Recent results on 2-particle angular correlations from ALICE

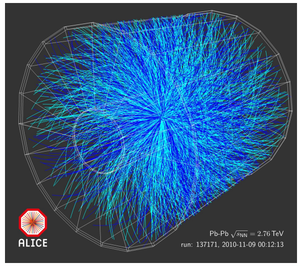
The 37th Winter Workshop on Nuclear Dynamics (WWND2022)
Puerto Vallarta, Mexico

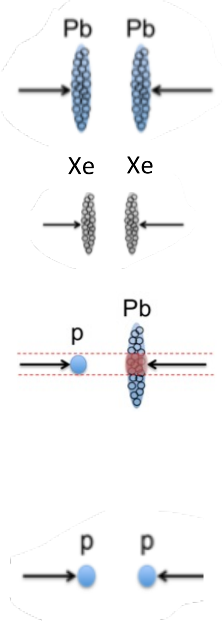
1. Overview of ALICE
2. Correlations & Techniques
3. Selected Recent Results
4. Summary

Sumit Basu (On behalf of the ALICE Collaboration)

Lund University, Sweden

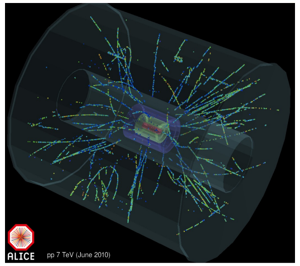
Event Display Pb–Pb





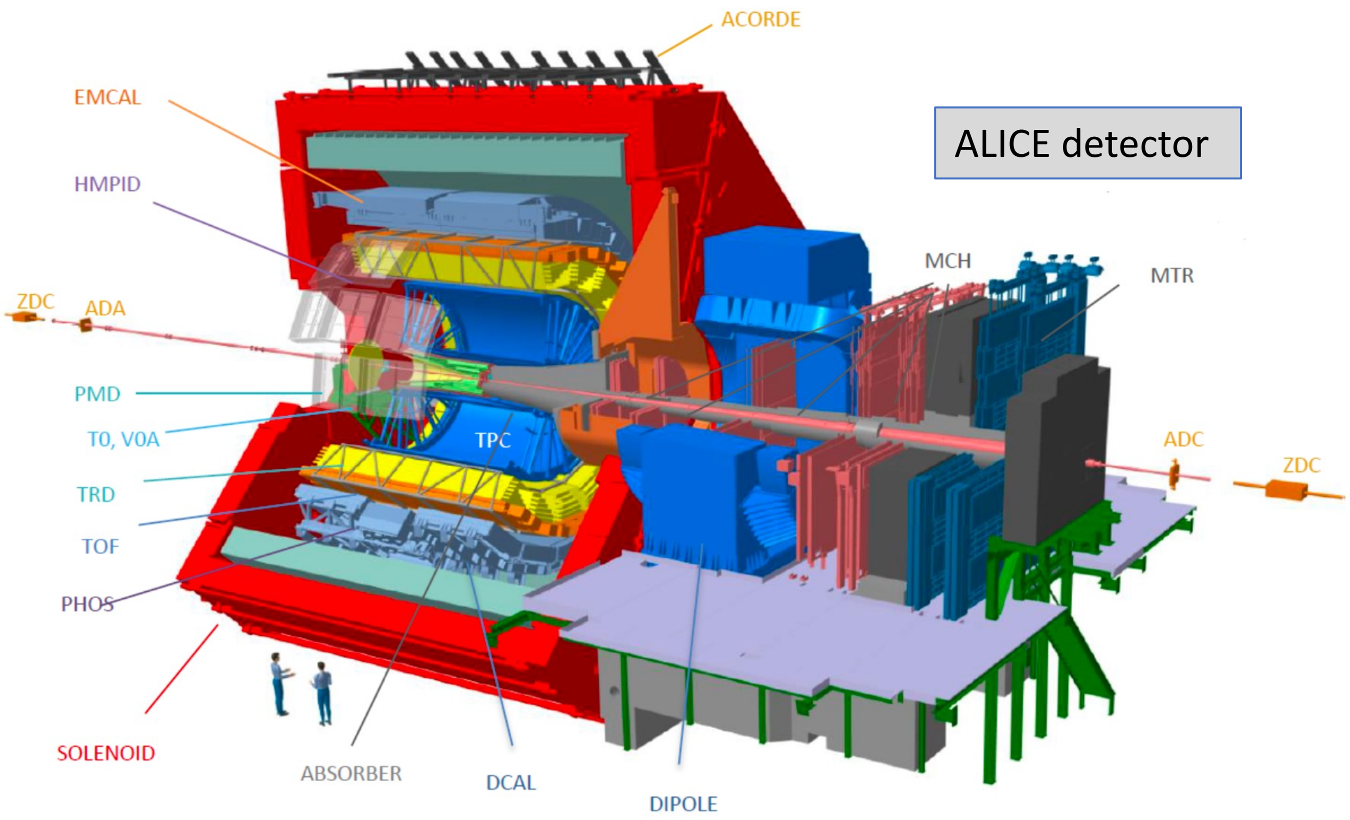
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02
Xe-Xe	2017	5.44
p-Pb	2013 2016	5.02 5.02, 8.16
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13

Run 1 Run 2

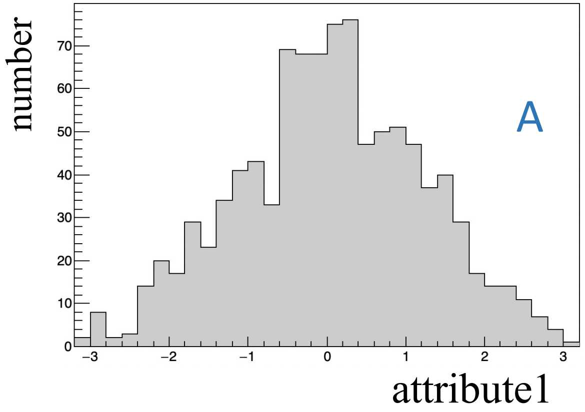


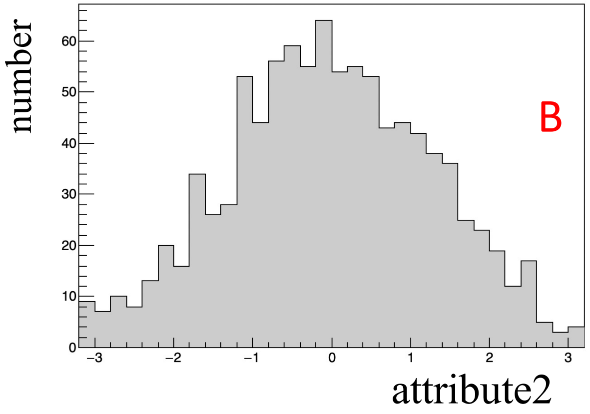
Event Display pp

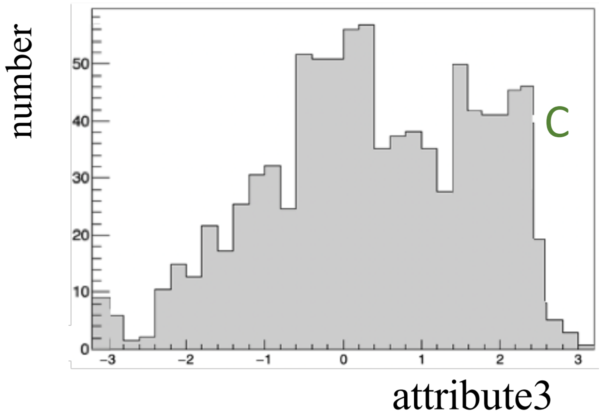
ALICE detector



Imagine that we have a population of n things, each with multiple attributes







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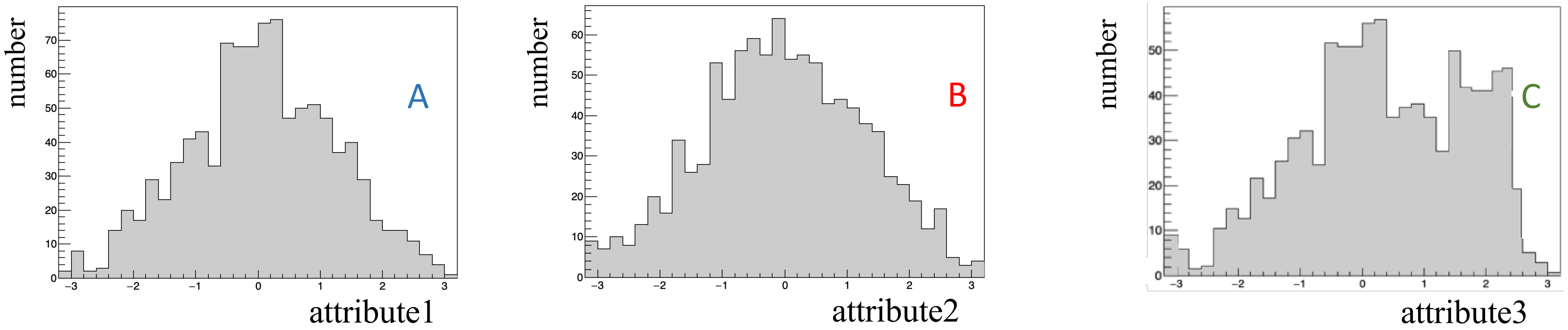
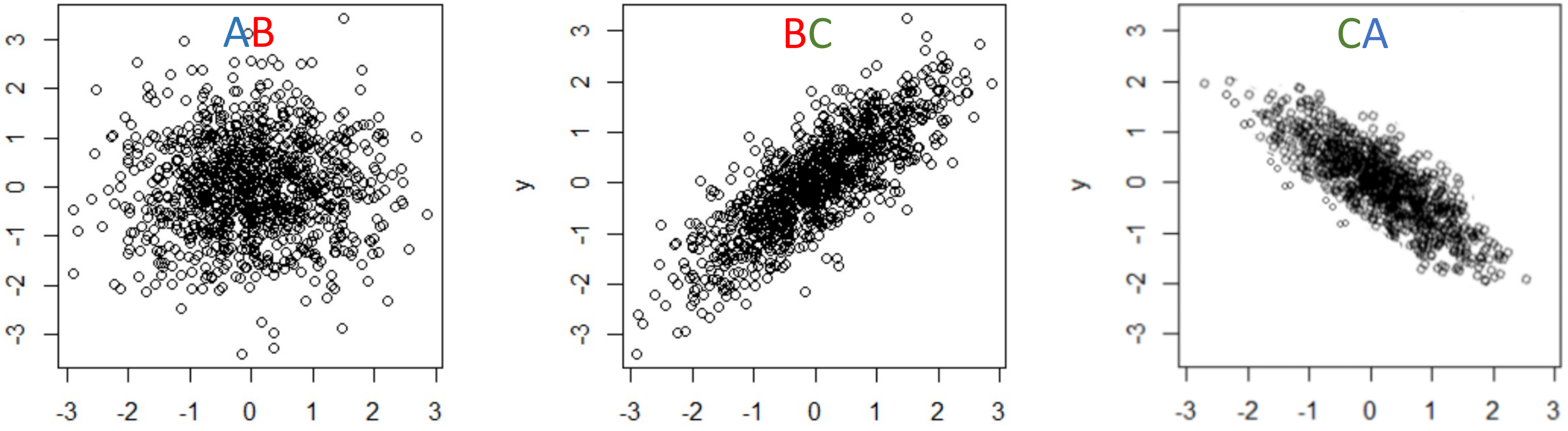


That is not all we can learn though – make the two-dimensional plot!



("number axis" are out of the page)

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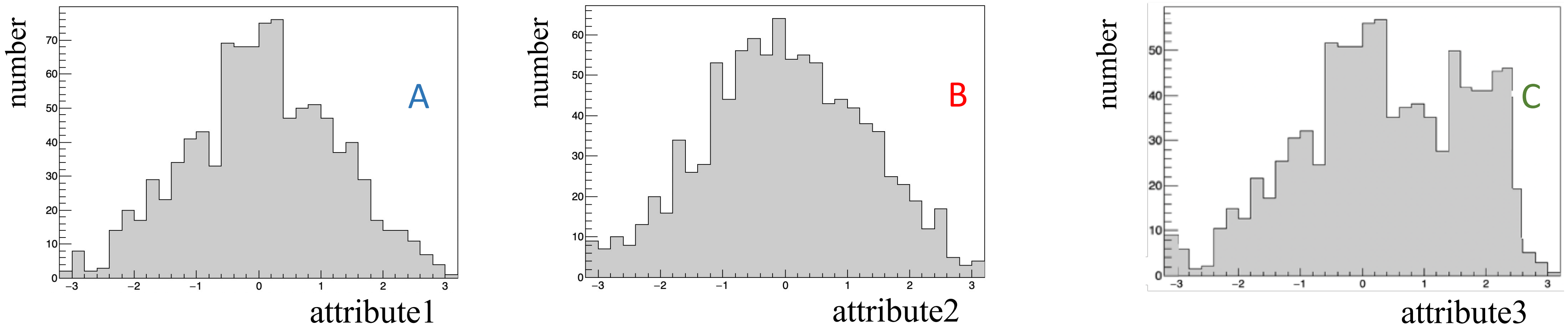

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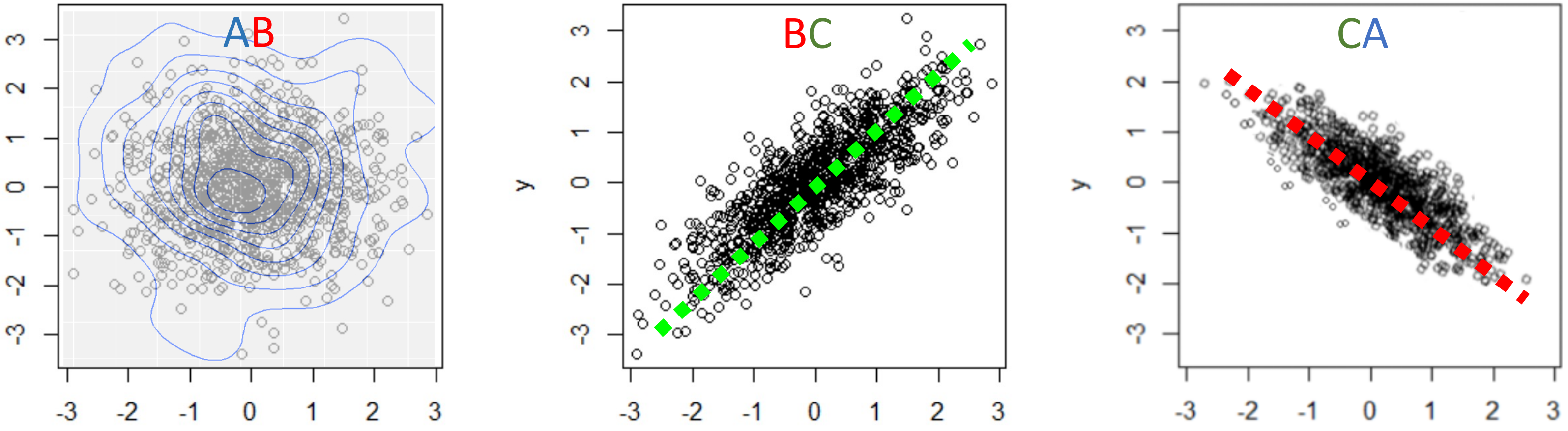

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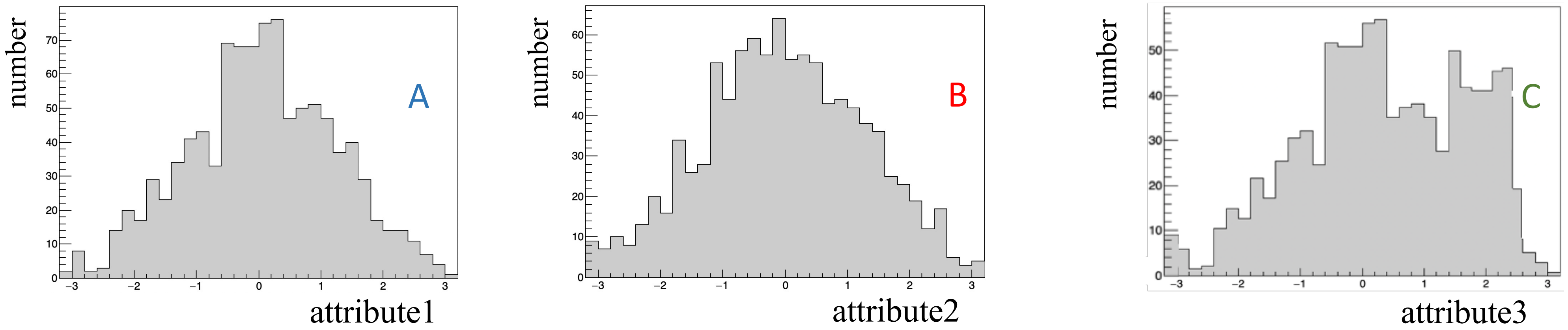

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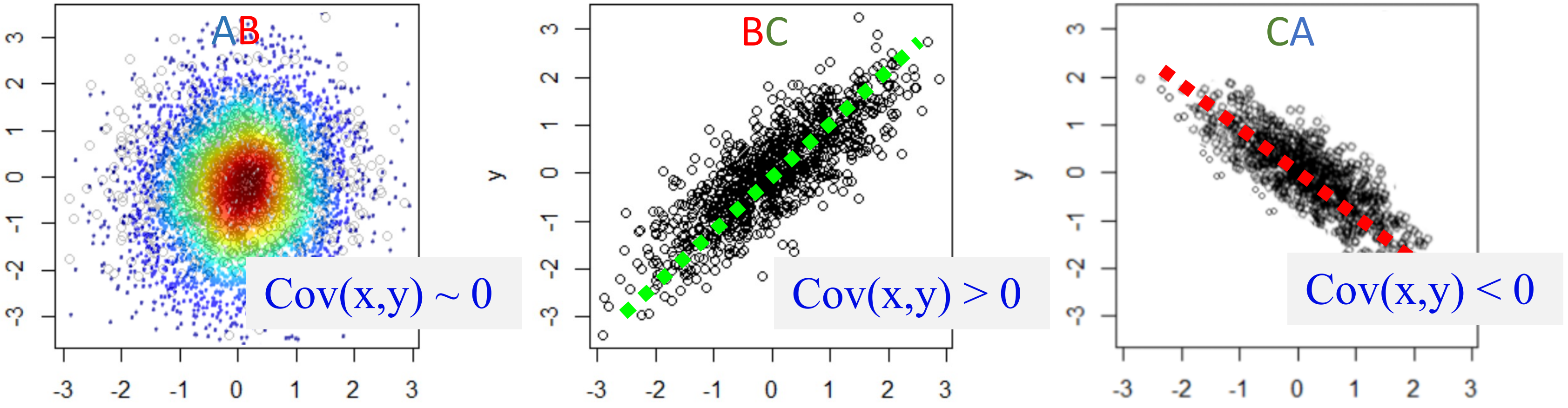

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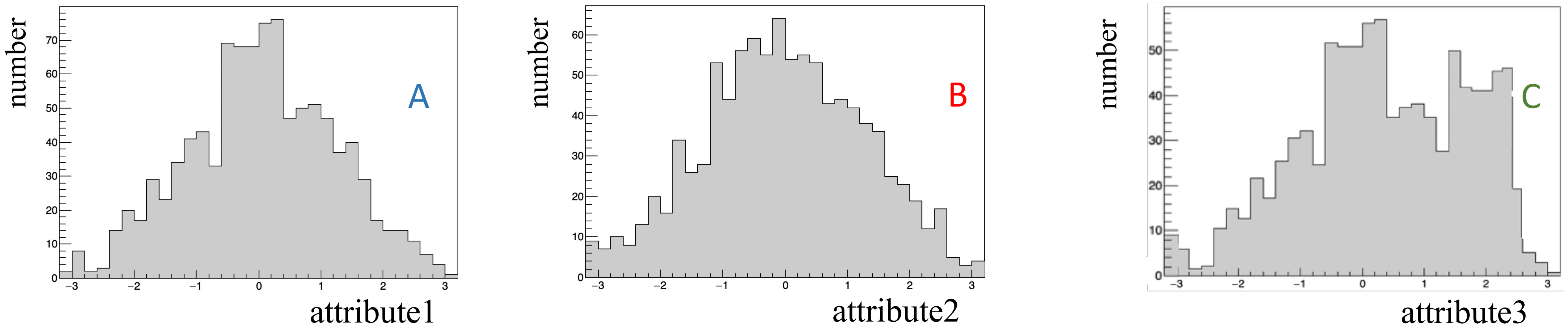

Studying the correlation of the two variables has resulted in New knowledge!

