Based on Eur. Phys. J. C **85**, 323 (2025)

# Probing QGP formation in pp collisions with Balance Functions

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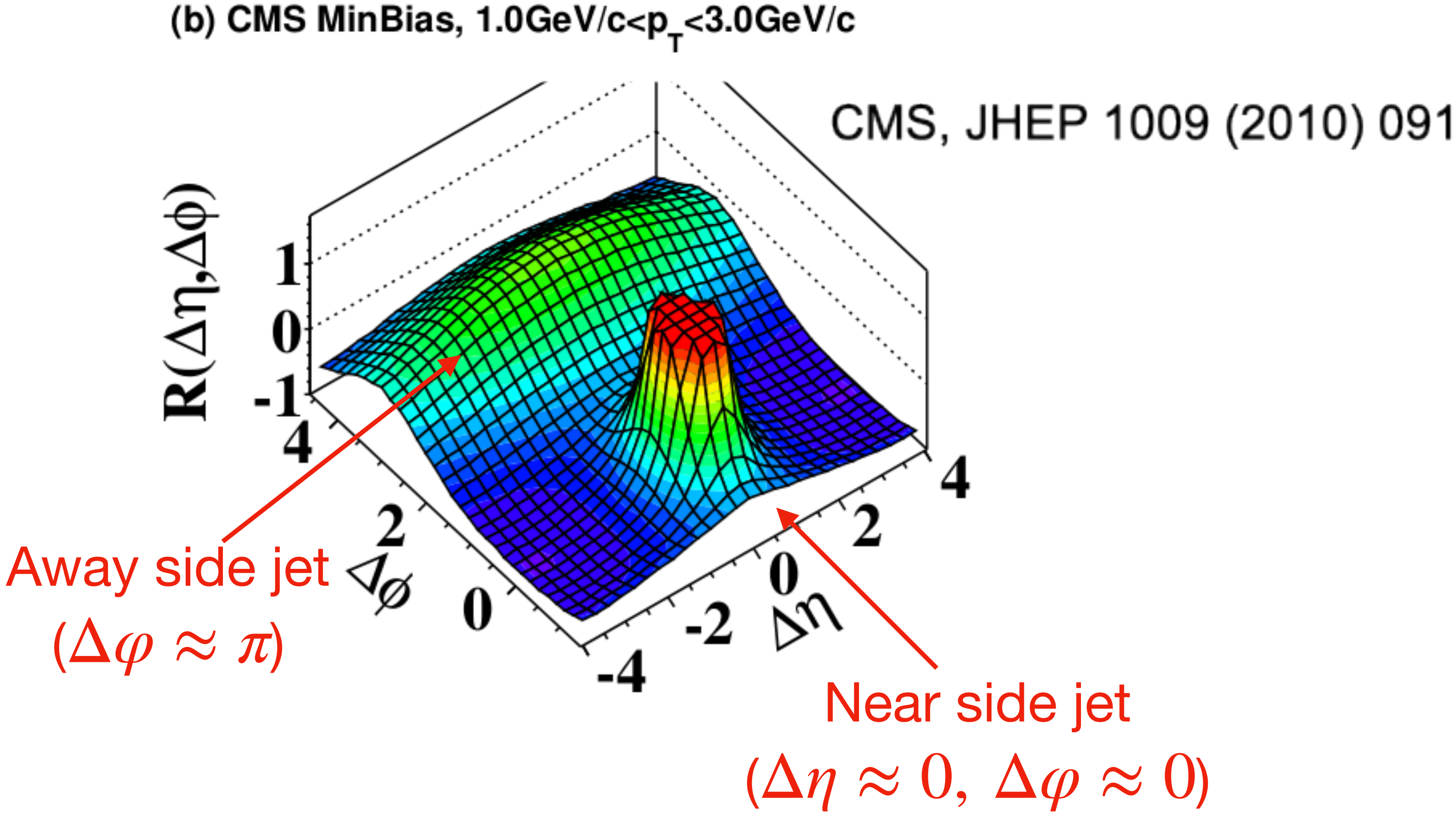
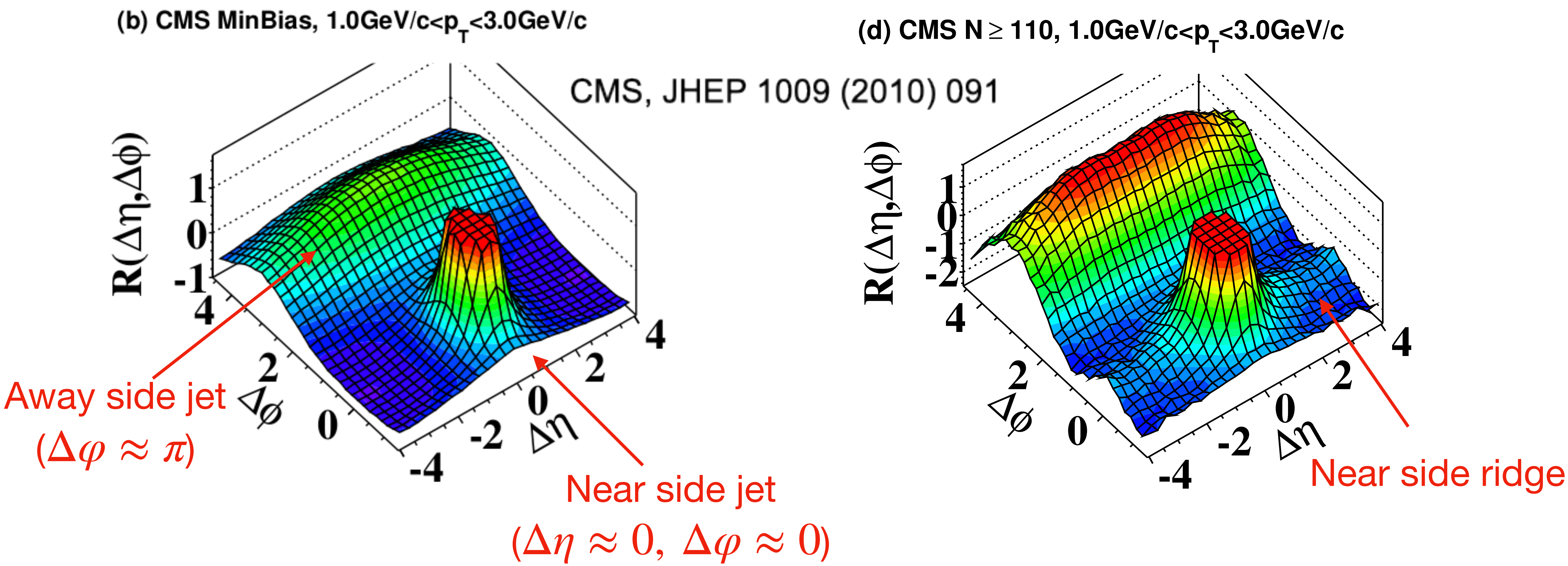
# Introduction




- Near side jet peak influenced by HBT and resonance decay effects

# Introduction



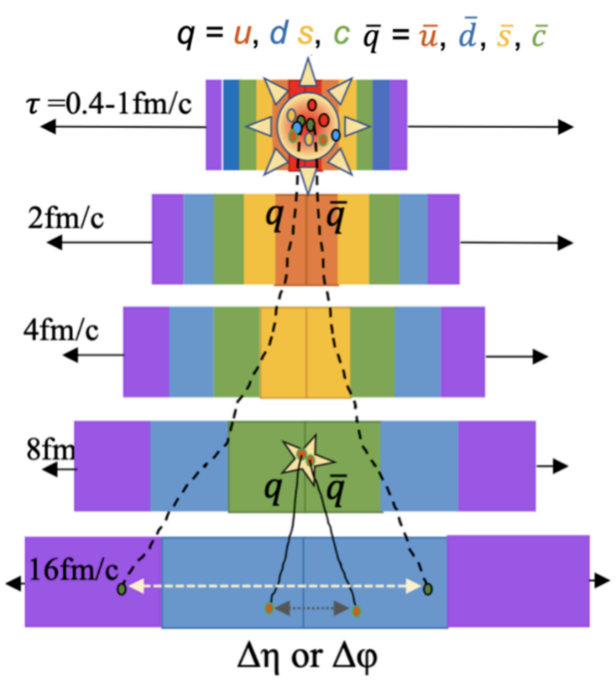

- Near side jet peak influenced by HBT and resonance decay effects
- Collective phenomena shown to exist in small collision systems
- Initial or final state effects?

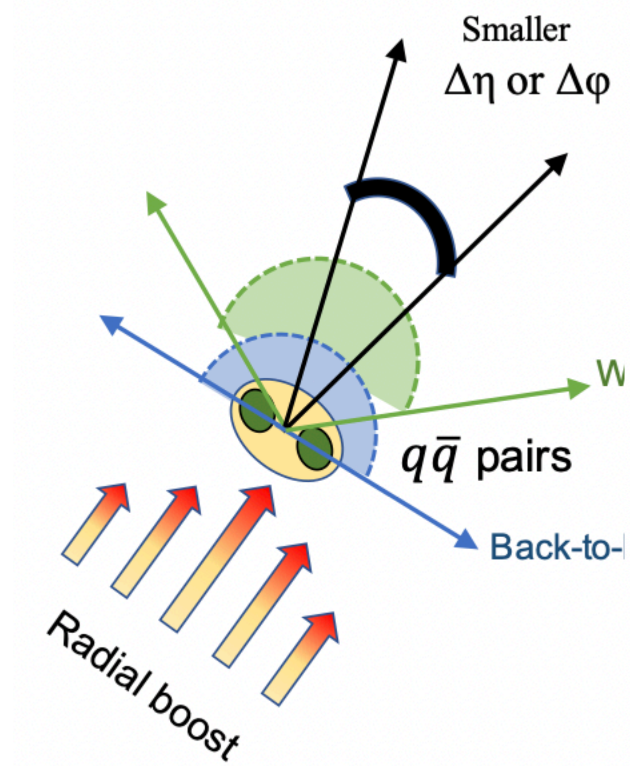
**Correlation measurements can help to distinguish between the two regimes**

# Clocking hadronization

Difference in conditional densities

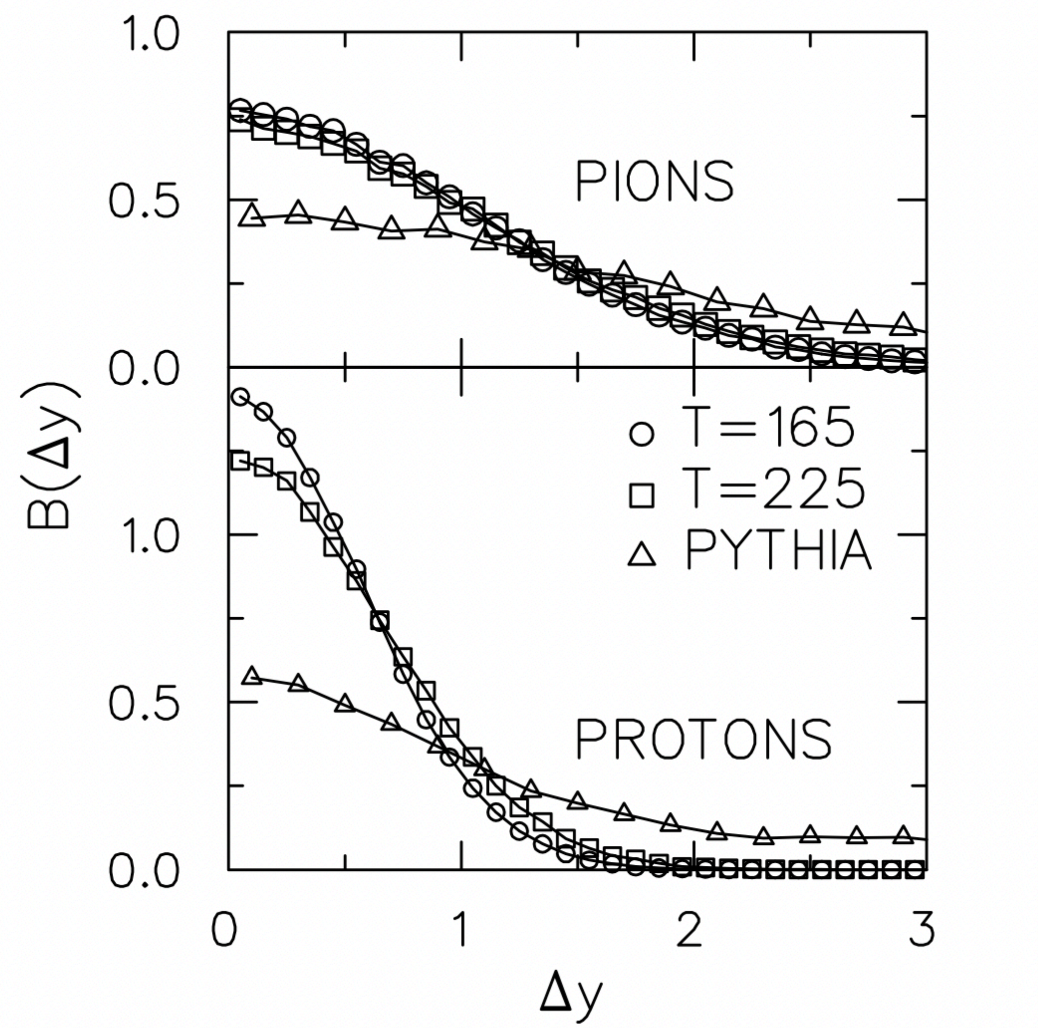
$$B(\Delta\eta, \Delta\varphi) \equiv \frac{1}{2}\left(\frac{\rho_2^{+-} - \rho_2^{--}}{\rho_1^{-}} + \frac{\rho_2^{-+} - \rho_2^{++}}{\rho_1^{+}}\right)$$




arXiv:2110.05134 **[hep-ph]**

Bass, Danielewicz, Pratt, PRL 85, 2689 (2000)



