Charge balance function & fluctuation with CMS

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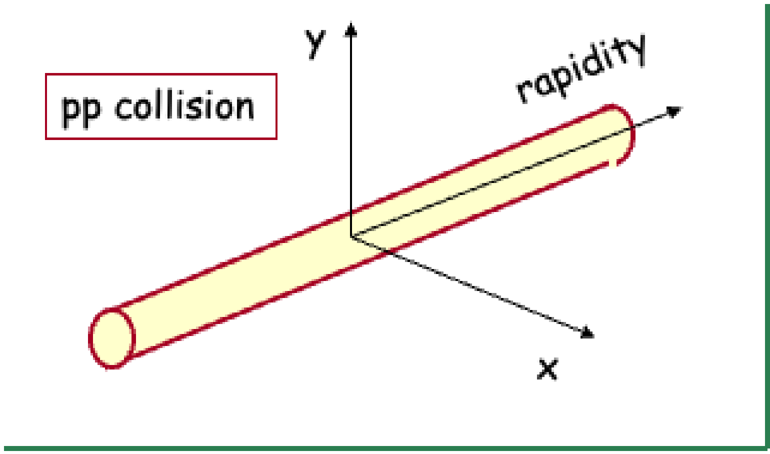
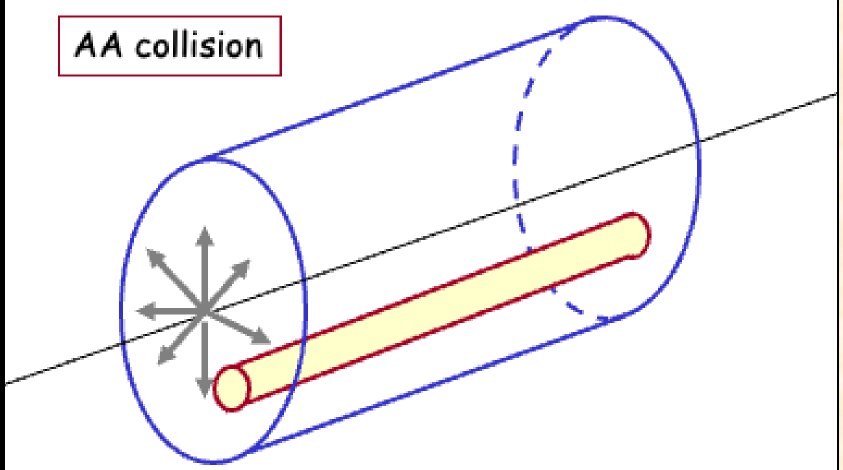
Outline

- Correlation functions, balance functions, fluctuations
- Main results from CMS charge-particle balance functions measurements
  - Centrality (multiplicity) and p_T dependence
  - Widening of the rapidity correlations with centrality
  - Narrowing of the Charge Balance Function with centrality
  - Azimuthal Balance functions in $\Delta\phi$ and diffusion
  - Integrals of Balance funtions
  - Dynamical net-ch fluctuations using $\nu_{(+-,dyn)}$
- Summary
- CMS new measurements in progress

Correlation: 'Elementary NN' vs 'AA' collisions



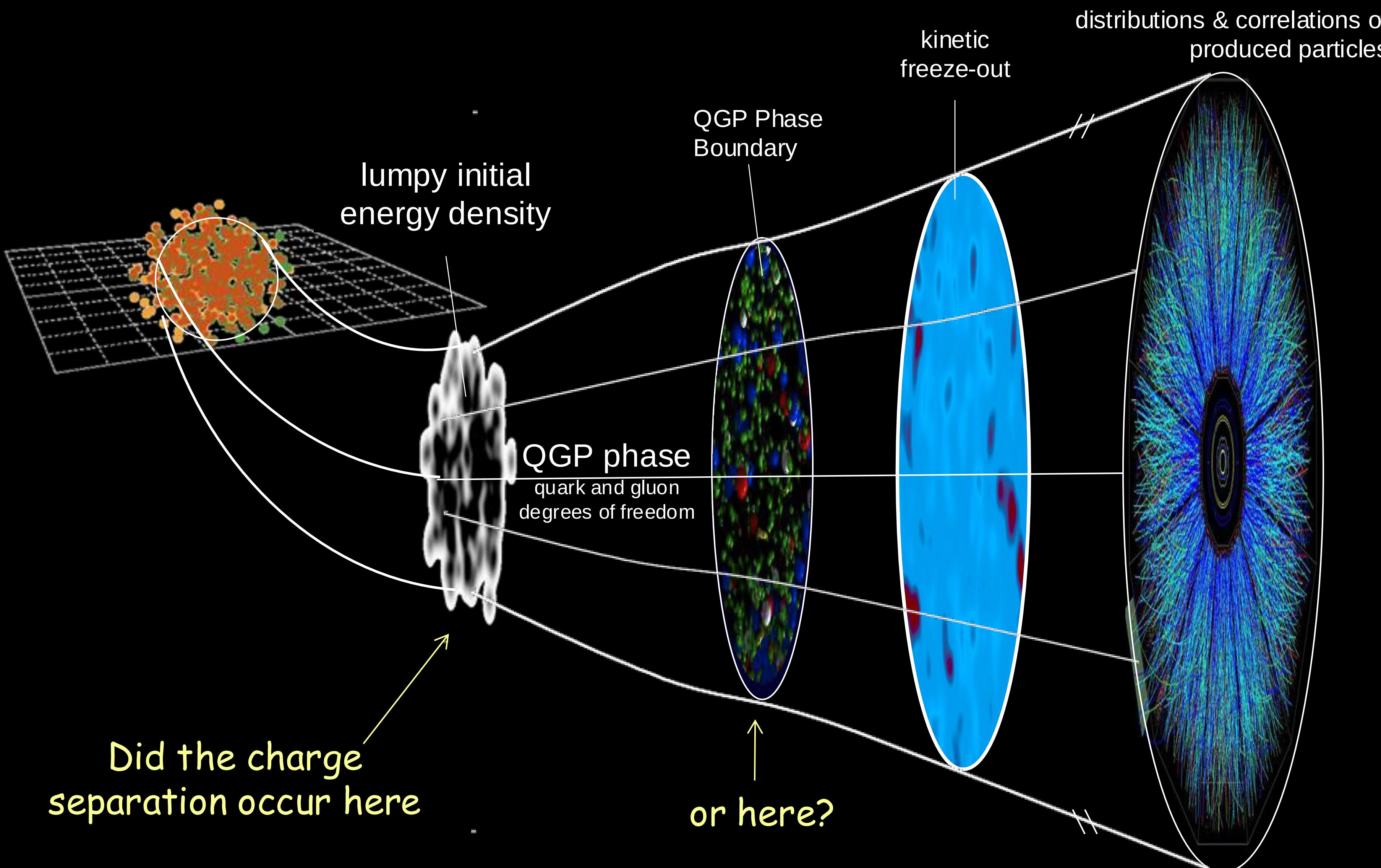


- Correlations are due to local charge(s) conservation, resonances, due to fluctuations in number of produced strings, e.g. number of qq-collisions

- Long range rapidity correlations ("bump" – narrow in phi and wide in rapidity, charge independent)
- Narrowing of the charge balance function: ($\Delta p_z \approx m_t \sinh(\Delta y)$ – increase in mt -> decrease in rapidity separation [same as in S. Pratt et al, in "late hadronization scenario"]
- Charge correlation in phi – Azimuthal Balance function