→ ...knowing the value of one variable constrains the possible values of the other variable.

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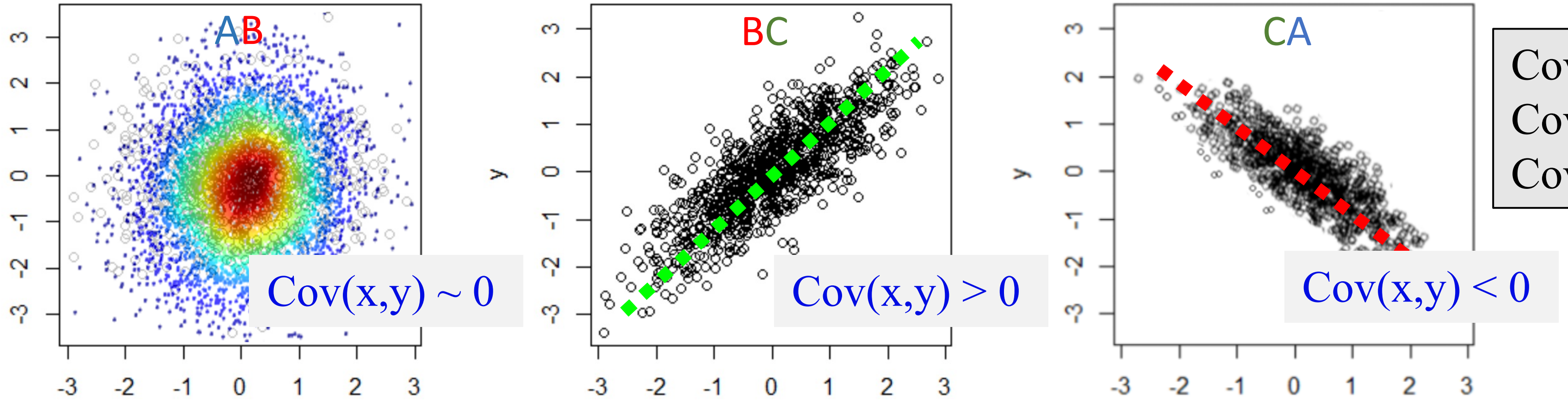
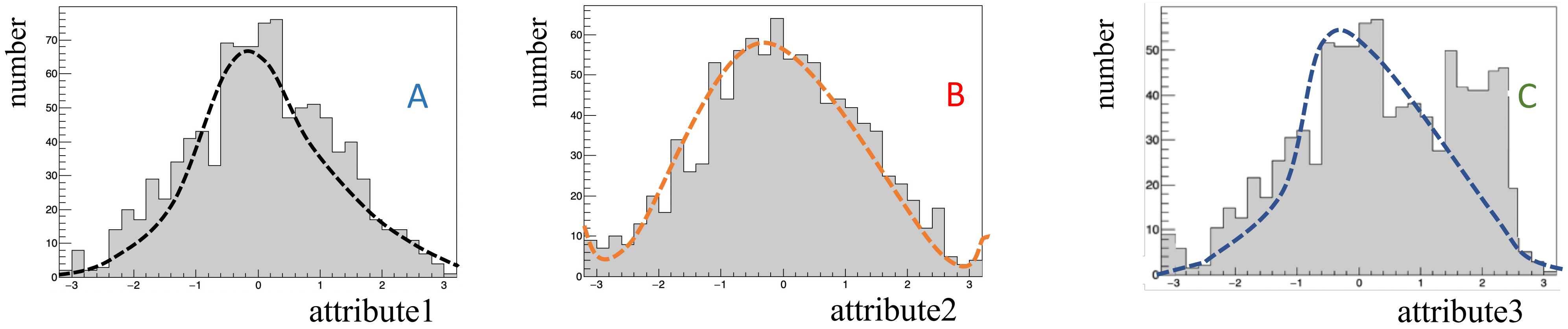


Cov.	> 0	correlated
Cov.	~ 0	uncorrelated
Cov.	< 0	anticorrelated

Quantify the amount of correlation with the **covariance**: $\mathrm{Cov}(x,y) = \langle xy \rangle - \langle x \rangle \langle y \rangle$ → (for density) $C_2 = \rho_2 - \rho_1 \rho_1$

Imagine that we have a population of n things, each with multiple attributes



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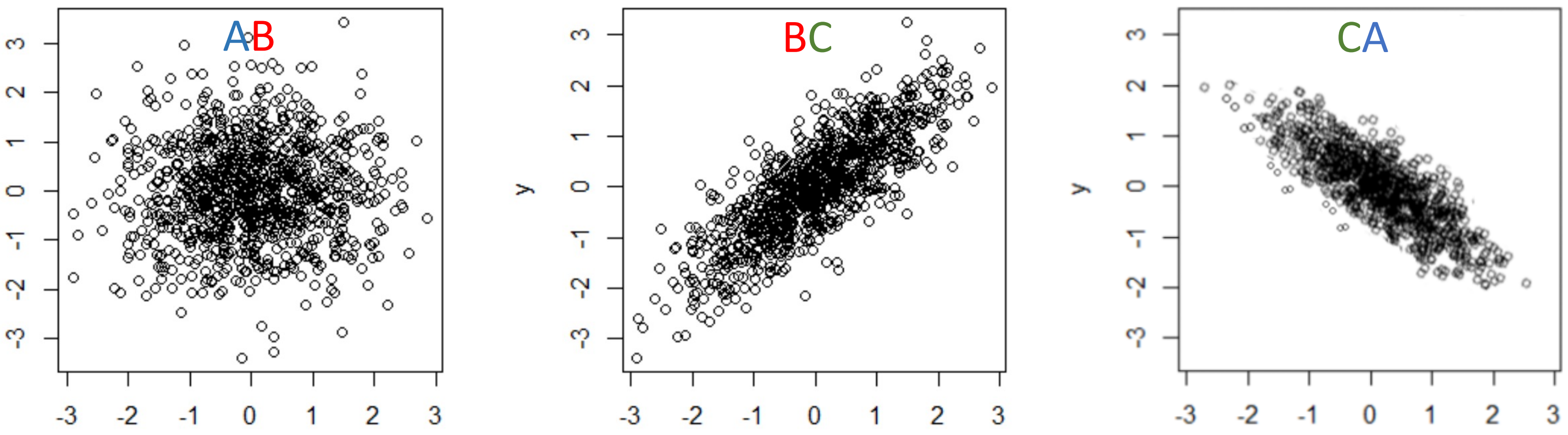
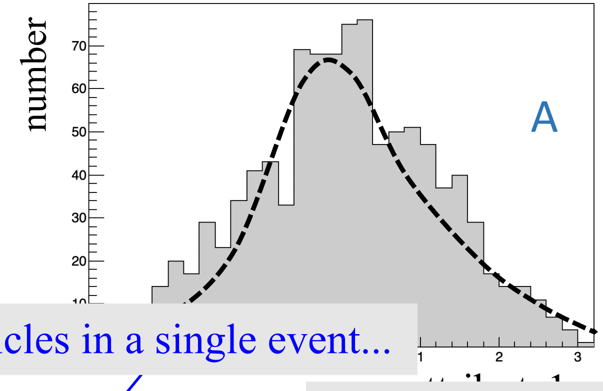
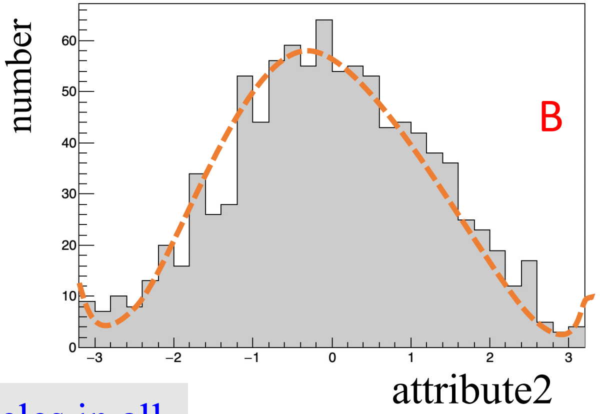
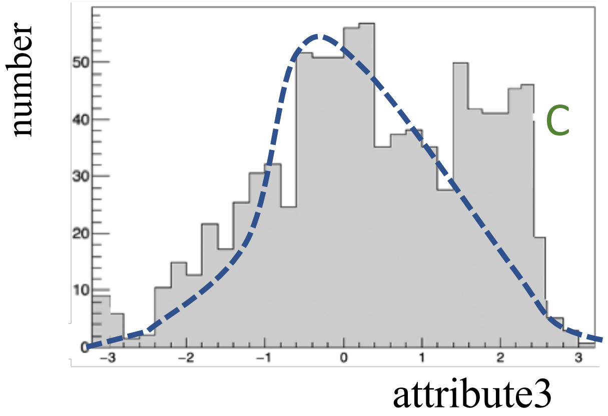


Experimentally: The average values of specific powers of deviates give cumulants & cumulant ratios (or moments and moments products)....







No. of particles in a single event...

Average No. of particles in all "similar" events...

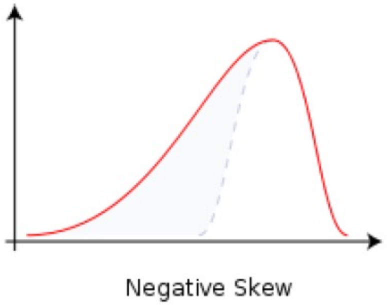
$$\delta x \equiv x - \langle x \rangle$$

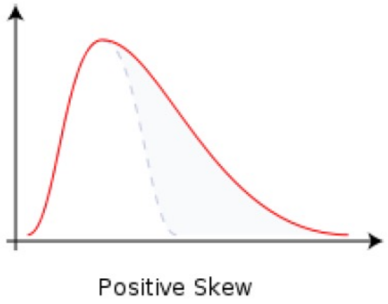
$$\kappa_{2x} \equiv \langle\langle x^2 \rangle\rangle \equiv \langle (\delta x)^2 \rangle$$

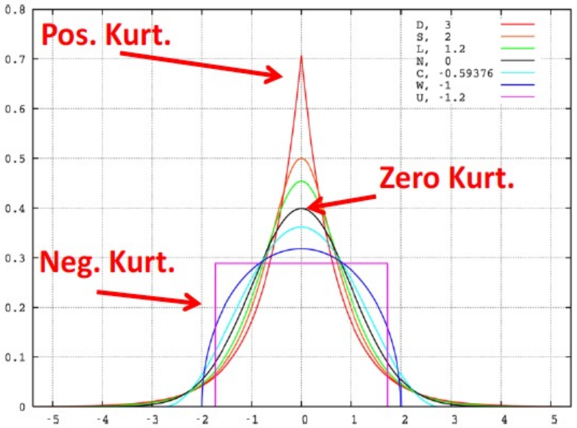
$$\kappa_{3x} \equiv \langle\langle x^3 \rangle\rangle \equiv \langle (\delta x)^3 \rangle$$

$$\kappa_{4x} \equiv \langle\langle x^4 \rangle\rangle \equiv \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2$$

$$\text{skewness} = \frac{\kappa_3}{\kappa_2^{3/2}}, \quad \text{kurtosis} = \frac{\kappa_4}{\kappa_2^2}$$







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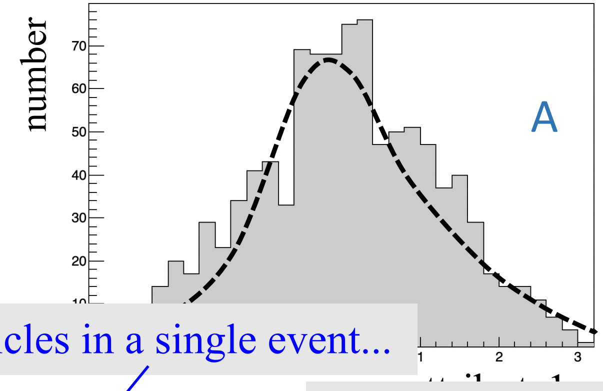

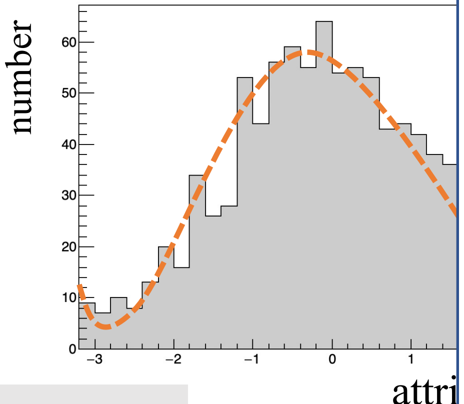

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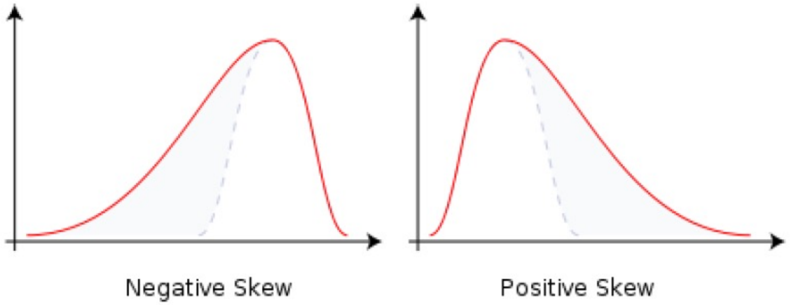
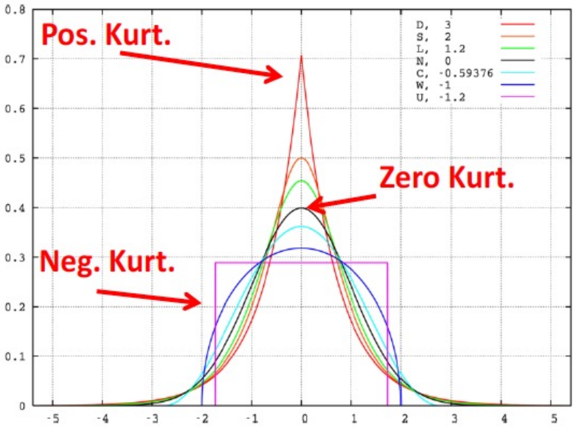




Fluctuations are the **integral** of the Correlations

$$\text{Multiplicity Cumulants} = \text{Poisson} + [\text{deviations from Poisson}]$$

$$K_1 = \langle N \rangle$$

$$K_2 = \langle N \rangle + c_2$$

$$K_3 = \langle N \rangle + 3c_2 + c_3$$

$$K_4 = \langle N \rangle + 7c_2 + 6c_3 + c_4$$

$$c_k = \int C_k(y_1, ..., y_k)\, dy_1 ... dy_k$$

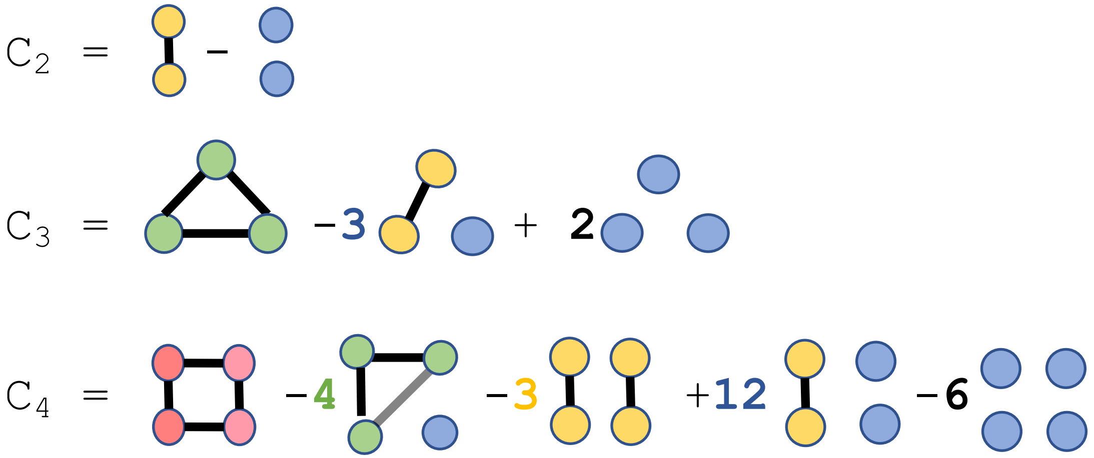
"Correlation Functions"

$$C_2 = \rho_2 - \rho_1\rho_1$$

$$C_3 = \rho_3 - 3\rho_2\rho_1 + 2\rho_1\rho_1\rho_1$$

$$C_4 = \rho_4 - 4\rho_3\rho_1 - 3\rho_2\rho_2 + 12\rho_2\rho_1\rho_1 - 6\rho_1\rho_1\rho_1\rho_1$$

Explicit subtraction of lower-order correlations…



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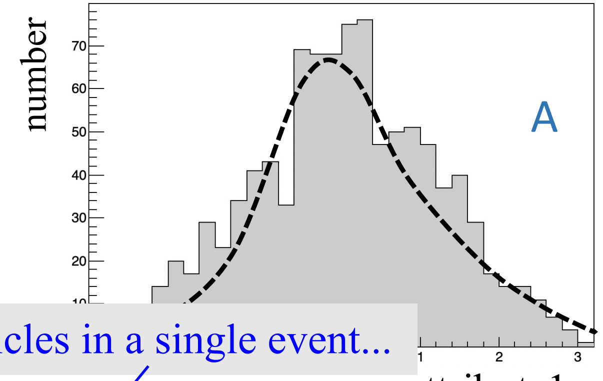

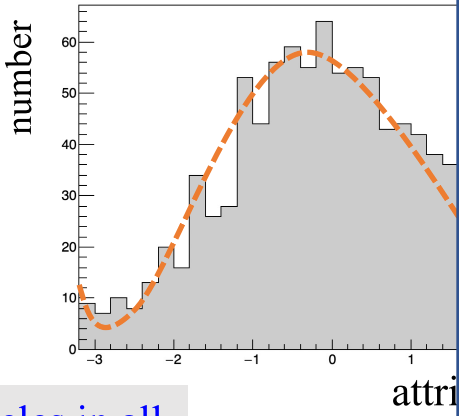

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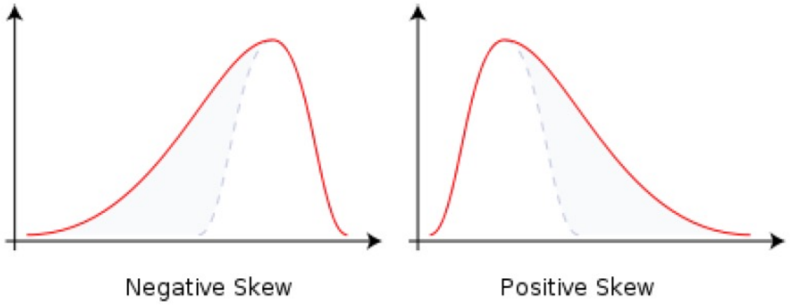

