Shedding light on the baryon production via angular correlation studies with ALICE

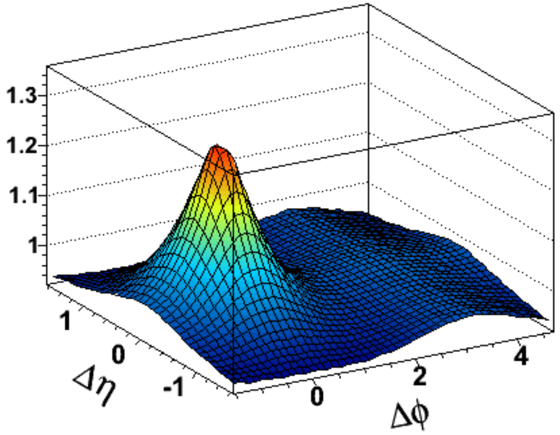
Małgorzata Anna Janik
for the ALICE Collaboration

EPS HEP 2025

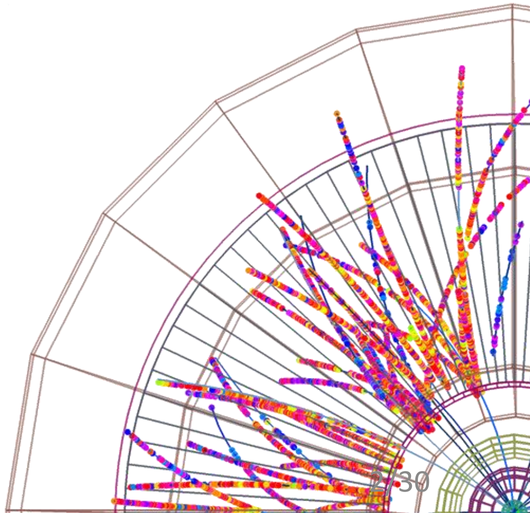
Motivation

Two-particle ΔηΔφ angular correlations:

- give access to information about particle distribution in space,



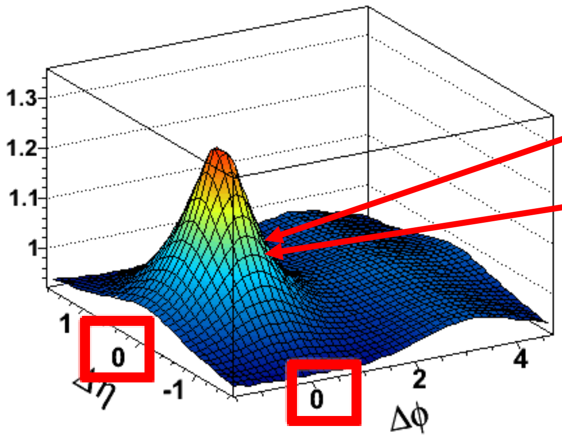
- technique to study wide range of correlation sources.

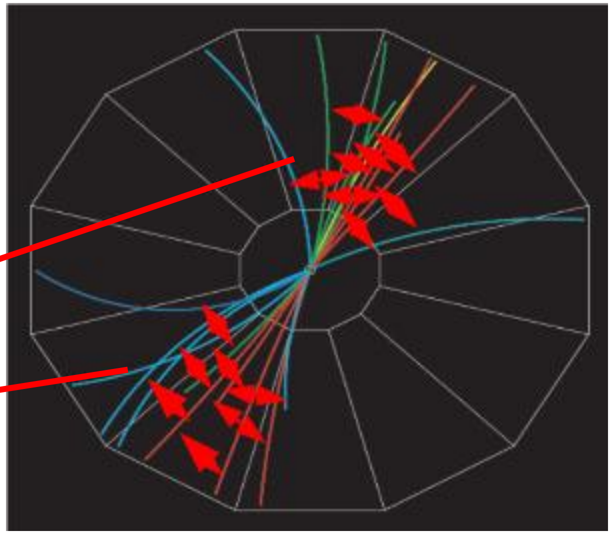


Motivation

Two-particle $\Delta\eta\Delta\varphi$ angular correlations:

- give access to information about particle distribution in space,

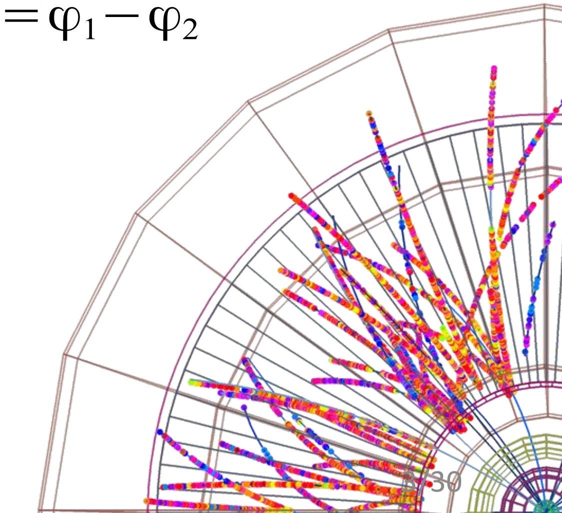




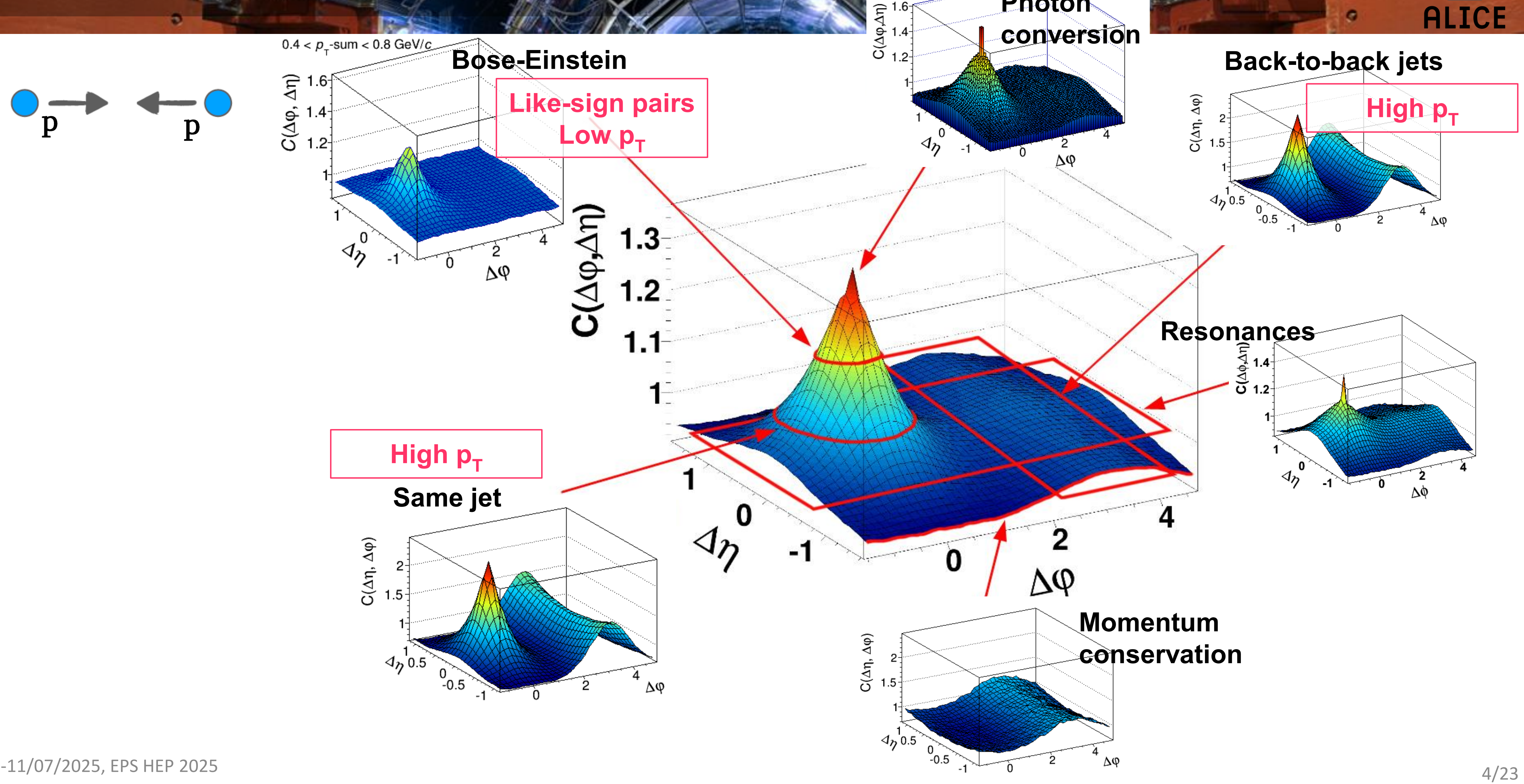
$\Delta\eta = \eta_1 - \eta_2$

$\Delta\varphi = \varphi_1 - \varphi_2$

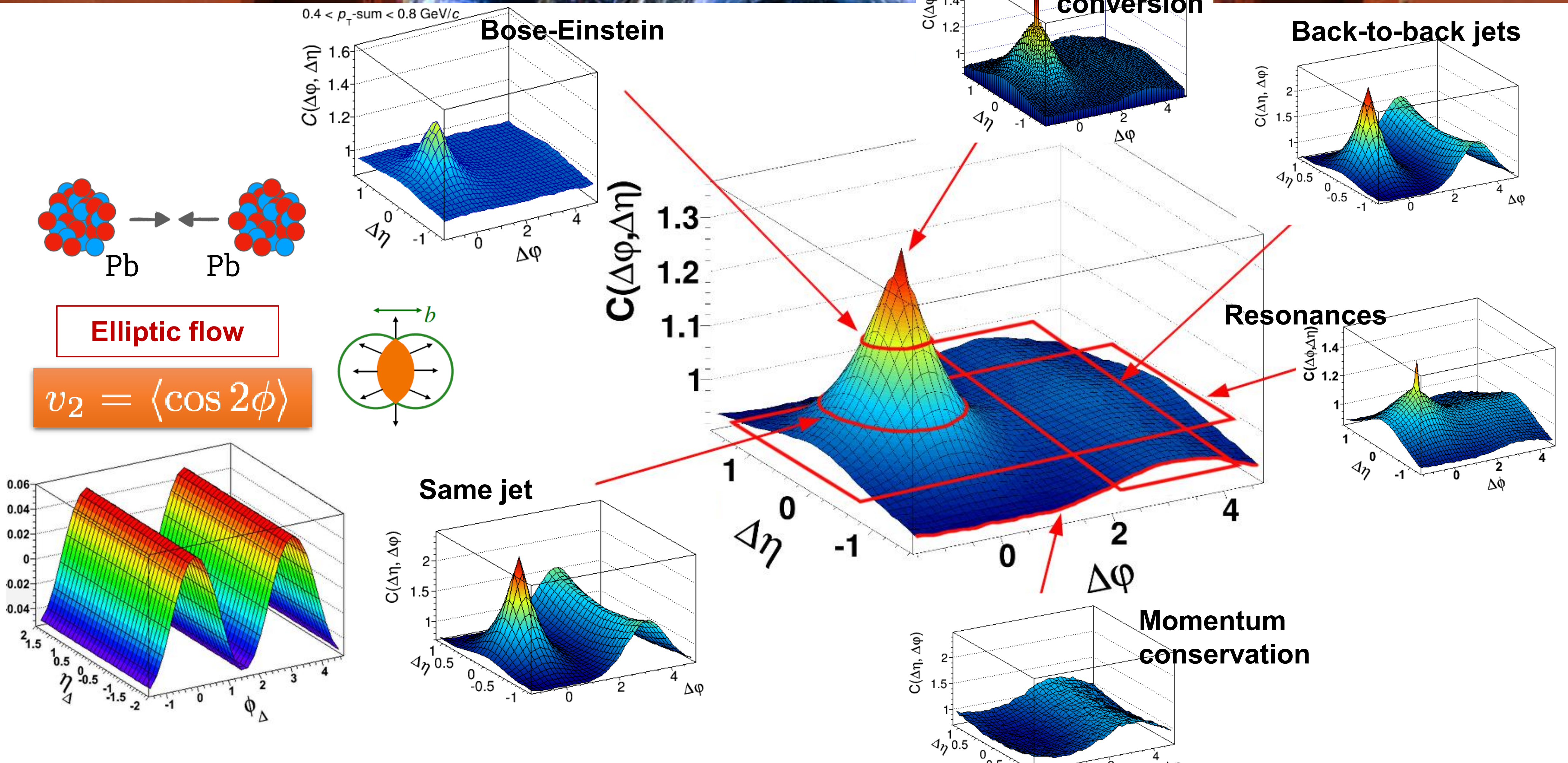
- technique to study wide range of correlation sources.



Contributions to correlation function



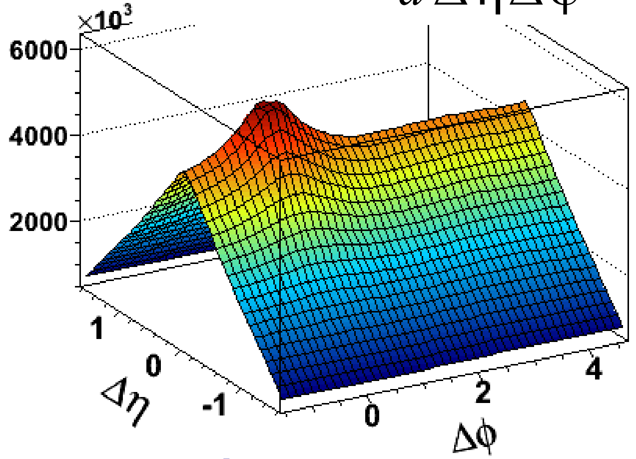
Contributions to correlation function



Correlation function construction

Signal distribution

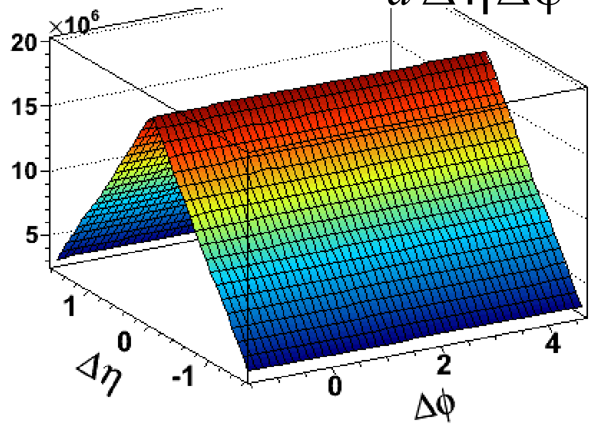
$$S(\Delta\eta, \Delta\varphi) = \frac{d^2 N^{signal}}{d\Delta\eta\Delta\varphi}$$



Same event pairs

Uncorrelated reference

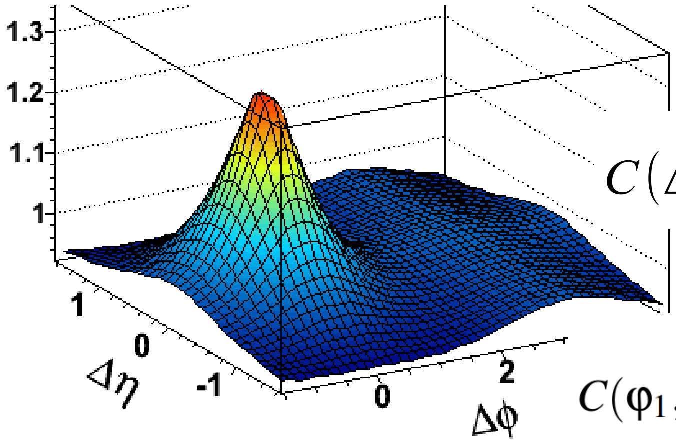
$$B(\Delta\eta, \Delta\varphi) = \frac{d^2 N^{mixed}}{d\Delta\eta\Delta\varphi}$$



Mixed event pairs

$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

Correlation function

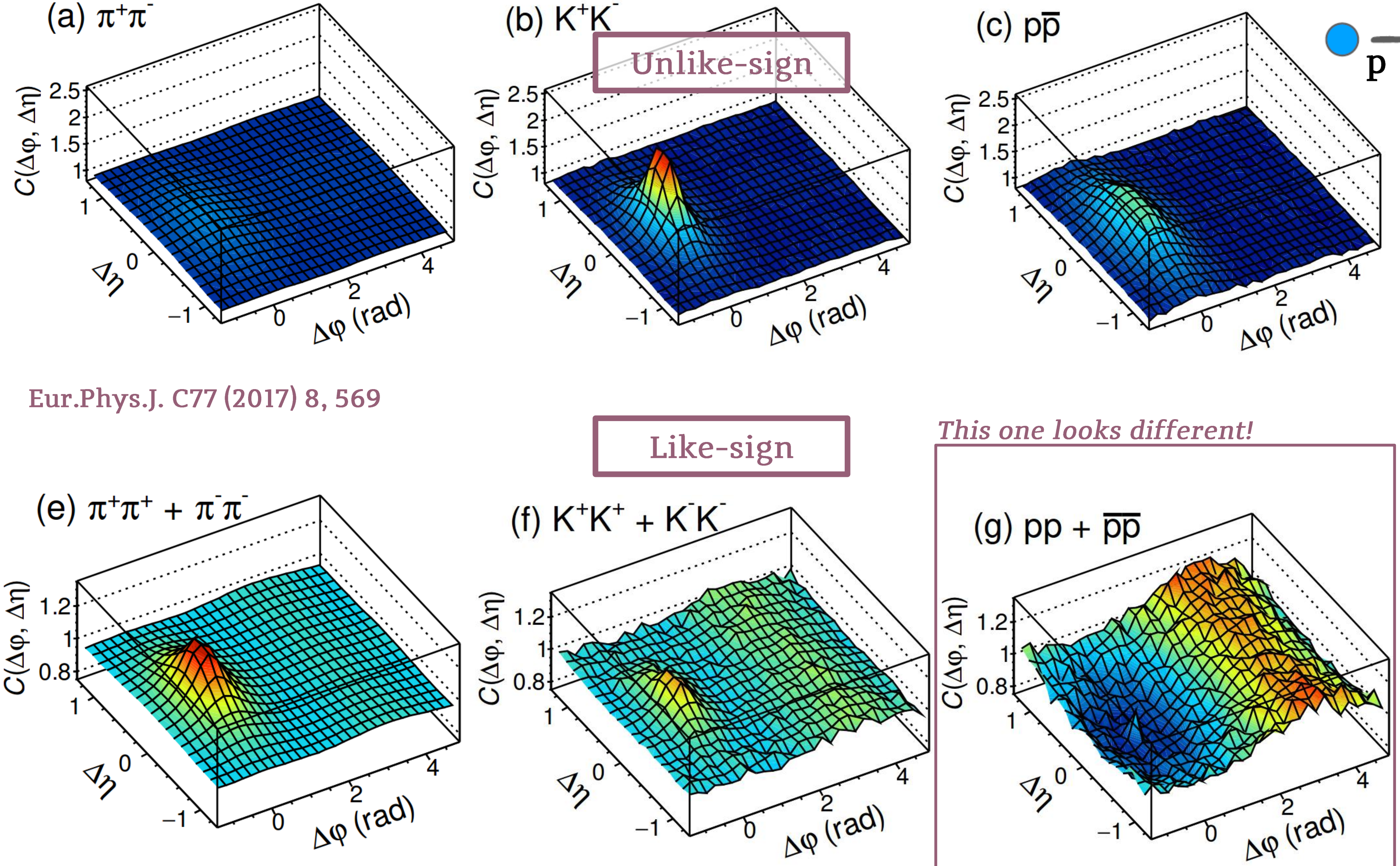


$$C(\Delta\eta, \Delta\varphi) = \frac{N^{mixed}_{pairs}}{N^{signal}_{pairs}} \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\varphi)}$$

$$C(\varphi_1, \eta_1, \varphi_2, \eta_2) = \frac{P_{12}(\varphi_1, \eta_1, \varphi_2, \eta_2)}{P_1(\varphi_1, \eta_1) P_2(\varphi_2, \eta_2)}$$