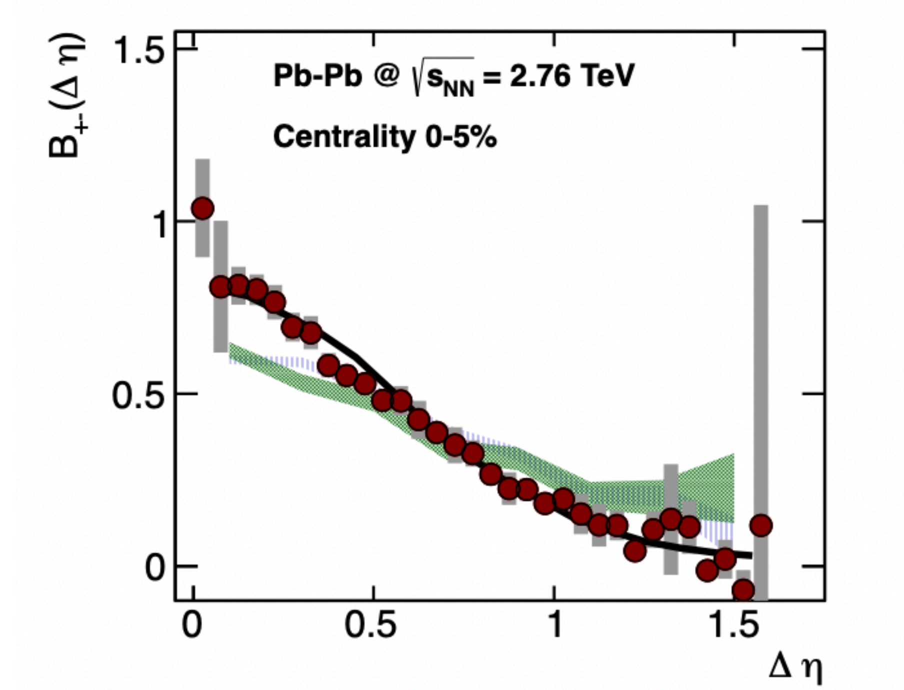

Measurement of correlations of charges with their respective anti-charge

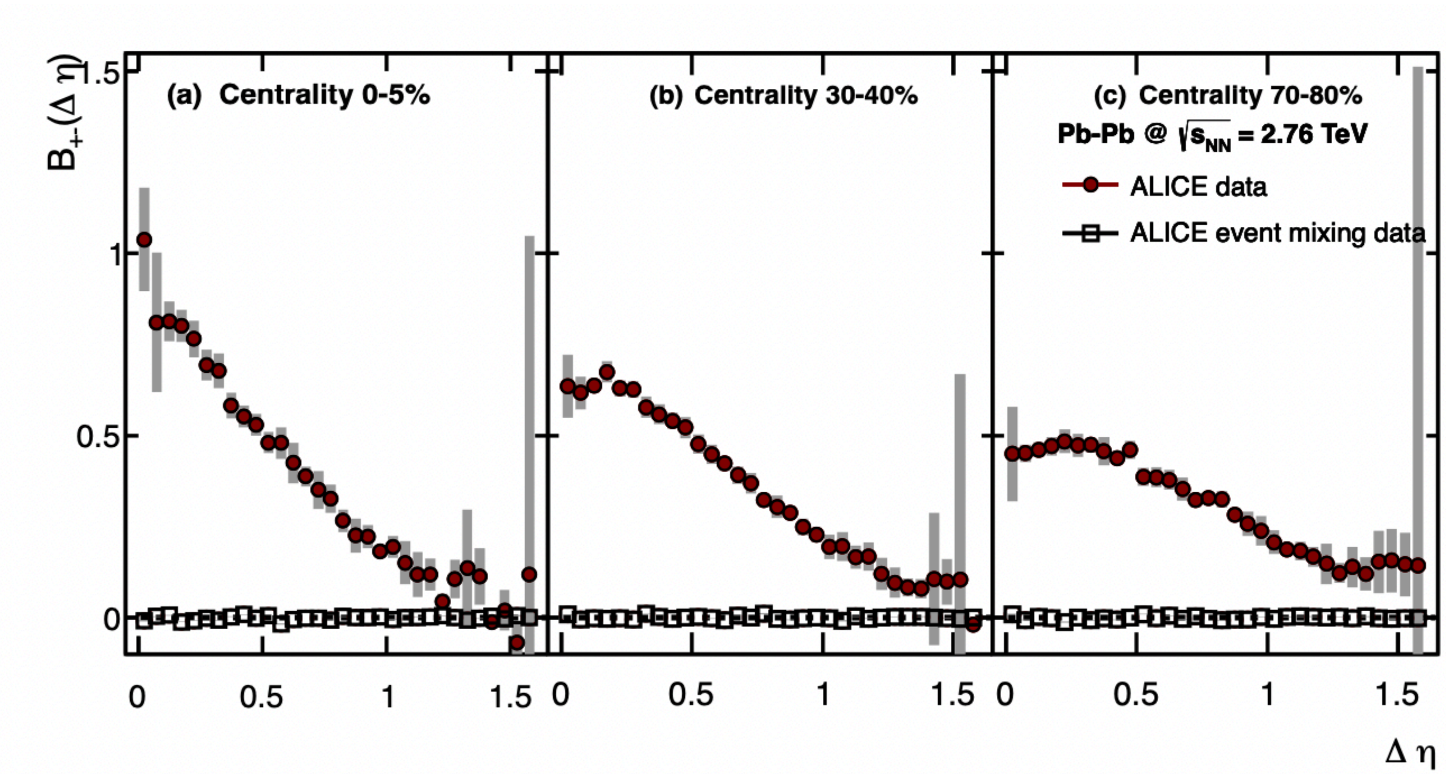
**Investigate late-stage hadronization and formation of quark-gluon plasma**

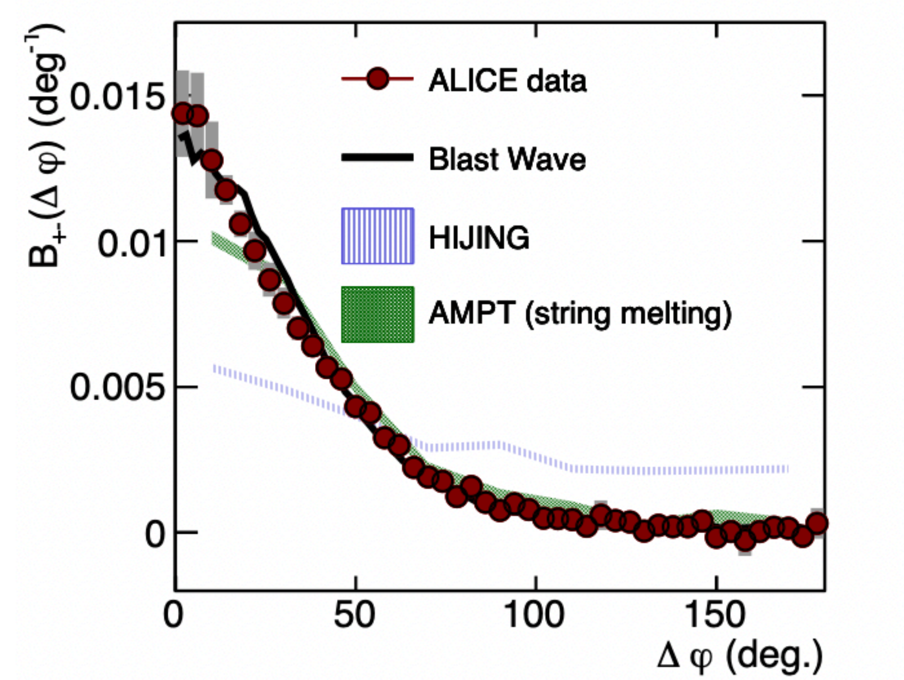
# Balance function at ALICE and STAR

arXiv:1509.07255 **[nucl-ex]**
arXiv:1301.3756 **[nucl-ex]**

- Balance function reproduced by models with hydro evolution of medium
- Do correlations survive in thermal models as in QCD string ones?



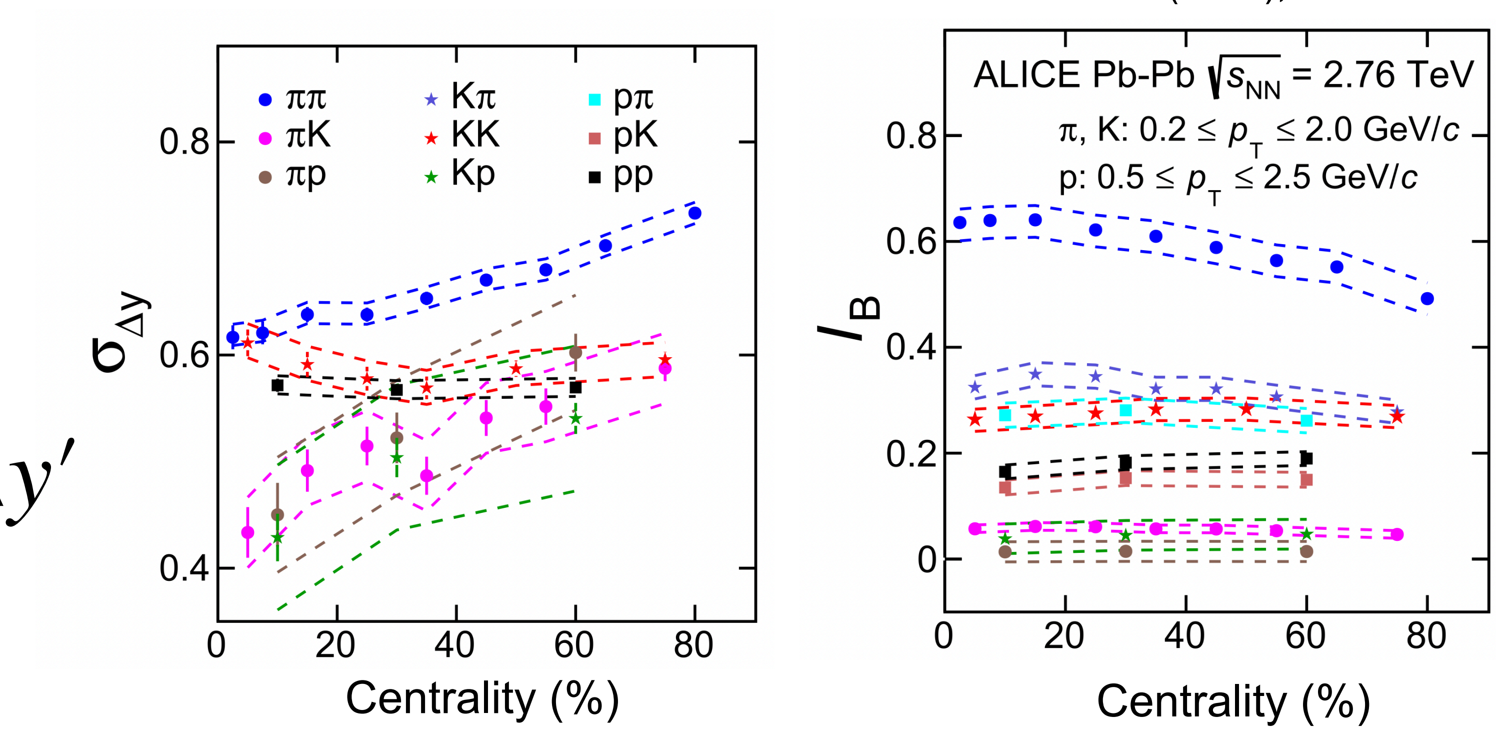
# Integrals of Balance Function

- $B^{KK}, B^{pp}$ almost independent of collision centrality in data mesurements of Pb-Pb collisions

