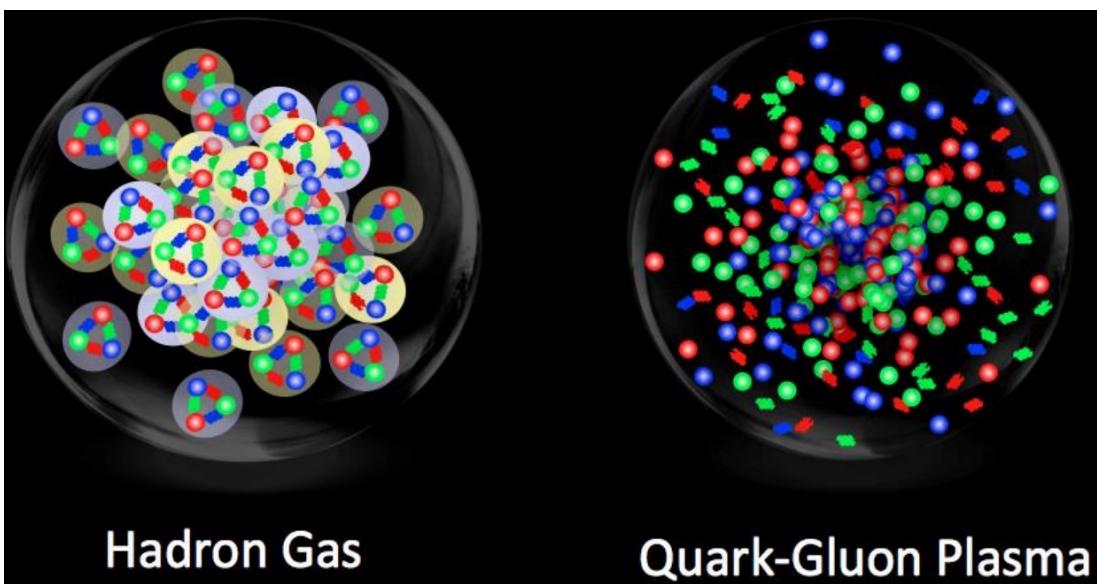
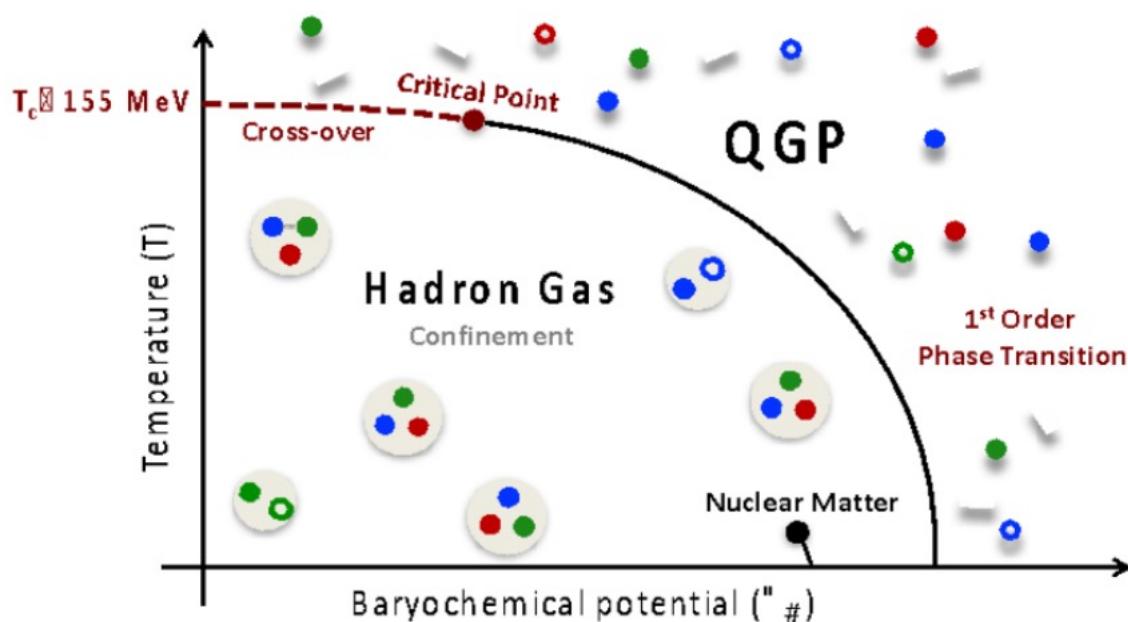


NET-CHARGE FLUCTUATIONS AND BALANCE FUNCTIONS WITH THE CMS EXPERIMENT

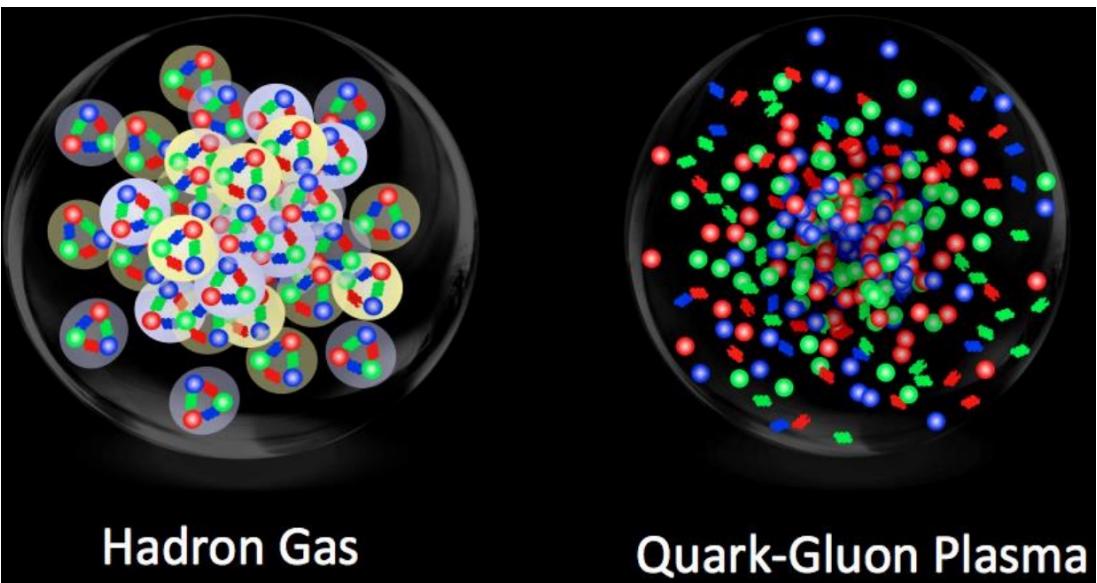
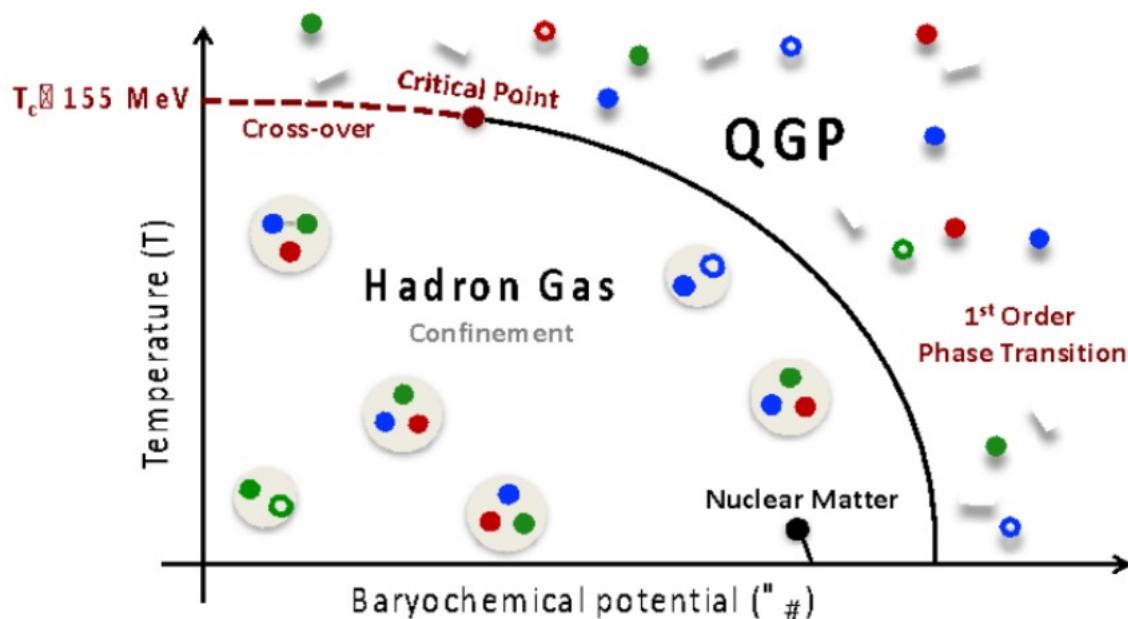
Shengquan Tuo
(Vanderbilt University)
for the CMS Collaboration

Introductions – Net-charge fluctuations



- Fluctuations in conserved quantities such as the net baryon number or net electric charge act as signals that characterize transition from hadronic to QGP phase

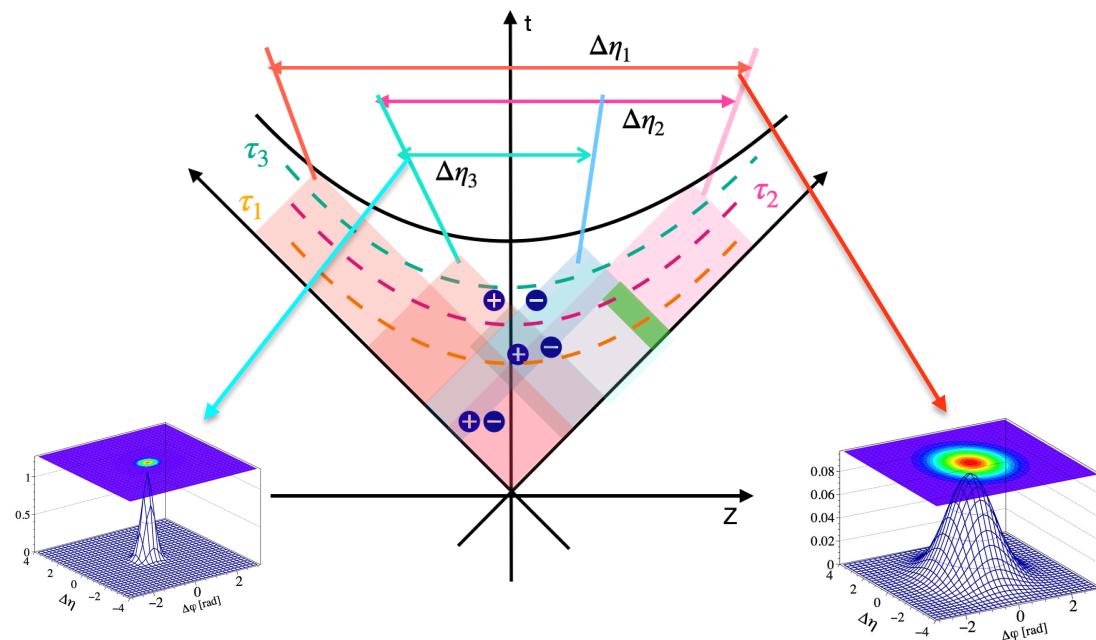
Introductions – Net-charge fluctuations



- Fluctuations in conserved quantities such as the net baryon number or net electric charge act as signals that characterize transition from hadronic to QGP phase
- Net-charge fluctuations are proportional to the square of charges in the system
 - Fluctuations in HG phase are proportional to $q^2 \rightarrow 1, 4$
 - QGP system with charges $1/3$ and $2/3$ corresponds to charge fluctuations proportional to $1/9$ and $4/9$
- Net-charge fluctuations in the HG phase are larger than in QGP

