



# Overview of recent ALICE results on particle correlations and fluctuations

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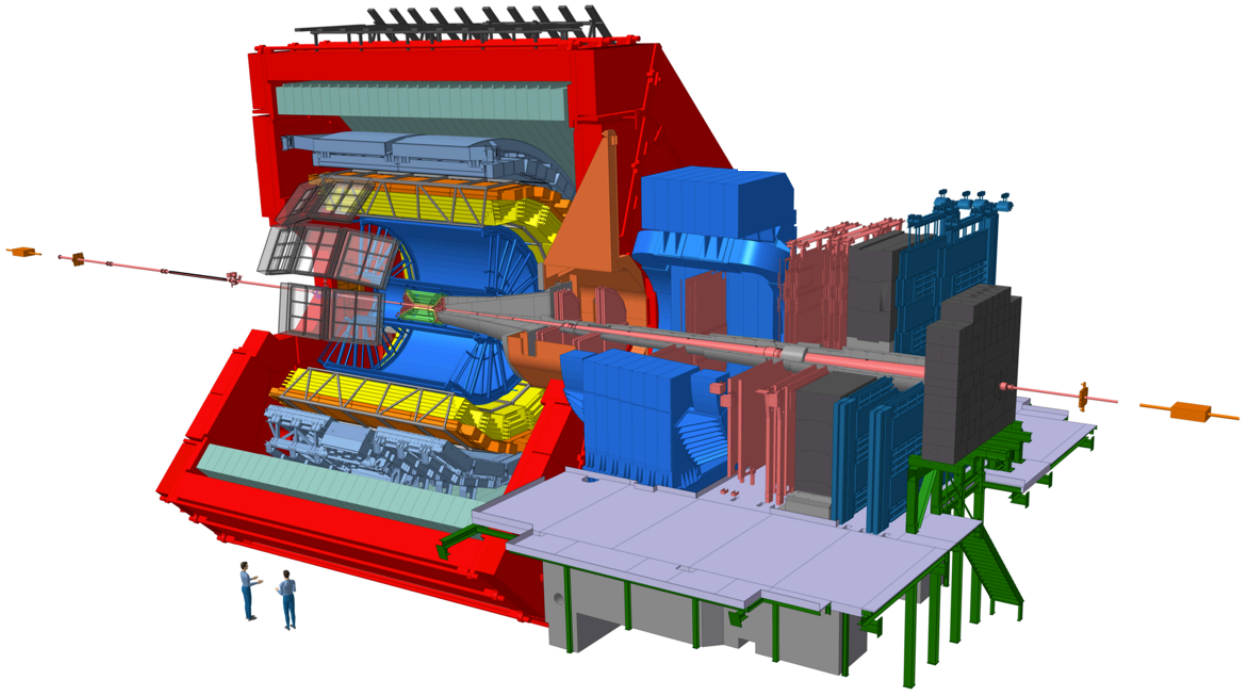
for the ALICE Collaboration

Lomonosov Conference 2021
August 19

# ALICE detector and datasets

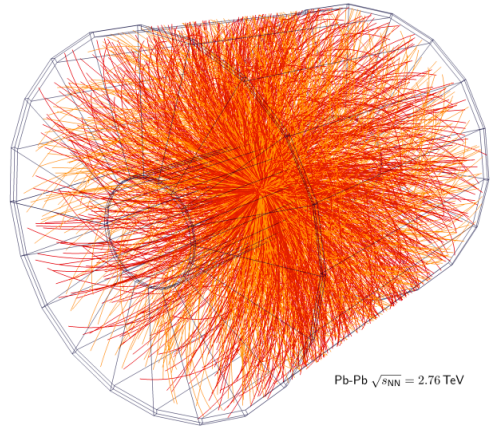


Runs 1&2 (2009-2018):

| System | Energy |
|---|---|
| pp | 0.9, 2.76, 7, 8, 13 TeV |
| p-Pb | 5.02, 8 TeV |
| Pb-Pb | 2.76, 5.02 TeV |
| Xe-Xe | 5.44 TeV |

**Inner Tracking System (ITS)**
**|η|<0.9,** tracking + triggering + particle identification (PID)

**Time Projection Chamber (TPC)**
**|η|<0.8,** tracking + PID




**Time Of Flight (TOF)**
**|η|<0.8,** PID

**VZERO detector**
two forward scintillator arrays, triggering + centrality

**Zero-Degree Calorimeters**
centrality + triggering

- minimum bias triggers
- rare triggers (muons, EMCAL, PHOS, high mult pp, etc.)

# Recent ALICE papers on correlations and fluctuations

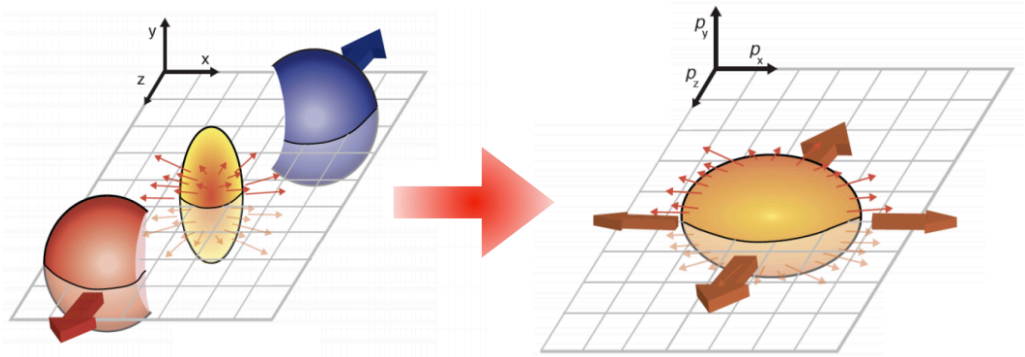
**FLOW** **CORRELATIONS** **EbyE FLUCTUATIONS** **FEMTOSCOPY**

| | |
|---|---|
| Long- and short-range correlations in high-multiplicity pp collisions at 13 TeV | **JHEP 05 (2021) 290** |
| Measurements of mixed harmonic cumulants in Pb-Pb collisions at 5.02 TeV | **PLB (2021) 136354** |
| ΛK femtoscopy in Pb-Pb collisions at 2.76 TeV | **PRC 103 (2021) 055201** |
| πK femtoscopy and the lifetime of the hadronic phase in Pb−Pb collisions at 2.76 TeV | **PLB 813 (2021) 136030** |
| Event-by-event multi-harmonic correlations of different flow amplitudes in Pb-Pb 2.76 TeV | arXiv:2101.02579 |
| Charged Particle Multiplicity Fluctuations in Pb–Pb collisions at 2.76 TeV | arXiv:2105.05745 |
| Exploring the NΛ-NΣ coupled system with high precision correlation techniques in pp | arXiv:2104.04427 |
| Kaon-proton strong interaction at low relative momentum via femtoscopy in Pb-Pb | arXiv:2105.05683 |
| Experimental evidence for an attractive p-$\phi$ interaction in pp | arXiv:2105.05578 |
| Investigating the role of strangeness in baryon−antibaryon annihilation in pp | arXiv:2105.05190 |
| $K^0_S$ and Λ correlations in pp collisions at 13 TeV | arXiv:2107.11209 |
| Anisotropic flow of identified hadrons in Xe-Xe collisions at 5.44 TeV | arXiv:2107.10592 |
| Polarization of Λ hyperons along the beam direction in Pb-Pb at 5.02 TeV | arXiv:2107.11183 |

A lot of new results!