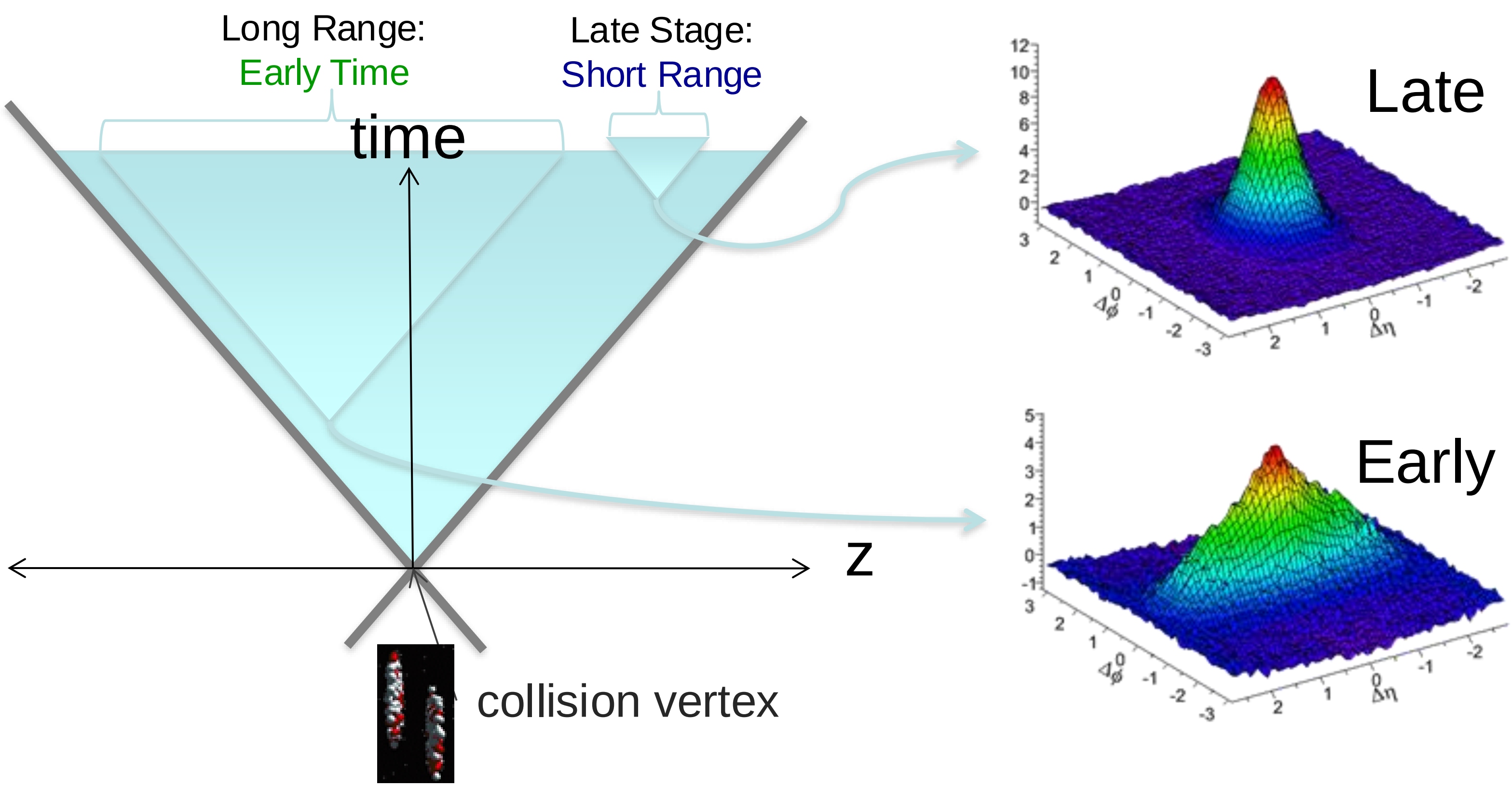
Everything evolving with centrality!

Expansion of the Little Bang



Charge ordering of the ridge and it's width may distinguish

Width of correlations from initial state



The longitudinal width of the correlation is related to the time the correlation was established★

late stage correlation will be narrow in Δη, early times wide

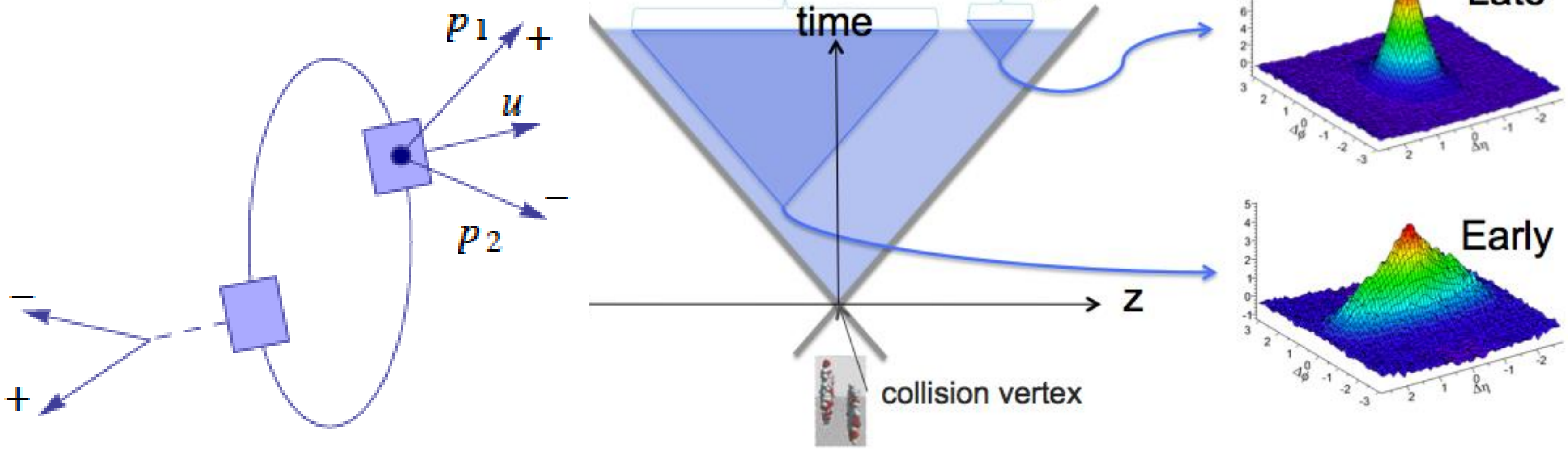
★Dumitru, Gelis, Venugopalan, McLerran: Nucl. Phys.A 810:91,2008

Charge conservation at freezeout

Charge ordering is not unique to jet physics:

-Correlation of conserved charges (Balance Functions): in this case the correlations existed already at the production moment would be modified by radial flow.

P. Bozek and W. Broniowski, arXiv:1204.3580

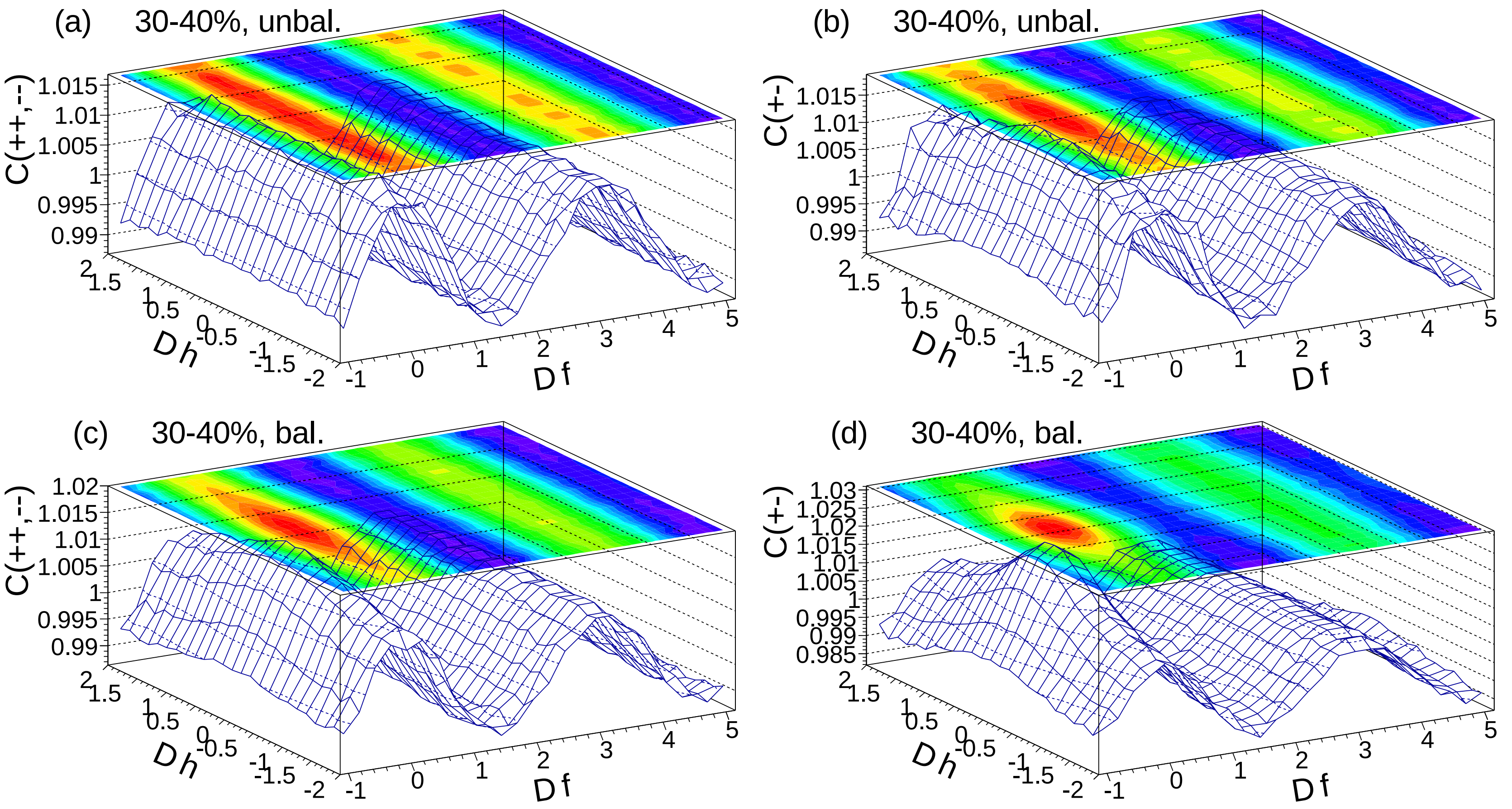


Correlations from the freeze-out surface must be shorter range

Effect on correlations

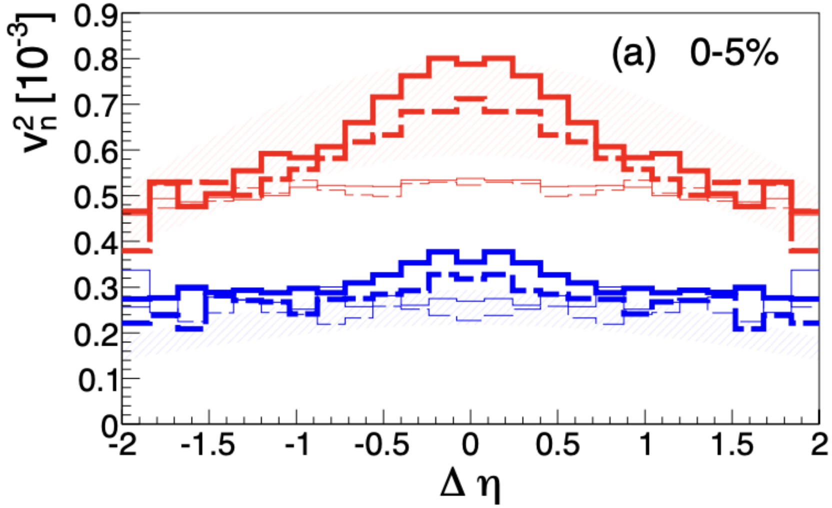
When you enforce charge conservation at the phase boundary, you develop a narrow charge dependent structure

