Lunds Universitet

SQM 2022

The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

ALICE

Measurement of charge, strangeness, and baryon number balance functions in pp and Pb–Pb collisions in ALICE

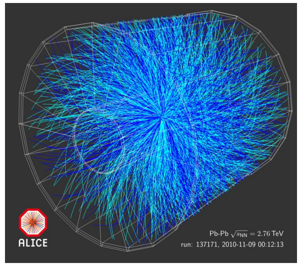
20th International Conference on Strangeness in Quark Matter (SQM 2022)
13–17 Jun 2022, Busan, Republic of Korea

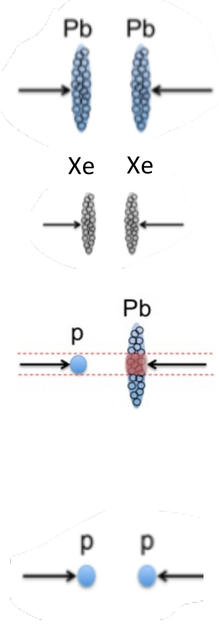
Sumit Basu (On behalf of the ALICE Collaboration)

Lund University, Sweden

Lund University

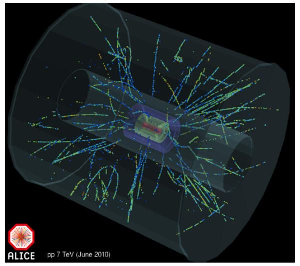
Event Display Pb–Pb





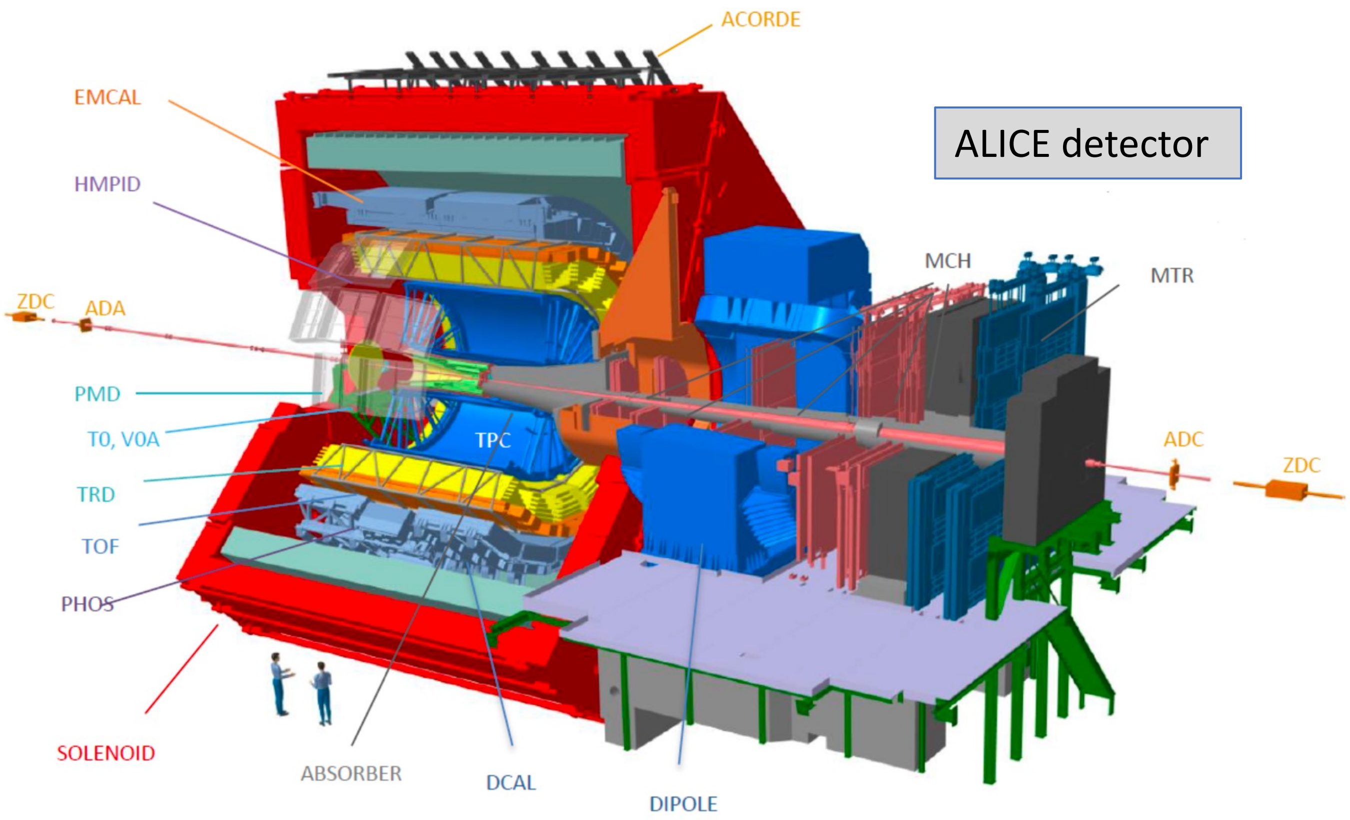
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02
Xe-Xe	2017	5.44
p-Pb	2013 2016	5.02 5.02, 8.16
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13

Run 1 Run 2



Event Display pp

ALICE detector

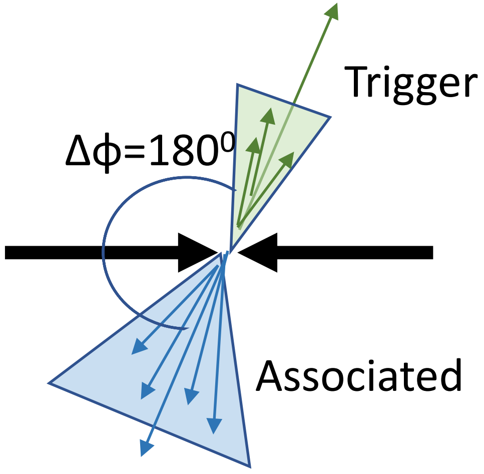


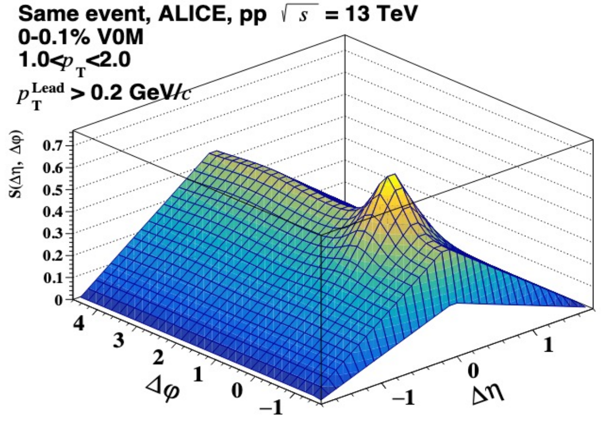
Technique

1. Angular correlation between trigger and associated particles is mesured:

$$C(\Delta\varphi,\Delta\eta) = \frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\varphi d\Delta\eta} = \frac{S(\Delta\varphi,\Delta\eta)}{M(\Delta\varphi,\Delta\eta)}$$

$$\Delta\varphi = \varphi_{trig} - \varphi_{assoc}\,, \Delta\eta = \eta_{trig} - \eta_{assoc}$$





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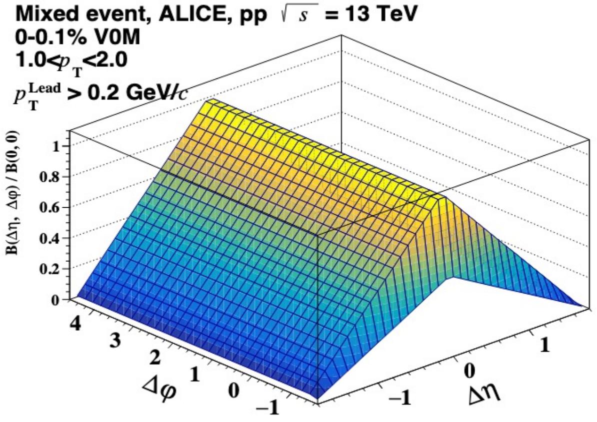

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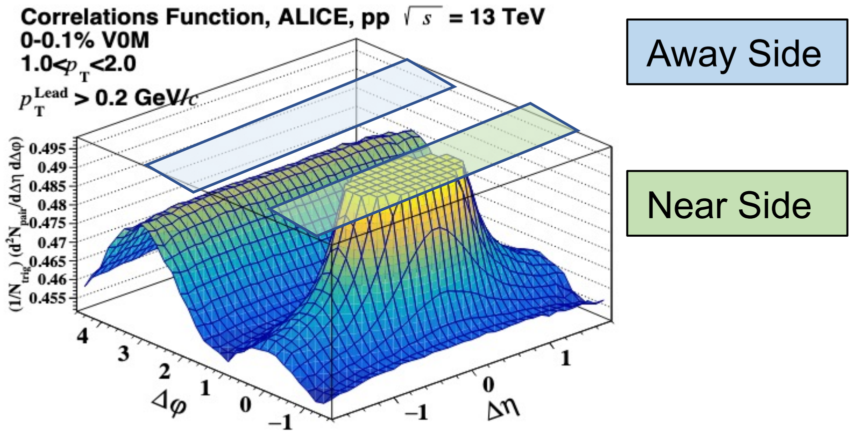
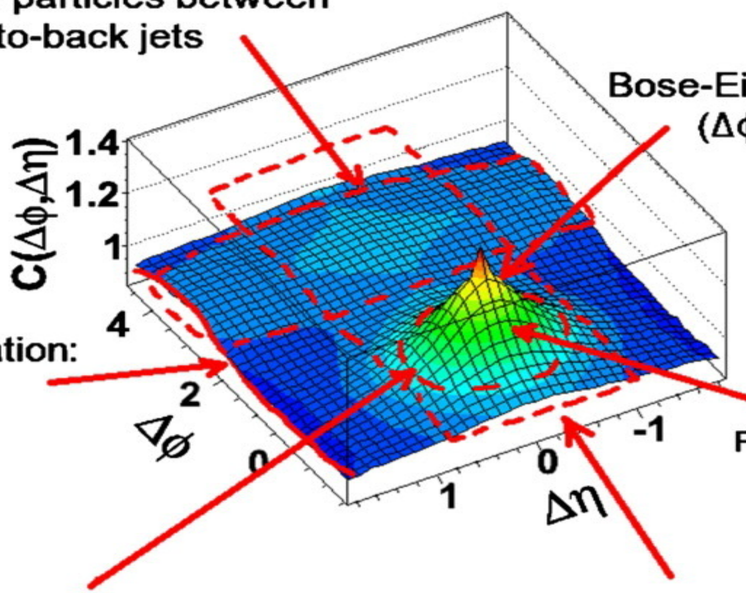


