Sixth Annual Conference on Large Hadron Collider Physics
Bologna (Italy) – 4 to 9 June 2018

New results on collectivity in small systems with ALICE

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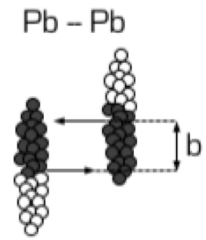
on behalf of the ALICE Collaboration

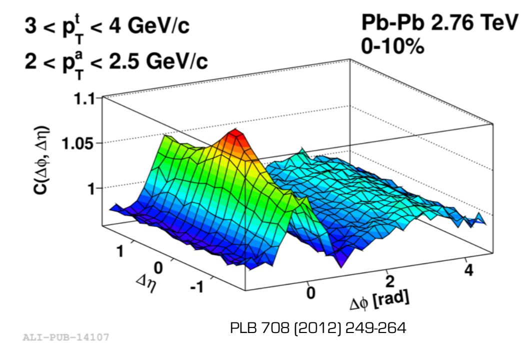
Istituto Nazionale di Fisica Nucleare

Introduction

Heavy ion systems

- Studied to characterize the QGP properties
- Hot and dense matter created in heavy ion collisions largely proven to behave collectively

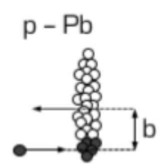


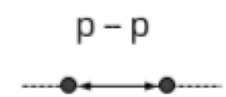


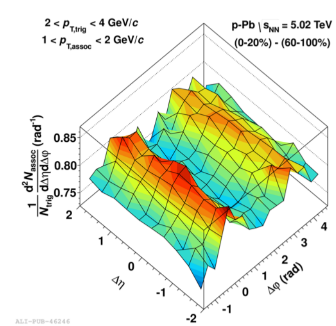
PLB 708 (2012) 249-264

Small systems

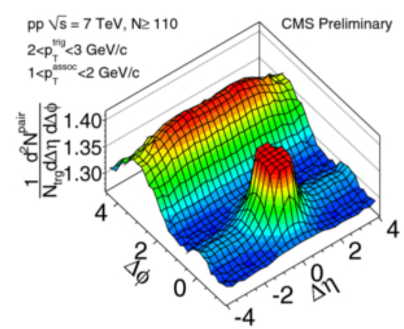
- Smaller size colliding objects and average multiplicity in final state
- Traditionally
  - pp: benchmark for heavy-ion physics and microscopic production mechanism study
  - p-Pb: intermediate reference and initial state effects study environment
- Several "collective"-like phenomena are also observed in high multiplicity pp and p-Pb collisions







Phys. Lett. B 719, 29-41

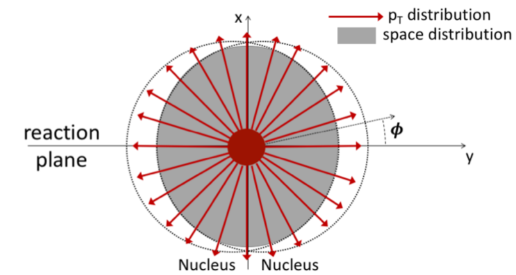


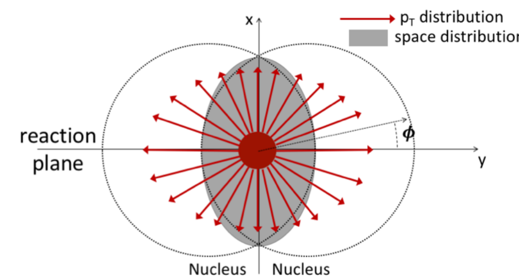
Phys. Lett. B 708, 249-264

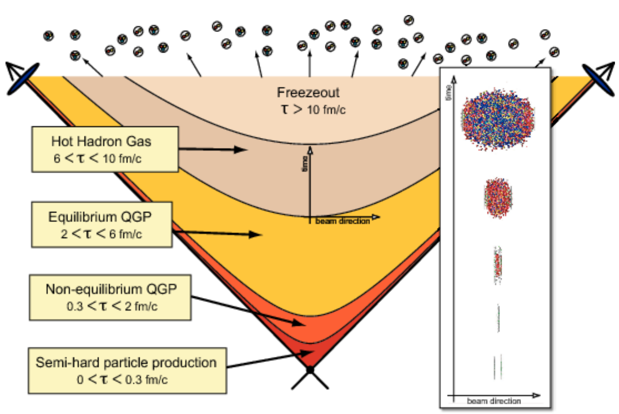
Introduction

In hydrodynamic description of heavy ion collisions fireball expected to expand through:

- Isotropic radial flow (important in central collisions)
  - Common expansion velocity of partons
  - Observables: spectra shape, baryon/meson anomaly
- Anisotropic transverse flow
  - Initial spatial anisotropy translates into final momentum anisotropy (in semi-peripheral collisions)
  - Fluctuations of initial spatial distribution translates into final momentum anisotropy (in central collisions)
  - Observables: multi-particle correlations





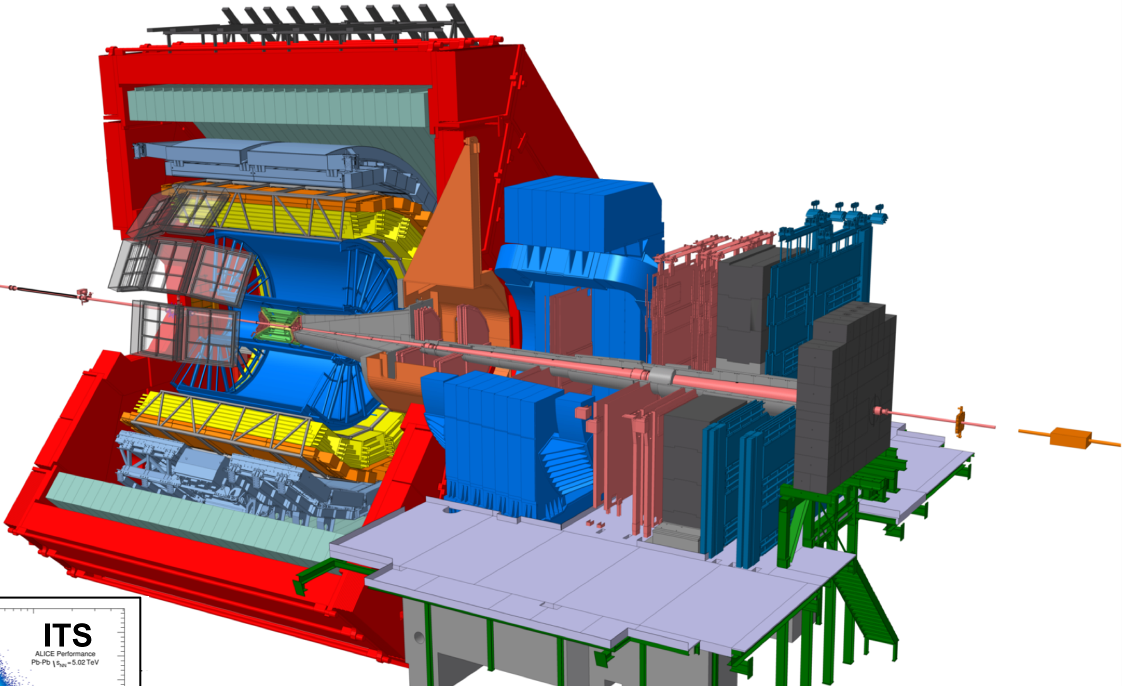


Origin of collectivity

- *Initial state correlations* : particles produced with momentum correlations at partonic level → survive through the fireball stages → converted into hadron final state momentum correlations
- *Final state correlations* : space anisotropies converted into momentum anisotropies via hydrodynamical flow → final state interactions generate the final state correlations

A Large Ion Collider Experiment

Multi-purpose detector at the LHC with unique particle identification capabilities and tracking down to very low momenta



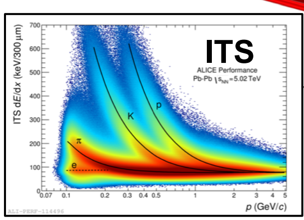
Central Barrel Detectors (|η| < 1)

Inner Tracking System (**ITS**)
- Tracking
- Vertexing
- Triggering
- Low momentum PID

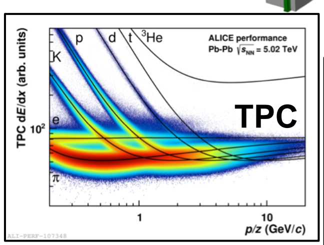
Time-Projection Chamber (**TPC**)
- Tracking
- PID

