Azimuthal correlations as a probe of collective behaviour in photoproduction and Deep Inelastic Scattering at HERA

JHEP 12 (2021) 102, arXiv:2106.12377; JHEP 04 (2020) 070, arXiv:1912.07431

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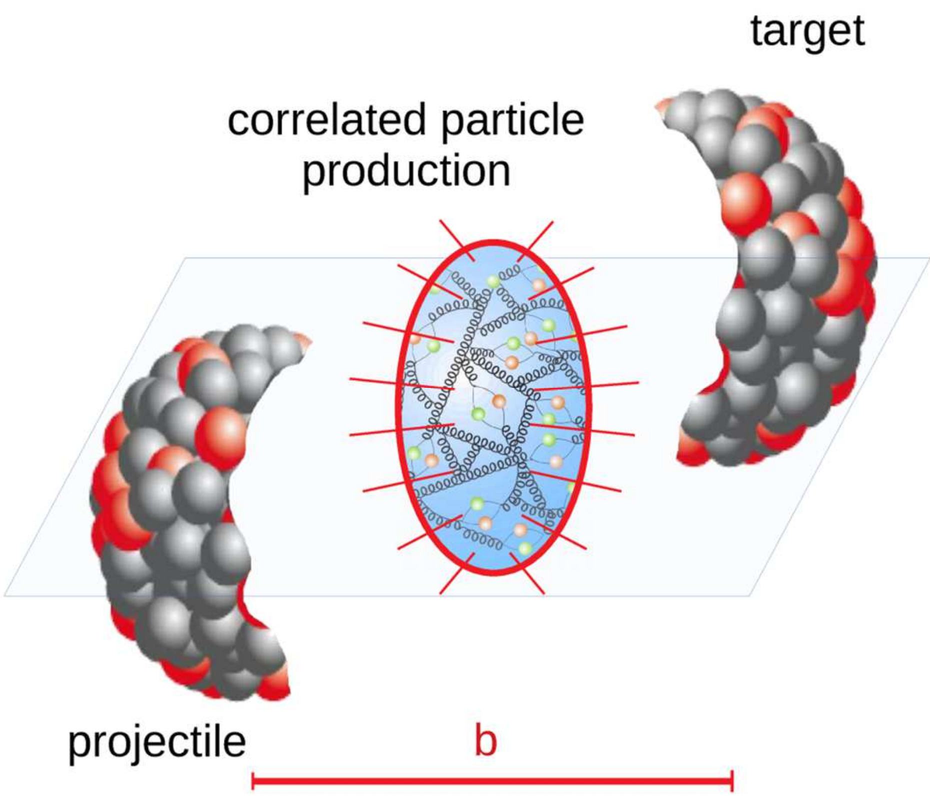
for the ZEUS Collaboration

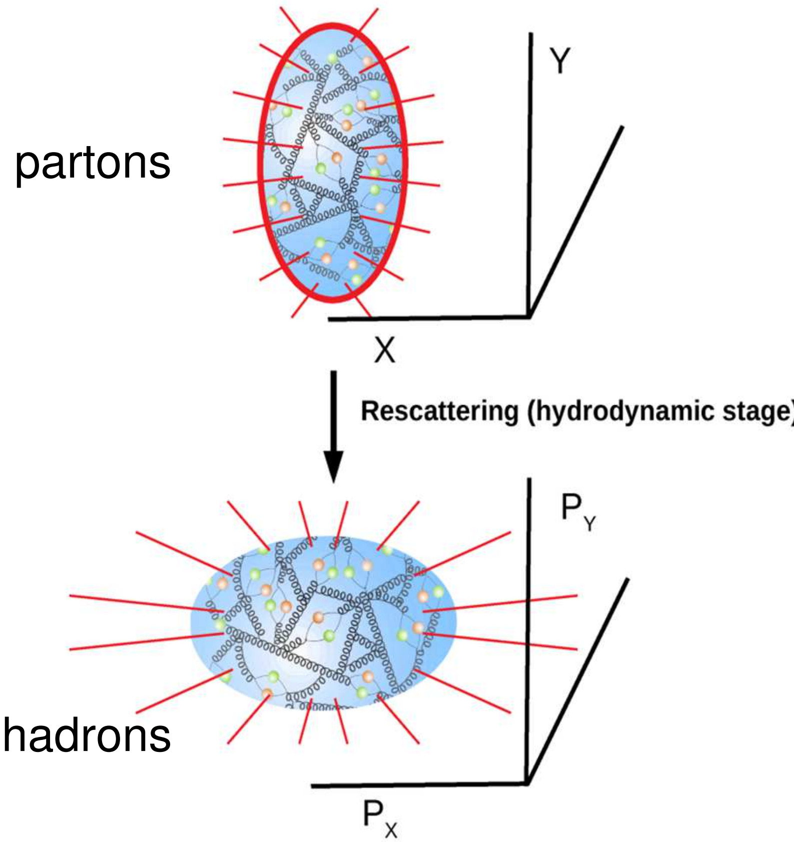
DIS 2022,
Santiago de Compostela, Spain,
May 3, 2022

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

Long range collective effects in Heavy Ion collisions

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





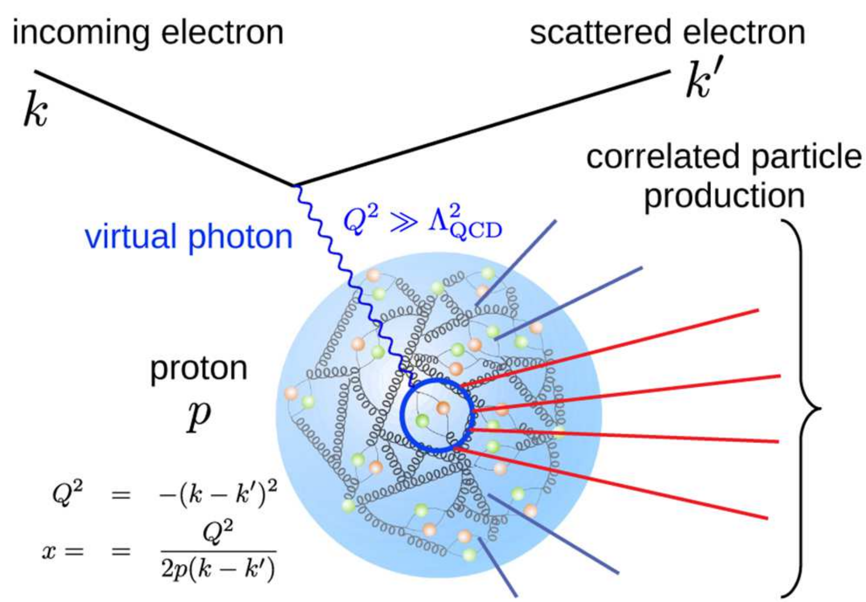
long range correlations in large hadron multiplicity final states keep a "memory" of this evolution

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 pA, pp, γp, 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.



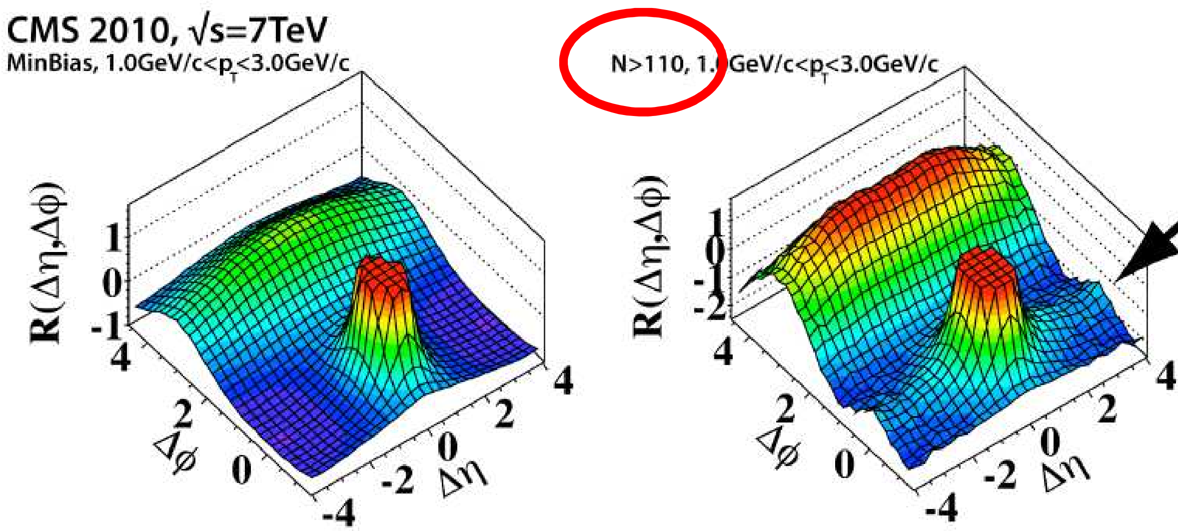
In photoproduction: ~ $1/\Lambda_{QCD}^2$

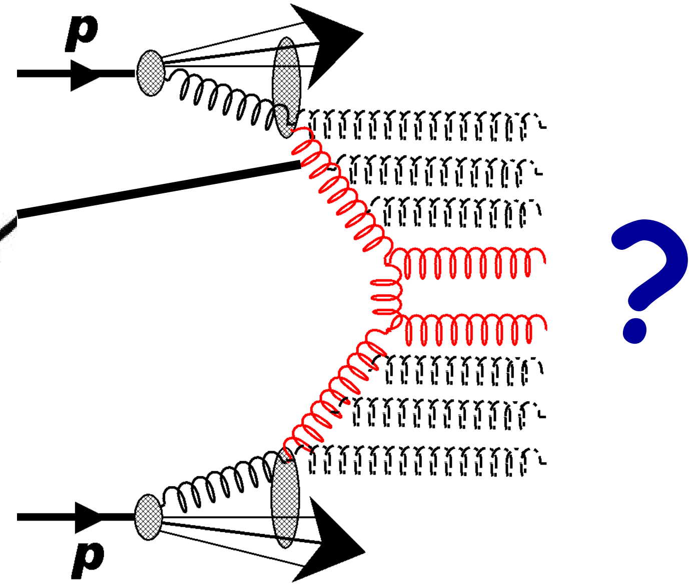
Do "conventional" particle physics models describe the observed correlations?

Long range two-particle correlations in pp in CMS

most-cited non-Higgs ATLAS/CMS physics result:
(rivalling LHCb pentaquarks and flavour anomalies)

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?

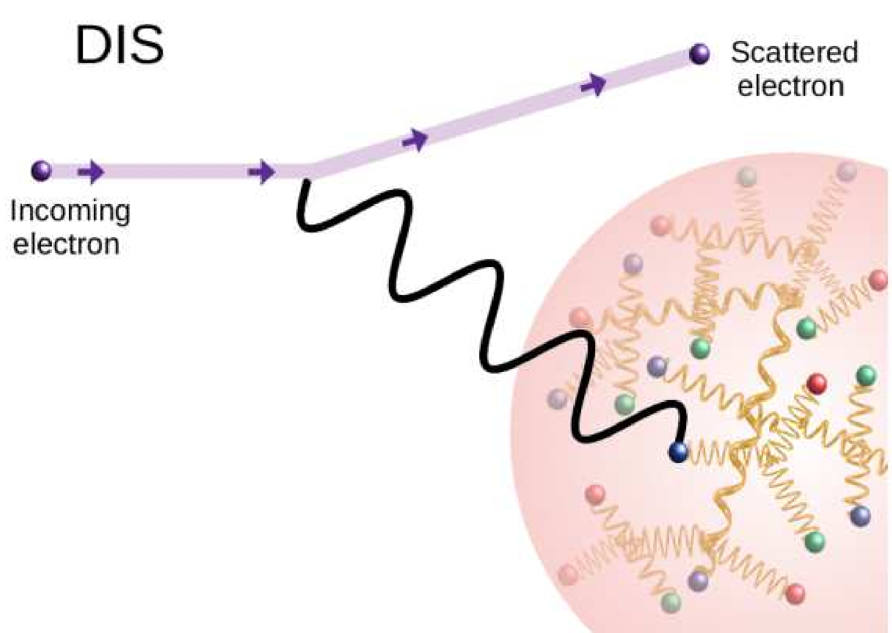
Deep Inelastic Scattering vs. Photoproduction

DIS (and direct photoproduction):

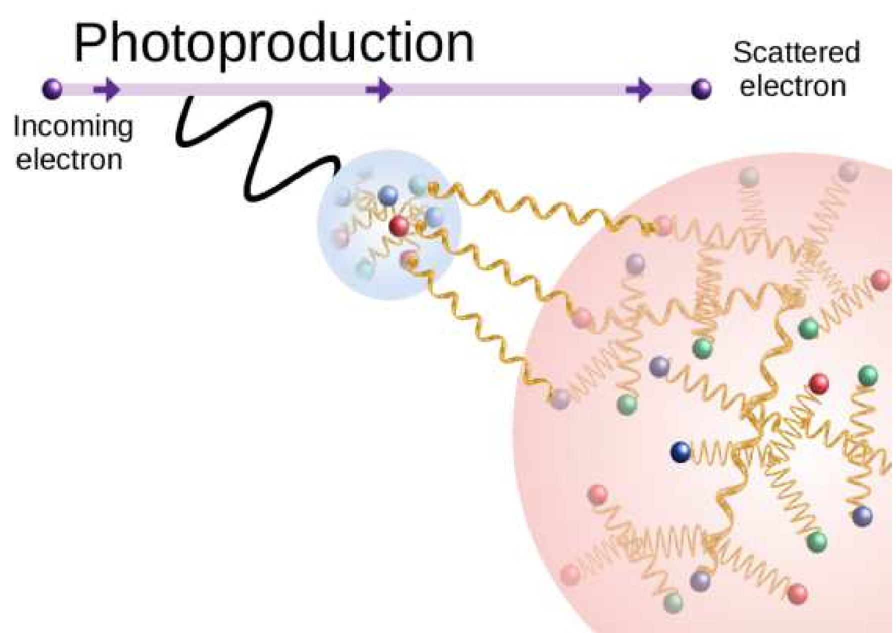
"small" virtual photon hits single quark

Photoproduction (γp) (~90% "resolved" at low scales):

"large" quasi-real photon gets "resolved" into partons and can make "collective" interactions



(a) *Neutral current deep inelastic scattering.*

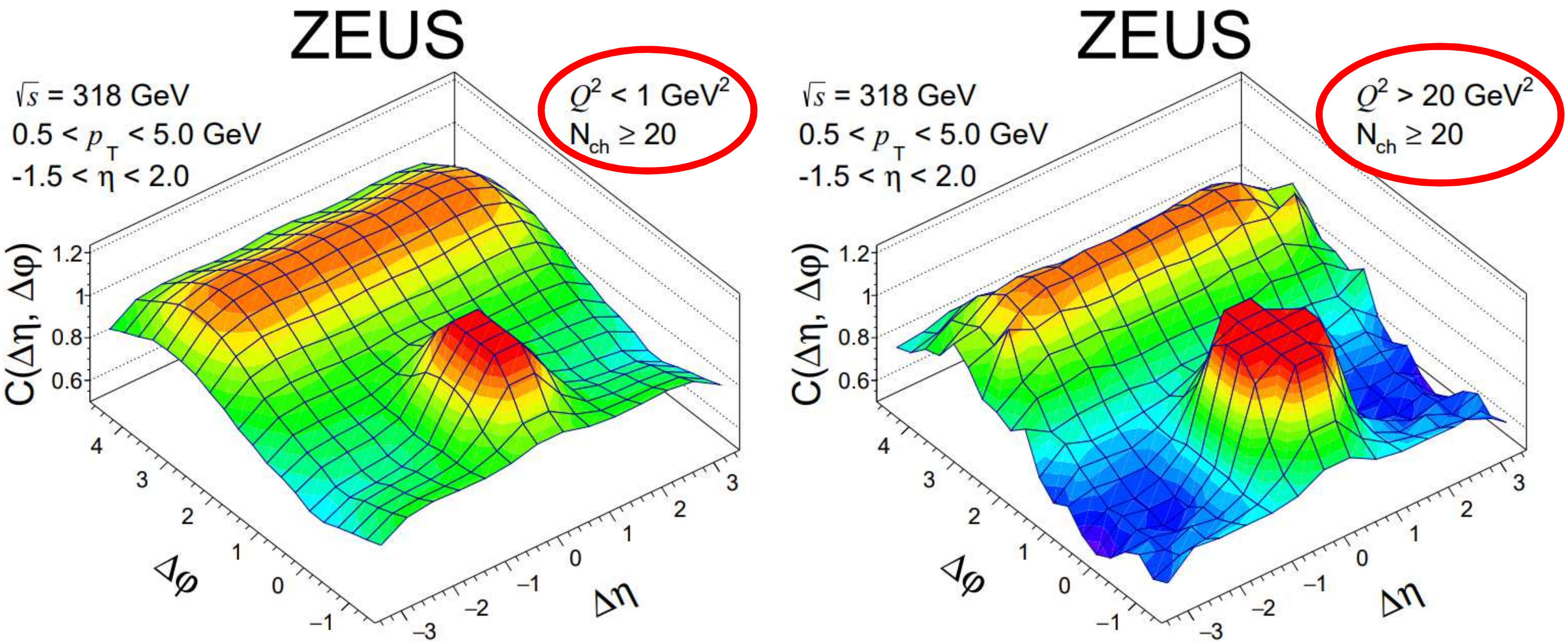


(b) *Resolved photoproduction.*

Long range two-particle correlations in $\gamma p/ep$ in ZEUS

JHEP 12 (2021) 102, arXiv:2106.12377

Photoproduction: **DIS:** (see also JHEP 04 (2020) 070)