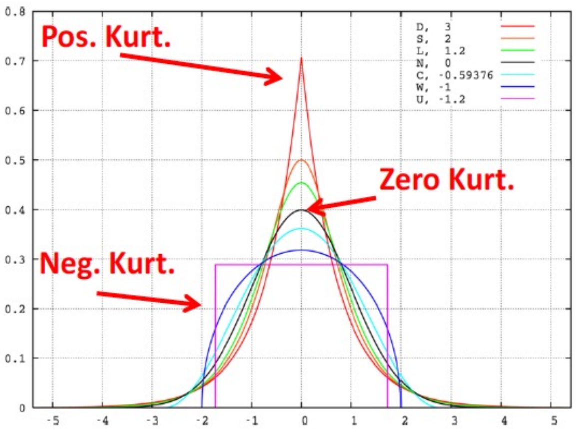

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ALICE

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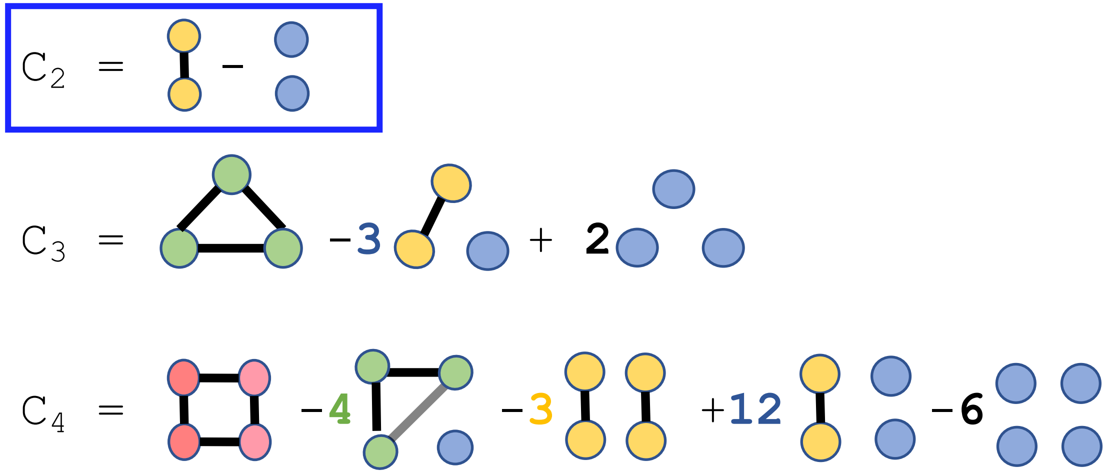
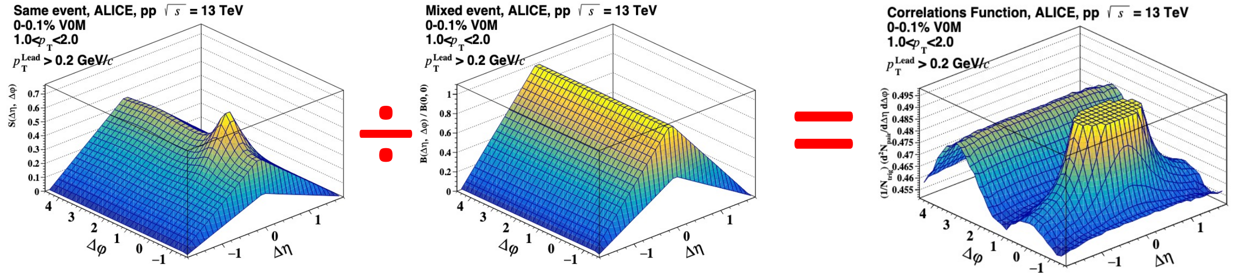


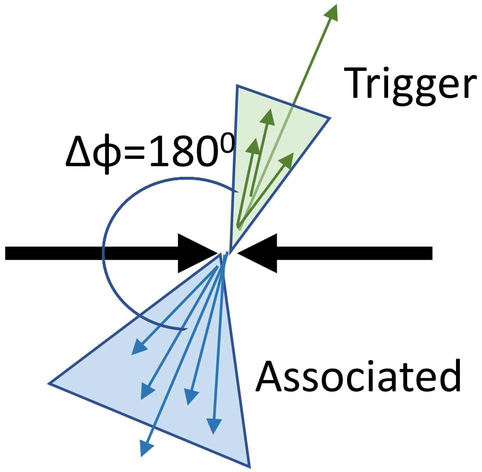
Technique

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

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

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





Technique

2. Background contribution is subtracted:

$$B(\Delta\varphi) = B_0\left(1 + 2\sum_n V_n \cos(n\Delta\varphi)\right)$$

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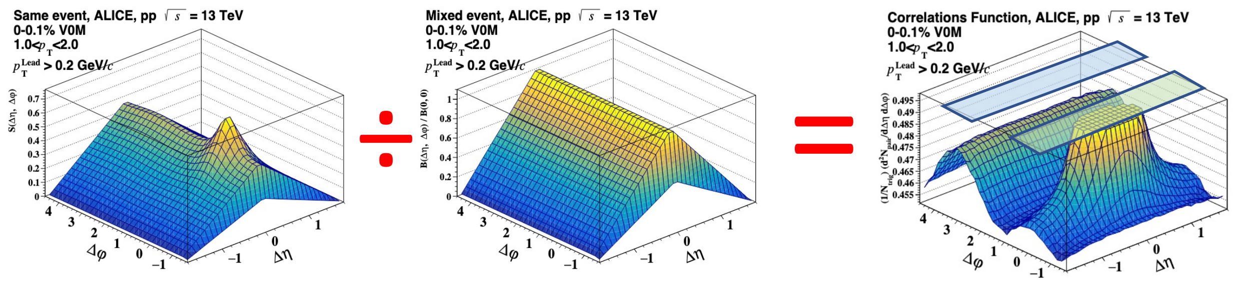
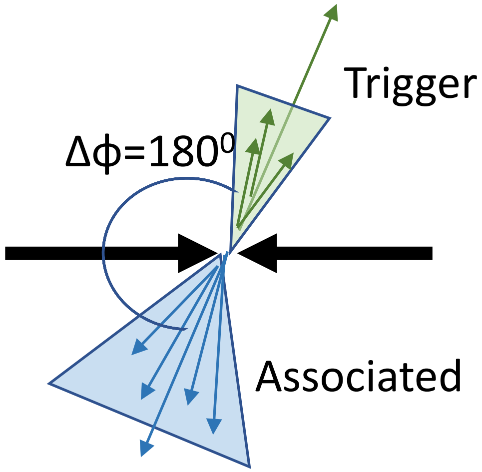
Away Side

Near Side





Result Extraction

I. Width Δη or width $\Delta\varphi$ can be calculated

II. Yield calculation: $Y_J^{\Delta\varphi} = \int_{\Delta\varphi_1}^{\Delta\varphi_2} \frac{dN}{d\Delta\varphi} d\Delta\varphi$

III. Yield and I_{AA} are calculated:

$$I_{AA} = \int J_{AA}(\Delta\varphi) d\Delta\varphi \Big/ \int J_{pp}(\Delta\varphi) d\Delta\varphi$$

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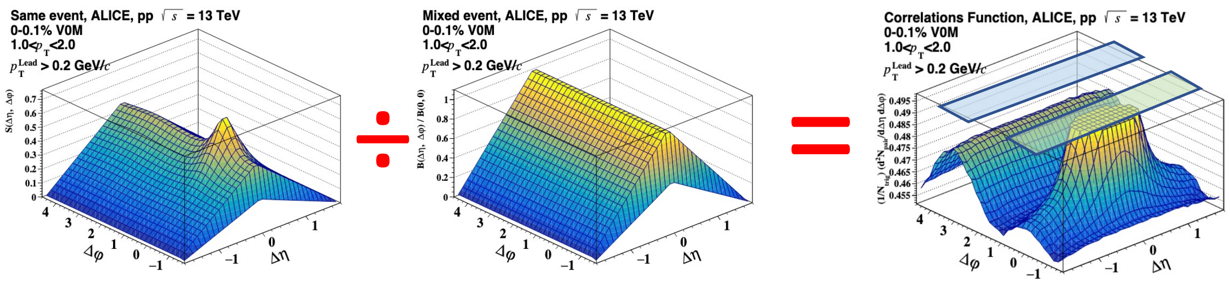

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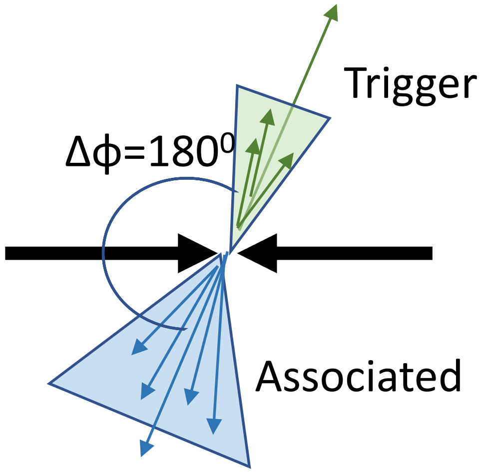
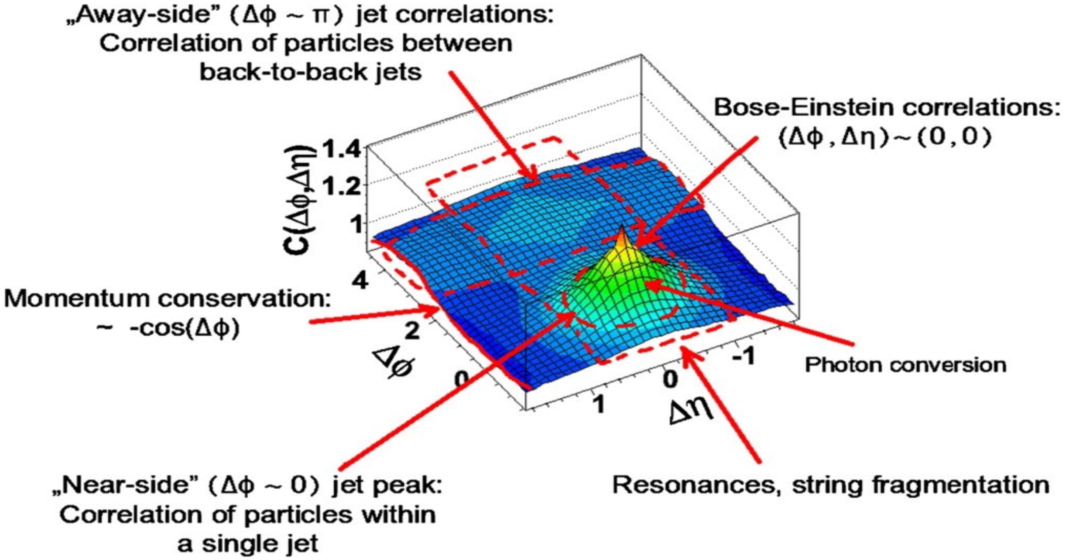


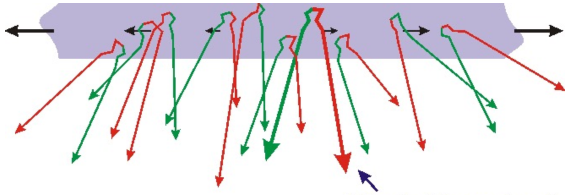


Physics Motivation

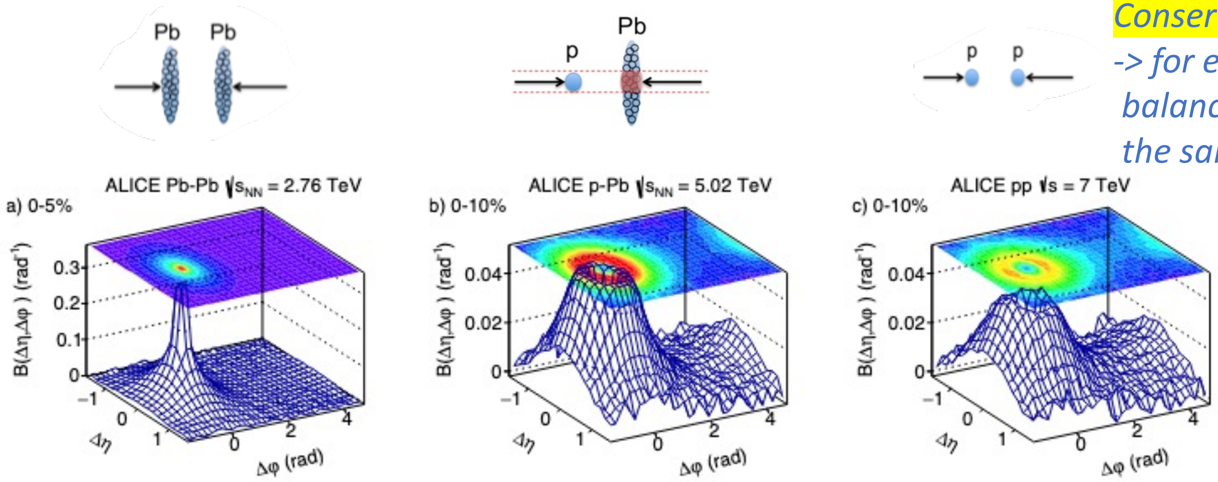
May want to scale C_2 by the number of uncorrelated pairs:

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

Balance Function (2-Particle correlations)



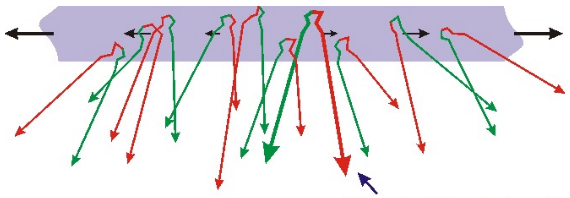
Conservation of quantum numbers.
-> for each general charge, an opposite balancing charge produced at approx. the same space–time.



Eur. Phys. J. C 76 (2016) 86 Phys. Rev. C 100, 044903 (2019)

Old Result

Balance Function (2-Particle correlations)



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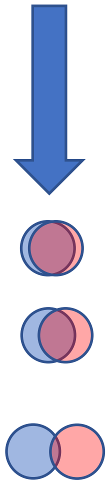

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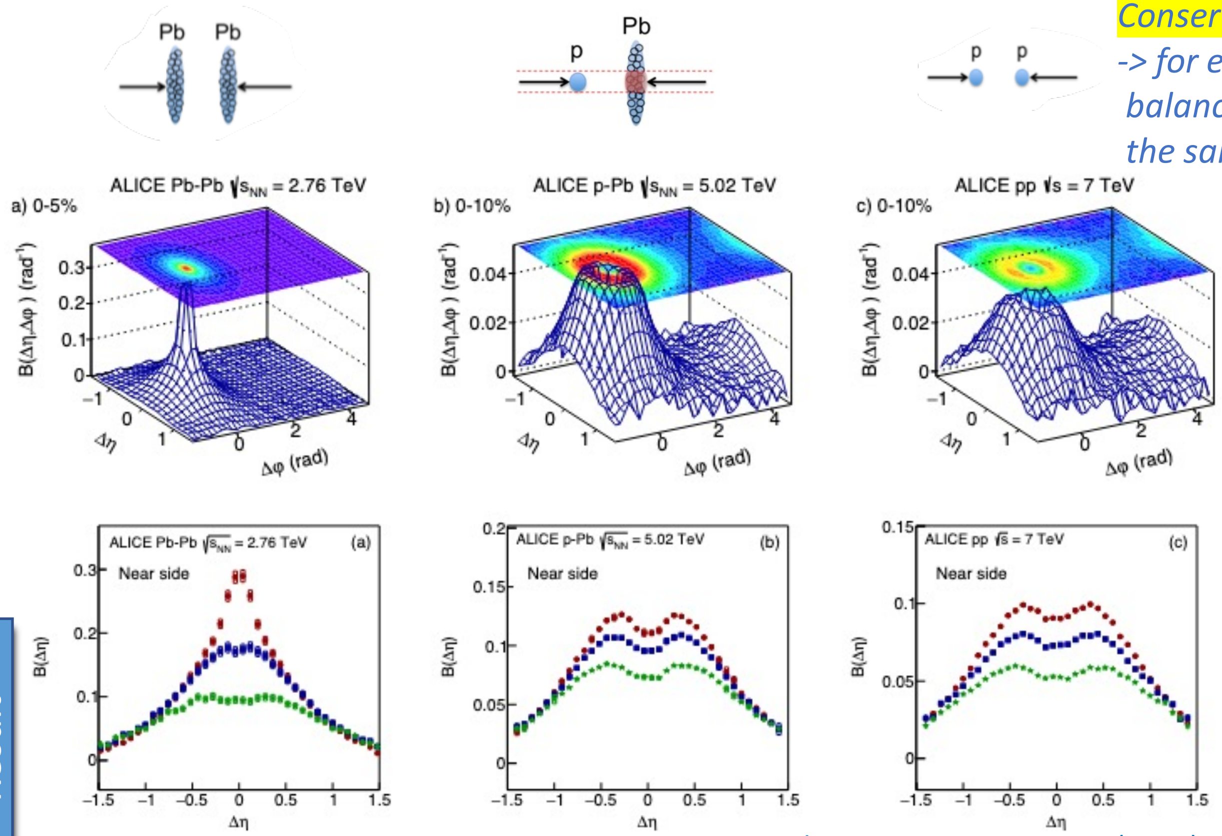

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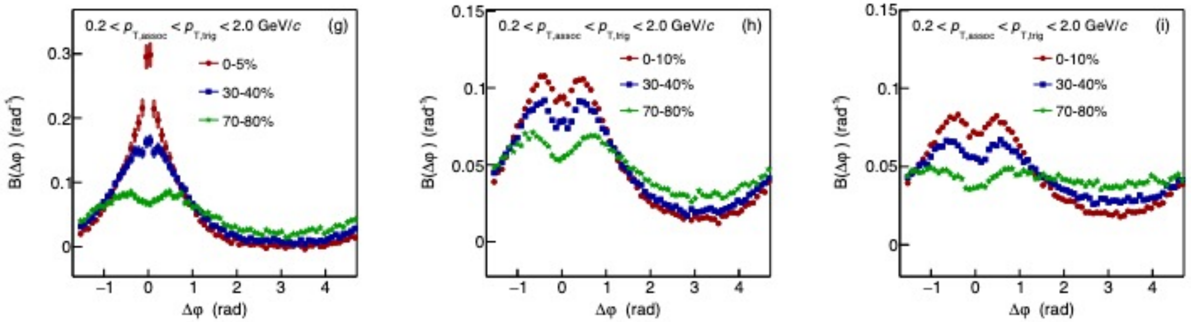
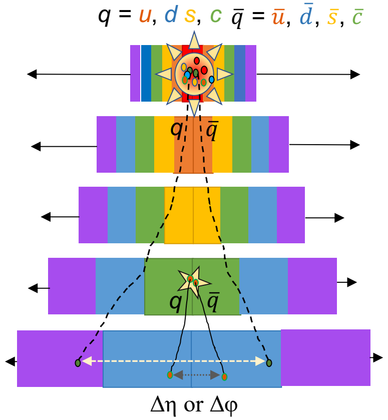
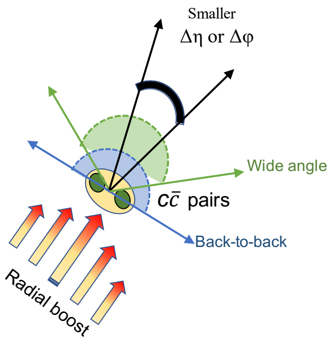




(a) Clocking Hadronization



(b) Kinematic lensing due to radial boost

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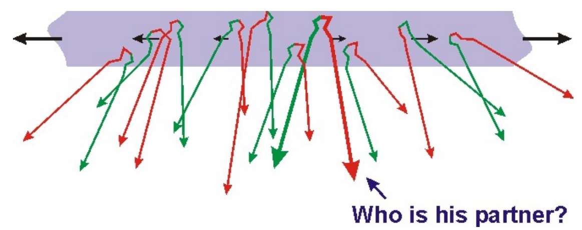