$S(\Delta\varphi,\Delta\eta)$ $M(\Delta\varphi,\Delta\eta)$ $C(\Delta\varphi,\Delta\eta)$



1. Width Δη or width $\Delta\varphi$:
   → Dynamics of particle production
   → System size evolution
2. Integral or Yield calculation:

$$\rightarrow I = \int_{\Delta\eta_1}^{\Delta\eta_2} \int_{\Delta\varphi_2}^{\Delta\varphi_2} \frac{d^2N}{d\Delta\eta d\Delta\varphi} d\Delta\eta\Delta\varphi$$

May want to scale C_2 by the number of uncorrelated pairs:

$$R_2 = \frac{C_2}{\rho_1 \times \rho_1} \Rightarrow R_2 = \frac{\rho_2}{\rho_1 \times \rho_1} - 1$$

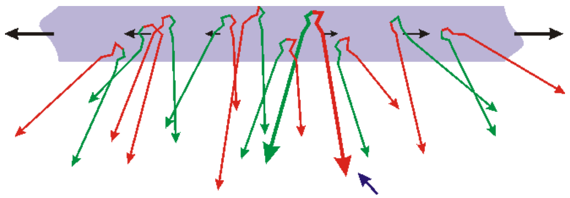
$C\,(\Delta\varphi, \Delta\eta)$ or $C_2\,(\Delta\varphi, \Delta\eta)$: Cumulant

$R_2\,(\Delta\varphi, \Delta\eta)$: Normalized Cumulant

ρ_2 = Pair particle density

ρ_1 = Single particle density

Balance Function (2-Particle correlations)



Conservation of quantum numbers.
-> for each general charge, an opposite balancing charge produced at approx. the same space–time.

Cumulant $C_2(x_1,x_2)=\rho_2(x_1,x_2)-\rho_1(x_1)\rho_1(x_2)$ $x\equiv\{y,\varphi,p_T\}$ $\rho(x)=\frac{1}{\sigma}\frac{d\sigma}{dx}$

Normalized Cumulant $R_2(x_1,x_2)=\frac{C_2(x_1,x_2)}{\rho_1(x_1)\rho_1(x_2)}$

R_2 is a robust observable!
Single track efficiencies cancel out of the ratio

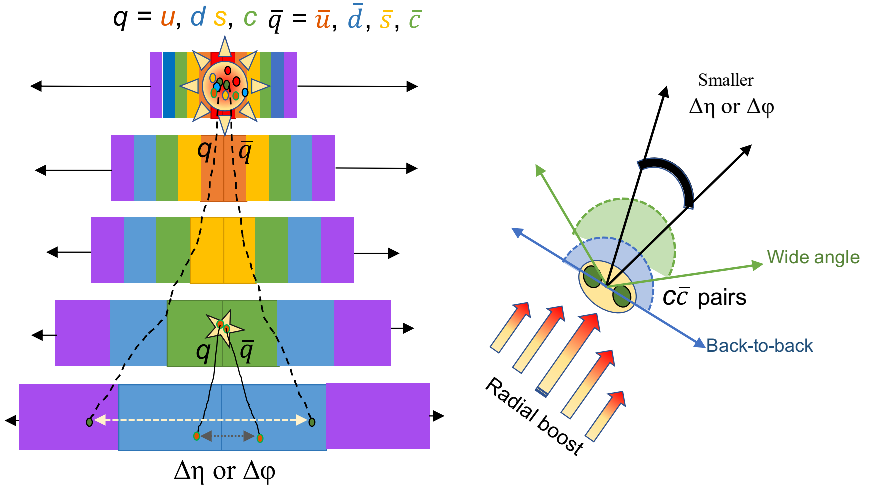
4 different charge combinations for R_2:
(+ -), (- +), (+ +), and (- -)

Charge Independent (CI) combinations $CI=\frac{1}{2}\{LS+US\}$ $LS=\frac{1}{2}\{(++)+(--)\}$

Charge Dependent (CD) combinations $CD=\frac{1}{2}\{US-LS\}$ $US=\frac{1}{2}\{(+-)+(-+)\}$

R_2^{CD} is proportional to the Balance Function

$$B(\Delta x)\approx\frac{dN_{ch}}{dx}R_2^{CD}=\frac{dN_{ch}}{dx}\frac{1}{2}\left[R_2^{+-}-R_2^{++}+R_2^{-+}-R_2^{--}\right]$$

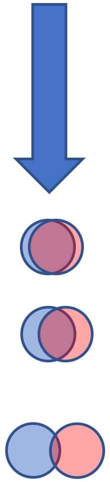


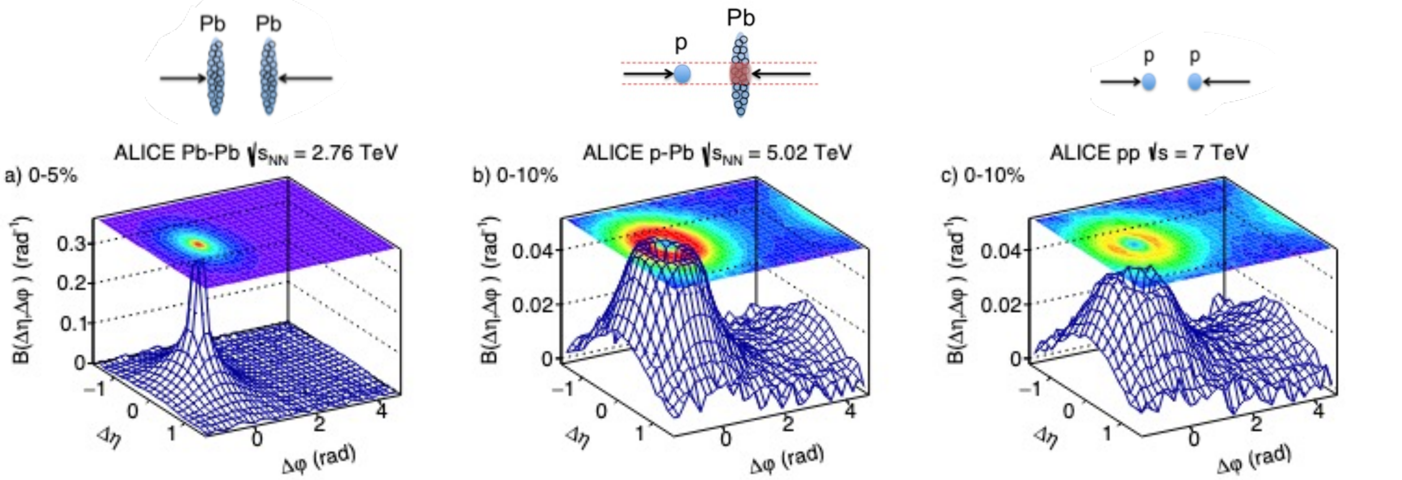
(a) Clocking Hadronization
(b) Kinematic lensing due to radial boost

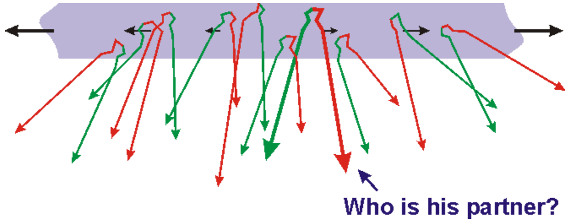
Balance Function (identified hadrons) in Pb–Pb

Eur. Phys. J. C 76 (2016) 86

Phys. Rev. C 100, 044903 (2019)







Conservation of quantum numbers.

-> for each general charge, an opposite balancing charge produced at approx. the same space–time.

		h	π	k	p
Q	h	✓			
Q	π		?	?	?
Q S	k		?	?	?
Q B	P		?	?	?

Balance Function (identified hadrons) in Pb–Pb

ALICE, Eur. Phys. J. C 76 (2016) 86

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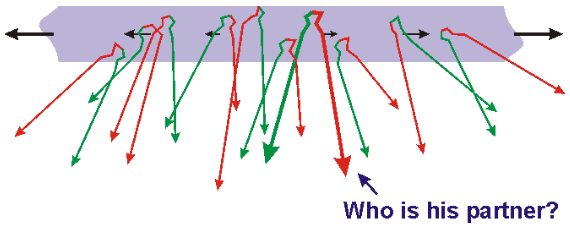

