Exploring the baryon correlation puzzle in pp, p–Pb, and Pb–Pb collisions at the LHC energies

Daniela Ruggiano
on behalf of the ALICE Collaboration
Warsaw University of Technology

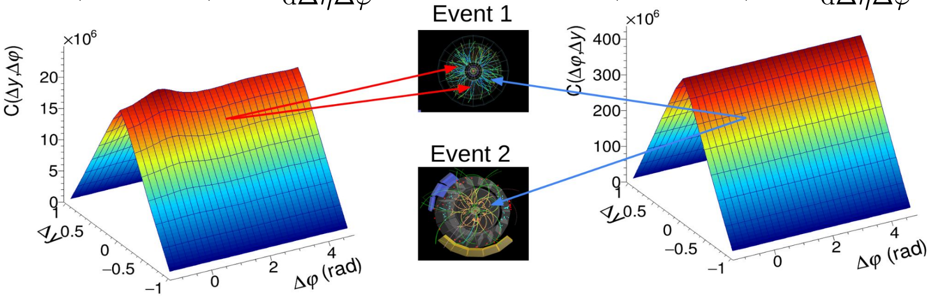
$\Delta\eta\Delta\varphi$ experimental correlation function

Signal distribution

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

Background distribution

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



Same-event pairs **Mixed-event pairs**

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

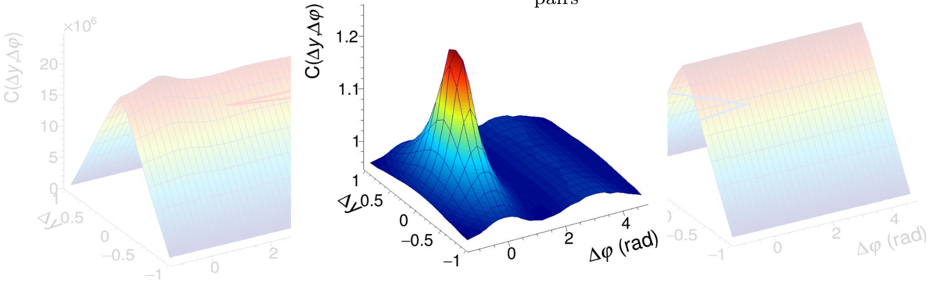
$$\Delta\varphi = \varphi_1 - \varphi_2$$

Credits to Małgorzata Janik

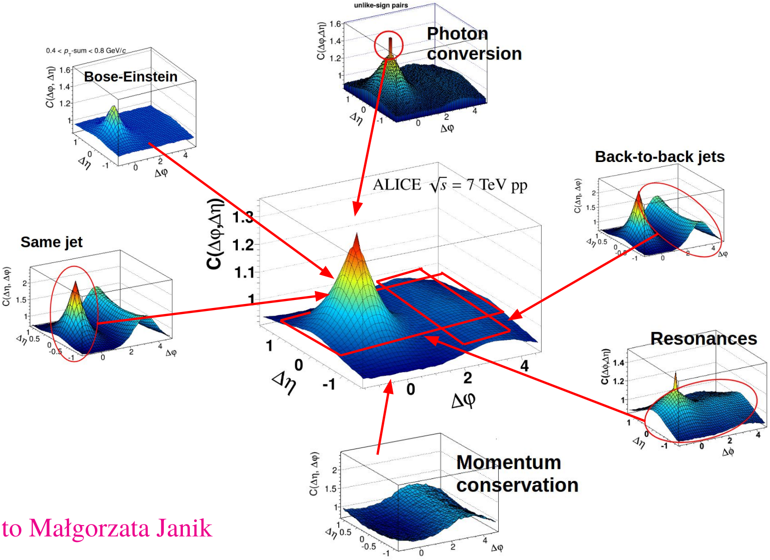
$\Delta\eta\Delta\varphi$ experimental correlation function

Probability ratio correlation Function

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

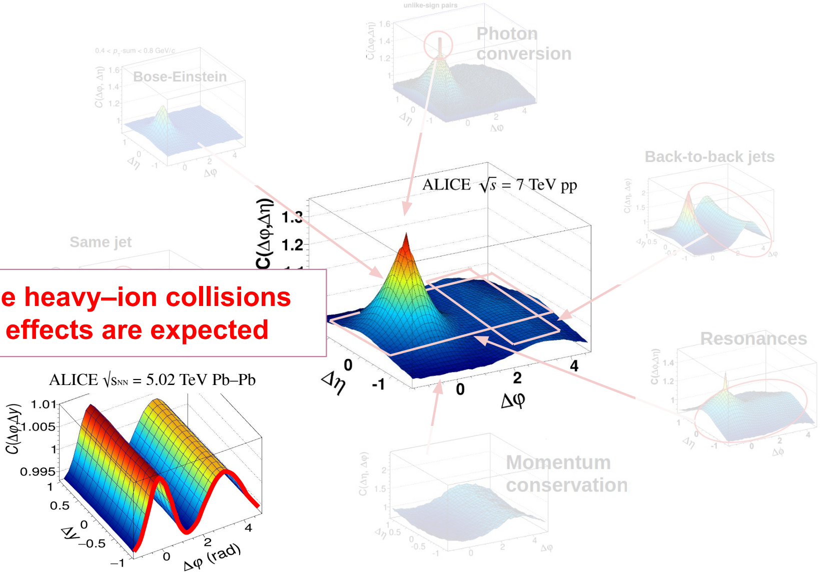


Anatomy of Angular Correlations



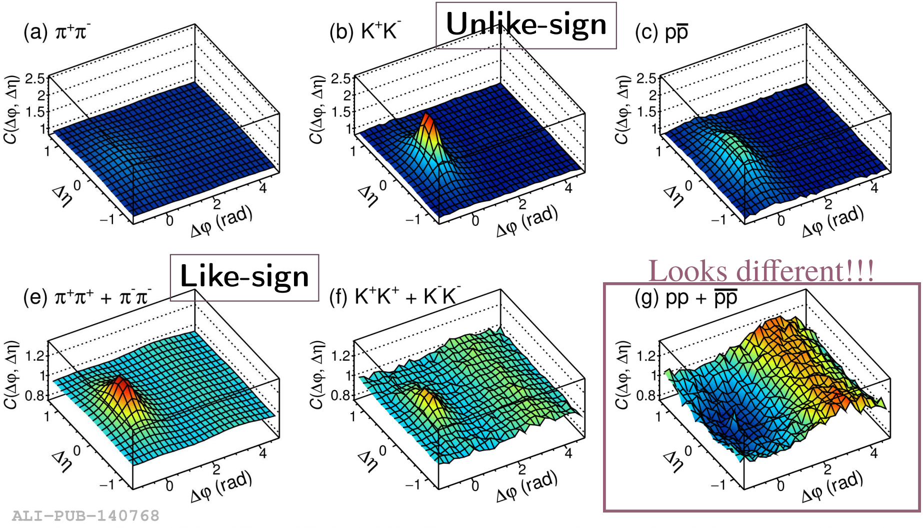
Credits to Małgorzata Janik

Anatomy of Angular Correlations



In the heavy–ion collisions flow effects are expected

$\Delta\eta\Delta\varphi$ of identified particles



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

What does it mean?

Anticorrelation in (0,0) from theory side:

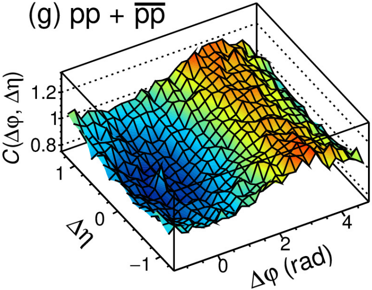
Two primary hadrons with the same baryon number are separated by at least two steps in “rank” – **it’s not likely to find two baryons or two antibaryons very close to each other.**

R.D. Field and R.P. Feynman, Nucl.Phys.B136(1978)131

Possible explanations:

- Different p_{T} ranges;
- Coulomb repulsion;
- Fermi-Dirac quantum statistics;
- Strong Final-State interaction;
- Other baryons;

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



Do we understand the anticorrelation?

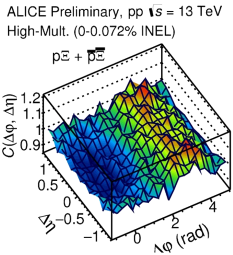
- **Is this a common effect for all baryons?**
- Correlation functions were measured also for ΛΛ and pΛ pairs;

◦ Λ baryons are neutral:

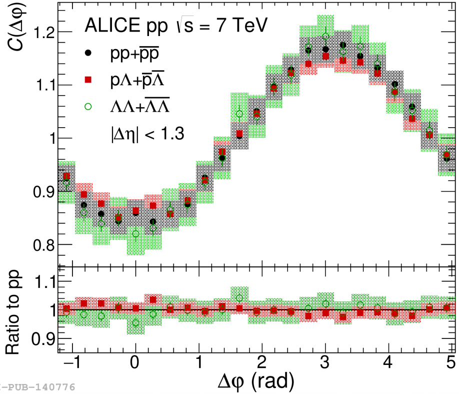
→ **NO Coulomb repulsion**

◦ **p** and Λ are not identical:

→ **no effect from Fermi-Dirac QS**

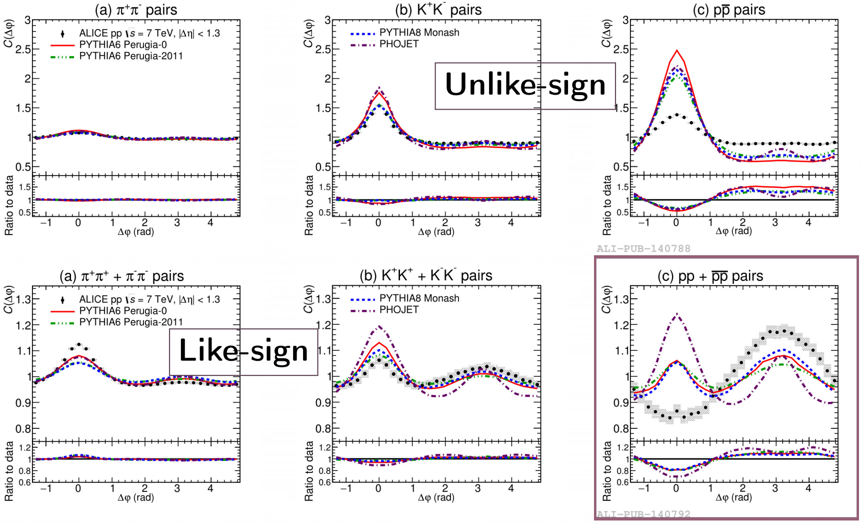


J.High Energ.Phys.2024,102(2024).