ΔηΔφ of identified particles

7 TeV
p p



Unlike-sign

Eur.Phys.J. C77 (2017) 8, 569

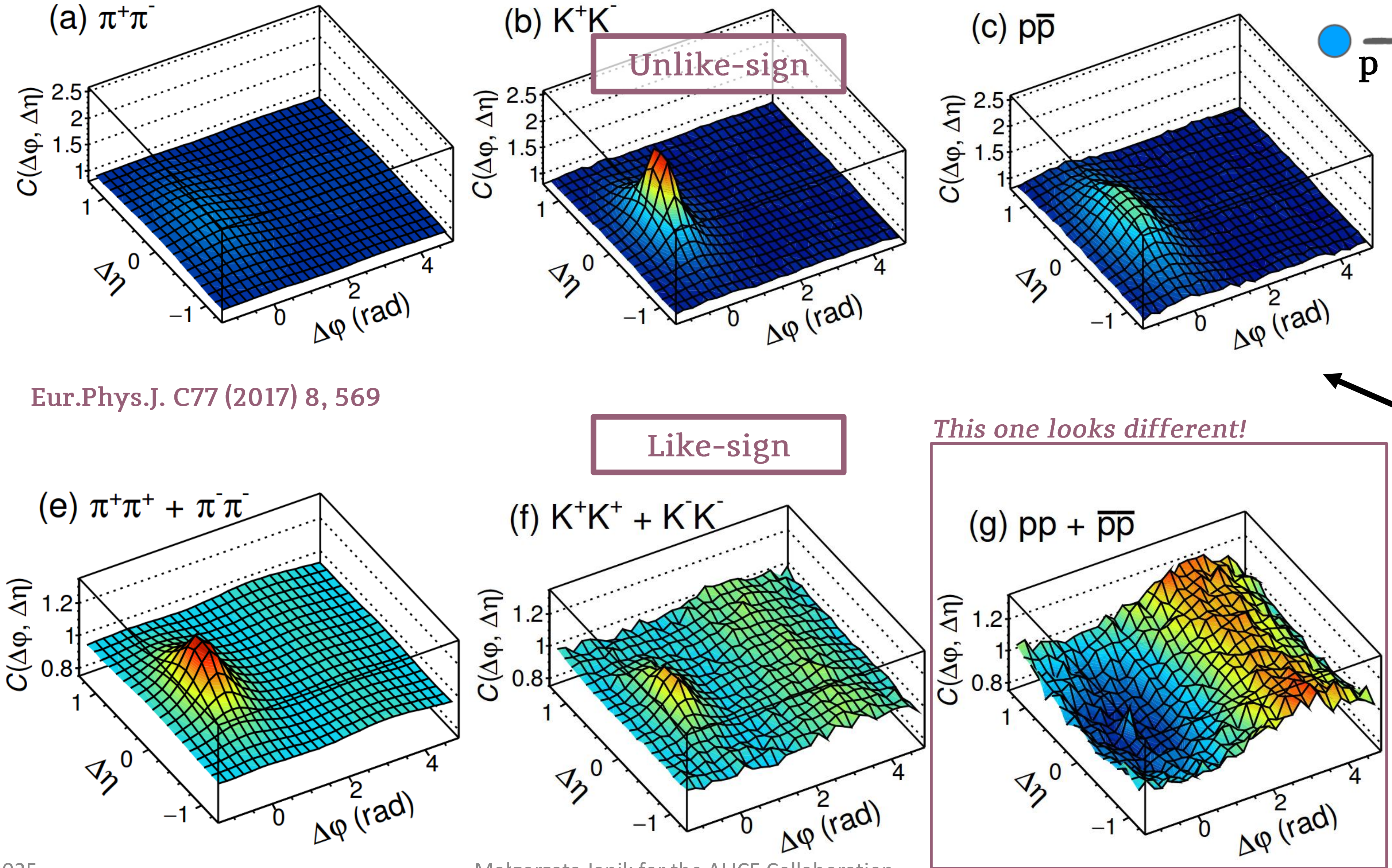
Like-sign

This one looks different!

ΔηΔφ of identified particles

7 TeV
p p

Unlike-sign



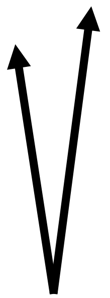
Eur.Phys.J. C77 (2017) 8, 569

Like-sign

This one looks different!

Anti-correlation in (0,0)

Surprising! Observed only for protons

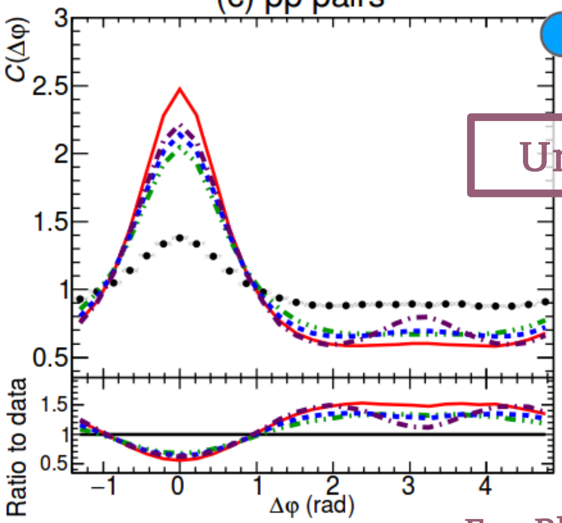


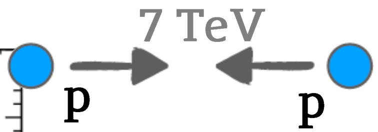
Near-side peak in (0,0): ***mainly from minijets, visible for (almost) all functions***

MC models do not reproduce

The models failed to reproduce the results for baryons:

- distinct near-side peak in MC, not present in data





Unlike-sign

Eur.Phys.J. C77 (2017) 8, 569

Results argue against the hypothesis that the combination of energy and baryon-number conservation is enough to explain the anticorrelation, since both local & global conservation laws are implemented in all studied models.

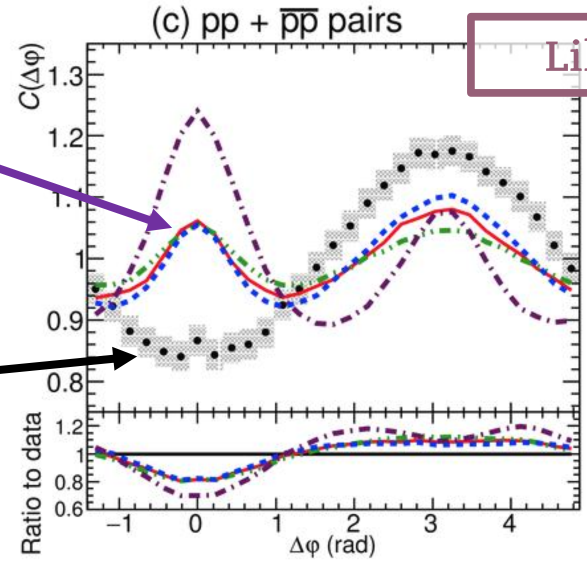
Lines: MC models

- PYTHIA6 Perugia-0
- PYTHIA6 Perugia-2011
- PYTHIA8 Monash
- PHOJET

Points: data

- ALICE pp $\sqrt{s}$ = 7 TeV, $|\Delta\eta| < 1.3$

This one looks different!



Like-sign

ΛΛ and pΛ correlation functions

Run 3

ALICE

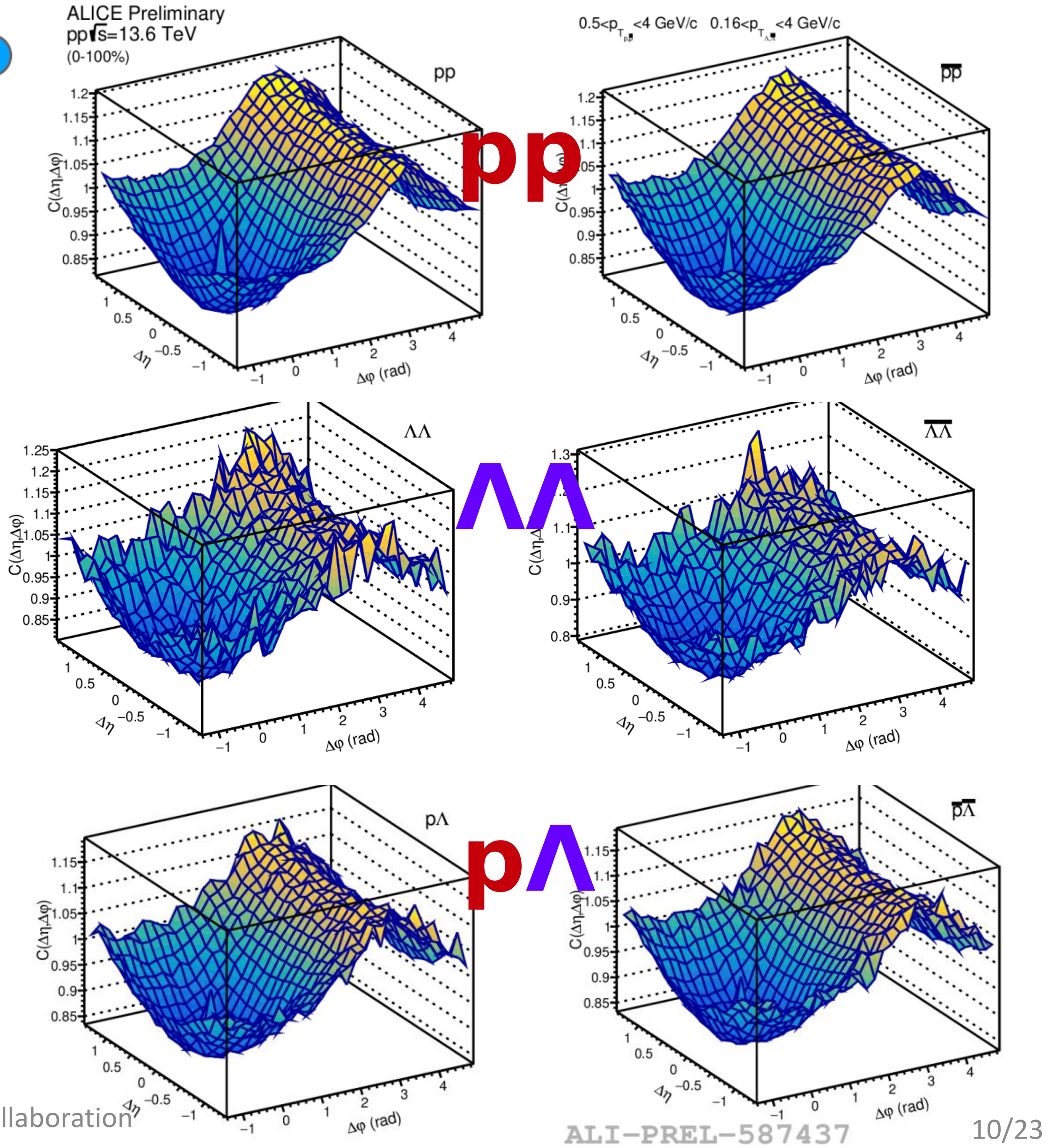
- Useful to check if effect persists for other baryons than protons – is this a common effect for all baryons?

- Correlation functions were calculated for ΛΛ and pΛ pairs

- Λ baryons are neutral → no Coulomb repulsion

- p and Λ are not identical → no effect from Fermi-Dirac statistics

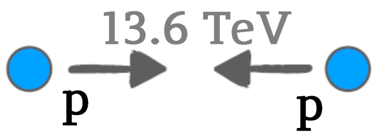
- **All observations from pp can be extended to ΛΛ and pΛ**



ΛΛ and pΛ correlation functions

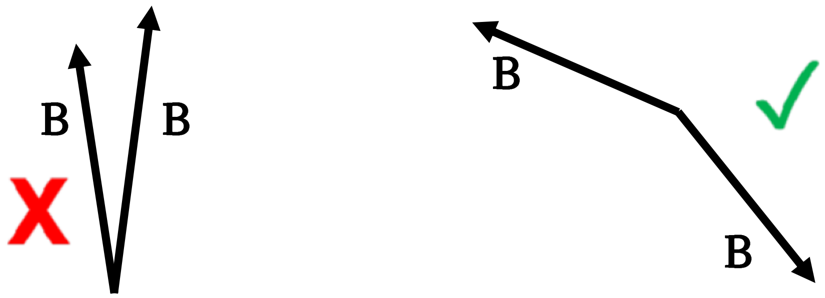
ALICE

Run 3

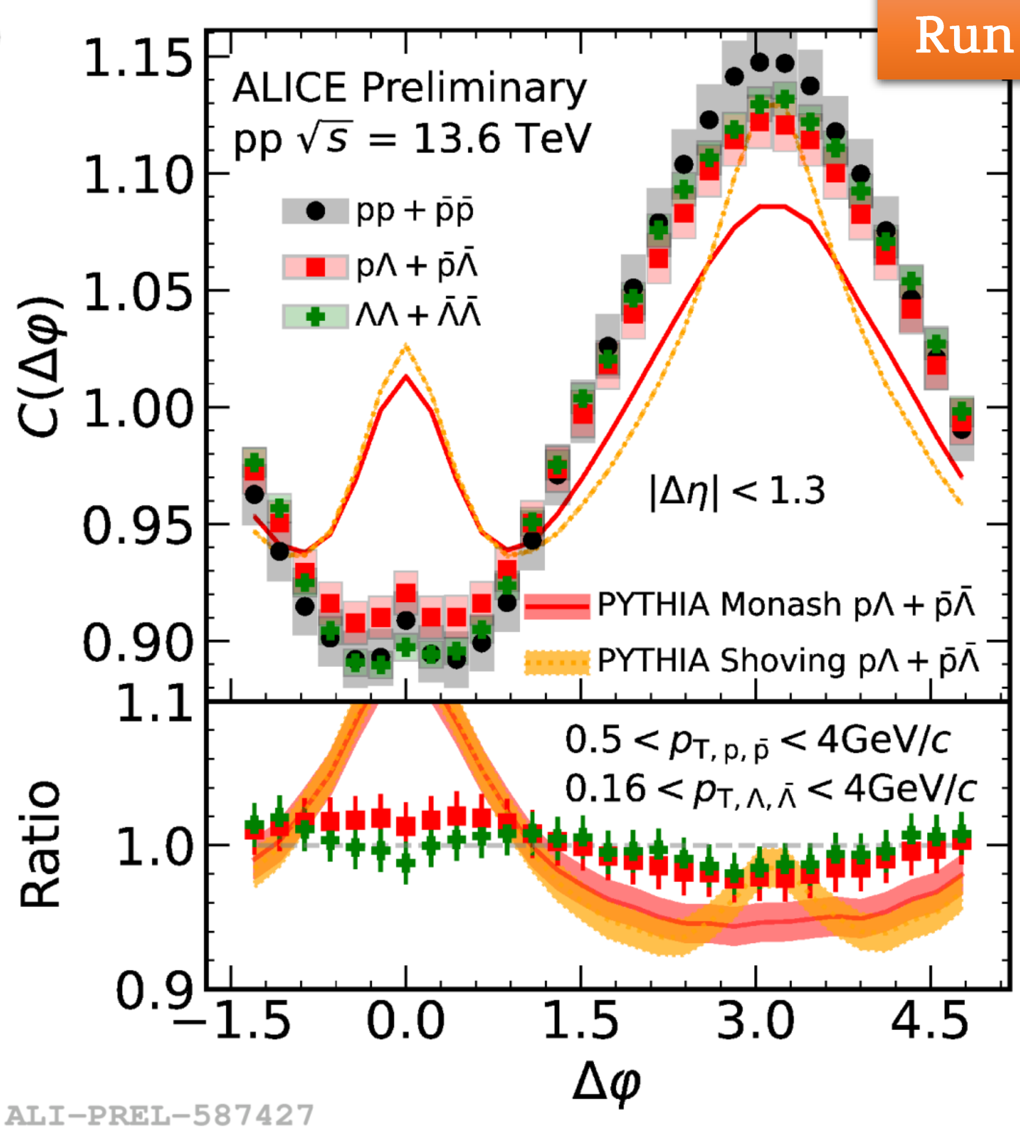


Anti-correlation in (0,0):

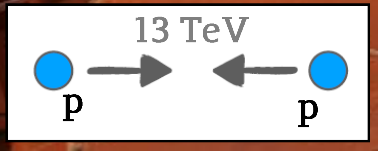
- probability of producing two baryons close in phase space is **lower** than in other directions

