Exploring QGP Signature in Small System: Insights from ALICE in Pb-Pb and pp Collisions

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ALICE

INFN BARI
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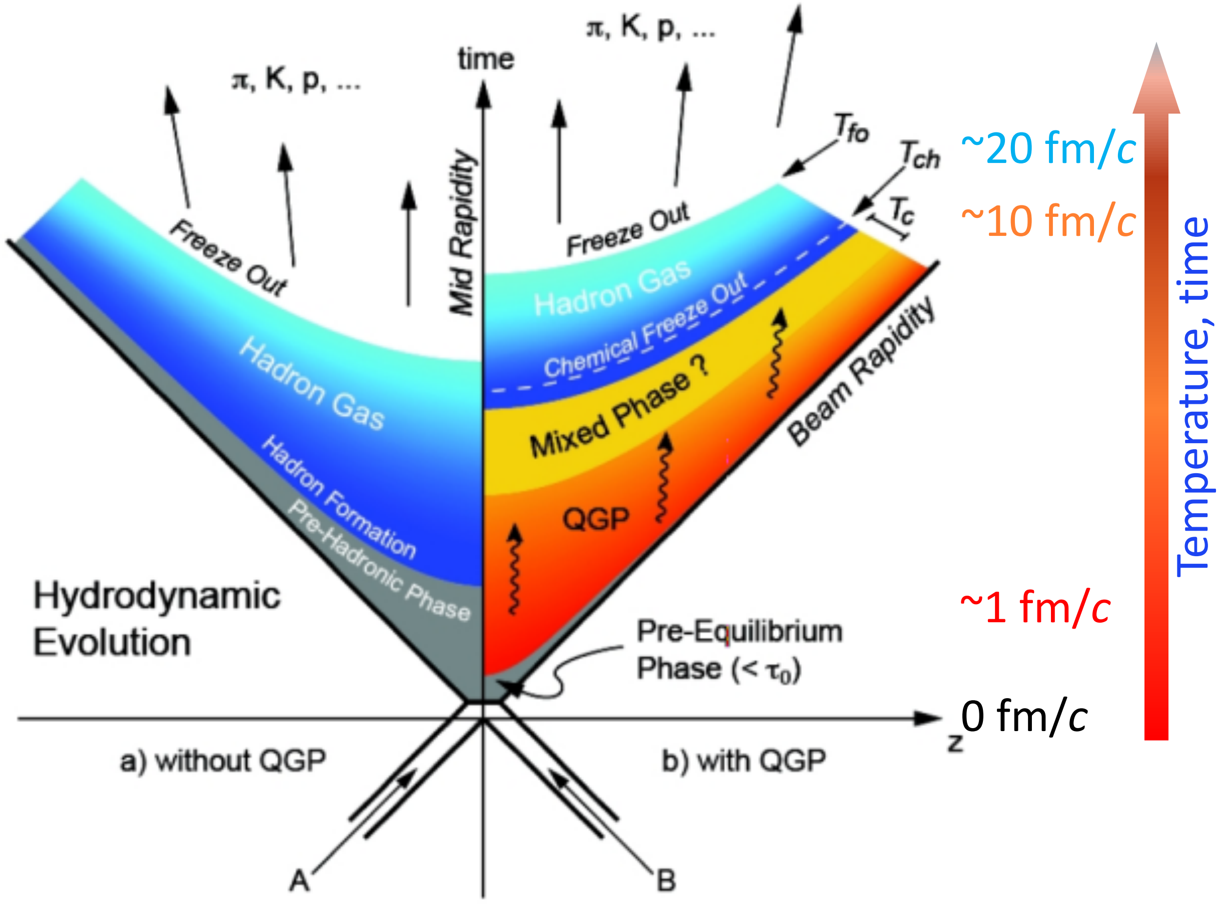
QCD@Work
International Workshop on QCD
Theory and Experiment
Jun 18 – 21, 2024, Trani - Italy

Formation of QGP: Time evolution dynamics

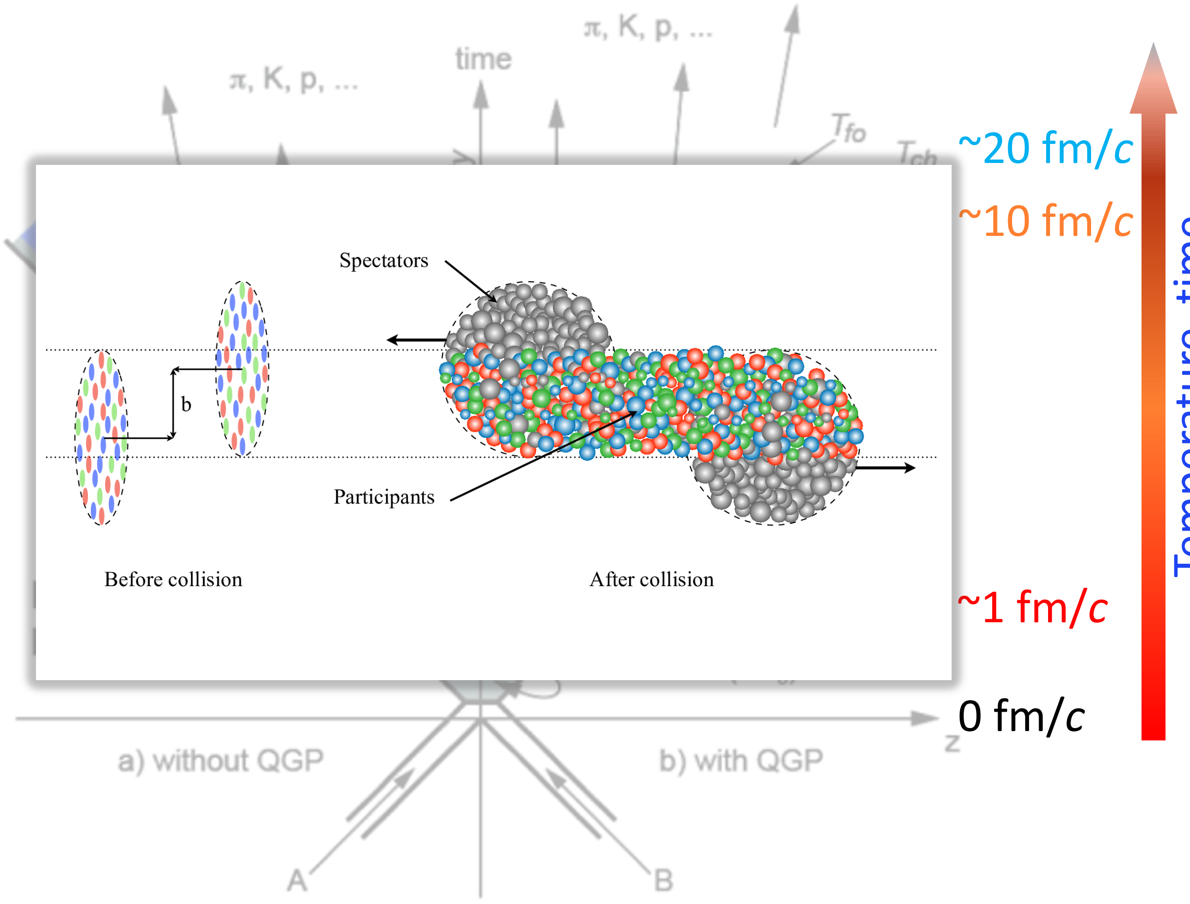
Quark-gluon plasma (QGP): A hot and dense medium of deconfined partons



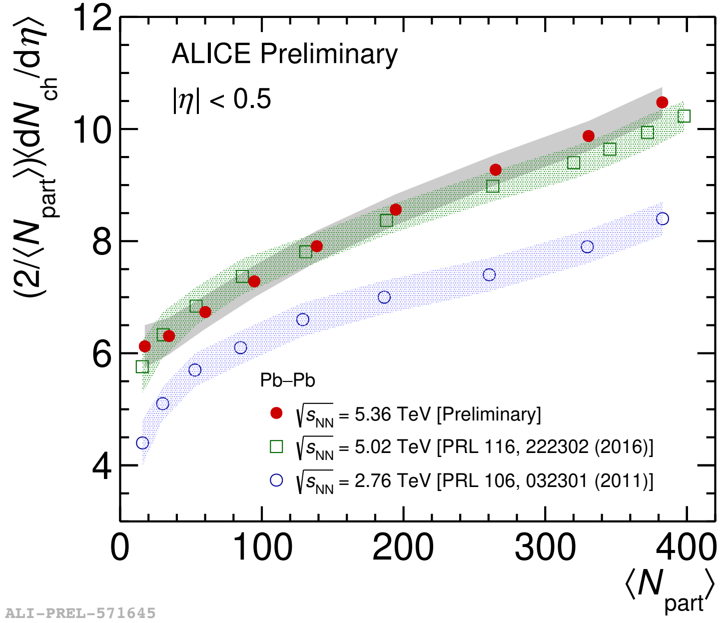
- **Initial state:**
  → collision of two Lorentz-contracted nuclei
- **QGP formation:**
  fast thermalization, $\tau \approx 1$ fm/c
  → deconfined medium expanding hydrodynamically
- **Phase transition (cross-over) to hadron gas**
  (T_c = 156.5 +/- 1.5 MeV, Nucl. Phys. A 982 (2019) 847)
  → Color confinement: **hadronization**
- **Chemical freeze-out** ($T_{ch} \approx 153$ MeV)
  → inelastic collisions stop: particle abundances fixed
- **Kinetic freeze-out** ($T_{fo} \approx 100$ MeV)
  → elastic collisions stop: particle spectra fixed
- Particles fly towards detectors