Eur.Phys.J.C(2017)77:569

Mesons and baryons compared to MC models



MC models can reproduce qualitatively meson correlations, but not those of baryons

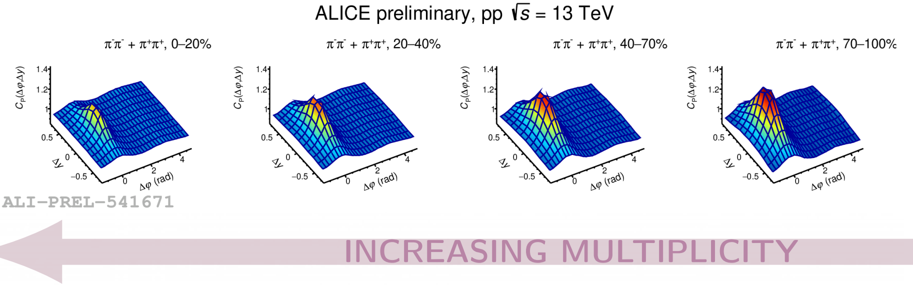
ALICE Collaboration, Eur.Phys.J.C(2017)77:569

What more can be explored?

A new piece of the puzzle is added by exploring the behavior of baryons-both like-sign and unlike-sign protons-across different multiplicity classes and collision systems at LHC energies.

Interpretation of the probability ratio

- **Difficult to compare results over different multiplicities/centralities;**
  - Difference in multiplicities due to a trivial scaling of 1/N
  - pp, p–Pb, and Pb–Pb results show differences in multiplicities
    - are not easily comparable



Rescaled two-particle correlation function

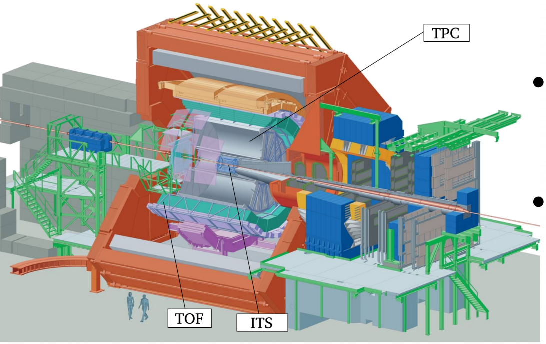
- **How to overcome the trivial scaling $1/\mathrm{N}$?**
  - Use a **rescaled two-particle correlation function** $(\mathrm{C_R})$

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

  - $N_\mathrm{av} = \frac{1}{2\pi}\left\langle \frac{\mathrm{d}N_\mathrm{a}}{\mathrm{d}\varphi} \right\rangle$ is the average number of particle type produced in the analyzed multiplicity/centrality classes;
  - a is the particle type analyzed (PID);
  - In pp and p–Pb analysis C_R was defined as C_C;
    - Name of the correlation function finalized after pp and p–Pb approvals.

Data samples & settings

- RUN 2 data:
  - pp collisions at 13 TeV registered by ALICE in 2016, 2017 and 2018.
  - p–Pb collisions at 5.02 TeV registered by ALICE in 2017.
  - Pb–Pb collisions at 5.02 TeV registered by ALICE in 2015.



- Tracking:
  - Inner Tracking System (**ITS**);
  - Time Projection Chamber (**TPC**);
- Particle Identification:
  - Time Projection Chamber (**TPC**);
  - Time of Flight (**TOF**);
- Kinematic cuts:
  - $|y| < 0.5$;
  - pions : $0.2 < p_{\mathrm{T}} < 2.5$ GeV/c;
  - kaons : $0.5 < p_{\mathrm{T}} < 2.5$ GeV/c;
  - protons : $0.5 < p_{\mathrm{T}} < 2.5$ GeV/c.

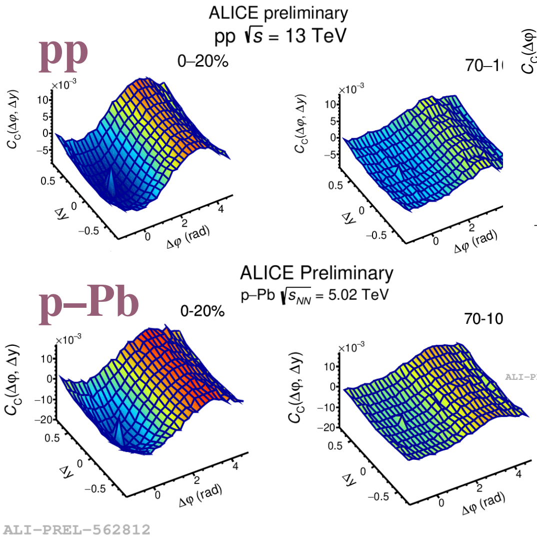
Analysis

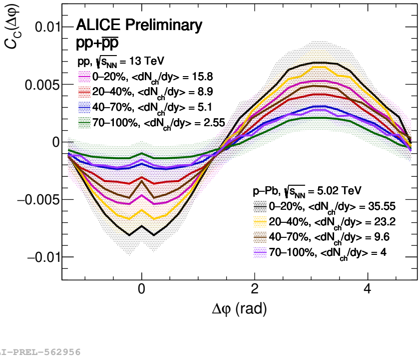
This analysis is focused on...

- Identified particle pairs of pions, kaons and protons;
- Probability and rescaled two-particle correlation functions;
- Different multiplicity classes analyzed for pp, and p–Pb:
  - 0–20%, 20–40%, 40–70%, 70–100%
- Different centrality classes analyzed for Pb–Pb:
  - 0–20%, 20–40%, 40–50%, 50–60%, 60–70%, 70–80%, 80–90%

$\Delta y \Delta \varphi$ correlation functions

Like-sign protons





The anticorrelation persists in pp at 13 TeV and p–Pb at 5.02 TeV:

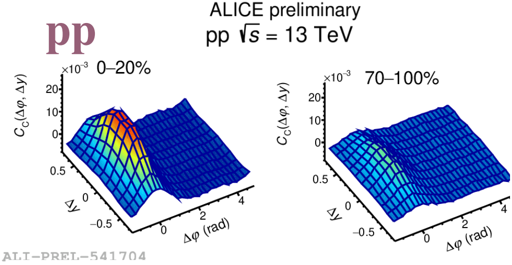
- It becomes stronger for higher multiplicity classes.
- $C_{\mathrm{C}} = C_{\mathrm{R}}$

https://arxiv.org/abs/2403.02549

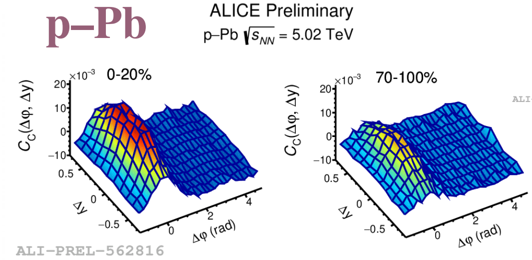
$\Delta y \Delta \varphi$ correlation functions

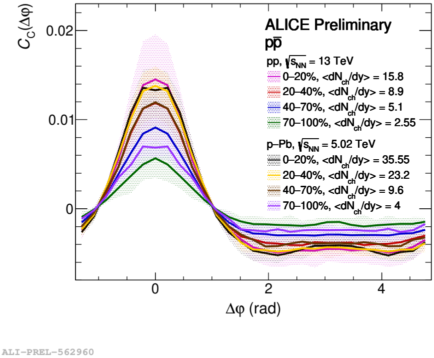
Unlike-sign protons

pp



p–Pb





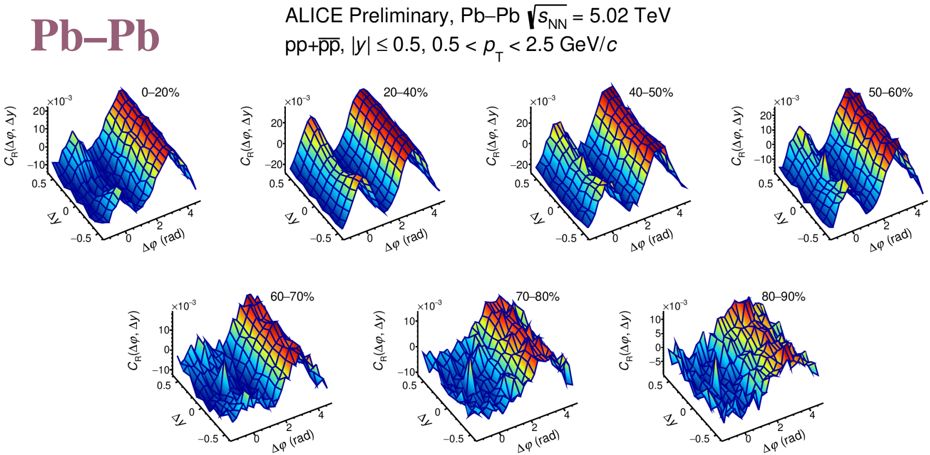
- The higher the multiplicity, the stronger the correlation;
- The annihilation phenomenon is observed in the highest multiplicity in p–Pb collision.
- $C_C = C_R$

https://arxiv.org/abs/2403.02549

$\Delta y \Delta \varphi$ correlation functions

Like-sign protons

Pb–Pb



ALI-PREL-585620

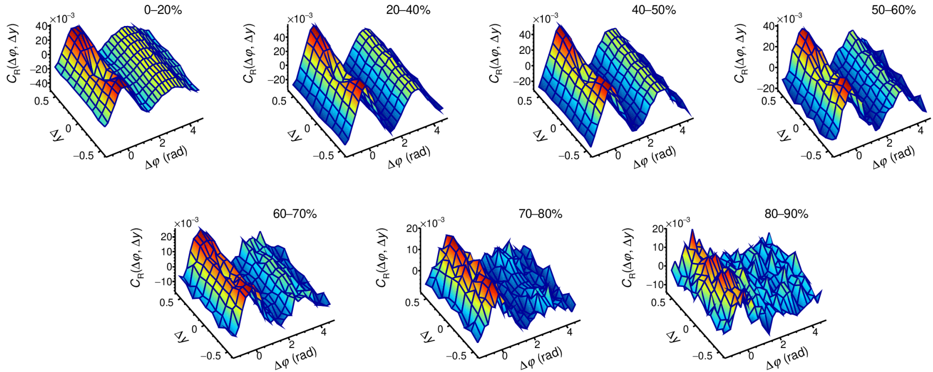
- The azimuthal flow effect appears at the mid centrality classes;
- The anticorrelation is stronger than the flow, and shows a clear dip in the semicentral collisions, where the influence of the flow is the strongest.

$\Delta y \Delta \varphi$ correlation functions

Unlike-sign protons

Pb–Pb

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



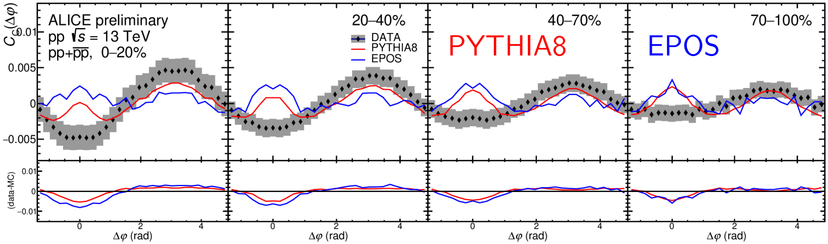
ALI-PREL-585624

- The azimuthal flow effect appears at the mid centrality classes;
- The annihilation phenomenon is strongly observed in all centralities, even where the influence of the flow is strong like in semicentral collisions.

