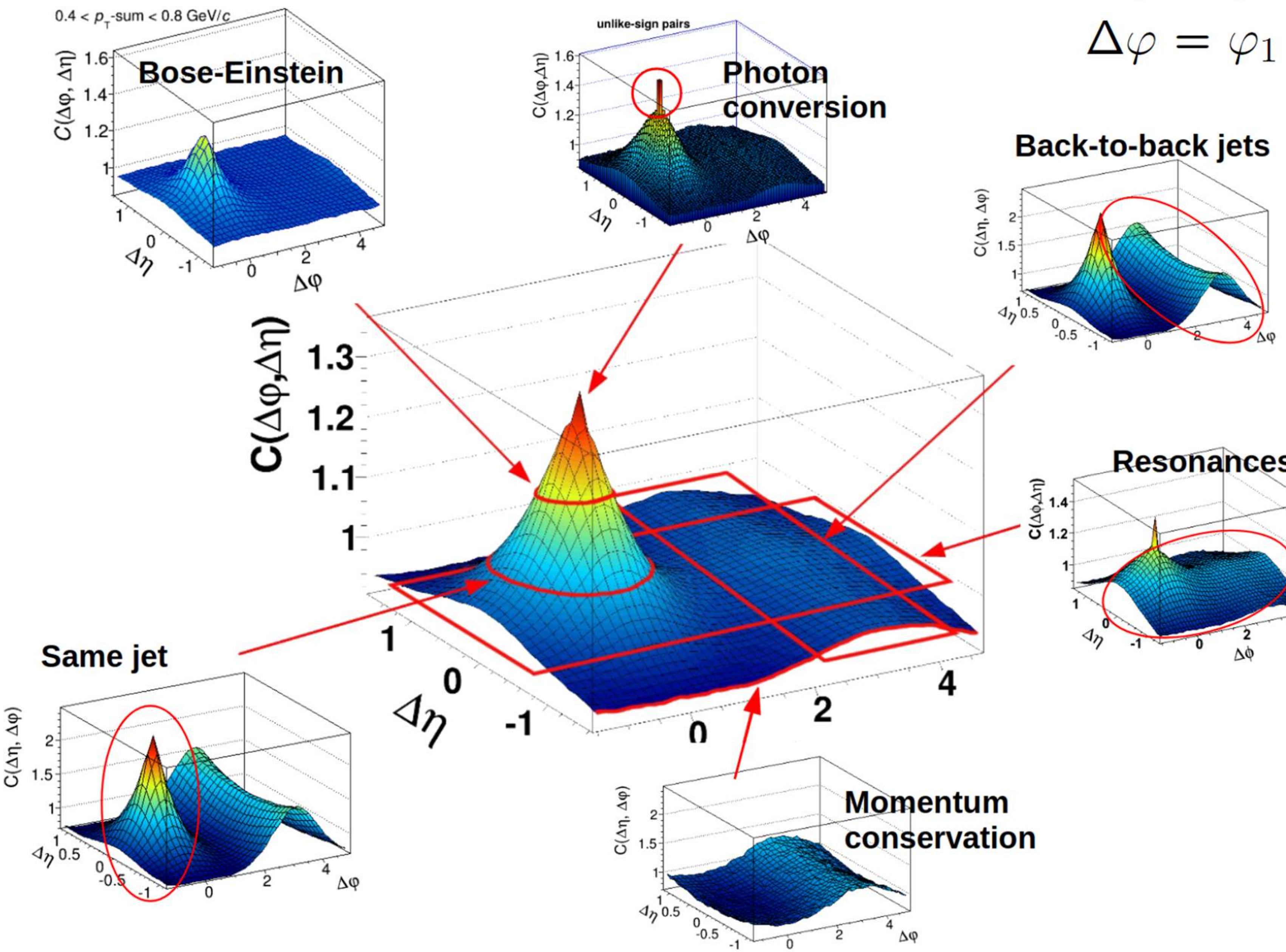
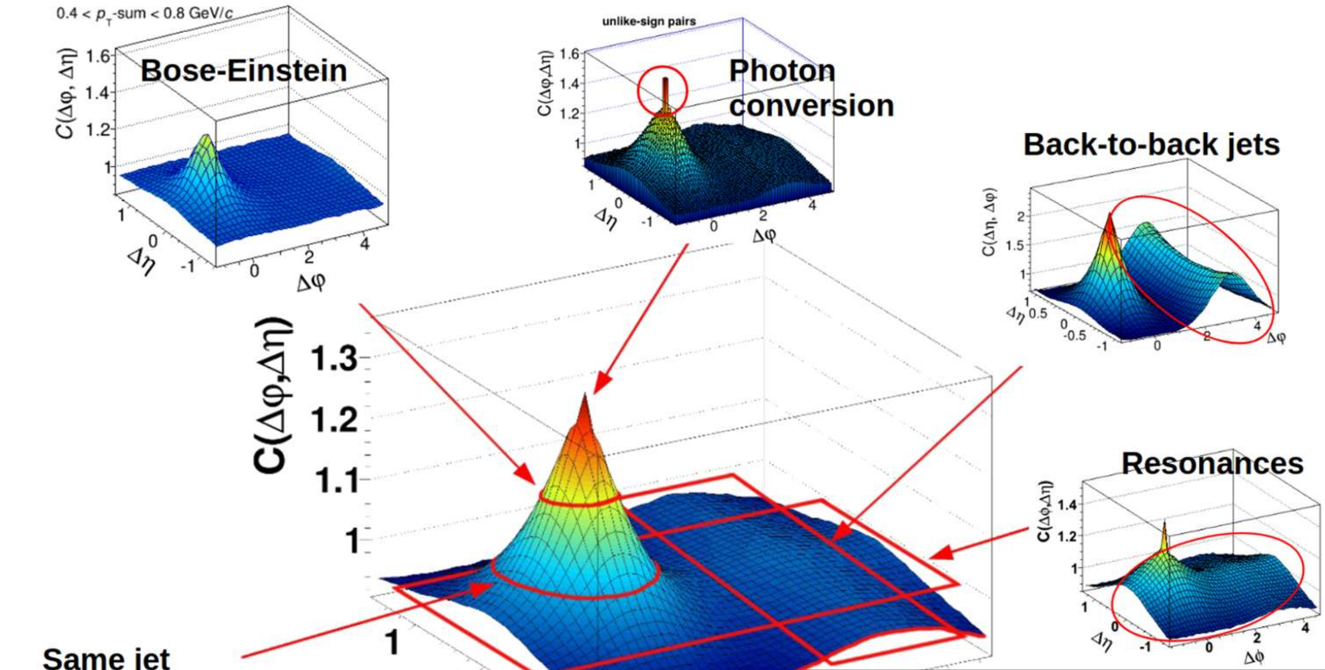
Exploring the baryon correlation puzzle via angular correlations from ALICE

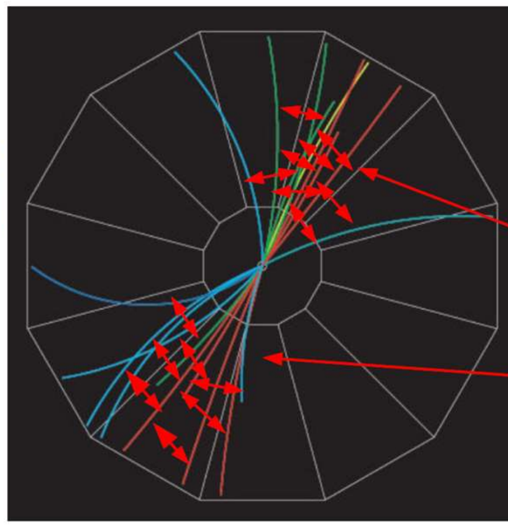
Małgorzata Anna Janik
on behalf of the ALICE Collaboration
Warsaw University of Technology

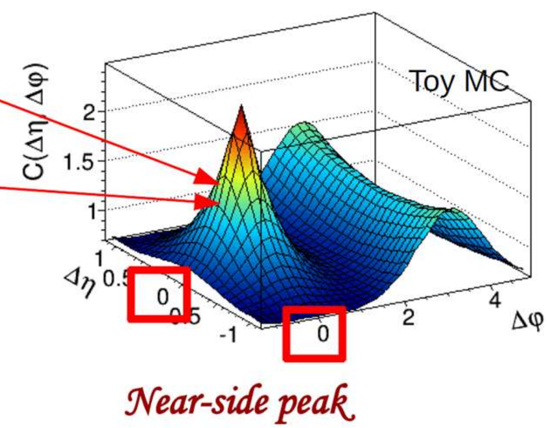
$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$



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



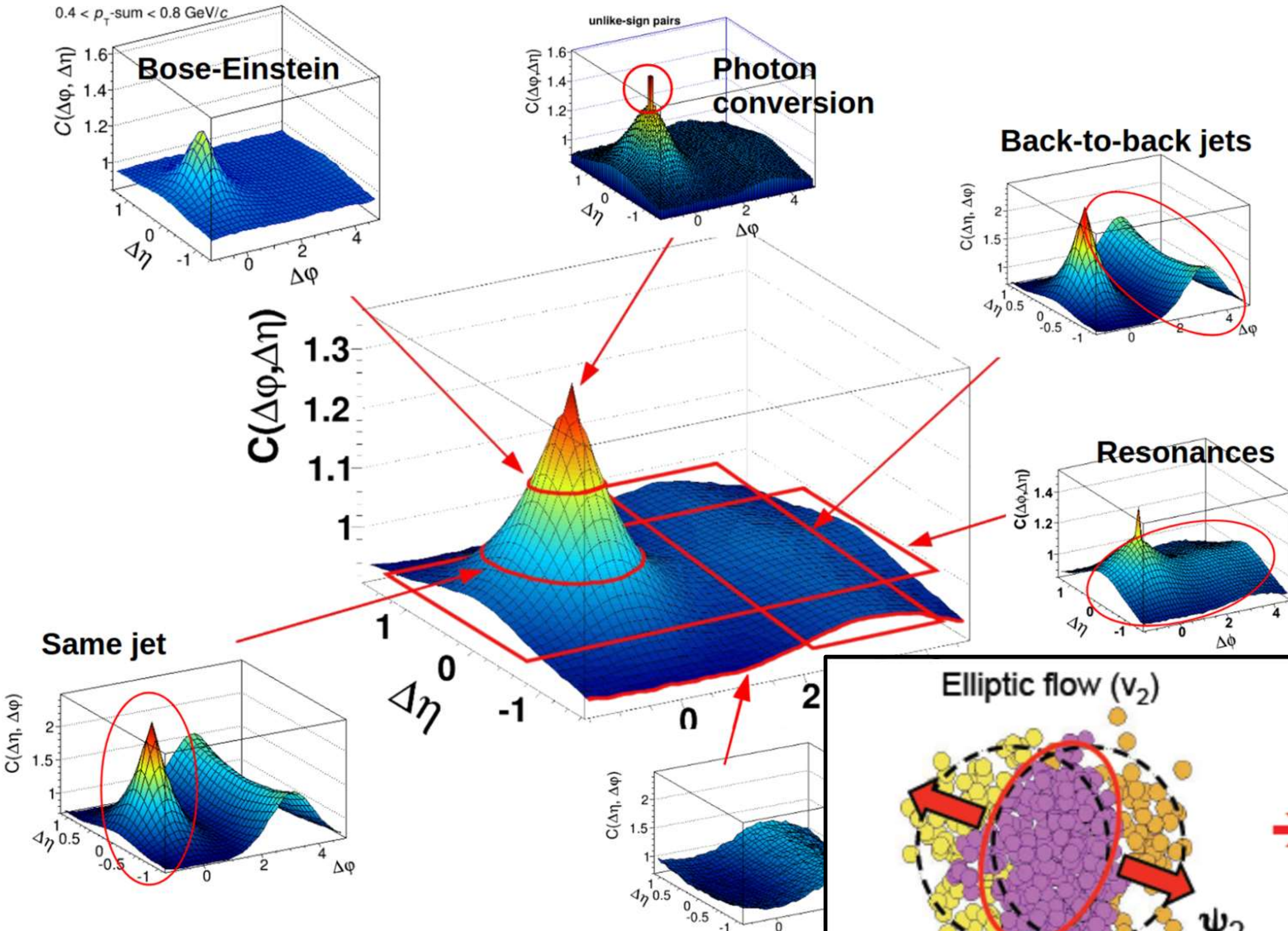


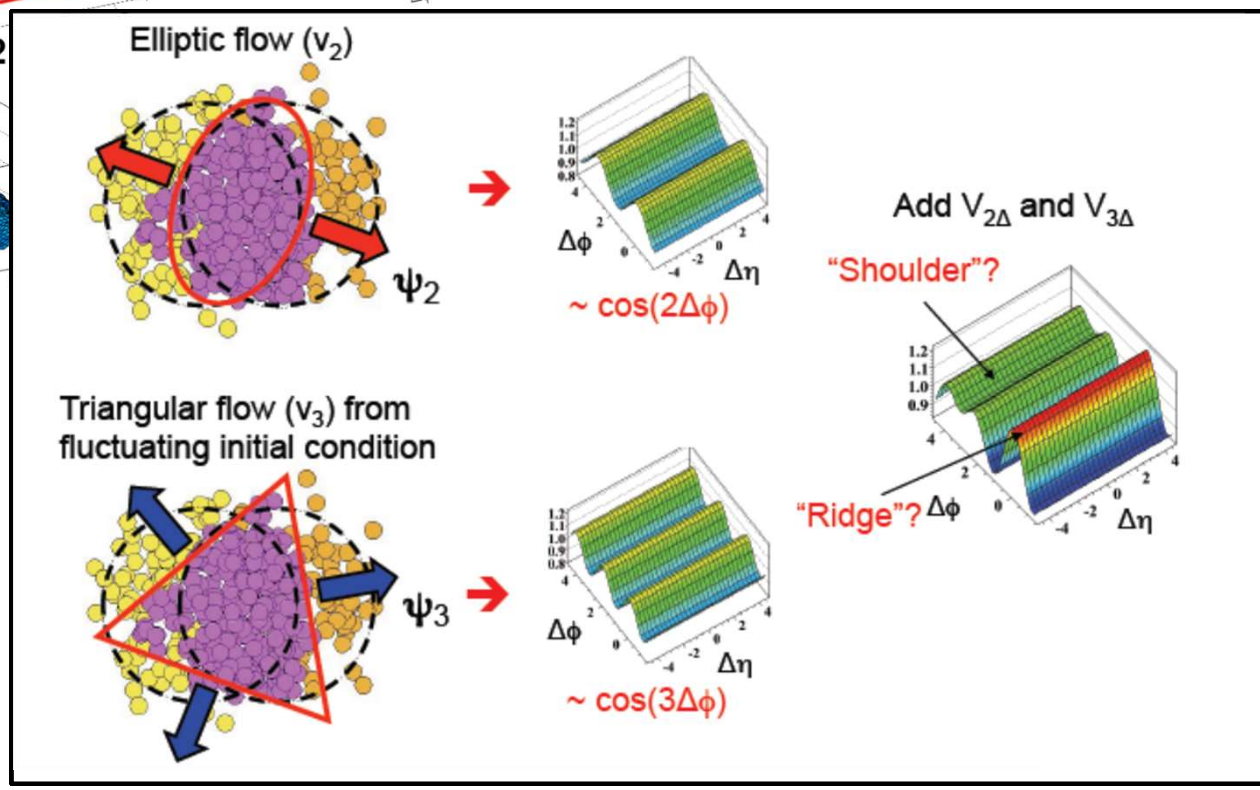


For particles from the same jet (red):

