Particle production and dynamics in pp collisions — results from the CLASH project —

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CLASH project

- Collaboration between theorists and experimentalists to develop understanding of collisions from small to large systems
  - supported by a Wallenberg project grant, PIs: Peter Christiansen & Leif Lönnblad

How do microscopic interactions in QCD lead to the build up of emergent collective behavior?

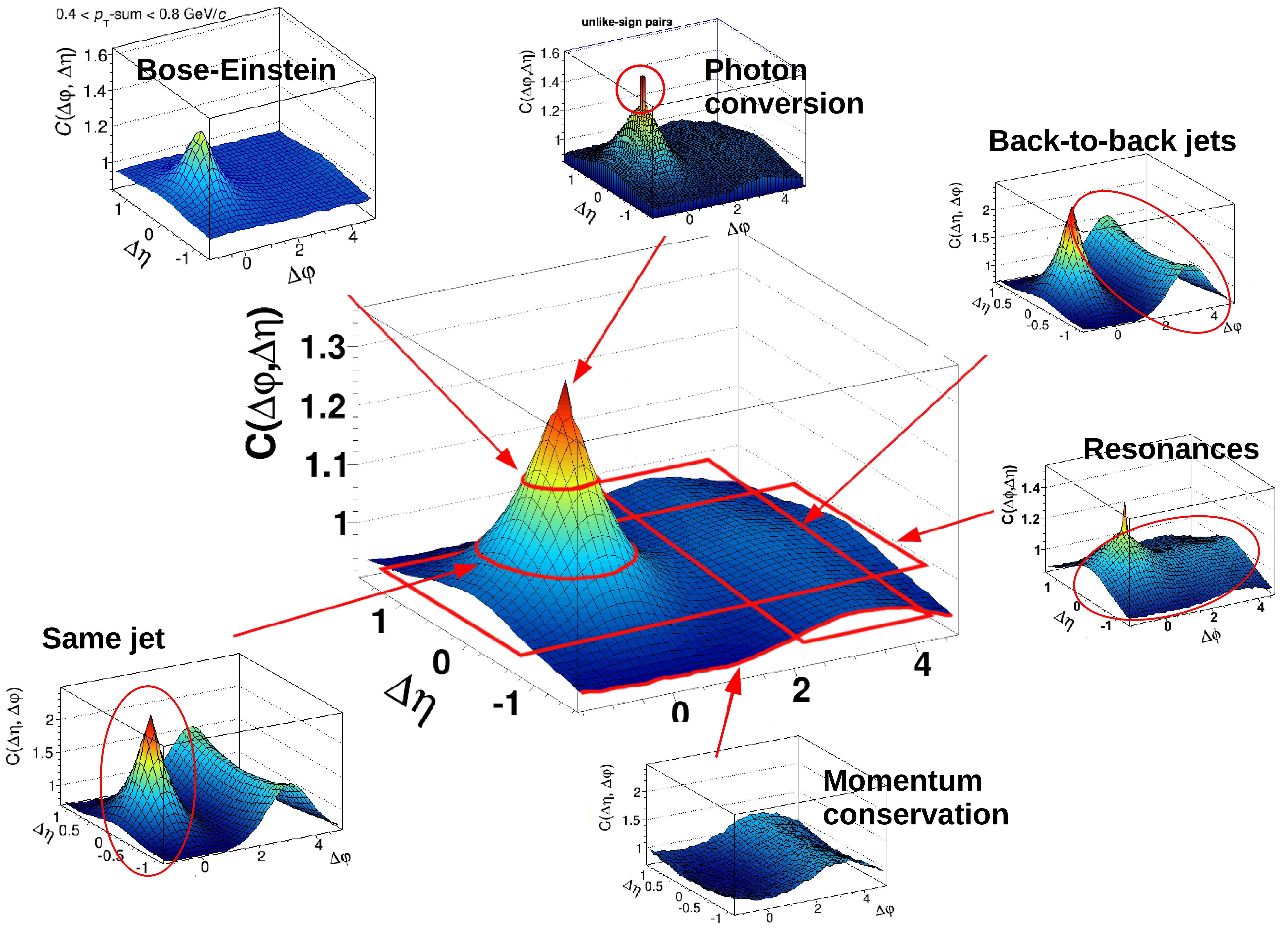
- Main theoretical focus: Can we build a model of heavy-ion collisions based on Pythia?
  → Angantyr
- Main experimental foci:

1. Using correlation measurements, can we understand the production, hadronization and dynamics of conserved quantum numbers?
2. Using event shape observables, can we isolate the mechanisms leading to strangeness enhancement and multiplicity-dependent hadrochemistry?

Two-particle correlations and balance functions

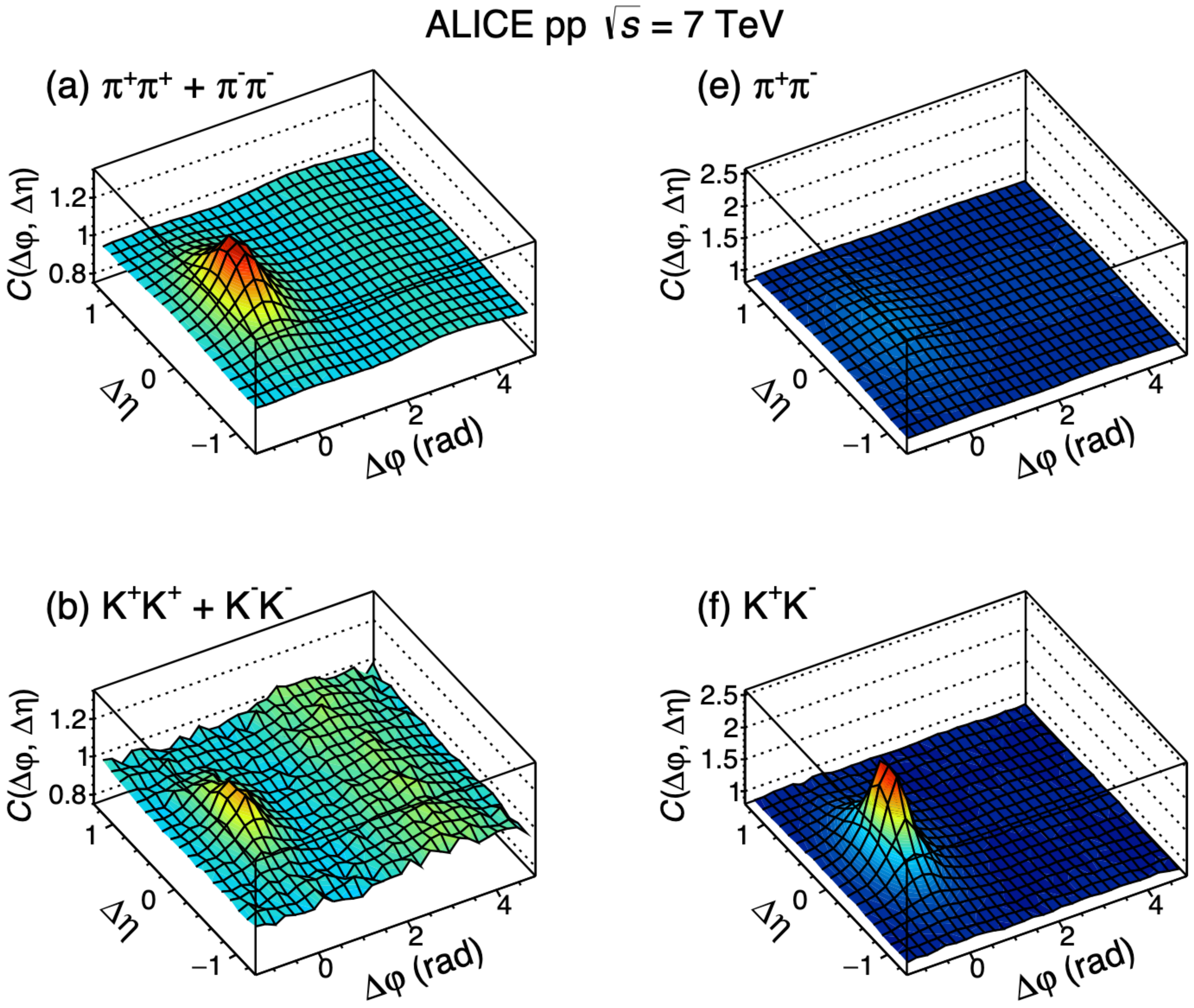
Correlation functions

- 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

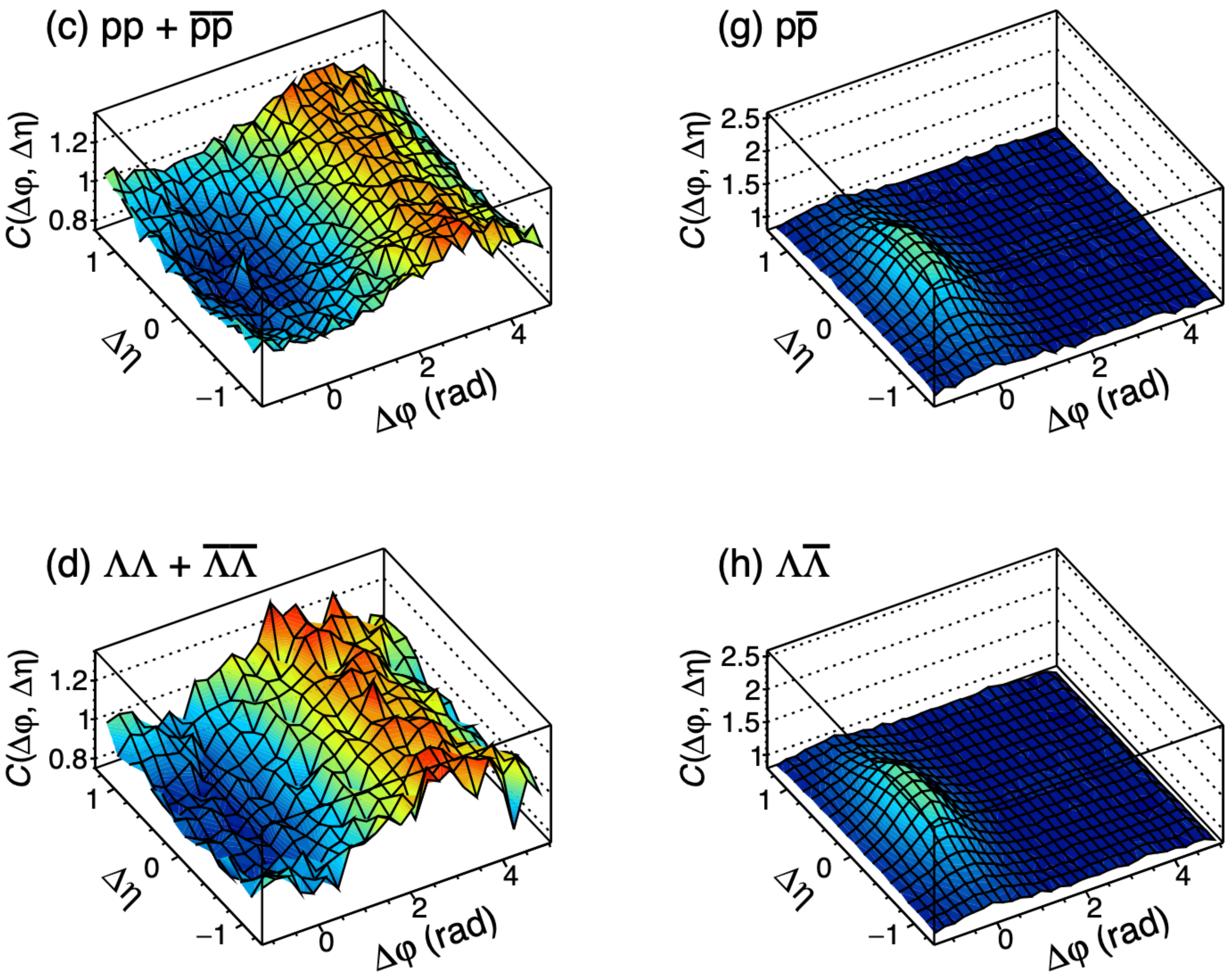
Correlation functions of mesons



- 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
arXiv:1612.08975 [nucl-ex]

Local baryon number conservation?

ALICE, EPJC 77 (2017) 569
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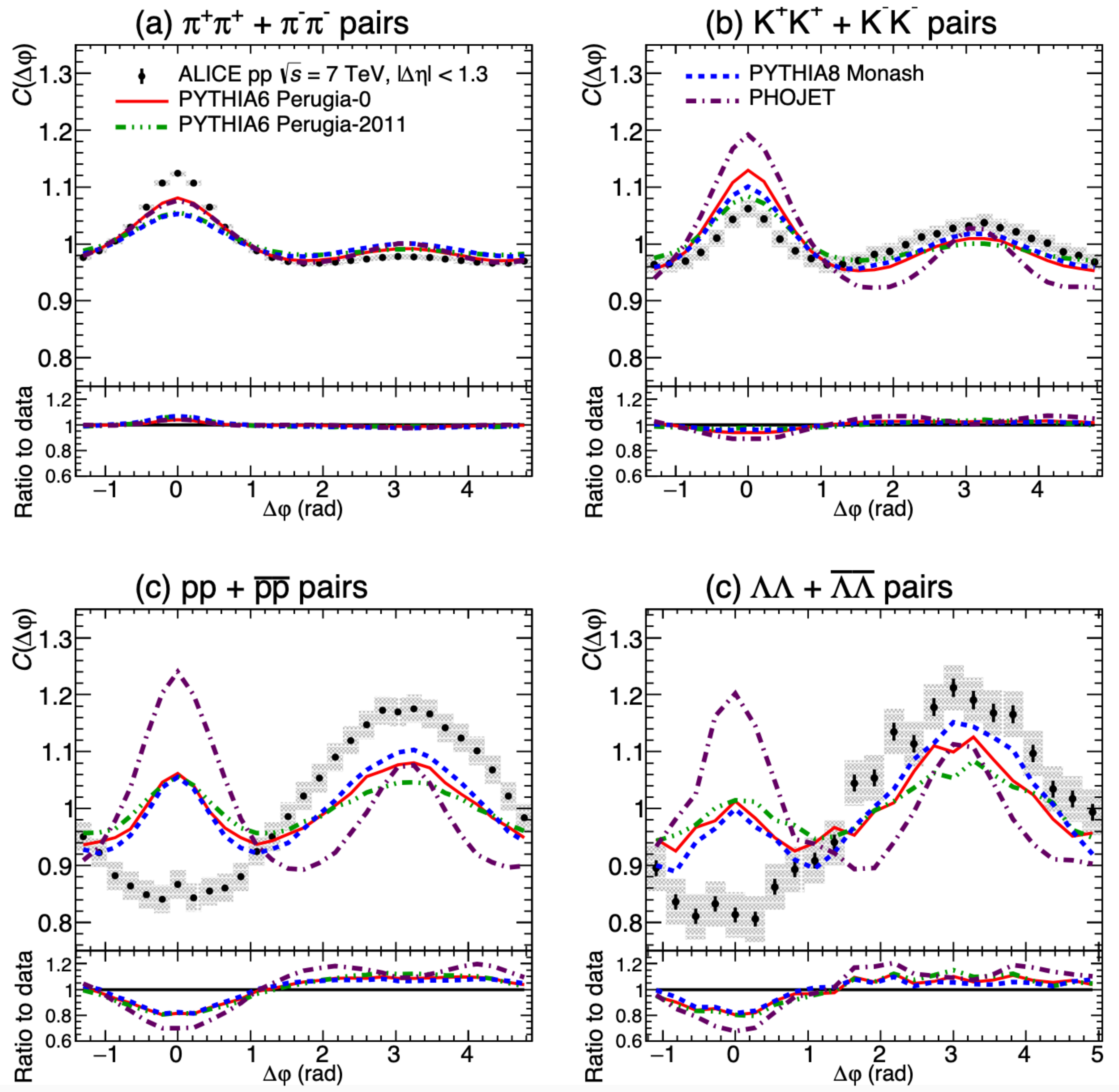
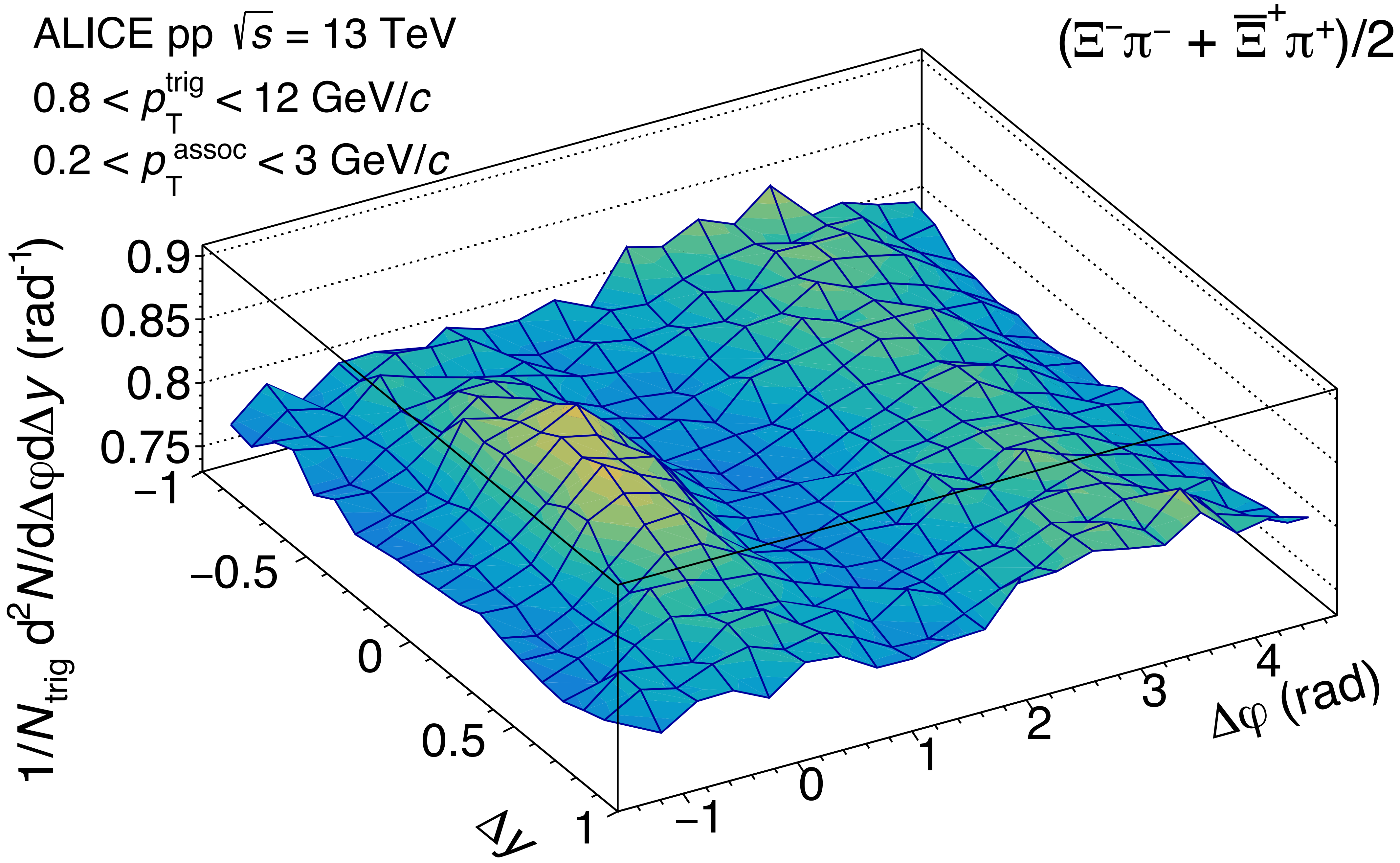


