Two-particle azimuthal correlations as a probe of collective behaviour in Deep Inelastic Scattering at HERA

JHEP 2004 (2020) 070, arXiv:1912.07431

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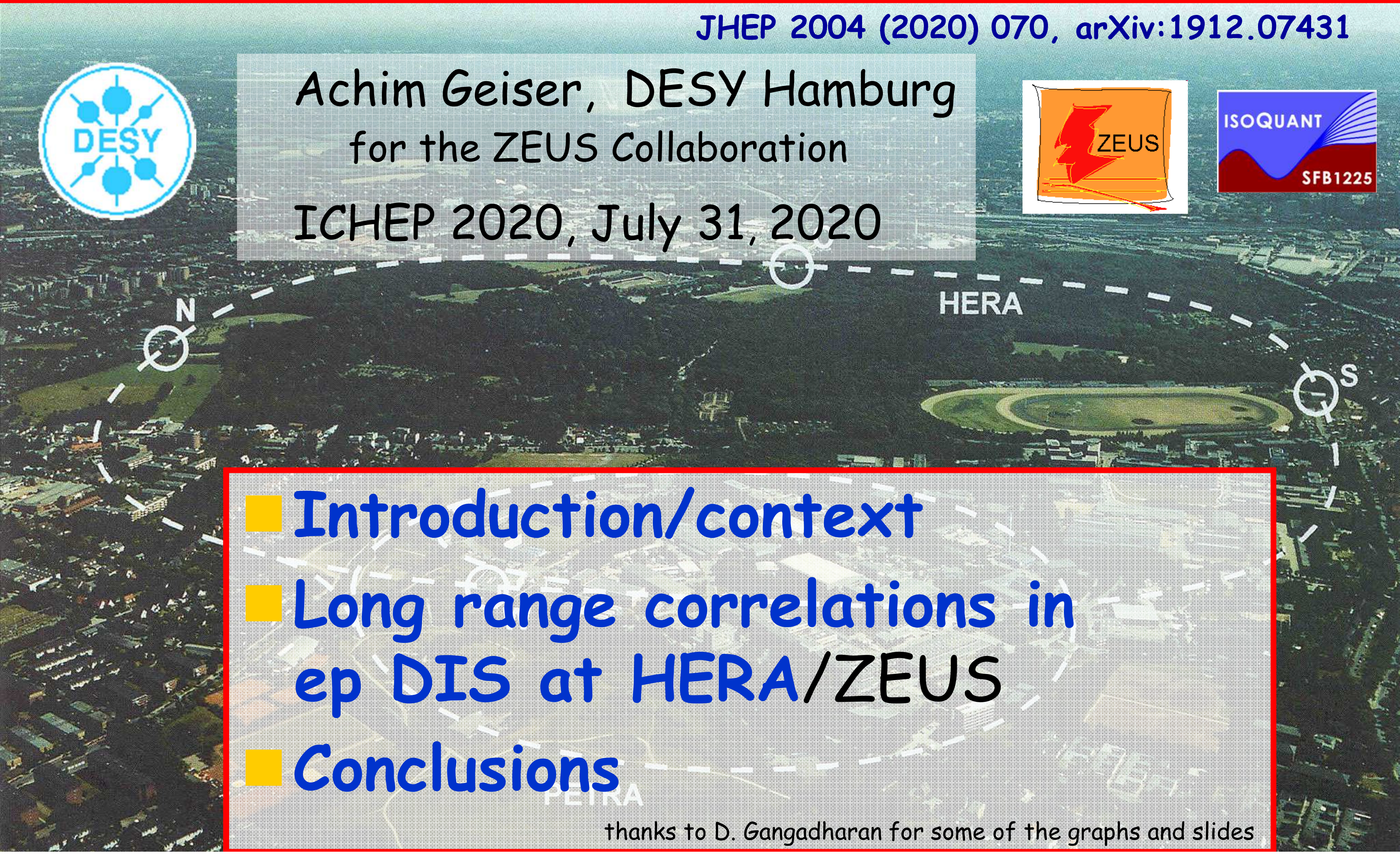
for the ZEUS Collaboration

ICHEP 2020, July 31, 2020

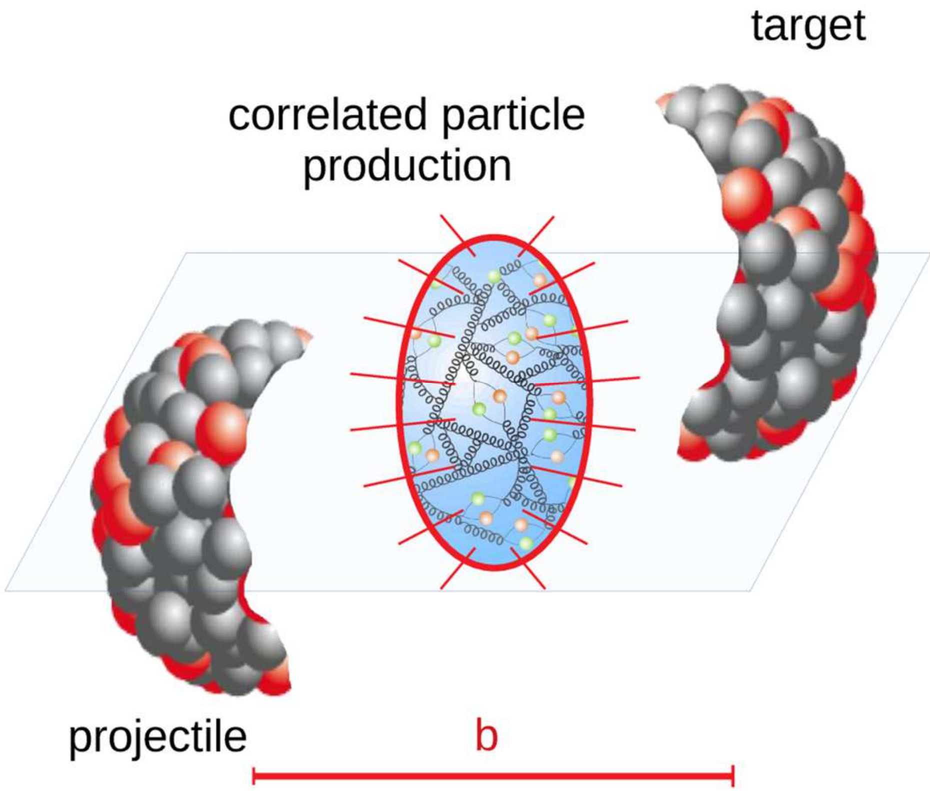


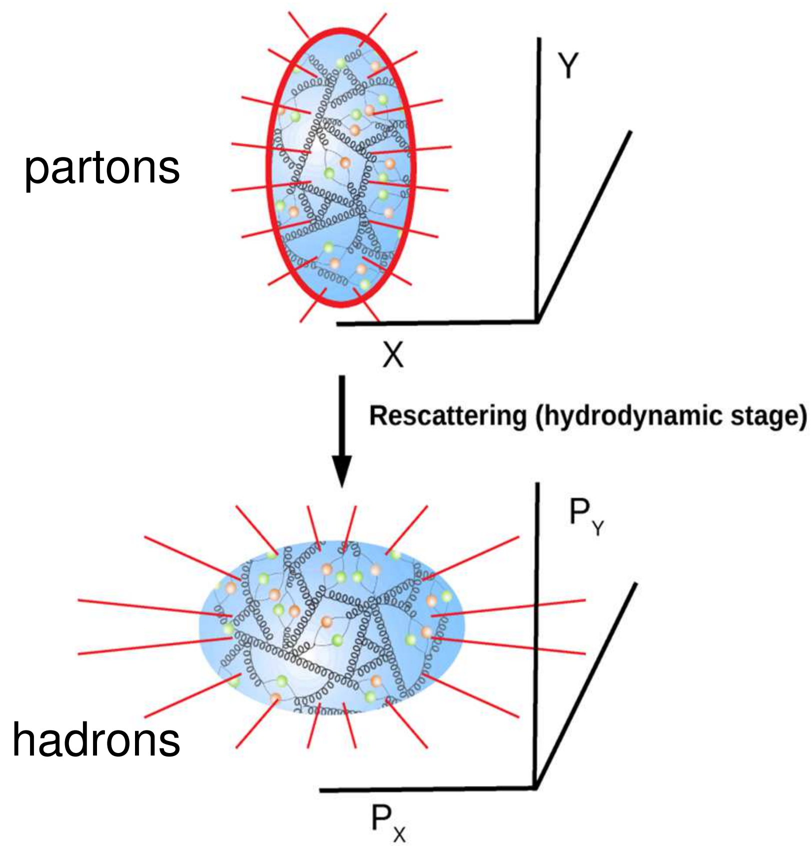
- Introduction/context
- Long range correlations in ep DIS at HERA/ZEUS
- Conclusions

thanks to D. Gangadharan for some of the graphs and slides

Long range collective effects in Heavy Ion collisions

nonperturbative QCD evolution of large (parton) multiplicity final states described by hydrodynamic models





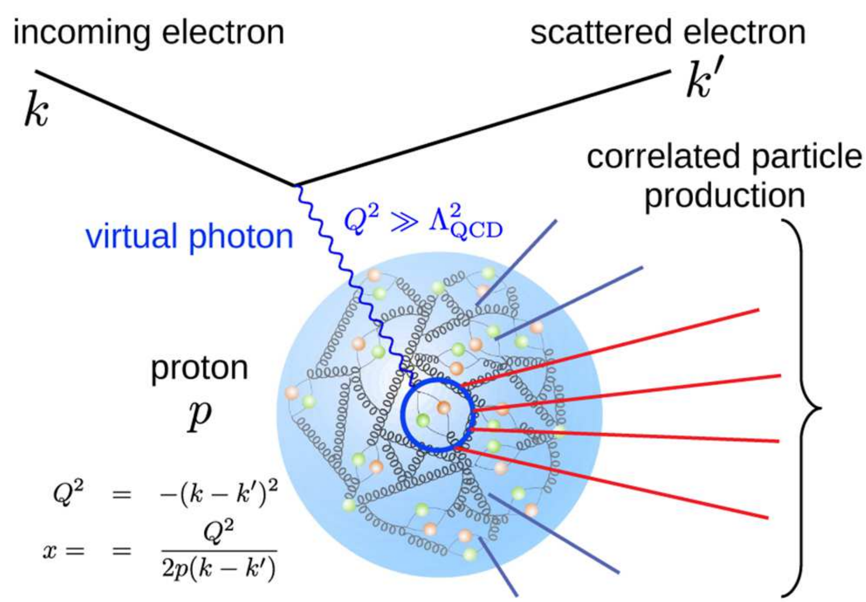
long range correlations in large hadron multiplicity final states keep a "memory" of this evolution

The Question

Is the hydrodynamic evolution model specific to "large" initial state systems such as heavy ion collisions?

Or does it also apply to "smaller" initial states such as pPb, pp, or even ep or e^+e^-, provided that the "final state" (indicated by final state multiplicity) **is large enough?**

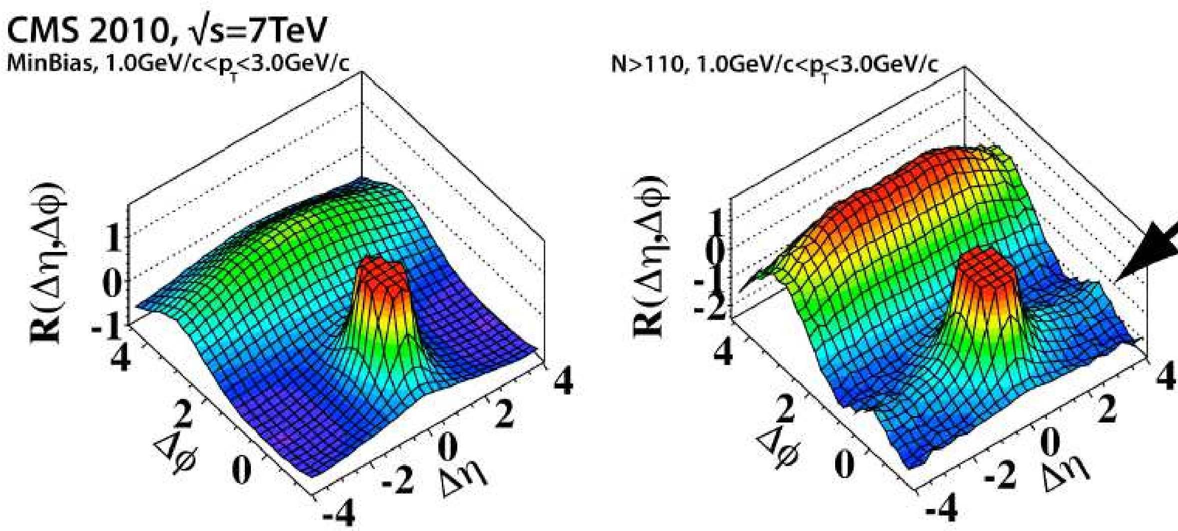
In Deep Inelastic Scattering (DIS):
"size" of initial state interaction inversely proportional to virtuality Q^2 of exchanged photon.

