Flow and polarization of multi-strange hadrons with ALICE at the LHC

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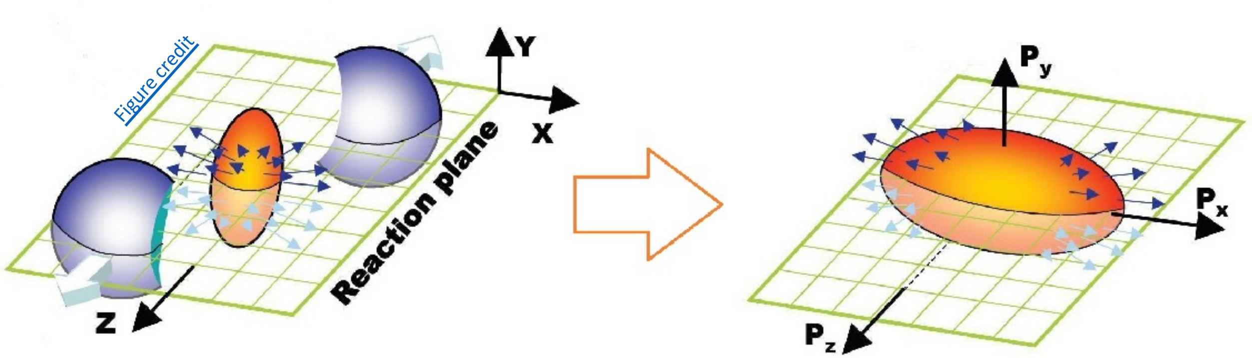
University and INFN - Trieste

Studying QGP with elliptic flow

Eccentricity in the initial state of a heavy-ion collision is converted to momentum **anisotropy in the final state** distributions of particles → the second-order coefficient of the Fourier expansion is referred to as **elliptic flow**



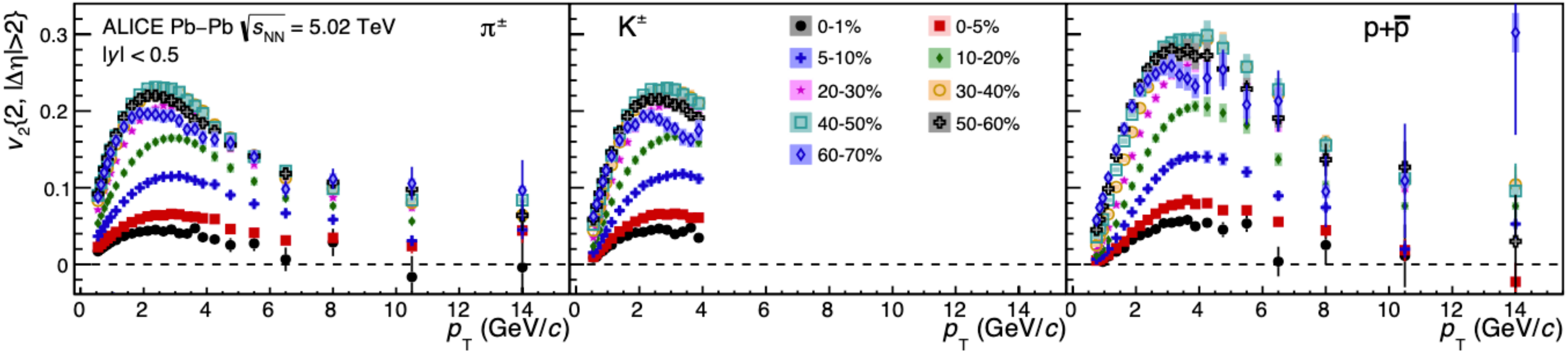
$$v_2 = \langle \cos 2(\varphi - \psi_{RP}) \rangle$$

- Elliptic flow can be used to probe the **transport coefficients** of the QGP (i.e. shear viscosity and bulk viscosity), the **initial state** of the collision and its **fluctuations**

- **Strange hadrons** are good candidates because they have small hadronic cross sections → their flow is **less affected by the hadronic phase interactions**

→ Flow in pp and p-Pb collisions in talk by W. Wu Thu 18th 11:02

Elliptic flow of hadrons vs centrality and p_T

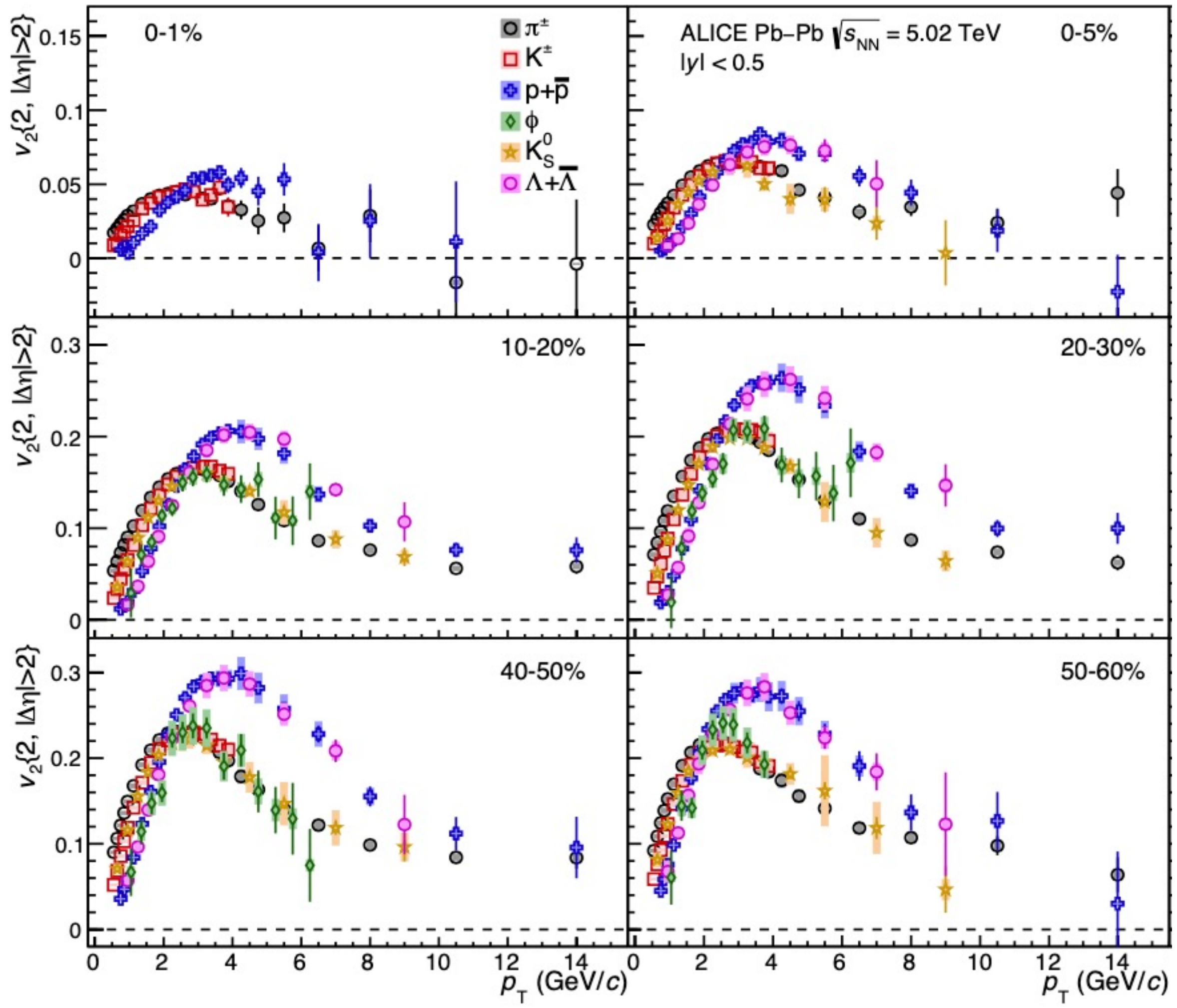


ALICE, JHEP 09 (2018) 006

For all species, v_2 increases from central to peripheral collisions up to 40-50%
→ Due to the larger initial state eccentricity in more peripheral collisions

The magnitude of v_2 in the 50-60% class is compatible to the one measured in 40-50%
→ Due to a convolution of several effects, e.g. smaller lifetime of the fireball that does not allow for the development of v_2

Particle dependence of elliptic flow



ALICE, JHEP 09 (2018) 006

p_T < 3 GeV/*c*: mass ordering

At fixed p_T, v_2 is larger for particles with smaller mass

→ Due to **interplay** between **elliptic and radial flow**

3 < p_T < 6 GeV/*c*: meson and baryon grouping

v_2(baryons) > v_2(mesons)