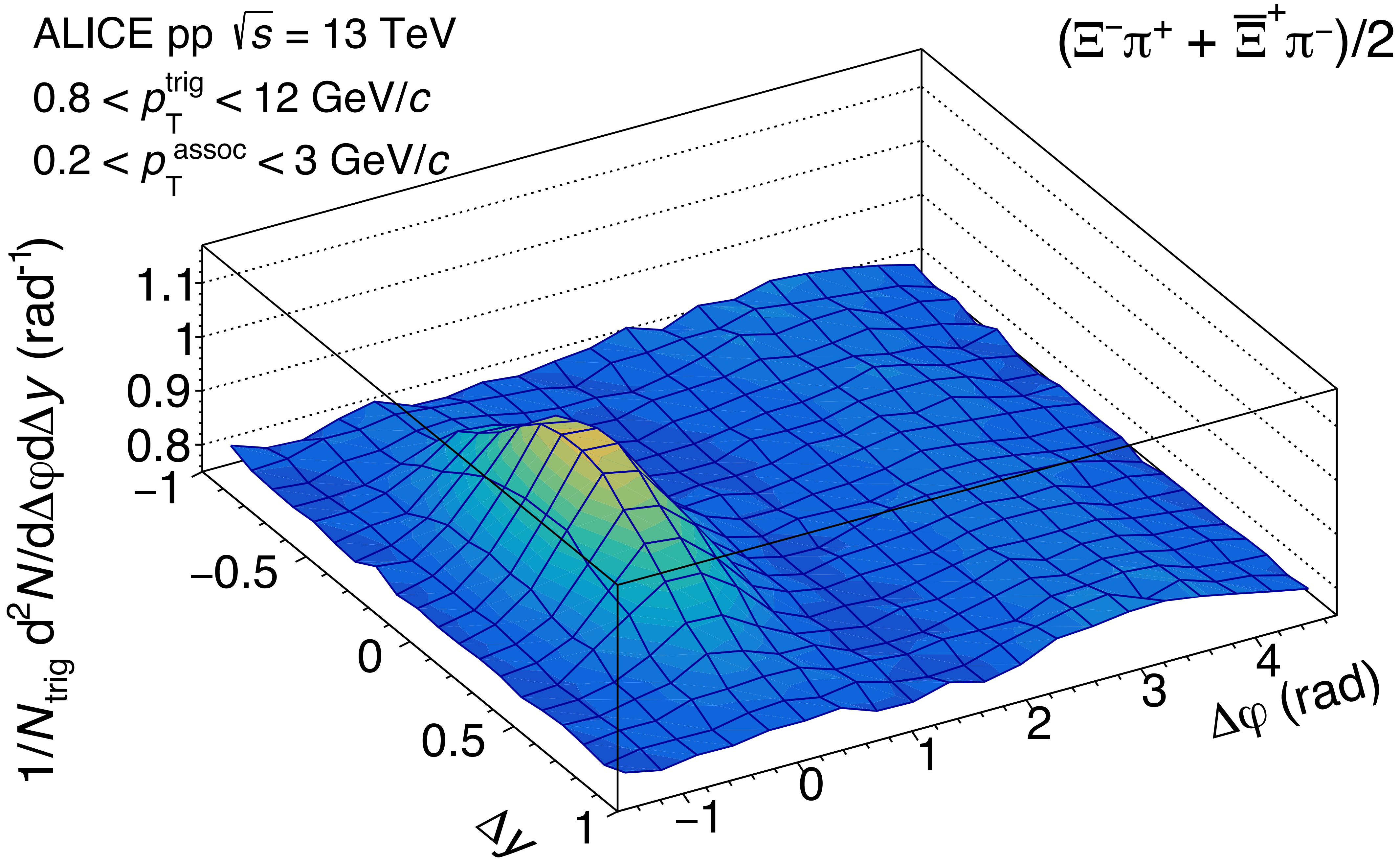
- Is the depletion due to local conservation of baryon number?
- String hadronization models would suggest that two baryons produced in a single fragmentation should be separated by at least one antibaryon
- Production of two baryons would also be suppressed if the parton energy is small compared to 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, JHEP 09 (2024) 102
arXiv:2308.16706 [hep-ex]

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

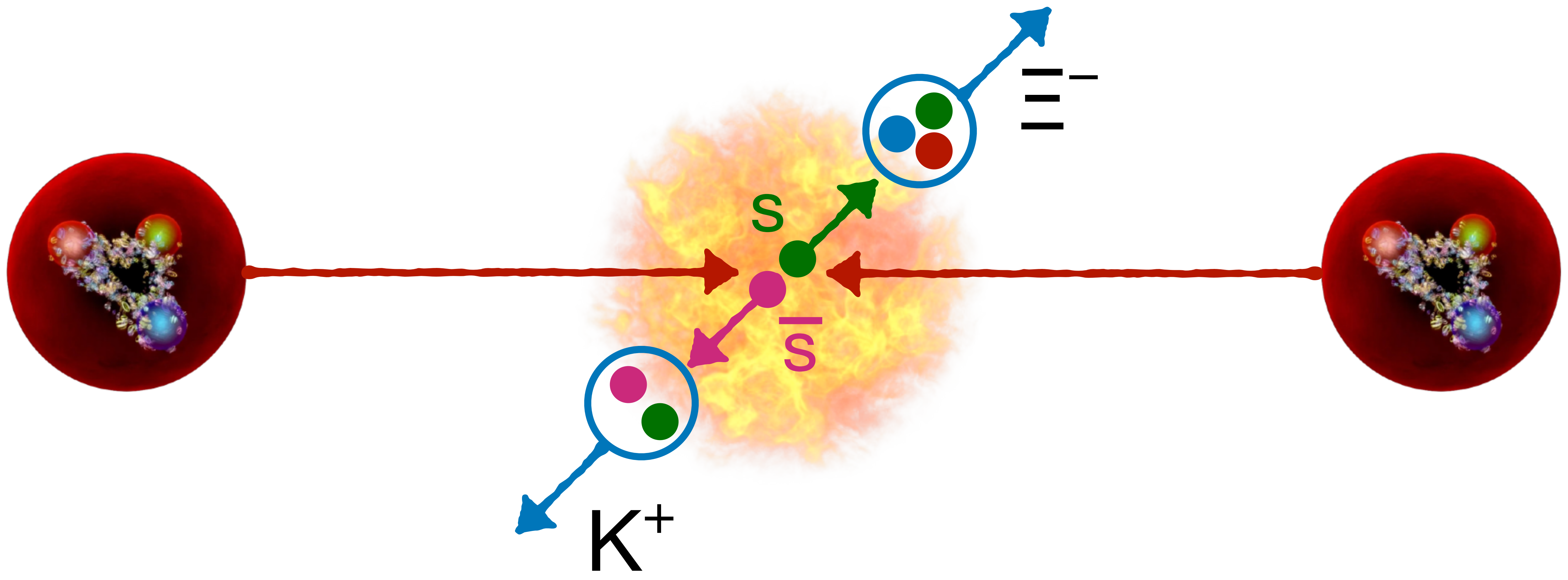




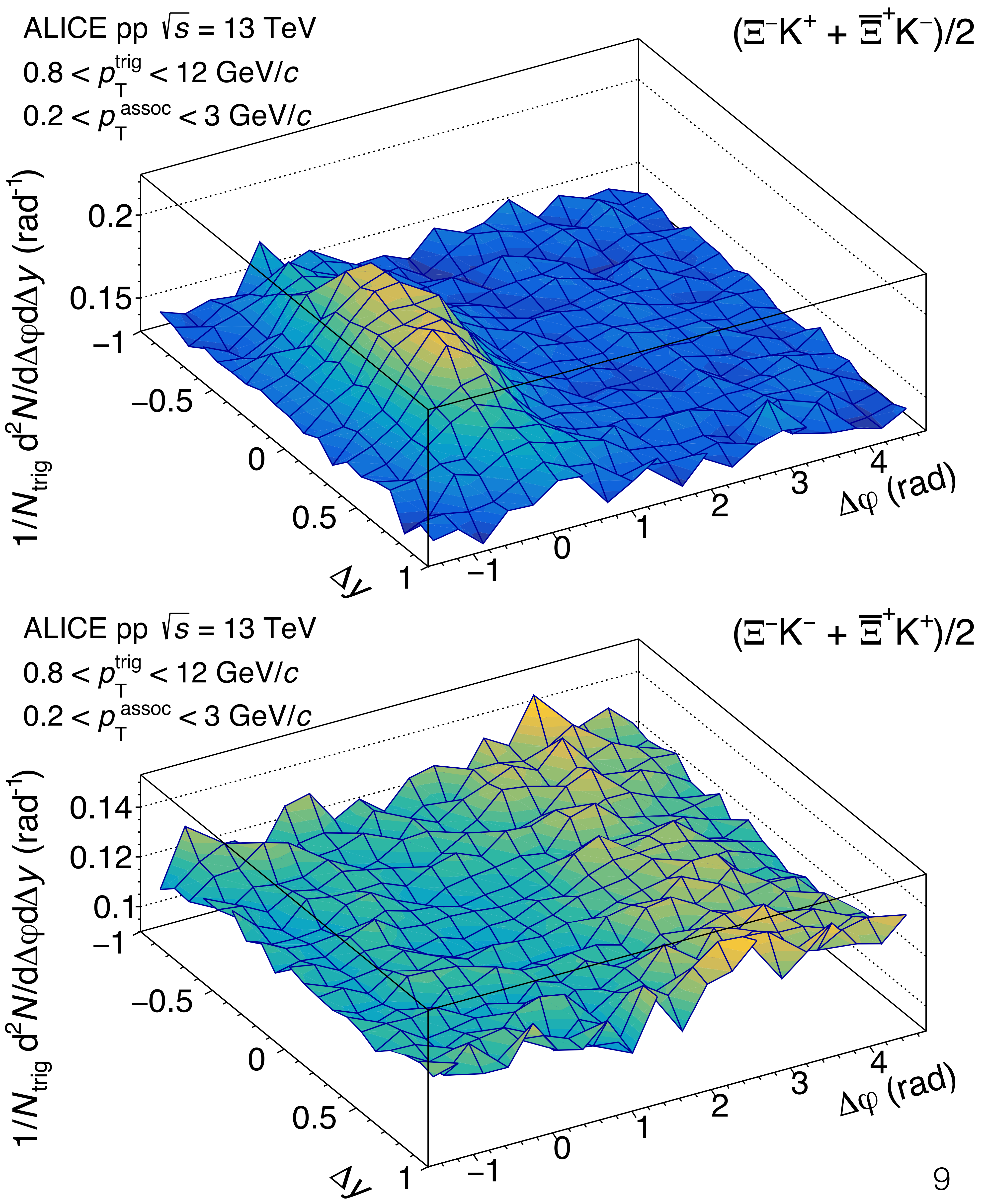
Balance functions

ALICE, JHEP 09 (2024) 102
arXiv:2308.16706 [hep-ex]

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



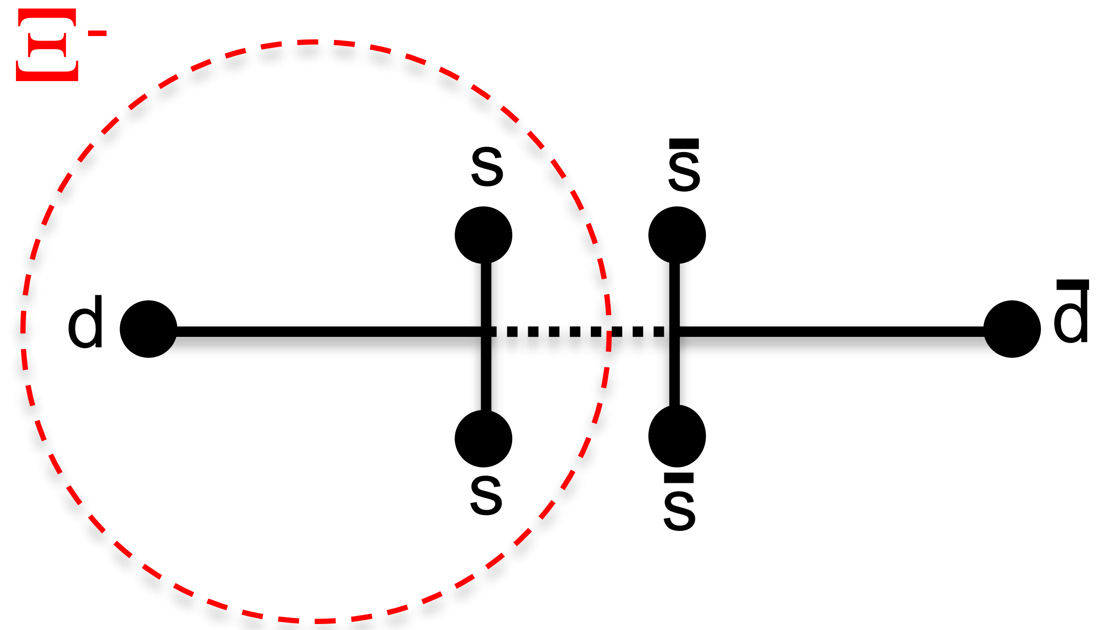
- Example: Ξ^-K^+ correlations share a s-sbar pair which could come from the same production process
  → but there are also Ξ^-K^+ pairs where the s-sbar is not from the same string, model these with Ξ^-K^- correlations and subtract