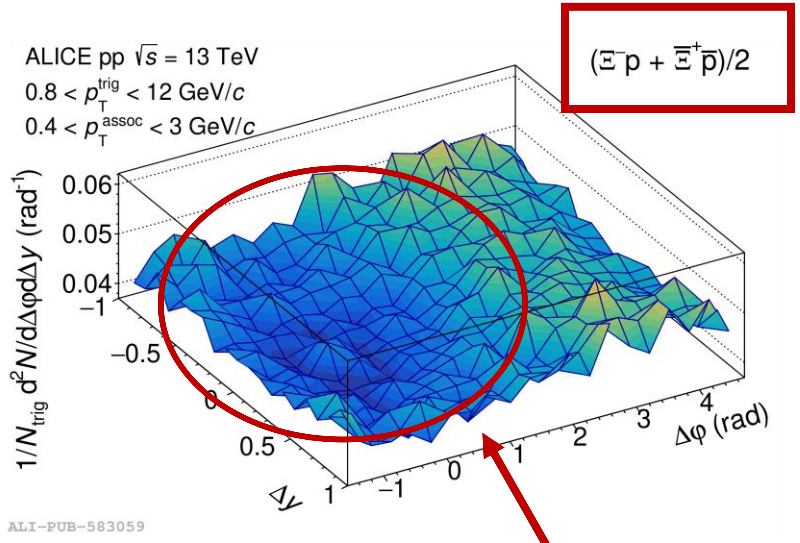


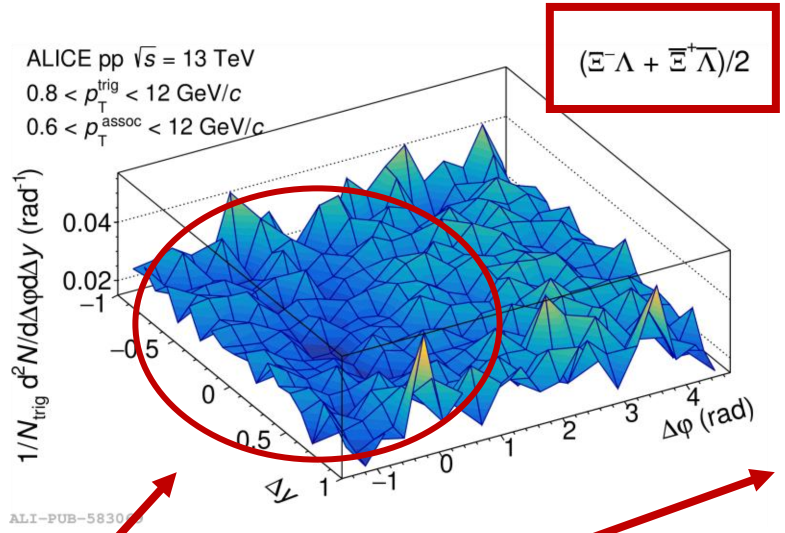
+ **MC models do not reproduce**
+ **no minijet collimation observed**
+ **special rules for baryon production?**

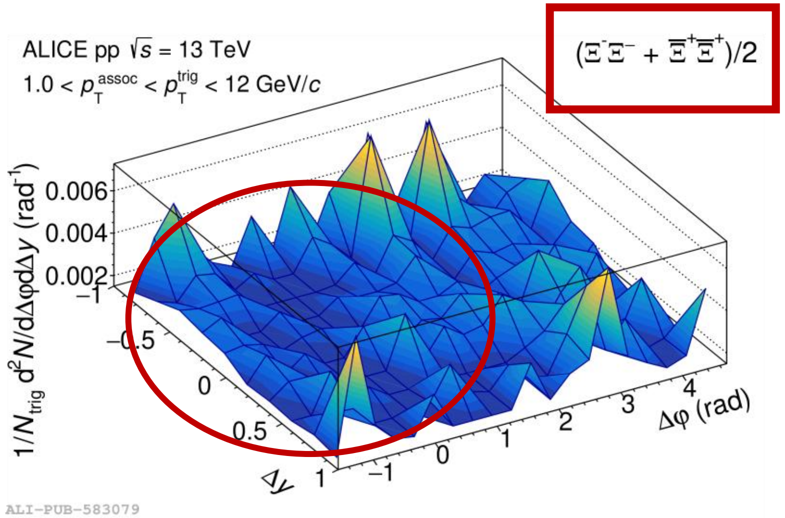


Ξ-baryon correlations





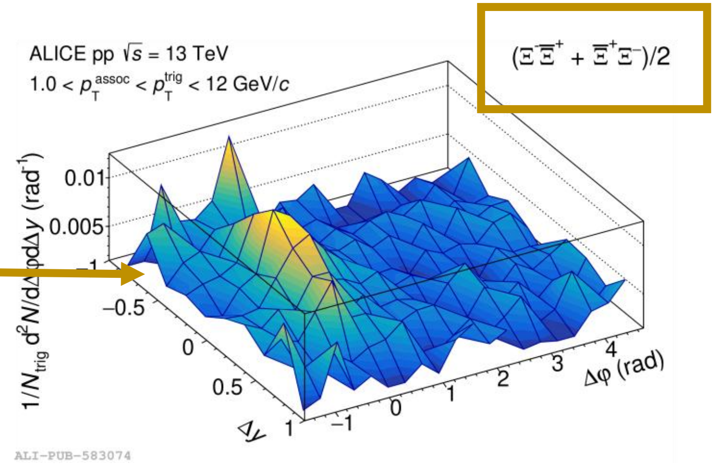




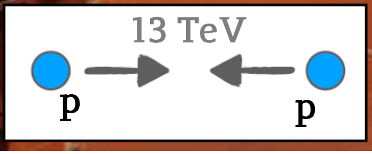
ALICE Collaboration, *JHEP* 09 (2024) 102

Anti-correlation present for all baryon pairs with the same baryon number.

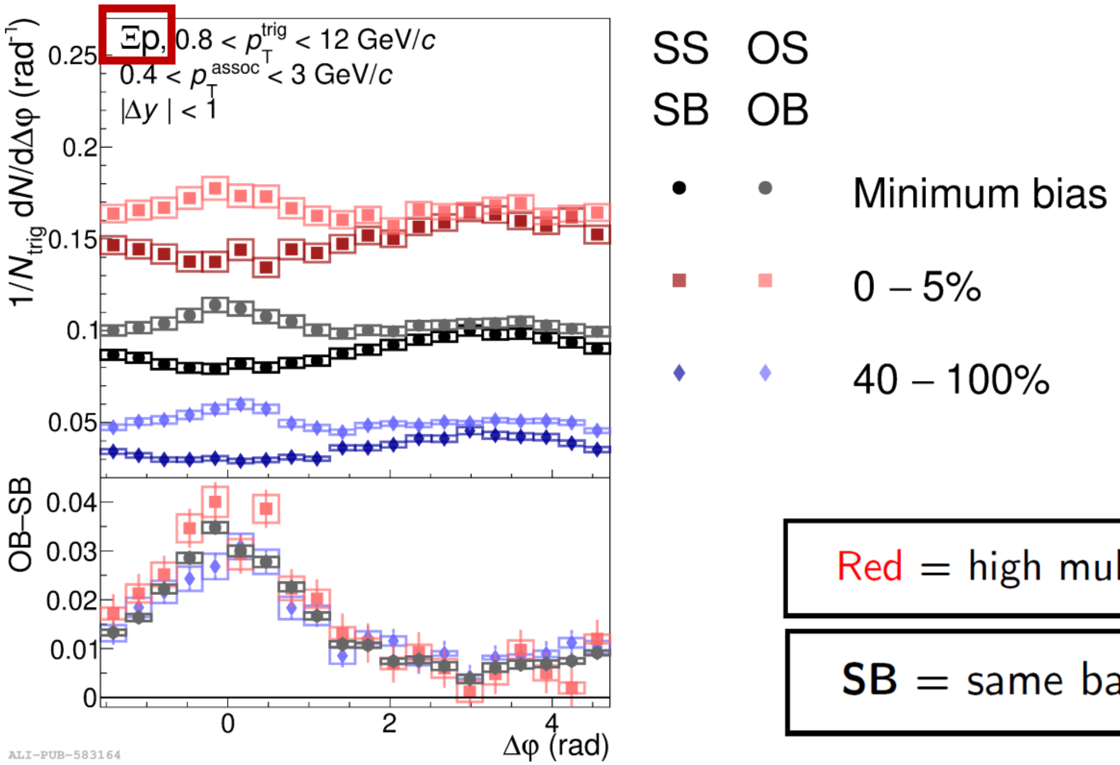
Near-side peak for baryon pairs with opposite baryon number.



Ξ-p correlations multiplicity dependence



ALICE Collaboration, *JHEP* 09 (2024) 102

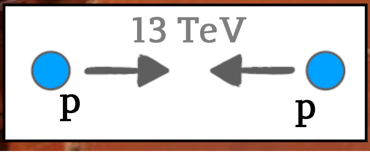


Red = high multiplicity, Grey = minimum bias, Blue = low multiplicity

SB = same baryon number, **OB** = opposite baryon number

- anticorrelation persists in heavier baryon—baryon pairs
- visible for both high- and low-multiplicities

Ξ-Λ correlations multiplicity dependence



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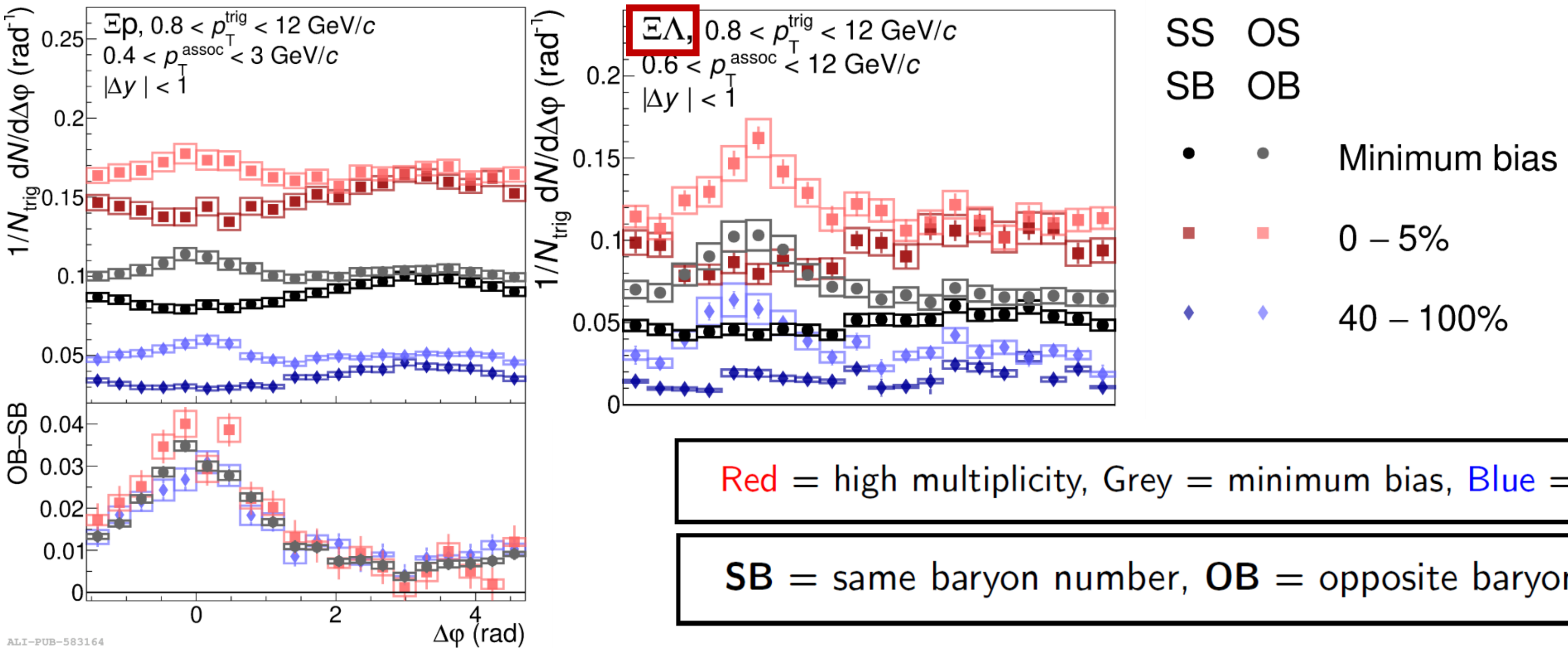

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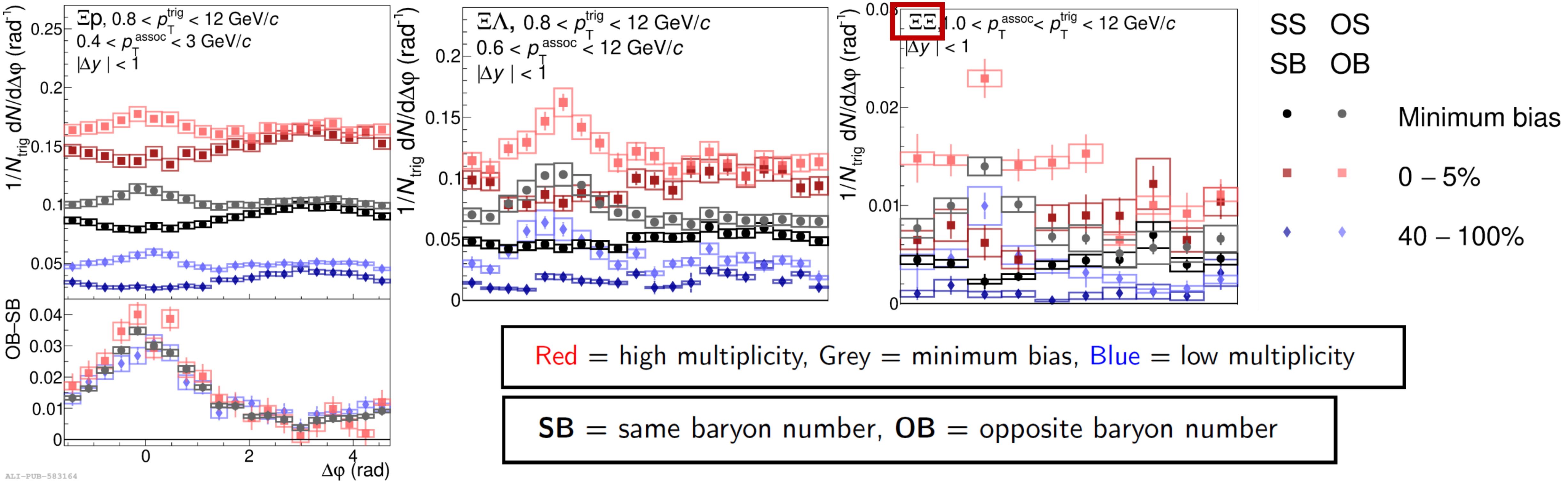
Ξ-Ξ correlations multiplicity dependence

13 TeV
p p

ALICE Collaboration, *JHEP* 09 (2024) 102



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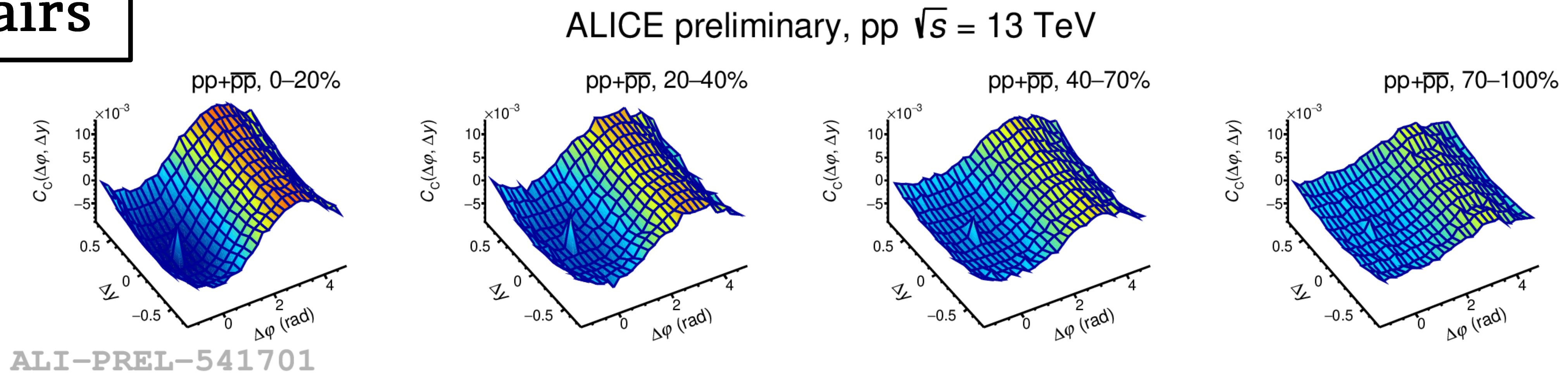
System & multiplicity dependence

pp pairs

13 TeV

pp



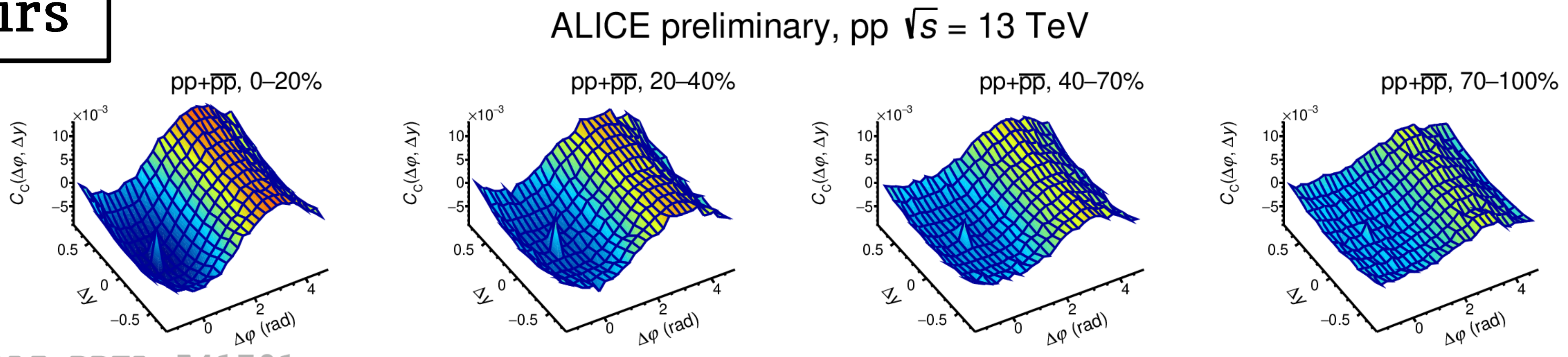
The anticorrelation persists in pp at 13 TeV:
→ It becomes stronger for higher multiplicity classes