P. Bozek and W. Broniowski, arXiv:1204.3580

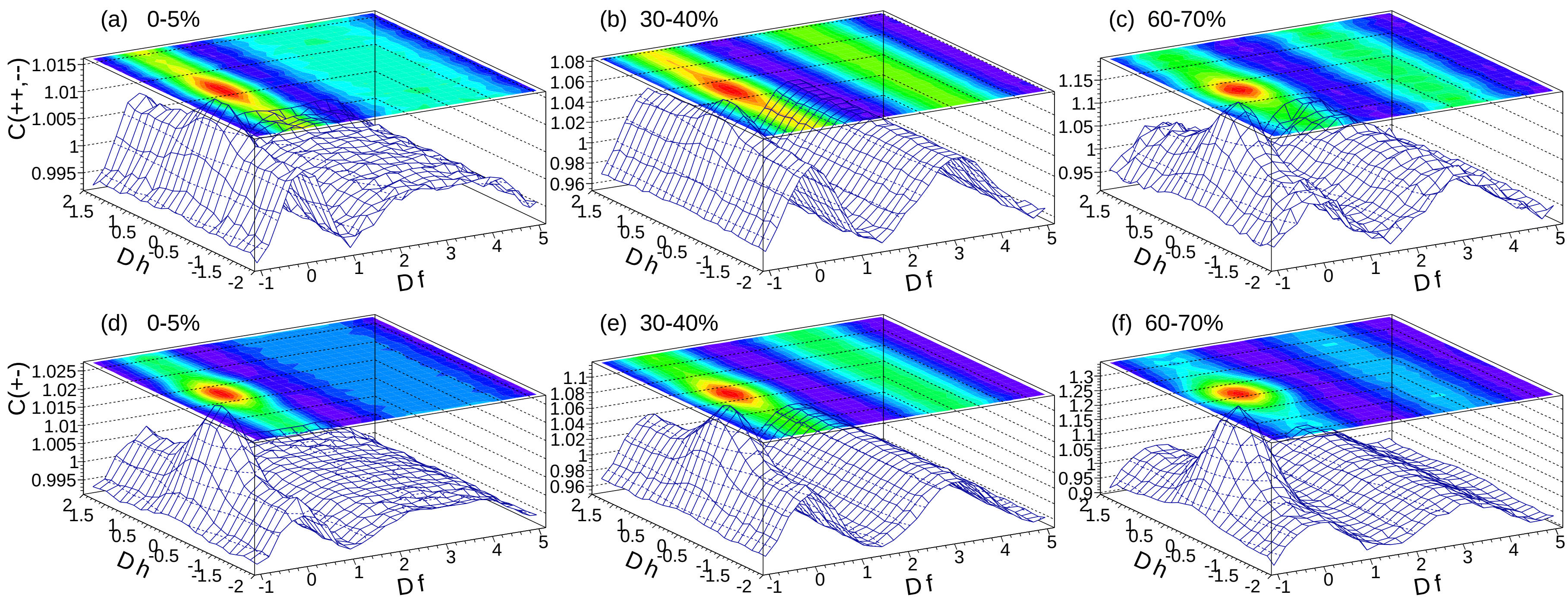


Effect on correlations

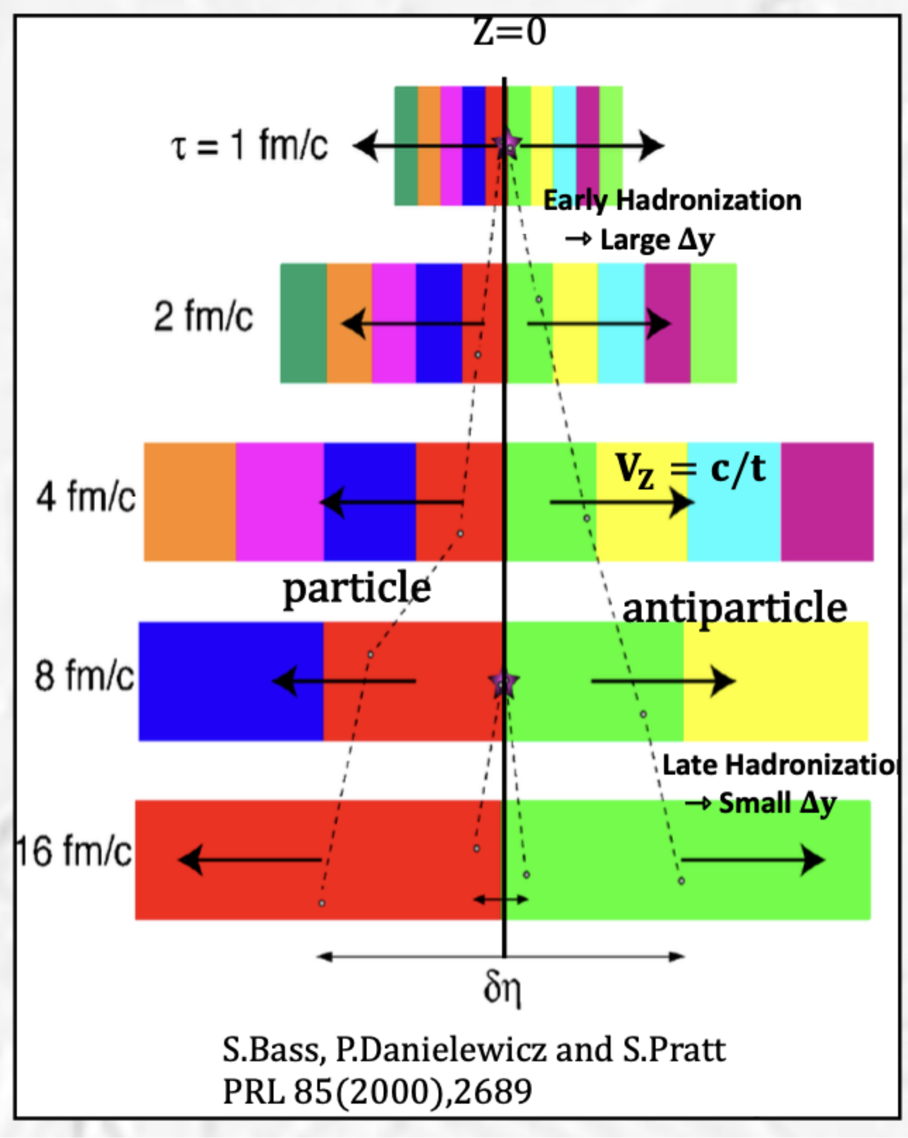
Calculation nicely captures trends in the data. Charge ordering is a general feature not requiring jets



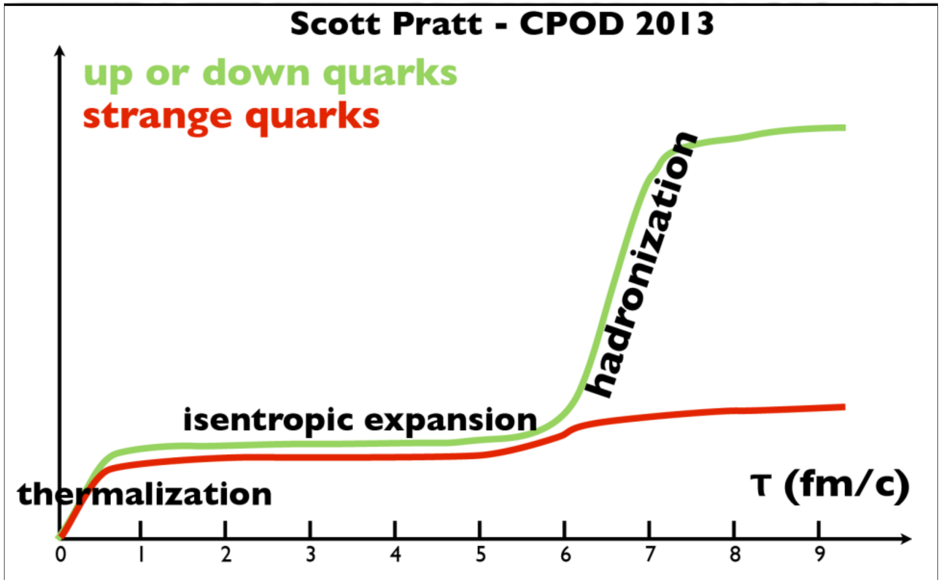
P. Bozek and W. Broniowski, arXiv:1204.3580