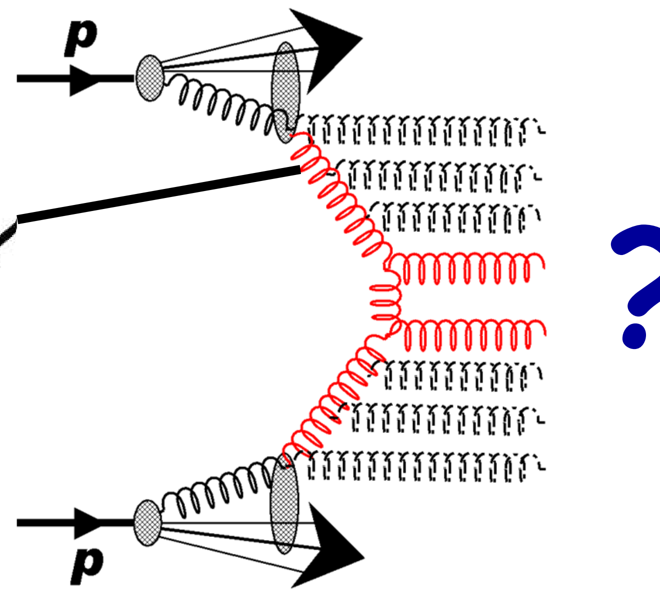


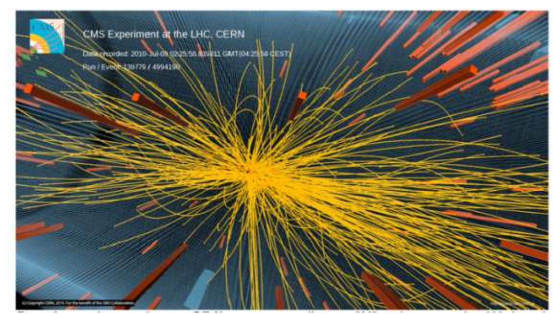
Do "conventional" particle physics models describe the observed correlations?

Long range two-particle correlations in pp in CMS

JHEP 09 (2010) 091, arXiv:1009.4122







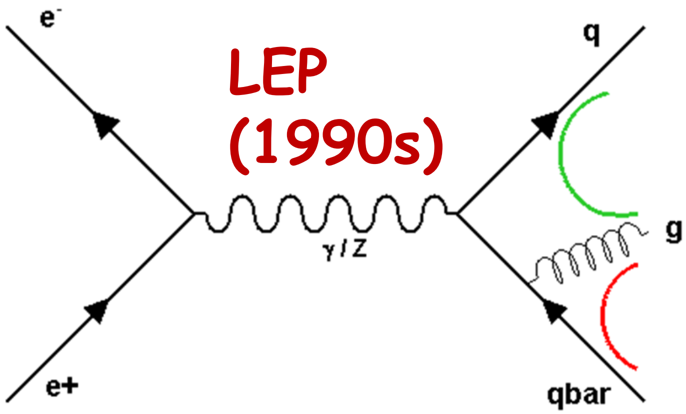
Hydrodynamic effects similar to heavy ion case?

Or simply a rediscovery of colour strings/dipoles as a source of gluon radiation (parton showers) between (semi-)hard partons and proton remnant ?

Or the same QCD just described by different approximations?

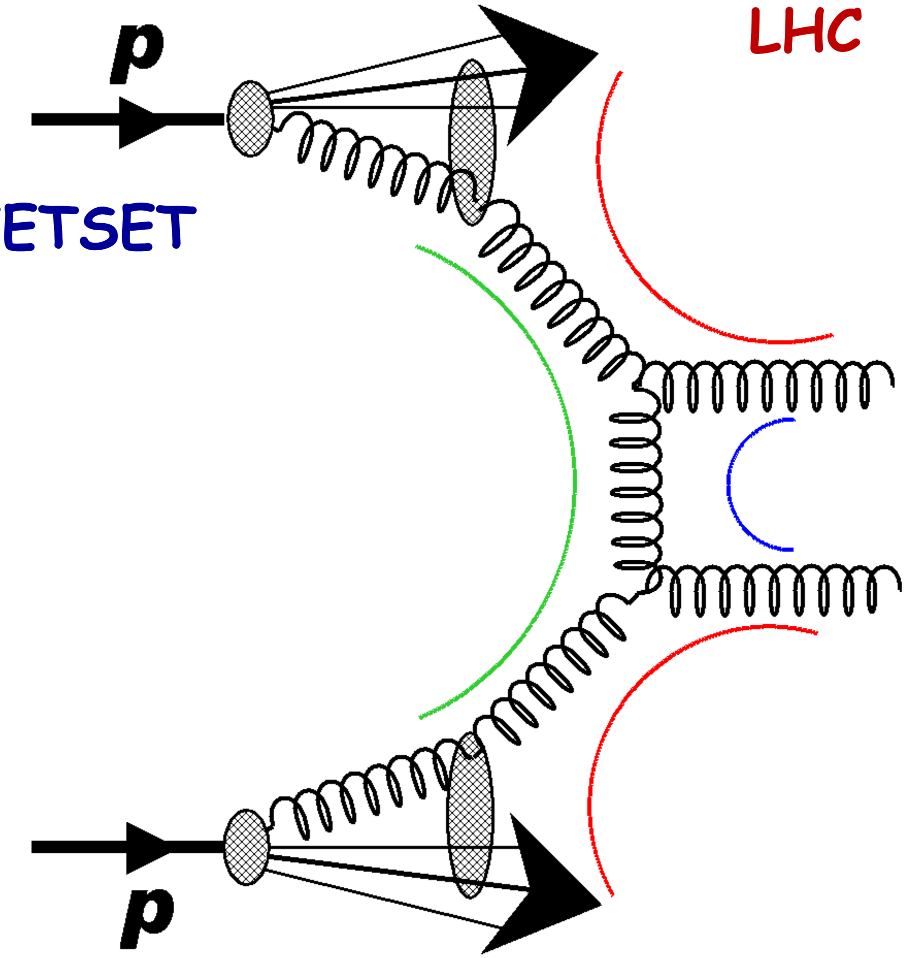
Colour strings in e+e-, ep, and pp

LEP
(1990s)



PYTHIA/JETSET

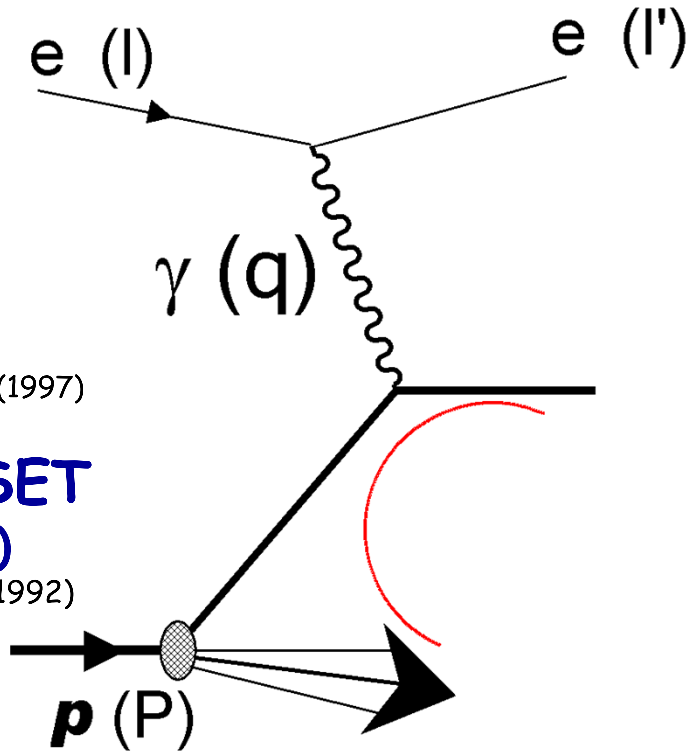
LHC



DIS (HERA):

Ariadne dipole model
Comp. Phys. Comm. 101, 108 (1997)

Lepto + JETSET (from PYTHIA 6)
Comp. Phys. Comm. 71, 15 (1992)



"Ridge" in long range pp correlations at CMS

JHEP 09 (2010) 091, arXiv:1009.4122

in general:
effects not restricted to very high multiplicity!

angular correlations
only partially described by PYTHIA 8 parton shower +hadronization model

"visible" ridge arises in data at very high multiplicities only

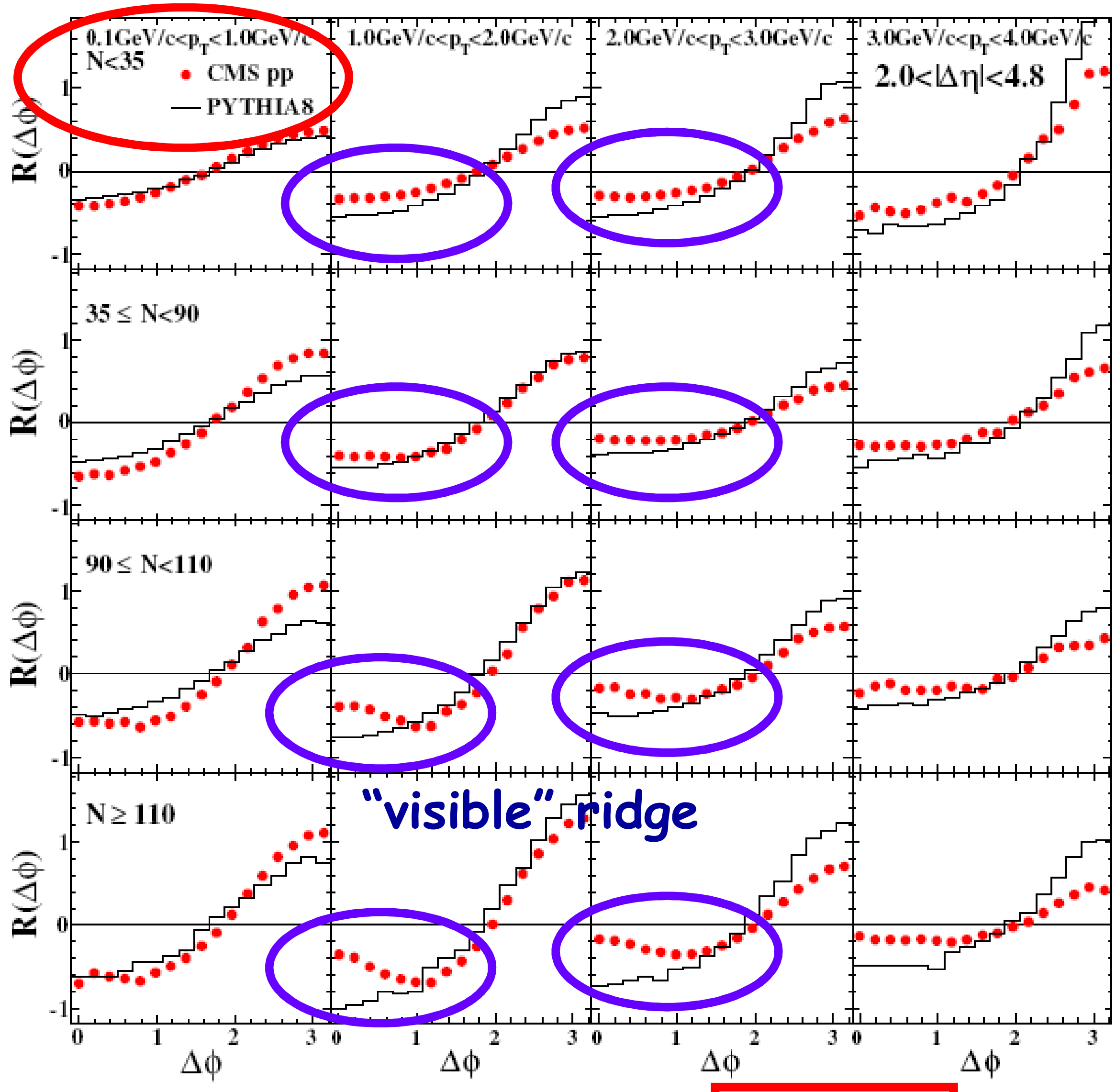
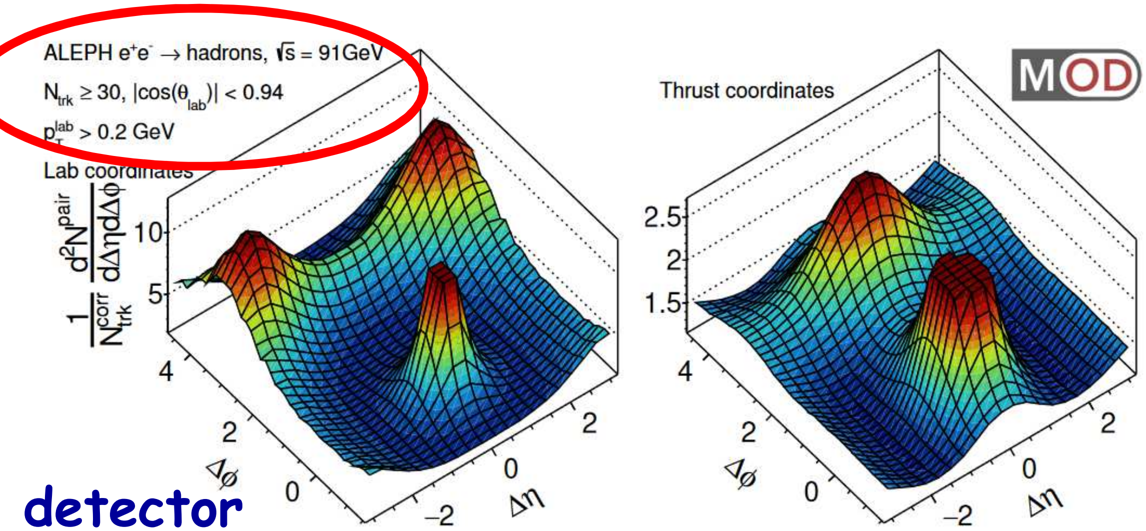