- Cumulative integral of balance function

$$I^{\alpha\bar{\beta}} = \int_{\Delta y} B^{\alpha\bar{\beta}}(\Delta y')d\Delta y'$$

ALICE PLB 833 (2022), 137338



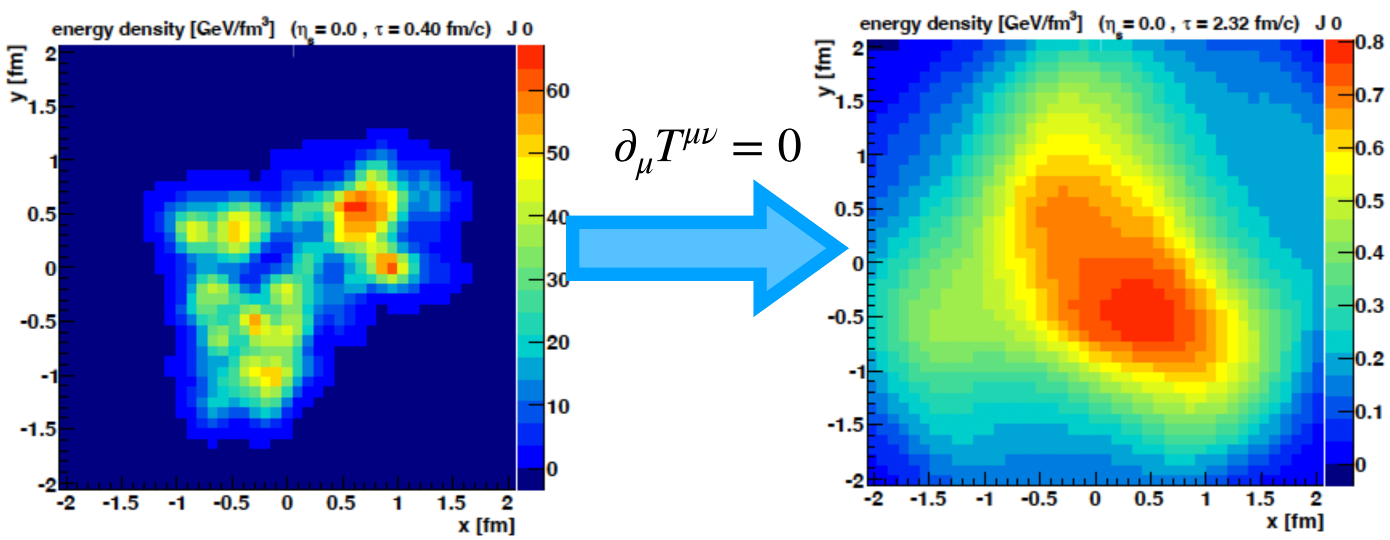

In full acceptance $I^{\alpha\beta}(4\pi) \to 1$

In finite acceptance it shows the degree to which charges are balanced -> affected by production and transport

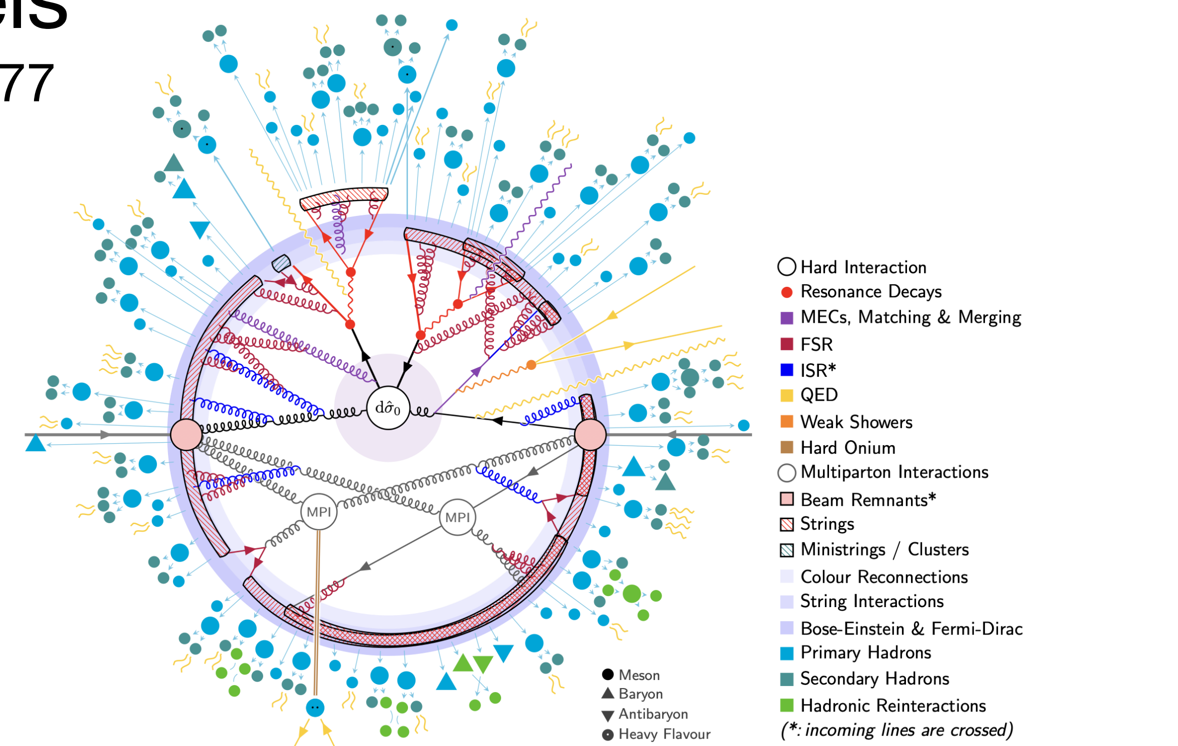
# Monte Carlo Models

We look at two state of the art models

K. Werner, arXiv: 2306.10277




C. Bierlich et al., arXiv: 2203.11601




- Macroscopic model:EPOS4
  - Core-corona model with statistical hadronization
  - Core is micro-canonical and conserves charges
- Microscopic model:PYTHIA8
  - QCD strings with LUND fragmentation
  - Implicit quantum number conservation

Difference in particle production mechanisms and system evolution results in different correlations

# Generalized Balance Functions

General Balance Function definition arXiv:2209.10420 **[hep-ph]**

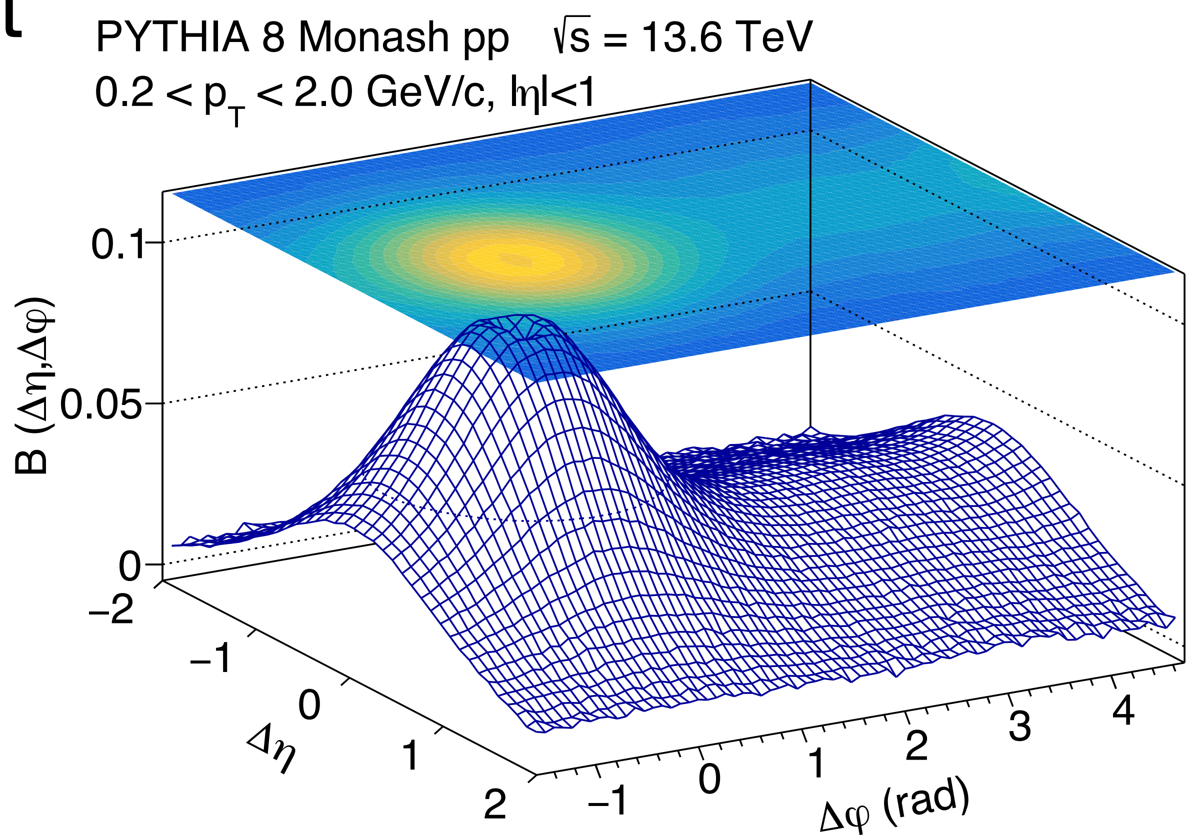
$$B(\Delta\eta, \Delta\varphi) = \frac{1}{2}\{\rho_1^{\bar{\beta}}(R_2^{\alpha\bar{\beta}} - R_2^{\bar{\alpha}\bar{\beta}}) + \rho_1^{\beta}(R_2^{\bar{\alpha}\beta} - R_2^{\alpha\beta})\}$$

Normalized second order cumulant

$$R_2^{\alpha\beta}(\Delta\eta, \Delta\varphi) = \frac{\rho_2^{\alpha\beta}(\Delta\eta, \Delta\varphi)}{\rho_1^{\alpha}\rho_1^{\beta}} - 1$$