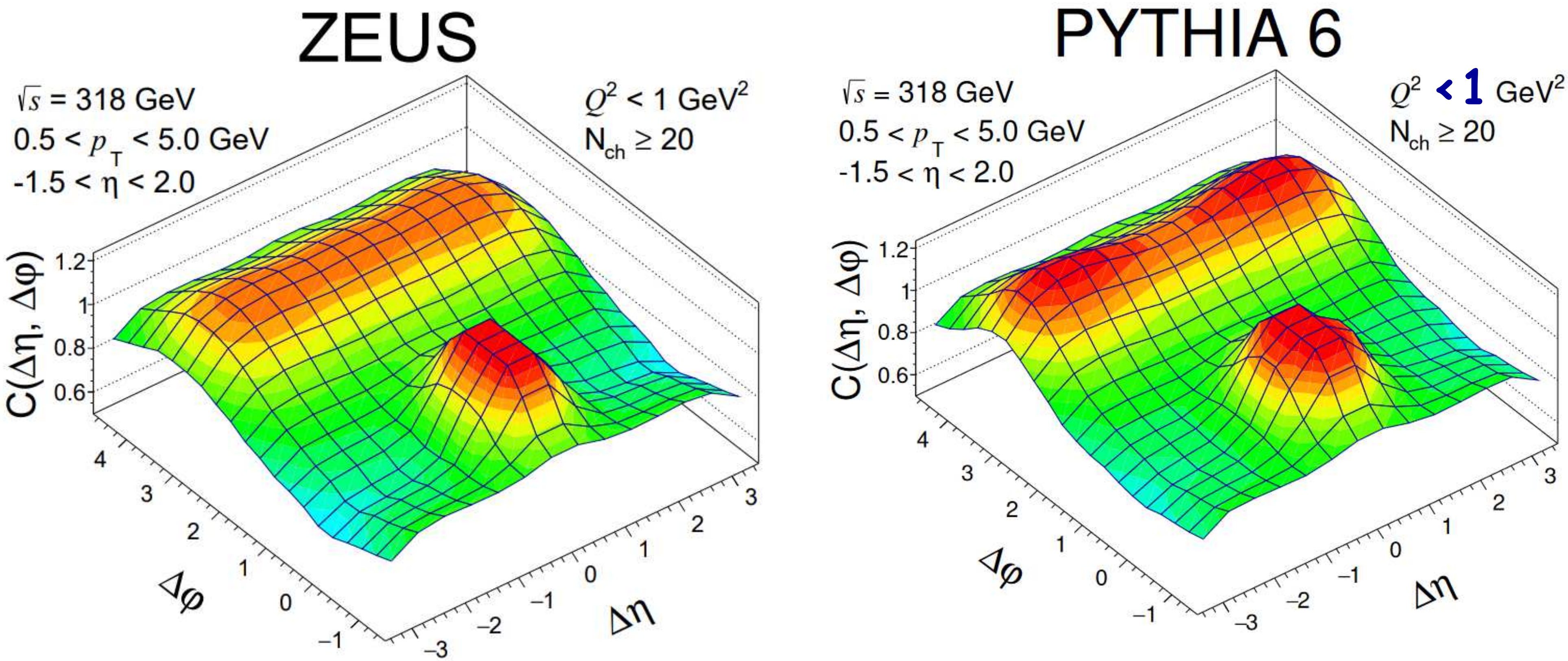
No evidence for "hydrodynamic" long range correlations at highest statistically accessible multiplicities N_{ch}~20-40. Other correlations?

Long range two-particle correlations in γp/ep in ZEUS

JHEP 12 (2021) 102, arXiv:2106.12377

+ additional material

Photoproduction:



All measurements **fully corrected to true particle level !**

Observed correlations quite reasonably **described by PYTHIA** (LO+PS)

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

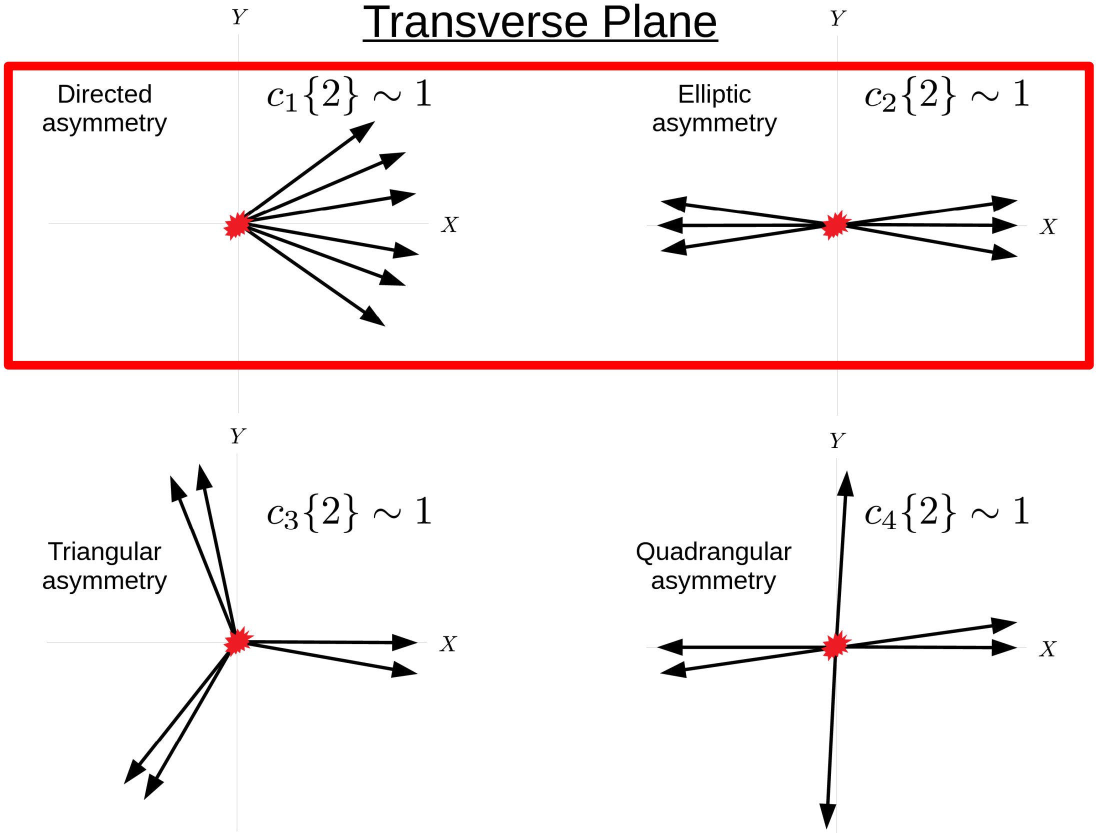
cumulants

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

double average track pairs/events

DIS electron excluded

Transverse Plane



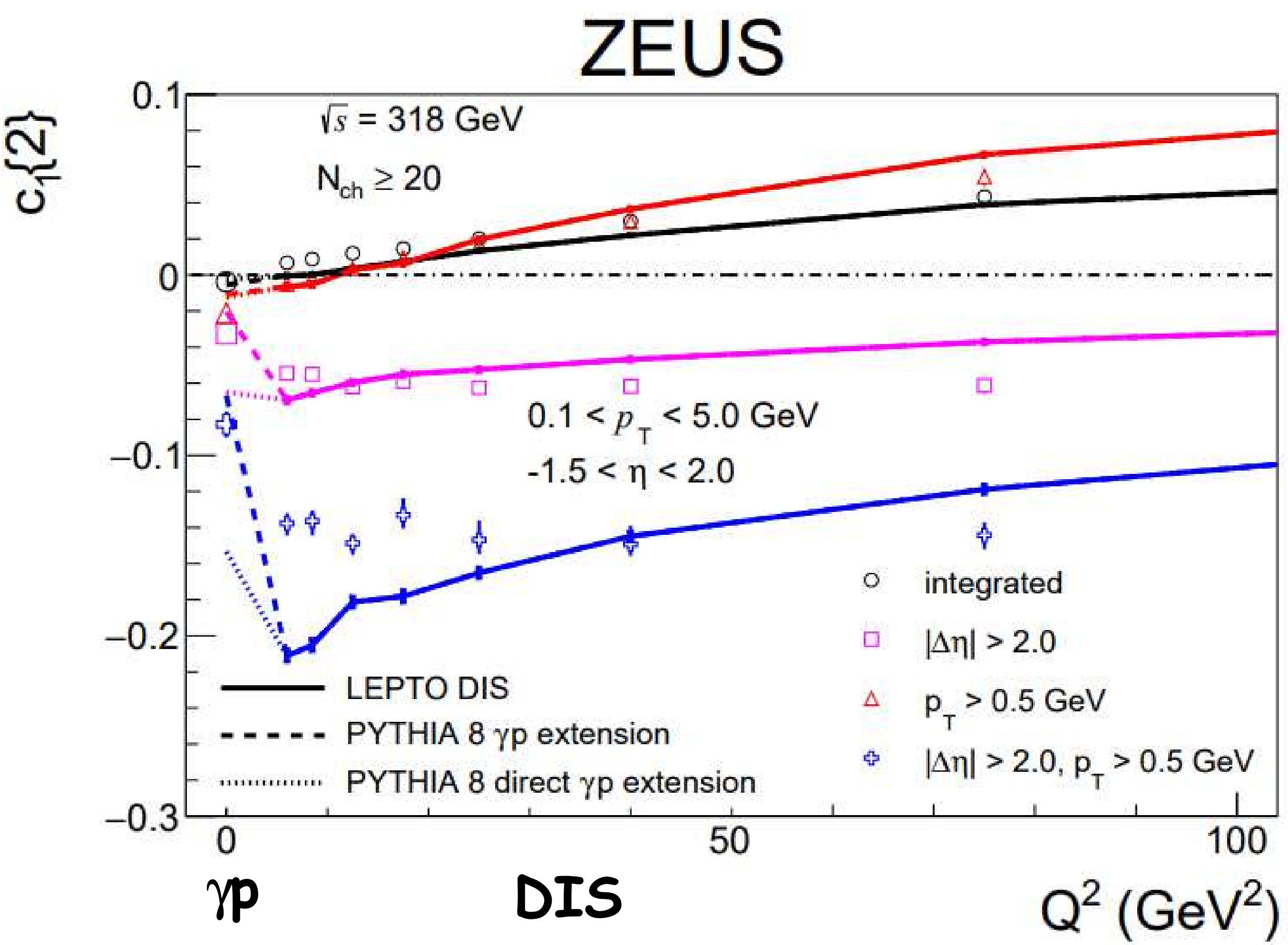
fully corrected
for single and correlated two-particle reconstruction efficiencies

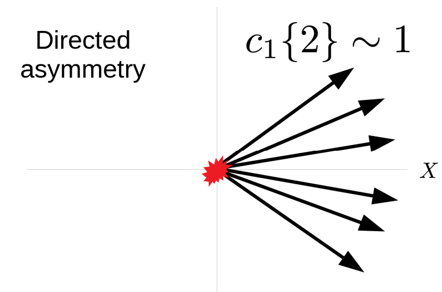
$$c_n\{2\} = \sum_{e}^{N_{\rm ev}} \left[\sum_{i,j>i}^{N_{\rm rec}} w_{ij} \cos\left[n(\varphi_i - \varphi_j)\right] \right]_e \Bigg/ \sum_{e}^{N_{\rm ev}} \left[\sum_{i,j>i}^{N_{\rm rec}} w_{ij} \right]_e$$

Azimuthal correlations $c_1\{2\}$ versus Q^2

"directed" correlations

JHEP 12 (2021) 102, arXiv:2106.12377





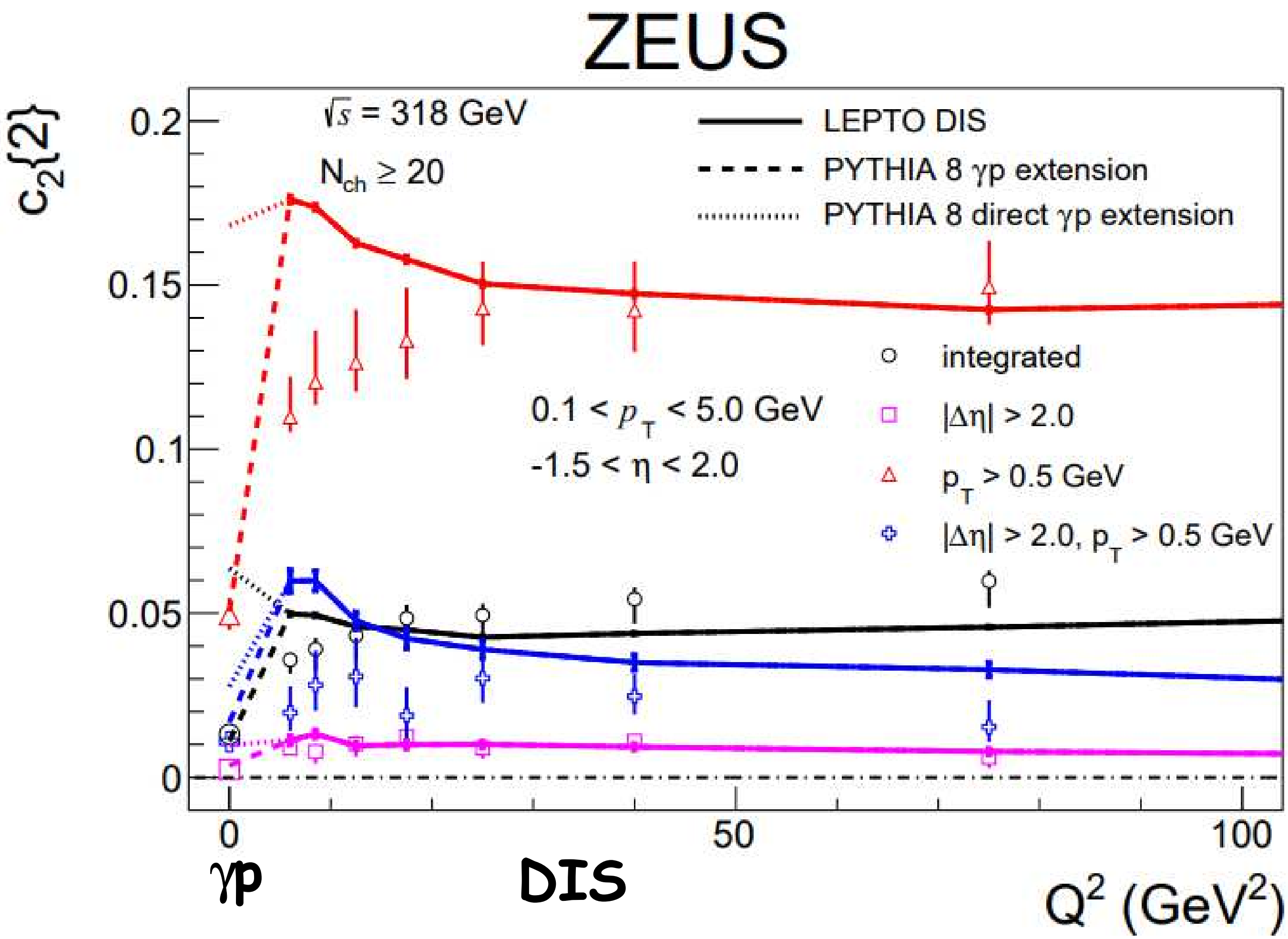
qualitative differences photoproduction -> DIS reasonably described by MC models

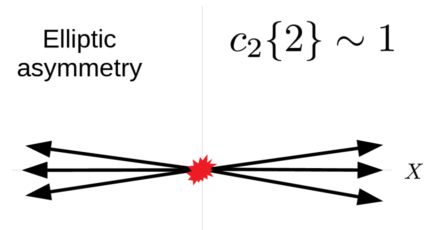
step at Q^2>0 GeV^2 due to **transition**
"resolved" -> "direct"
(99%) (100%)?

Azimuthal correlations $c_2\{2\}$ versus Q^2

"elliptic" correlations

JHEP 12 (2021) 102, arXiv:2106.12377





qualitative differences photoproduction -> DIS reasonably described by MC models

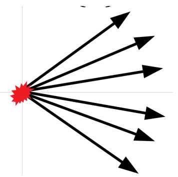
threshold at Q^2>0 GeV^2 due to **transition** **"resolved" -> "direct"** **(99%)** **(100%)?**

Azimuthal correlations $c_1\{2\}$ and $c_2\{2\}$ vs. $|\Delta\eta|$

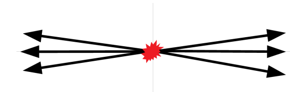
Photoproduction:

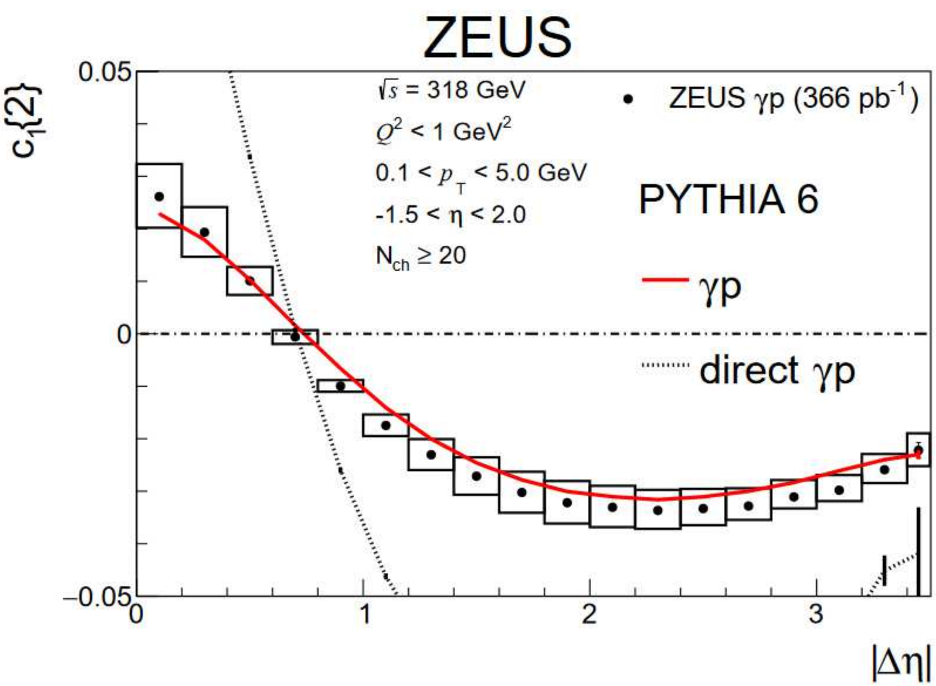
JHEP 12 (2021) 102, arXiv:2106.12377

"directed" correlations

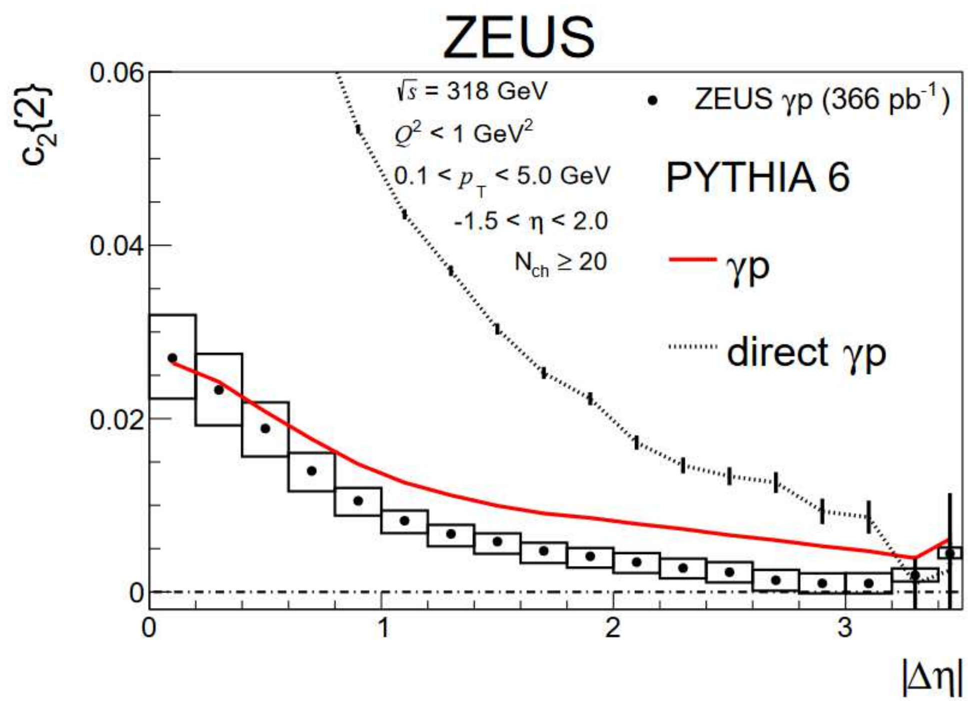


"elliptic" correlations





(a) $c_1\{2\}$ versus $|\Delta\eta|$.