Time-of-flight detector (**TOF**)
- PID

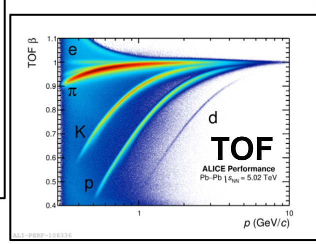
High Momentum PID (**HMPID**)
- PID



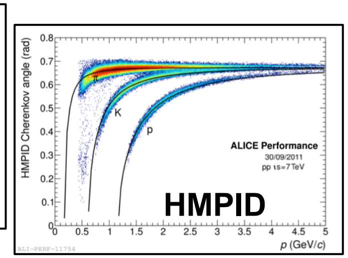
ITS $\sigma_{dE/dx}$ ~ 10-15%



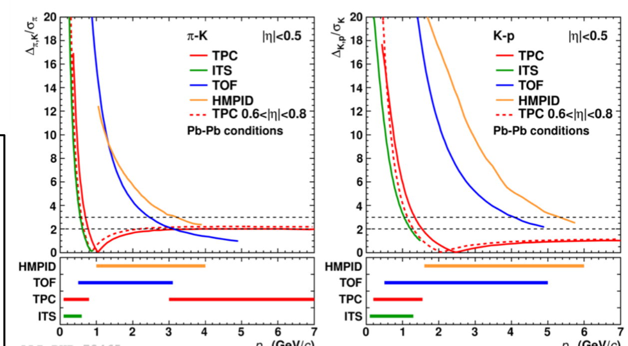
TPC $\sigma_{dE/dx}$ ~ 5%



TOF $\sigma_{Time\ Of\ Flight}$ ~ 56 ps



HMPID $\sigma_{Cherekov\ Angle}$ ~ 3 mrad



Int. J. Mod. Phys. A 29 (2014) 24

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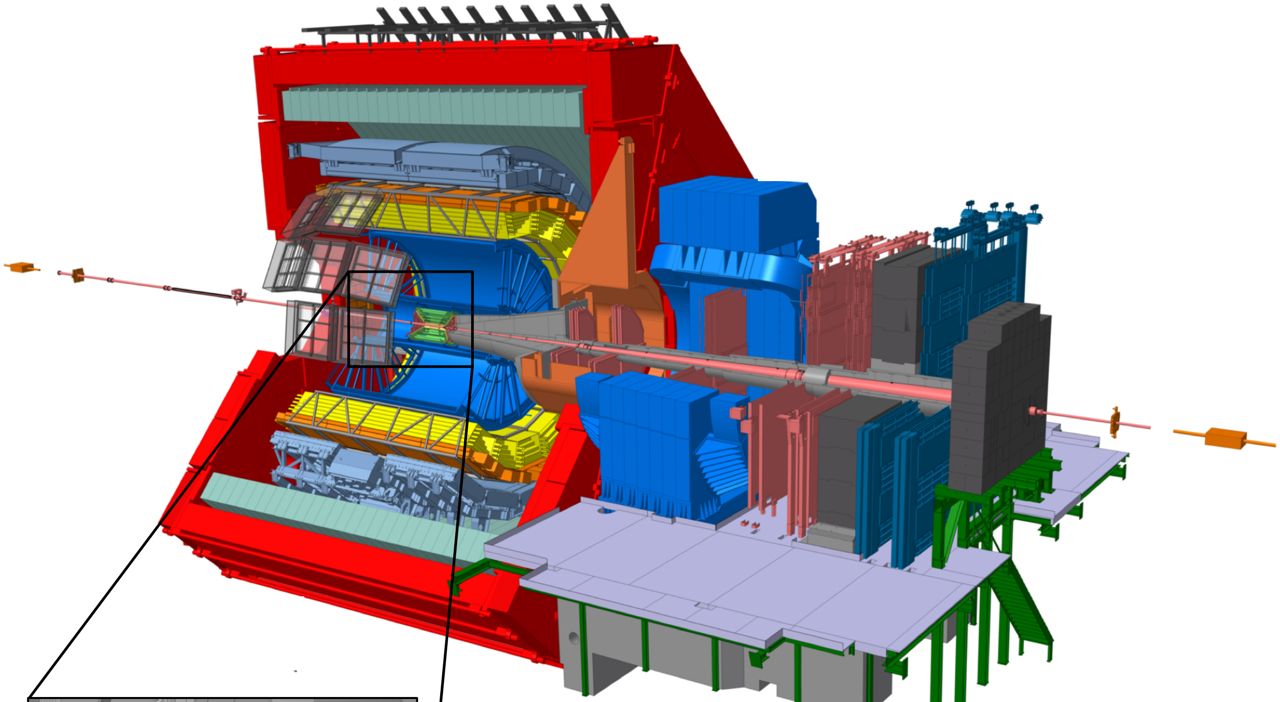
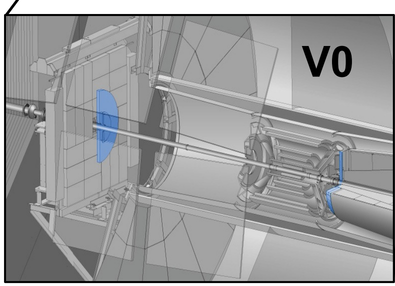
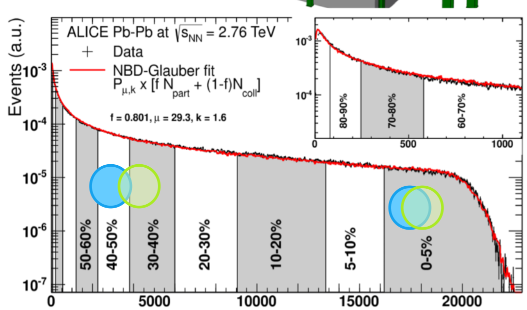




2.8 < η < 5.1 (V0A : Pb-going)
-3.7 < η < -1.7 (V0C : p-going)



PRC 88 (2013) 044909

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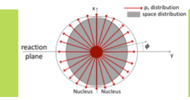
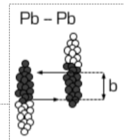
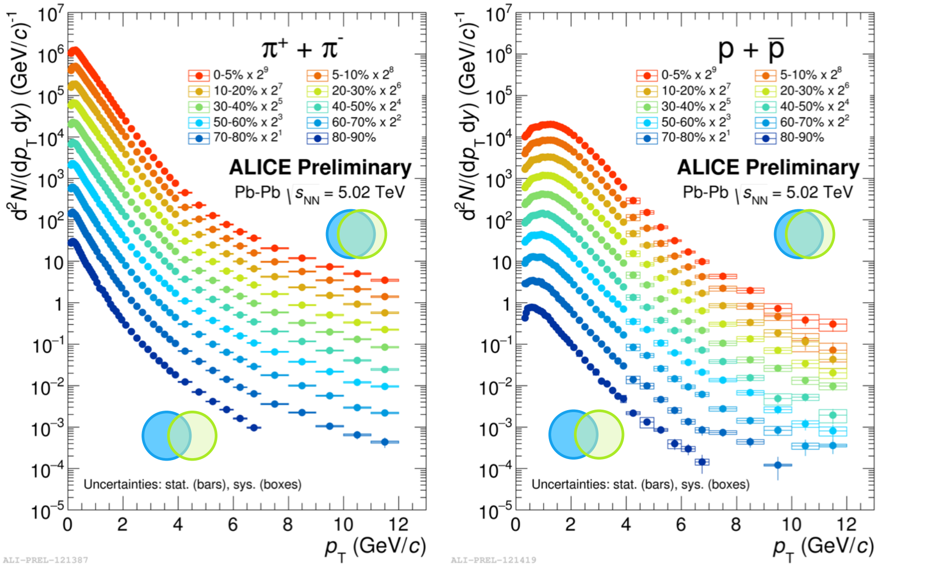
V0
- Triggering
- Event multiplicity determination

Results



Radial flow: hardening of p_T spectra





- Spectra became harder with increasing multiplicity
- Effect more pronounced for heavier particles

Results

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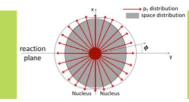

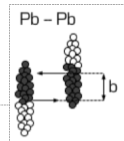

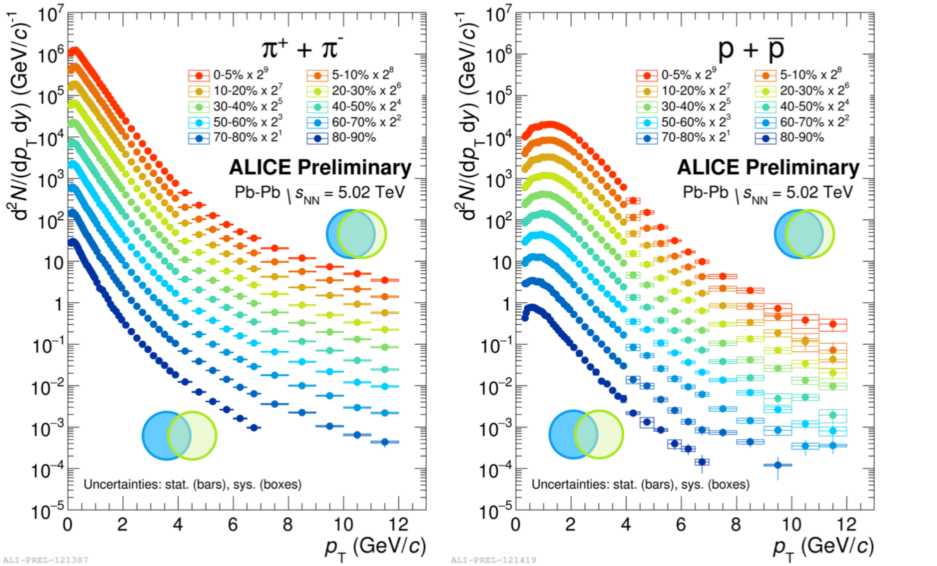

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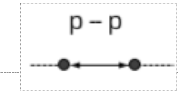

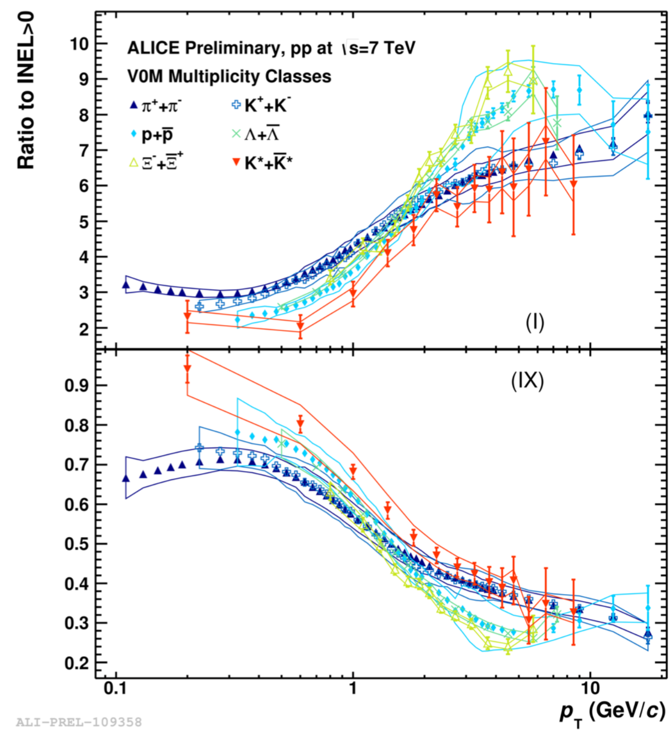

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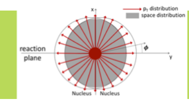


Radial flow: blast-wave fit

Hydro-motivated Blast-wave model

Assumptions: locally thermalized medium, expanding collectively with common velocity field and undergoing an istantaneus common freeze-out

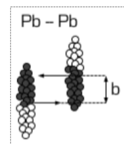
$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T sinh(\rho)}{T_{kin}}\right) K_1\left(\frac{m_T cosh(\rho)}{\beta_T}\right) rdr$$

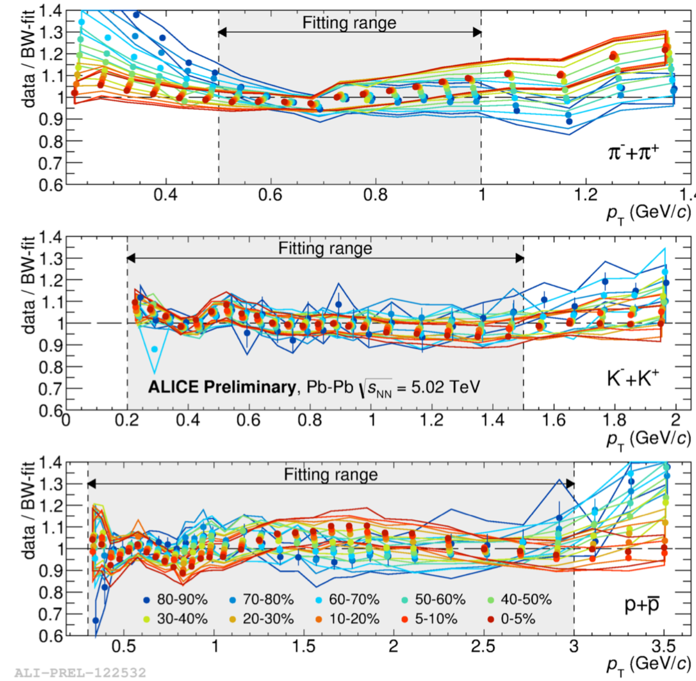
With:

- $m_T = \sqrt{m^2 + {p_T}^2}$, transverse mass
- $\rho = tanh^{-1}(\beta_T)$, boost angle
- $\beta_T(r) = \beta_s \left(\frac{r}{R}\right)^n$, transverse velocity distribution

And:

- $\langle\beta_T\rangle$: radial velocity
- T_{kin} : kinetic freeze-out temperature
- n : exponential of velocity profile

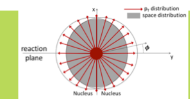


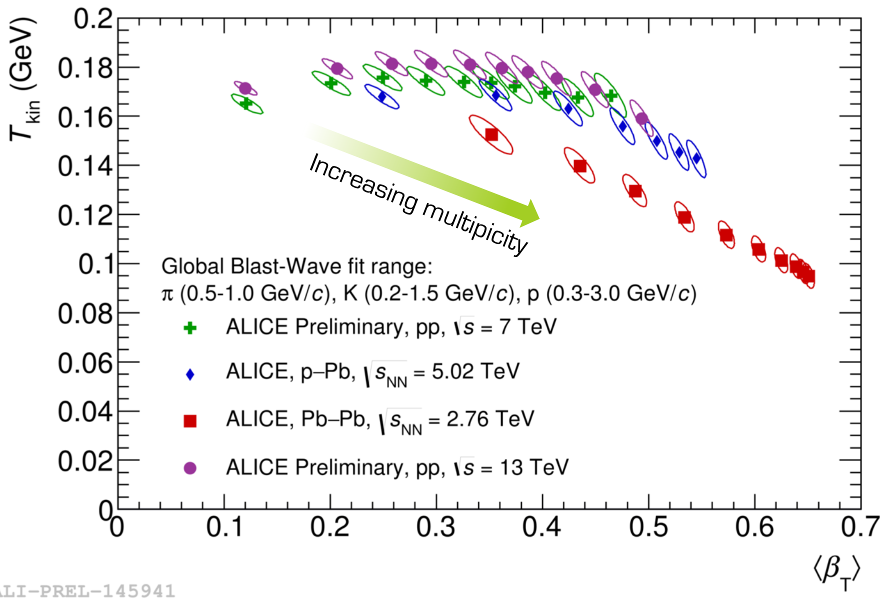


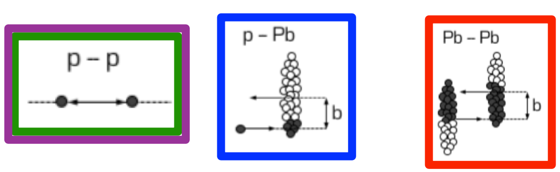
- Simultaneus fit of p_T spectra for many light flavor particles (π, K, p)
- Good description of in central Pb-Pb collisions → **Strong radial flow with common velocity and freezeout temperature**
- Caveat: limited fit ranges