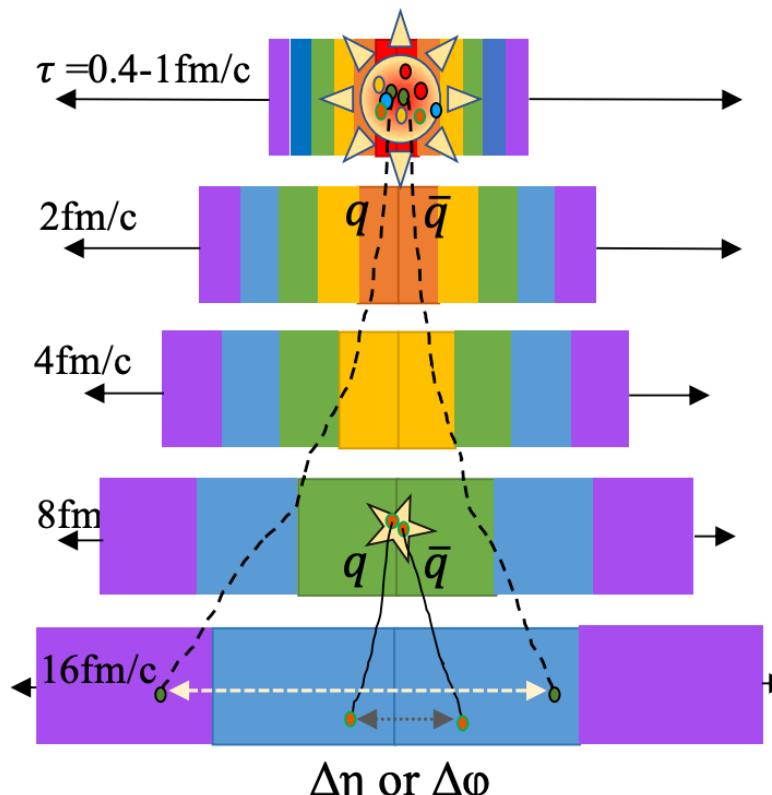
Phys. Rev. Lett. 85, 2076 (2000)

Introductions – Balance functions



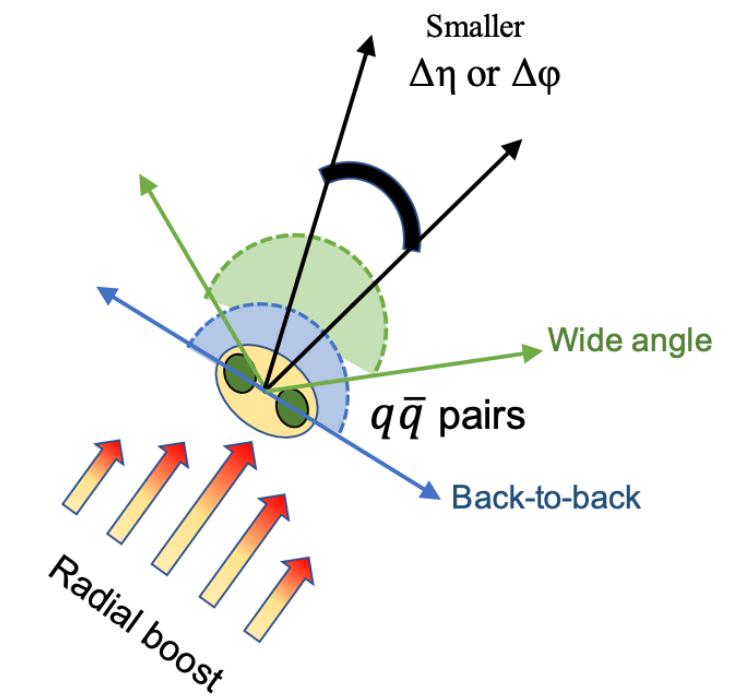
Short range

Long range



(a) Clocking Hadronization
of $q\bar{q}$ pairs

Eur. Phys. J. C (2021) 81:1024



(b) Kinematic Lensing
due to radial boost

- Longitudinal width of the correlation is related to time the correlation is established
- The width is also affected by the radial flow effect

Observable and method

- Net charge $Q = N_+ - N_-$
- Total charge $N_{\text{ch}} = N_+ + N_-$
- Net-charge fluctuations

$$\nu_{(+-, \text{dyn})} = \frac{\langle N_+(N_+ - 1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_-(N_- - 1) \rangle}{\langle N_- \rangle^2} - 2 \frac{\langle N_+ N_- \rangle}{\langle N_- \rangle \langle N_+ \rangle}$$

- D measure: $D = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{\text{ch}} \rangle}$, with $\langle N_{\text{ch}} \rangle \nu_{(+-, \text{dyn})} \approx D - 4$.
Phys. Rev. Lett. 85, 2076 (2000)

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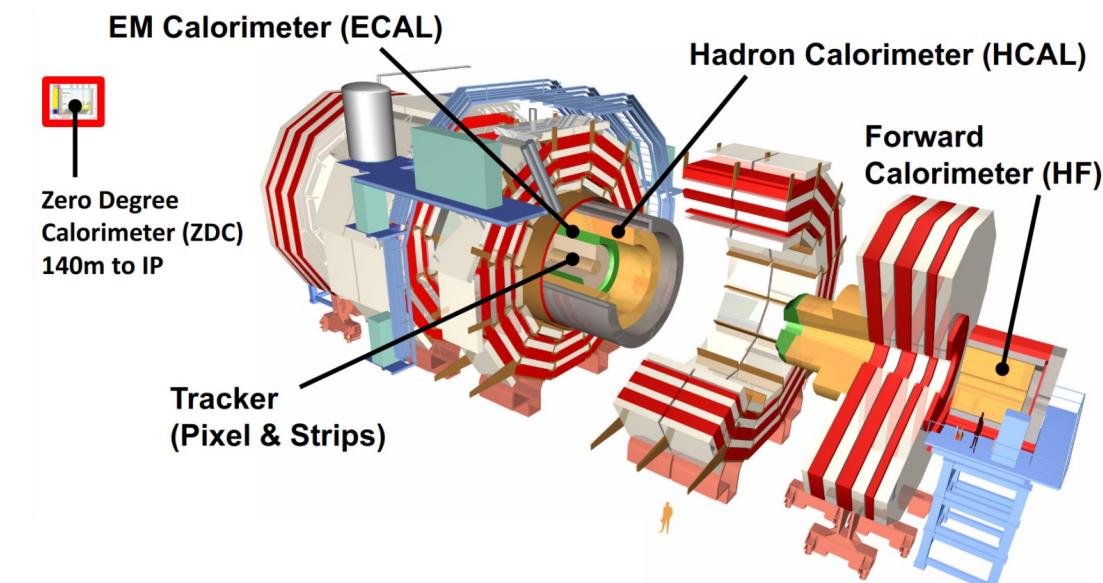
$$\nu_{(+-, \text{dyn})} = \frac{\langle N_+(N_+ - 1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_-(N_- - 1) \rangle}{\langle N_- \rangle^2} - 2 \frac{\langle N_+ N_- \rangle}{\langle N_- \rangle \langle N_+ \rangle}$$

Phys. Rev. Lett. 85, 2076 (2000)

- D measure: $D = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{\text{ch}} \rangle}$, with $\langle N_{\text{ch}} \rangle \nu_{(+-, \text{dyn})} \approx D - 4$.

- Theoretical models (including lattice QCD) predict the D-measure equal to 1.0 - 1.5 for the QGP phase and 3 for HG
- Fluctuations may get diluted in the rapidly expanding medium due to the diffusion of particles in Δn

CMS tracker: $|\eta| < 2.4$, $|\Delta n| < 4.8$



Balance functions

- Balance functions are constructed from four possible charge combinations

$$B(\Delta\eta, \Delta\varphi) = \frac{1}{2} [C(+,-) + C(-,+)] - [C(-,-) + C(+,+)]$$

$$B(\Delta\eta, \Delta\varphi) = \frac{1}{2} [US - LS]$$

$$US = C(+,-) + C(-,+)$$

$$LS = C(+,+)$$

- Balance functions are sensitive to
 - Late or early hadronization
 - Radial flow

$$\langle |\Delta\eta| \rangle = \frac{\sum_i B(\Delta\eta_i) |\Delta\eta_i|}{\sum_i B(\Delta\eta_i)}$$

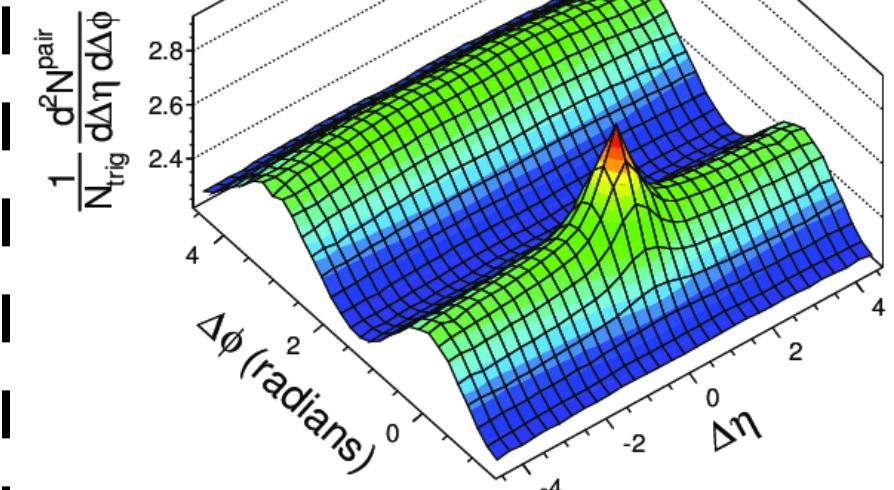
$$\langle |\Delta\varphi| \rangle = \frac{\sum_i B(\Delta\varphi_i) |\Delta\varphi_i|}{\sum_i B(\Delta\varphi_i)}$$

Quark Matter 2023, Houston

Phys. Lett. B 724 (2013) 213

(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{\text{trk}}^{\text{offline}} < 260$