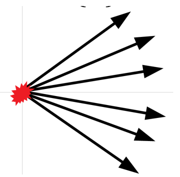


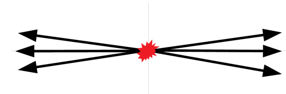
(b) $c_2\{2\}$ versus $|\Delta\eta|$.

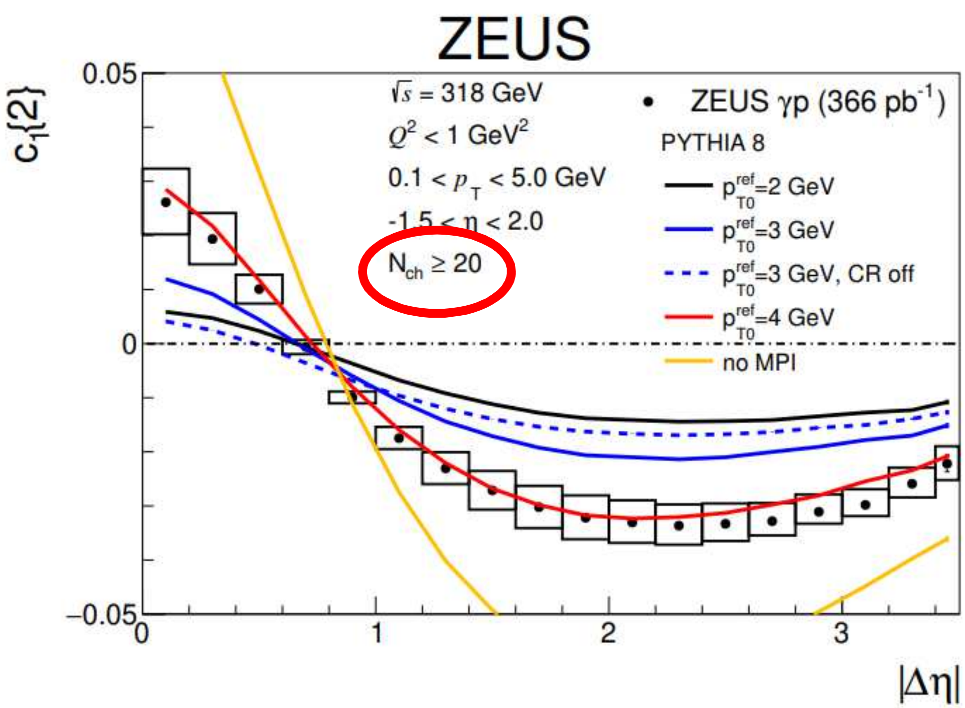
Data fully corrected to truth level, including all systematics. Reasonably described by "default" PYTHIA-6 model used for efficiency corrections

Azimuthal correlations $c_1\{2\}$ and $c_2\{2\}$ vs. $|\Delta\eta|$

JHEP 12 (2021) 102, arXiv:2106.12377

"directed" correlations 

"elliptic" correlations 



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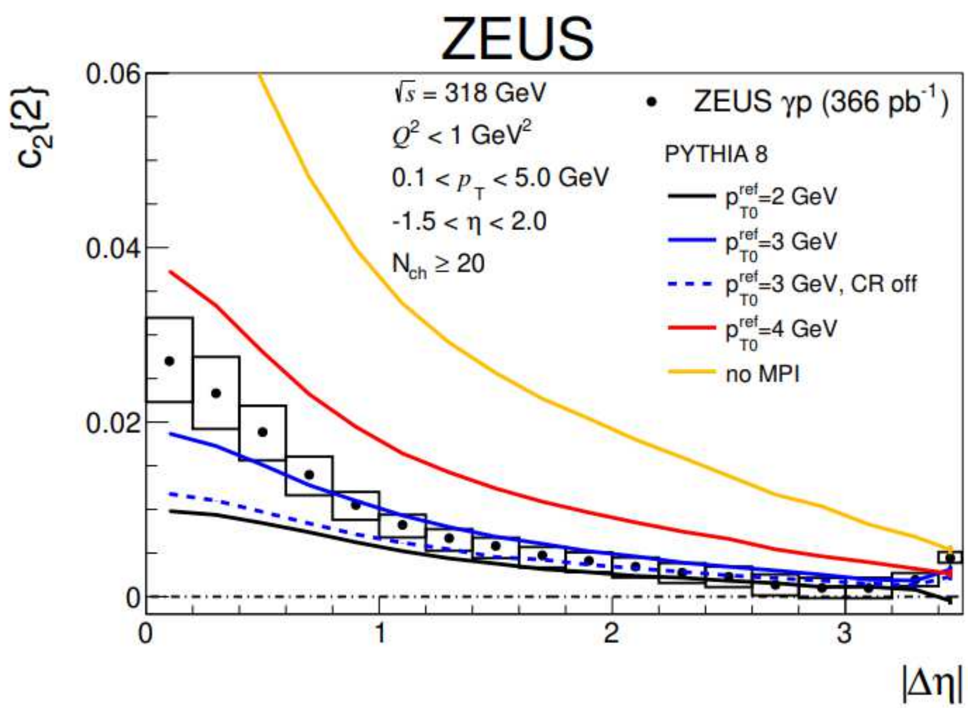


(b) $c_2\{2\}$ versus $|\Delta\eta|$.

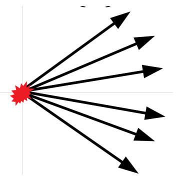
reasonably described by PYTHIA-8 models with p_{T0} = 3±1 GeV, governing multi-parton interactions (2-8 parton interactions)

Four-particle azim. corr. $c_1\{4\}$ and $c_2\{4\}$ vs. p_T

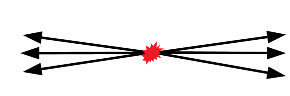
Four-particle cumulants:

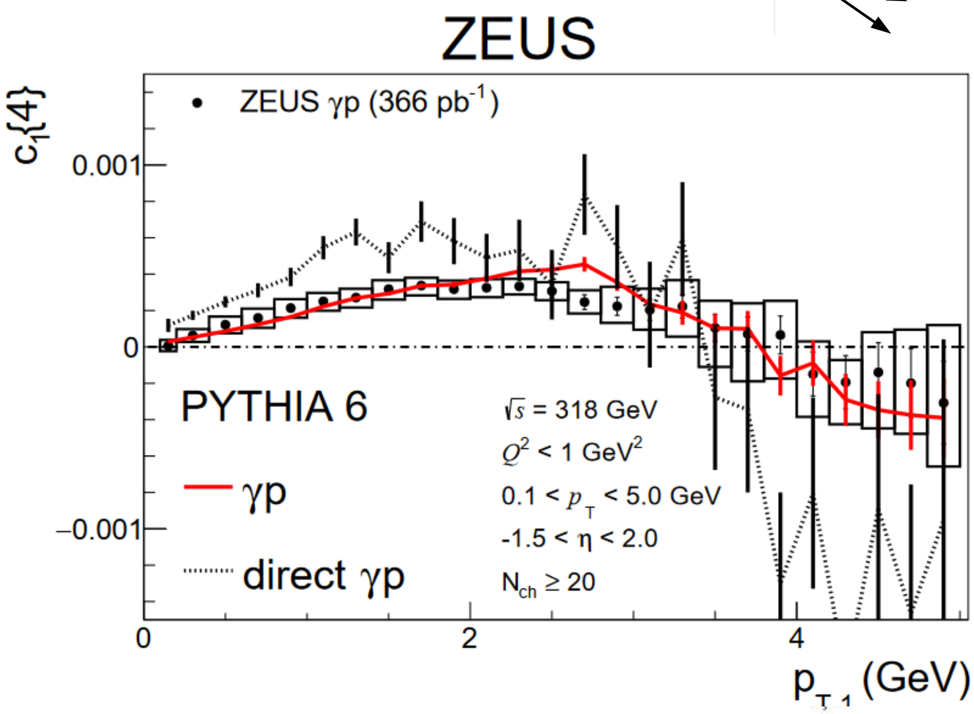
JHEP 12 (2021) 102, arXiv:2106.12377

"directed" correlations

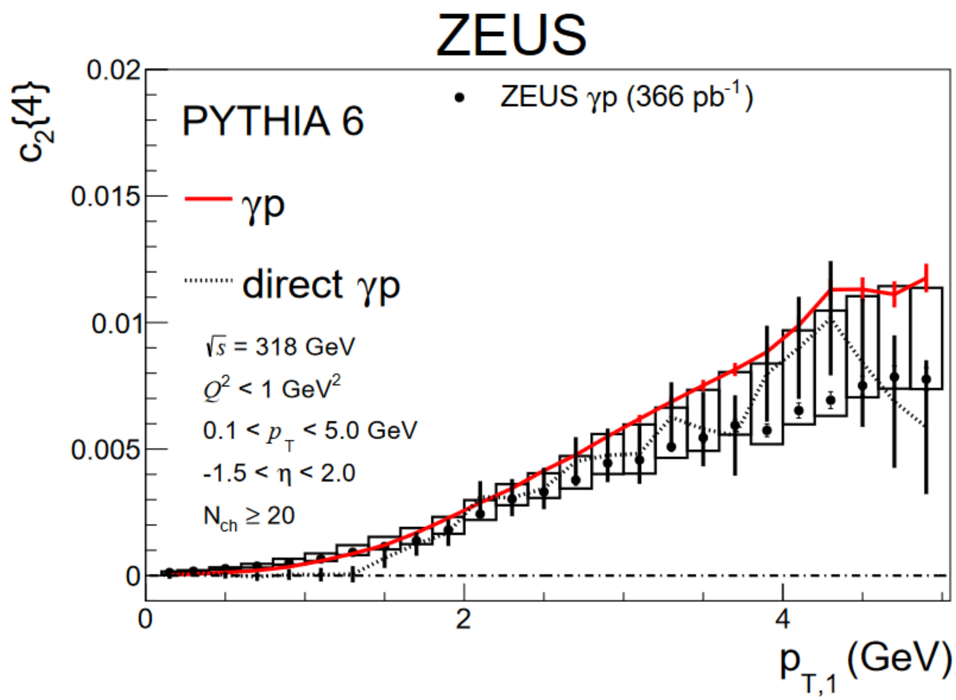


"elliptic" correlations





(a) $c_1\{4\}$ versus $p_{T,1}$.



(b) $c_2\{4\}$ versus $p_{T,1}$.

reasonably described by default PYTHIA-6 model used for efficiency corrections

Four-particle azim. corr. $c_1\{4\}$ and $c_2\{4\}$ vs. p_T

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JHEP 12 (2021) 102, arXiv:2106.12377

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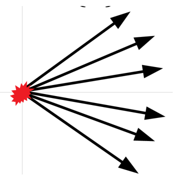
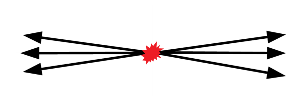
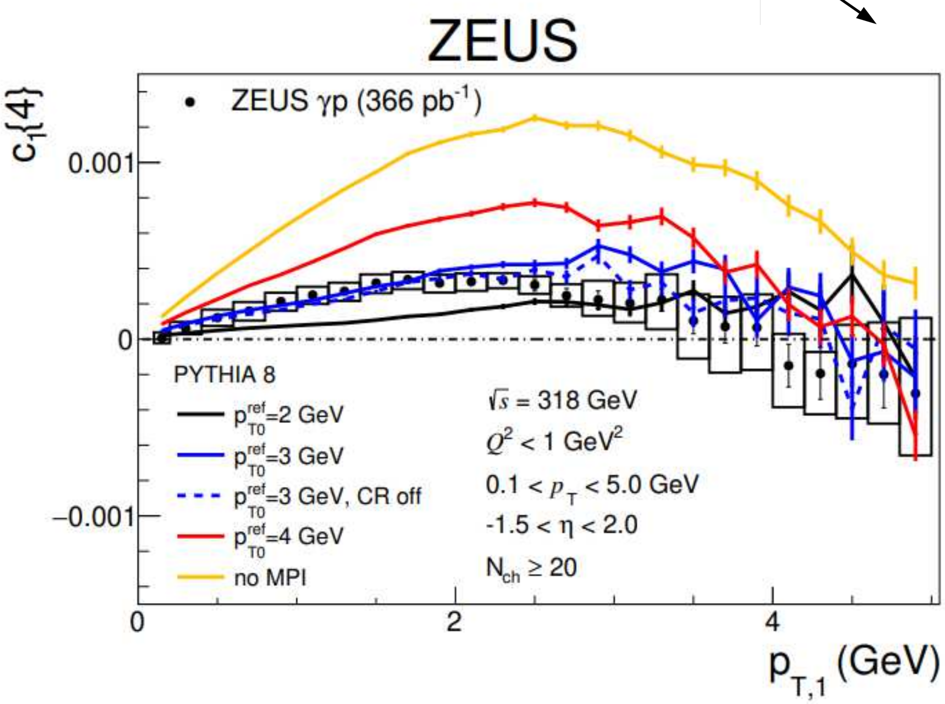


"elliptic" correlations





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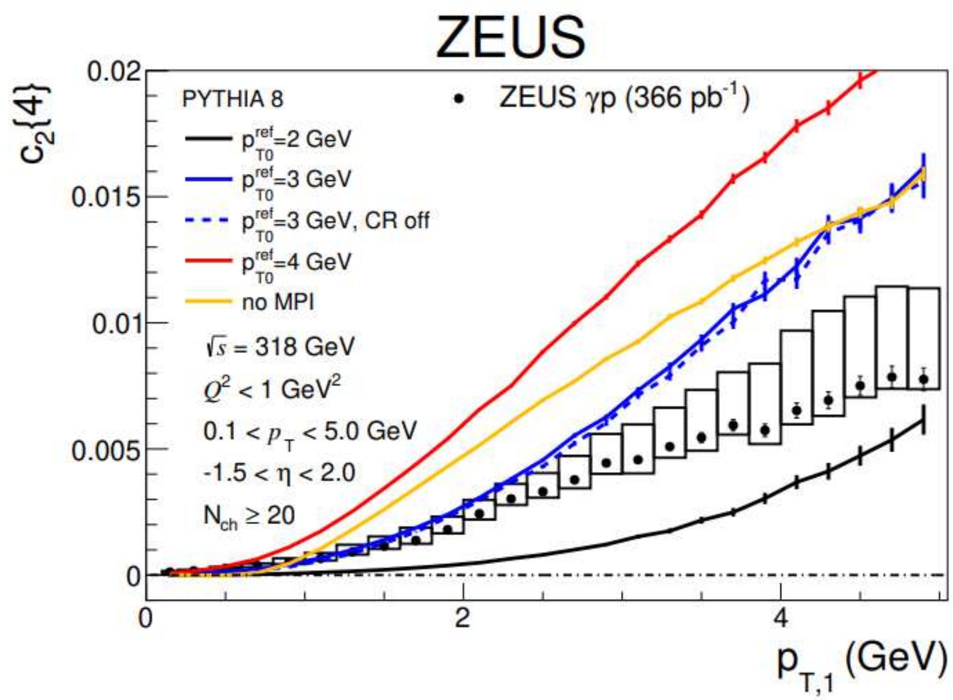


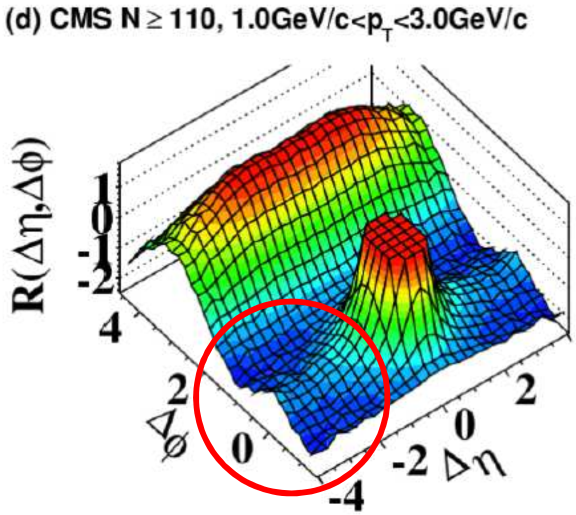
(b) $c_2\{4\}$ versus $p_{T,1}$.