System & multiplicity dependence

pp pairs

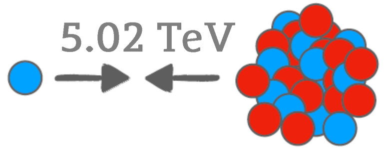
13 TeV

pp

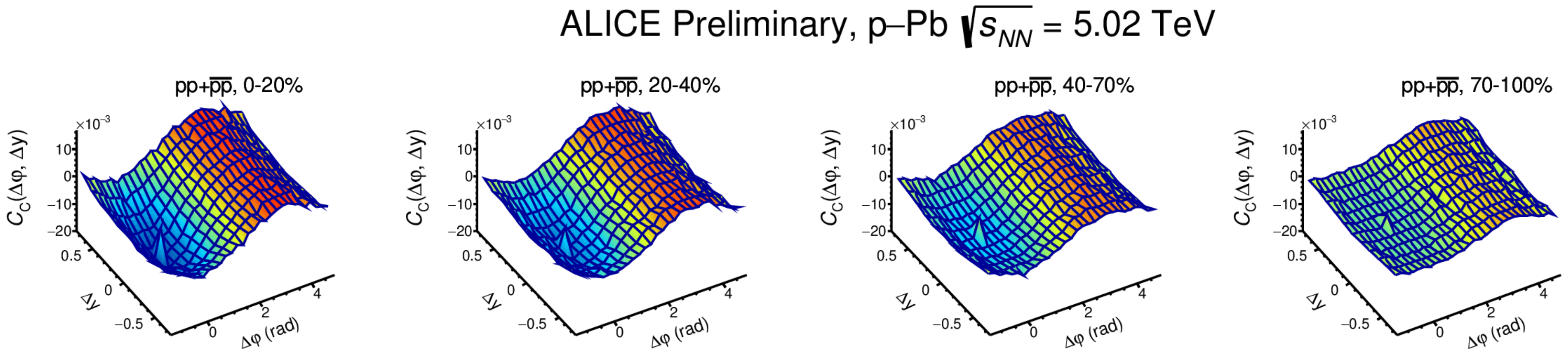


ALI-PREL-541701

5.02 TeV



p-Pb



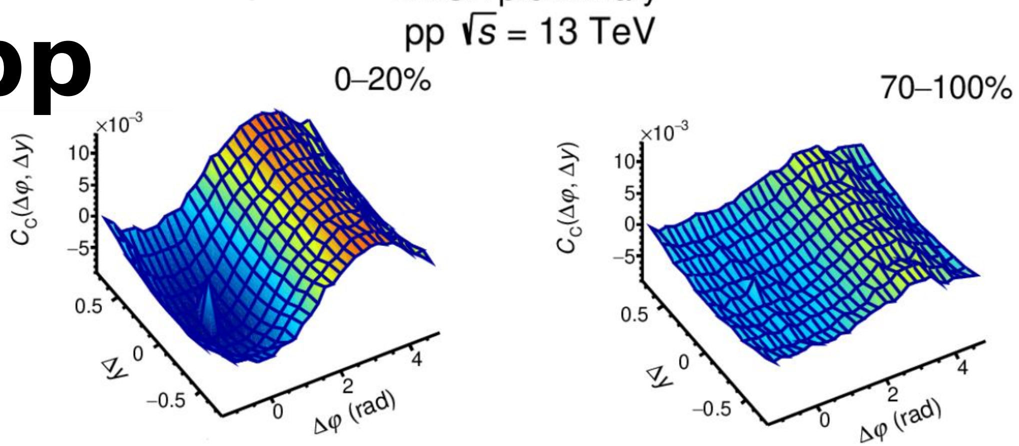
ALI-PREL-562812

The anticorrelation persists in pp at 13 TeV and p–Pb at 5.02 TeV:
→ It becomes stronger for higher multiplicity classes

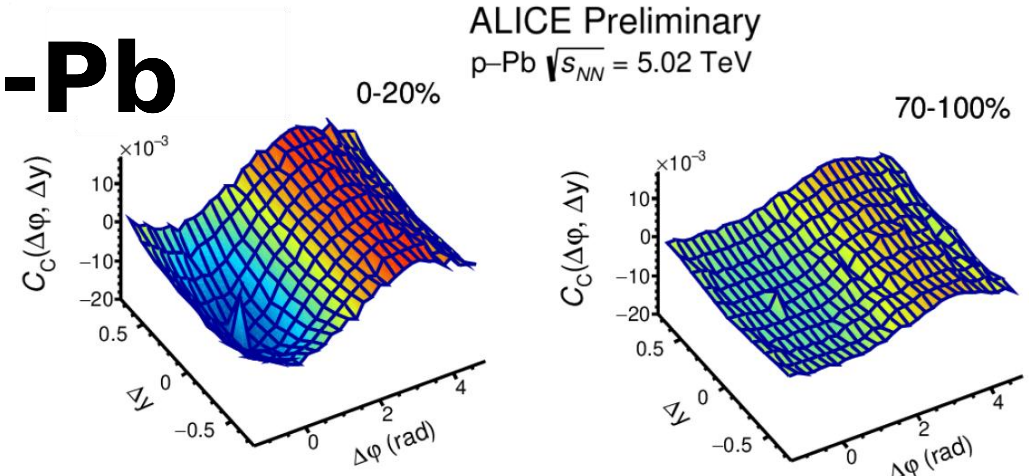
System & multiplicity dependence

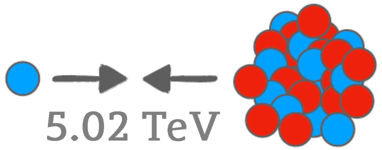
13 TeV

pp

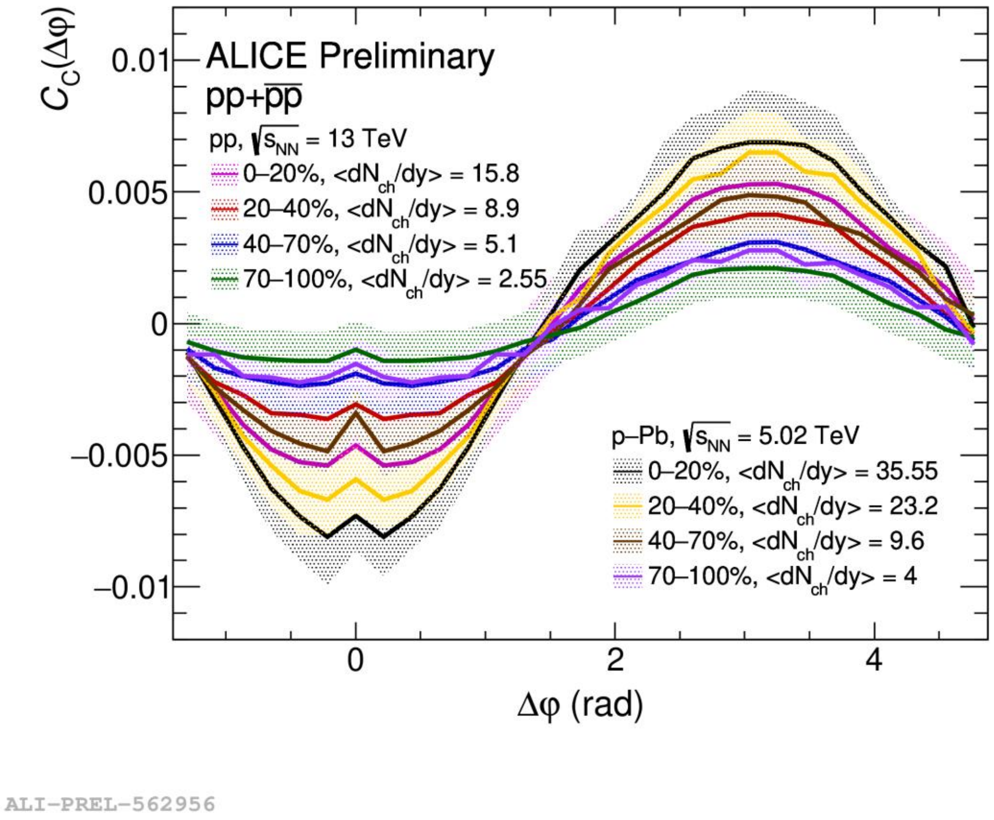


p-Pb



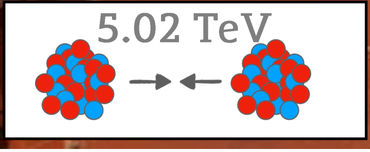


5.02 TeV



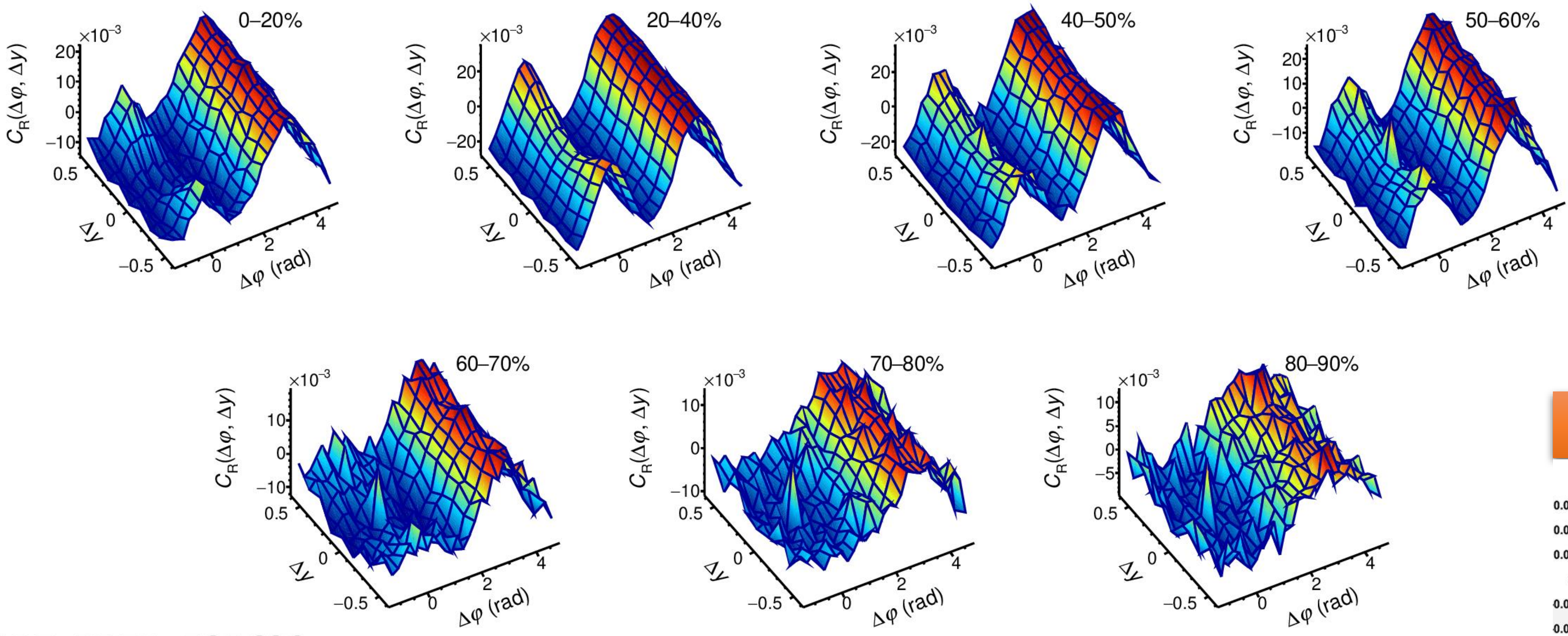
The anticorrelation persists in pp at 13 TeV and p–Pb at 5.02 TeV:
→ It becomes stronger for higher multiplicity classes

Heavy-ion collisions

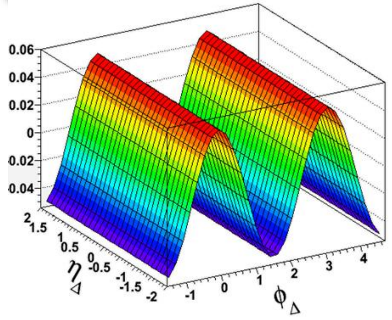


Pb-Pb

ALICE Preliminary, Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
pp+$\overline{\mathrm{p}}\overline{\mathrm{p}}$, $|y| \leq 0.5$, $0.5 < p_T < 2.5$ GeV/c



$$v_2 = \langle \cos 2\phi \rangle$$



- The azimuthal flow effect appears at the mid centrality classes;
- The anticorrelation visible even with the flow modulation, and shows a clear dip in the semicentral collisions, where the influence of the flow is the strongest.

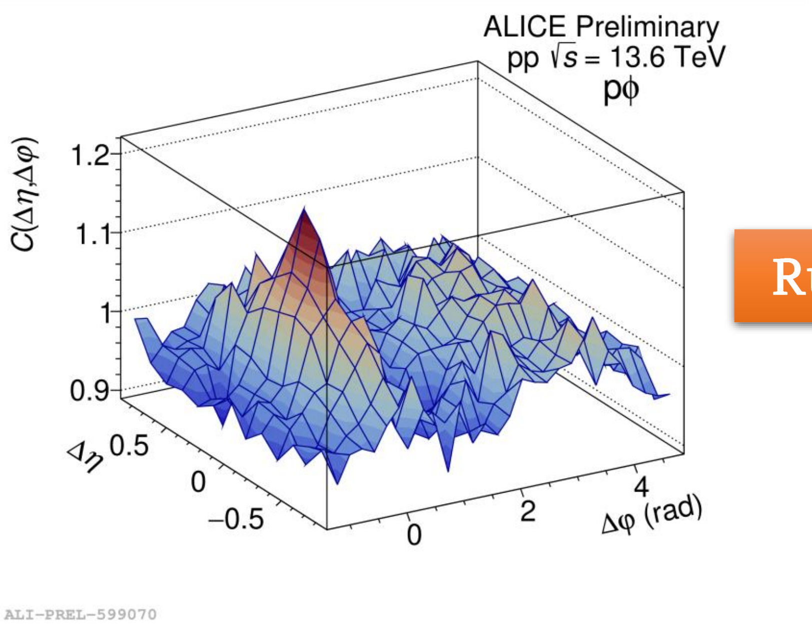
Mass matters? ϕ meson

13.6 TeV
p p

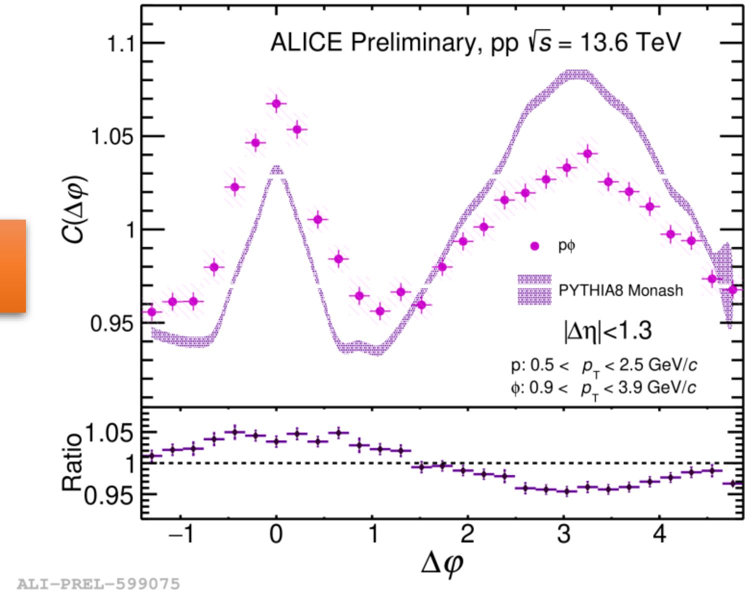
Baryons are heavier than studied mesons (pions, kaons).

Can the source of the anticorrelation be explained by the influence of **mass?**

→ study of the p-ϕ angular correlations $m_\phi \approx m_p$.



Run 3



Distinct near-side peak!
No anti-correlation.