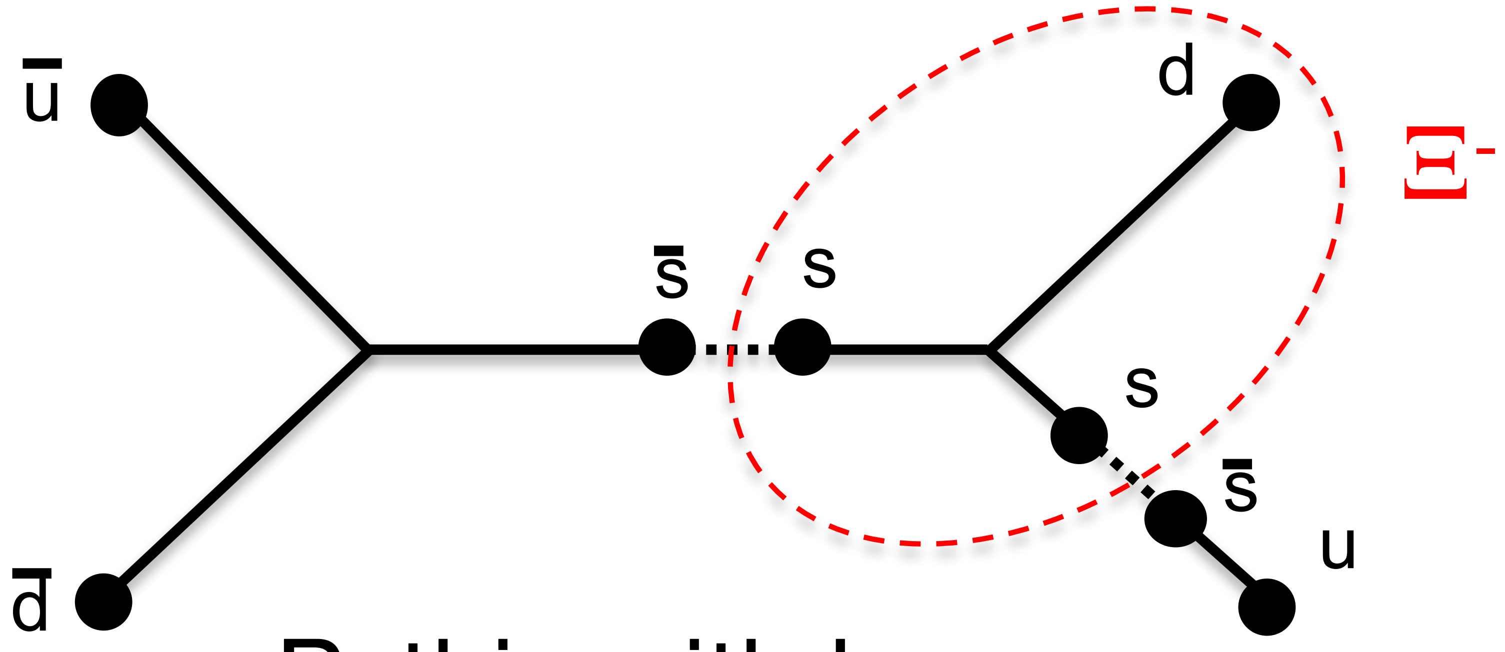
Balance functions

ALICE, JHEP 09 (2024) 102
arXiv:2308.16706 [hep-ex]

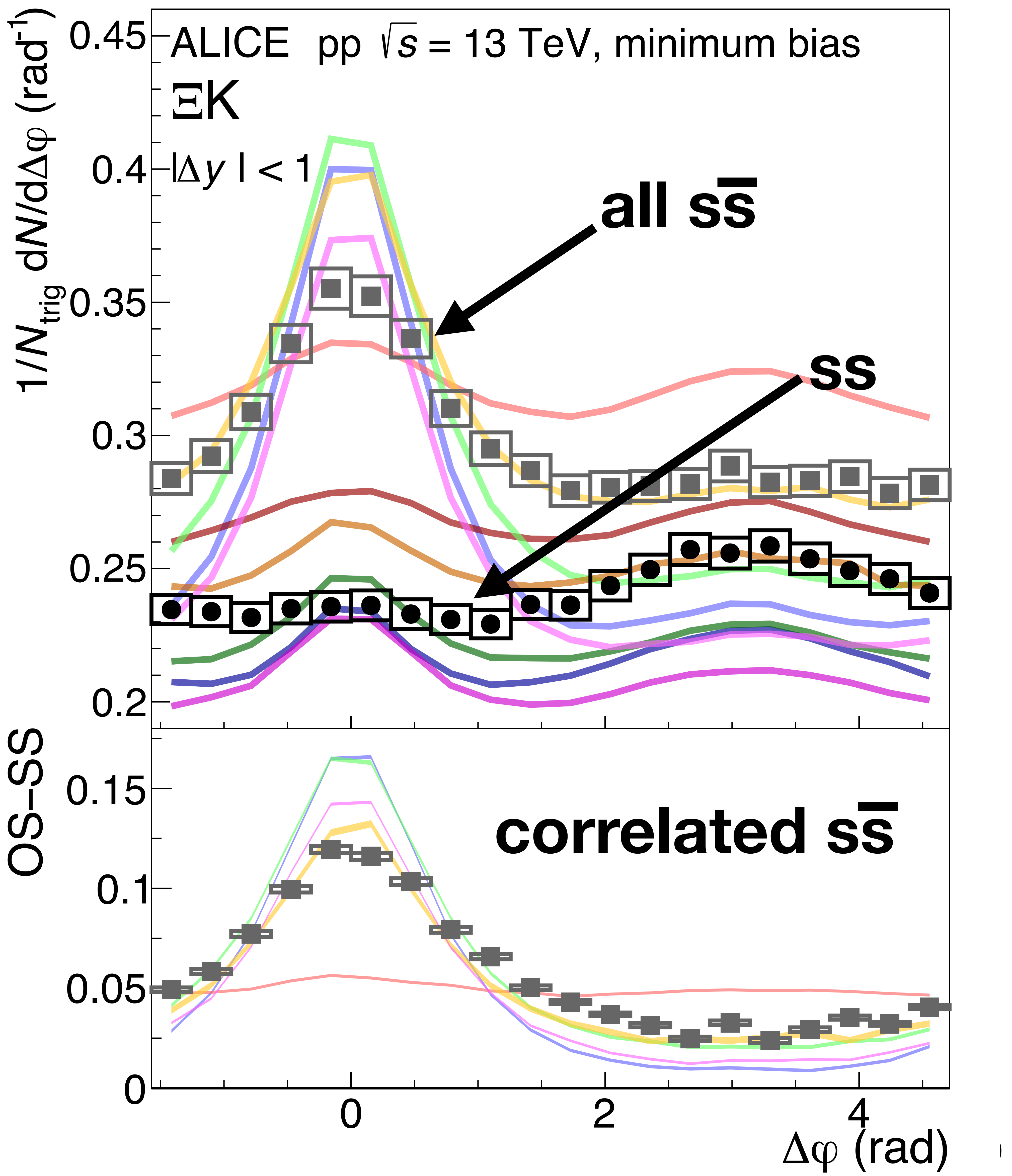
- Is strangeness conserved locally or globally?
- Do we observe the presence of a thermal strangeness reservoir (global, non-local correlations), as expected by EPOS/SHM?
- Do high-density regions in high-multiplicity events cause new string topologies to "turn on"?



diquark breaking in Pythia (default)



Pythia with baryon junctions



Ξπ balance functions

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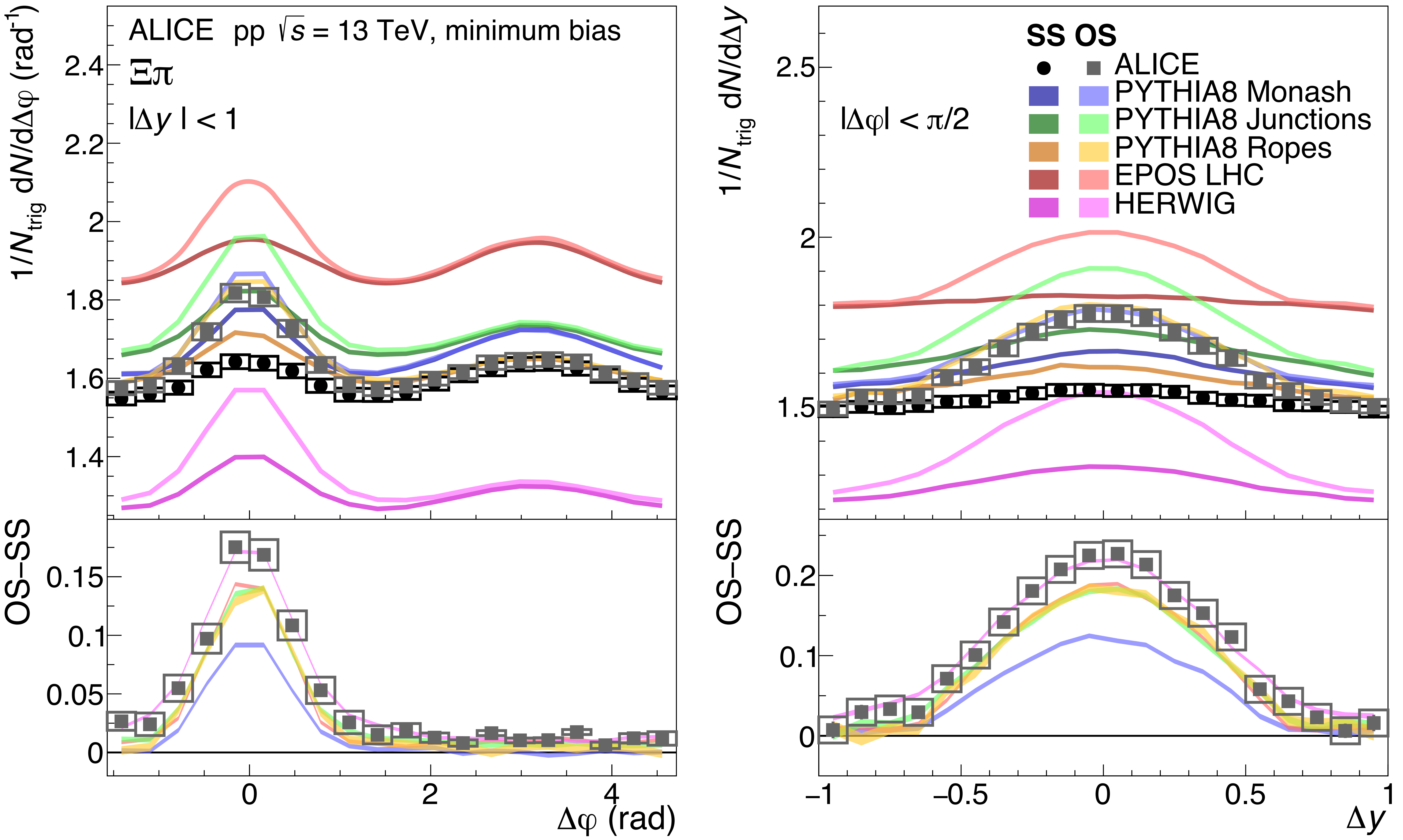
arXiv:2308.16706 [hep-ex]



- Ξπ balance functions probe electric charge balancing
- Pythia describes overall yields well, tuned to single-particle spectra
- Pythia, EPOS, and Herwig also get balance right

ΞK balance functions

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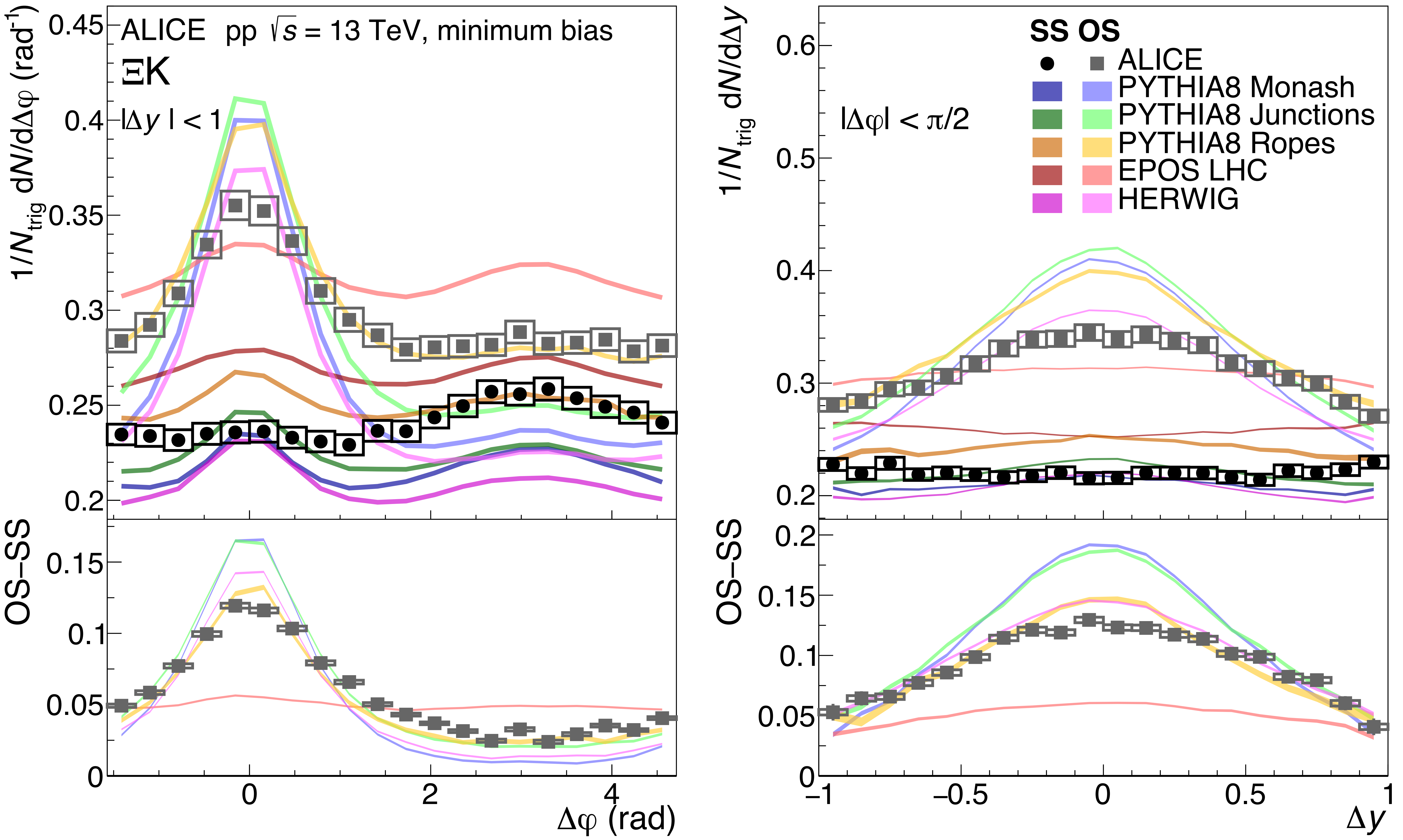
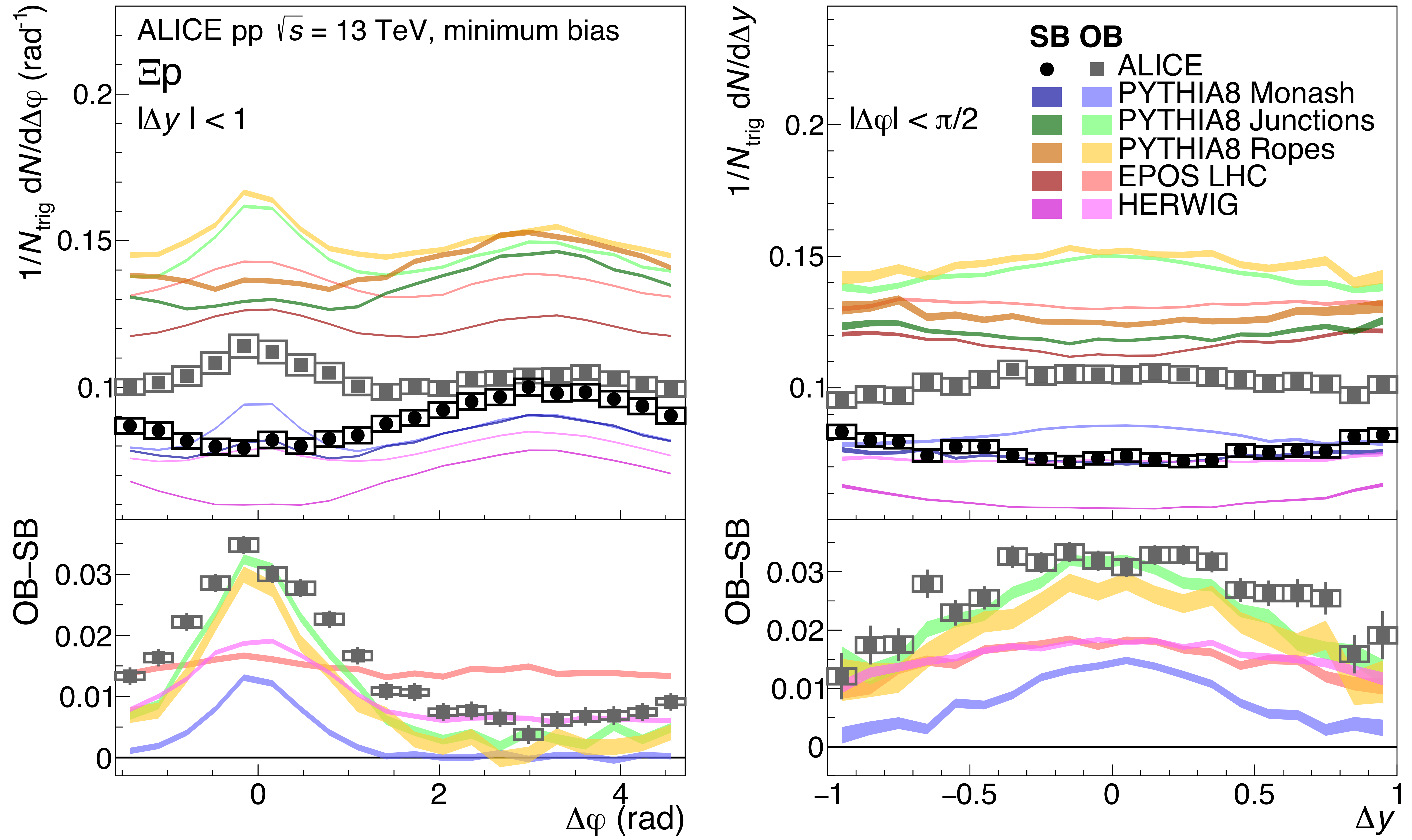
arXiv:2308.16706 [hep-ex]