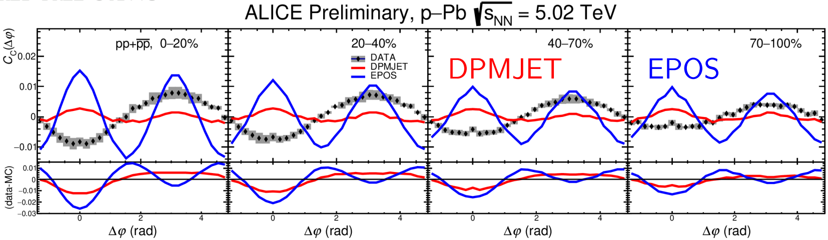
Can baryonic correlations be reproduced by models?

Model comparison in small systems

Like-sign protons



ALI−PREL−541773

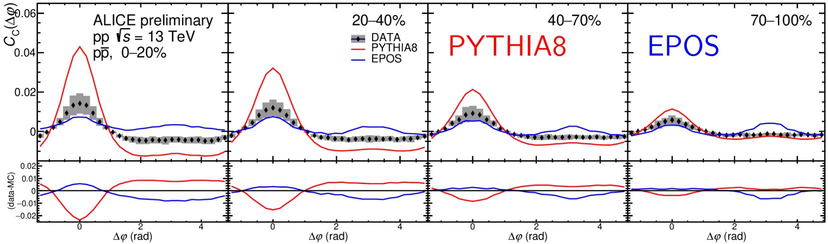


ALI−PREL−562908

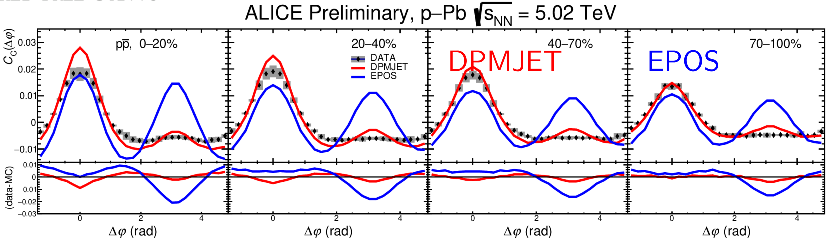
The models fail to reproduce the anticorrelations in both pp and p–Pb collision systems

Model comparison in small systems

Unlike-sign protons



ALI-PREL-541776

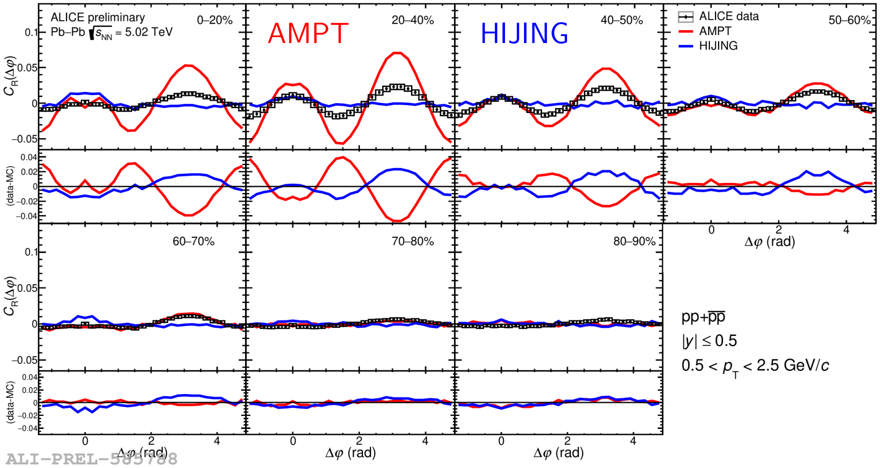


ALI-PREL-562912

The models qualitatively reproduce the near-side region, but not the away-side.

Model comparison in Pb–Pb

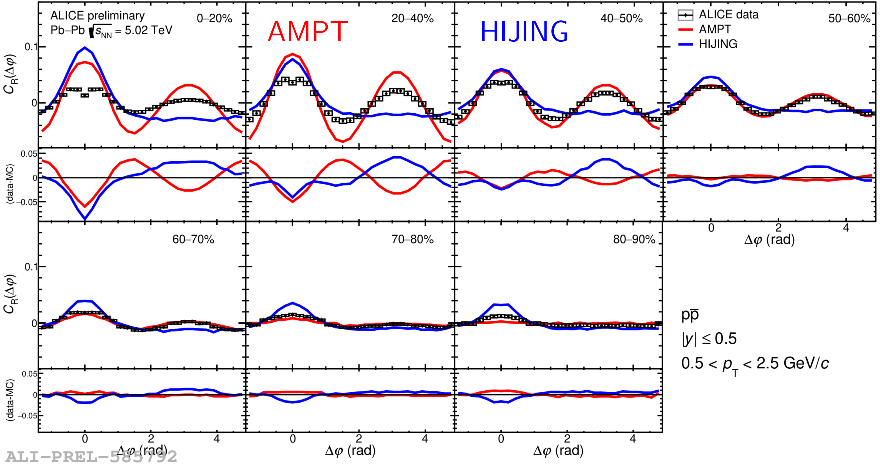
Like-sign protons



- AMPT model reproduces the data qualitatively but not quantitatively;
- HIJING fails to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

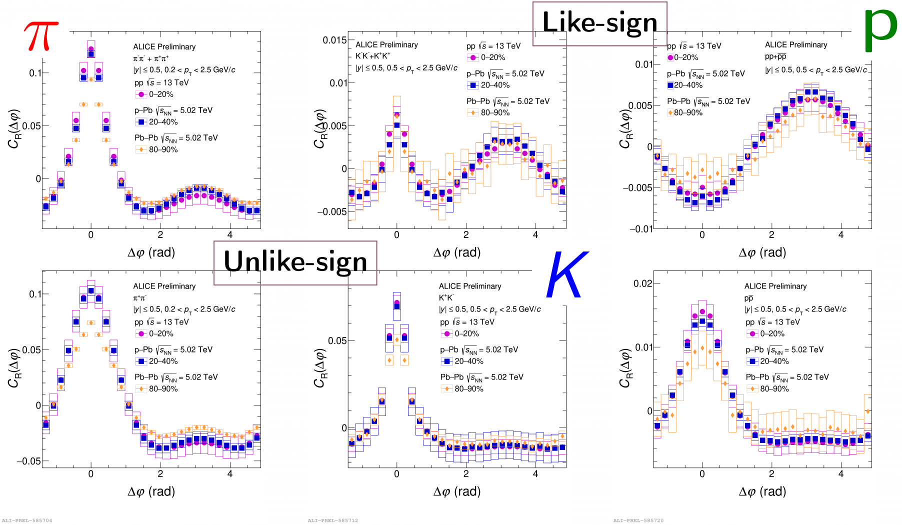
Unlike-sign protons



- AMPT model reproduces qualitatively but not quantitatively the data;
- HIJING fails to reproduce the data
  - anisotropic flow not included in the model.

pp, p–Pb, and Pb–Pb comparison

pp, p–Pb and Pb–Pb comparison



Comparison of pp, p–Pb and Pb–Pb collision systems at the LHC energies for all particle types and all centralities

Conclusion

- The study of anticorrelation across different multiplicity classes has been conducted, revealing that the phenomenon persists and intensifies with higher multiplicity.
- The study of the anticorrelation over different multiplicity classes has been extended to different collision systems, showing that the phenomenon persists even in HIC and shows stronger behavior than expected.
- The comparison of the three collision systems suggests that the physics in pp and p–Pb collisions are similar while differing from those in Pb–Pb collisions, as expected.

This analysis raises many open questions to which we currently do not have answers. We will not address any inquiries now but anticipate that the findings will prompt further questions. We now look forward to insights from theorists to help address these issues.

THANK YOU!

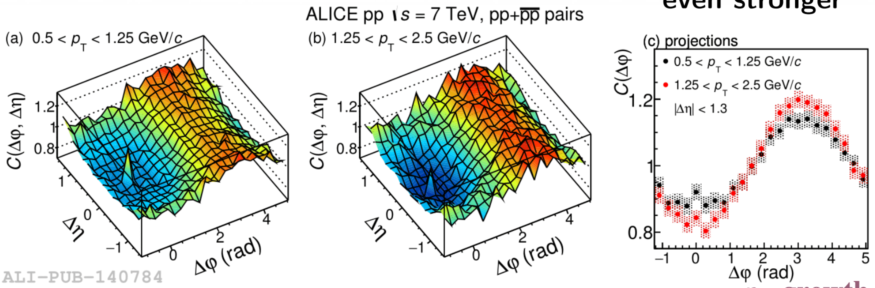
BACKUP-SLIDES

Baryon correlation puzzle

- **Dependence on p_T**

$$p_{\mathrm{T}_{\mathrm{sum}}} = |\vec{p}_{\mathrm{T}_1}| + |\vec{p}_{\mathrm{T}_2}|$$

Anticorrelation even stronger

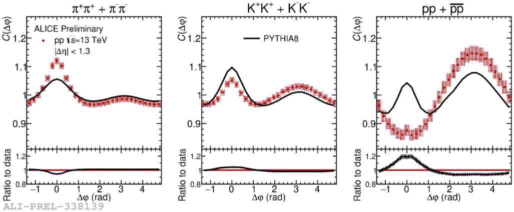


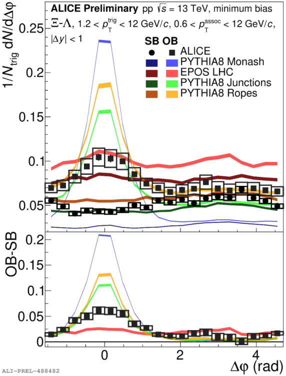
p_T **growth**

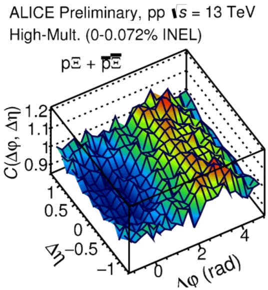
ALICE Collaboration, Eur.Phys.J.C(2017)77:569

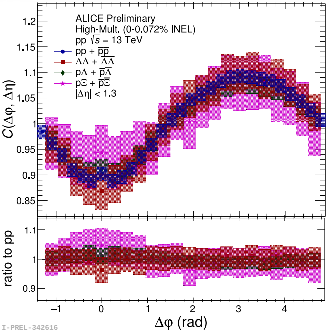
ALICE at 13 TeV, pp data

- **Anticorrelations persist for all baryons and for higher mass multistrange baryons**





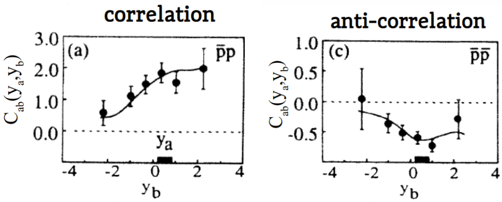




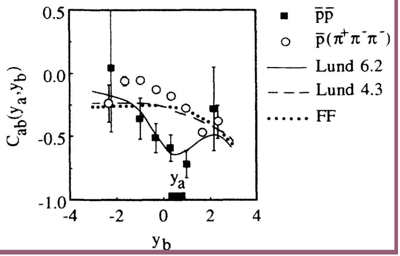
Rapidity correlation in e^+e^-

From the mechanism of jet production: Two primary hadrons with the same baryon number are separated by at least two steps in "rank" – it's not likely to find two baryons or two antibaryons very close to each other.