→ Reproduced by models implementing hadronization via **quark coalescence**

→ Interpreted as evidence that **quark degrees of freedom** dominate the stage when v_2 develops

p_T > 10 GeV/c:

v_2 depends only weakly on p_T and $v_2(\pi) \sim v_2(p)$

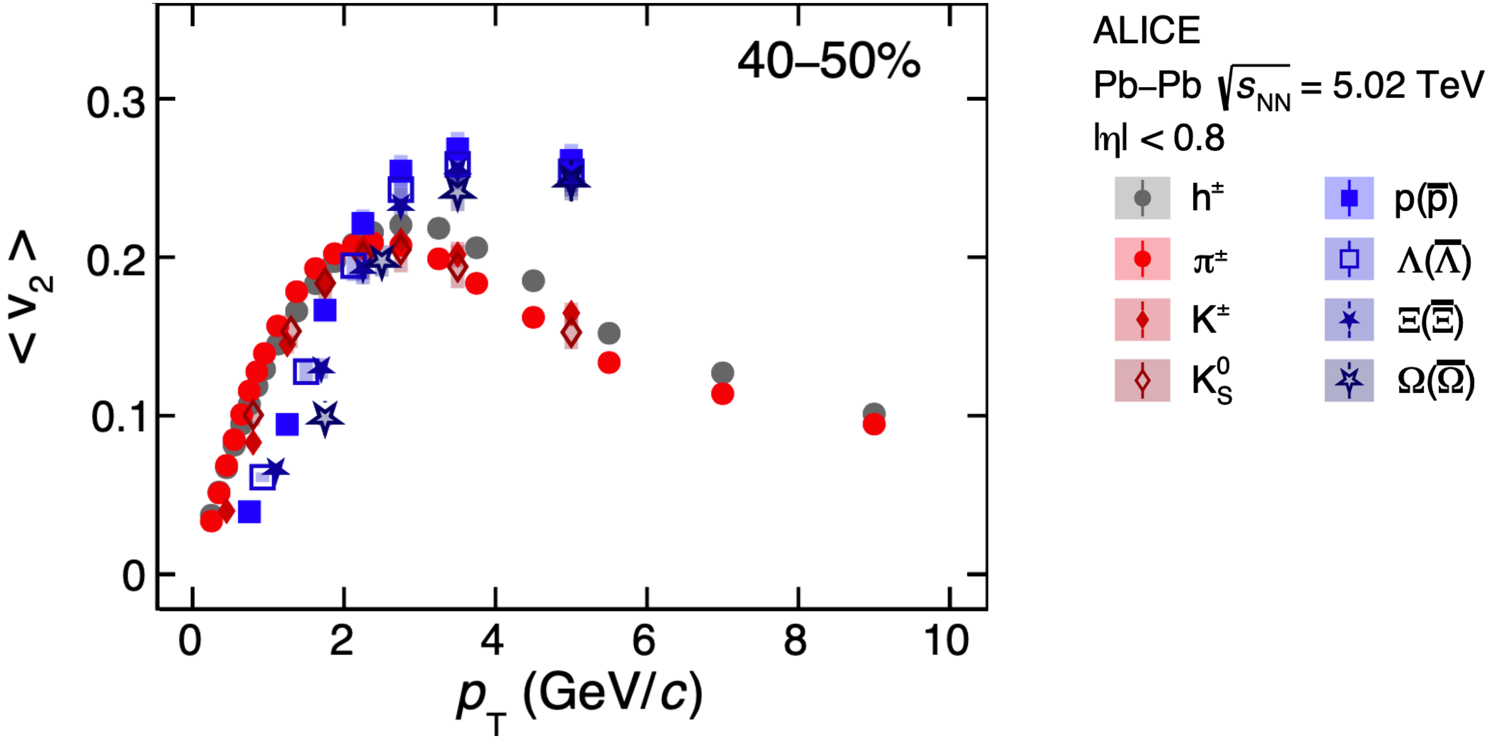
→ $v_2 \neq 0$ is the result of the **path-length dependence of the energy loss** of hard partons interacting with the QGP

Elliptic flow of multi-strange hadrons in Run 2

ALICE, JHEP 05 (2023) 243

Measurement of $\langle v_2 \rangle$ performed with the 2- and 4-particle cumulants

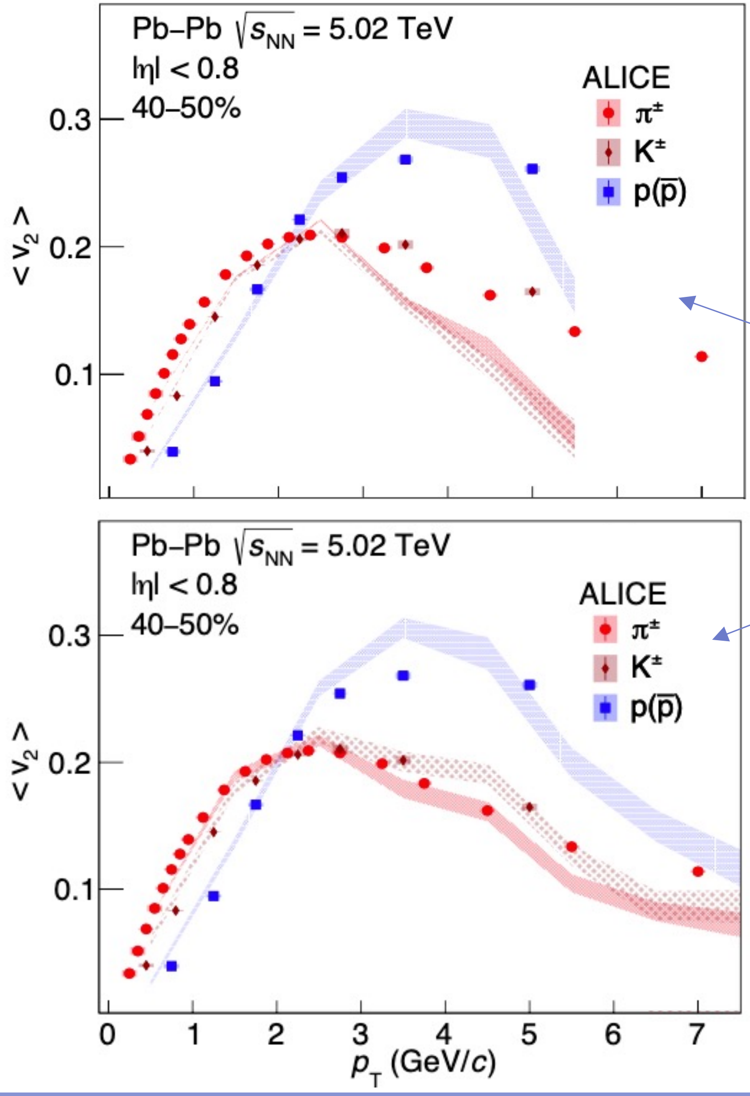
$$\langle v_2 \rangle \approx \sqrt{\frac{v_2^2\{2\} + v_2^2\{4\}}{2}}$$



- Also multi-strange hadrons **Ξ and Ω** exhibit **mass ordering for p_T < 3 GeV/*c*** and are **grouped with baryons at intermediate p_T** values
- The measurement of Ξ and Ω flow is limited to the centrality range 10-50% and p_T < 6 GeV/*c*

→ **Run 3 data will allow for an extension of p_T and centrality intervals**

Comparison with model calculations



Comparison with predictions of CoLBT hydrodynamic model with (3+1)-D viscous hydro initialised at $\tau_0 = 0.6$ fm/c, shear viscosity η/s = 0.10 and freeze-out temperature T = 150 MeV

W. Zhao *et al.*, PRL 128 (2022) 022302

Hydrodynamic + fragmentation:

- **underestimate** $\langle v_2 \rangle$ of pion and kaon for p_T > 3 GeV/c
- **predicts** the baryon/meson **crossing** with protons

Hydrodynamic + coalescence + fragmentation:

- provides a **better description** of the data

- **Coalescence** mechanisms important to provide connection between low and high p_T regions
- The **crossing point** develops also **in absence of coalescence**

ALICE, JHEP 05 (2023) 243

Studying QGP with hyperon polarization

In non central heavy-ion collisions, **elliptic flow** is expected to generate a **non-zero vorticity component along the beam axis** with a quadrupole strucuture in the transverse plane
→ due to the spin-orbit coupling, this leads to **a longitudinal component of particle spin polarization**

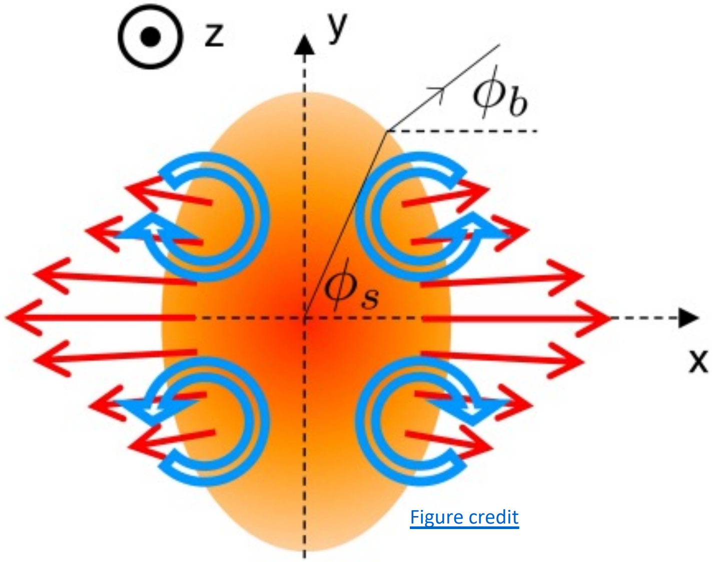


Figure credit

The polarization can be experimentally measured via **parity violating weak decays** like $\Lambda \rightarrow p\,\pi$, in which the daughter baryon is preferentially emitted in the direction of the spin of the hyperon

The polarization along the beam axis is sensitive to:

- the **QGP evolution at later times** wrt the global polarization
- the **bulk viscosity** of the QGP
- the **dynamics of the spin** degrees of freedom