Formation of QGP: System size dependent

Quark-gluon plasma (QGP): A hot and dense medium of deconfined partons



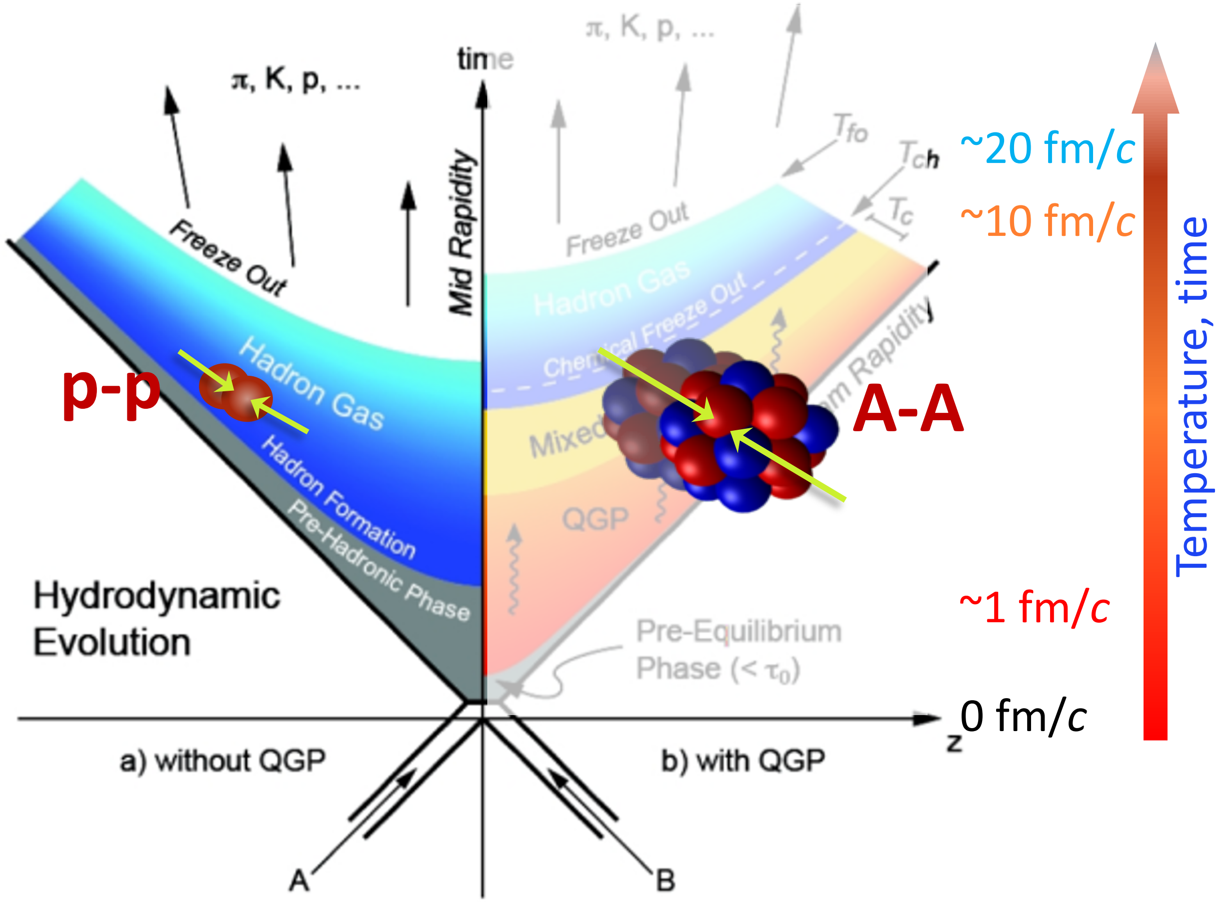
- Higher charged multiplicity, N_{ch} corresponding to increases of the participant nucleon N_{part}, as observed in Pb-Pb system



- Production of QGP in AA systems is found proportional to N_{ch}, hence, N_{part}
- Whereas in **pp system $N_{part} = 2$, in minimum bias no QGP expected** and used for reference for physics of AA system

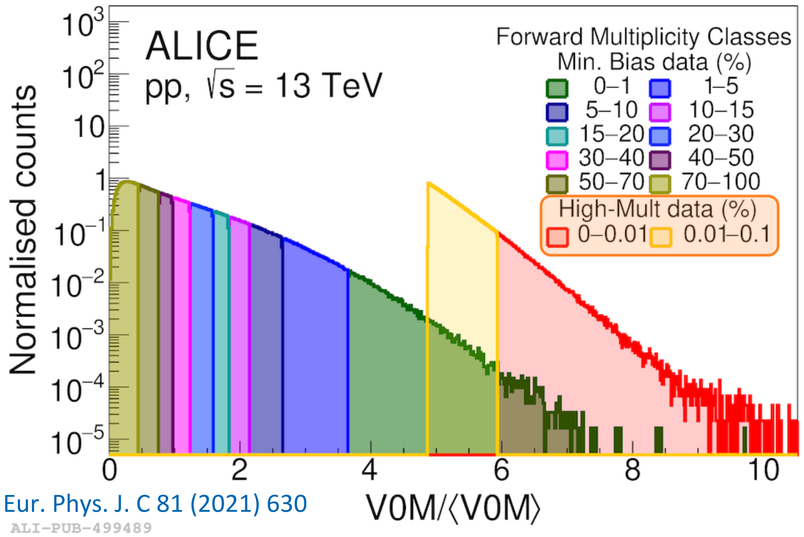
Formation of QGP: In different systems

Quark-gluon plasma (QGP): A hot and dense medium of deconfined partons



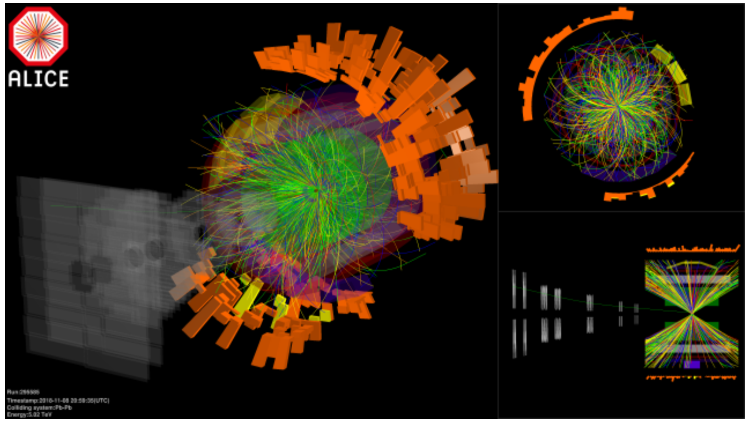
- Multiplicity N_{ch} **can vary a lot in pp collisions**. Sometimes comparable with peripheral AA, where QGP is produced.
- Hardening of p_T spectra, strangeness enhancement, baryon/meson ratio, anisotropic flow and correlation effects are also found in pp collisions if multiplicity dependence is studied.
- Can N_{ch} indexing the onset QGP in small system?