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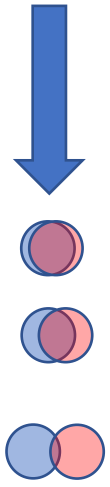
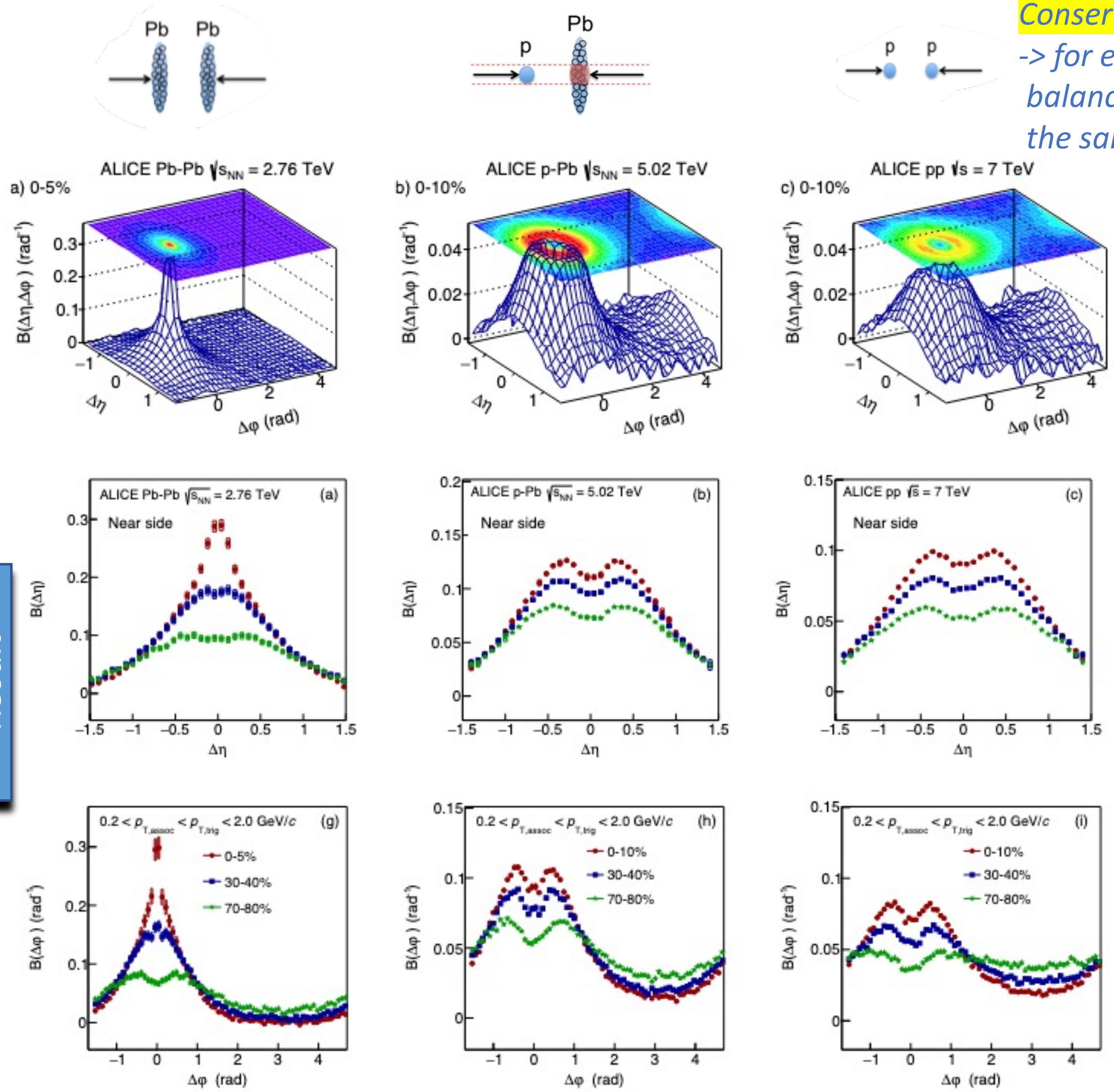
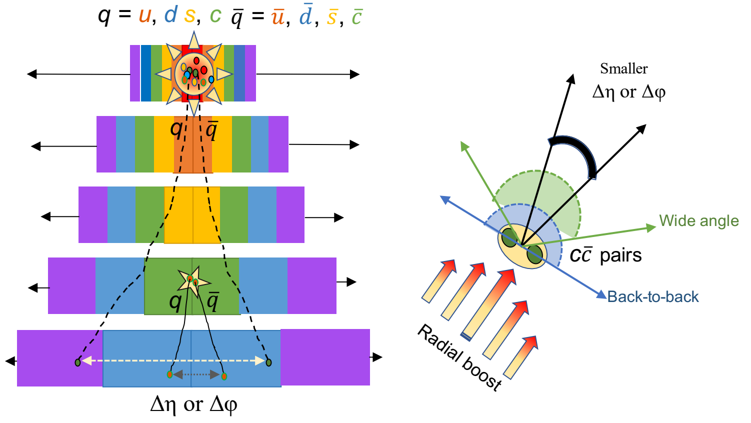


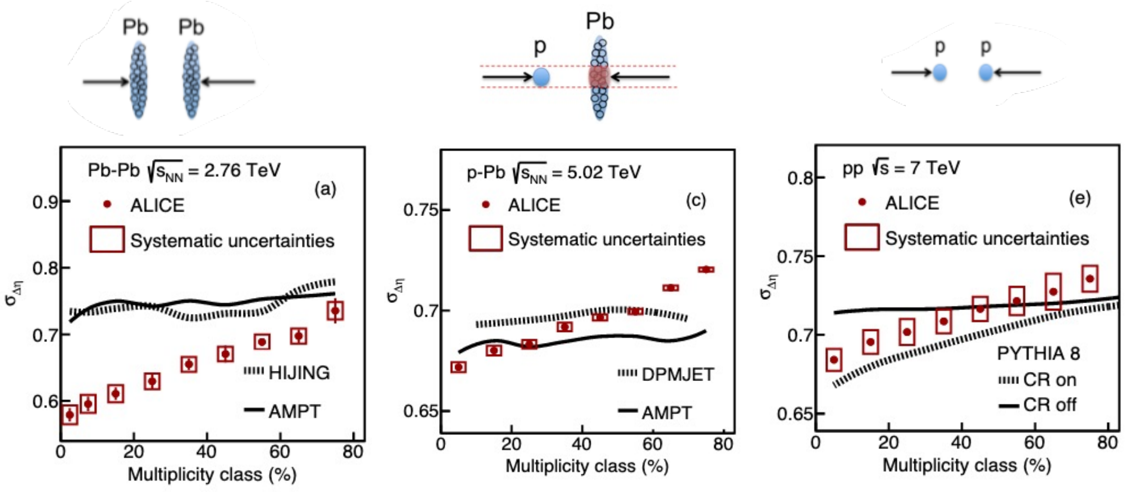
Old Result





(a) Clocking Hadronization

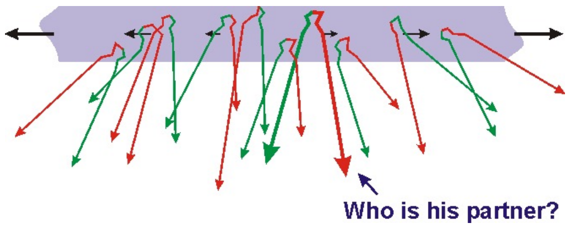
(b) Kinematic lensing due to radial boost



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

Phys. Rev. C 100, 044903 (2019)

Balance Function (2-Particle correlations)



Species Dependence

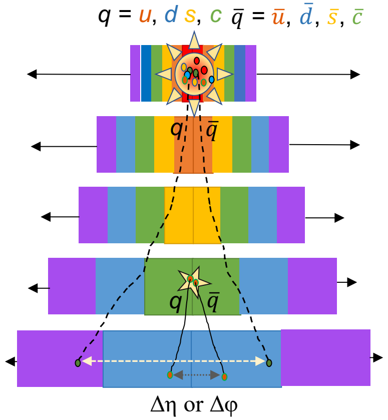
		h	π	k	p
Q	h	✓			
Q	π		?	?	?
Q S	k		?	?	?
Q B	P		?	?	?

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

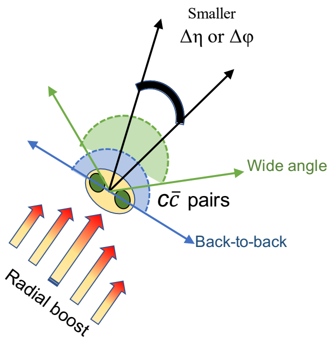
Cumulant $C_2(x_1,x_2) = \rho_2(x_1,x_2) - \rho_1(x_1)\rho_1(x_2)$ $\quad x \equiv \{y, \varphi, p_T\}$ $\quad \rho(x) = \frac{1}{\sigma}\frac{d\sigma}{dx}$

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



(a) Clocking Hadronization



(b) Kinematic lensing due to radial boost

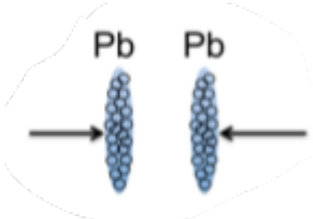
4 different charge combinations for R_2:
(+ -), (- +), (+ +), and (- -)

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

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

$$LS = \frac{1}{2}\{(++) + (--)\}$$

$$US = \frac{1}{2}\{(+-) + (-+)\}$$



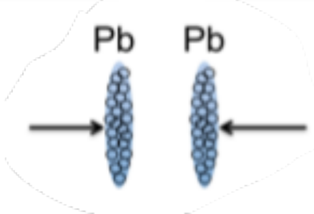
R_2^{CD} is proportional to the Balance Function

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

Balance Function (2-Particle correlations)

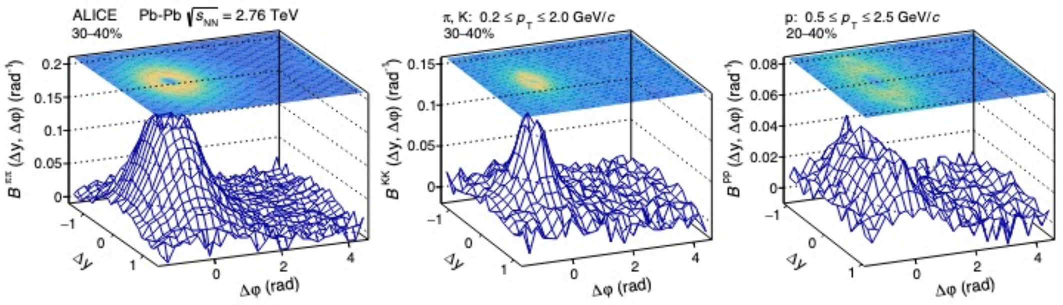
Species Dependence

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



New Result

$\pi^{\pm}$–$\pi^{\pm}$ K$^{\pm}$–K$^{\pm}$ $p(\overline{p})$–$p(\overline{p})$

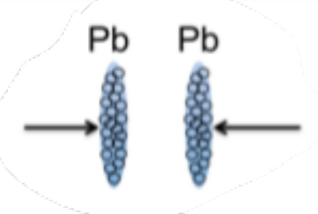


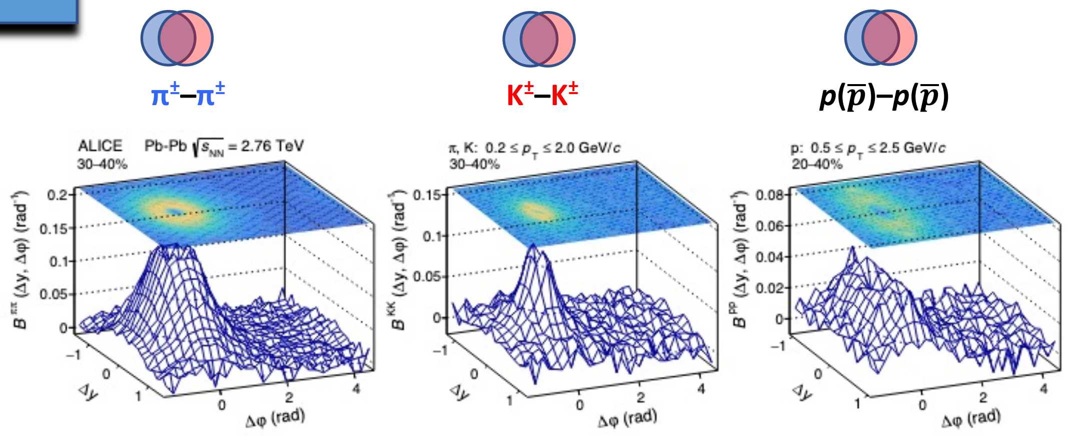
arXiv:2110.06566 [nucl-ex]

Balance Function (2-Particle correlations)

Species Dependence

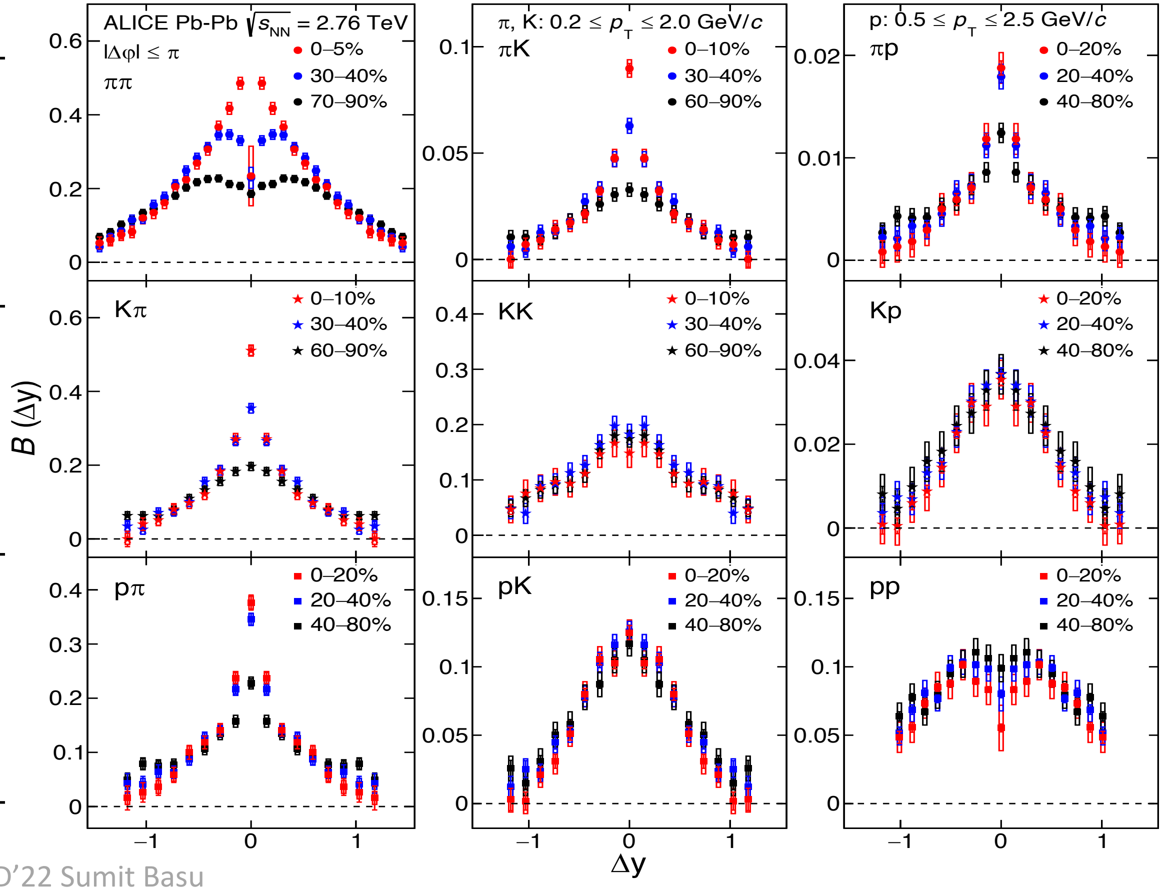
		h	π	k	p
Q	h	✓			
Q	π		?	?	?
Q S	k		?	?	?
Q B	P		?	?	?





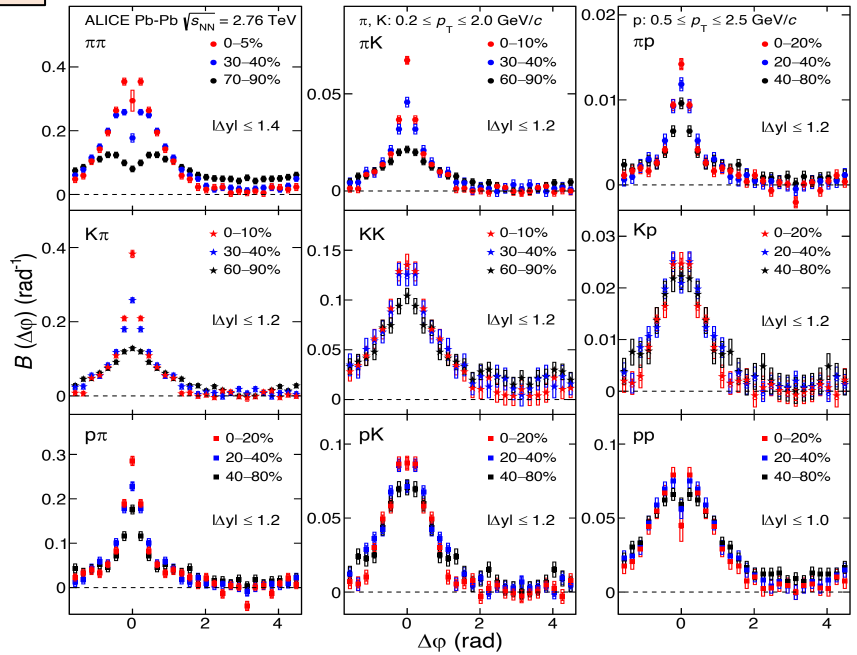
arXiv:2110.06566 [nucl-ex]

Δy

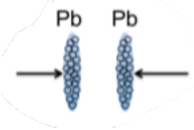


New Result

$\Delta\varphi$



Balance Function (2-Particle correlations)

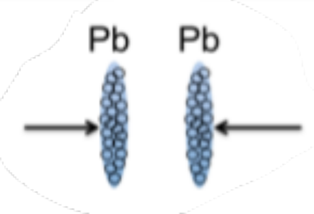


New Result

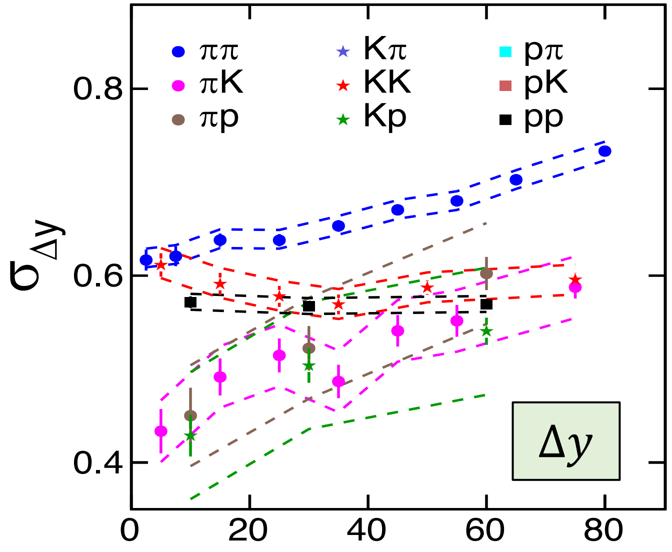
ALICE

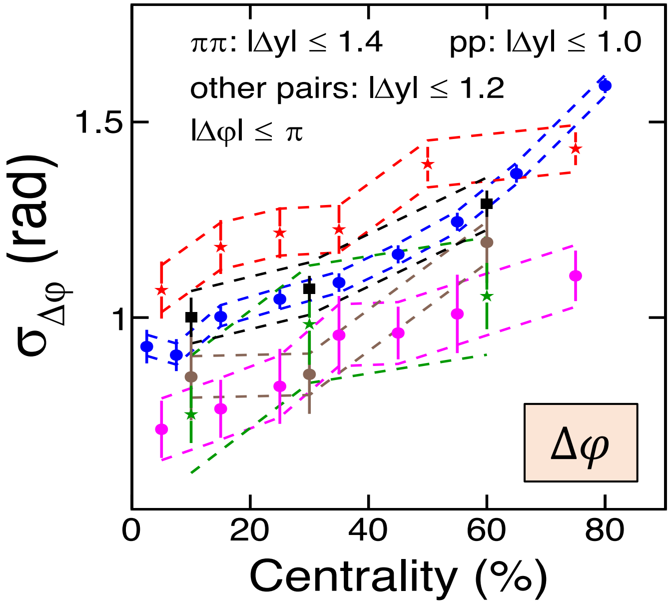
Species Dependence

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

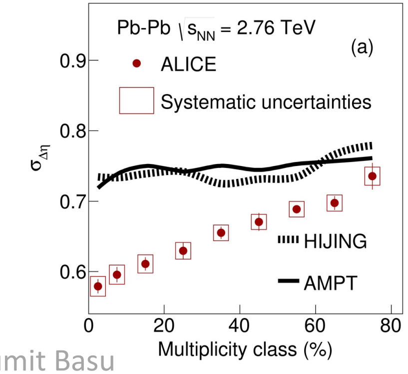


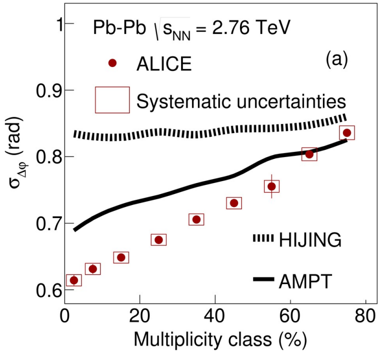
arXiv:2110.06566 [nucl-ex]