$1 < p_T^{\text{trig}} < 3$ GeV/c
 $1 < p_T^{\text{assoc}} < 3$ GeV/c

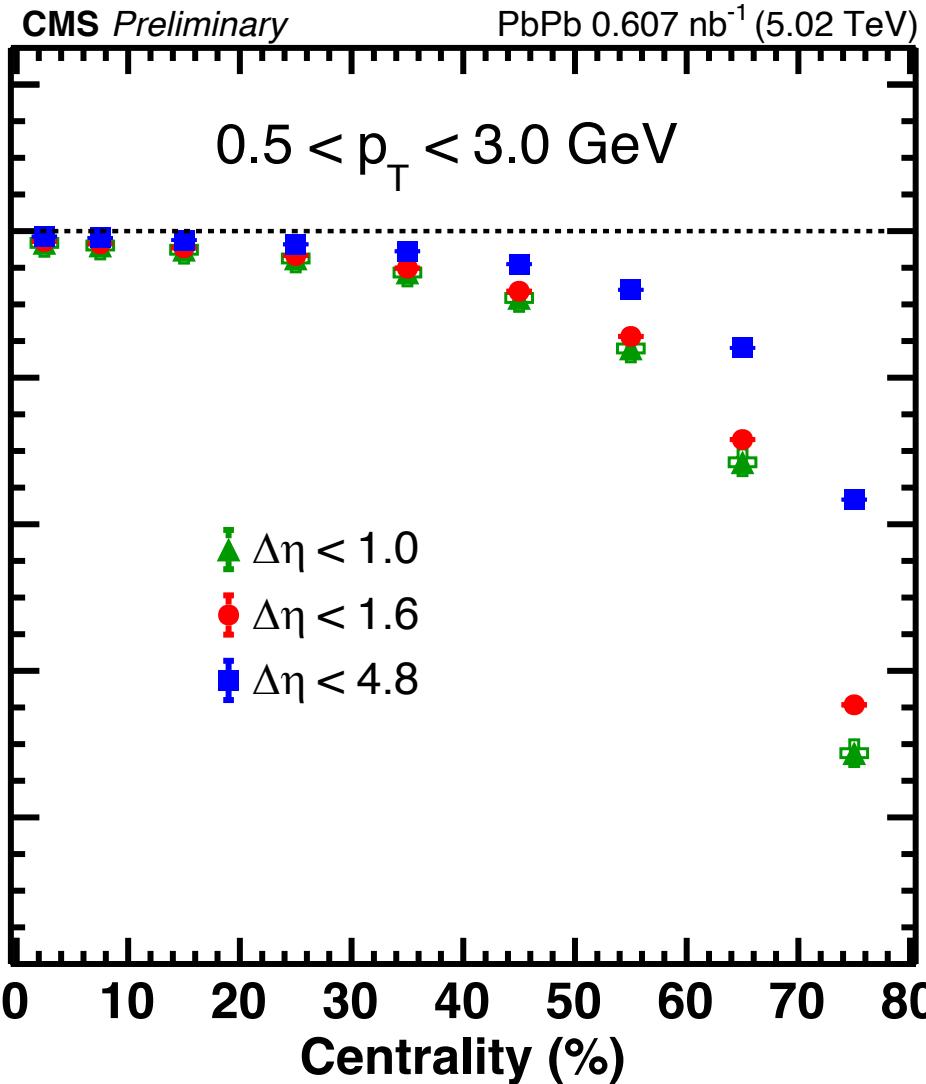


Charge hadron correlation functions

Results

- Using datasets with
 - 2018 PbPb data at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$
 - 2016 pPb at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$
 - 2017 pp at 5.02 TeV

Net-charge fluctuations – Centrality



$$\nu_{(+-, \text{dyn})} = \langle \left(\frac{N_+}{\langle N_+ \rangle} - \frac{N_-}{\langle N_- \rangle} \right)^2 \rangle - \frac{1}{\langle N_+ \rangle} - \frac{1}{\langle N_- \rangle} = \nu_{+-} - \nu_{\text{stat}}$$

$$\nu_{(+-, \text{dyn})} = \frac{\langle N_+(N_+-1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_-(N_--1) \rangle}{\langle N_- \rangle^2} - 2 \frac{\langle N_+ N_- \rangle}{\langle N_+ \rangle \langle N_- \rangle}$$

$\nu_{\text{dyn}} = 0$; no dynamical fluctuation

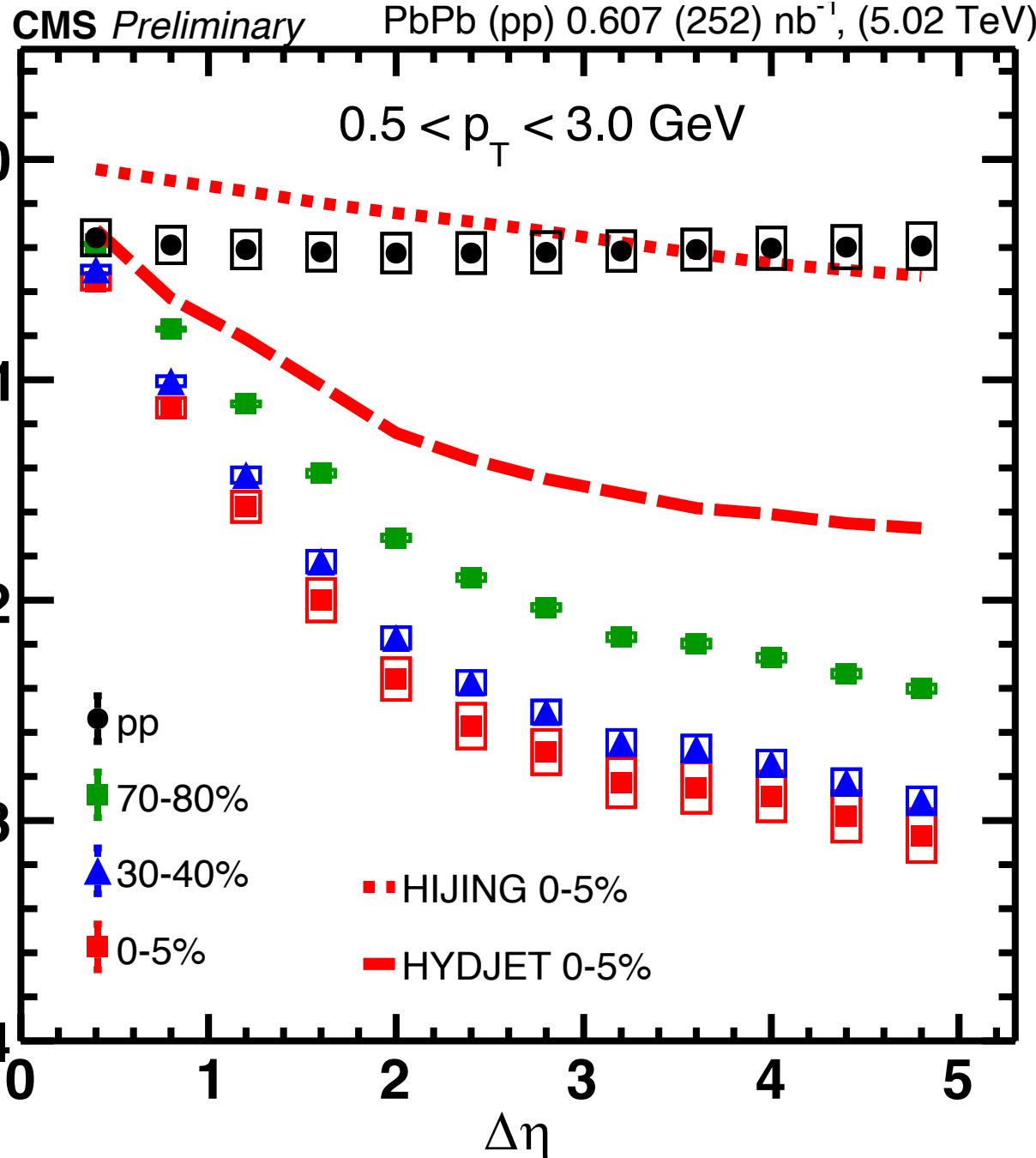
$\nu_{\text{dyn}} > 0$; same sign correlations dominates

$\nu_{\text{dyn}} < 0$; significance of opposite sign correlations dominates



- ✓ $|\nu_{\text{dyn}}|$ value decreases with the increase of η window
- ✓ Smaller $|\nu_{\text{dyn}}|$ value towards the central collision signifies the equilibration of + and - charges