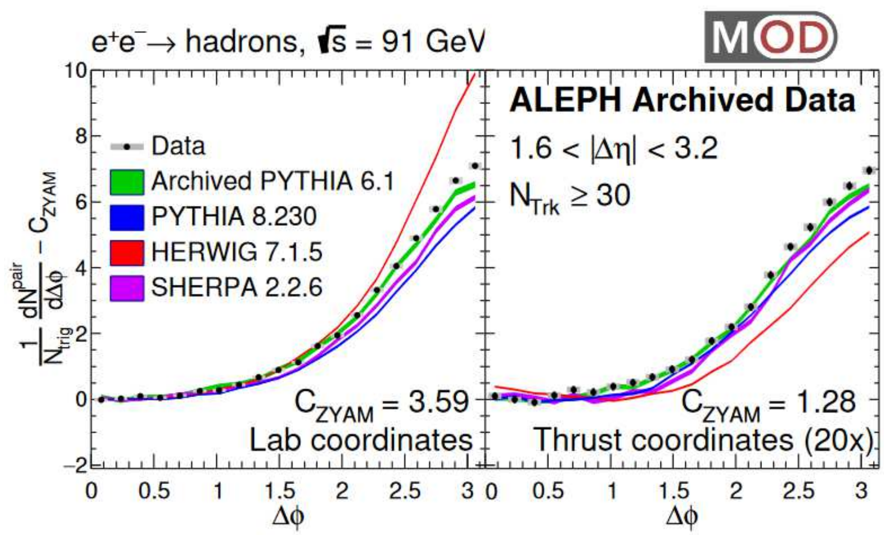
Figure 8: Projections of 2-D correlation functions onto $\Delta\phi$ for $2.0 < |\Delta\eta| < 4.8$ in different p_T and multiplicity bins for fully corrected 7 TeV pp data and reconstructed PYTHIA8 simulations. Error bars are smaller than the symbols.

Two-Particle correlations in e^+e^- collisions

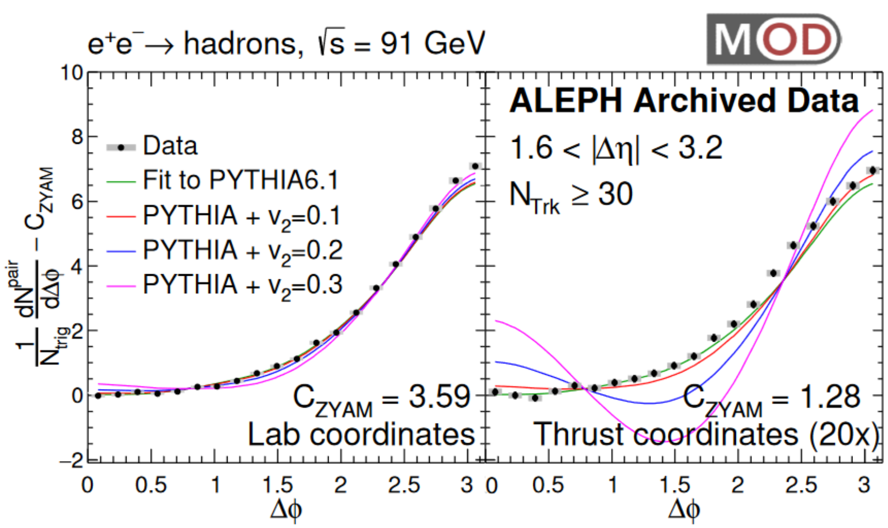
at $\sqrt{s}$=91 GeV, archived ALEPH data

Phys. Rev. Lett. 123 (2019) 212002, arXiv:1906.00489





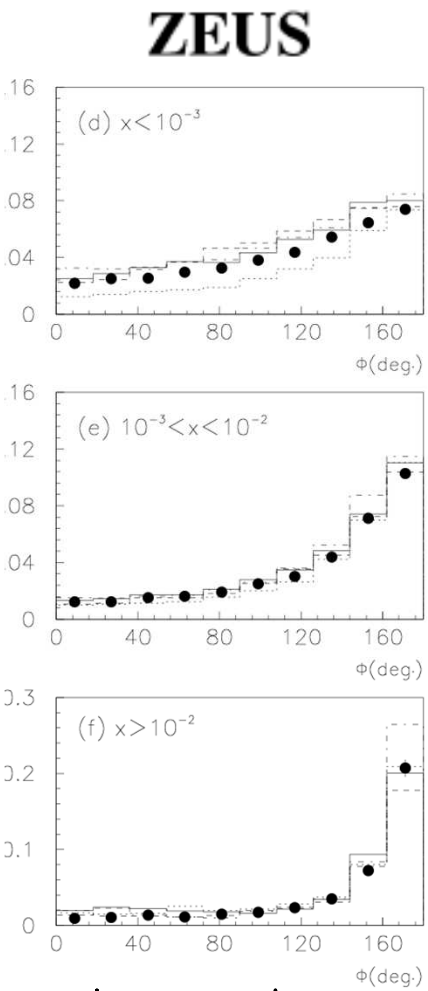
detector level



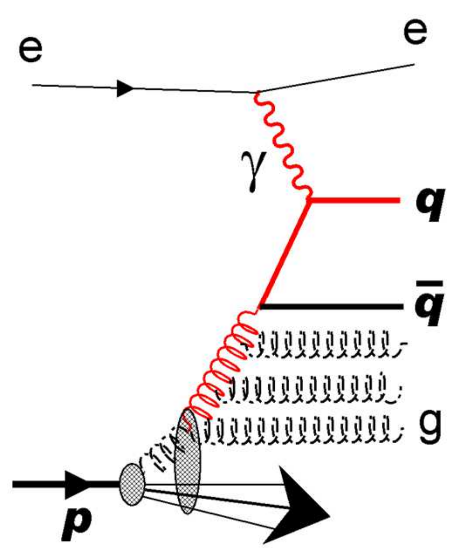
- no visible ridge (moderate multiplicities)
- PYTHIA 6 (tuned on LEP data) gives very good description of ALEPH e^+e^- data
- no extra long range correlations (v_2>0) needed

Observation of colour strings/dipoles

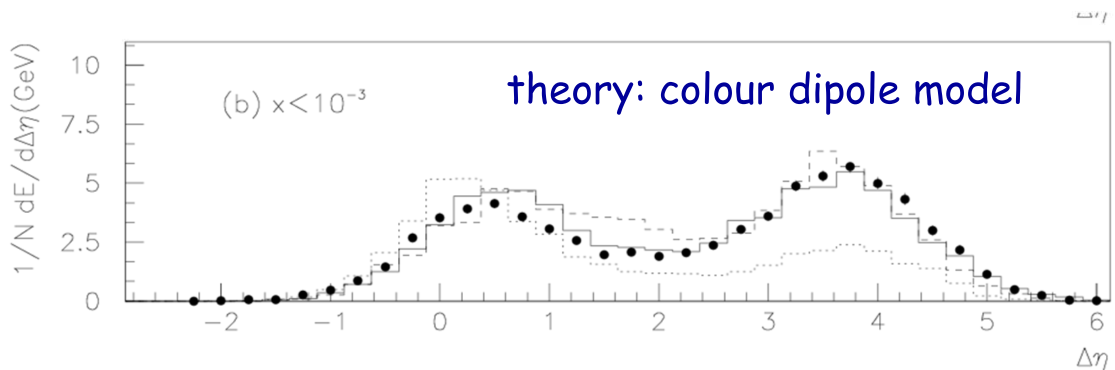
in hadronic energy flow in DIS at HERA: Z. Phys. C59 (1993) 231



angle w.r.t. electron



"In the low x region, the peak in the hadronic energy flow in the direction of the current jet is shifted [...] towards the proton remnant with most of the energy appearing between the position of the expected jet peak and that of the proton remnant."



rapidity difference w.r.t. expected QPM jet

see also H1, DESY-94-033

Observation of colour strings/dipoles

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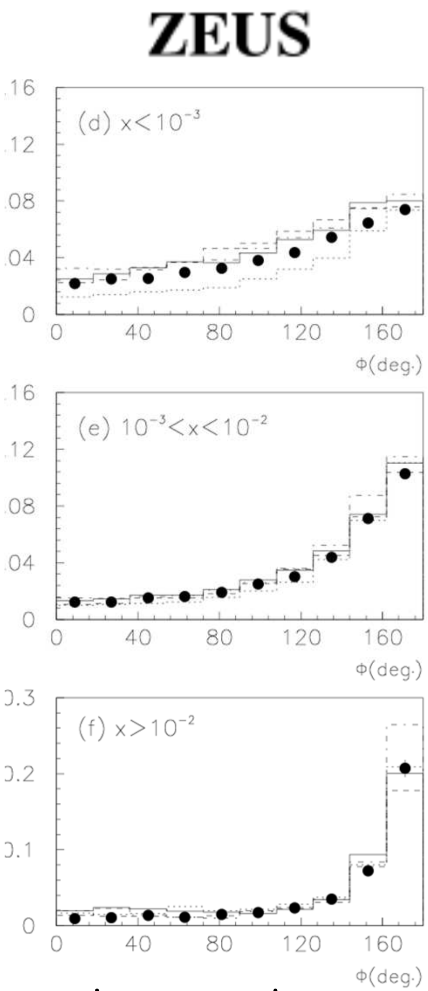
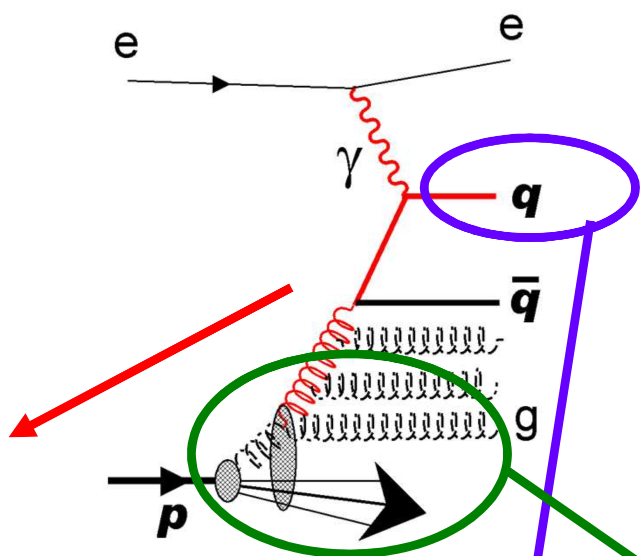
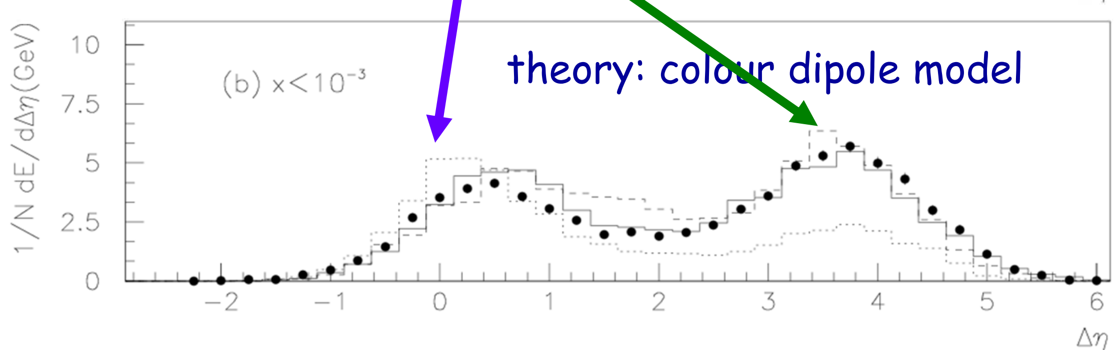


angle w.r.t. electron



"In the low x region, the peak in the hadronic energy flow in the direction of the current jet is shifted [...] towards the proton remnant with most of the energy appearing between the position of the expected jet peak and that of the proton remnant."