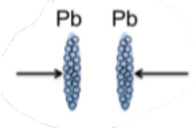


Eur. Phys. J. C 76 (2016) 86





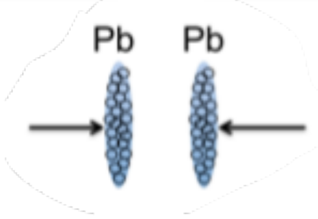
Balance Function (2-Particle correlations)



New Result

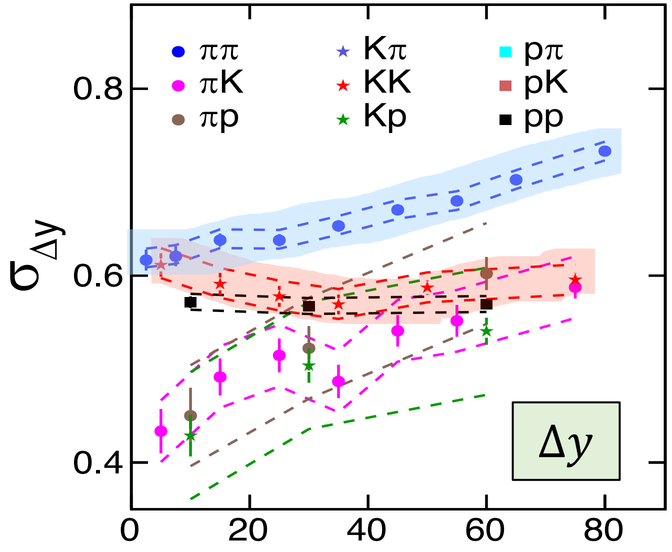
Species Dependence

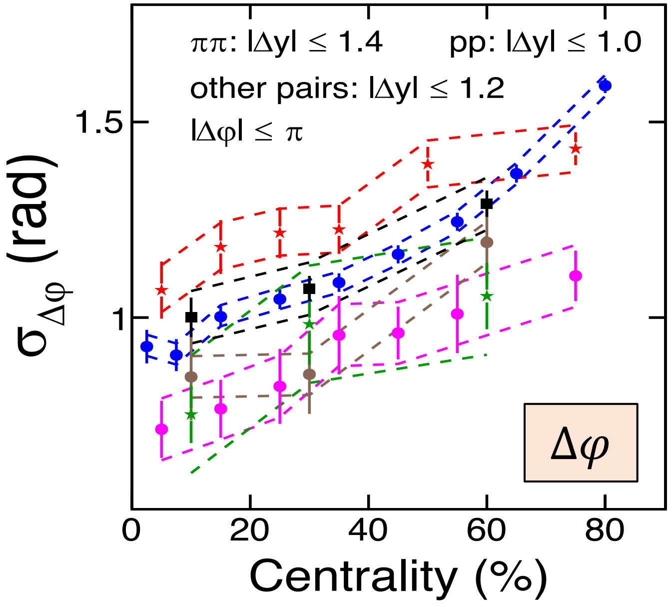
			h	π	k	p
Q		h	✓			
Q		π		?	?	?
Q	S	k		?	?	?
Q	B	P		?	?	?

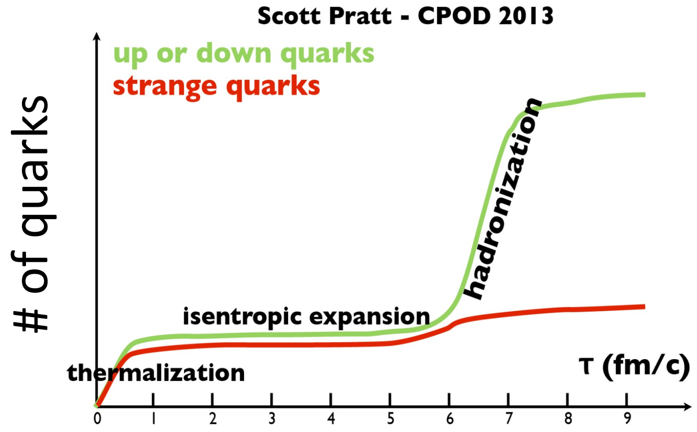


arXiv:2110.06566 [nucl-ex]

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







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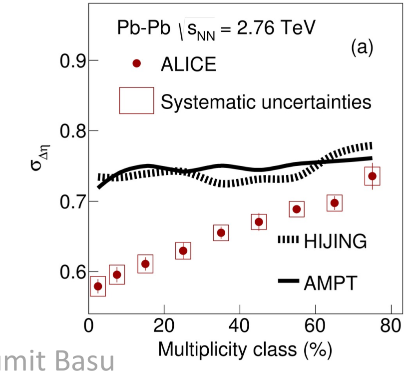
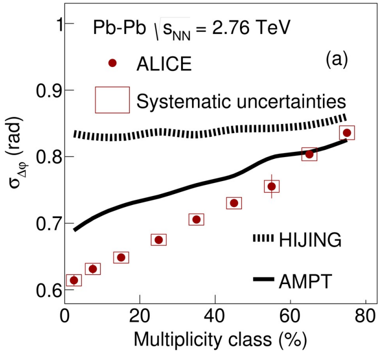
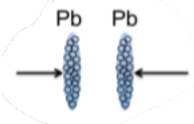




- Azimuthal narrowing for all species → radial flow focusing
- Qualitatively consistent with radial flow and two-wave quark production

Balance Function (2-Particle correlations)



New Result

ALICE

Species Dependence

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

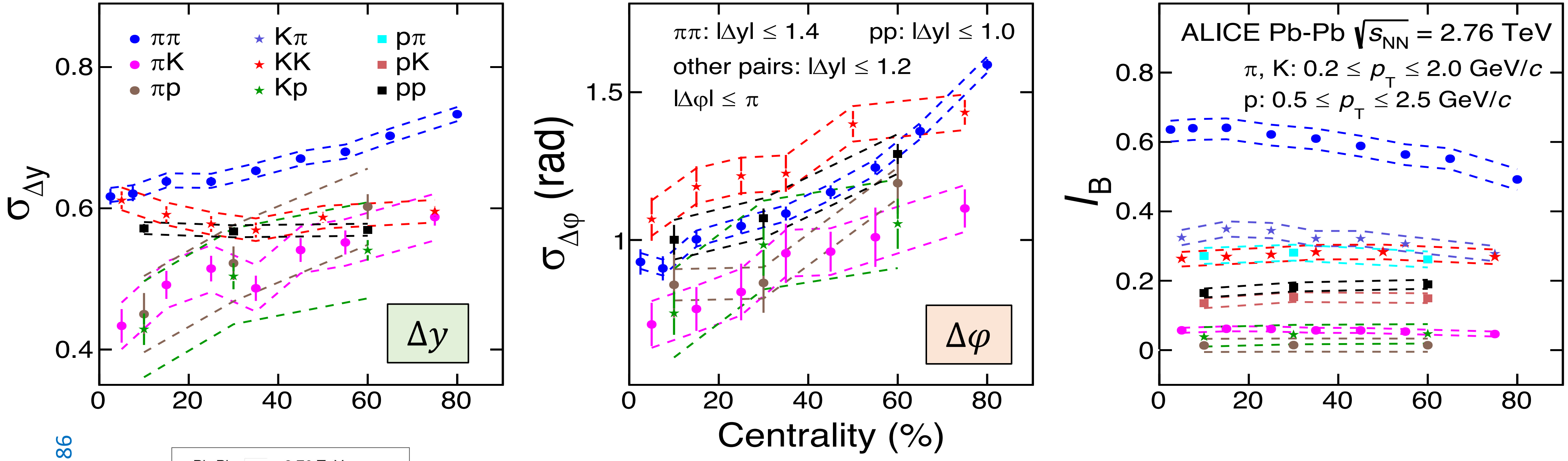
$$I_B = \int_{-\infty}^{\infty} B_{\pi^\pm h^\pm}(d\eta, d\varphi) d\eta d\varphi dp_T = 1$$

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

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

arXiv:2110.06566 [nucl-ex]

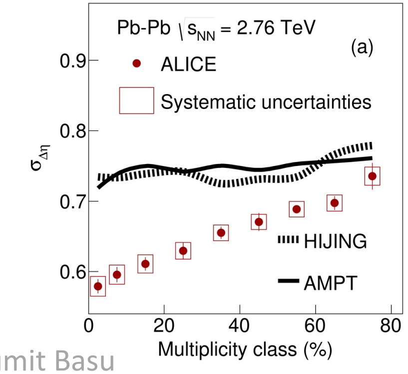
BF Integral

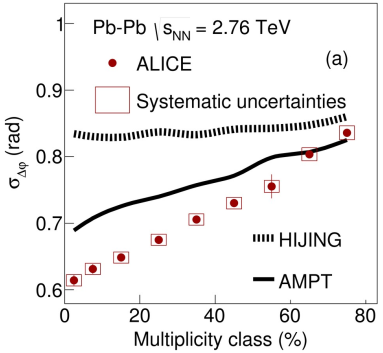


= Pairing Probabilities

Pairing probabilities are very different from single hadron ratios.
→ Kπ not larger than KK by K/π ratio; pp larger than pK.

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





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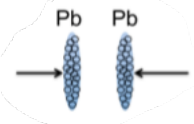

New Result

Species Dependence

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Q	h	✓			
Q	π		?	?	?
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Q B	P		?	?	?

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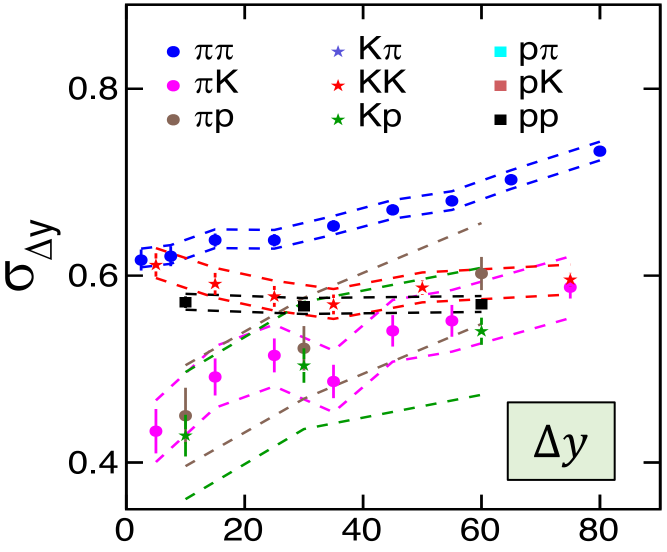
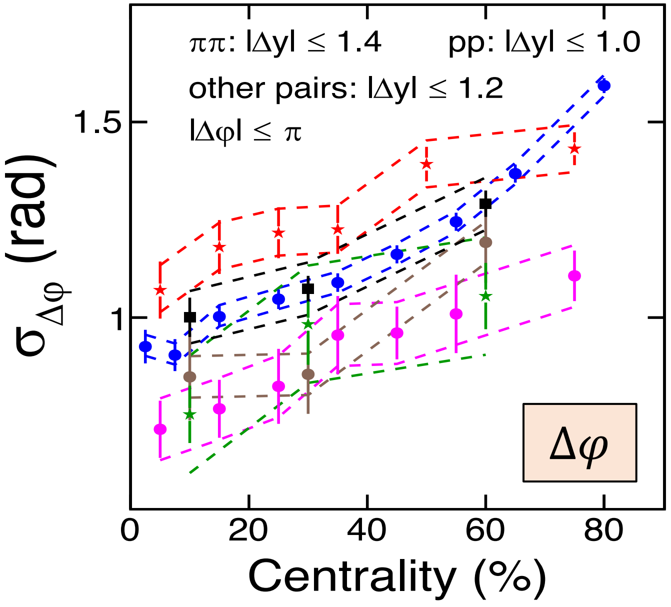
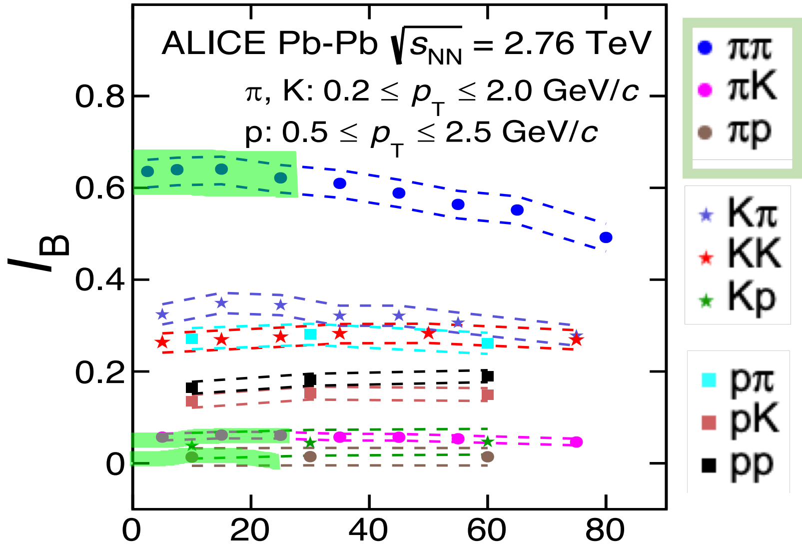
arXiv:2110.06566 [nucl-ex]

BF Integral







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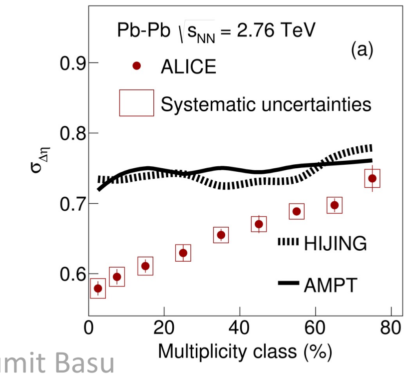
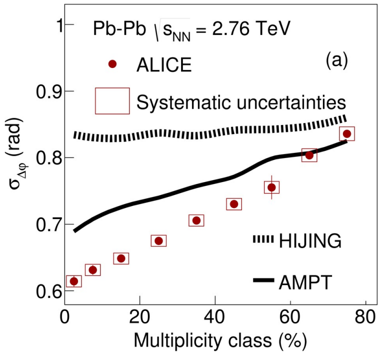
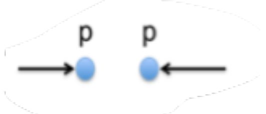
Eur. Phys. J. C 76 (2016) 86





→ Low p_T particles mostly balance by low p_T particles

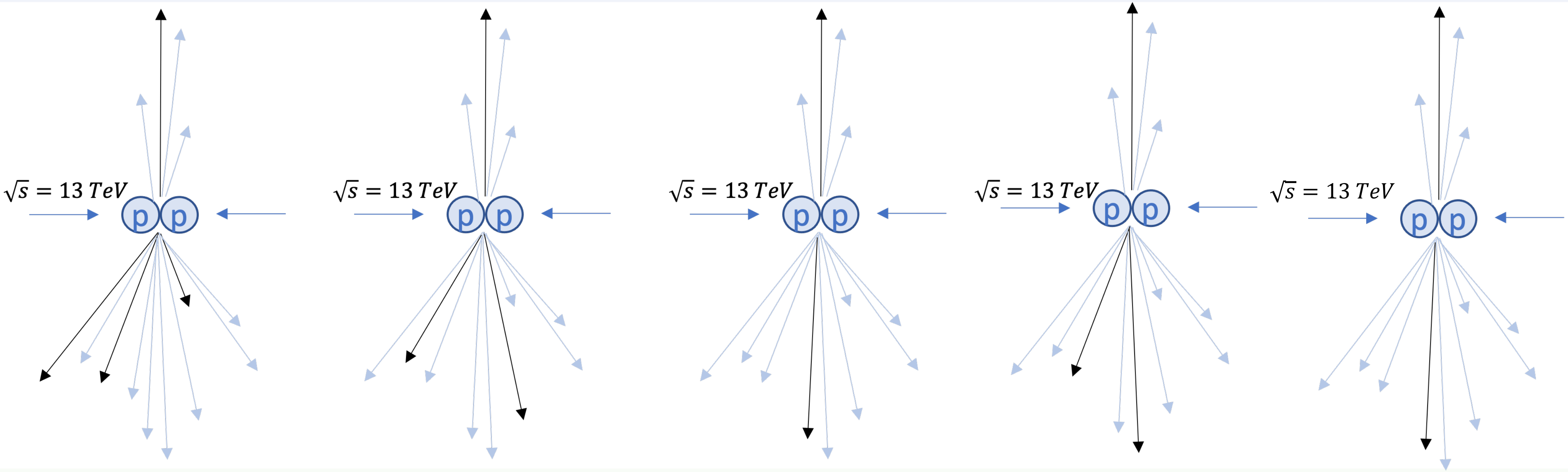
Ξ−hadron correlations in pp collisions at √s = 13 TeV



New Result

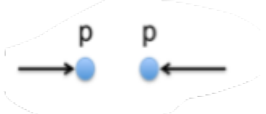
ALICE

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



	Ξ−π	Ξ−K	Ξ−p	Ξ−Λ	Ξ−Ξ
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 (Subtracting same quantum number correlation)	$\pi^-(\bar{u}d)$	$K^-(u\bar{s})$	$p(uud)$	$\Lambda(uds)$	$\Xi(ssd)$

