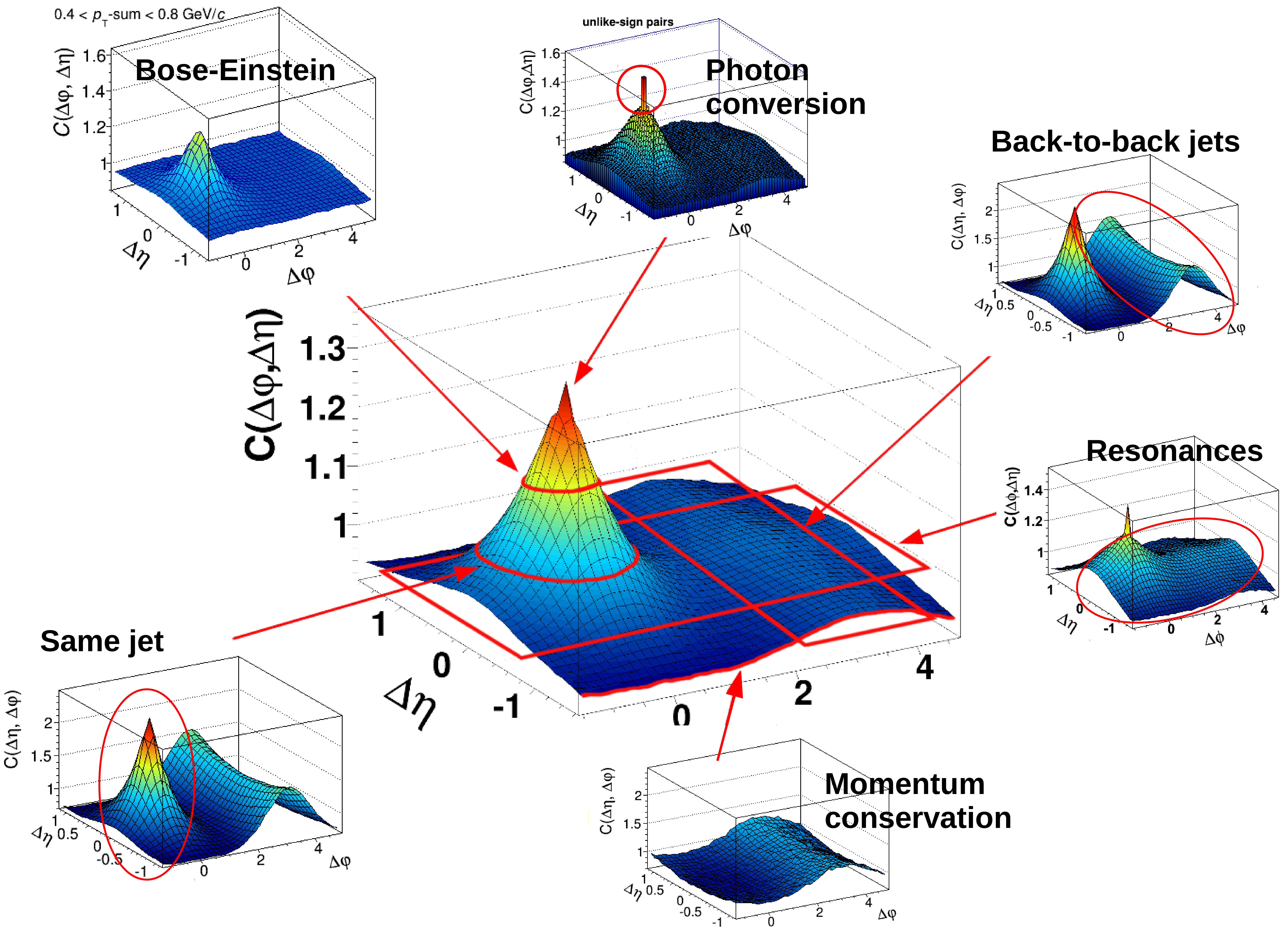
Probing particle production mechanisms with correlations and fluctuations

Alice Ohlson (Lund University), QCD Challenges, 2-6 September 2024

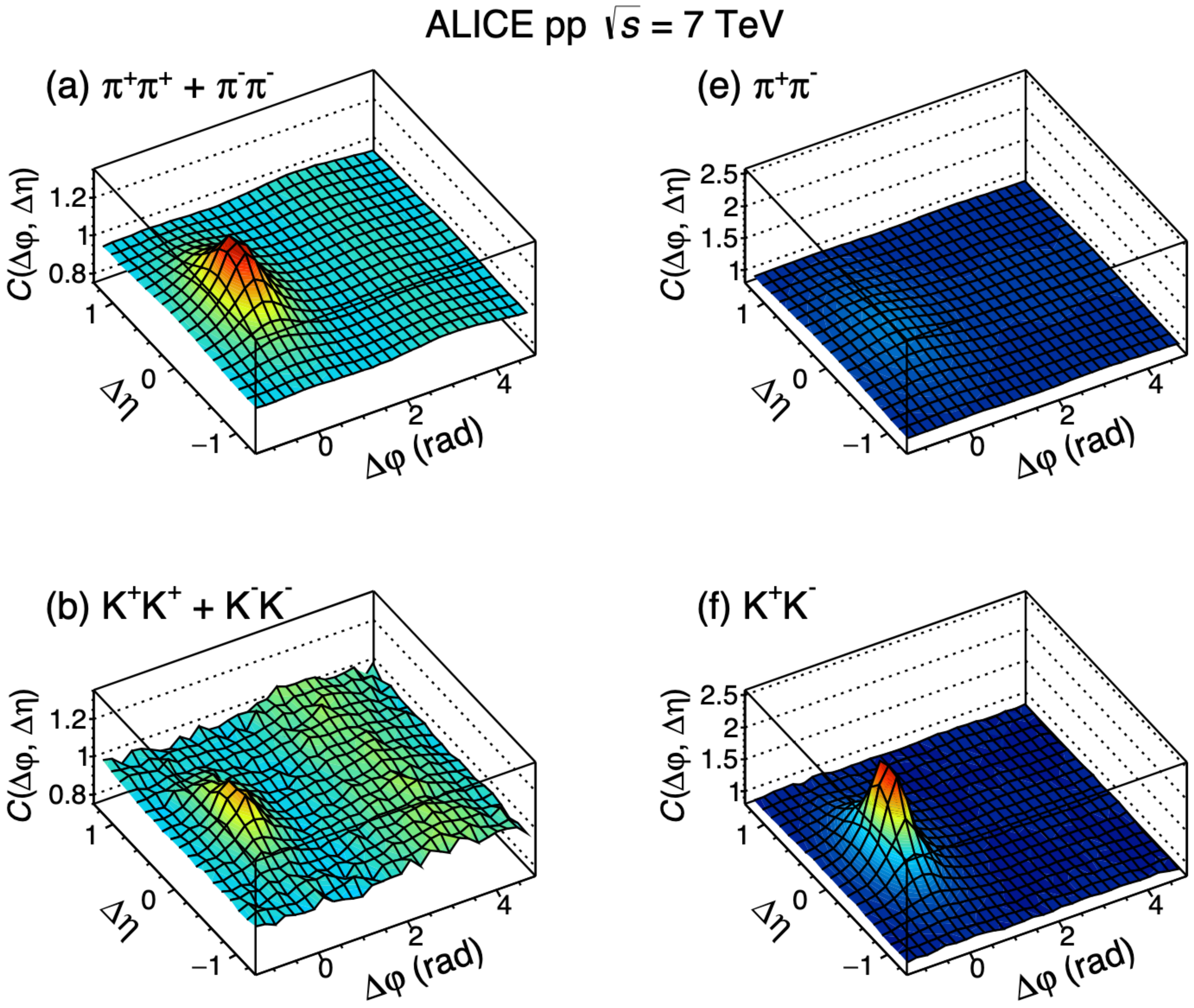
Correlation functions

- Distribution of pairs of particles in angular ($\Delta\varphi = \varphi_1 - \varphi_2$, $\Delta\eta = \eta_1 - \eta_2$) space
- Sensitive to a wide variety of physics based on selection of particle species, momenta, etc
- Correlation function normalized to unity
  $C(\Delta\varphi, \Delta\eta) = 1$ no correlation
  > 1 correlation
  > 1 anticorrelation



Images from Małgorzata Janik

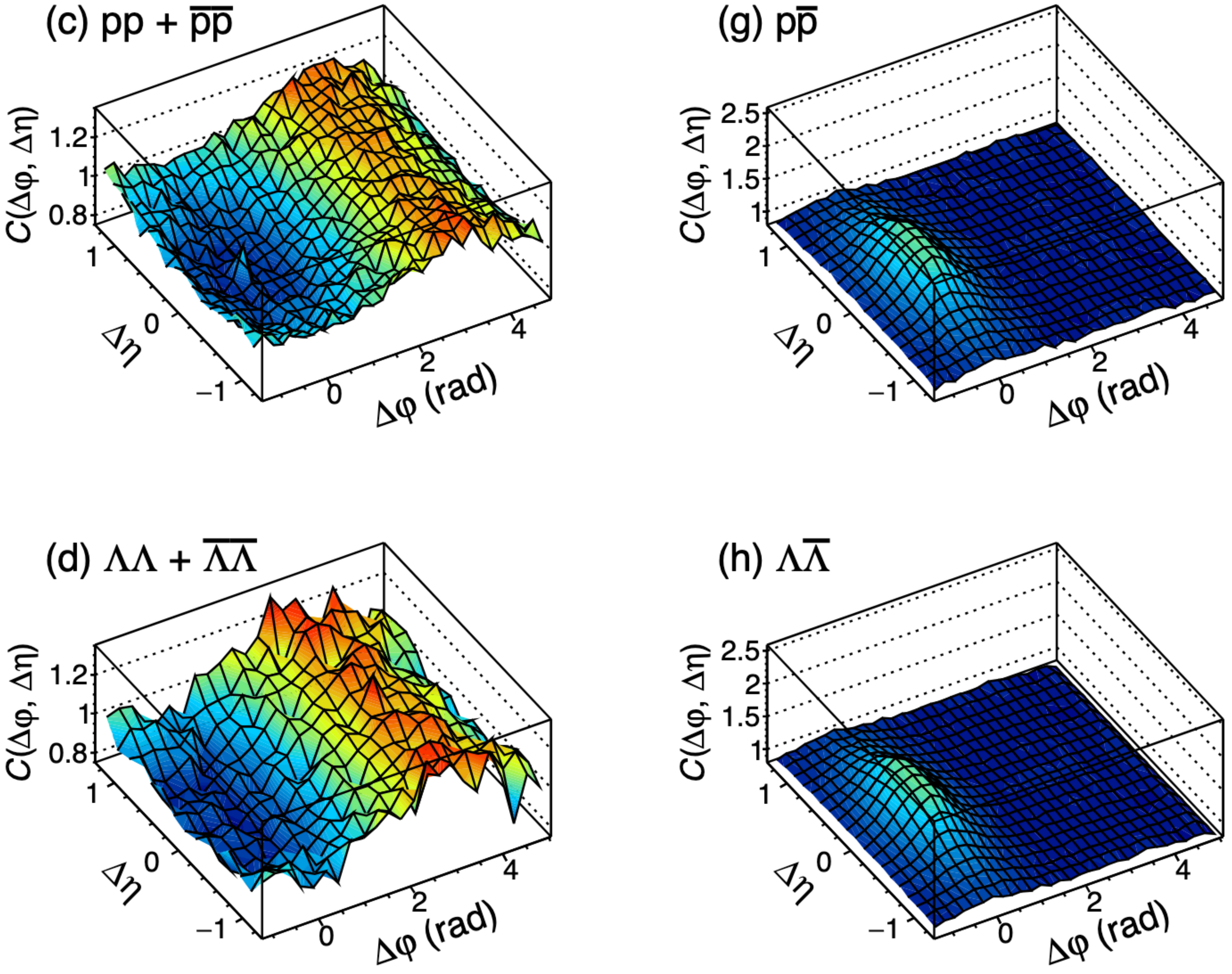
Correlation functions of mesons



- Meson-(anti)meson correlation functions show familiar features
  - nearside peak due to (mini)jet fragmentation, resonance decays, femtoscopic correlations (for identical particle pairs)
  - awayside ridge from back-to-back (mini)jets