more in backup



rapidity difference w.r.t. expected QPM jet

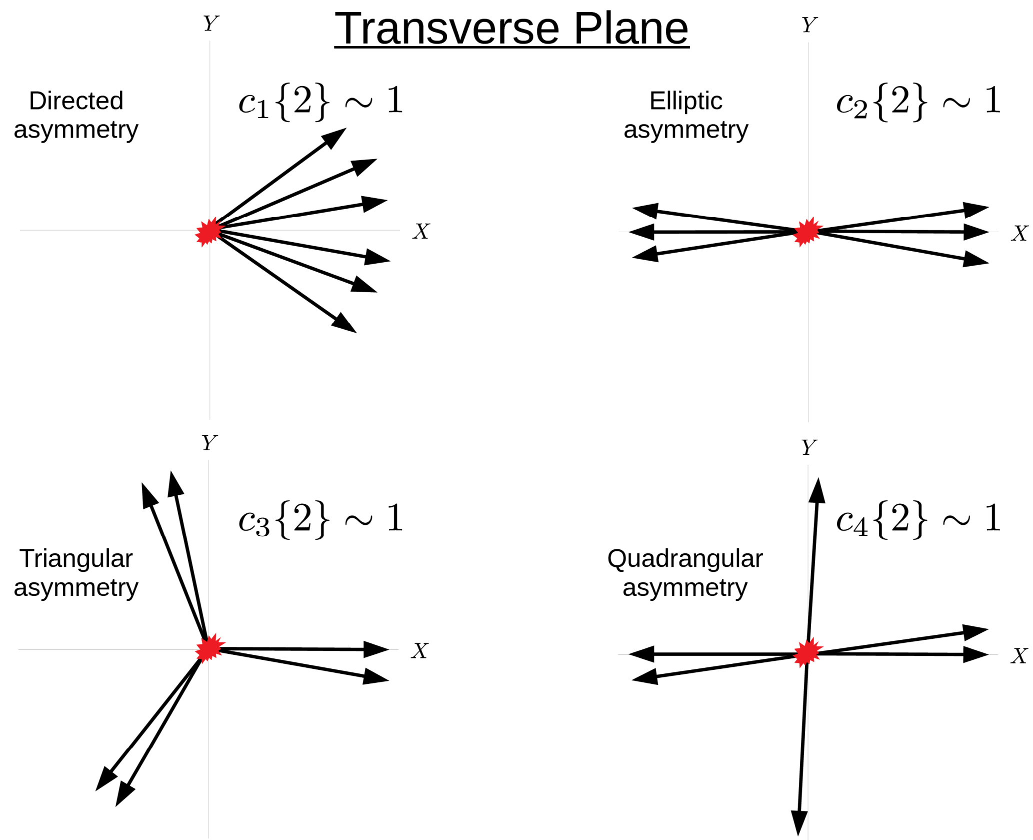
see also H1, DESY-94-033

Main observable for new ZEUS analysis: two-particle azimuthal correlations $c_n\{2\}$

$$c_n\{2\} = \langle\langle \cos n(\varphi_i - \varphi_j) \rangle\rangle$$

double average track pairs/events

DIS electron excluded

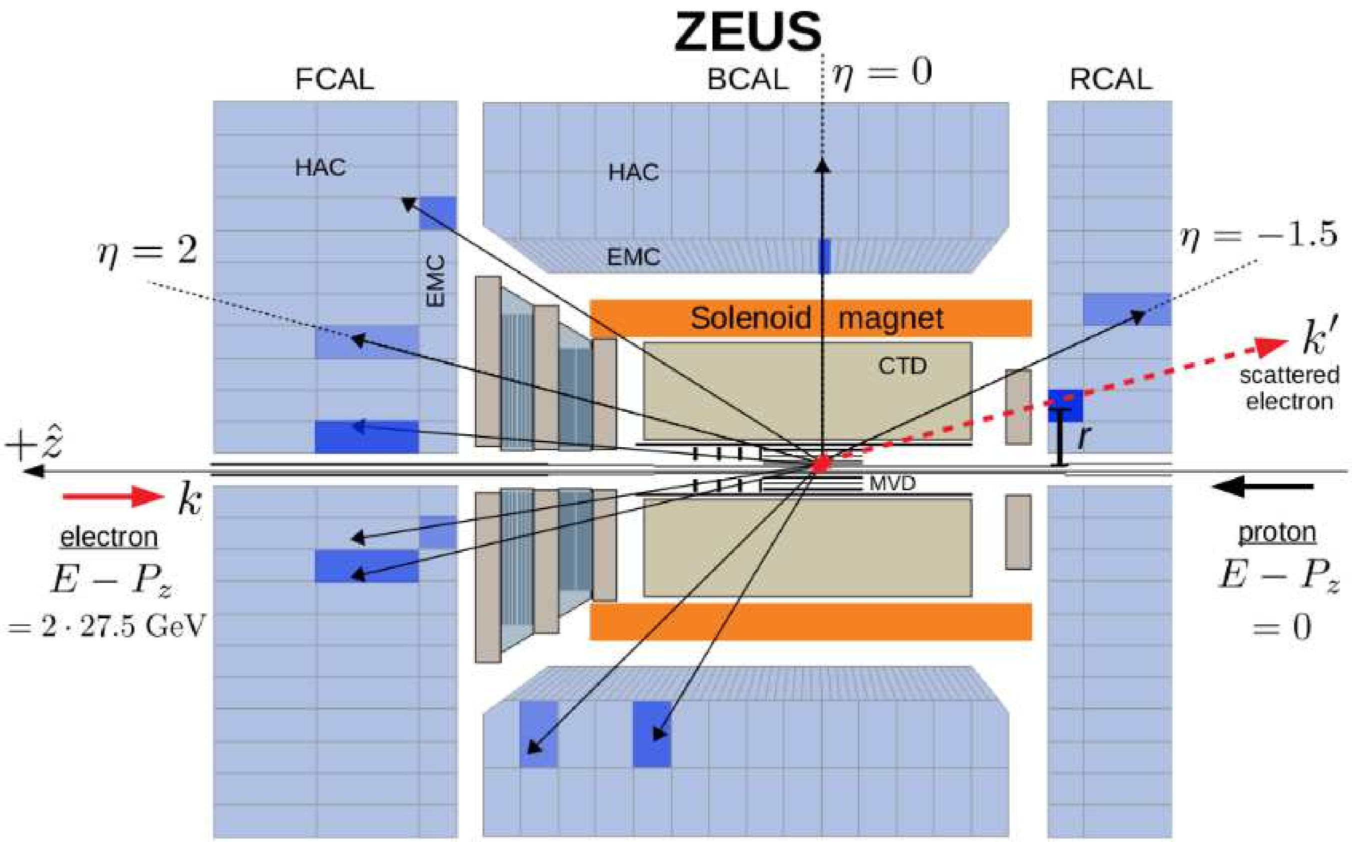


fully corrected
for single and correlated two-particle reconstruction efficiencies

$$c_n\{2\} = \sum_e^{N_{\rm ev}} \left[\sum_{i,j>i}^{N_{\rm rec}} w_{ij} \cos\left[n(\varphi_i - \varphi_j)\right] \right]_e \Bigg/ \sum_e^{N_{\rm ev}} \left[\sum_{i,j>i}^{N_{\rm rec}} w_{ij} \right]_e$$

DIS event and track selection

tracking in 1.4 T magnetic field (CTD+MVD)



Event selection (46 M)

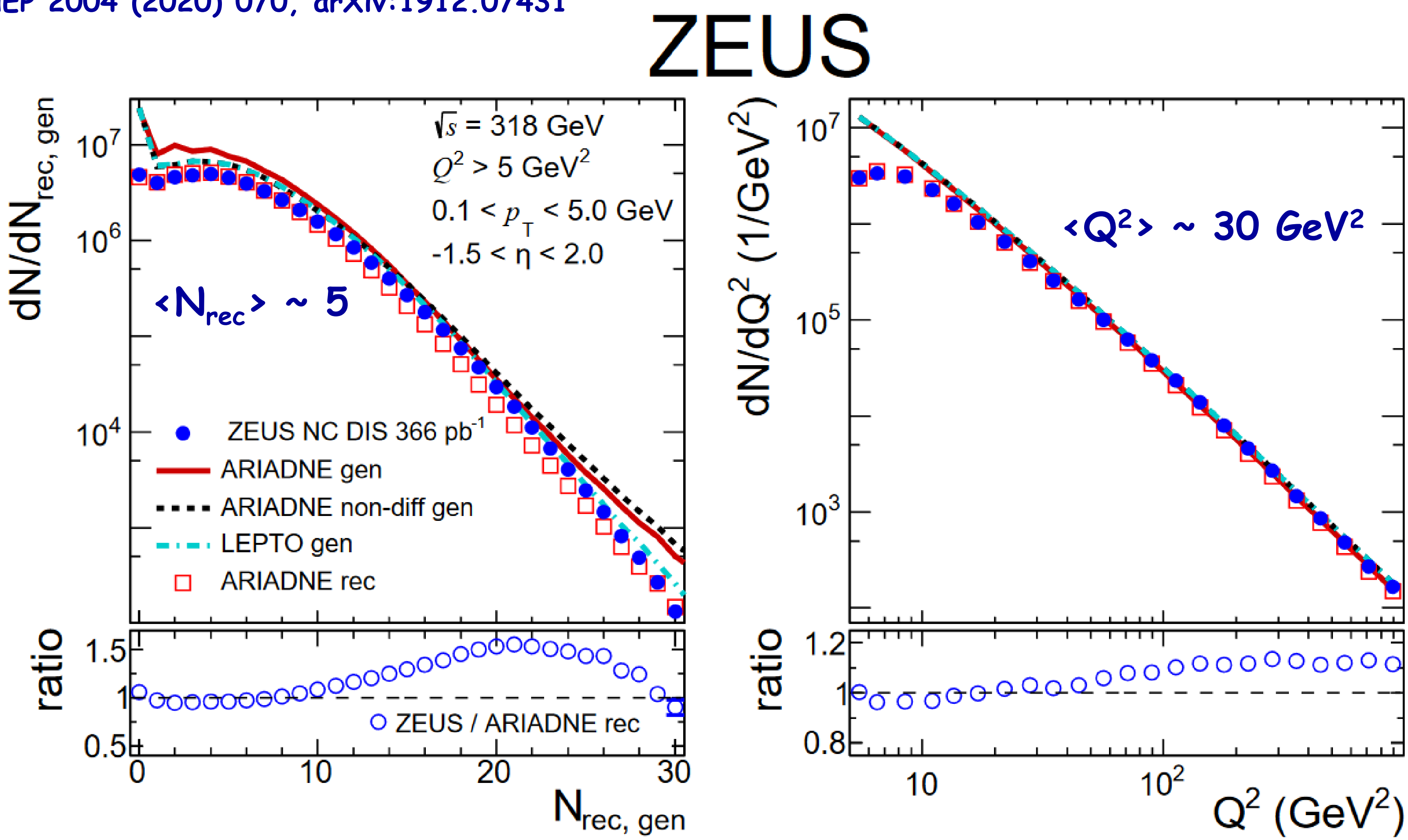
- DIS triggers
- $Q^2 = -(k - k')^2 > 5$ GeV^2
- $k'_0 > 10$ GeV
- $r > 15$ cm
- $\theta_e > 1$ rad
- $47 < \sum (E_i - P_{z,i}) < 69$ GeV
- $|V_z| < 30$ cm

Track selection for correlation analysis

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

General DIS event distributions (rec vs. gen)

JHEP 2004 (2020) 070, arXiv:1912.07431



general properties (blue points)
reasonably described by Ariadne MC (red boxes)

DIS: inclusive track distributions (rec vs. gen)

