40th International Conference on High Energy Physics (ICHEP2020), 28 July – 6 August 2020, Prague, Czech Republic

Study of hadronization through the measurement of light-flavour particle production in different colliding systems with ALICE

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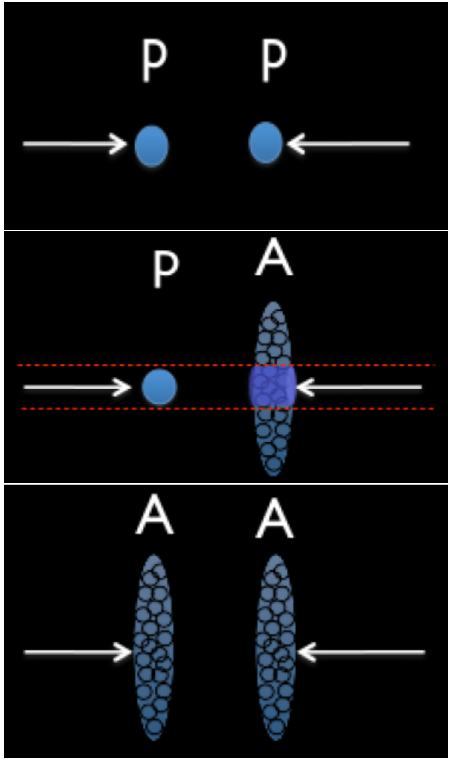
Goals of the ALICE experiment

ALICE is designed to study the physics of strongly interacting matter under extremely high temperature and energy densities to investigate the properties of the **quark-gluon plasma**.

- proton-proton collisions:
  - **high energy QCD reference.**
  - pp data at $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8, 13 TeV
- proton-nucleus collisions:
  - **initial state/cold nuclear matter.**
  - p-Pb data at $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV
- nucleus-nucleus collisions:
  - **quark-gluon plasma formation!**
  - Pb-Pb data at $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV, and Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV



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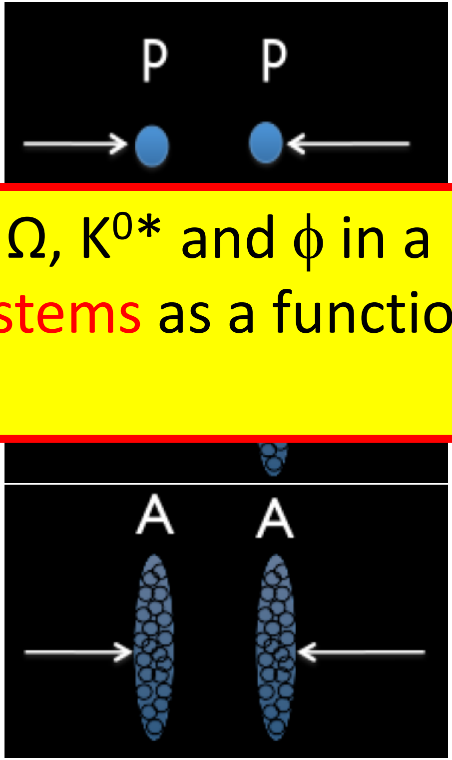
ALICE is designed to study the physics of strongly interacting matter under extremely high temperature and energy densities to investigate the properties of the **quark-gluon plasma**.

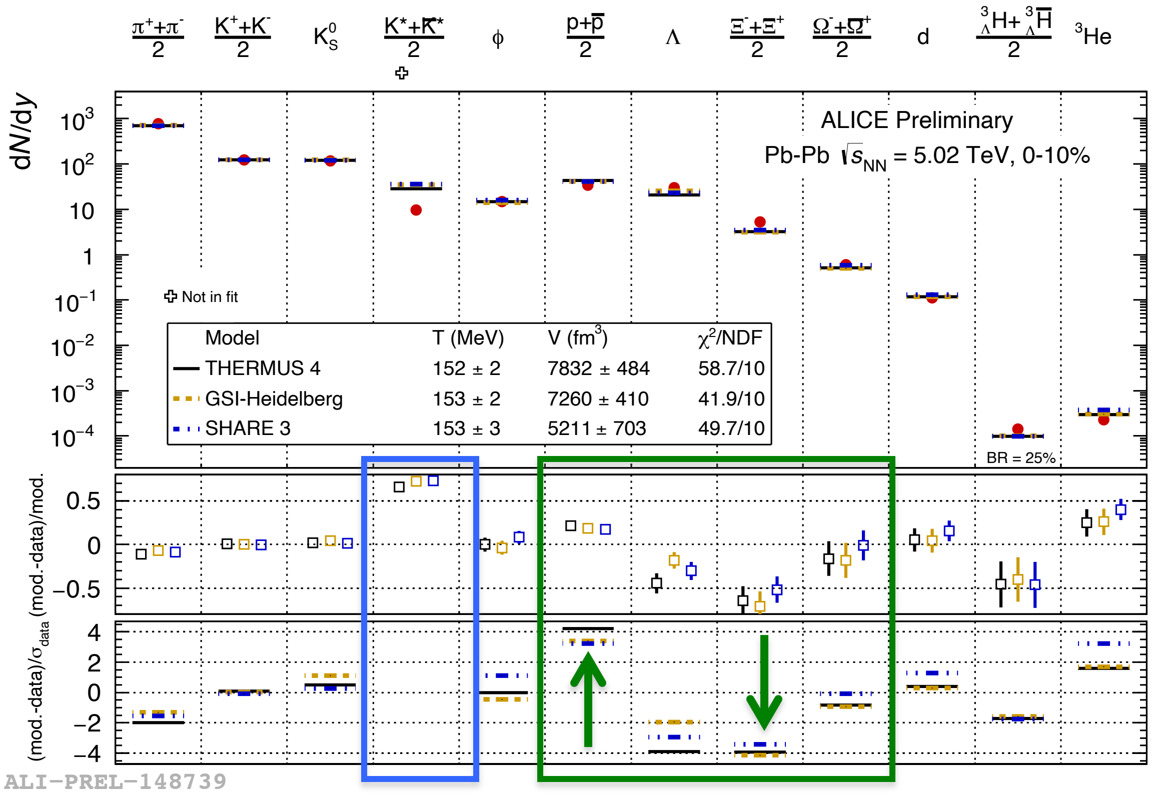
- proton-proton collisions:
  - **high energy QCD reference.**
  - pp data at $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8, 13 TeV

ALICE has measured the yields of π, K, p, K^0_s, Λ, Ξ, Ω, K^{0*} and ϕ in a wide momentum range and in several colliding systems as a function of event multiplicity.

- nucleus-nucleus collisions:
  - **quark-gluon plasma formation!**
  - Pb-Pb data at $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV, and Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV



Hadron yield: statistical hadronization model



Production of (most) light-flavour hadrons in **Pb-Pb at 5.02 TeV** is described (χ^2/ndf ≈ 4-6) by thermal models with a **single chemical freeze-out** temperature, **T_{ch} ≈ 153 MeV** (slightly lower than at 2.76 TeV, T = 156 MeV)

Deviation for **K^{*0} resonance → re-scattering** in the late hadronic phase (excluded from fit)

Tensions for protons and multi-strange: incomplete hadron spectrum, baryon annihilation in hadronic phase, interacting hadron gas, flavour-dependent freeze-out...?