- ΞK balance functions probe strangeness balancing
- 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

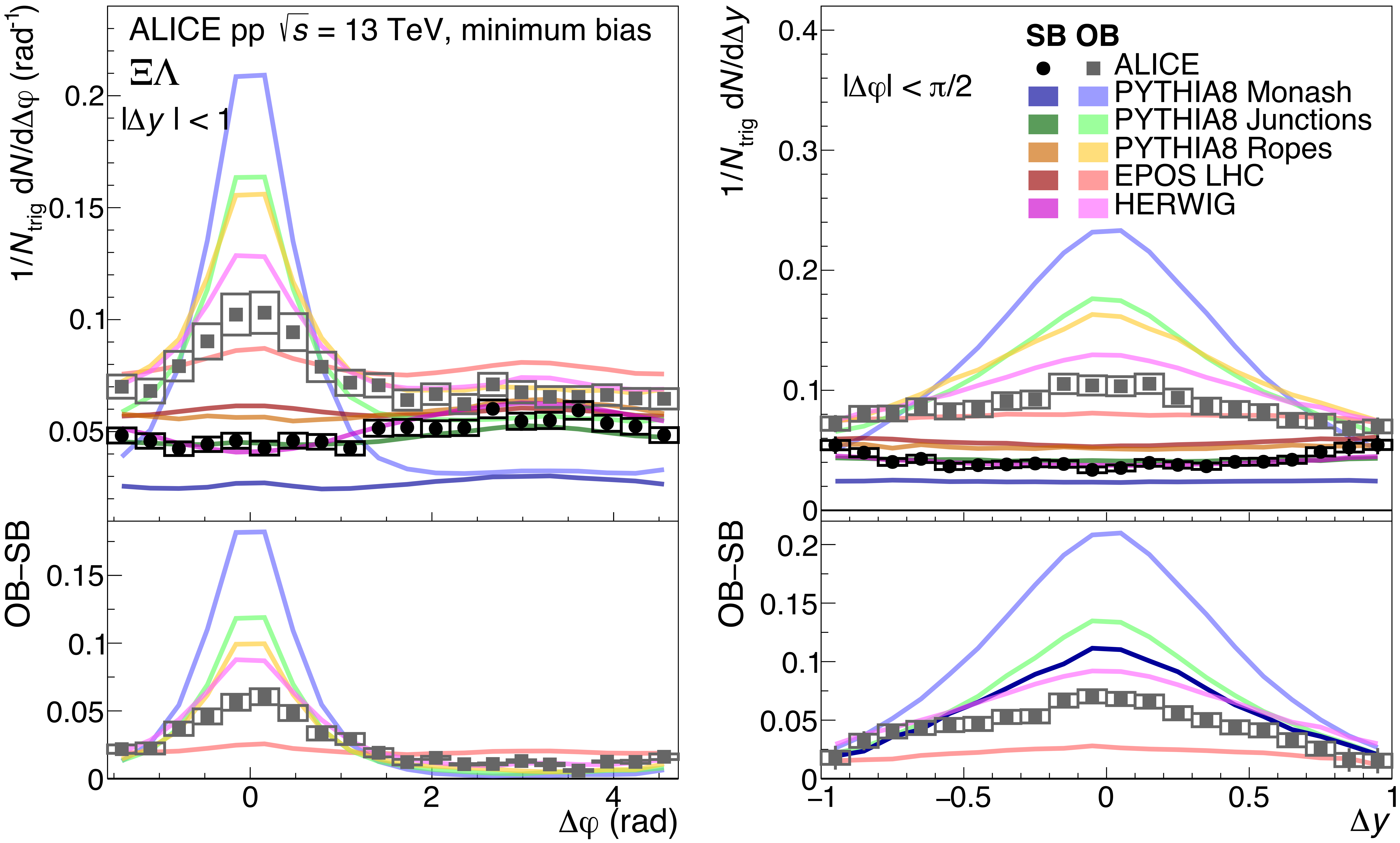
ALICE, JHEP 09 (2024) 102
arXiv:2308.16706 [hep-ex]



- Ξp balance functions probe baryon number conservation
- 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

ΞΛ balance functions

ALICE, JHEP 09 (2024) 102
arXiv:2308.16706 [hep-ex]



- ΞΛ balance functions probe both strangeness and baryon number balancing
- Similar observations as in ΞK correlations, Pythia predicts a narrower peak than observed in data

Multiplicity dependence

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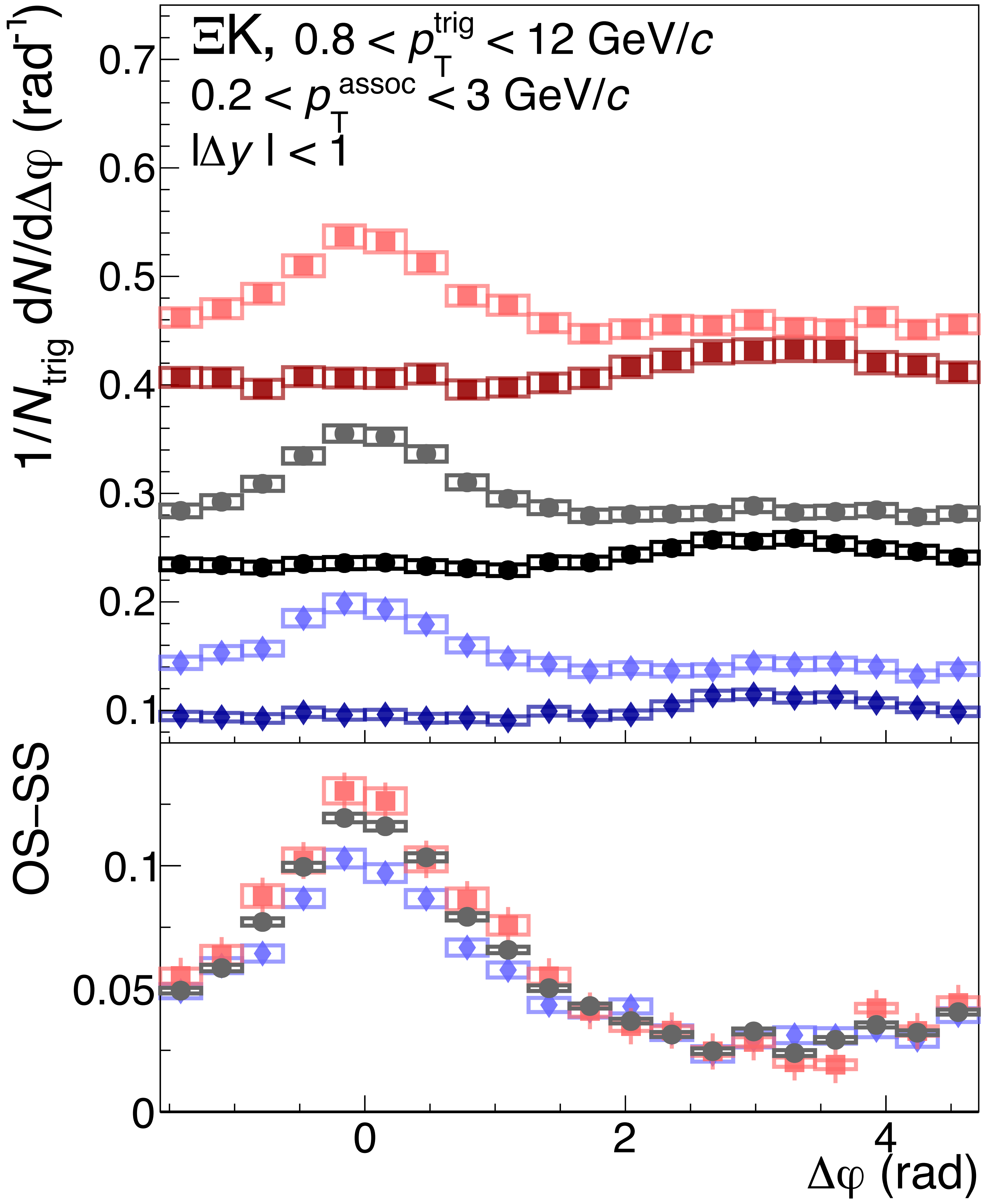
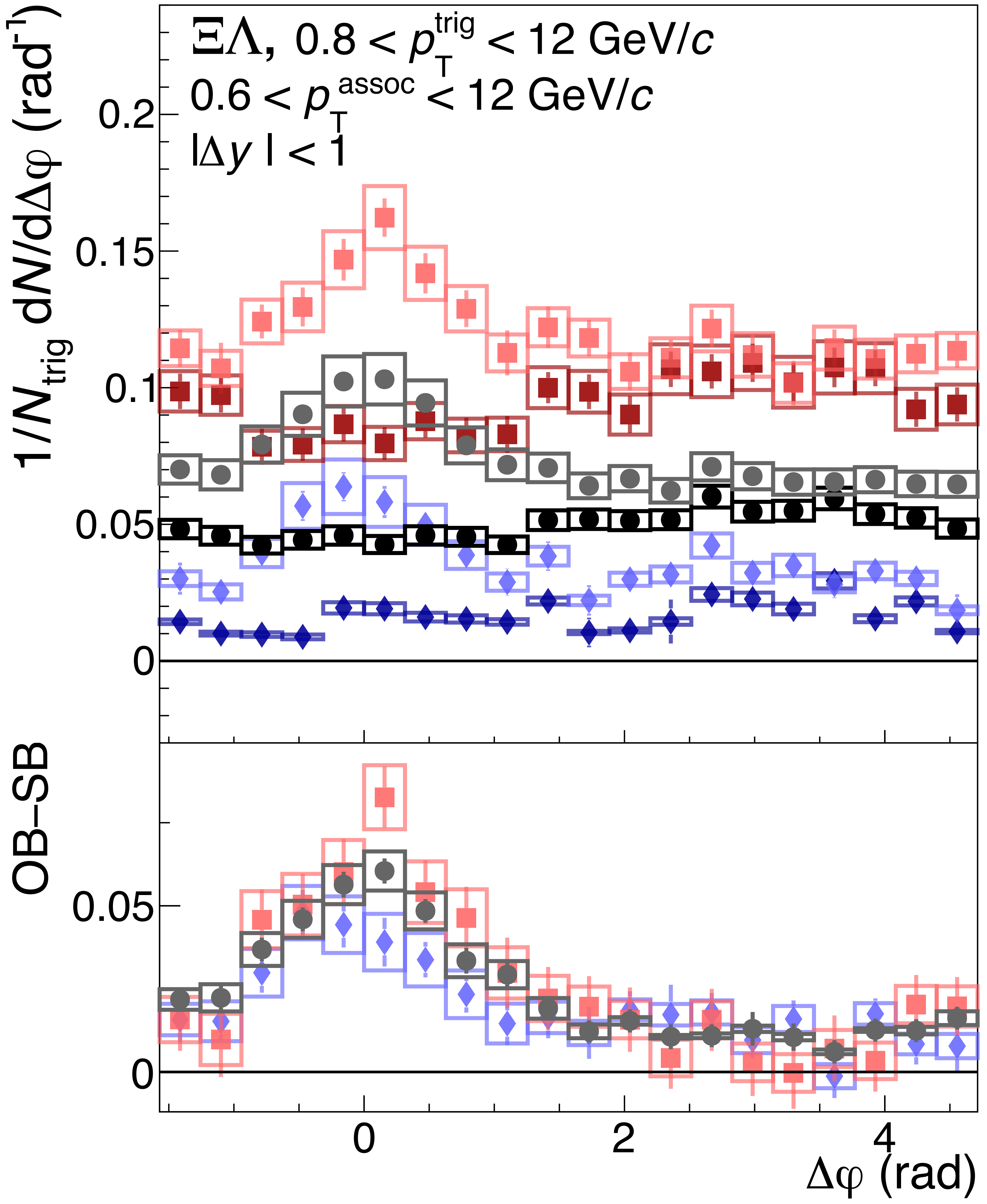
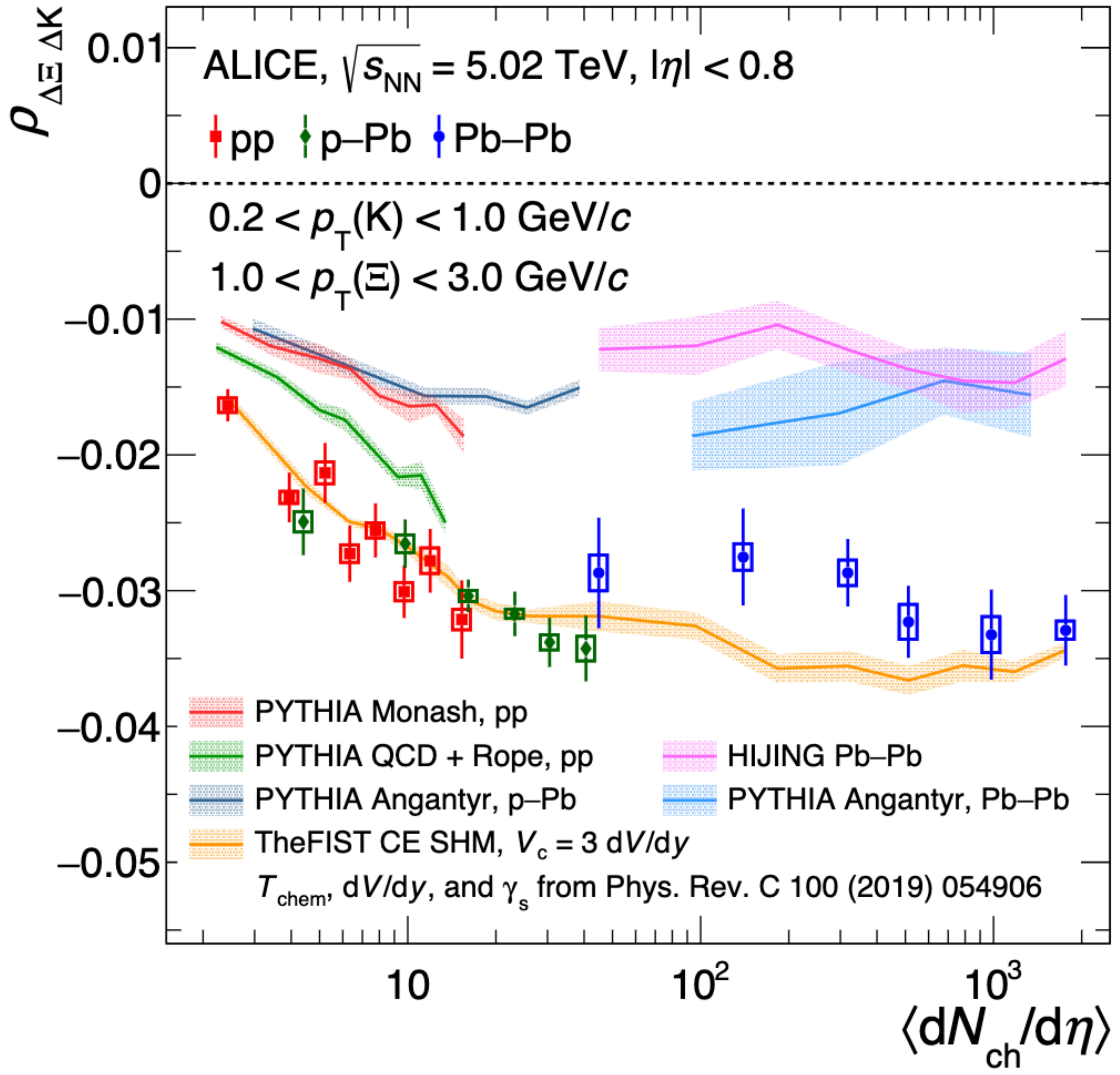
arXiv:2308.16706 [hep-ex]