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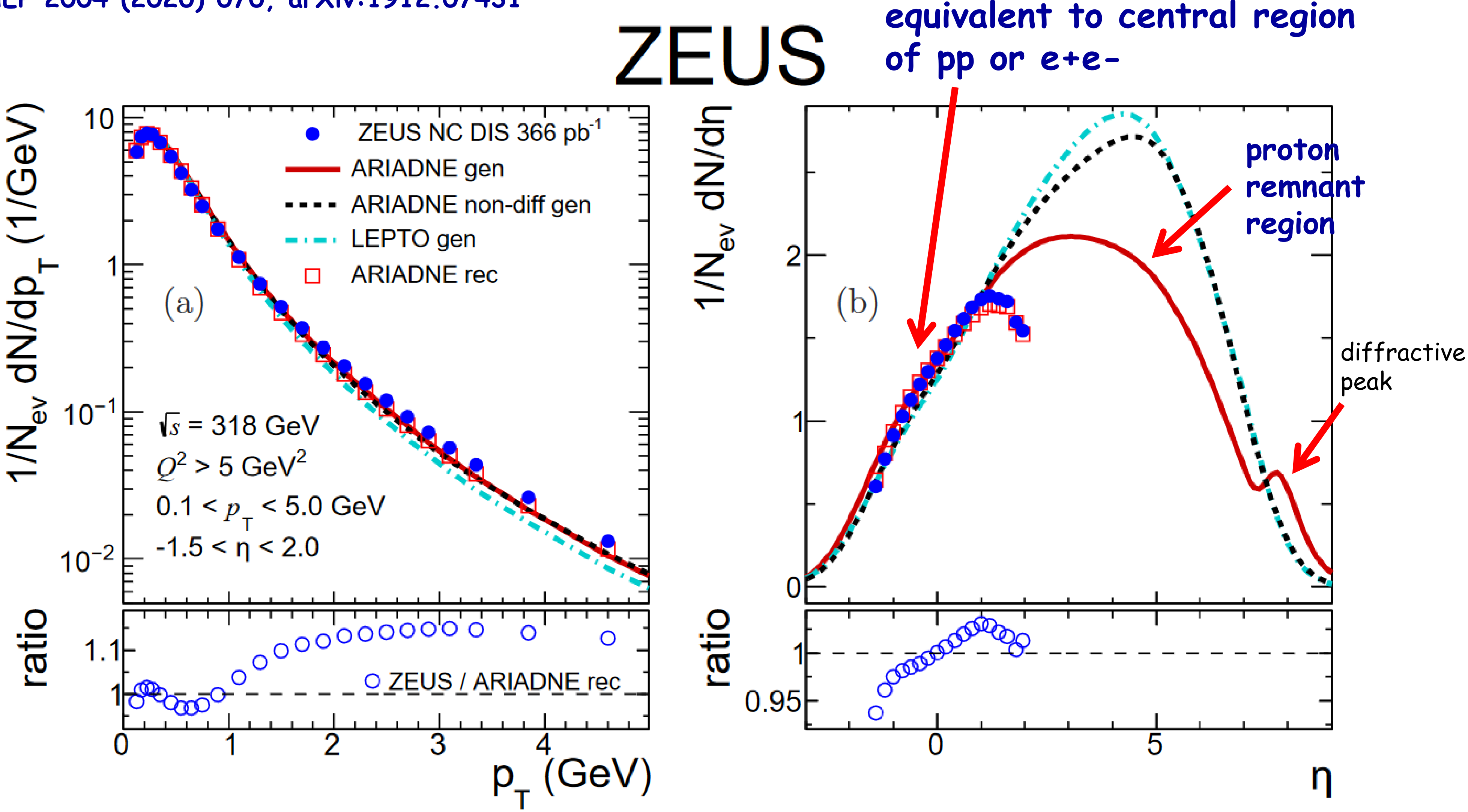

general properties (blue points)
reasonably described by Ariadne MC (red boxes)

"Ridge" figures in DIS

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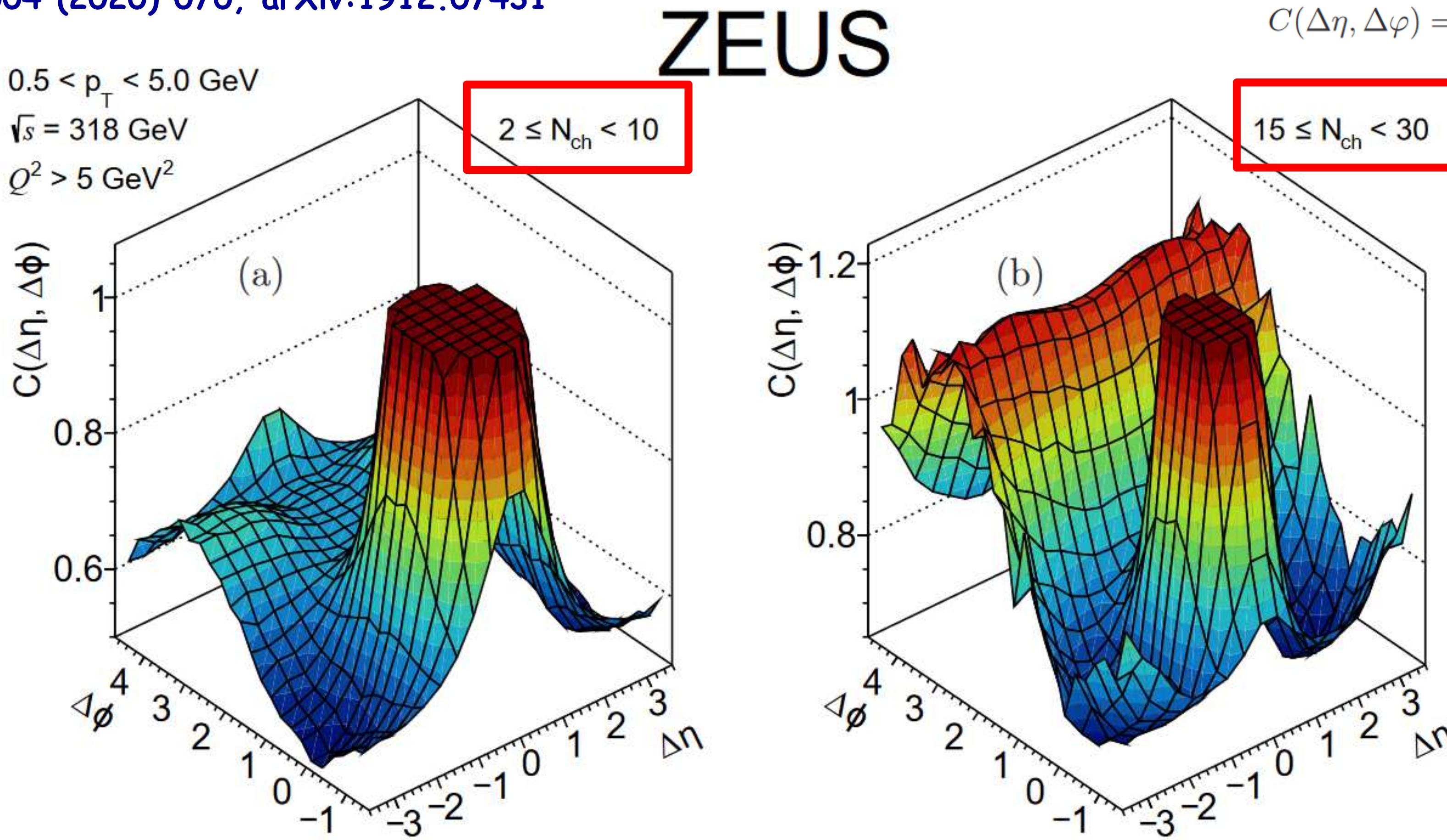
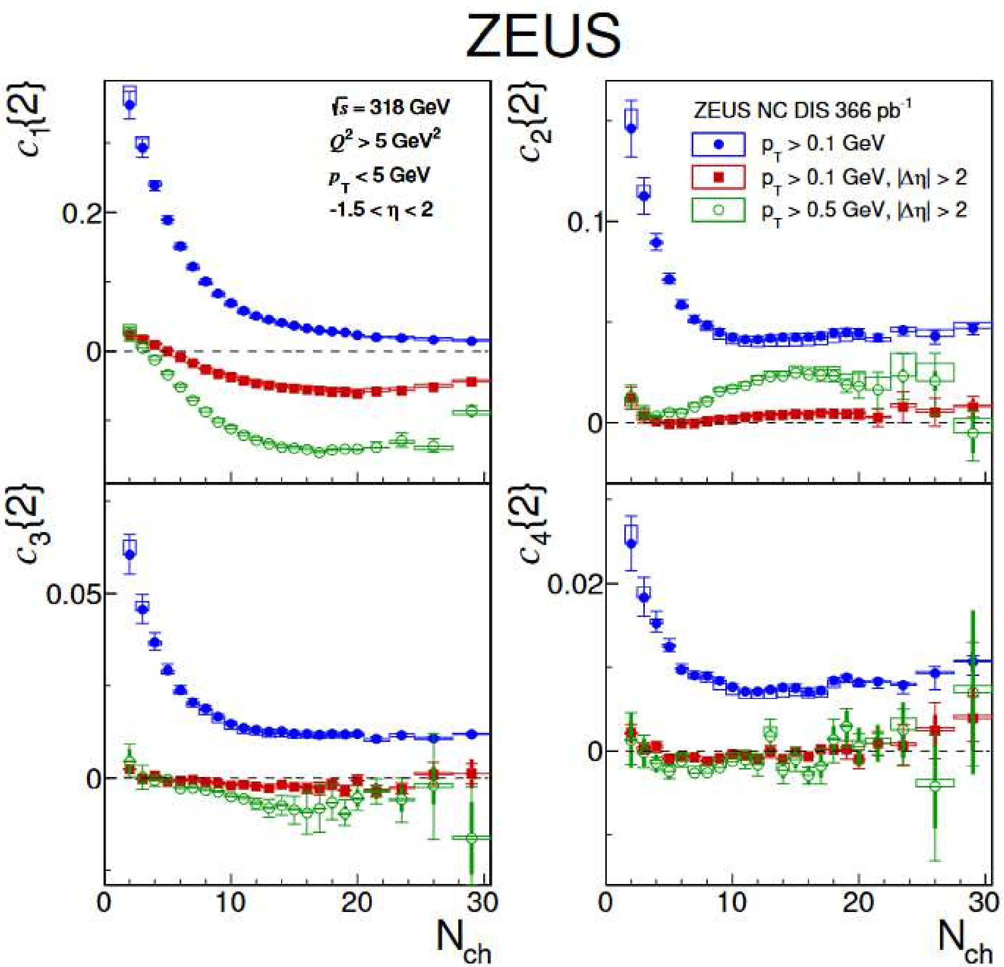
$$C(\Delta\eta, \Delta\varphi) = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$$



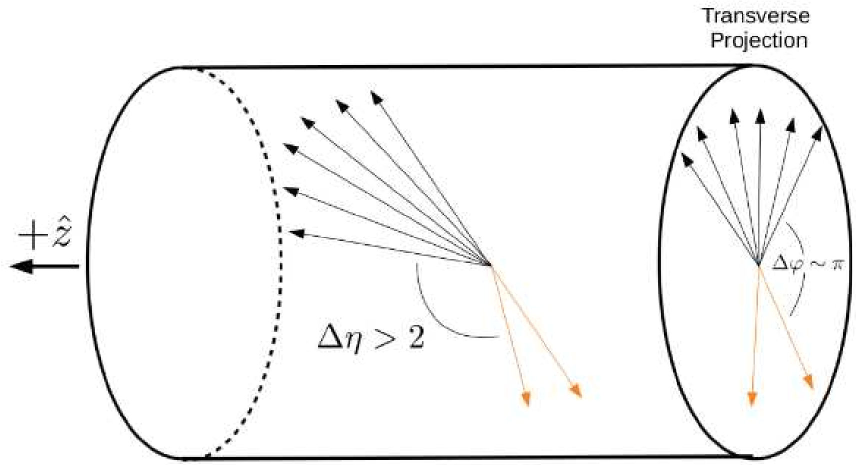
- **Jet peak centered at Δφ ~ Δη ~ 0 (includes single DIS recoil jet)**
- **Away side ridge in high N_{ch} events dominated by "dijet" topologies**
- **No visible double ridge at "high" N_{ch}**

Azimuthal correlations $c_n\{2\}$ versus multiplicity

fully corrected to gen level, full systematics (see backup)



- Short-range ($|\Delta\eta| \sim 0$) correlations are strongest at low N_{ch}. **(blue)**
- Long-range correlations ($|\Delta\eta| > 2$, orange-black pairs) of the first harmonic are dominant and negative. **(red (low p_T) and green (high p_T))**