Clocking Hadronization



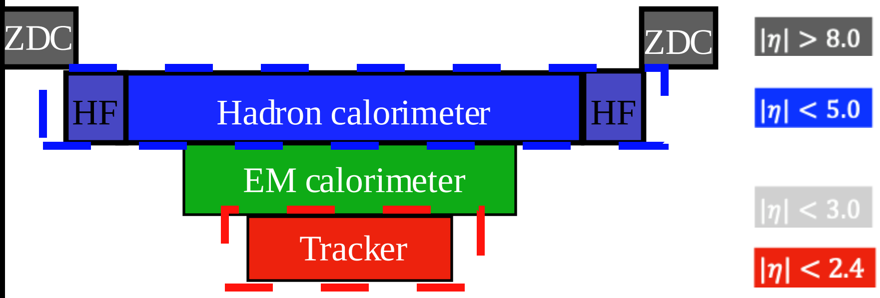
- "Two-wave" picture of particle production mechanism

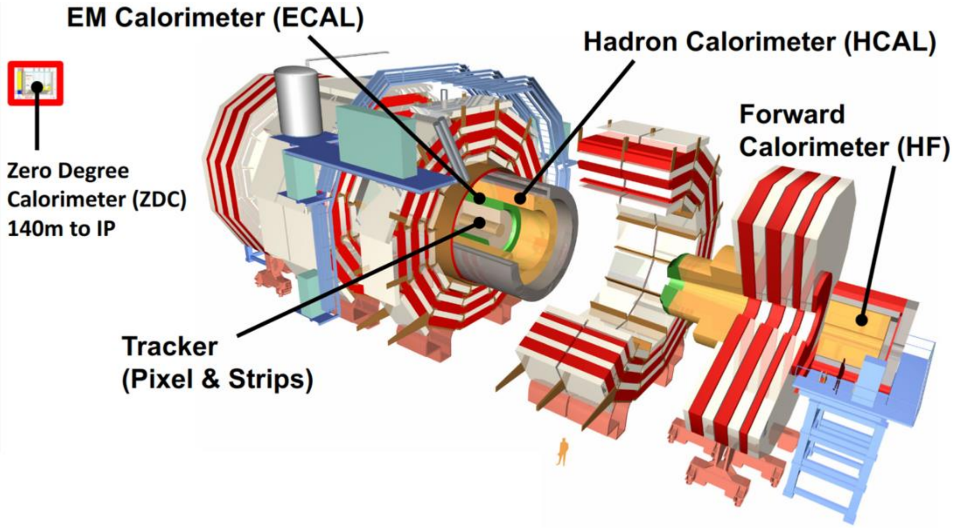


- Used to 'claim' for late hadronization in central collisions and early hadronization in peripheral collisions

CMS detector and data set

Data set: PbPb 2018 data set at $\sqrt{s_{NN}}$ = 5.02 TeV
pPb 2016 data set at $\sqrt{s_{NN}}$ = 8.16 TeV





Why CMS Detector?
- Good precision
- Large rapidity coverage

Ideal for capturing balancing partners and initial state fluctuations

Kinematic selection:
- $p_T > 0.5$ GeV/c (PbPb)
  $p_T > 0.4$ GeV/c (pPb)
- $|\eta| < 2.4$

Charge Balance function in PbPb

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

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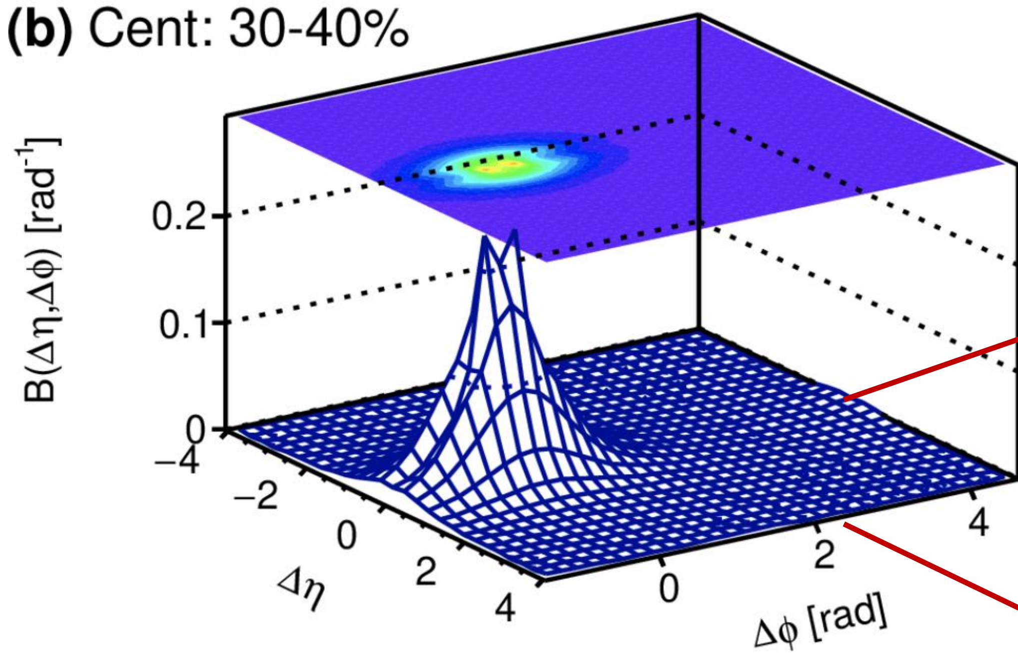
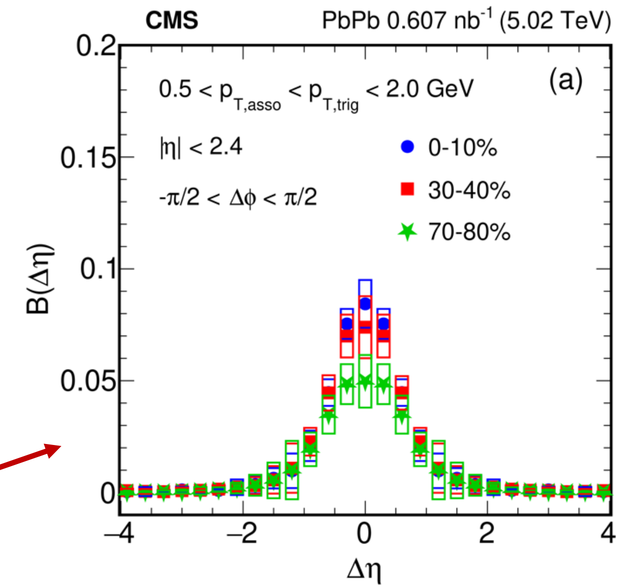
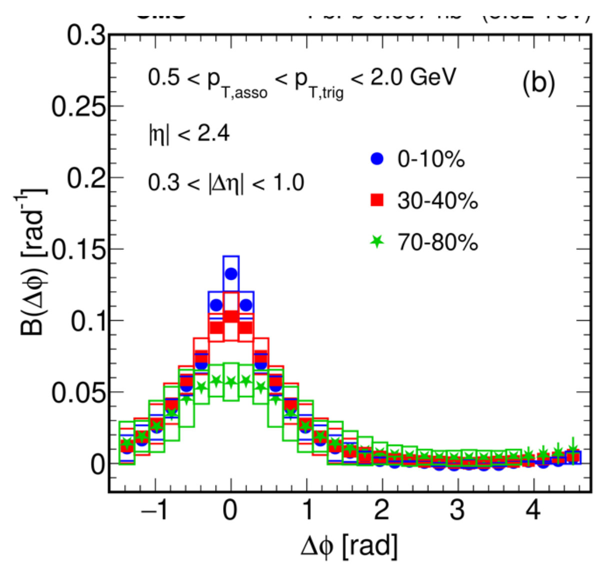