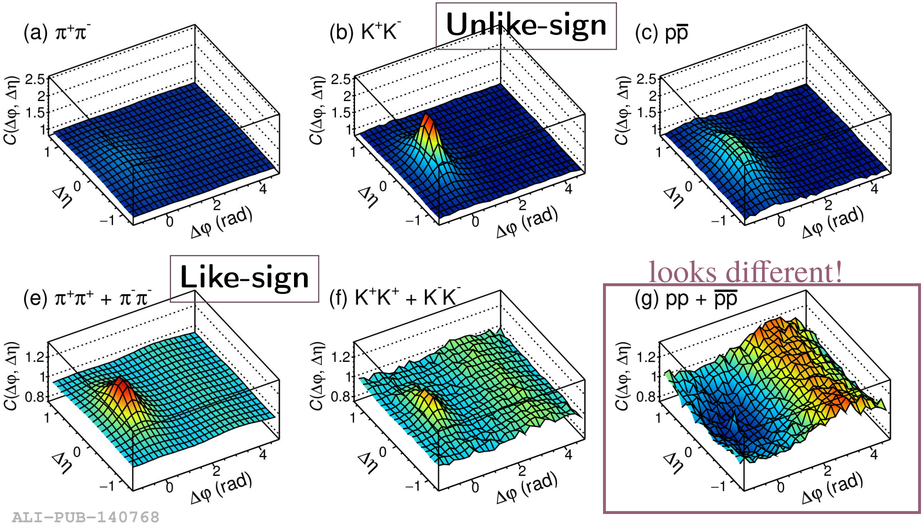
- centered at $\Delta\varphi = \Delta\eta = 0$

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





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



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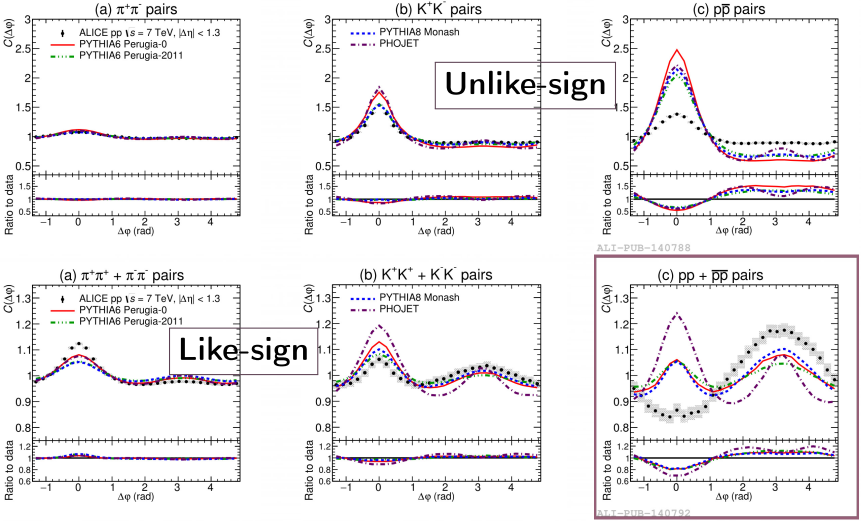
Mesons and baryons compared to MC models



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

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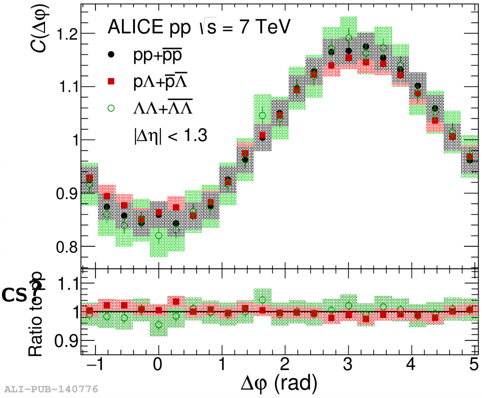
Baryon correlation puzzle

- **Other baryons?**
  - Anticorrelation is a common effect of all baryons;
- **Coulomb repulsion?**
  - Λ baryons are neutral → no Coulomb repulsion
- **Fermi-Dirac Quantum Statistics?**
  - **p** and Λ are not identical no effect from Fermi-Dirac QS



All features observed in pp are also seen for ΛΛ and pΛ correlations

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

Theoretical developments

Ł. Graczykowski,
Polish Heavy-Ion Workshop, Kielce 2023,
https://indico.cern.ch/event/891677/contributions/5682601/

1. Strong interaction, QS:
    1. M. Janik, Ł. Graczykowski, Phys.Rev.C 104 (2021) 5, 054909
2. AMPT
    1. L.Y. Zhang et al., Phys. Rev. C 98 (2018) 3, 034912
    2. L.Y. Zhang et al., Phys. Lett. B 829 (2022) 137063
3. PYTHIA
    1. N. Demazure, V. Gonzalez, F. Llanes-Estrada Few Body Systems 64 (2023) 57
    2. Y. Patley, B. Nandi, S. Dash, V. Gonzalez, C. Pruneau, https://arxiv.org/abs/2408.09923 (2024)
    3. L. Lönnblad, H., Euro.Phys.J.C Volume 83, 1105, (2023)
4. HERWIG
    1. PHENOmenal meeting, https://indico.cern.ch/event/1352906/

HERWIG
PHENOmenal meeting,
https://indico.cern.ch/event/1352906/

Wishlist of Herwig for ALICE

- All $C_{B,M}(\Delta\phi/\eta)$, $C_{B,\bar{B}}(\Delta\phi/\eta)$, $C_{B,B'}(\Delta\phi/\eta)$ and $C_{M,M'}(\Delta\phi/\eta)$ correlations, where $B, B' \in \{p, \Lambda, \Sigma^{(*)}, \Xi^{(*)}, \Delta, \Omega\}$ and $M, M' \in \{\pi, \eta, K, \rho, \phi\}$
- Especially same-and opposite-sign charge/flavour/baryon number
- Are charm and/or bottom particle correlations possible?
- Divided in multiplicity bins like [Ruggiano 2023; Acharya et al. 2023]
- Analyses for [Ruggiano 2023; Acharya et al. 2023] in `Rivet`

Slide from Stefan Kiebacher

Experimental developments in ALICE

Done:

1. Energy dependence (7 TeV → 13 TeV)
2. Multi-strange baryons (Ξ – hadron)
3. Multiplicity dependence
4. System dependence (pp, p-Pb, Pb-Pb)

In progress:

1. Correlations with Λ, Ξ, Ω in Run 3
2. Correlations p – ϕ (comparable mass, different # of quarks)

Outlook:

1. Correlations with heavy flavour
   - D-mesons
   - $\Lambda^{+}c$
2. Analysis of jet composition (how many baryons in jets?)

Angular correlations between charged Ξ and identified hadrons

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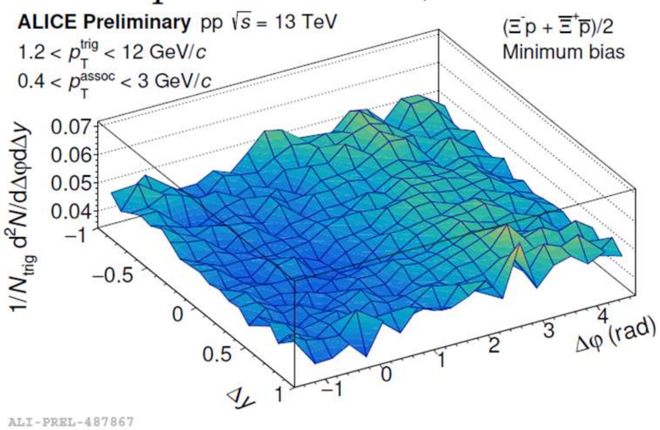
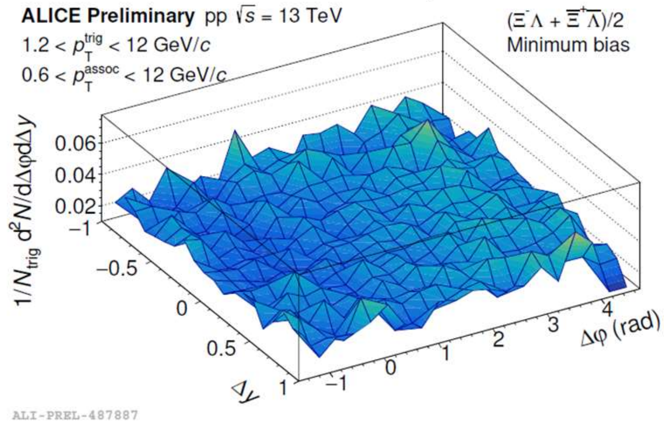
JHEP 09 (2024) 102

Ξ correlations for baryons

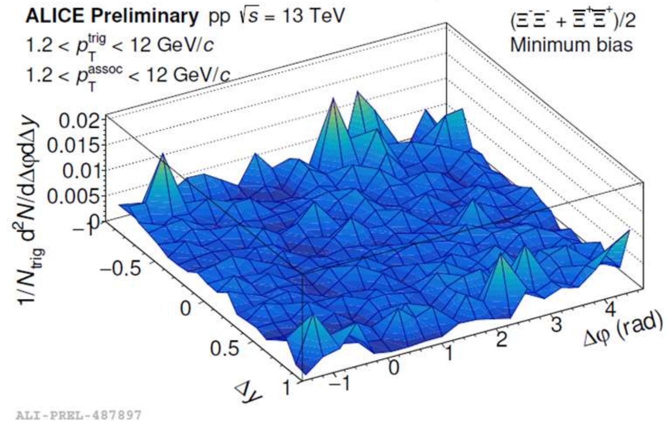
Ξ − p correlations, same *B*:



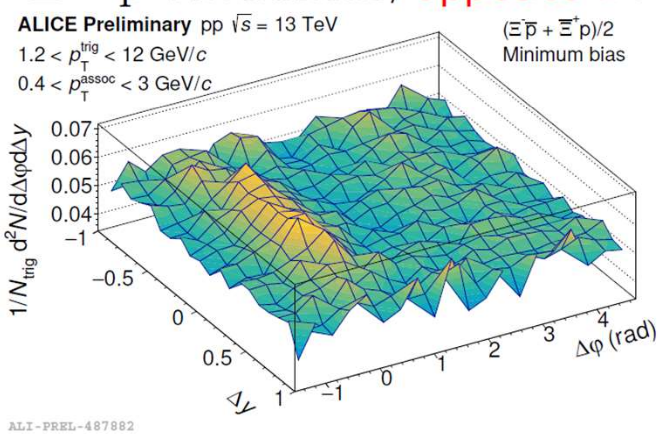
Ξ − Λ correlations, same *B*:



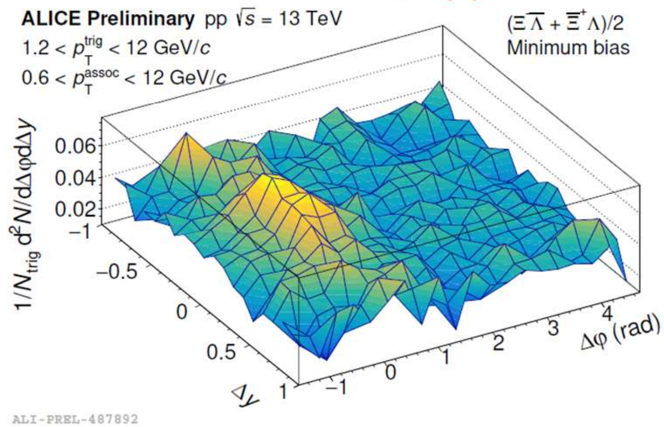
Ξ − Ξ correlations, same *B*:



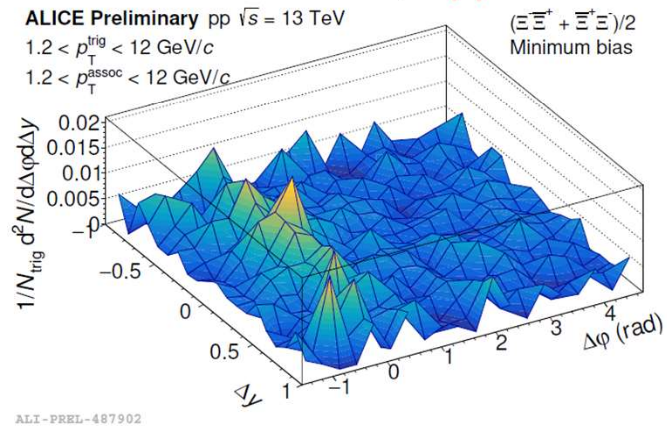
Ξ − p correlations, opposite *B*:



Ξ − Λ correlations, opposite *B*:



Ξ − Ξ correlations, opposite *B*:



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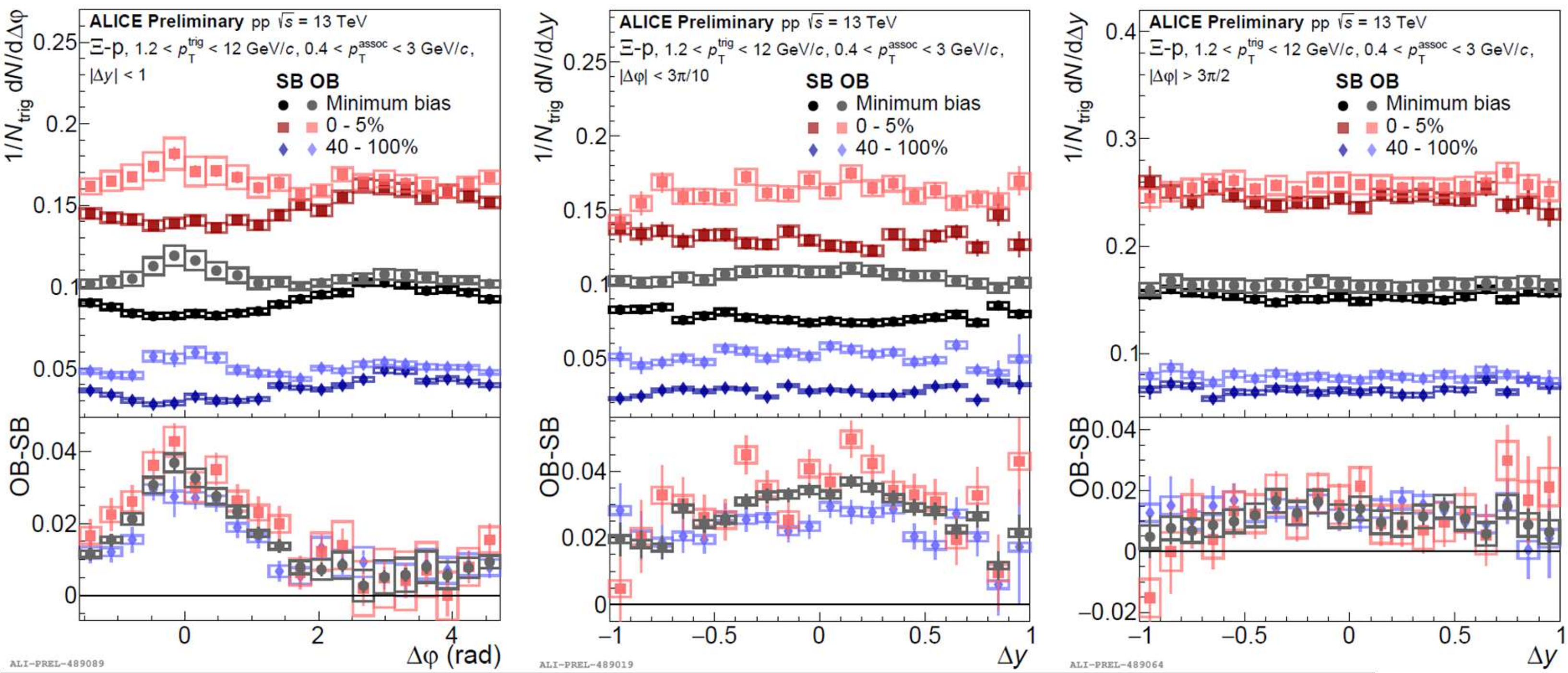
Ξ - p correlations, multiplicity dependence

Δφ projection:

Δy projection, near side:

Δy projection, away side:



- Projections
- Multiplicity dependence

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

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

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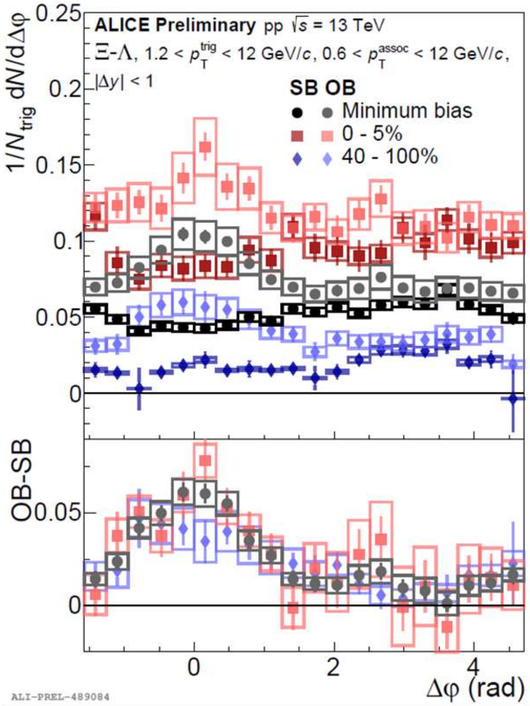
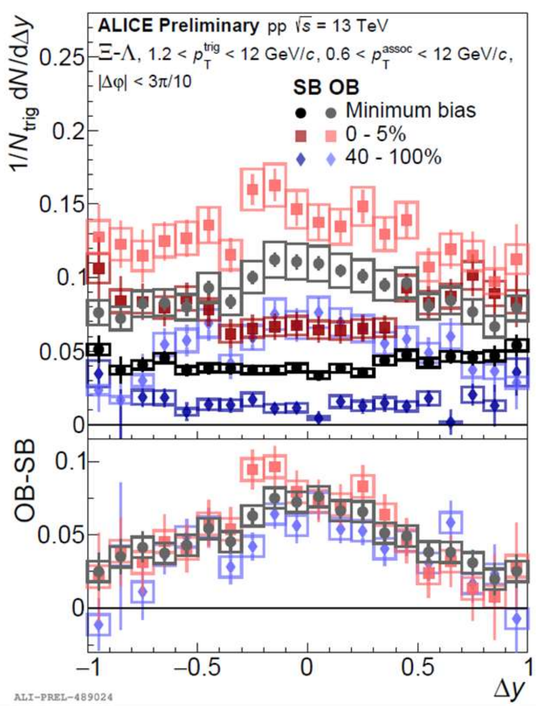
Ξ - Λ correlations, multiplicity dependence

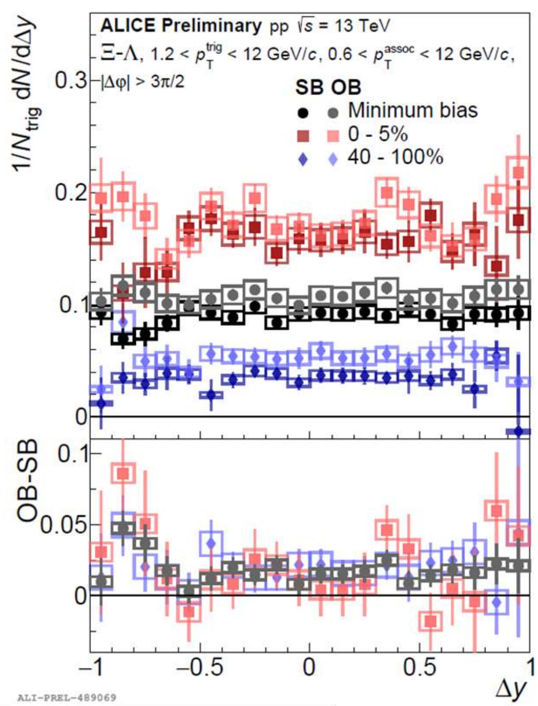
Δφ projection:



Δy projection, near side:



Δy projection, away side:



- Projections
- Multiplicity dependence

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

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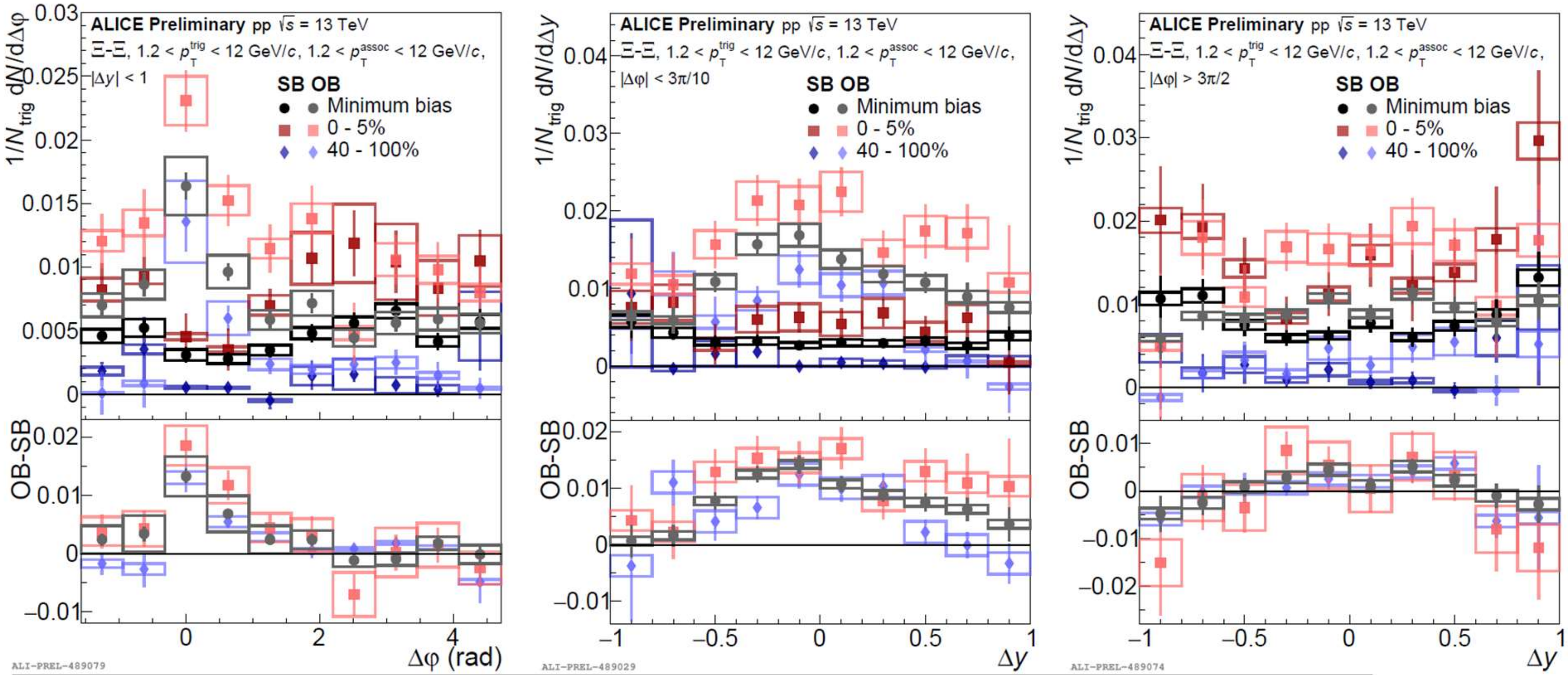
Ξ - Ξ correlations, multiplicity dependence

$\Delta\varphi$ projection: Δy projection, near side: Δy projection, away side:



- Projections
- Multiplicity dependence

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

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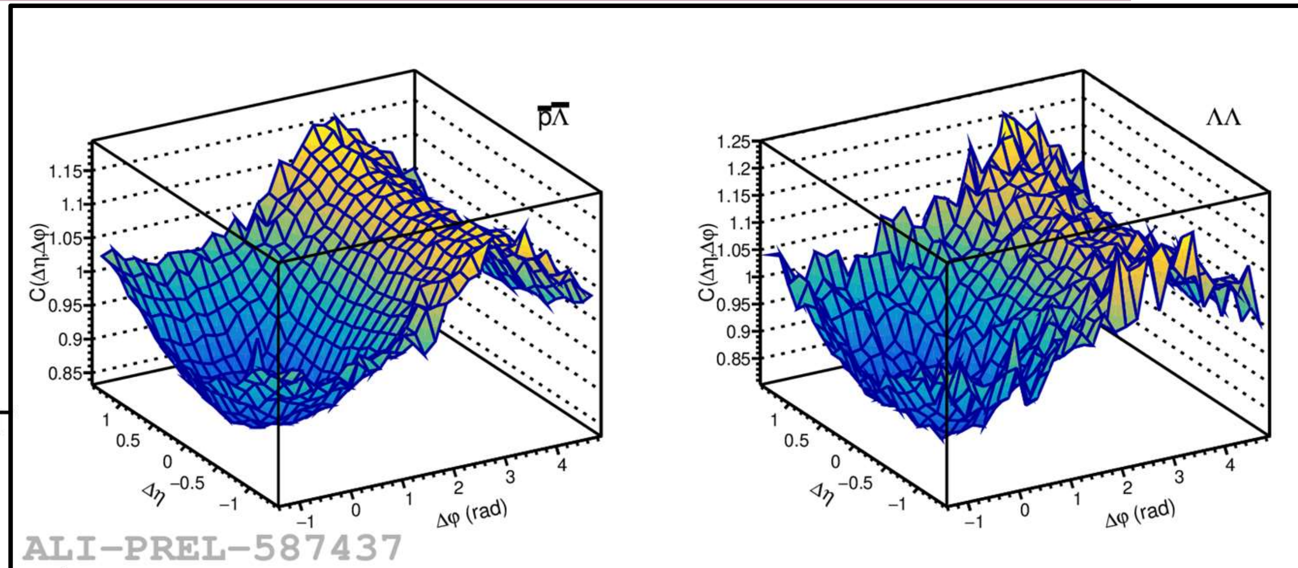
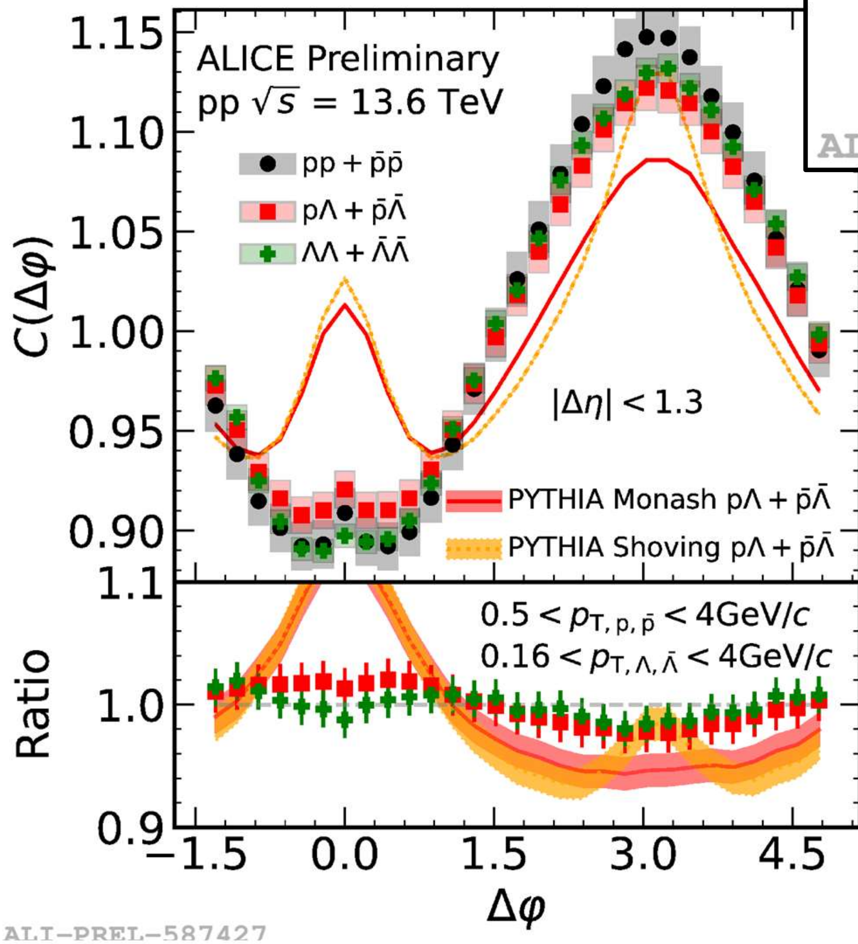
Angular correlations with strange hadrons





