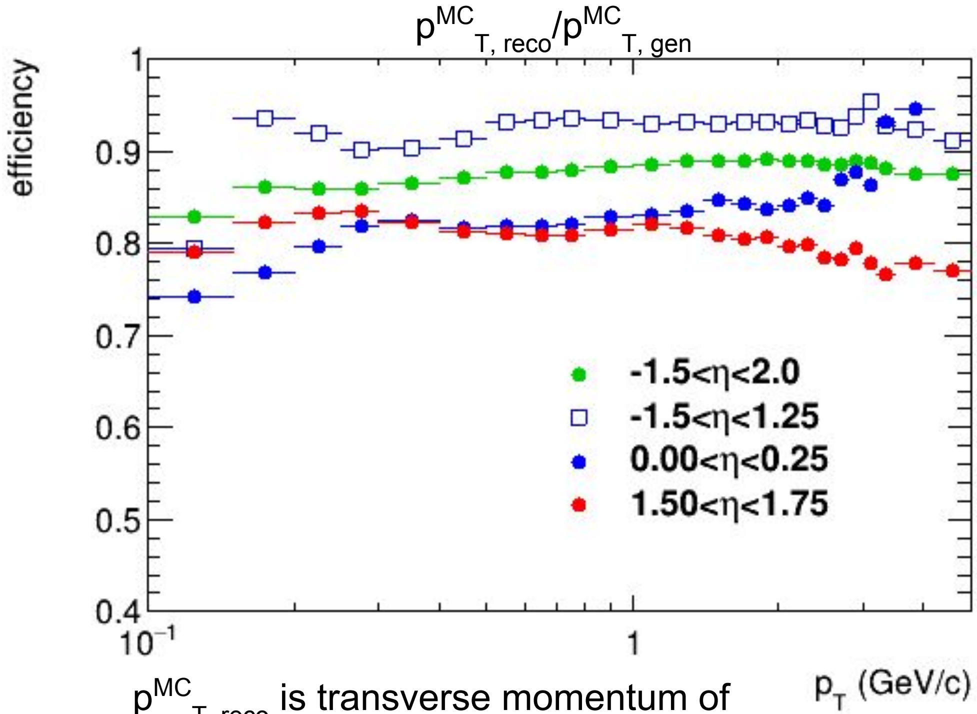
$\langle c_n \rangle = \Sigma\, w_i w_j \cos(n\varphi_i^a - n\varphi_j^b) \,/\, \Sigma\, w_i w_j$

Determining p_T-η efficiency

<u>Charged primary particle</u>:

- Charged particle with lifetime τ > 1 cm/c
- Particles with parents with lifetime τ > 1 cm/c in the decay chain are rejected

Specie	Width Γ (GeV)	Mean proper lifetime τ (ps)	(cm/c)
p^+	0	∞	∞
γ	0	∞	∞
K^0	0	∞	∞
e^-	0	∞	∞
n	7.478×10^{-28}	$8.861 \times 10^{+14}$	$2.656 \times 10^{+13}$
μ^-	2.996×10^{-19}	$2.212 \times 10^{+06}$	$6.63 \times 10^{+04}$
K^0_L	1.287×10^{-17}	$5.148 \times 10^{+04}$	1543
π^+	2.528×10^{-17}	$2.621 \times 10^{+04}$	785.7
K^+	5.317×10^{-17}	$1.246 \times 10^{+04}$	373.6
Ξ^0	2.27×10^{-15}	291.9	8.751
Λ	2.501×10^{-15}	264.9	7.943
Ξ^-	4.02×10^{-15}	164.8	4.941
Σ^-	4.45×10^{-15}	148.9	4.464
K^0_S	7.351×10^{-15}	90.14	2.702
Ω^-	8.071×10^{-15}	82.1	2.461
Σ^+	8.209×10^{-15}	80.72	2.42



$p^{MC}_{T,\,reco}$ is transverse momentum of reconstructed primary particle

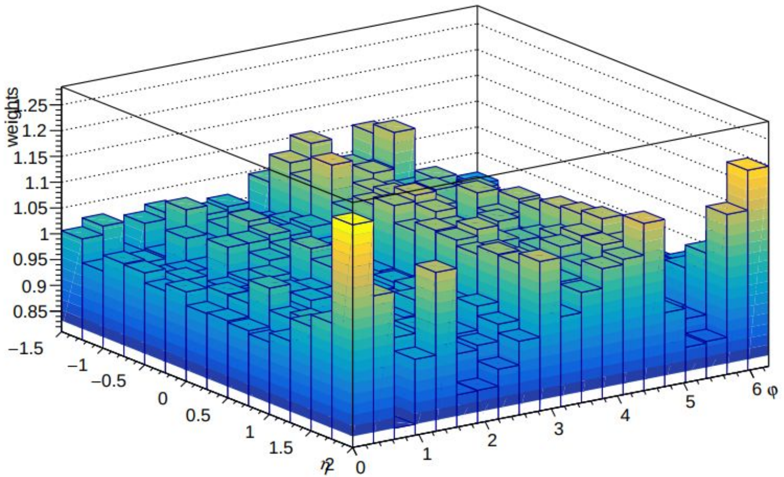
The efficiency is calculated for DIS events, same event selection for generated and reconstructed particles

Determining φ-weights from data

Particle yields are measured in *η-φ-charge-M* bins, after weighting with acquired p_T-*η-charge* weights in the previous slides.

In each *η-charge-M* slice, weights are calculated to make *φ* uniform while maintaining the integral in the slice.

05e, M=10, positive



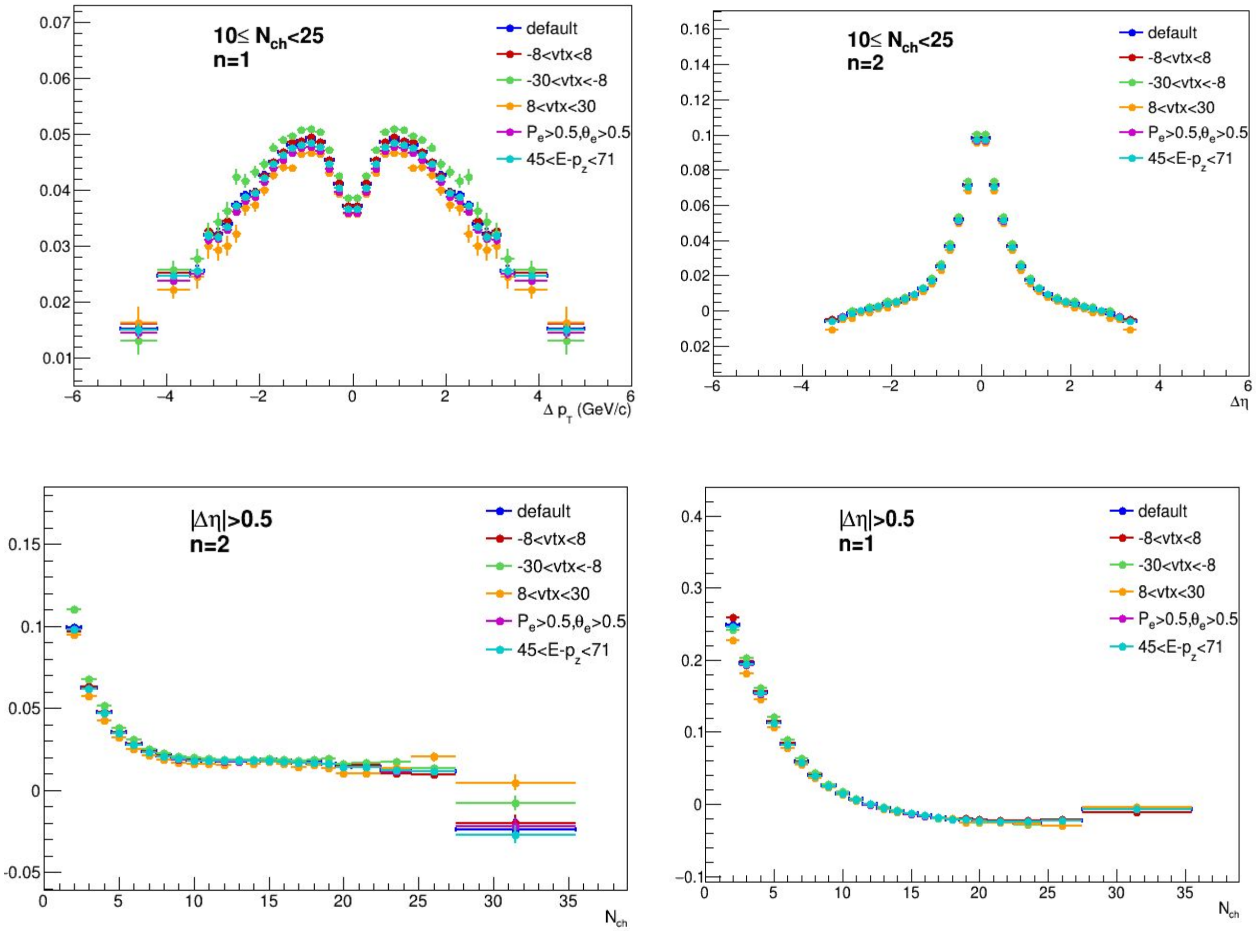
Systematic uncertainties

Study of systematics

Class	Default	Variation
DIS event selection	$47 < E\text{-}p_z < 69$	$45 < E\text{-}p_z < 71$
	$\theta_e > 1.0$ $P_e > 0.9$	$\theta_e > 0.5$ $P_e > 0.8$
	Chimney cut, radius cut, CAL crack cut	
Event quality selection	$-30 < Z_{vtx} < 30$ cm	$-30 < Z_{vtx} < -8$ cm $-8 < Z_{vtx} < 8$ cm $8 < Z_{vtx} < 30$ cm
MC closure		Check generated vs reconstructed correlations
Trigger efficiency		Check generated correlations for MC events vs generated for reconstructed events
Consistency of periods	Sum of all periods	Periods individually

Event selection

The variation from the event selection is relatively minor. Variations are added to the systematic uncertainty (z vertex variations are taken as a group with largest deviation).