→ I will highlight only some papers
+ some recent preliminaries

# Flow in A–A collisions

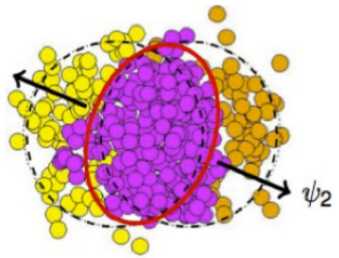



spatial anisotropy
$\varepsilon_n$ coefficients

momentum anisotropy
$v_n$ coefficients

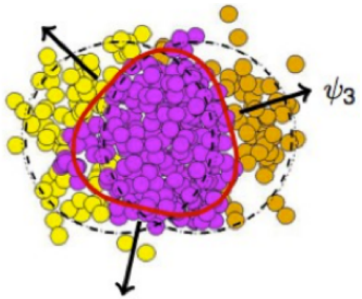
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

$v_n$ quantify the event *azimuthal anisotropy*




## $v_2$ – elliptic flow

reflects the almond-shaped **geometry** of the interaction volume

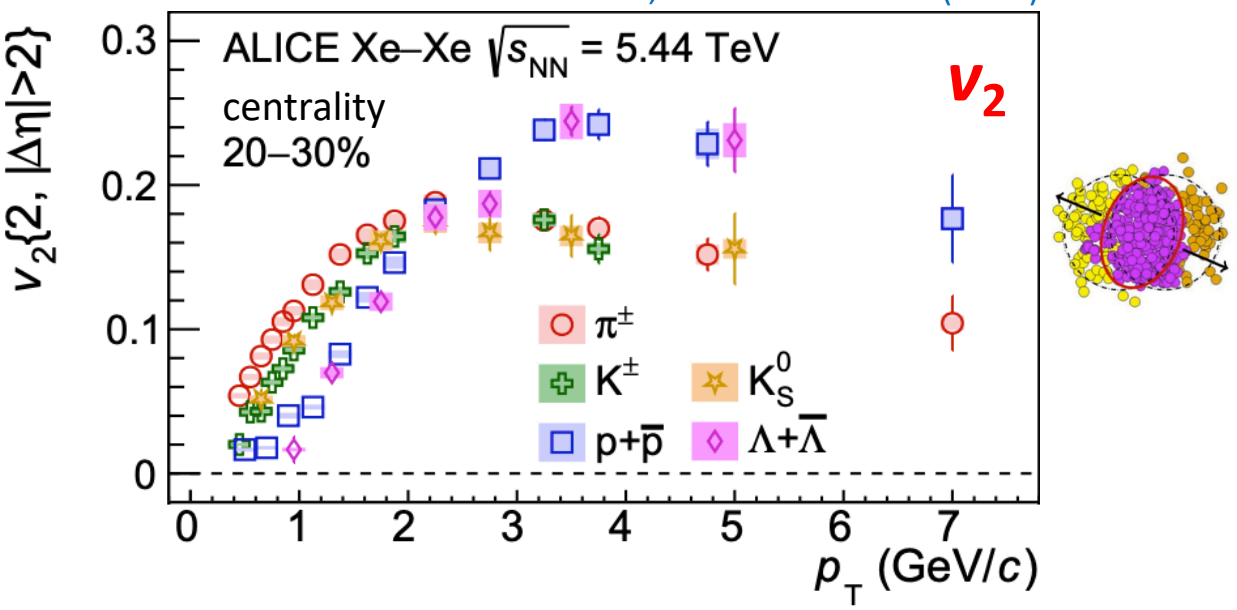


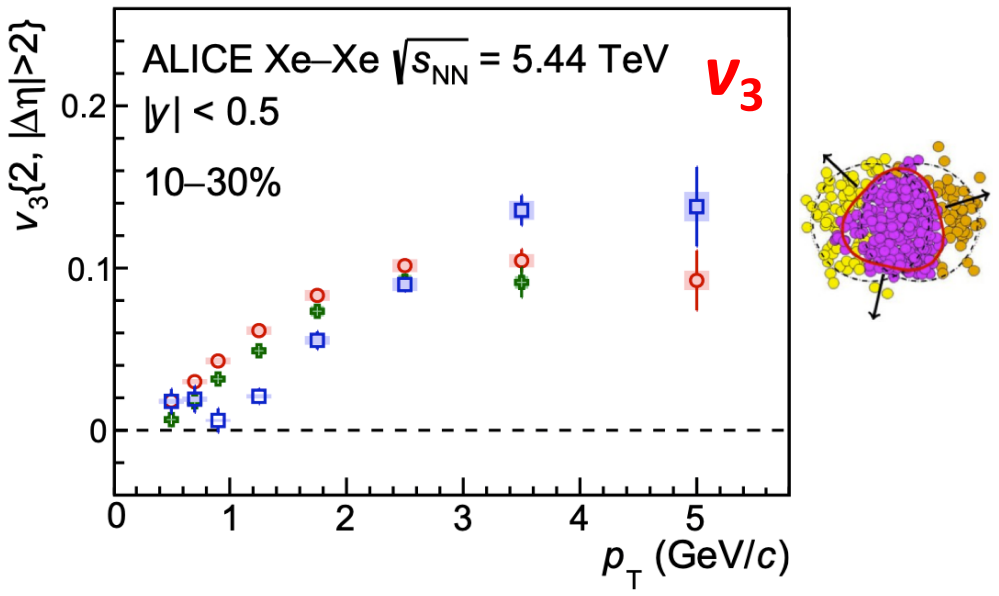

## $v_3$ – triangular flow

originates from event-by-event **fluctuations** of nucleon positions

# Flow of identified hadrons in Xe–Xe

ALICE, arXiv:2107.10592 (2021)