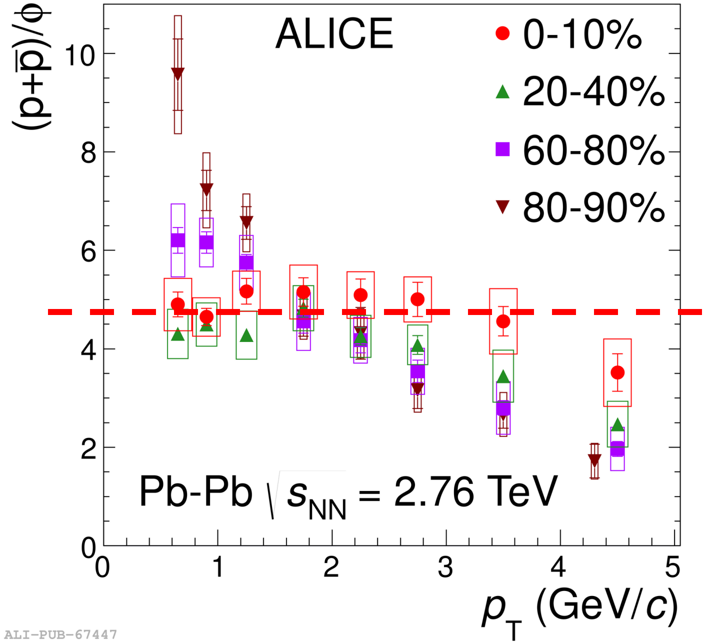
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

Hadronization processes – p_T differential ratios

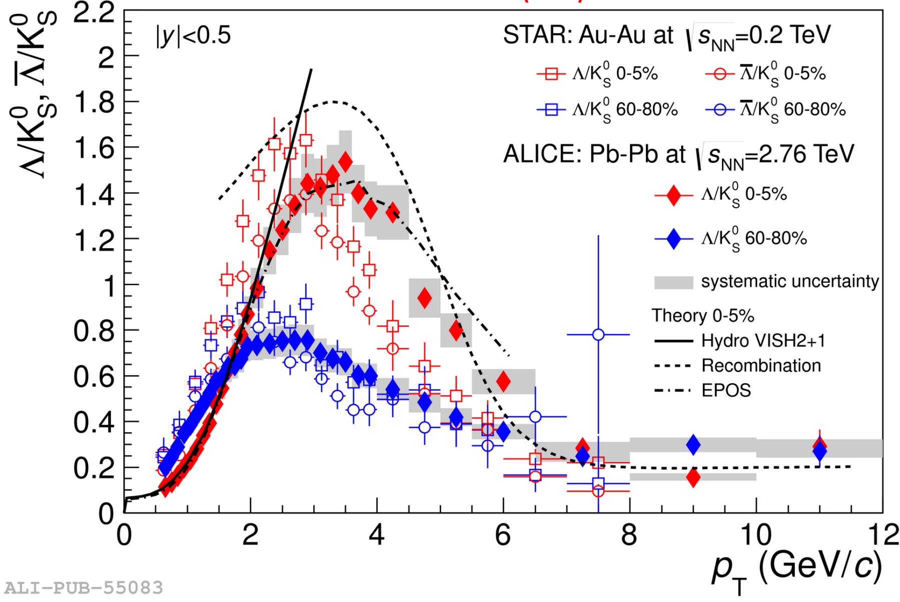
In central Pb-Pb collisions the baryon/meson ratios shows a peak at intermediate p_T

- Mass ordering → hydrodynamic (radial flow, $p = mv\gamma$)
- Particle type ordering → quark recombination

Phys. Rev. C 91 024609 (2015)



PRL 111 (2013) 222301

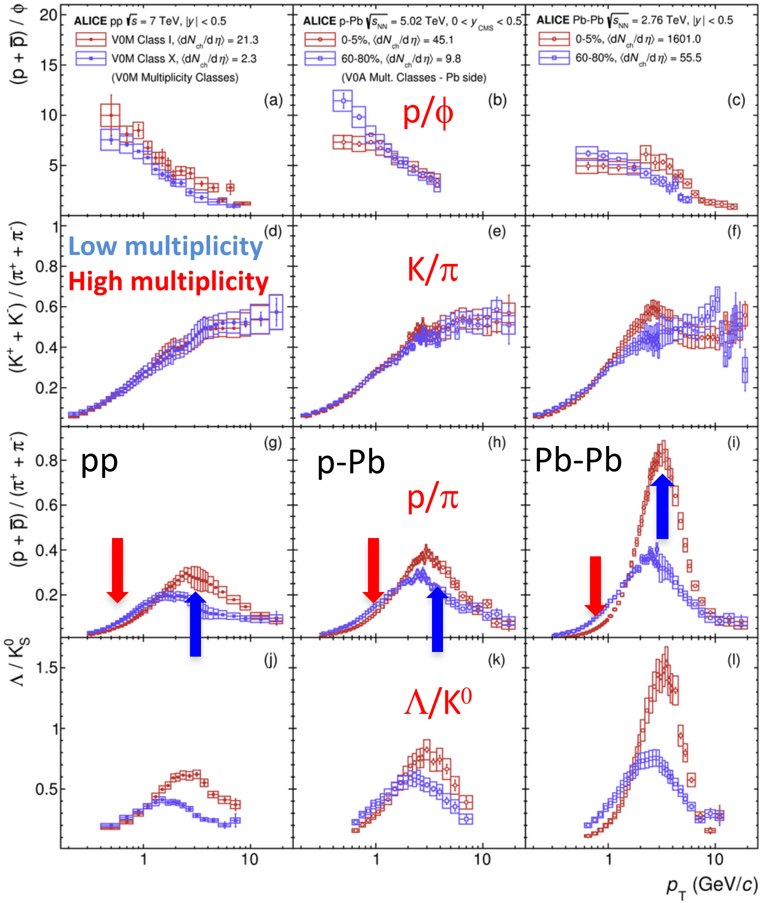


p/ϕ flat: a meson and a baryon with the same mass (connected to mass!) → explained by hydrodynamic

- but also by models with recombination [V. Greco at al, Phys.Rev. C 92 (2015) 054904]

Hadronization processes - p_T differential ratios

Phys. Rev. C 99, 024906

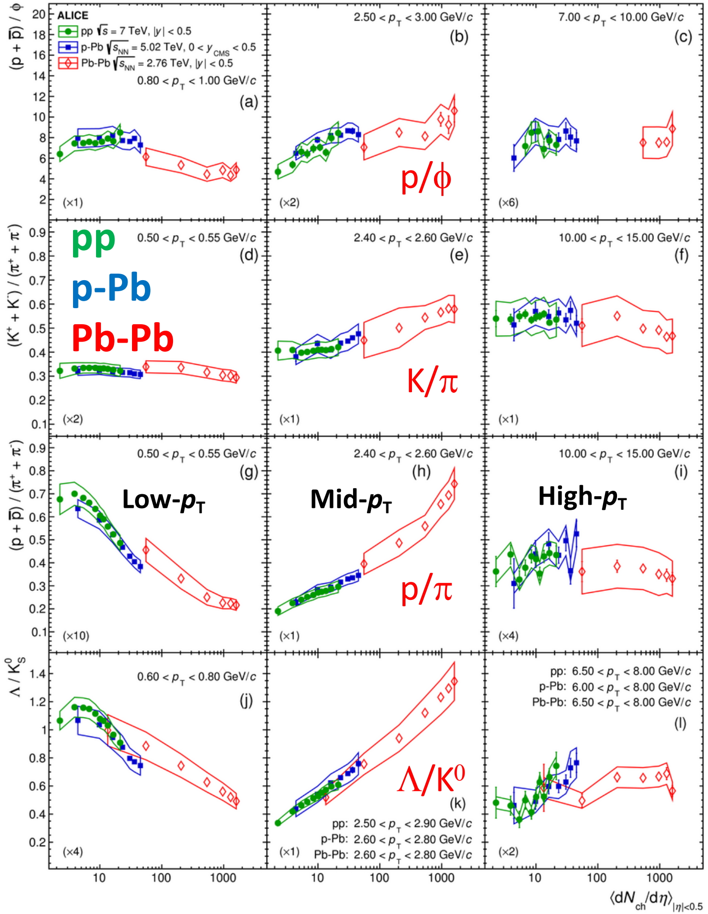


Qualitatively similar features observed for bulk particle production in pp, p-Pb and Pb-Pb