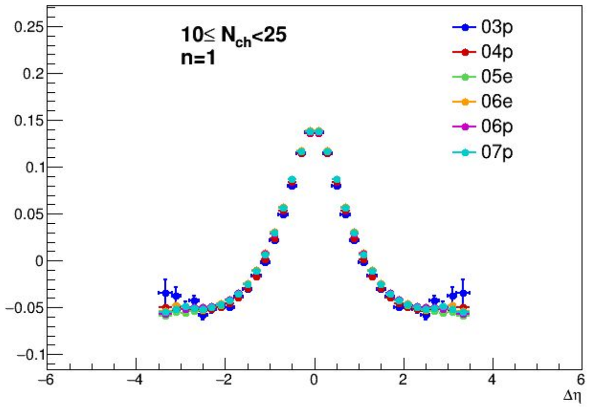


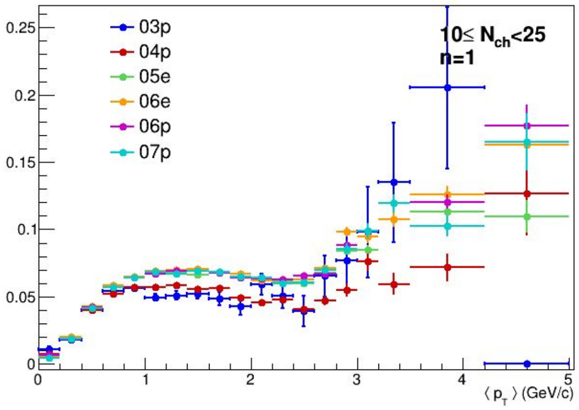
Period consistency

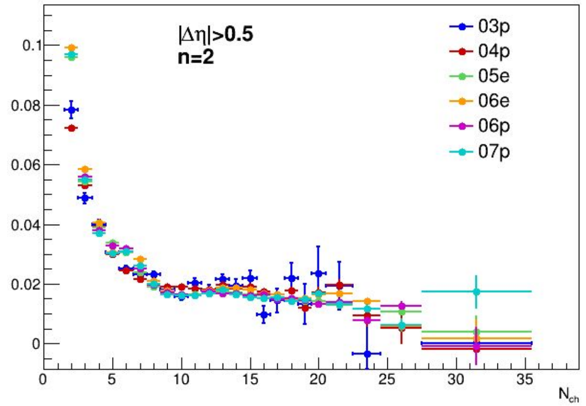
The results from different periods should be consistent.

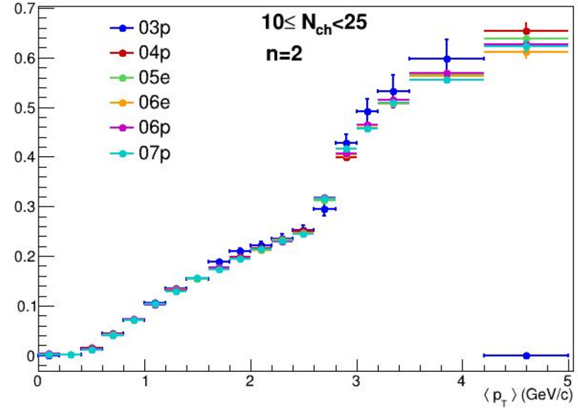
Some deviation for 03p/04p is observed, as for very low multiplicity correlations.

Deviations are added to the systematic uncertainty, excluding 03p due to low significance.









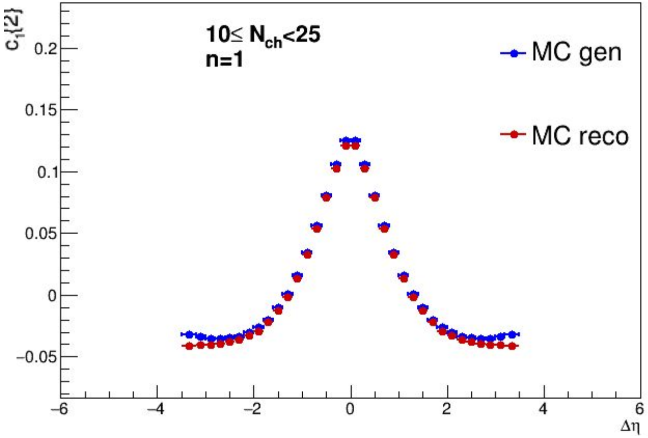
MC closure

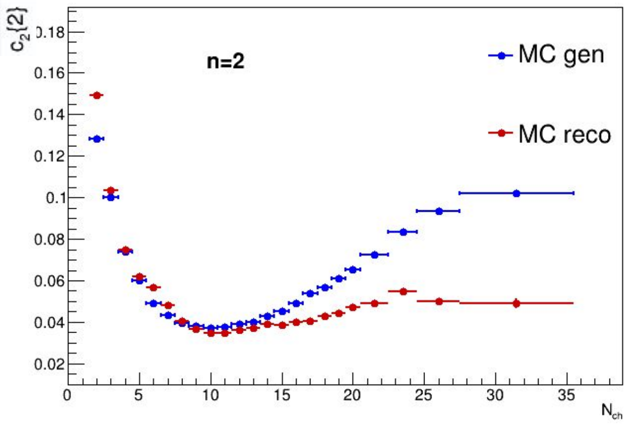
The correlations on true level are compared to the reconstructed correlations.

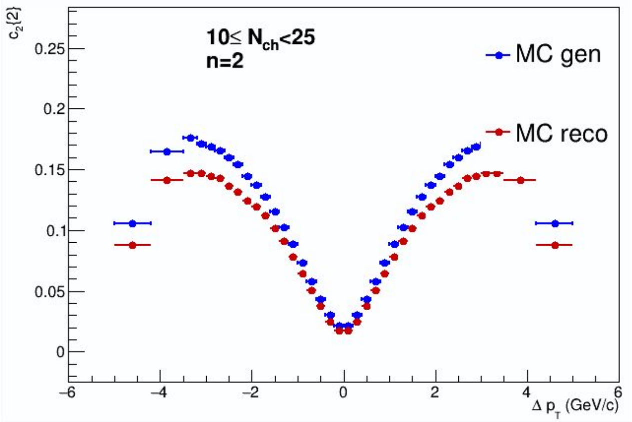
If the trigger is efficient, contamination is low and corrections for detector acceptance are effective, the correlations should match.

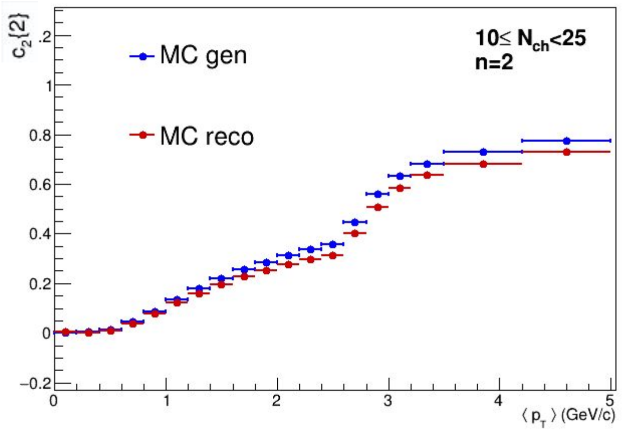
In several places significant deviations are observed, as is visible on the right, while others are smaller. The discrepancy is added as a systematic uncertainty on the data.

For final results this has to be more carefully studied.









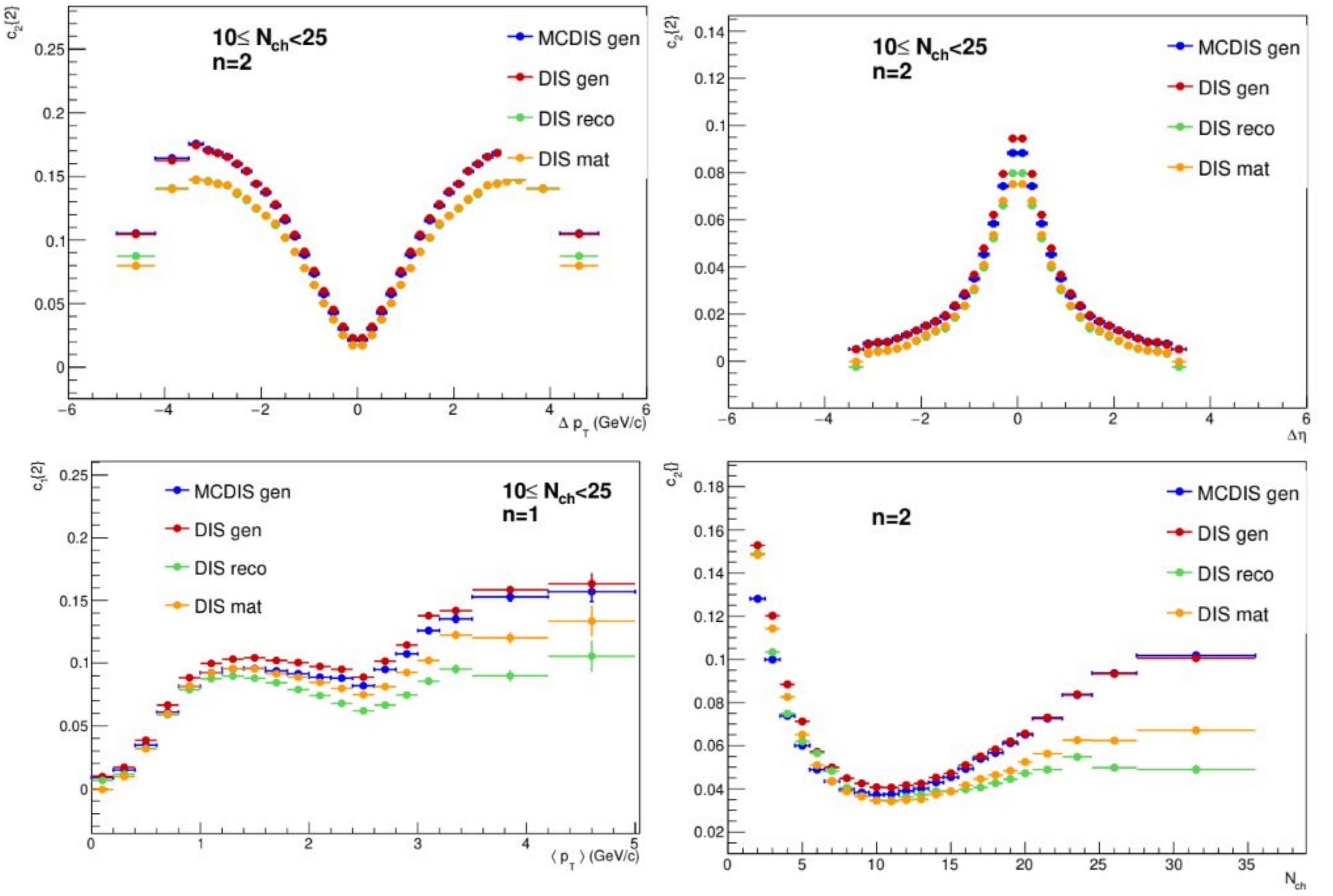
DIS/secondaries

MCDIS:
True level cuts on the electrons

DIS:
In addition DIS selection on the recontruction parameters (and event quality selection)