- 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

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



ALICE, Phys. Rev. Lett. 134 (2025) 022303
arXiv:2405.19890 [nucl-ex]

- Correlation coefficient between net-Ξ and net-K

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

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

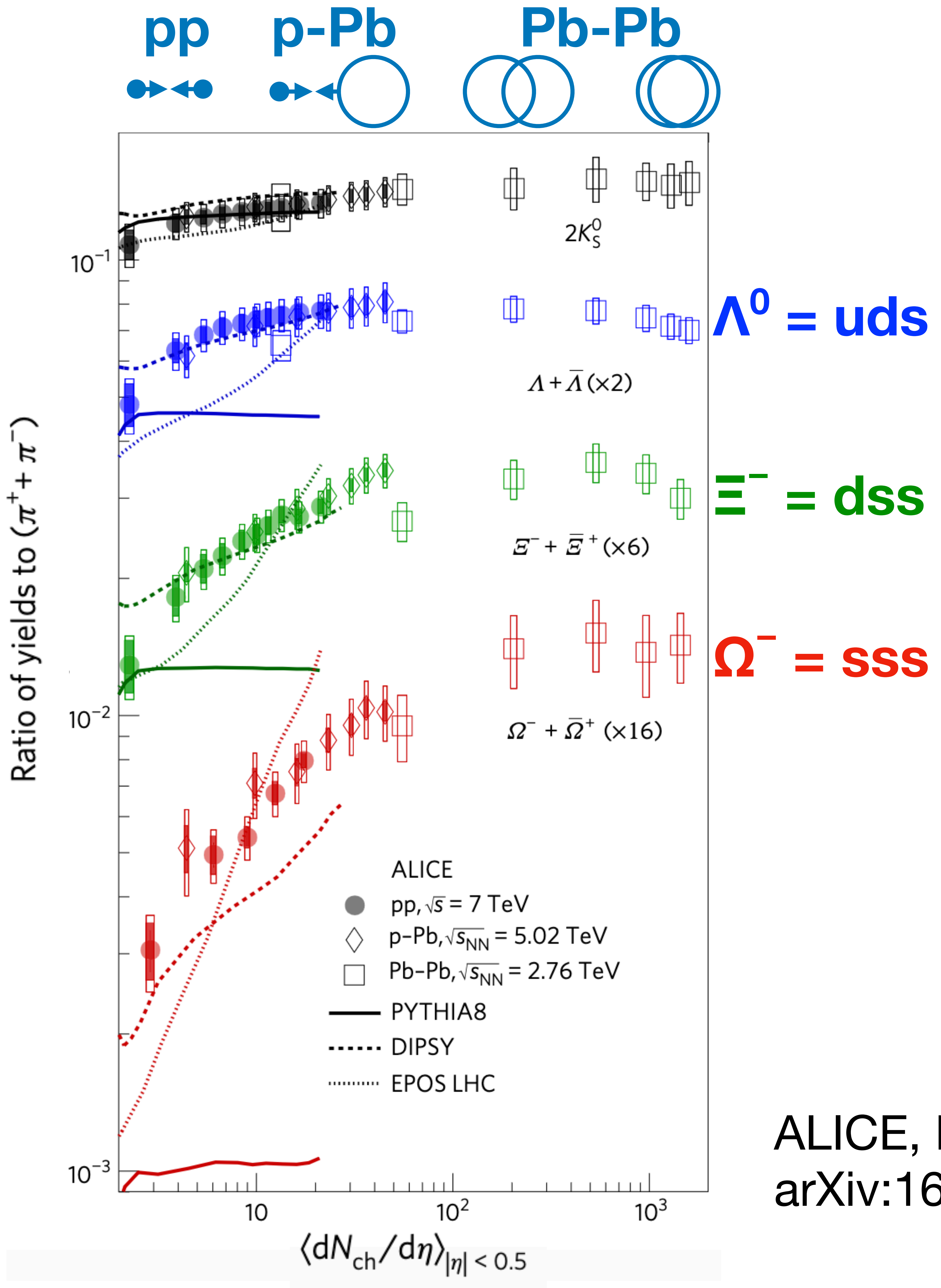
$$\kappa_2(A) = \langle N_A^2 \rangle - \langle N_A \rangle^2$$

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

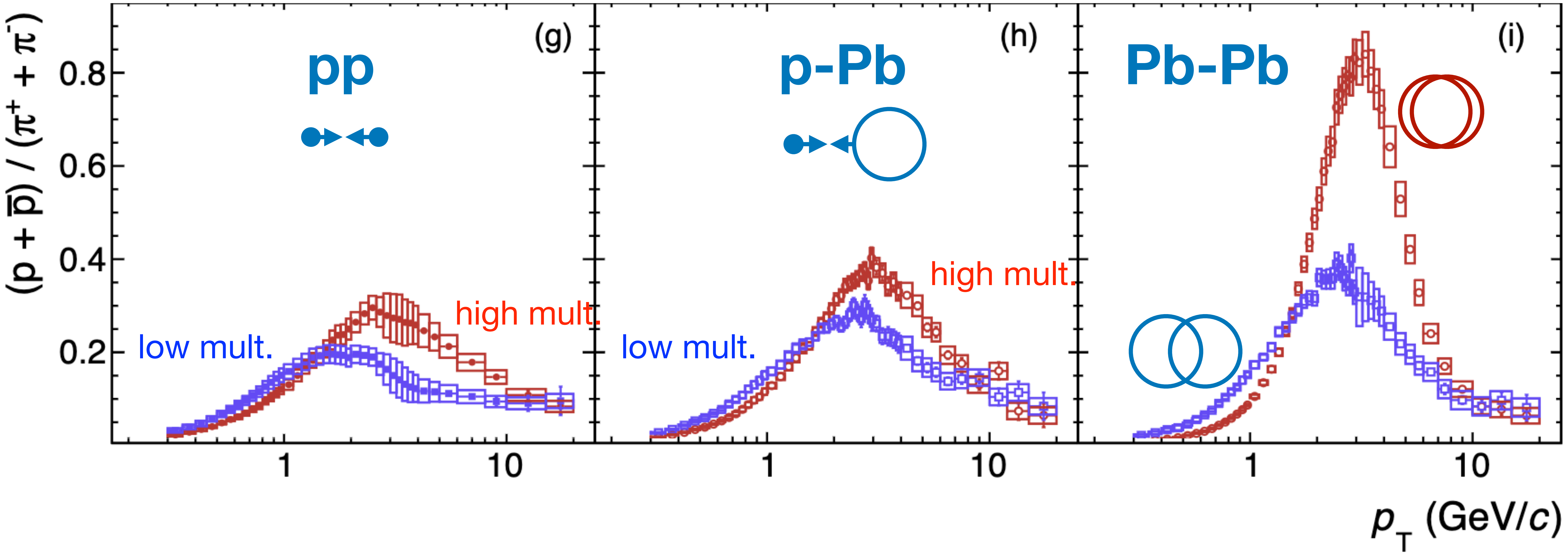
- Smooth/monotonic trend from small to large systems
- Agreement with Thermal FIST indicates correlation over a larger volume than string-based models
- No “simple picture” → both local and global conservation/correlations are important

Strangeness enhancement and the baryon-to-meson-ratio vs event shape

Strangeness and baryon number in pp collisions



- Observed enhancement of strange-hadron yields with increasing multiplicity
- Baryon-to-meson ratio shows characteristic shift/enhancement in high-multiplicity pp collisions



- **Is multiplicity the main driver of this physics?**

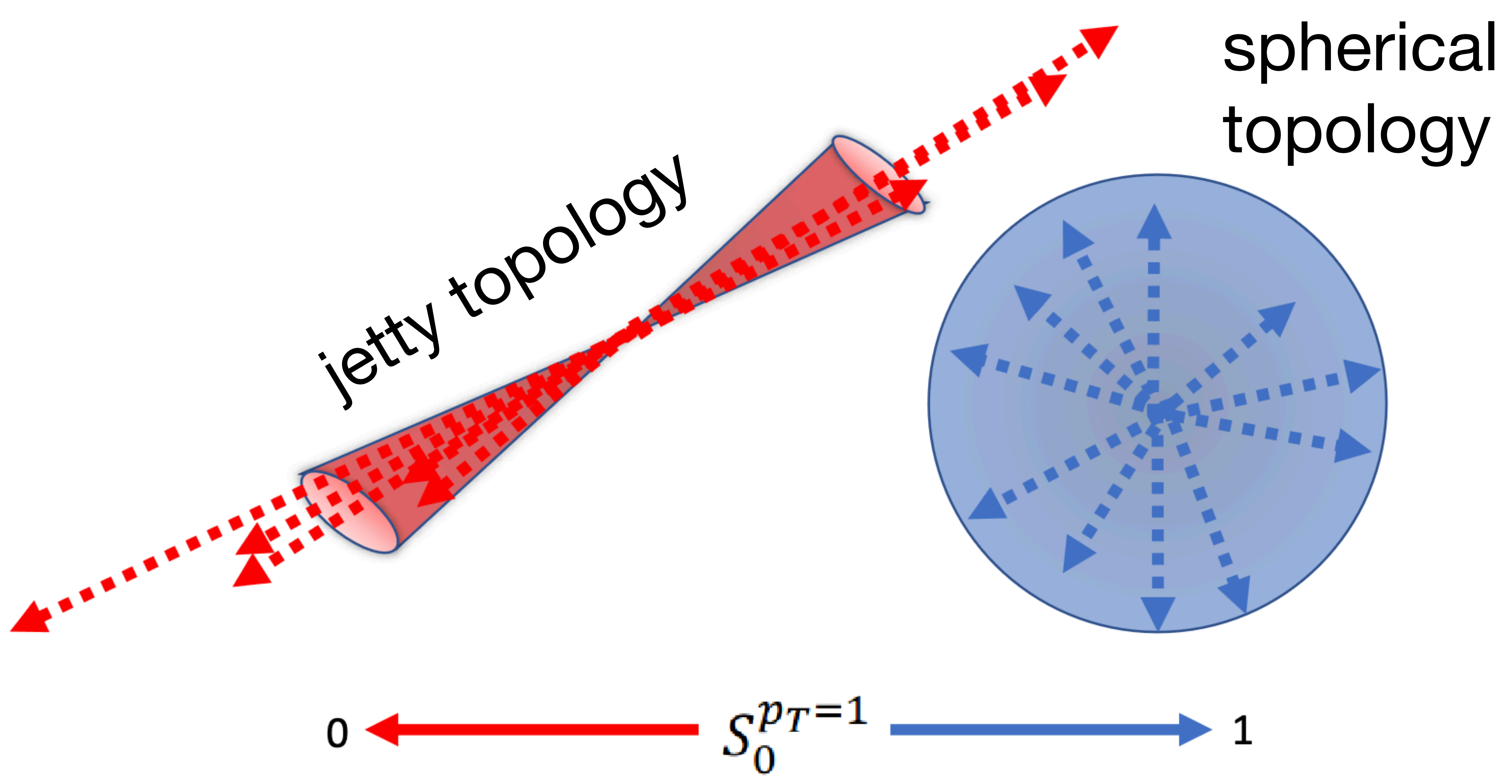
ALICE, Nature Physics 13 (2017) 535
arXiv:1606.07424 [nucl-ex]

ALICE, Phys. Rev. C 99 (2019) 024906
arXiv:1807.11321 [nucl-ex]

Event shapes: S_O

ALICE, JHEP 05 (2024) 184
arXiv:2310.10236 [nucl-ex]

- Events classified according to (mid-rapidity and forward) multiplicity and spherocity



$$S_{\mathrm{O}}^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\sum_i |\hat{p_{\mathrm{T},i}} \times \hat{n}|}{N_{\mathrm{tracks}}} \right)^2$$

S_O vs multiplicity

ALICE, JHEP 05 (2024) 184
arXiv:2310.10236 [nucl-ex]