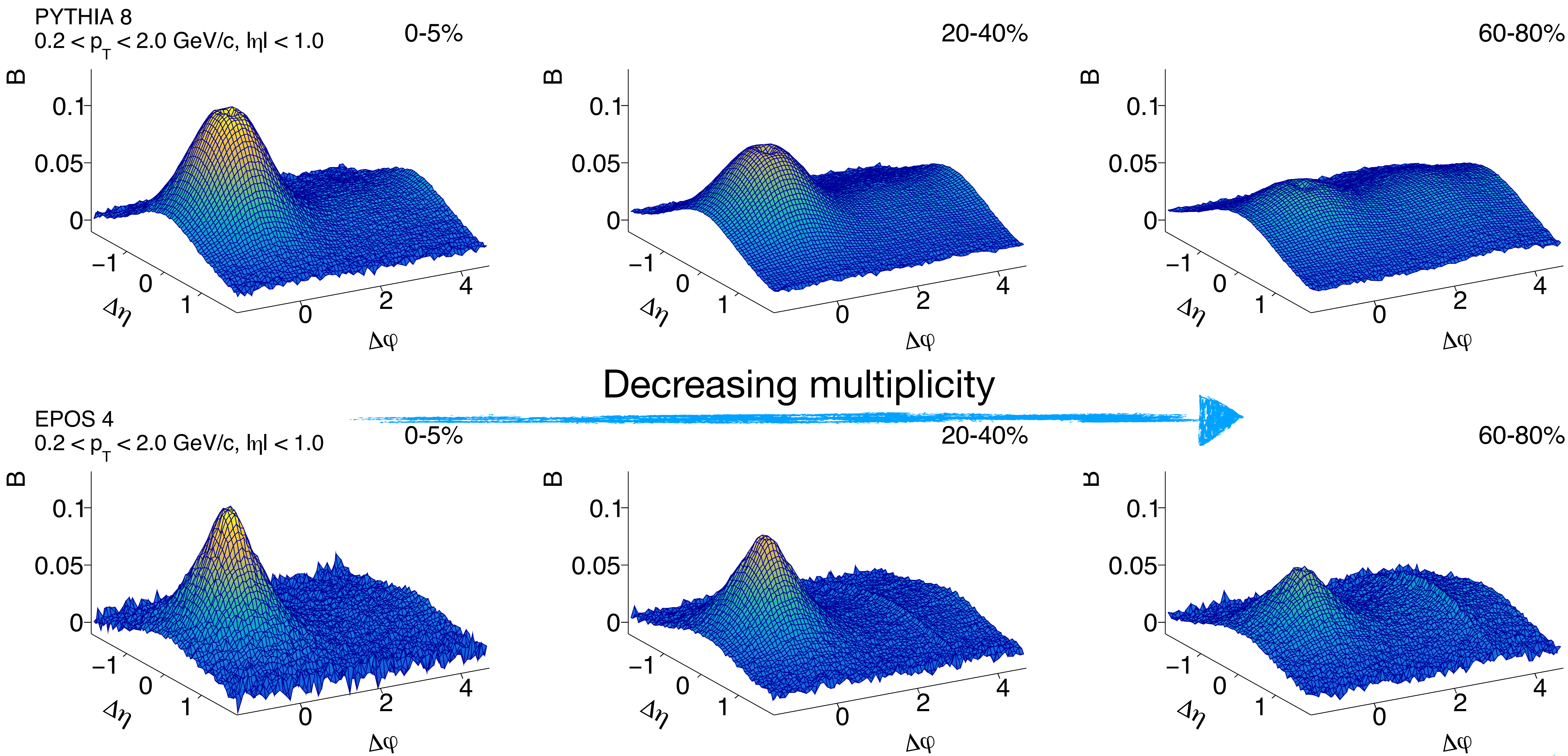
$$\rho_2^{\alpha\beta} = \frac{d^2N^{\alpha\beta}}{d\Delta\eta d\Delta\varphi}$$

$$\rho_1^{\alpha} = \frac{d^2N^{\alpha}}{d\eta d\varphi}$$




This method is not affected by acceptance factors and robust against efficiency corrections

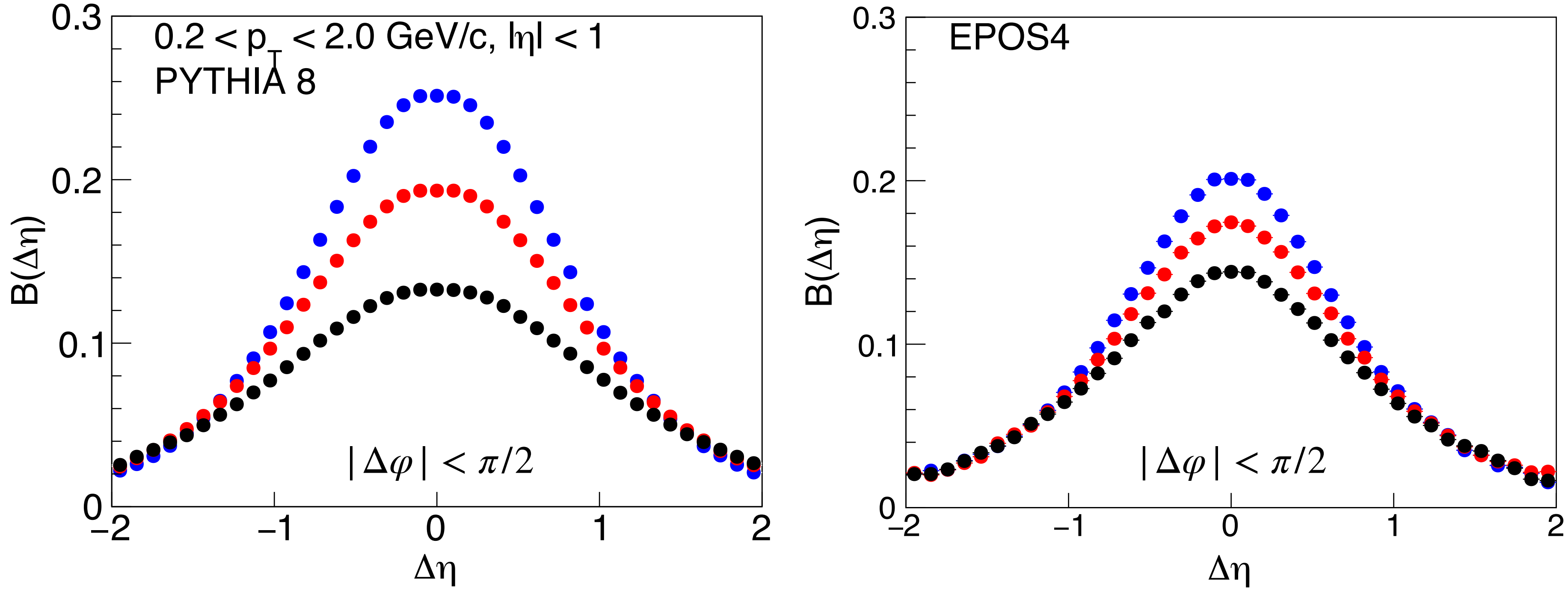
# Charge Balance Function




- Near side peak of PYTHIA shows decay contribution
- Very peculiar correlation in away side for EPOS