DIS reco:
Measured as in data

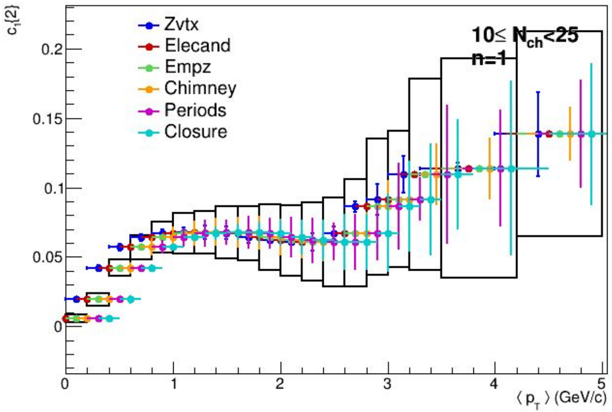
DIS mat:
Measured as in data but only with tracks matched to primary tracks

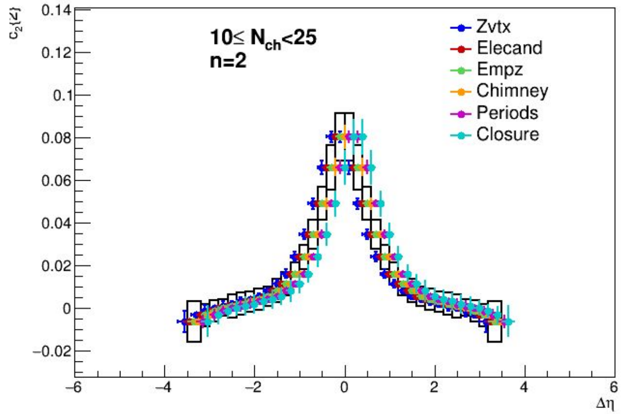


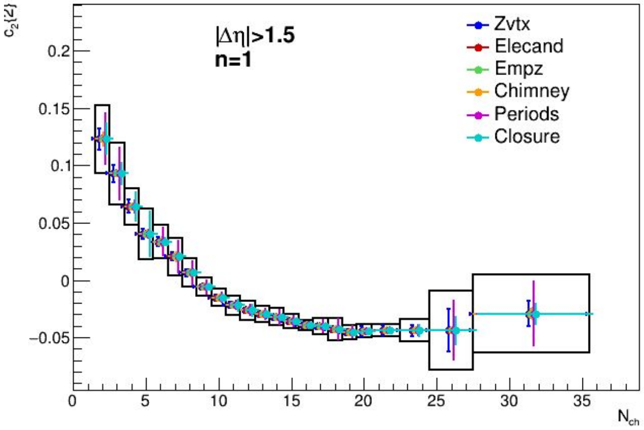
Overview

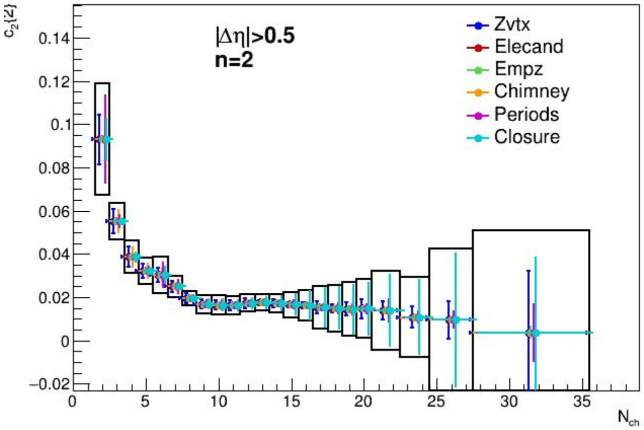
A compilation with the contributions to the systematic uncertainty. The black boxes show the total uncertainty. Points are shifted for clarity.

It is clear that the MC closure and DIS event selection effects are largest, although not always in the same places.





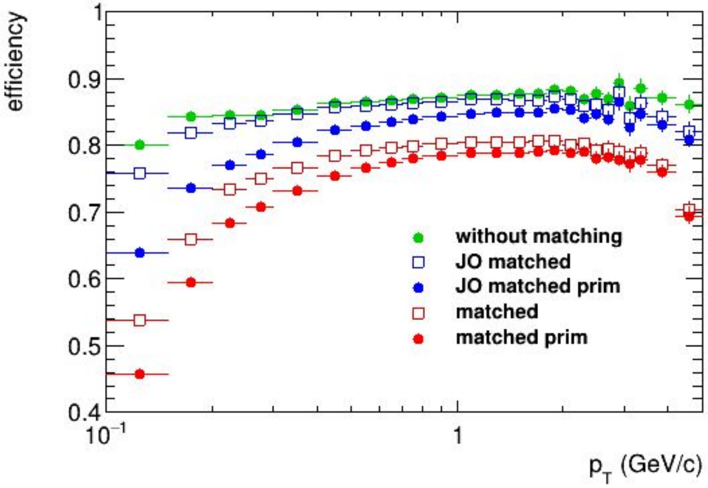




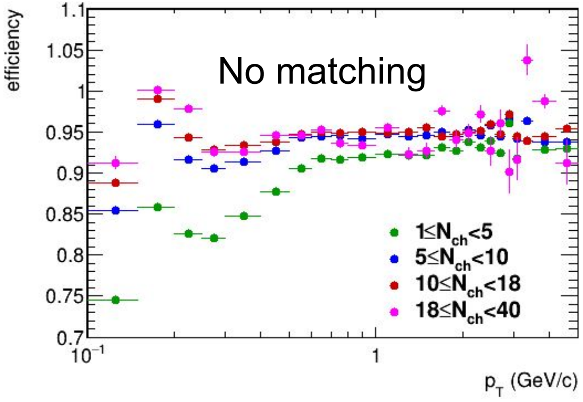
Variation of tracking efficiency

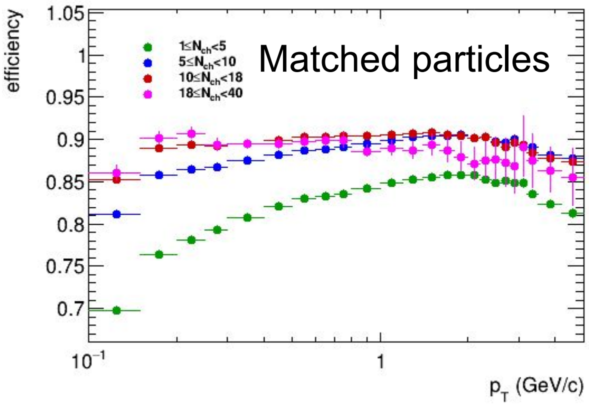
I intended to run with this efficiency as a check but unfortunately something went wrong

Difference between open squares and solid circles is the rejection of secondary particles