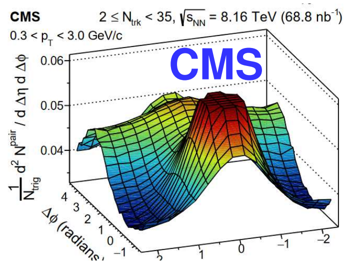
reasonably described by PYTHIA-8 models with p_{T0} = 3±1 GeV , governing multi-parton interactions (2-8 parton interactions)

example candidate for cross-experiment archived/open data analysis: "Ridge" in long range particle correlations

unexpected „Ridge" observed in CMS 2010 pp data

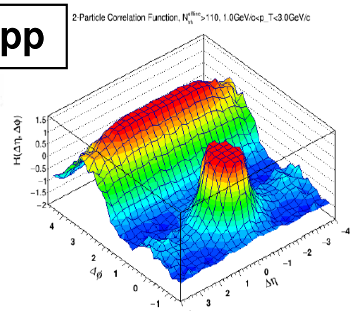
CMS paper
JHEP 1009 (2010) 091



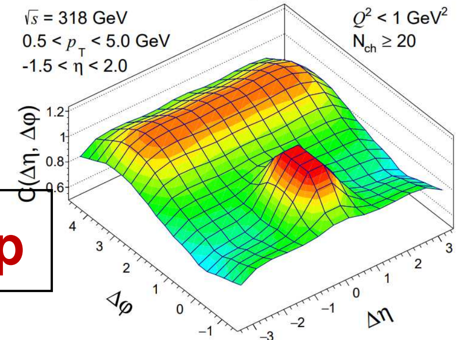


CMS Open Data
(summer student on office desktop)

pp

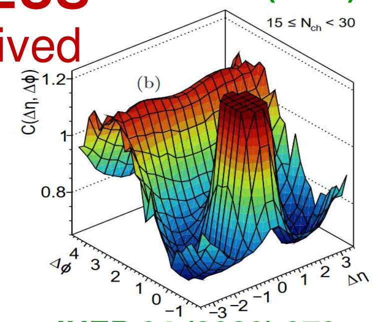


γp



ZEUS archived data

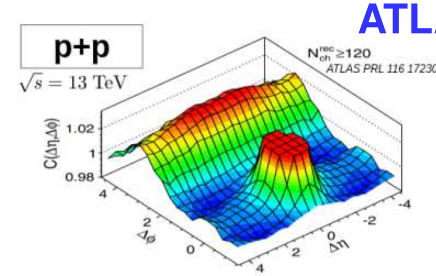
JHEP 12 (2021) 102



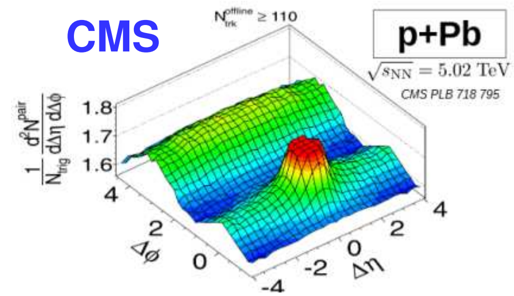
JHEP 04 (2020) 070

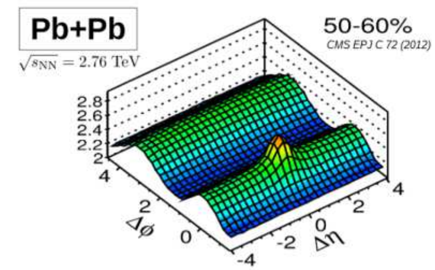
not complete!

ATLAS



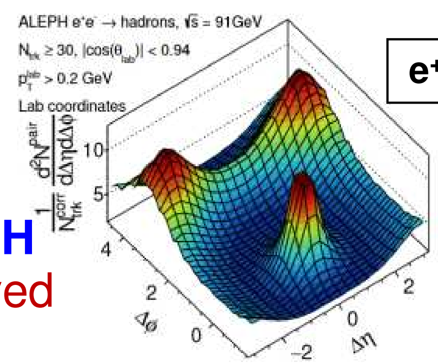
CMS





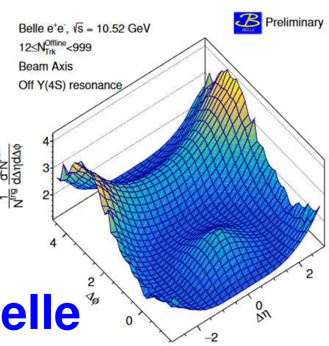
CMS Open Data available

e⁺e⁻



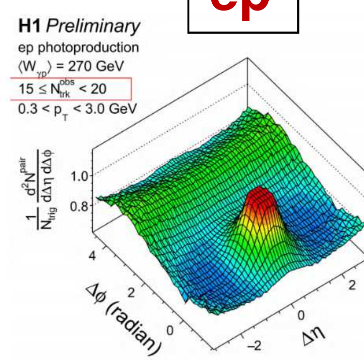
ALEPH archived data

Phys. Rev. Lett. 123 (2019) 212002



Belle

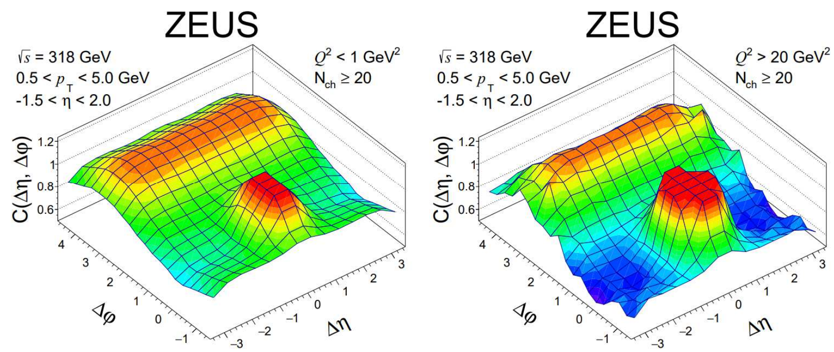
ep



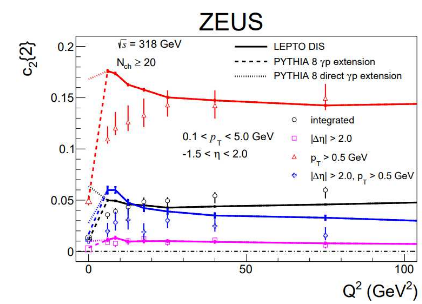
H1 archived data

Summary and conclusions

- Two- and four-particle azimuthal correlations in "high" multiplicity γp and ep collisions were measured using ZEUS data from HERA, following a "HI-like" analysis approach.
  Nice example for value of data preservation.
  (topic was not originally forseen)



- The data are reasonably described by existing particle physics MC models. The biggest qualitative differences between γp and DIS are confirmed to arise from resolved photon contributions for which multiparton interactions (PYTHIA model) seem essential.
  Room for further model improvements!



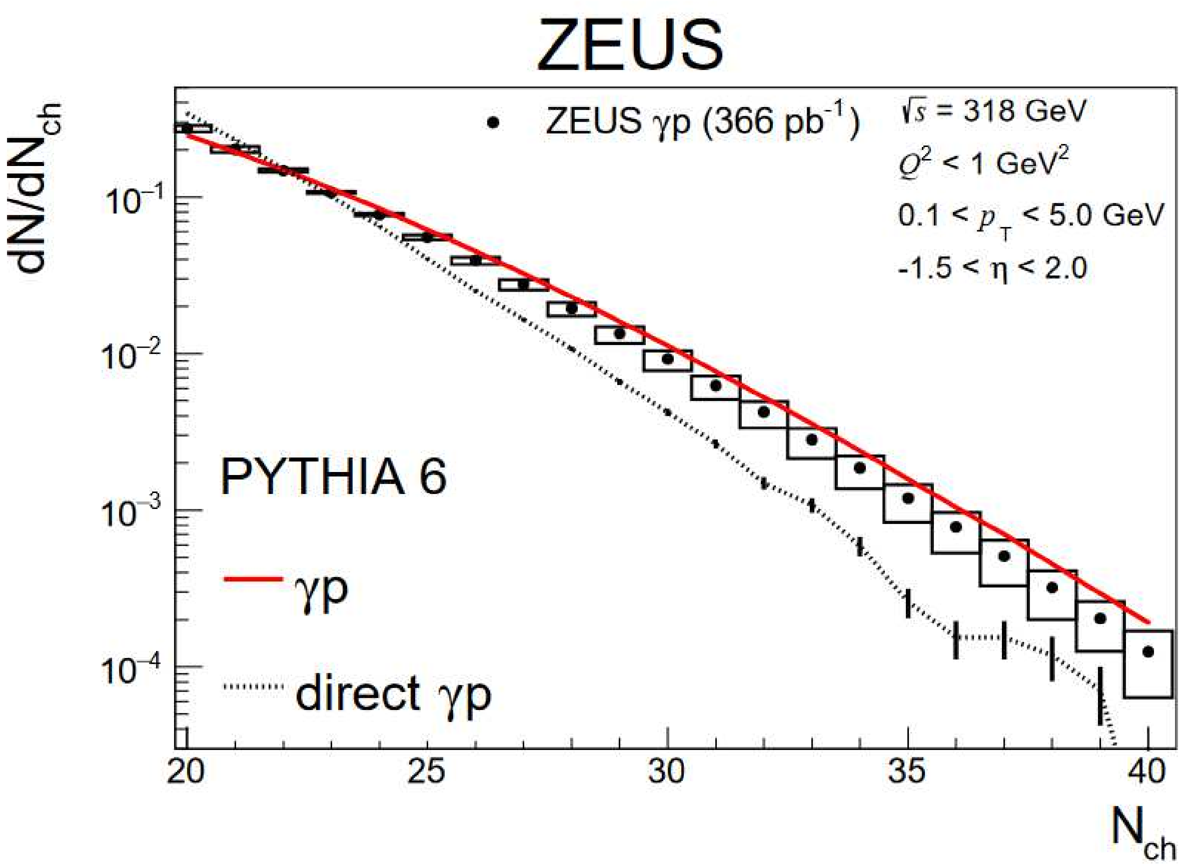
- No evidence for the occurrence of heavy-ion-like hydrodynamic correlation effects (on top of the correlations implemented in the MCs), such as a double ridge structure, has been observed in γp and ep collisions, but multiplicities remain below those achieved in pp collisions

Backup

Multiplicity distribution in photoproduction

JHEP 12 (2021) 102, arXiv:2106.12377

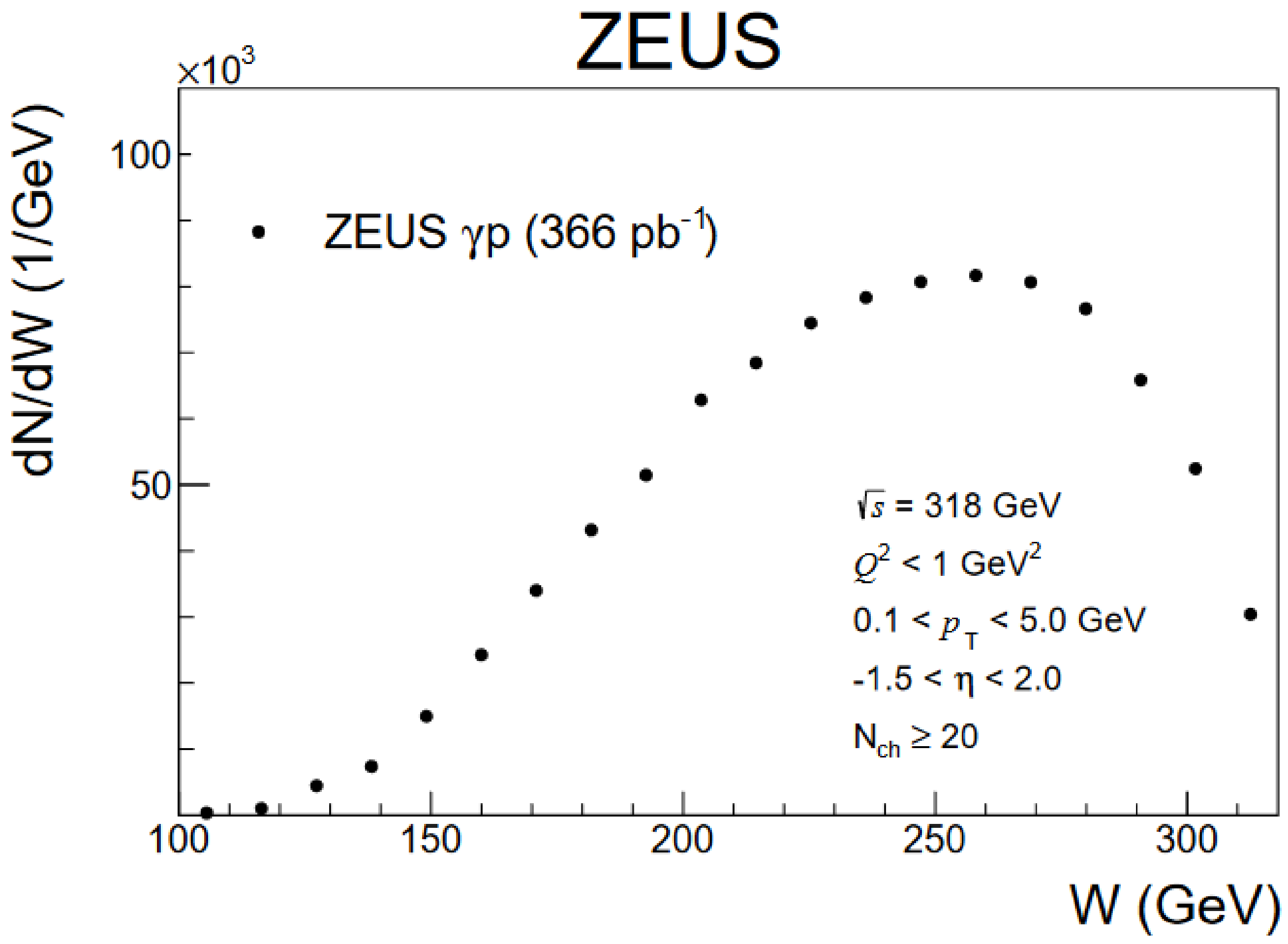
fully corrected to gen level, full systematics



W distribution for photoproduction w. kin. cuts

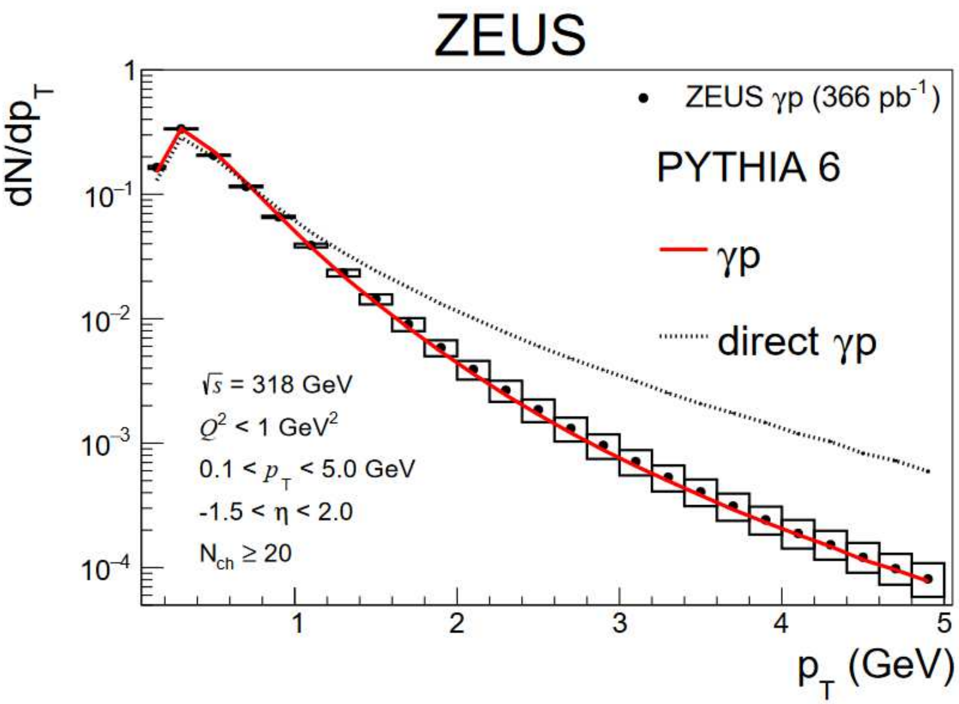
JHEP 12 (2021) 102, arXiv:2106.12377, additional material

fully corrected to gen level

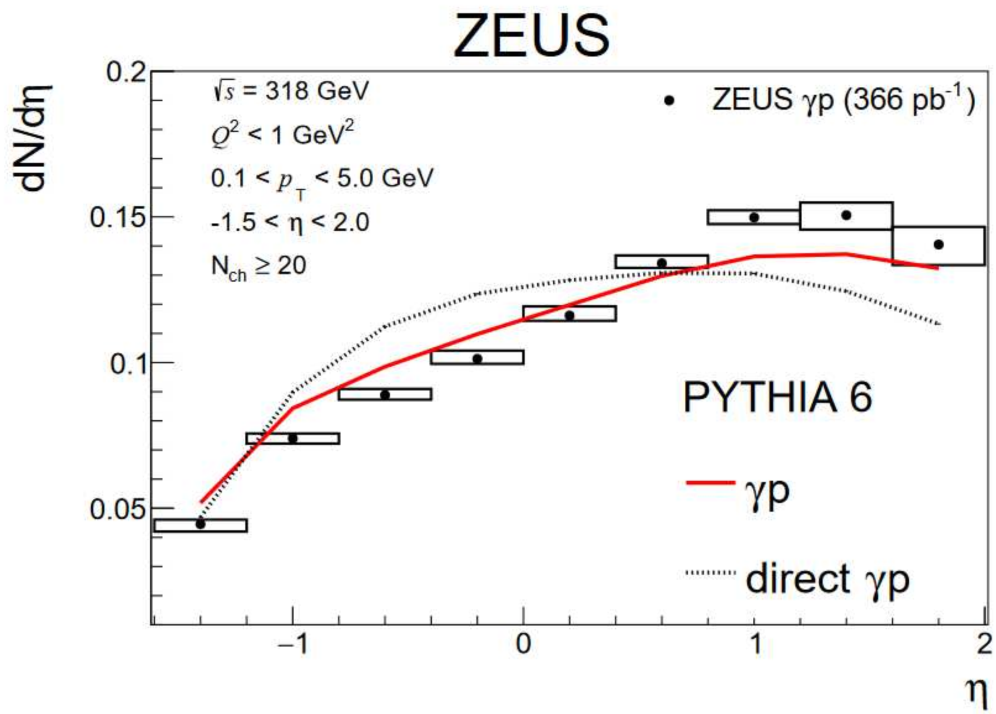


p_T and $|\Delta\eta|$ distributions in photoproduction

JHEP 12 (2021) 102, arXiv:2106.12377



(a) $c_1\{2\}$ versus $|\Delta\eta|$.