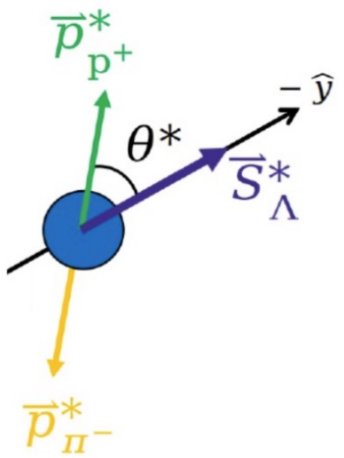
S. Voloshin and T. Niida, Phys. Rev. C 94 (2016) 021901(R)

Polarization of Λ along the beam direction

In the parity violating decay $\mathbf{\Lambda} \rightarrow \mathbf{p}\ \boldsymbol{\pi}$, the daughter proton is preferentially emitted in the direction of the spin of the Λ

The angular distribution of protons in the Λ rest frame is:

$$4\pi \frac{dN}{d\Omega^*} = 1 + \alpha_{\rm H}\, P_H \cos\theta^*$$

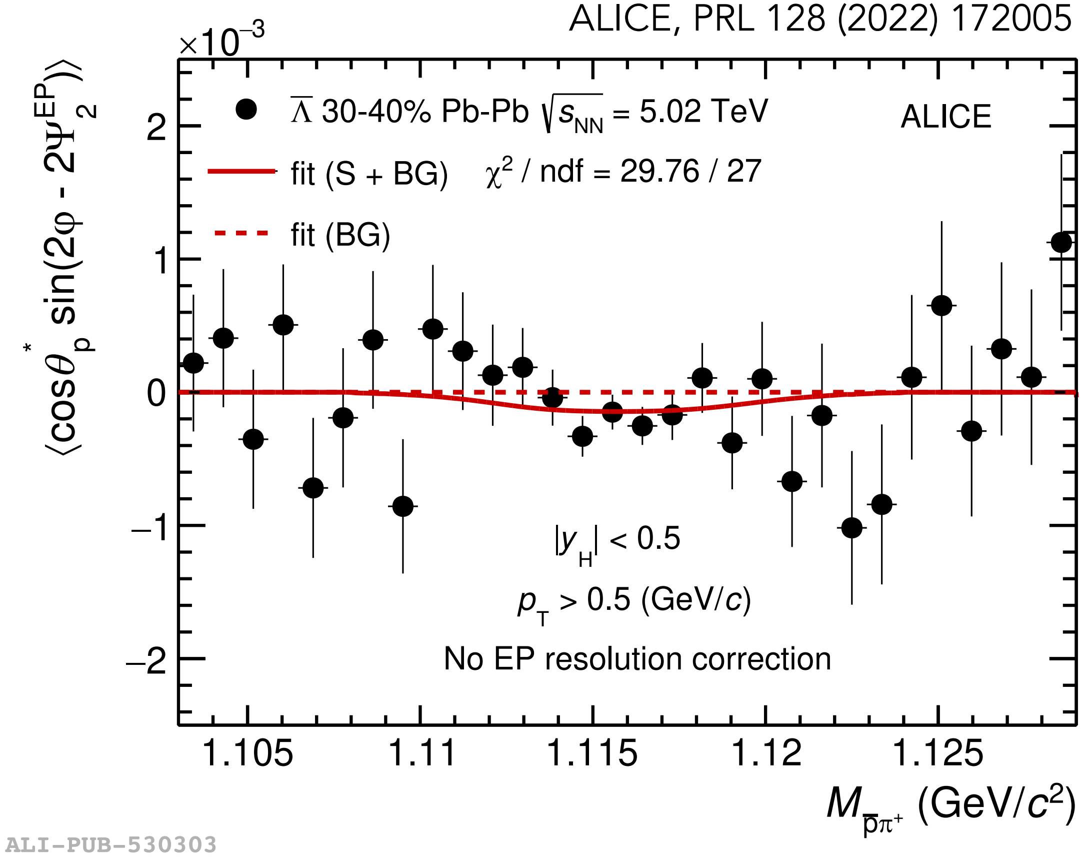


$\alpha_{\rm H}$ = hyperon decay parameter
$P_{\rm H}$ = hyperon polarization

$$P_z = \frac{\langle \cos\theta^* \rangle}{\alpha_{\rm H} \langle \cos^2\theta^* \rangle}$$

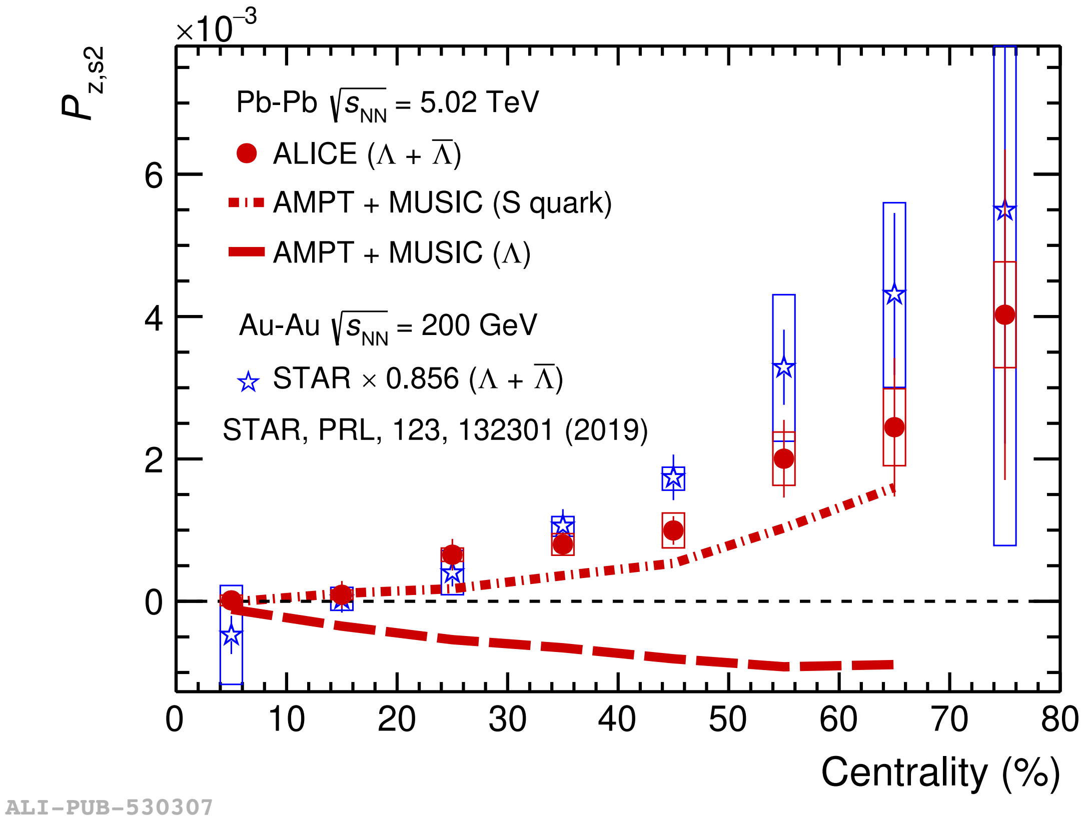
$$P_{z,s2} = \langle P_z \sin 2(\varphi - \psi_2) \rangle$$

ALICE, PRL 128 (2022) 172005



$P_{z,s2}$ is esimated as **a function of the invariant mass** of the Λ, in order to account for combinatorial background contamination

Polarization of Λ along the beam direction



ALICE, PRL 128 (2022) 172005

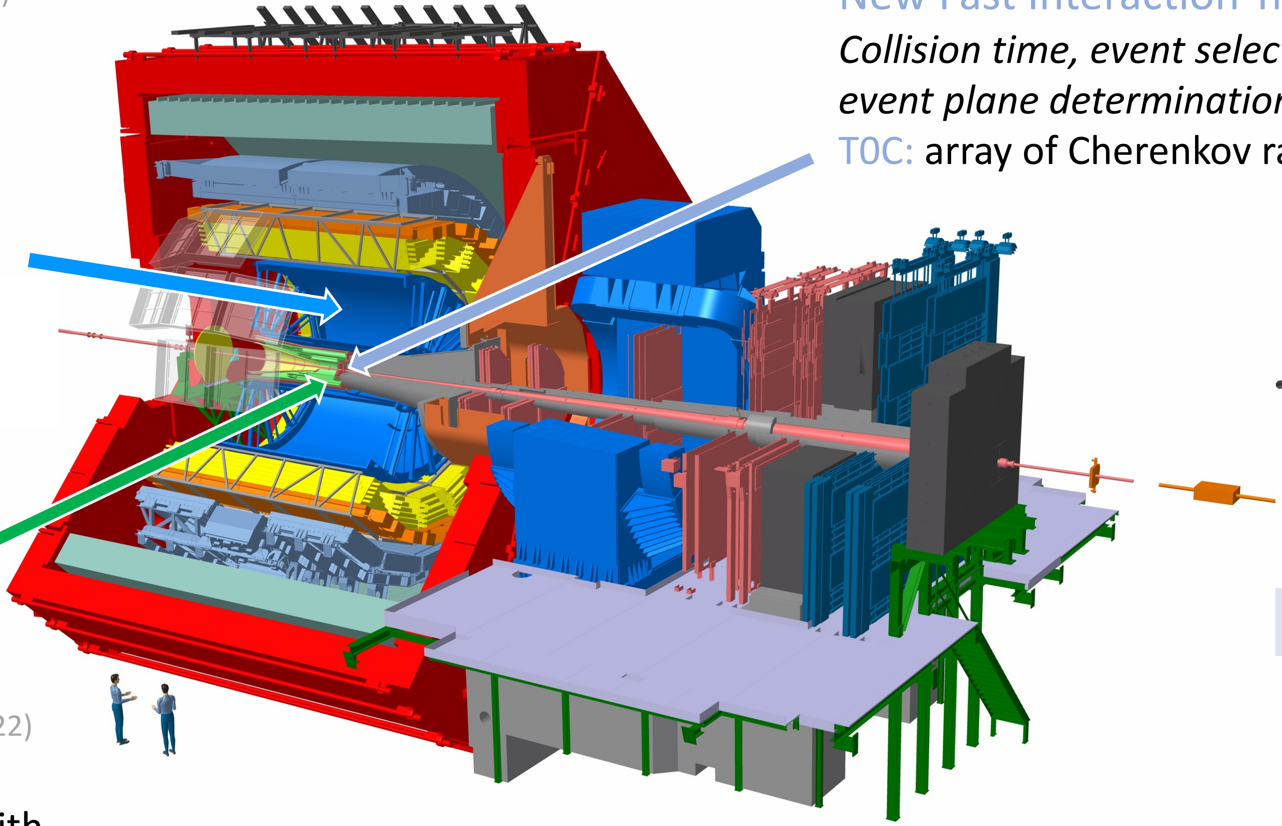
$P_{z,s2}$ **increases with decreasing centrality**, likely due to increasing elliptic flow contribution