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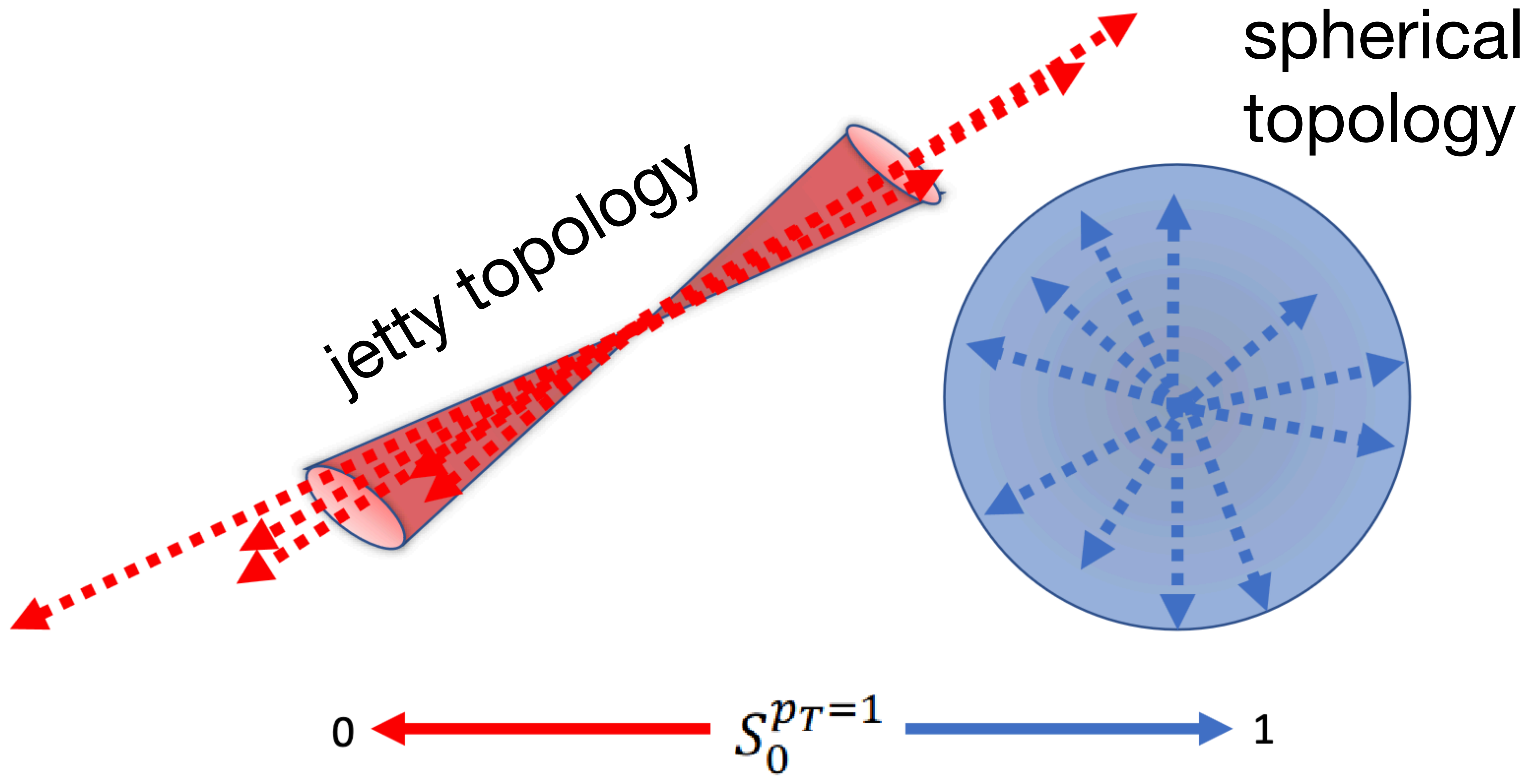

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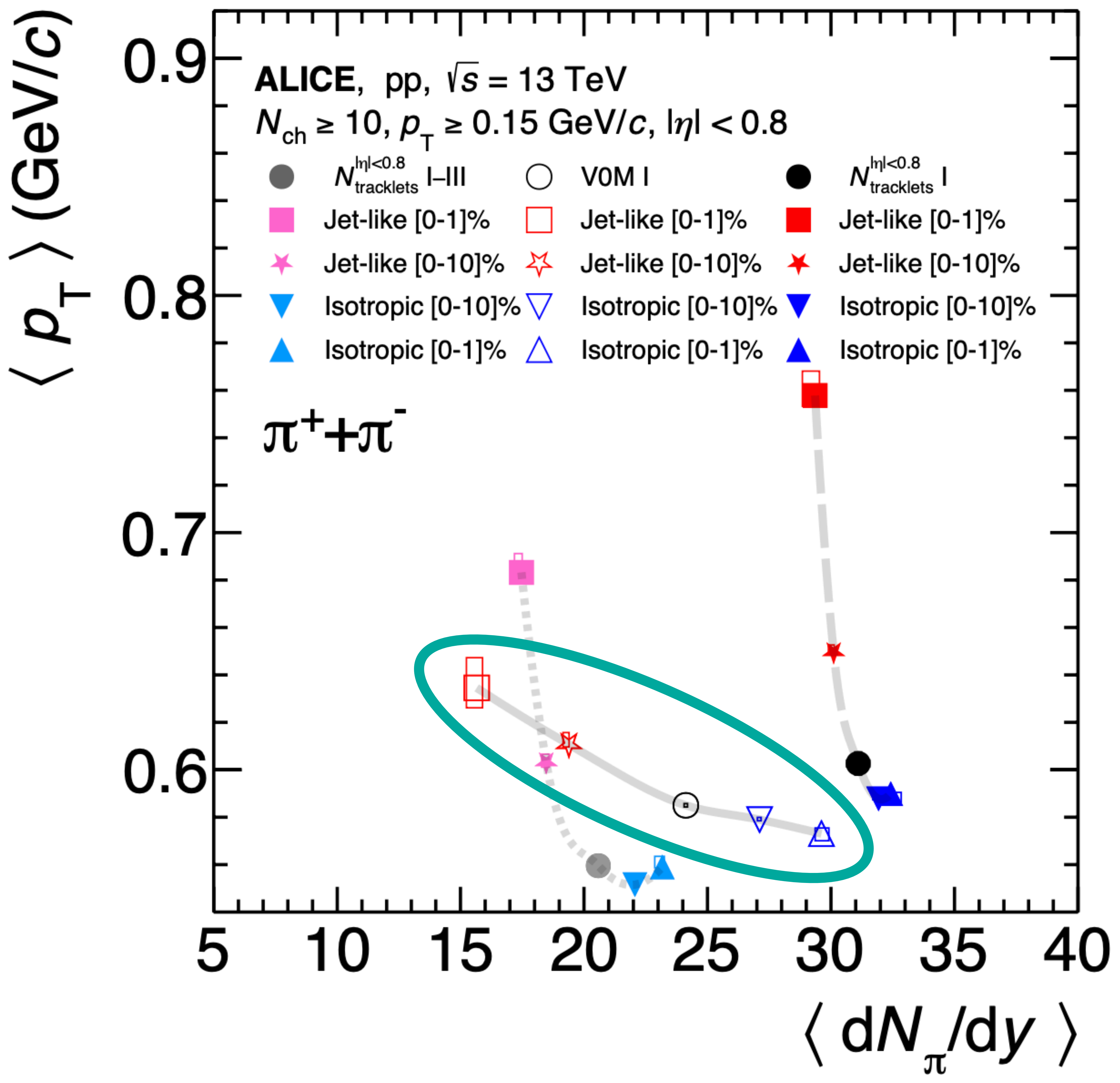

- Very high (0-1%) forward multiplicity → varying S_O mostly changes N_π with only a limited effect on $\langle p_T \rangle$

S_O vs multiplicity

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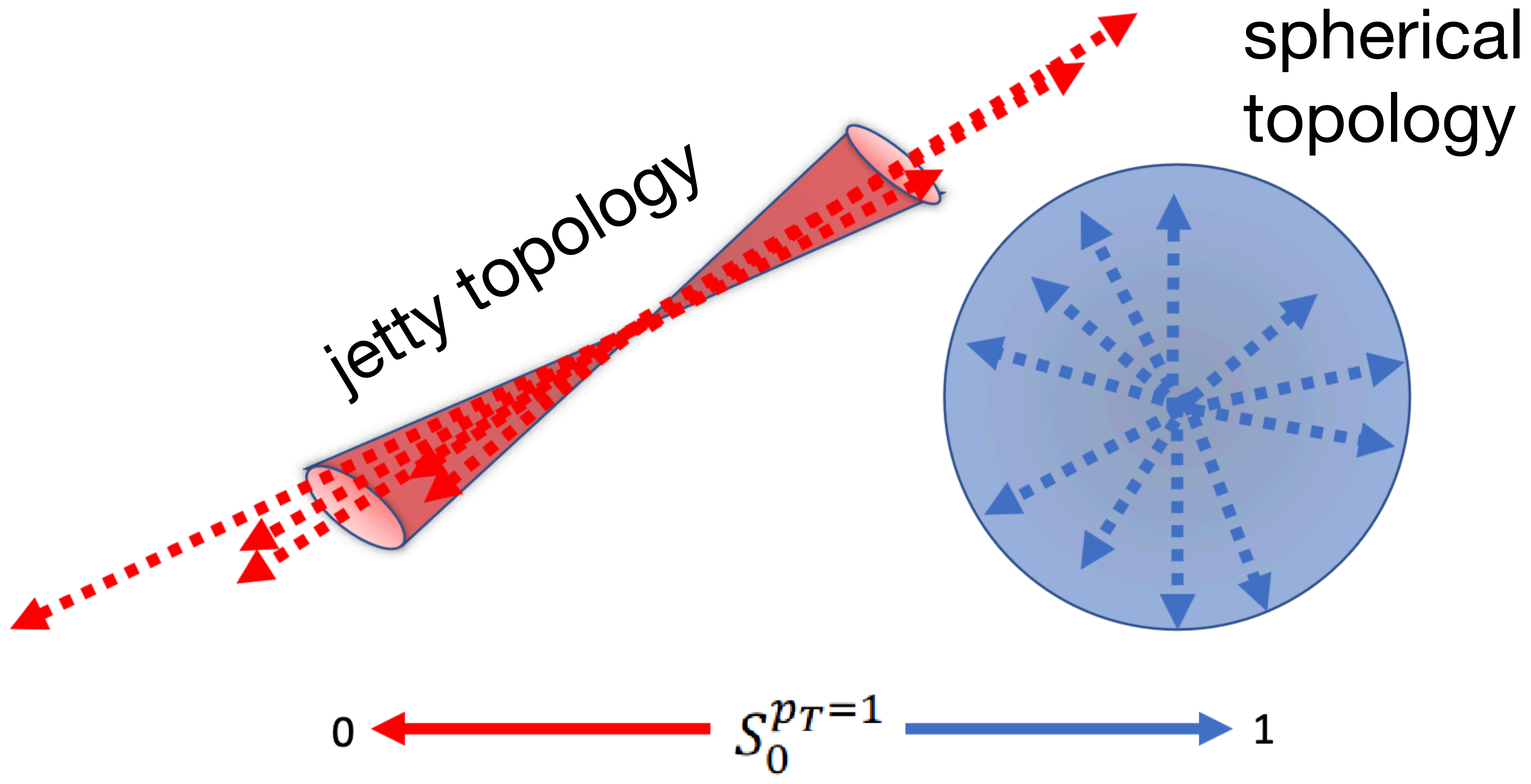

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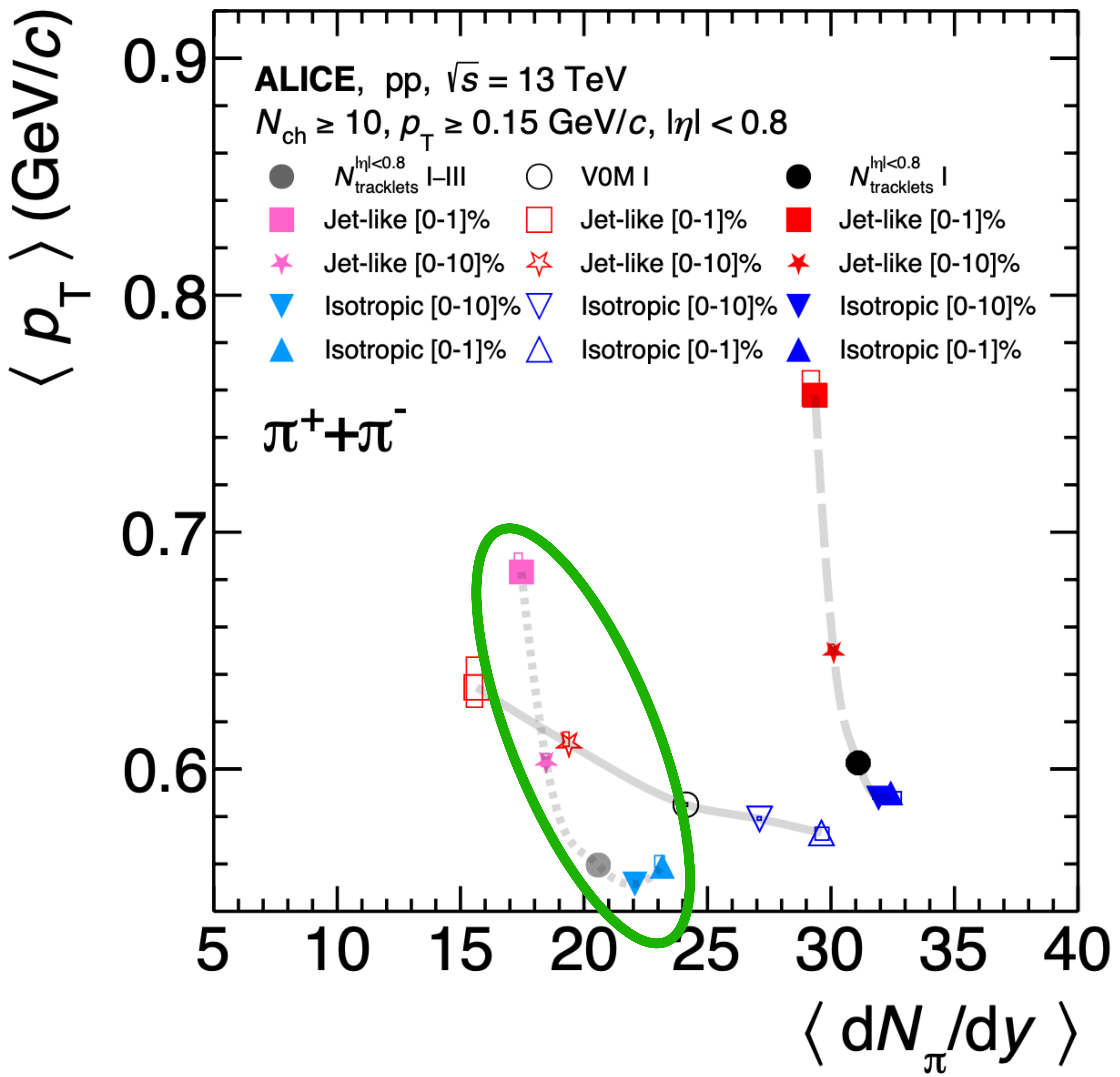
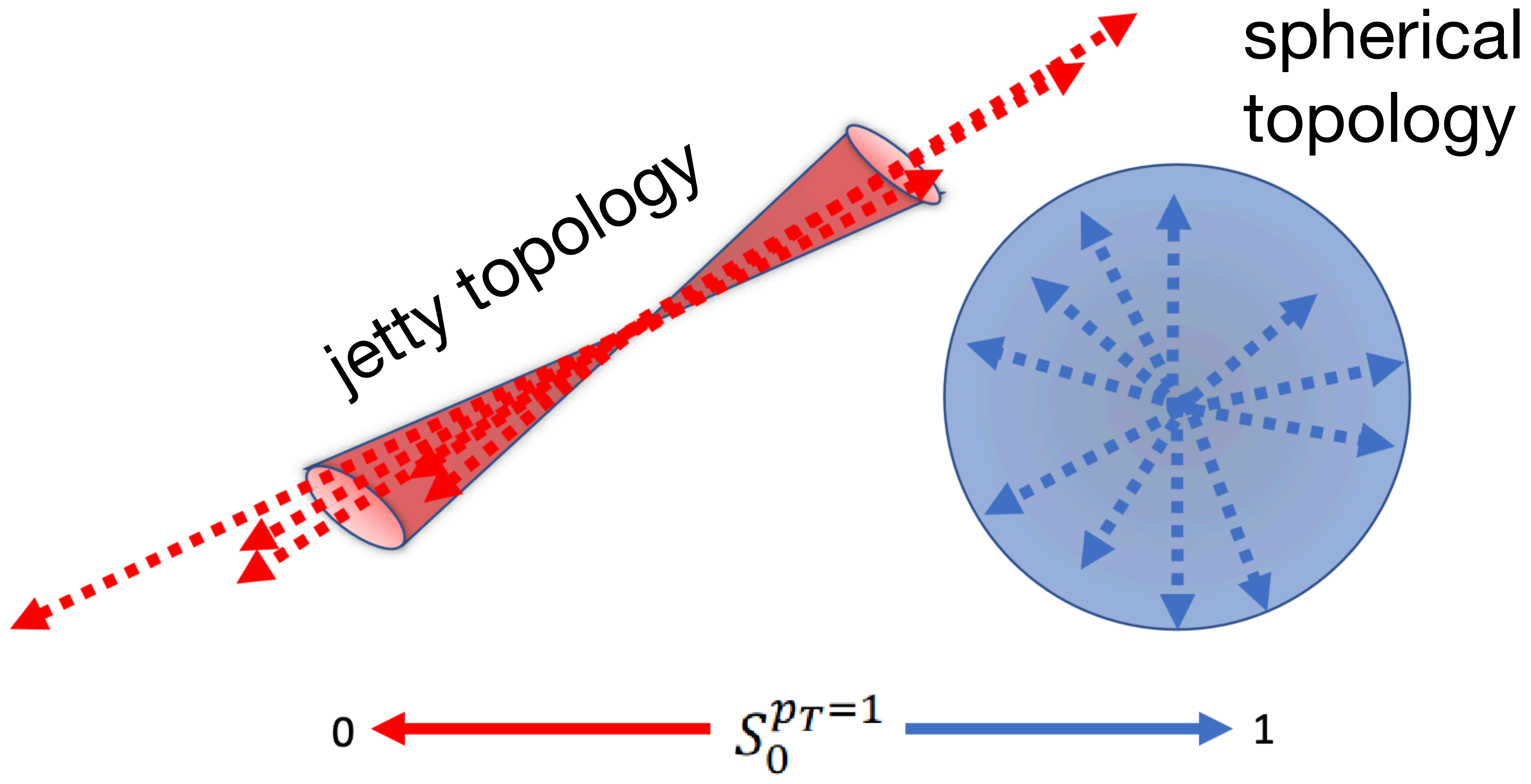