**Strong dependence of multiplicity for both models**

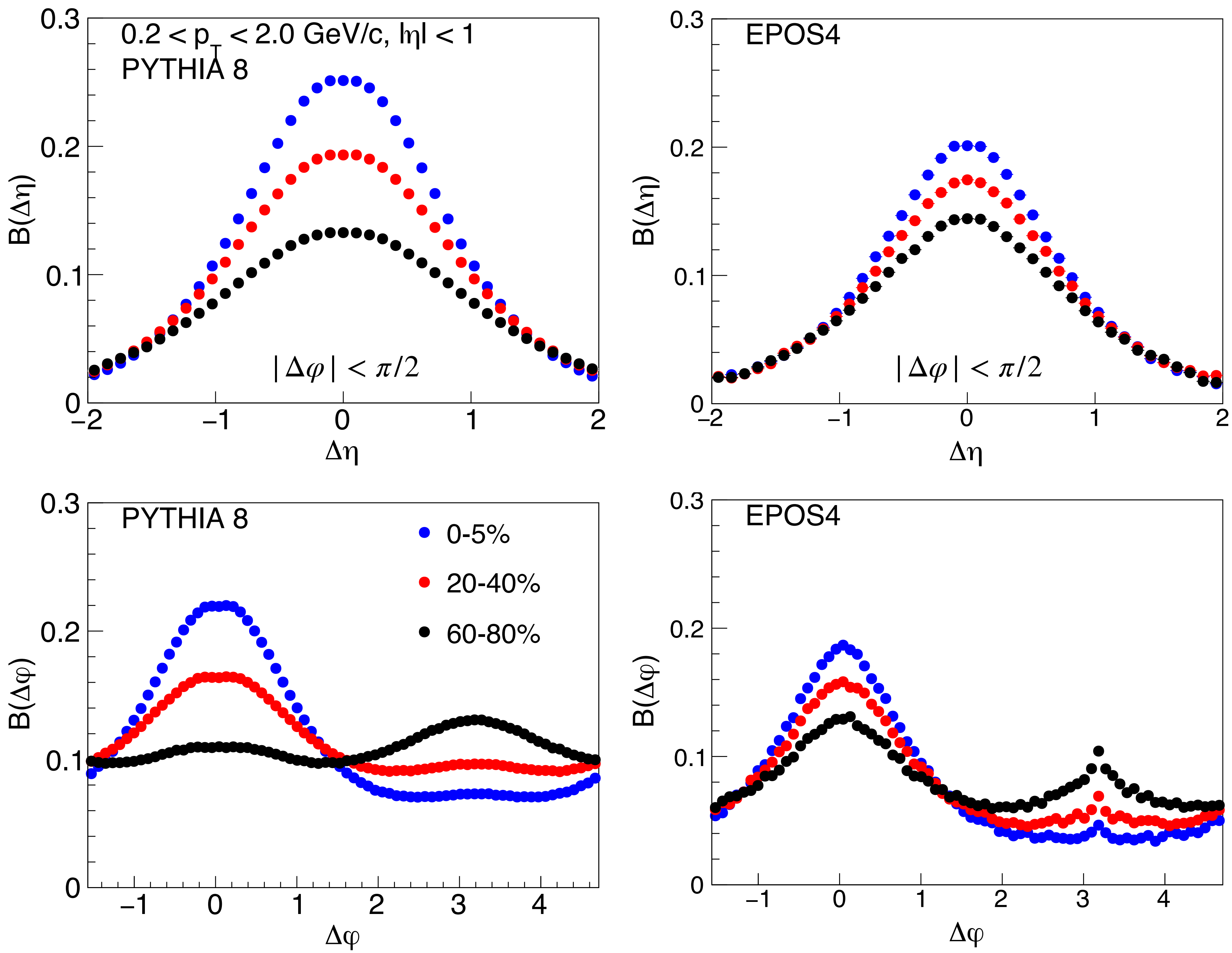
# Projections of Charge BF




Scaling of near side peak is different

Widths of projections are similar but evolve differently with multiplicity

# Projections of Charge BF



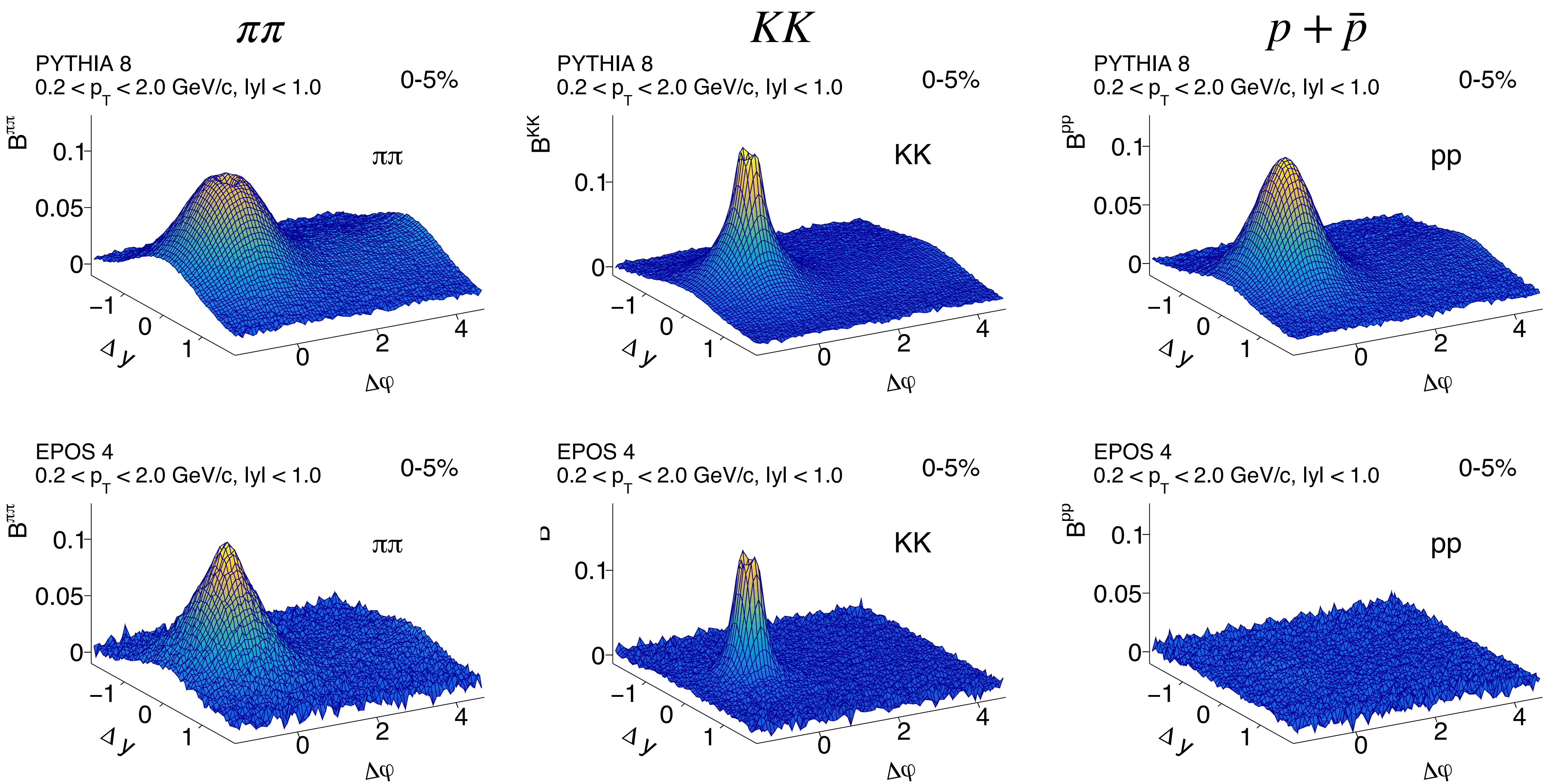

Scaling of near side peak is different

Widths of projections are similar but evolve differently with multiplicity

Unexpected structure in away side seen in EPOS -> depends on multiplicity

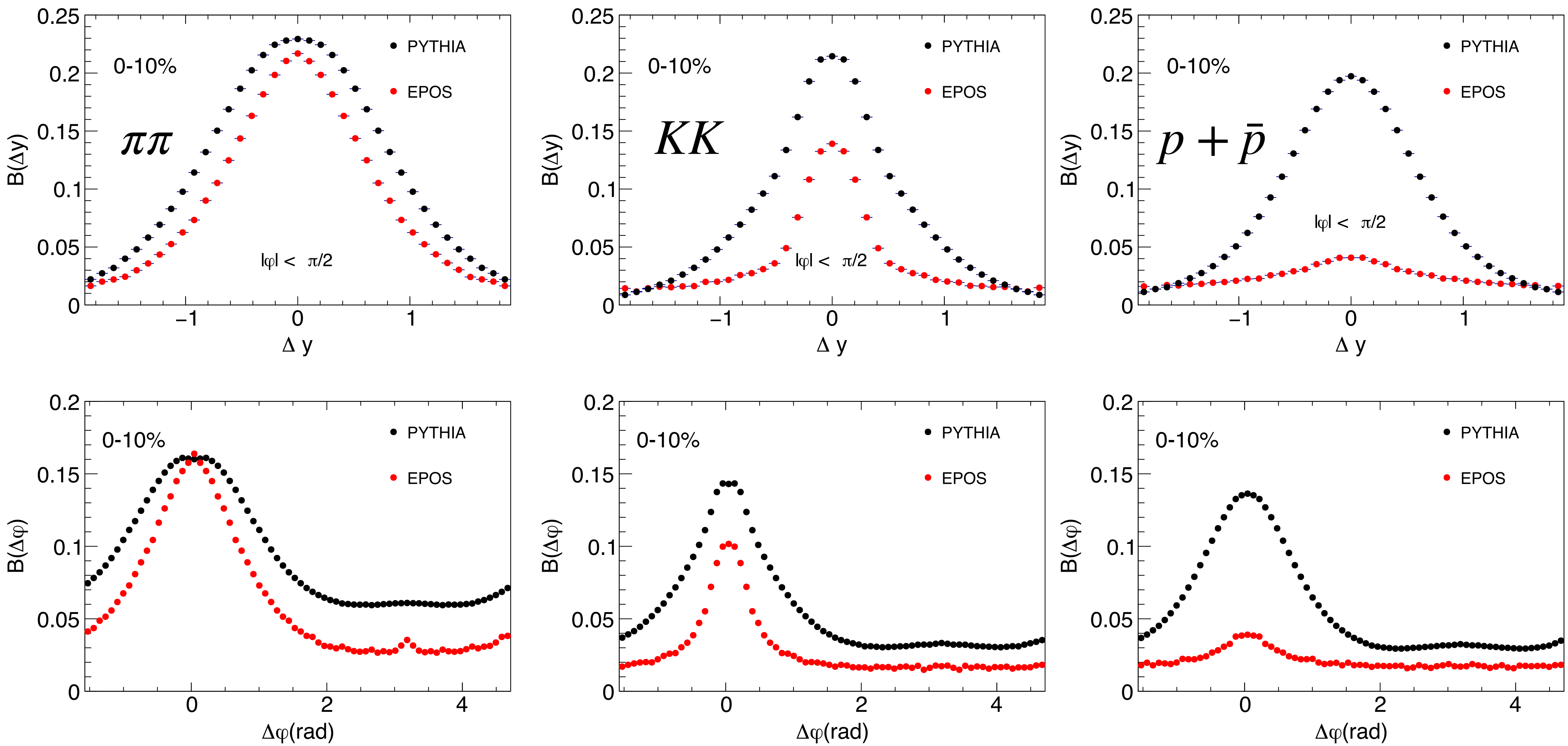
Impact of micro-canonical decay in EPOS?

# Identified Particle BF



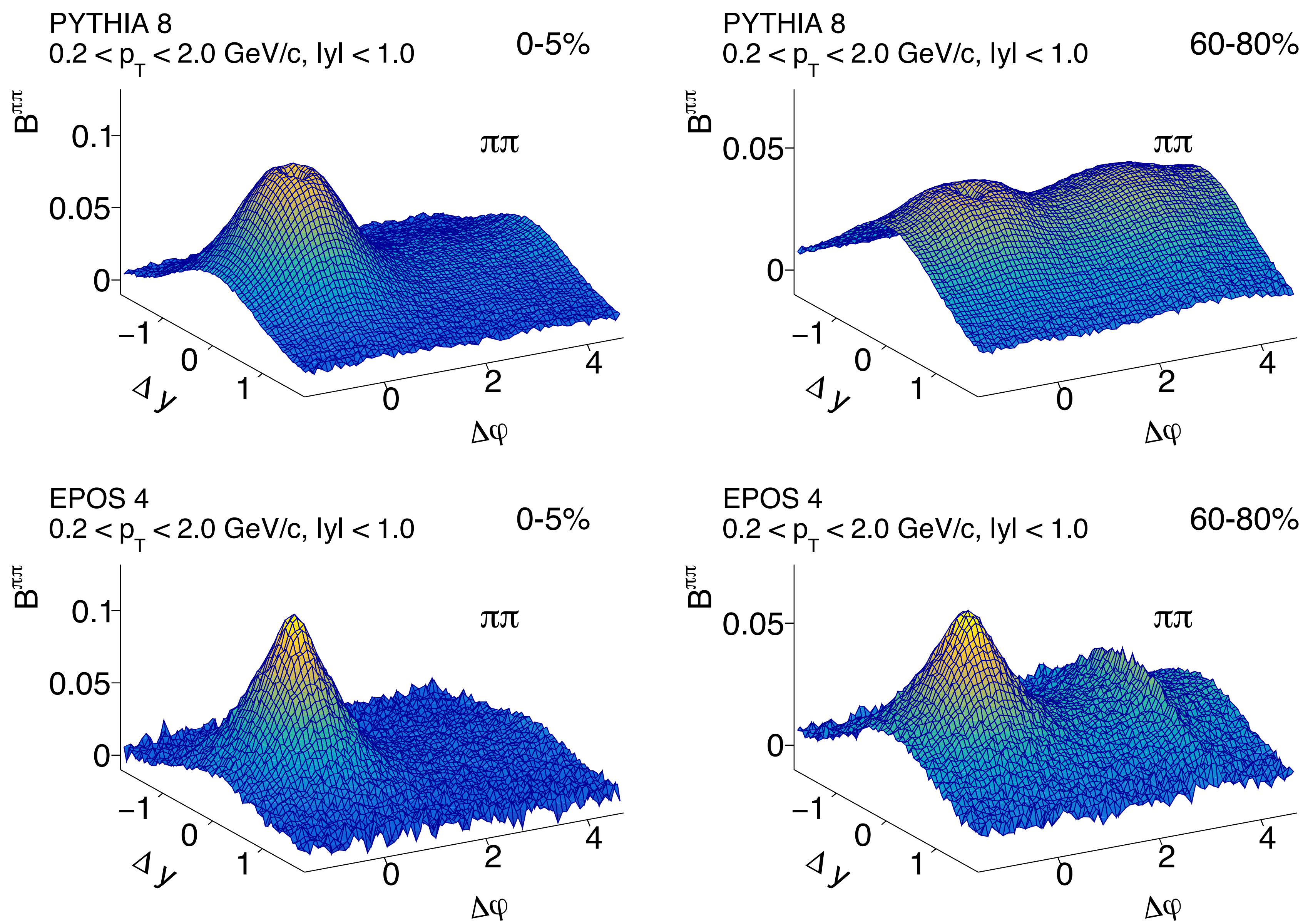

**Particle balancing shows underlying production mechanisms**

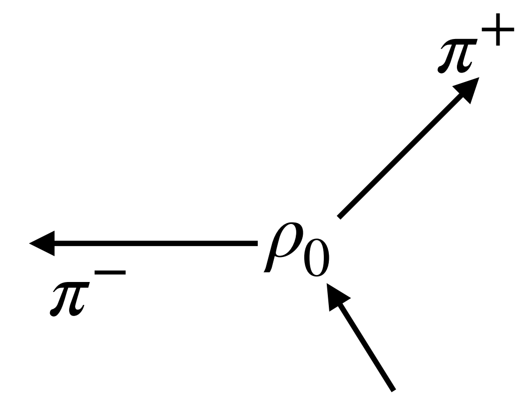
# Identified Particle BF




- Essentially flat away side for kaons and protons in EPOS
- Proton balancing shows divergence of models for baryon balancing

# $\pi\pi$ balance with multiplicity



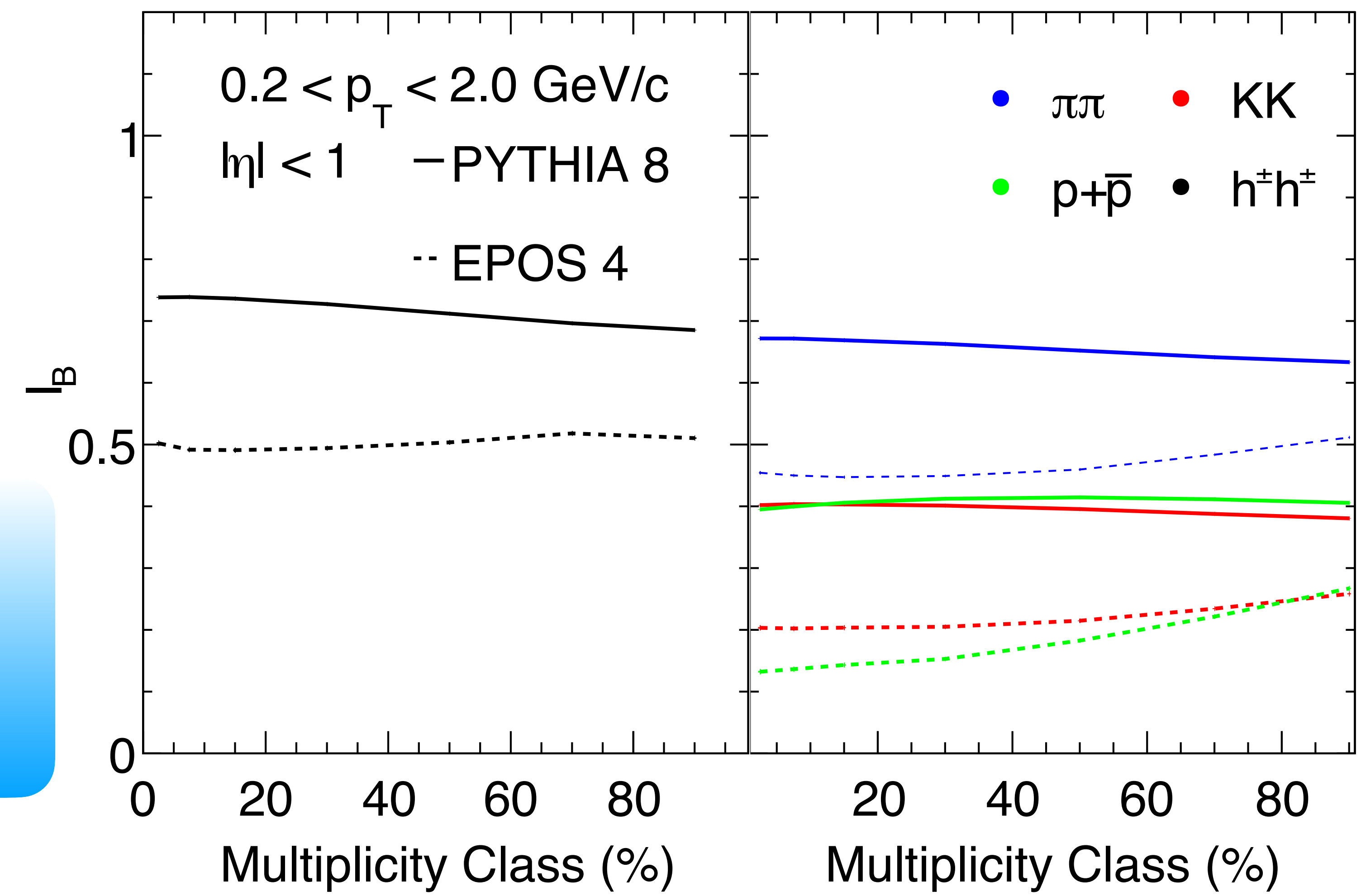




- Anti-correlation for pions in low multiplicity collisions
- EPOS increases correlation strength in the away side