👉 In ALICE, a detailed studies to search of QGP in pp system



Eur. Phys. J. C 81 (2021) 630

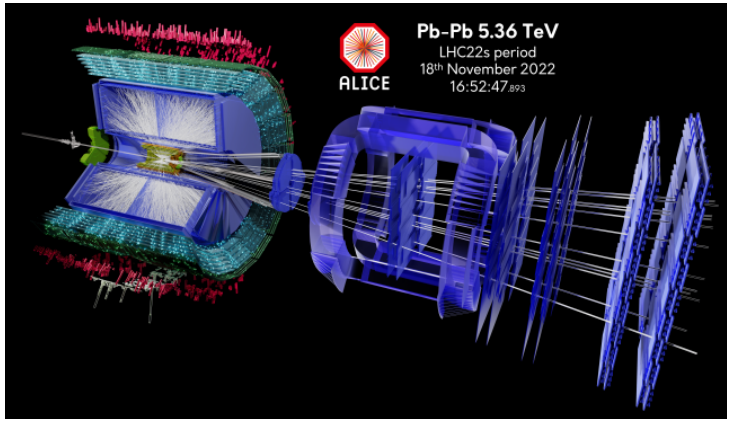
A Large Ion Collider Experiment



ALICE upgrade during long shutdown 2

Run 2 → Run 3

- ✓ Continuous readout → More statistics
- ✓ Better vertexing and higher efficiency at low p_T



Run 2 sub-detectors

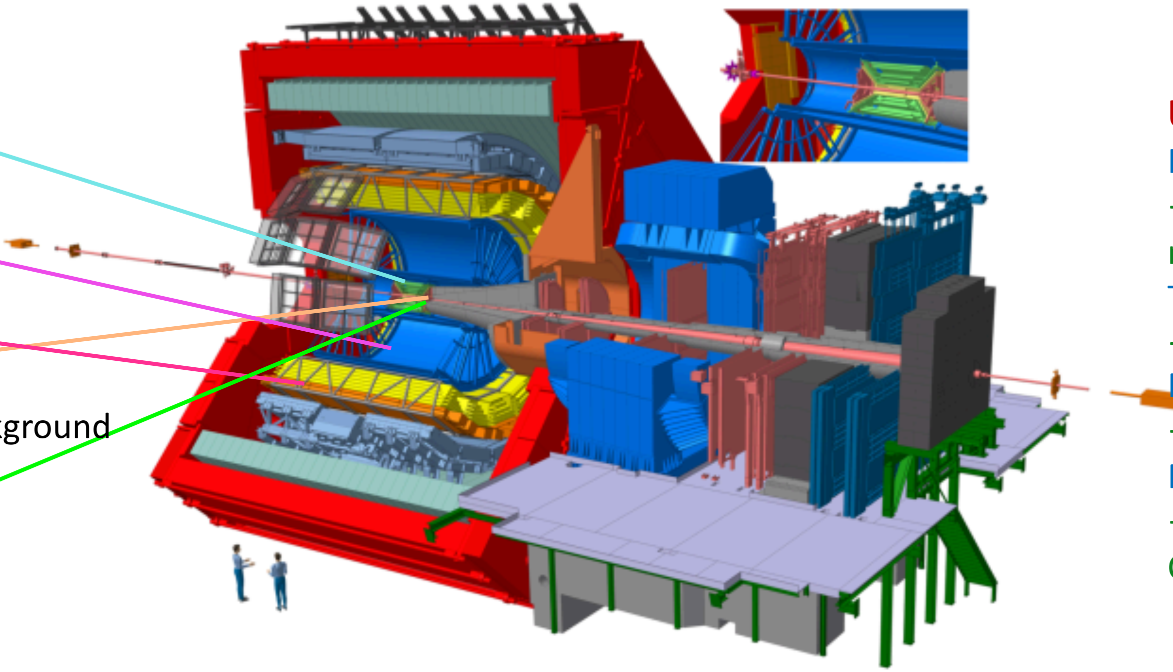
Inner Tracking System
- tracking, vertex, PID at low p

Time Projection Chamber
- tracking, PID via dE/dx

Time Of Flight
- PID via β

V0M
- trigger, multiplicity estimators, background suppression

Forward Multiplicity Detector
- Multiplicity at forward region



Upgrade in Run 3

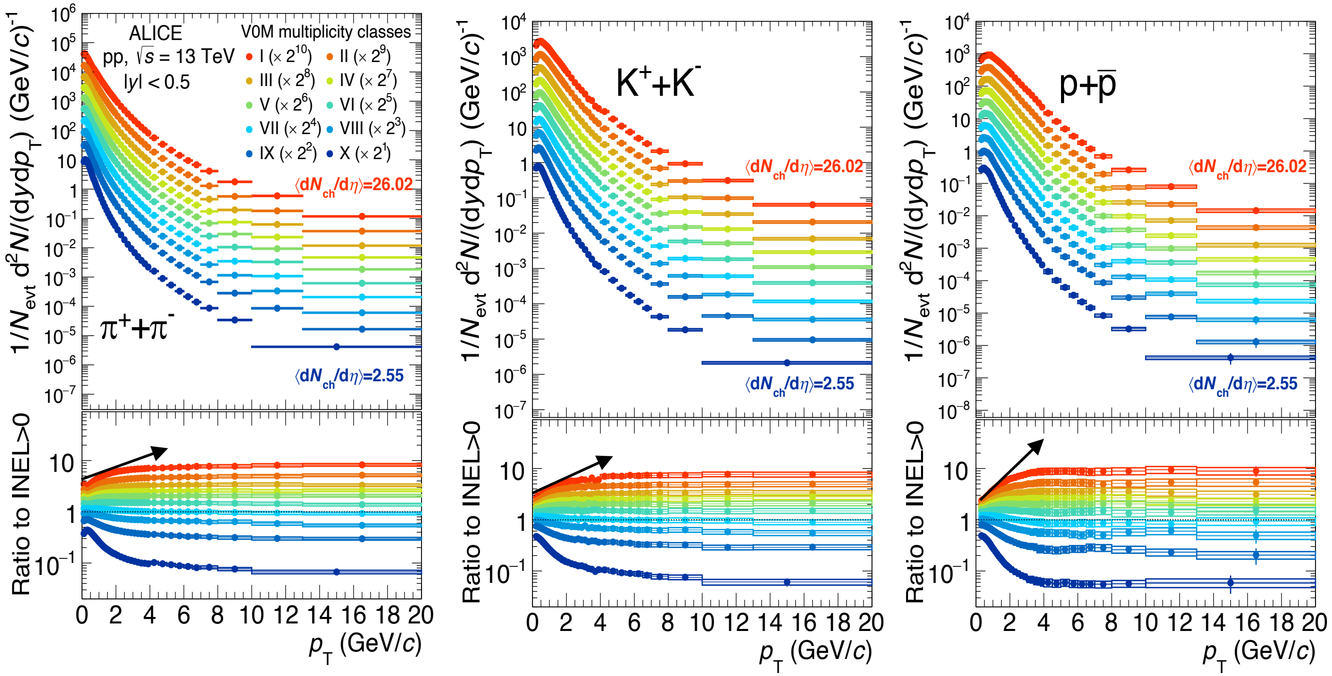
Inner Tracking System (ITS)
→ 7 layers MAPS, improved resolution, less material

Time Projection Chamber (TPC)
→ Gas Electron Multiplier (GEM)

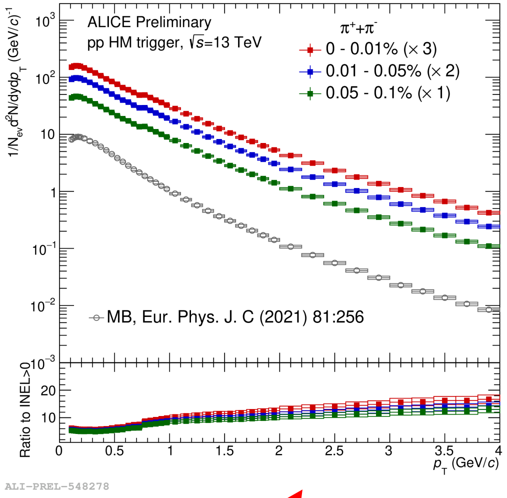
Fast Interaction Trigger (FIT)
→ New trigger detector

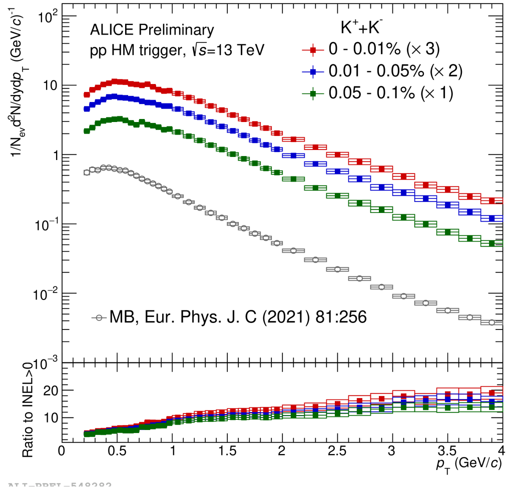
Readout upgrades
→ TOF, TRD, Muon Spectrometer, ZDC, Calorimeters