- High (0-10%) mid-rapidity multiplicity → varying S_O mostly changes $\langle p_T \rangle$ without major changes in N_π

S_O vs multiplicity

ALICE, JHEP 05 (2024) 184
arXiv:2310.10236 [nucl-ex]

- Events classified according to (mid-rapidity and forward) multiplicity and spherocity



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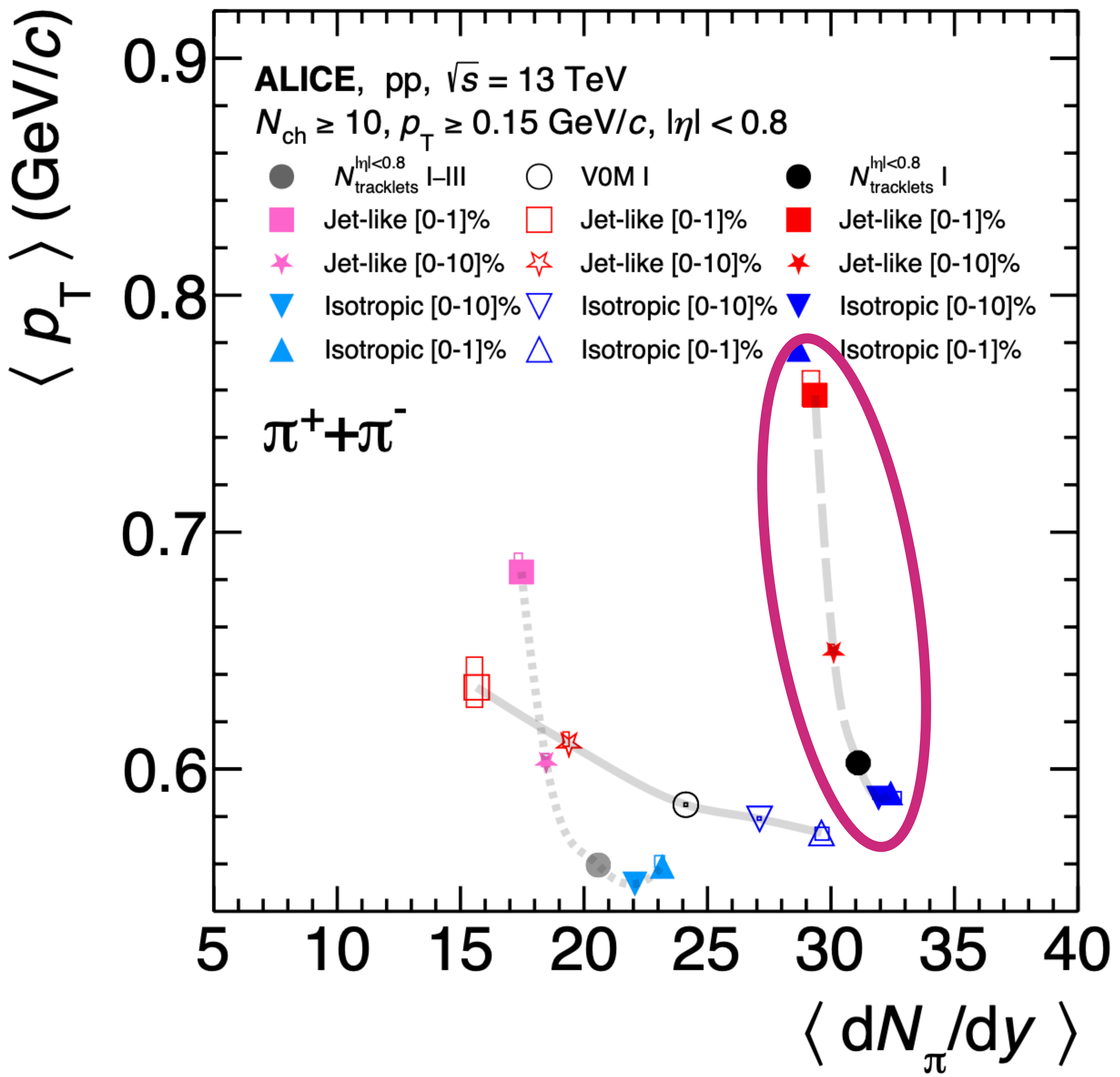
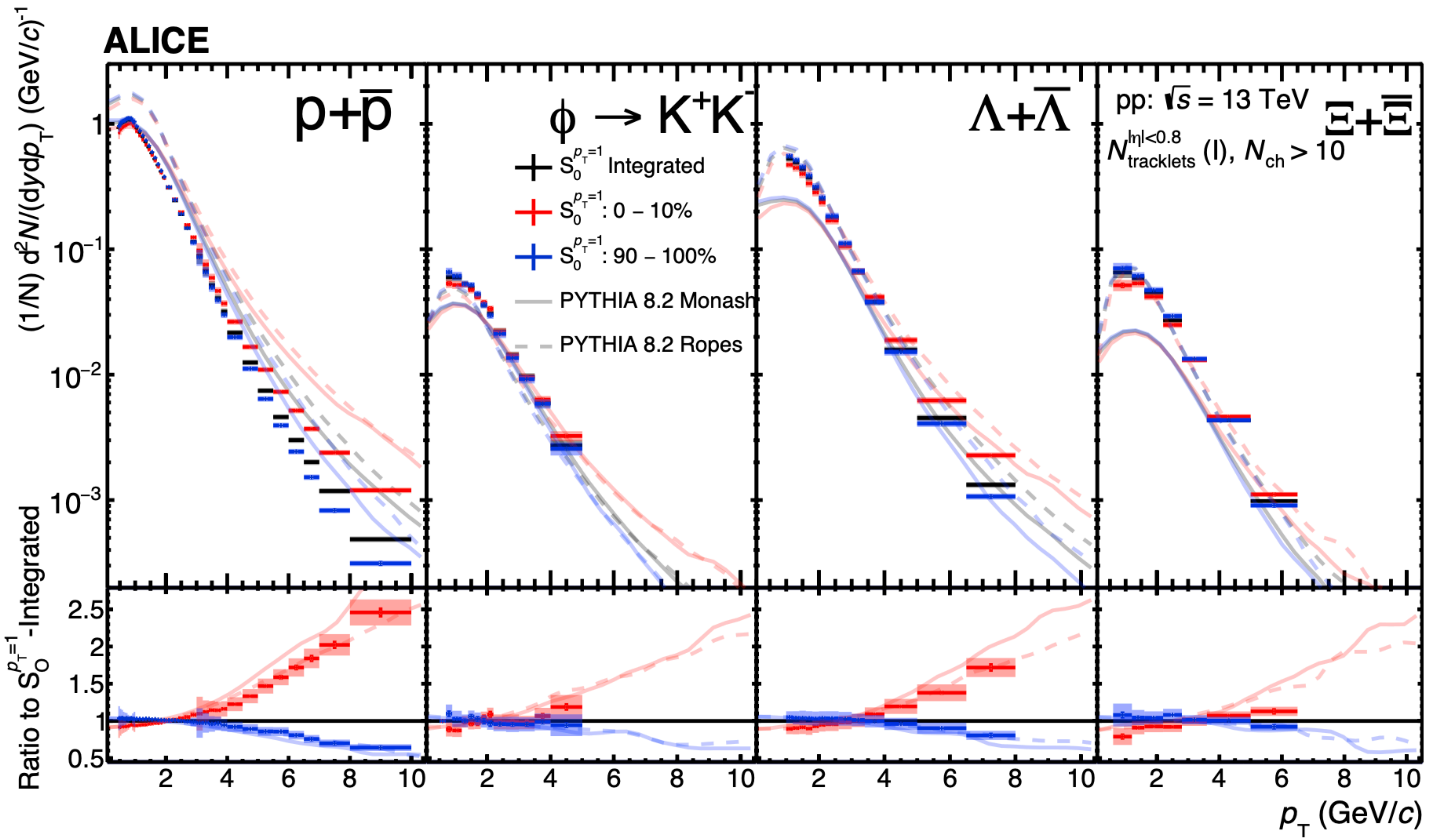


- Very high (0-1%) mid-rapidity multiplicity → varying S_O changes $\langle p_T \rangle$ without significant change in N_π

Spectra vs S_O

ALICE, JHEP 05 (2024) 184
arXiv:2310.10236 [nucl-ex]



- Measured p_T spectra of $\pi^{\pm}$, $K^{\pm}$, K^0_S, K^{*0}, ϕ, p, Λ, $\Xi^{\pm}$ for
  - 0-100% S_O
  - 0-10% S_O — jetty
  - 90-100% S_O — spherical
  - high mid-rapidity and forward rapidity multiplicity
- Spectra are harder in jetty events

Spectra vs S_O

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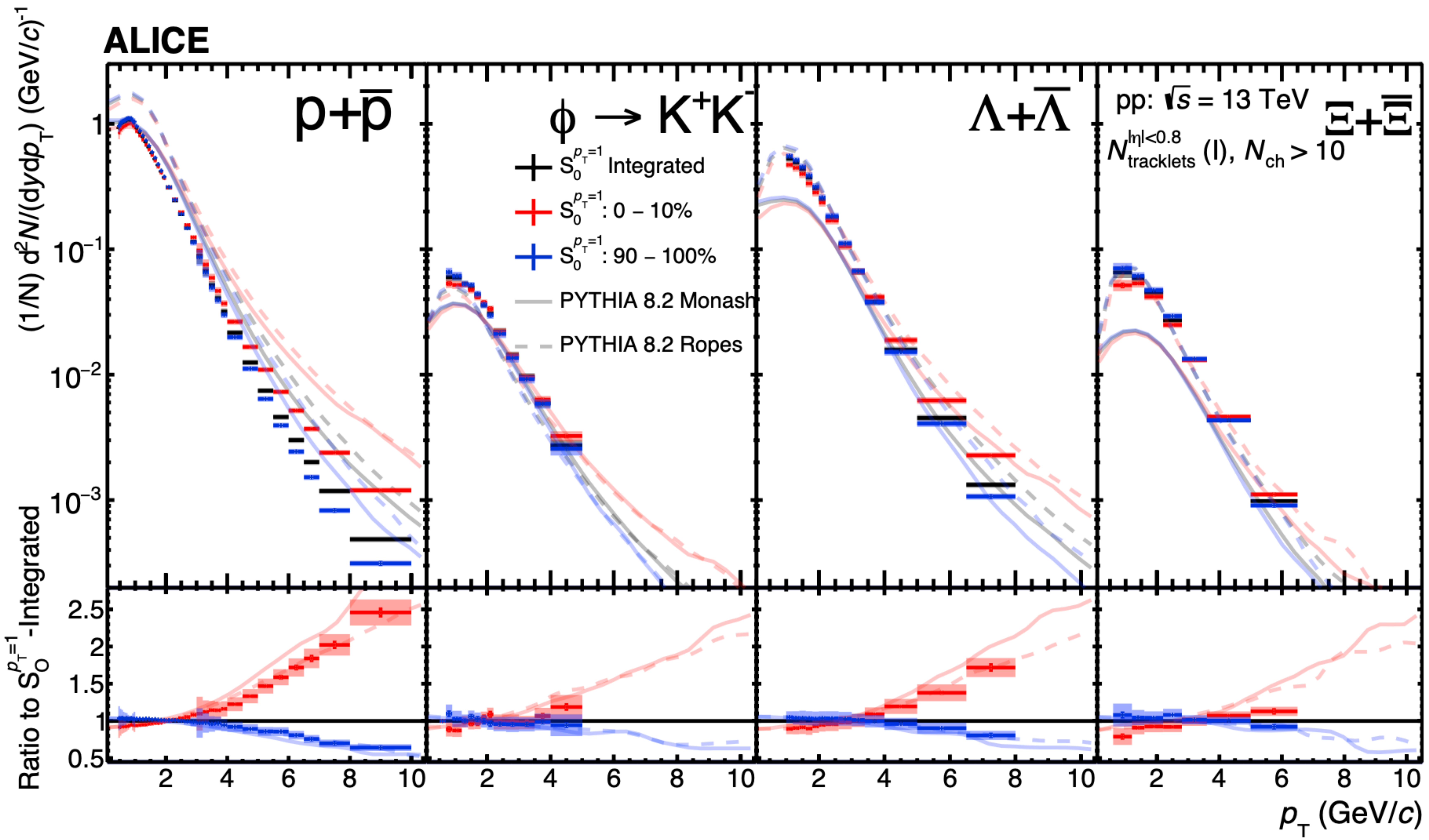

- Measured p_T spectra of $\pi^{\pm}$, $K^{\pm}$, K^0_S, K^{*0}, ϕ, p, Λ, $\Xi^{\pm}$ for
  - 0-100% S_O
  - 0-10% S_O — jetty
  - 90-100% S_O — spherical
  - high mid-rapidity and forward rapidity multiplicity
- Spectra are harder in jetty events
- Comparisons to Pythia shown here, Herwig and EPOS-LHC are in the paper