Results

Radial flow: blast-wave fit



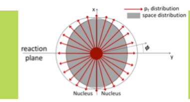




- In **Pb-Pb** collisions
  - Large $\langle\beta_T\rangle$ for central collisions
- Similar exercise done in pp and p-Pb collisions
  - **pp vs p-Pb**: $\langle\beta_T\rangle$ and T_{kin} compatible at mid-low multiplicity
  - **p-Pb vs Pb-Pb**: parameters show similar trend

    → Consistent with presence of radial flow in p-Pb collisions

Results



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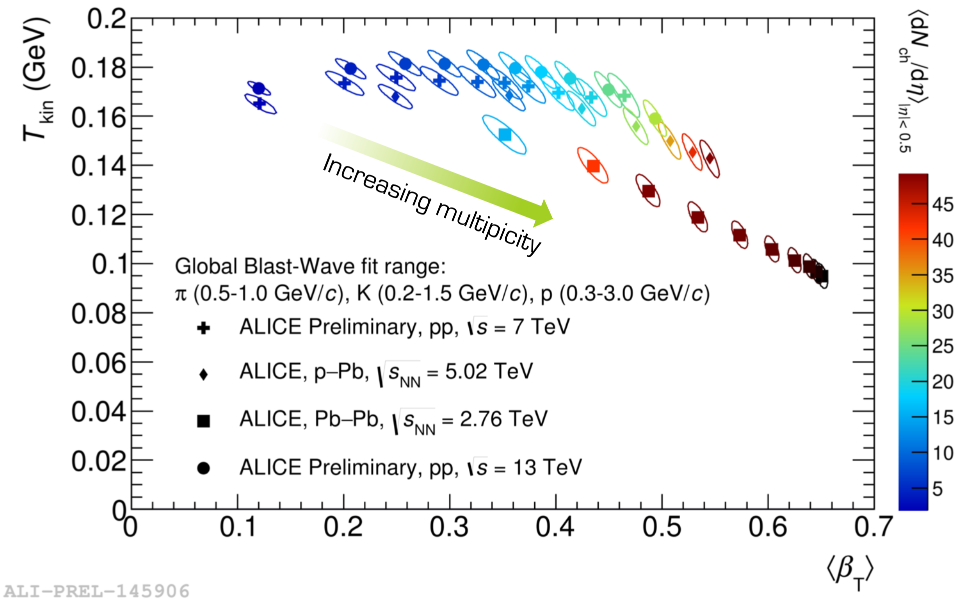

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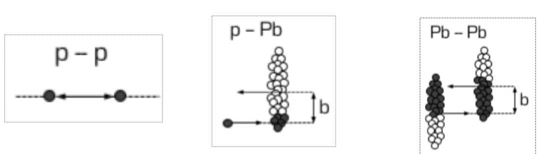

- In **Pb-Pb** collisions
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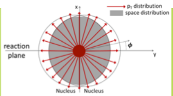
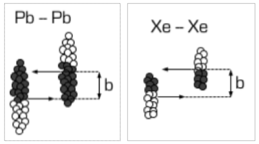
- Similar exercise done in pp and p-Pb collisions
  - **pp vs p-Pb**: $\langle\beta_T\rangle$ and T_{kin} compatible at mid-low multiplicity
  - **p-Pb vs Pb-Pb**: parameters show similar trend
    - → Consistent with presence of radial flow in p-Pb collisions
    - → At similar $\langle dN_{ch}/d\eta\rangle$
      - ○ T_{kin} is similar
      - ○ $\langle\beta_T\rangle$ is significantly higher for p-Pb collisions
- Trend observed in pp reproduced by Pythia8 with color reconnection

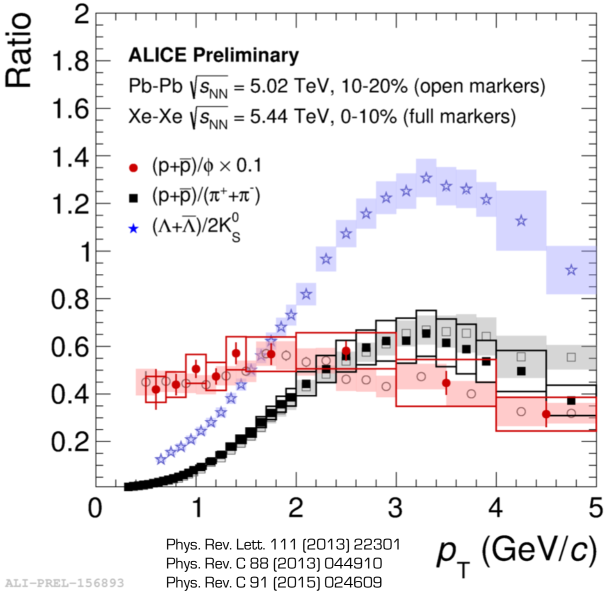
Results

Radial flow: baryon/meson anomaly



- In central Pb–Pb collisions
  - ✓ p/π, Λ/K^0_S enhancement at intermediate p_T





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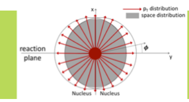

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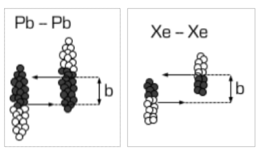

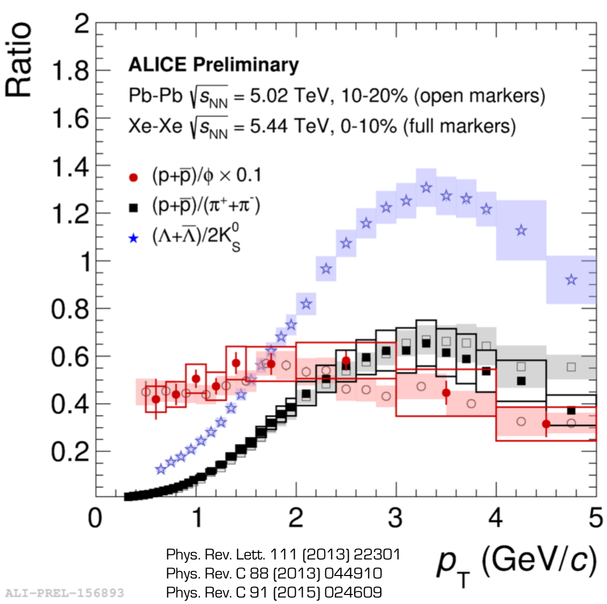

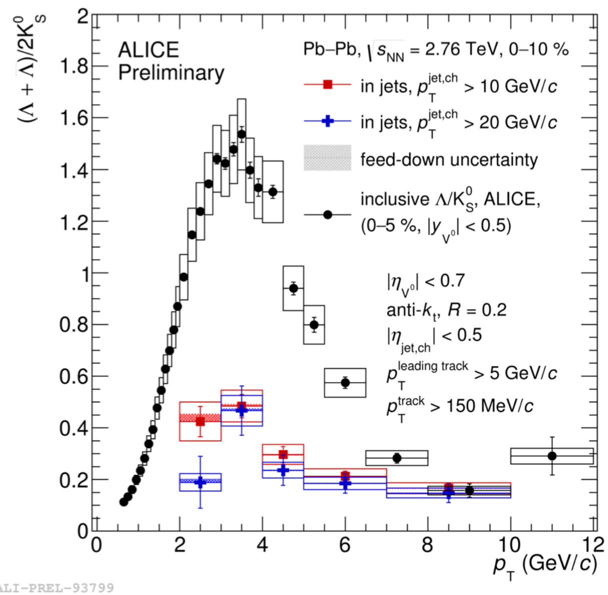

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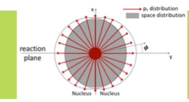

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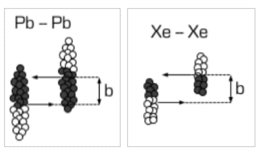
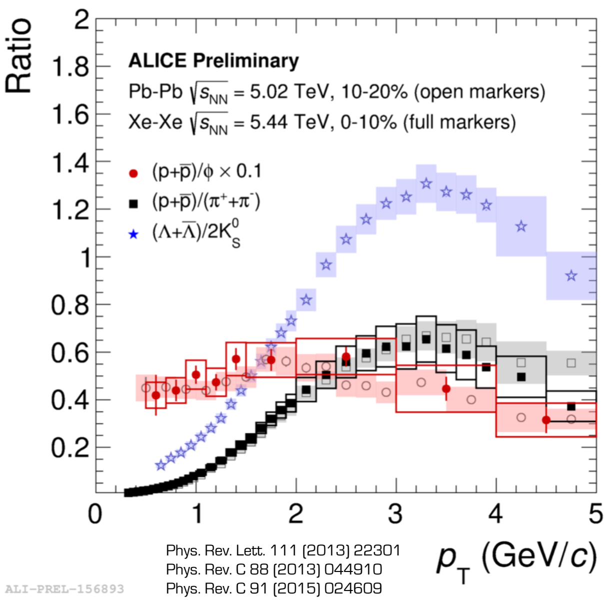
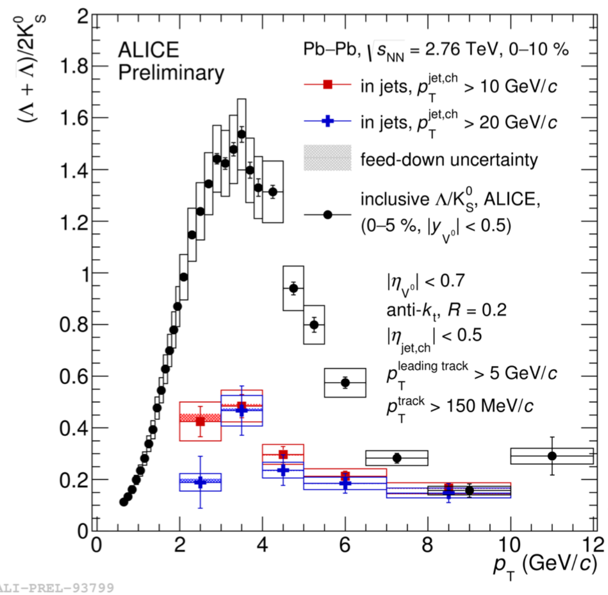
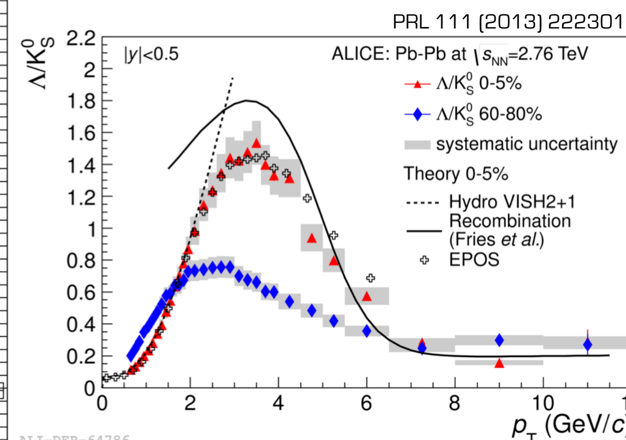
- In central Pb–Pb collisions
  - ✓ p/π, Λ/K^0_S enhancement at intermediate p_T
  - ✓ Effect arising in the bulk and not from the jets
  - ✓ Models → Effect consistent with a flow boost pushing particles from low to high p_T
    - **Hydro** describes only the rise < 2 GeV/c
    - **Recombination** reproduces the effect at intermediate p_T but overestimates towards lower p_T
    - **EPOS** (with flow) gives good description of data