Hardening of p_T spectra in small system



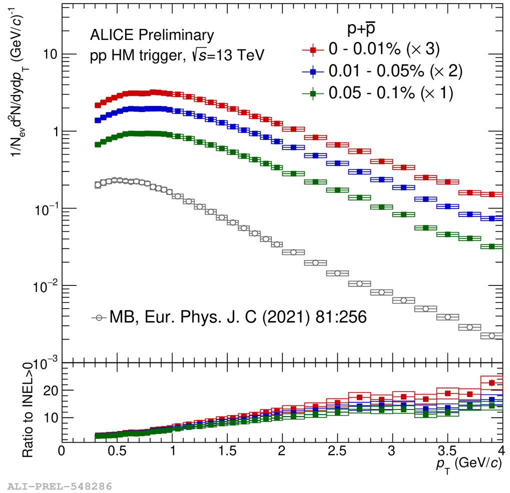
Eur. Phys. J. C (2020) 80:693





pp, $\sqrt{s}$ = 13 TeV HM classes

- Slight centrality dependent hardening of p_T spectra

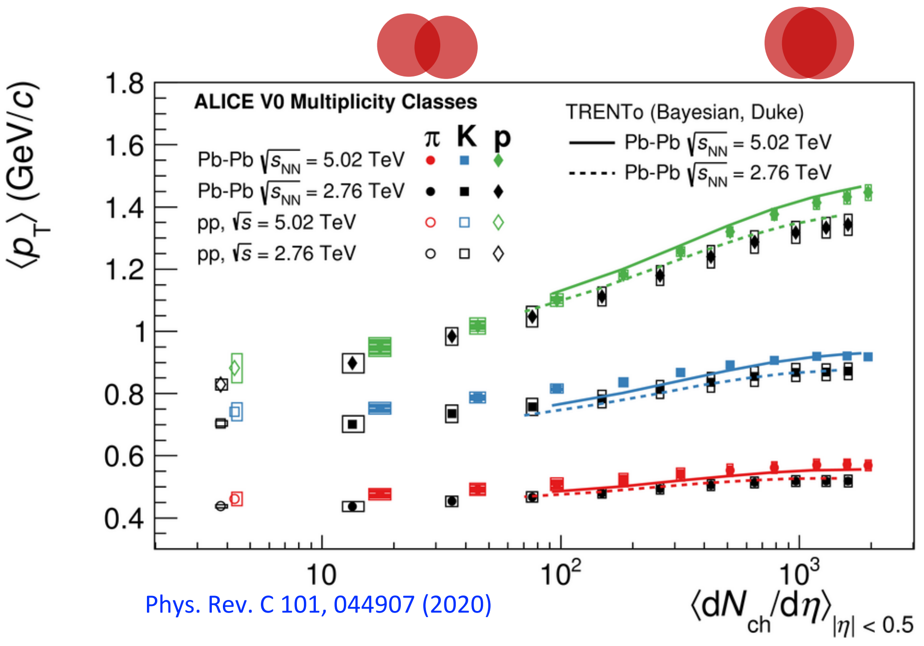


π → K → p → mass

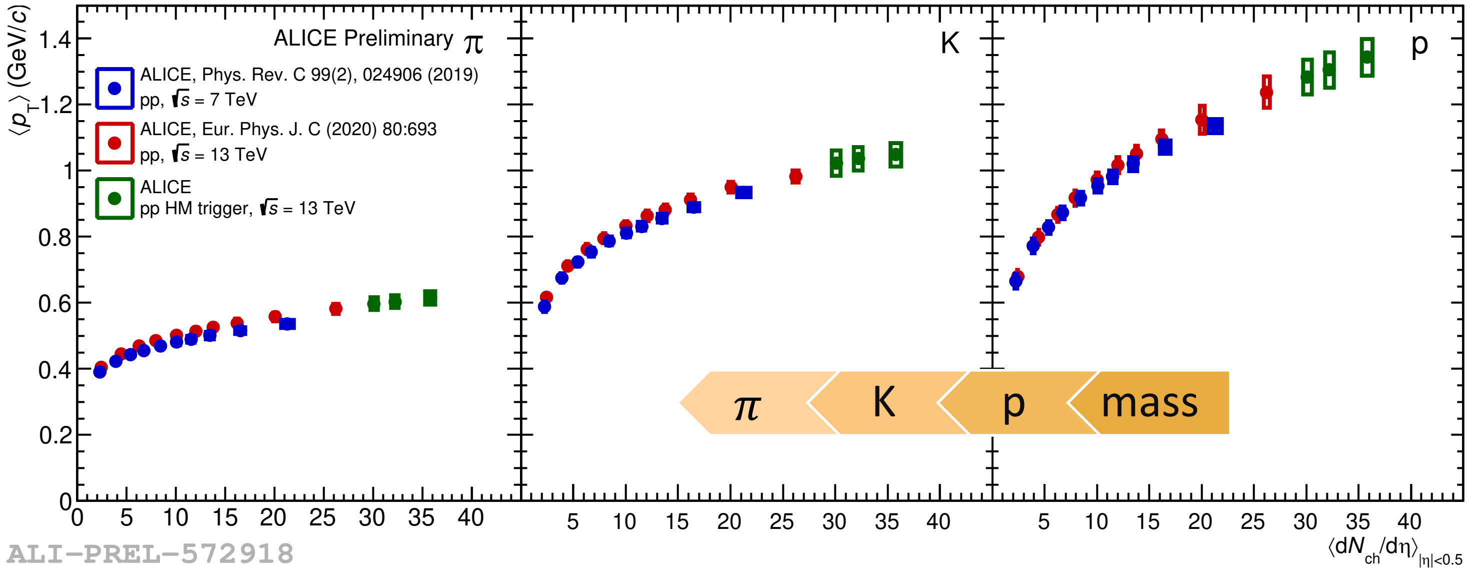
Hardening of the spectra

- At low p_T region mass and multiplicity dependent hardening of the spectra is observed similar to AA system
- At higher p_T (> 8 GeV/c) slope of the spectra are independent of the multiplicity class, as expected from pQCD.
- $\langle p_T \rangle$ **increases similar to radial flow** as the multiplicity increases

$\langle p_T \rangle$ measurement in small and large collision systems



Phys. Rev. C 101, 044907 (2020)



- The common feature of **multiplicity dependent** $\langle p_T \rangle$ increases with a **steeper trend with higher hadron masses** in pp collisions following Pb–Pb collisions
- supporting the picture of a **collective evolution in small systems** (similar to radial flow)

Blast-wave model and radial flow as collectivity

Boltzmann-Gibbs blast-wave model*: a three-parameter simplified hydrodynamical model

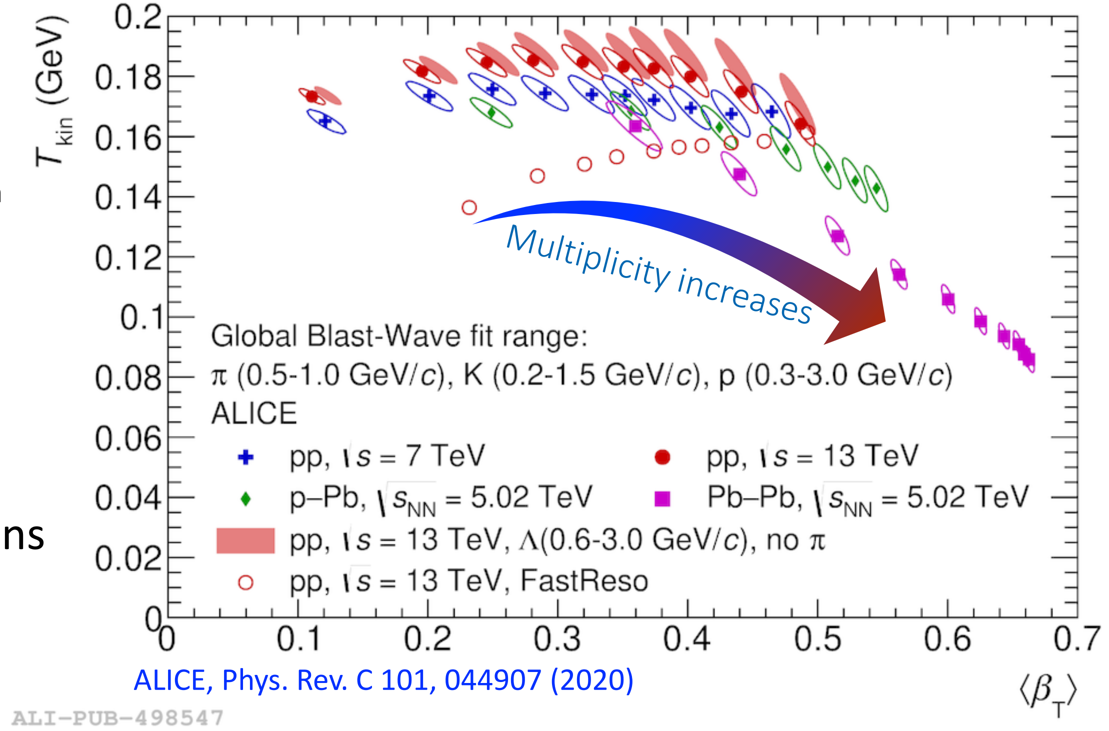
*Phys. Rev. C 48 (1993) 2462

- Assumes a locally thermalized medium expands with common velocity-> calculate radial flow (β_T)
- The expansion undergoes an instantaneous kinetic freezeout -> T_{kin}

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

$$\rightarrow m_T = \sqrt{m^2 + p_T^2} \quad \rho = \tanh^{-1}(\beta_T) \quad \beta_T(r) = \beta_s\left(\frac{r}{R}\right)^n$$

- **Large systems:** **Largest $\boldsymbol{\beta_T}$** and **lowest $\boldsymbol{T_{\mathrm{kin}}}$** for central Pb-Pb collisions
- **Small systems:** **pp** **and** **p-Pb** **show a similar trend** and values are comparable. The evolution is mostly in the $\boldsymbol{\beta_T}$ for small system.