Multiplicity dependent p_T-correction

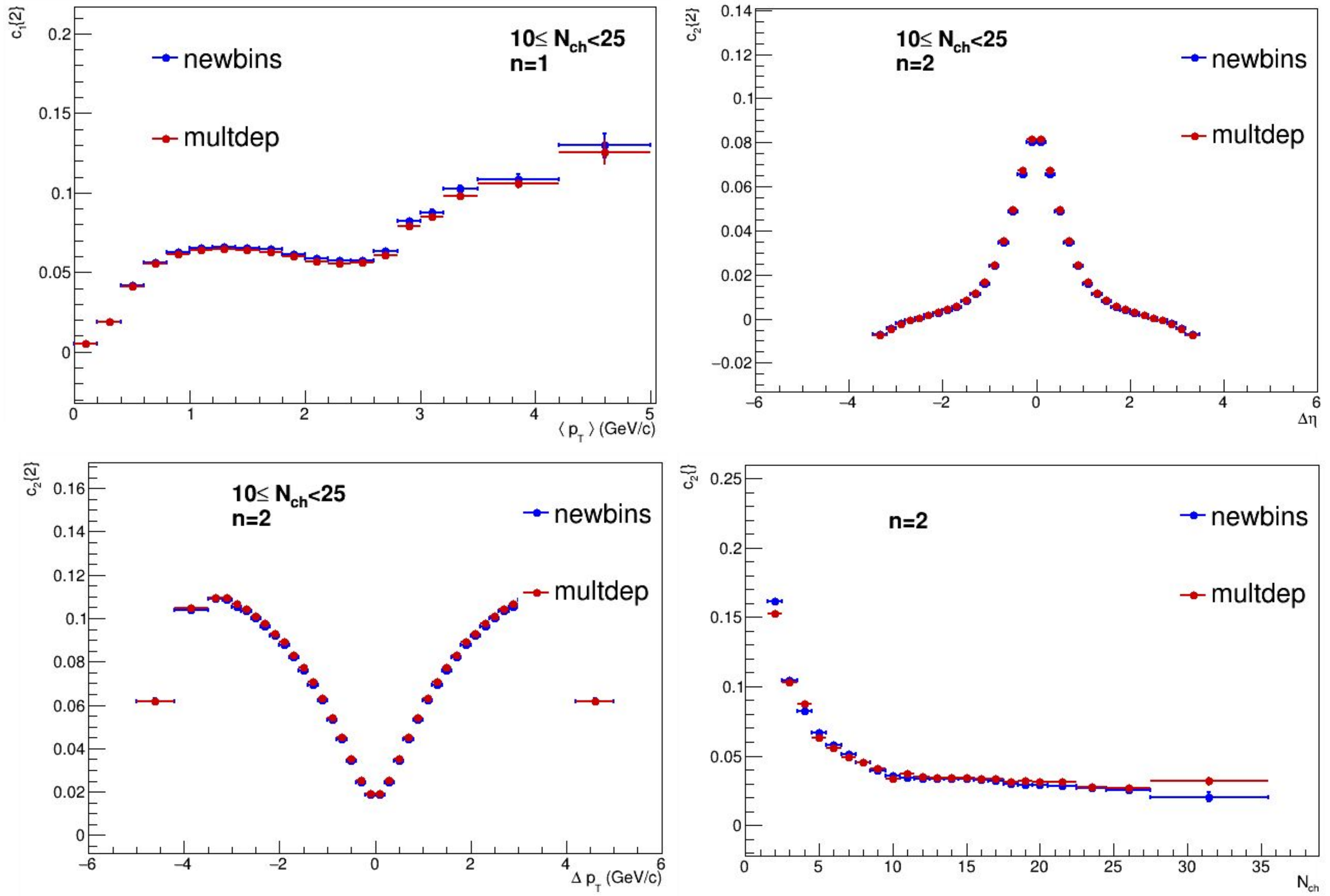




Reran corrections with multiplicity dependence

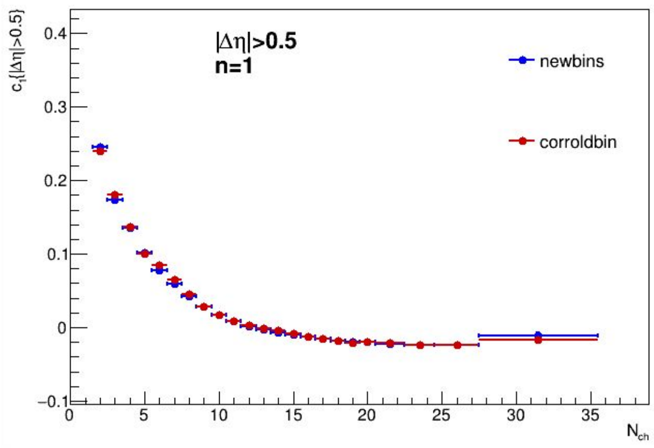
Mult-dependence

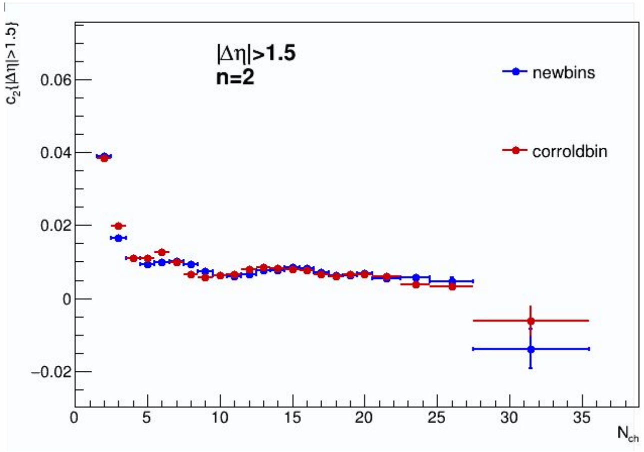
The effect of corrections using multiplicity dependent weights is small

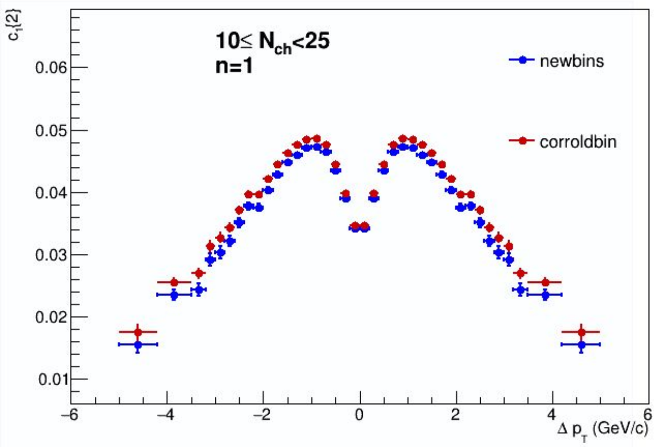


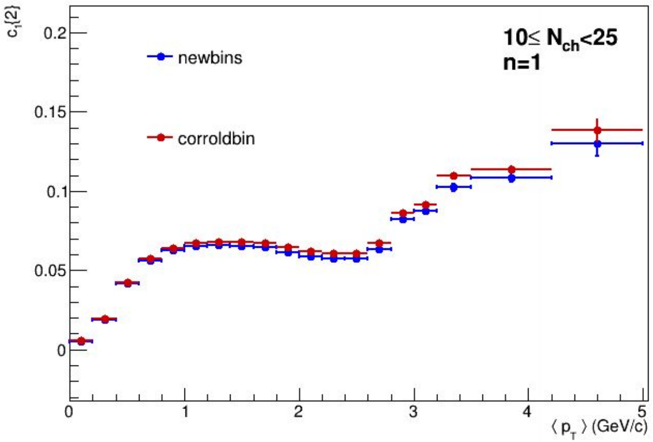
Correction binning

Using finer binning at low p_T (50 MeV/c instead of 100 MeV/c for p_T< 300 MeV/c) and courser η bins (0.25 instead of 0.2) gives largely consistent results.