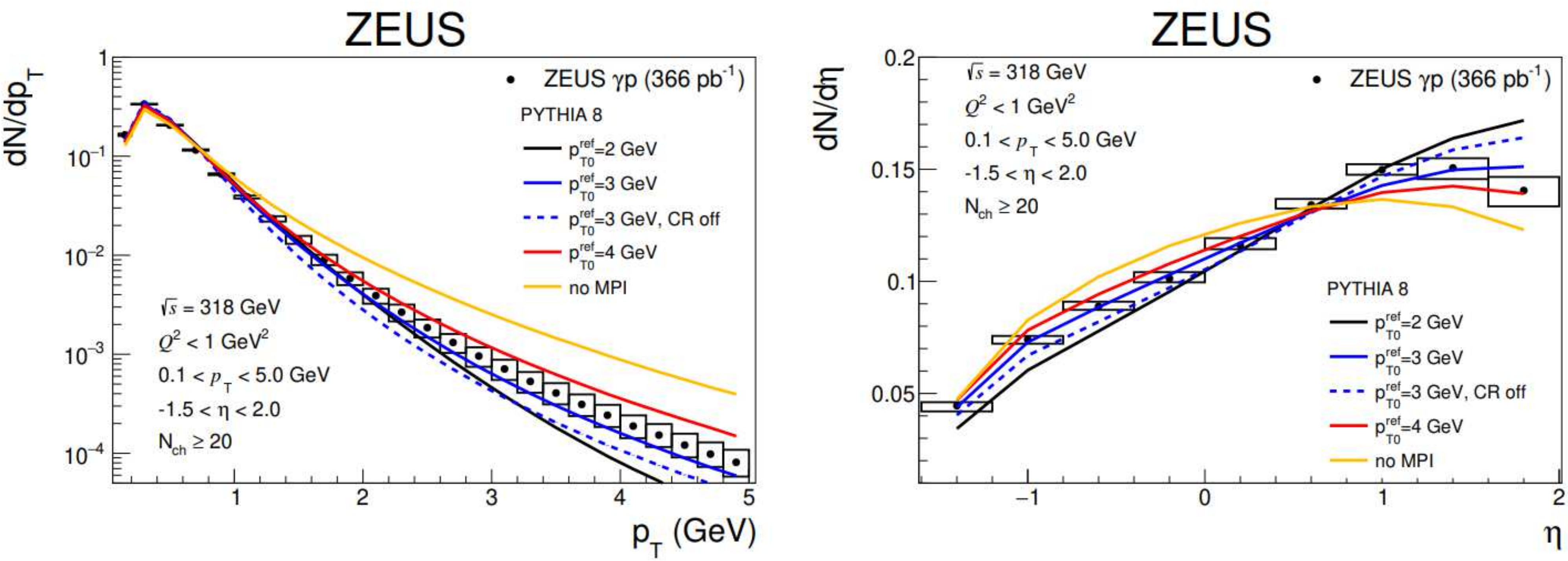


(b) $c_2\{2\}$ versus $|\Delta\eta|$.

reasonably described by PYTHIA-6 “default” model used for efficiency corrections

p_T and $|\Delta\eta|$ distributions

JHEP 12 (2021) 102, arXiv:2106.12377



(a) $c_1\{2\}$ versus $|\Delta\eta|$.

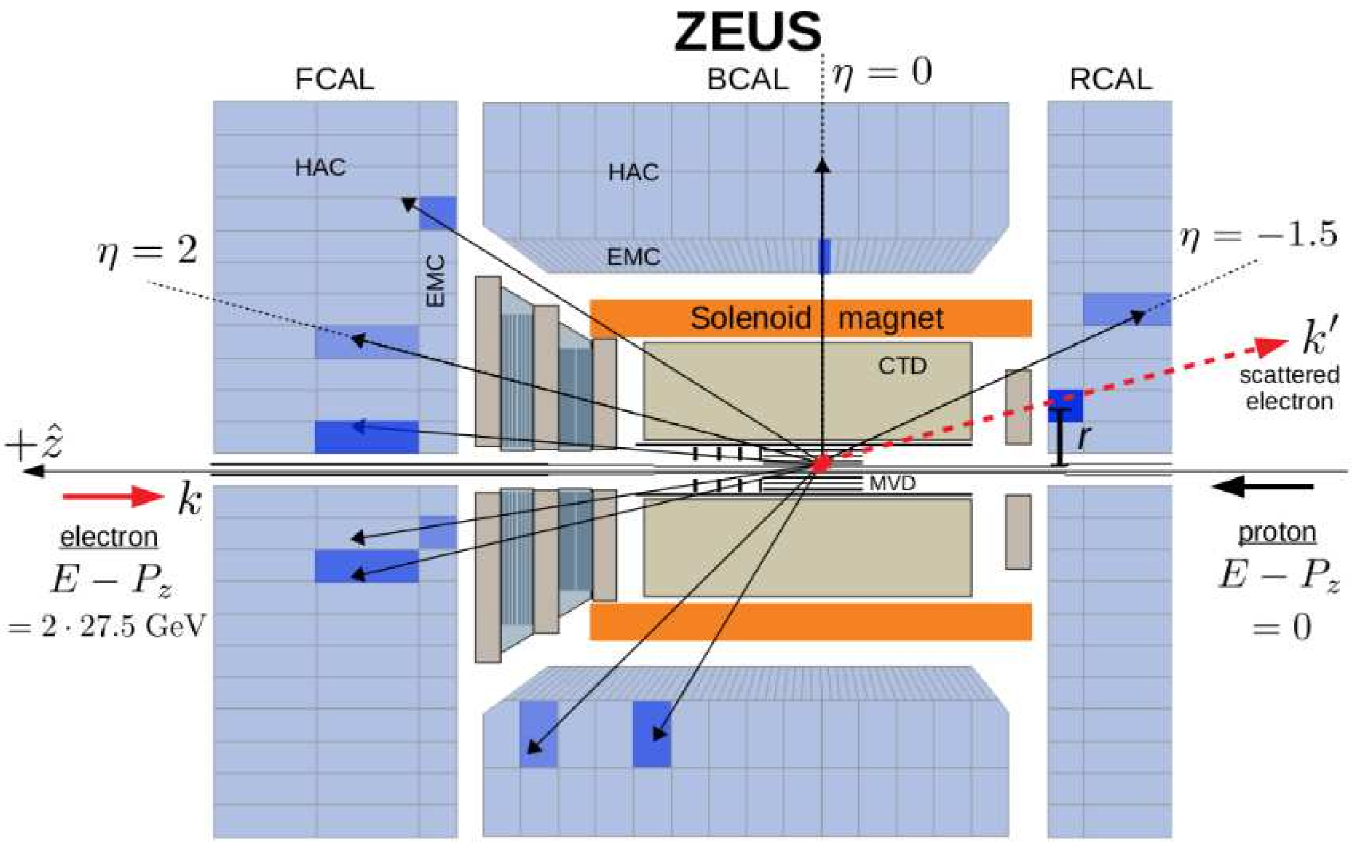
(b) $c_2\{2\}$ versus $|\Delta\eta|$.

reasonably described by PYTHIA-8 models with p_{T0} = 3±1 GeV

DIS event and track selection

tracking in 1.4 T magnetic field (CTD+MVD)

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



Event selection (46 M)

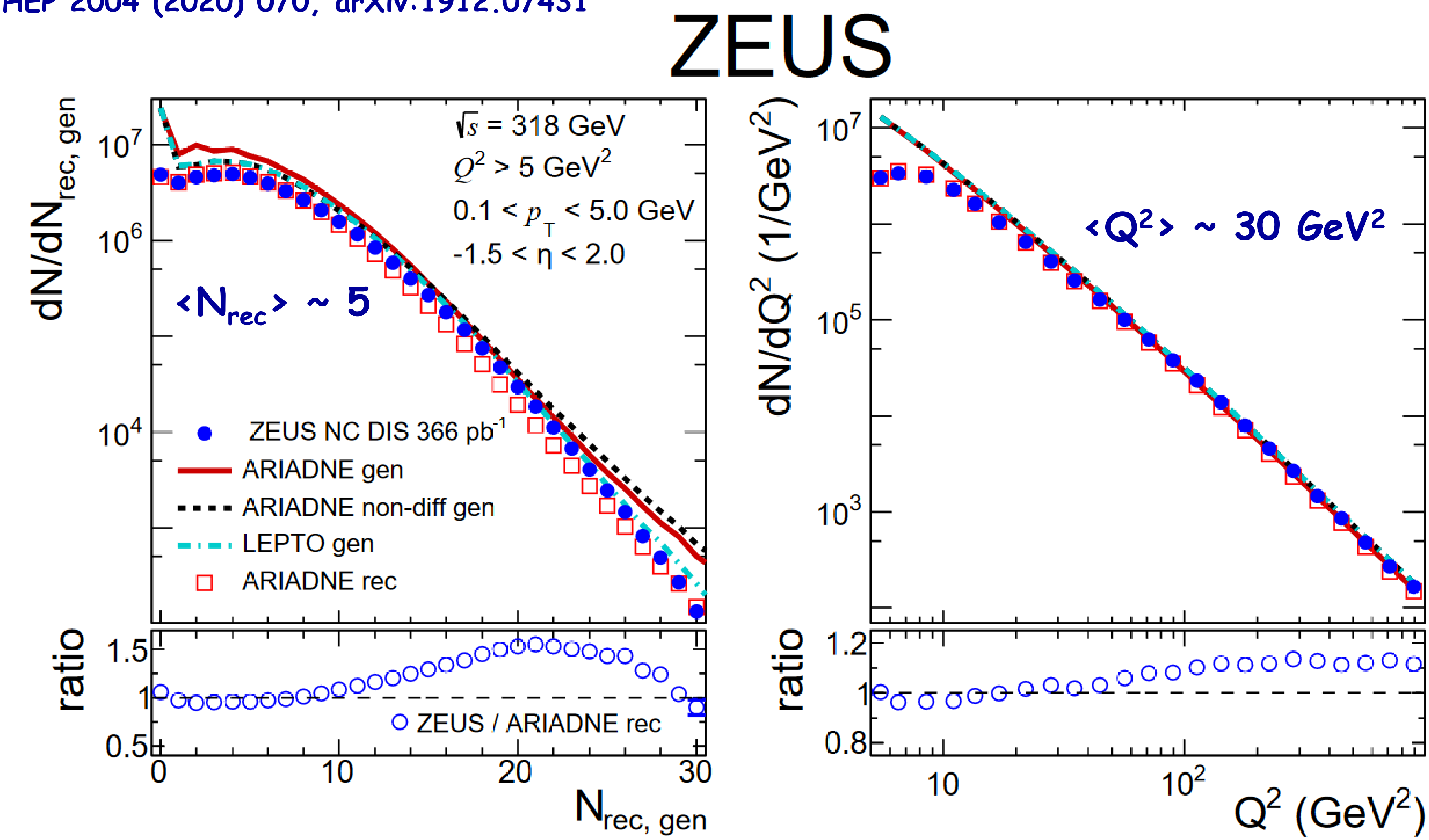
- DIS triggers
- $Q^2 = -(k - k')^2 > 5\ \text{GeV}^2$
- $k'_0 > 10$ GeV
- $r > 15$ cm
- $\theta_e > 1$ rad
- $47 < \sum(E_i - P_{z,i}) < 69$ GeV
- $|V_z| < 30$ cm

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)

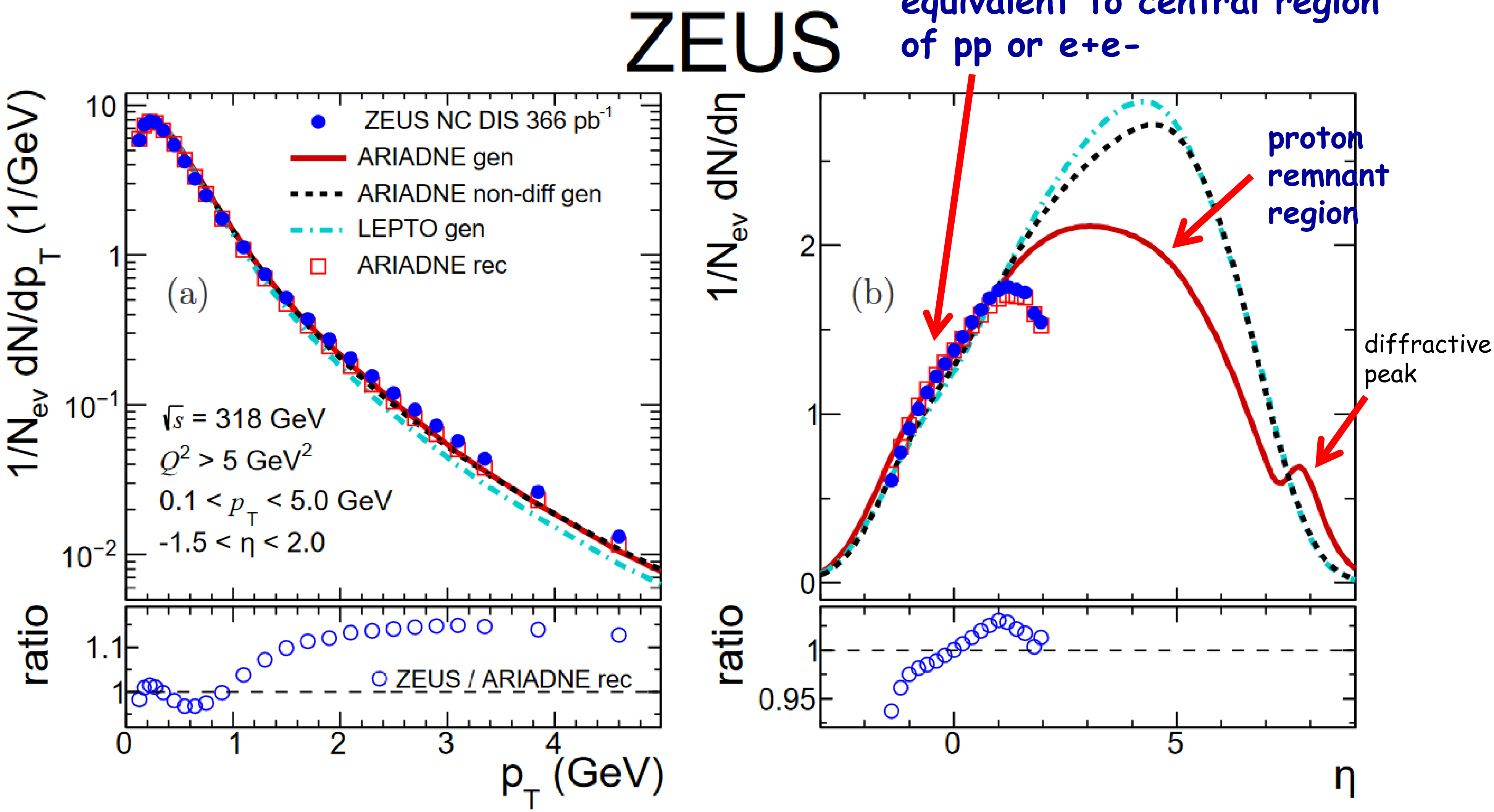
JHEP 2004 (2020) 070, arXiv:1912.07431



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

DIS: inclusive track distributions (rec vs. gen)