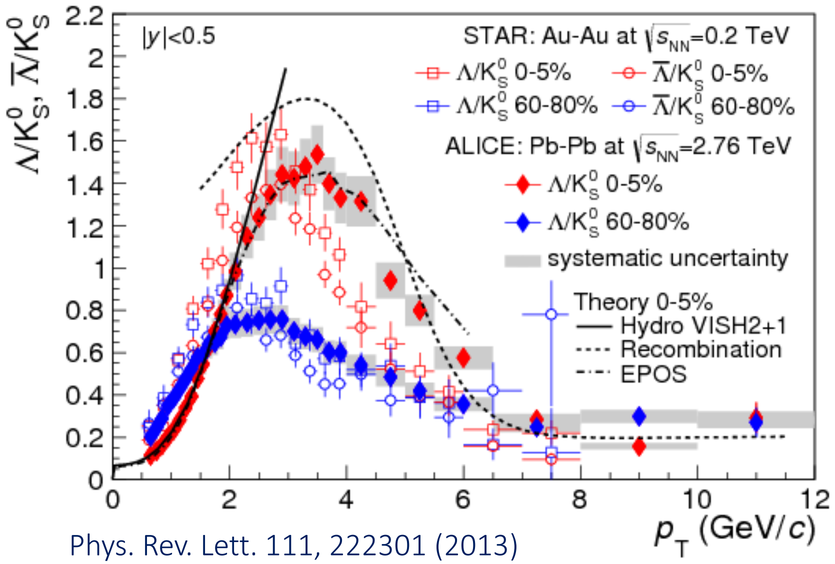


ALICE, Phys. Rev. C 101, 044907 (2020)

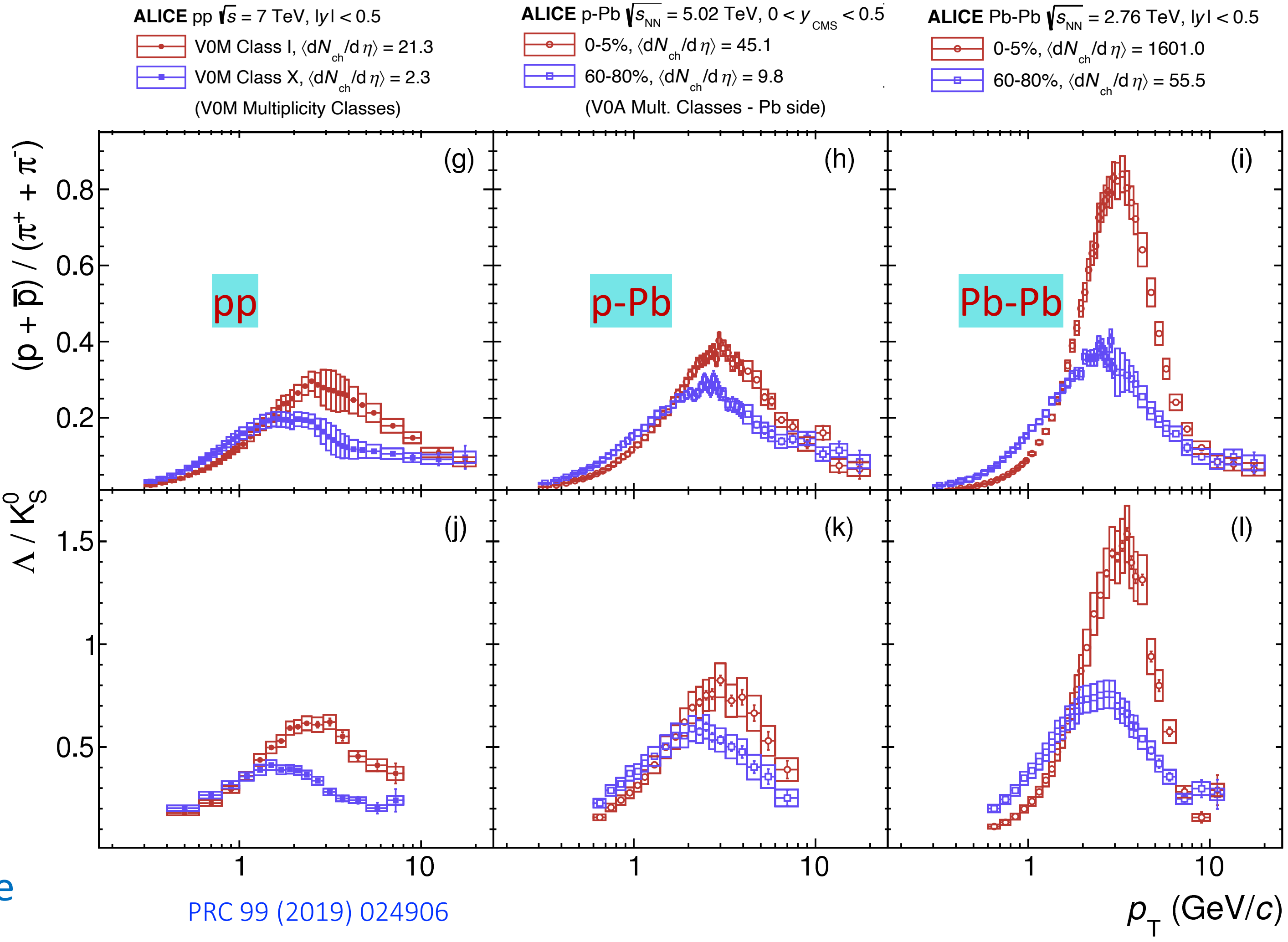
➢ Continuous evolution as a function of the event multiplicity is found in small systems

➢ Radial flow effect can be observed in small system

Signature of radial flow as collective effect



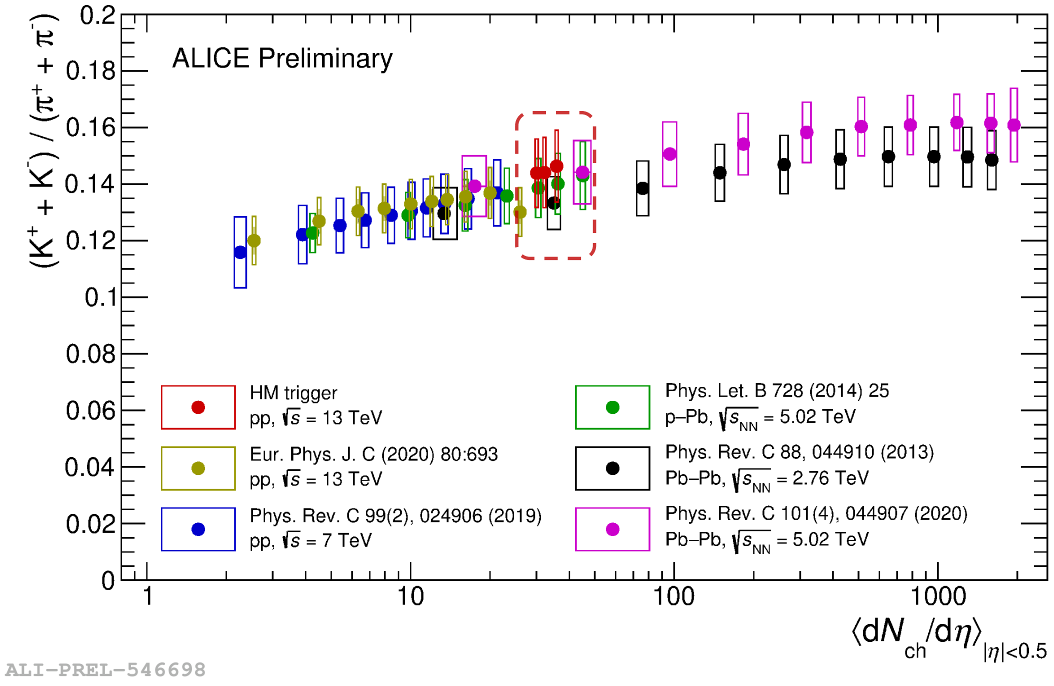
Phys. Rev. Lett. 111, 222301 (2013)