Run 3 analysis
in progress…

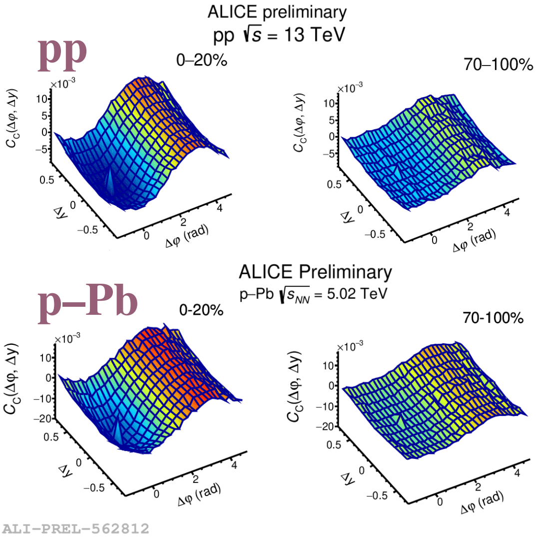
→ Correlations with Λ, Ξ, Ω

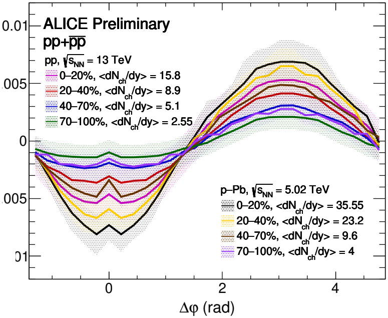
Multiplicity and system (pp / p-Pb / Pb-Pb) dependence

Publication in progress...

$\Delta y \Delta\varphi$ correlation functions

Like-sign protons





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

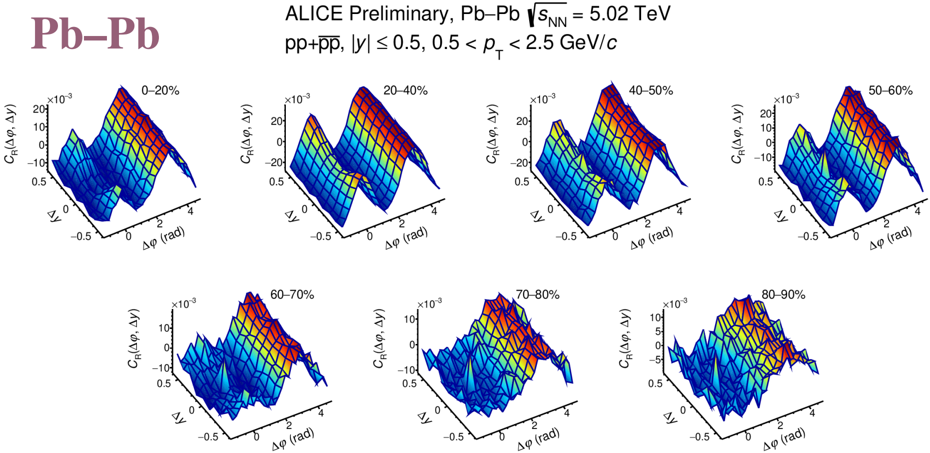
- It becomes stronger for higher multiplicity classes.

https://arxiv.org/abs/2403.02549

$\Delta y \Delta \varphi$ correlation functions

Like-sign protons

Pb–Pb



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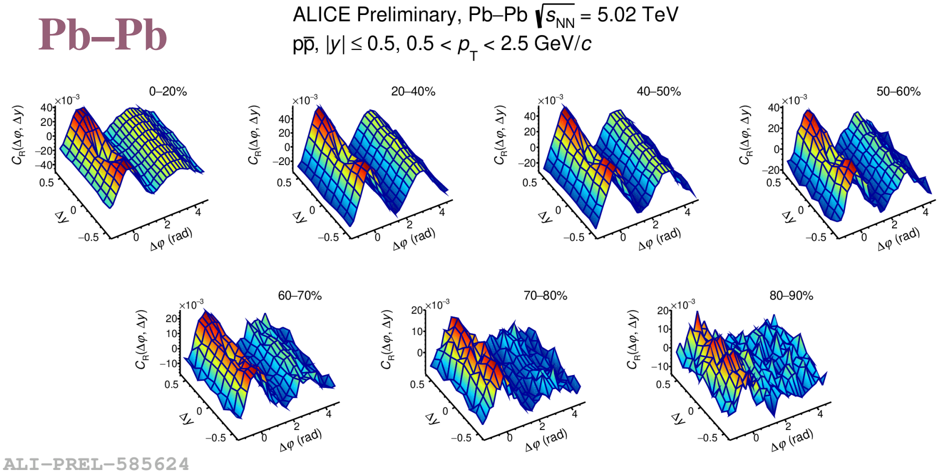
- The azimuthal flow effect appears, especially at the mid centrality classes;
- The anticorrelation is strong for all centralities, shows a clear dip

$\Delta y \Delta \varphi$ correlation functions

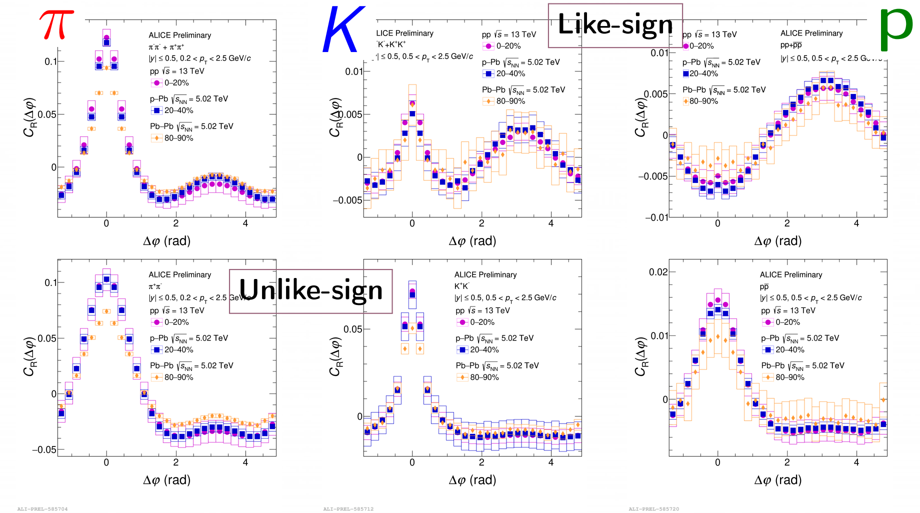
Unlike-sign protons

Pb–Pb



- The azimuthal flow effect appears at the mid centrality classes;
- The annihilation phenomenon – a sharp dip in (0,0) – is observed in all centralities

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

Conclusions

- Plethora of new experimental results:
  - The study of **correlations with Ξ baryons** shows that the anti-correlation effect persists also for heavier, multi-strange baryons (for $p-\Xi$, $\Lambda-\Xi$, $\Xi-\Xi$).
  - 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.

Outlook

- Ongoing studies:
  - Study of p–ϕ pairs (similar mass, but no baryon number).
  - Study of baryonic particles pairs at the maximum energy and luminosity provided in Run 3; comparison of p–p, $p - \Xi$, $p - \Omega$, etc.; study the influence of strangeness.
- Future plans:
  - Study of charm particle correlations (D–mesons and Λ_c^+ baryons with identified particles).
  - Jet composition studies. Differences in baryon/meson production in quark and gluon jets.

Thank you

BACKUP SLIDES

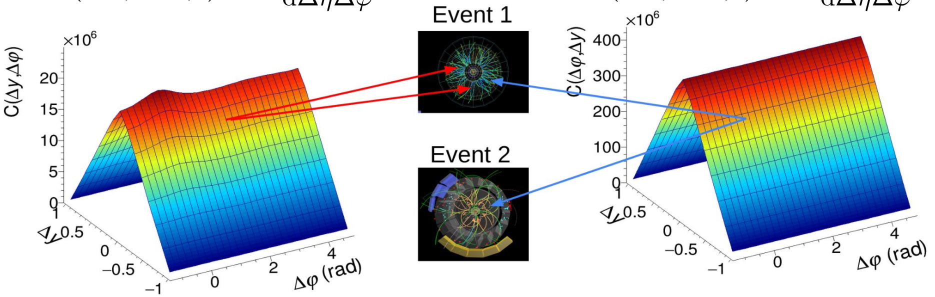
$\Delta\eta\Delta\varphi$ experimental correlation function

Signal distribution

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

Background distribution

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



Same-event pairs

Mixed-event pairs

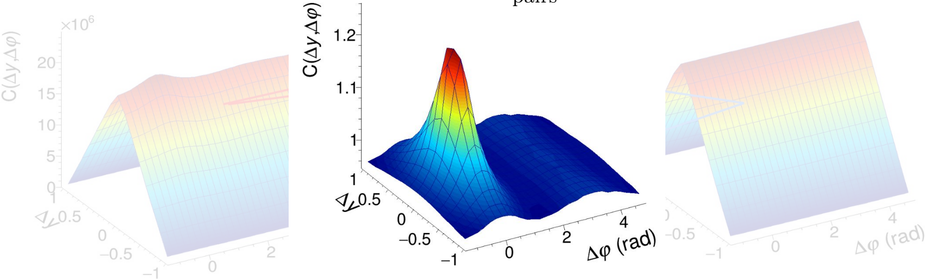
$\Delta\eta = \eta_1 - \eta_2$

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

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

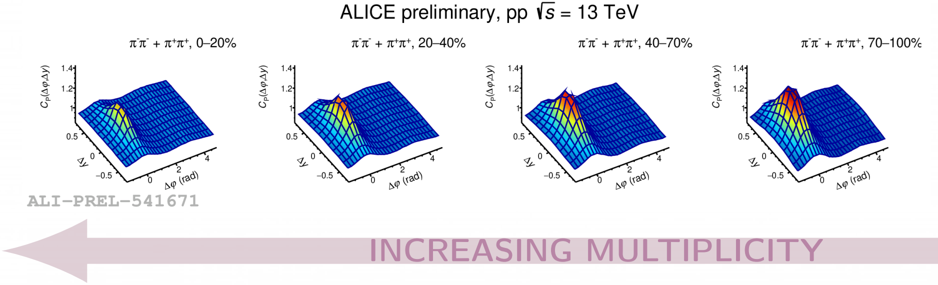
Probability ratio correlation function

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



Limitation of the probability ratio definition

- **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/N?**
  - Use a **rescaled two-particle correlation function** ($\mathrm{C_R}$)

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

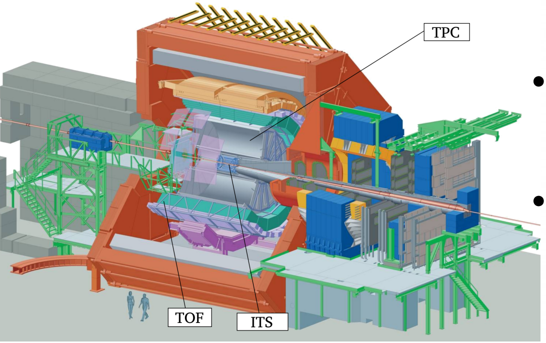
  - $N_\mathrm{av} = \frac{1}{2\pi}\left\langle \frac{\mathrm{d}N_\mathrm{a}}{\mathrm{d}\varphi} \right\rangle$ is the average number of particle type produced in the analyzed multiplicity/centrality classes;
  - *a* is the particle type analyzed (PID);
  - definition inspired by STAR Collaboration

$$R_2(\Delta y, \Delta\varphi) = \frac{\langle n \rangle^2}{\langle n(n-1) \rangle} \frac{\rho_2(\Delta y, \Delta\varphi)}{\rho_1(y_1, \varphi_1)\rho_1(y_2, \varphi_2)} - 1$$

Physical Review C 101, 014916 (2020)

Data samples & settings

- 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.