Net-charge fluctuations – $\Delta\eta$

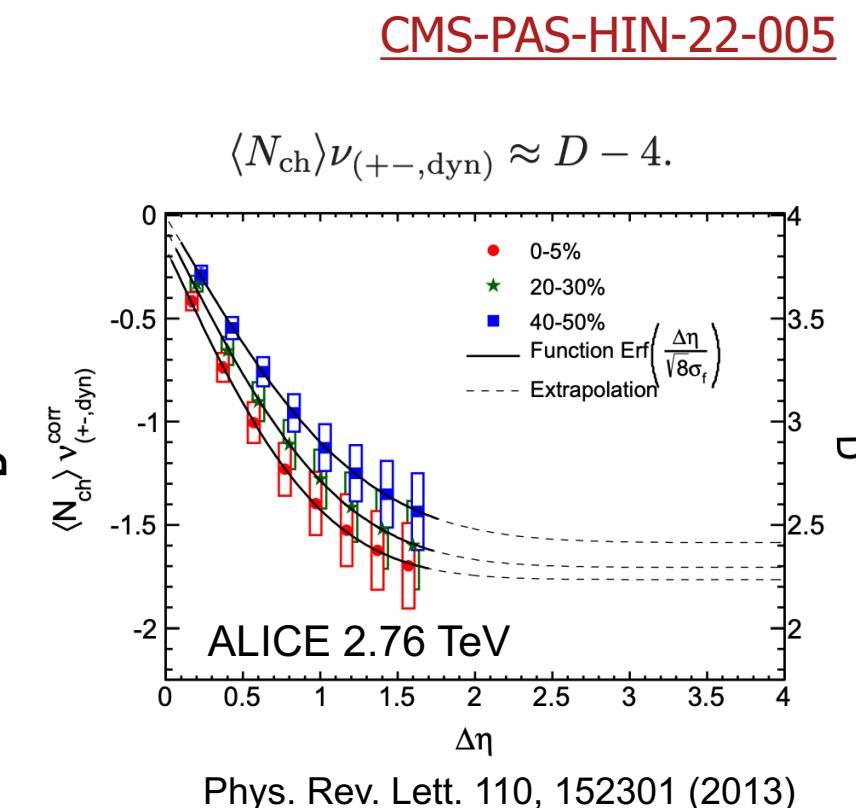
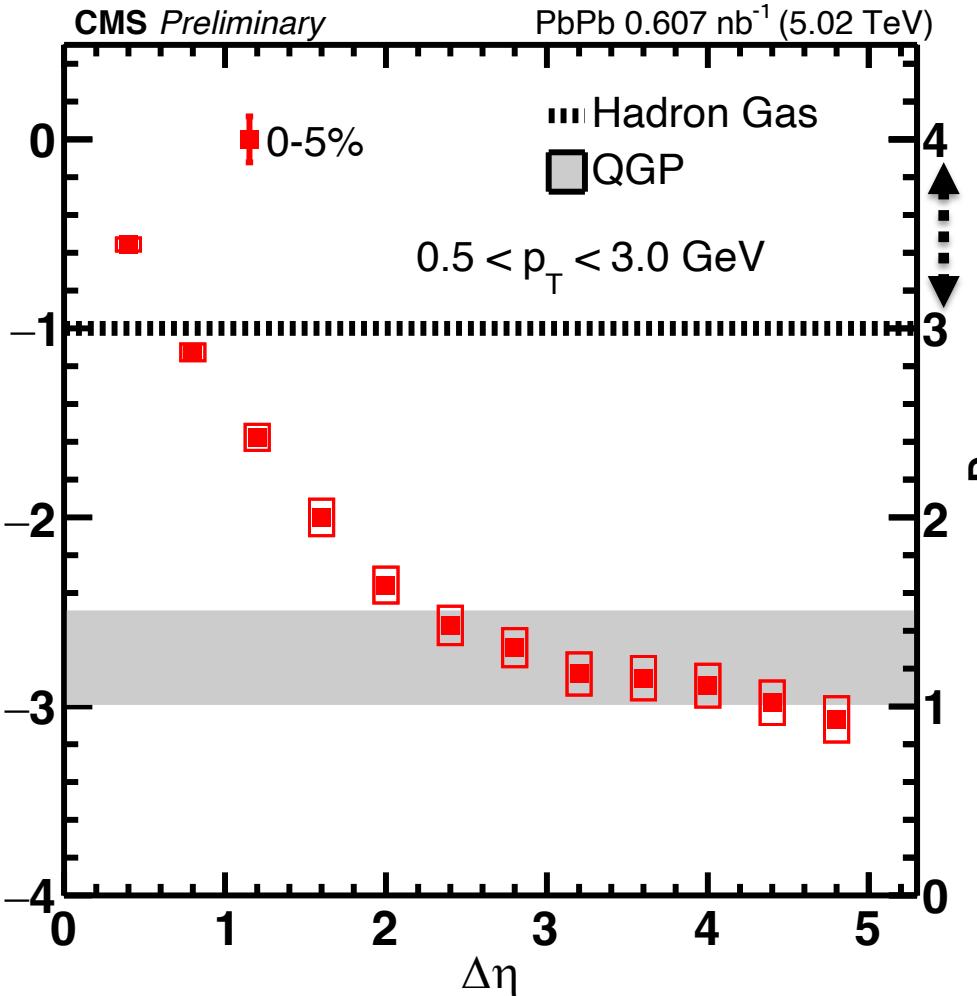
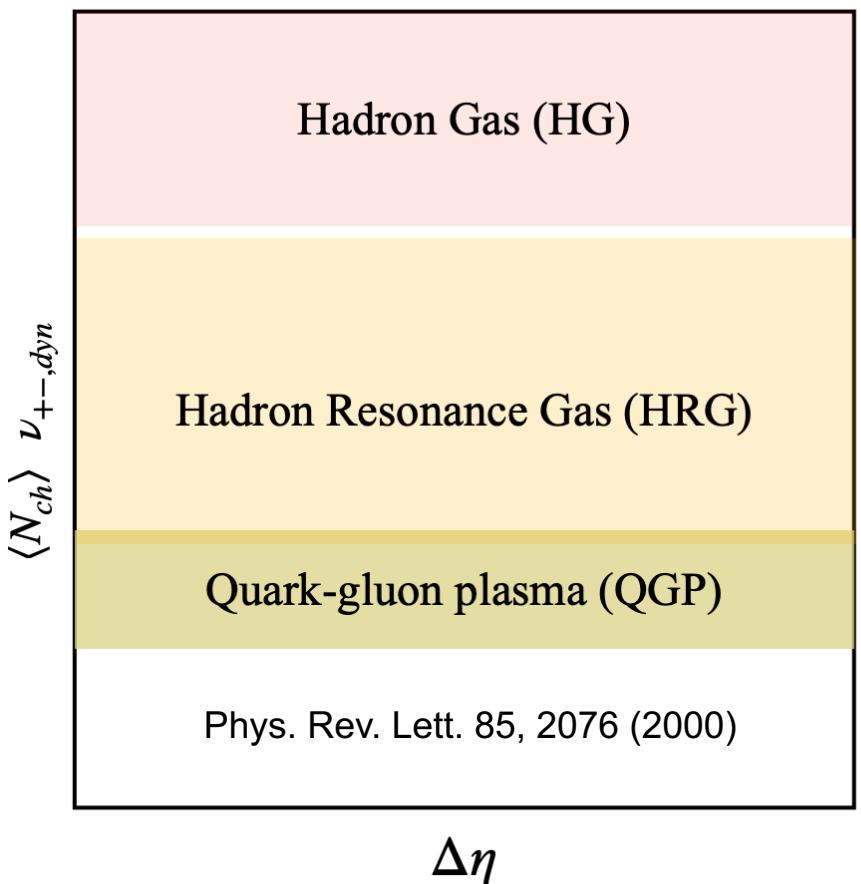


CMS-PAS-HIN-22-005

- ✓ Fluctuations decrease with the increase of $\Delta\eta$ windows
- ✓ HIJING and HYDJET could not explain the experimental data results properly
- ✓ Fluctuations diluted due to diffusion of charged hadrons in rapidity during the evolution of the system



Net-charge fluctuations – D measure

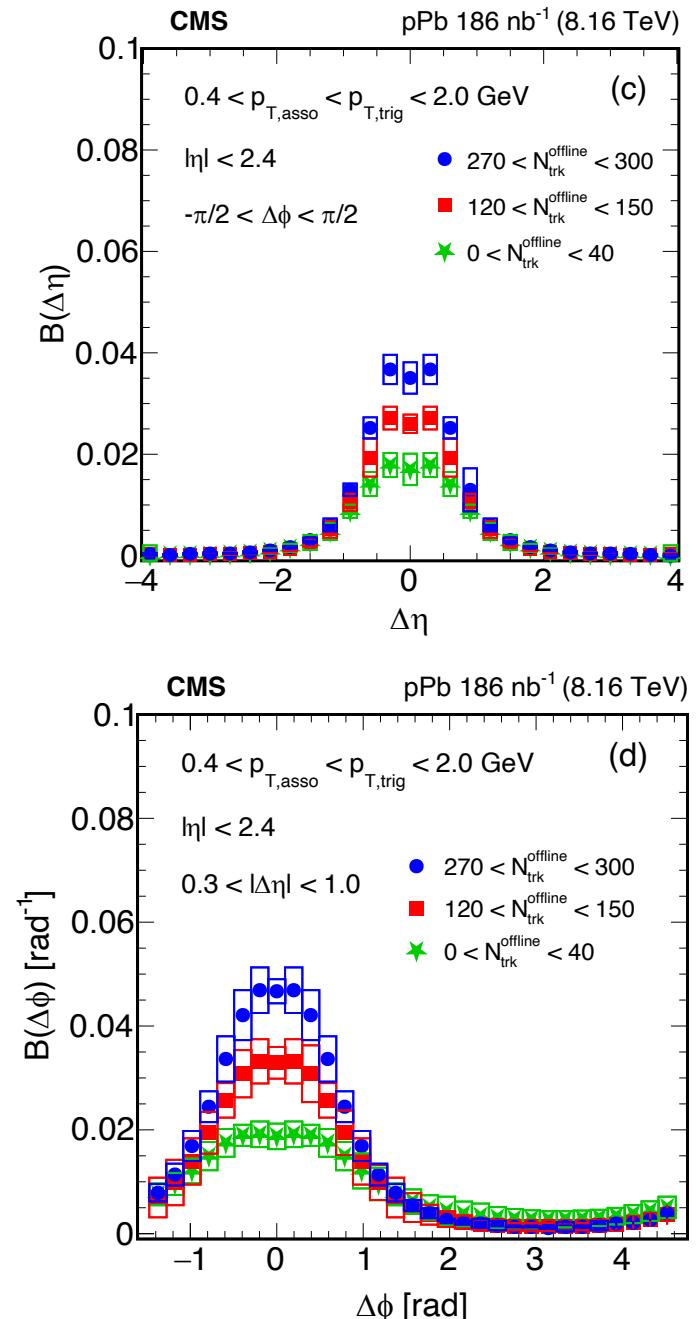
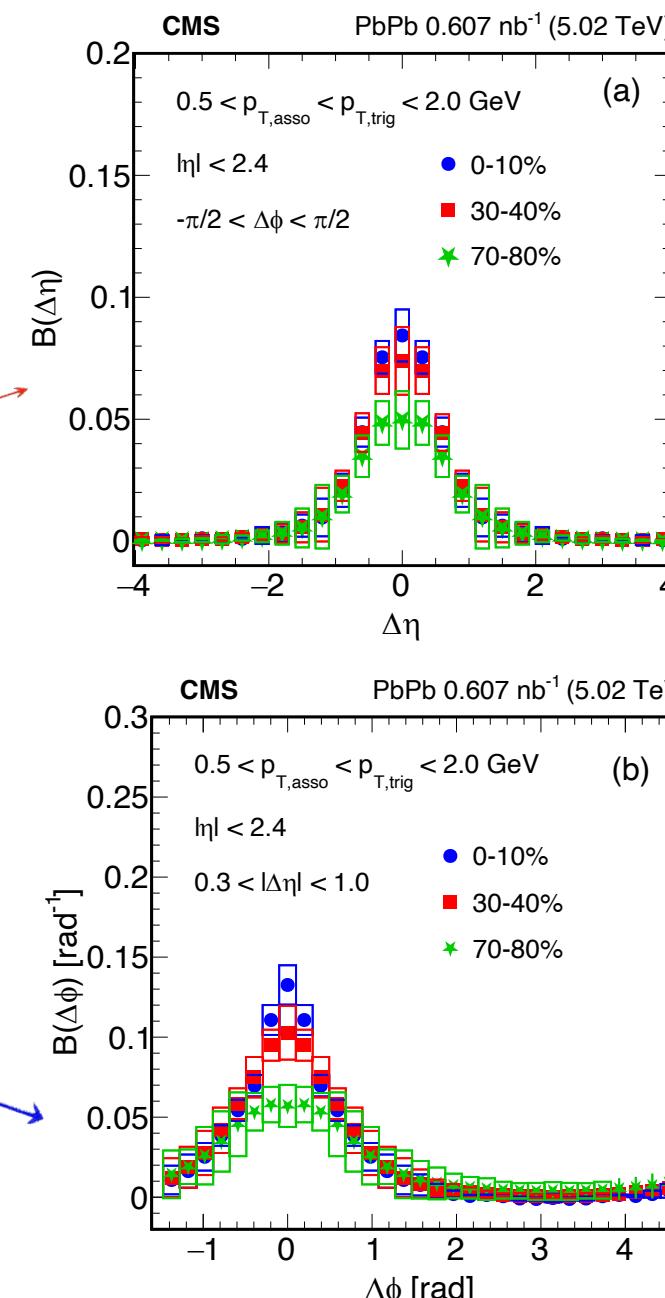
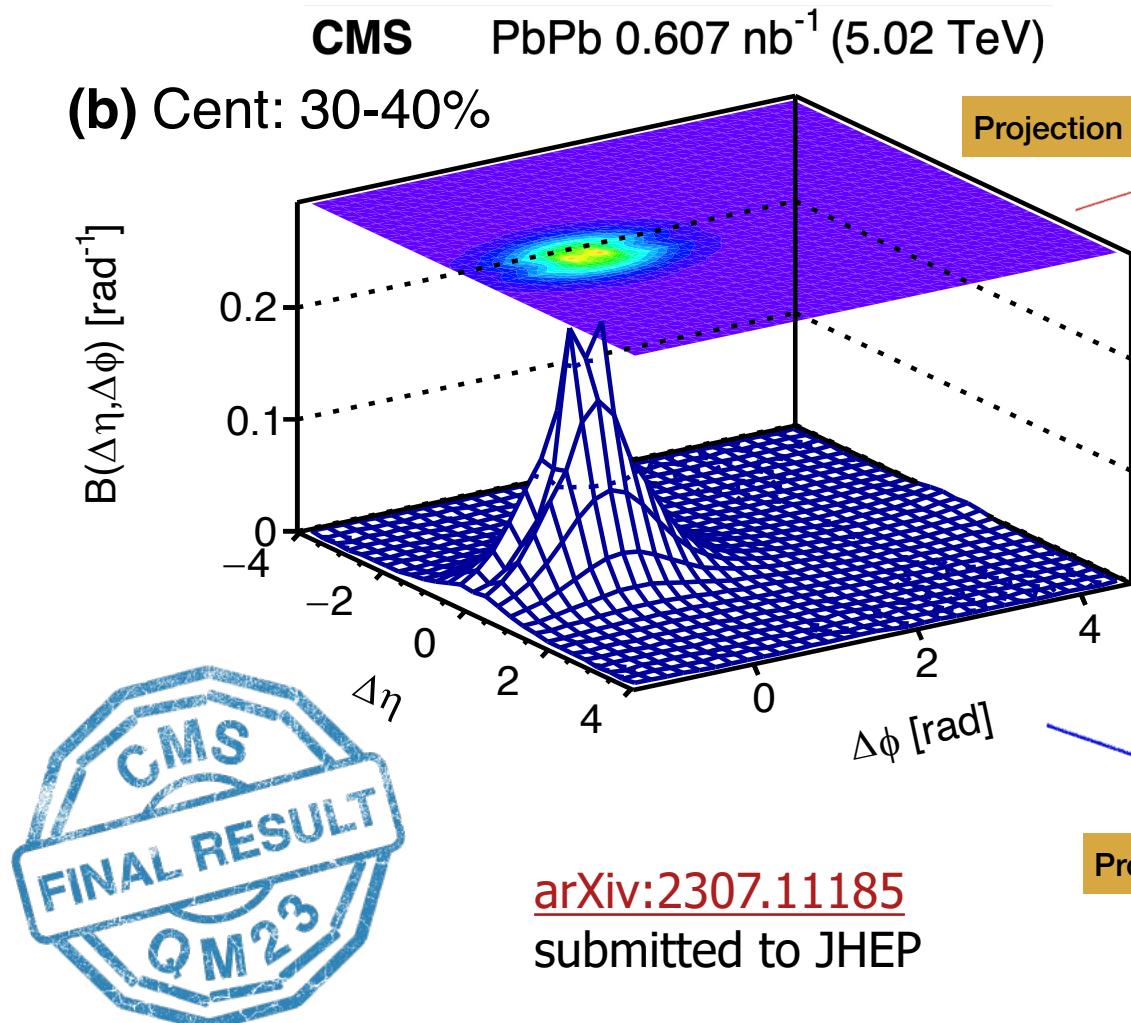