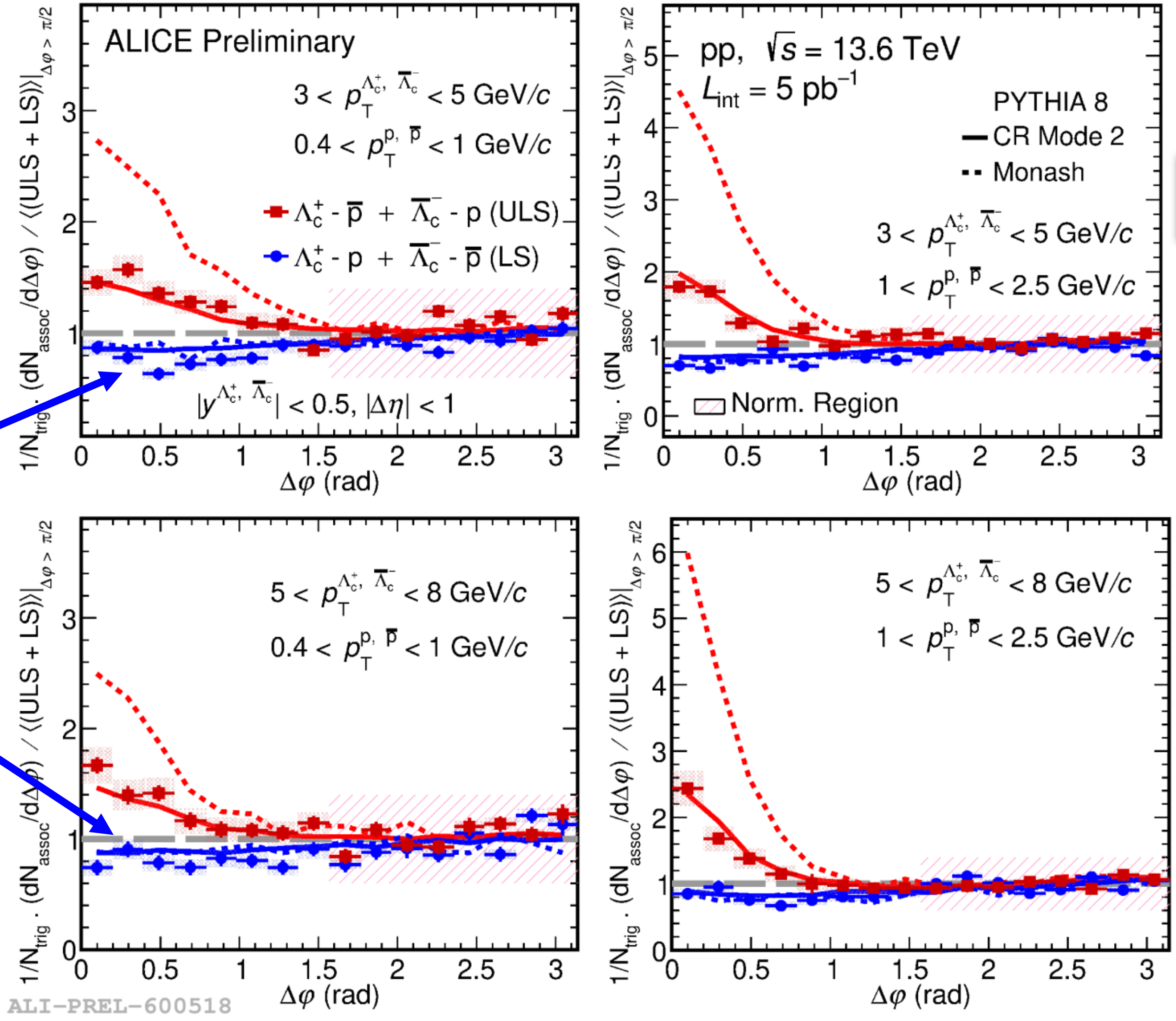
p (MeV/c²)	ϕ (MeV/c²)
938	1019

Charm baryon

Will picture change for the **charm baryons**?

→ ALICE studied p-Λ_c^+ correlations.

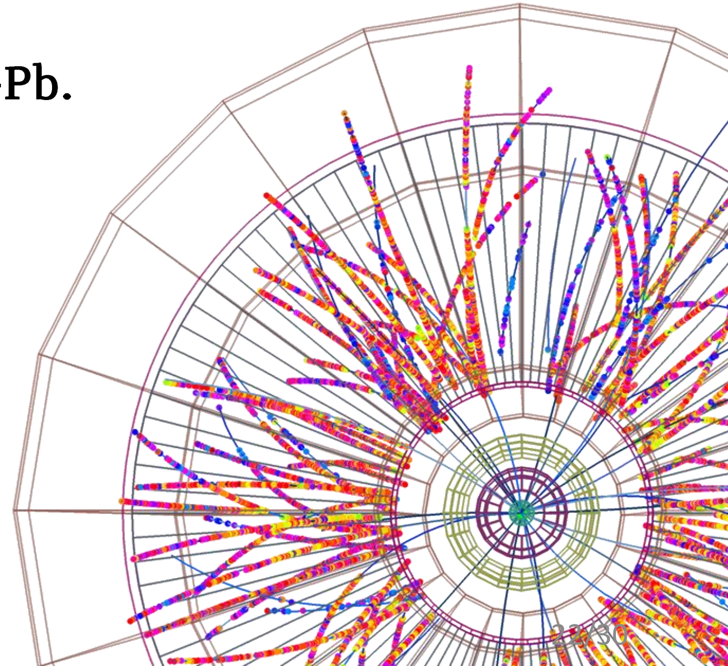
Anti-correlation visible for baryon—baryon in all studied transverse momentum ranges.



Run 3

Summary

- **Baryon correlations puzzle**: surprising anti-correlation not reproduced by models.
- Plethora of new experimental results:
  - All observed effects persist at the **highest energies of 13.6 TeV**.
  - **Correlations with Ξ baryons** show that the anti-correlation persists for heavier, multi-strange baryons (for p Ξ, Λ Ξ, Ξ Ξ).
  - Study of anticorrelation across **different multiplicity classes** reveals that the phenomenon intensifies at higher multiplicity.
  - Anticorrelation present in **different collision systems: p-Pb and Pb-Pb.**
  - Study of **p–ϕ pairs** supports statement that anti-correlation is connected to baryons, **and is not an effect of mass**.
  - **Λ_c^+-p** pairs reveal that **effects persists also for charm baryons**!
- **Outlook:** results require careful revision of the understanding of baryon production processes.

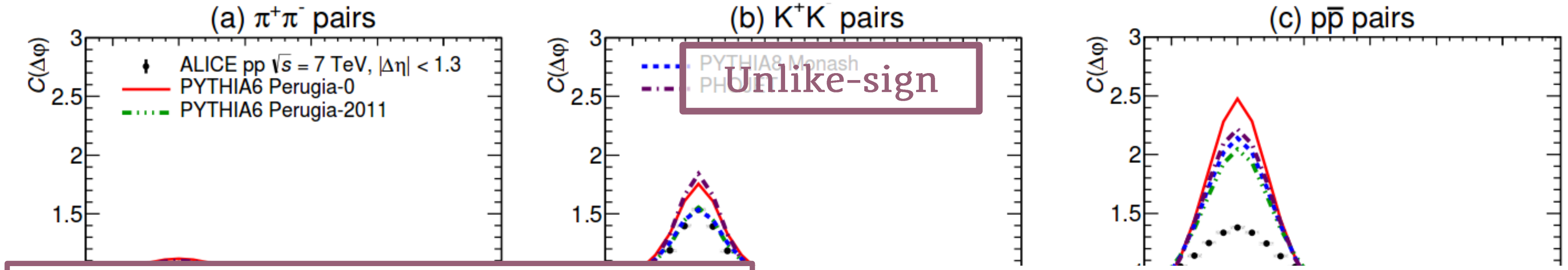


Thank you

Backup slides: theory

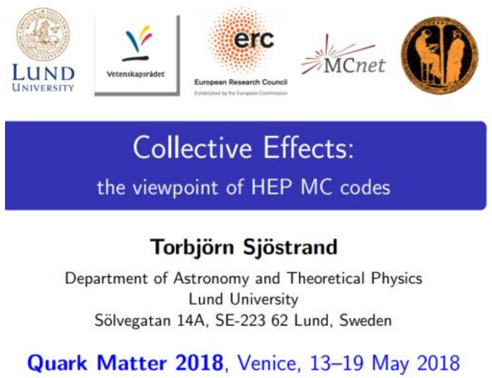
PHOJET, PYTHIA 6 and PYTHIA 8

ALICE, Eur. Phys. J. C 77 (2017) 569



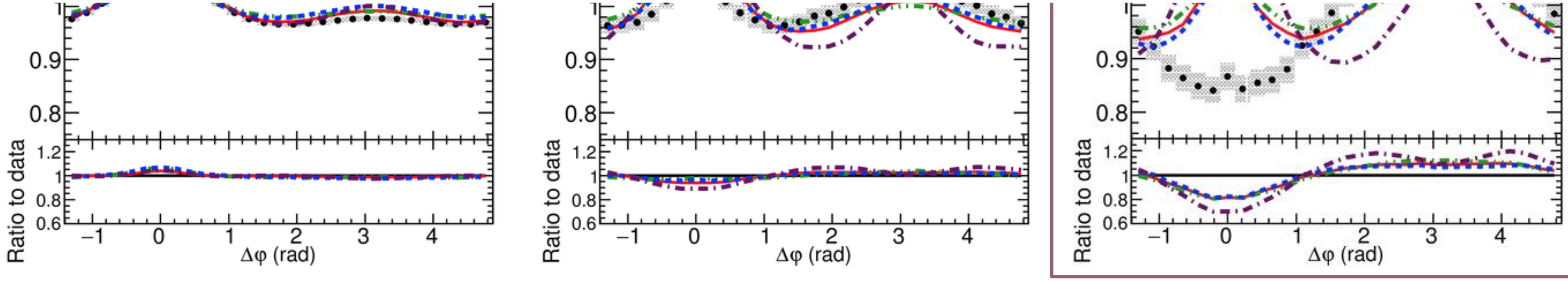
Unlike-sign

T. Sjostrand, QM 2018, plenary talk
https://indico.cern.ch/event/656452/contributions/2899749/



Nucl. Phys. A 982 (2019) 43-49

"The real problem is baryon production. [...] so it is clear we still lack some fundamental insight on baryon production, at least in the string context."



CALM

Nucl. Phys. A 956 (2016) 886-889

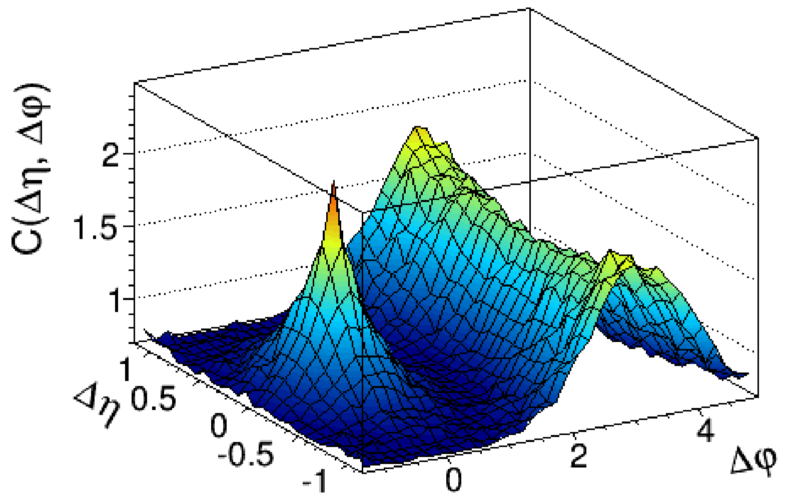
“Toy” Monte Carlo:
Inclusion of conservation of energy, momentum and all quantum numbers local to the emission

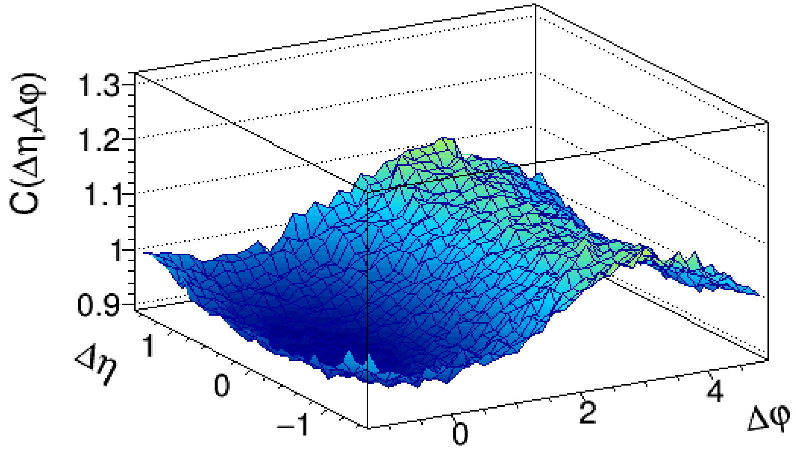
Our toy MC reproduces the standard “jet” correlation shape with near-side peak and away-side ridge

BUT

Two-particle baryon-baryon correlation in data shows only global energy-momentum conservation features

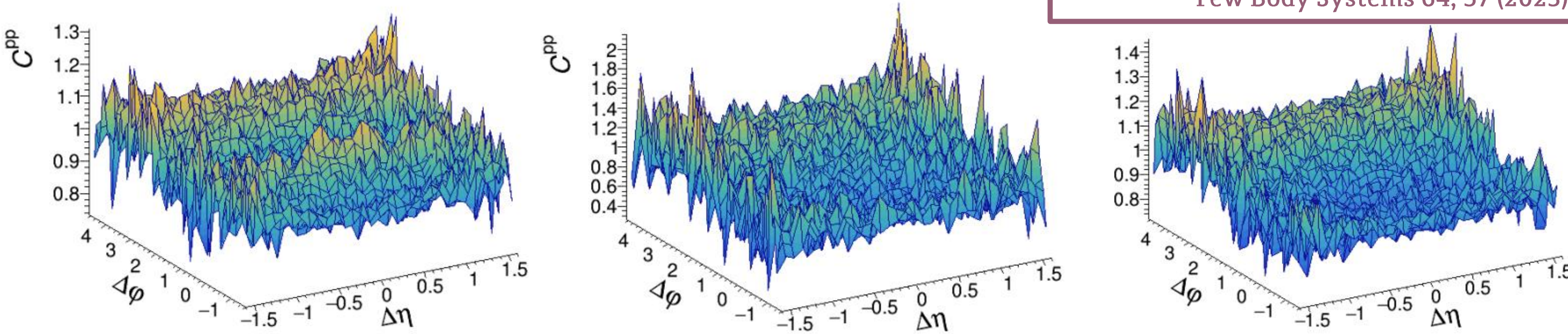
Yet, baryons **are** produced in jets (see e.g. proton-antiproton correlations), just no more than one



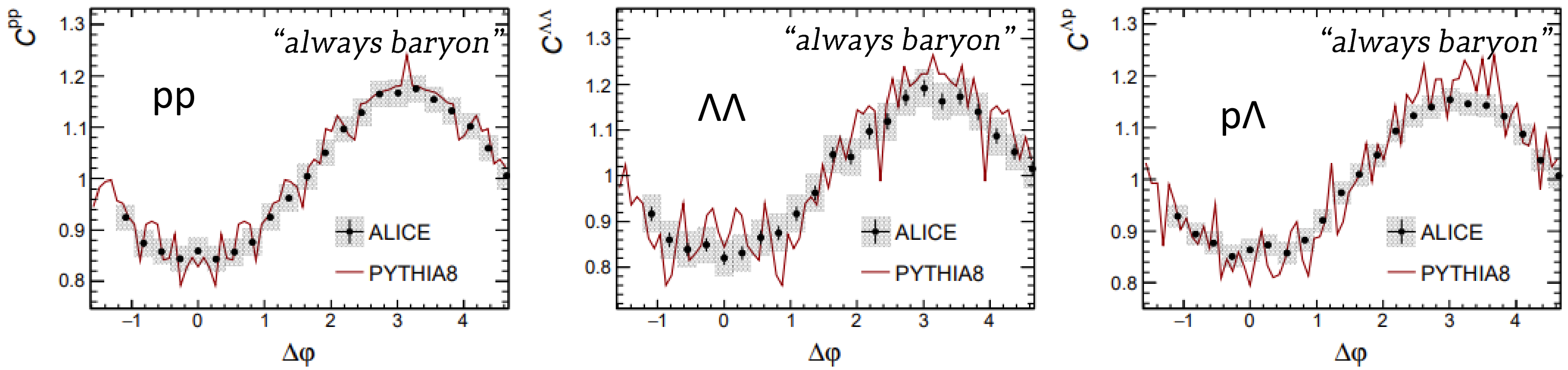


Modified PYTHIA

N. Demazure, V. Gonzalez, F. Llanes-Estrada
Few Body Systems 64, 57 (2023)



(a) pp C correlation with unmodified PYTHIA (b) pp C correlation, one-baryon per string policy (c) pp C correlation, always-baryon policy



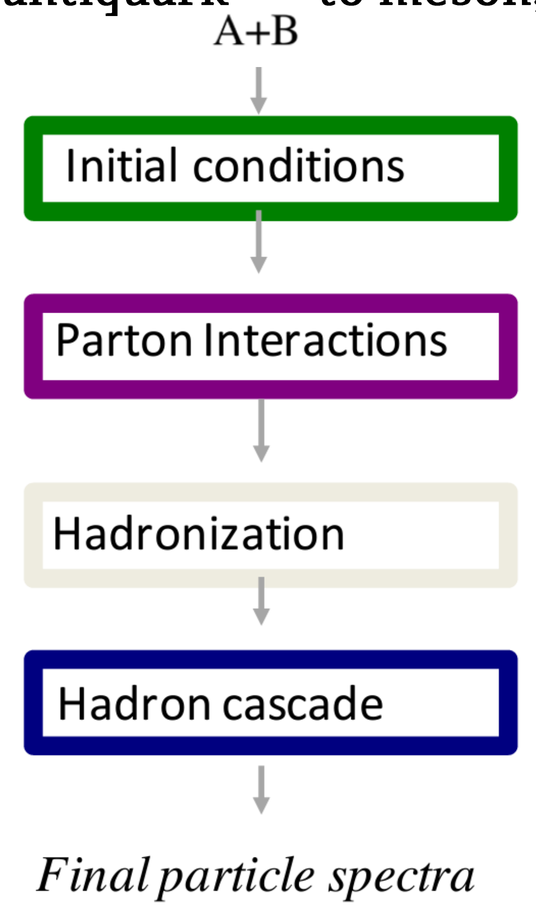
- Two modifications to PYTHIA string fragmentation allow the model to describe the data:

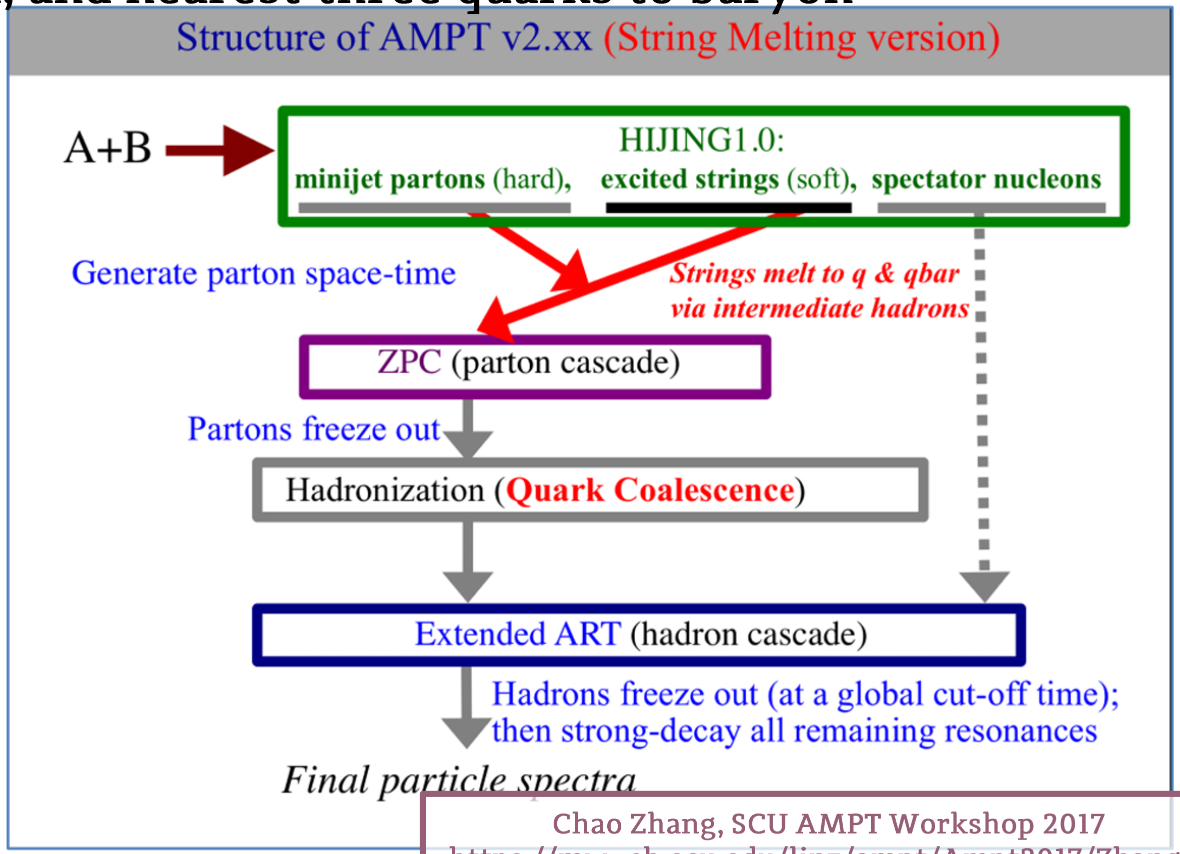
  → *one baryon* – each string must *produce at most one baryon* (a way to impose Pauli principle to baryons, but lowers the baryon-to-meson ratio)

  → *always baryon* – each string must *always produce one baryon* (no

AMPT model

- Contains *4 main components* to describe the whole phase space of heavy-ion collisions
- *String melting*: convert hadrons from string fragmentation into quarks and antiquarks
- *Coalescence*: when partons stop interacting, combine nearest quark and antiquark to meson, and nearest three quarks to baryon





Chao Zhang, SCU AMPT Workshop 2017
https://myweb.ecu.edu/linz/ampt/Ampt2017/ZhangC.pdf

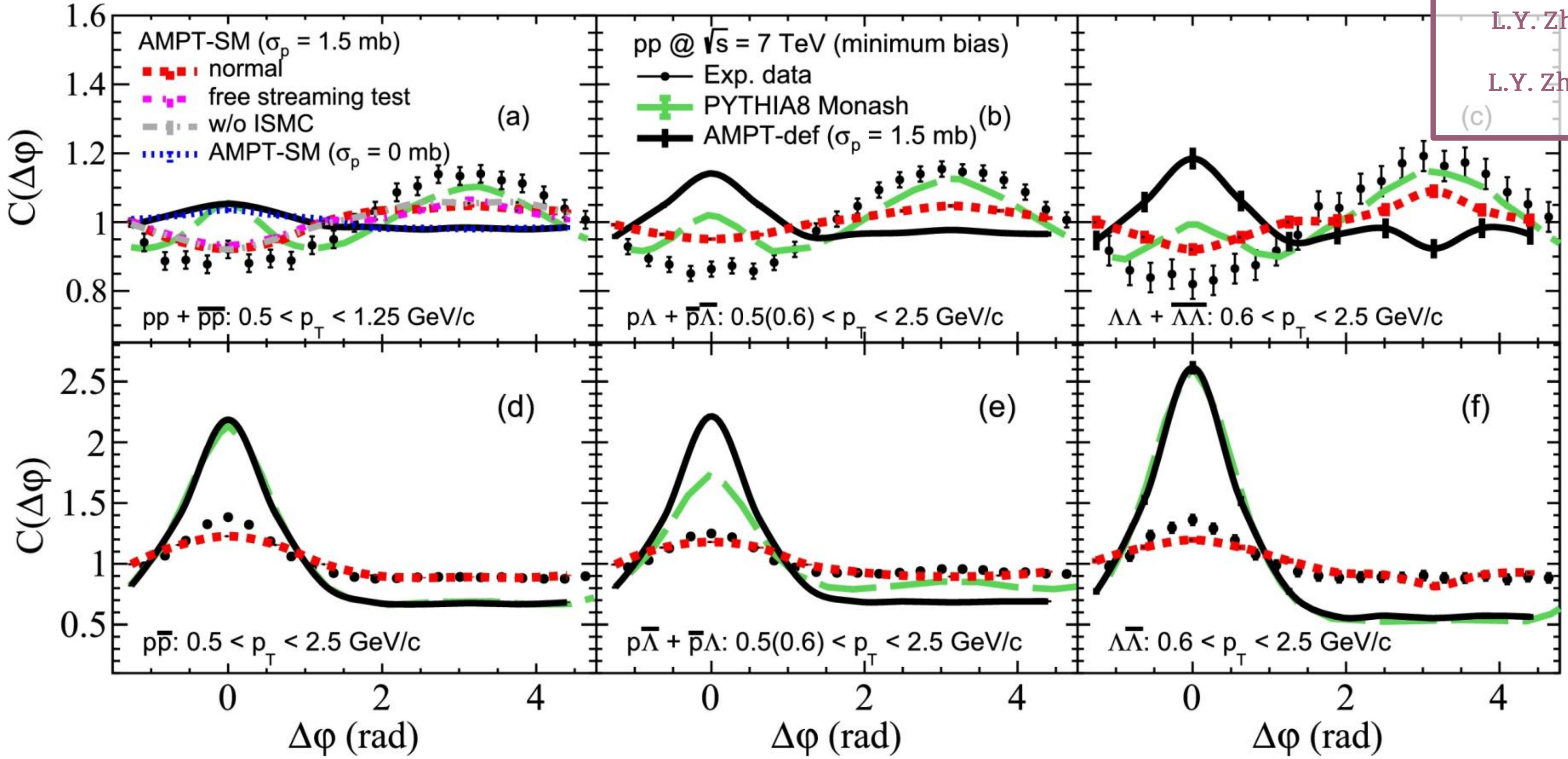
Modified AMPT

- *Improved* coalescence (removed separate conservation for mesons and baryons)
- String melting (SM) → parton degrees of freedom are expected in the initial state

→ AMPT-SM with non-zero parton cross section desrcibes the data

→ test of SM with parton cross section set to 0 mb does not describe the data

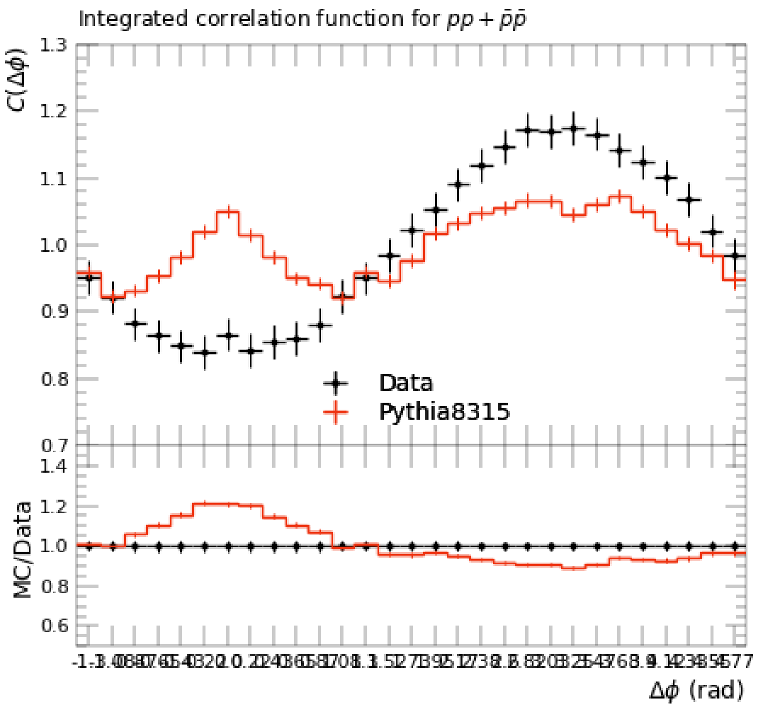
- If initial state momentum correlation (ISMC) are removed → the result is similar to standard AMPT-SM version → describes anticorrelation

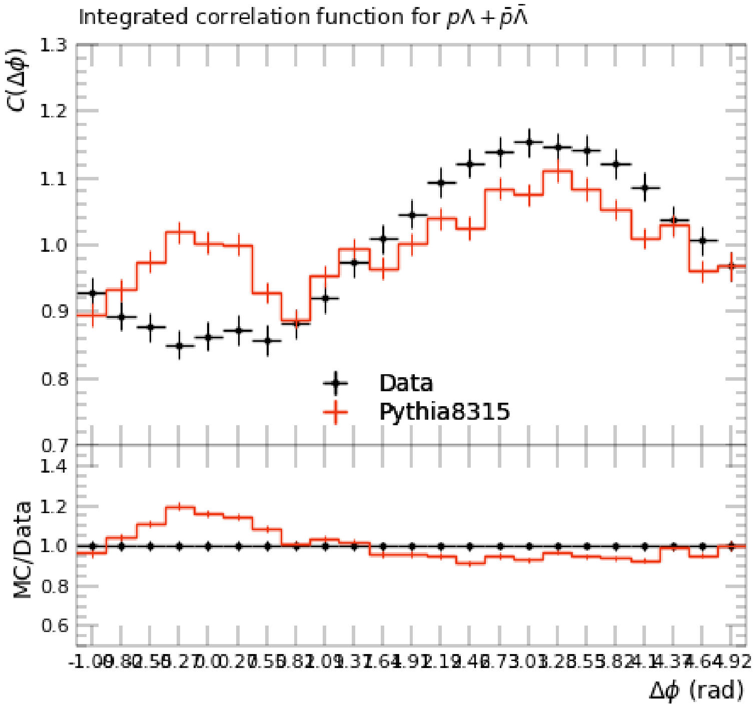


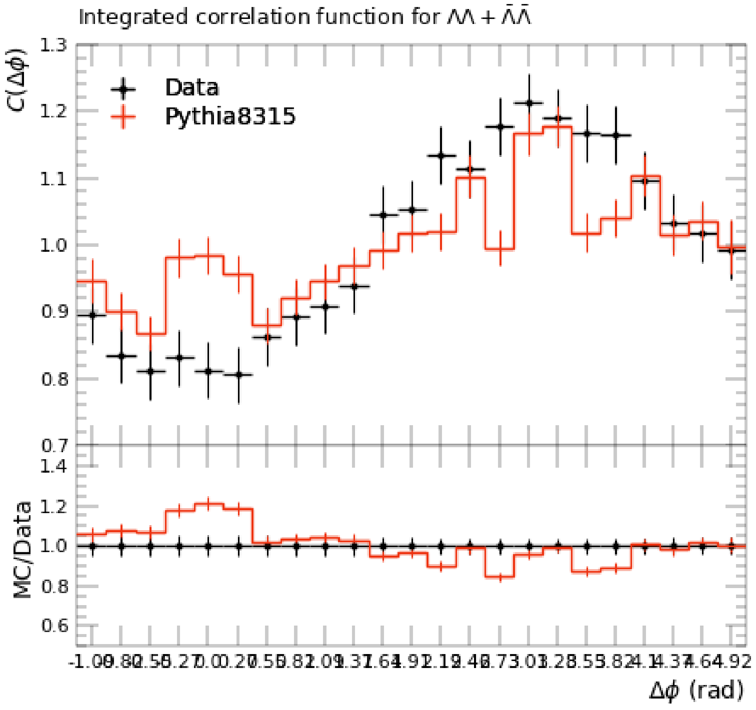
L.Y. Zhang et al., Phys. Rev. C 98 (2018) 3, 034912
L.Y. Zhang et al., Phys. Lett. B 829 (2022) 137063

Pythia 8.315 (after bugfix)

Still similar behaviour

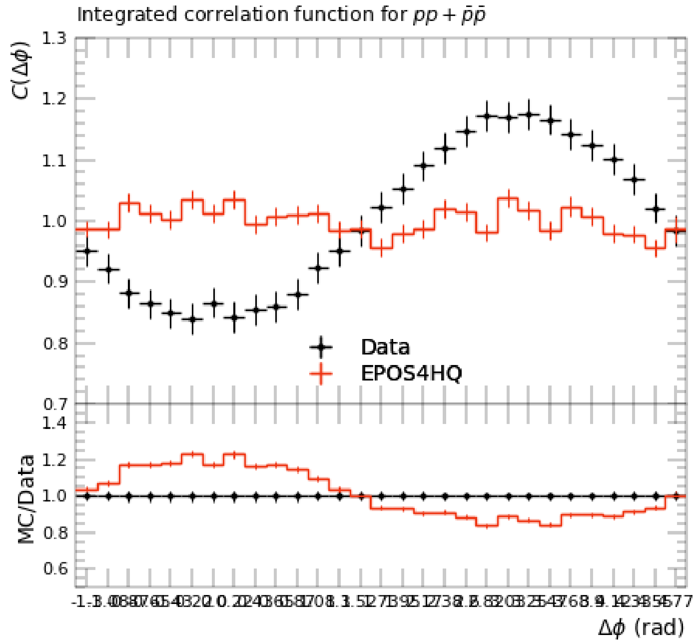


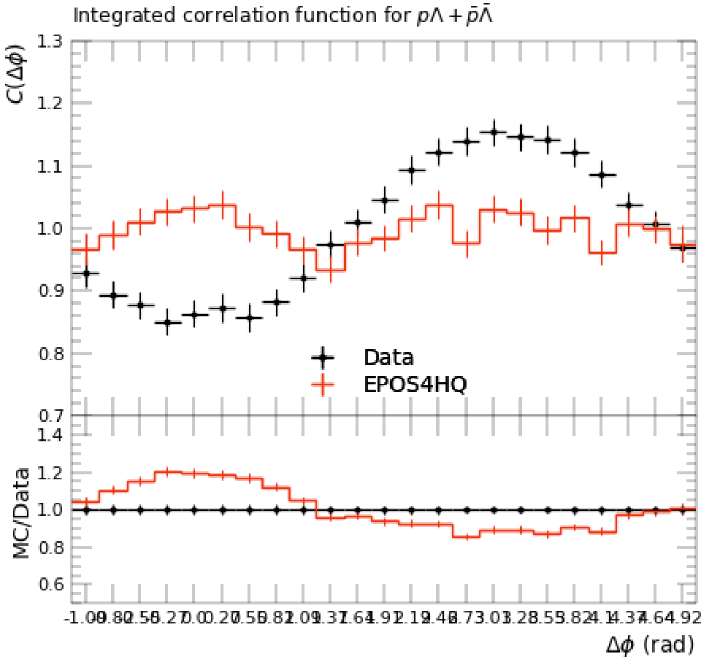


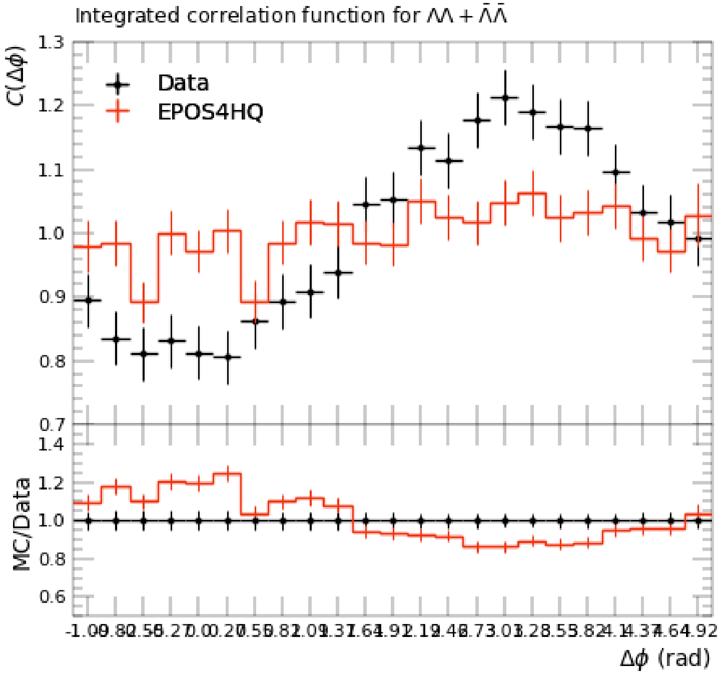


EPOS4 (HQ)