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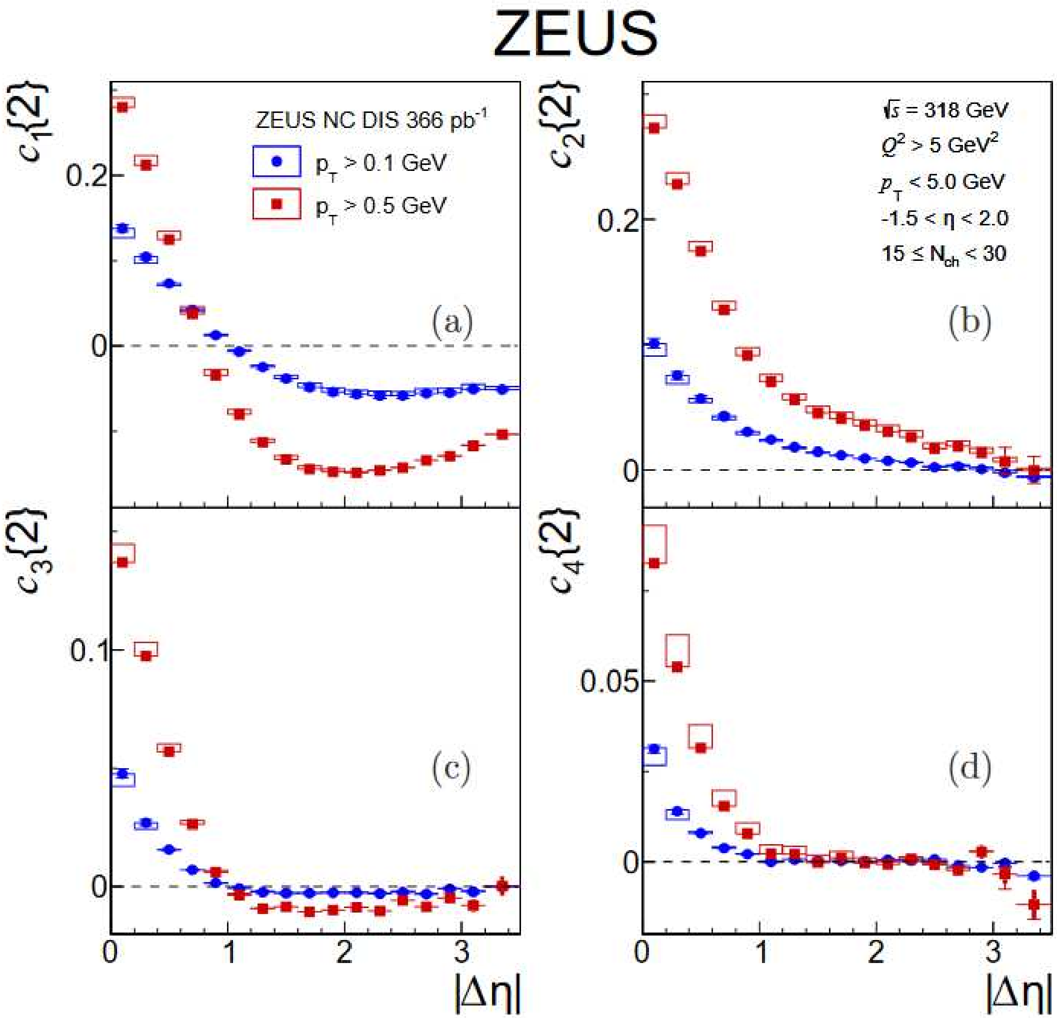
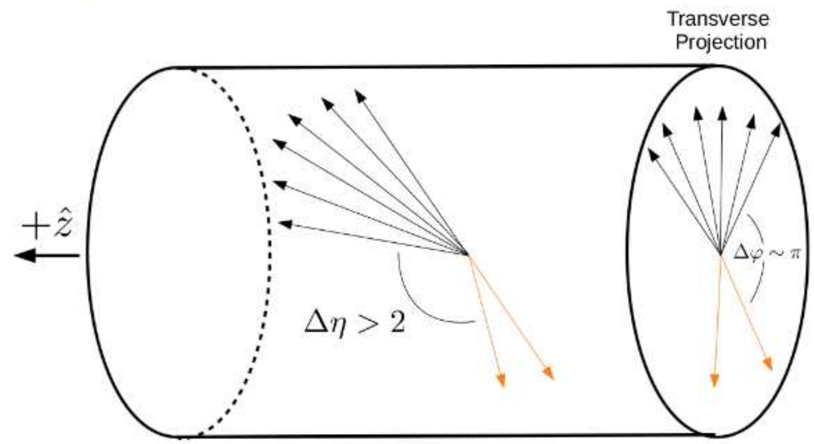
Azimuthal correlations $c_n\{2\}$ versus $\Delta\eta$

fully corrected to gen level, full systematics (see backup)



- 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 (postive) $c_1\{2\}$ ($c_2\{2\}$) for $p_T > 0.5$ GeV extend out to $|\Delta\eta| \sim 3$.
- Large directed and elliptic anisotropy → tilted dijet.



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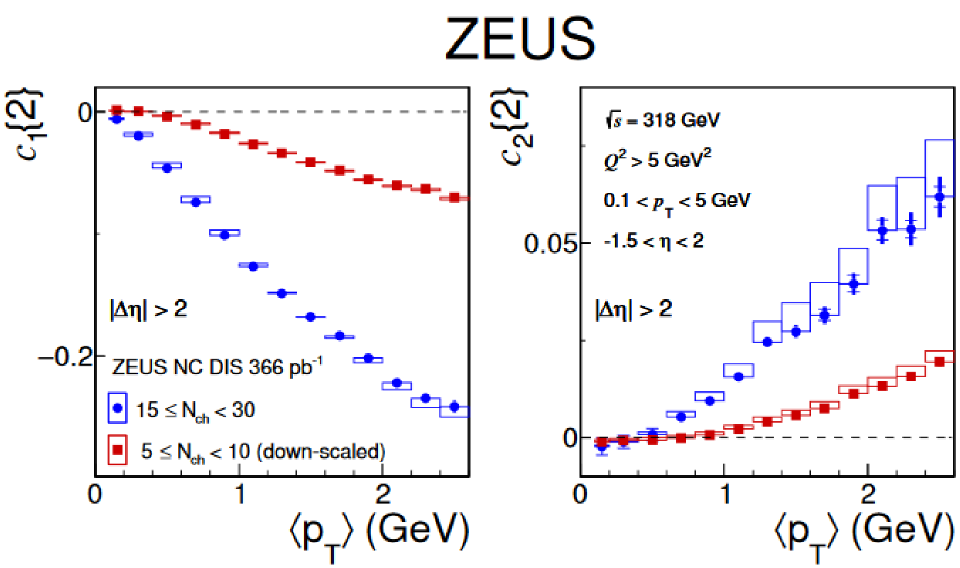
$c_1\{2\}$ ("mono-jettiness") and $c_2\{2\}$ ("di-jettiness") vs. p_T

fully corrected to gen level, full systematics (see backup)



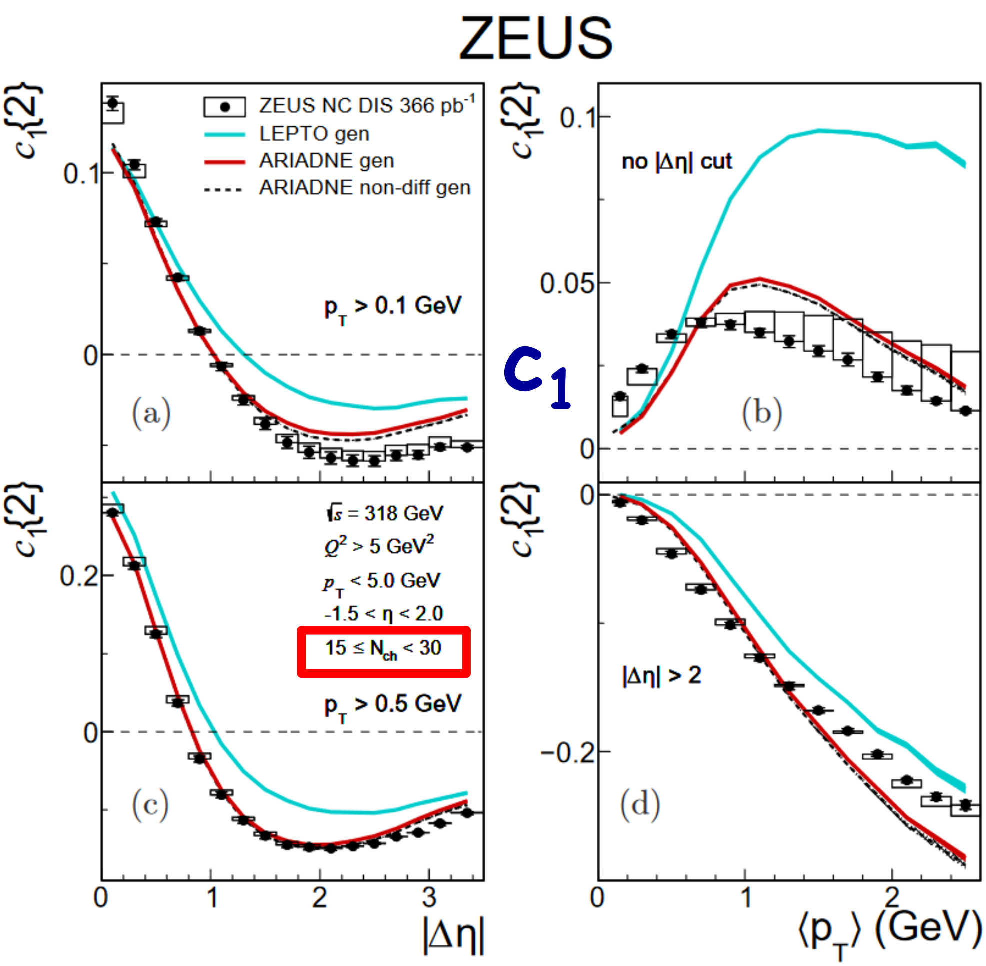
- Correlations at low N_{ch} were down-scaled by $\langle N_{\text{ch}}\rangle_{\text{low}} / \langle N_{\text{ch}}\rangle_{\text{high}}$.
- Scaling factor inspired by observations in heavy-ion collisions where non-collective behaviour contributes to $c_n\{2\}$ as $1/N_{\text{ch}}$.
- The observed excess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

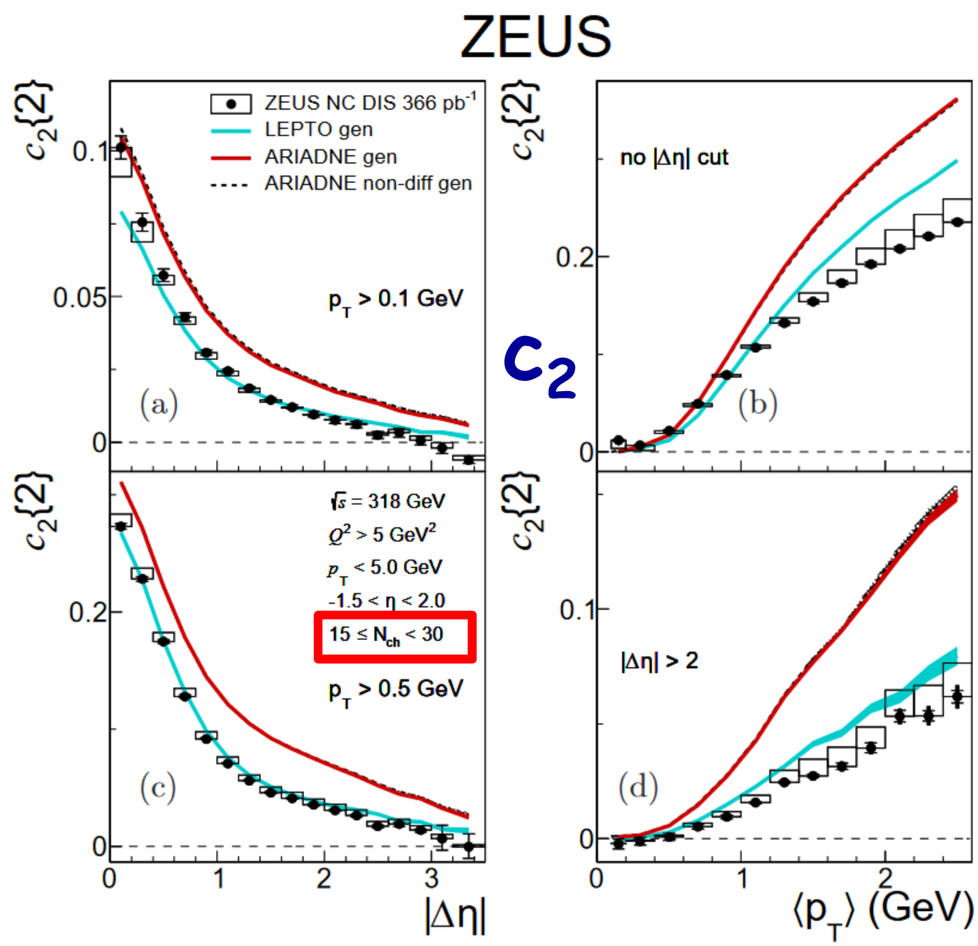
JHEP 2004 (2020) 070, arXiv:1912.07431

Comparison to MC model predictions

fully corrected to gen level, w. system. JHEP 2004 (2020) 070, arXiv:1912.07431

similar plots at reconstructed level see backup





$c_1\{2\}$ reasonably described by Ariadne dipole model (LO+PS)

$c_2\{2\}$ reasonably described by Lepto + JETSET model ("Pythia 6", LO+PS)