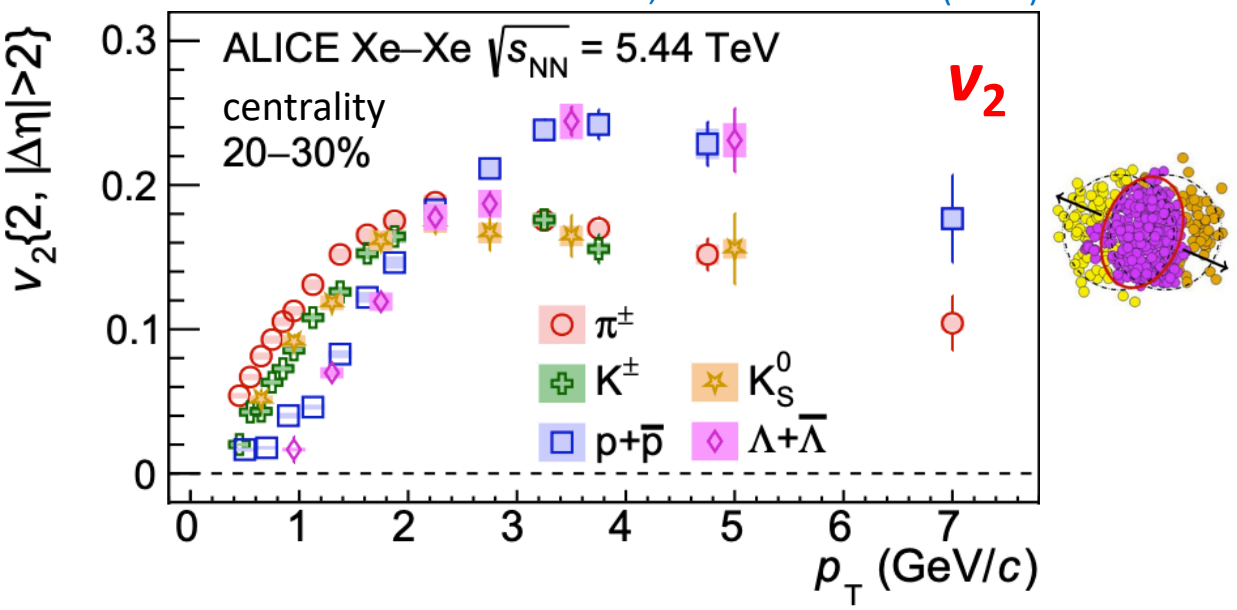


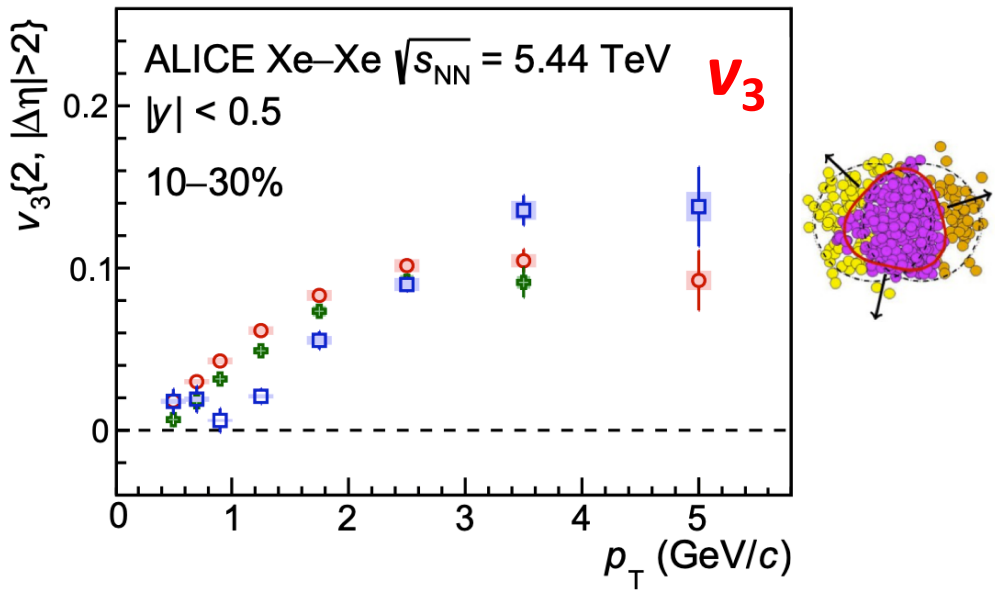




- Clear “mass ordering” at $p_T$ < 2–3 GeV/$c$
- Grouping according to particle type (meson and baryon) – quark coalescence?
- Evolution with $p_T$ and centrality is similar to that reported in Pb–Pb collisions

# Flow of identified hadrons in Xe–Xe

ALICE, arXiv:2107.10592 (2021)

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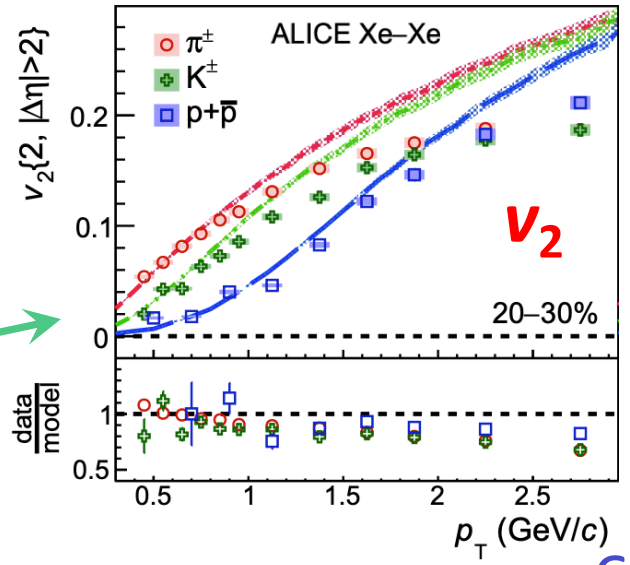
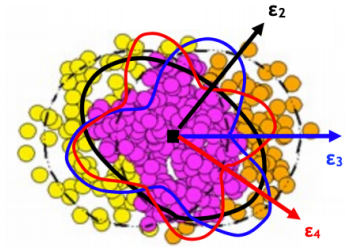
*lines:* IP-Glasma + MUSIC (hydro) + UrQMD:
Schenke, et al., PRC 102 4, (2020) 044905