3+1 D hydro model MUSIC + AMPT initial conditions predicts correct sign polarisation if shear-induced polarisation is included and the hyperon inherits quark s polarisation at the hadronisation stage

B. Fu et al., Phys. Rev. Lett. 127 (2021) 142301

Run 3 data will allow for **more differential** and precise measurement of hyperon longitudinal polarization, including **Ξ and Ω baryons**

ALICE at the LHC in Run 3



Upgraded TPC JINST 16, P03022 (2021)

Main tracking detector, vertexing, PID (dE/dx)

- MWPCs replaced with GEMs
- Continuous readout up to interaction rate of 50 kHz in Pb-Pb collisions

Upgraded ITS NIM 1032, 166632 (2022)

Tracking, vertexing

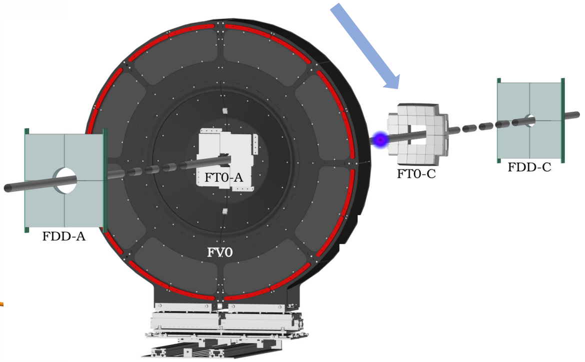
- 7 layers of silicon detectors with reduced material budget
- First layer closer to the beam pipe (L0 at 22 mm)

→ Talk by J. Liu, Thu 18th 10:45

New Fast Interaction Trigger (FIT) NIM 1039, 167021 (2022)

Collision time, event selection, centrality estimation, event plane determination

T0C: array of Cherenkov radiators at forward rapidity

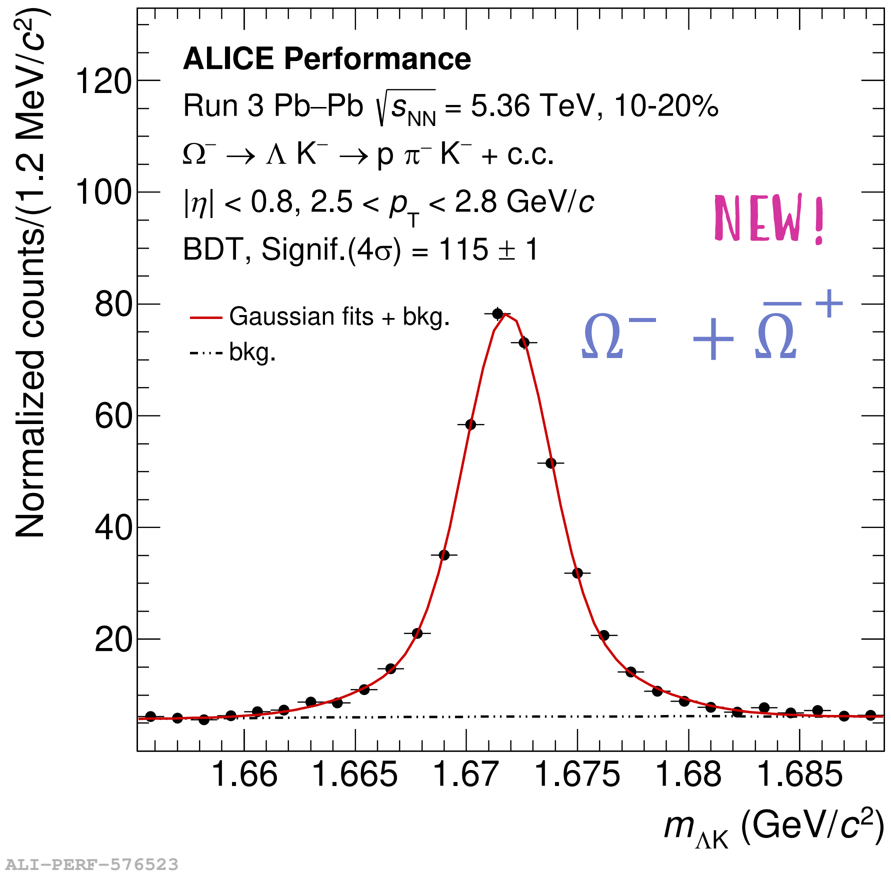


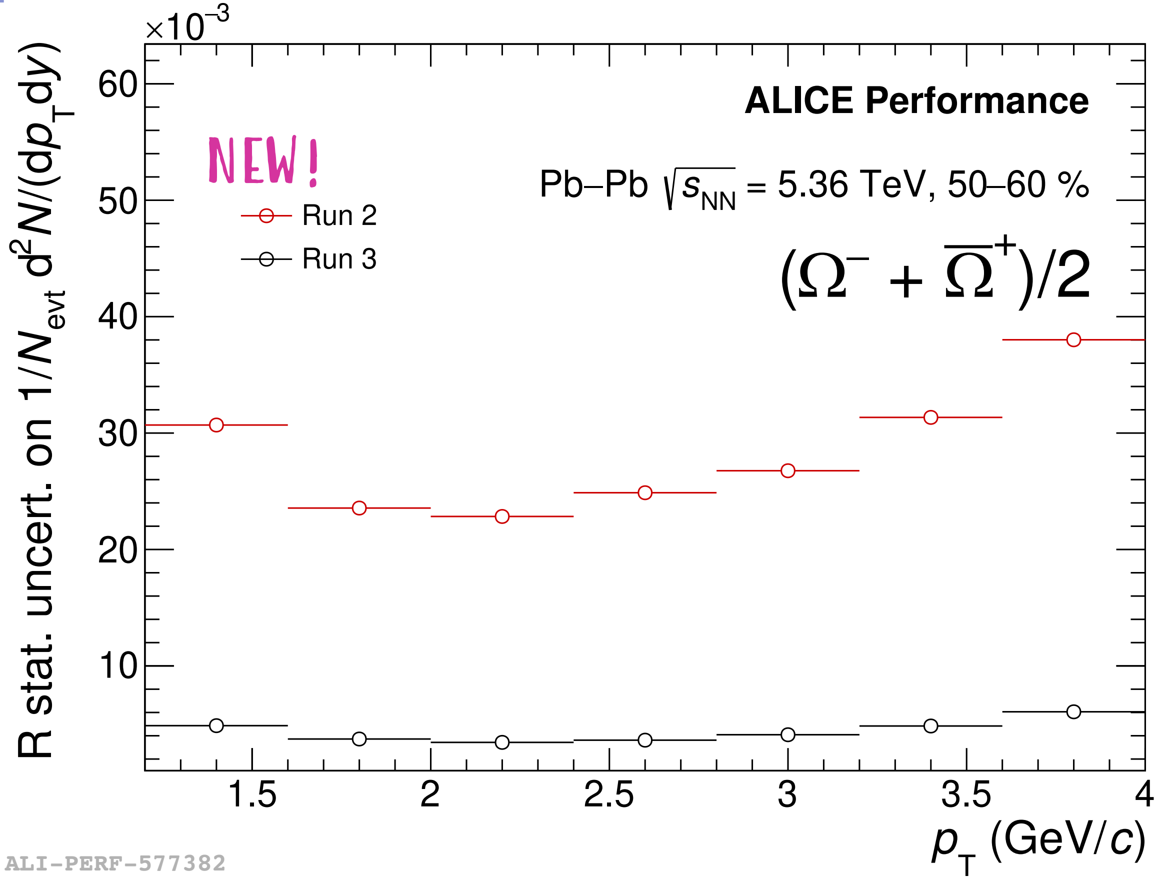
→ Talk by Y. Melikyan, Fri 19th 8:48

New O^2 framework CERN-LHCC-2015-006, ALICE-TDR-019

- Common **O**nline-**O**ffline computing system
- Process data throughput x 100 wrt Run 2

Identification of a high purity sample of cascades





The application of Boosted Decision Tree (**BDT**) allows for the identification of a **high-purity sample** of cascades

Statistical uncertainty of Ω yields decreased by a factor 6 wrt Run 2 → **large data sample** collected in Run 3 allows for **more differential measurement** of flow