Δη

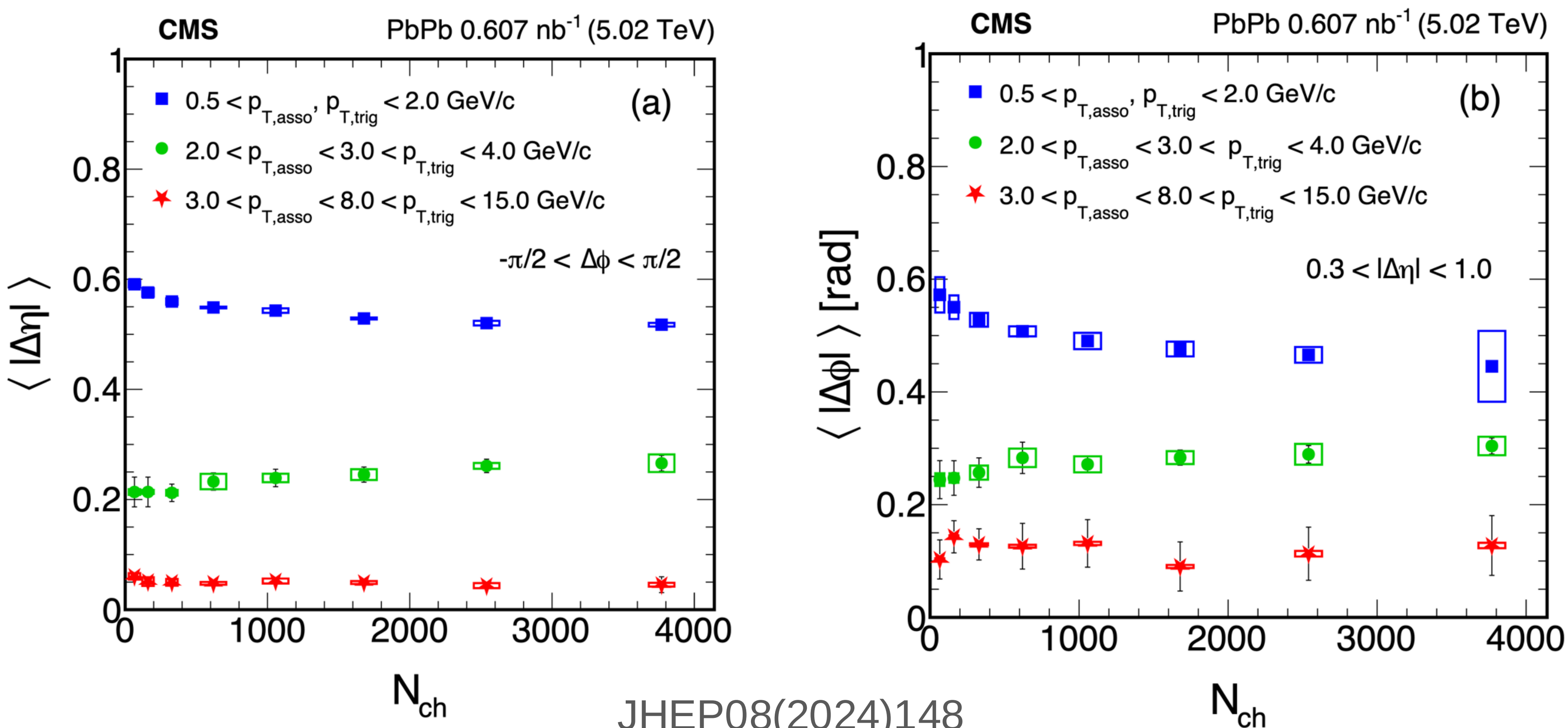


Δϕ



Narrowing of the charge balance function is observed from peripheral to central PbPb collisions in Δη and Δϕ.

Quantifying balance function width in PbPb



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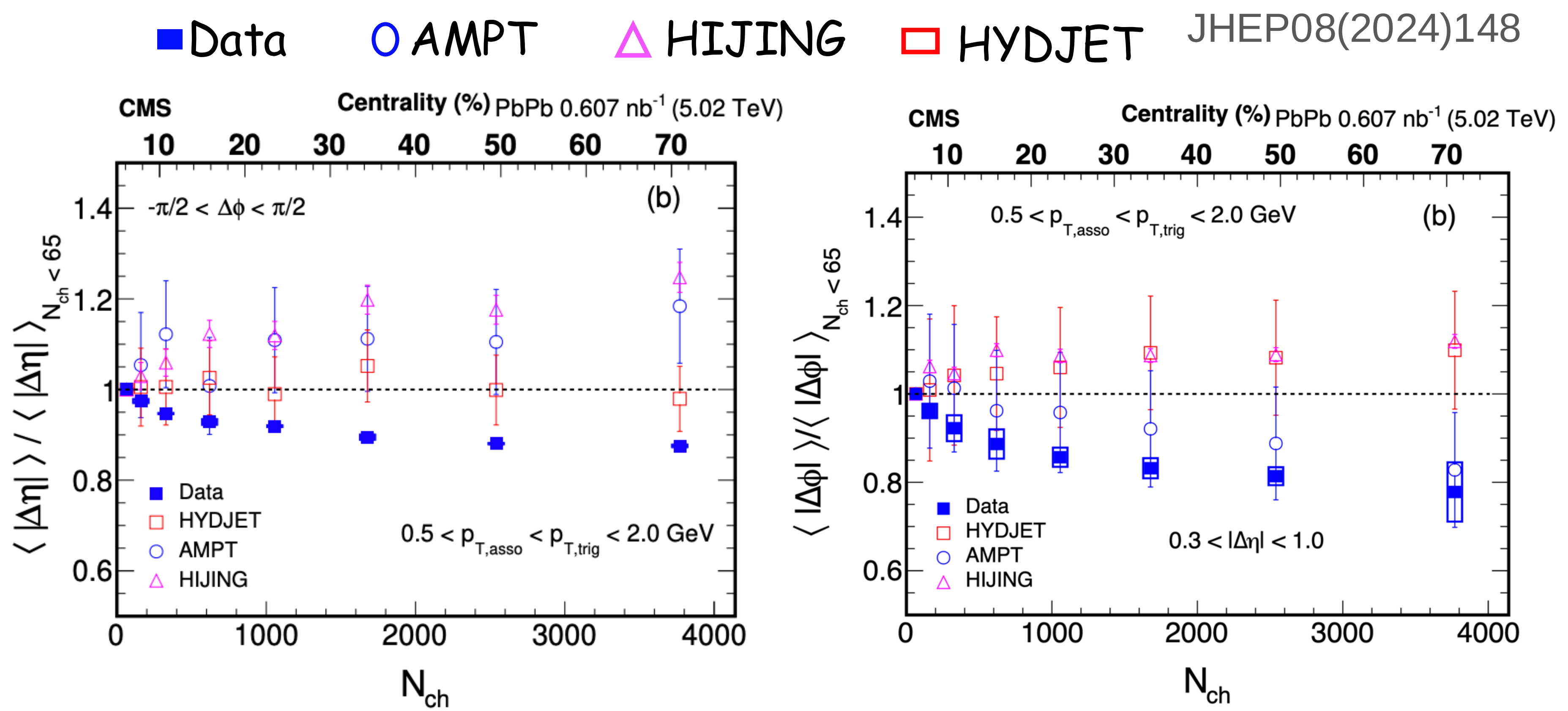
$$\langle|\Delta\eta|\rangle = \frac{\sum_i B(\Delta\eta_i)|\Delta\eta_i|}{\sum_i B(\Delta\eta_i)}$$

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

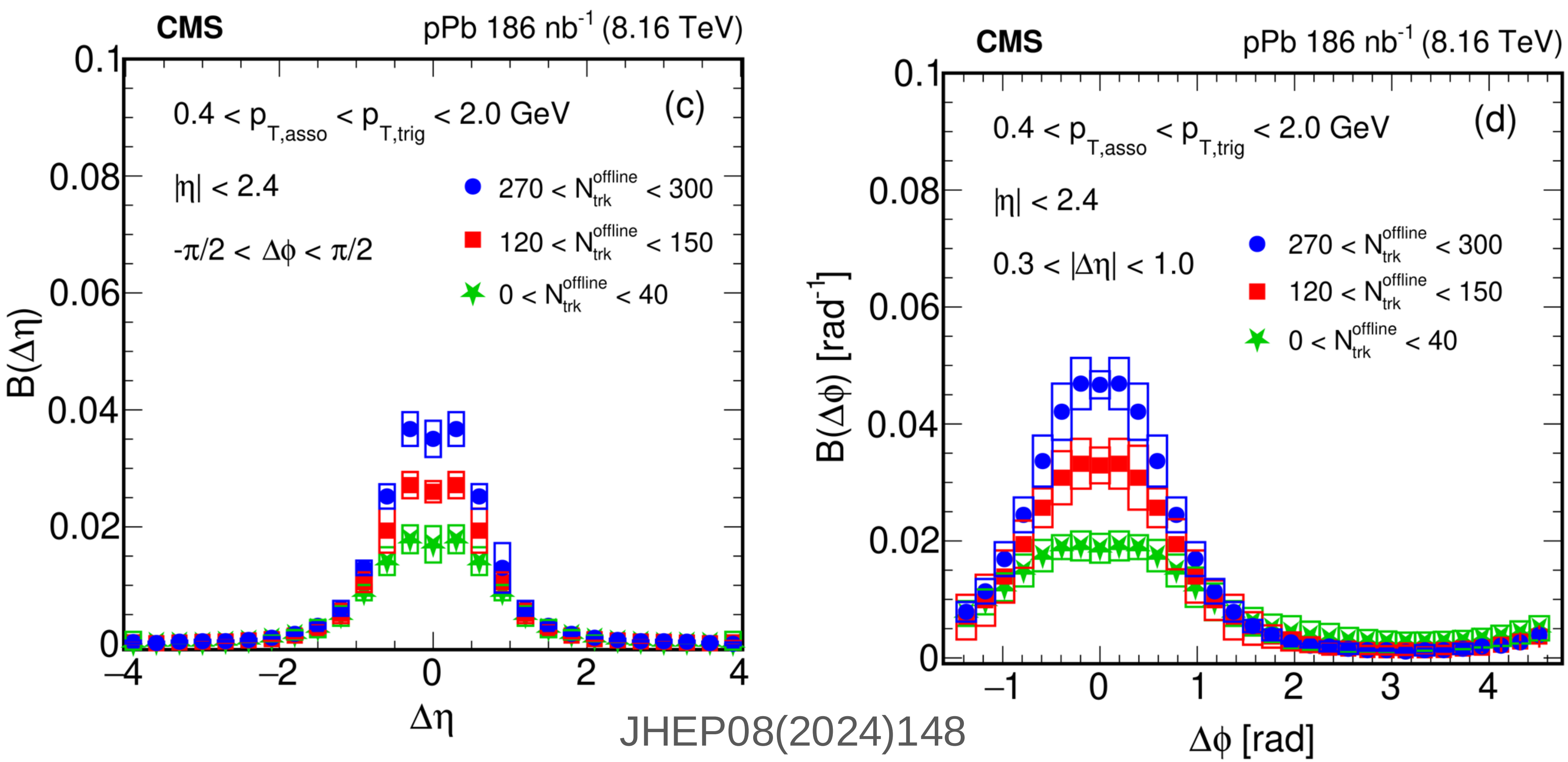
Low multiplicity (peripheral) — Decrease $\Delta\eta$, $\Delta\phi$ (narrower) → High multiplicity (central)

Comparison to MC with and w/o radial flow



- ❑ Data not described by either HYDJET , HIJING or APMT in Δη.
- ❑ Azimuthal balance function (Δϕ) : AMPT shows similar trend as in data → could be connection to radial flow effect in AMPT!