- in qualitatively similar way: depletion at low p_T, enhancement at intermediate p_T
- In Pb-Pb explained by radial flow or recombination (both collective effects)

Hadronization processes - p_T differential ratios

Phys. Rev. C 99, 024906



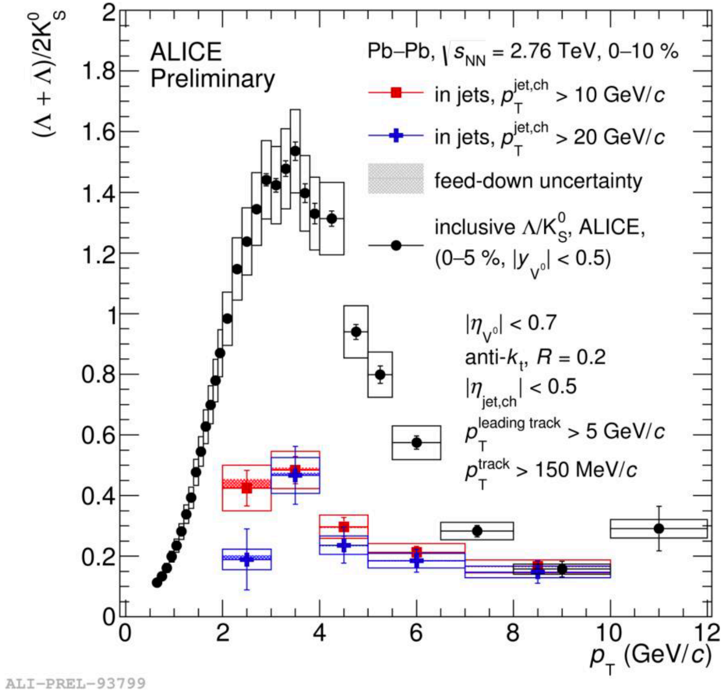
Qualitatively similar features observed for bulk particle production in pp, p-Pb and Pb-Pb

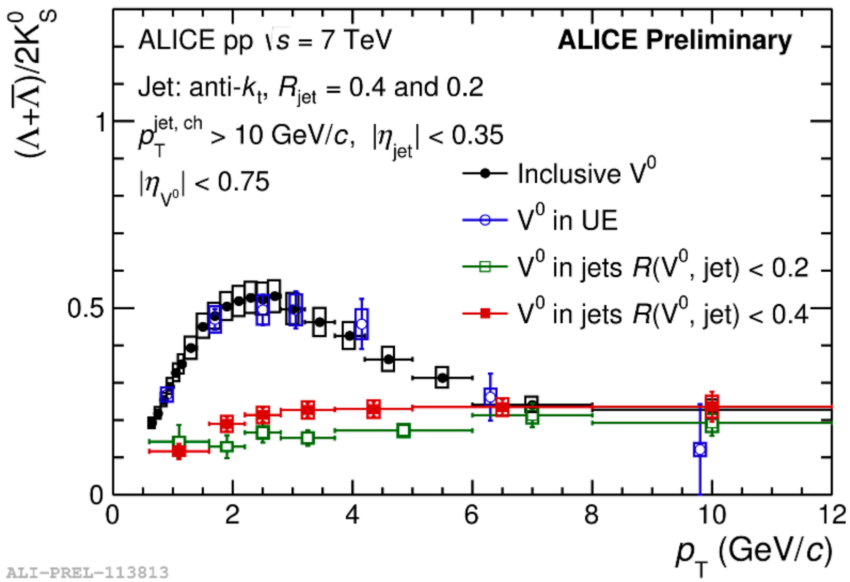
- in qualitatively similar way: depletion at low p_T, enhancement at intermediate p_T
- In Pb-Pb explained by radial flow or recombination (both collective effects)

Similar progression with $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$ is observed at a fixed p_T for the p/π ratio across different systems

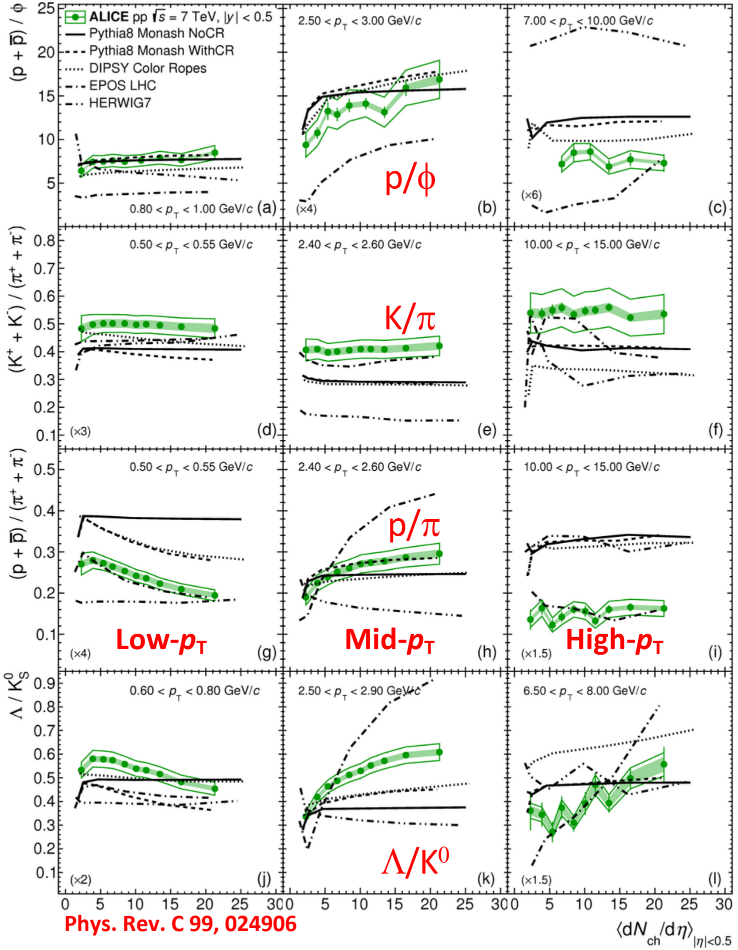
Hadronization processes - p_T differential ratios

Baryon/meson ratios vs p_T is different in-jet and out-of-jet!