Song, Phys. Lett. B 658 (2008) 279
Fries et al., Ann. Rev. Nucl. Part. Sci. 58 (2008) 177
Werner, Phys. Rev. Lett. 109 (2012) 102301

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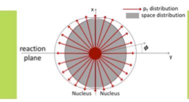

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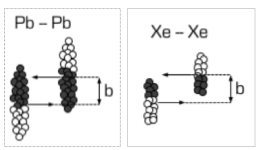
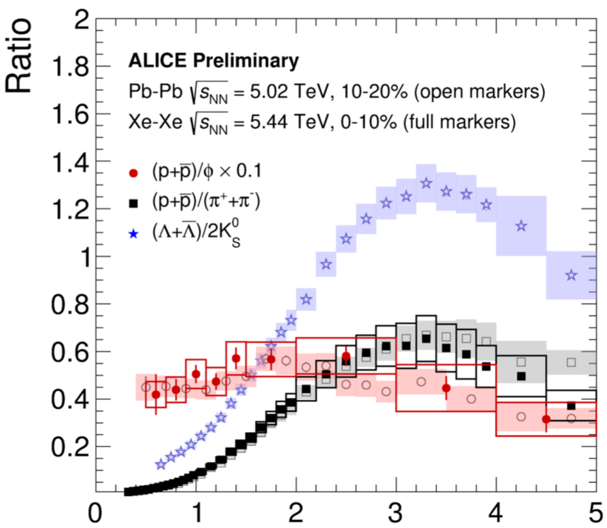
    - **Hydro** describes only the rise < 2 GeV/*c*
    - **Recombination** reproduces the effect at intermediate p_T but overestimates towards lower p_T
    - **EPOS** (with flow) gives good description of data
  - ✓ p/φ independent of p_T → Similar mass drives similar spectral shape
    - Can be also explained by models with recombination (Phys.Rev. C 92 (2015) 054904)





Phys. Rev. Lett. 111 (2013) 22301
Phys. Rev. C 88 (2013) 044910
Phys. Rev. C 91 (2015) 024609

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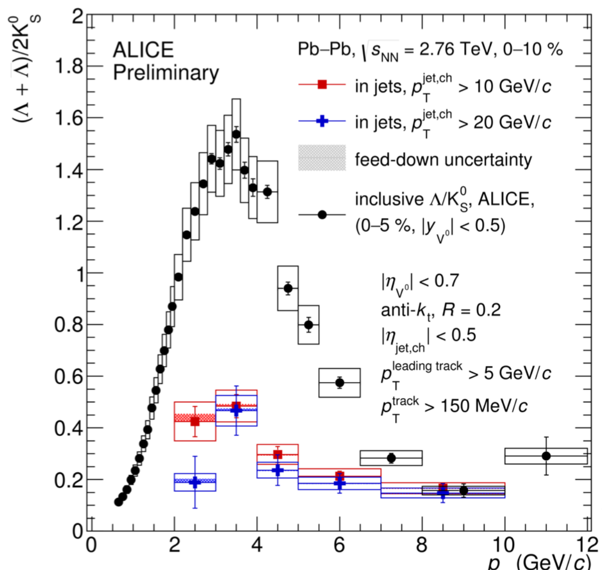

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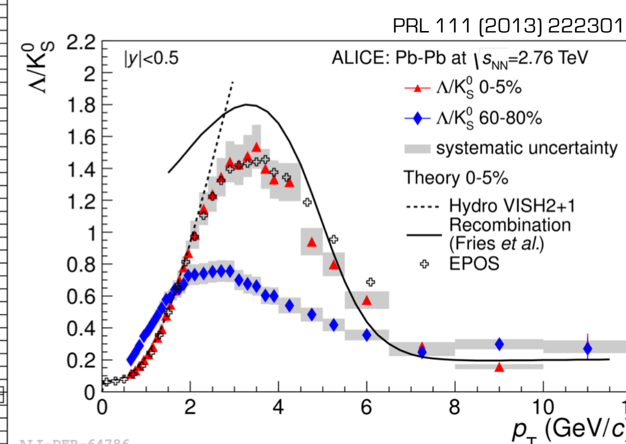

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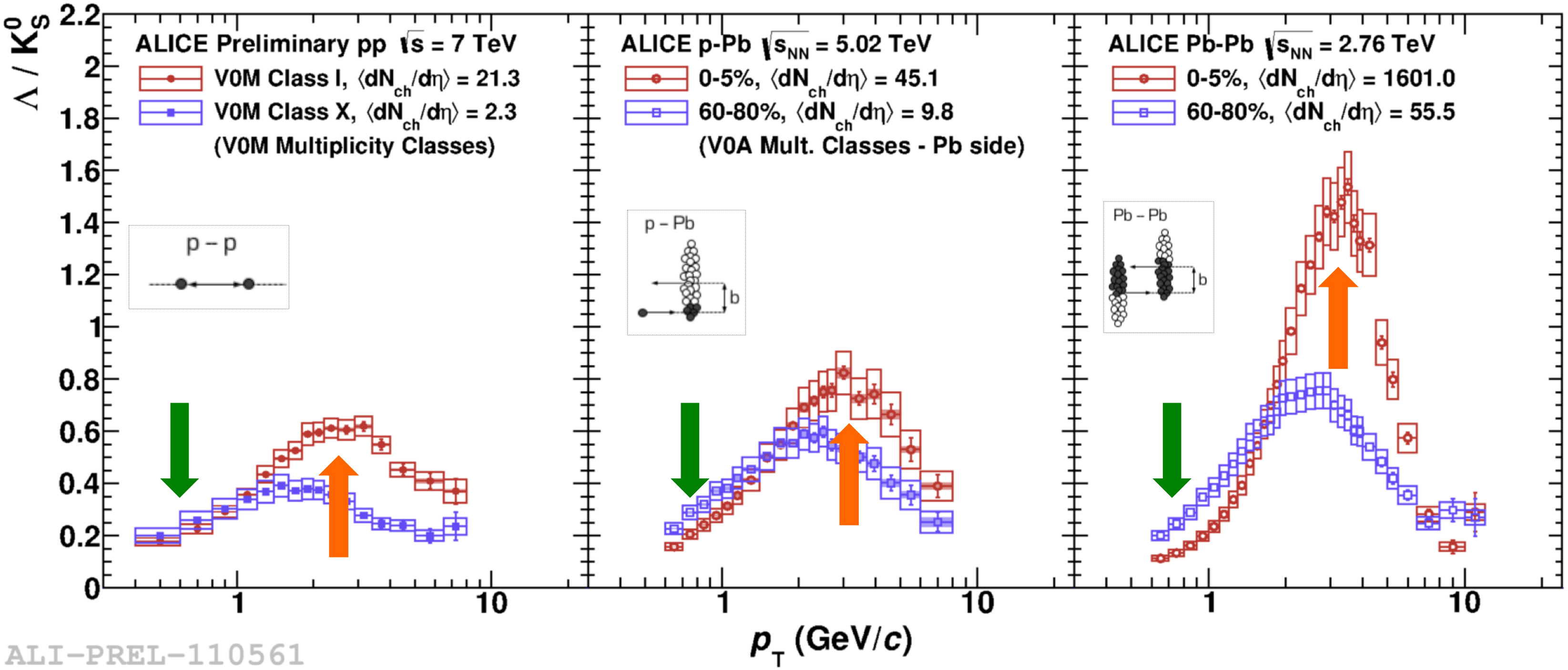
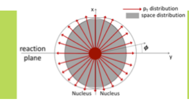
Results

Radial flow: baryon/meson anomaly



- Across the three systems Λ/K^0_S evolves
  - ✓ with multiplicity in qualitatively similar way: **depletion** at low p_T, **enhancement** at intermediate p_T

Results



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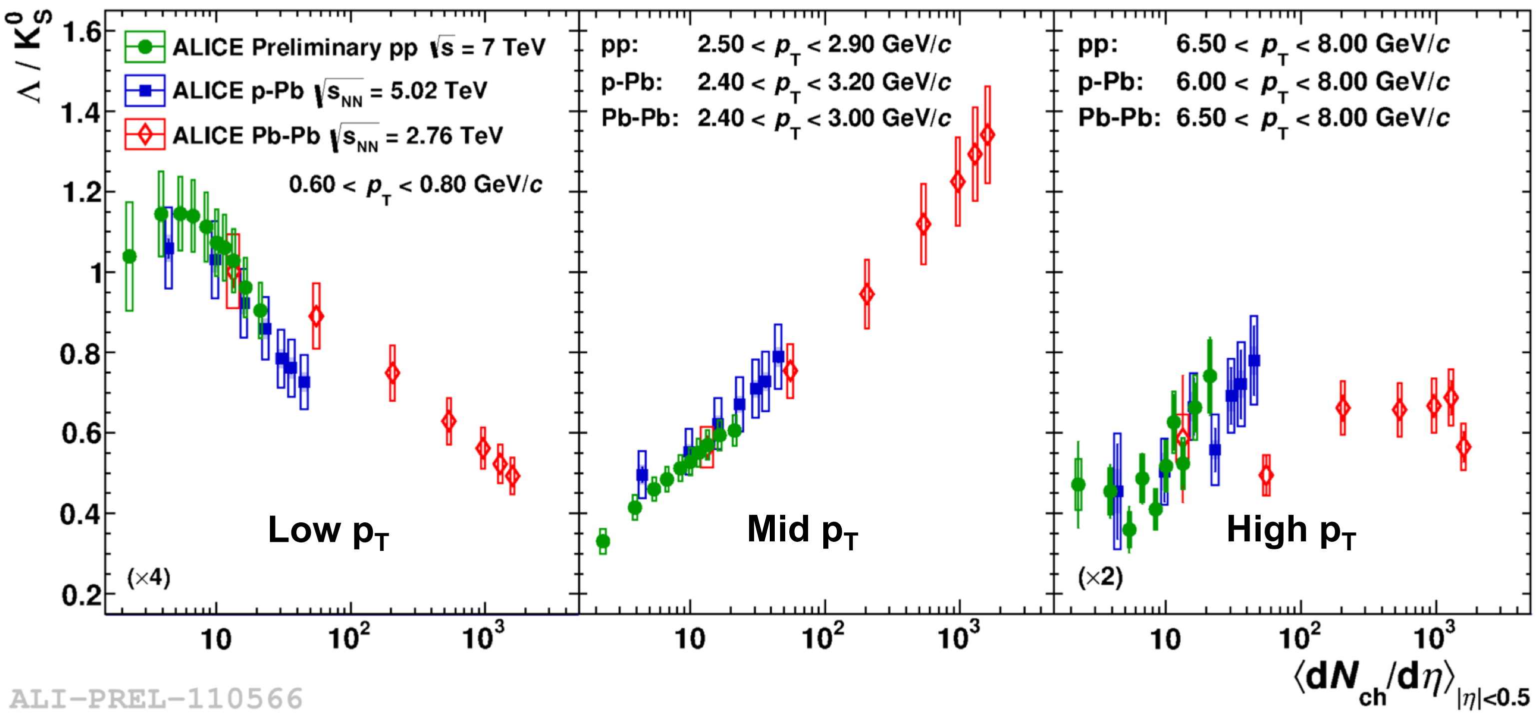
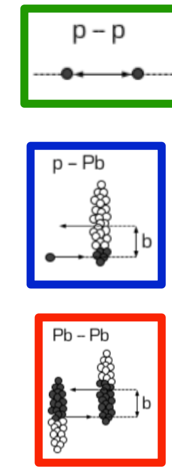
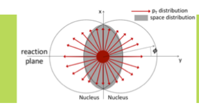




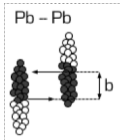
- Across the three systems Λ/K^0_S evolves
  - ✓ with multiplicity in qualitatively similar way: depletion at low p_T, enhancement at intermediate p_T
  - ✓ rather **smoothly for given p_T** intervals