Baryon-to-meson ratios

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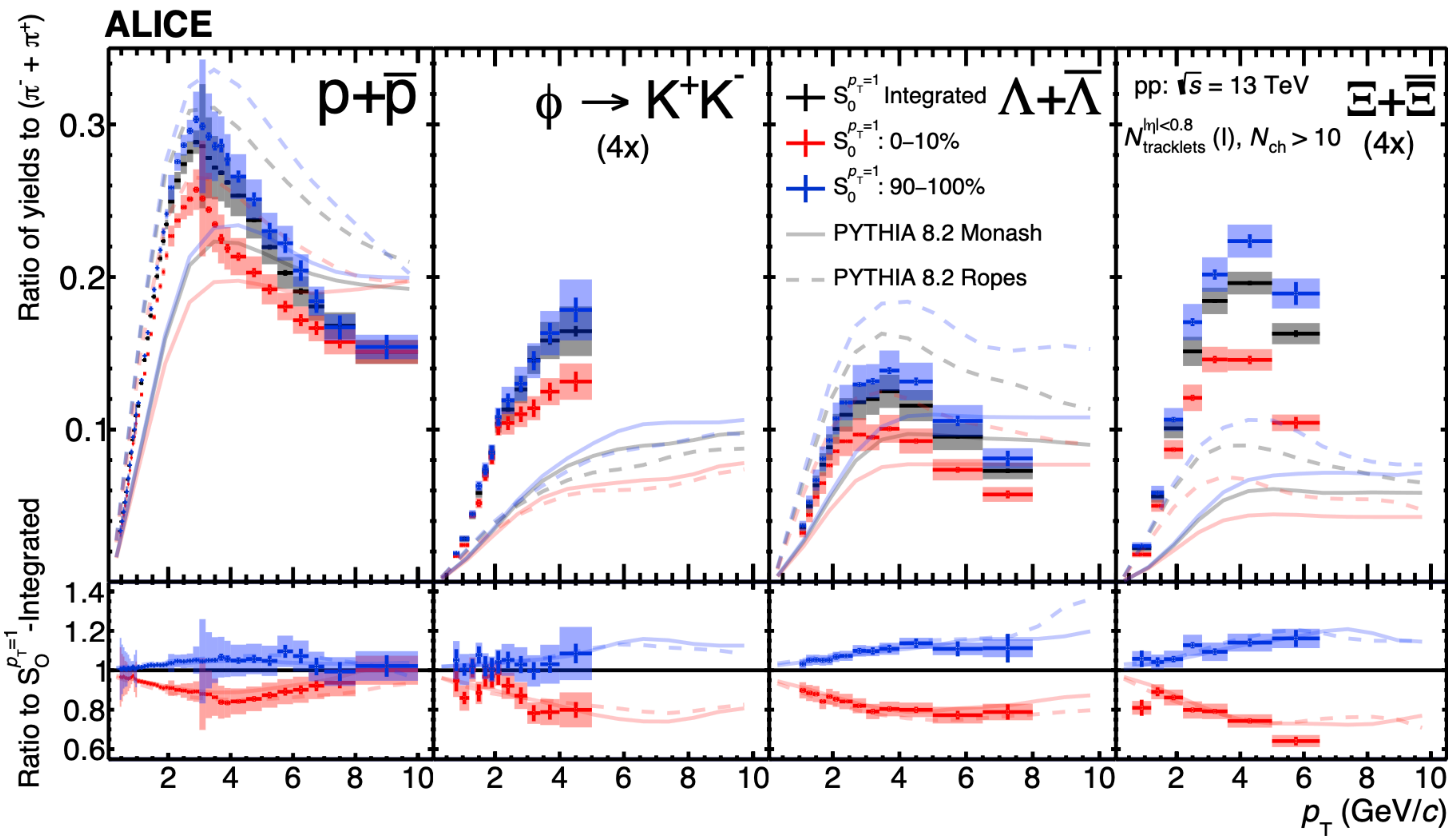

- Baryon-to-meson ratios (p/π, Λ/π, Ξ/π) in spherical events are similar to SO-integrated high-multiplicity events
- Double ratios described well by Pythia, Herwig, EPOS-LHC

Strangeness vs S$_O$

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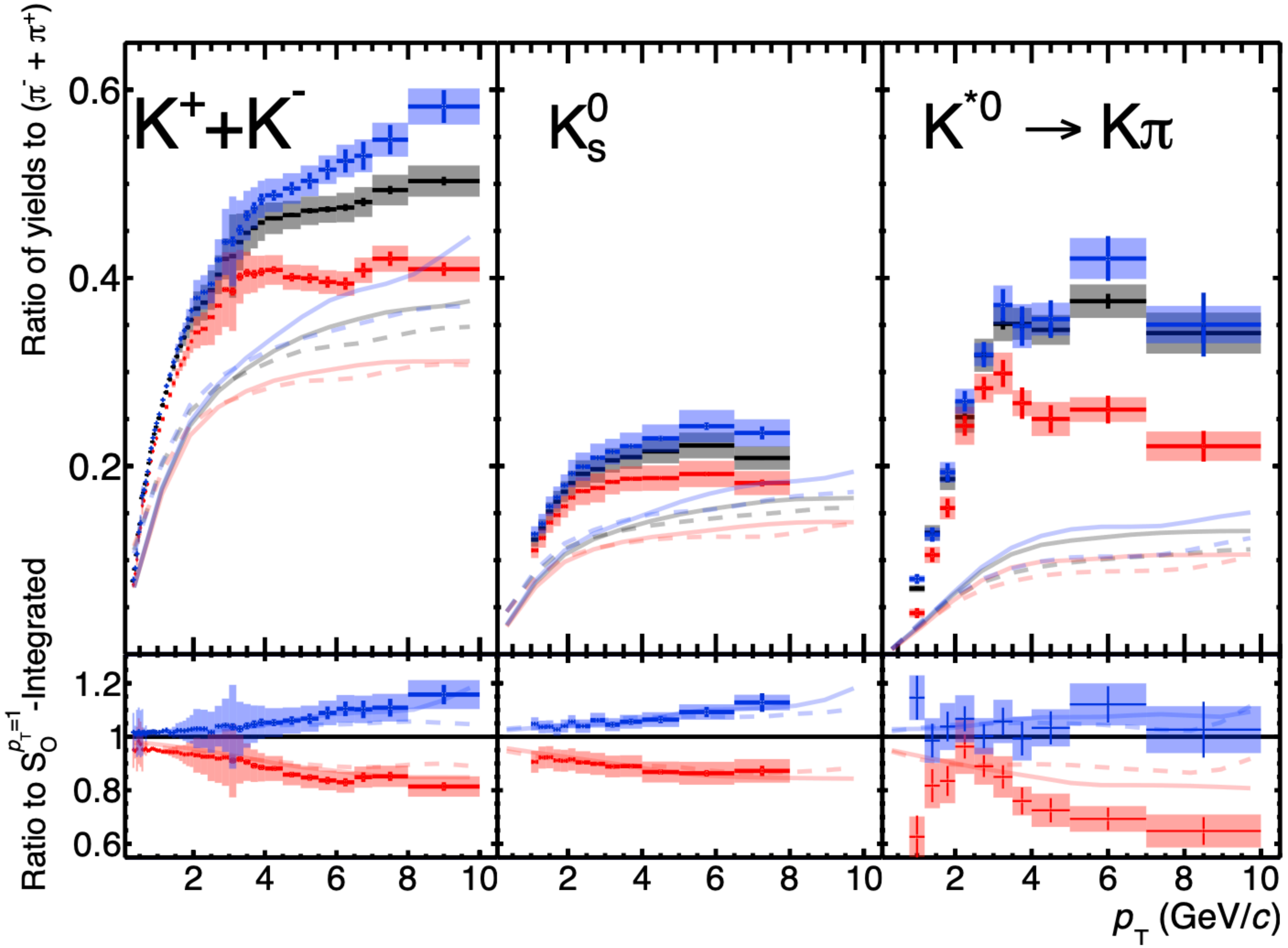
arXiv:2310.10236 [nucl-ex]



- Enhancement of strangeness production (relative to pions) in spherical events is similar to S$_O$-integrated high-multiplicity events
- Strong suppression in jetty events
- Double ratios described well by Pythia and EPOS-LHC
- Average high-multiplicity events are dominated by soft processes; hard processes are rare and have little impact on bulk observables

Strangeness vs S_O

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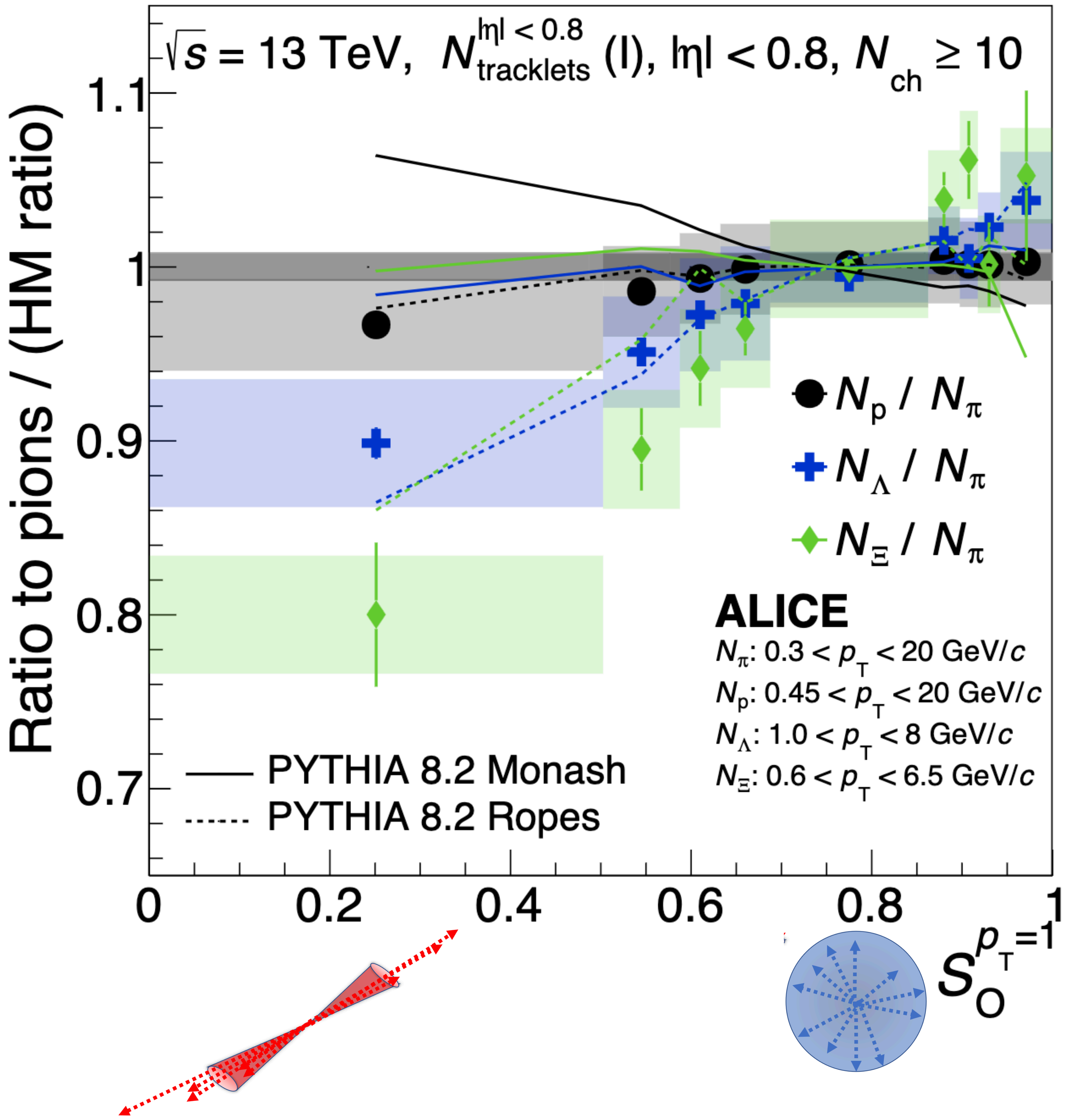
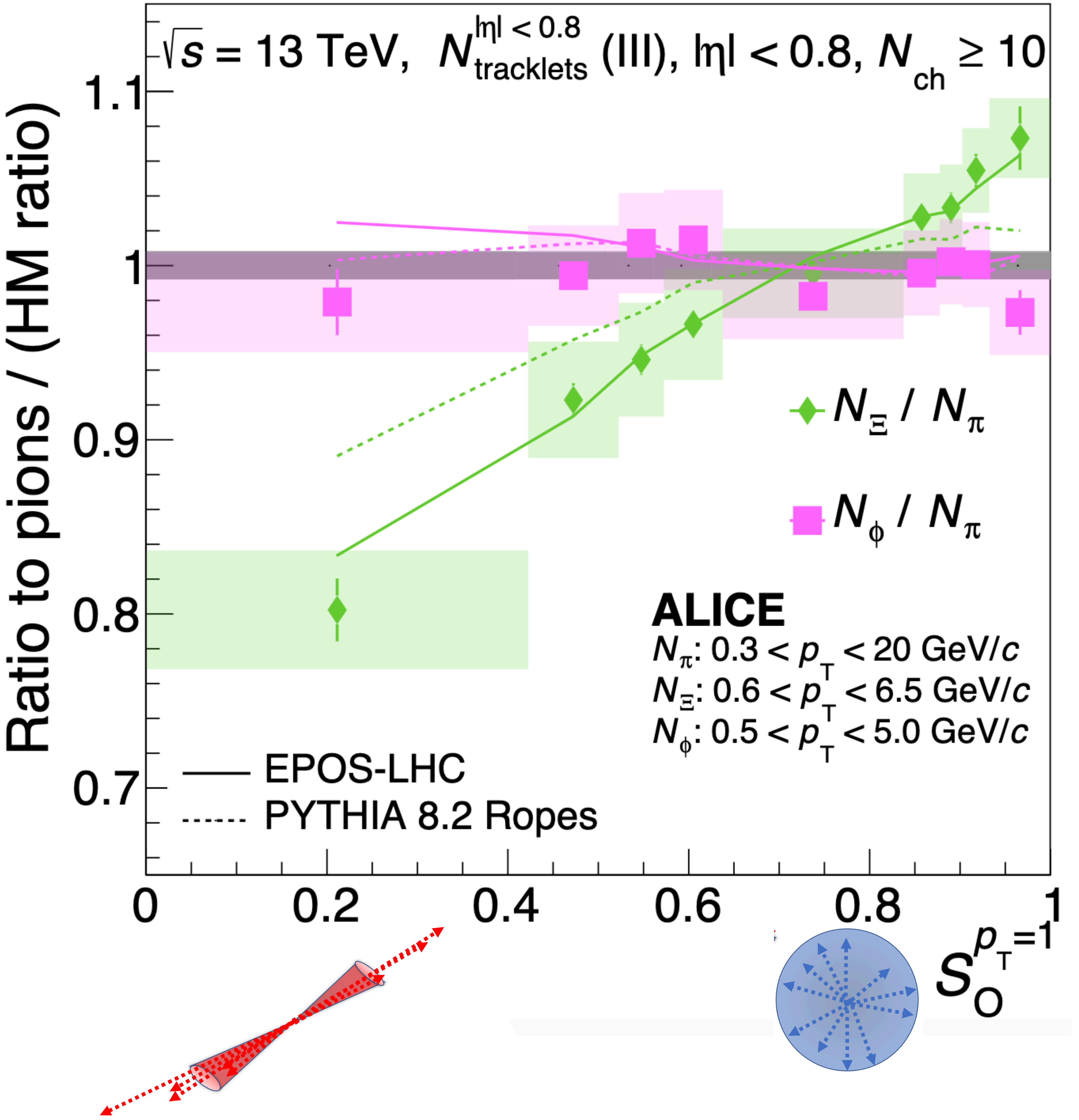


- Strangeness enhancement observed with increasing spherocity when multiplicity is roughly fixed at midrapidity (only ~10% variation in the mean mult.)
- Would need ~60-70% variation in multiplicity to explain the magnitude of Ξ suppression in jetty events
- When midrapidy multiplicity (~N_π) is fixed, change in spherocity leads to selecting events of different hardness (⟨p_T⟩) and gives us a greater lever arm for varying strangeness production

What about the ϕ?

ALICE, JHEP 05 (2024) 184
arXiv:2310.10236 [nucl-ex]



- Is the ϕ strange? (Σ|S| = 2 or |ΣS| = 0?)
- No enhancement observed
  → ϕ behaves as a non-strange hadron
- However, data is consistent with Pythia 8.2 where the ϕ is effectively doubly-strange
  → is this a baryon vs meson effect?

Still an open question…

Conclusions and further thoughts…

- Big question: How do the microscopic particle production and interaction mechanisms in QCD lead to novel behavior such as collective flow, strangeness enhancements, and baryon-to-meson enhancement?
- What are the production mechanisms and subsequent dynamics of hadrons carrying conserved charge like strangeness and baryon number?
  - Balance functions allow us to probe the relative orientation of balancing charges
  - Ξπ, ΞK, Ξp balance functions measured in pp, with detailed comparison to models
  - No clear sign of “turn on” of new production mechanisms at high multiplicity
  - Next steps: Λ-h and Ξ-h BFs in Pb-Pb, other particle species (charm!), 3-particle BF,…
- Are these emergent behaviors driven by multiplicity alone, or are there other physics mechanisms at play?
  - Identified particle spectra measured vs transverse spherocity and multiplicity
  - Behavior observed in high multiplicity collisions is seen in spherical collisions, less so in jetty events
  - Strangeness enhancement vs S_O, but multiplicity also plays a role