ALICE

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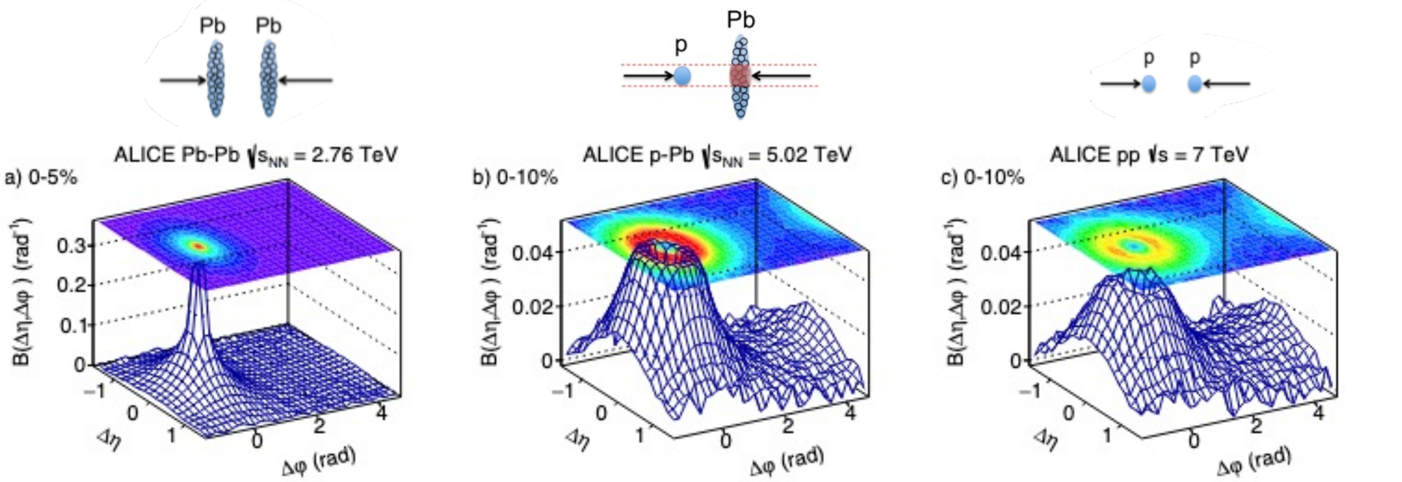
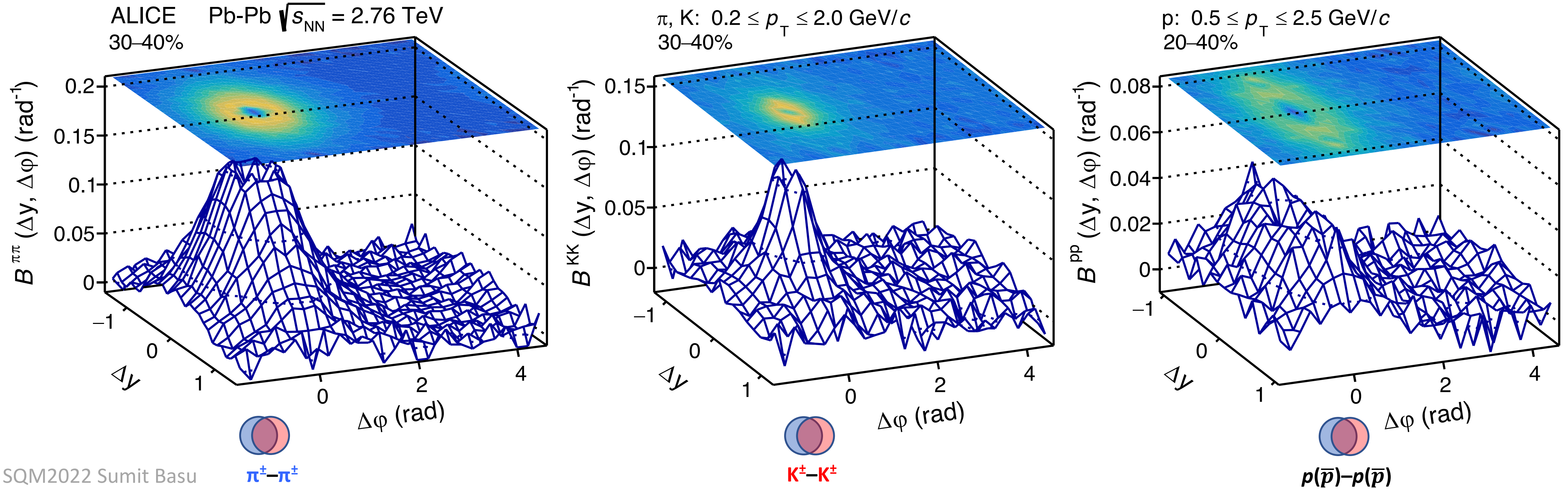
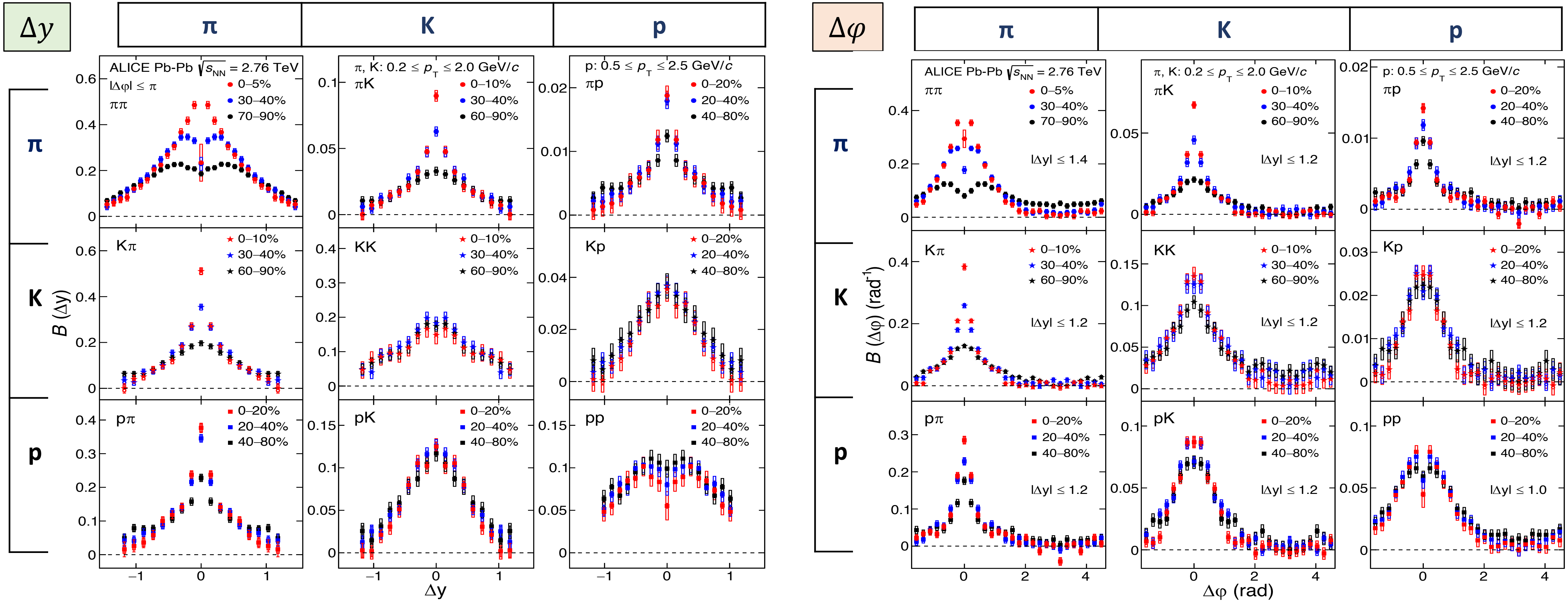


ALICE Collaboration, arXiv:2110.06566 [nucl-ex]



Projections of Balance Function in Δη and Δφ

ALICE Collaboration, arXiv:2110.06566 [nucl-ex]



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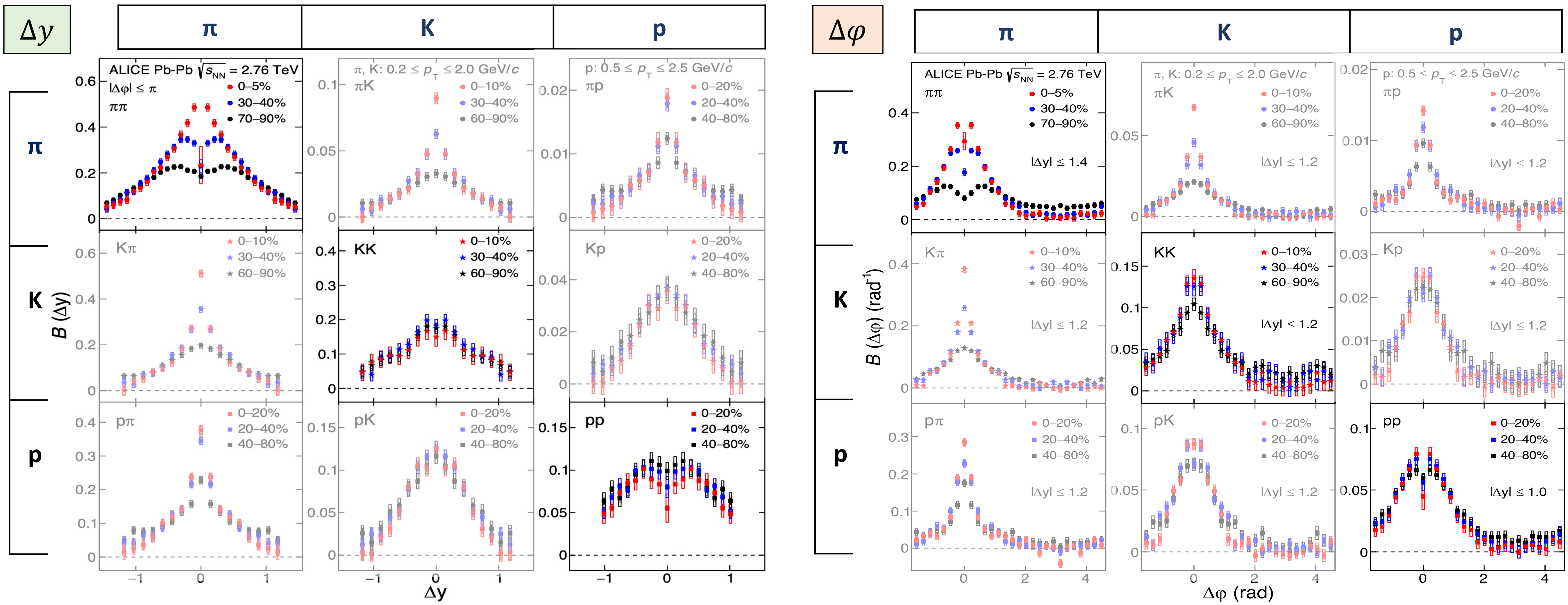
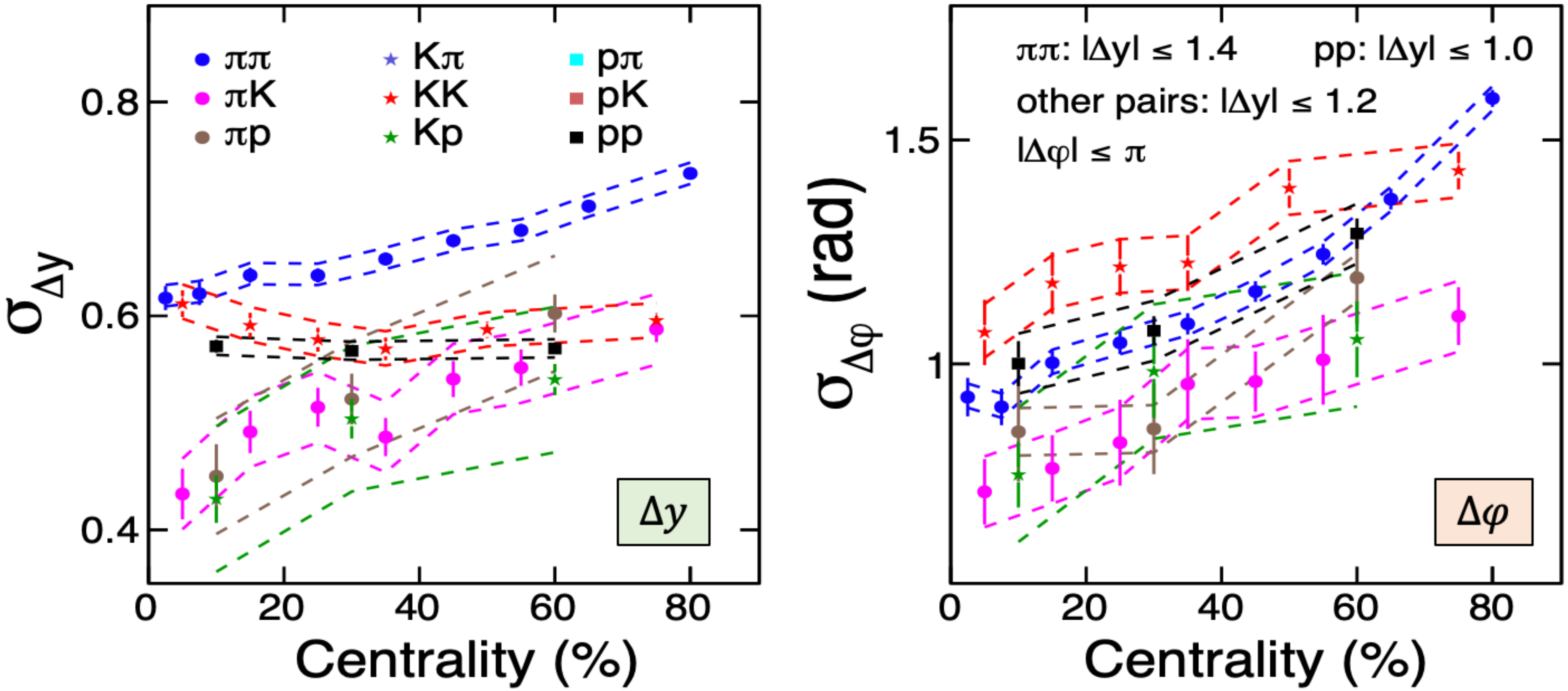


- **ππ pairs** → clear centrality dependence, **KK pairs →** no centrality dependence
  -> qualitatively consistent with two-wave quark production model
- **pp** and cross-species pairs moderate centrality dependence.