- Comparing to ALICE, CMS results reach lower values of D-measure at larger $\Delta\eta$
- With larger $\Delta\eta$, D-measure reaches the fluctuations predicted with QGP



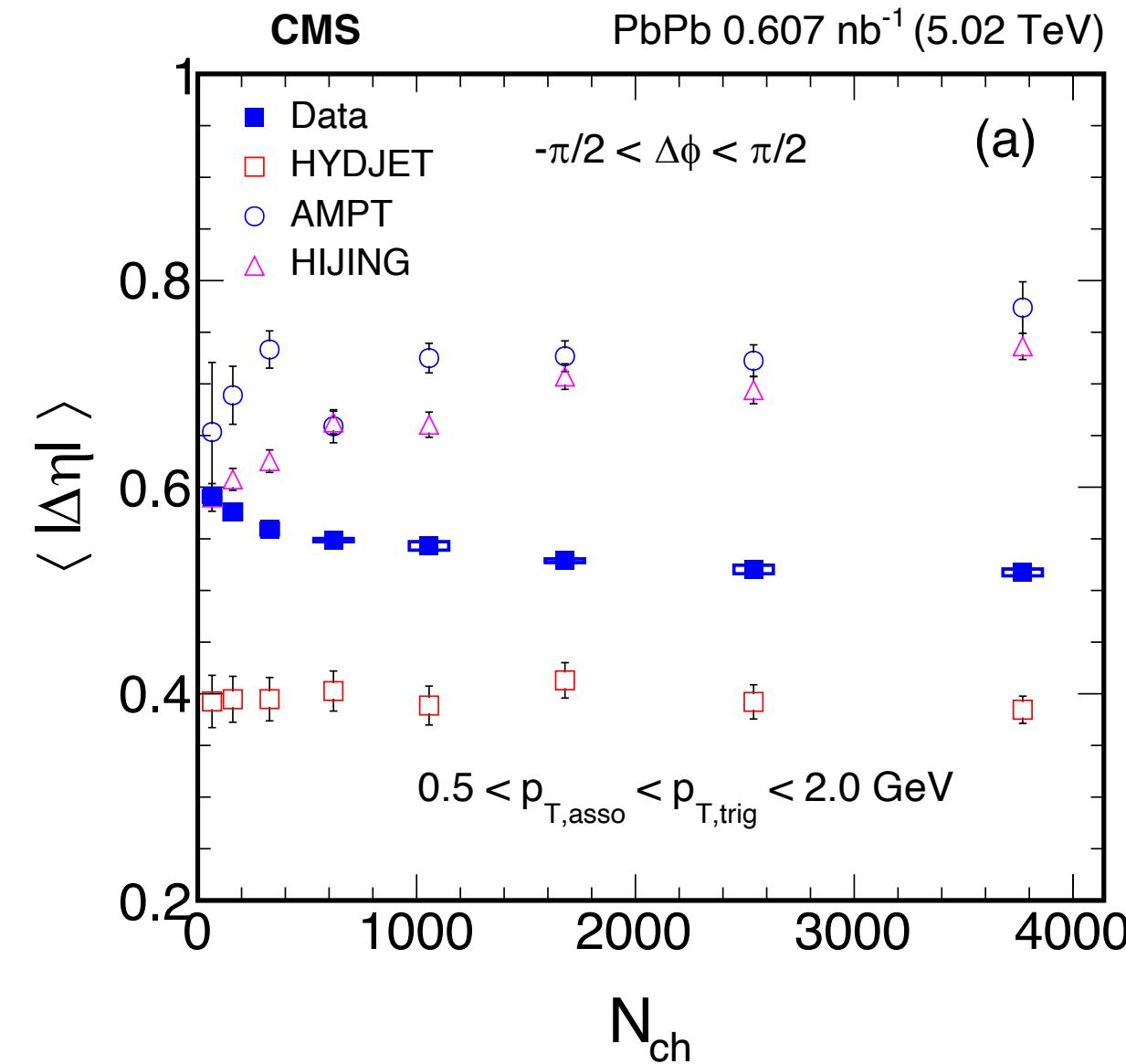
Balance functions – PbPb and pPb

$$B(\Delta\eta, \Delta\varphi) = \frac{1}{2} [C(+,-) + C(-,+)] - [C(-,-) - C(+,+)]$$

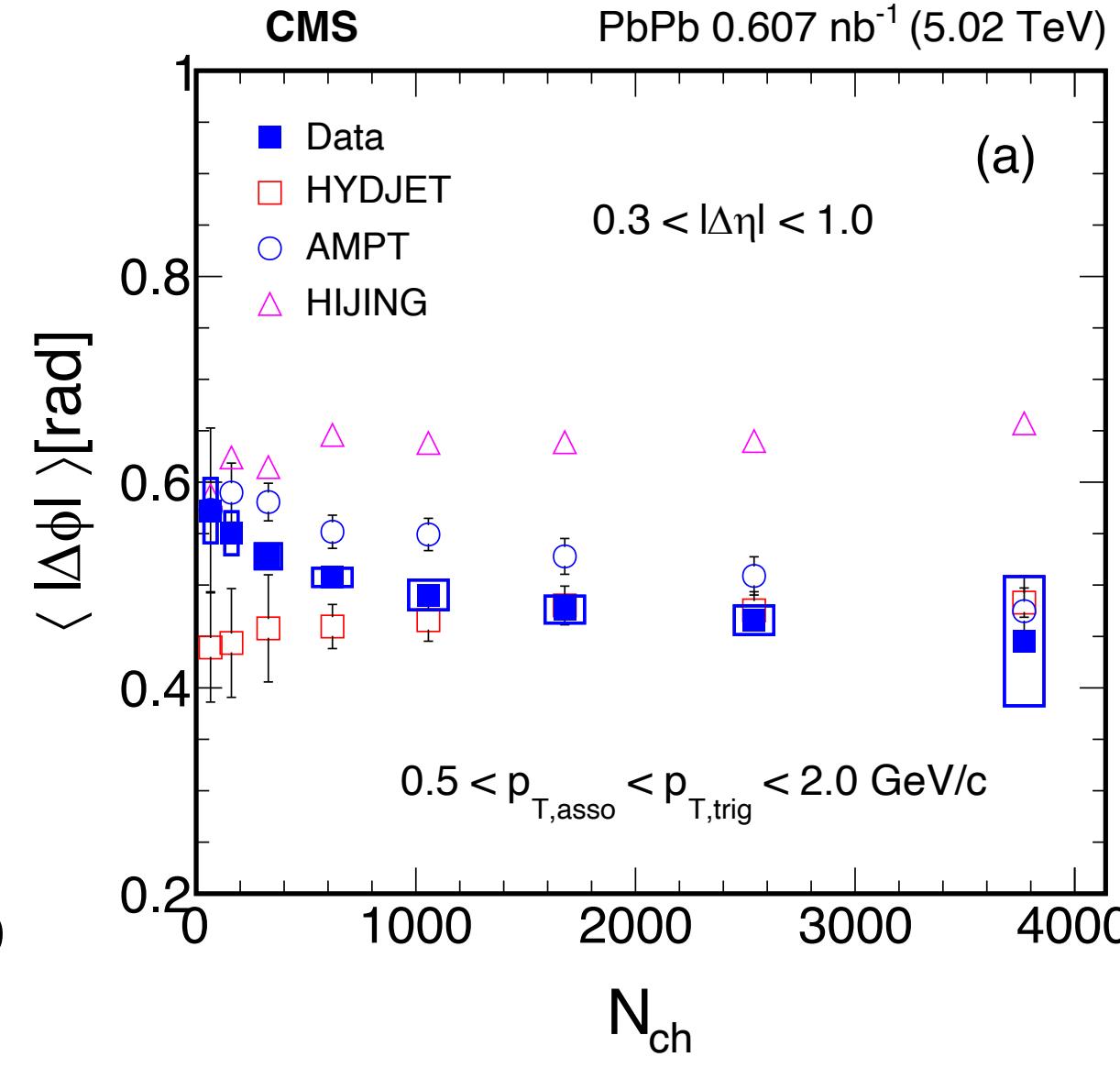


$\langle |\Delta\eta| \rangle$ and $\langle |\Delta\varphi| \rangle$ vs. multiplicity class – PbPb