ALICE, EPJC 77 (2017) 569
arXiv:1612.08975 [nucl-ex]

Correlation functions of baryons



- Baryon-antibaryon correlation functions show familiar features
- Baryon-baryon correlations show *nearside dip* and awayside ridge
- It appears that forming multiple baryons (or multiple antibaryons) close in phase space is strongly suppressed
- Many hypotheses (Fermi-Dirac statistics, Coulomb repulsion) were ruled out as the cause of this effect
- pΛ correlations show the same effect

ALICE, EPJC 77 (2017) 569
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Local baryon number conservation?

ALICE, EPJC 77 (2017) 569
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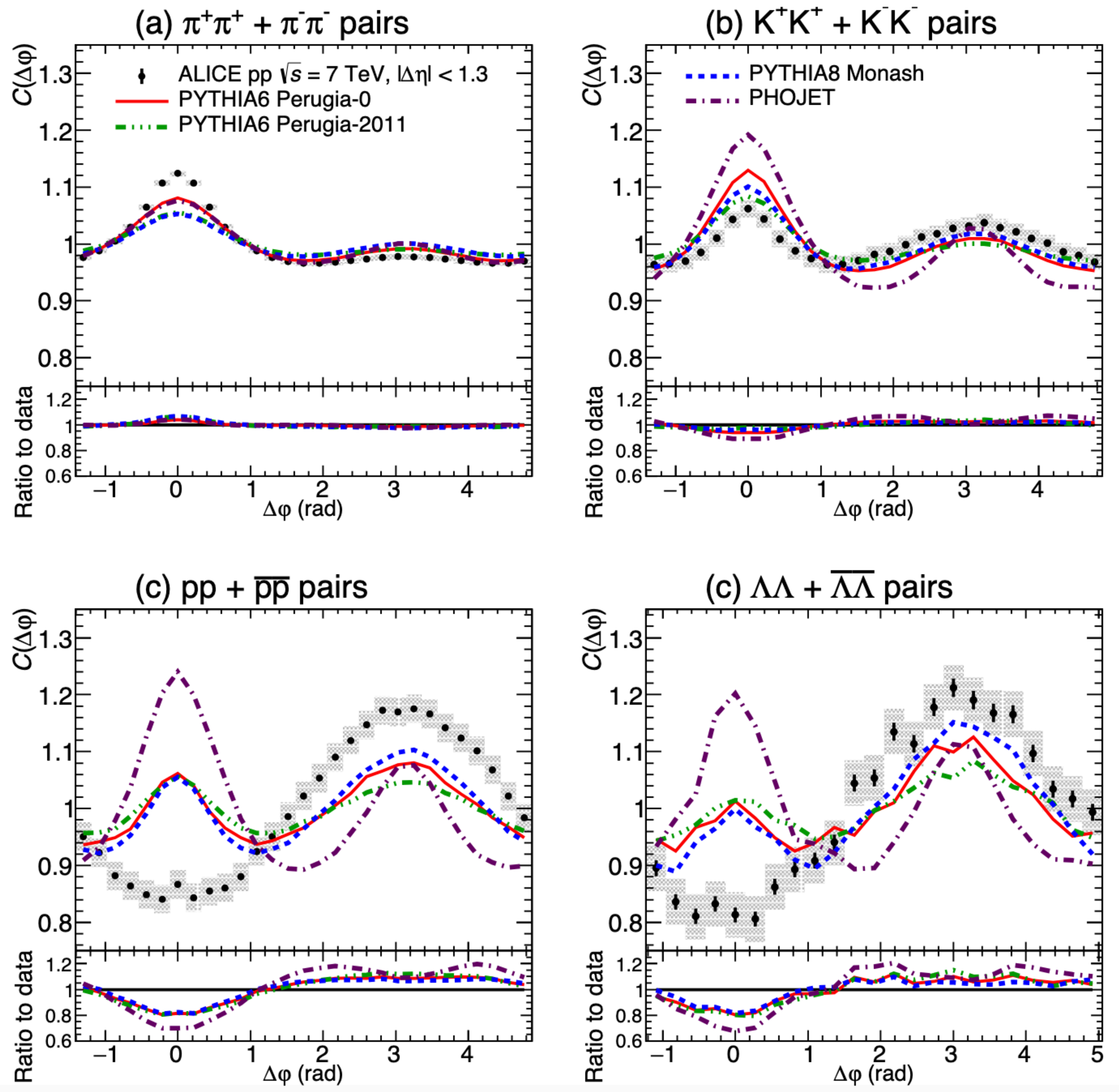
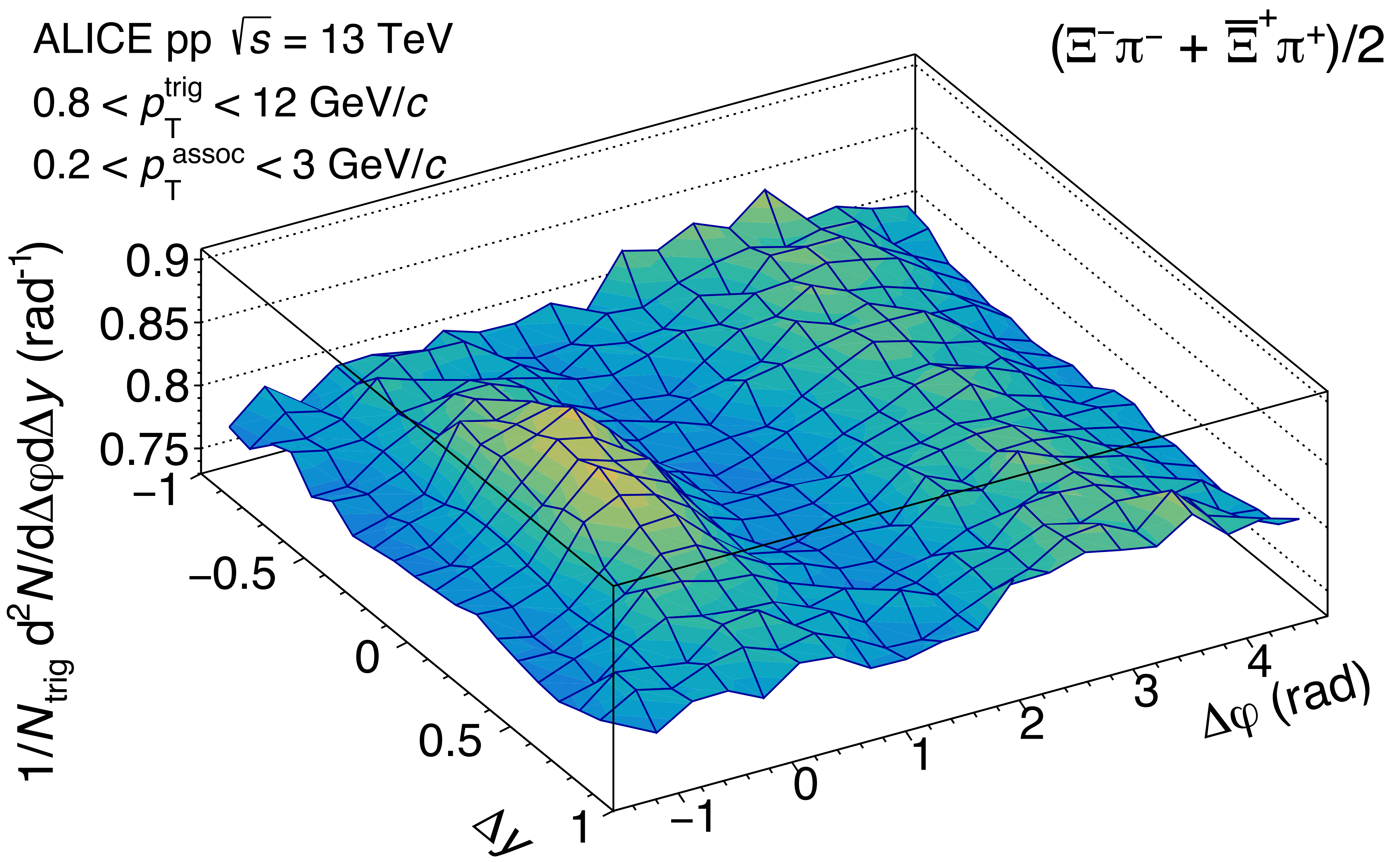