# Integrals of Balance Function

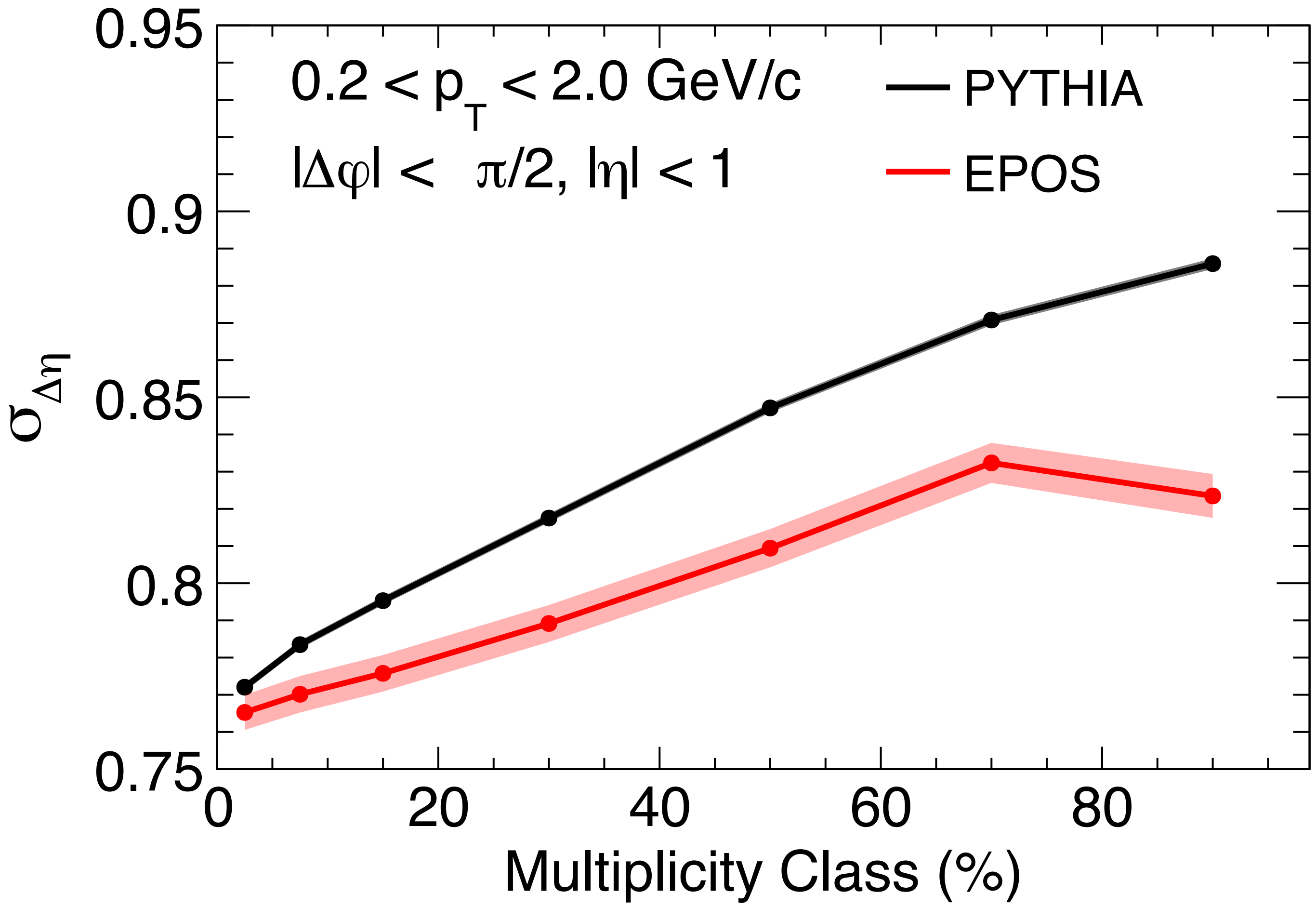
- Cumulative integral of balance function

$$I^{\alpha\bar{\beta}} = \int_{\Delta y} B^{\alpha\bar{\beta}}(\Delta y')d\Delta y'$$




- Charged particles almost independent of collision multiplicity
- Different balancing trends for PYTHIA and EPOS with growing multiplicity

# Longitudinal width of charge BF



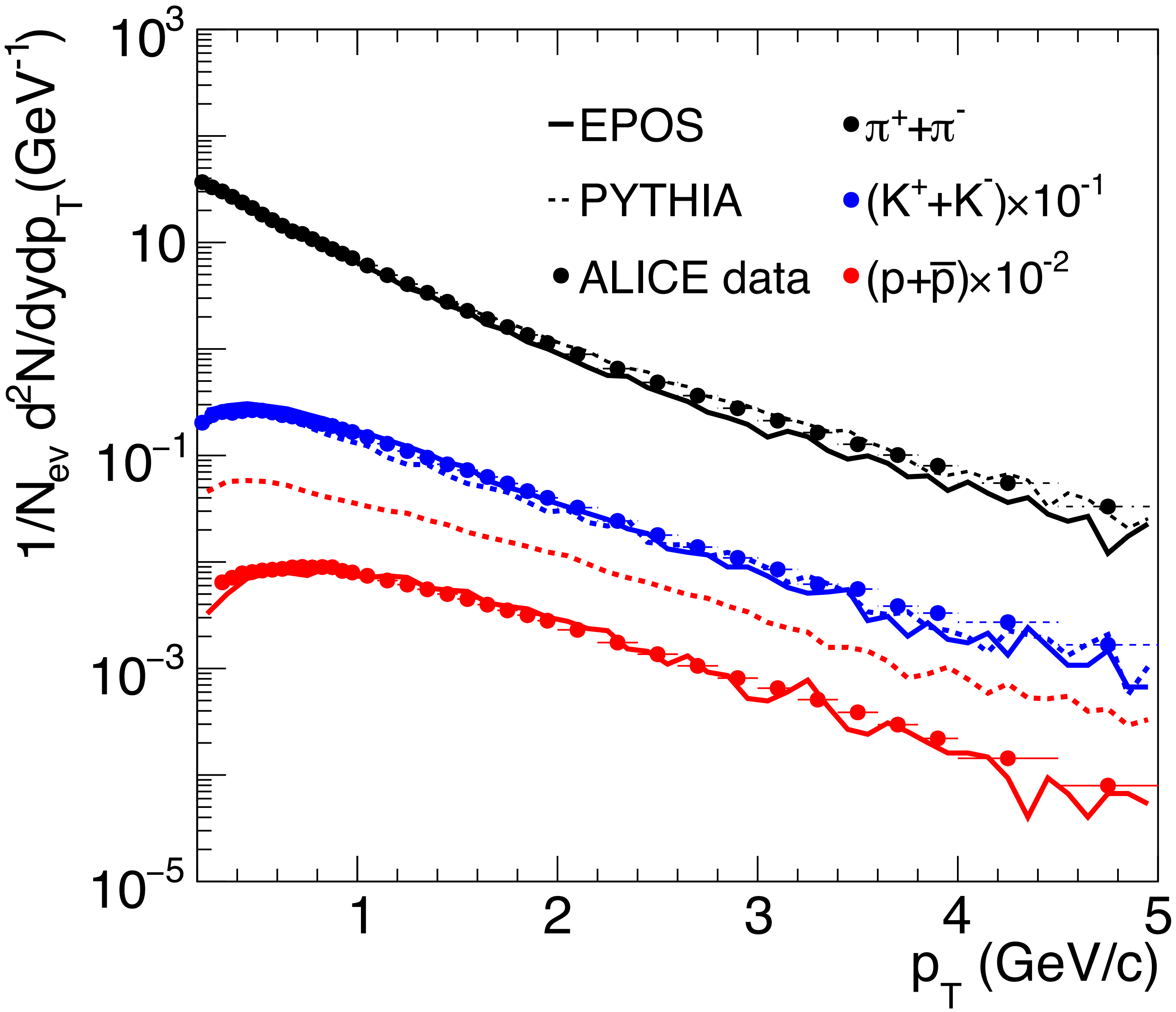

$$\sigma^2_{\Delta\eta} = \frac{\sum_{i,j} [O(\Delta\eta_i, \Delta\varphi_j) - O_{offset}]\Delta\eta_i^2}{\sum O(\Delta\eta_i, \Delta\varphi_j)}$$

- Width evolution with multiplicity is showing unexpected trend in PYTHIA
- Widths estimate the near side peak

# Summary

- Different models can be distinguished from balance function measurements
- Evidence for different decay mechanisms
- Opposite trends for integrals
- Extensive measurements of balance functions can improve models