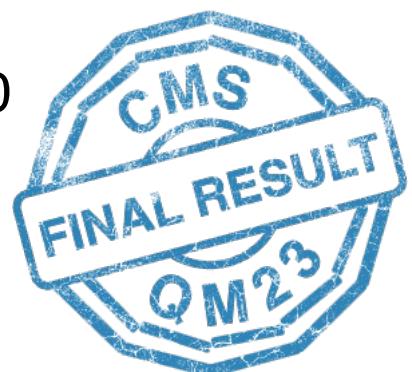
arXiv:2307.11185
submitted to JHEP



- Narrowing of the balance function with increasing multiplicity in $\Delta\eta$ and $\Delta\varphi$

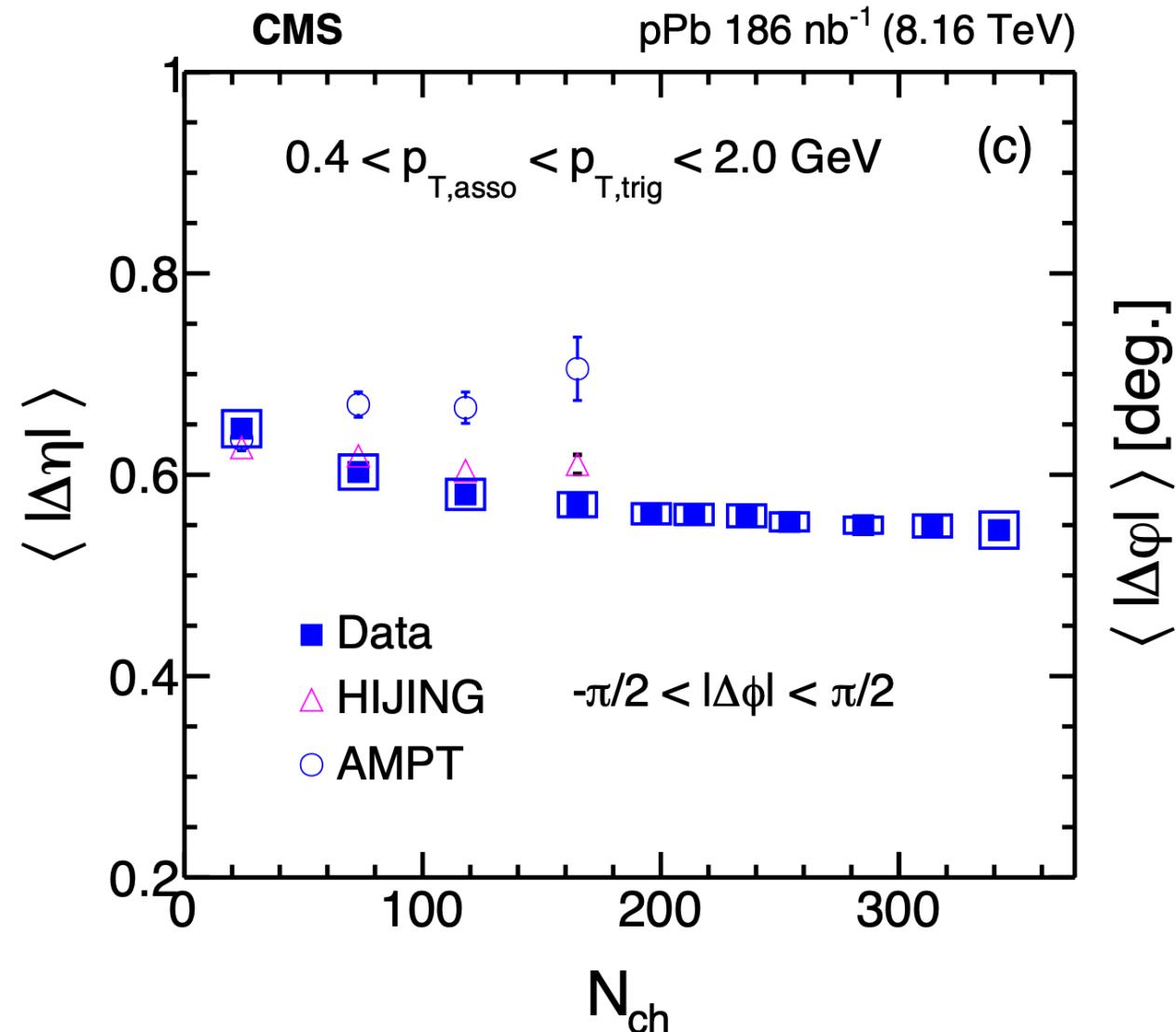


- Data not described by models in $\Delta\eta$
- Narrowing in $\Delta\varphi$ described by AMPT

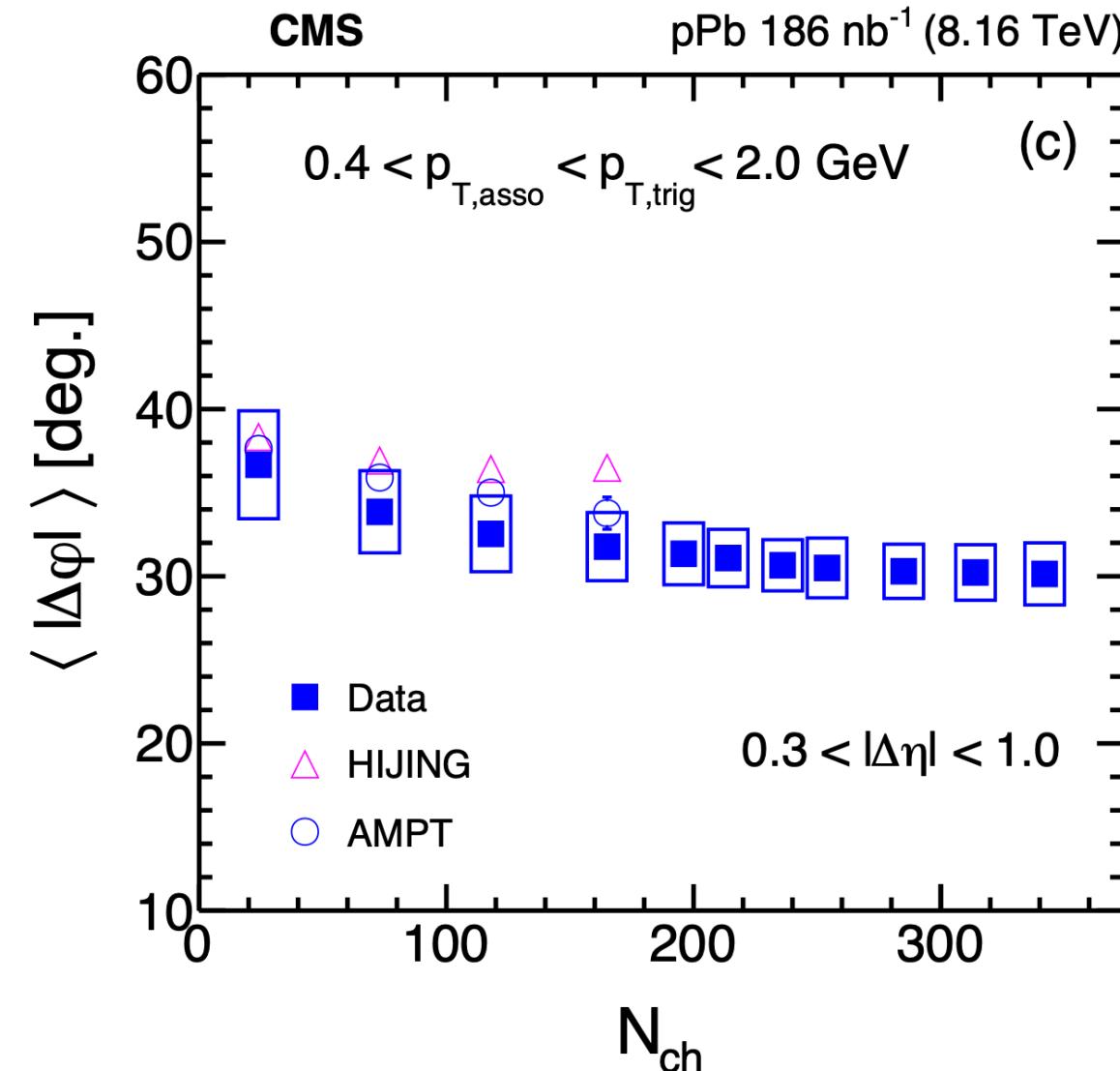


$\langle |\Delta\eta| \rangle$ and $\langle |\Delta\varphi| \rangle$ vs. multiplicity class – pPb

arXiv:2307.11185
submitted to JHEP



- Narrowing of the balance function with increasing multiplicity in $\Delta\eta$ and $\Delta\varphi$



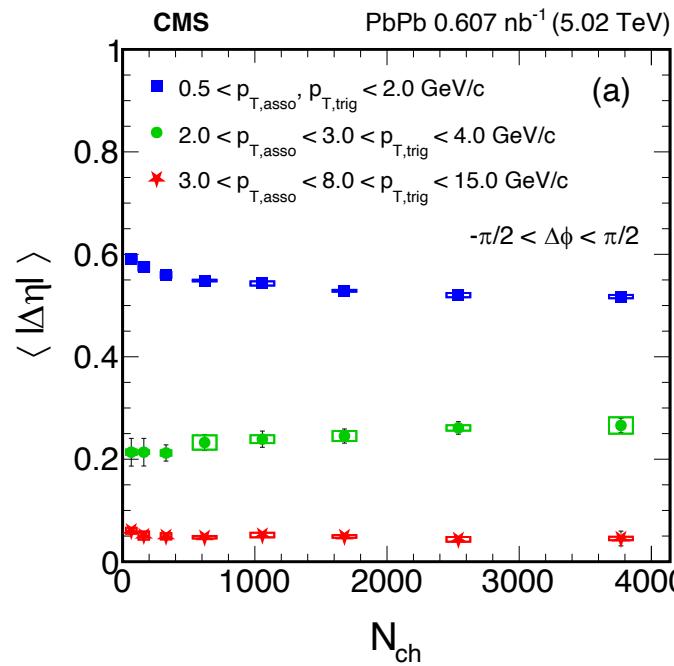
- Narrowing in $\Delta\varphi$ described by AMPT