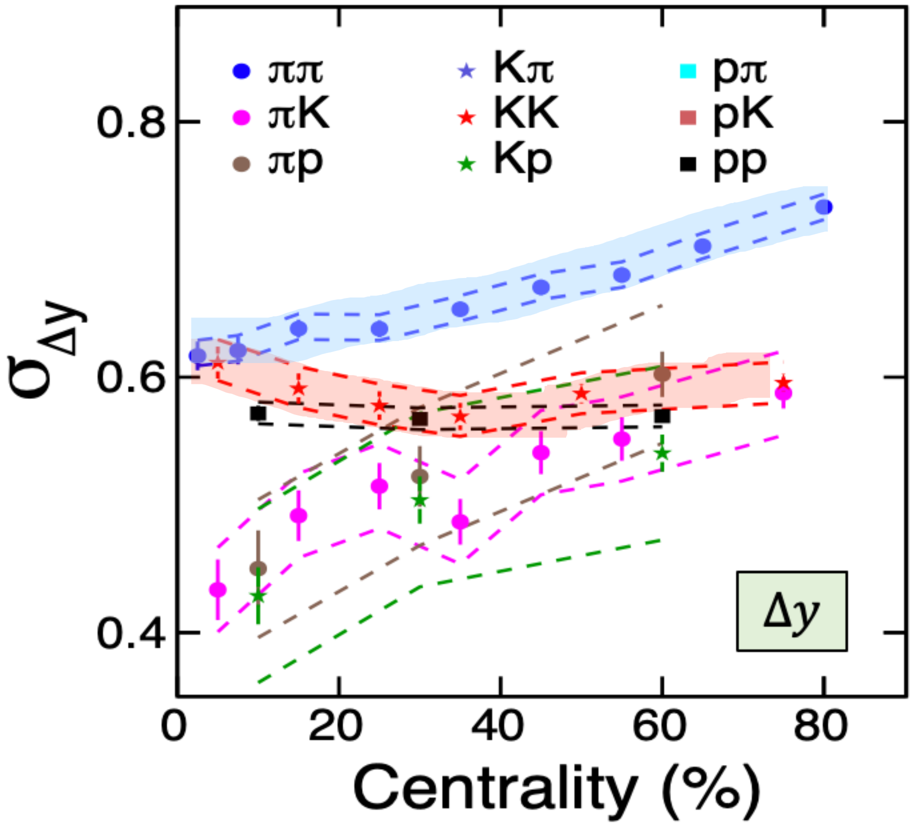
Width of Balance Function in Δη and Δφ

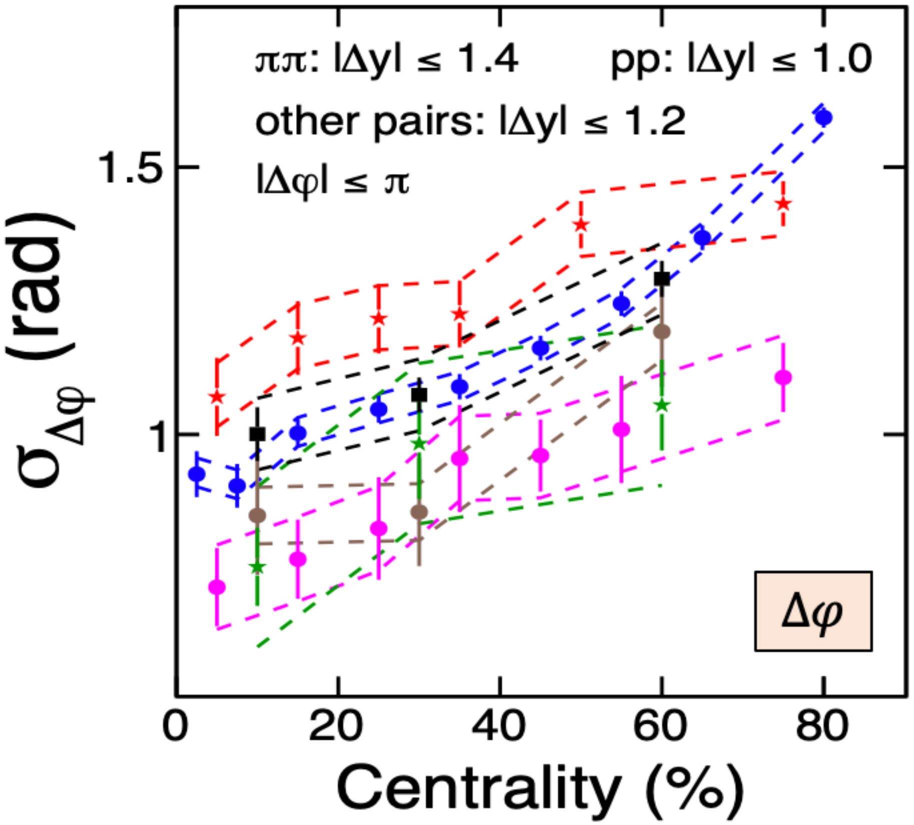
arXiv:2110.06566 [nucl-ex]



Width of Balance Function in Δη and Δφ

arXiv:2110.06566 [nucl-ex]

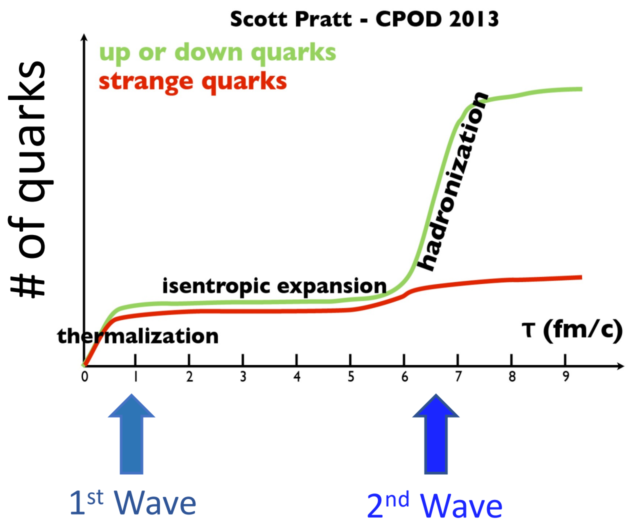




- KK and pp widths no centrality dependence
- π π and cross-species pairs narrow towards central collisions.

- Azimuthal narrowing for all species → radial flow focusing
- Qualitatively consistent with radial flow and two-wave quark production

Two-wave quark production model



Integral of Balance Function (2-Particle correlations)

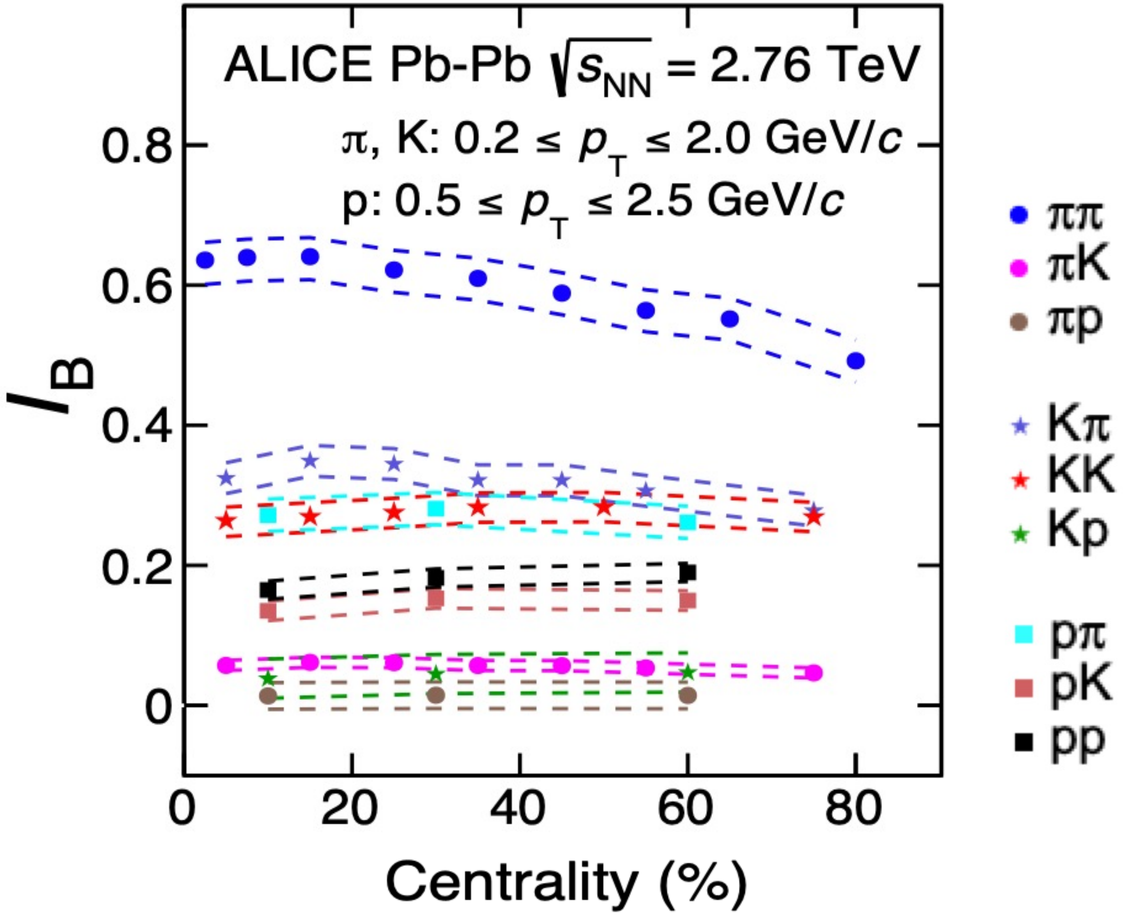
$$I_B = \int_{-\infty}^{\infty} B_{\pi^\pm h^\pm}(d\eta, d\varphi) d\eta d\varphi dp_T = 1$$