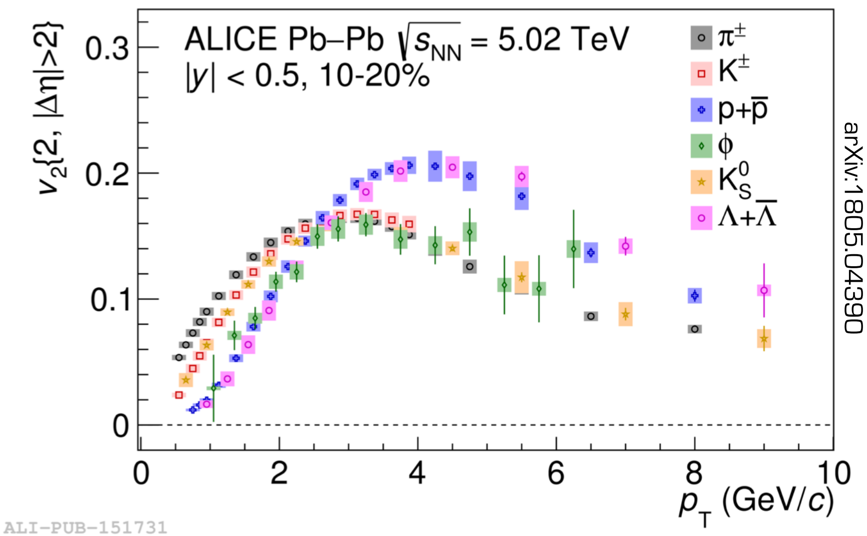
→ Points toward one common driving mechanism in all system

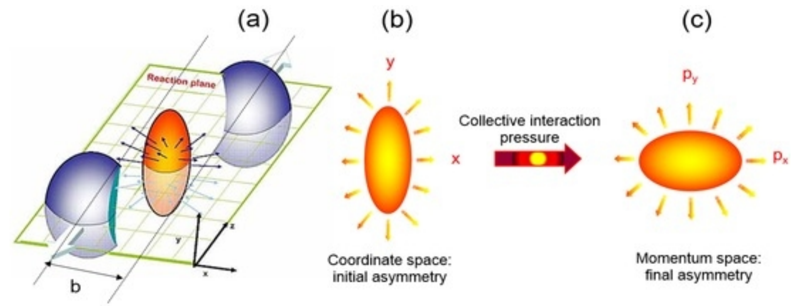
Results



Anisotropic flow: v_2 coefficients (2 particle correlation)





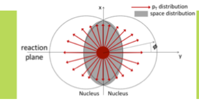


Initial geometry and event-by-event fluctuations cause azimuthal anisotropy with respect to common symmetry plane

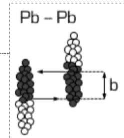
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n cos[n(\varphi - \Psi_n)]\right]$$

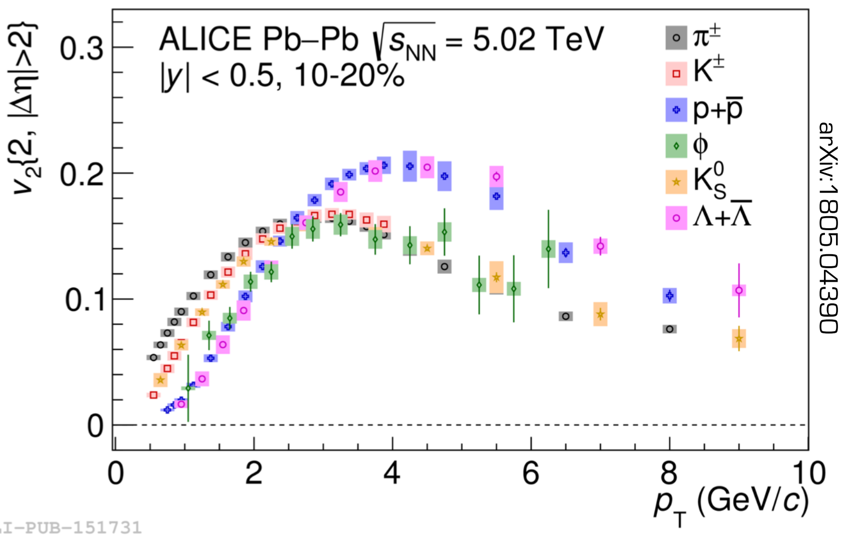
- In Pb-Pb collisions
  - → **Mass ordering** (hydrodynamic flow, hadron re-scattering)
  - → **Baryon/meson grouping** (recombination/coalescence)

Results



Anisotropic flow: v_2 coefficients (2 particle correlation)





- In Pb-Pb collisions
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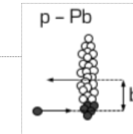
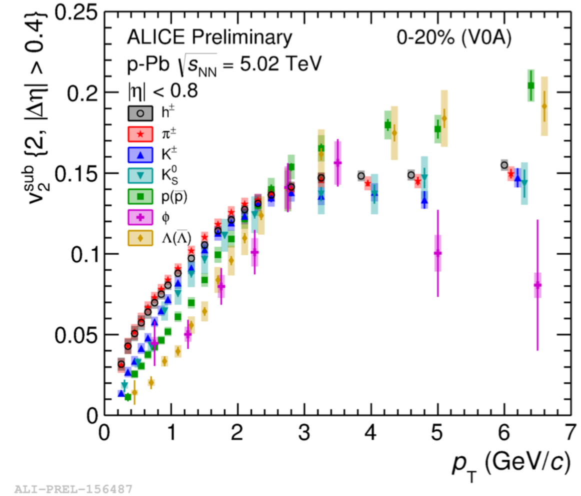
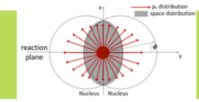


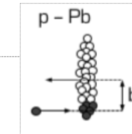


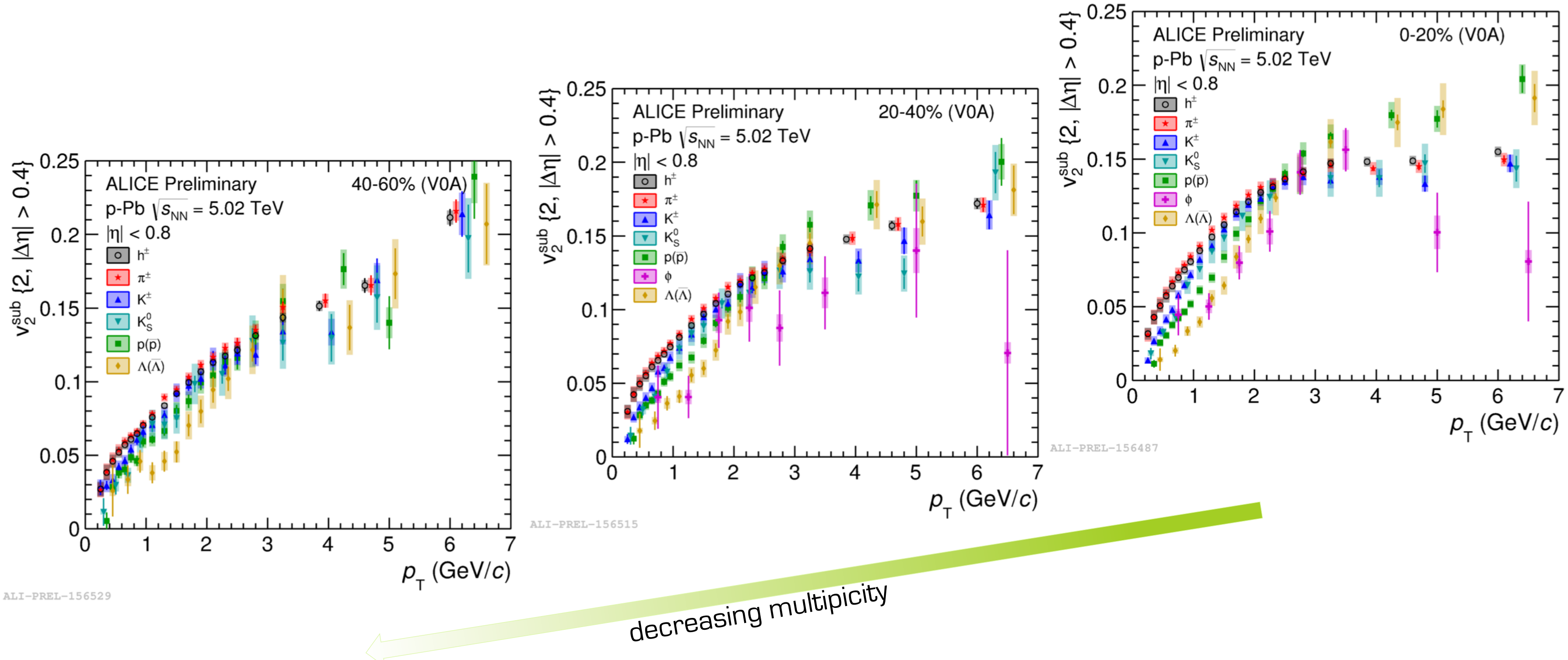
- Non-flow subtracted $v_2(p_T)$
- Similar features as Pb-Pb measurements
  - → Clear mass ordering (low p_T region)
    - Qualitatively predicted by hydro
  - → Indication of baryon/meson grouping (intermediate p_T)

Results

Anisotropic flow: v_2 coefficients (2 particle correlation)

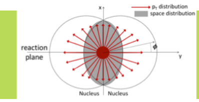




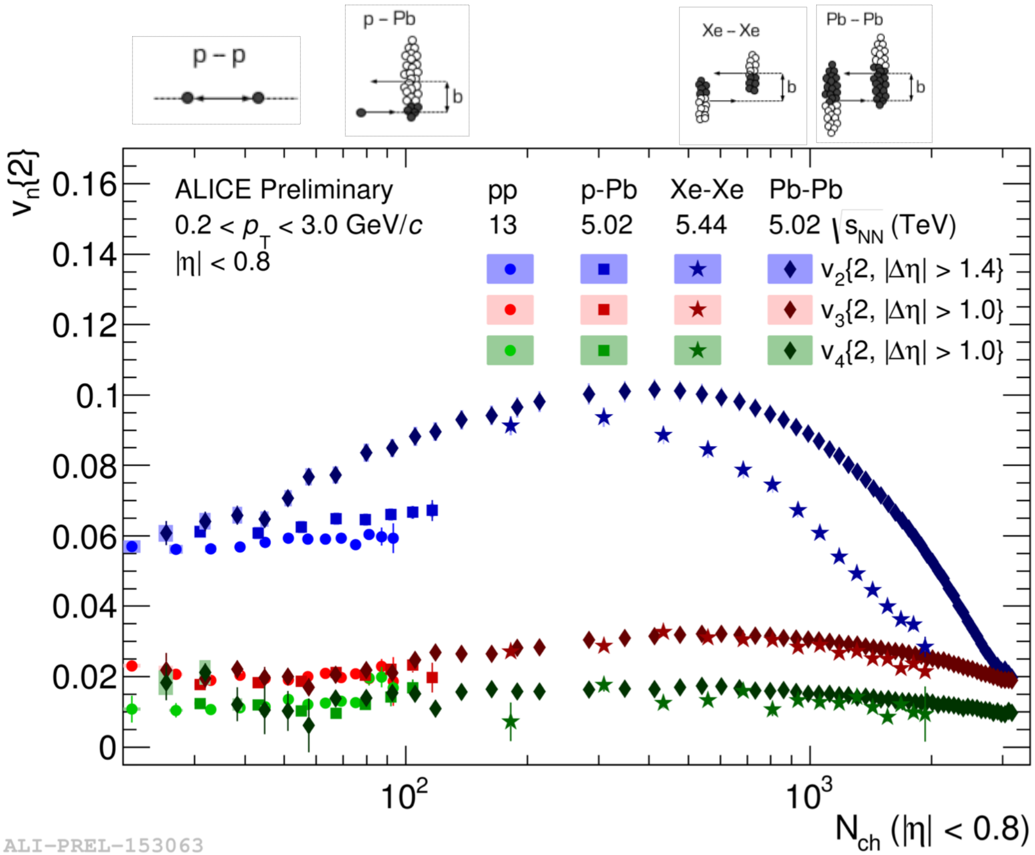


- Mass ordering and baryon/meson grouping persists but slowly vanishes towards low multiplicity events

Results



Anisotropic flow: v_n coefficients (2 particle correlation)