Hadronization processes - p_T differential ratios



Phys. Rev. C 99, 024906

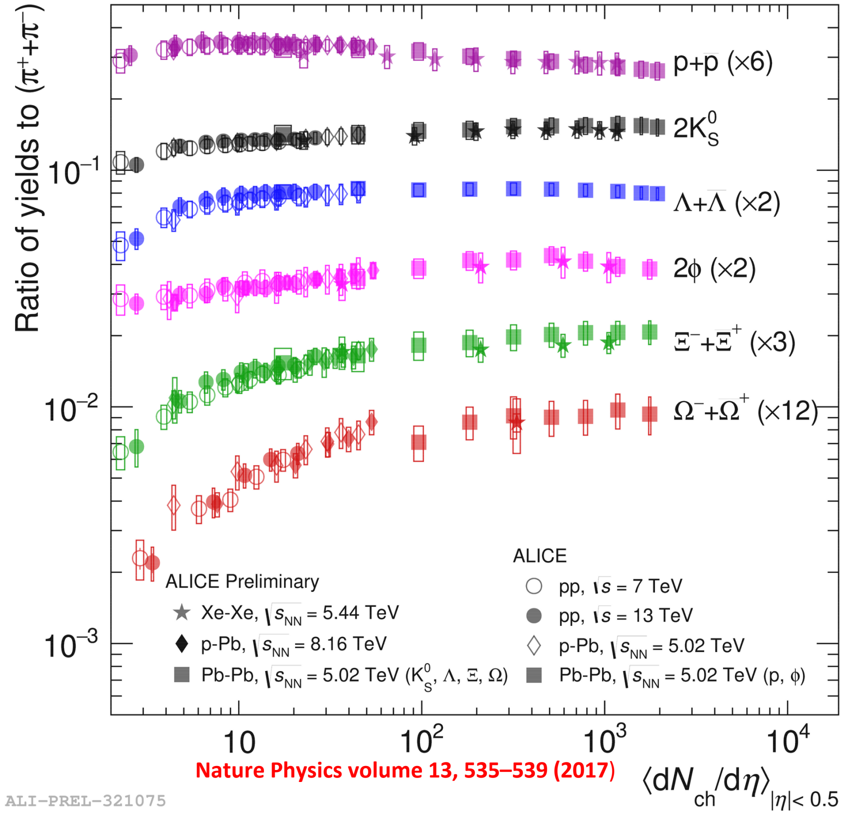
PYTHIA with Color Reconnection describes rather well the trend.

- in pp collisions, radial flow can be mimicked by QCD effects.

→ Let's look at particle composition of the system to investigate if it also shows similarities in the chemical particle composition.

Hadronization processes - strangeness

p_T-integrated yield ratios to $(\pi^+ + \pi^-)$ vs multiplicity

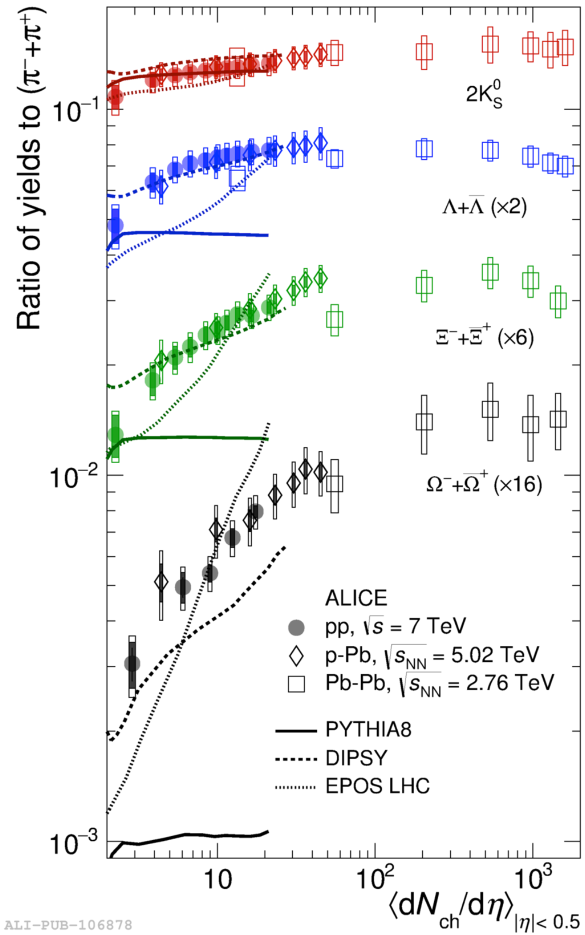


Nature Physics volume 13, 535–539 (2017)

The p_T-integrated particle ratios show an increasing trend from low multiplicity pp to central Pb-Pb collisions for strange hadrons

Hadronization processes - strangeness

Nature Physics volume 13, 535–539 (2017)



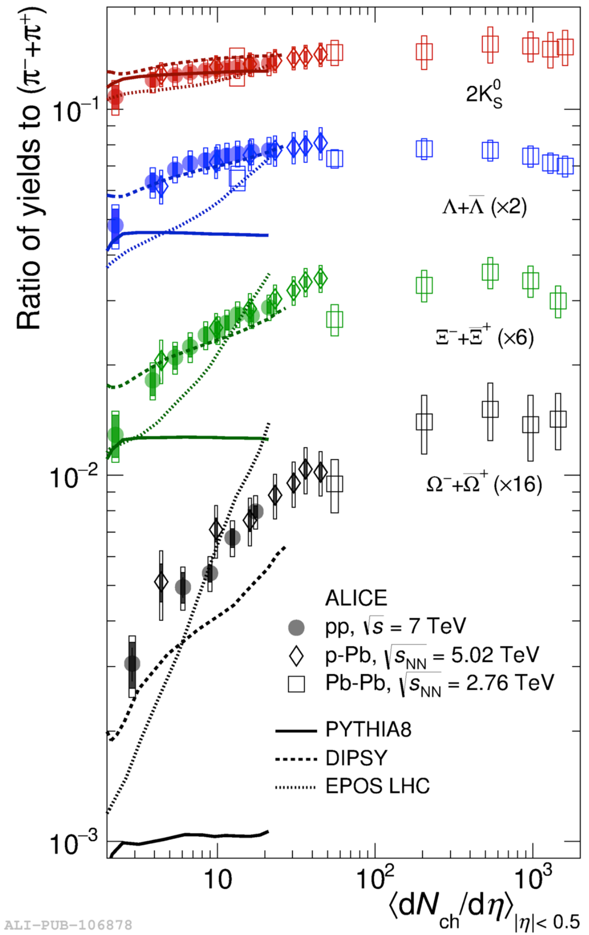
radial flow can be mimicked without hydro collectivity but strangeness enhancement cannot!

further developments are needed to obtain a complete microscopic understanding of strangeness production

In pp strange particle ratio to π increases
→ Is the enhancement due to
(a) Mass?
(b) baryon/meson nature of the particle?
(c) strangeness content?