JHEP 2004 (2020) 070, arXiv:1912.07431

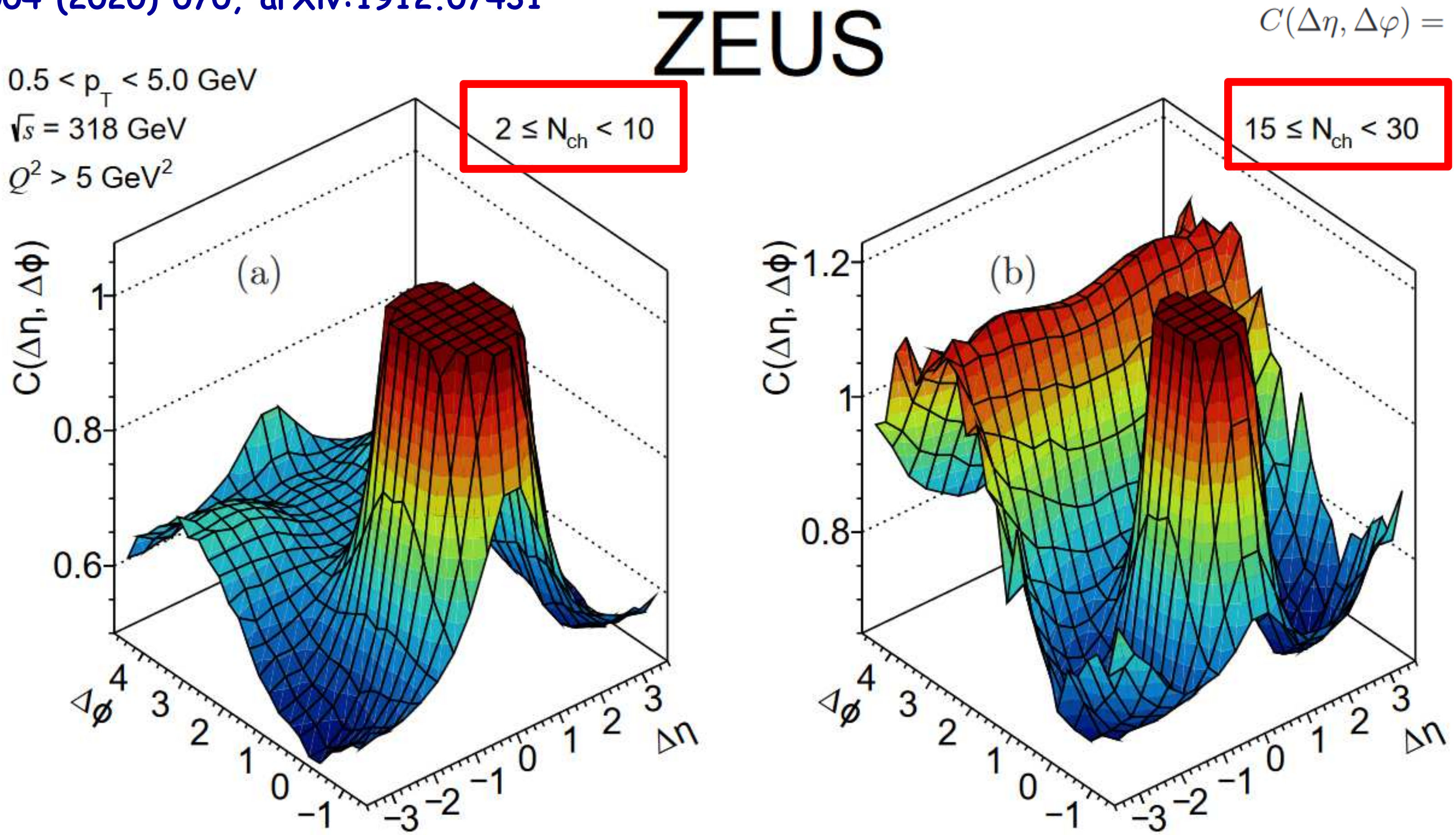


general properties (blue points)
reasonably described by Ariadne MC (red boxes)

"Ridge" figures in DIS

JHEP 2004 (2020) 070, arXiv:1912.07431

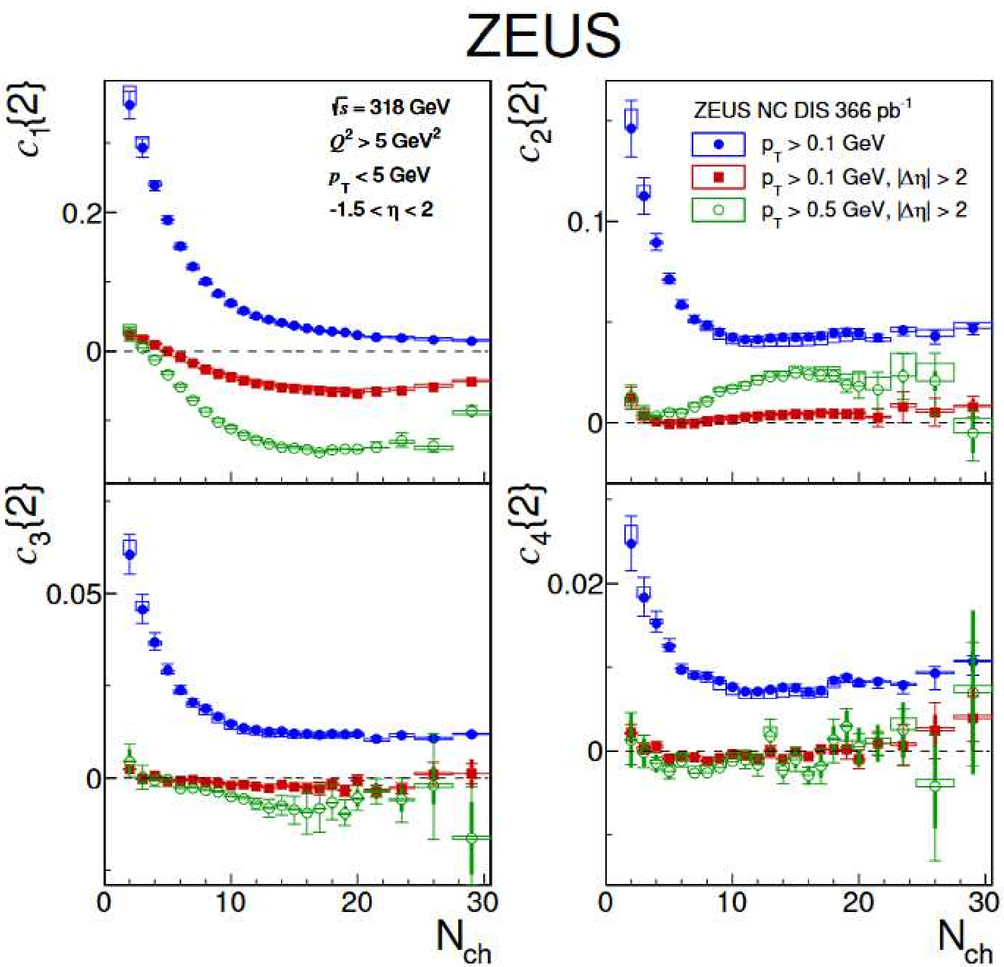
$$C(\Delta\eta, \Delta\varphi) = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$$



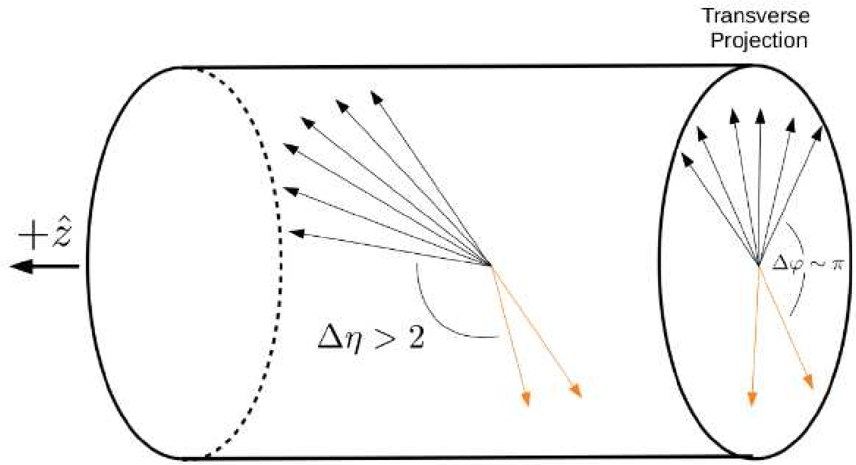
- **Jet peak centered at $\Delta\phi \sim \Delta\eta \sim 0$ (includes single DIS recoil jet)**
- **Away side ridge in high N_{ch} events dominated by "dijet" topologies**
- **No visible double ridge at "high" N_{ch}**

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

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



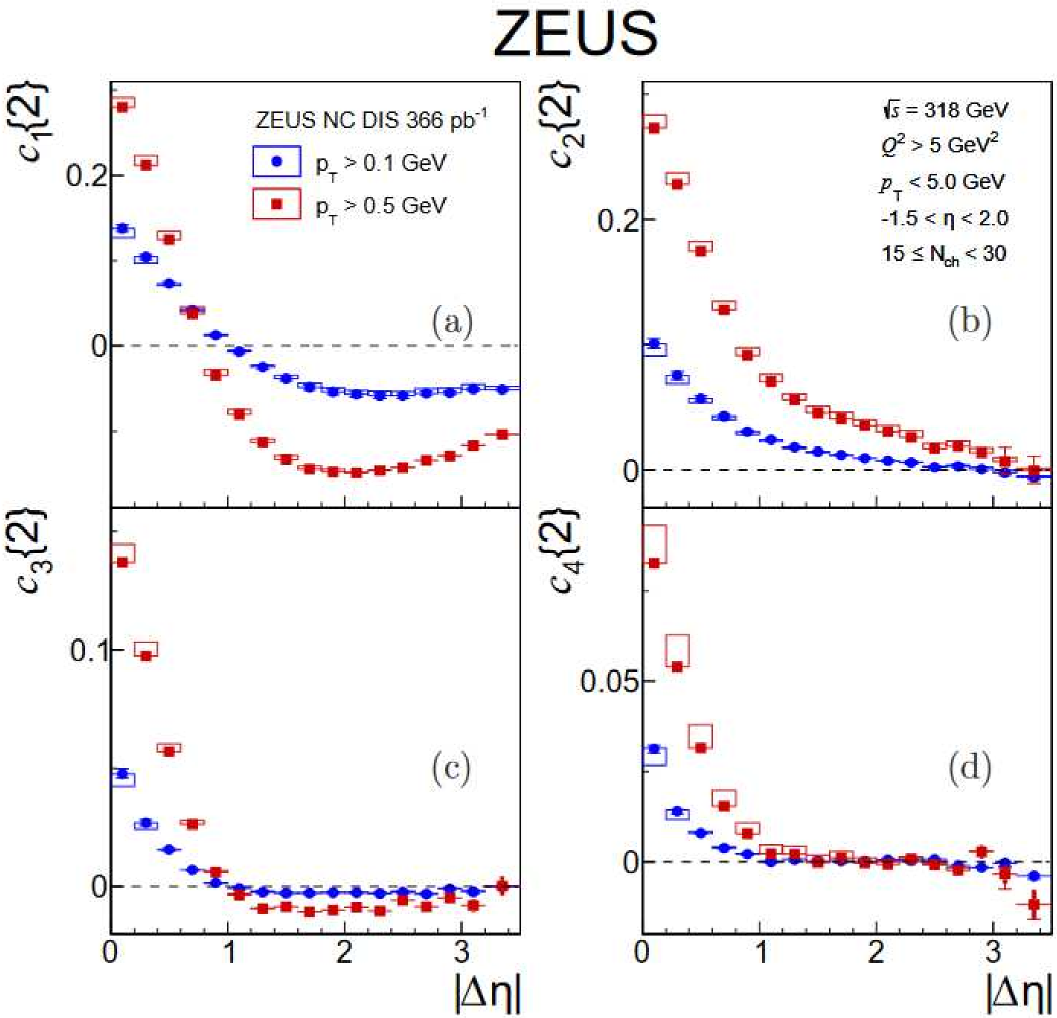
- Short-range ($|\Delta\eta| \sim 0$) correlations are strongest at low N_{ch}. (blue)
- Long-range correlations ($|\Delta\eta| > 2$, orange-black pairs) of the first harmonic are dominant and negative. (red (low p_T) and green (high p_T))



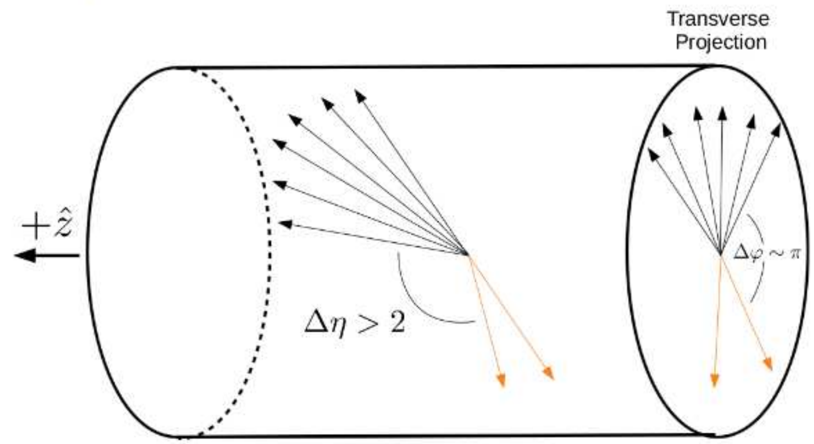
JHEP 2004 (2020) 070, arXiv:1912.07431

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

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



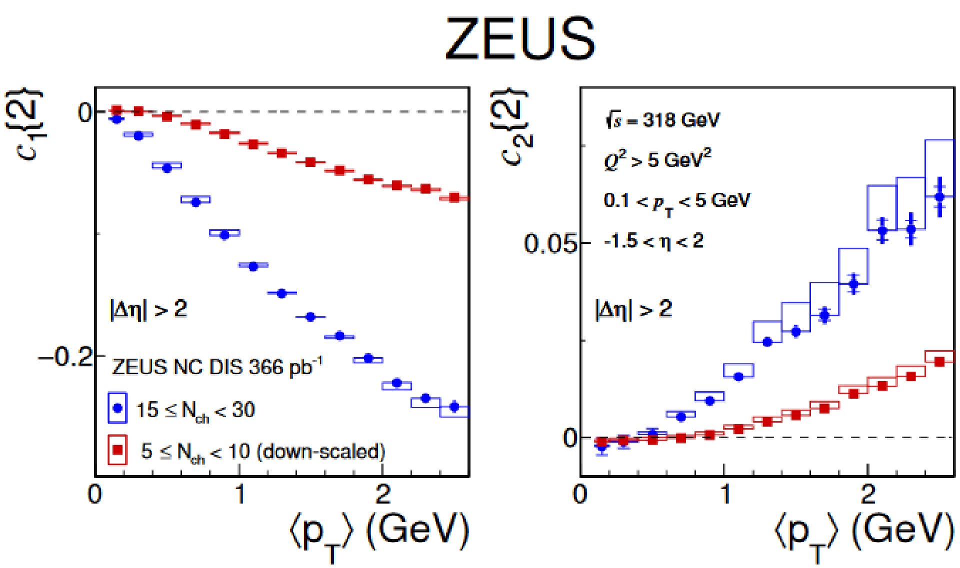
- The correlations with $p_{\mathrm{T}} > 0.5$ GeV (red) are more pronounced than those at low p_{T} (blue) as expected from particles in jet-like structures.
- Negative (postive) $c_1\{2\}$ ($c_2\{2\}$) for $p_{\mathrm{T}} > 0.5$ GeV extend out to $|\Delta\eta| \sim 3$.
- Large directed and elliptic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



JHEP 2004 (2020) 070, arXiv:1912.07431

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

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



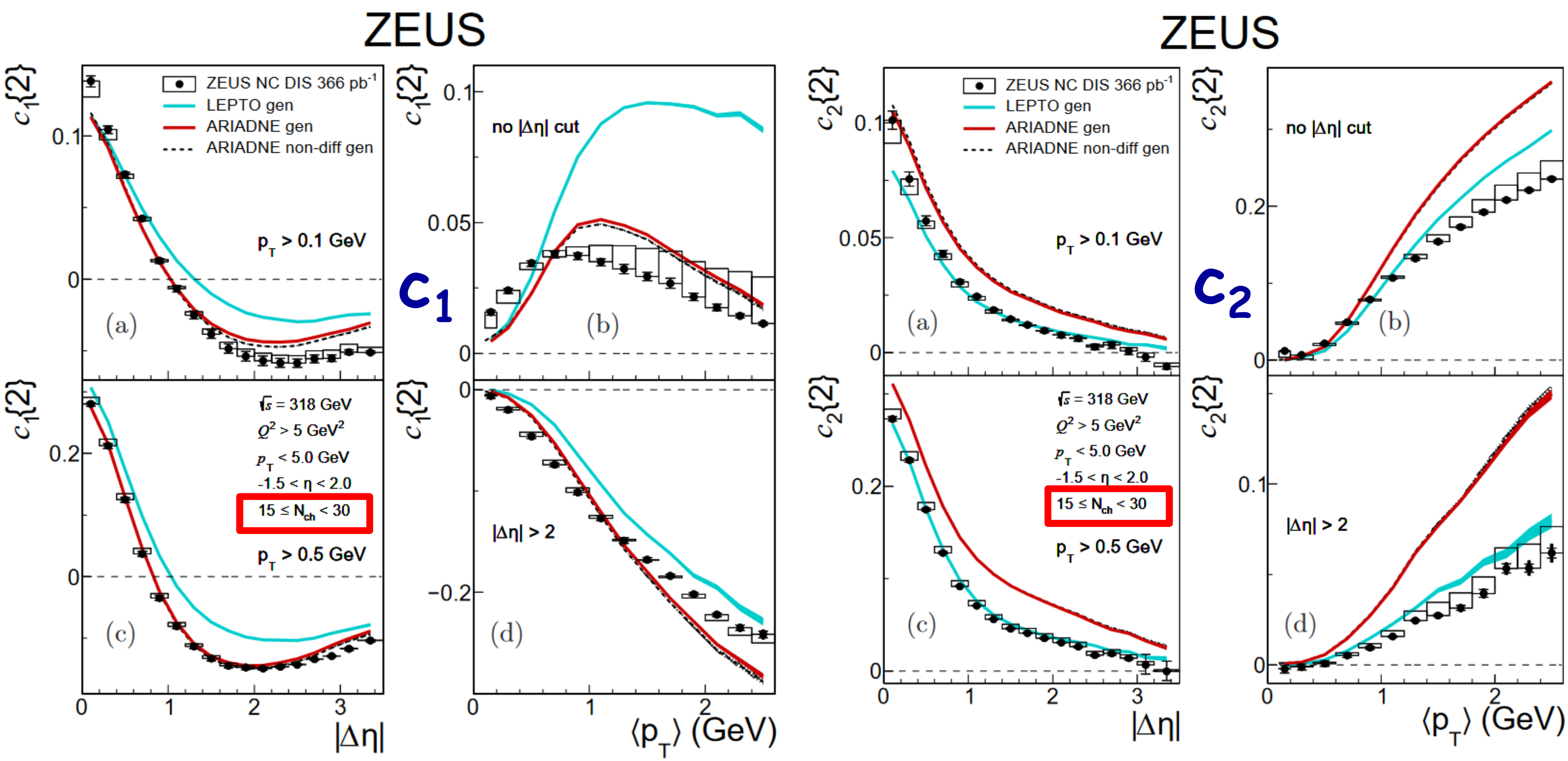
- Correlations at low N_{ch} were down-scaled by $\langle N_{\mathrm{ch}}\rangle_{\mathrm{low}} / \langle N_{\mathrm{ch}}\rangle_{\mathrm{high}}$.
- Scaling factor inspired by observations in heavy-ion collisions where non-collective behaviour contributes to $c_n\{2\}$ as $1/N_{\mathrm{ch}}$.
- The observed excess correlation at high N_{ch} wrt low N_{ch} is stronger for $c_1\{2\}$ than $c_2\{2\}$.
- Therefore, the $1/N_{\mathrm{ch}}$ 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