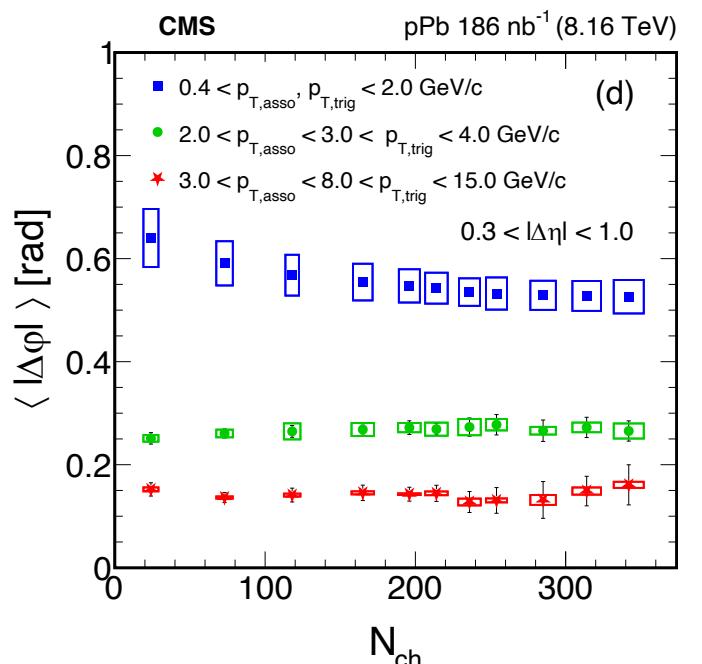
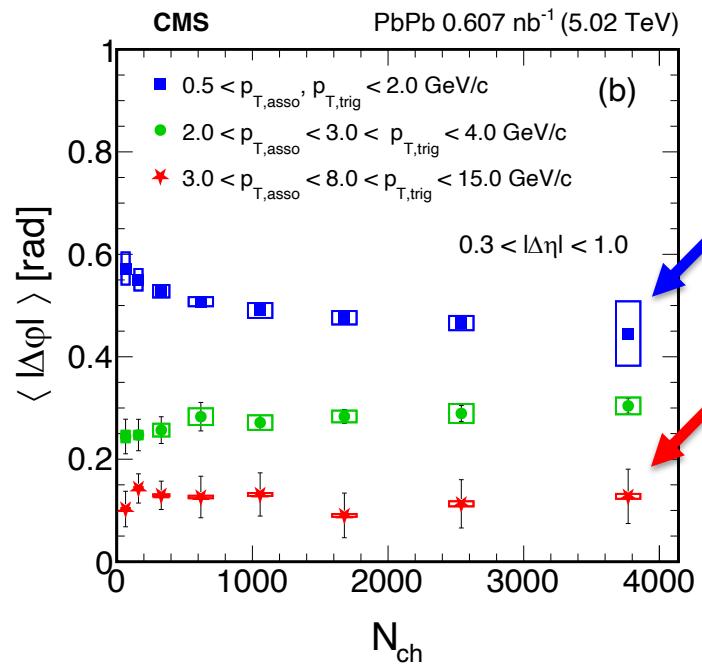
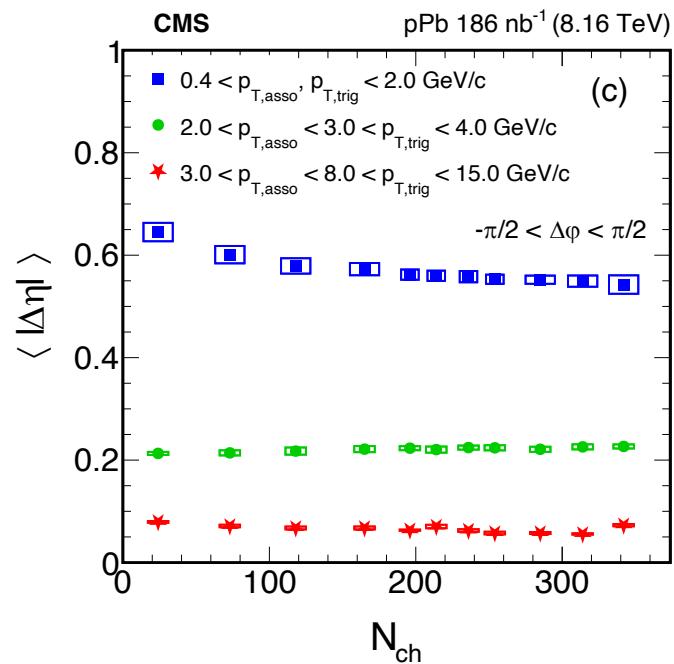
$\langle |\Delta\eta| \rangle$ and $\langle |\Delta\varphi| \rangle$ – p_T dependence

arXiv:2307.11185
submitted to JHEP

PbPb



pPb



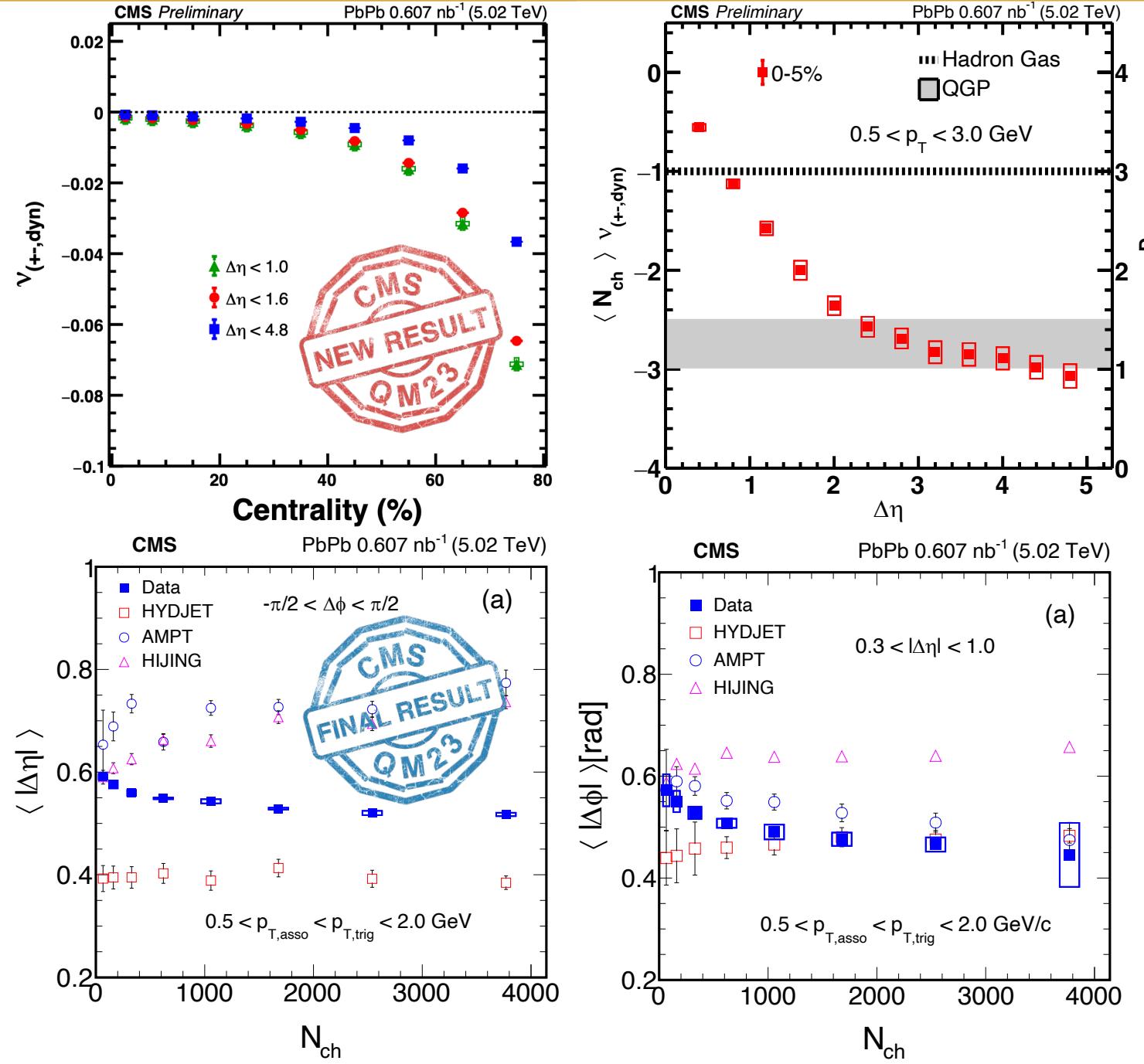
Low p_T

Higher p_T

- Balance function become narrower with increasing in p_T
- Less multiplicity dependence is observed for higher p_T
- Narrowing of the balance functions in low- p_T region is the effect from the bulk