Charge Balance function in pPb



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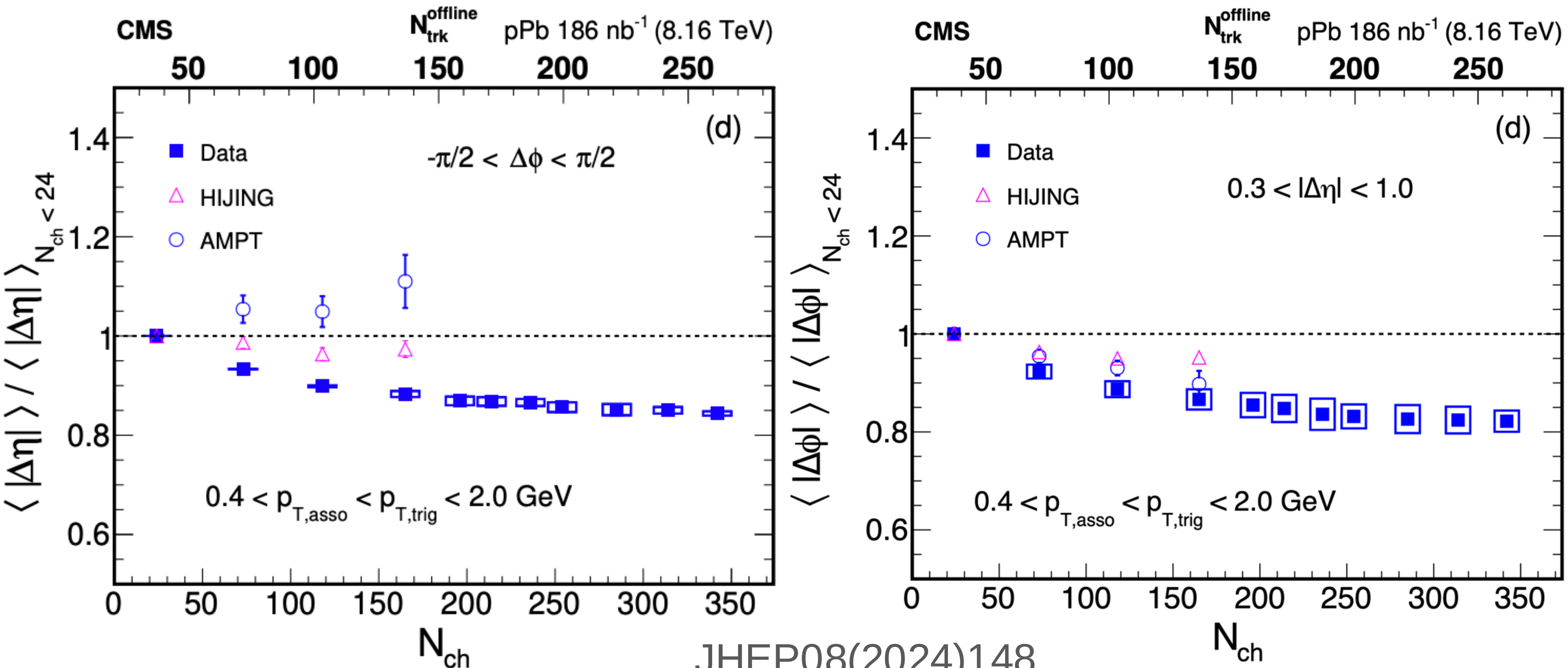
- Narrowing is observed from low to high multiplicity events in pPb collisions in Δη and Δϕ.
- More radial flow effect and/or late hadronization in pPb system?

Quantifying balance function width in pPb



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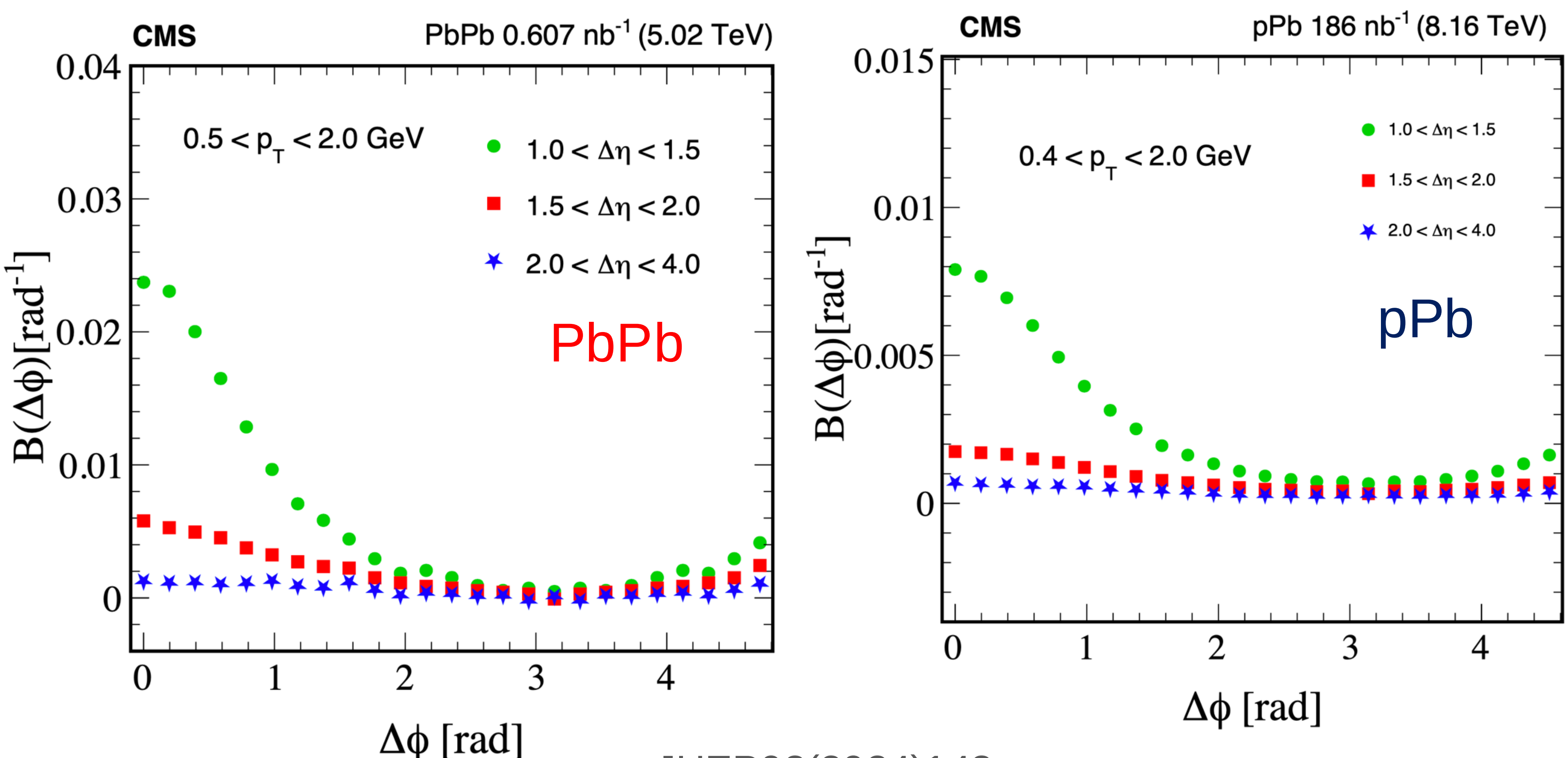
- A similar trend is observed in pPb collisions:
  - Narrowing of the balance function with increasing multiplicity in $\Delta\eta$ and $\Delta\varphi$.
  - Narrowing in $\Delta\varphi$ described by AMPT connection to radial flow.

Testing diffusion of Balance function



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The tails (higher Δη projections) of the Balance functions are broader
☞ could be due to extra diffusion of charge in the early stages of the collisions and/or collective radial flow?