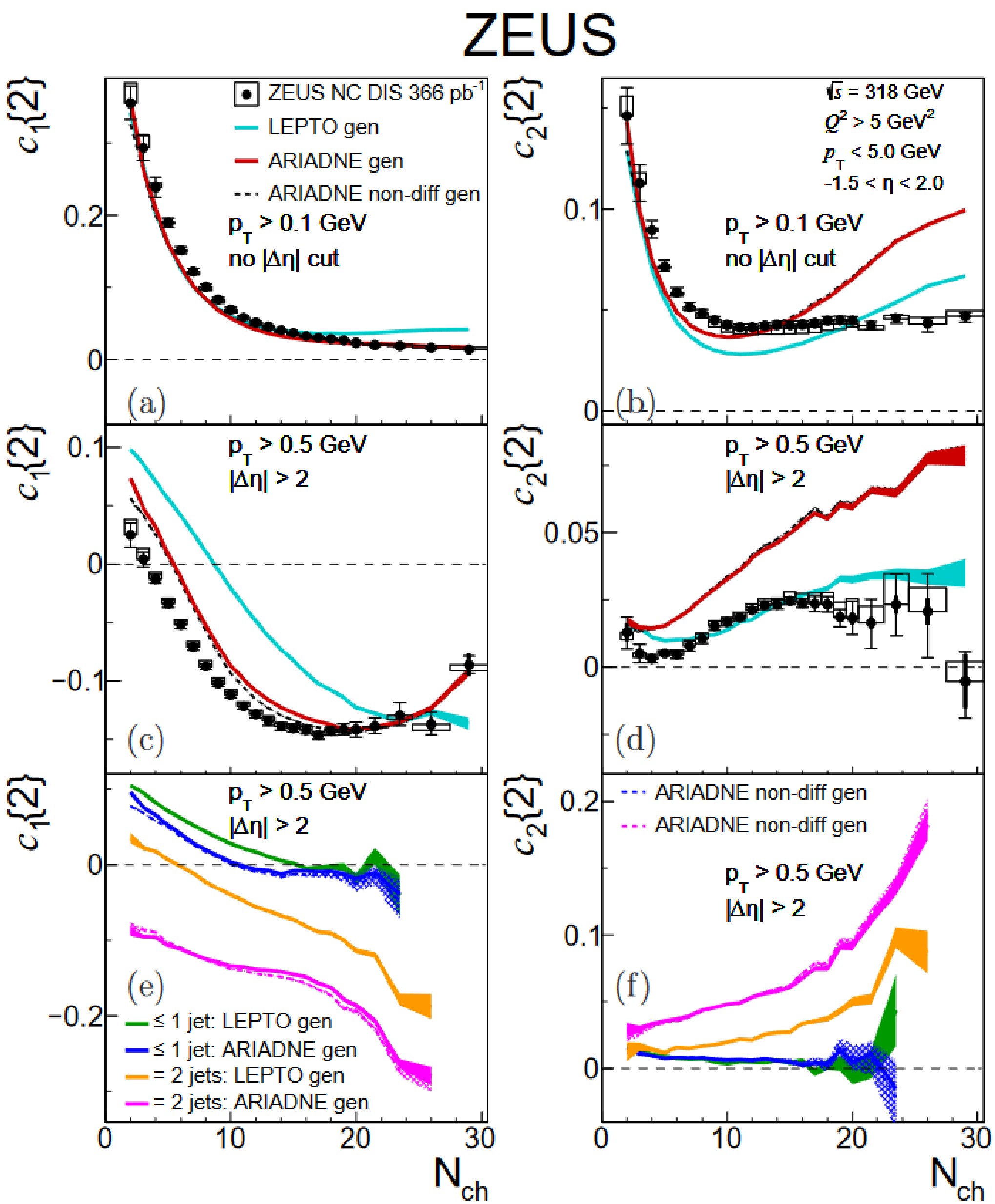


$c_1\{2\}$ reasonably described by Ariadne dipole model (LO+PS)

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

Comparison to MC model predictions

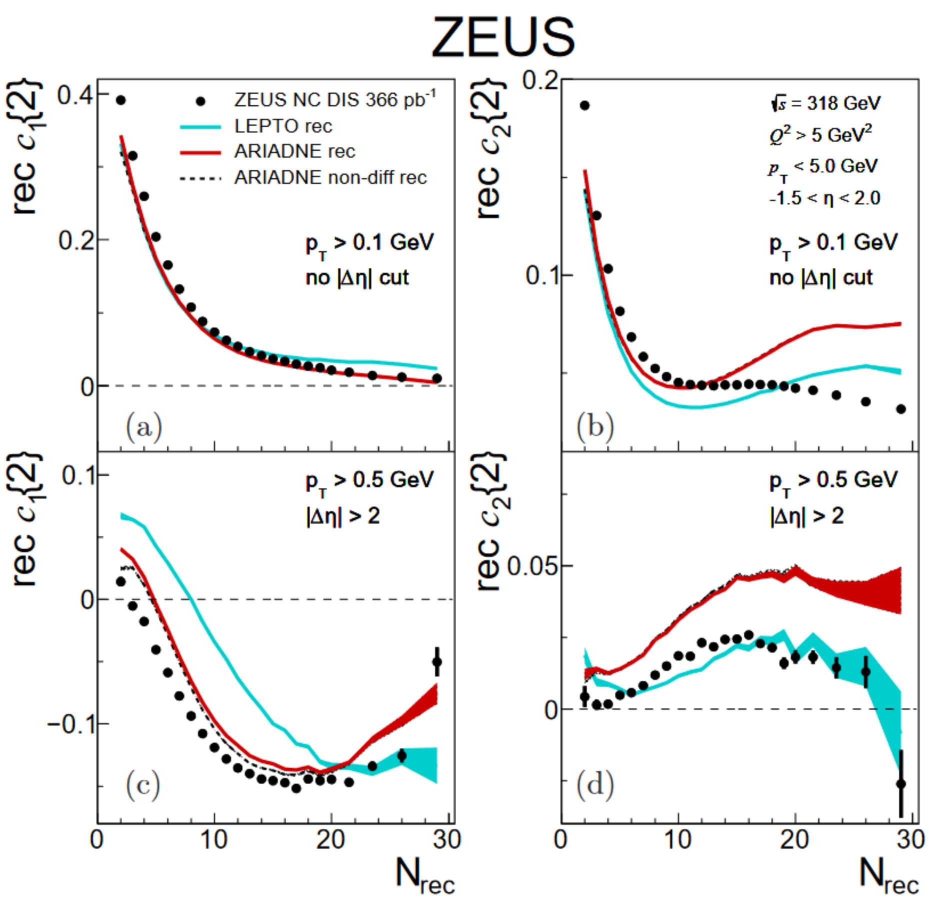
JHEP 2004 (2020) 070, arXiv:1912.07431

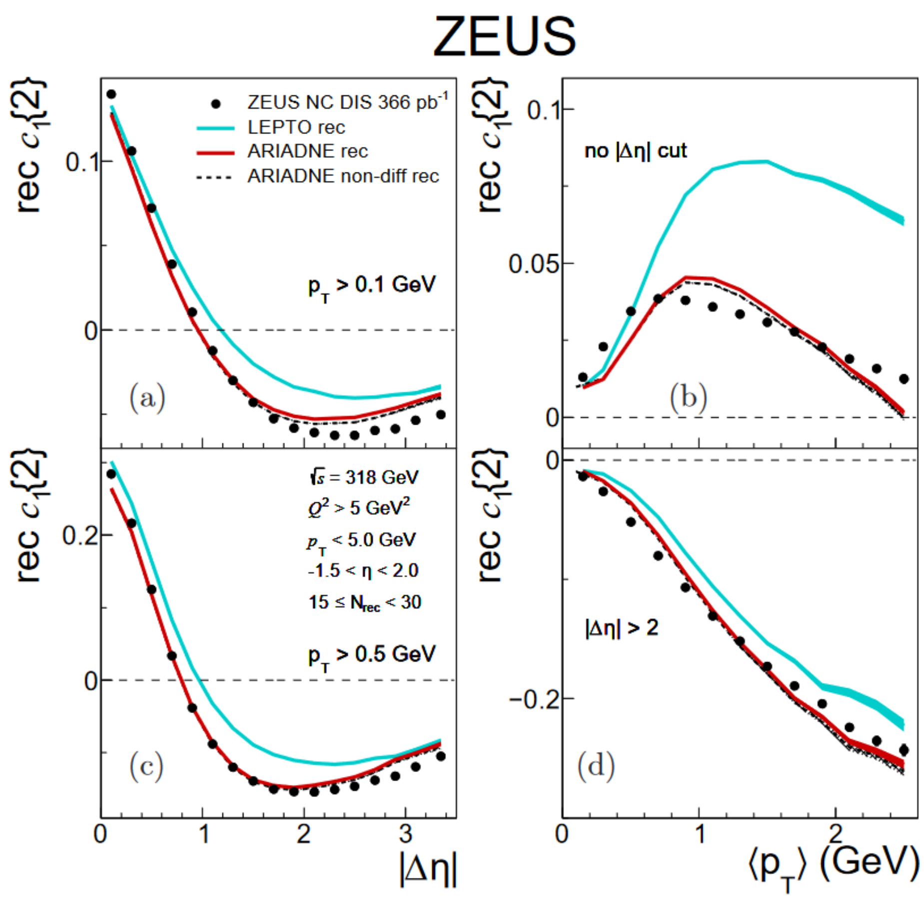


- $c_1\{2\}$ is better described by the ARIADNE generator.
- $c_2\{2\}$ is better described by the LEPTO generator.
- Neither model works well in the full kinematic interval (top right).
- The diffractive component in ARIADNE only slightly influences $c_n\{2\}$.
- Massless jets were reconstructed from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

Comparison to MC model predictions

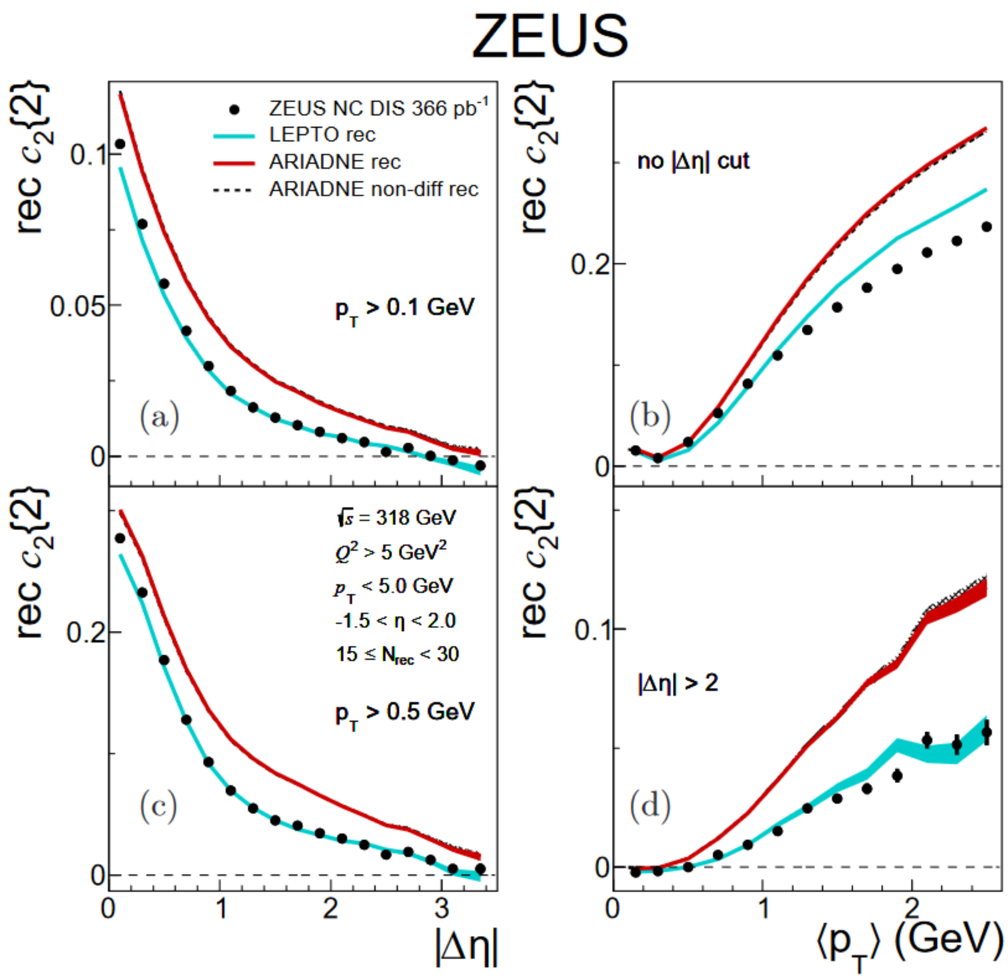
at reconstruction level (w/o systematic uncertainties)





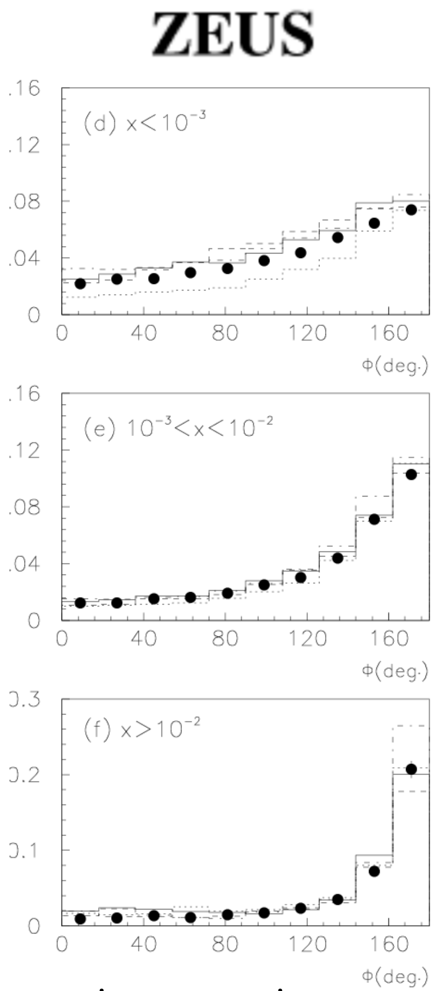
Comparison to MC model predictions

at reconstruction level (w/o systematic uncertainties)

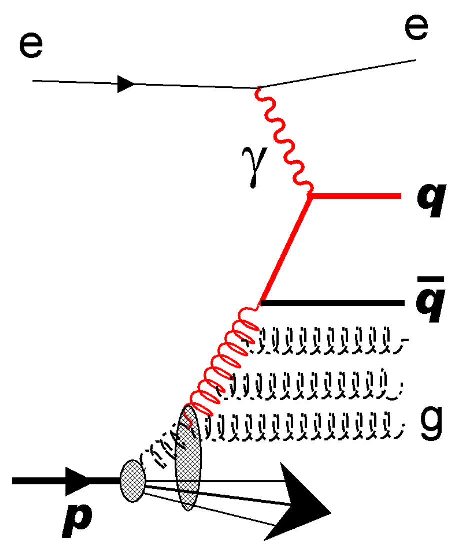


Observation of colour strings/dipoles

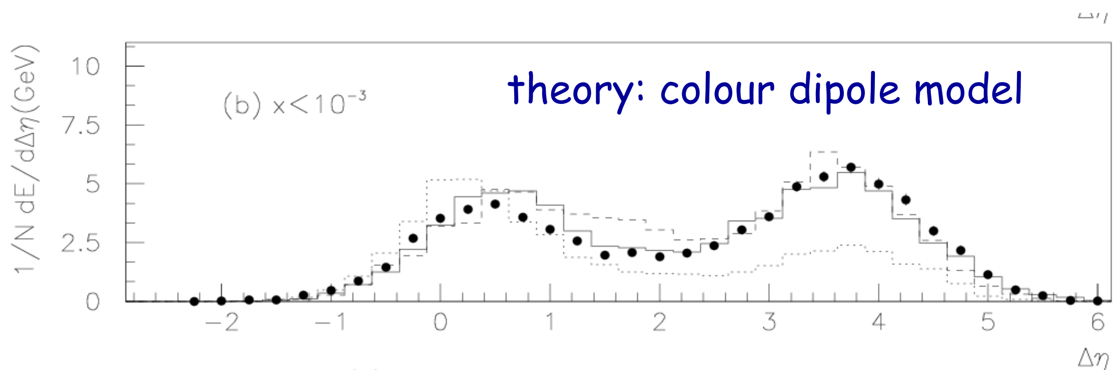
in hadronic energy flow in DIS at HERA: Z. Phys. C59 (1993) 231



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."