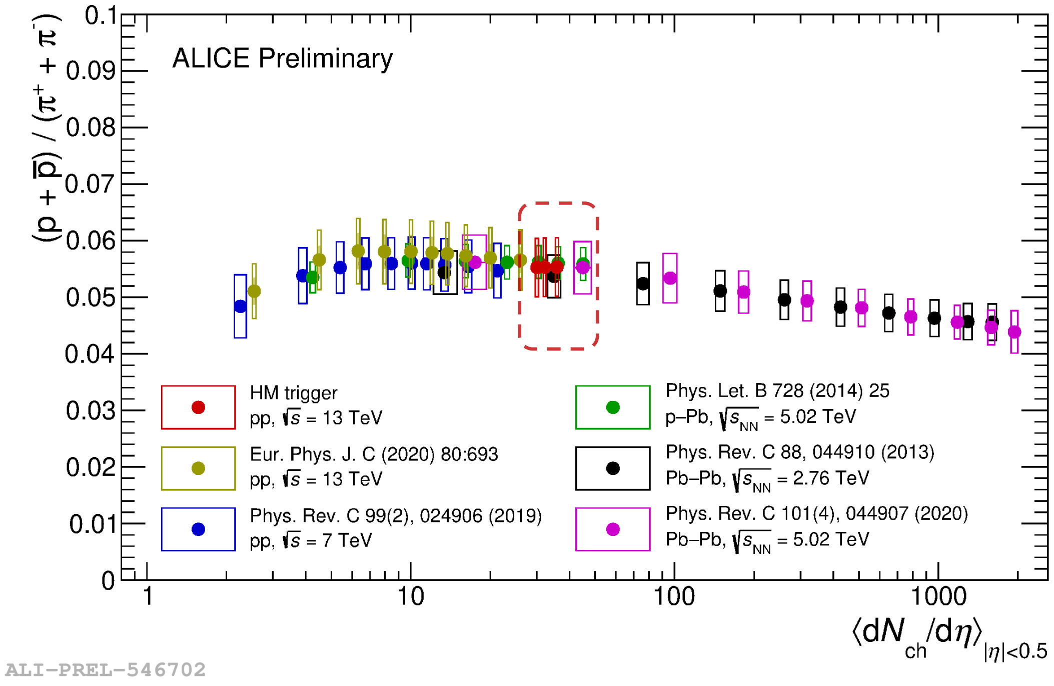


PRC 99 (2019) 024906

- **Boost of heavier particle** at mid p_T, found in all pp, p-Pb and Pb-Pb systems
- Centrality dependent **baryon/meson ratio** can be explained by **common expansion velocity of partons**
  - Results supports the radial flow is more effective for baryons than for mesons

Ratio of particles (K/π and p/π)



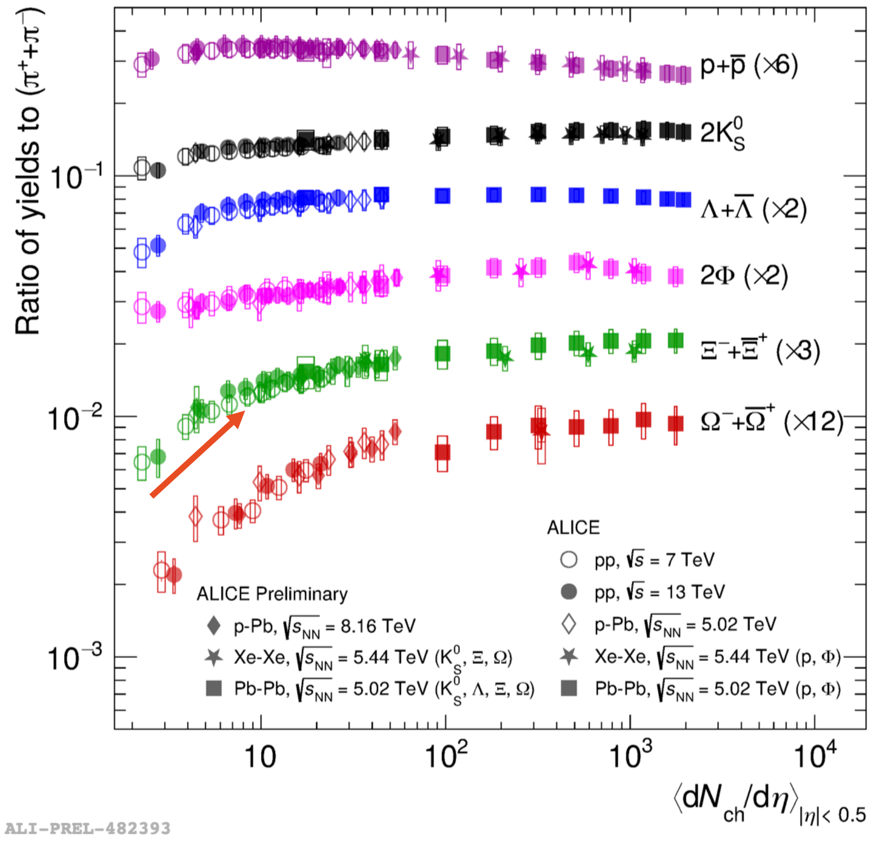


- **Smooth transition of ratio of the particles** from pp to Pb–Pb collisions
  - The HM pp results follow the smooth transition
  - Universal scaling of hadron chemistry with charged particle multiplicity
- Increasing trend of the K/π ratio →Strangeness enhancement?
- Decreasing trend in the p/π interpreted as antibaryon-baryon annihilation

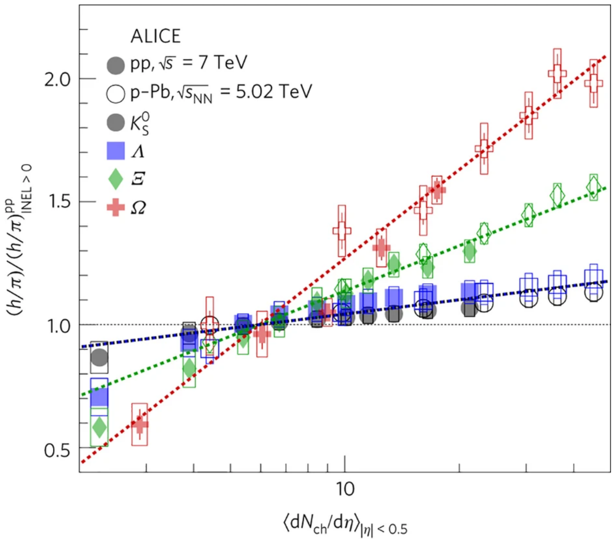
Strangeness production across different systems

Strange (s) quark produced thermally during collision, $T \sim m_s$
- Originally proposed as a **signature of QGP in nuclear collisions**
- Multi-strange hadrons production

➢ Smooth evolution with the multiplicity across different collision systems (pp, p−Pb, Pb−Pb, Xe-Xe) and energies
  - **Strangeness enhancement with particle multiplicity** is independent of collision system and energy
  - High multiplicity pp results matches with the semi-peripheral AA
  - A common underlying physics might have among all different collision systems



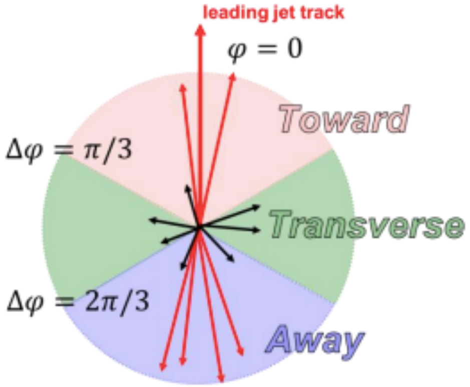
Strange content hierarchy: SE(Ω) > SE(Ξ) > SE(Λ, K^0_S)