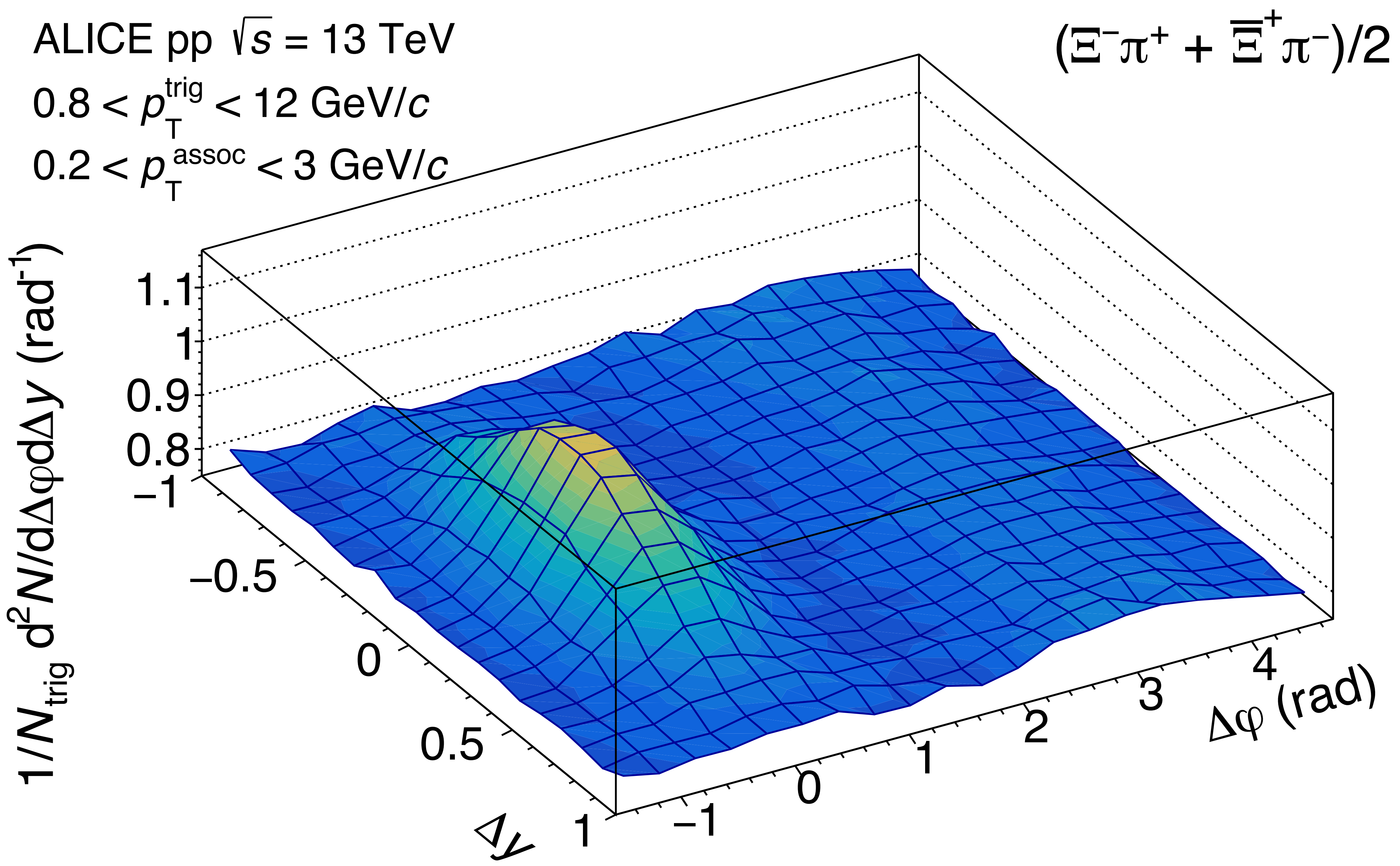
- Is the depletion due to local conservation of baryon number?
- String hadronization models would suggest that two baryons produced in a single fragmentation should be separated by at least one antibaryon
- Production of two baryons would also be suppressed if the parton energy is small compared to the energy required to produce 2 baryons + 2 antibaryons
- However, Pythia and Phojet do not show the dip, but can produce multiple baryons close together

Per-trigger yields

ALICE, arXiv:2308.16706 [hep-ex]
accepted by JHEP

- Per-trigger yield: Y(Δφ, Δη) is the number of particles associated with the trigger particle at a relative separation (Δφ, Δη)