- Good description of π/K/p $v_2$ at $p_T$ < 1 GeV/$c$



# Correlations between different flow amplitudes in Pb–Pb

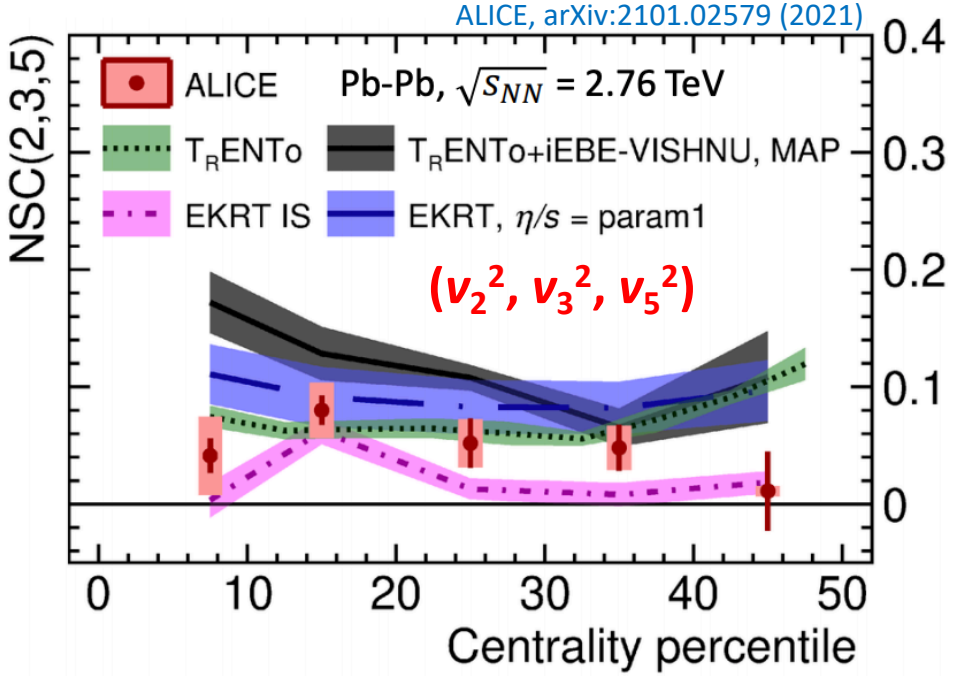



$$\mathrm{SC}(k,l,m) = \langle v_k^2 v_l^2 v_m^2 \rangle - \langle v_k^2 v_l^2 \rangle \langle v_m^2 \rangle - \langle v_k^2 v_m^2 \rangle \langle v_l^2 \rangle - \langle v_l^2 v_m^2 \rangle \langle v_k^2 \rangle + 2 \langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle$$

Normalized symmetric cumulants: $\mathrm{NSC}(k,l,m) = \frac{\mathrm{SC}(k,l,m)}{\langle v_k^2 \rangle \langle v_l^2 \rangle \langle v_m^2 \rangle}$

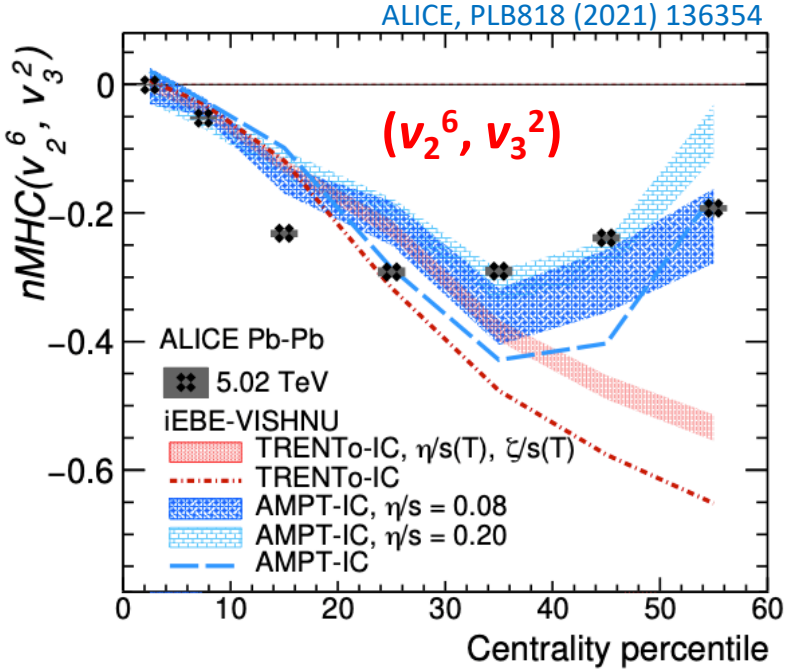
- Non-trivial correlation among three flow coefficients:

ALICE, arXiv:2101.02579 (2021)




- Higher moments such as ($v_2^4$, $v_3^2$), ($v_2^6$, $v_3^2$) etc. are extracted as well using Mixed Harmonic Cumulants:

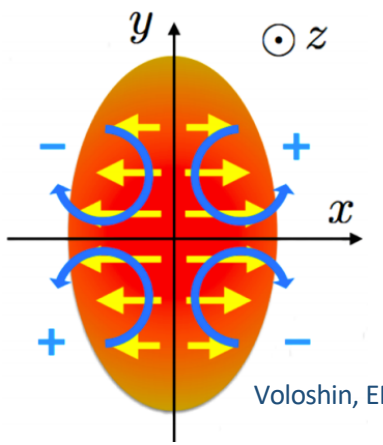
ALICE, PLB818 (2021) 136354



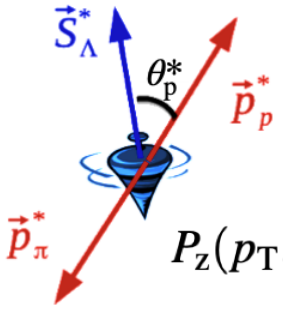

- Further constraints on initial conditions and evolution of the QGP

# Local Λ polarization in Pb–Pb

ALICE arXiv:2107.11183 (2021)




Voloshin, EPJ Web of Conf. 171, 07002 (2018)

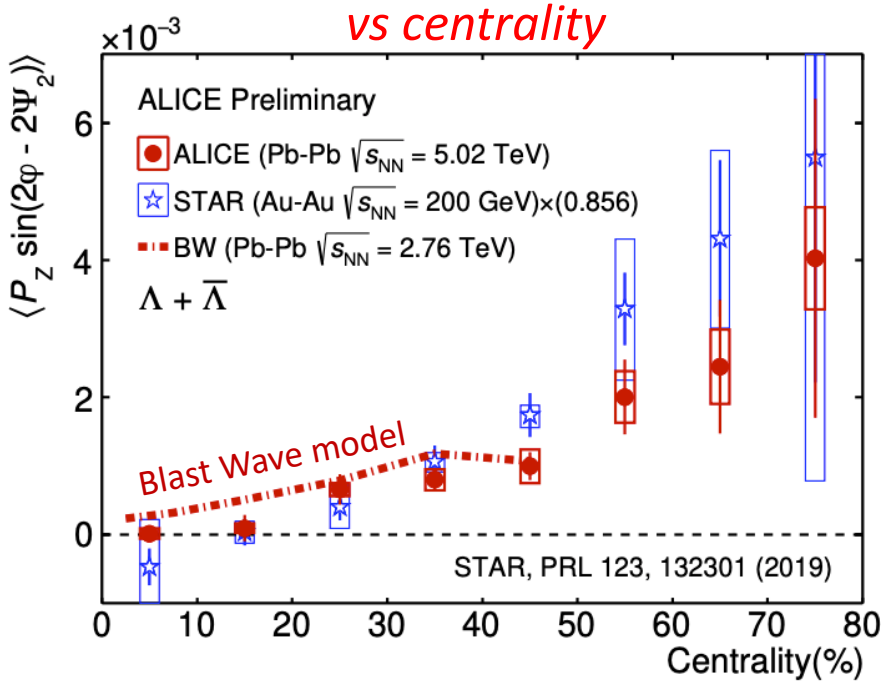



$$\Lambda \rightarrow p + \pi^- \quad \text{(BR: 63.9%, } c\tau \sim 7.9 \text{ cm)}$$