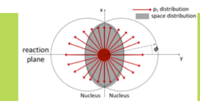


$v_n\{2\}$

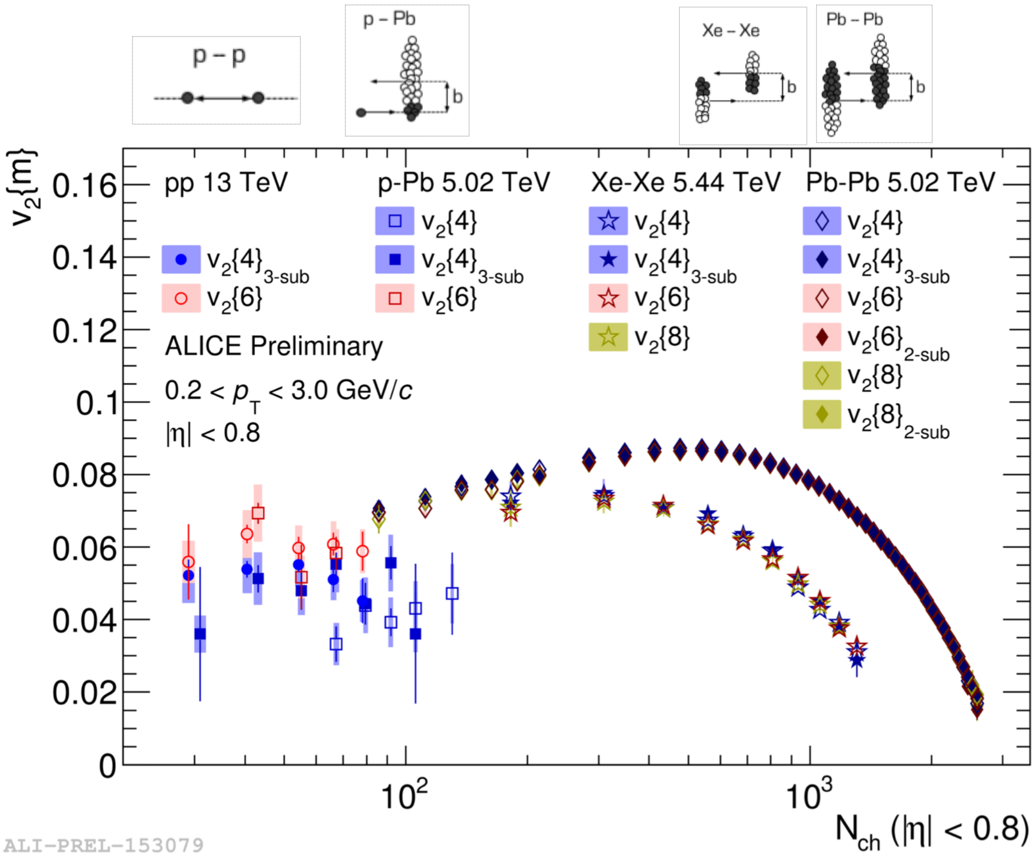
- Heavy-ion collisions
  - Clear multiplicity depencence (consequence of collision geometry)
  - Ordering $v_2 > v_3 > v_4$
- Small systems
  - Comparable values with Pb-Pb at low N_{ch}
  - Weak multiplicity dependence
  - Ordering $v_2 > v_3 > v_4$
  - → Cannot be explained solely by non-flow

Collectivity can be better probed with multi-particle cumulants

Results



Anisotropic flow: v_n coefficients (multi-particles correlation)



$v_2\{m\}$ (m>2)

- Heavy-ion collisions
  - Long-range: signal doesn't change with subevent method

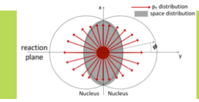
    $v_2\{4\} \sim v_2\{4\}_{3\text{-sub}}$, $v_2\{6\} \sim v_2\{6\}_{2\text{-sub}}$, $v_2\{8\} \sim v_2\{8\}_{2\text{-sub}}$
  - Multi-particle: $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$
- Small systems
  - Real $v_2\{4\}_{3\text{-sub}}$ (extracted for first time in pp collisions with ALICE)
  - $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\}$ (agreement can be improved using subevent method in $v_2\{6\}$)

<u>**Origin of collectivity in small collision systems**</u>

- **2-particle correlations**: described by final state models
- **Multi-particle correlations**: not described quantitatively by any model so far

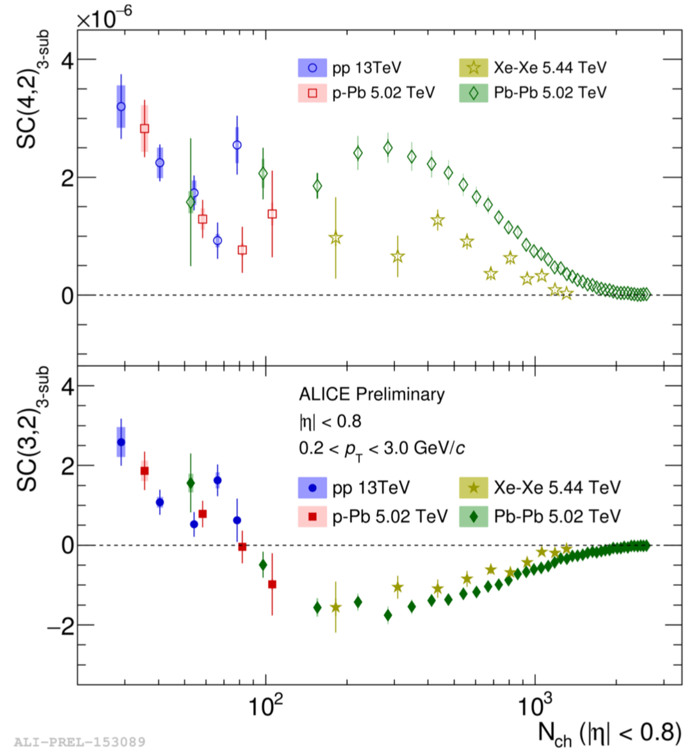
→ **v_n(m) measurements alone cannot distinguish between initial and final state approaches**

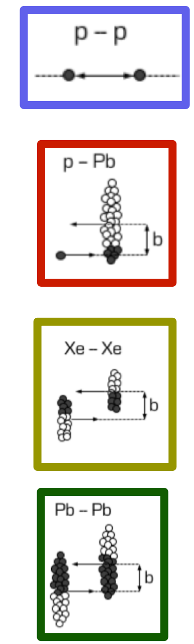
Results



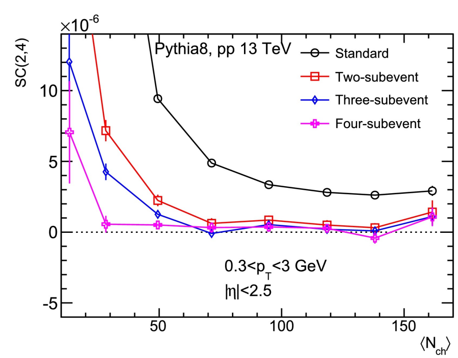
Anisotropic flow: Symmetric Cumulants

- Constraining initial condition in small systems is crucial to improve the undestanding: Symmetric Cumulants
  - → sensitive to initial conditions
  - → clear suppression of non-flow effects

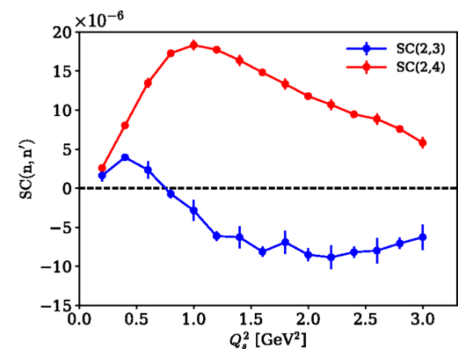




- **Positive correlation between v_2 and v_4** in all collision systems
- **Anti-correlation between v_2 and v_3** at large multiplicities (link to initial eccentricity correlations) → **Transition** to positive correlation in small and large systems
- Not described by non-flow only models, but qualitatively predicted by model with initial state correlations



PLB 777 (2018) 201



PRL 120, 042002 (2018)

Summary

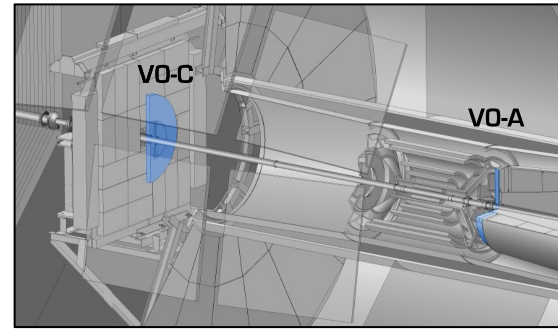
- Many observables do show a smooth transaction from heavy-ion to small systems as a funtion of event particle multiplicity
- Clear evidence of collective behaviour observed in small systems
- At the moment, the origin of collectivity in small systems is not clear
  - Symmetric Cumulants provide tight constrains to theoretical calculations

Backup

Backup

Centrality/Multiplicity determination

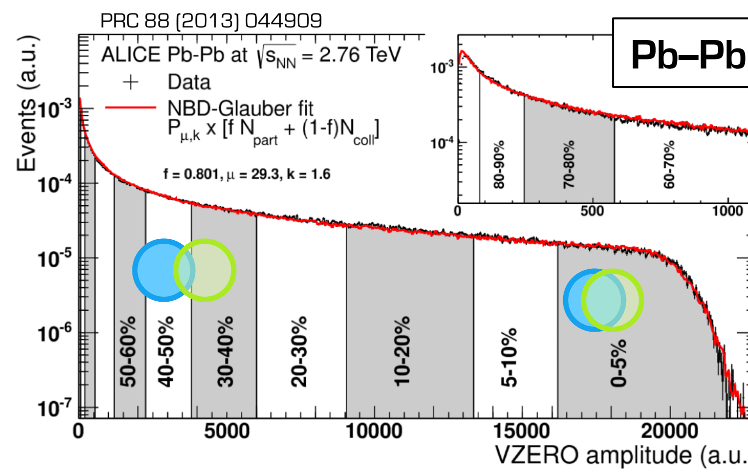
- The centrality/multiplicity classes requires the following steps:
  1. the V0 amplitude distribution is fitted with Glauber MC
  2. absolute scale is defined, through the definition of anchor point, as the amplitude of the V0 equivalent to 90% of hadronic cross-section
  3. data are divided into several percentiles selecting on signal amplitude measured in the V0



The V0 detector is composed of a pair of forward scintillator hodoscopes placed at $2.8 < \eta < 5.1$ (V0-A) and $-3.7 < \eta < -1.7$ (V0-C)