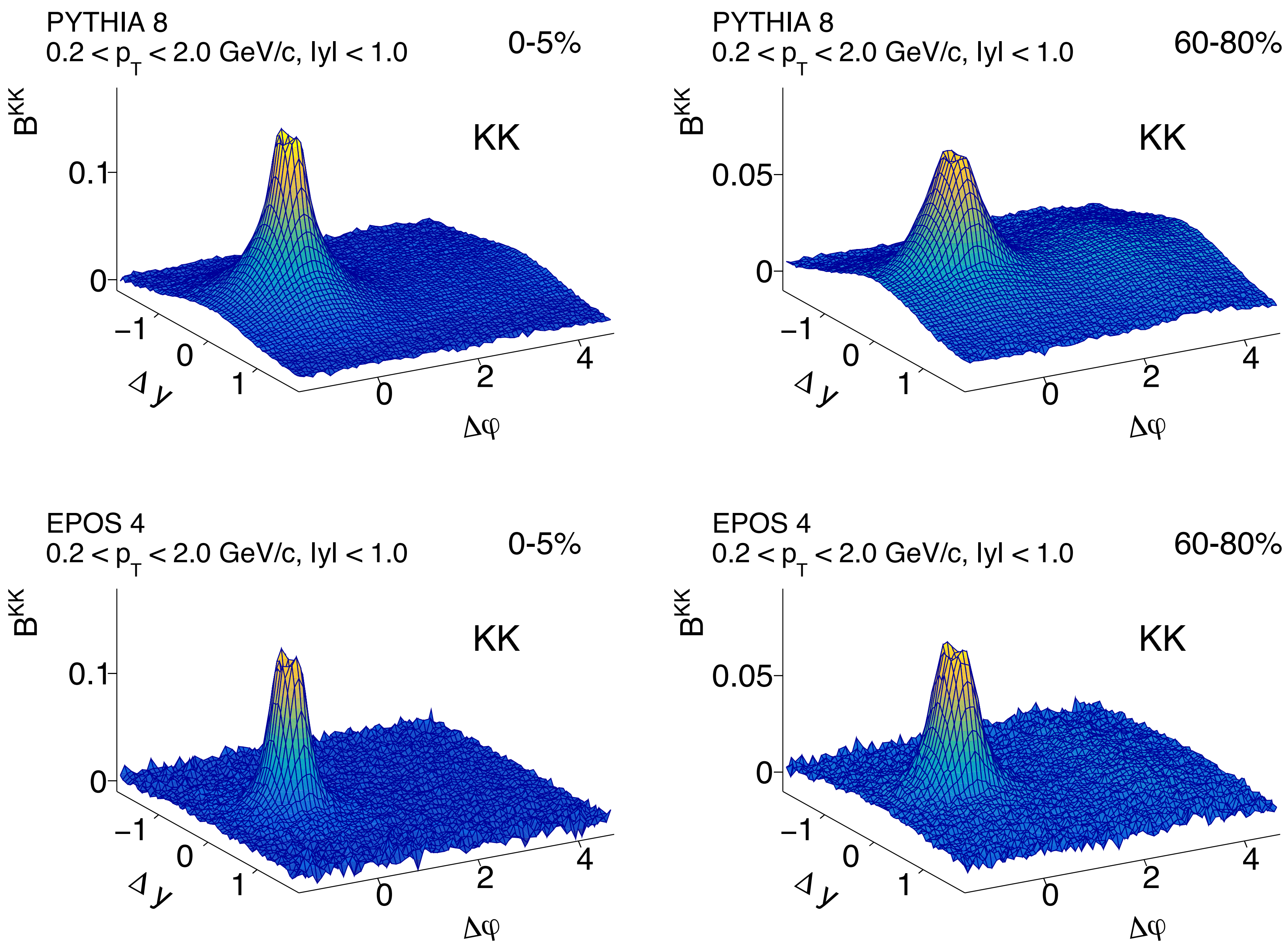
# Back-up




| Multiplicity Class | $\langle p_T \rangle$ | | $\sigma_{\Delta\eta}$ (GeV/$c$) | |
|---|---|---|---|---|
| Model | PYTHIA | EPOS | PYTHIA | EPOS |
| 0-5% | 0.680 | 0.688 | 0.772 | 0.765 |
| 5-10% | 0.669 | 0.671 | 0.783 | 0.770 |
| 10-20% | 0.655 | 0.659 | 0.795 | 0.775 |
| 20-40% | 0.627 | 0.638 | 0.817 | 0.789 |
| 40-60% | 0.592 | 0.597 | 0.847 | 0.809 |
| 60-80% | 0.564 | 0.556 | 0.870 | 0.832 |
| 80-100% | 0.547 | 0.533 | 0.885 | 0.823 |

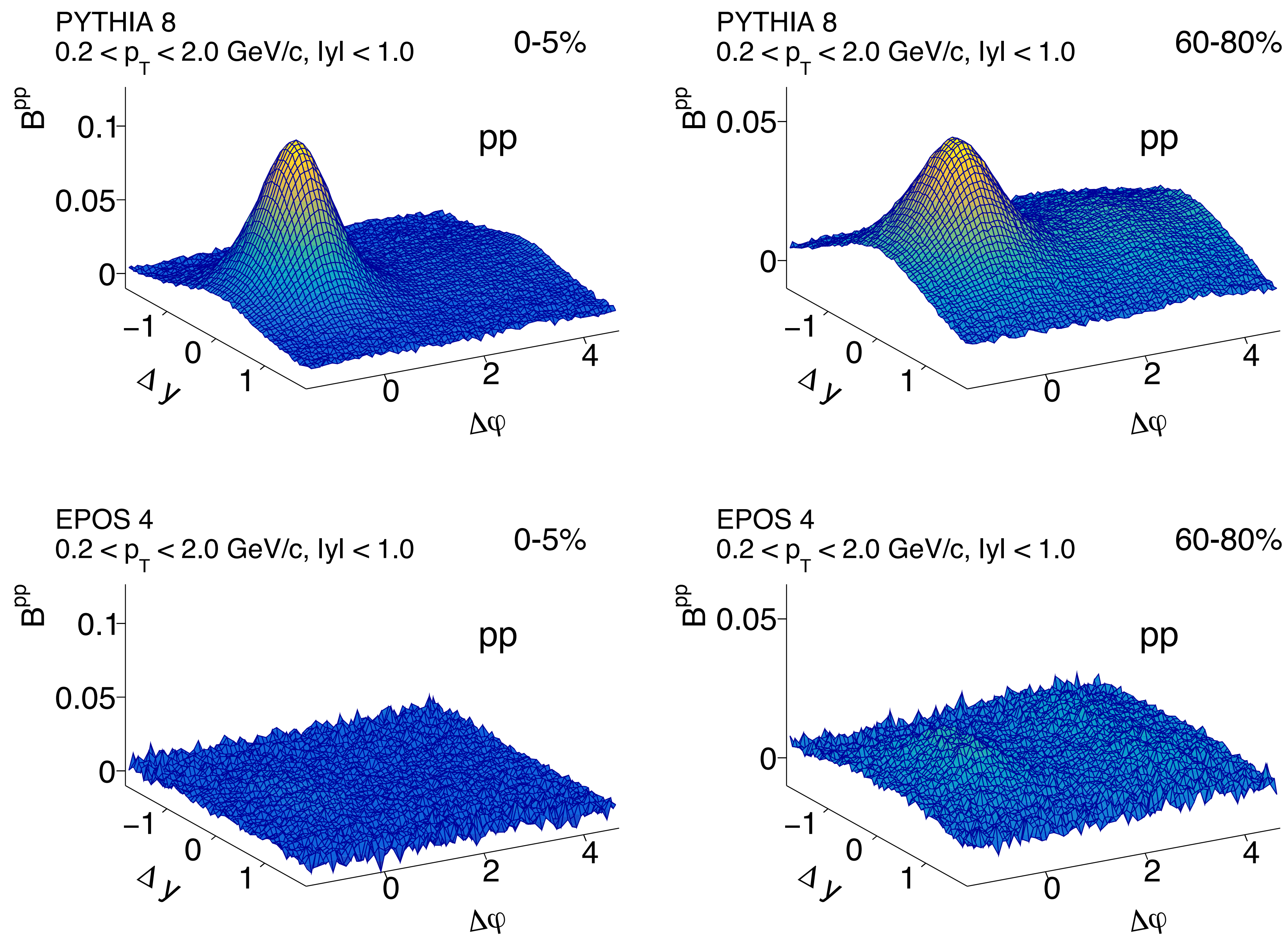
$\langle p_{\mathrm{T}} \rangle$ evolution with multiplicity -> decrease with multiplicity

# $KK$ balance with multiplicity




- EPOS increases correlation strength in the away side

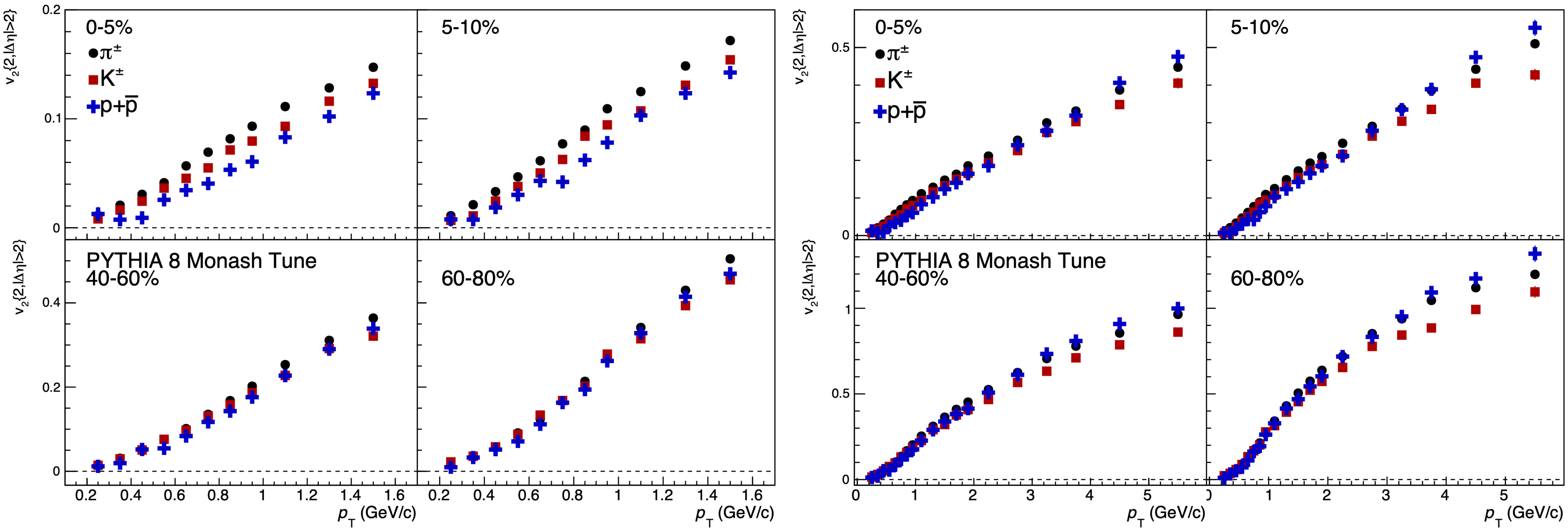
# $p + \bar{p}$ balance with multiplicity