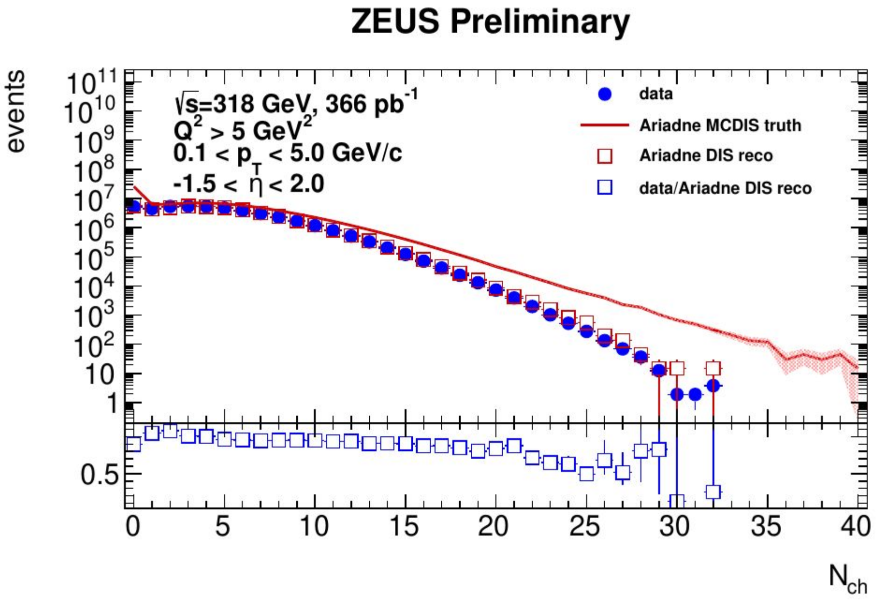






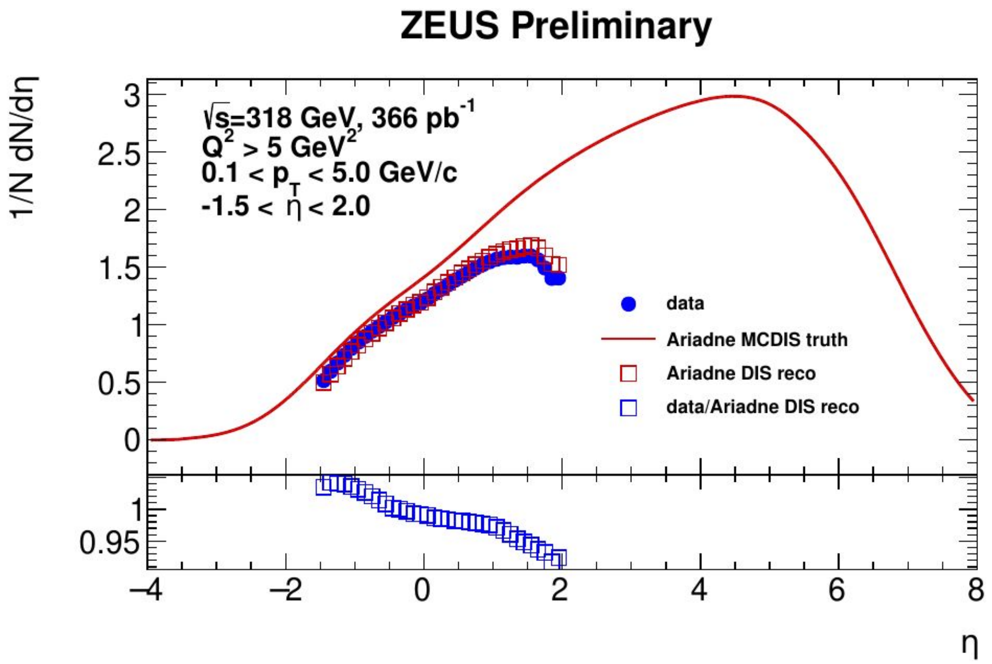
Control figures

Multiplicity distrubution



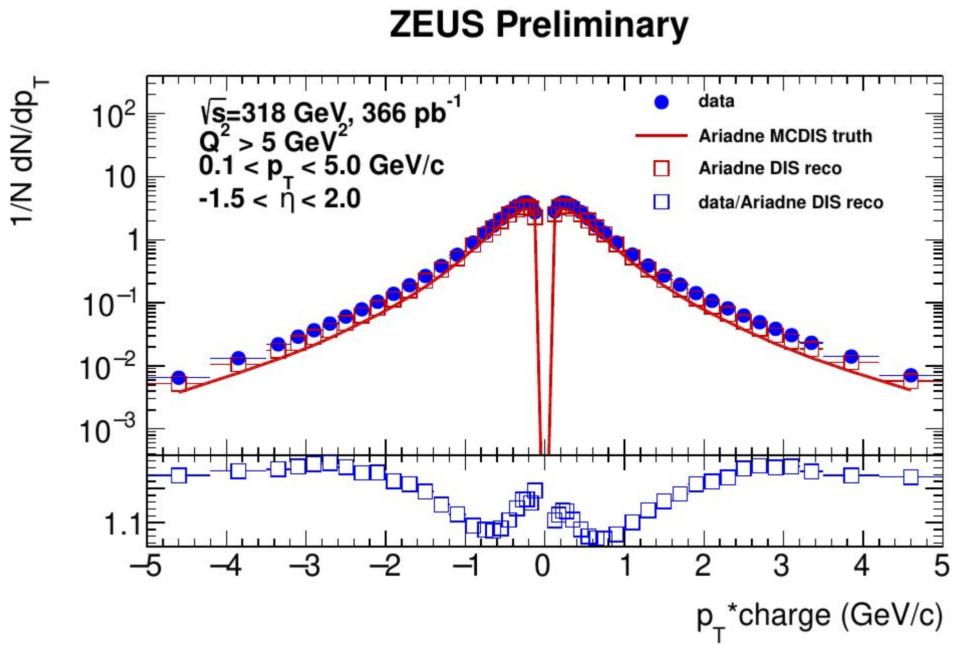
Open squares show the agreement with data (it is normalized to data for $N_{ch} > 2$)
Red line is the true N_{ch}. It is normalized relative to Ariadne DIS reco.

Eta distrubution



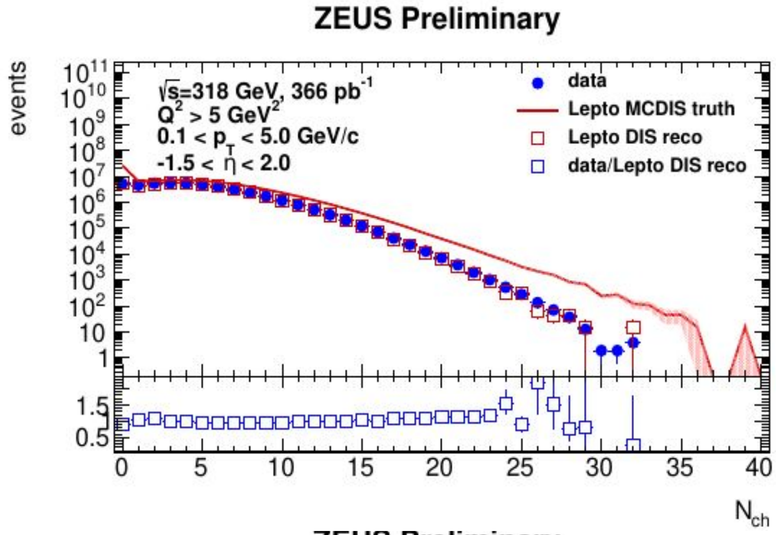
Open squares show the agreement with data.
Red line is the true N_{ch}.
All are histograms are scaled by the number of events in which the tracks were measured.

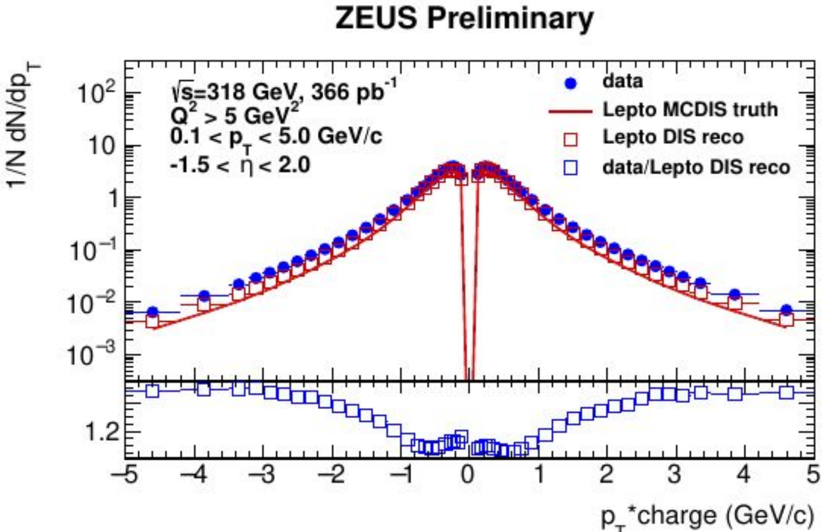
p_T distrubution

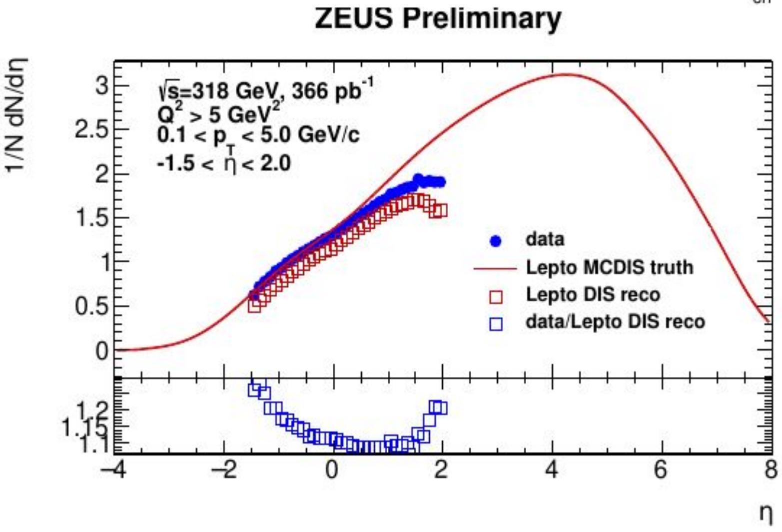


Open squares show the agreement with data.
Red line is the true N_{ch}.
All are histograms are scaled by the number of events in which the tracks were measured.
(remove 0-100 MeV/c for theory)

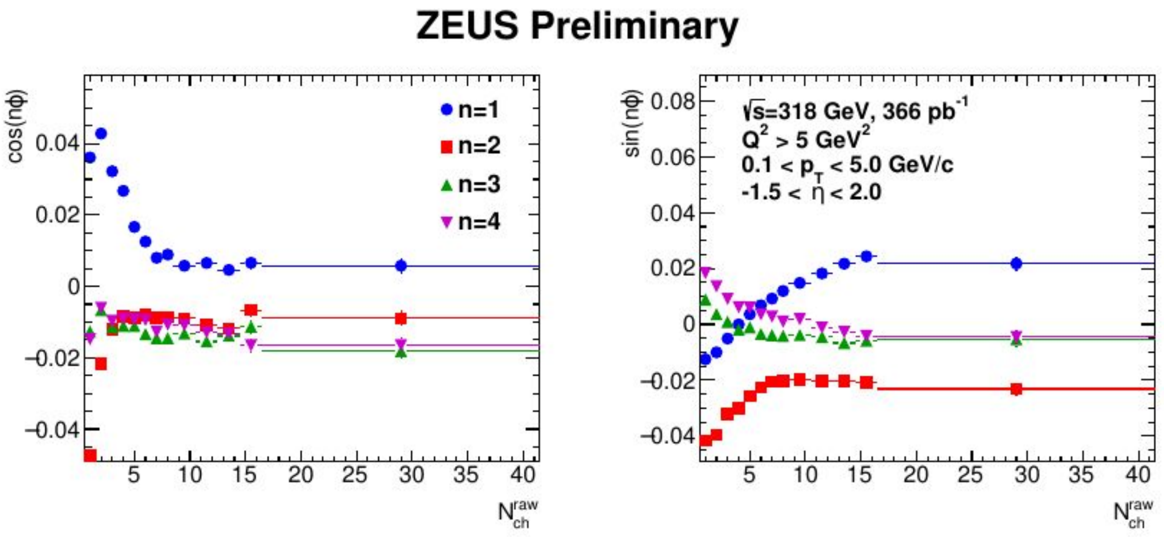
Same for Lepto







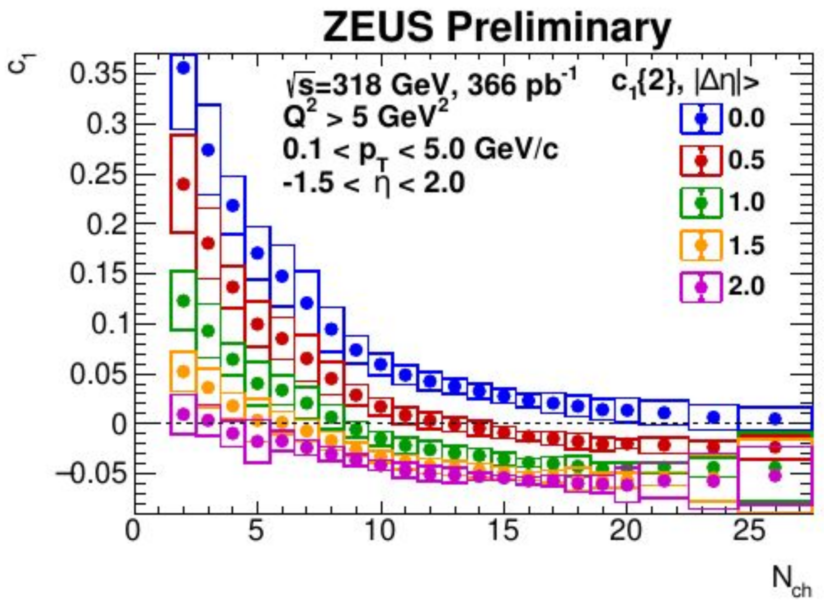
Magnitude of non-uniform acceptance in the correlation