Nucl.Phys.B136(1978)131



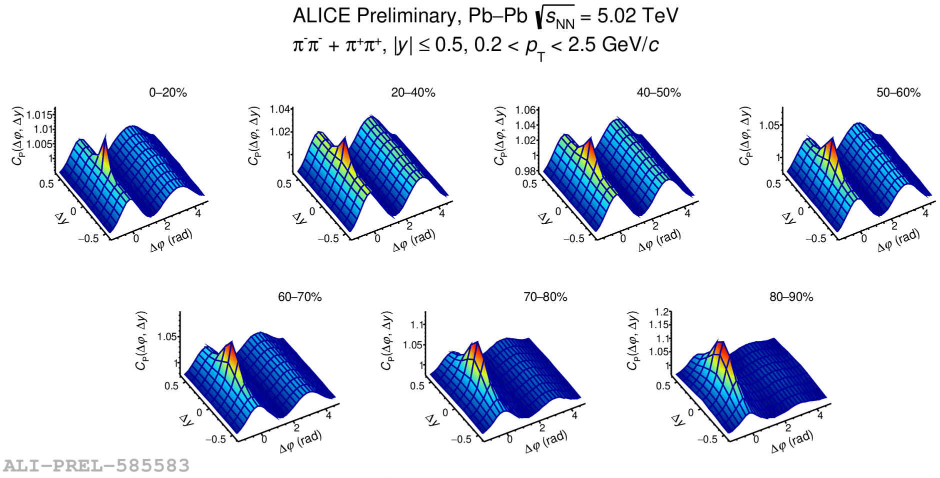
Models at lower energies agree with data: **LUND 6.2**



Local baryon number conservation is partially responsible for anticorrelation at 29 GeV TPC/Two Gamma Collaboration, Phys.Rev.Lett. 57 (1986) 3140

$\Delta y \Delta \varphi$ correlation functions

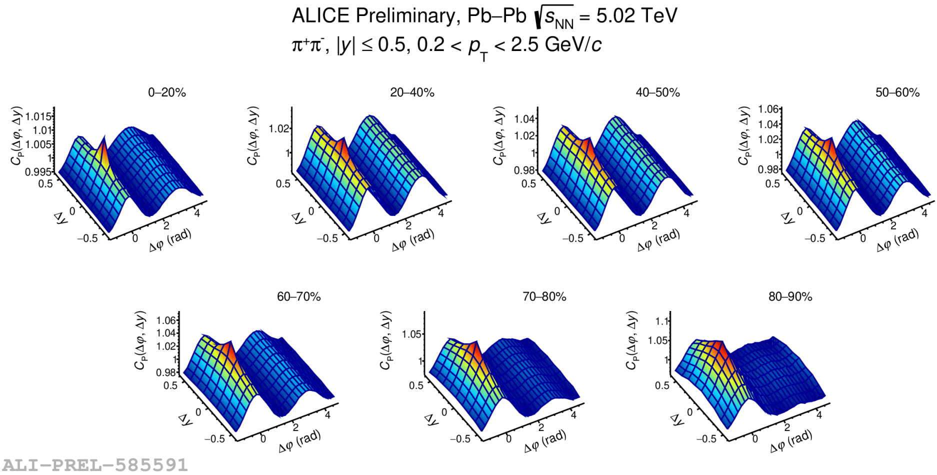
Like-sign pions



- The lower the centrality, the lower the flow effect;
- The correlations are performed using probability ratio definition;

$\Delta y \Delta \varphi$ correlation functions

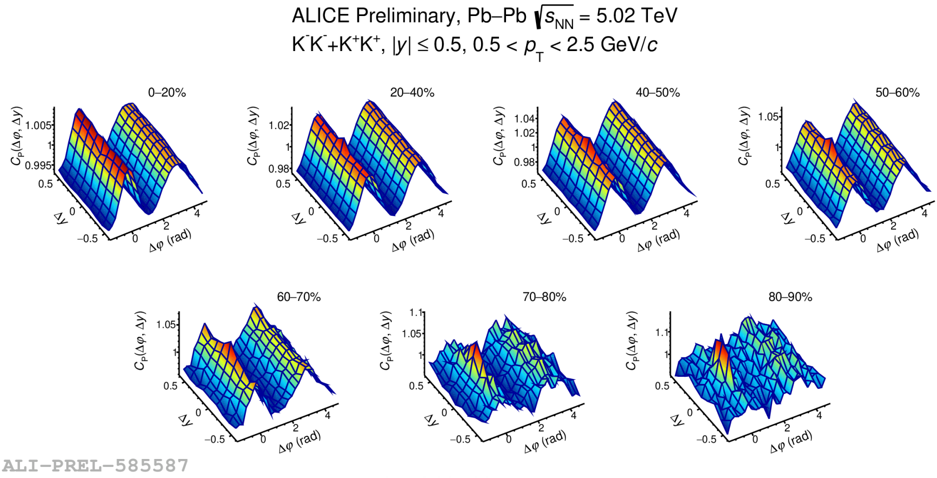
Unlike-sign pions



- The lower the centrality, the lower the flow effect;
- The correlations are performed using probability ratio definition;

$\Delta y \Delta \varphi$ correlation functions

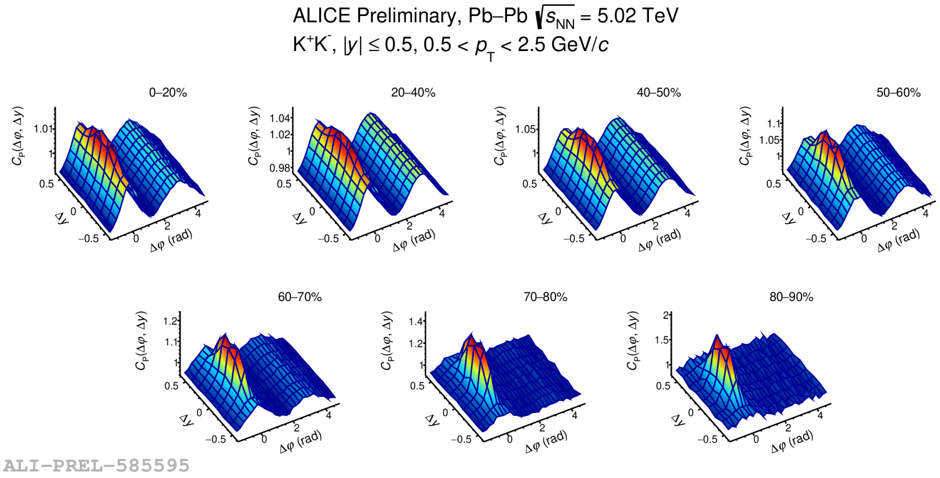
Like-sign kaons



- The lower the centrality, the lower the flow effect;
- The correlations are performed using probability ratio definition;

$\Delta y \Delta \varphi$ correlation functions

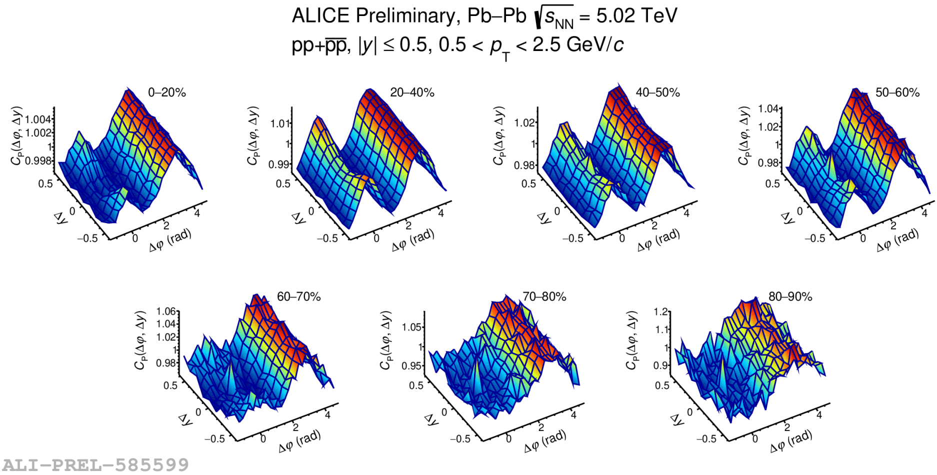
Unlike-sign kaons



- The lower the centrality, the lower the flow effect;
- The correlations are performed using probability ratio definition;

$\Delta y \Delta \varphi$ correlation functions

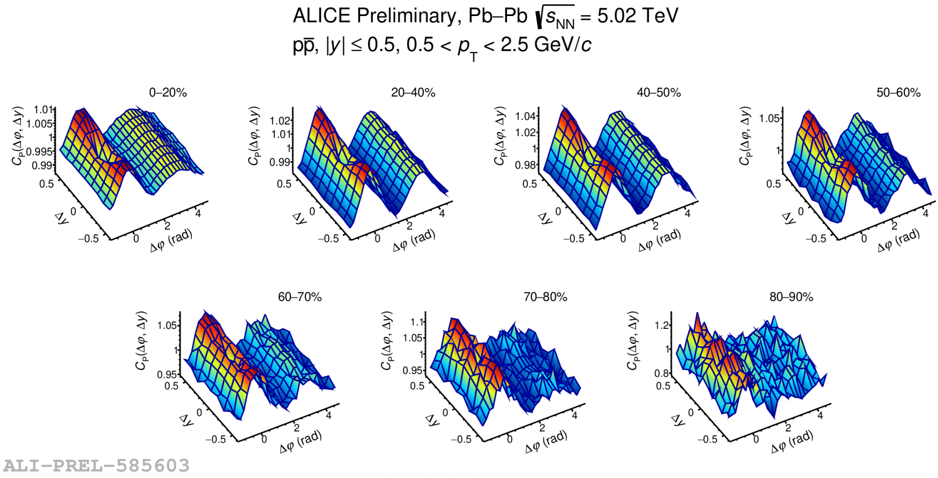
Like-sign protons



- The lower the centrality, the lower the flow effect;
- The correlations are performed using probability ratio definition;