Inclusive charge BFs and their integrals

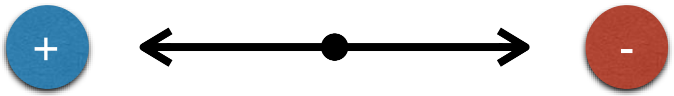
Let $\alpha = \beta = +$; $\bar{\alpha} = \beta = -$

$$B^{+|-}(y_1|y_2) = \frac{\rho_2^{+-}(y_1,y_2)}{\rho_1^{-}(y_2)} - \frac{\rho_2^{--}(y_1,y_2)}{\rho_1^{-}(y_2)}$$

CHARGE CONSERVATION:

Creation of $\alpha = +$ **must be accompanied** by the production of $\alpha = -$:

Integral of $B^{+|-}(y_1|y_2)$:



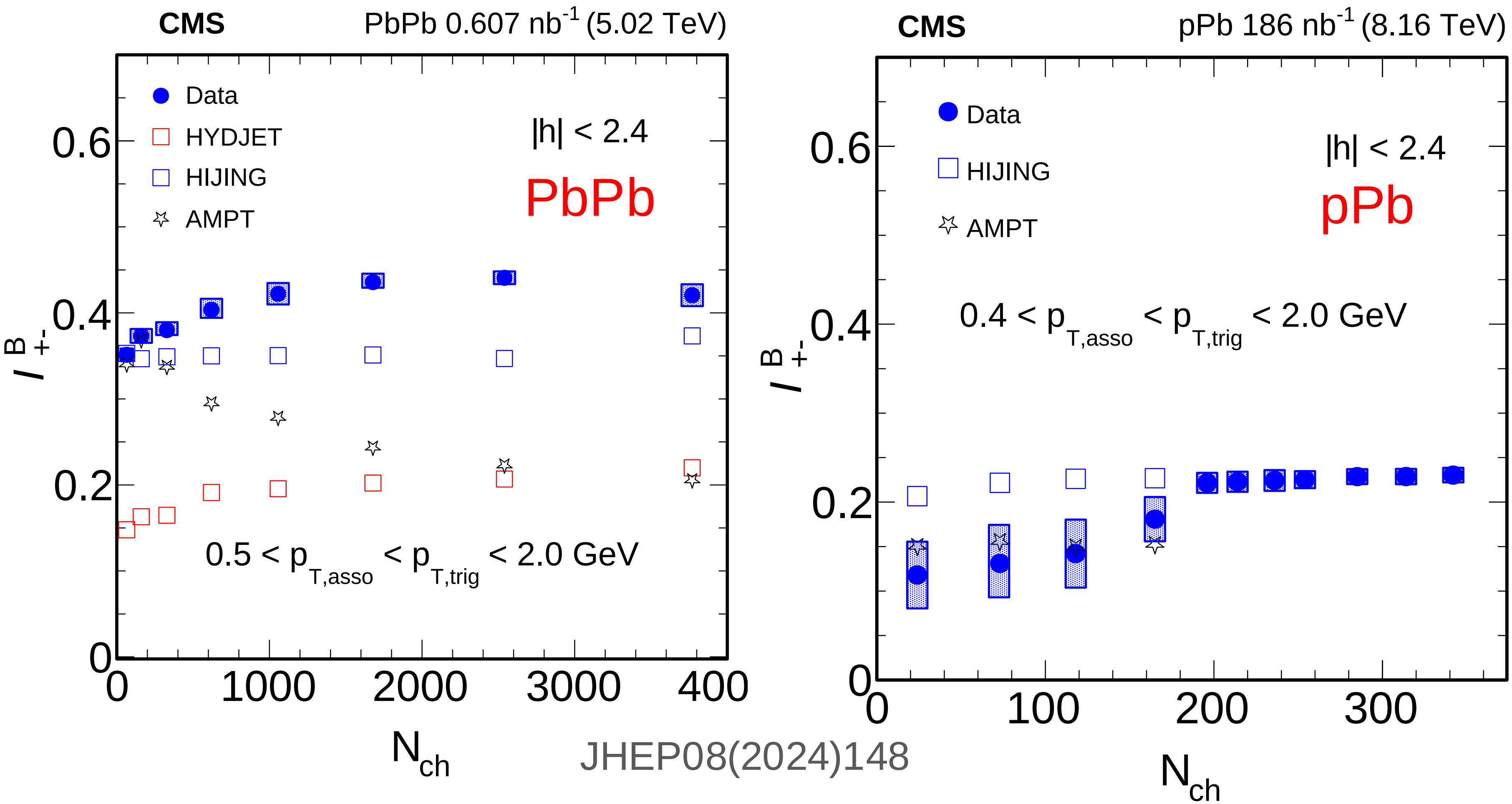
$$I^{+|-}(y_2|\Omega) \equiv \int_{\Omega} dy_1 B^{+|-}(y_1|y_2)$$

In the 4π , full p_T acceptance limit yields.

$$\lim_{\Omega \to 4\pi} I^{+|-}(y_2|\Omega) \to 1$$

courtesy: Claude Pruneau

Inclusive charge BFs and their integrals



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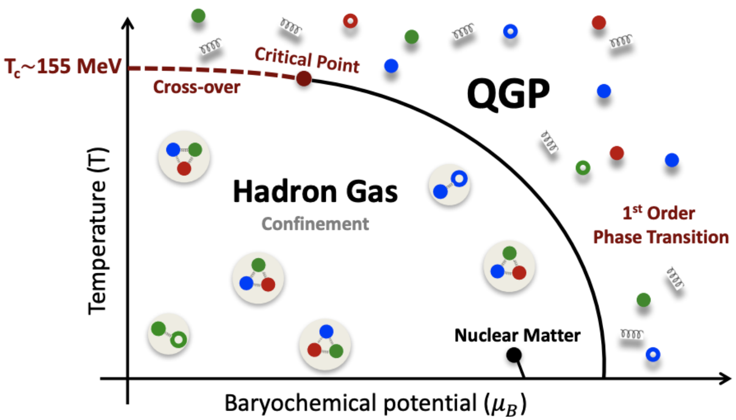
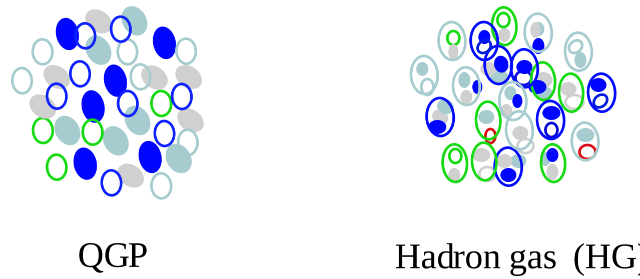
Width of acceptance + Balance function determine the Integral

Dynamical net-charge fluctuations

✓ Fluctuations in hadron gas is higher than in QGP medium.

Relevant charge carriers





$q = \pm\frac{1}{3}, \pm\frac{2}{3}, q^2 = \frac{1}{9}, \frac{4}{9}$ $\quad q = \pm 1, \pm 2, q^2 = 1,4$

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

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

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

$\nu_{dyn} < 0$; opposite sign dominates

Why E-by-E fluctuations?

✓ To study the properties of the phase transition.

✓ To locate the critical end point.

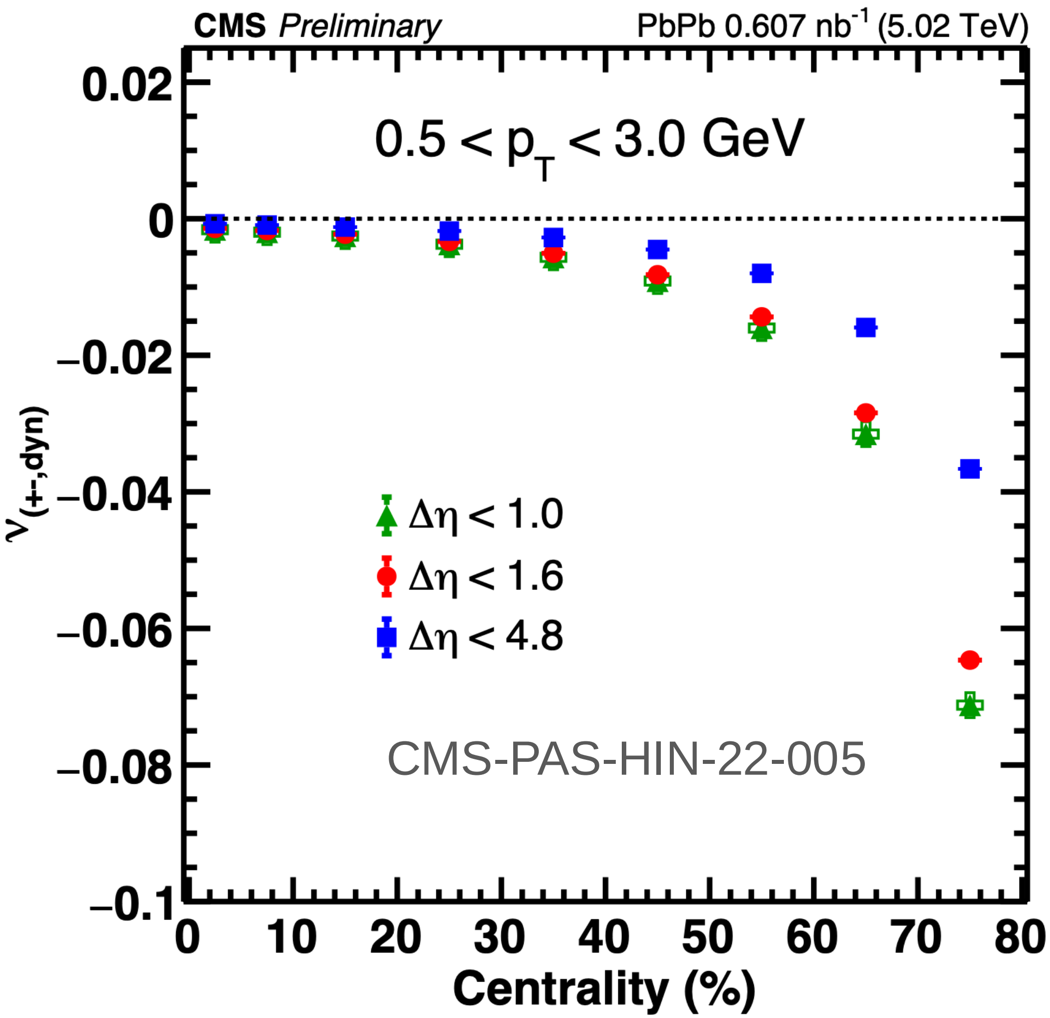
C. Pruneau, S. Gavin, and S. Voloshin Phys. Rev. C 66 (2002), 044904

Relation to correlation:

- "Fluctuations" are determined by the 'average' value of the correlation function over p_T-region under study.