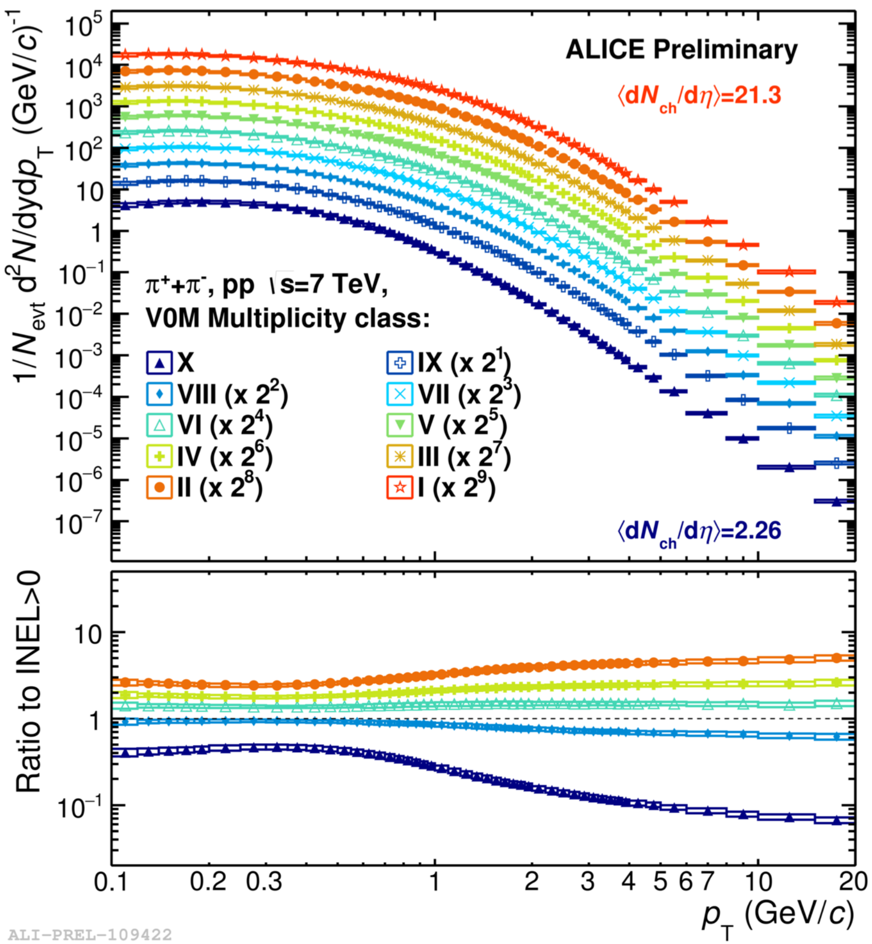
- V0 amplitude distribution
  - **Pb–Pb and pp:** sum of amplitudes in the two V0 scintillators, V0-A&V0-C ("V0M")
  - **p–Pb:** amplitude by V0-A (placed on the outgoing Pb side)
- $\langle dN_{ch}/d\eta \rangle$ is measured in $|\eta| < 0.5$ to avoid "auto-biases" in multiplicity determination

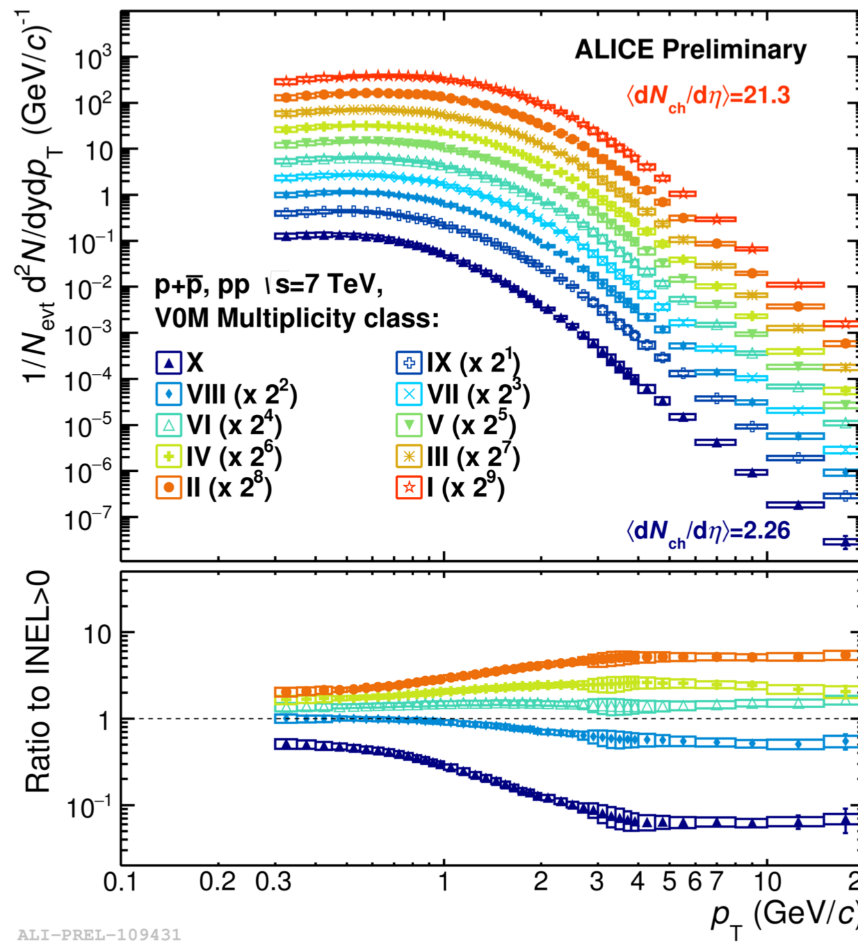
$\langle dN_{ch}/d\eta \rangle$			
Centrality/Multiplicity class (Pb–Pb/p–Pb/pp)	Colliding system		
	Pb–Pb ($\sqrt{s_{NN}}$ = 2.76 TeV)	p–Pb ($\sqrt{s_{NN}}$ = 5.02 TeV)	pp ($\sqrt{s}$ = 7 TeV)
0-5%/0-5%/0-0.95%	1601±60	45±1	21.3±0.6
70-80%/60-80%/48-68%	35±2	9.8±0.2	3.90±0.14



Backup

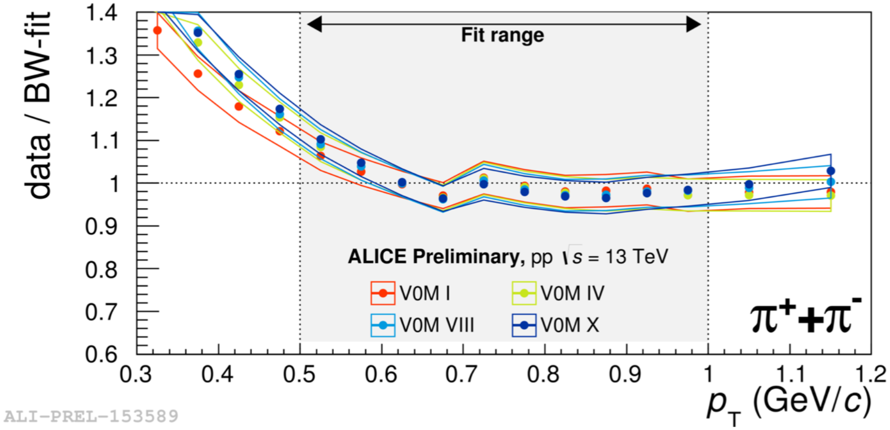
p_T spectra in pp collisions vs multiplicity

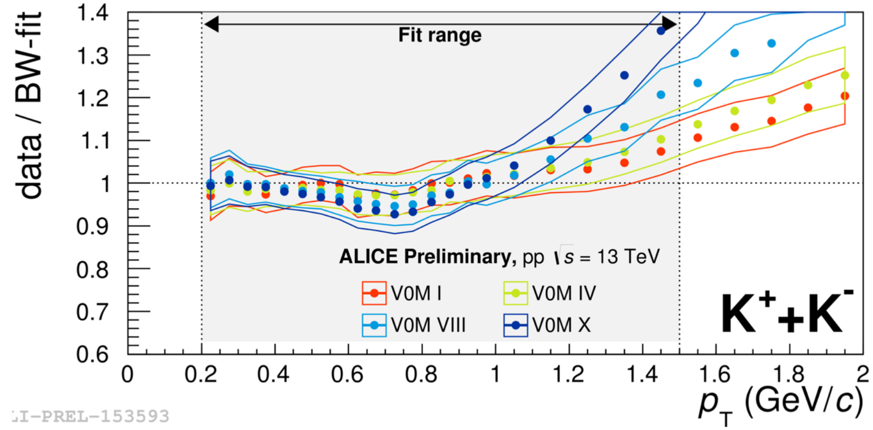


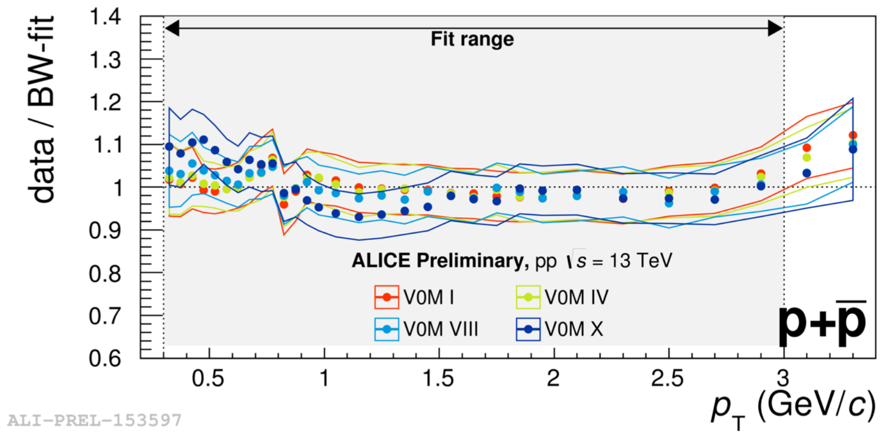


Backup

Blast-wave fit in pp collisions vs multiplicity



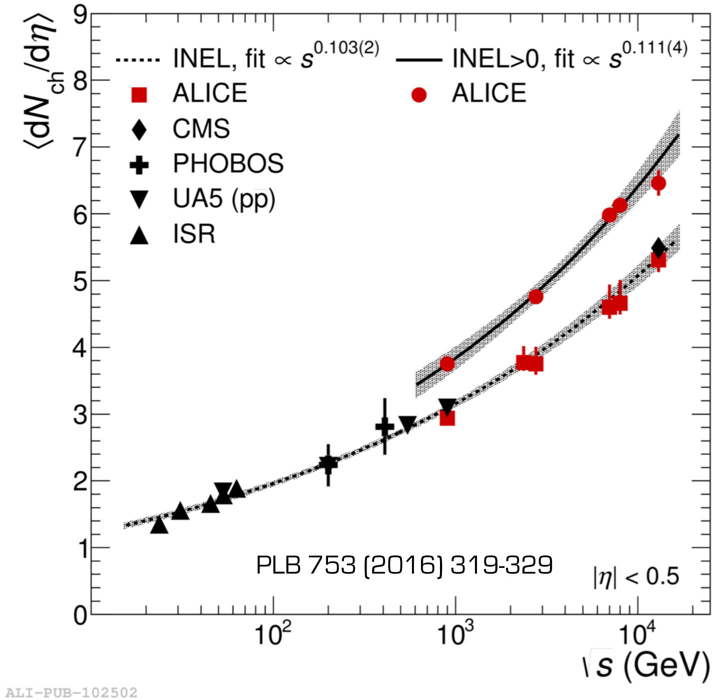




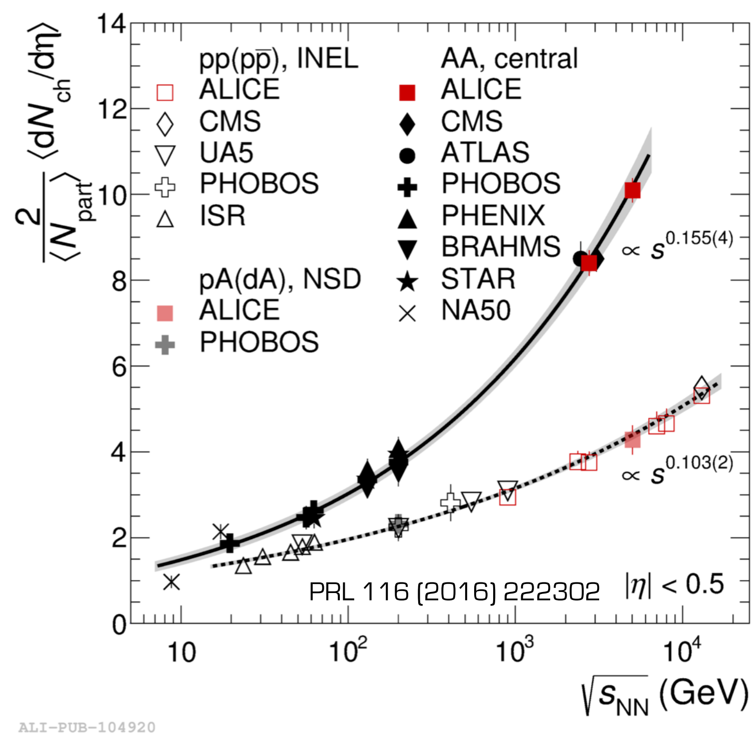
Backup

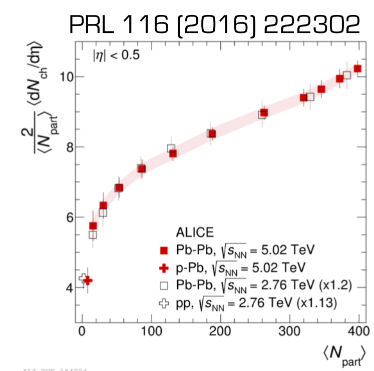
Charged particle production vs energy

In **pp at 13 TeV** $\langle dN_{ch}/d\eta \rangle$ increases with $\sqrt{s}$ following a power law, along the trend from lower center of mass energies
→ About **20% increase** from 7 to 13 TeV