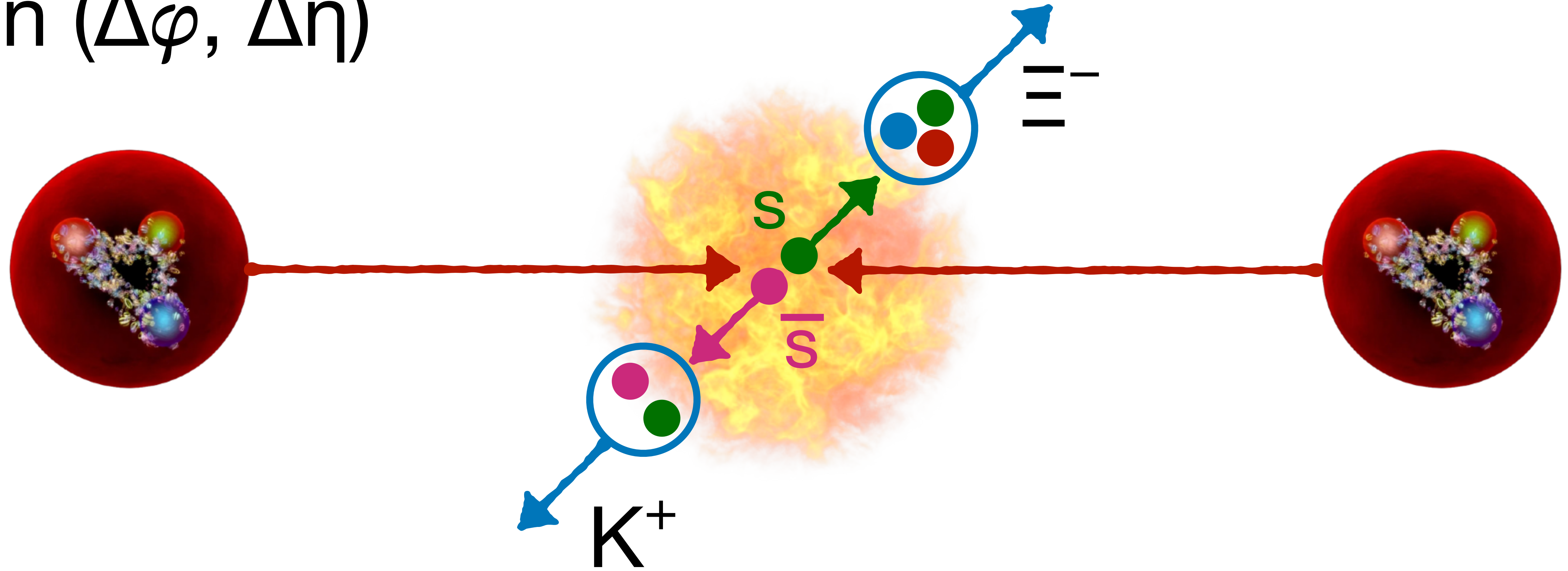




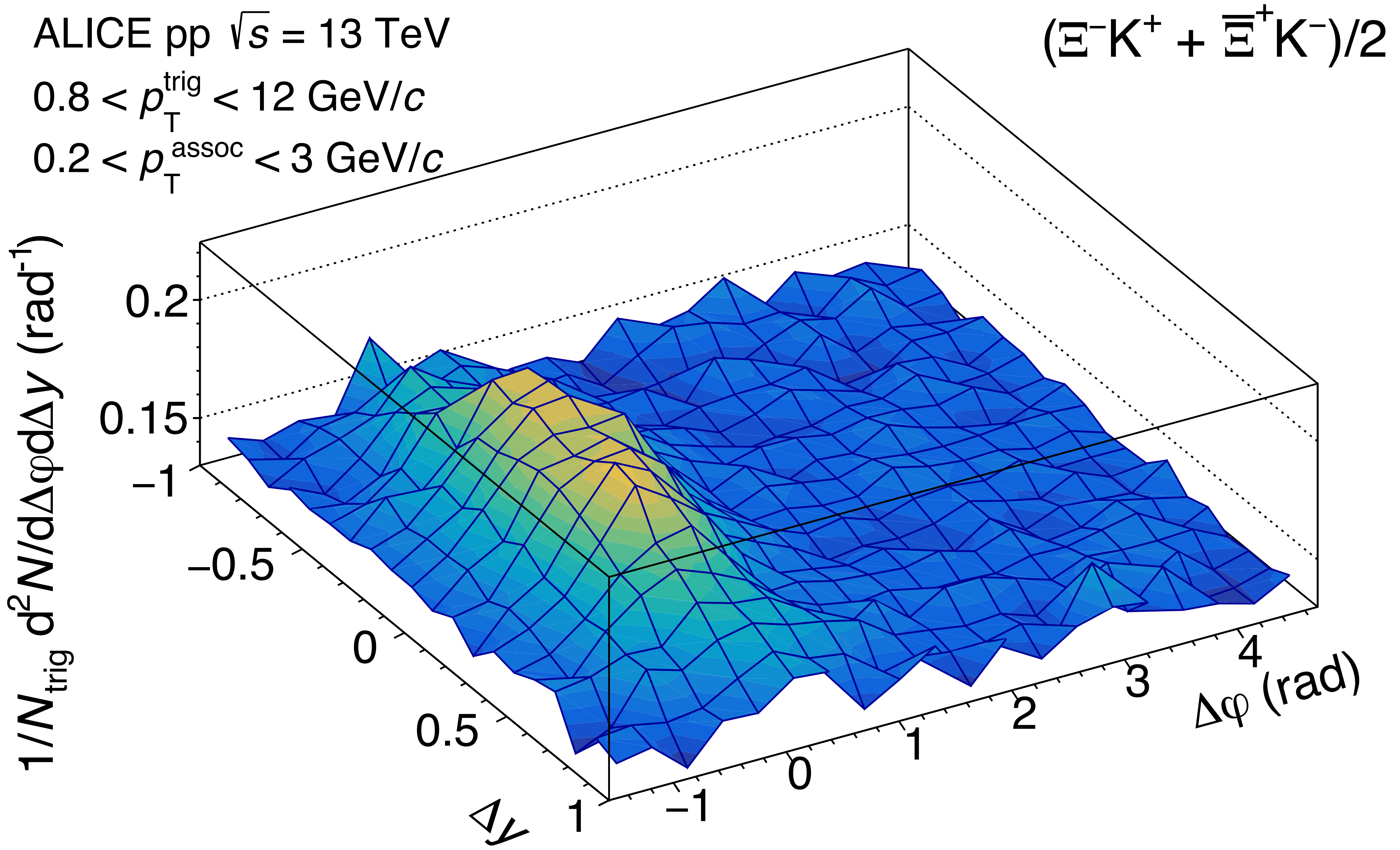
Balance functions

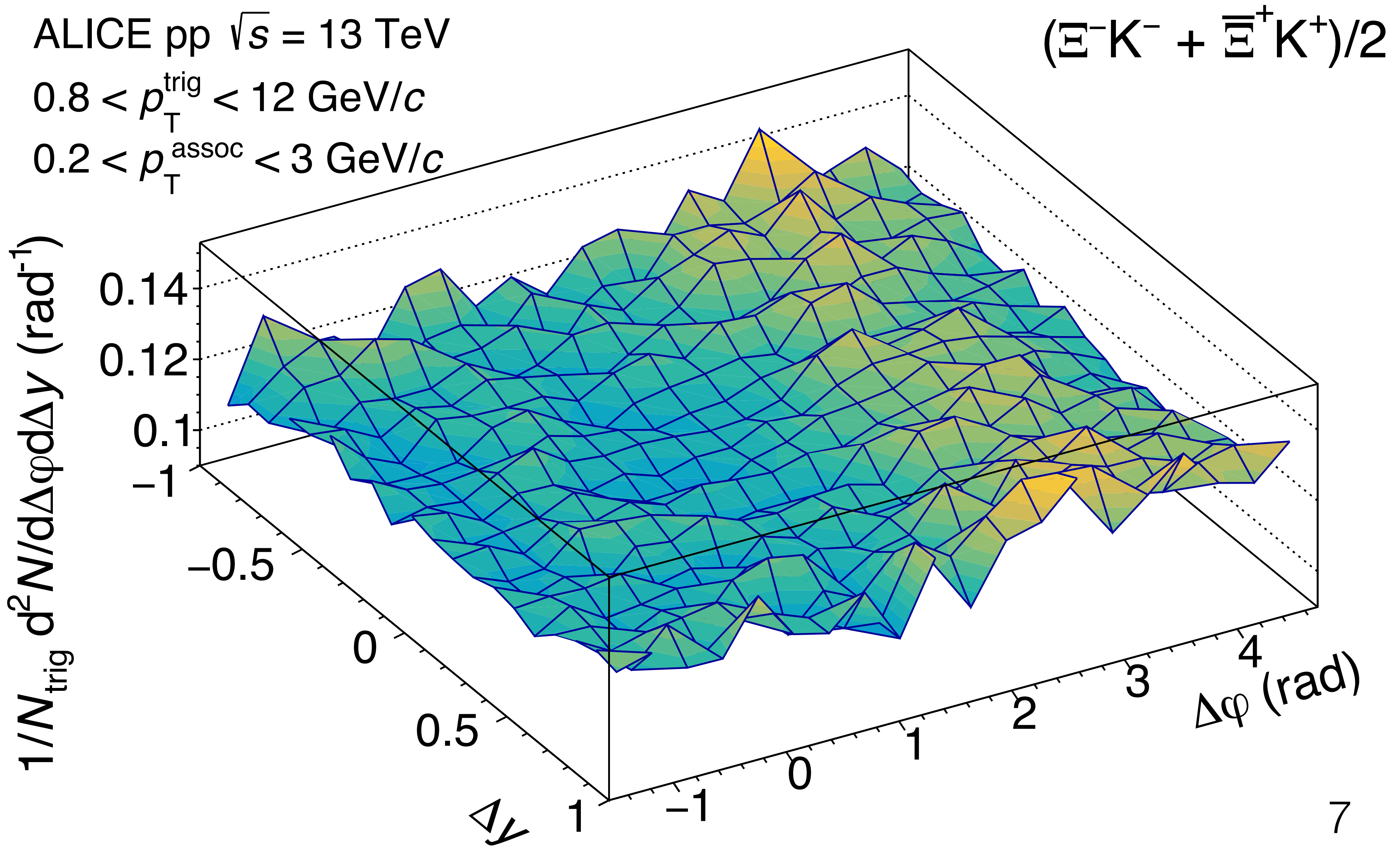
ALICE, arXiv:2308.16706 [hep-ex]
accepted by JHEP

- Balance functions: correlation functions indicate where balancing charges end up in ($\Delta\varphi$, $\Delta\eta$)



- Example: Ξ^-K^+ correlations share a s-sbar pair which could come from the same string breaking
  → but there are also Ξ^-K^+ pairs where the s-sbar is not from the same string, model these with Ξ^-K^- correlations and subtract