Comparison to MC model predictions

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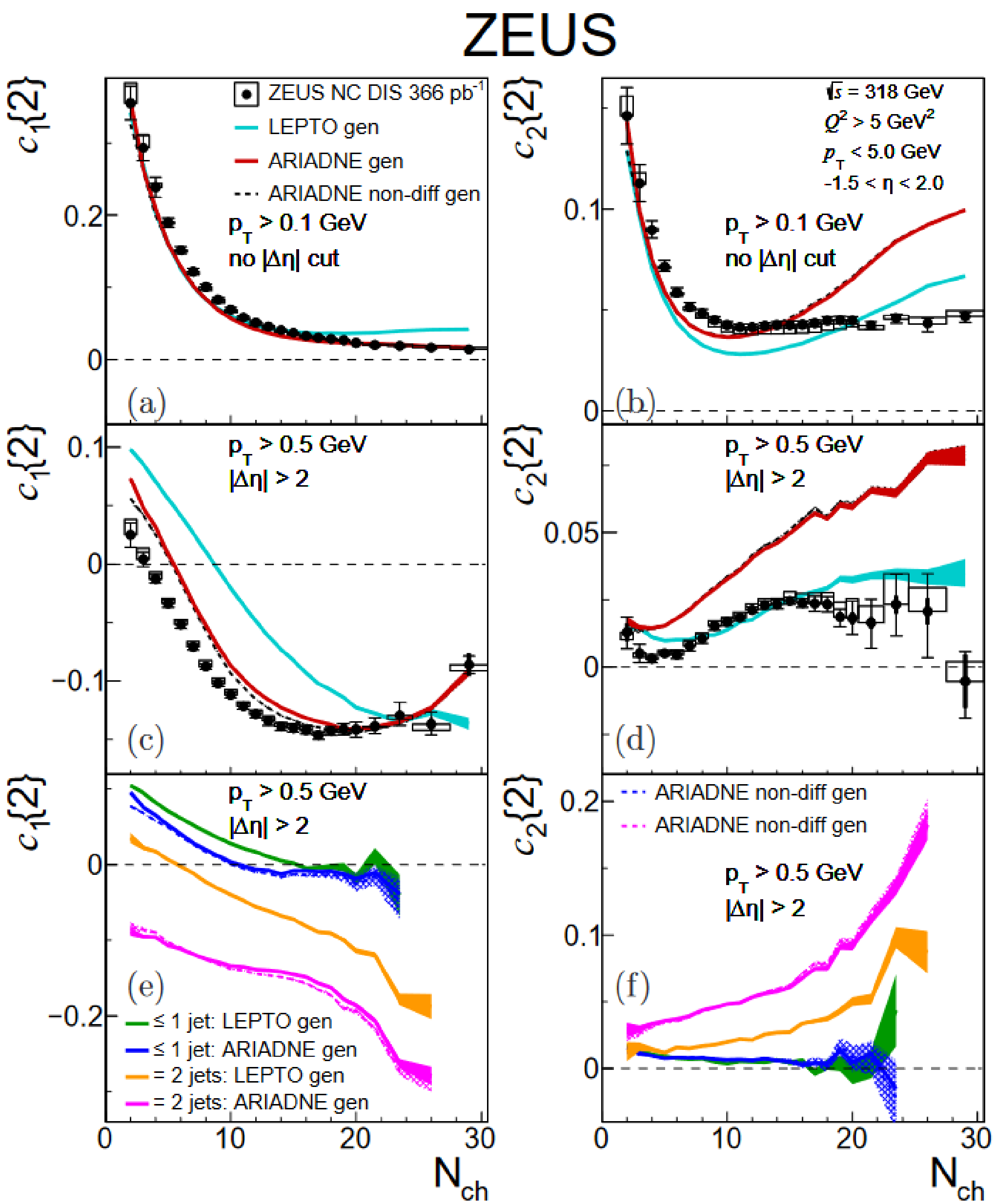
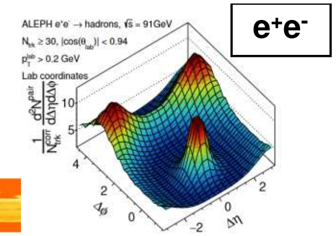
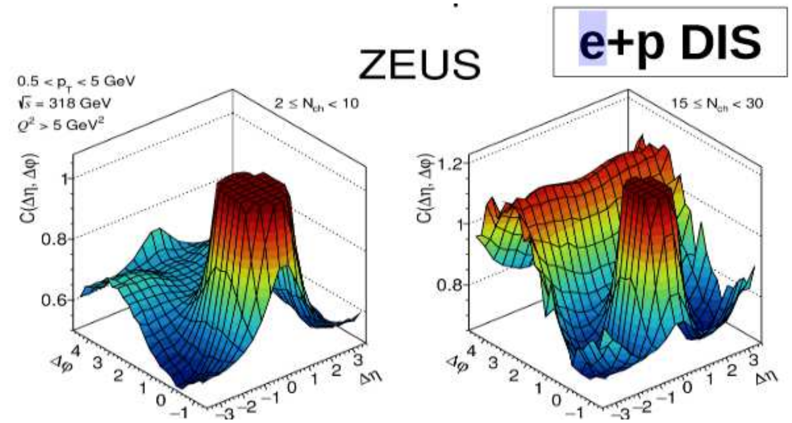


- $c_1\{2\}$ is better described by the ARIADNE generator.
- $c_2\{2\}$ is better described by the LEPTO generator.
- Neither model works well in the full kinematic interval (top right).
- The diffractive component in ARIADNE only slightly influences $c_n\{2\}$.
- Massless jets were reconstructed from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

Summary and conclusions



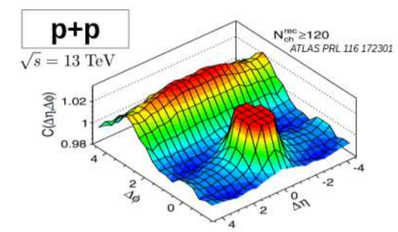


- **Two-particle azimuthal correlations in ep DIS collisions have been measured using ZEUS data from HERA, following a "HI-like" analysis approach.**

  Nice example for value of data preservation.

  (topic was not originally forseen)

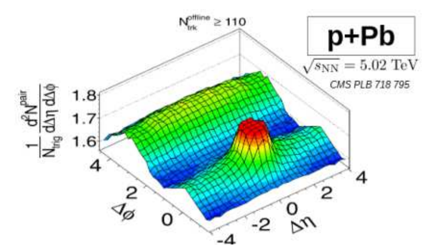
  data sets not (yet) openly available, but "low threshold" arrangements with ZEUS for access to data possible ("open ended" analysis with limited person power)

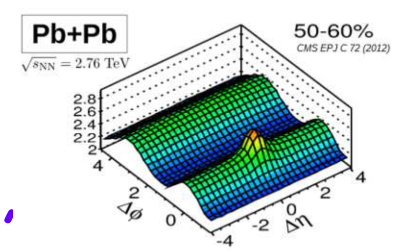


- **The data are reasonably described by existing particle physics MC models.**

  Different distributions are described best by different models, while none of the considered LO+PS models (ARIADNE dipole model, LEPTO + JETSET string model) describes the data everywhere.

  Room for improvement!



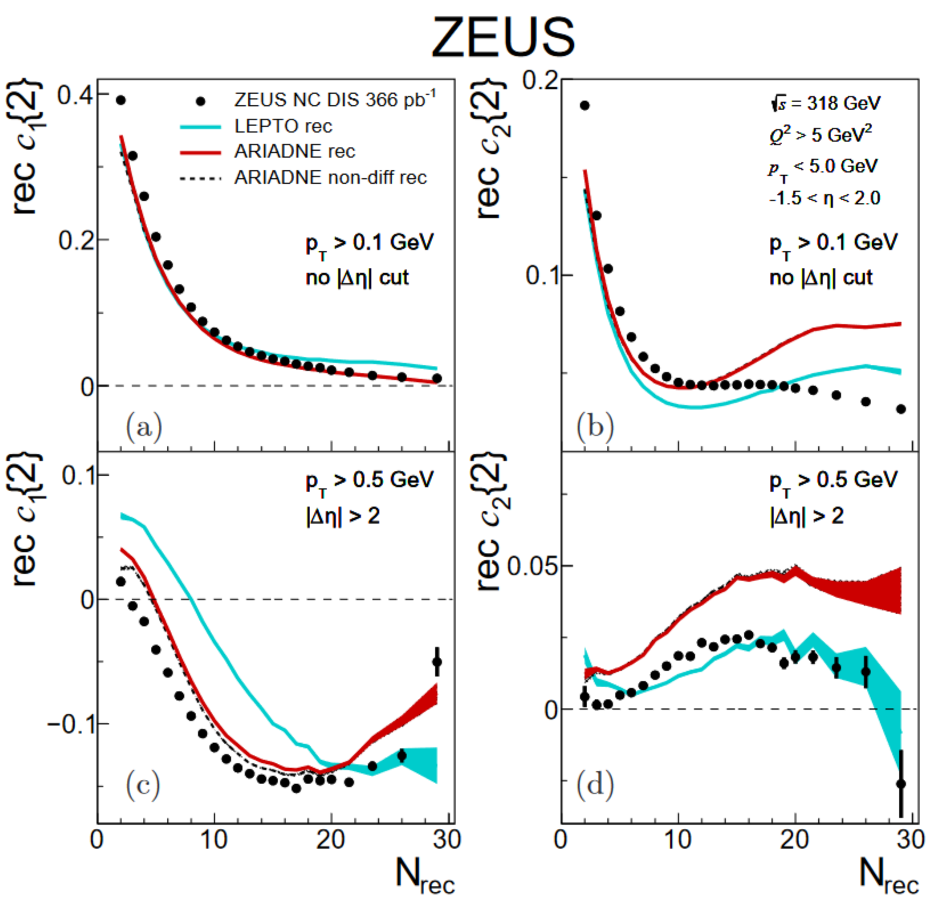


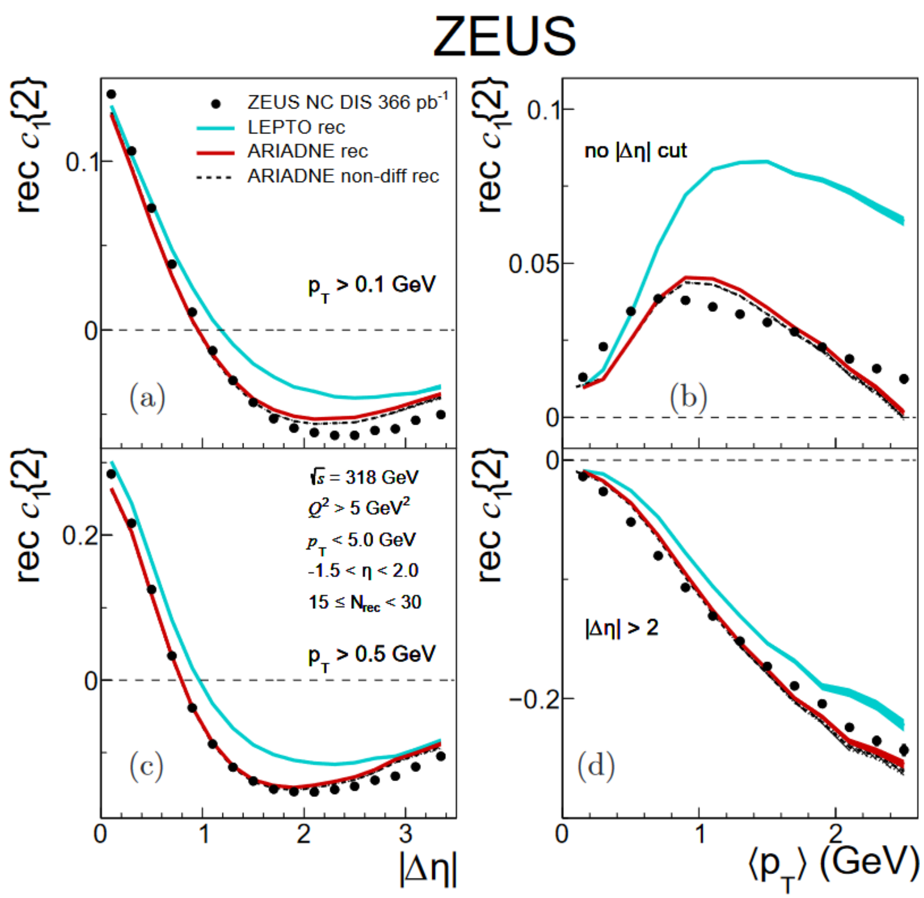
- **No evidence for the occurrence of heavy-ion-like hydrodynamic correlation effects** (on top of the correlations implemented in the MCs), **such as a double ridge, has been observed in ep DIS collisions**