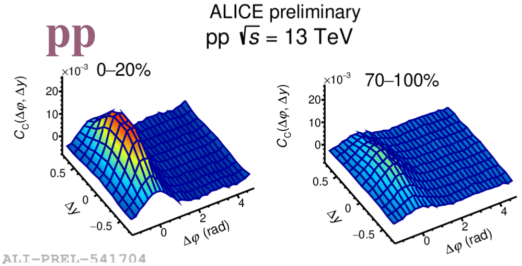


- Tracking:
  - Inner Tracking System (**ITS**);
  - Time Projection Chamber (**TPC**);
- Particle Identification:
  - Time Projection Chamber (**TPC**);
  - Time of Flight (**TOF**);
- Kinematic cuts:
  - $|y| < 0.5$;
  - pions : $0.2 < p_{\mathrm{T}} < 2.5$ GeV/c;
  - kaons : $0.5 < p_{\mathrm{T}}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

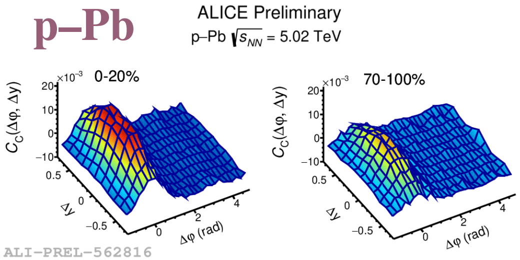
$\Delta y \Delta \varphi$ correlation functions

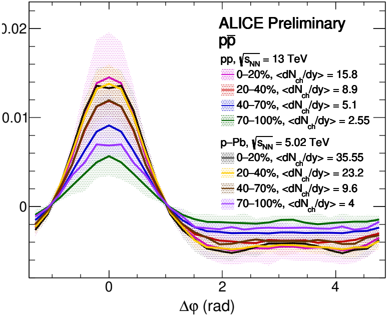
Unlike-sign protons

pp



p–Pb





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

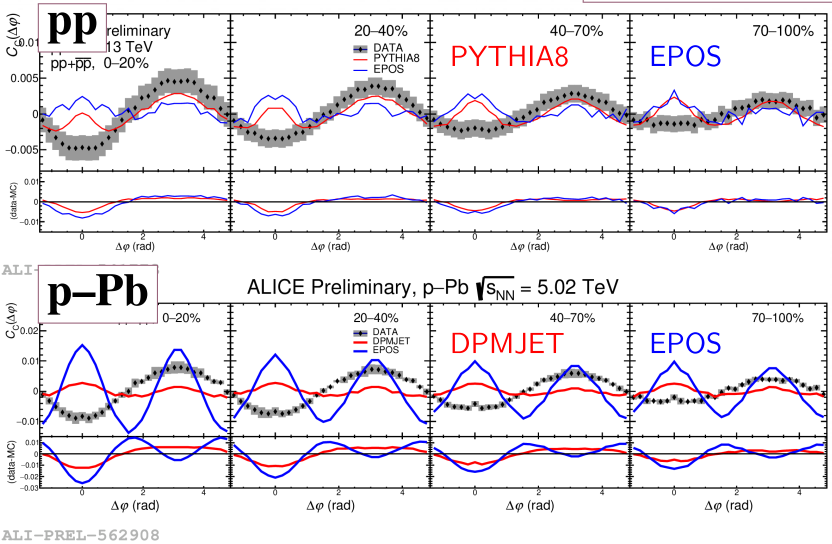
https://arxiv.org/abs/2403.02549

Can baryonic correlations be reproduced by models?

Model comparison in small systems

[Link presentation WPCF 2023]

Like-sign protons

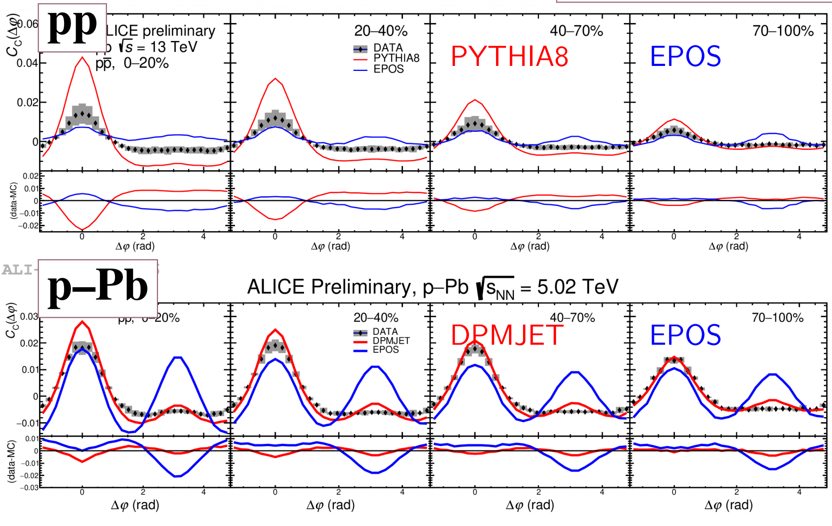


The models fail to reproduce the anticorrelations in both pp and p–Pb collision systems

Link presentation WPCF 2023

Model comparison in small systems

Unlike-sign protons



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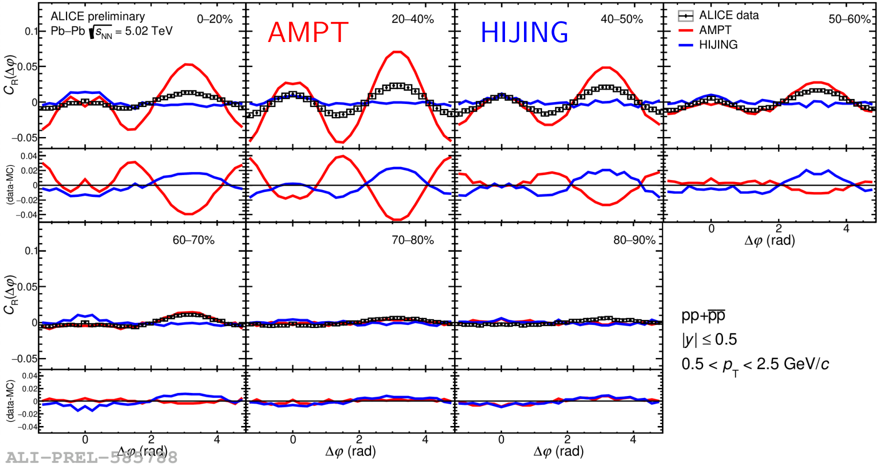
The models qualitatively reproduce the near-side region, but not the away-side.

Model comparison in Pb–Pb

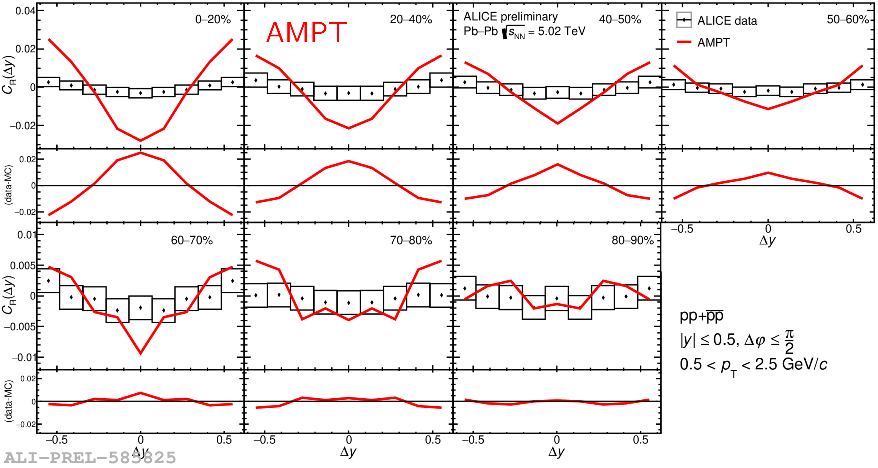
Like-sign protons



- 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

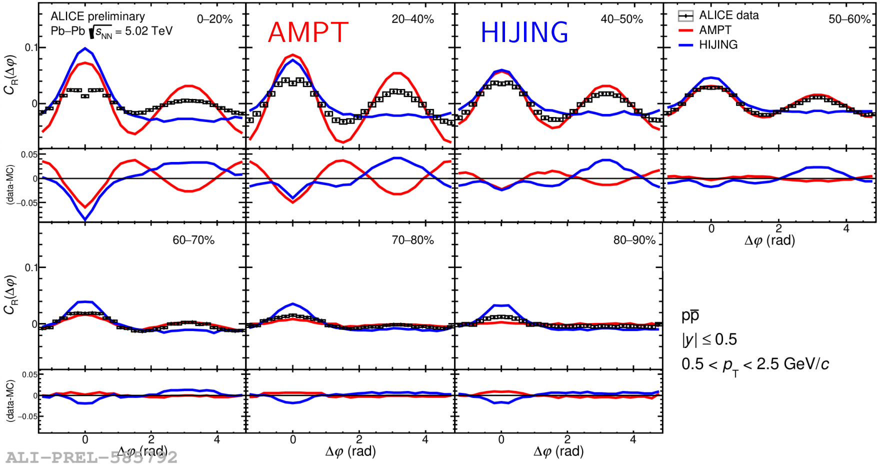
Like-sign protons



- AMPT model reproduces qualitatively the anticorrelation but not quantitatively;

Model comparison in Pb–Pb

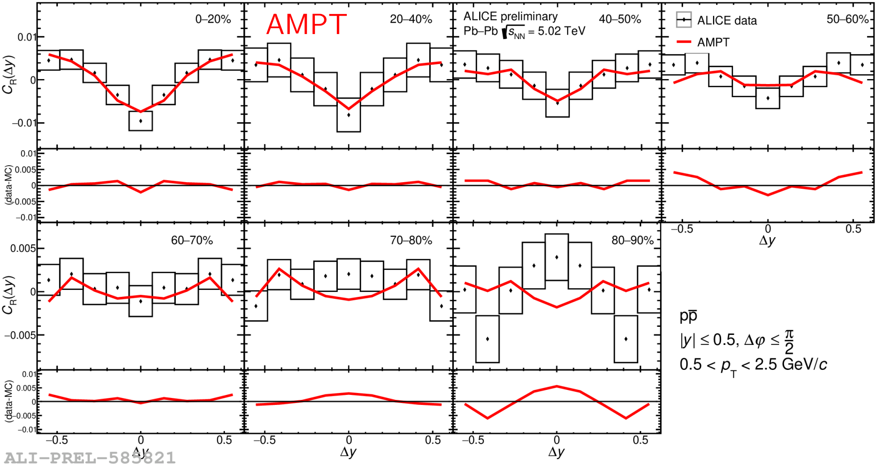
Unlike-sign protons



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

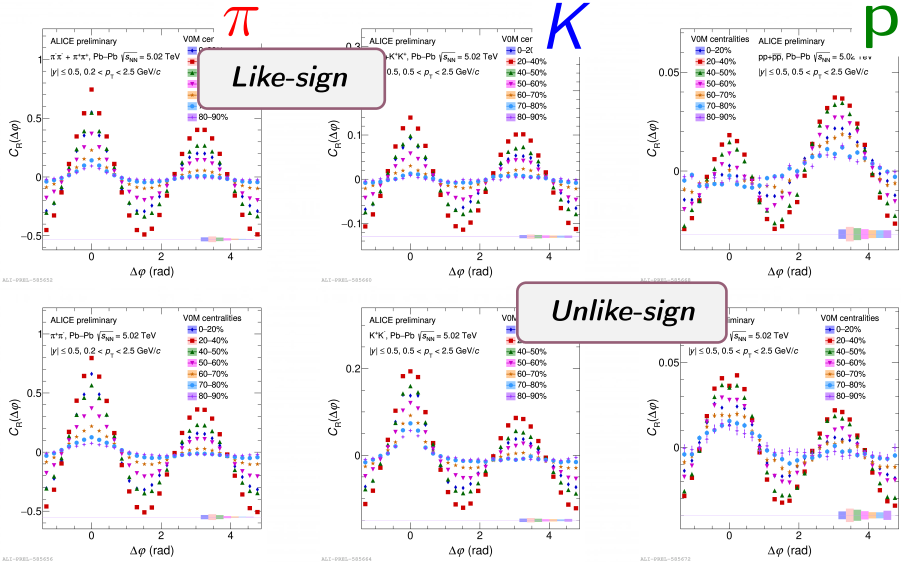
Model comparison in Pb–Pb

Unlike-sign protons



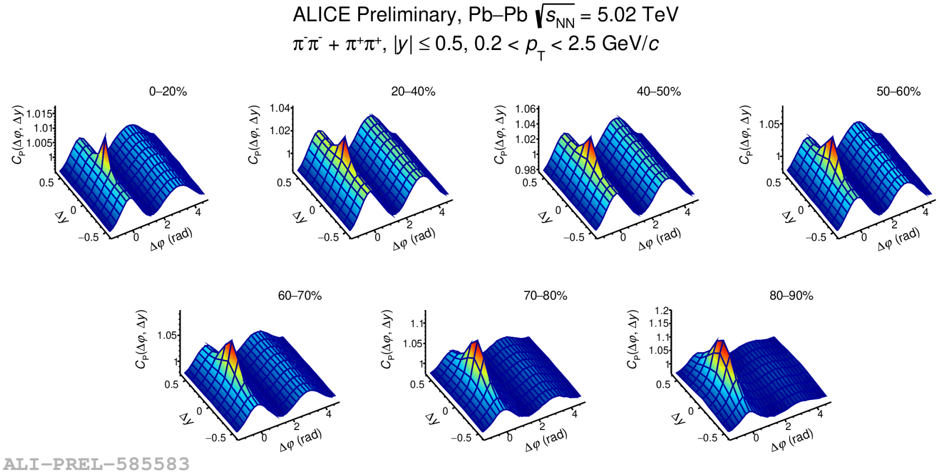
- AMPT model reproduces quite well the data