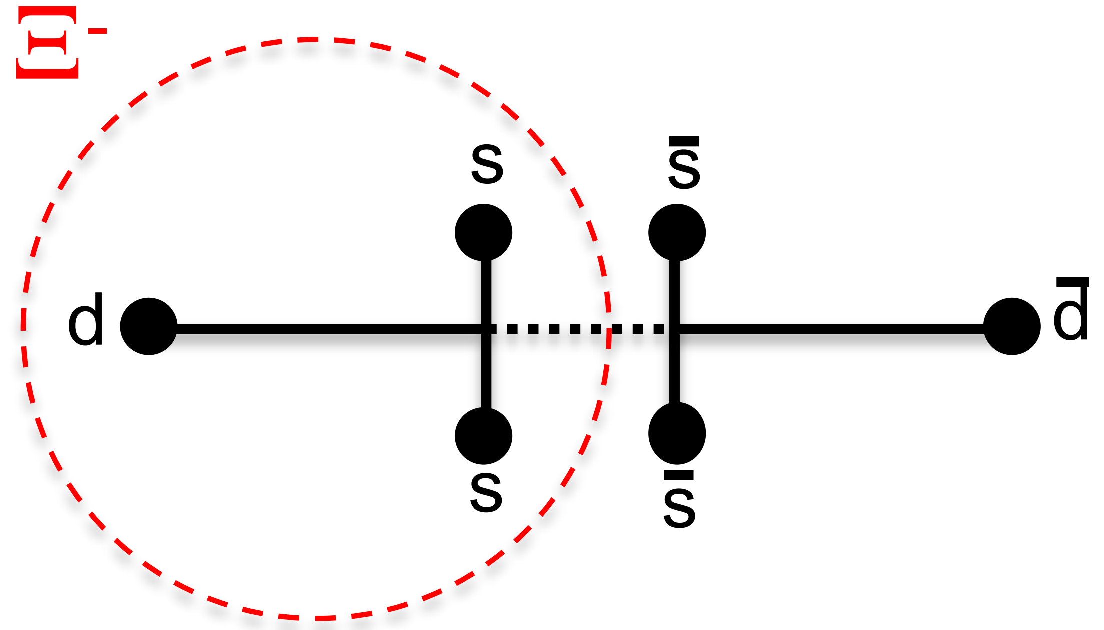




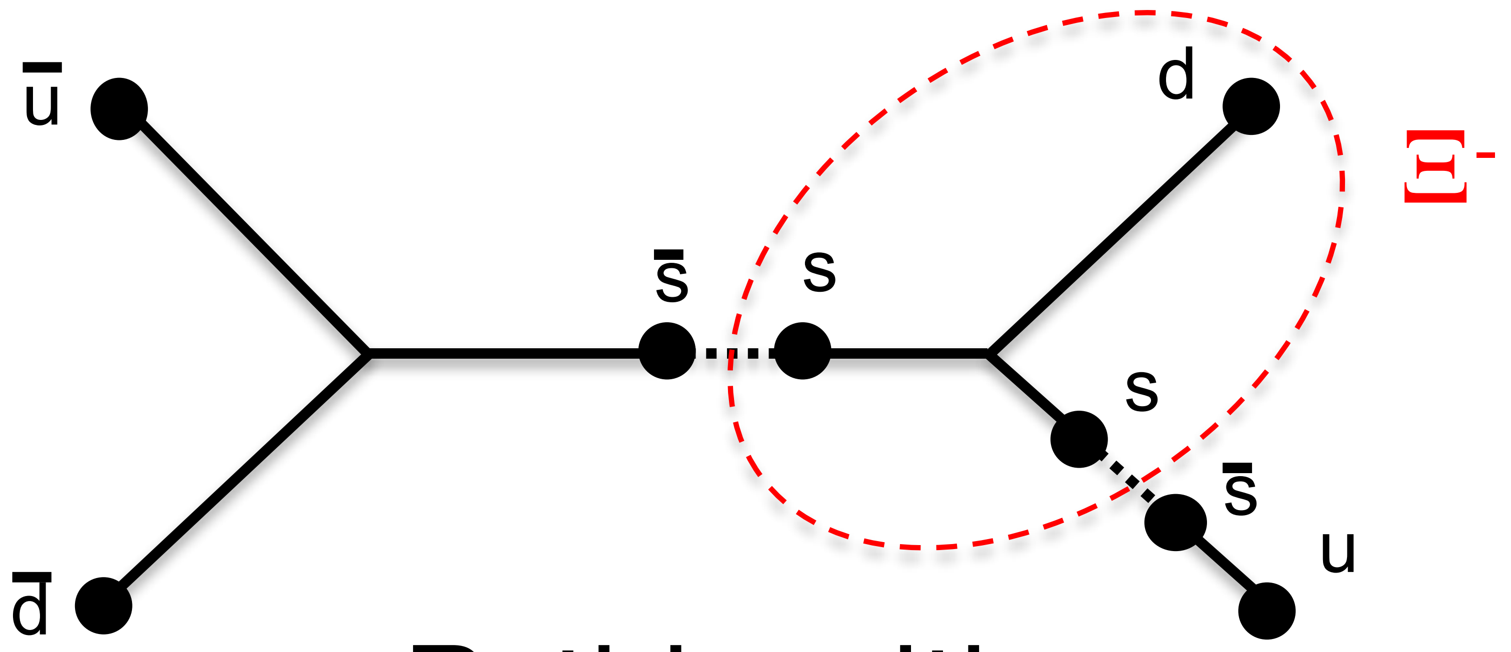
Balance functions

ALICE, arXiv:2308.16706 [hep-ex]
accepted by JHEP

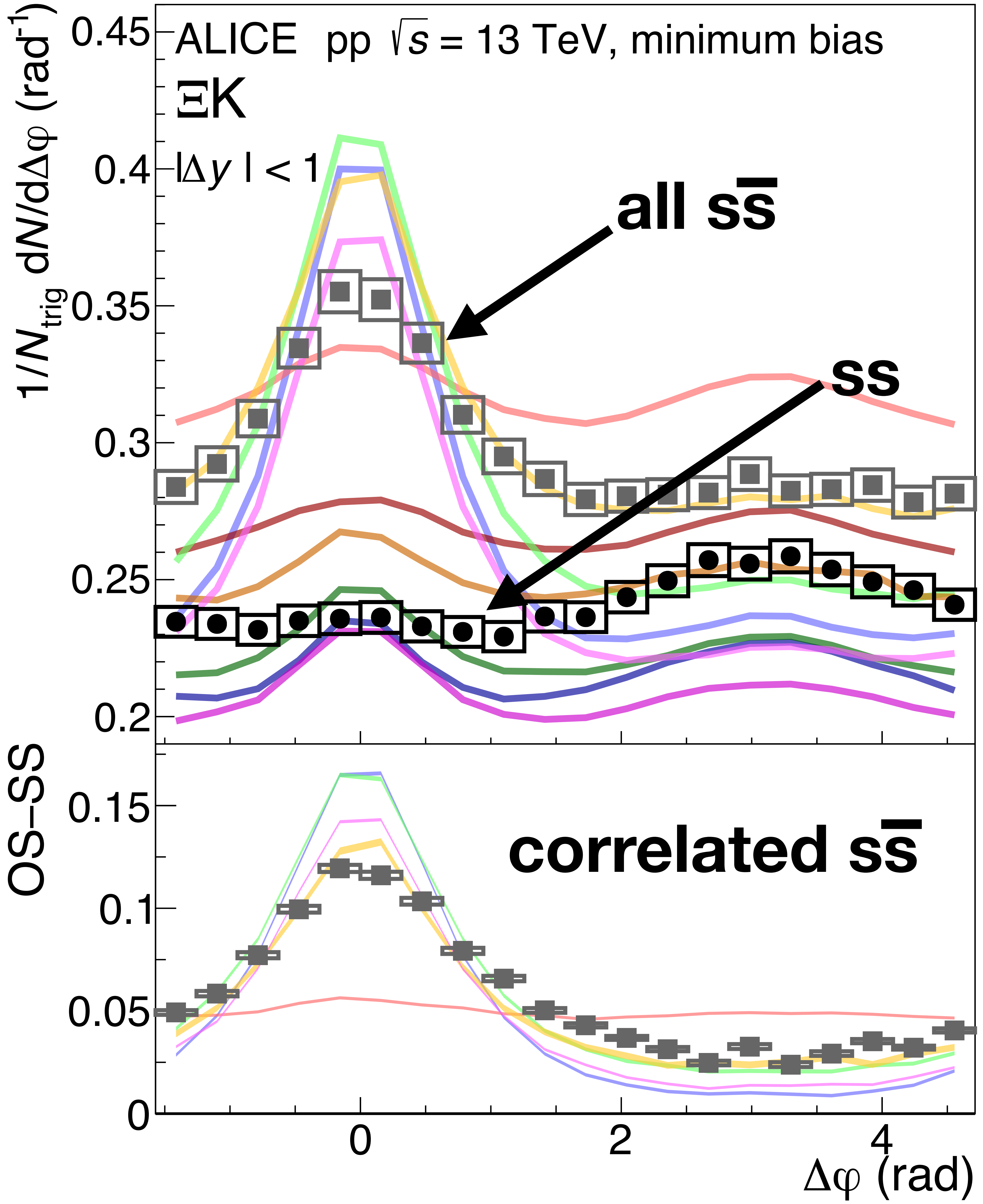
- Is strangeness conserved locally or globally?
- Do we observe the presence of a thermal strangeness reservoir (global, non-local correlations), as expected by EPOS/SHM?
- Do high-density regions in high-multiplicity events cause new string topologies to "turn on"?



diquark breaking in Pythia (default)

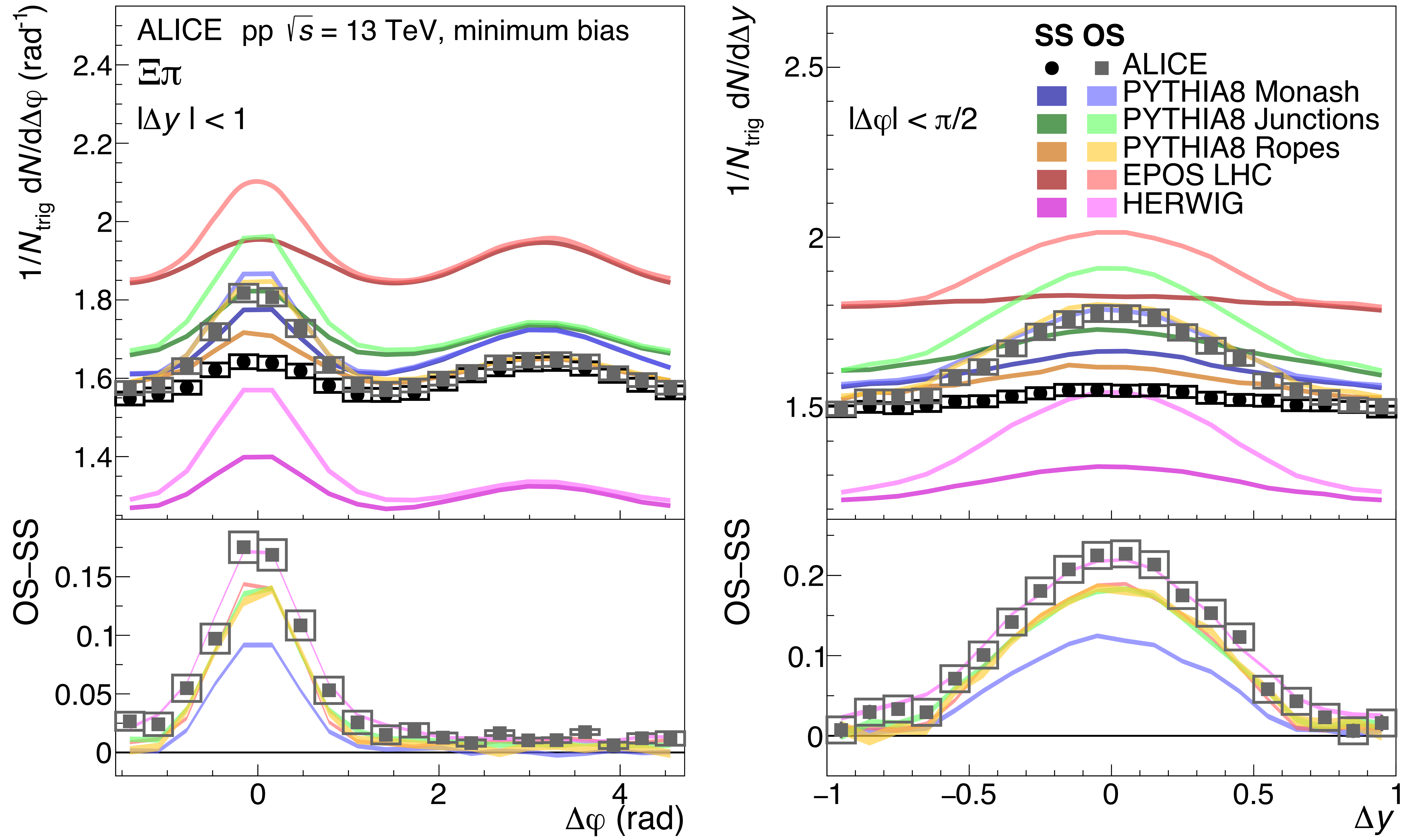


Pythia with baryon junctions



Ξπ balance functions

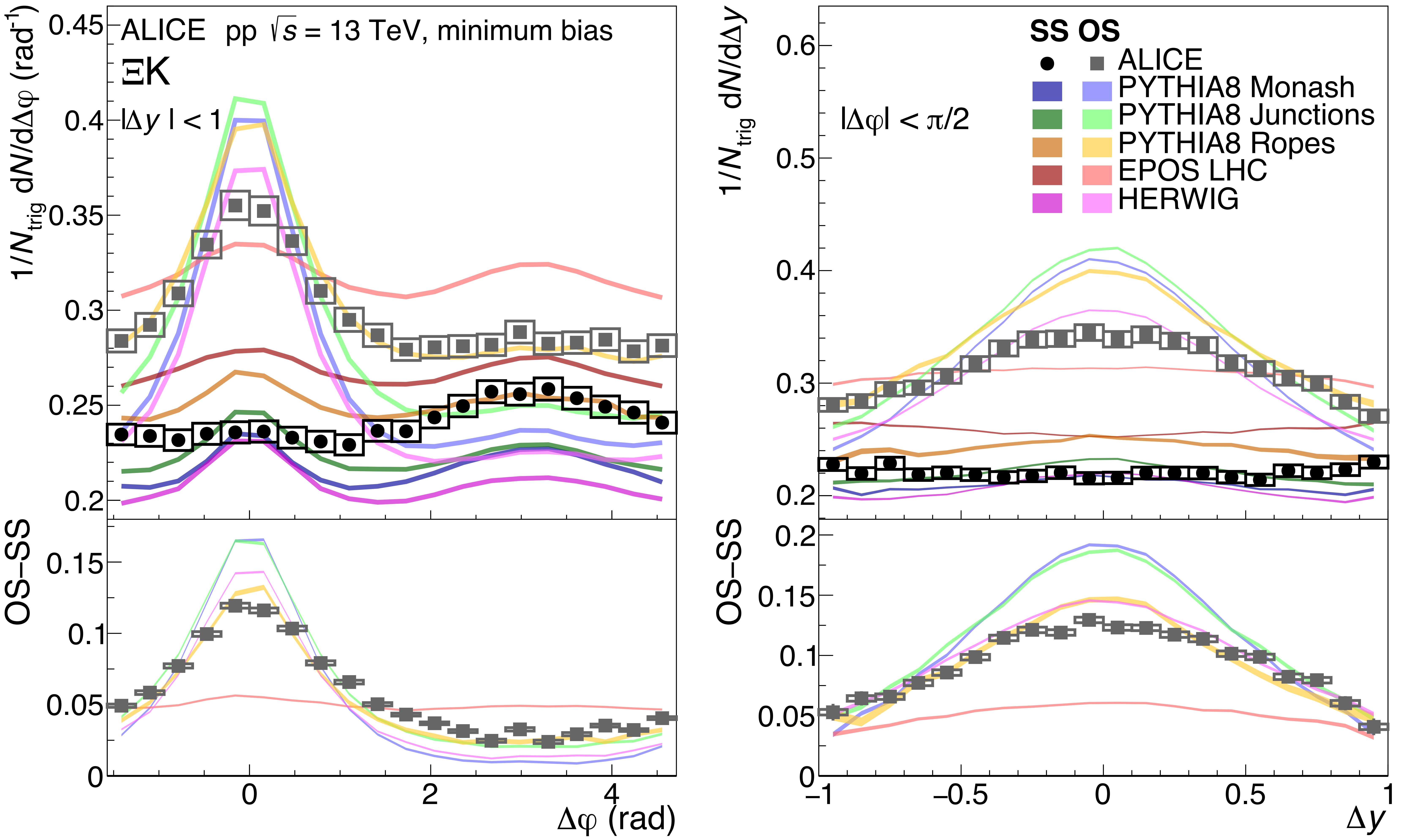
ALICE, arXiv:2308.16706 [hep-ex]
accepted by JHEP



- Pythia describes overall yields well, tuned to single-particle spectra
- Pythia, EPOS, and Herwig also get balance right