Backup

Comparison to MC model predictions

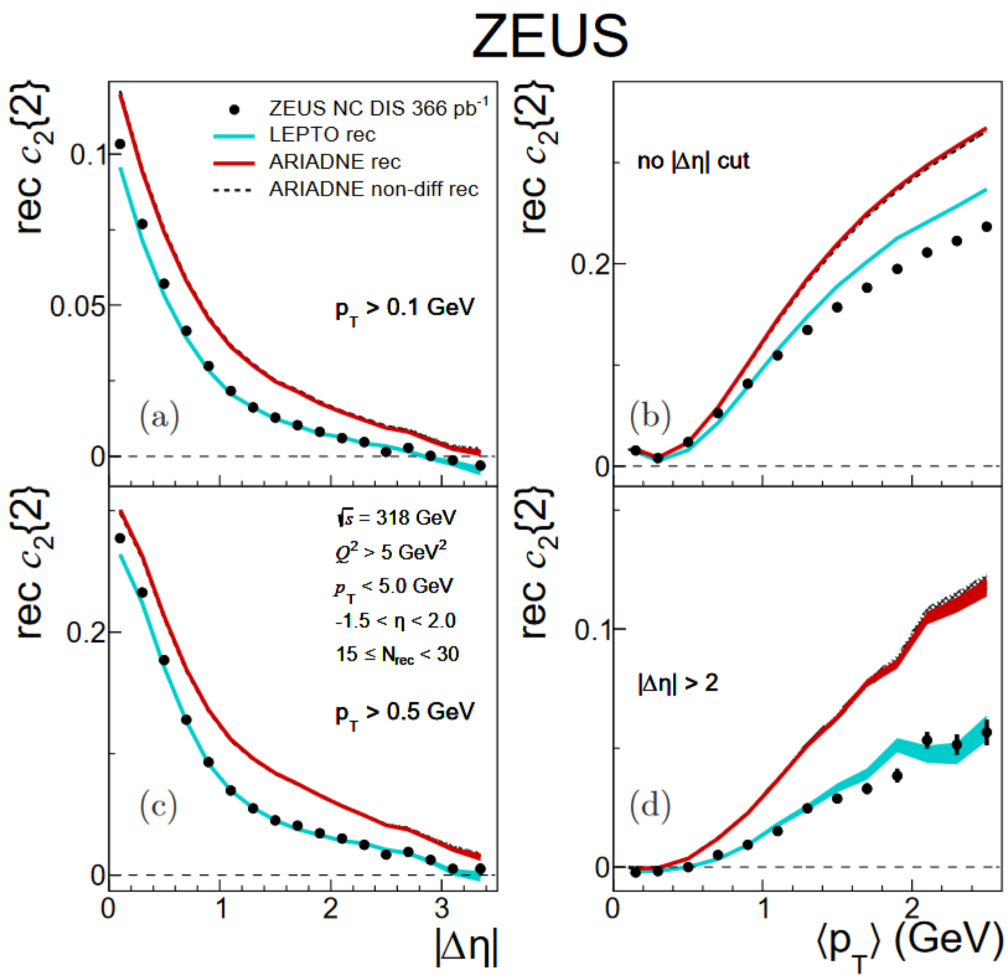
at reconstruction level (w/o systematic uncertainties)





Comparison to MC model predictions

at reconstruction level (w/o systematic uncertainties)



C. Catterall,

PhD thesis 1995

also studied

$\Delta\eta$ – $\Delta\phi$

correlations:

A "ridge" in momentum, azimuthally correlated with the struck quark, extends in η between the current and target peaks, evidence of QCD "string" interactions.

7.10 Correlations between $\Delta\eta$ and $\Delta\phi$

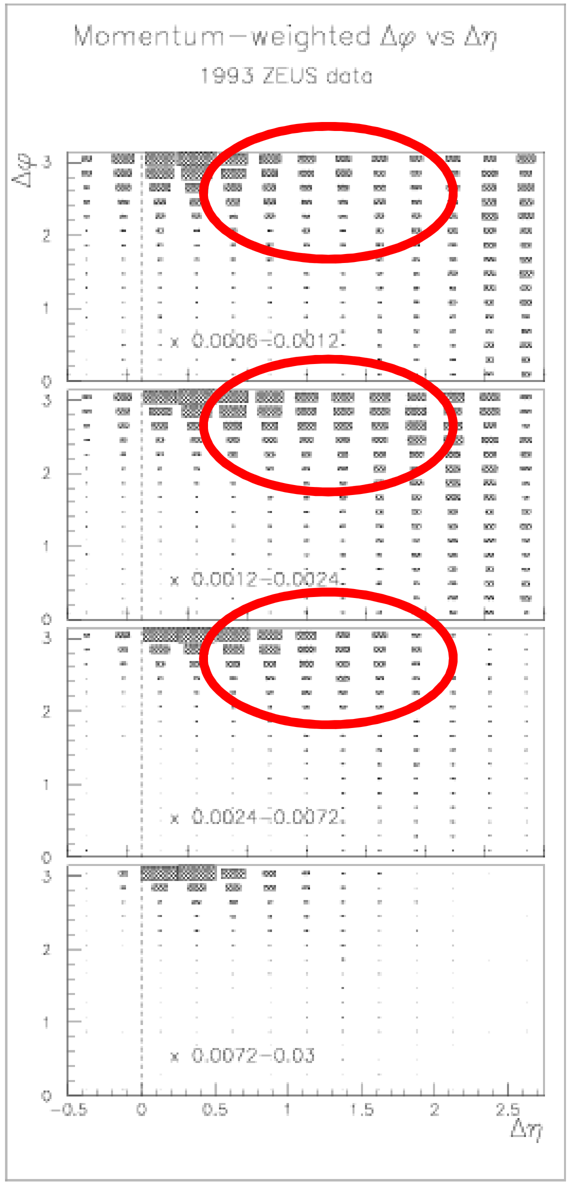


Figure 7.17: *Correlation between $\Delta\phi$ and $\Delta\eta$ in uncorrected ZEUS 1993 DIS data.*

Figure 7.17 shows the momentum flow in the $\Delta\phi$-$\Delta\eta$ plane, for 1993 ZEUS data which has not been corrected for detector effects. The most noticeable feature of these distributions is the correlation between $\Delta\eta$ and $\Delta\phi$ in the region of the current peak. Here, again, it is clear that the current peak is shifted forward from the QPM expectation of $\Delta\eta = 0$, but in azimuth occupies the expected region of $\Delta\phi = \pi$.

In the lower two bins of lower x, mometum flow associated with the remnant appears as a region of random azimuthal distribution at large $\Delta\eta$. For the higher x bins the remnant region is outside of the CTD acceptance.

It is interesting that a degree of correlation with $\Delta\phi = \pi$ extends forward well beyond the region of the current peak, and is discernable up to $\Delta\eta \approx 2$, which means that at two units of pseudorapidity forward from the nominal quark direction, the momentum flow is still affected in some way by the current.

This is perhaps the result of colour flow between the struck quark and the remnant, and of the forward pulling of the current peak, and is discussed further in the next chapter.

Also studied in momentum flow;
thesis C. Catterall, UCL 1995

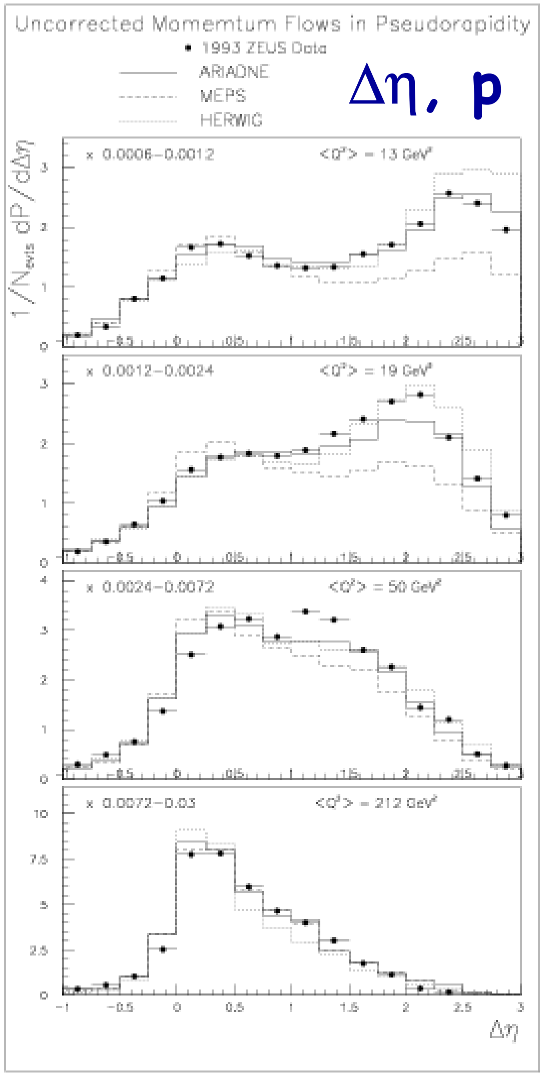


Figure 7.8: *Momentum flow versus* $\Delta\eta$ *showing 1993 ZEUS data and the Monte Carlo predictions of three theoretical models.*

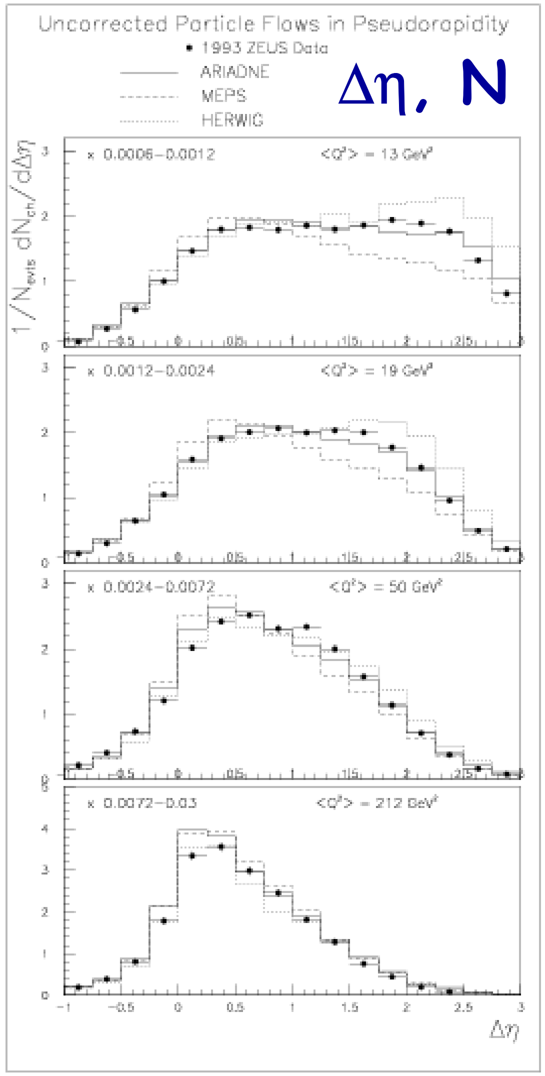


Figure 7.9: *Particle flow versus* $\Delta\eta$*, showing 1993 ZEUS data and the Monte Carlo predictions of three theoretical models.*

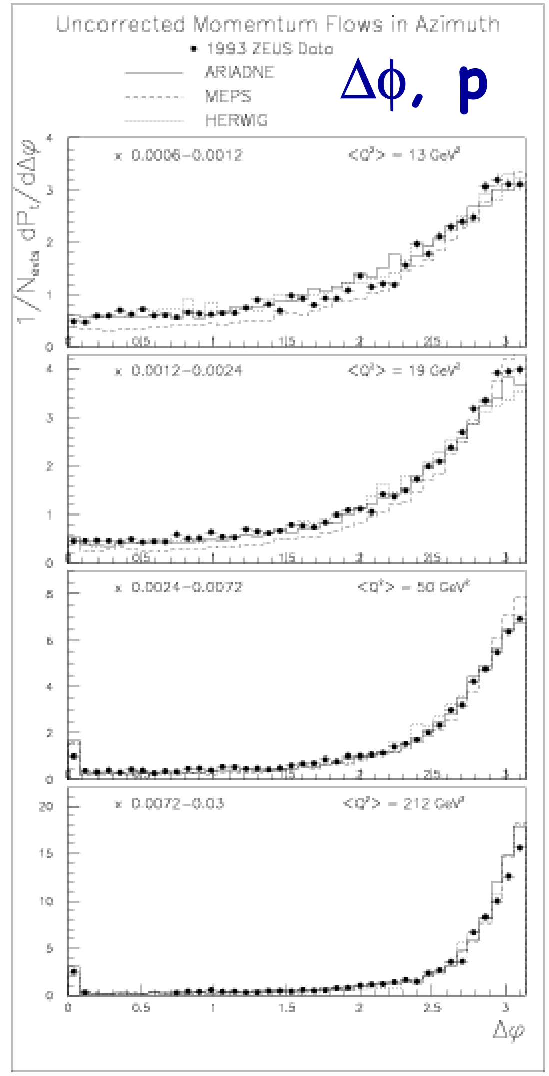


Figure 7.16: *Momentum flow versus* $\Delta\phi$*, (excluding matched electron tracks) showing 1993 ZEUS data and Monte Carlo predictions.*