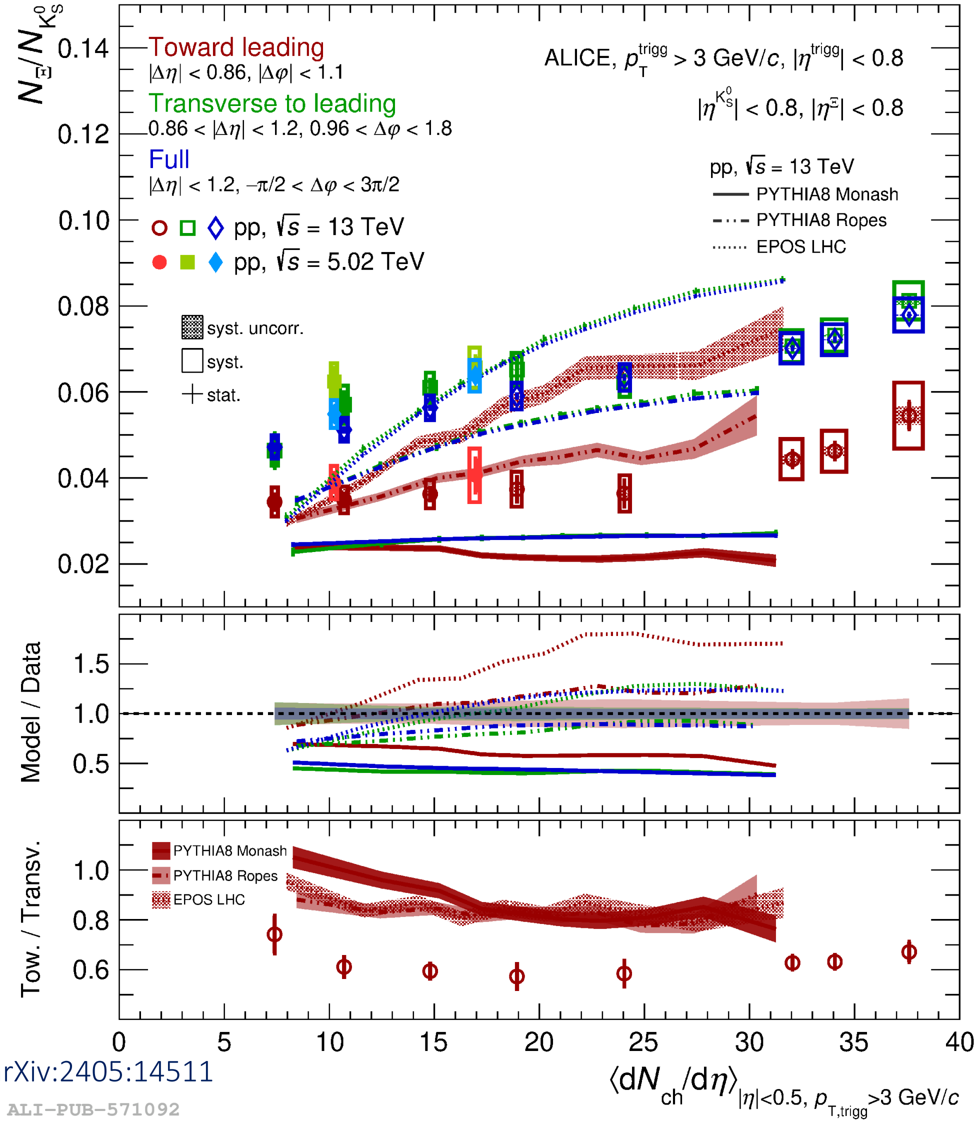
Nature Physics 13, 535-539 (2017)

Differential study of strange hadrons production

What is **the microscopic origin of strangeness enhancement** in small system?
- Hard scattering – Jet or Underlying events – soft process

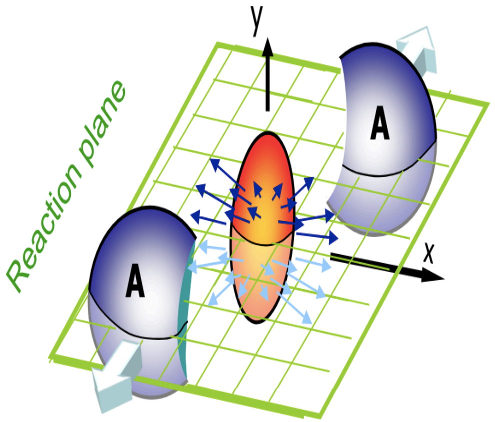


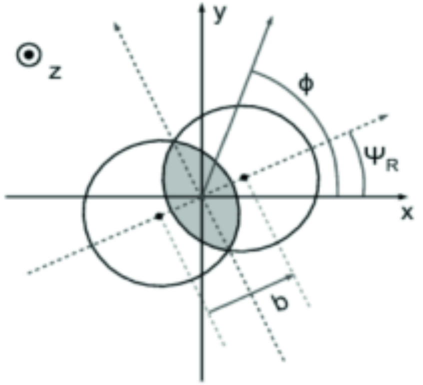
- Differential study of strangeness production inside and outside of jets represented by a leading particle ($p_T^{trig} > 3$ GeV/c)
- Ξ/K_S^0 ratio attributed that **enhancement of strangeness production** of Ξ (dss) with respect to K_S^0 (ds) has **increasing multiplicity in transverse-to-leading and also in toward-leading directions**
- Relative production of Ξ with respect to K_S^0 is **favoured in transverse-to-leading processes**

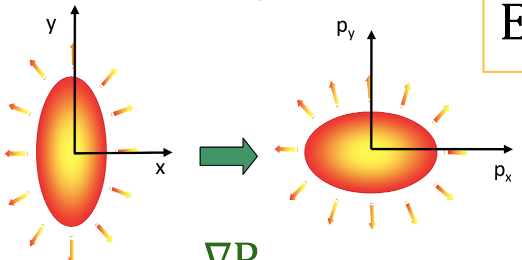


arXiv:2405:14511

Elliptic flow v_2 as a signature of QGP medium





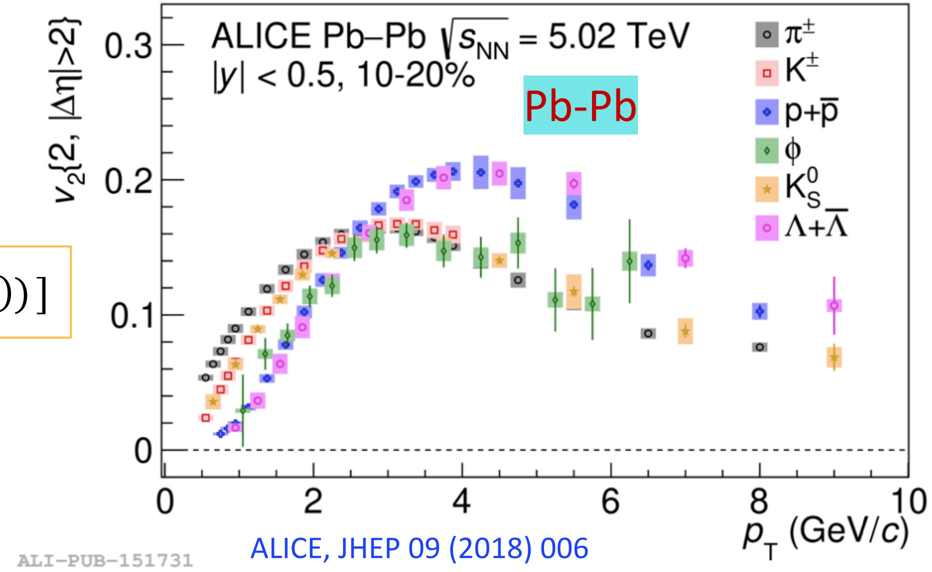


Initial geometry anisotropy → Final momentum anisotropy

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

$$v_n = \langle\cos(n(\phi-\Psi_n))\rangle$$

v_1 – directed flow, **v_2 – elliptic flow**, v_3 – triangular flow…



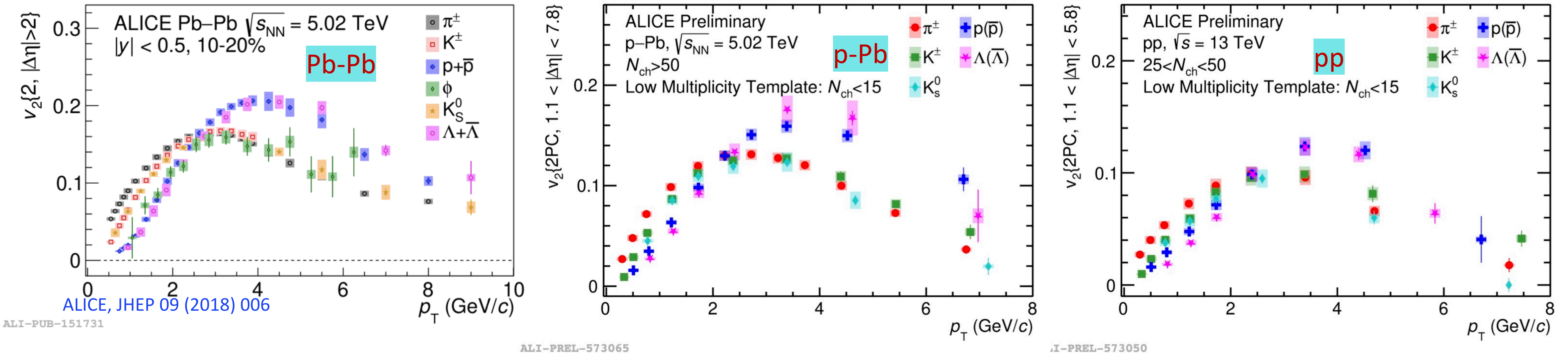
ALICE, JHEP 09 (2018) 006

- Anisotropic pressure gradients (larger push along the impact parameter)
- Anisotropic fluid velocities (anisotropic particle emission and collective flow) - **signature of QGP**