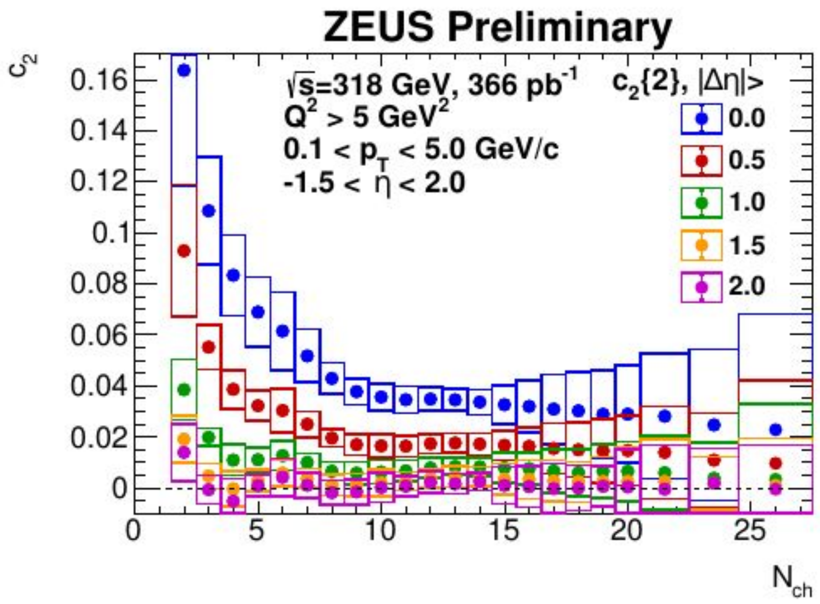
Average of the sine/cosine of the angles show the magnitude of the acceptance correction that is applied, which is of the order $<\cos(n\varphi)^2>+<\sin(n\varphi)^2> \cong 10^{-4}$

Results

Multiplicity dependent correlations with pseudorapidity gaps (1st and 2nd harmonic)

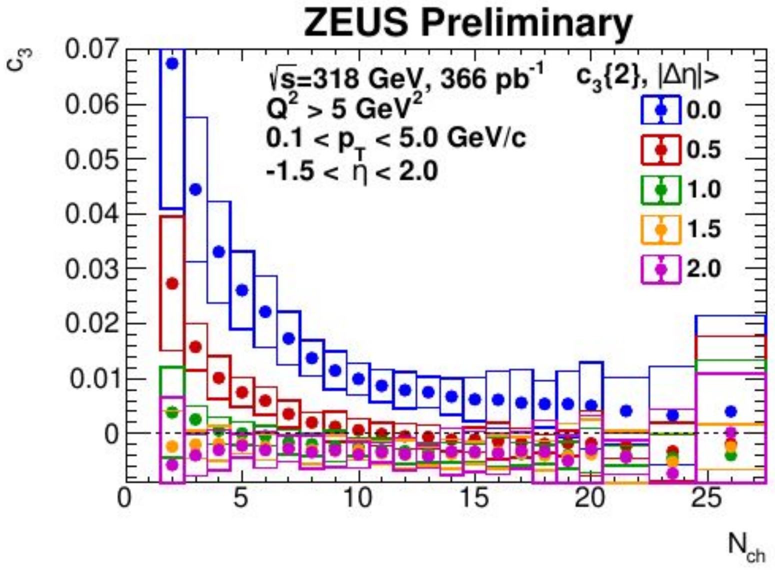


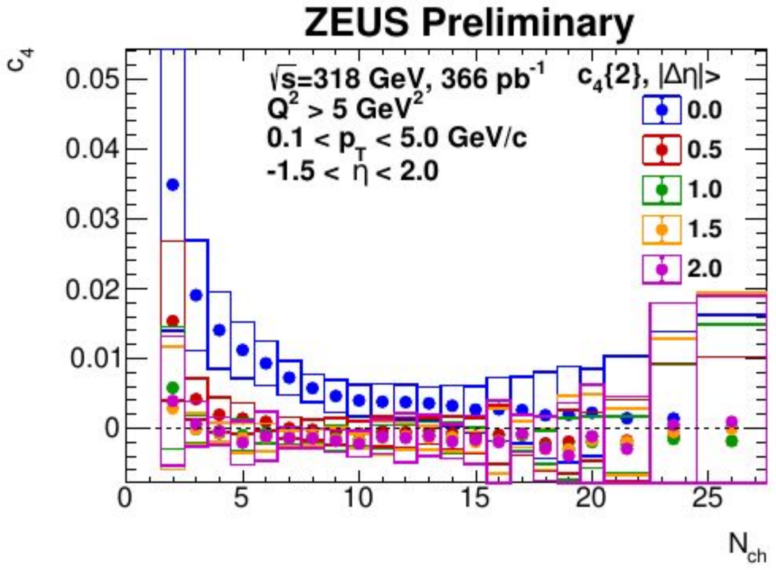
Zoomed in a bit, cleaned up legend



Increasing pseudo rapidity separation suppresses correlations. Consistent with 0 for $|\Delta\eta|>1.0$

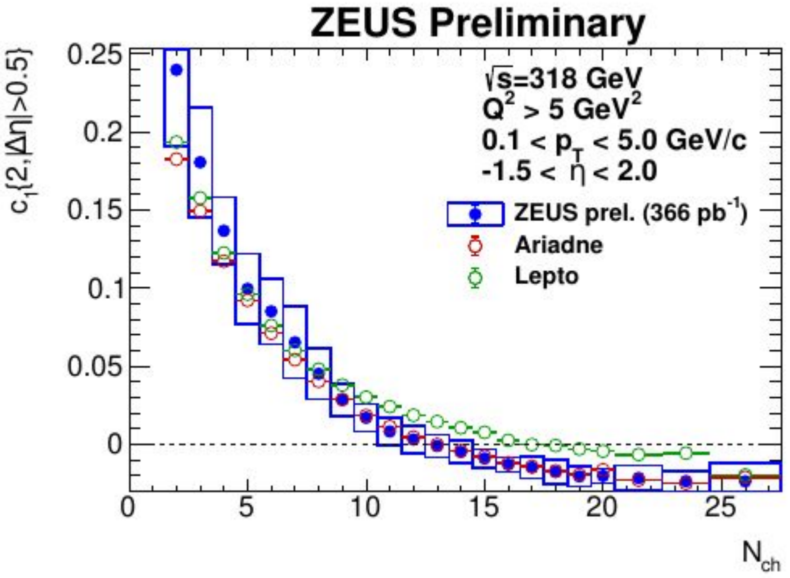
Multiplicity dependent correlations with pseudorapidity gaps (3st and 4nd harmonic)



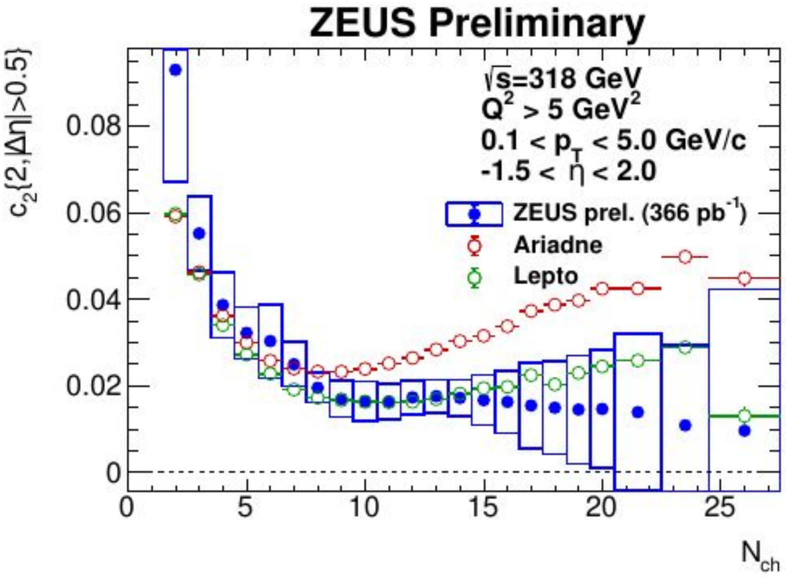


Increasing pseudo rapidity separation suppresses correlations. Consistent with 0 for |Δη|>0.5

Multiplicity dependent correlations with simulations



First harmonic is well described by Ariadne



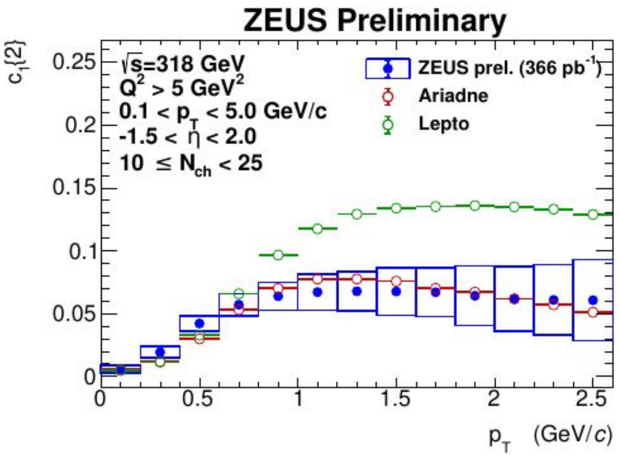
Second harmonic favors Lepto.