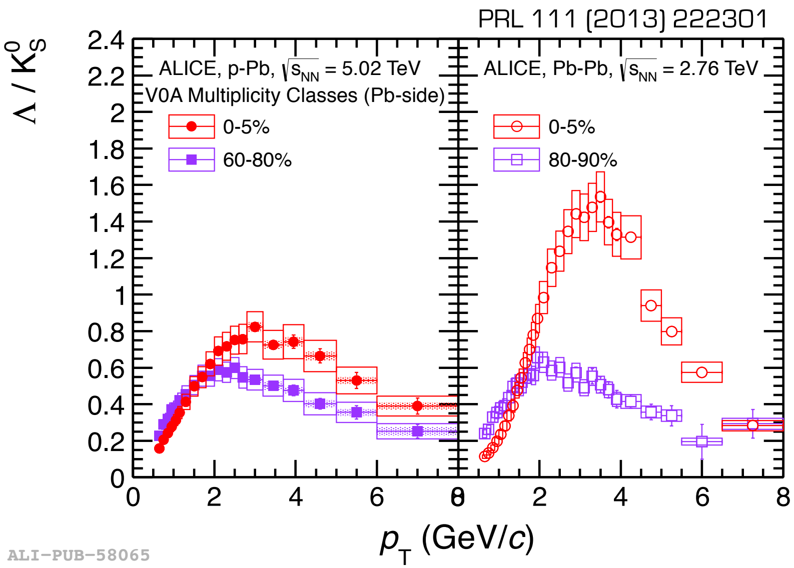
In **Pb-Pb at 5.02 TeV** $\langle dN_{ch}/d\eta \rangle / \langle N_{part} \rangle$ increases with $\sqrt{s}$ following a steeper power law than pp collisions
→ About **20% increase in 0-5% from 2.76 TeV to 5.02 TeV** (similar $\langle N_{part} \rangle$)





Backup

Baryon-to-meson ratio – Quantitative comparison

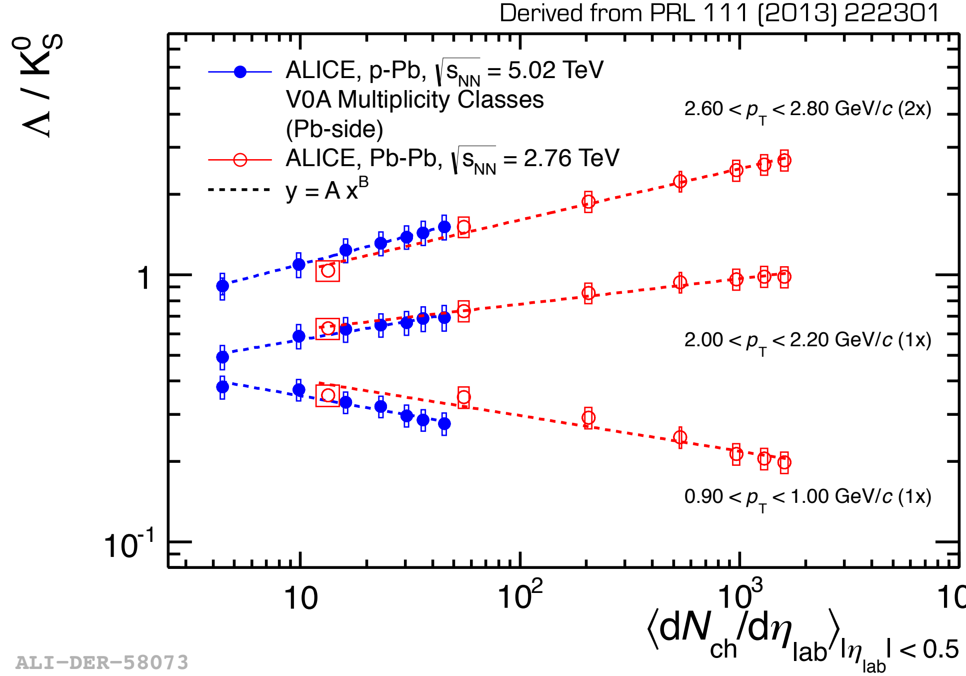


Λ/K^0_S ratio vs multiplicity

For a higher $\langle dN_{ch}/d\eta \rangle$, we see:

- Increase at mid- to high p_T
- Corresponding depletion at low p_T

Qualitatively same behavior as Pb–Pb



Quantitative comparison

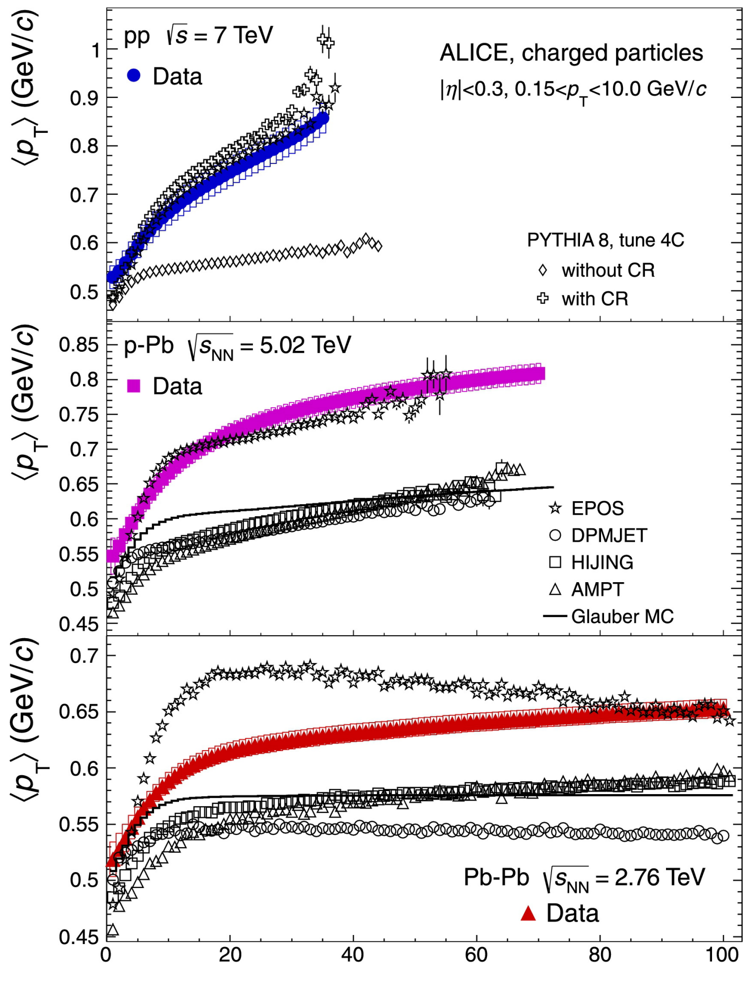
Fitting the ratio of the p_T integrated yields with a power law:

$$\Lambda/K^0_S = A \times \langle dN_{ch}/d\eta \rangle^B$$

Values for B parameter as a function of p_T compatible between Pb—Pb and p—Pb collisions

Results

Mean p_T vs multiplicity



PLB 727 (2013) 371-380

pp: high multiplicity through multiple parton interactions
incoherent production → same <p_T>
Color reconnection: strings from independent parton interactions do not independently produce hadrons, but fuse before hadronization → fewer but more energetic hadrons

p-Pb: features of both pp and Pb-Pb systems
Less saturation than in Pb-Pb → Higher <p_T>

Pb-Pb: high mu;tiplicity from superimposition of parton interactions, collective flow → moderate increase of <p_T>

Results

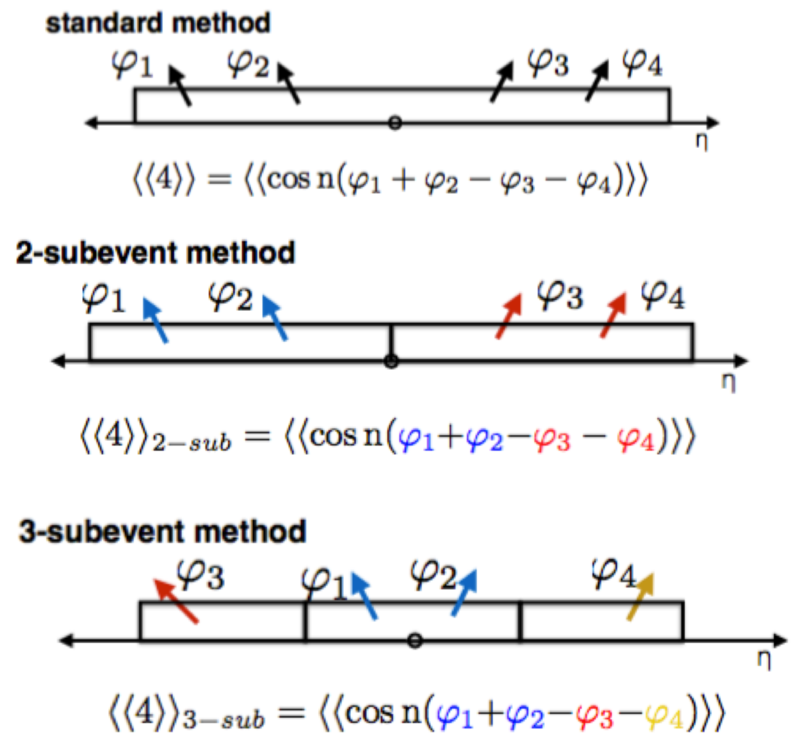
Anisotropic flow: subevent method

Non-flow: few particle correations not associated to the common symmetry plane

- Correlations between particles in jets, or from resonannce decays, etc.

Subevent method [J. Jia, M. Zhou, A. Trzupek, PRC 96 (2017) 034906]

- Enforces a space separation between particles that are being correlated
- Extended to multi-particle cumulants

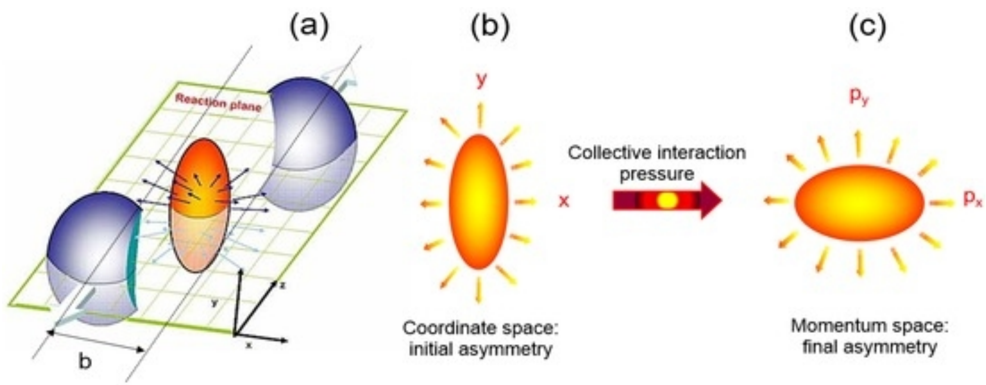


Subevent method further suppresses non-flow in multi-particle cumulants in pp collisions

Non-flow can be largely suppressed also in p-Pb collisions

Results

Anisotropic flow: v_2 coefficients (2 particle correlation)



Anisotropic flow harmonic coefficient obtained from Fourier expansion of azimuthal particle distributions in the final state relative to the symmetry plane

Initial geometry and event-by-event fluctuations cause azimuthal anisotropy with respect to common symmetry plane

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n cos[n(\varphi - \Psi_n)]\right]$$