ΞK balance functions

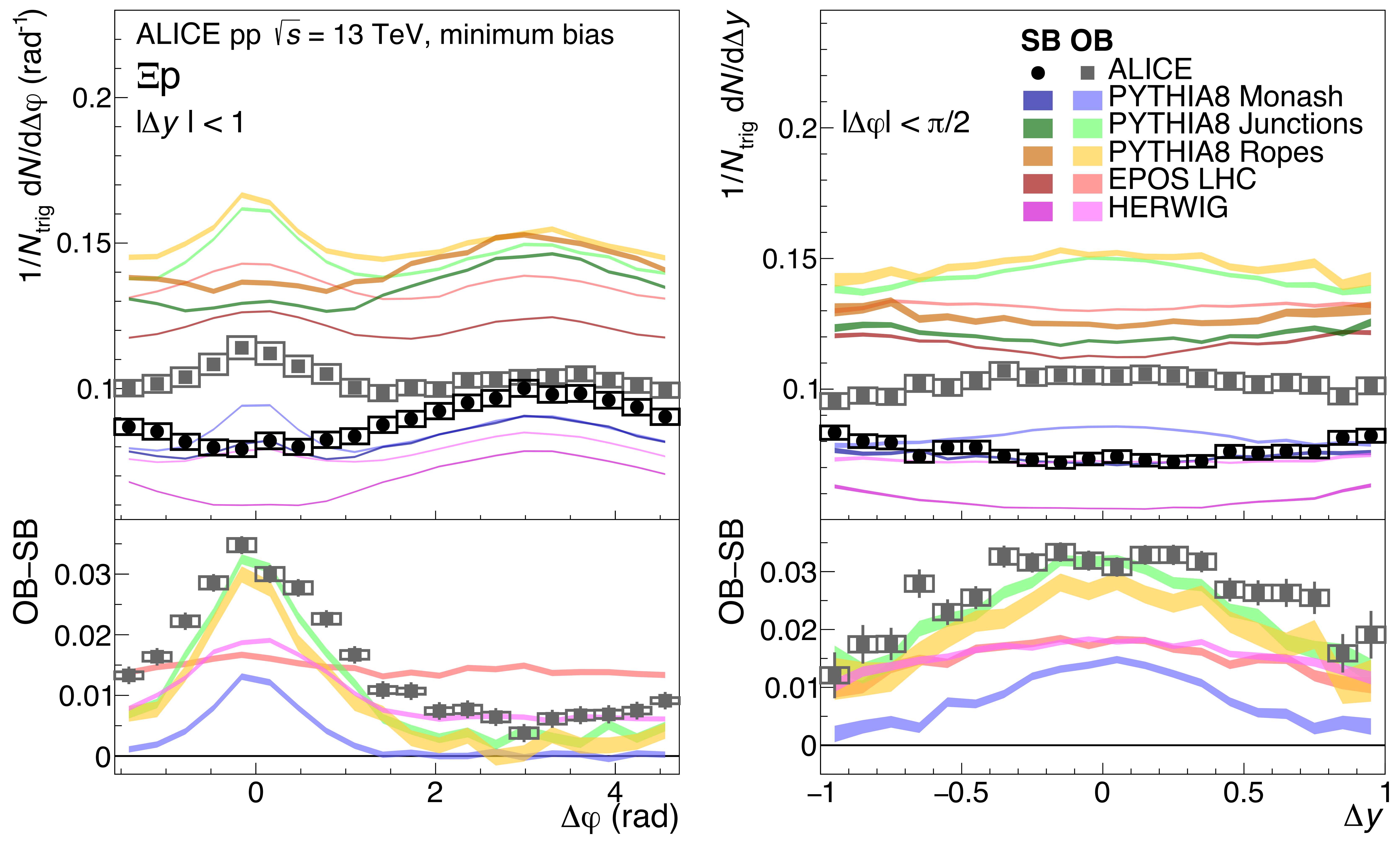
ALICE, arXiv:2308.16706 [hep-ex]
accepted by JHEP



- Wider NS peak in data than in Pythia → strange quarks produced earlier? more diffusion?
- EPOS has no local conservation of strangeness, predicts flat OS-SS difference, in contradiction to data

Ξp balance functions

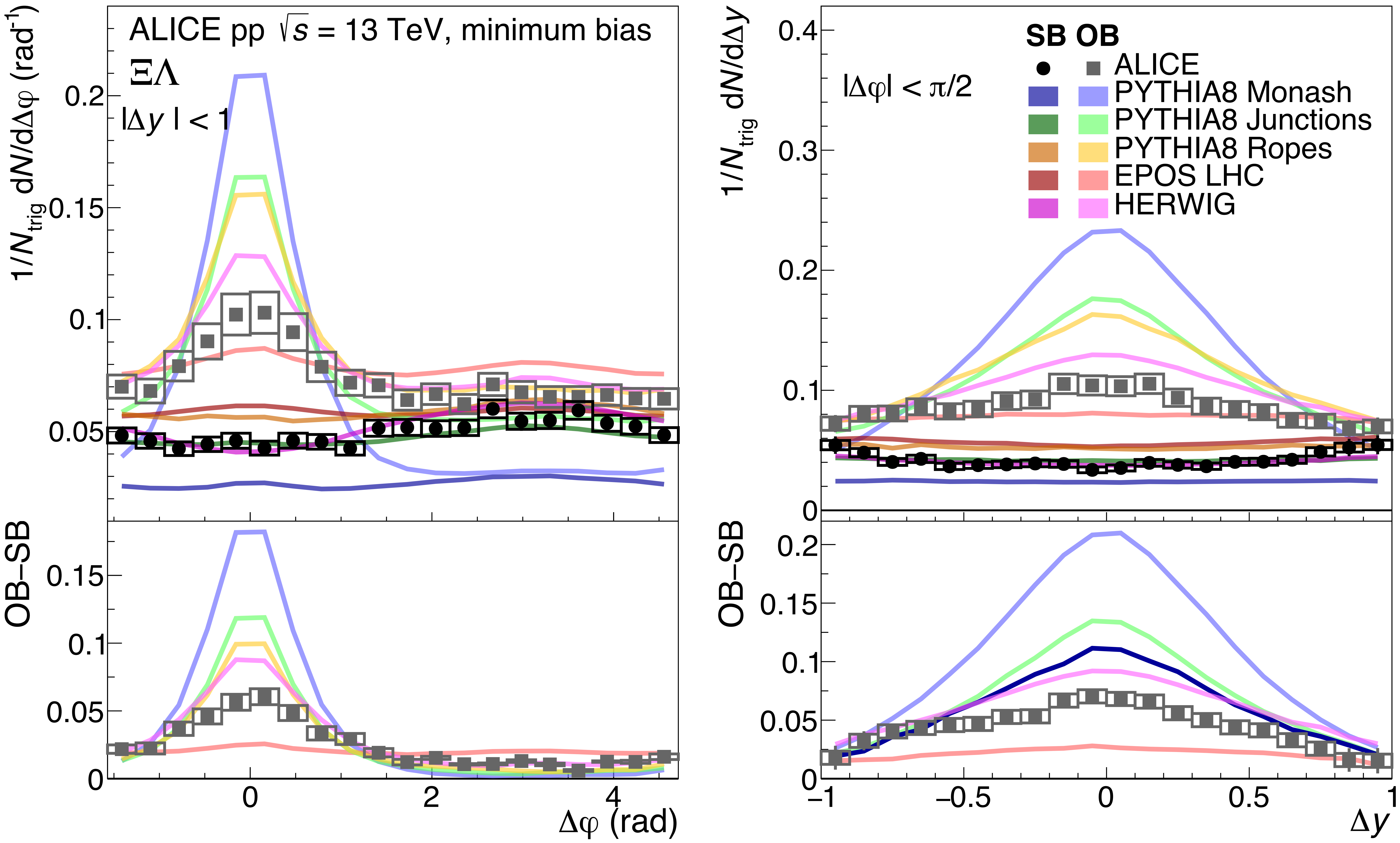
ALICE, arXiv:2308.16706 [hep-ex]
accepted by JHEP



- Junctions and ropes tunes of Pythia are able to get the shape of the OS-SS difference right, but overpredict overall yields
- EPOS predicts flat balance function, unsupported by data
- Herwig also does not get baryon balancing right

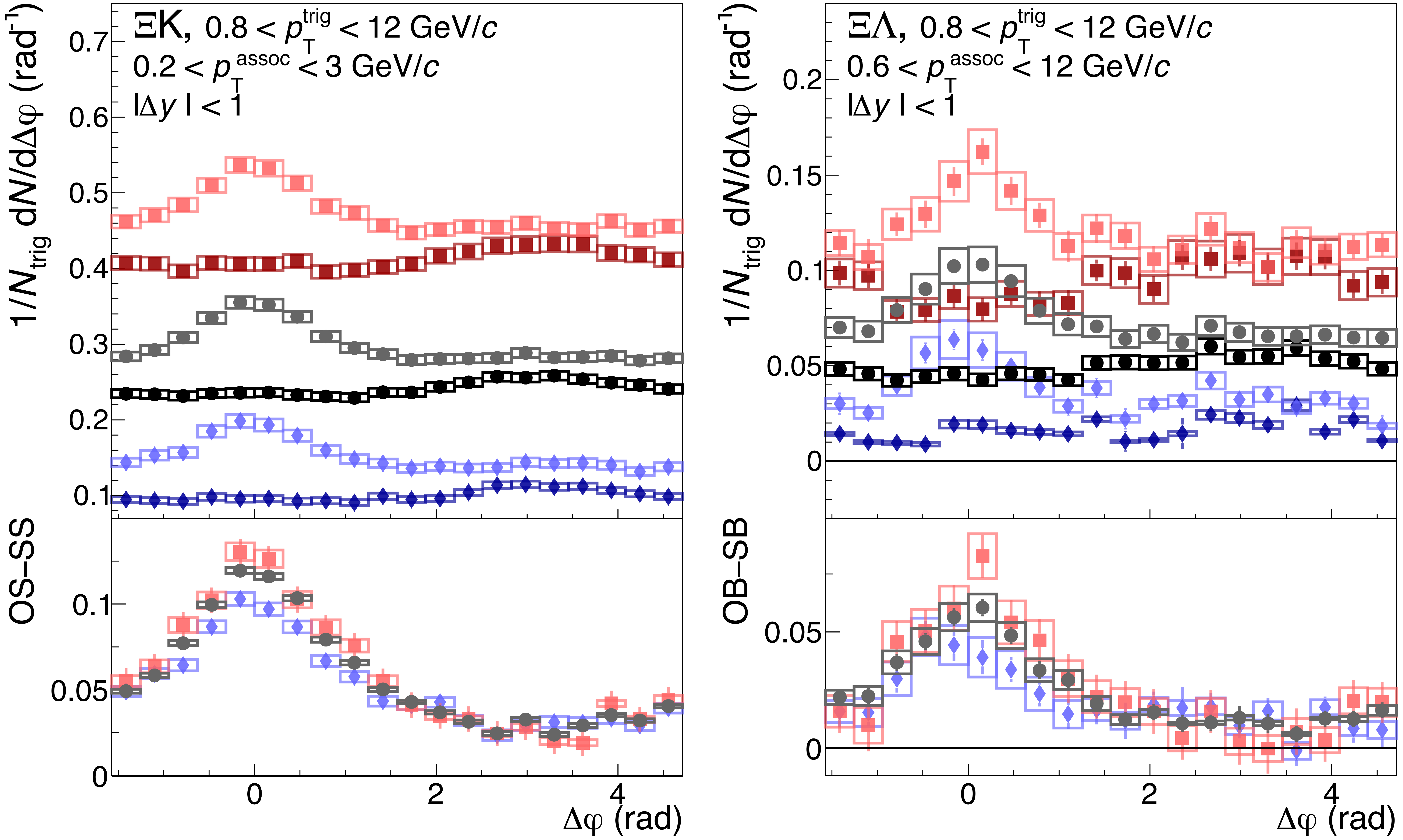
ΞΛ balance functions

ALICE, arXiv:2308.16706 [hep-ex]
accepted by JHEP



- Similar observations as in ΞK correlations, Pythia predicts a narrower peak than observed in data