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



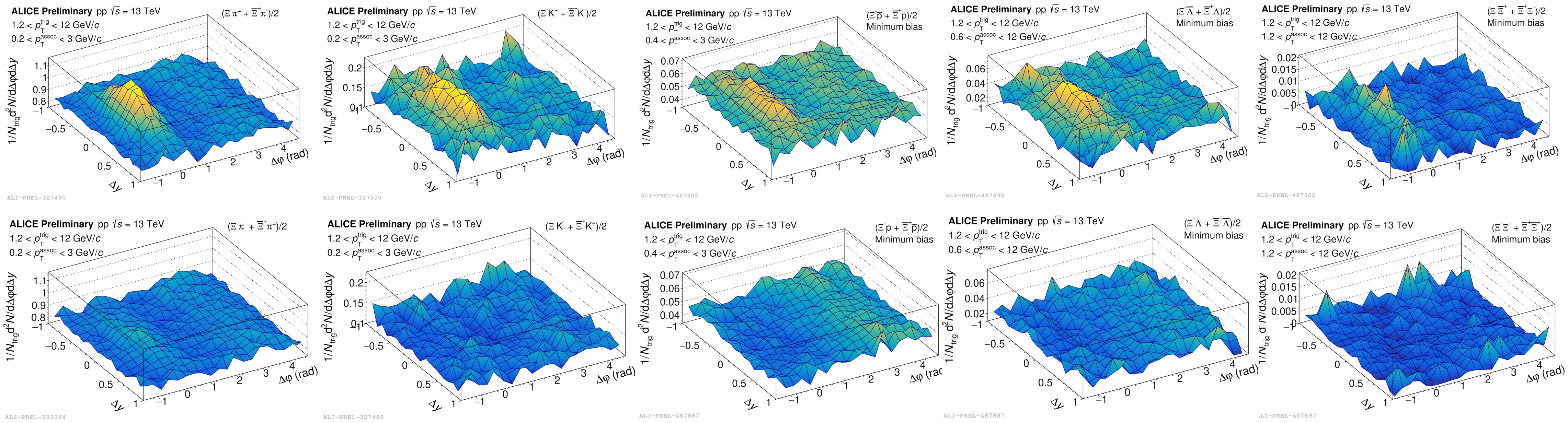
New Result

ALICE

Ξ−π | Ξ−K | Ξ−p | Ξ−Λ | Ξ−Ξ

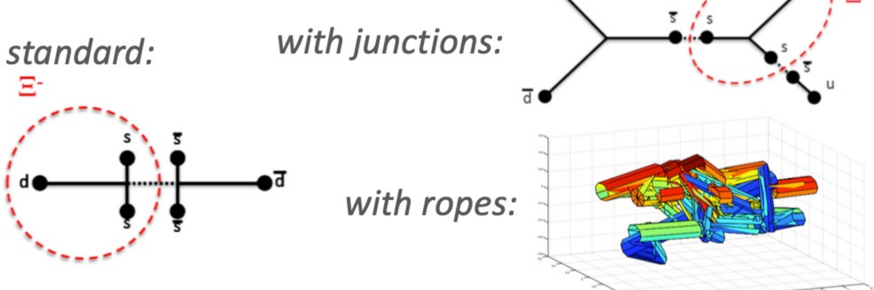
OS or US

SS or LS



→ *Results challenge hadronization models:*

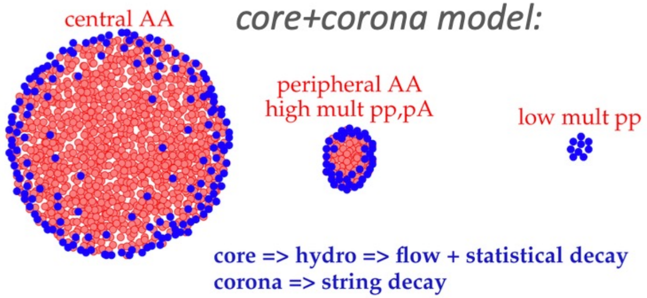
Lund string breaking (PYTHIA)



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

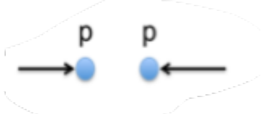
EPOS:

core+corona model:



K. Werner. hal-02434245 (2019)

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

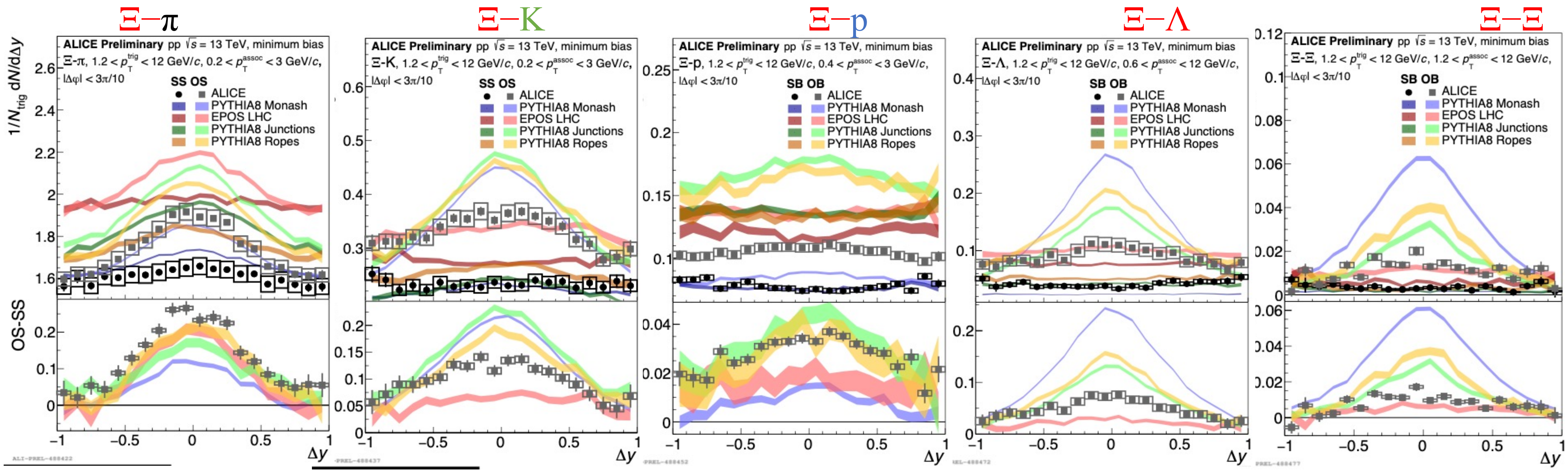


New Result

OS or US

OS-SS

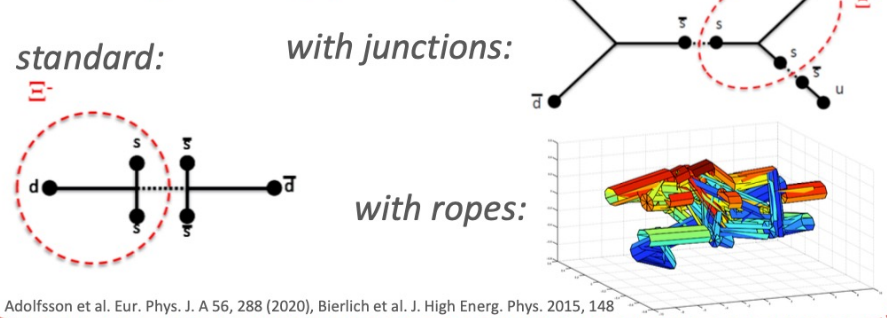
Δy



- Wider peak in data than in PYTHIA
- strange quarks produced at an earlier time
- Local conservation of quantum numbers → not implemented in EPOS

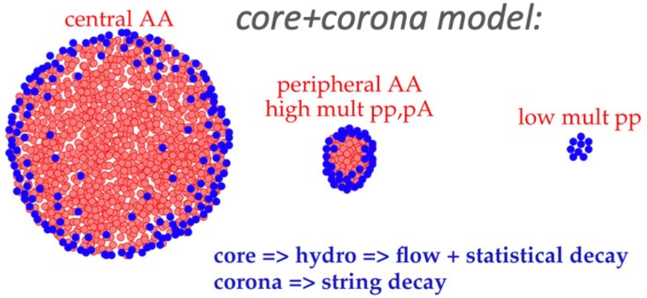
→ *Results challenge hadronization models:*

Lund string breaking (PYTHIA)



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

EPOS:



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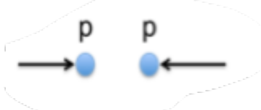
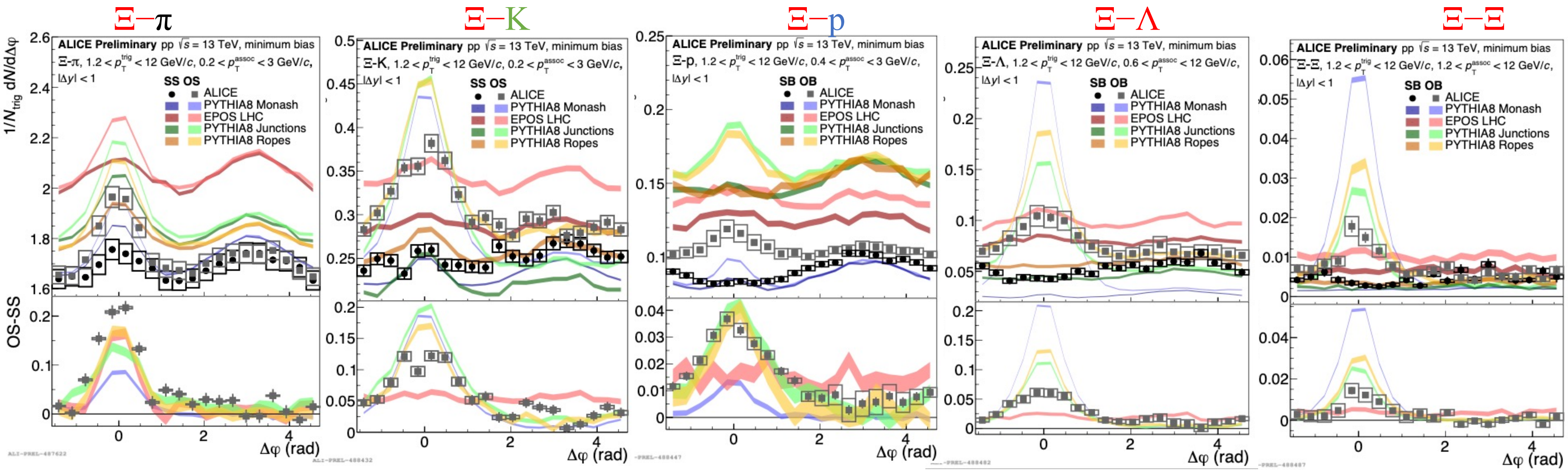


New Result

OS or US

OS-SS

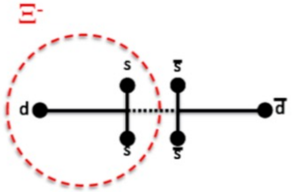
Δφ



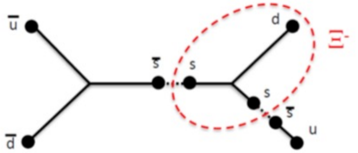
→ *Results challenge hadronization models:*

Lund string breaking (PYTHIA)

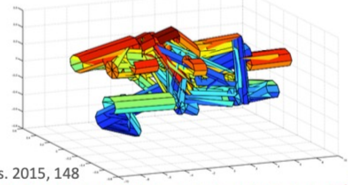
standard:



with junctions:



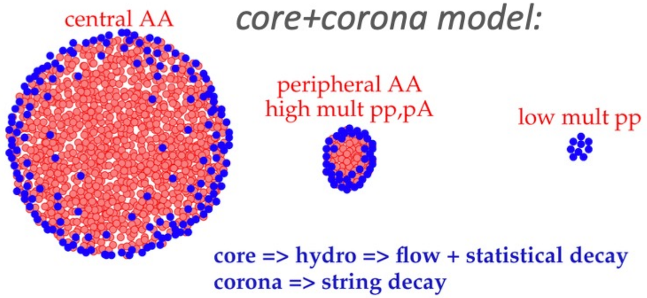
with ropes:



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

EPOS:

core+corona model:

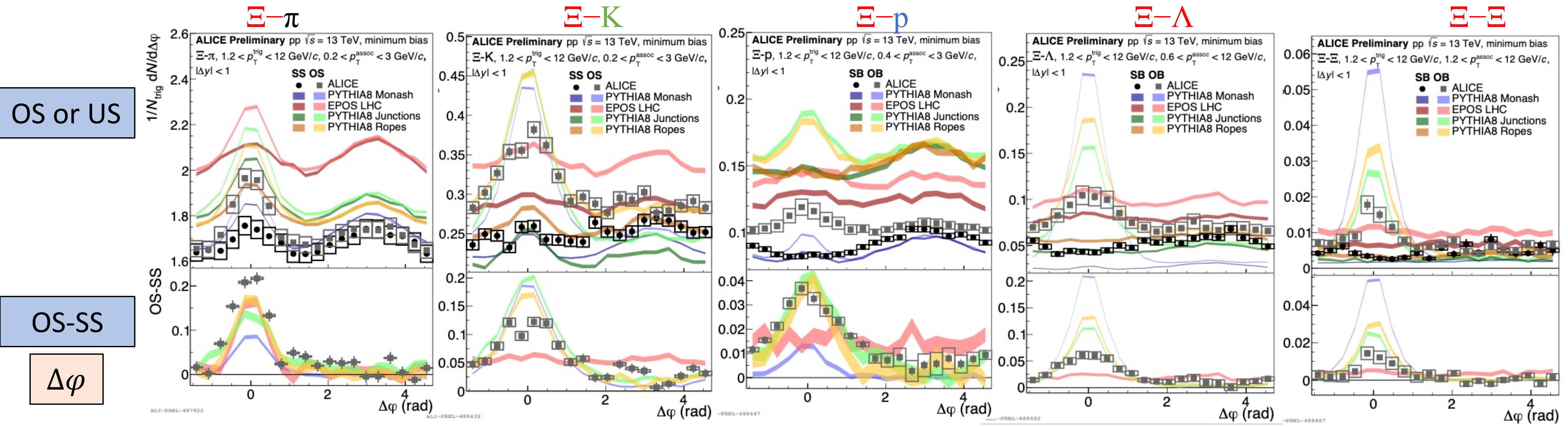


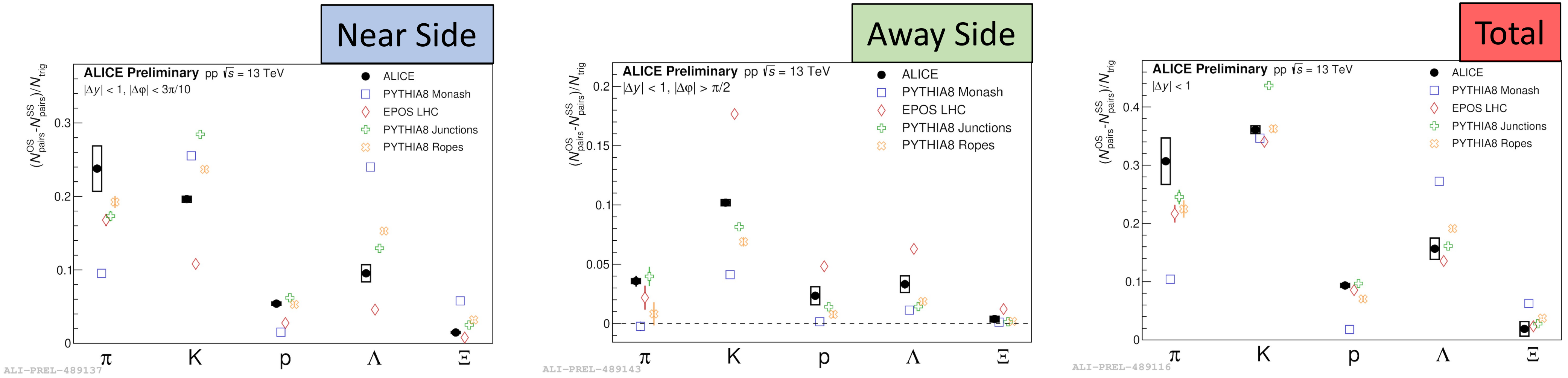
K. Werner. hal-02434245 (2019)

- 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

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

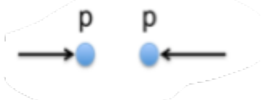
New Result





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

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

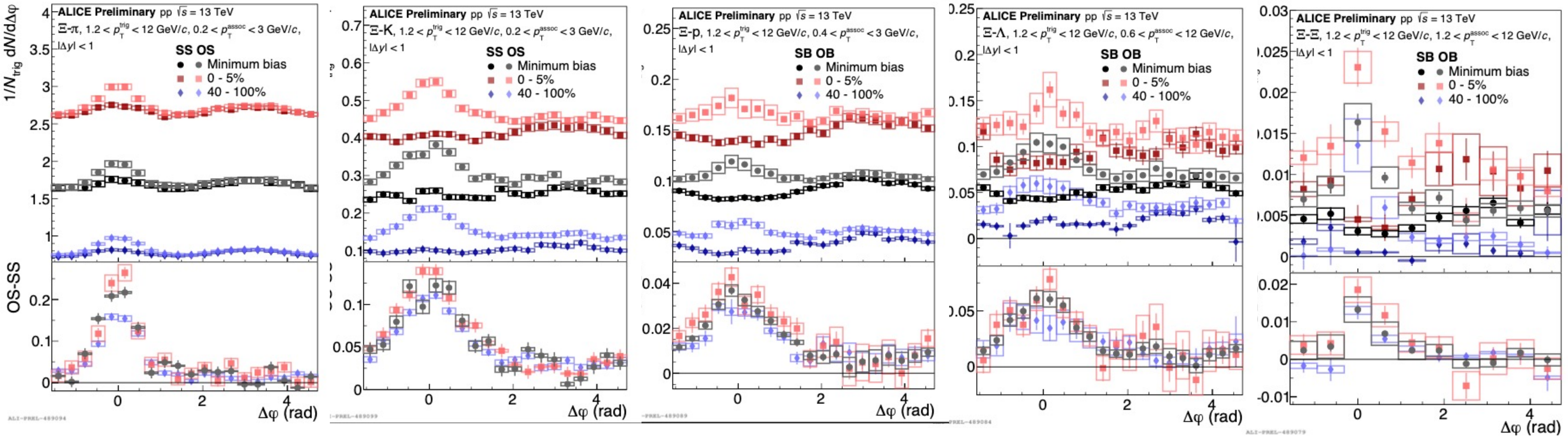


New Result

Multiplicity dependence

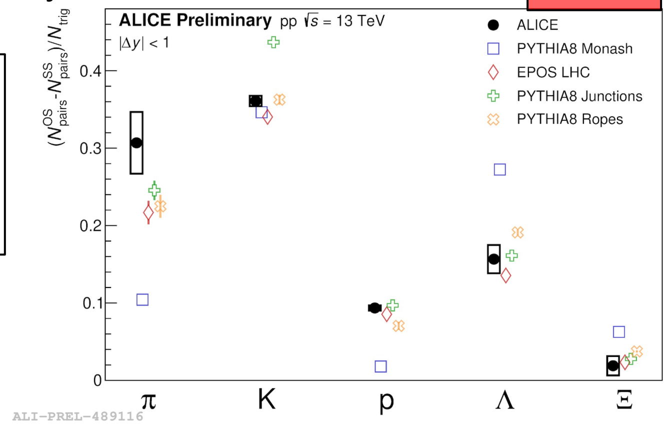
OS-SS

$\Delta\varphi$



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

Total



- 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

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

Pb–Pb $\sqrt{S_{NN}}$ = 2.76 TeV

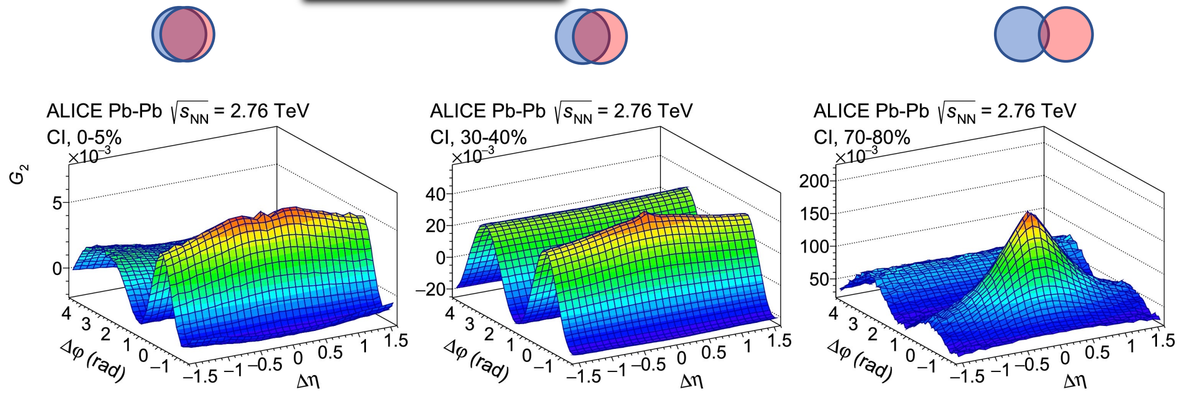
Old Result

PLB 804 (2020) 135375

2-Particle Transverse momentum correlations

- Look for the diffusion of transverse momentum currents through their correlations

$$G_2(\Delta\eta, \Delta\varphi) = \frac{\langle \sum_{i}^{n_{1,1}} \sum_{j \neq i}^{n_{1,2}} p_{\mathrm{T},i}\, p_{\mathrm{T},j} \rangle}{\langle n_{1,1} \rangle \langle n_{1,2} \rangle} - \langle p_{\mathrm{T},1} \rangle \langle p_{\mathrm{T},2} \rangle$$