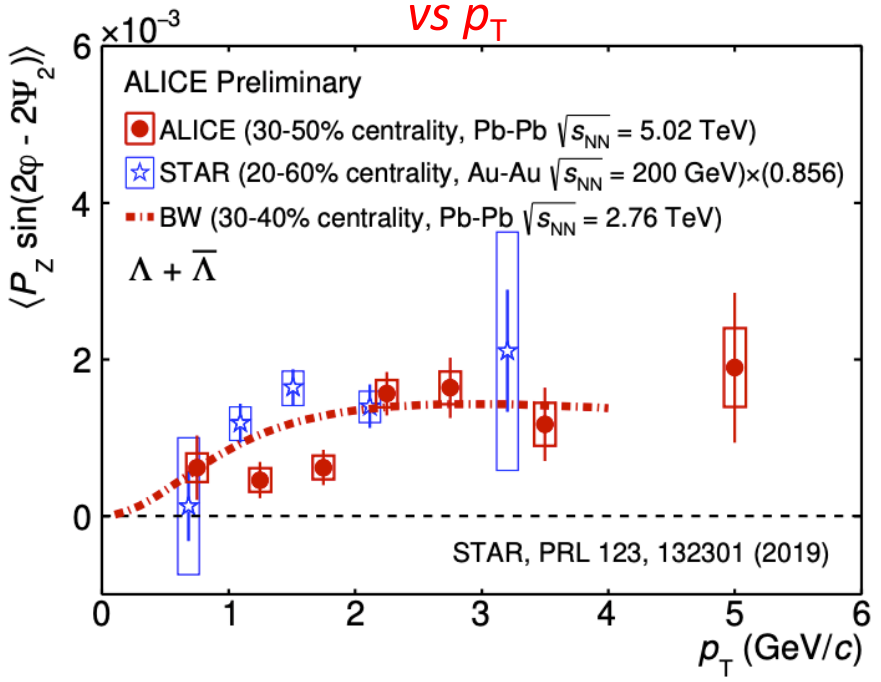
$$P_z(p_T, y_H, \varphi) = \frac{3<\cos\theta^*_p>}{\alpha_H}$$

- Vorticity along the beam direction due to strong $v_2$, with a "quadrupole" pattern → **polarization of particles**
- The effect is indeed observed at RHIC and now at LHC
- Blast Wave model explains dependences well

*vs centrality*

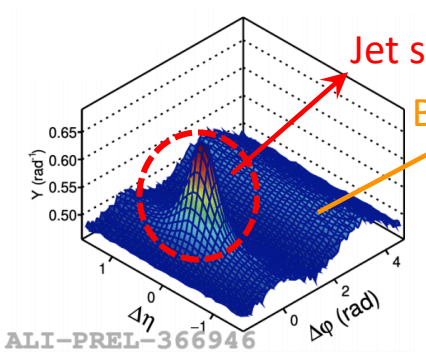



*vs $p_T$*



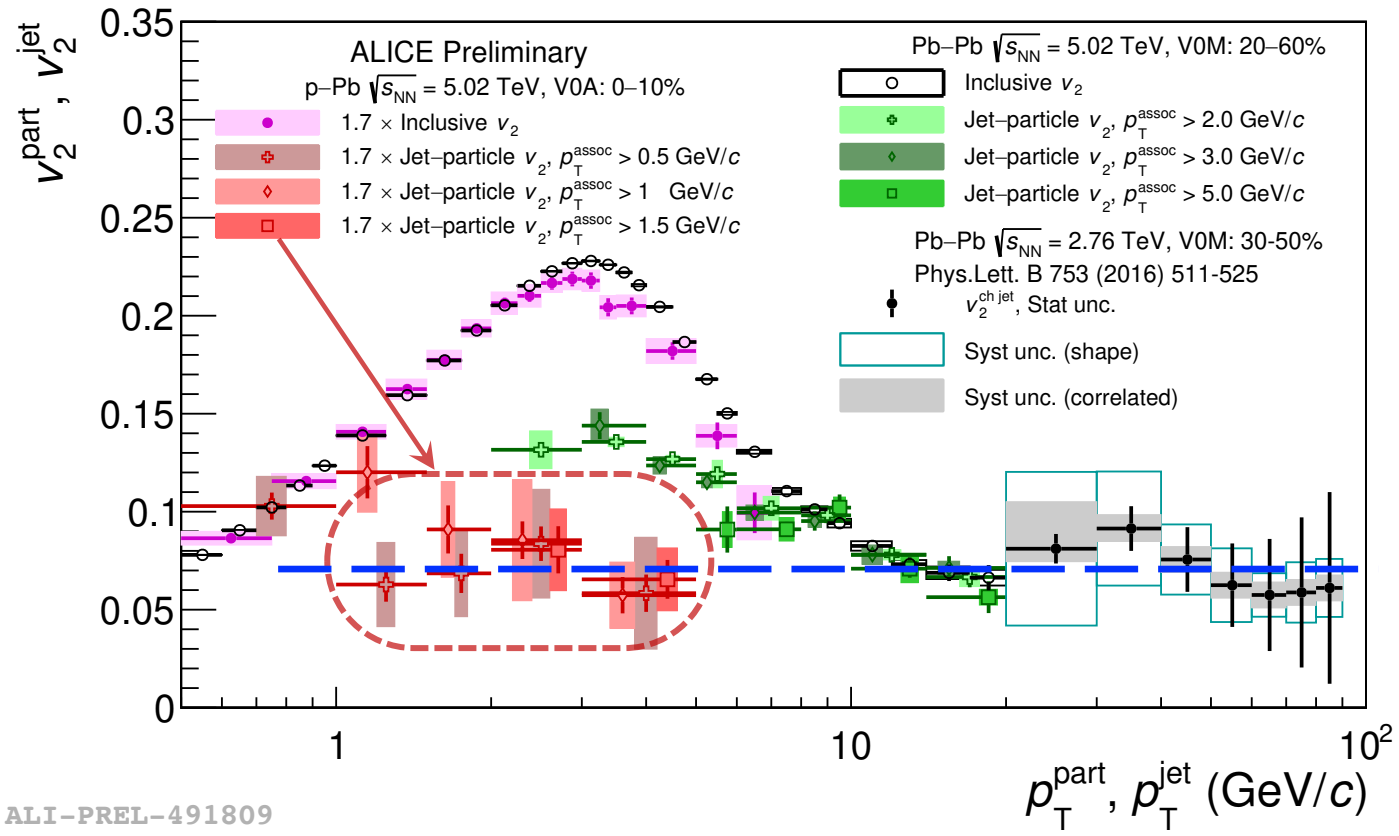

Blast Wave lines:
T. Niida, S. Voloshin (priv. comm.)