$\Delta y \Delta \varphi$ correlation functions

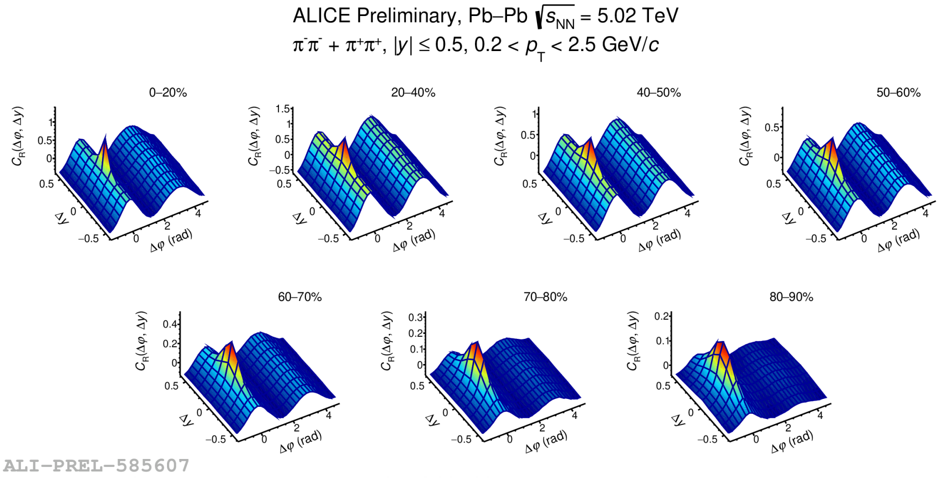
Unlike-sign protons



- The lower the centrality, the lower the flow effect;
- The correlations are performed using probability ratio definition;

$\Delta y \Delta \varphi$ correlation functions

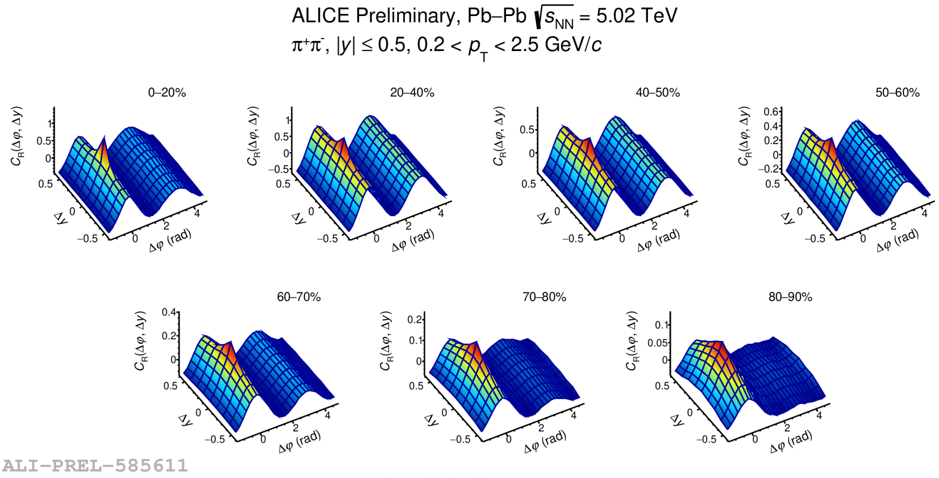
Like-sign pions



- The lower the centrality, the lower the flow effect;
- The correlations are performed using rescaled two-particle correlation function definition;

$\Delta y \Delta\varphi$ correlation functions

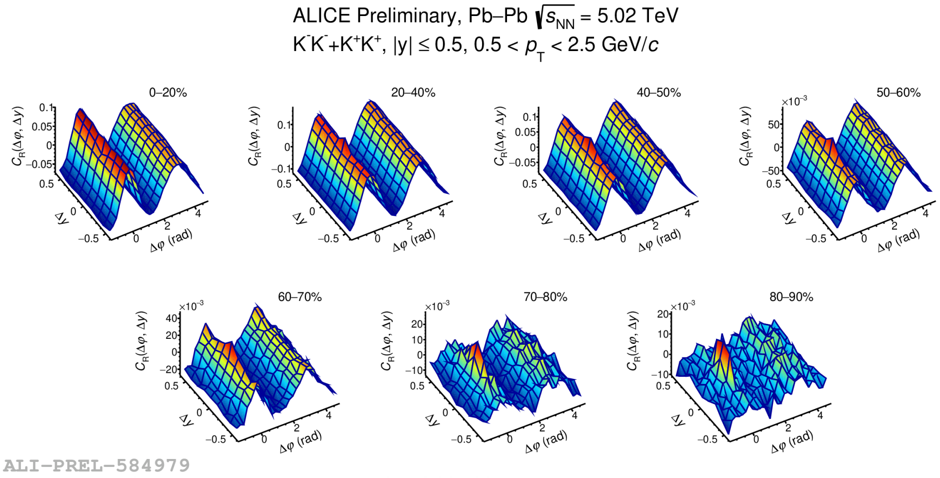
Unlike-sign pions



- The lower the centrality, the lower the flow effect;
- The correlations are performed using rescaled two-particle correlation function definition;

$\Delta y \Delta \varphi$ correlation functions

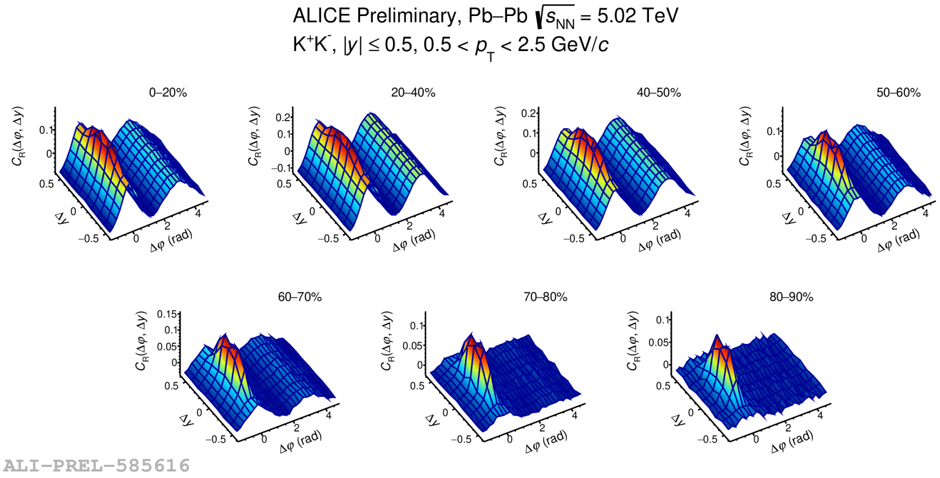
Like-sign kaons



- The lower the centrality, the lower the flow effect;
- The correlations are performed using rescaled two-particle correlation function definition;

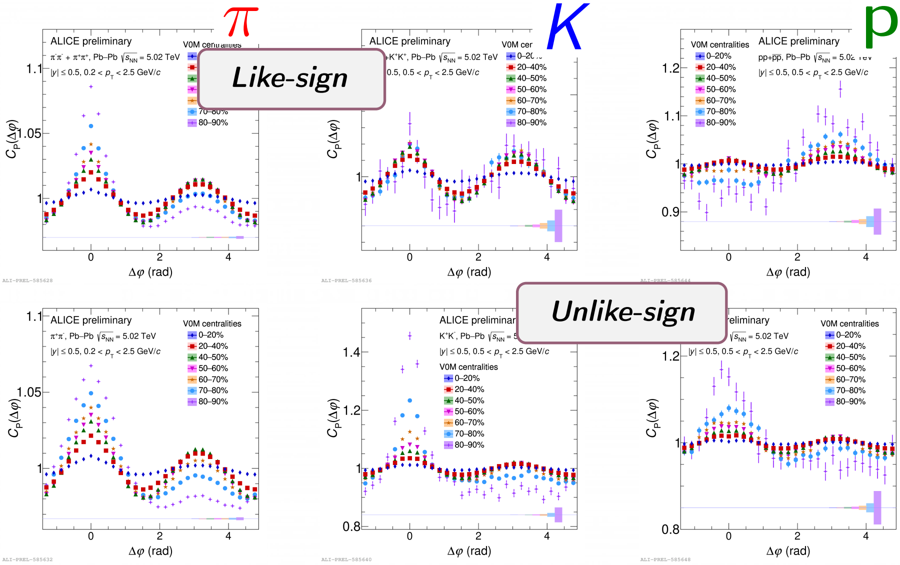
$\Delta y \Delta \varphi$ correlation functions

Unlike-sign kaons



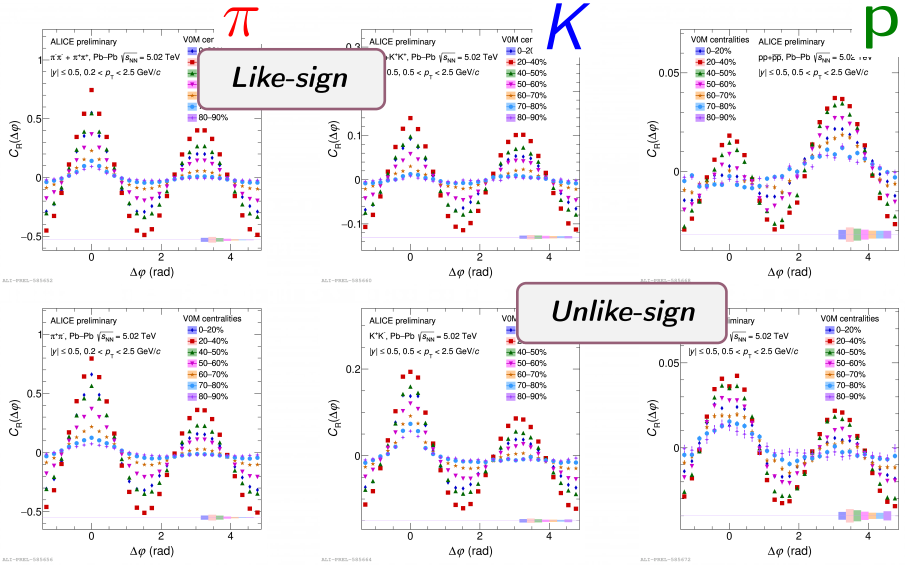
- The lower the centrality, the lower the flow effect;
- The correlations are performed using rescaled two-particle correlation function definition;

An overview of the meson and baryon in Pb–Pb



Projection on $\Delta\varphi$ using probability ratio definition

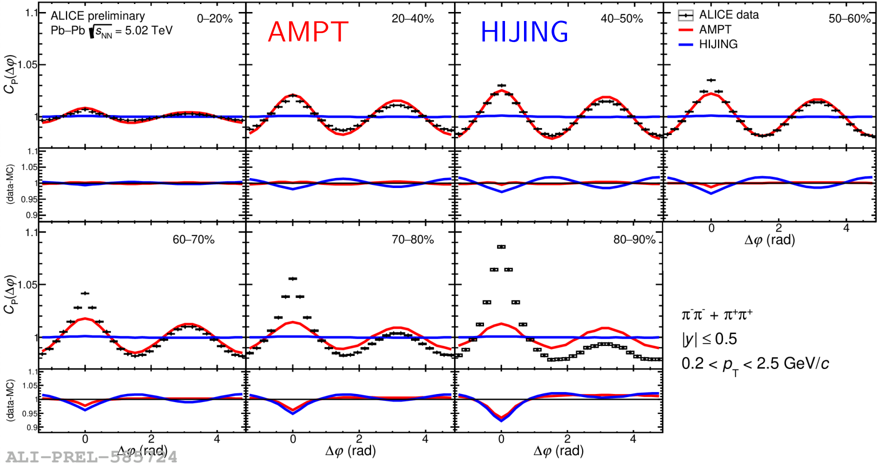
An overview of the meson and baryon in Pb–Pb



Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign pions

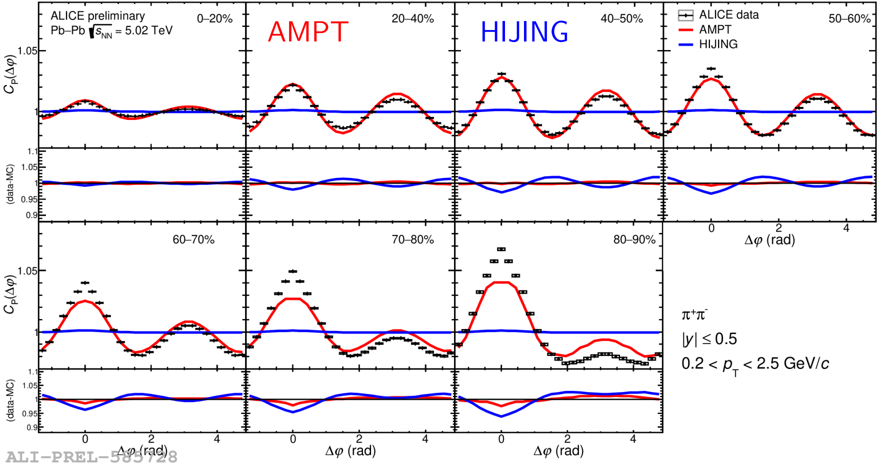


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign pions

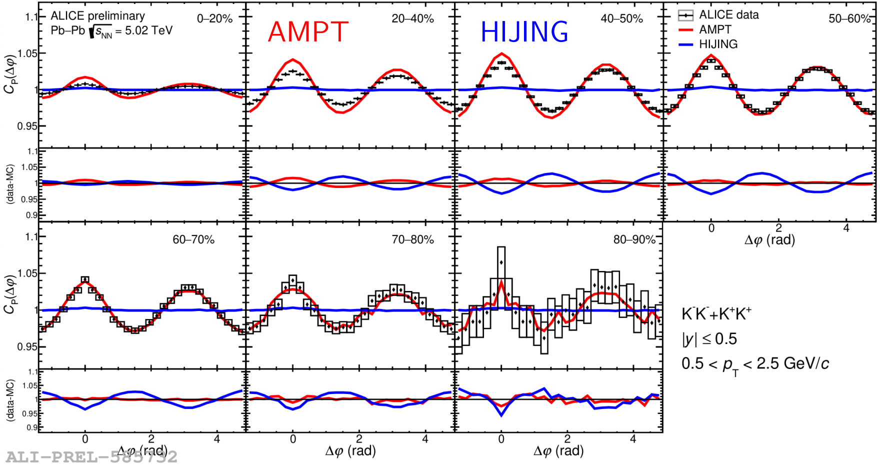


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign kaons

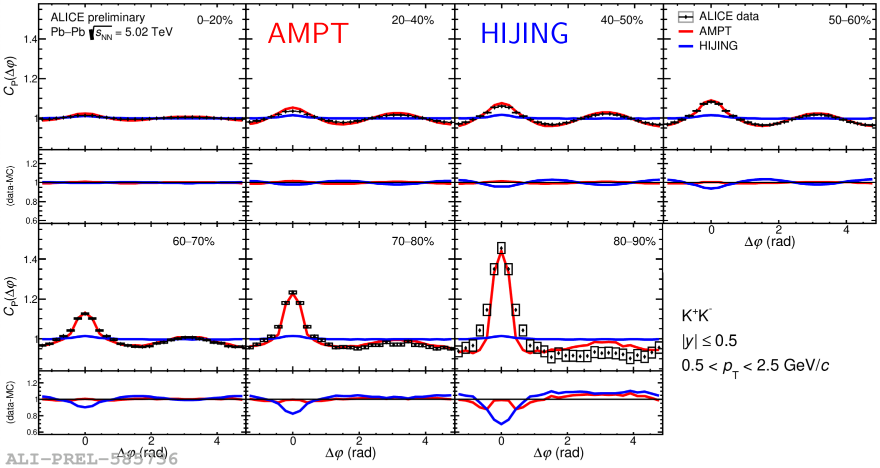


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign kaons

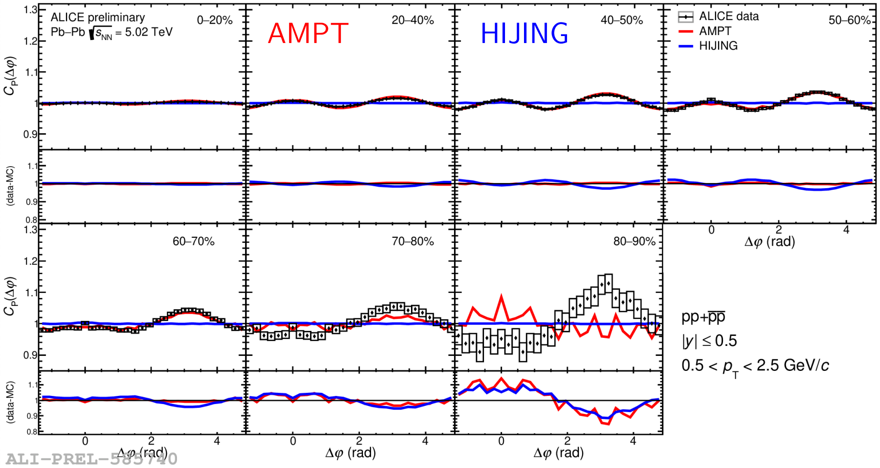


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign protons

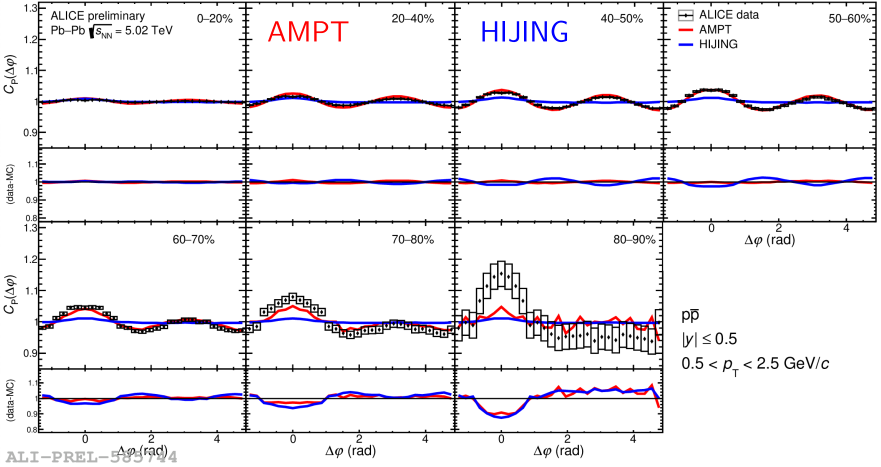


- AMPT model can't reproduce the anticorrelation;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign protons

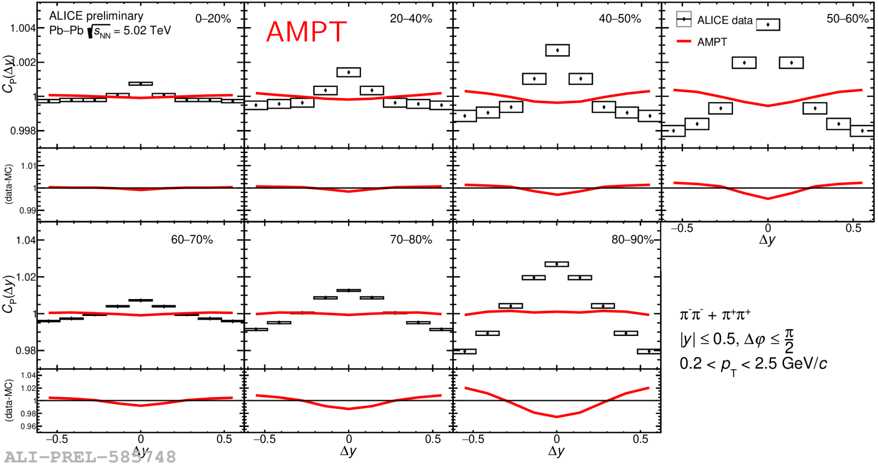


- AMPT model can reproduce qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign pions

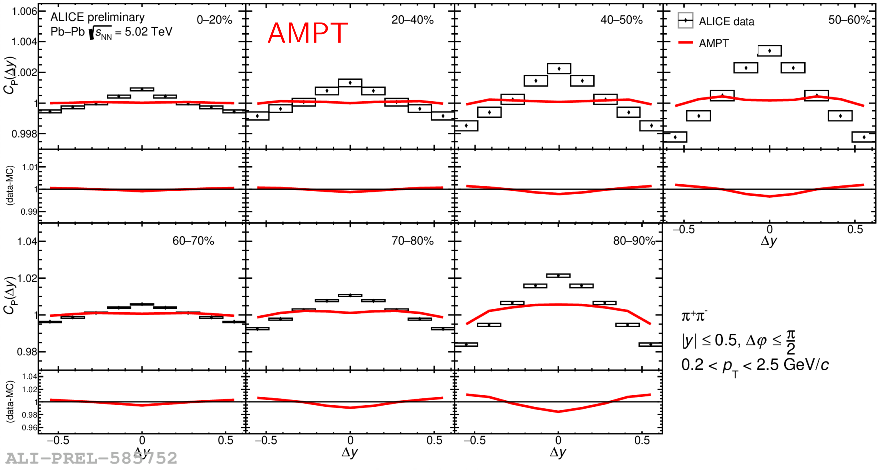


- AMPT model fail to reproduce the near side region;

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign pions

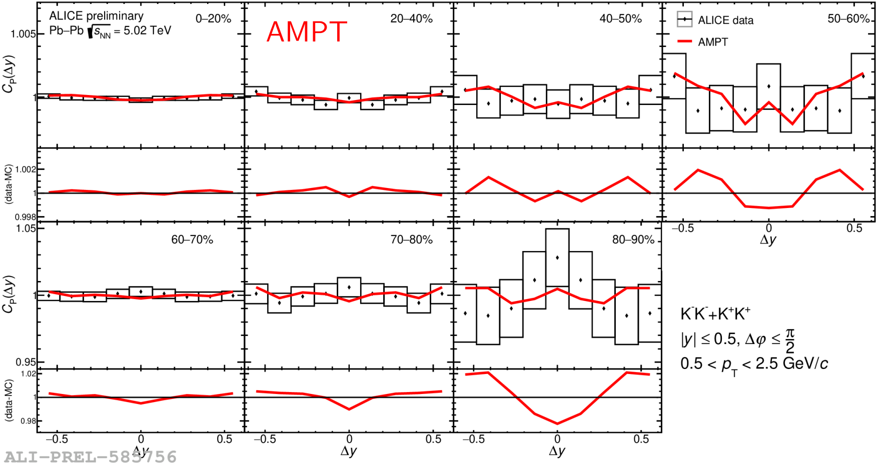


- AMPT model fail to reproduce the near side region;