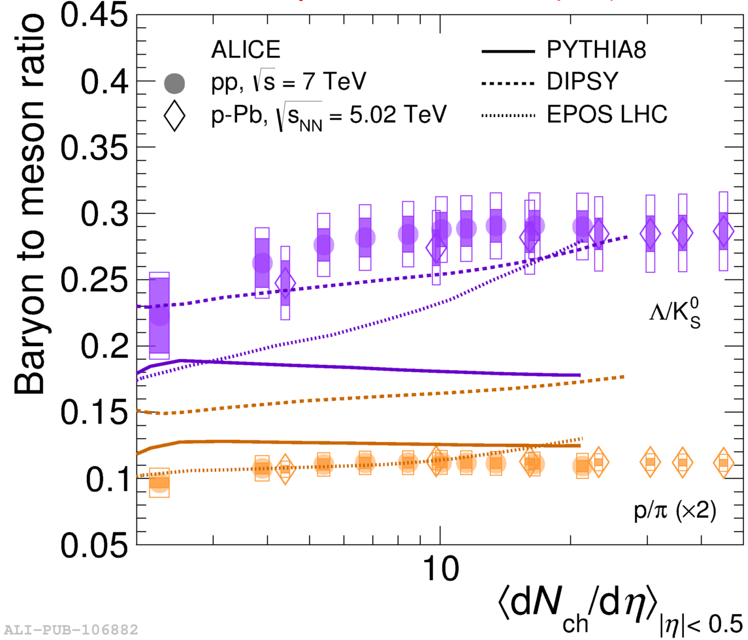
Hadronization processes: strangeness

Nature Physics volume 13, 535–539 (2017)



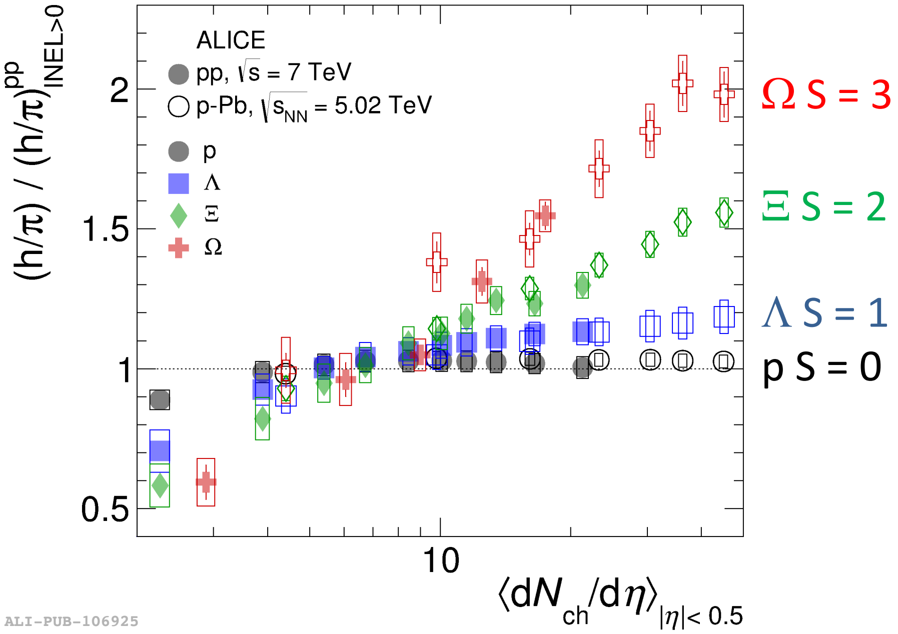
In p/π and Λ/K^0_s the only effect could be baryon/meson or mass, no net-strangeness difference → **the ratios are flat**

Nature Physics volume 13, 535–539 (2017)



Hadronization processes - strangeness

Nature Physics volume 13, 535–539 (2017)



Double-ratio in pp collisions (and p-Pb, also shown) evolves smoothly with multiplicity density.

Proton (S=0) is consistent with unity up to highest $\langle dN_{ch}/d\eta \rangle$

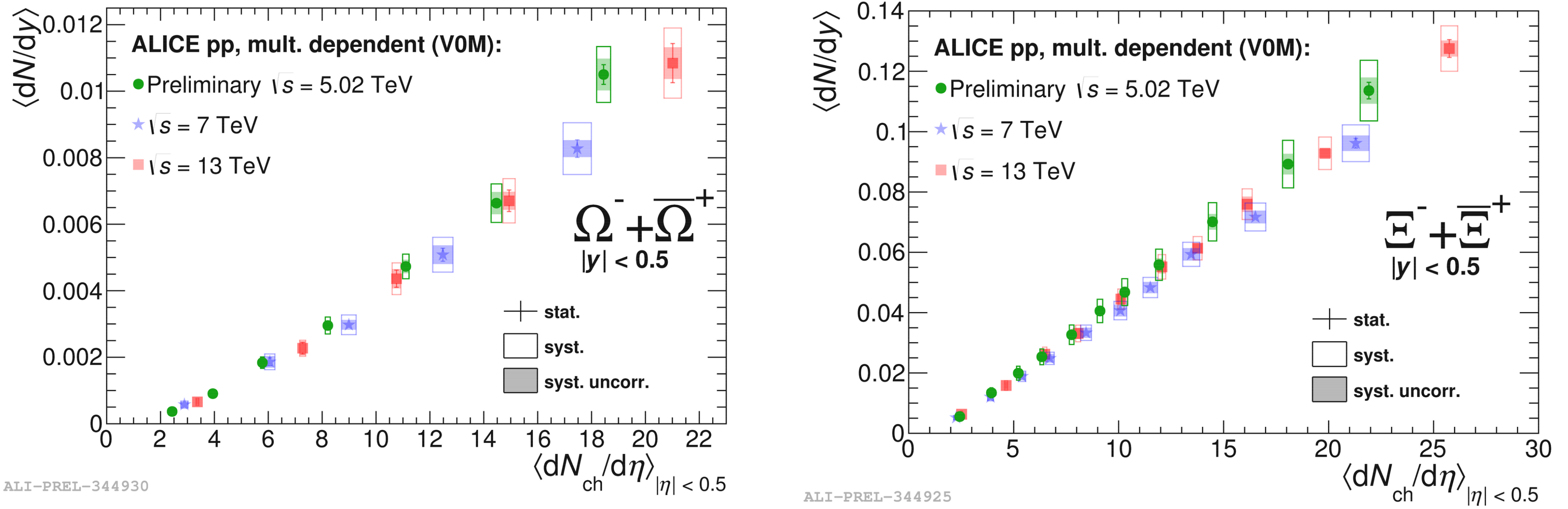
Hyperon production increases from low to high multiplicity in pp and p-Pb