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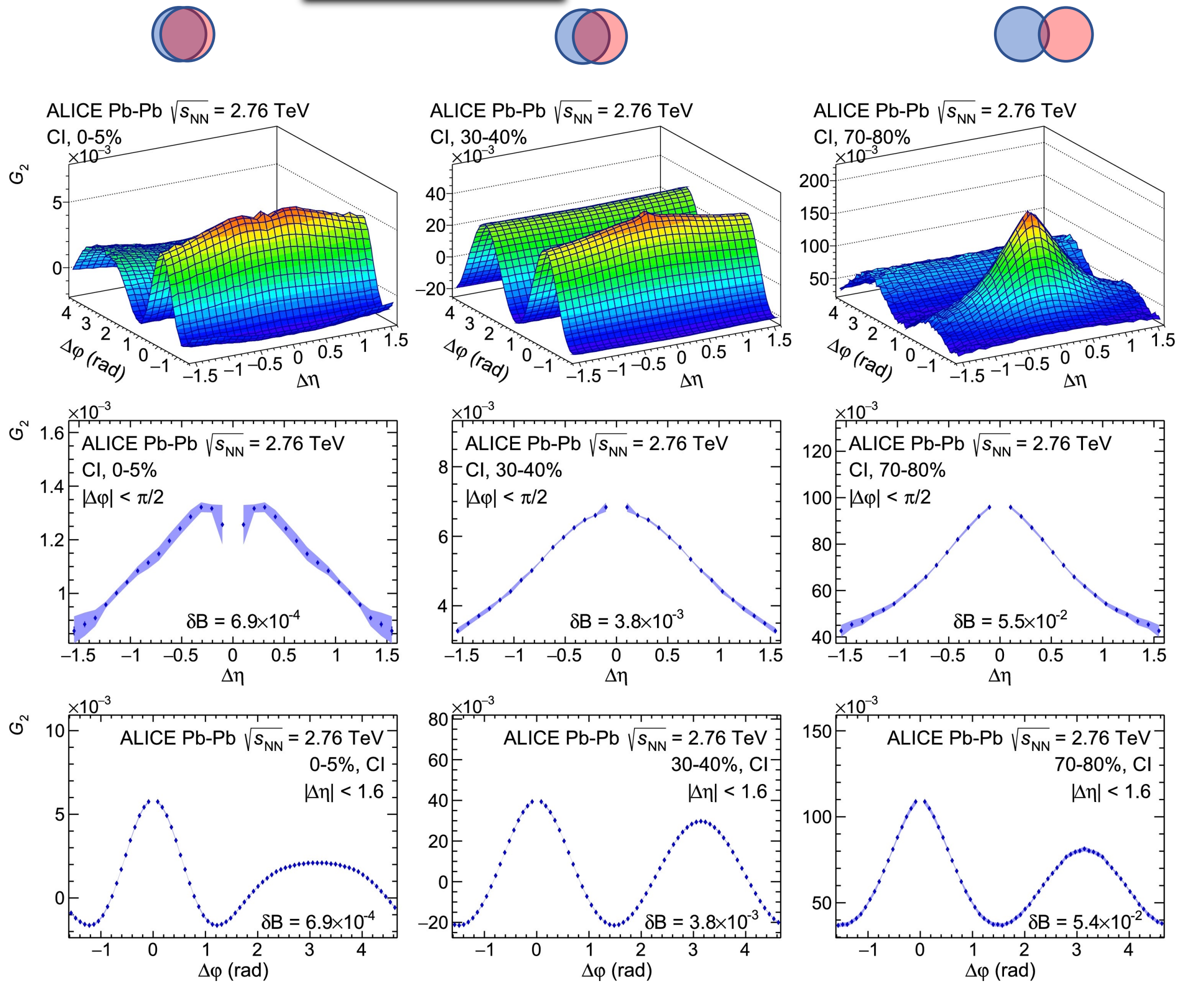

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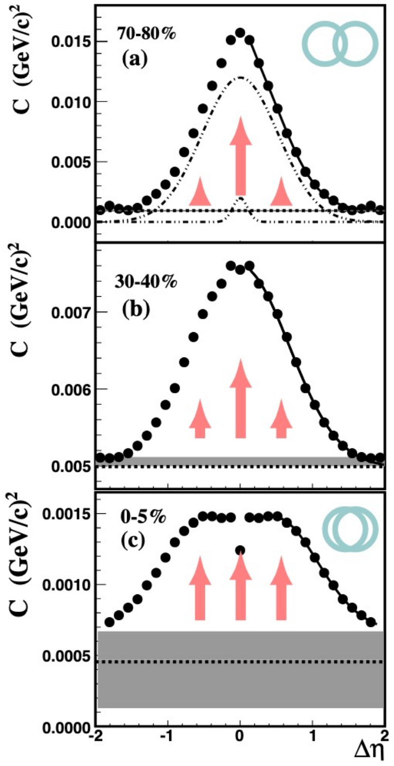
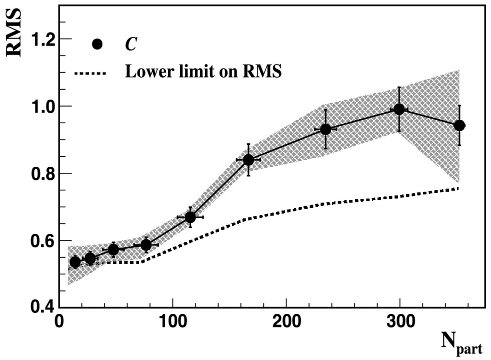
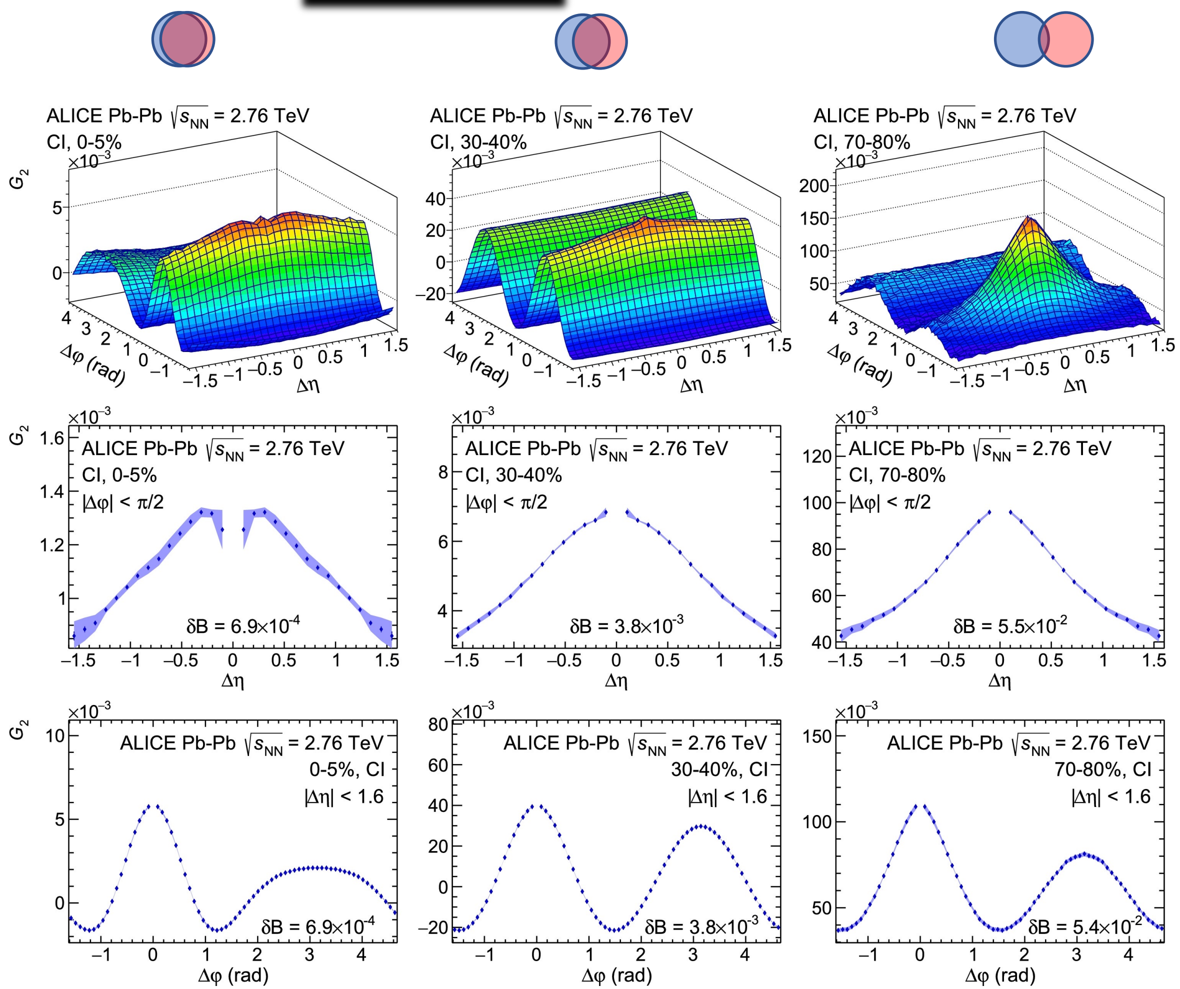


Au-Au $\sqrt{S_{NN}} = 200\ GeV$



STAR, PLB 704, 467–473 (2011)



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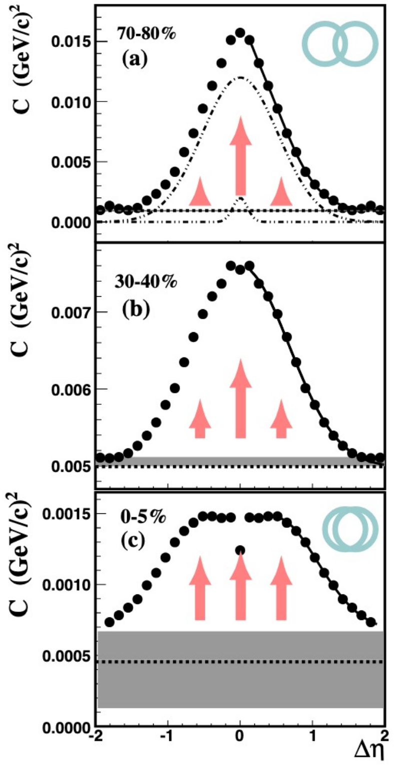

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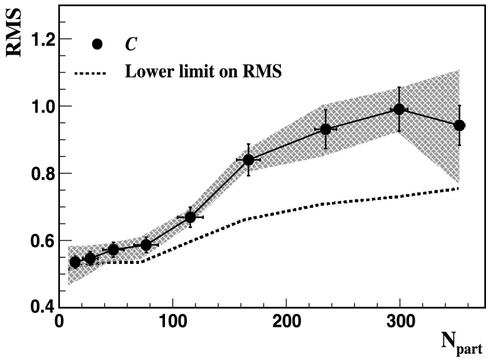

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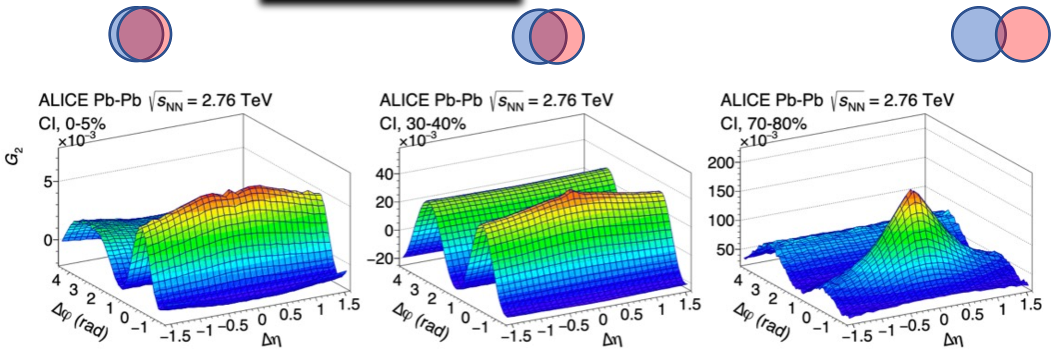
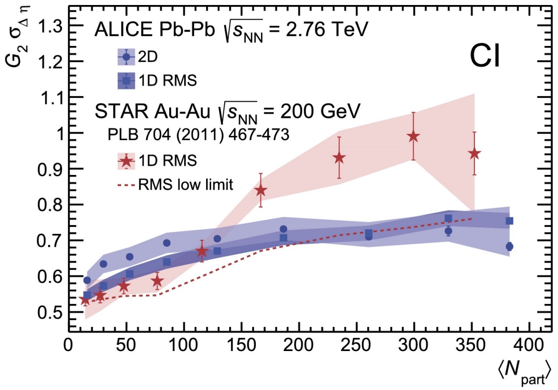
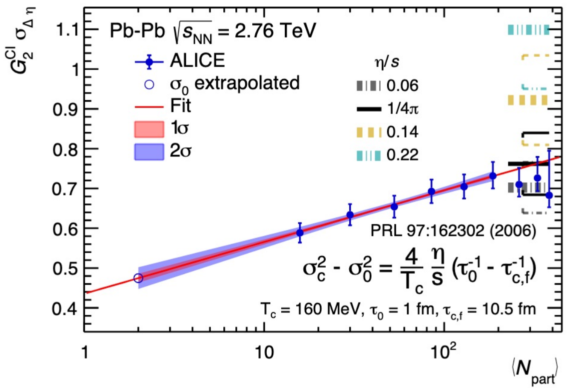


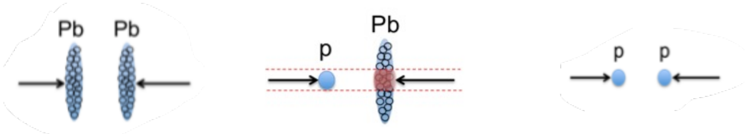
Fit with a generalized Gaussian in two dimensions

$$F(\Delta\eta,\Delta\varphi) = B + \sum_{n=2}^{6} a_n \times \cos(n\Delta\varphi) + A \times \frac{\gamma_{\Delta\eta}}{2\,\omega_{\Delta\eta}\,\Gamma\left(\frac{1}{\gamma_{\Delta\eta}}\right)} e^{-\left|\frac{\Delta\eta}{\omega_{\Delta\eta}}\right|^{\gamma_{\Delta\eta}}} \times \frac{\gamma_{\Delta\varphi}}{2\,\omega_{\Delta\varphi}\,\Gamma\left(\frac{1}{\gamma_{\Delta\varphi}}\right)} e^{-\left|\frac{\Delta\varphi}{\omega_{\Delta\varphi}}\right|^{\gamma_{\Delta\varphi}}}$$





How about small systems? p+p & p+Pb collisions?

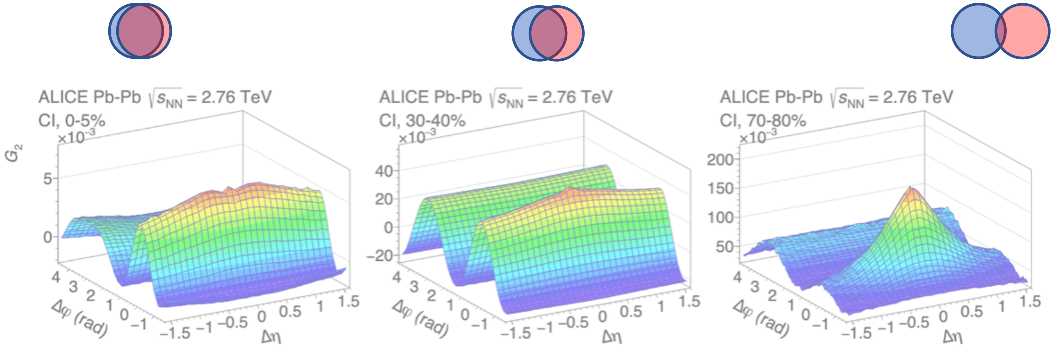


2-Particle Transverse momentum correlations

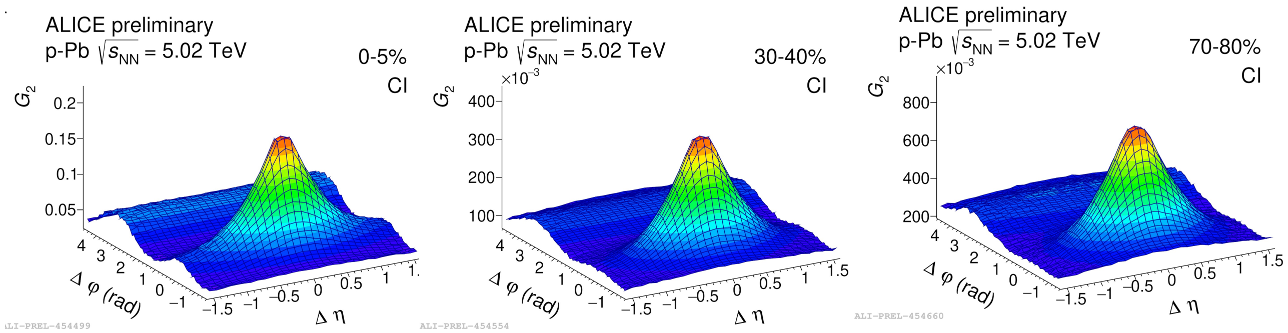
- Look for the diffusion of transverse momentum currents through their correlations

$$G_2\left(\Delta\eta,\Delta\varphi\right)=\frac{\langle\sum_{i}^{n_{1,1}}\sum_{j\neq i}^{n_{1,2}}p_{\mathrm{T},i}\,p_{\mathrm{T},j}\rangle}{\langle n_{1,1}\rangle\langle n_{1,2}\rangle}-\langle p_{\mathrm{T},1}\rangle\langle p_{\mathrm{T},2}\rangle$$