# Jet-particle $v_2$ in p–Pb and Pb–Pb




+$v_2$ calculated using forward detectors

$$v_2(\Delta\varphi, \Delta\eta) = \mathrm{S/(S+B)}^* v_2(\mathrm{Jet}) + \mathrm{B/(S+B)}^* v_2(\mathrm{Background})$$




- Positive jet-particle $v_2$ of p–Pb and Pb–Pb collisions!
  - lower than inclusive $v_2$
  - values are comparable with high-$p_T$ inclusive

Jet-quenching in p–Pb?
Final-state scatterings (AMPT)?..

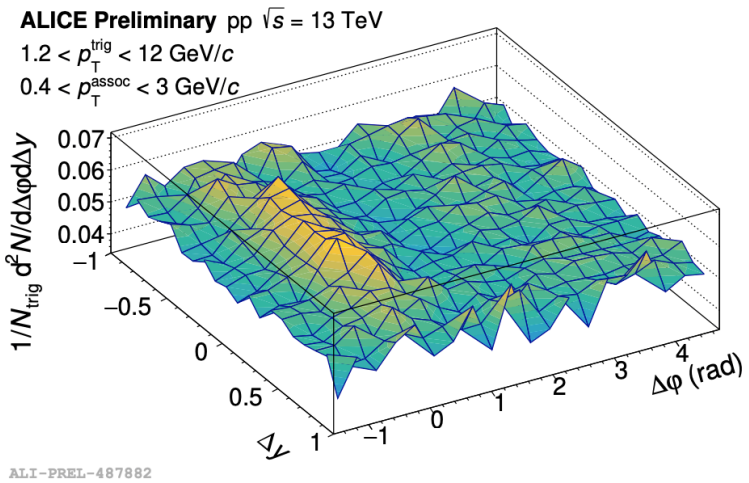
More details in EPS-HEP talk by S. Tang

# Ξ–hadron angular correlations in pp

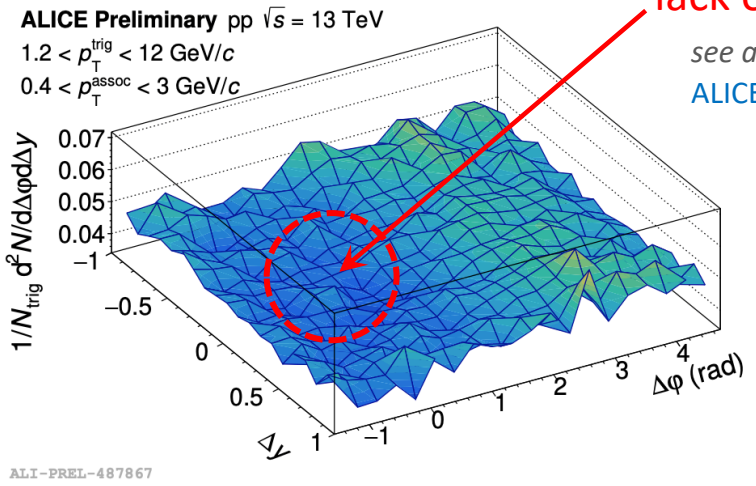
*Example*

Ξ–proton correlations:

opposite-sign




same-sign



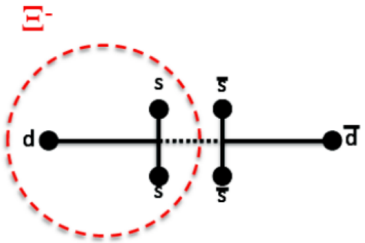

lack of pairs!

*see also*
ALICE Eur. Phys. J. C77 (2017) 569

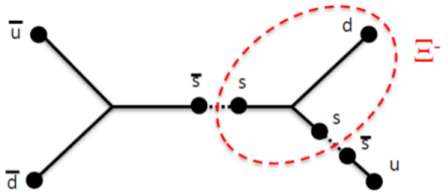
→ *Results challenge hadronization models:*

## Lund string breaking (PYTHIA8)

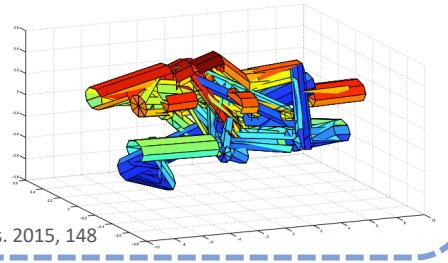
*standard:*




*with junctions:*



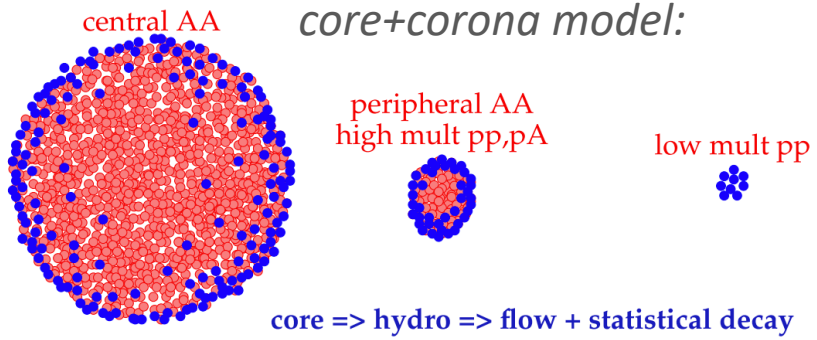

*with ropes:*



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

## EPOS:

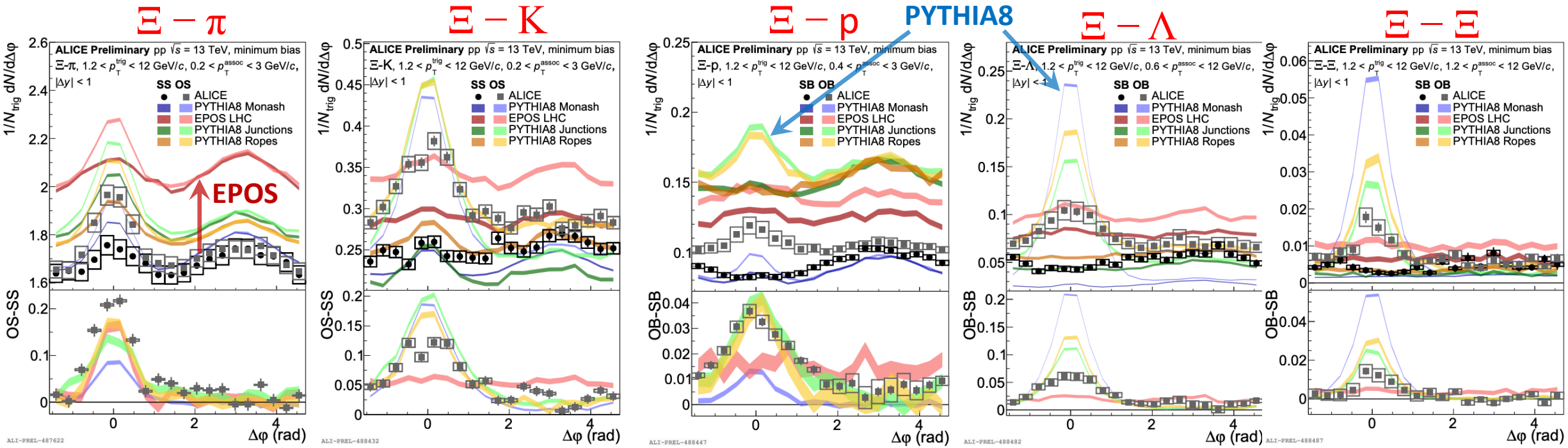
*core+corona model:*




K. Werner. hal-02434245 (2019)

# Ξ–hadron angular correlations in pp

Projections on Δφ:




- In general, PYTHIA and EPOS fail to describe data
  - Standard Lund string breaking to diquarks is challenged
  - Local conservation of quantum numbers needs to be implemented in EPOS to make meaningful comparisons

More details in SQM talk by J.Adolfsson

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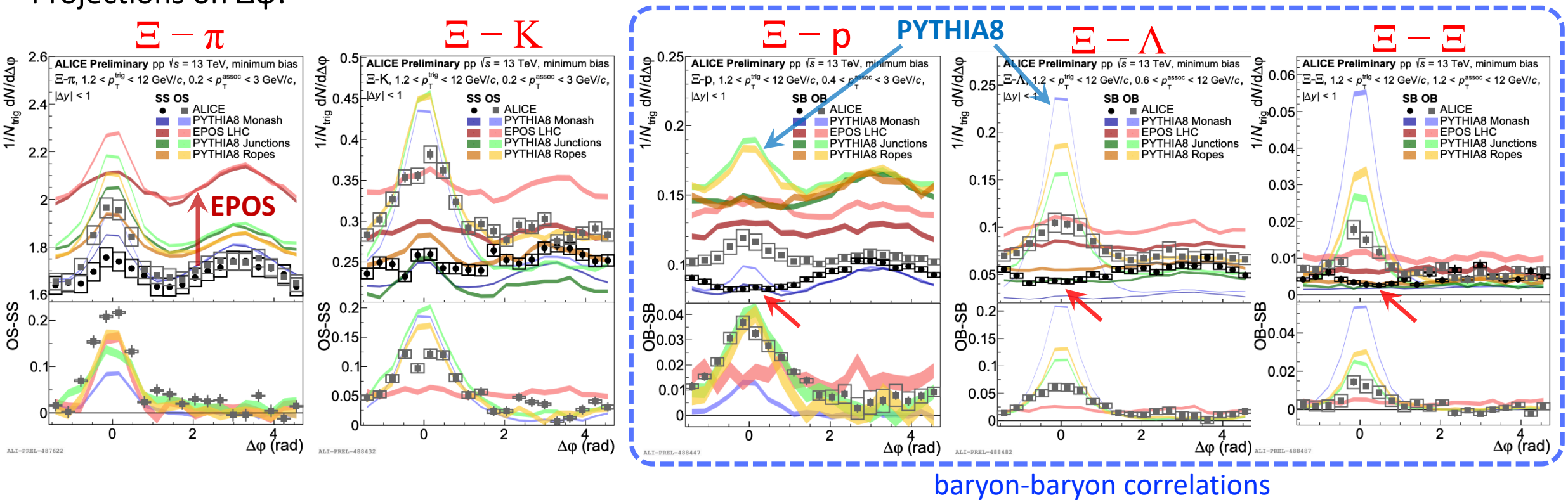


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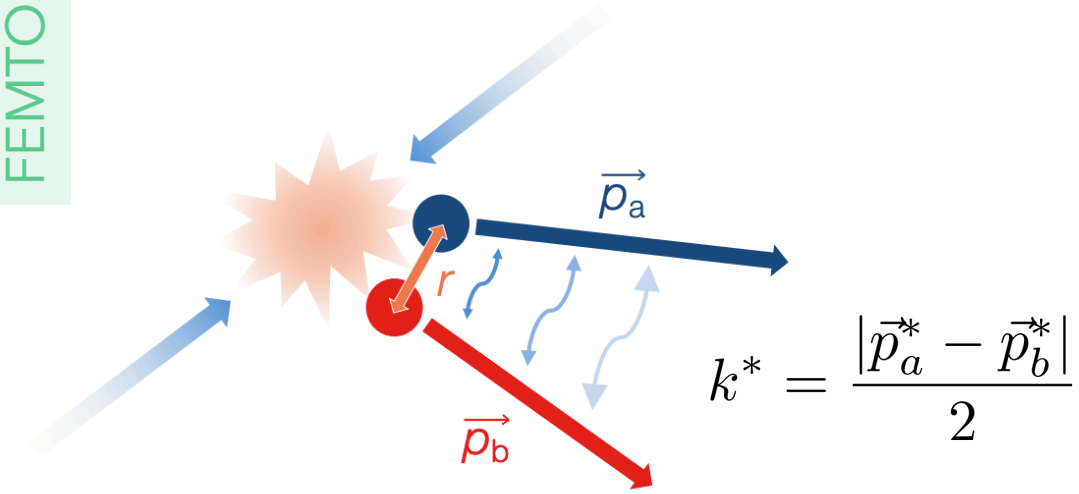
# Femtoscopy in small sources




$$k^* = \frac{|\vec{p}_a^* - \vec{p}_b^*|}{2}$$

$$C(k^*) = \int S(r) \left|\psi(\vec{k}^*, \vec{r})\right|^2 d^3r = \mathcal{N} \times \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