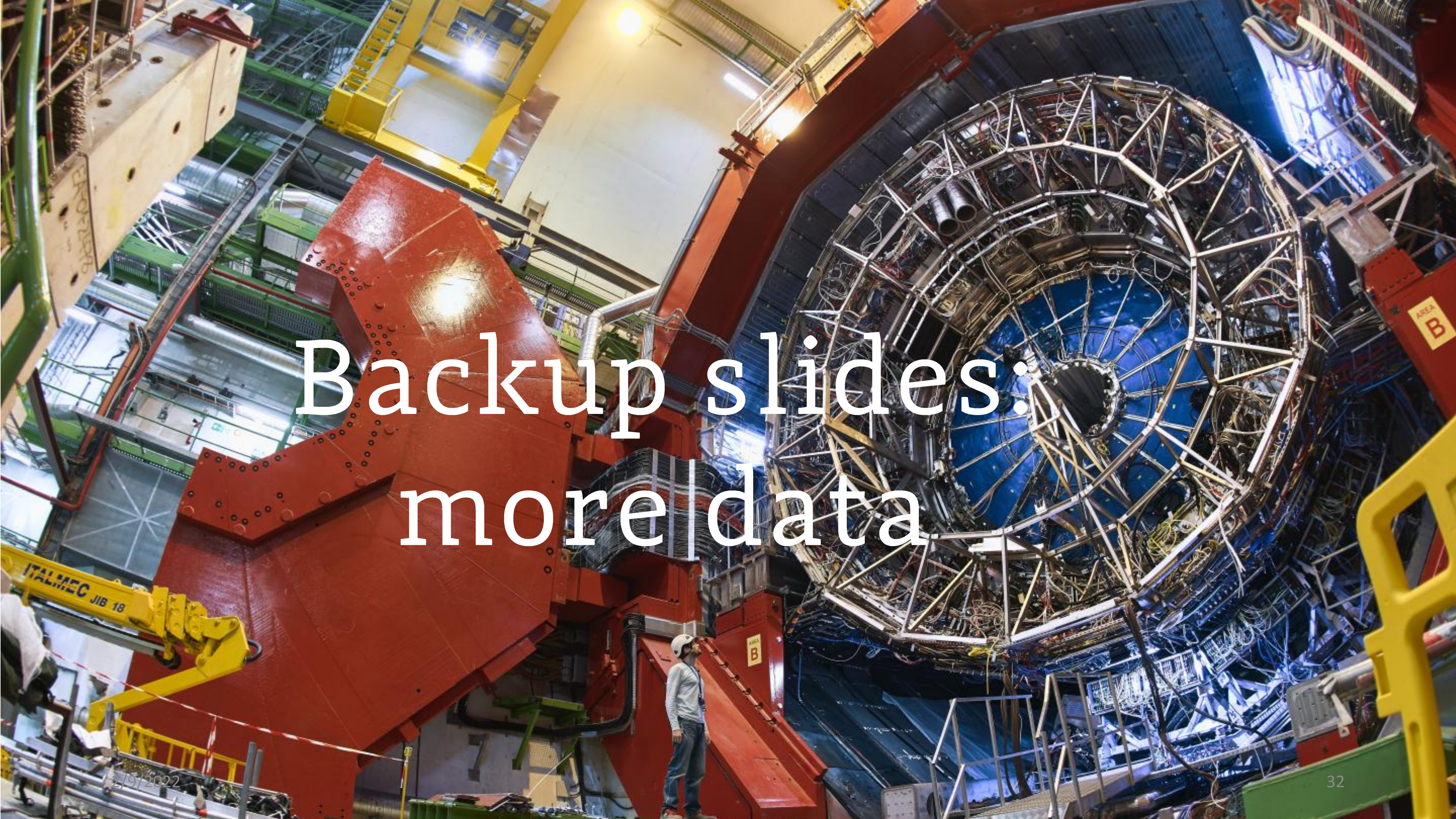
Still similar behaviour







Backup slides: more data



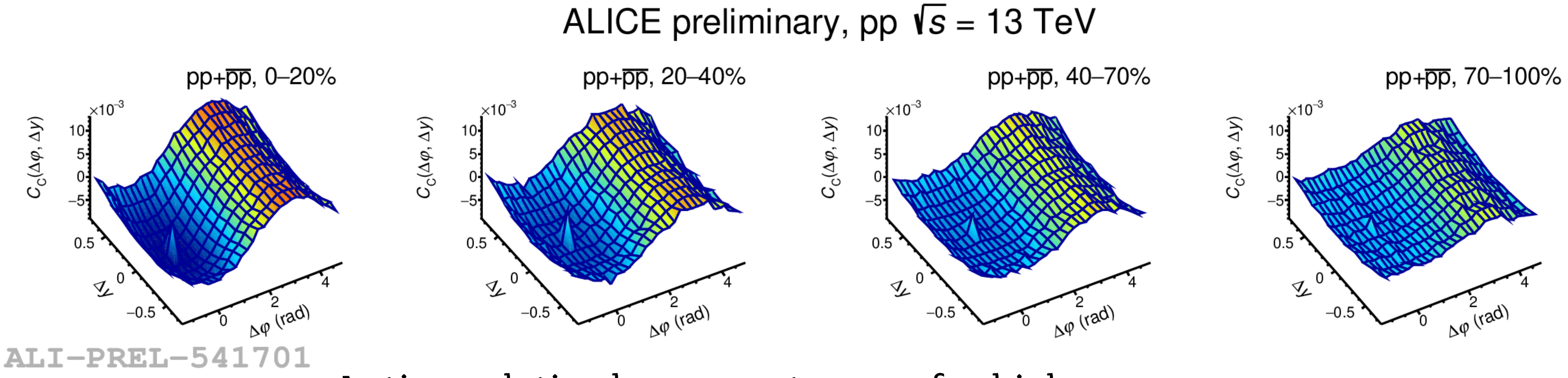
Multiplicity dependence

How to overcome the trivial multiplicity scaling?

- Use a **rescaled two-particle correlation function** (C_R)

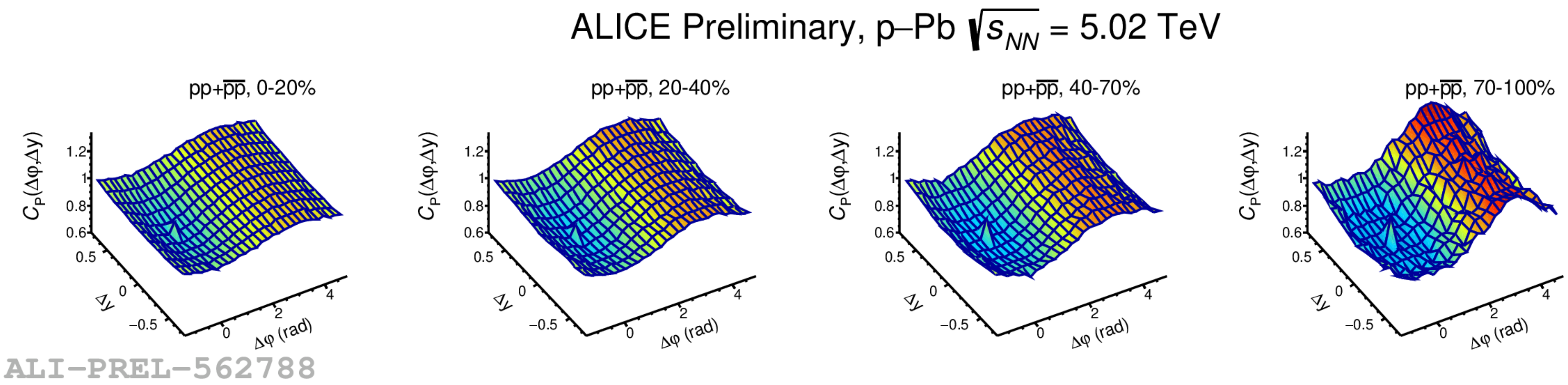
$$C_R(\Delta y, \Delta\varphi) = \frac{1}{2\pi}\left\langle \frac{dN_{av}}{d\varphi} \right\rangle (C_P - 1)$$

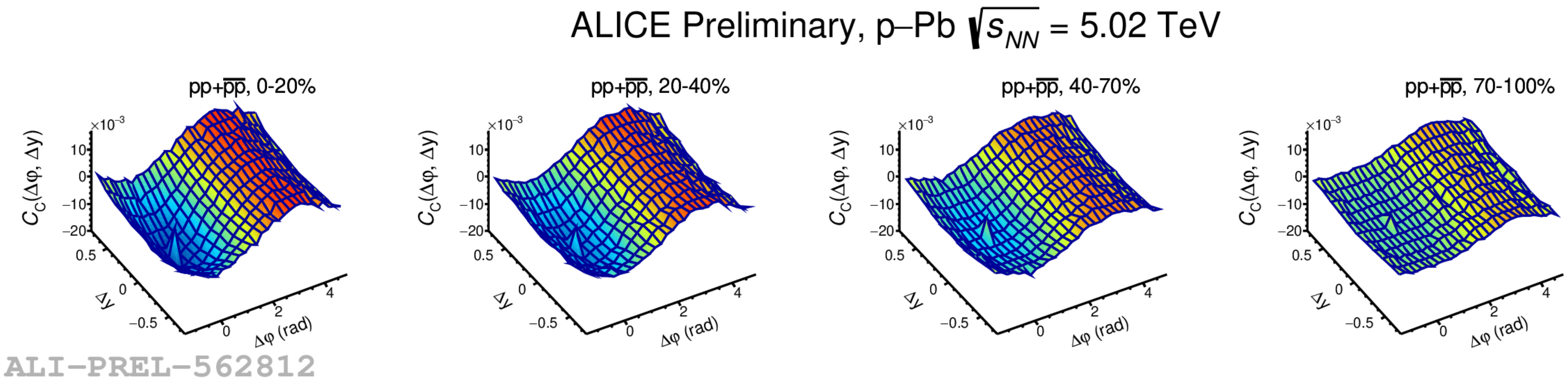
- $N_{av} = \frac{1}{2\pi}\left\langle \frac{dN_a}{d\varphi} \right\rangle$ is the average number of particle type produced in the analyzed multiplicity/centrality classes;
- a is the particle type analyzed (PID);



Anticorrelation becomes stronger for higher multiplicity classes

Multiplicity dependence

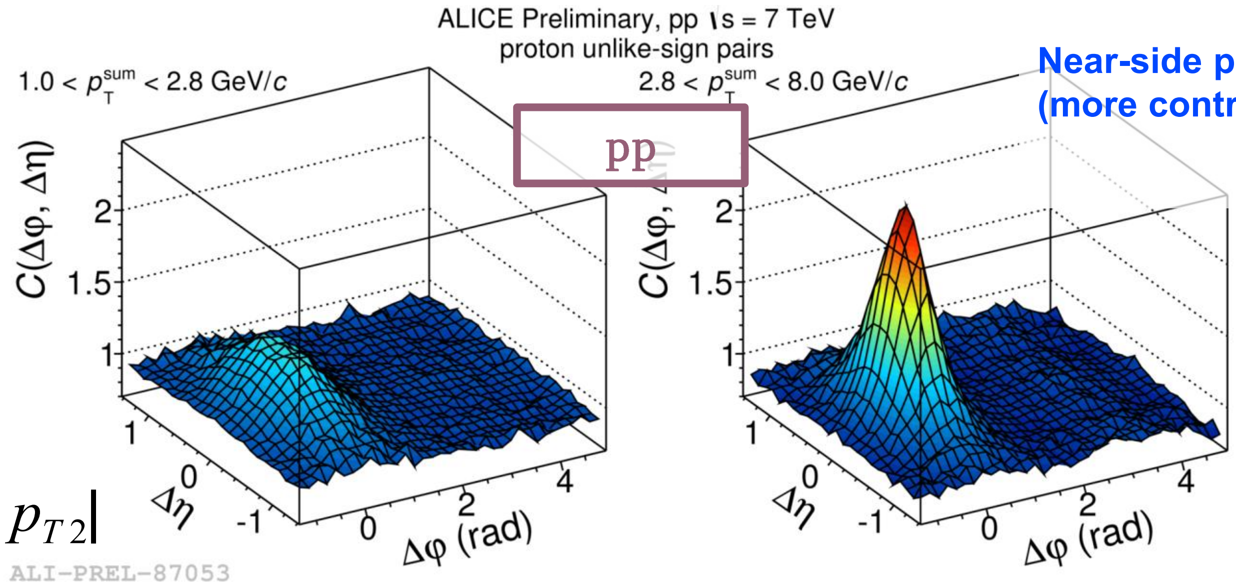




No anti-correlation.

ΔηΔφ correlation of baryons

Eur.Phys.J. C77 (2017) 8, 569

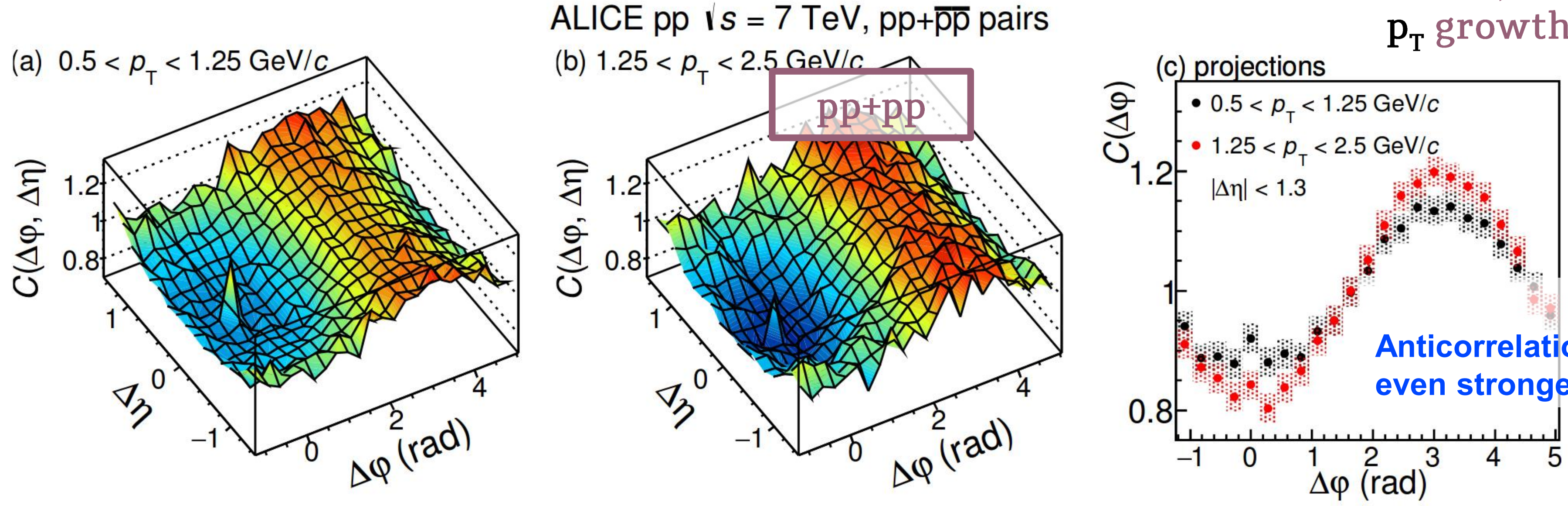


pp

Near-side peak grows with p_T
(more contribution from jets)