An overview of the meson and baryon in Pb–Pb



$\Delta y \Delta \varphi$ correlation functions

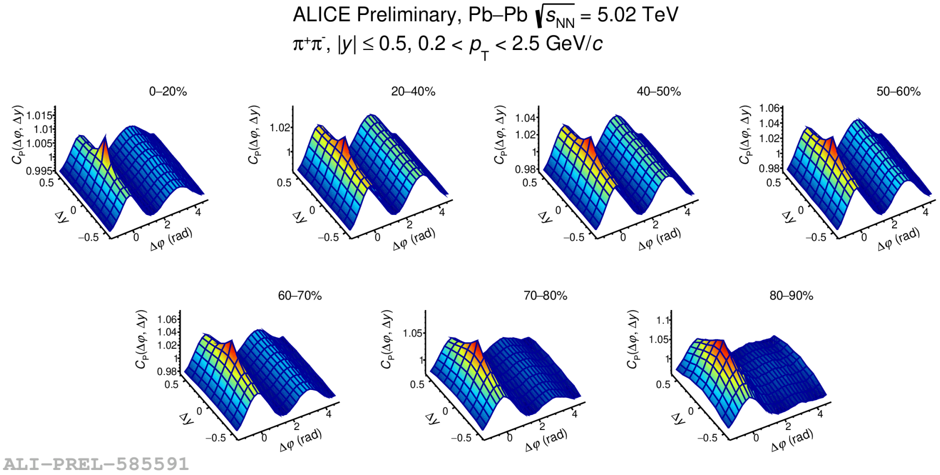
Like-sign pions



- 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;

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

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

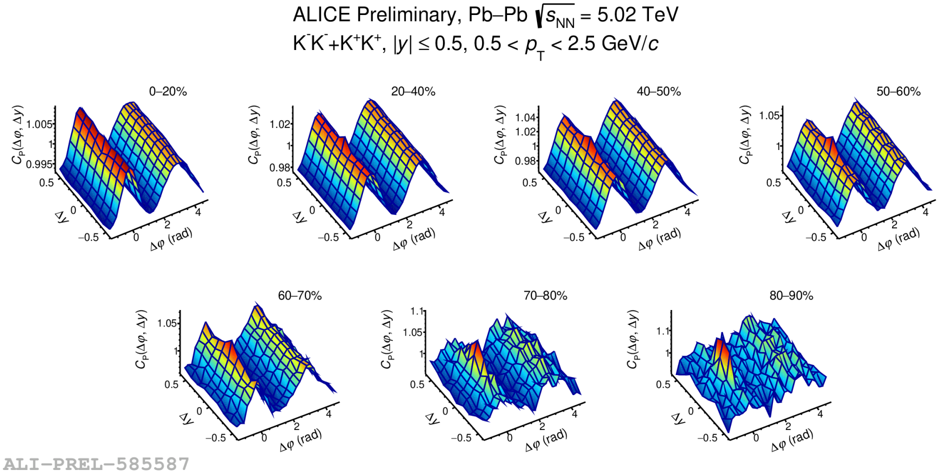
collision system	$dN_{ch}/d\eta$						
pp	0–20%	20–40%	40–70%			70-100%	
	19.1	9.18	5.1			2.55	
p–Pb	0–20%	20–40%	40–70%			70-100%	
	35.55	23.2	9.6			4	
Pb–Pb	0–20%	20–40%	40–50%	50–60%	60–70%	70–80%	80–90%
	1570	649	318	183	96.3	44.9	17.5

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

$\Delta y \Delta \varphi$ correlation functions

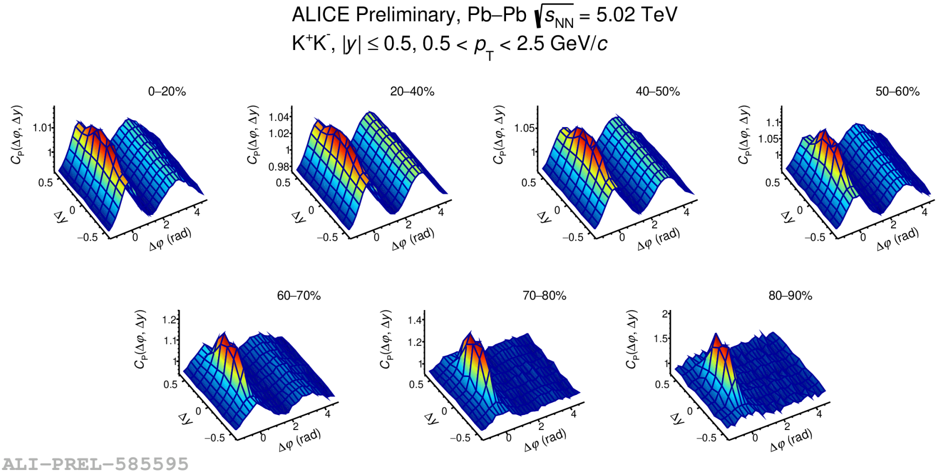
Like-sign kaons



- 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



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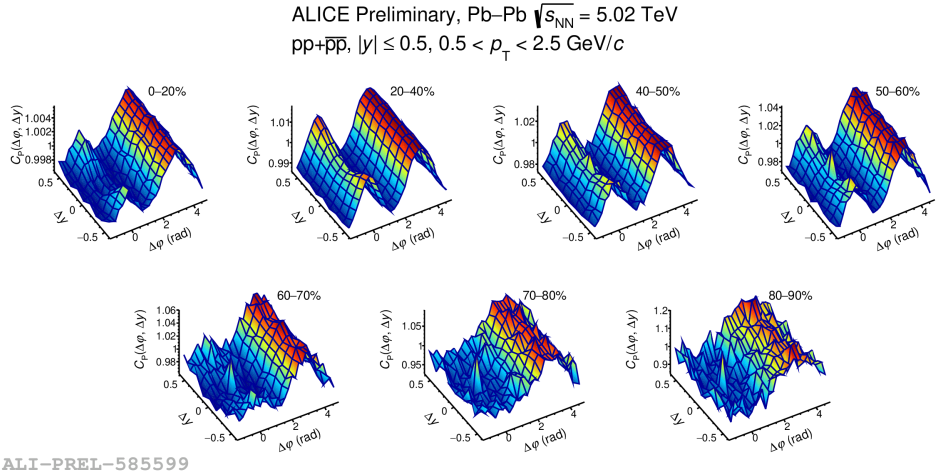
$\Delta y \Delta \varphi$ correlation functions

Like-sign protons



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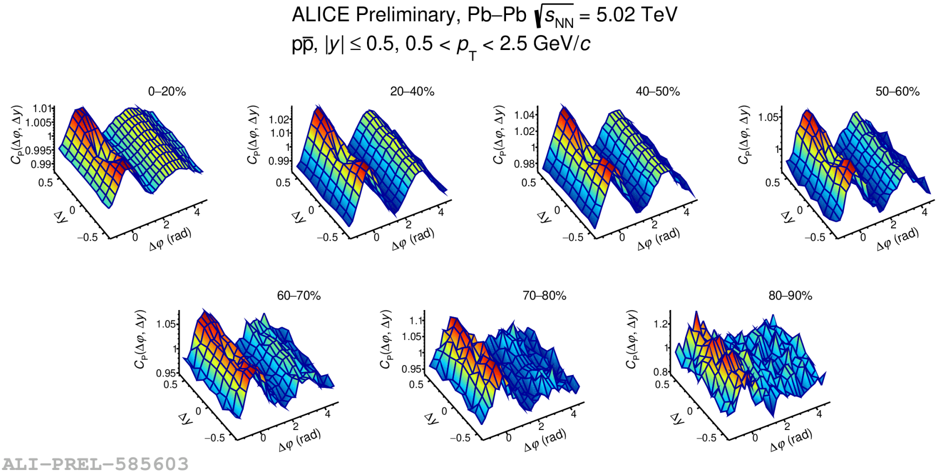
$\Delta y \Delta \varphi$ correlation functions

Unlike-sign protons



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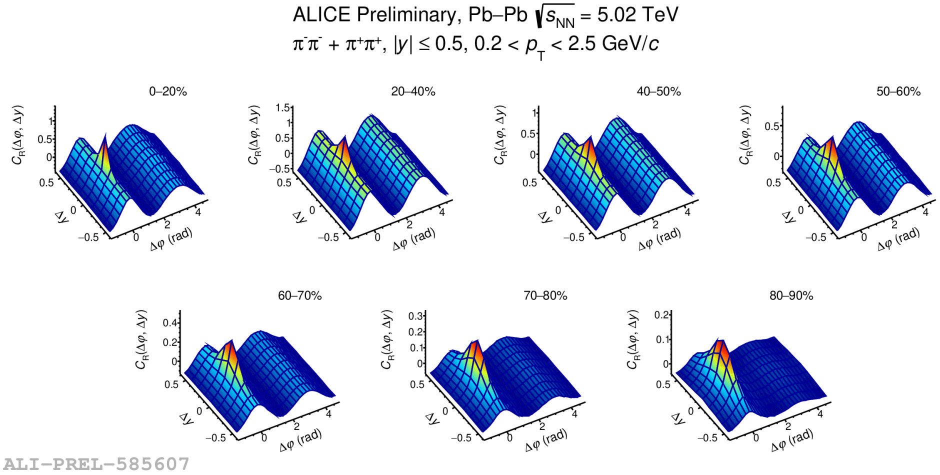
$\Delta y \Delta \varphi$ correlation functions

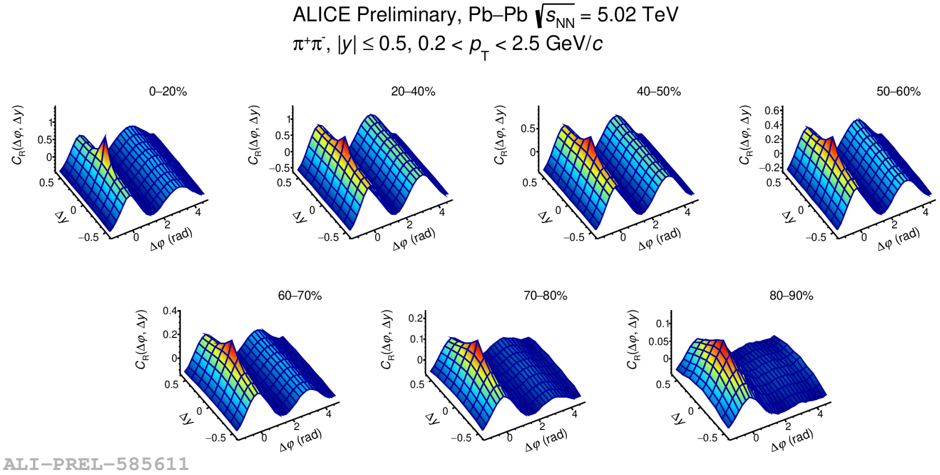
Like-sign pions



- 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



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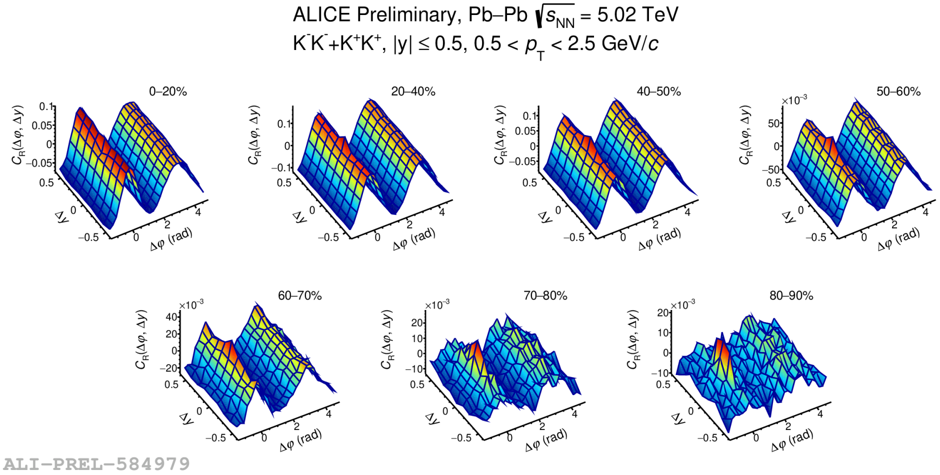
Like-sign kaons



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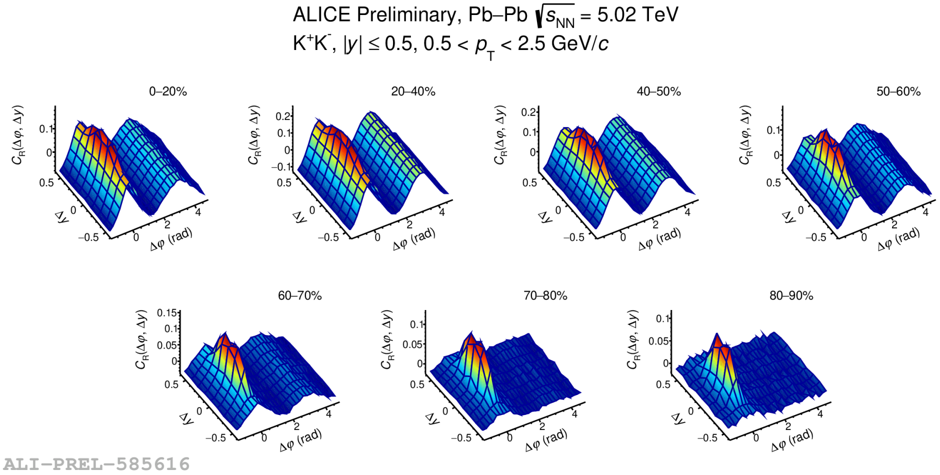
Unlike-sign kaons



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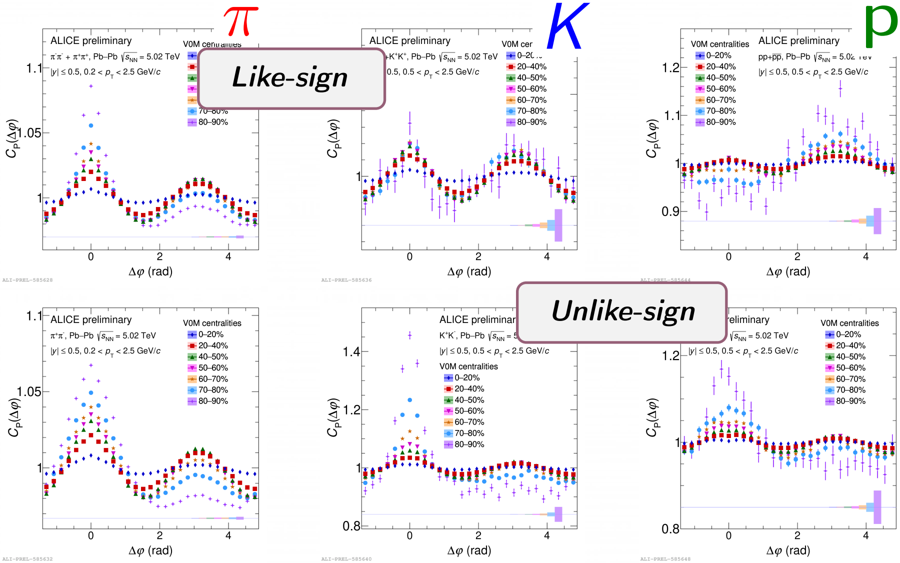
An overview of the meson and baryon in Pb–Pb