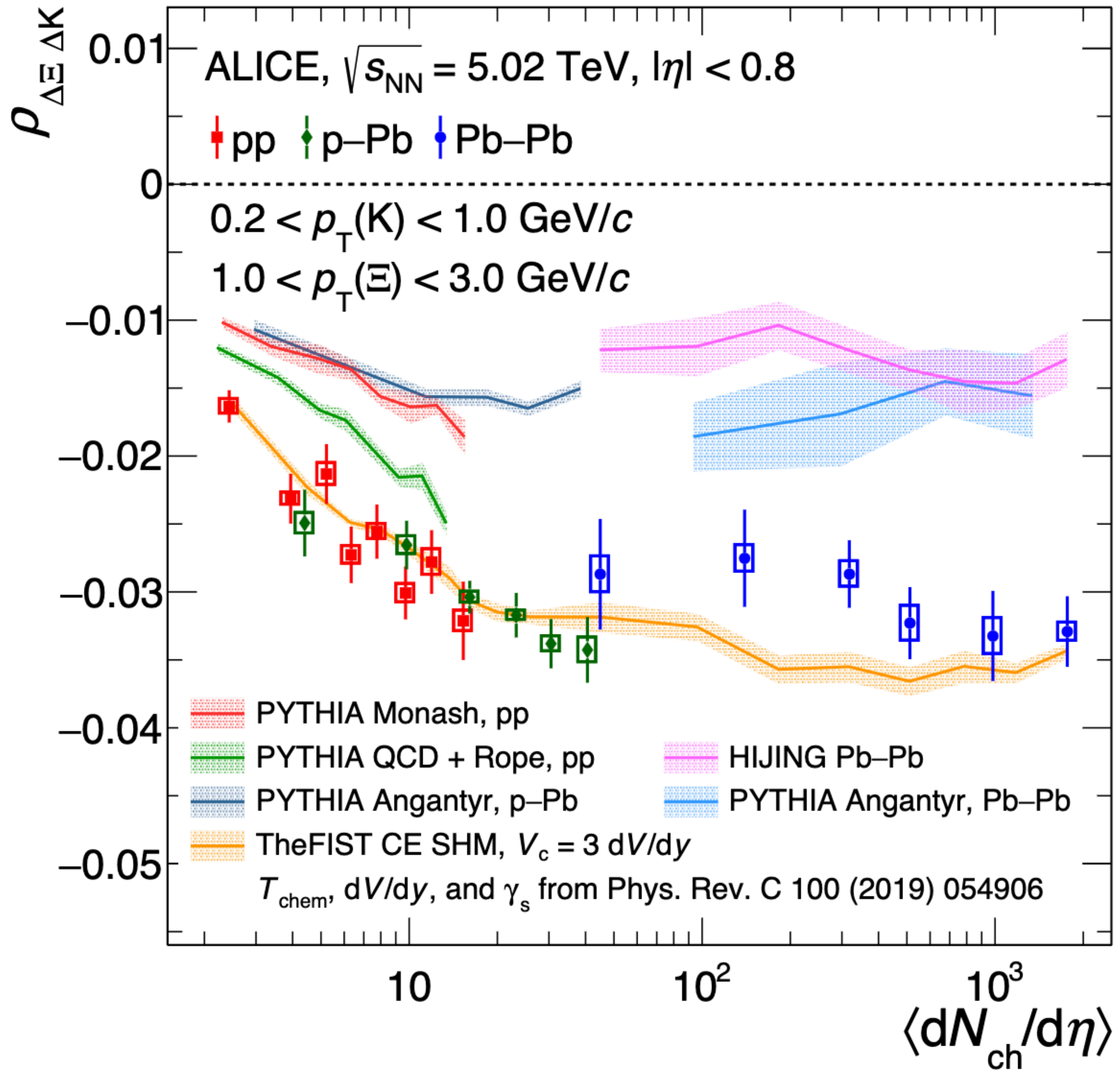
Multiplicity dependence



- No major multiplicity dependence observed → we don't see the "turn-on" of different particle production mechanisms at high multiplicity, for example
- More details, including integrated yields, in the paper

ALICE, arXiv:2308.16706 [hep-ex] accepted by JHEP

Strangeness correlations in pp, p-Pb, Pb-Pb



- Correlation coefficient between net-Ξ and net-K

$$\rho_{\Delta\Xi\Delta K} = \frac{\kappa_{11}(\Xi^-, K^-) - \kappa_{11}(\Xi^-, K^+) + \mathrm{ch.conj.}}{\sqrt{\kappa_2(\Delta\Xi)\,\kappa_2(\Delta K)}}$$

$$\kappa_{11}(A,B) = \langle N_A N_B \rangle - \langle N_A \rangle \langle N_B \rangle$$

$$\kappa_2(A) = \langle N_A^2 \rangle - \langle N_A \rangle^2$$

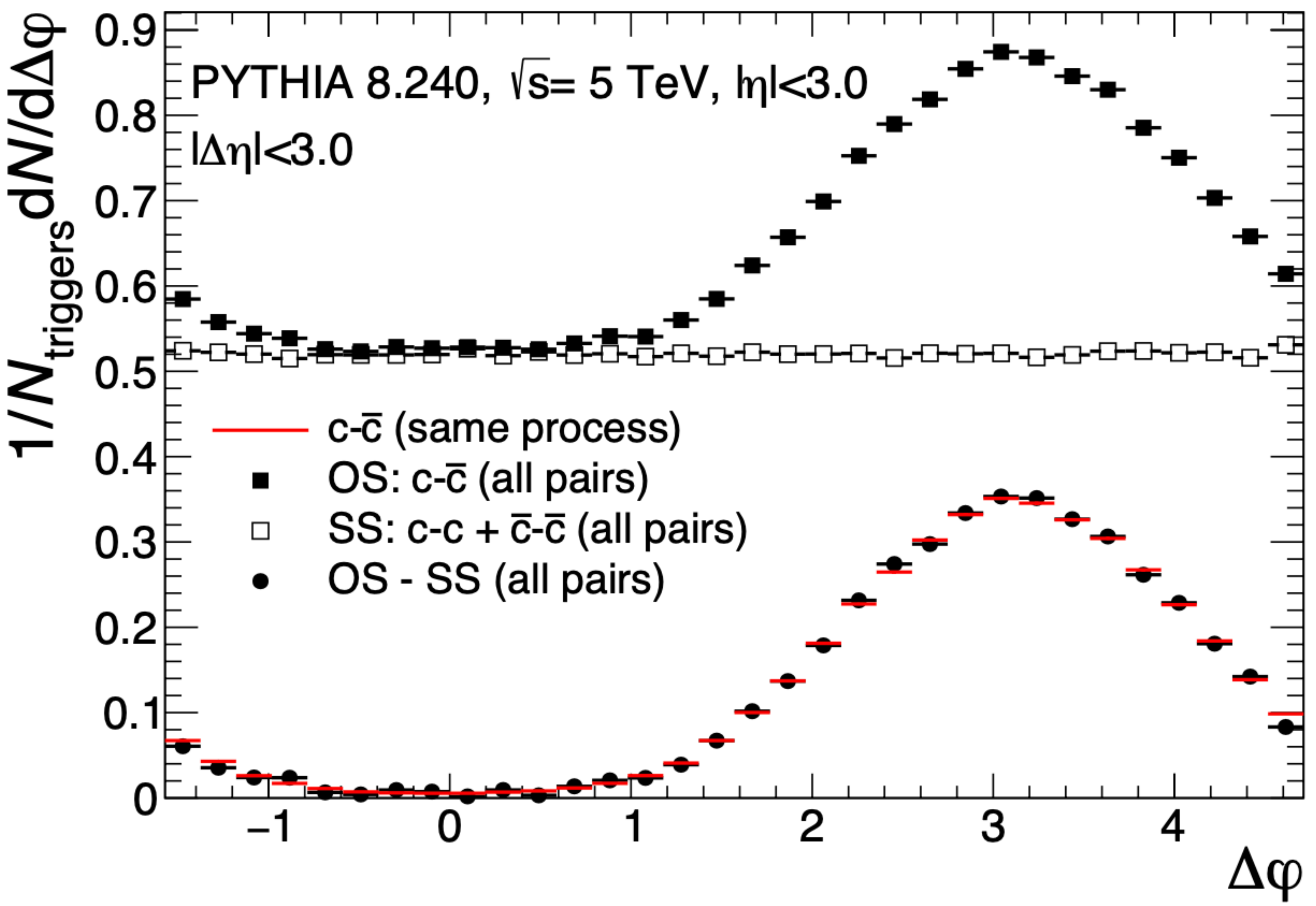
related to integral of OS-SS ΞK correlation function (with relative – sign)

- Smooth/monotonic trend from small to large systems
- Agreement with Thermal FIST indicates correlation over a larger volume than string-based models

ALICE, arXiv:2405.19890 [nucl-ex] submitted to PRL

- No “simple picture” → both local and global conservation/correlations are important