The larger the valence strange quark content, the steeper the slope

→ **the effect is due to strangeness!**

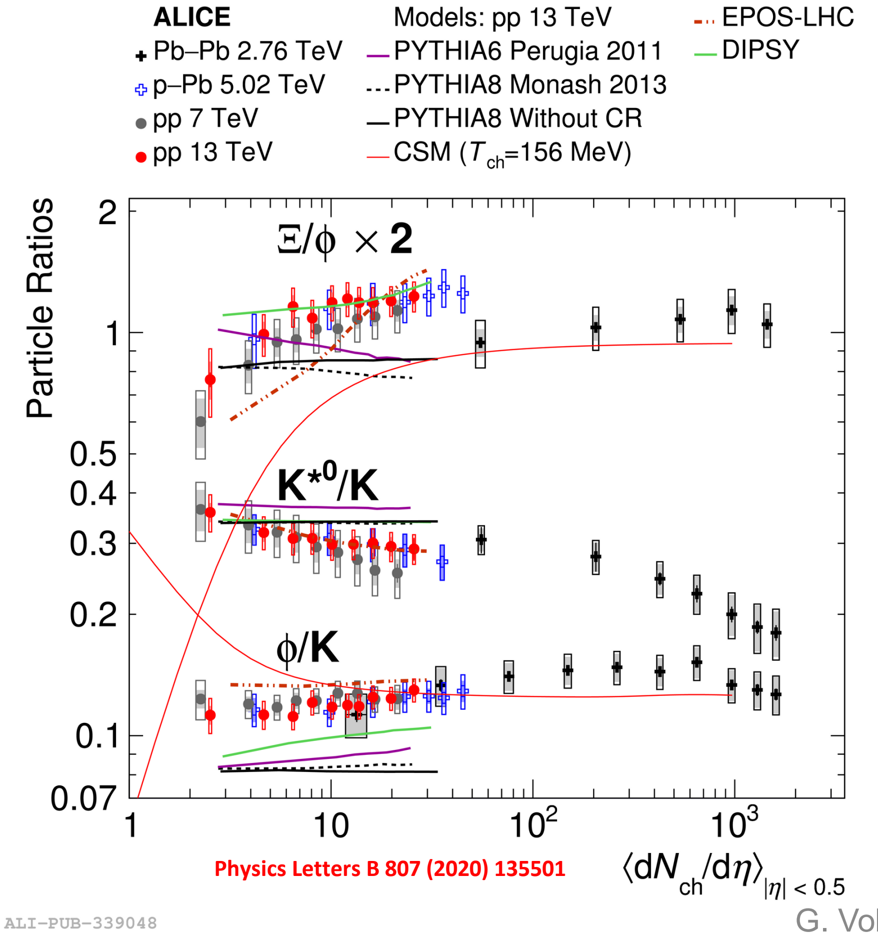
Is the same enhancement present at different energies?!
Is it collision-energy dependent or multiplicity driven?

Strangeness - p_T–integrated yield as a function of multiplicity



Strange hadron production measured in pp collisions at √s = 5, 7 and 13 TeV, it is collision energy independent at similar multiplicity!

Strangeness – the special case of the ϕ meson



ϕ meson behaves as if it had between 1 and 2 units of strangeness

The ϕ/K and Ξ/ϕ ratios are both fairly constant

- Ξ/ϕ ratio decreases with decreasing $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ for the lowest multiplicity collisions

Multiplicity evolution not consistent with simple descriptions of canonical suppression, qualitatively described by the DIPSY model (rope hadronization effects)

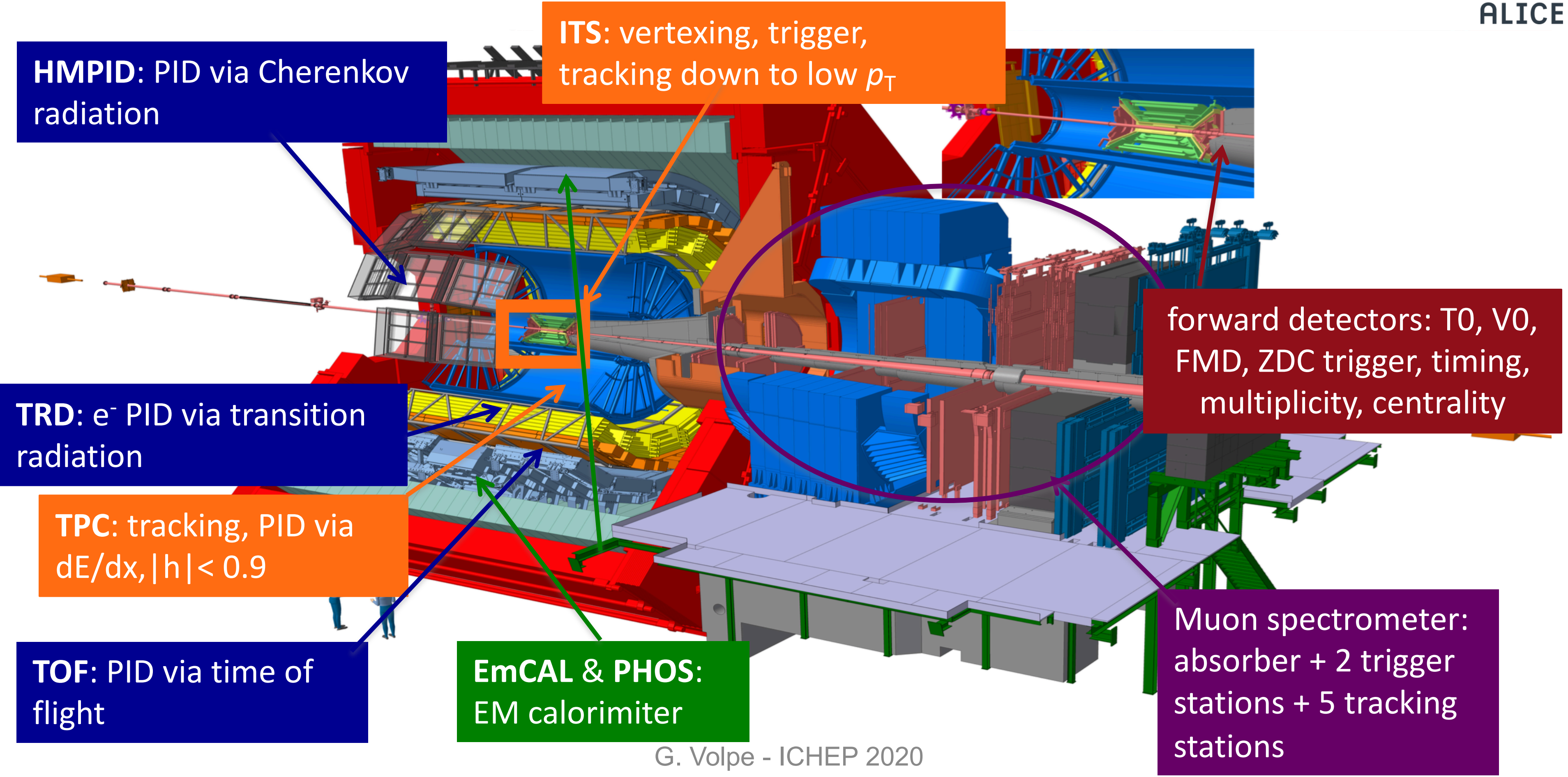
See Paraskevi Ganoti talk!
"Hadronic resonance production measured by ALICE at the LHC"

Conclusions

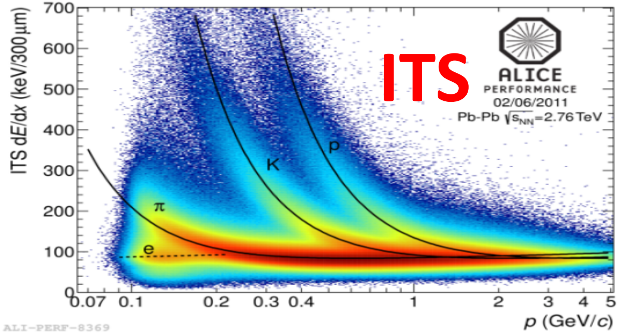
- ALICE has preformed a comprehensive study of π, K, p, K^0_s, Λ, Ξ, Ω, K^{0*} and ϕ production in different collision systems
- Production of (most) light-flavour hadrons in Pb-Pb at 5.02 TeV is described by statistical hadronization model with a single chemical freeze-out temperature (T_{ch} = 153 MeV).
- Yields and baryon/meson ratios evolve smoothly with multiplicity → connected to collectivity
- Enhancement of strangeness production observed from low to high-multiplicity pp events at different collision energy, poorly described by commonly used MC generators
- Measurements at different energies as a function of multiplicity seem to indicate that the hadrochemistry is driven by event activity regardless of collision energy.