Centrality dependence ν_{dyn}

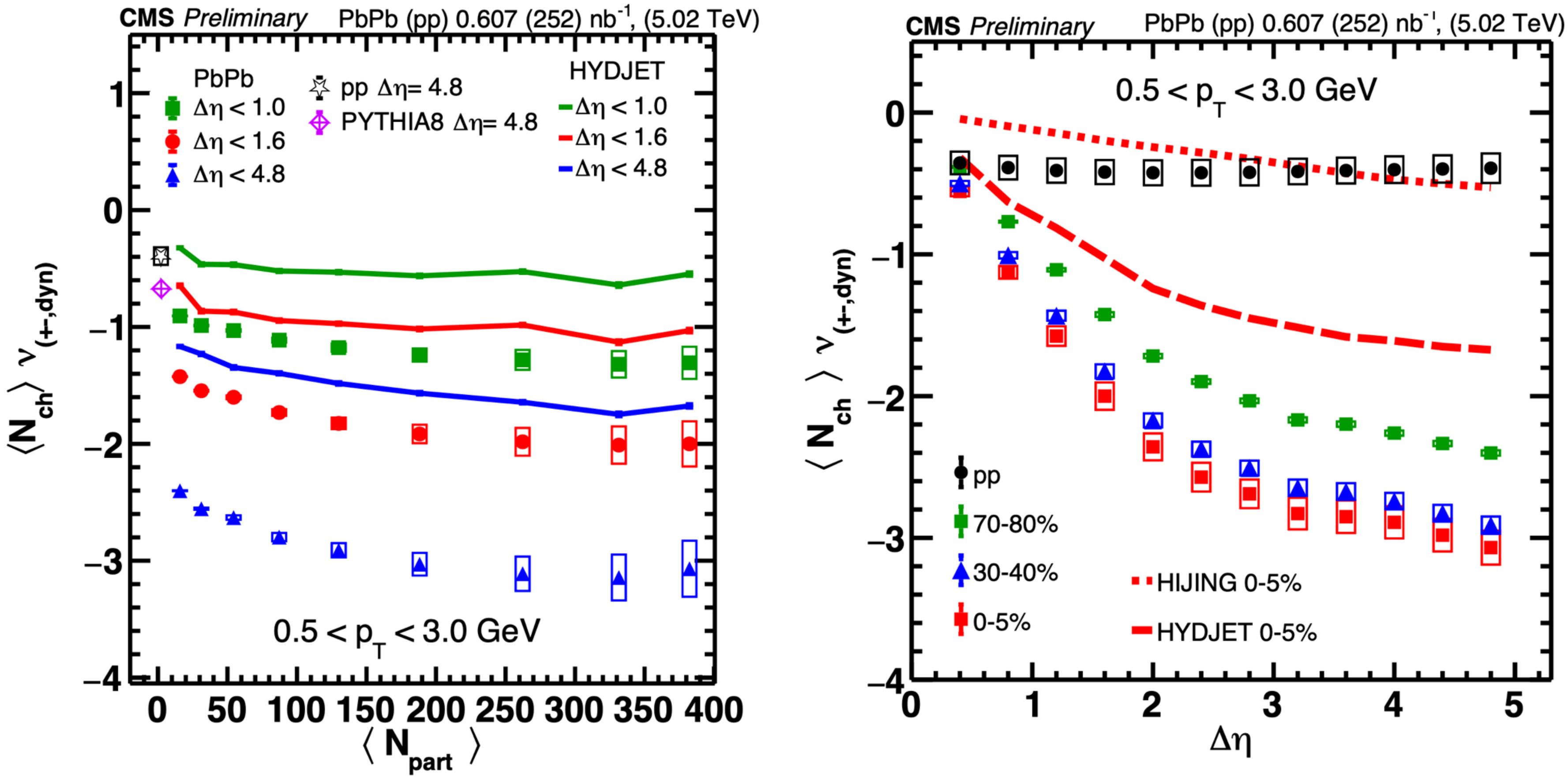
$$\nu_{(+-,dyn)} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$



- ✓ $\nu_{dyn} < 0 \Rightarrow$ Significance of opposite sign correlations dominate
- ✓ ν_{dyn} value decreases with the increase of η window
- ✓ Smaller | ν_{dyn} | value towards the central collision signifies the equilibration of + and – charges

$\langle N_{part} \rangle$ and $\Delta\eta$ dependence ν_{dyn}

CMS-PAS-HIN-22-005



✓ Fluctuations decreases with the increase of Δη windows.

✓ HIJING and HYDJET could not explain the experimental data results properly

Summary

- ✓ Narrowing of the BF width with increasing multiplicities is consistent with the delayed hadronization and radial flow effects
- ✓ Narrowing in $\Delta\varphi$ of the balance function from AMPT shows a similar trend observed in data.
- ✓ Width does not depend on multiplicity for higher p_T
- ✓ Tail of the BF is brooder could be an indication of extra diffusion
- ✓ v_{dyn} value decreases with the increase of $\Delta\eta$ windows and saturating towards central collisions.
- ✓ Negative values of v_{dyn} across all centrality shows correlation of opposite charges dominate.

New measurement in CMS (work in progress)

- What if I want to look inside a jet?

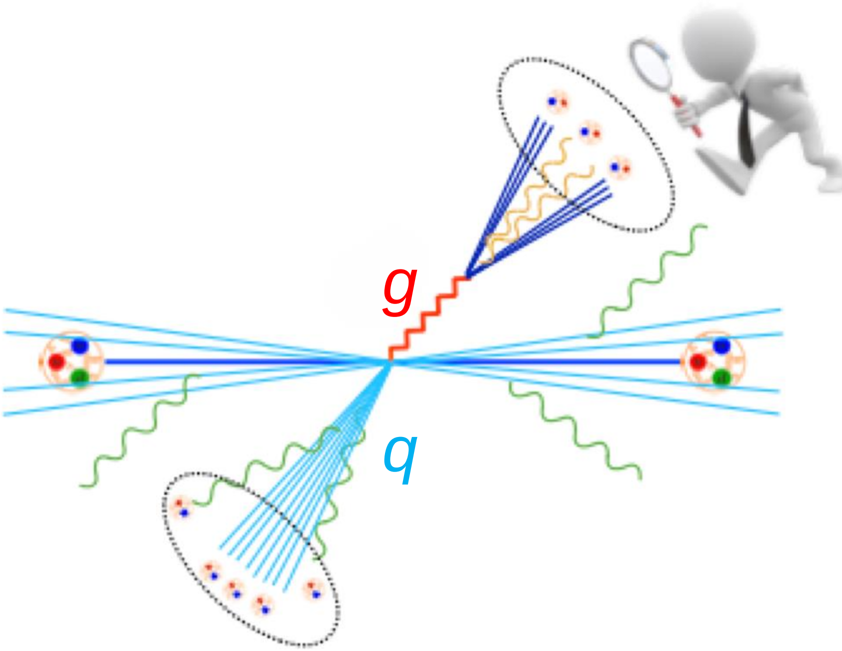
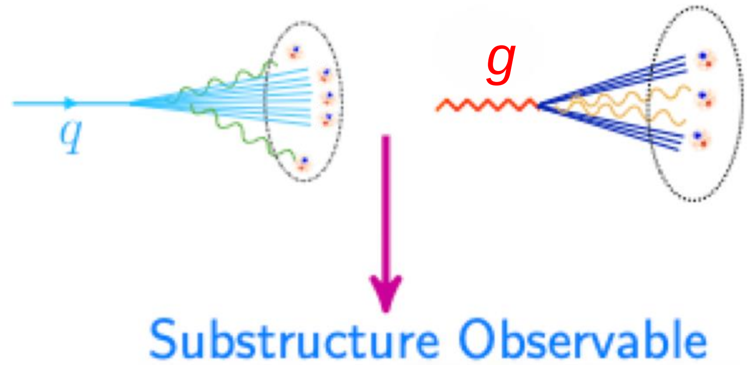


Figure courtesy: Ian Moult



- No flow features since ++ and +- (etc) in jets should "suffer" same differential attenuation (flow) from medium (if any)
- Narrow peak may change width with jet mass or virtuality

- **Jet substructure**: measure properties (charge, energy, etc) of radiation in a jet to extract information about its origin.

Charge BF, momentum-momentum correlation, and HBT within jet measurements are in progress within CMS