Analysis technique for flow calculation

The flow is calculated using the **scalar product method** in intervals of p_{T} and invariant mass

Number of Ξ in $(\Delta p_T, \Delta m)$

$$v_2(\Delta p_T, \Delta m) = \frac{1}{R_{SP}} \frac{1}{N_\Xi} \sum_{\Xi \in (\Delta p_T, \Delta m)} \overrightarrow{u_\Xi} \cdot \overrightarrow{Q_{T0C}}$$

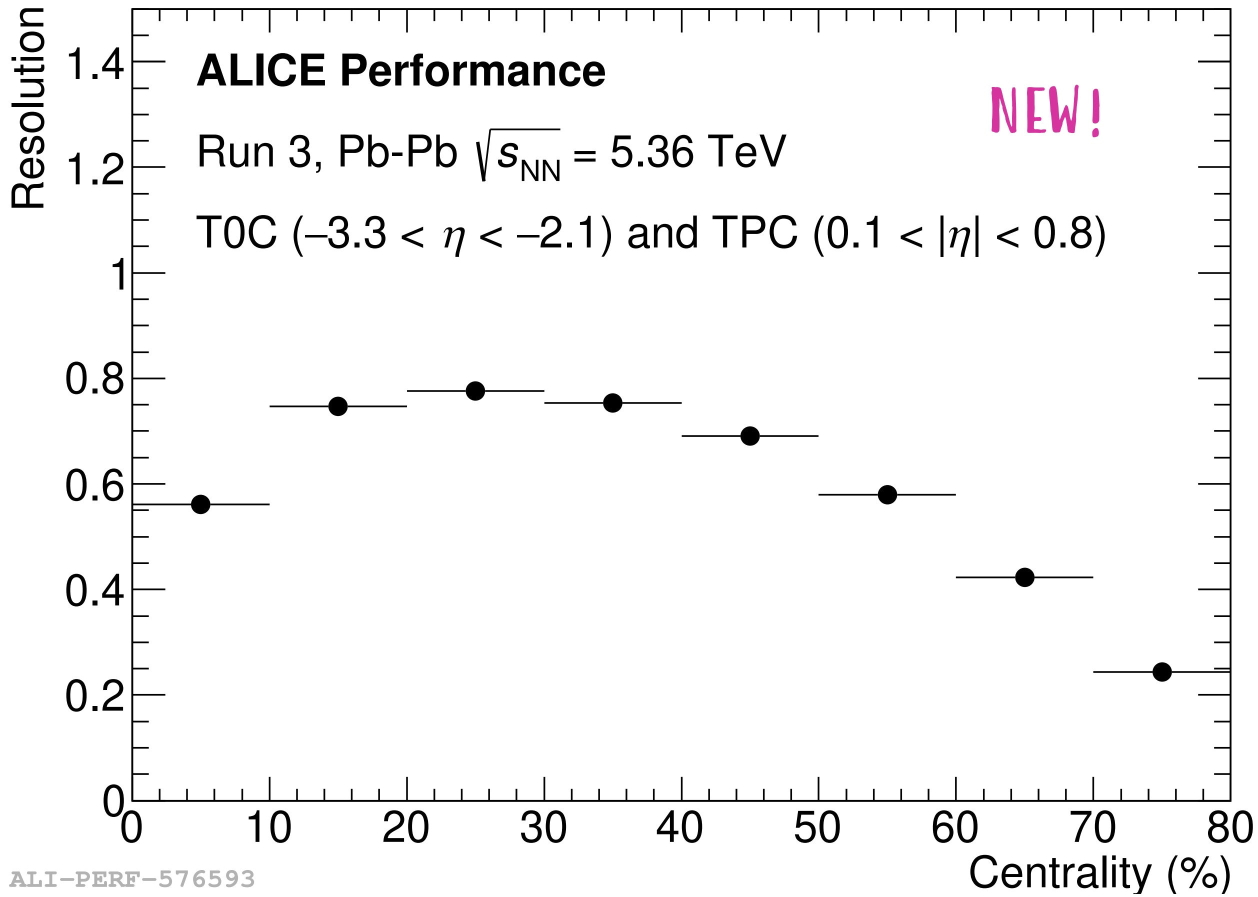
SP resolution

$$\overrightarrow{Q_{T0C}} = Q_{T0C}\, e^{2i\Psi}$$

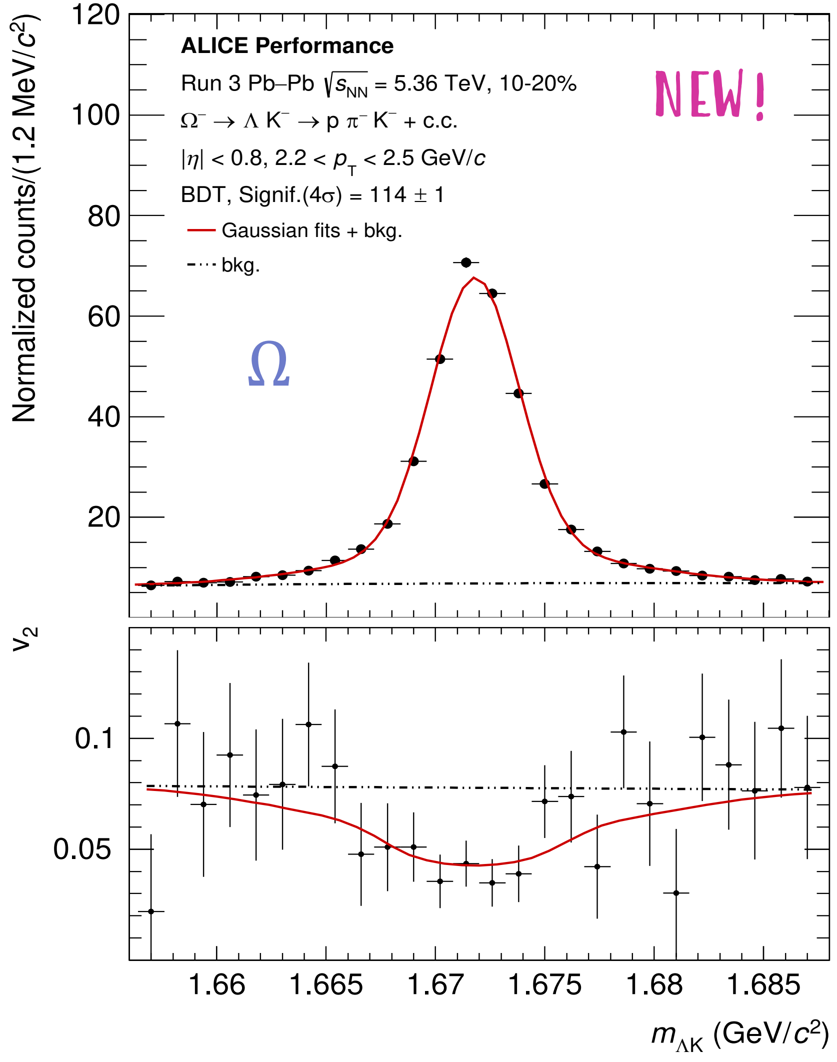
Event plane vector determined with T0C detector

$$\overrightarrow{u_\Xi} = e^{2i\varphi_\Xi}$$

φ_Ξ: azimuthal angle of Ξ



Elliptic flow calculation with Run 3 data



ALI-PERF-576519

The invariant mass distributions are fit with:

- a sum of two gaussians to describe the signal
- a second degree polynomial to describe the background (dotted black line)

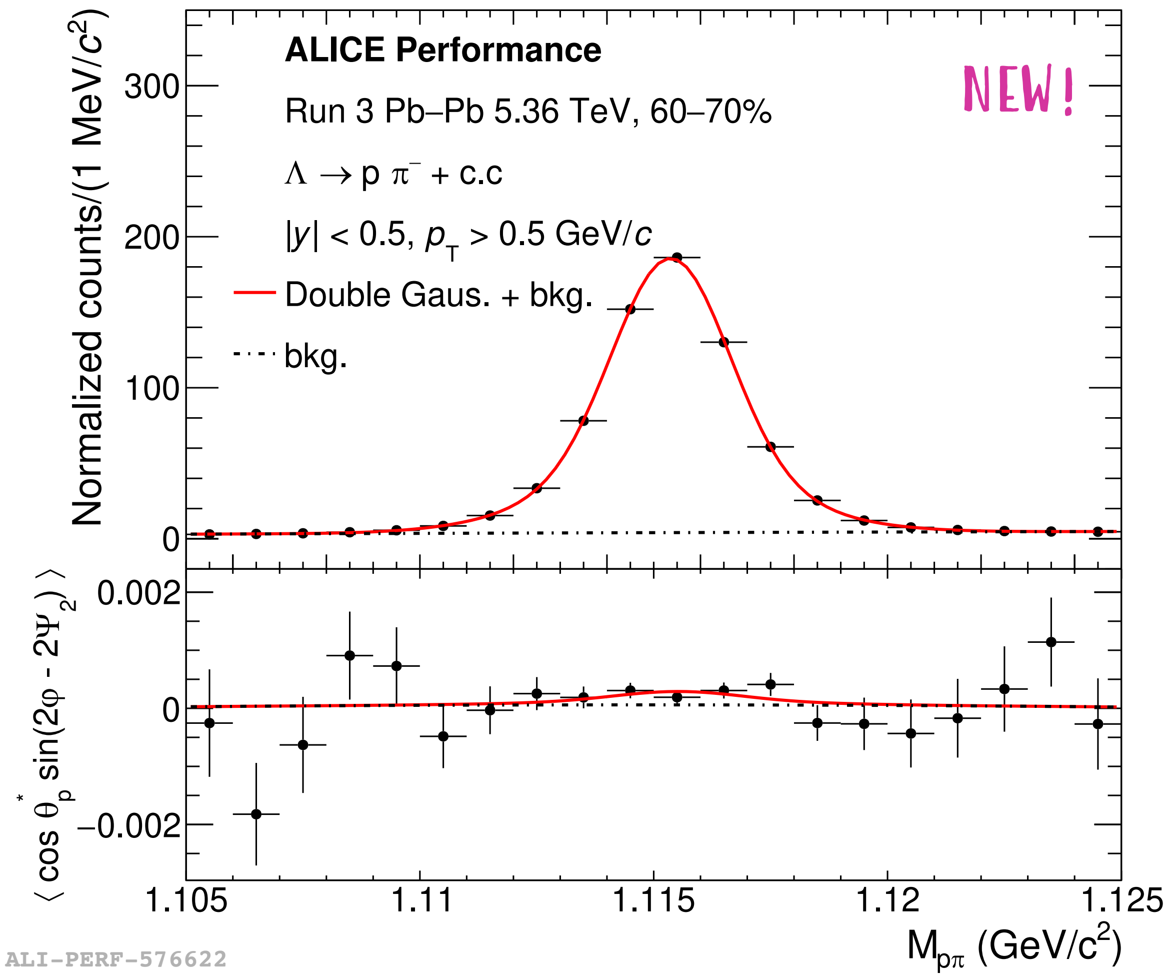
In Run 3 we have already collected 2.5 x 10^9 Pb-Pb collisions, **more than 10 times the Run 2** ones used to study the flow of multi-strange hadrons