PROBABILITY ratio

Model comparison in Pb–Pb

Like-sign kaons

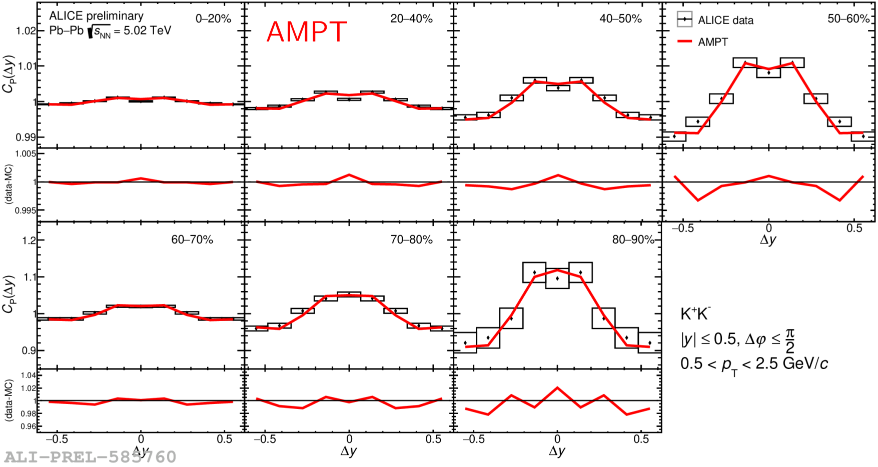


- AMPT model can reproduce the near side region;

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign kaons

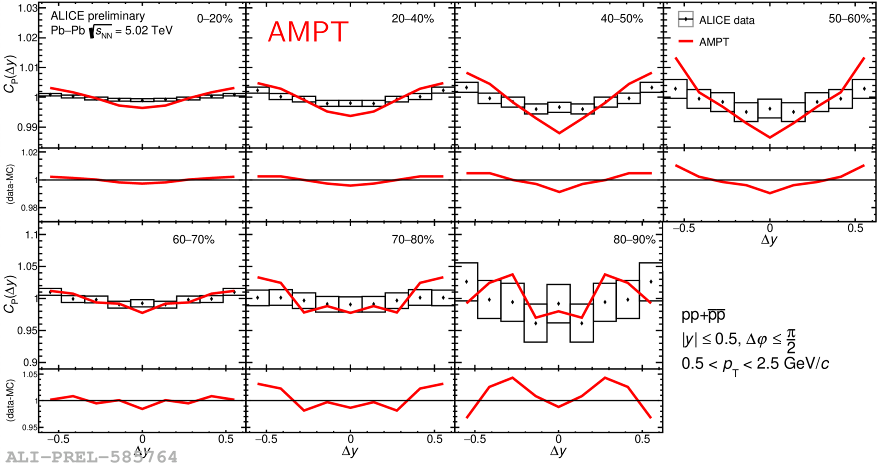


- AMPT model can reproduce the near side region;

Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign protons

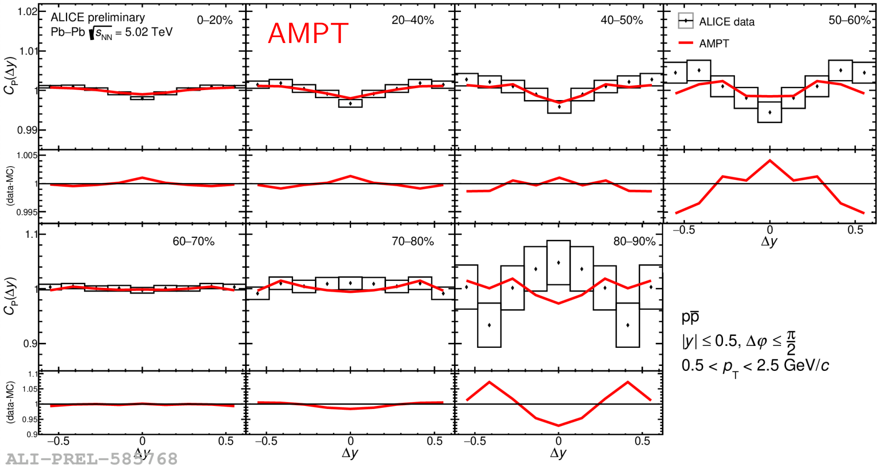


- AMPT model can reproduce qualitatively well the near side region;

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign protons



$p\bar{p}$

$|y| \leq 0.5$, $\Delta\varphi \leq \frac{\pi}{2}$

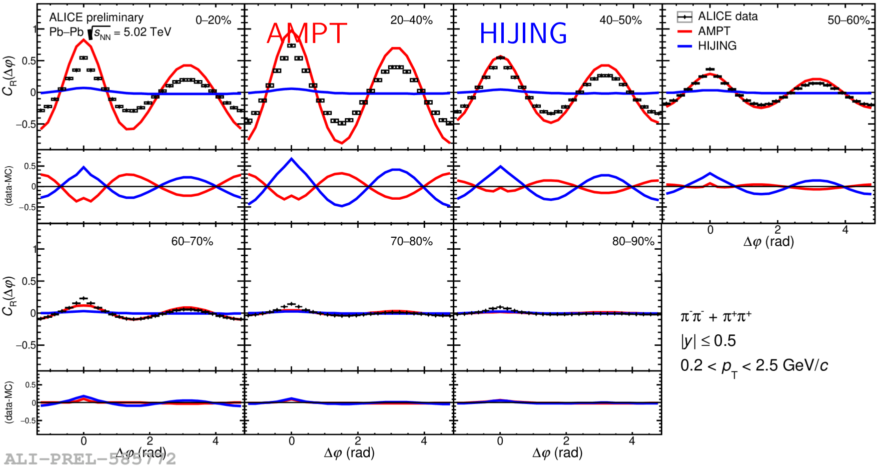
$0.5 < p_T < 2.5$ GeV/c

- AMPT model can reproduce the near side region;