Ideal Case: ∞ Acceptance

$$\equiv \int_{-\infty}^{\infty} B_{\pi^\pm \pi^\pm}(d\eta, d\varphi) d\eta d\varphi dp_T + \int_{-\infty}^{\infty} B_{\pi^\pm K^\pm}(d\eta, d\varphi) d\eta d\varphi dp_T + \int_{-\infty}^{\infty} B_{\pi^\pm p(\bar{p})}(d\eta, d\varphi) d\eta d\varphi dp_T$$

In Reality: Limited Acceptance

$$I_B = \int_{d\eta=-1.6}^{d\eta=1.6} \int_{d\varphi=-\frac{\pi}{2}}^{d\varphi=\frac{3\pi}{2}} B_{\pi^\pm h^\pm}(d\eta, d\varphi) d\eta d\varphi dp_T \lesssim 1$$



BF Integral = Pairing Probabilities

Integral of Balance Function (2-Particle correlations)

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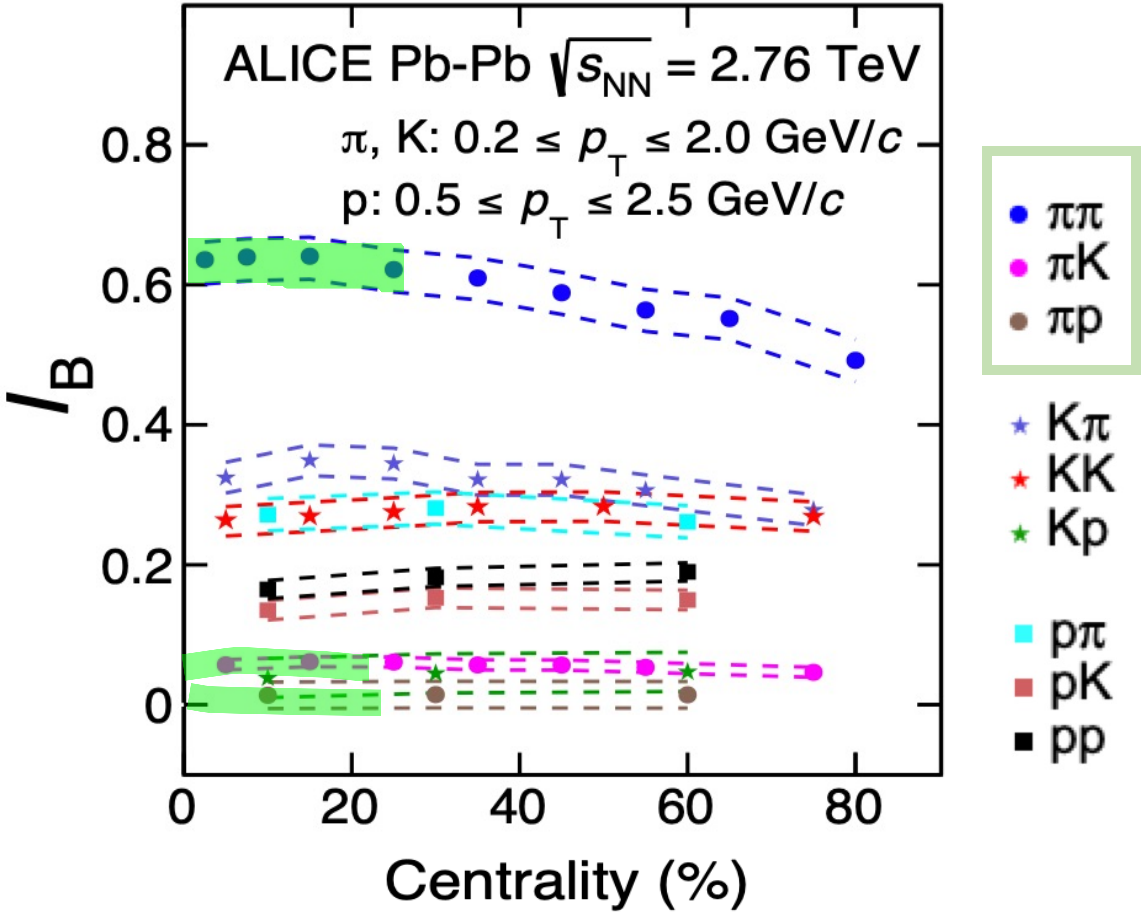

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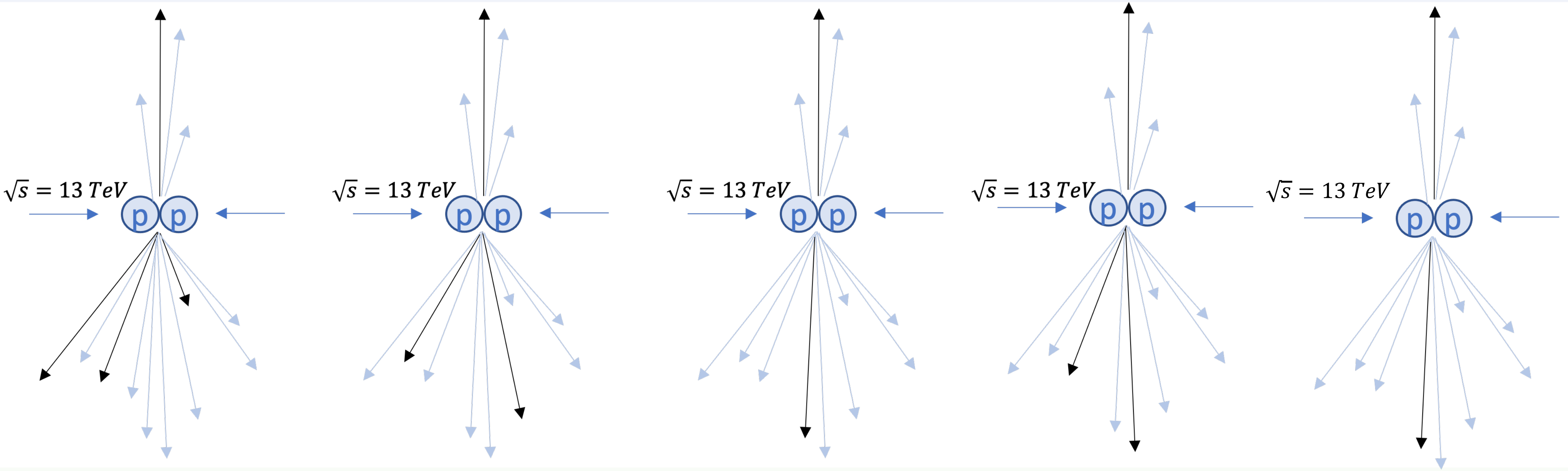
→ Pairing probabilities are very different from single hadron ratios.

→ Kπ not larger than KK by K/π ratio; pp larger than pK.

→ Low p_T particles mostly balance by low p_T particles

Ξ−hadron correlations in pp collisions at √s = 13 TeV

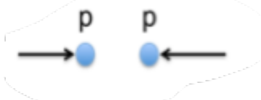
	Ξ−π	Ξ−K	Ξ−p	Ξ−Λ	Ξ−Ξ
Trigger	$\Xi(ssd)$	$\Xi(ssd)$	$\Xi(ssd)$	$\Xi(ssd)$	$\Xi(ssd)$



Associated	$\pi^{+}(u\bar{d})$	$K^{+}(u\bar{s})$	$\bar{p}(\bar{u}\bar{u}\bar{d})$	$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$	$\bar{\Xi}(\bar{s}\bar{s}\bar{d})$
(-)					
Background	$\pi^{-}(\bar{u}d)$	$K^{-}(u\bar{s})$	$p(uud)$	$\Lambda(uds)$	$\Xi(ssd)$

(Subtracting same quantum number correlation)