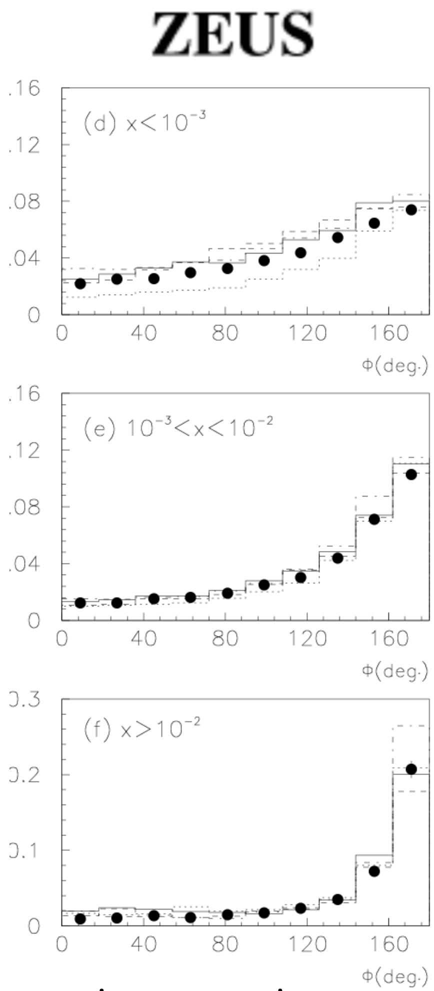


rapidity difference w.r.t. expected QPM jet

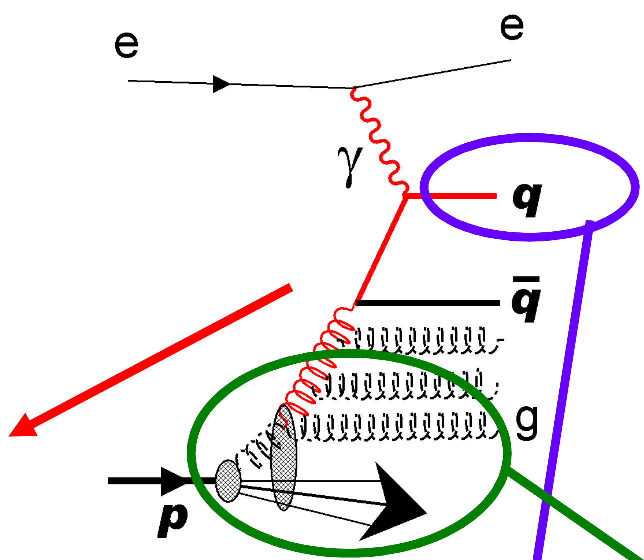
see also H1, DESY-94-033

Observation of colour strings/dipoles

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

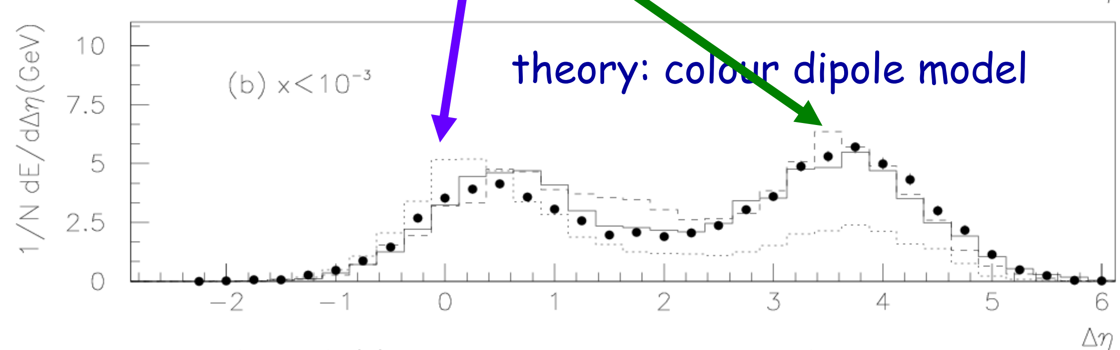


angle w.r.t. electron



"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."

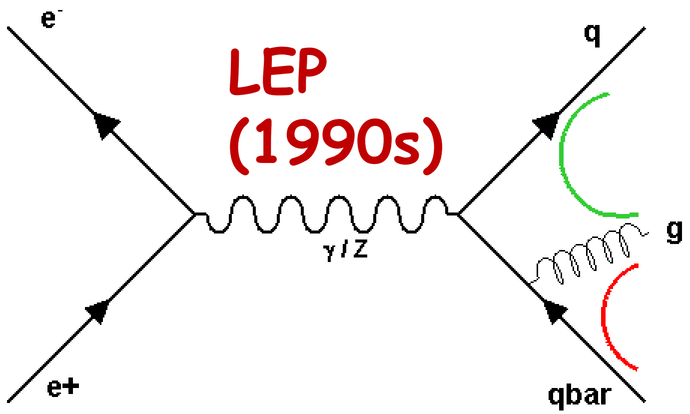
more in backup



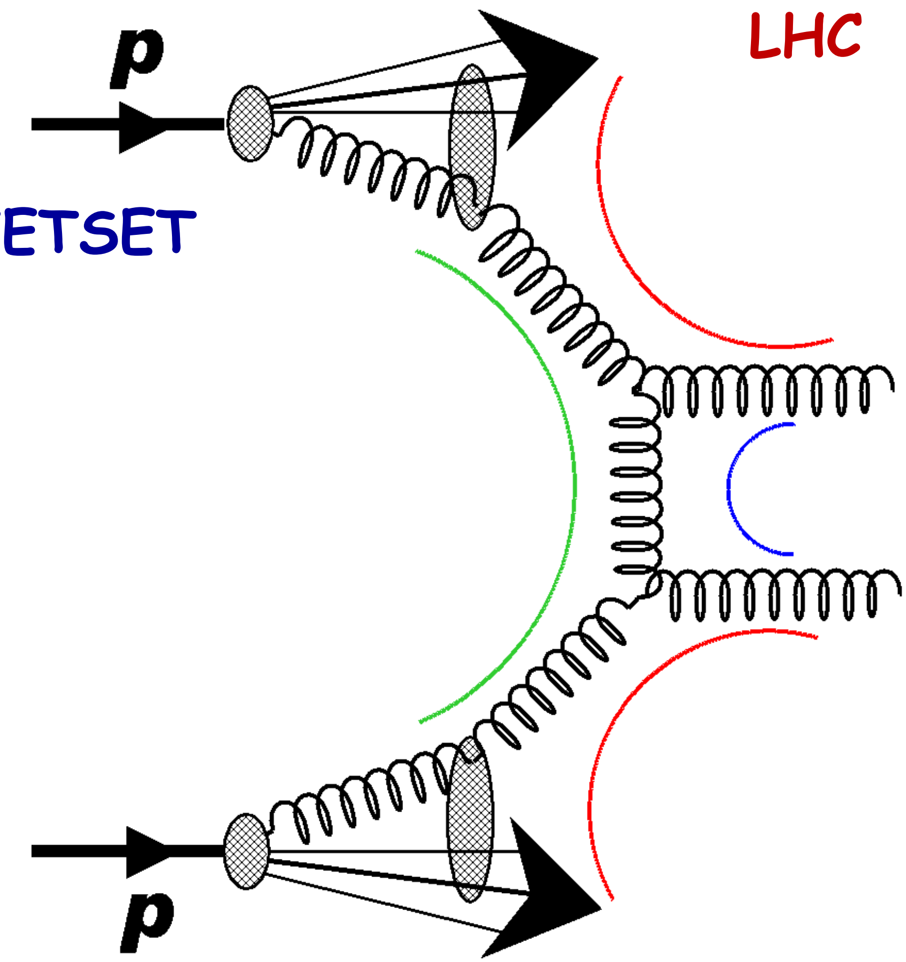
rapidity difference w.r.t. expected QPM jet

see also H1, DESY-94-033

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



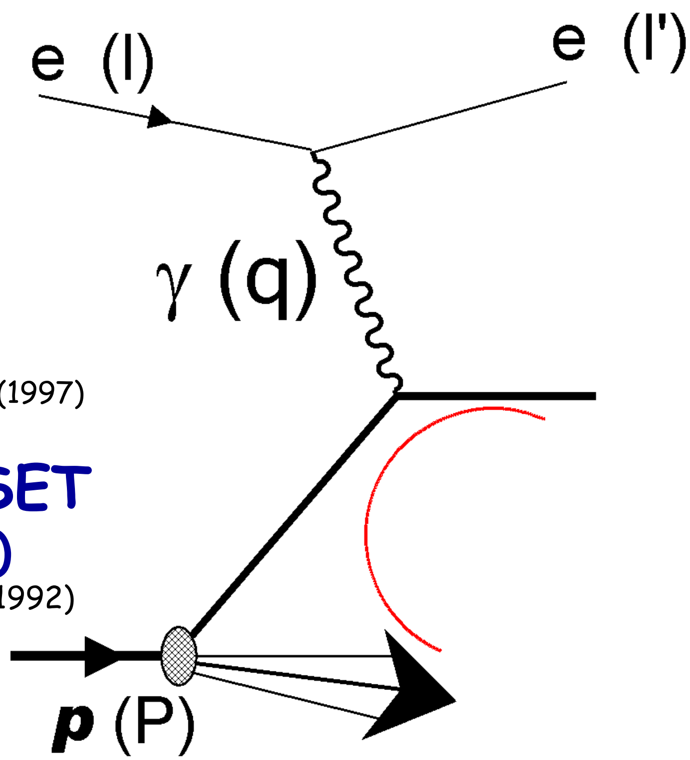
PYTHIA/JETSET



DIS (HERA):

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

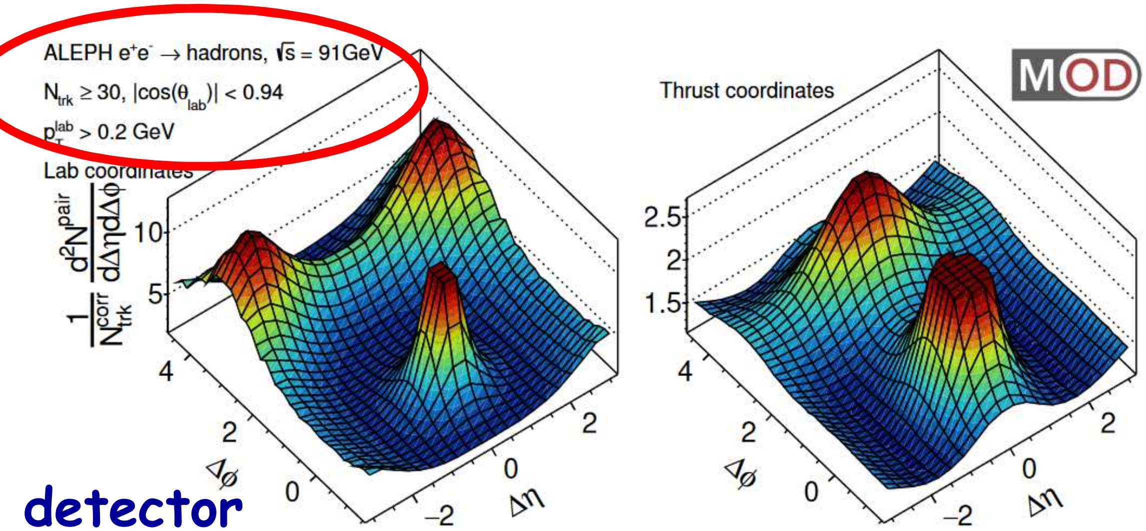
Lepto + JETSET (from PYTHIA 6)
Comp. Phys. Comm. 71, 15 (1992)

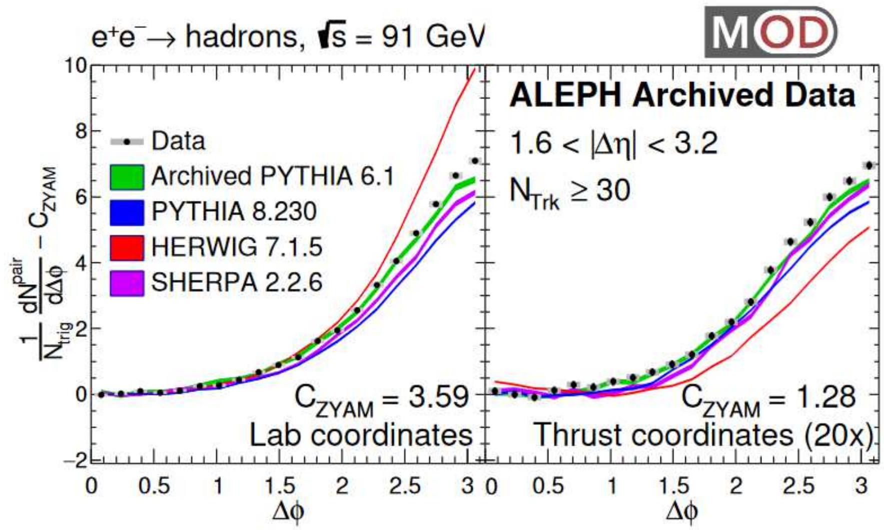


Two-Particle correlations in e^+e^- collisions

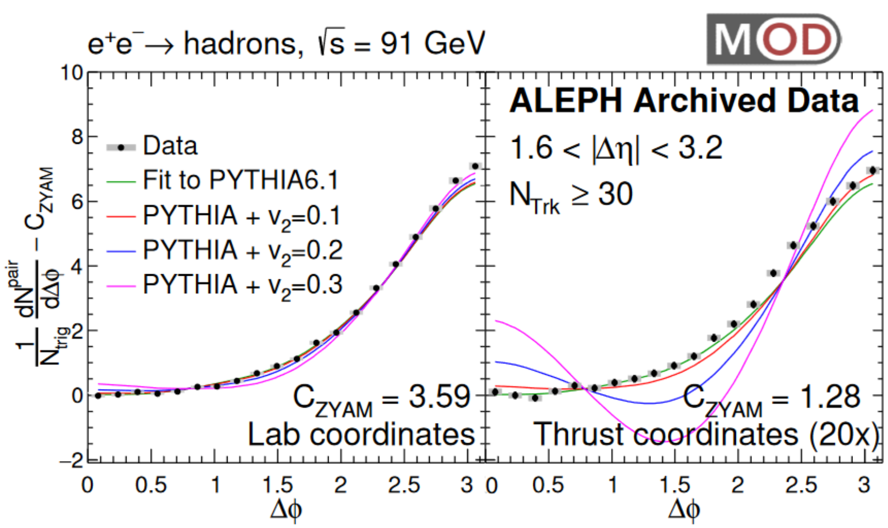
at $\sqrt{s}$=91 GeV, archived ALEPH data

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

“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

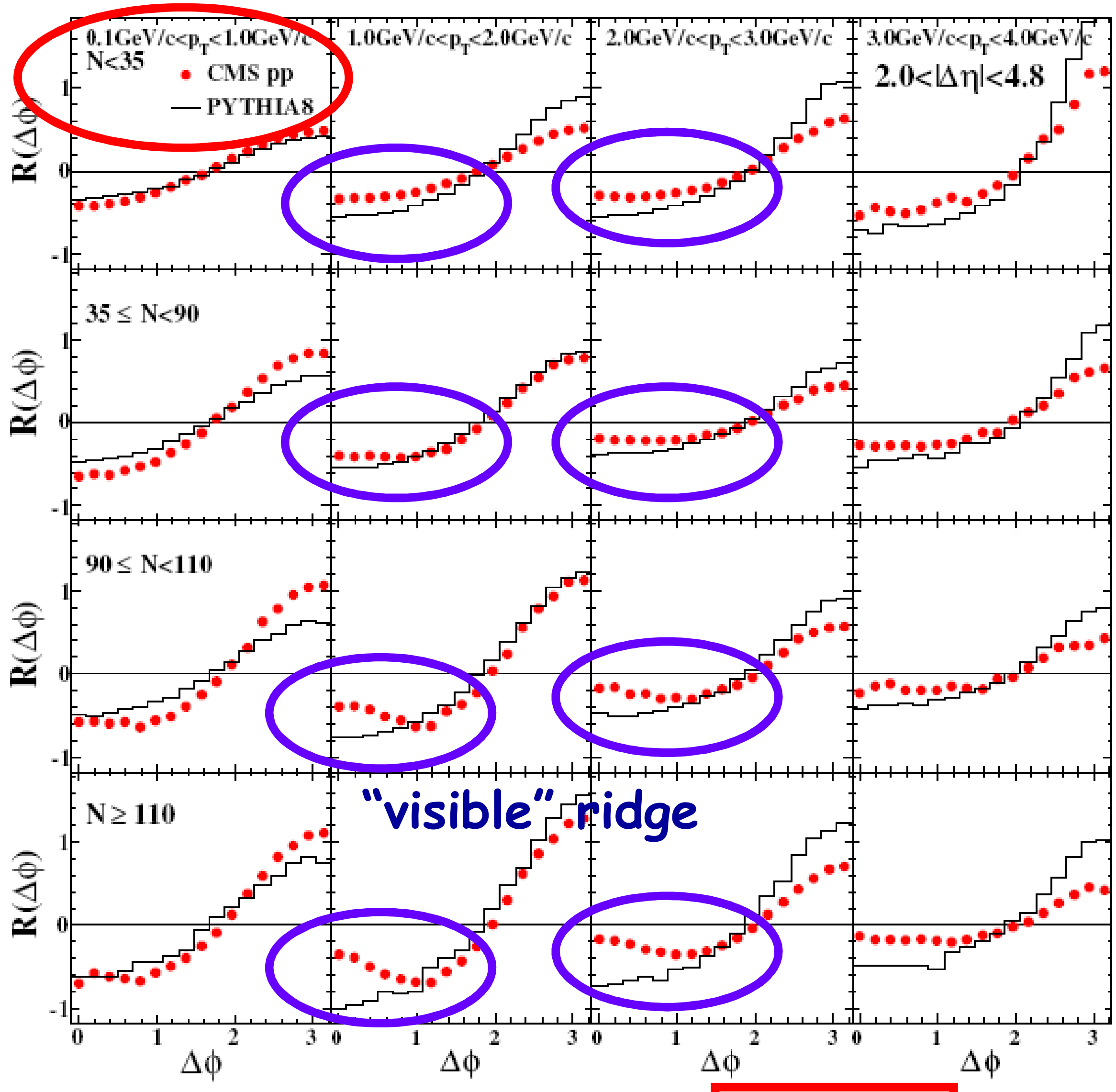


Figure 8: Projections of 2-D correlation functions onto $\Delta\phi$ for $2.0 < |\Delta\eta| < 4.8$ in different p_T and multiplicity bins for fully corrected 7 TeV pp data and reconstructed PYTHIA8 simulations. Error bars are smaller than the symbols.