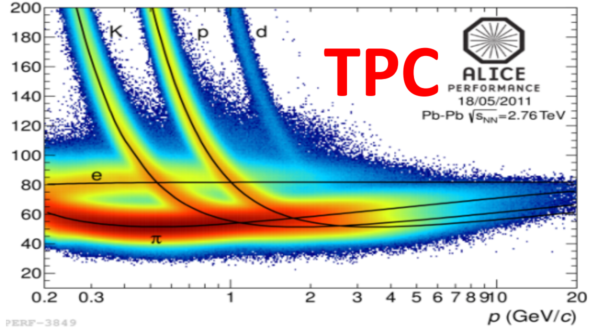
Backup

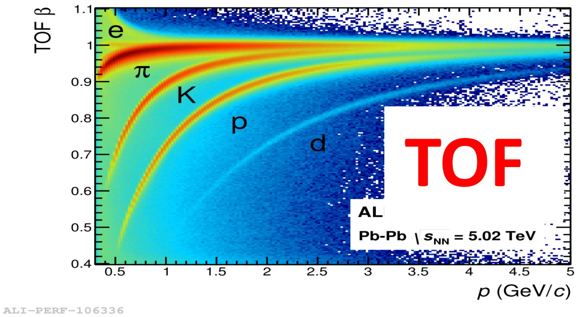
ALICE apparatus

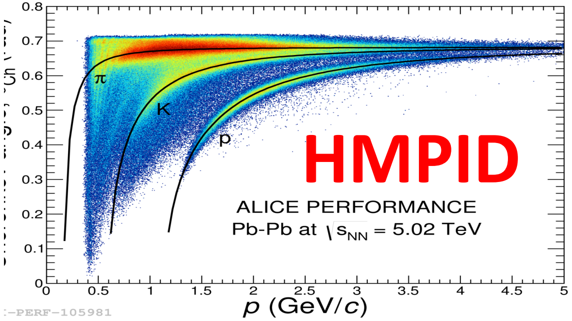


Charged hadron identification in ALICE



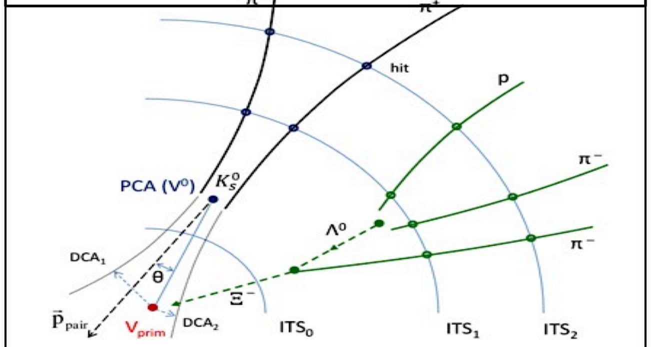


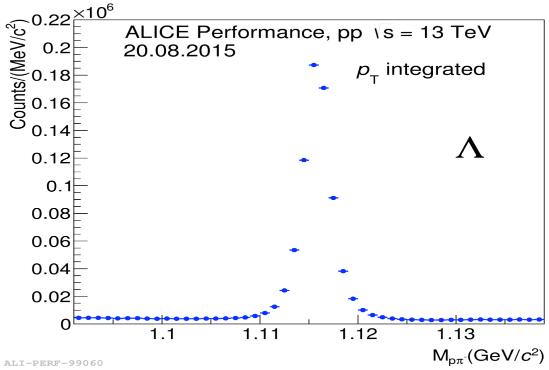




Topological PID

secondary vertex reconstruction + invariant mass analysis

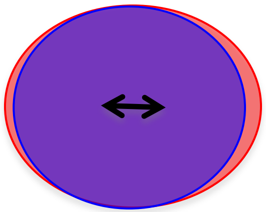




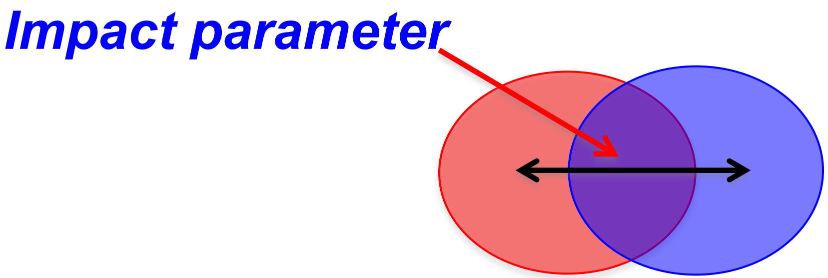
Particle identification via all known PID techniques in **0.1 GeV/c < p_T < 30 GeV/c**

Collision Geometry (centrality)

- Centrality: amount of overlap between nuclei
- Impact parameter: distance between centers of nuclei
- Impact parameter cannot be measured directly; measure
  - Charged-particle multiplicity (mostly $p^{\pm}$, $K^{\pm}$, p e anti-p)
  - Number of spectator neutrons (unaffected by collision)
  - Use models to map these measurements into impact parameter

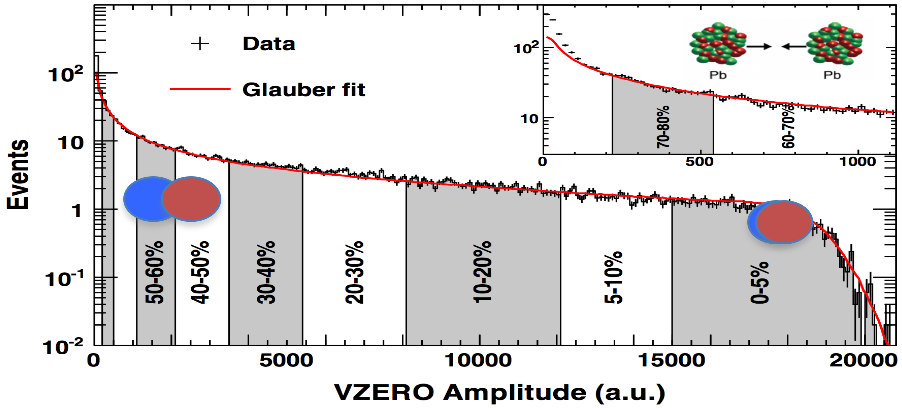


"Central"
Small impact parameter
Large system volume
Large charged-particle multiplicity

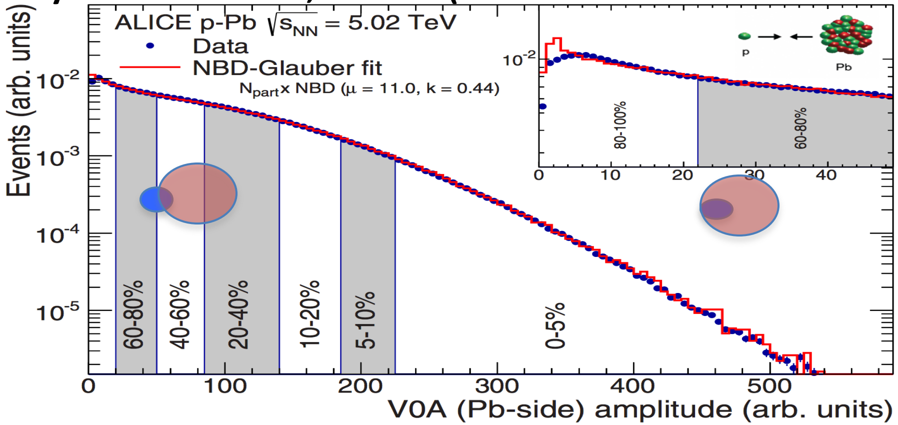


"Peripheral"
Large impact parameter
Small system volume
Samll charged-particle multiplicity