S. Voloshin and Y. Zhang, Z. Phys. C 70, (1996)

- At low p_T (p_T < 3 GeV/c) - **mass ordering of v_2** — interplay between anisotropic flow and the isotropic expansion (radial flow)
- Intermediate p_T (3< p_T < 8 GeV/c) —**meson-baryon splitting** — quark coalescence, sign of partonic collectivity

Elliptic flow v_2 measurement in large to small system

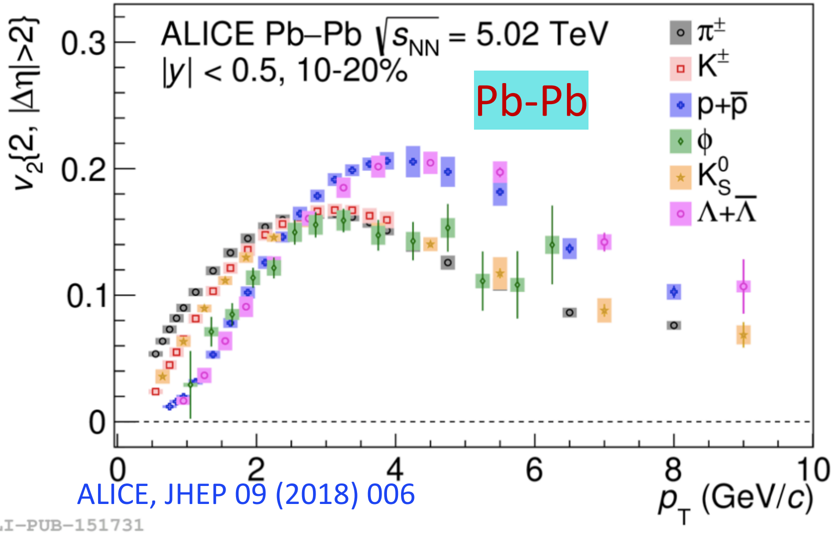


- v_2 measurement in high multiplicity p-Pb and pp systems
- At low p_T (p_T < 3 GeV/c) - **mass ordering of v_2**
  — interplay between anisotropic flow and the isotropic expansion (radial flow)
- Intermediate p_T (3< p_T < 8 GeV/c) —**meson-baryon splitting**
  — quark coalescence, sign of partonic collectivity
- Further missing points at extended p_T range, differential study require in Run 3 statistics

Differential measurement of **v_2 is consistent** within all three systems pp, p-Pb, Pb-Pb

Further check with model comparisons…

Elliptic flow v_2 measurement in large to small system



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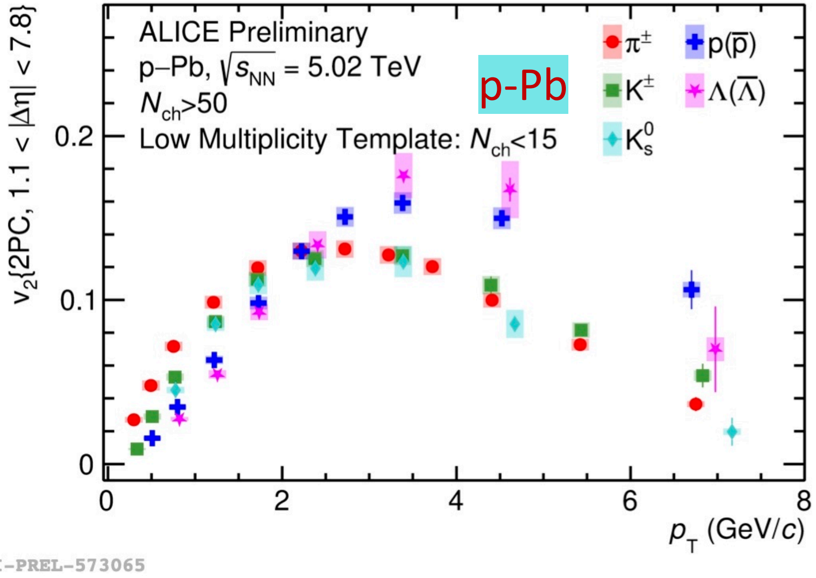

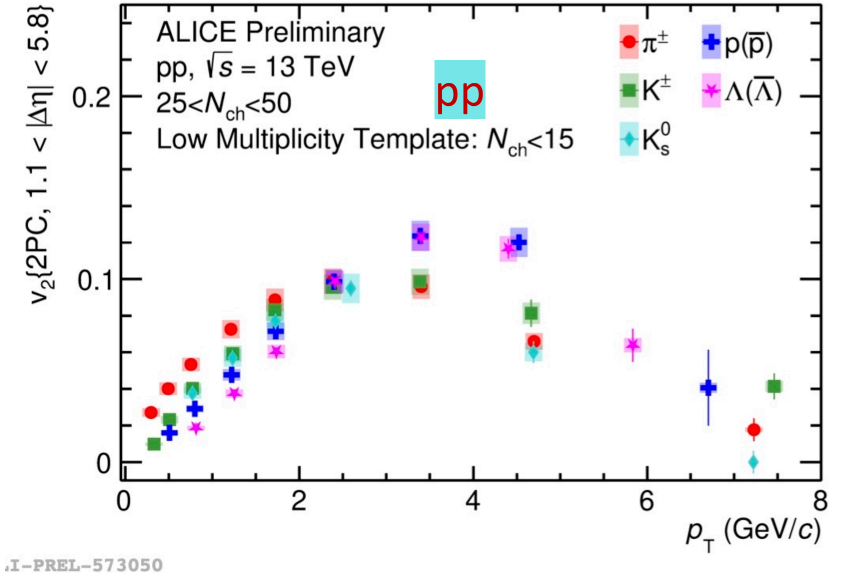

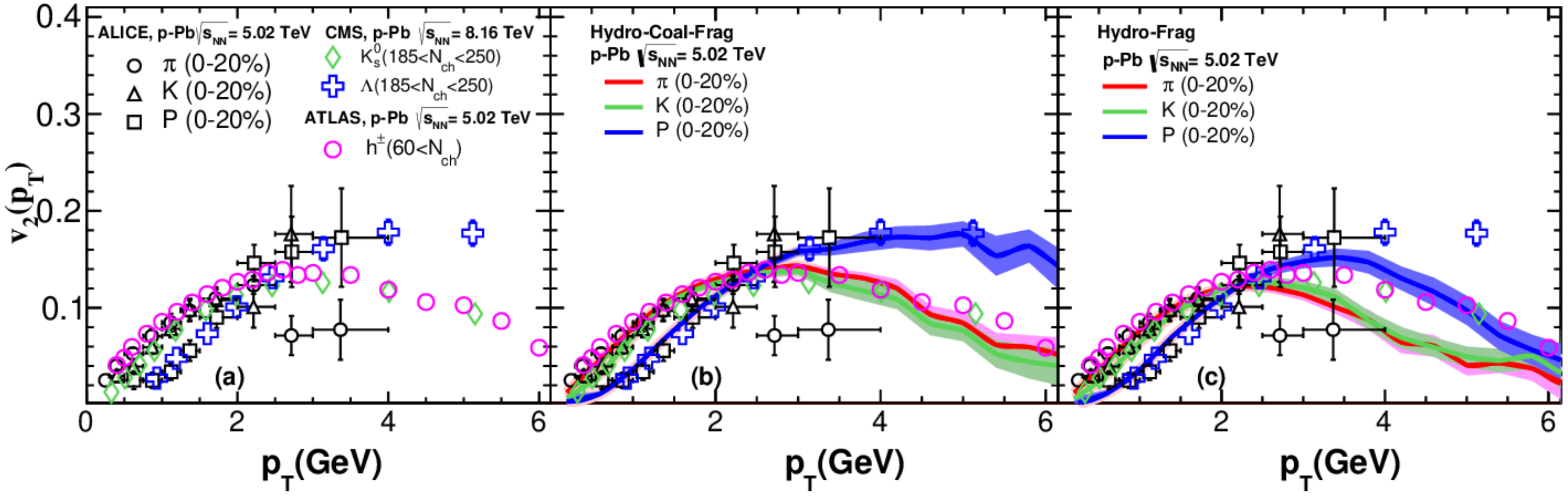

W. Zhao et al., Phys. Rev. Lett. 125, 072301 (2020)

- Hydrodynamics + Coalescence + Jet Fragmentation describes the flow
- Hydro + Frag fails
- No jet quenching yet!

Summary

- High multiplicity small system exhibits features of AA collisions
  - Multiplicity dependent **hardening of the p_T spectra**
  - **Radial flow (β_T, T_{kin}) effect** in particle dynamics
- **Hadron chemistry driven by multiplicity** and not by collision energy nor system
- **Baryon-to-meson effect is universal**
- **In- and out-of-jet** provide deeper insights on the origin of strangeness enhancement
- Elliptic flow study shows similar **mass ordering and meson-baryon splitting** in pp and p-Pb systems
  - The model study shows **hydrodynamics with coalescence and jet fragmentation can describe** the flow

THANK YOU

for your kind attention!