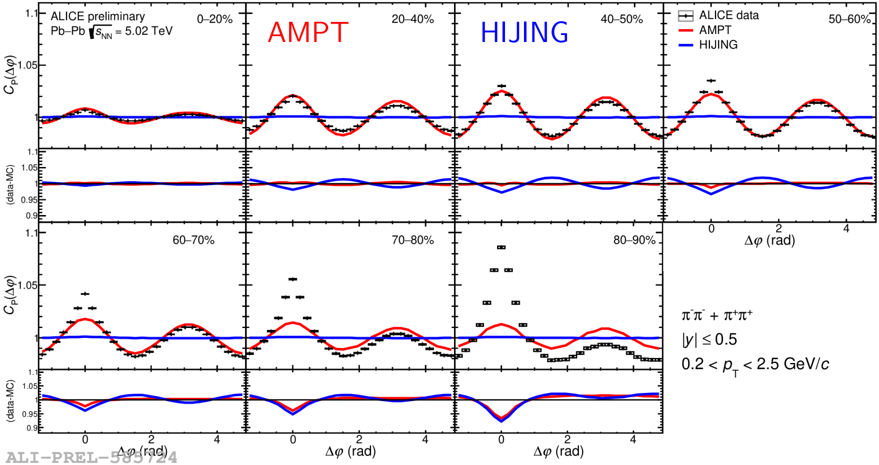


Projection on $\Delta\varphi$ using probability ratio definition

Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign pions

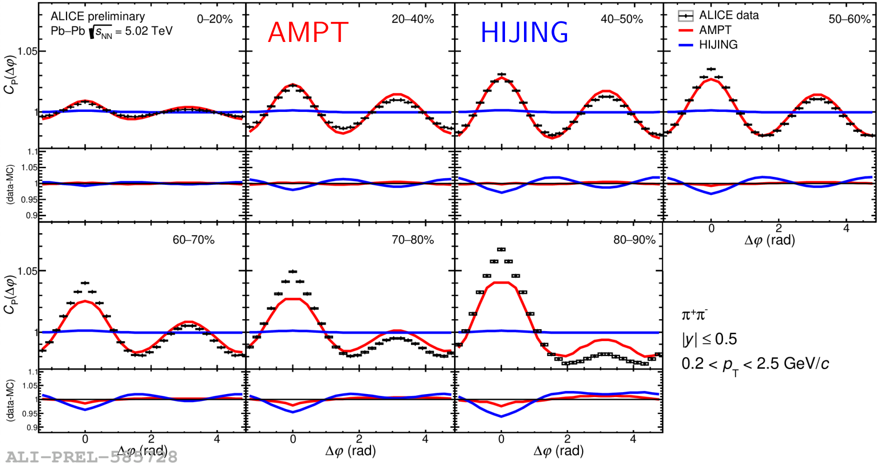


- AMPT model reproduce the data qualitatively but not quantitatively;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign pions



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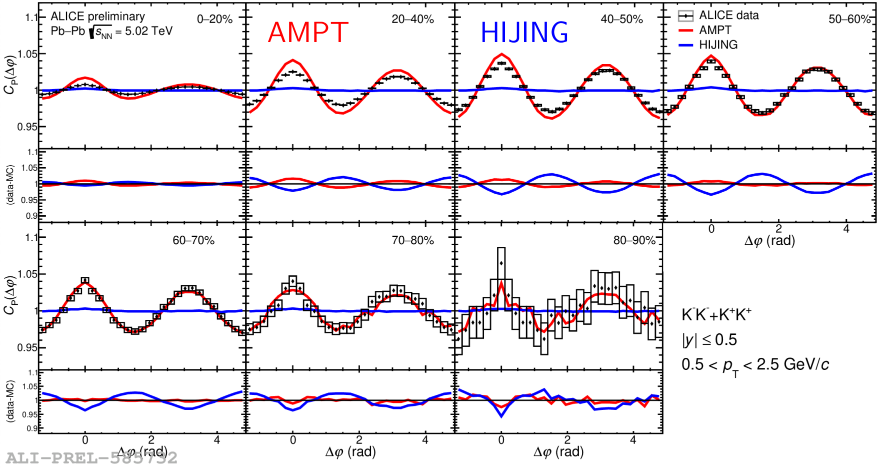
Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign kaons



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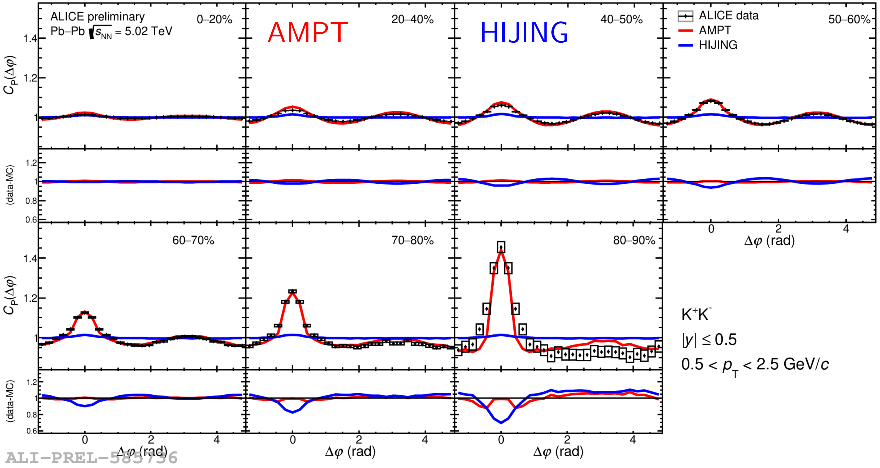
PROBABILITY ratio

Model comparison in Pb–Pb

Unlike-sign kaons



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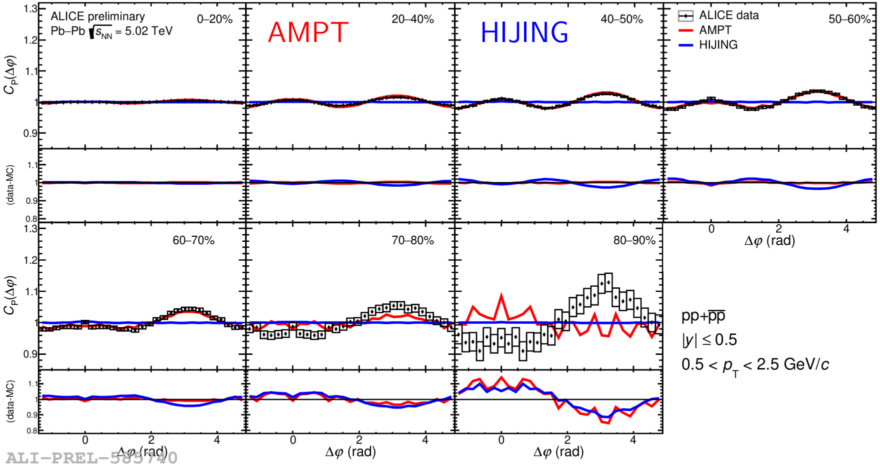
Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign protons

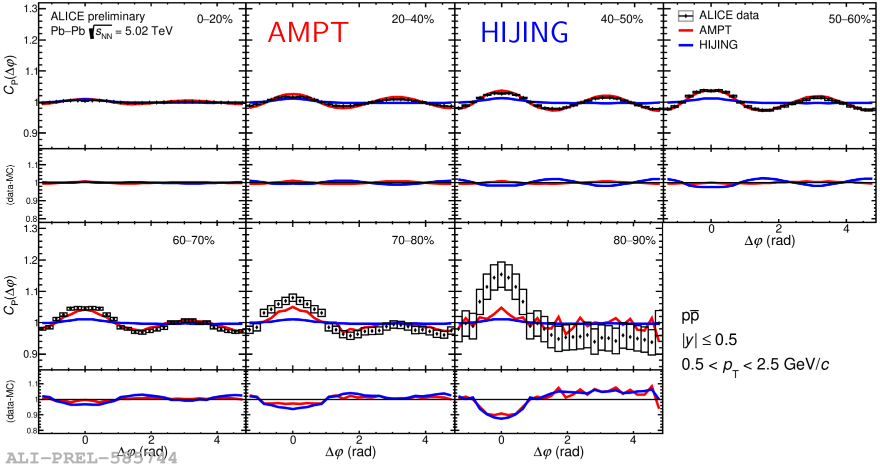


- AMPT model can't reproduce the anticorrelation;
- HIJING fail to reproduce the data
  - anisotropic flow not included in the model.

Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign protons



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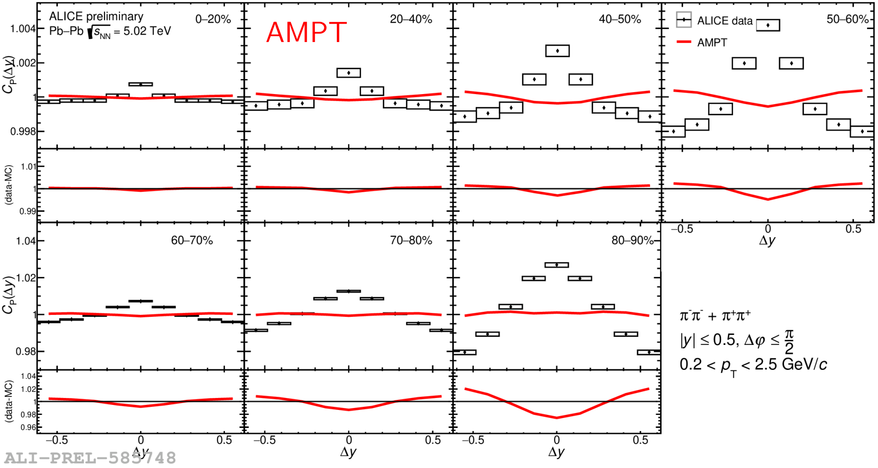
Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign pions



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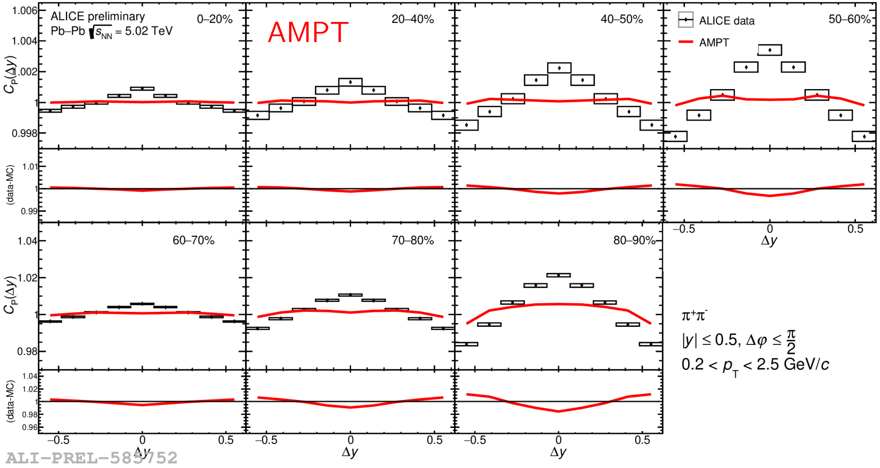
Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign pions



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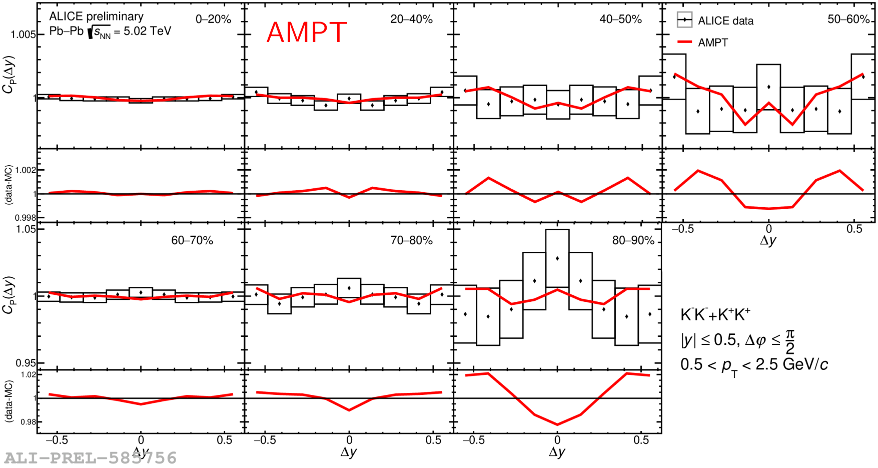
Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign kaons



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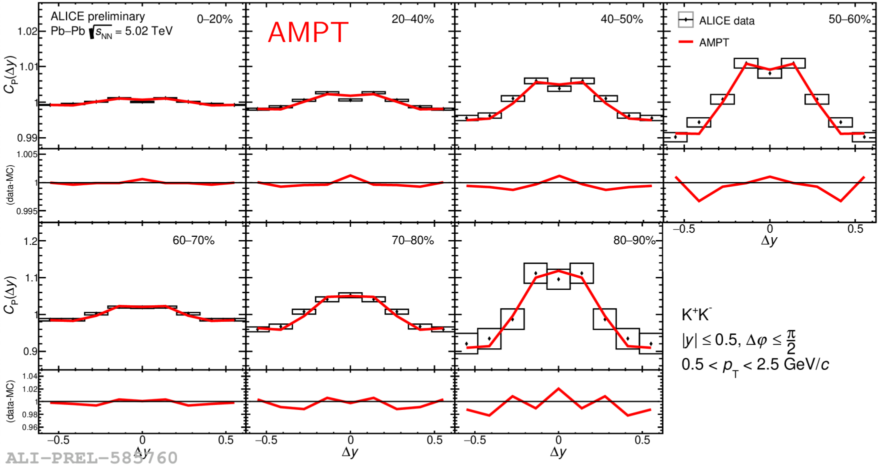
Model comparison in Pb–Pb