Ξ−hadron correlations in pp collisions at √s = 13 TeV



Ξ−π | Ξ−K | Ξ−p | Ξ−Λ | Ξ−Ξ

$\Xi^{+}h^{-}$

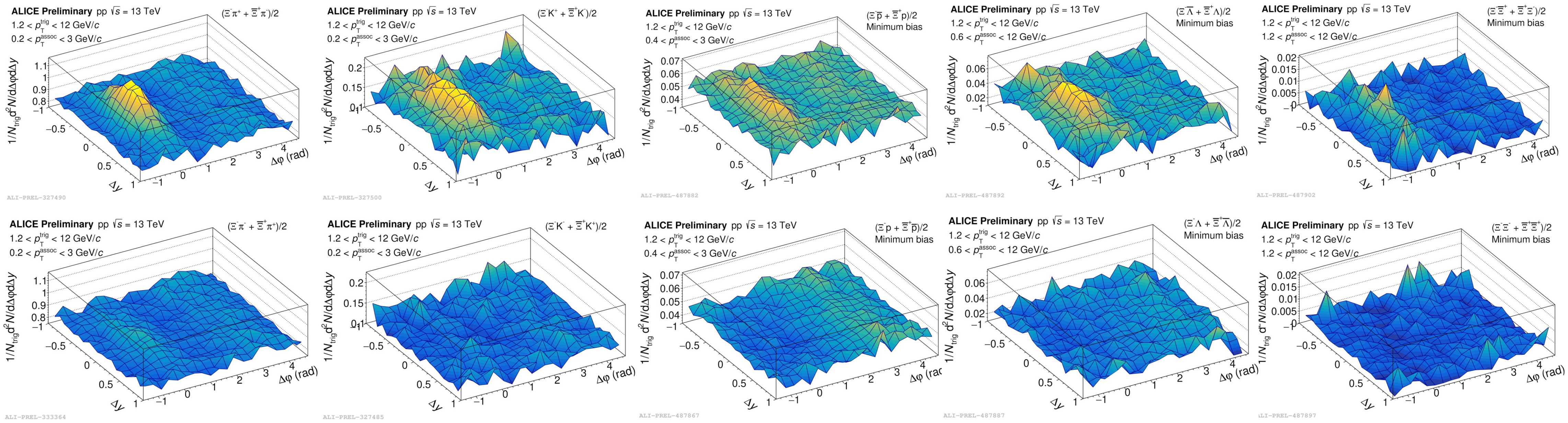
OS or US

$\Xi^{-}h^{+}$

$\Xi^{+}h^{+}$

SS or LS

$\Xi^{-}h^{+-}$



Associated	$\pi^{+}(u\bar{d})$	$K^{+}(u\bar{s})$	$\bar{p}(\bar{u}\bar{u}\bar{d})$	$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$	$\bar{\Xi}(\bar{s}\bar{s}\bar{d})$
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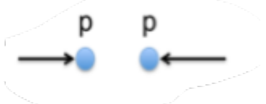
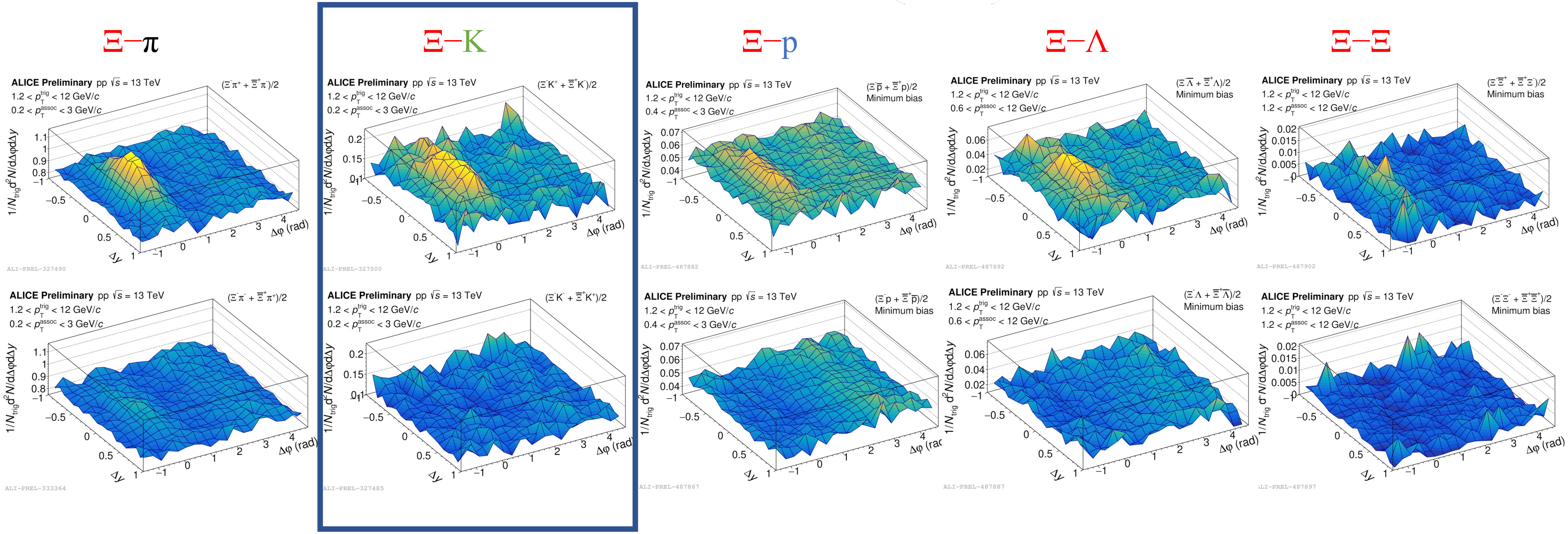
Ξ−hadron correlations in pp collisions at √s = 13 TeV



Ξ⁺h⁻
OS or US
Ξ⁻h⁺

Ξ⁺h⁺
SS or LS
Ξ⁻h⁺⁻



Associated	$\pi^+(u\bar{d})$	$K^+(u\bar{s})$	$\bar{p}(\bar{u}\bar{u}\bar{d})$	$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$	$\bar{\Xi}(\bar{s}\bar{s}\bar{d})$
(-)					
Background	$\pi^-(\bar{u}d)$	$K^-(u\bar{s})$	$p(uud)$	$\Lambda(uds)$	$\Xi(ssd)$

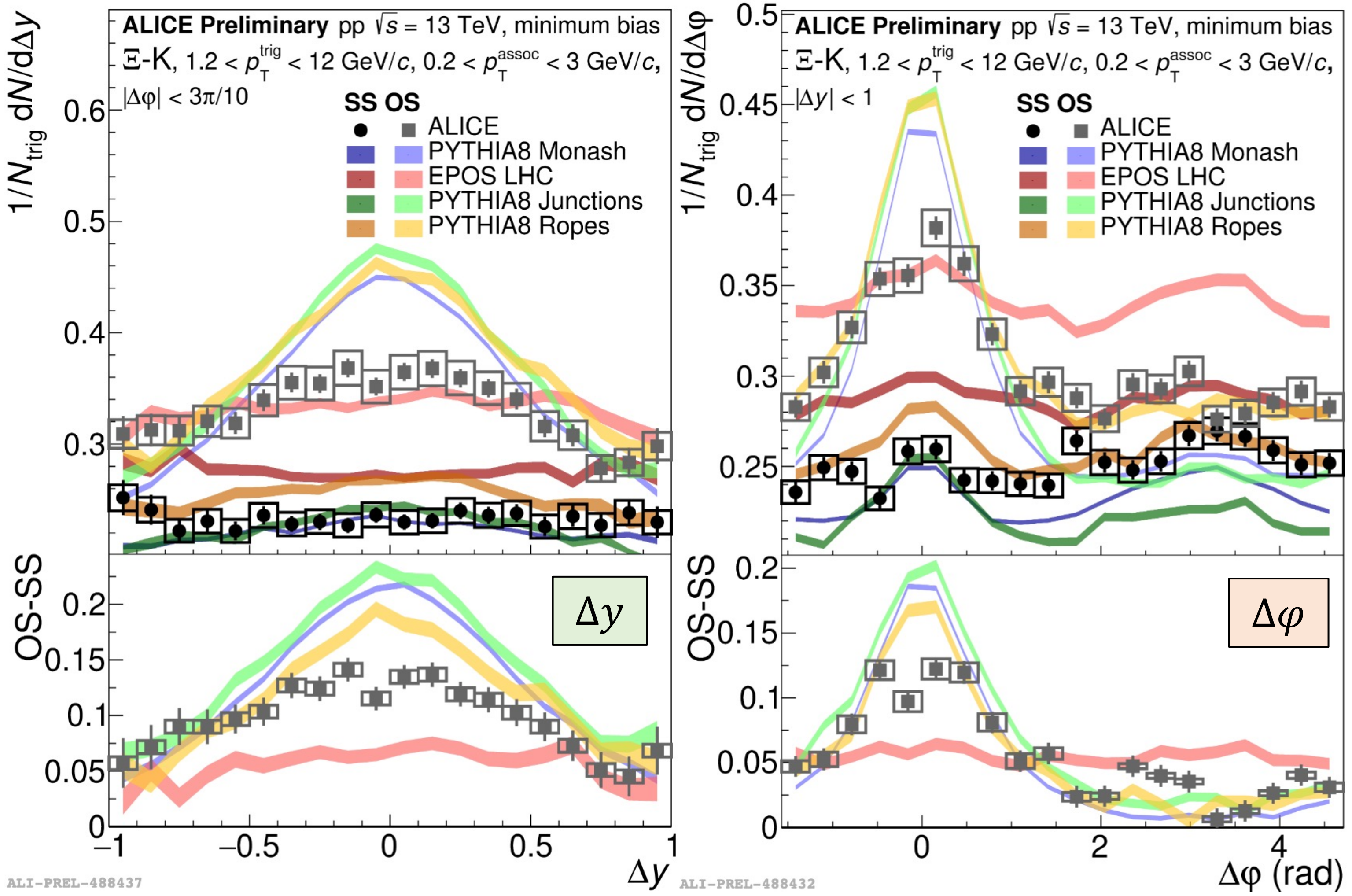
(Subtracting same quantum number correlation)