We will measure the elliptic flow of Ξ and Ω **more differentially in p_T and centrality** in order to probe:

- Hydrodynamic model description in the **most central** and the **most peripheral** collisions
- Meson-baryon grouping up to **larger p_T values**

→ ^{3}He and $^{3}_{\Lambda}$H flow in Run 3 in talk by L. Barioglio, Sat 20th 17:53

Polarization of Λ along the beam axis in Run 3



The invariant mass distributions are fit with:

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- a second degree polynomial to describe the background (dotted black line)

Thanks to Run 3 data:

- we will measure the longitudinal polarization of Λ **more differentially in p_T and centrality** in order to provide further constraints to the models
- we will be able to measure for the first time the longitudinal **polarization of Ξ and Ω**

Summary and outlook

- The elliptic flow of the multi-strange hadrons Ξ **and** Ω exhibit the same features measured for lighter hadrons, i.e. **mass ordering for p_{T} < 3 GeV/*c*** and **baryon-meson grouping at intermediate p_{T}**

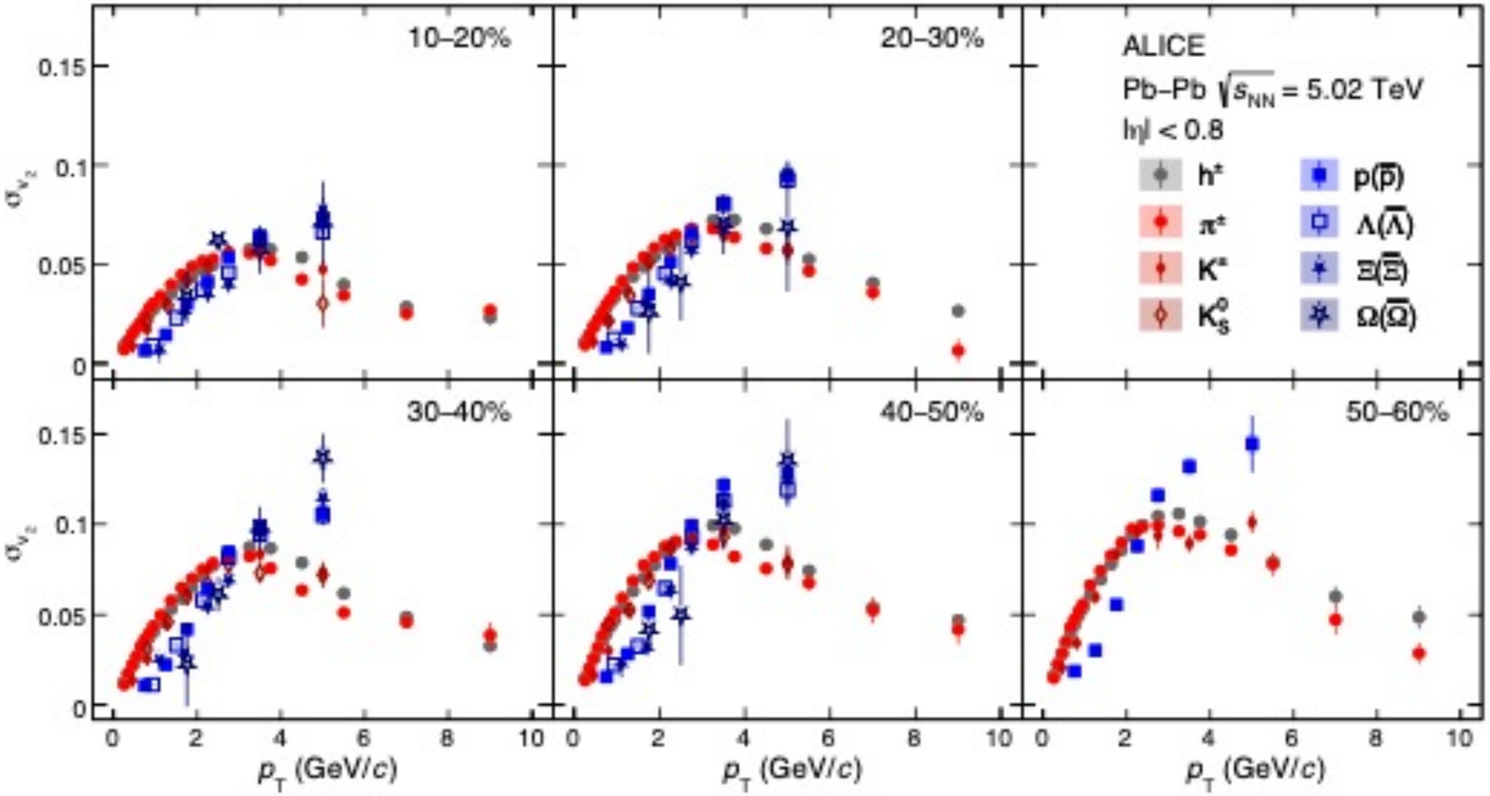
- **A significant z component of the Λ polarization** due to elliptic-flow induced vorticity was measured by ALICE for the first time at the LHC

- Thanks to a **x10 larger number of collected events in Run 3,** the elliptic flow of Ξ and Ω and the Λ polarization will be measured **more differentially in p_{T} and centrality**

- The first measurement of Ξ **and** Ω **longitudinal polarization** will become feasible

Backup

Standard deviation of v_2



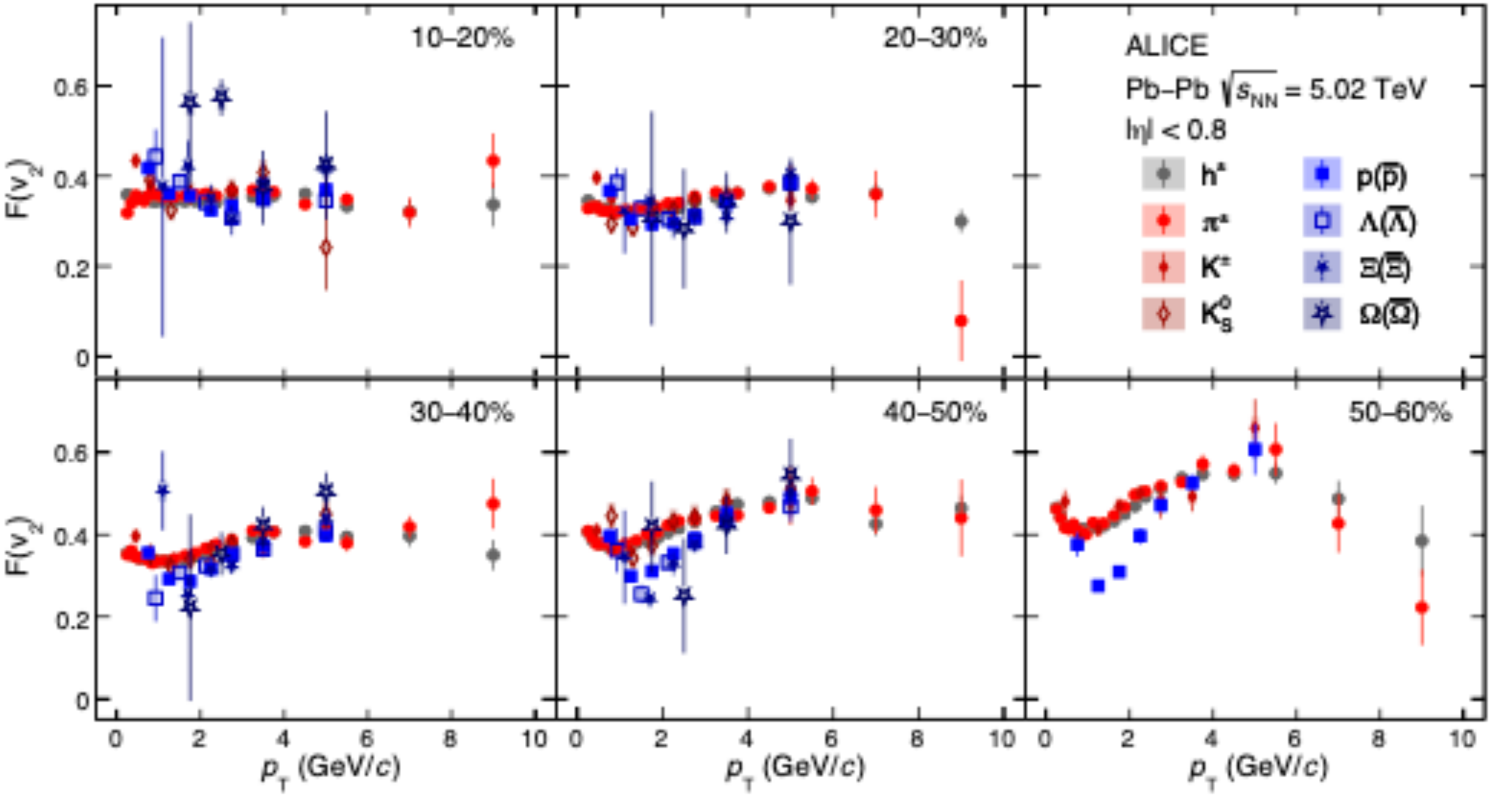
$$\langle v_n \rangle \approx \sqrt{\frac{v_n^2\{2\} + v_n^2\{4\}}{2}},$$