PROBABILITY ratio

Unlike-sign kaons



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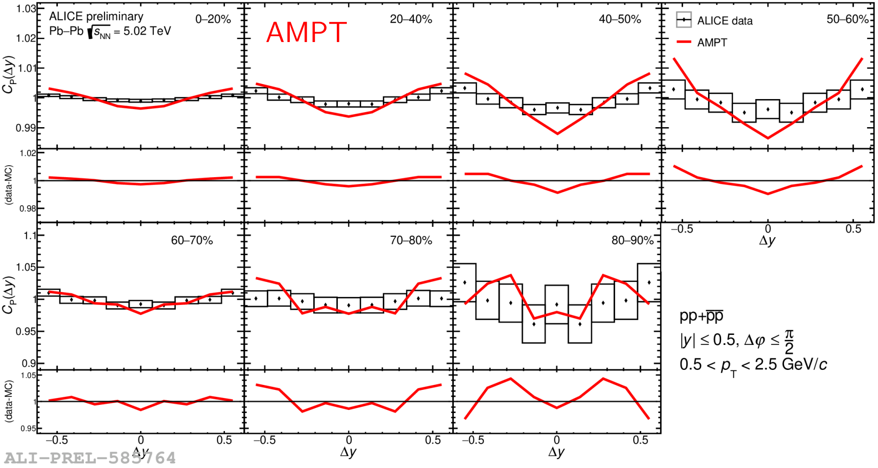
Model comparison in Pb–Pb

PROBABILITY ratio

Like-sign protons

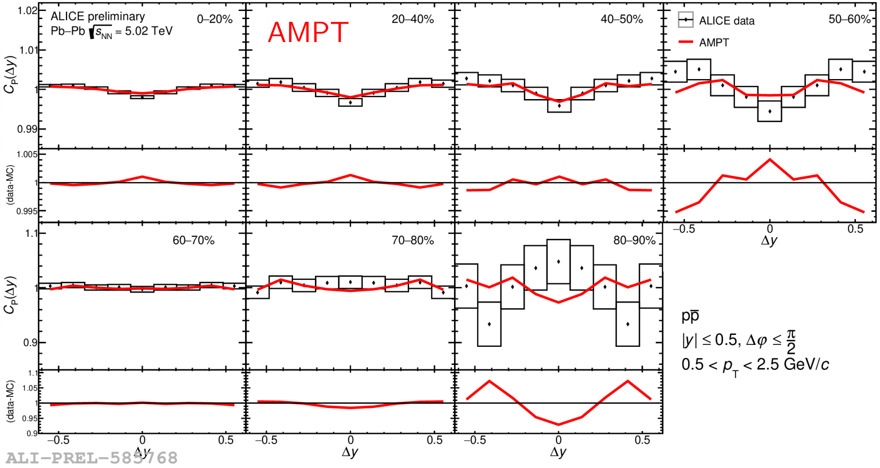


- AMPT model can reproduce qualitatively well the near side region;

PROBABILITY ratio

Model comparison in Pb–Pb

Unlike-sign protons



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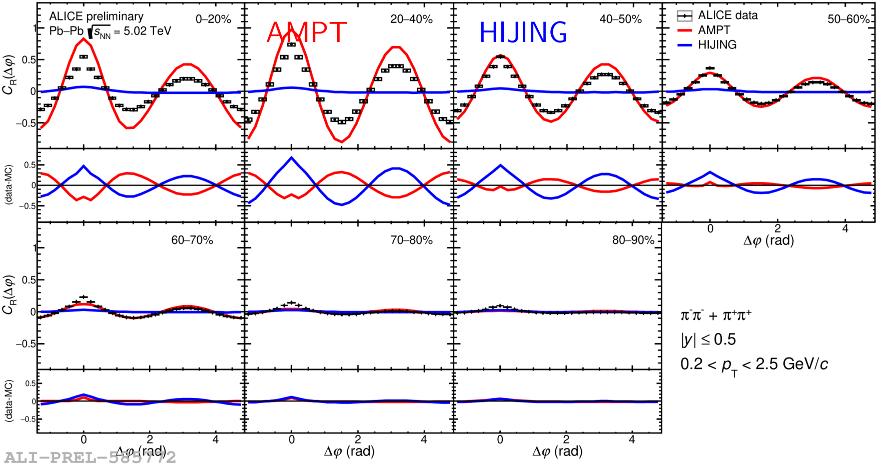
Model comparison in Pb–Pb

Rescaled two-particle CF

Like-sign pions



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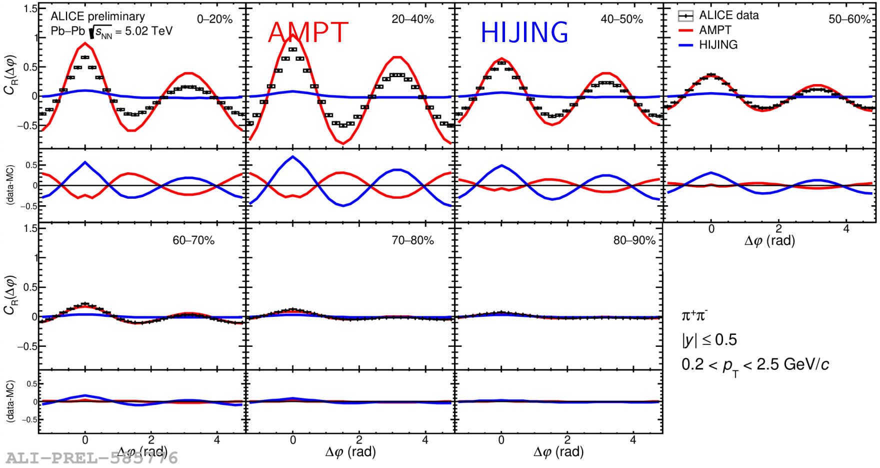

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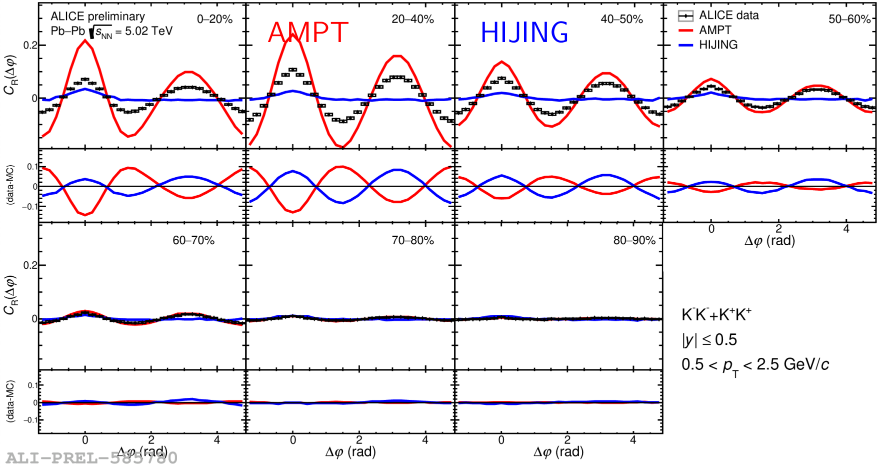

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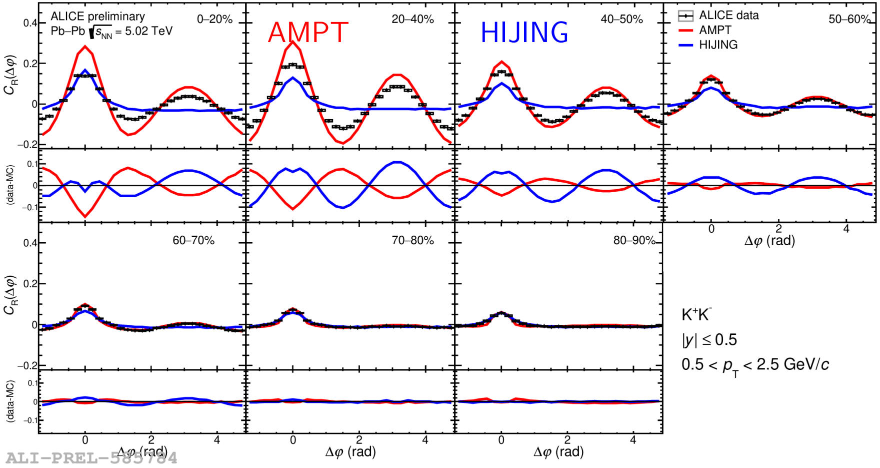

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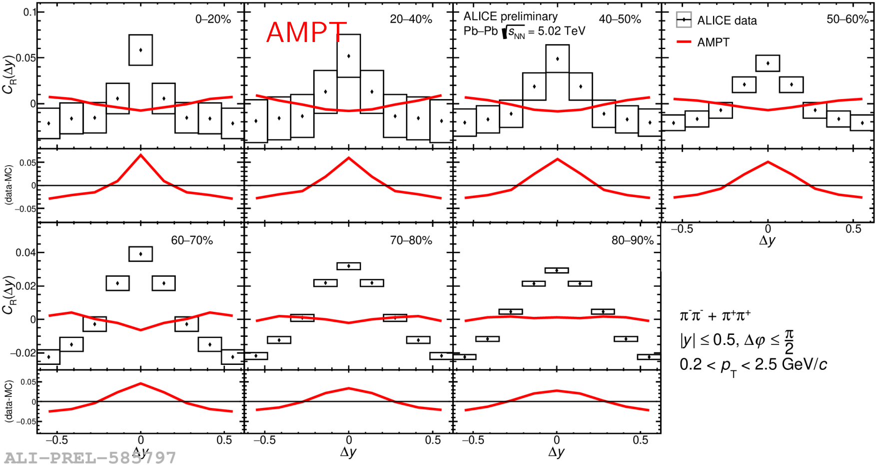

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Model comparison in Pb–Pb

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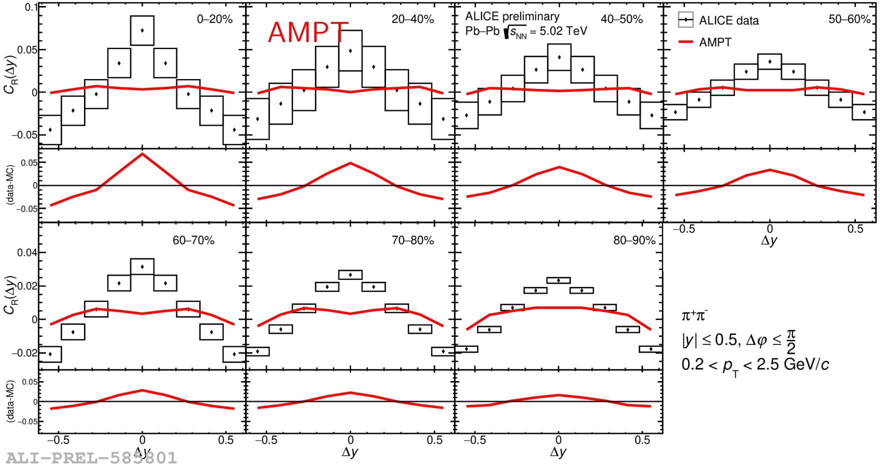

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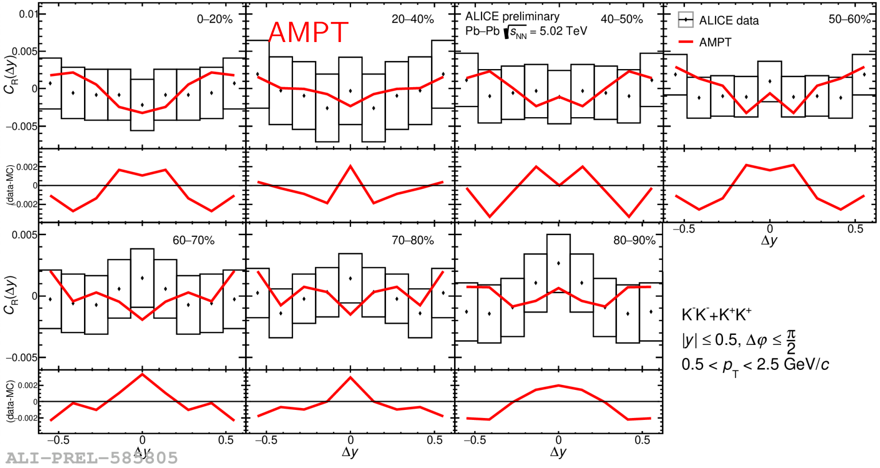

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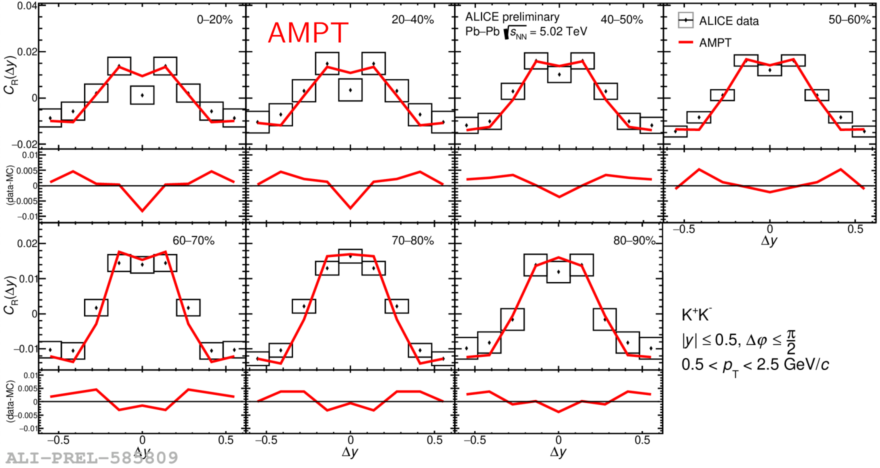
Model comparison in Pb–Pb

Rescaled two-particle CF

Unlike-sign kaons



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