Summary



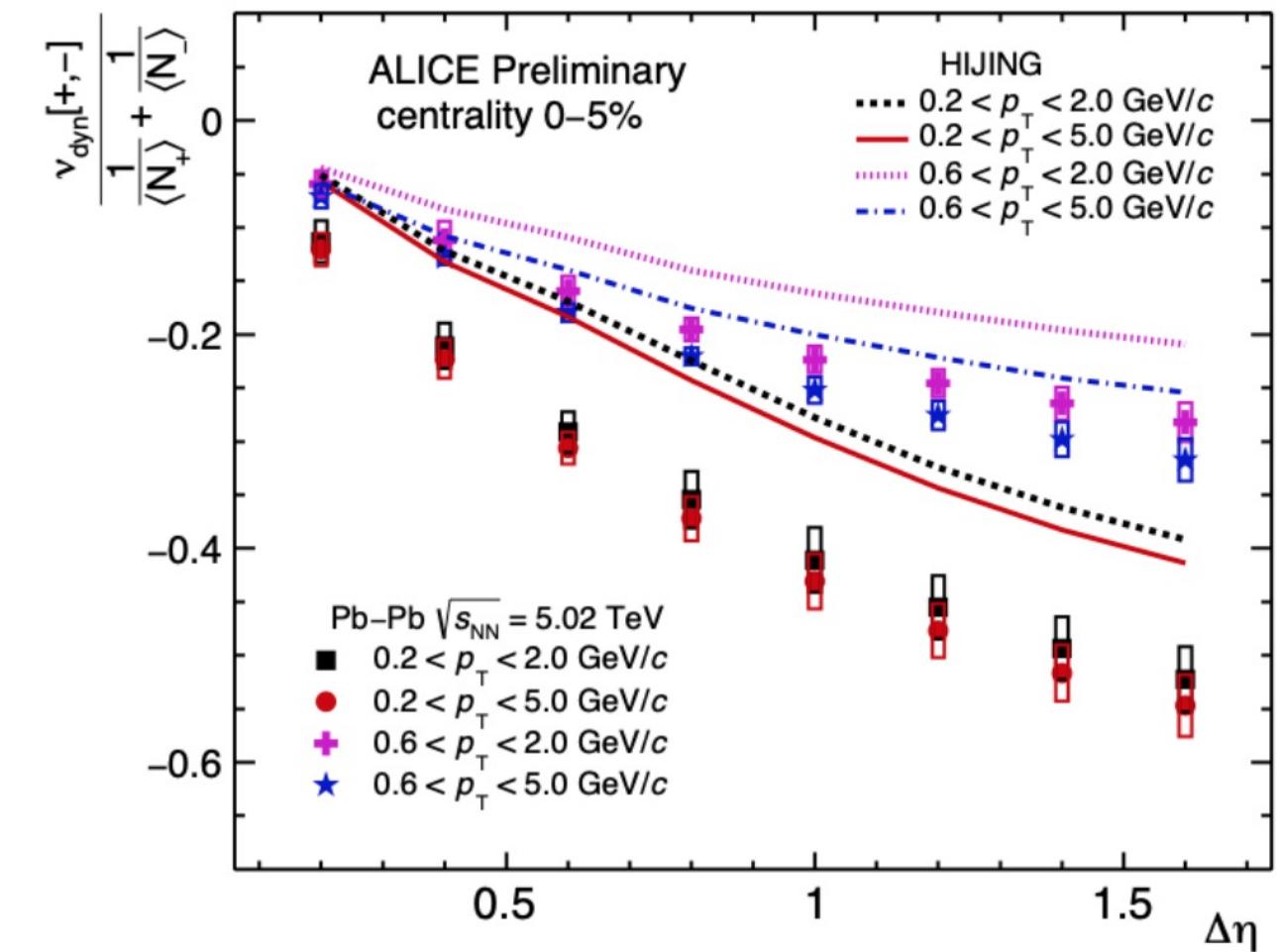
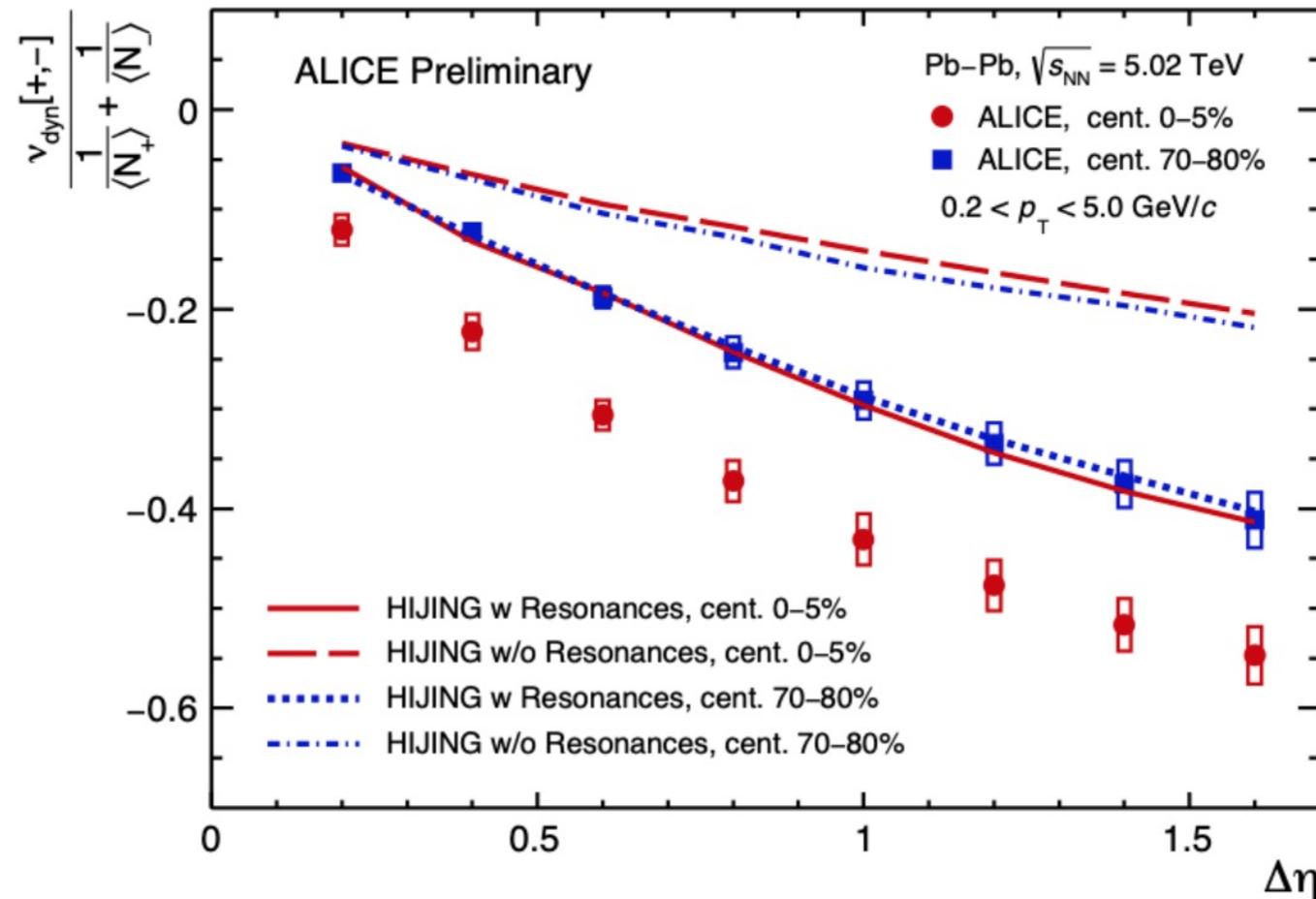
- v_{dyn} value decreases with the increase of $\Delta\eta$ windows and saturating towards central collisions
- ✓ D-measure reaches the fluctuations predicted with QGP
- Narrowing of the width with increasing multiplicities is consistent with the delayed hadronization
- Narrowing in $\Delta\phi$ of the balance function from AMPT shows a similar trend observed in data
- Width does not depends on multiplicity for higher p_T

A similar trend is observed in pPb collisions

Backup

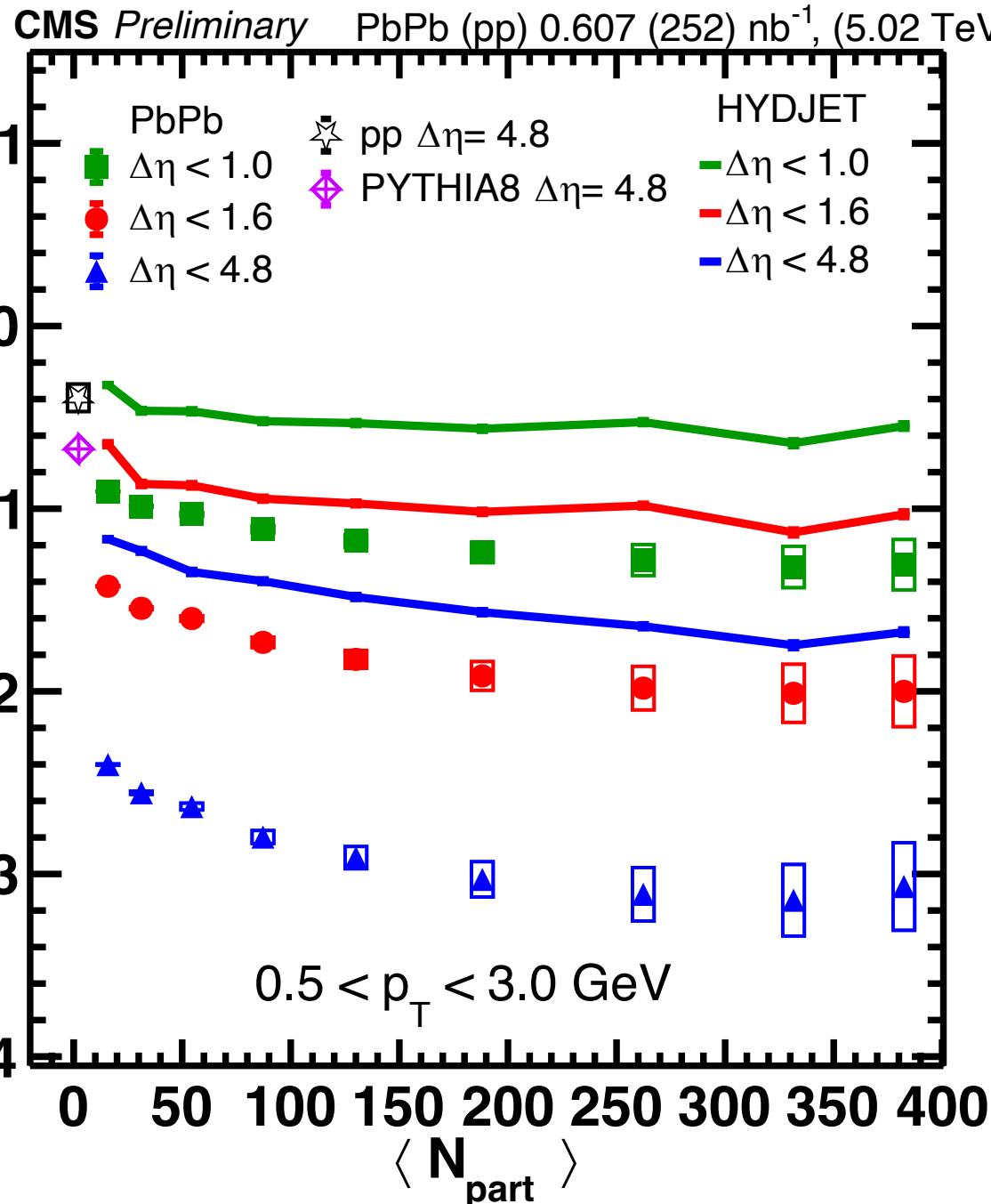
Resonance decays and minijets – net charge fluctuations

PoS EPS-HEP2021 (2022) 319



- The influence of resonance decays and minijets on net-charge fluctuations

Net-charge fluctuations – $\langle N_{part} \rangle$



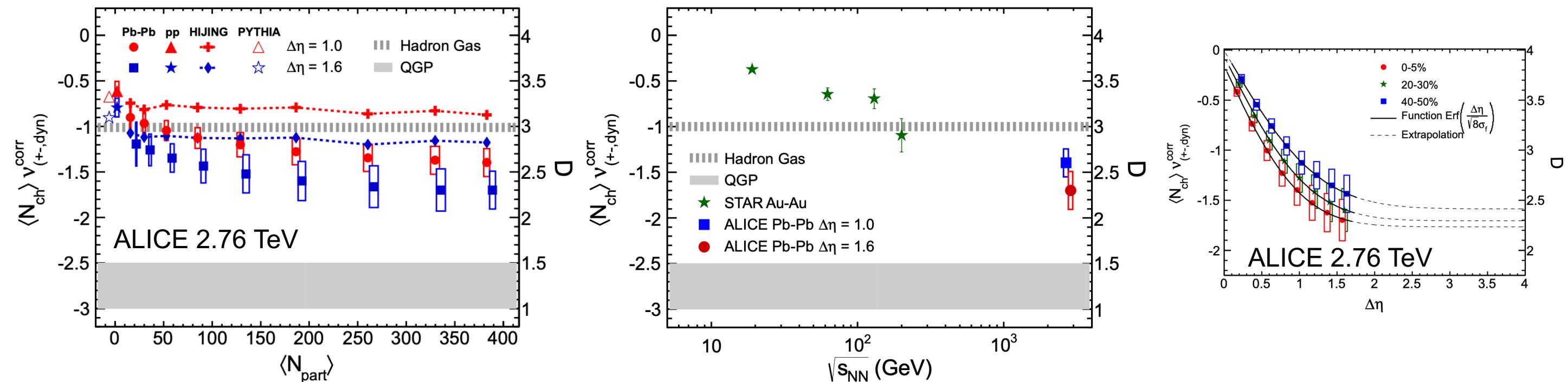
[CMS-PAS-HIN-22-005](#)

- ✓ Fluctuations decrease as $\langle N_{part} \rangle$ increases
- ✓ HYDJET could not explain the experimental data results properly
- ✓ Fluctuations diluted due to diffusion of charged hadrons in rapidity during the evolution of the system



Previous Measurements – net-charge fluctuations

- STAR: Limited by lower energy and rapidity window ($\Delta\eta = 1$)
Phys. Rev. C 79, 024906 (2009)
- ALICE: Limited by lower rapidity window ($\Delta\eta = 1.6$)
Phys. Rev. Lett. 110, 152301 (2013)



- This analysis measures the net-charge fluctuations to larger $\Delta\eta$ at a higher collision energy