- PYTHIA is very different from EPOS

# $v_2\{2, |\Delta\eta| > 2\}$ Monash tune

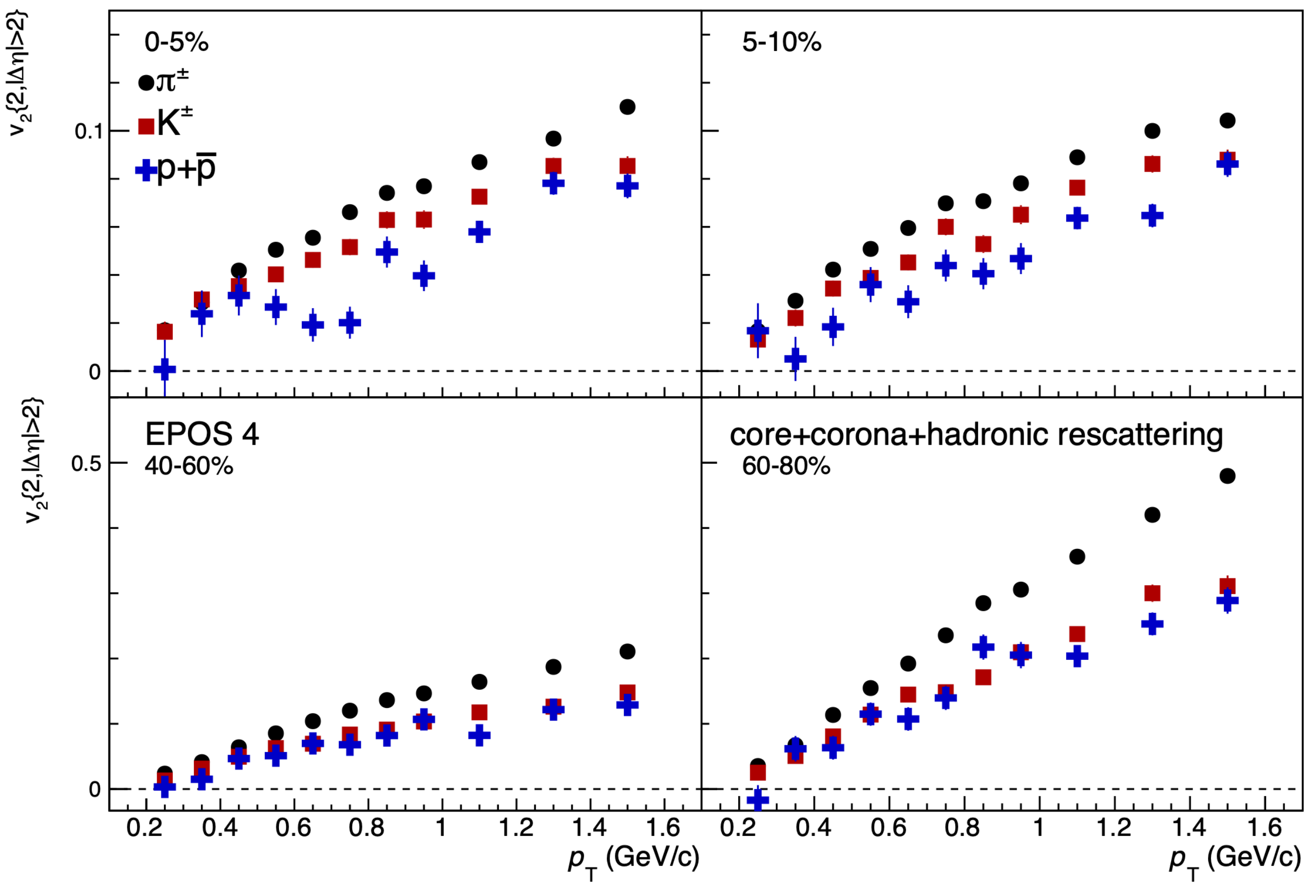
**Low $p_T$** | **High $p_T$**



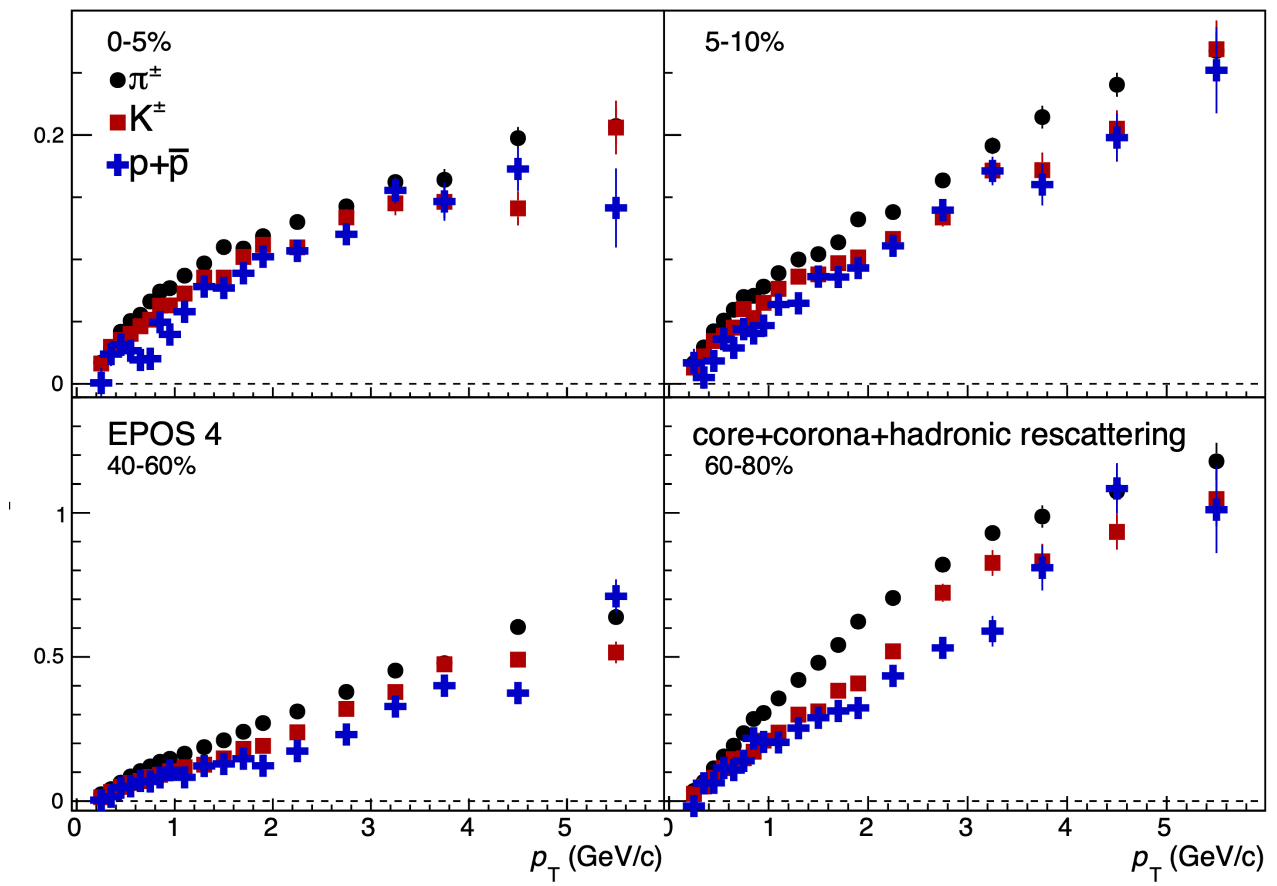

- Mass ordering at low $p_T$ at high multiplicity
- Crossing between baryon and meson $v_2$
- Evolution with multiplicity class
- No particle type grouping

# $v_2\{2, |\Delta\eta| > 2\}$ EPOS 4

**Low $p_T$**



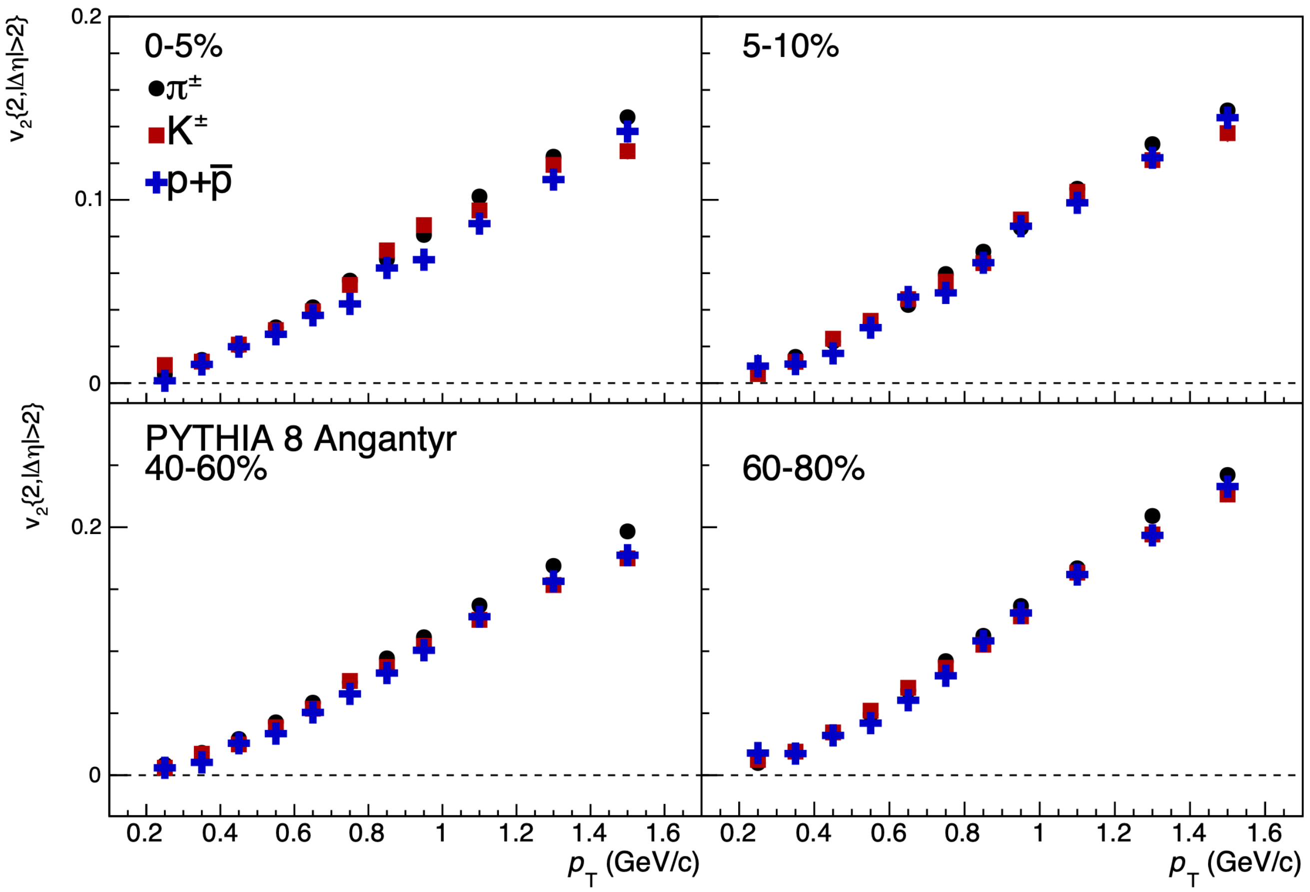

**High $p_T$**



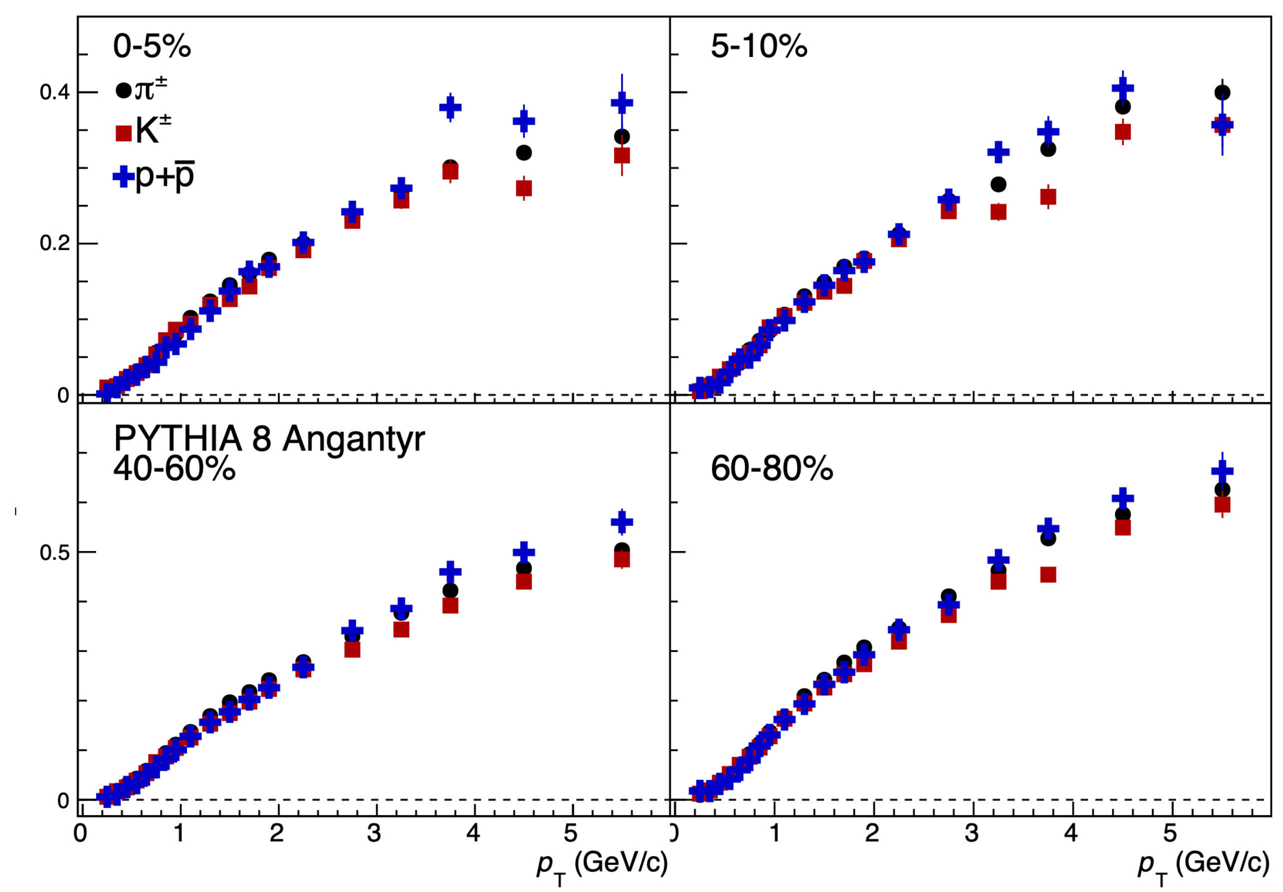

- Mass ordering at low $p_T$ at high multiplicity
- Evolution with multiplicity class
- No crossing between pion and proton $v_2$
- No particle type grouping

# $v_2\{2, |\Delta\eta| > 2\}$ Angantyr

**Low $p_T$**




**High $p_T$**




- Heavier particles have smaller $v_2$ than lighter ones
- Similarities between multiplicity classes
- Crossing between pion and proton $v_2$
- No particle type grouping