$$\sigma_{v_n} \approx \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}}.$$

$\langle v_2 \rangle$ and σ_{v_2} show the same qualitative features shown by $v_2\{2\}$ and $v_2\{4\}$, i.e. mass ordering at low p_T and meson-baryon grouping at larger p_T values

ALICE, JHEP 05 (2023) 243

Relative flow fluctuations



$$F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$

No dependence on p_T and particle species for central events

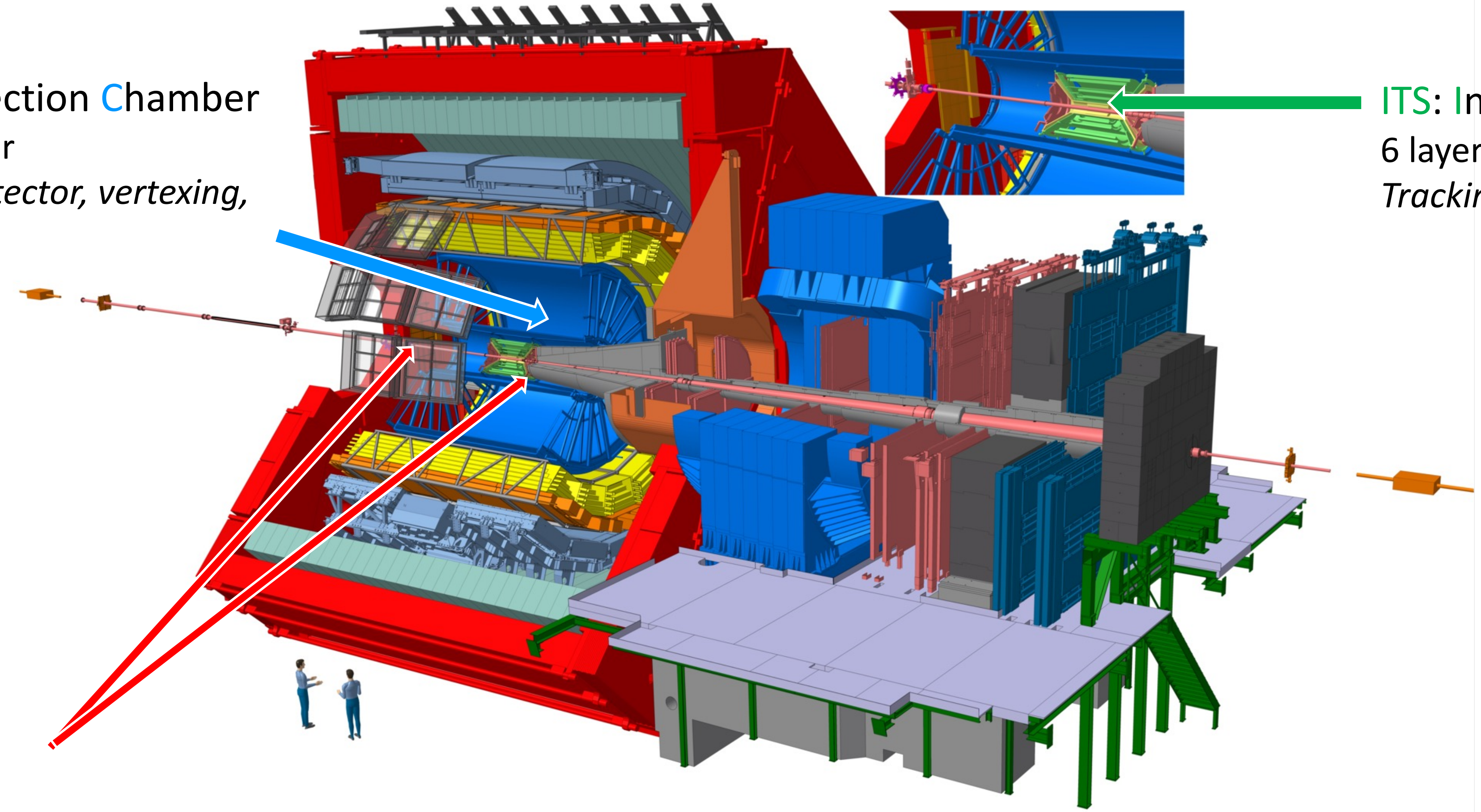
In 30-40% and more peripheral collisions:

- non monotonic beheaviour with p_T-dependent minimum (higher for baryons)
- F (baryons) < F (mesons) in $1 < p_T < 3$ GeV/c
- Compatible within uncertainties for $p_T > 3$ GeV/c

ALICE, JHEP 05 (2023) 243

ALICE at the LHC in Run 2

TPC: Time Projection Chamber
Gas-filled detector
Main tracking detector, vertexing, PID (dE/dx)



ITS: Inner Tracking System
6 layers of silicon detectors
Tracking, triggering, vertexing

V0A and V0C
Arrays of scintillators at forward rapidity
Triggering, event selection, centrality estimation, event plane determination

Analysis technique for flow calculation

The flow is calculated using the **scalar product method** in intervals of p_{T} and invariant mass

Number of Ξ in $(\Delta p_T, \Delta m)$

$$v_2(\Delta p_T, \Delta m) = \frac{1}{R_{SP}} \frac{1}{N_\Xi} \sum_{\Xi \in (\Delta p_T, \Delta m)} \overrightarrow{u_\Xi} \cdot \overrightarrow{Q_{T0C}}$$

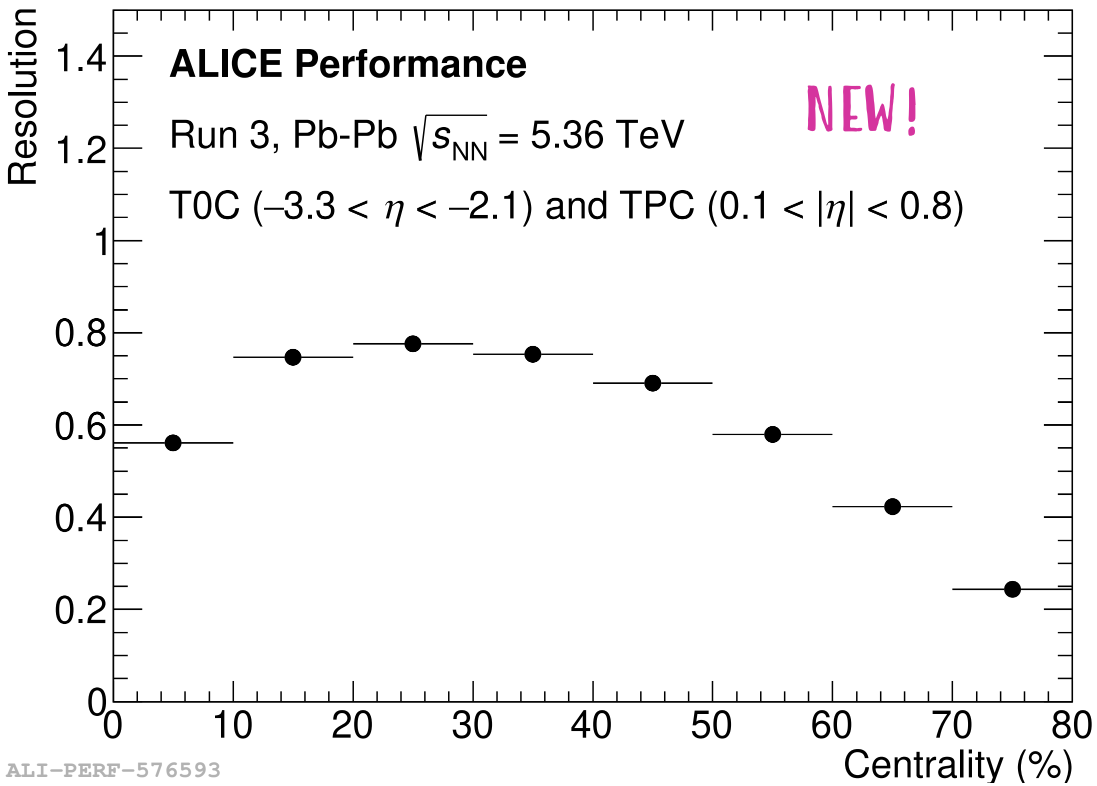
$$\overrightarrow{Q_{T0C}} = \|\overrightarrow{Q_{T0C}}\| e^{2i\Psi}$$