Model comparison in Pb–Pb

Rescaled two-particle CF

Like-sign pions

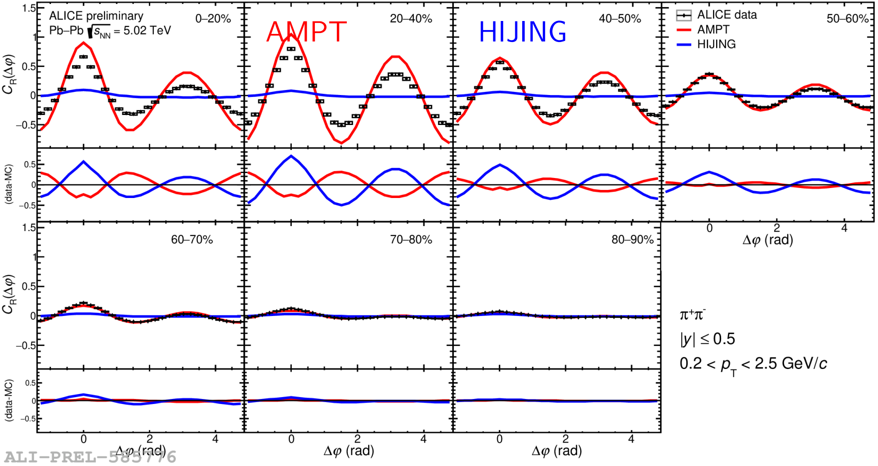


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

Rescaled two-particle CF

Unlike-sign pions

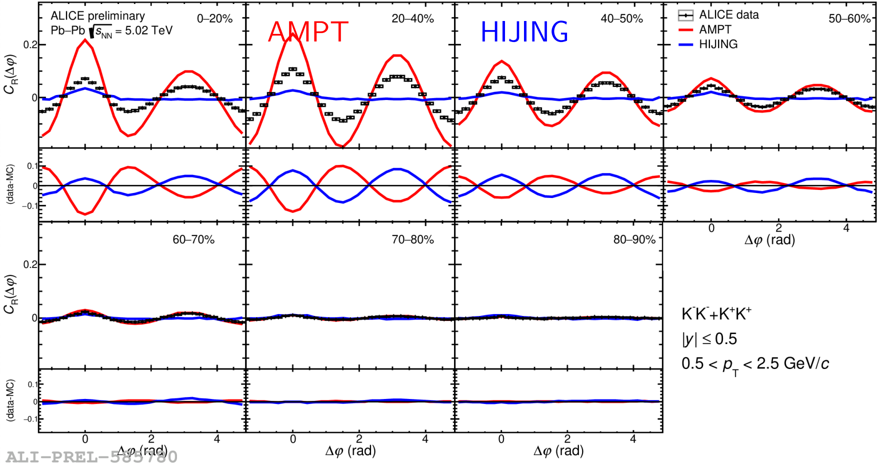


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

Rescaled two-particle CF

Like-sign kaons

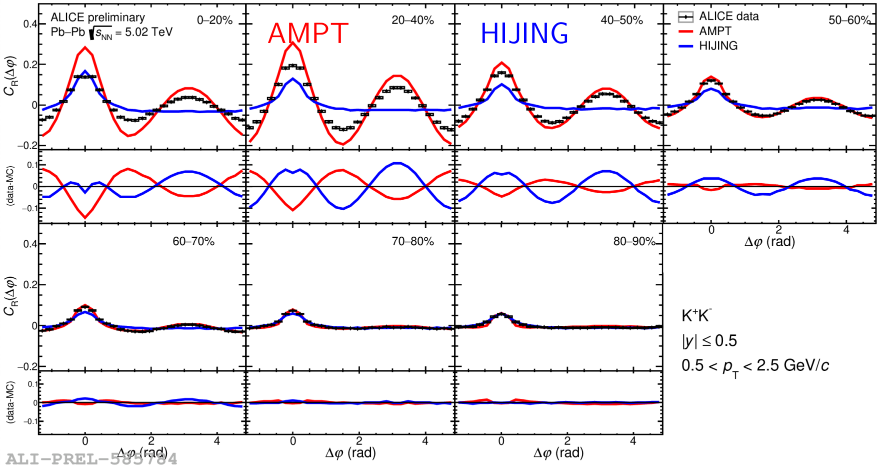


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

Rescaled two-particle CF

Unlike-sign kaons

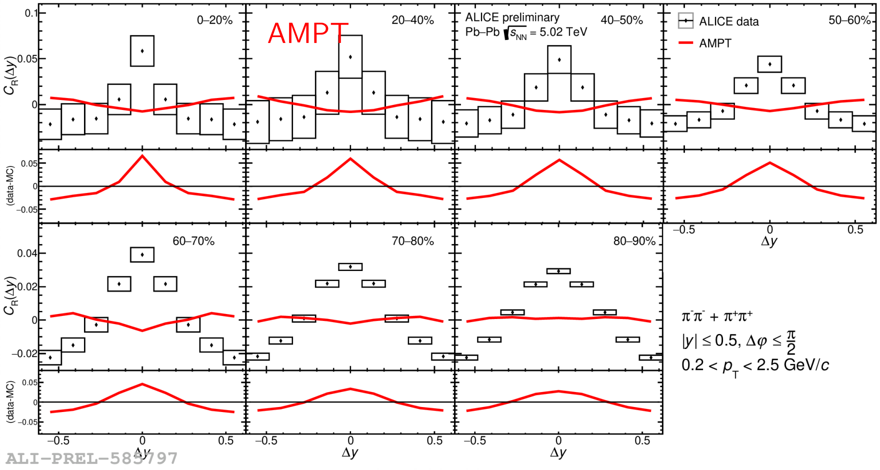


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

Rescaled two-particle CF

Like-sign pions

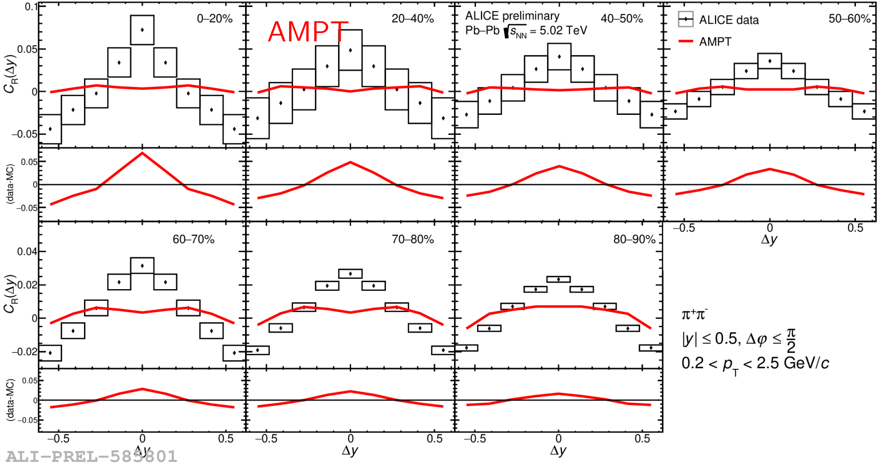


- AMPT model fail to reproduce the near side region;

Model comparison in Pb–Pb

Rescaled two-particle CF

Unlike-sign pions

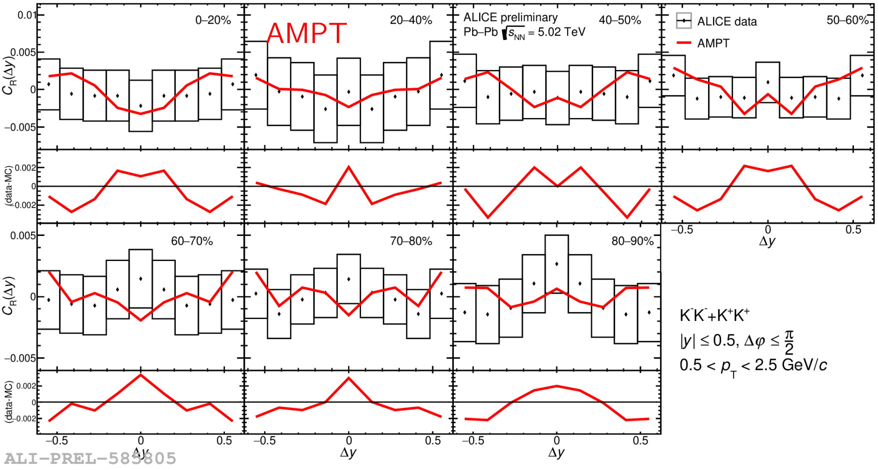


- AMPT model fail to reproduce the near side region;

Model comparison in Pb–Pb

Rescaled two-particle CF

Like-sign kaons

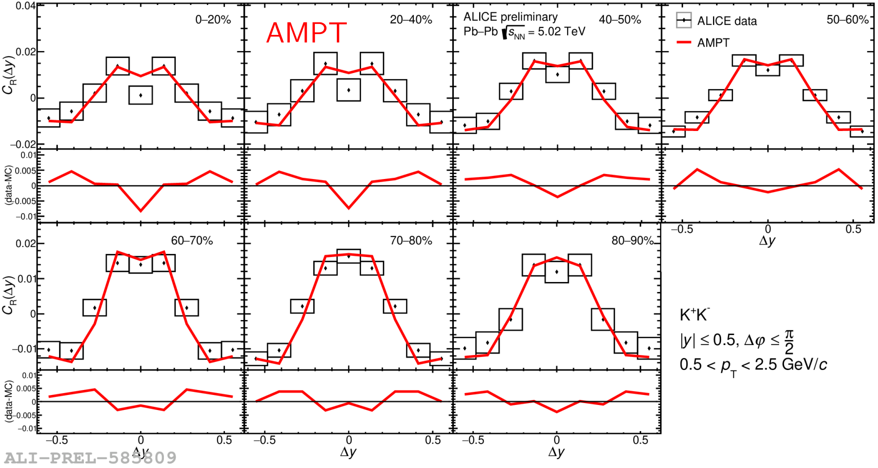


- AMPT model can reproduce qualitatively the near side region;

Model comparison in Pb–Pb

Rescaled two-particle CF

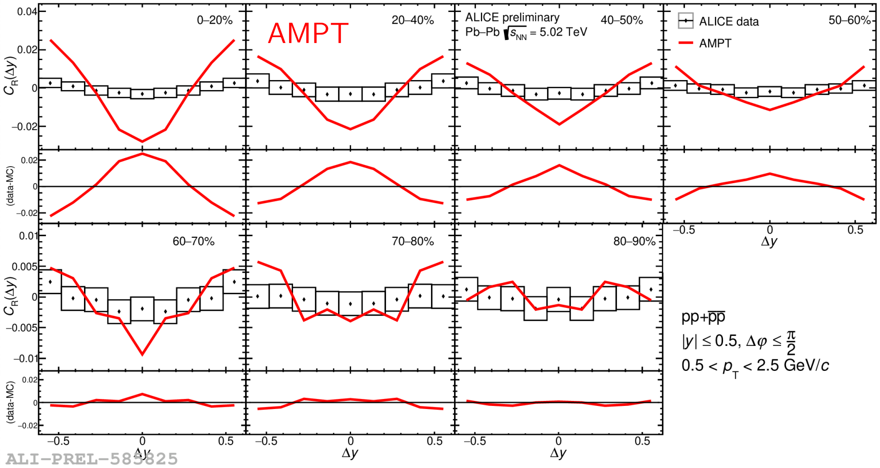
Unlike-sign kaons



- AMPT model can reproduce qualitatively the near side region;

Model comparison in Pb–Pb

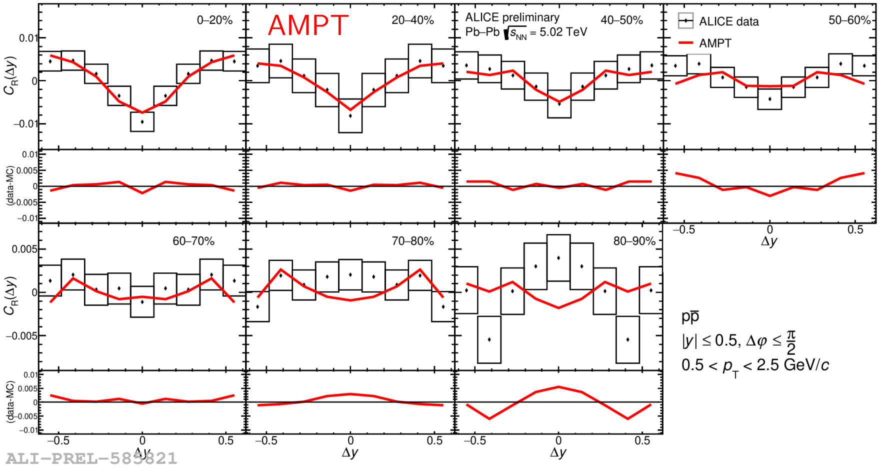
Like-sign protons



- AMPT model reproduces qualitatively the anticorrelation but not quantitatively;

Model comparison in Pb–Pb

Unlike-sign protons



- AMPT model reproduces quite well the data

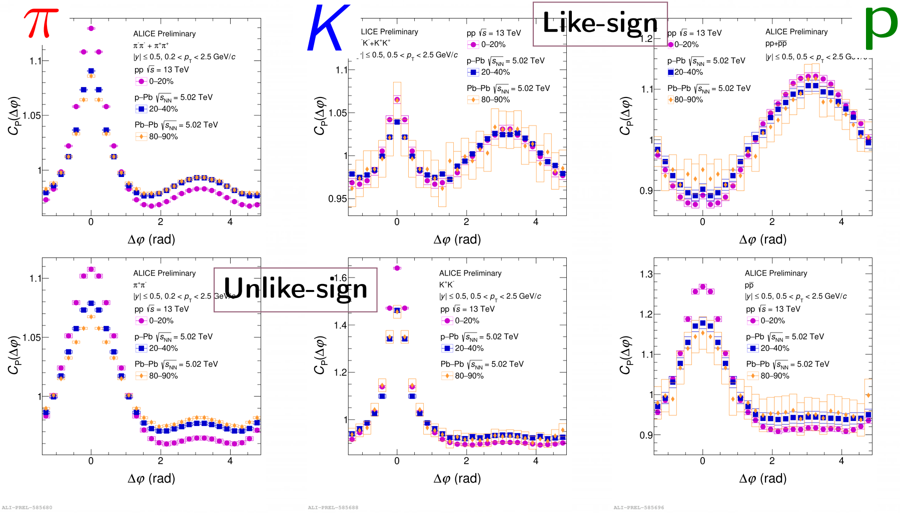
pp, p–Pb, and Pb–Pb comparison – $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$

The $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ values were adjusted to the multiplicity/centrality classes used.

collision system	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$						
pp	0–20%	20–40%	40–70%			70-100%	
	19.1	9.18	5.1			2.55	
p–Pb	0–20%	20–40%	40–70%			70-100%	
	35.55	23.2	9.6			4	
Pb–Pb	0–20%	20–40%	40–50%	50–60%	60–70%	70–80%	80–90%
	1570	649	318	183	96.3	44.9	17.5

Based on the values got from literature, the closest values are:
- 0–20% in pp with 20–40% in p–Pb and 80–90% in Pb–Pb

pp, p–Pb and Pb–Pb comparison



Comparison of pp, p–Pb and Pb–Pb collision system at the LHC energies for all particle types and all centralities using probability ratio definition