Projection of Ξ−K correlations in Δη and Δφ

Ξ−K

OS & US

OS-SS

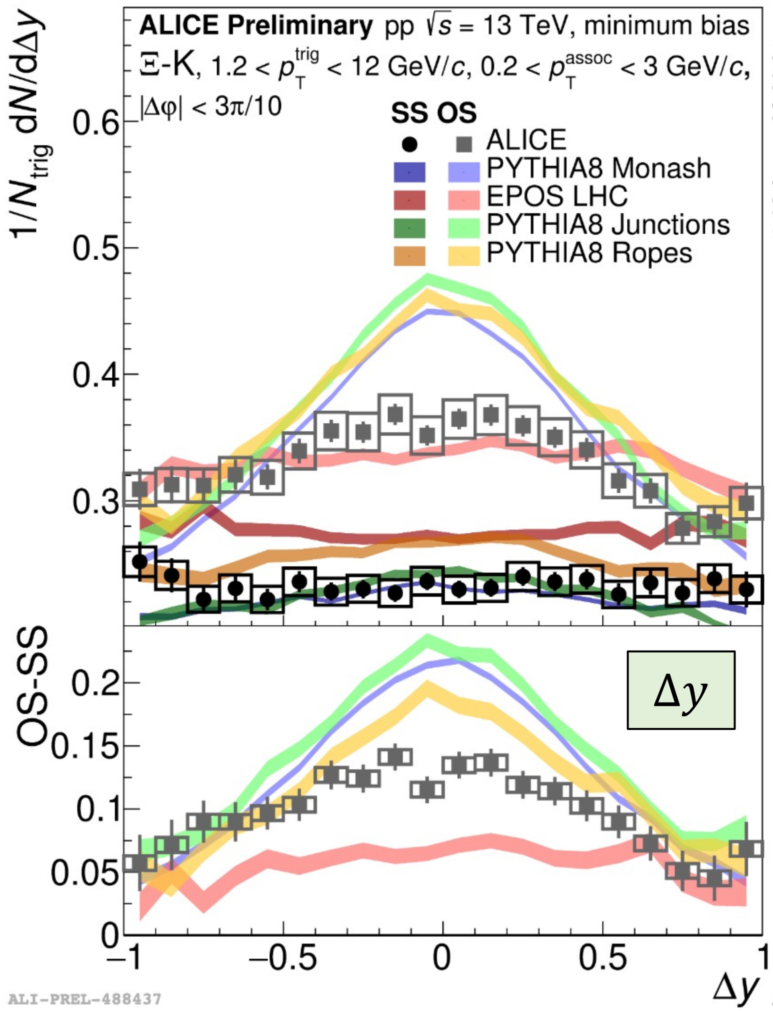


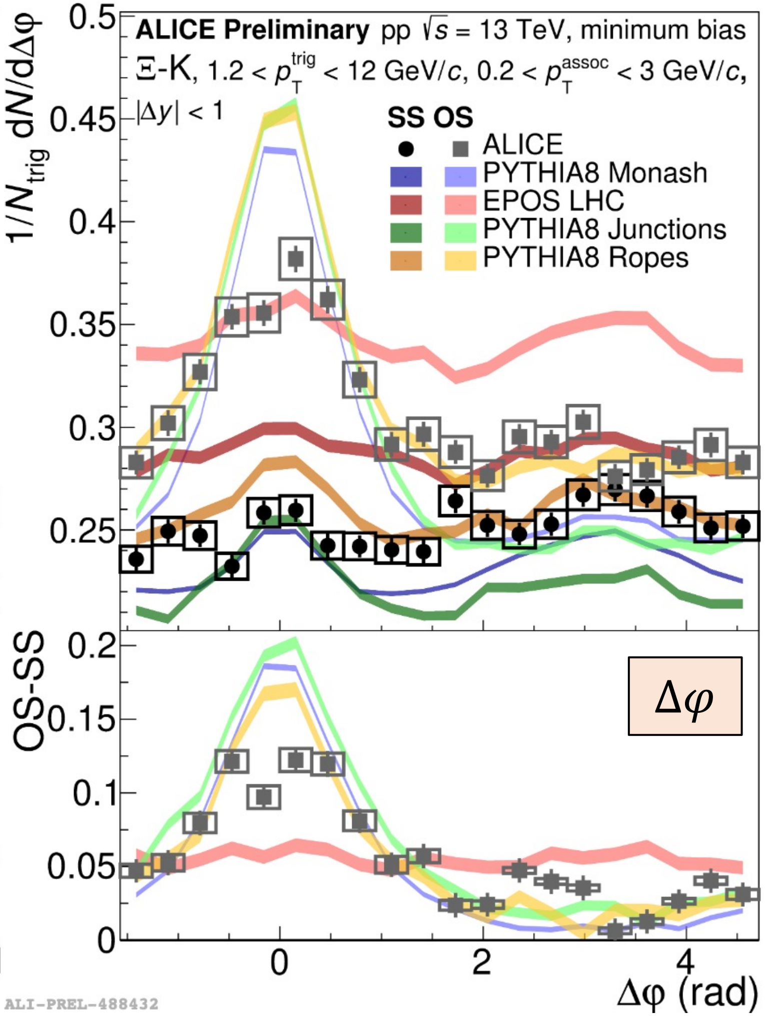
Projection of Ξ−K correlations in Δη and Δφ

Ξ−K

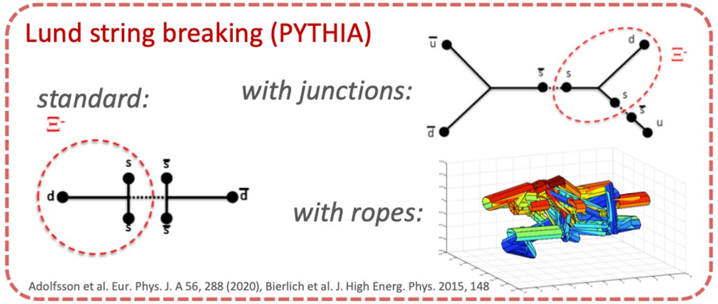
OS & US

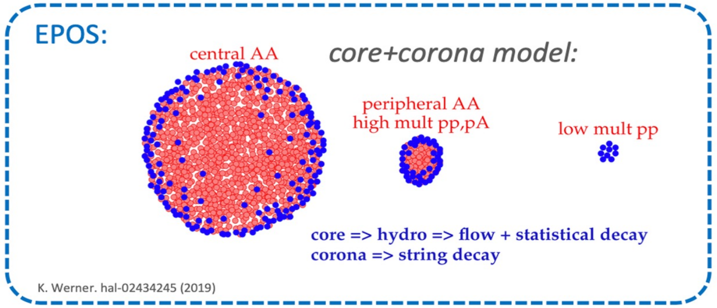
OS-SS





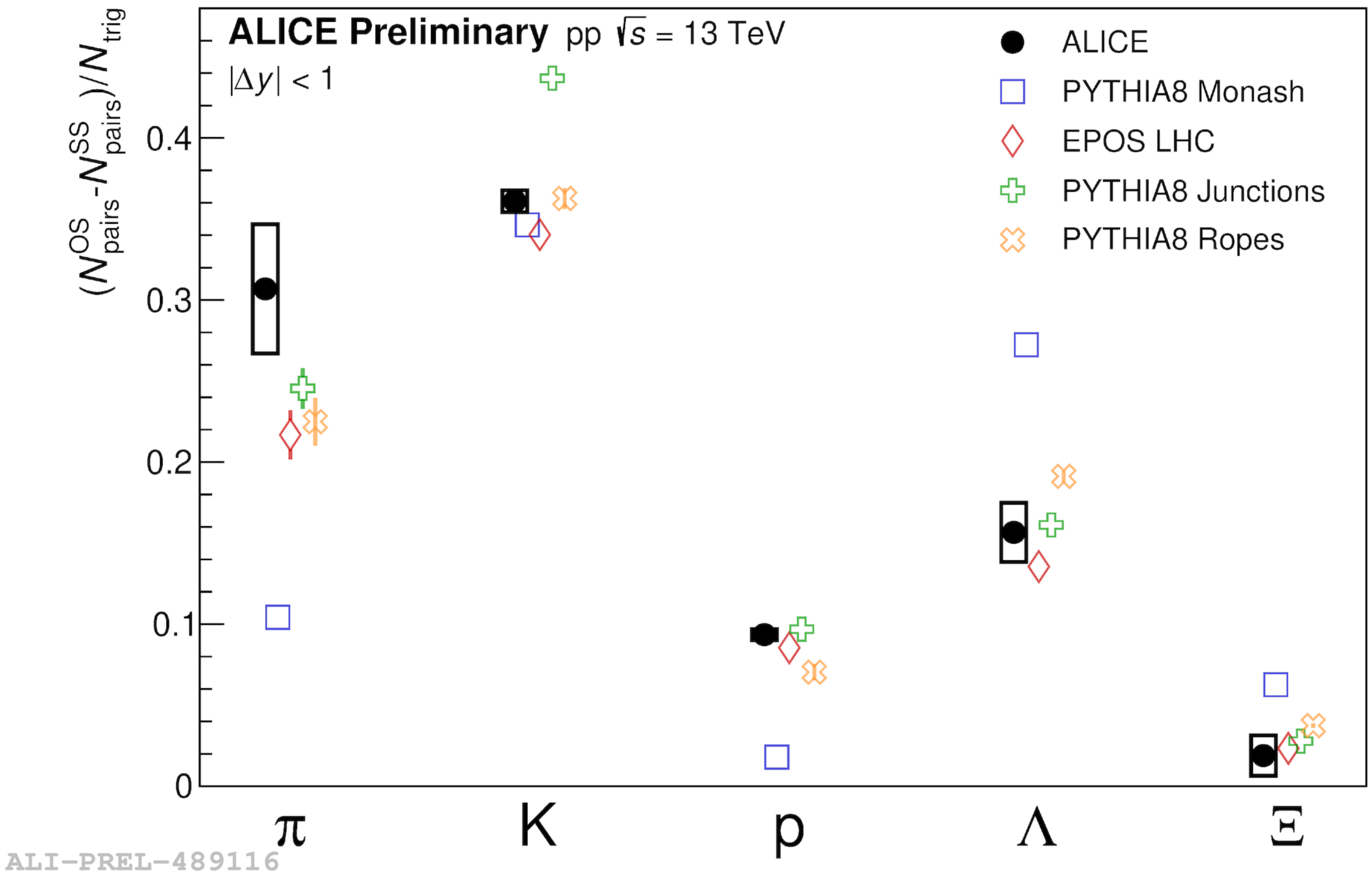
→ *Results challenge hadronization models:*





- Wider peak in data than in PYTHIA → strange quarks produced at an earlier time
- Local conservation of quantum numbers → not implemented in EPOS
- Junction model reduces peak amplitude → favors this baryon production mechanism over diquark breaking

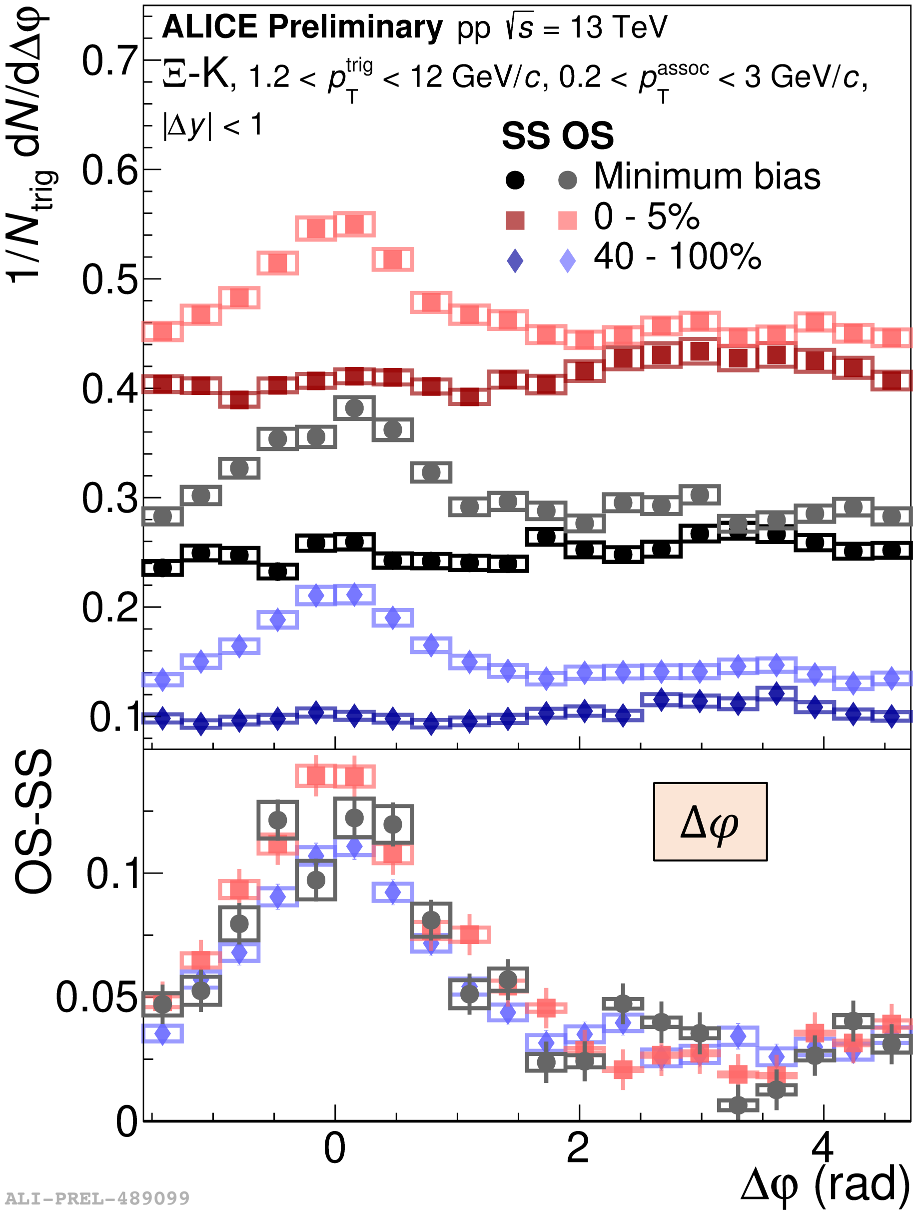
Integral of Ξ−hadron correlations for |Δy| < 1



Differences in per-trigger yields between opposite- and same-sign or baryon number particles, integrated over the volume within |Δy| < 1, for all particles and models

How electric charge, strangeness, and baryon number of the trigger are balanced in phase space.