Emission source

Wave function

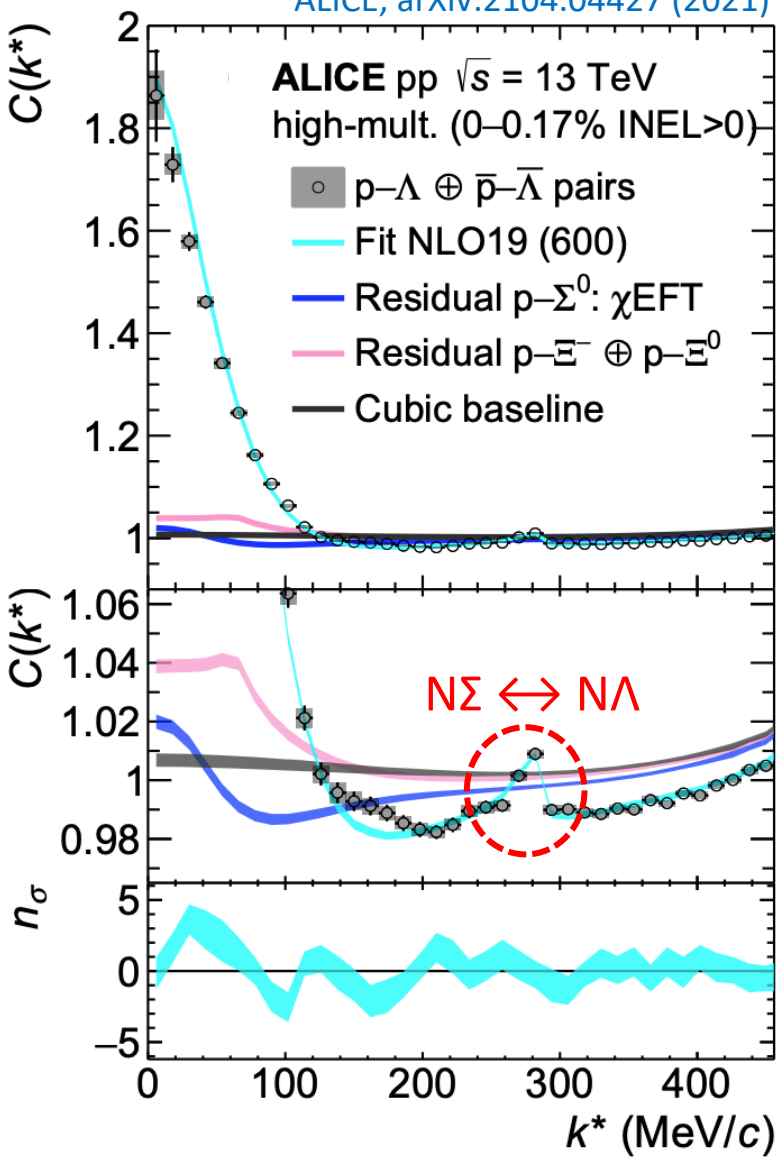
Recent ALICE papers based on **pp** data:

PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
arXiv:2104.04427
arXiv:2105.05578
arXiv:2105.05190

# High-precision pΛ interaction in pp collisions

ALICE

ALICE, arXiv:2104.04427 (2021)




$\Lambda^0 = uds$ $I(J^P) = 0(\frac{1}{2}^+)$
1115.6 MeV

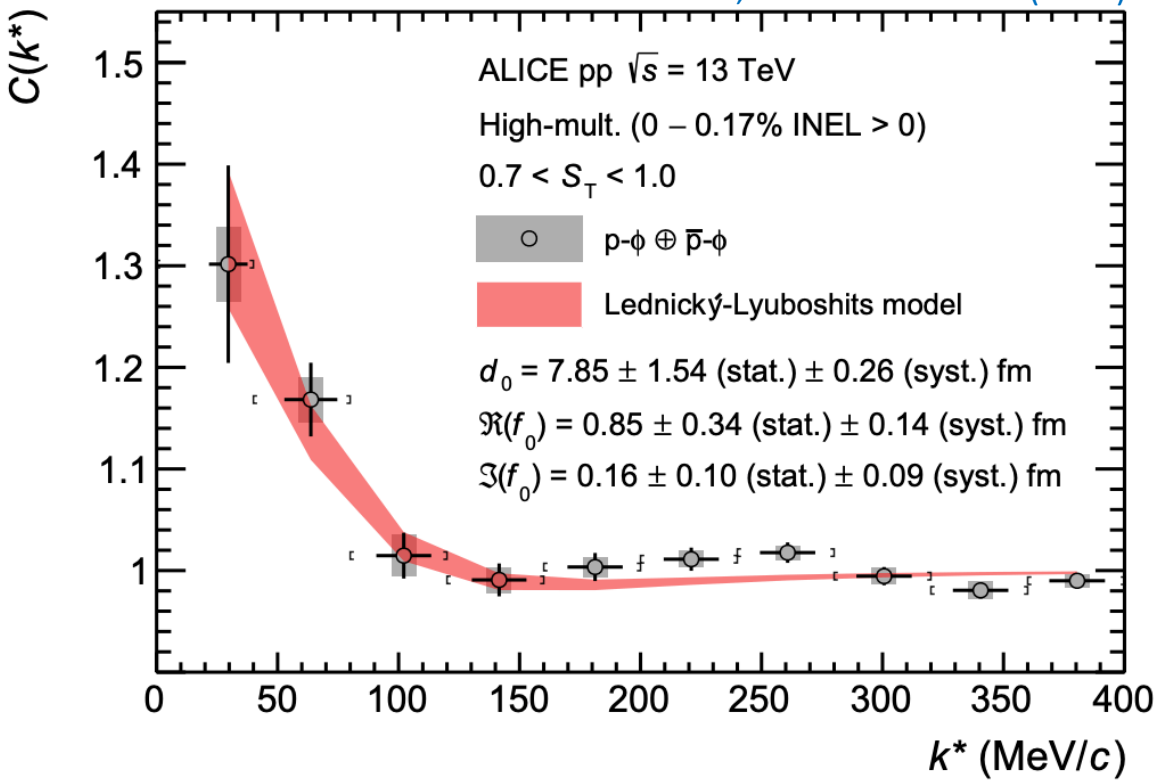
$\Sigma^0 = uds$ $I(J^P) = 1(\frac{1}{2}^+)$
1189.4 MeV

- Extension of the kinematic range to much lower $k^*$
- First experimental evidence of opening of the NΣ 2-body channel:
  a cusp-like structure at $k^*$ = 289 MeV/$c$ due to the NΣ ↔ NΛ coupling
- Sensitivity to different strength of ΣN coupling:
  $n_\sigma$ = 3.7 correspondence with recent NLO19 χEFT

Haidenbauer et al., Eur. Phys. J. A 56 (2020) 91

# Proton-$\phi$ interaction

ALICE, arXiv:2105.05578 (2021)




- First experimental evidence of the attractive strong interaction between a proton and a $\phi$ meson
- Fit with Lednický–Lyuboshits model:

$$C(k^*) = \sum_S \rho_S \left[ \frac{1}{2} \left| \frac{f(k^*)}{r_0} \right|^2 \left( 1 - \frac{d_0}{2\sqrt{\pi} r_0} \right) + \frac{2\Re f(k^*)}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{\Im f(k^*)}{r_0} F_2(2k^* r_0) \right]$$

Sov. J. Nucl. Phys. 35 (1982) 770

$\Re(f_0)$ = **0.85** ± 0.34 *(stat.)* ± 0.14 *(syst.)* fm
$\Im(f_0)$ = 0.16 ± 0.10 *(stat.)* ± 0.09 *(syst.)* fm
$d_0$ = 7.85 ± 1.54 *(stat.)* ± 0.26 *(syst.)* fm

- Imaginary part of the scattering length vanishes within uncertainties
  → **inelastic processes do not play a prominent role, elastic interaction dominates**

# Summary

- ALICE continues to provide many interesting results on flow, correlations and fluctuations
- Analysis of Runs 1&2 data continues – more excited results to come!
- Preparations for Run 3, where many observables will benefit from more statistics and larger ALICE acceptance, are ongoing
- Feasibility studies are done also for possible O-O & p-O runs at the LHC

arXiv:2103.01939

*Thank you for your attention!*

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