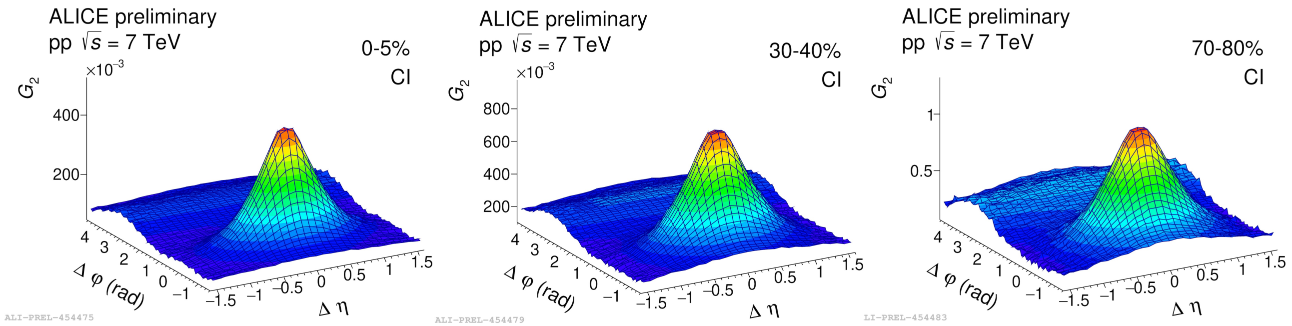
Pb–Pb 2.76 TeV

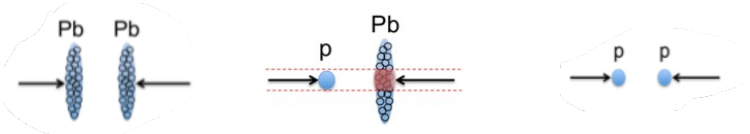


p–Pb 5.02 TeV



pp 7 TeV





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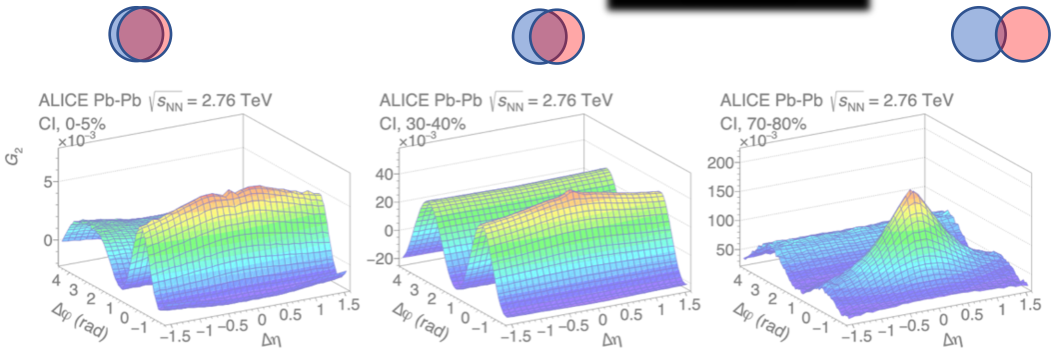
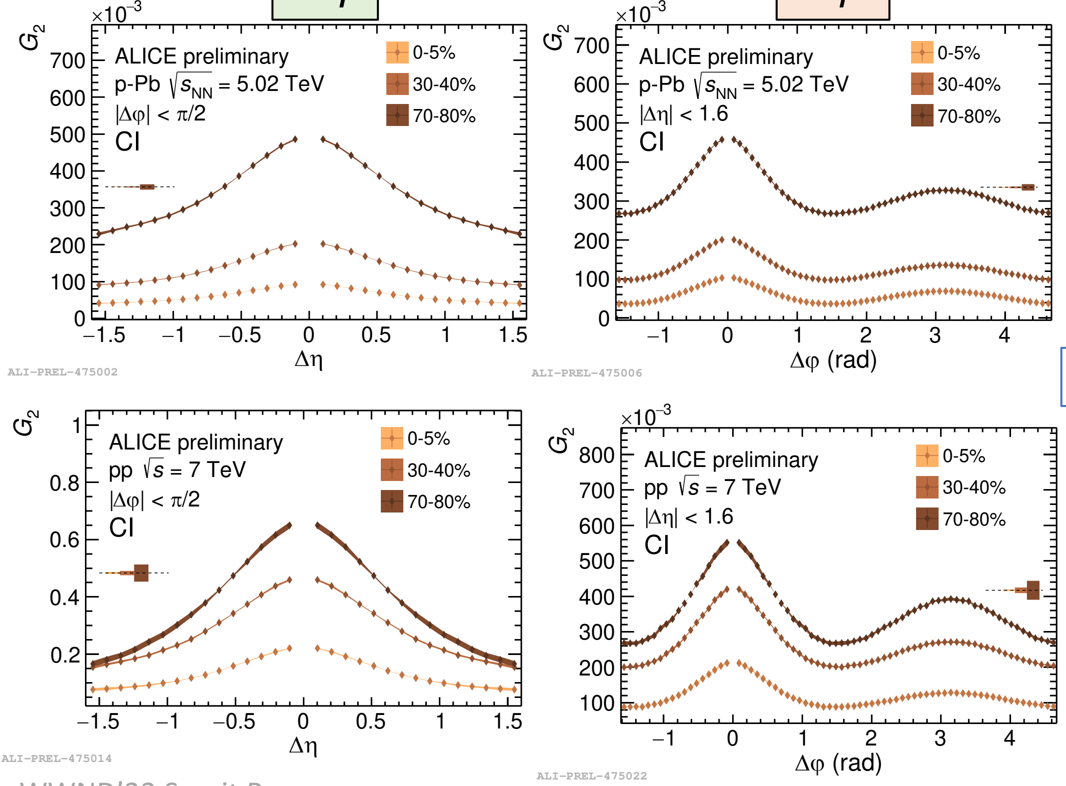
Pb–Pb 2.76 TeV

New Result



Δη

Δφ



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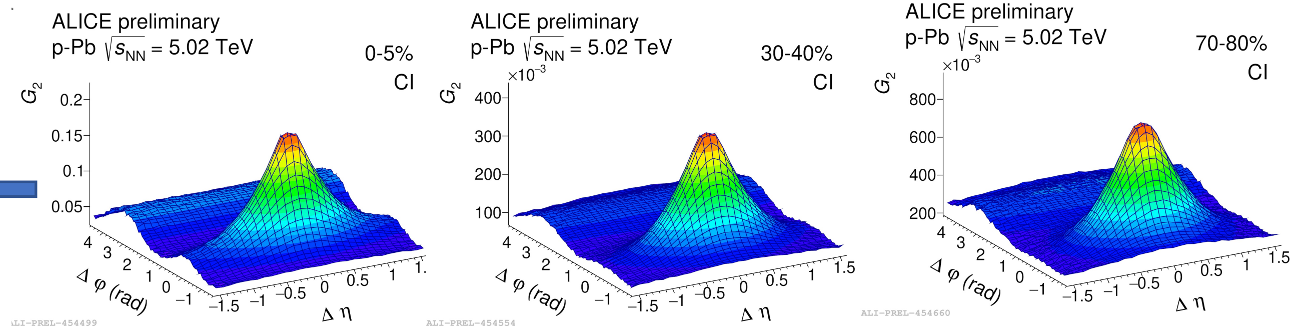
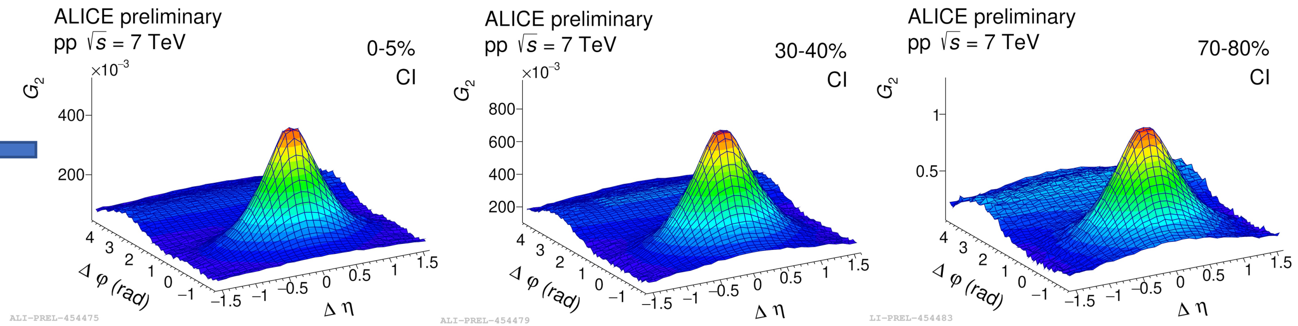
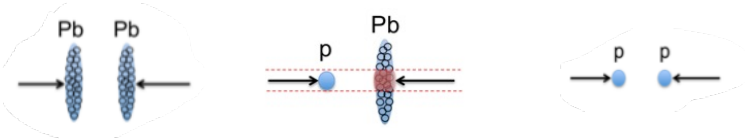


Projection

pp 7 TeV





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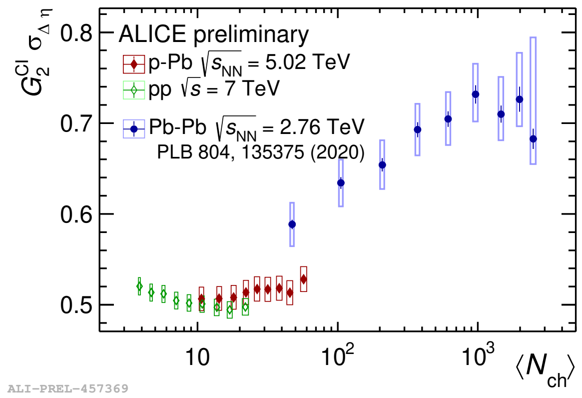
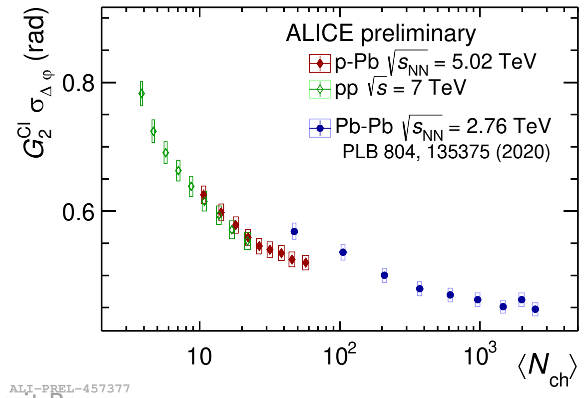


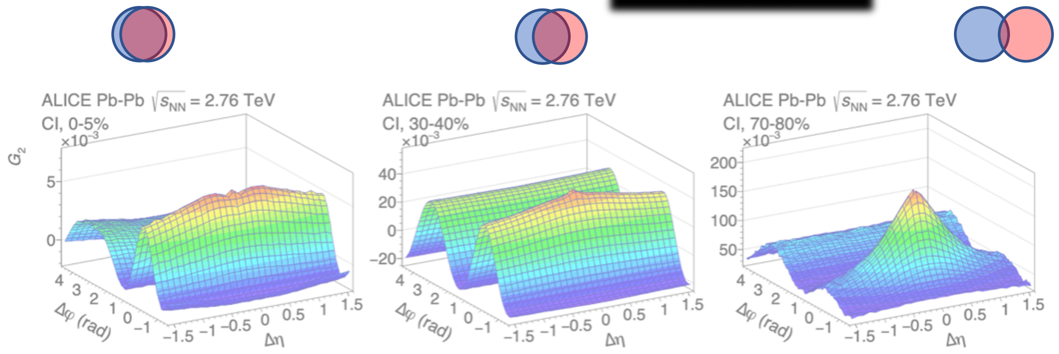
- Completely different longitudinal evolution



- Azimuthal narrowing consistent along the three systems

Pb–Pb 2.76 TeV

New Result



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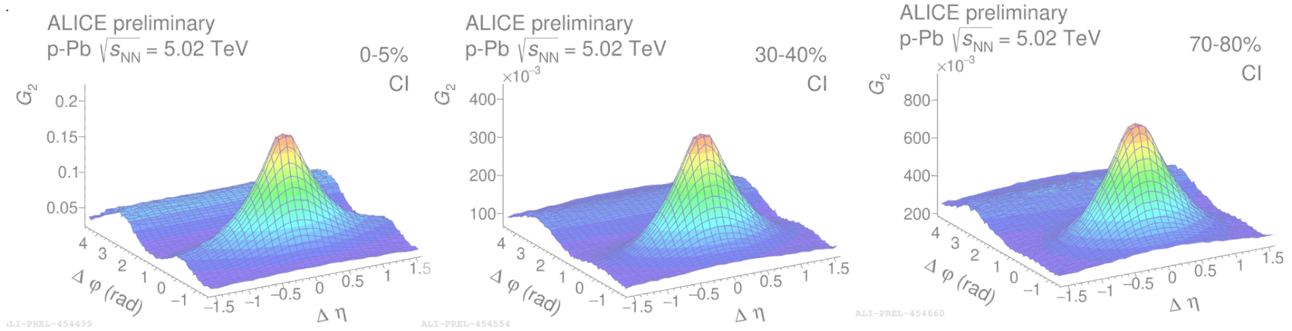
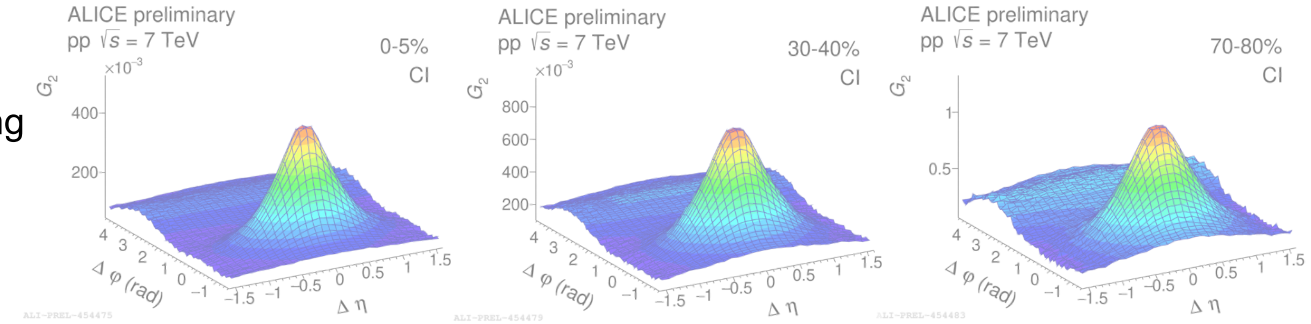
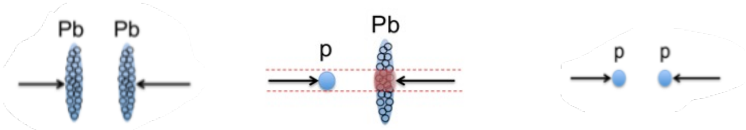


pp 7 TeV



LUNDS UNIVERSITET



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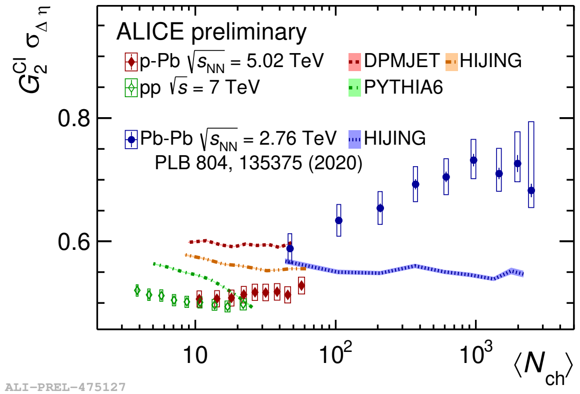
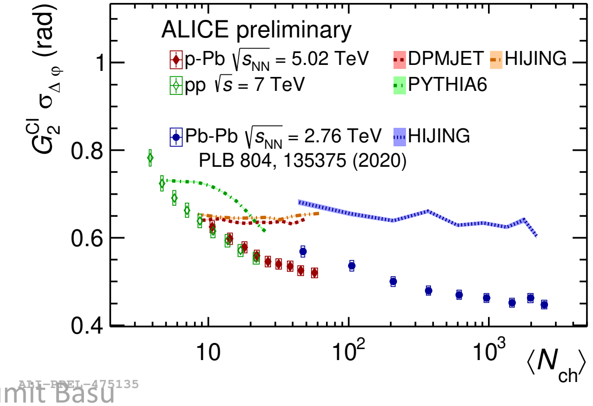
MC Comparison





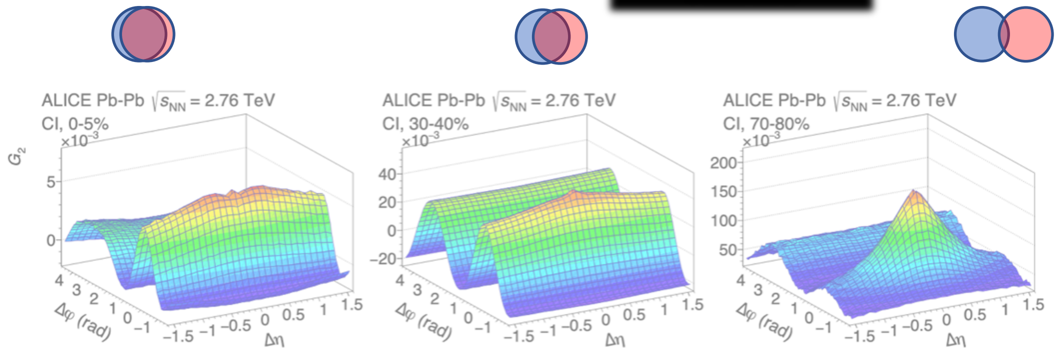
- Pythia8 Monash captures the azimuthal narrowing on both correlators

In small systems, → fluid-like system produced is too small or too short lived (Or not produced quasi-equilibrated fluid)

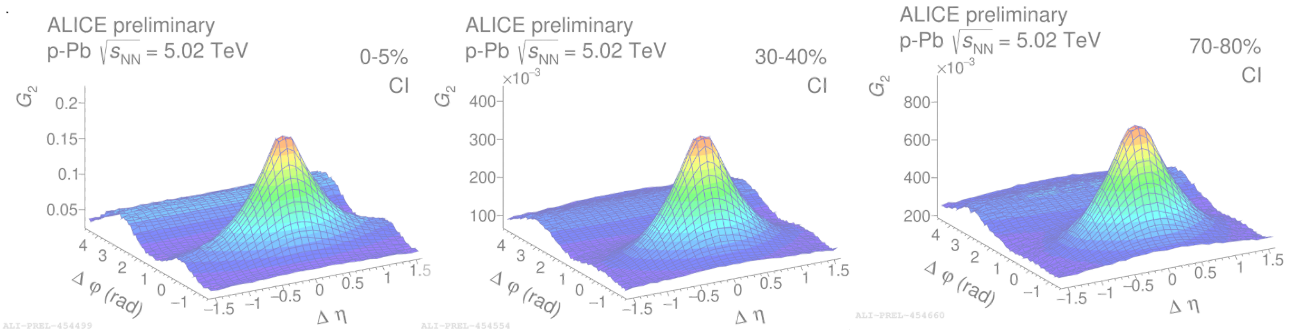
Pb–Pb 2.76 TeV

New Result

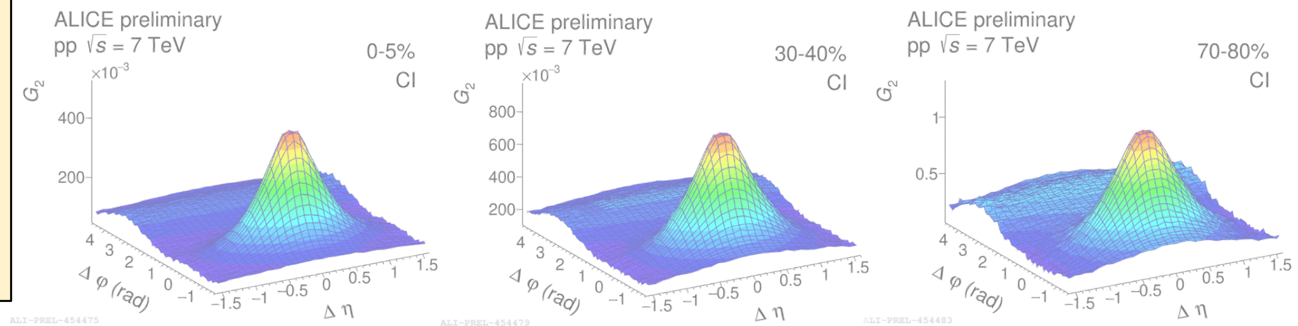
ALICE



p–Pb 5.02 TeV



pp 7 TeV



Summary & outlook

- Balance function for Identified primary hadrons (**π**, K , p) pairs for Pb-Pb collision at $\sqrt{s_{\mathrm{NN}}} = 2.76\ TeV$ are presented.
  Narrowing of azimuthal widths for all specie pairs → Radial flow focusing (kinematic lensing), different width evolution behavior in Δη → Qualitatively consistent with radial flow and two-wave quark production mechanism.

- 2-particle correlation function for double strange baryon (Ξ-h) pairs for pp collision at $\sqrt{s} = 13\ TeV$ are presented.
  Multiplicity dependence very similar for all correlation measurements → 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.

- Transverse momentum correlation for all collision system (pp, p–Pb, Pb–Pb) are presented. Azimuthal narrowing consistent in all three systems, changes behavior in the longitudinal dimension from narrowing to broadening when going from pp to p–Pb and to Pb–Pb → Fluid-like system produced is too small or too short lived, in small system.

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

Thank you !!!