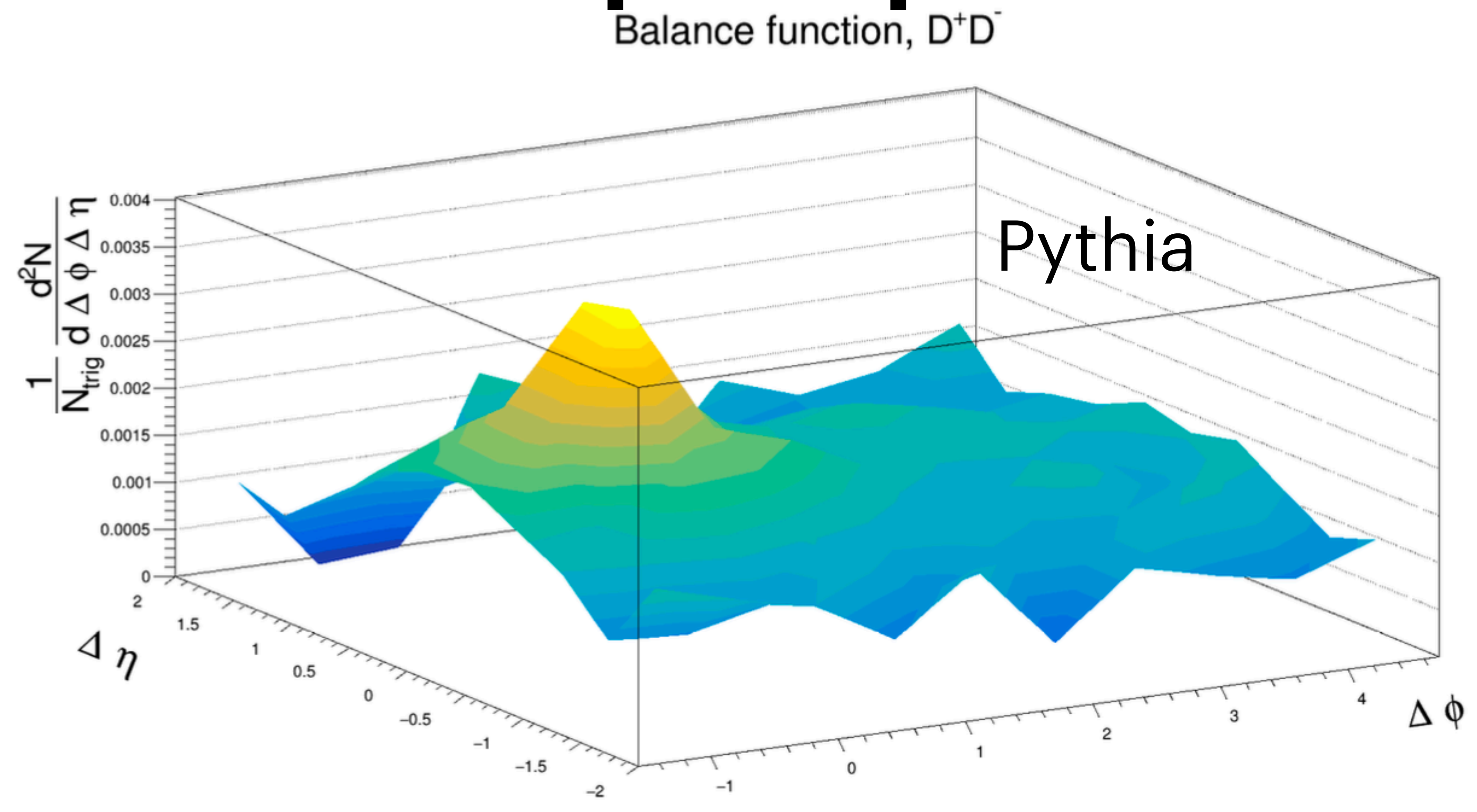
Future prospects: balance functions with charm

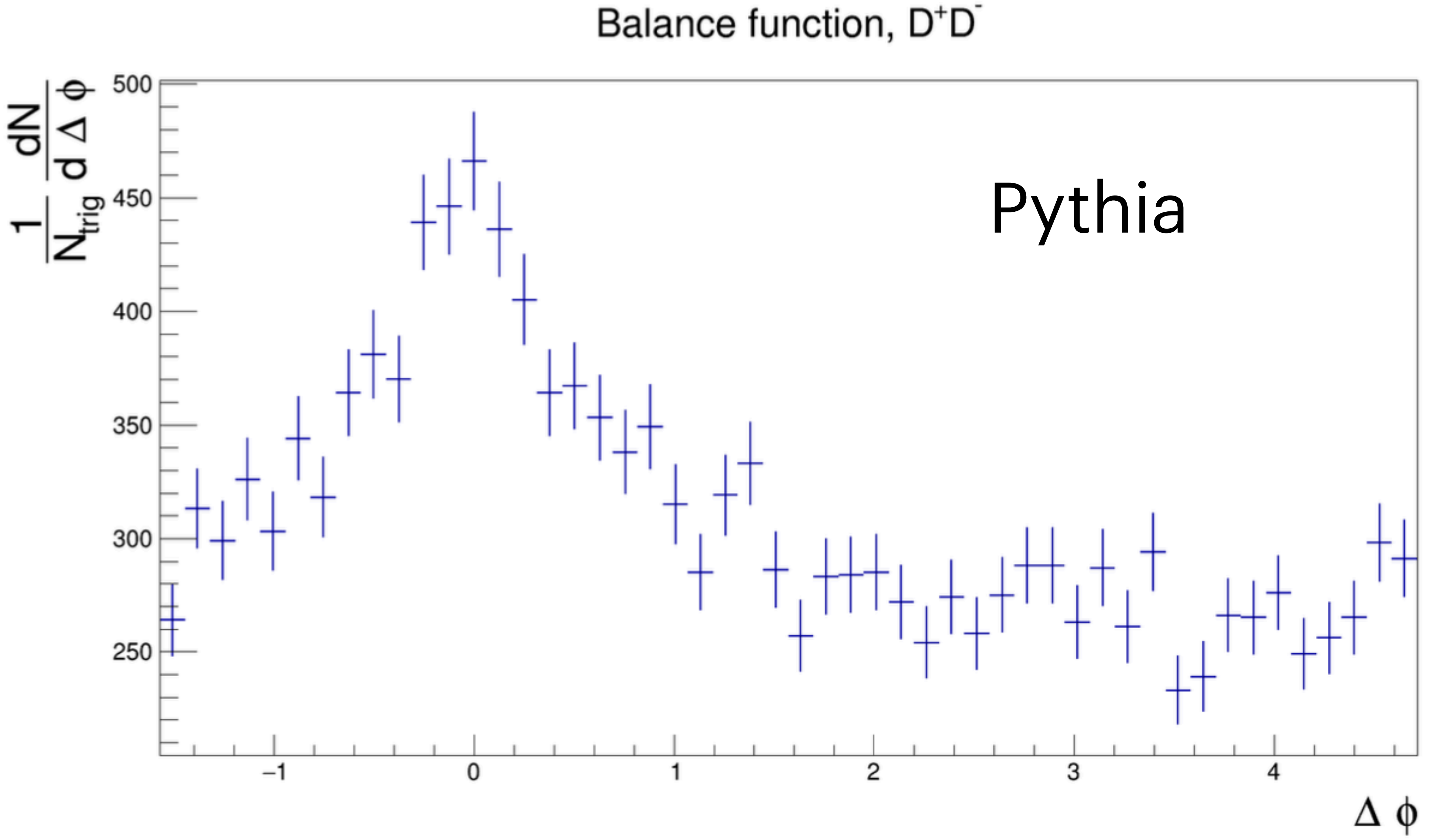


- Charm qualitatively different: produced in hard scatterings, so in the string picture it is always at the end of strings
- Back-to-back structure observed, when charm is produced in the initial hard scattering in Pythia

S. Basu, P. Christiansen, AO, D. Silvermyr
EPJC 81 (2021) 11
arXiv:2110.05134 [hep-ph]

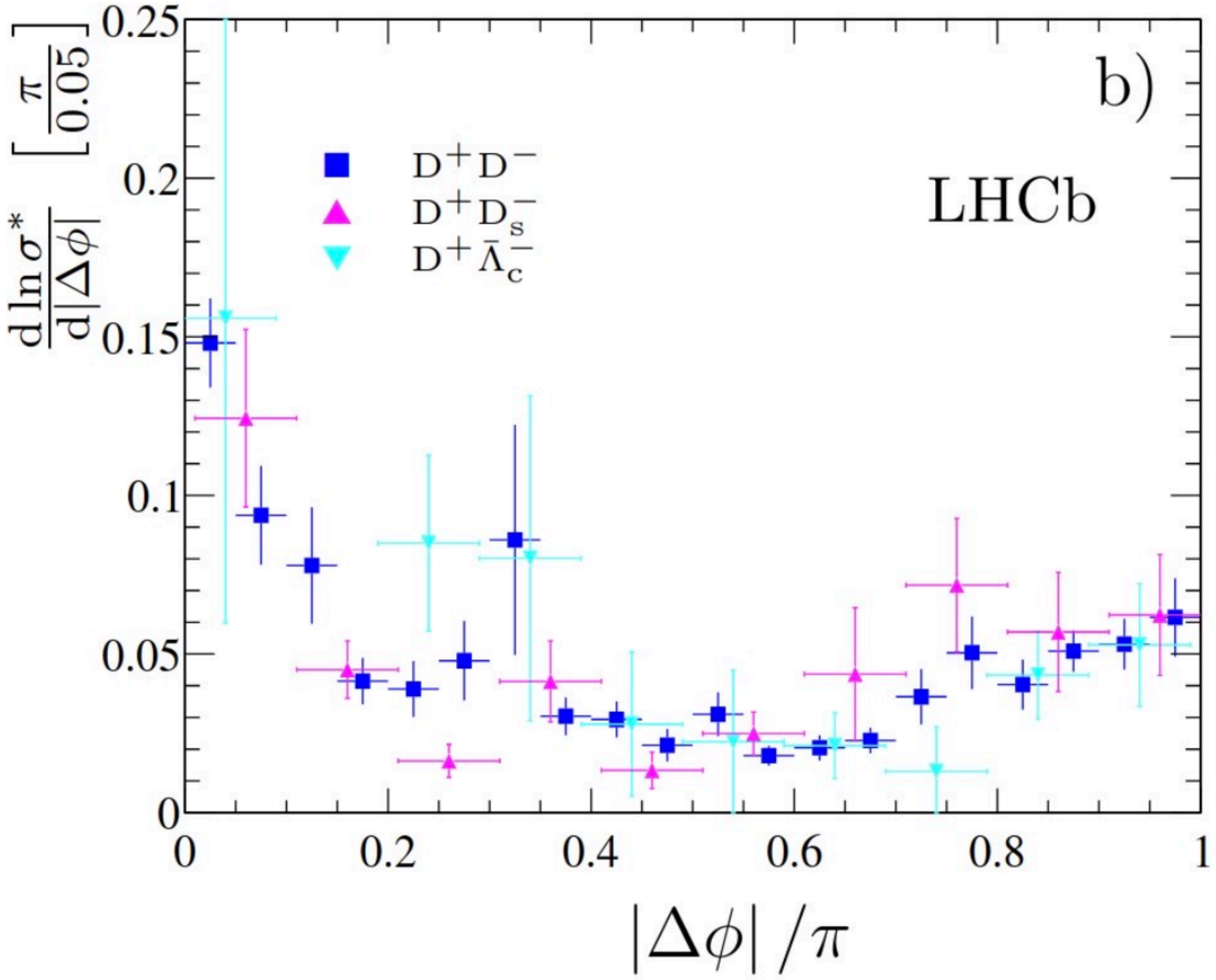
Future prospects: balance functions with charm





LU Bachelors thesis by T. Bonneview Wallstedt

- In minimum bias Pythia, c-cbar pairs are more likely produced through gluon splittings, appear in a nearside peak



LHCb, JHEP 06 (2012) 141
arXiv:1205.0975 [hep-ex]

Summary

- Balance functions are correlations that indicate where balancing charges end up in ($\Delta\varphi$, $\Delta\eta$)

  → general consensus that this is an interesting and powerful technique that we should continue to explore

- Many ideas to extend this technique further, e.g.:
  - Balance functions with charm
  - Different combinations/ratios of associated yields to probe various physics questions, e.g. strangeness production
  - 3- and 4-particle correlations