$$p_T^{sum} = |p_{T1}| + |p_{T2}|$$

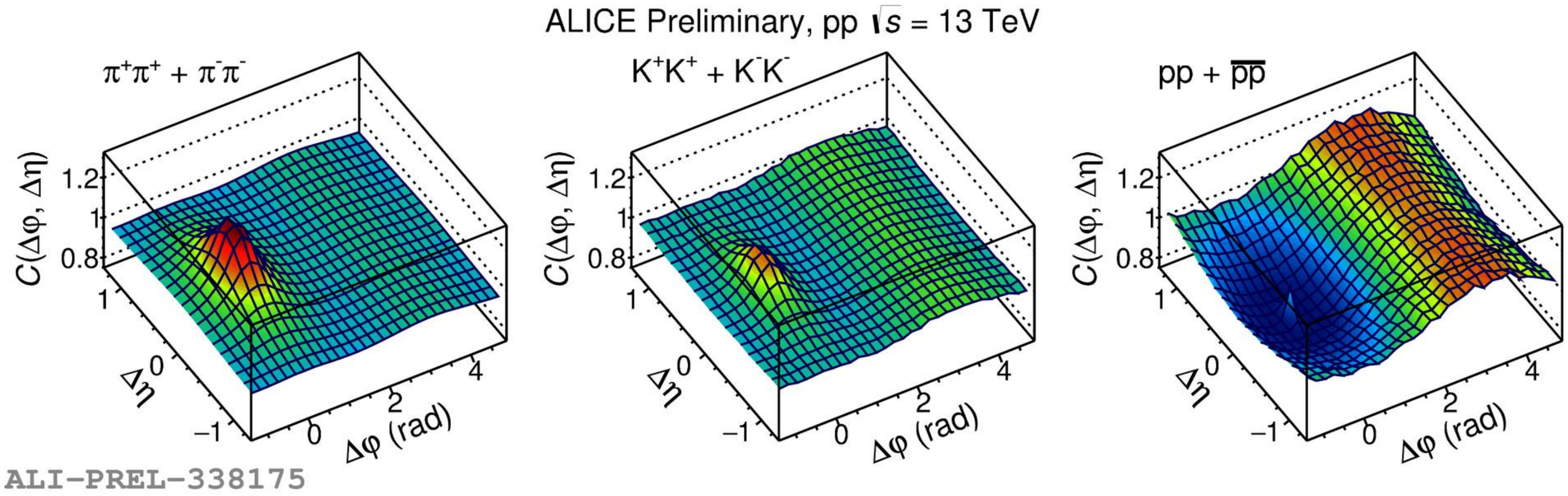
p_T growth

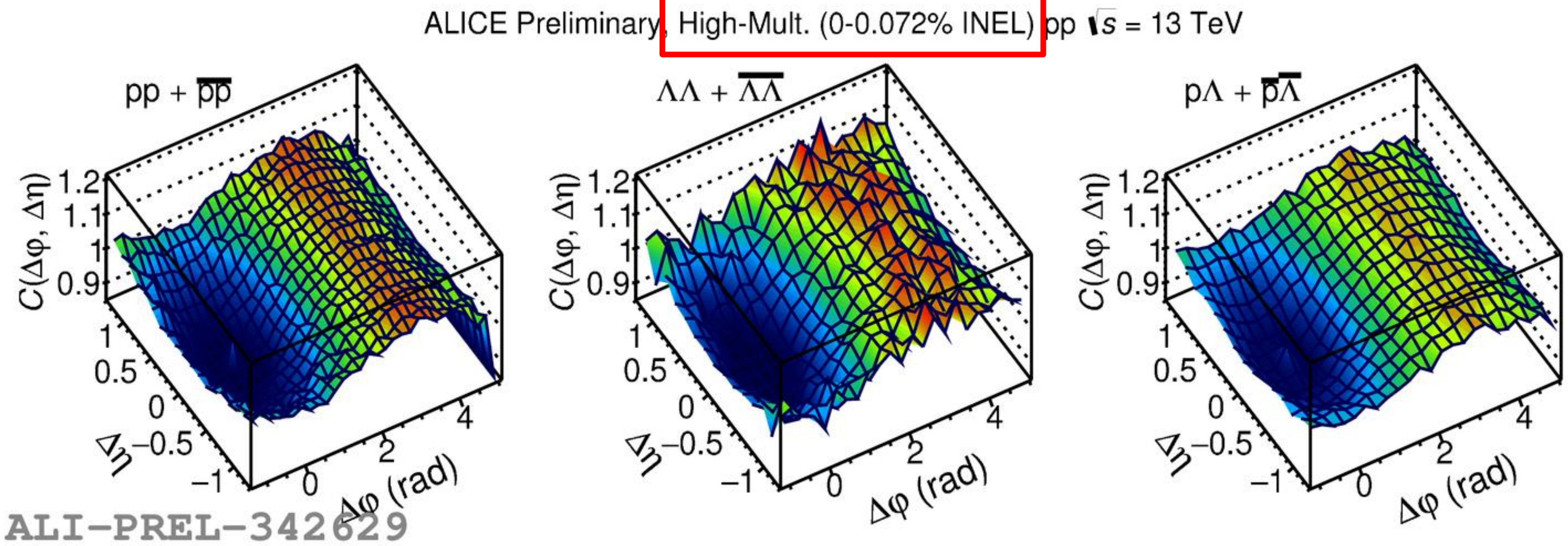


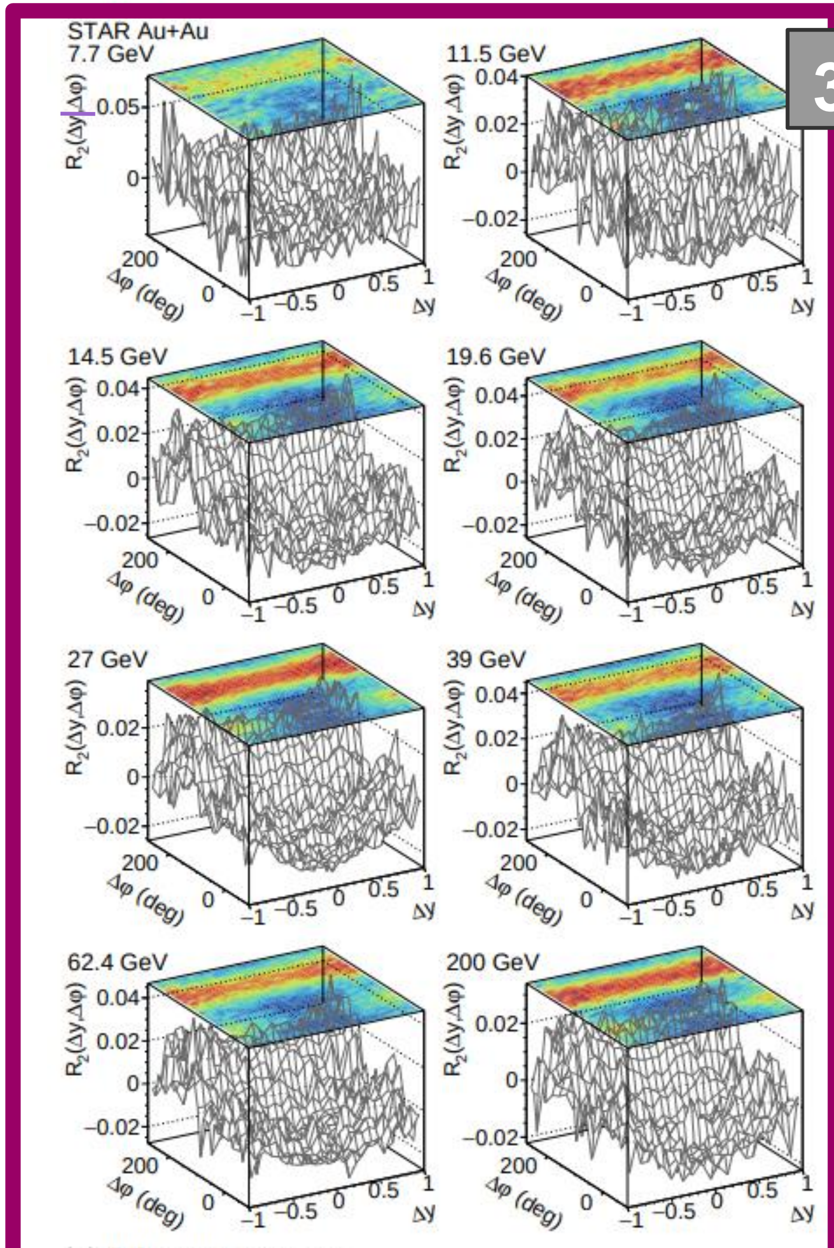
pp+pp

Anticorrelation
even stronger

Higher energy / multiplicity?







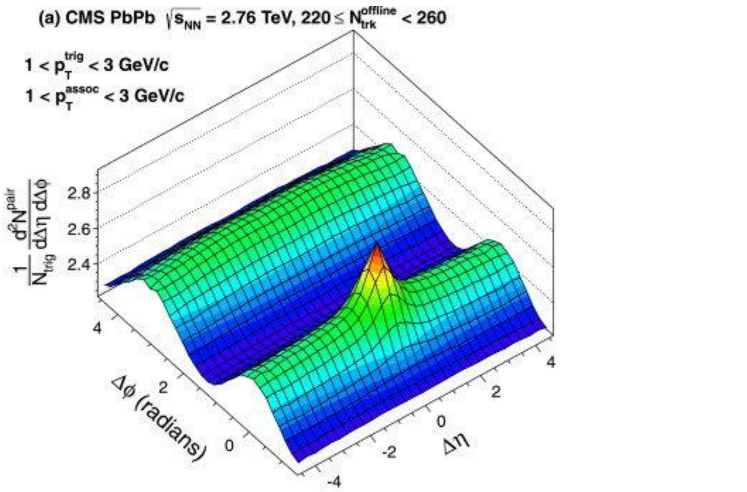
(a) Like-sign protons

30-40%

Au+Au collision energy

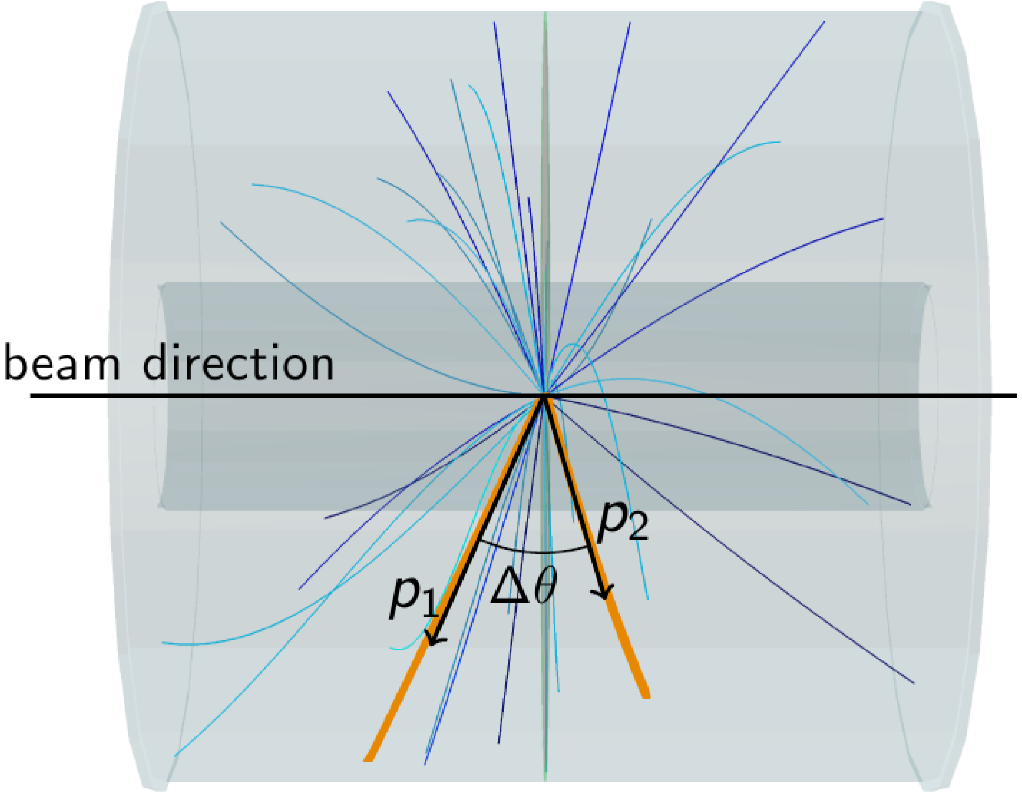
STAR, Phys. Rev. C 101, 014916 (2020)

- The anticorrelation effect is present for Au-Au results
- It is convoluted with the flow double-ridge structure



CMS, Phys. Lett. B 724 (2013) 213

Correlation function construction



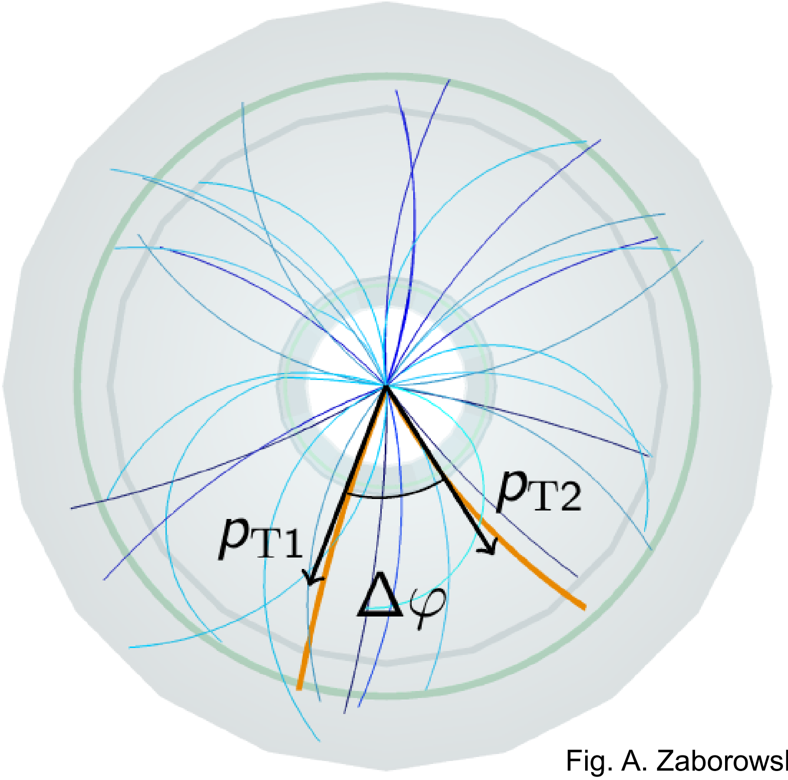


Fig. A. Zaborowska

p - particle momentum;
θ - polar angle;
η - pseudorapidity: $$\eta = -\ln\left(tg\frac{\theta}{2}\right)$$

p_T - transverse momentum;
φ - azimuthal angle;

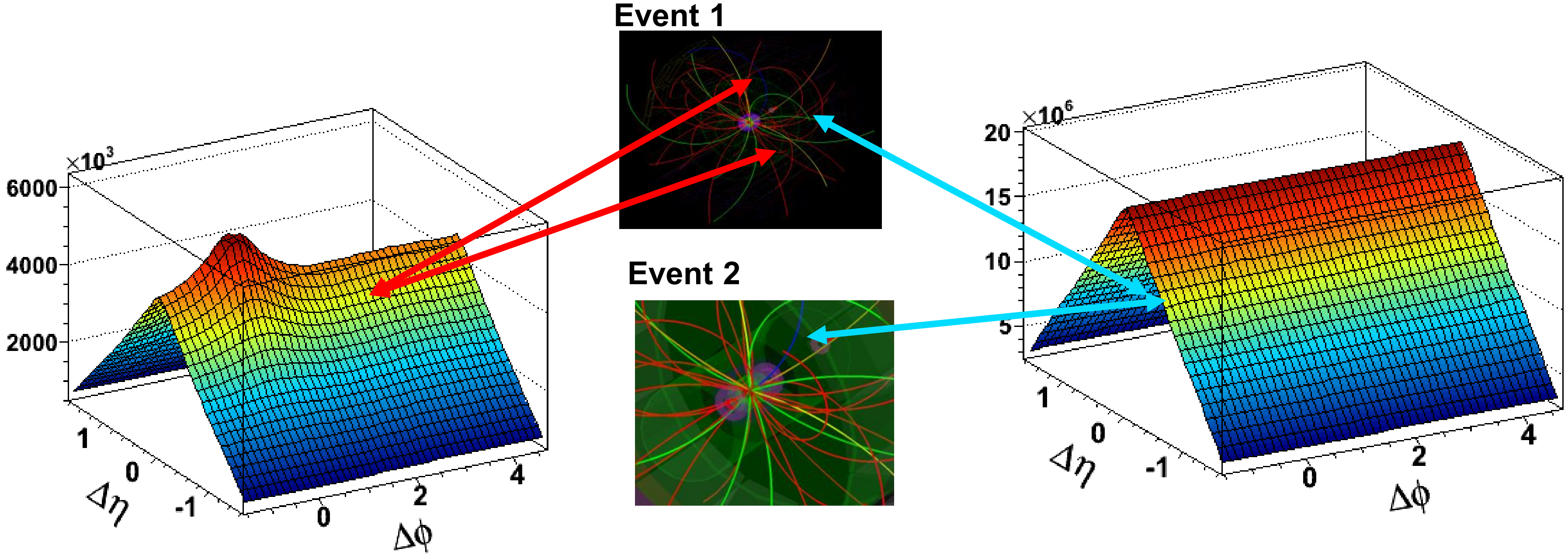
Correlation function construction

Signal distribution

$$S(\Delta\eta, \Delta\varphi) = \frac{d^2 N^{signal}}{d\Delta\eta\Delta\varphi}$$

Uncorrelated reference

$$B(\Delta\eta, \Delta\varphi) = \frac{d^2 N^{mixed}}{d\Delta\eta\Delta\varphi}$$

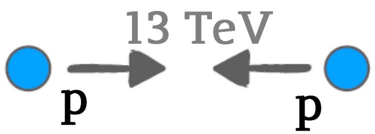


Same event pairs

Mixed event pairs

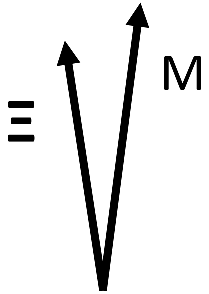
$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

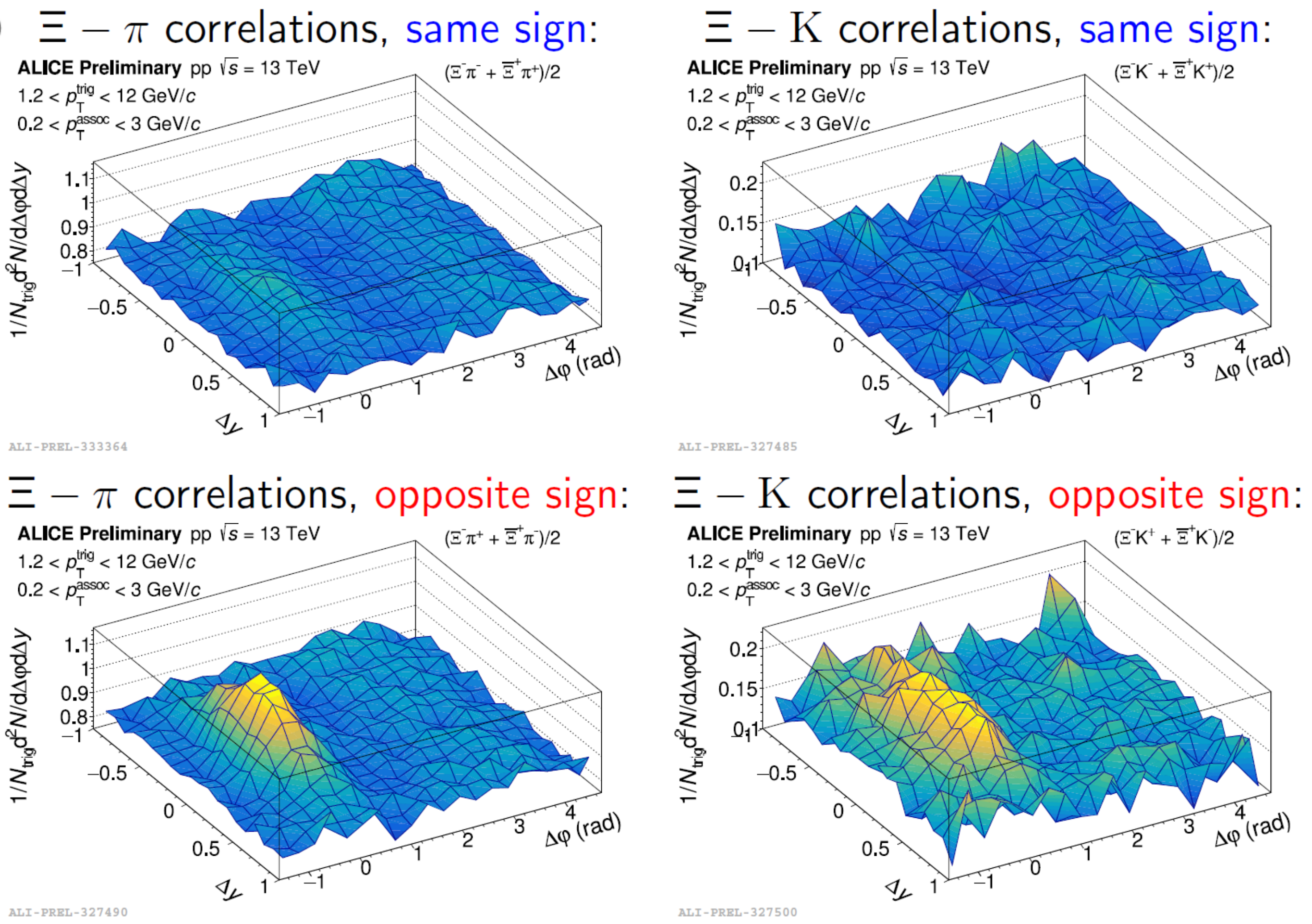
Ξ correlations for mesons



No anti-correlation for baryon-meson pairs.

Near-side peak present.





ALICE Collaboration, *JHEP* 09 (2024) 102