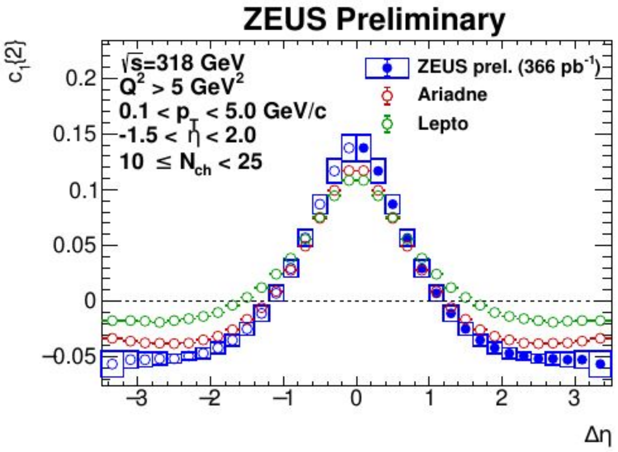
Differential $c_1\{2\}$ comparisons with MC

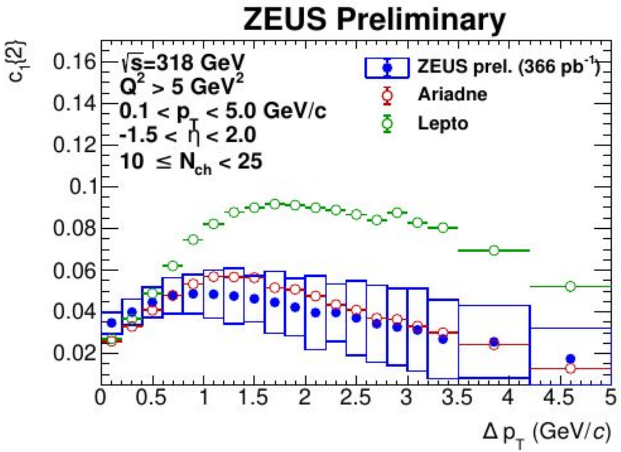
First harmonic has good agreement with Ariadne simulation.

Restricted mean p_T -> no artefact from upper pt cut, better visibility at low p_T

For Δη : open circles below Δη<0
Why: reflection of positive Δη, no independent datapoints (style used more often in heavy ion field)

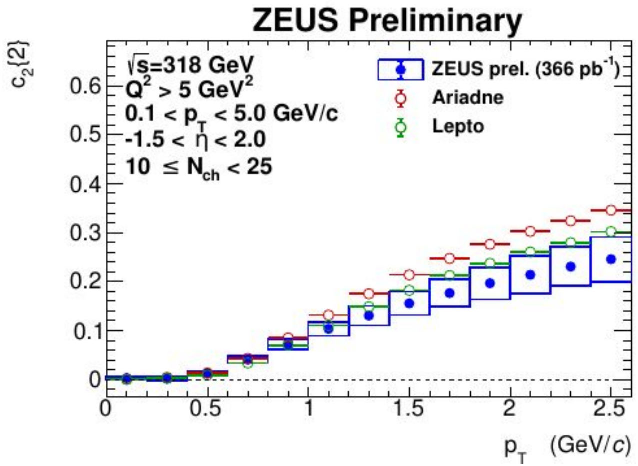


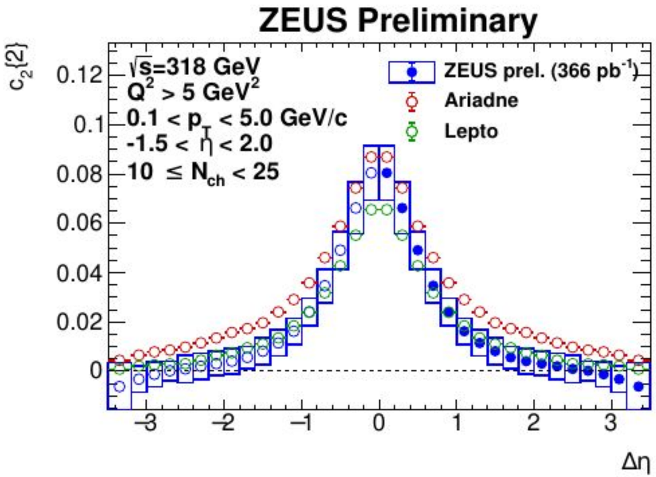


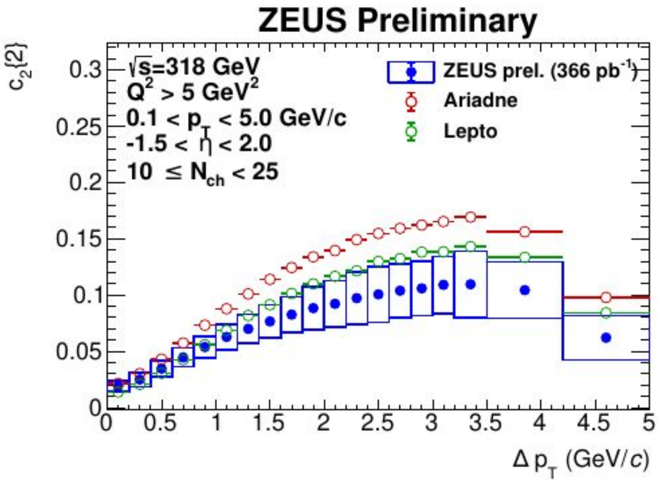


Differential $c_2\{2\}$ comparisons with MC

Second harmonic has better agreement with Lepto, especially for for larger pseudorapidity separation







Physics messages

- Reported measurement for the correlations for different harmonics, and as a function of multiplicity, pair pseudorapidity, pair transverse momentum, pair Δp_T
- Correlations as a function of rapidity separation approach 0 for large $\Delta\eta$ except for $c_1\{2\}$, where it changes sign towards negative, which is a signature of momentum conservation.
- New data from ZEUS adds new information to the ongoing efforts at LHC and RHIC for the search for collective effects in high multiplicity events for small collision systems.
- Comparisons to different Monte Carlo generators tuned to Hera data are able to reproduce overall features of the multiplicity dependence of the correlations.

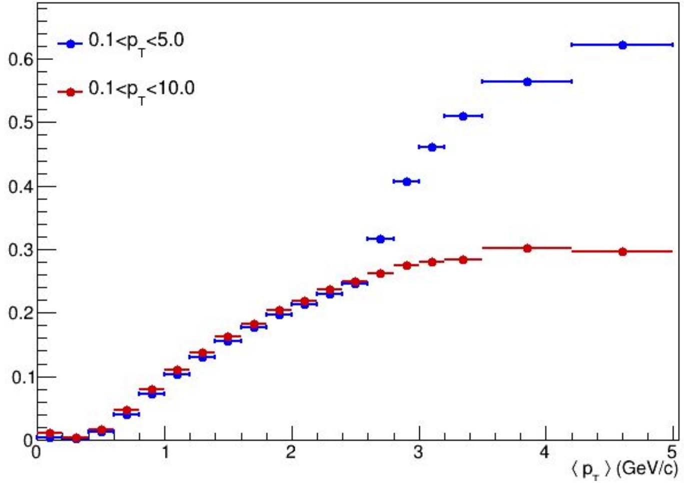
Backup

Kink in c_n vs $<p_T>$

It was asked why there is a kink observed in the correlation vs pair mean transverse momentum.

The momentum range of the selected particles has the effect that for $<p_T>$ > 2.5 GeV/c, both particles in the pair need high momentum.
If the upper momentum is extended to 10 GeV/c, the kink disappears.

$c_2\{2\}$



MC track matching

Track matching

Matching in the orange tree with Mcmatquality==1 is fairly inefficient, ~10% of reconstructed tracks can't find a match to a generated particle.

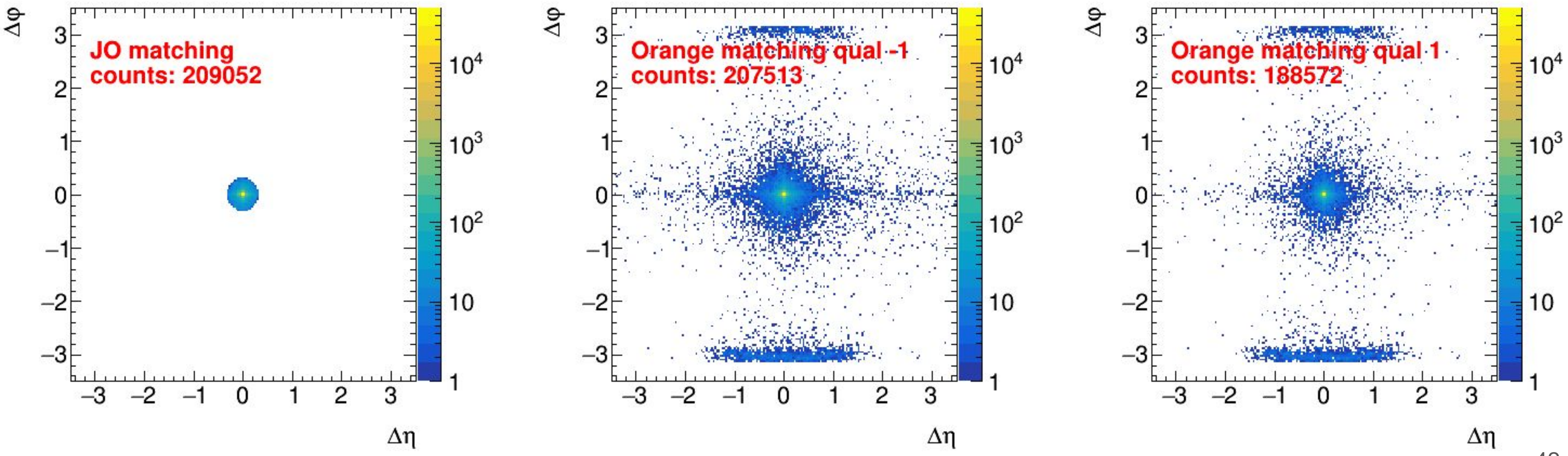
Attempt at a new matching algorithm:

Look for the closest match in $(\eta^{T}-\eta^{R})^2+(\varphi^{T}-\varphi^{R})^2$,

with requirement $(p_T^{\,T}-p_T^{\,R})/p_T^{\,T} < 0.3$

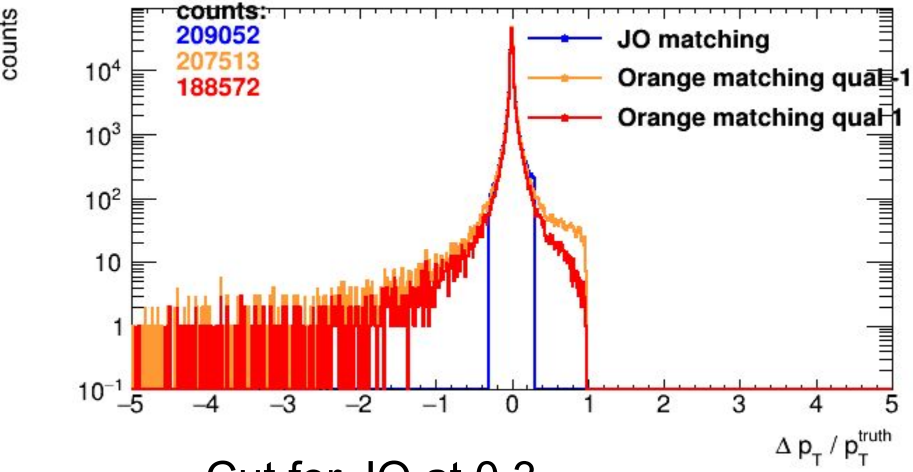
MC track matching ΔηΔφ

For generated primary particles
with p_T>0.1 GeV/c and -1.5<η<2

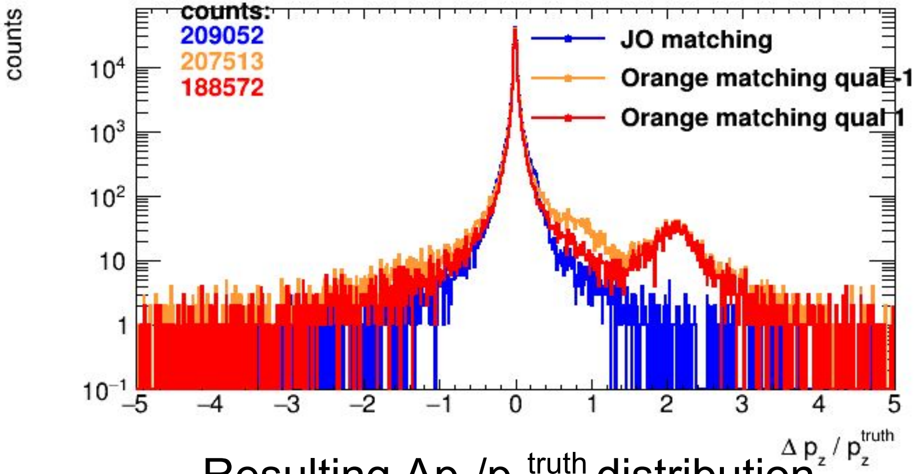


MC track matching $\Delta p_T/p_T^{truth}$, $\Delta p_z/p_z^{truth}$

For generated primary particles
with p_T>0.1 GeV/c and -1.5<η<2



Cut for JO at 0.3



Resulting $\Delta p_z/p_z^{truth}$ distribution for JO narrower

Unmatched tracks

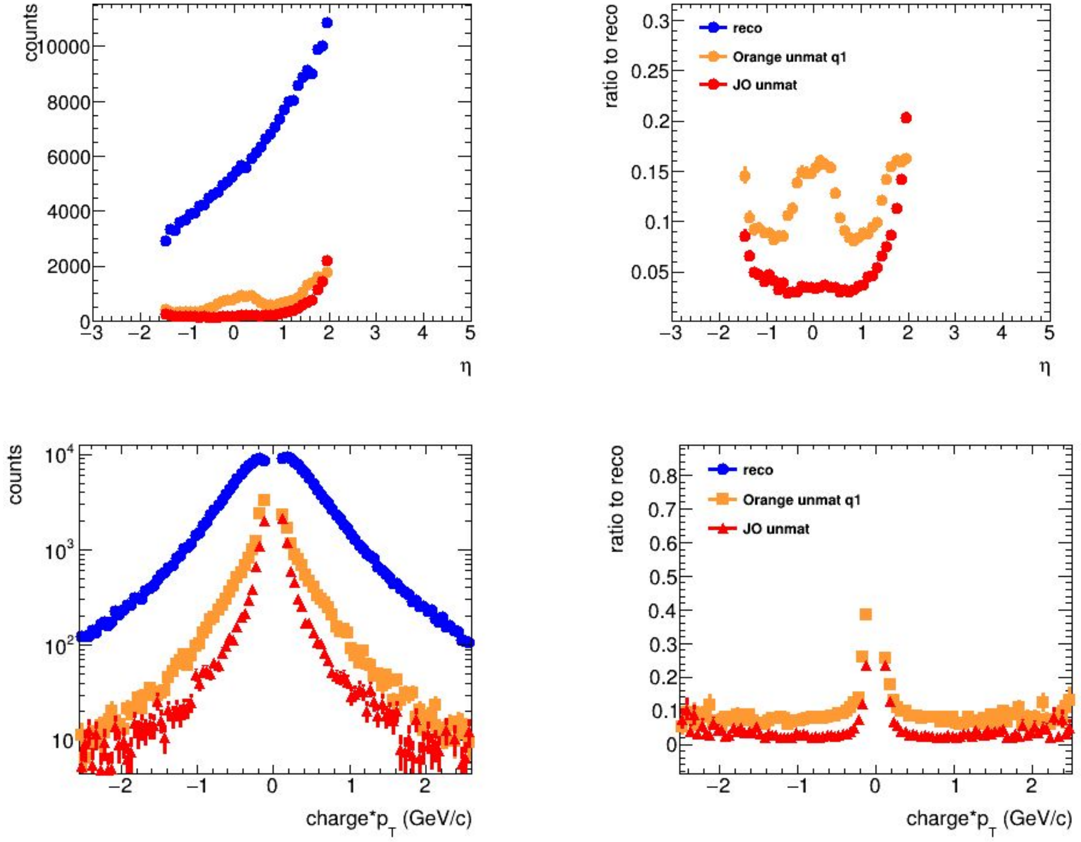
For reconstructed particles with p_T>0.1 GeV/c and -1.5<η<2

Matching efficiency for selected tracks at ~87% for orange quality = 1.

Matching efficiency for selected tracks at ~95% for JO.

ratio

η

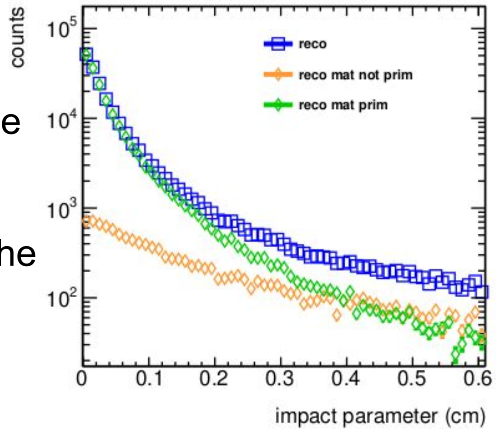


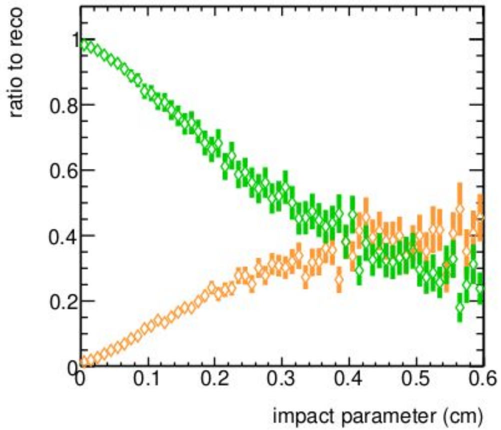
p_T*charge

Contamination of secondaries in reconstructed tracks

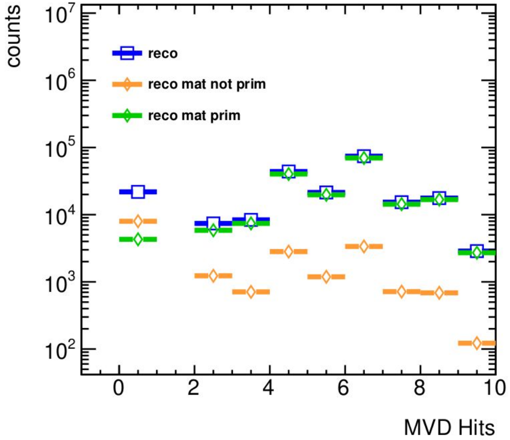
Check whether the selected reconstructed particles fulfill the definition of primary particle, if not, the particle is a secondary particle.

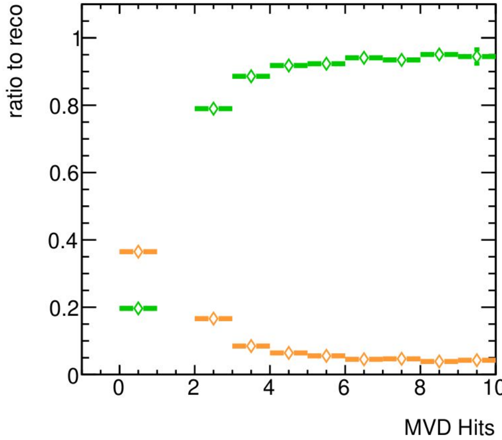
At an impact parameter of ~0.5 cm, the fraction of primary drops below secondary
→cut at 0.5 (previously 1.0) cm.





For 0 MVD hits, there are more secondary than primary particles
→require MVD hits > 0
(previously no cut)





Unmatched tracks

For reconstructed particles with p_T>0.1 GeV/c and -1.5<η<2, impact parameter<0.5 cm and MVD hits>0

Matching efficiency for selected tracks at ~90% for orange quality = 1.

Matching efficiency for selected tracks at ~98% for JO.

ratio

η

p_T*charge