Multiplicity dependence of Ξ−hadron correlations



Multiplicity Dependence Same Sign & Opposite Sign

OS-SS

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

- Similar relative difference seen for π, K, p
- No evidence of multiplicity dependence on Ξ production mechanism
  →underlying quark distributions are the same
- Quantitatively points towards common origin of baryon production

Summary & outlook

		h	π	k	p
Q	h	✓			
Q	π		✓	✓	✓
Q S	k		✓	✓	✓
Q B	P		✓	✓	✓

- Balance function for **π**, K , p pairs for Pb-Pb collision at $\sqrt{s_{\mathrm{NN}}} = 2.76\ TeV$
  - Species dependent width evolution behavior in Δη
  - Narrowing of azimuthal widths for all specie pairs
    - → Radial flow focusing (kinematic lensing) & Two-wave quark production mechanism.

- 2-particle correlation (Ξ-h) pairs for pp collision at $\sqrt{s} = 13\ TeV$
  - No multiplicity dependence in correlation structure for all pairs
    - → common origin of Ξ/strangeness production across multiplicity.
  - Ξ−strangeness correlation peak is much wider in data than in PYTHIA
    - → Strange quarks are produced earlier in the event than from Lund string model alone.
  - Local conservation of quantum numbers needs to be implemented in EPOS.

- Currently, Run 3 preparations are ongoing , where many observables will benefit from more statistics and larger ALICE acceptance.
  - → ALICE continues to provide many interesting results on correlations and fluctuations, So Stay tuned!!!

Thank you !!!

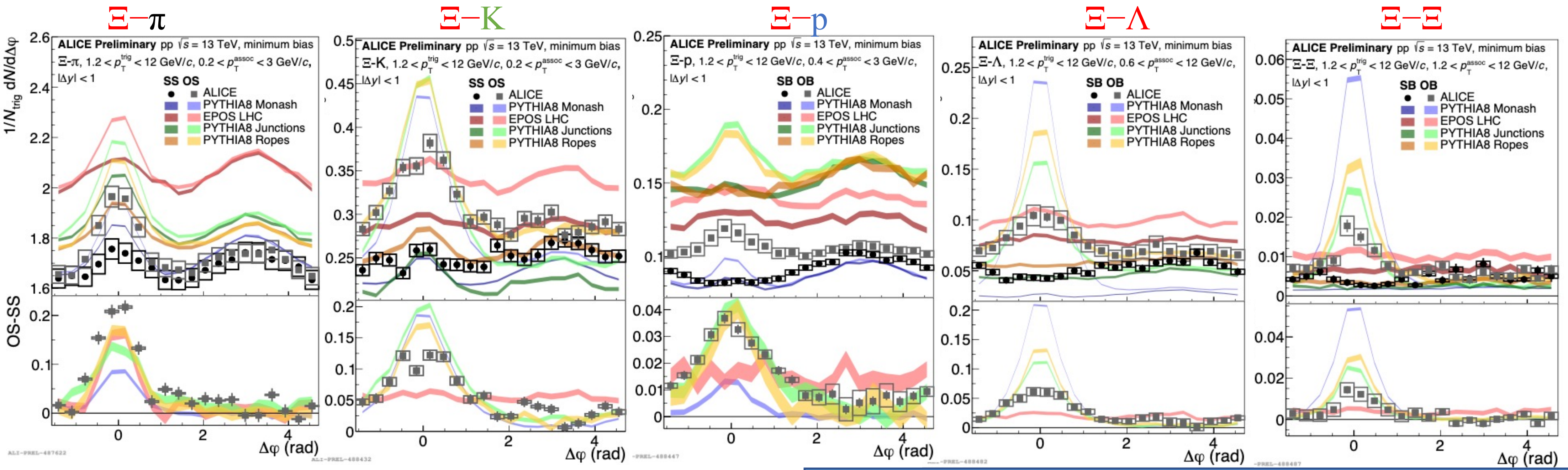
Back Up

Back Up Slides - I

OS or US

OS-SS

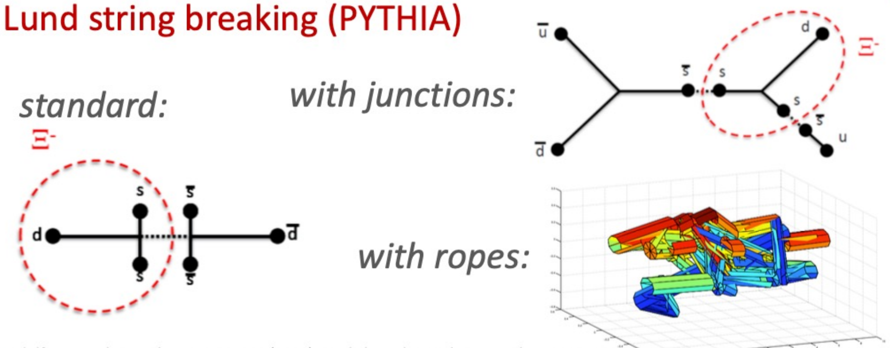
Δφ



Ξ−hadron correlations in pp collisions at √s = 13 TeV

→ *Results challenge hadronization models:*

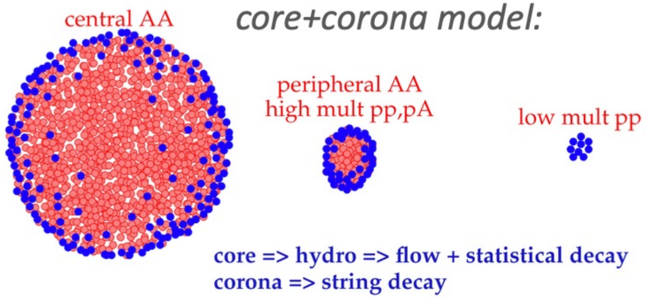
Lund string breaking (PYTHIA)



Adolfsson et al. Eur. Phys. J. A 56, 288 (2020), Bierlich et al. J. High Energ. Phys. 2015, 148

EPOS:

core+corona model:



K. Werner. hal-02434245 (2019)

Back Up Slides - II

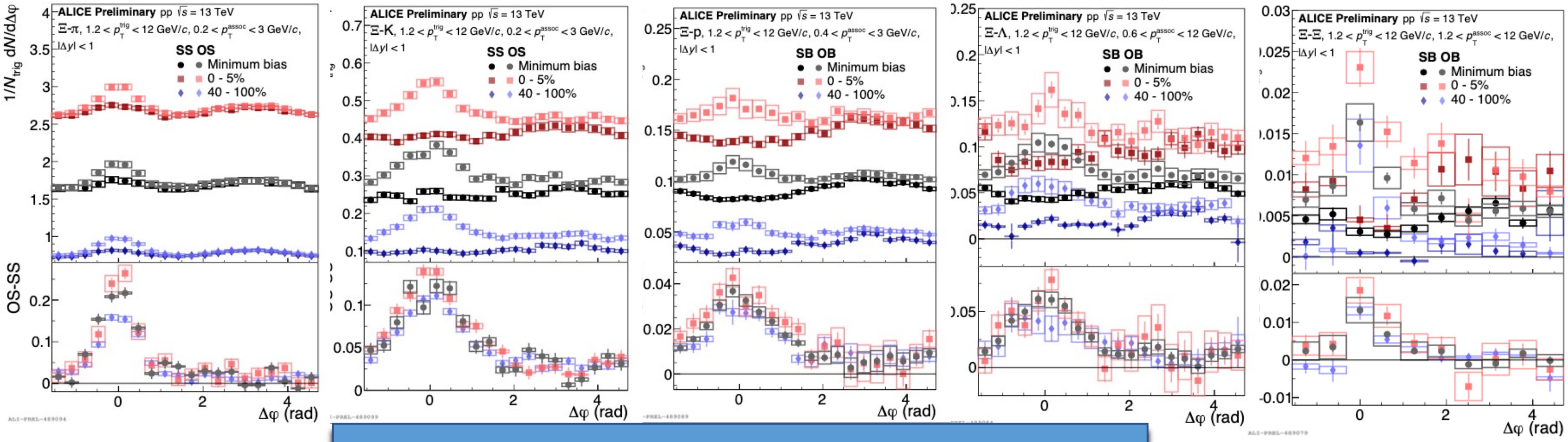
Red = high multiplicity
Grey = minimum bias
Blue = low multiplicity

Multiplicity dependence

OS-SS

Δφ

Ξ−π Ξ−K Ξ−p Ξ−Λ Ξ−Ξ



Multiplicity dependence of Ξ−hadron correlations

- Similar relative difference seen for π, K, p
- No evidence of multiplicity dependence on Ξ production mechanism
  →underlying quark distributions are the same
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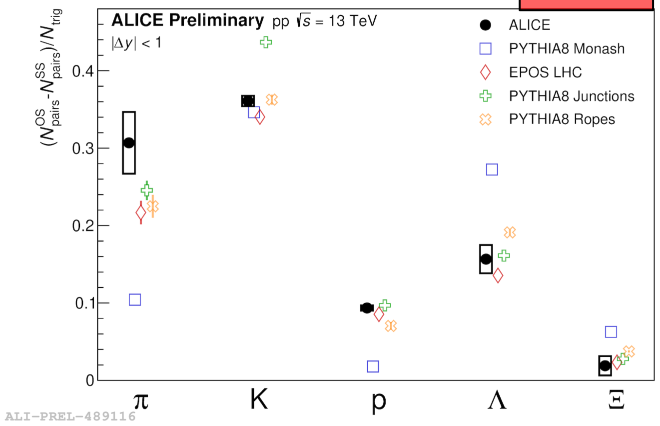
Total



How electric charge, strangeness, and baryon number of the trigger are balanced in phase space.