SP resolution

$$\overrightarrow{u_\Xi} = e^{2i\varphi_\Xi}$$

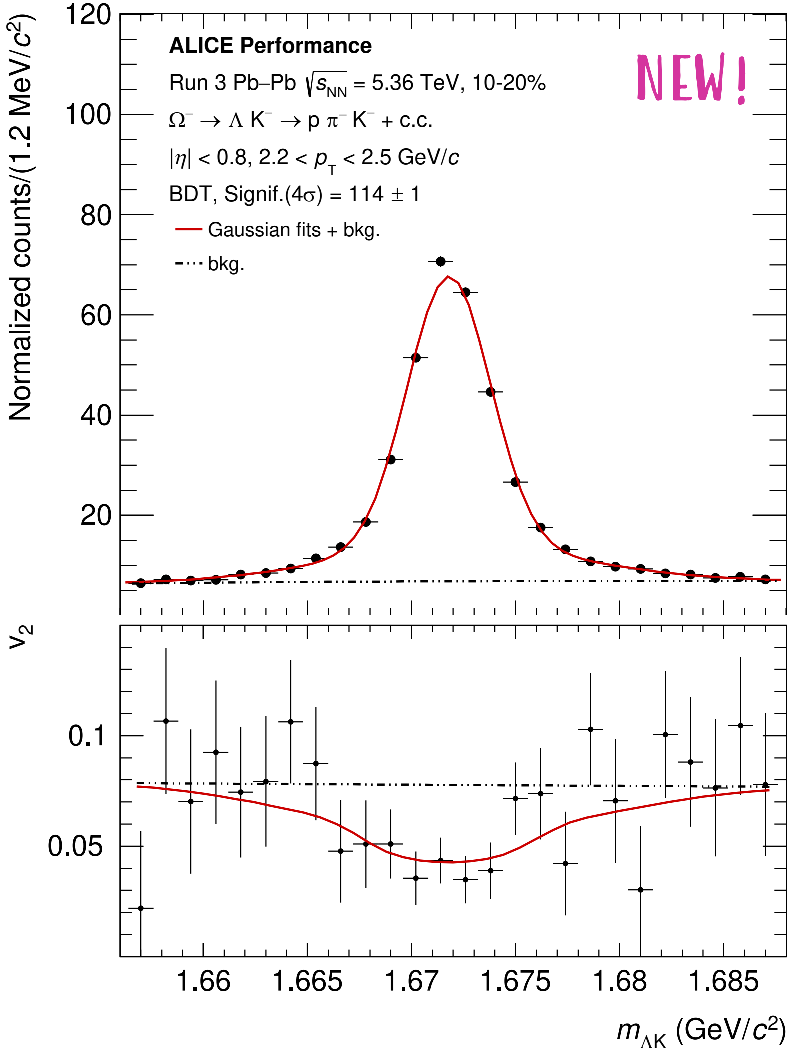
$$Q_x(TPC) = \sum_{Ntracks} p_{\mathrm{T},tr} \cos 2\varphi_{tr} \ / N_{tracks} \qquad Q_x(T0C) = \sum_{T0C\ channels} A_{ch} \cos 2\varphi_{ch} \Big/ \sum_{T0C\ channels} A_{ch}$$

$$Q_y(TPC) = \sum_{Ntracks} p_{\mathrm{T},tr} \sin 2\varphi_{tr} \ / N_{tracks} \qquad Q_y(T0C) = \sum_{T0C\ channels} A_{ch} \sin 2\varphi_{ch} \Big/ \sum_{T0C\ channels} A_{ch}$$



$$R_{SP} = \sqrt{\frac{\langle \overrightarrow{Q_{T0C}} \cdot \overrightarrow{Q_{TPCa}} \rangle \langle \overrightarrow{Q_{T0C}} \cdot \overrightarrow{Q_{TPCc}} \rangle}{\langle \overrightarrow{Q_{TPCa}} \cdot \overrightarrow{Q_{TPCc}} \rangle}}$$

Elliptic flow calculation with Run 3 data



ALI-PERF-576519

The invariant mass distributions are fitted with:

- a sum of two gaussians to describe the signal
- a second degree polynomial to describe the background (dotted black line)

The v_2 vs invariant mass distributions is fitted with:

$$v_2^{tot}(M_{\Lambda K}) = v_2^{sig} \frac{N_{sig}}{N_{sig} + N_{bkg}}(M_{\Lambda K}) + v_2^{bkg}(M_{\Lambda K}) \frac{N_{bkg}}{N_{sig} + N_{bkg}}(M_{\Lambda K})$$

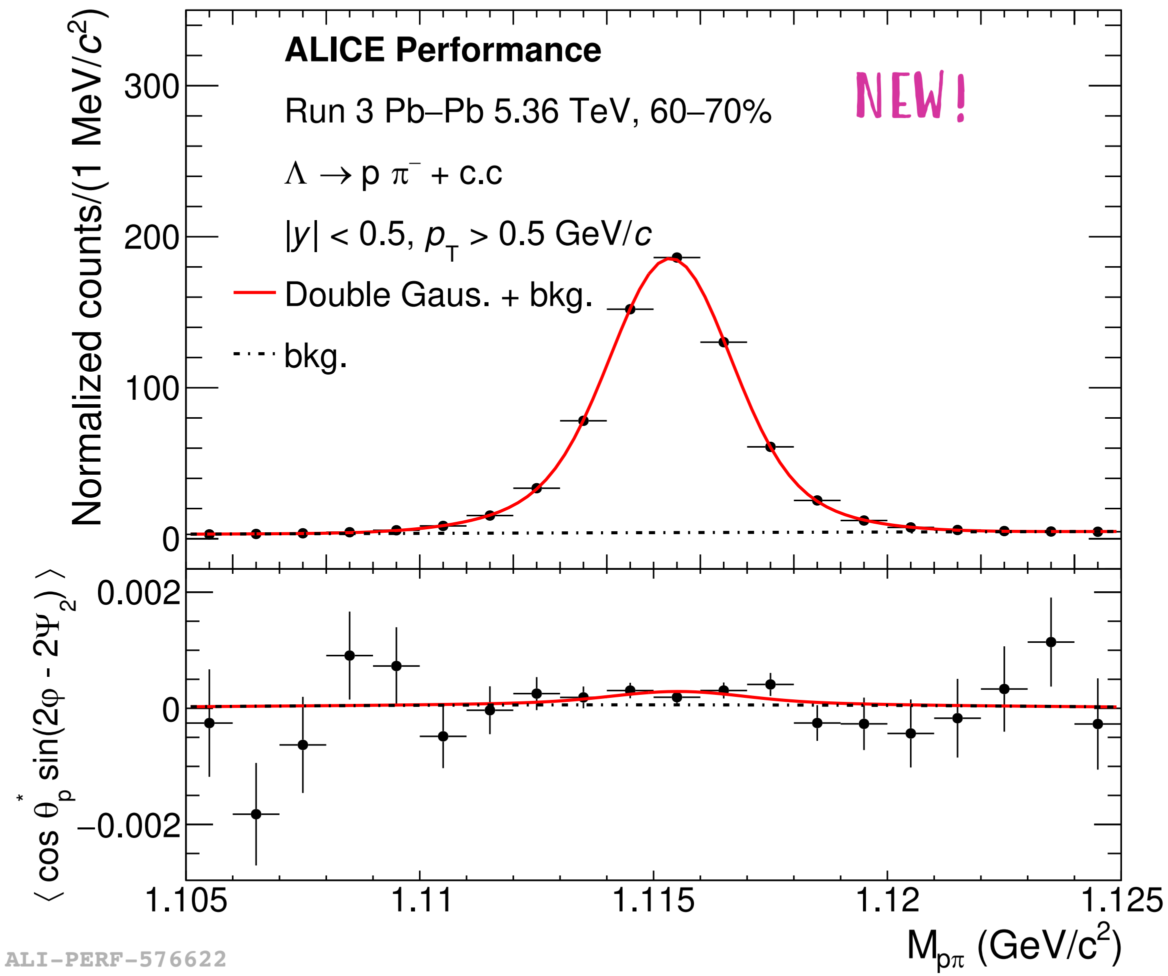
Fraction of background = integral bkg fit function / integral of total fit function

Fraction of signal = 1 - fraction of background

v_2^{bkg} is assumed to depend linearly on the invariant mass:

$v_2^{bkg}(M_{\Lambda K}) = A + BM_{\Lambda K}$

Polarization of Λ along beam axis



The $P_{z,s2}$ vs invariant mass distributions is fitted with:

$$P^{tot}_{z,s2}(M_{p\pi}) = P^{sig}_{z,s2}\frac{N_{sig}}{N_{sig}+N_{bkg}}(M_{p\pi}) + P^{bkg}_{z,s2}(M_{p\pi})\frac{N_{bkg}}{N_{sig}+N_{bkg}}(M_{p\pi})$$

Fraction of background =
integral bkg fit function / integral of total fit function

Fraction of signal = 1 - fraction of background

$P^{bkg}_{z,s2}$ is assumed to depend linearly on the invariant mass:

$$P^{bkg}_{s,s2}(M_{p\pi}) = A + BM_{p\pi}$$