Multiplicity (centrality) measurement in ALICE



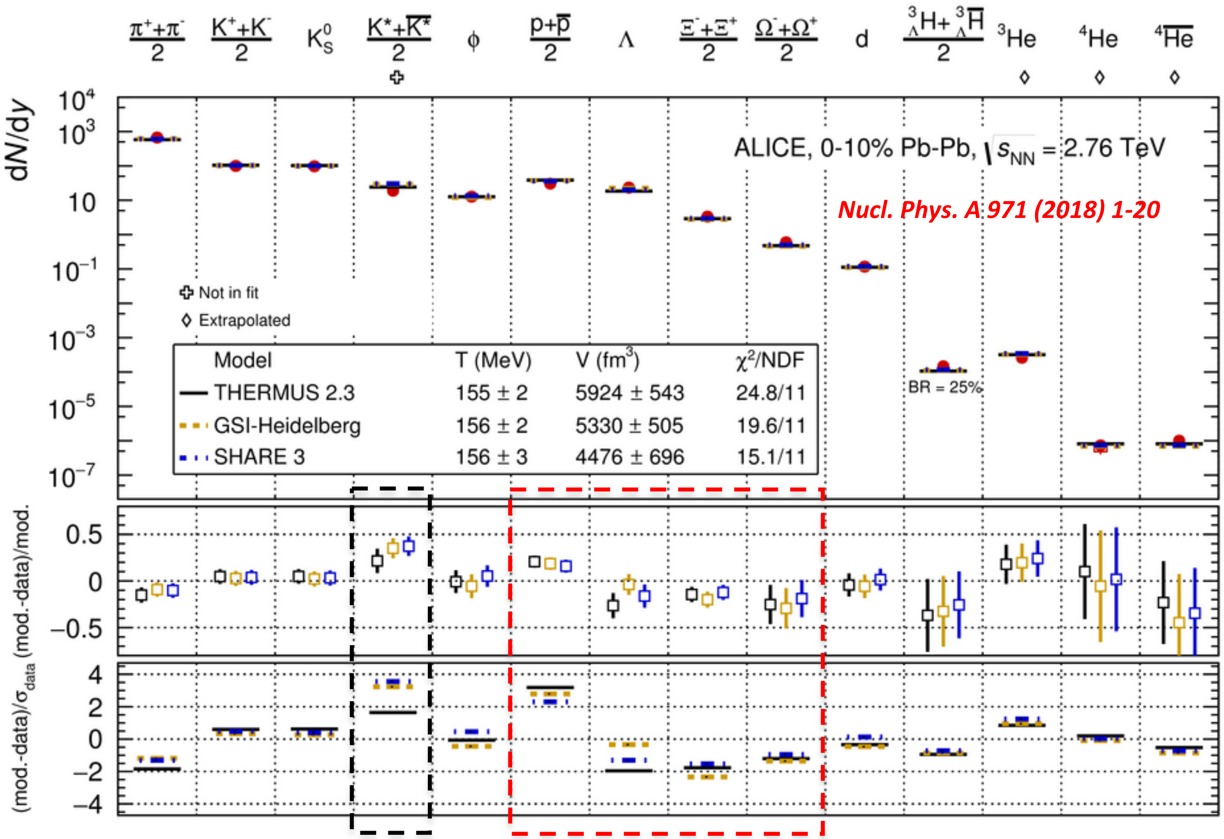
Phys. Rev. Lett. 106, 032301 (2011)



Phys. Rev. C 91 (2015) 064905

- Multiplicity is defined as the number of charged particles per event in $|\eta| < 0.5$
- Linked through the impact parameter to the collision centrality in Pb–Pb (**Glauber model**)
- ALICE measures the event activity at forward rapidity with the **V0 scintillators** placed at: $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C)
- Wide range of measured multiplicities
  - from $\langle dN_{ch}/d\eta \rangle \approx 2$ in low multiplicity pp collisions
  - to $\langle dN_{ch}/d\eta \rangle \approx 1600$ in central Pb–Pb collisions

Hadron yield: thermal model fit to Pb-Pb 2.76 TeV (0-10%)



Describes hadron production assuming **chemical equilibrium**

Production of (most) light-flavour hadrons in **Pb-Pb at 2.76 TeV** is described (χ^2/ndf ≈ 2) by thermal models with a **single chemical freeze-out** temperature, **T_{ch} ≈ 156 MeV**

Deviation for short-lived **K^{*0} resonance** that suffers from **re-scattering** in the late hadronic phase (excluded from fit)

Tensions between protons and multi-strange: incomplete hadron spectrum, baryon annihilation in hadronic phase, interacting hadron gas, ...?

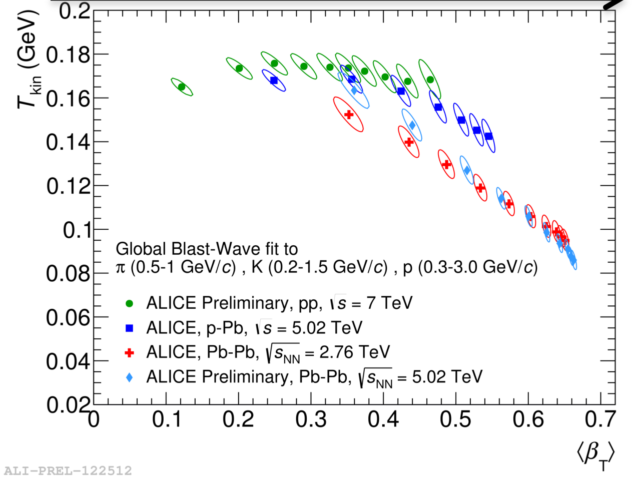
THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

Collectivity in small system: p_T spectra

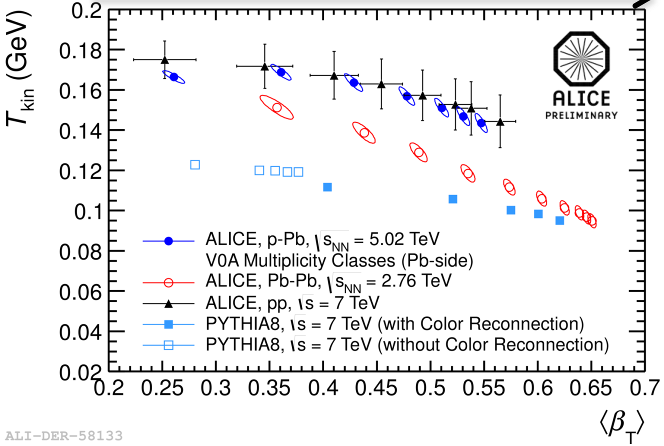
- Simultaneous **Global Blast-Wave** (simplified hydrodynamic model) fit to the π, K, p spectra:
  - in **Pb-Pb** increasing of $\langle \beta_T \rangle$ with centrality.
- In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity

At similar multiplicity, $\langle \beta_T \rangle$ is larger for smaller systems

Increasing multiplicity



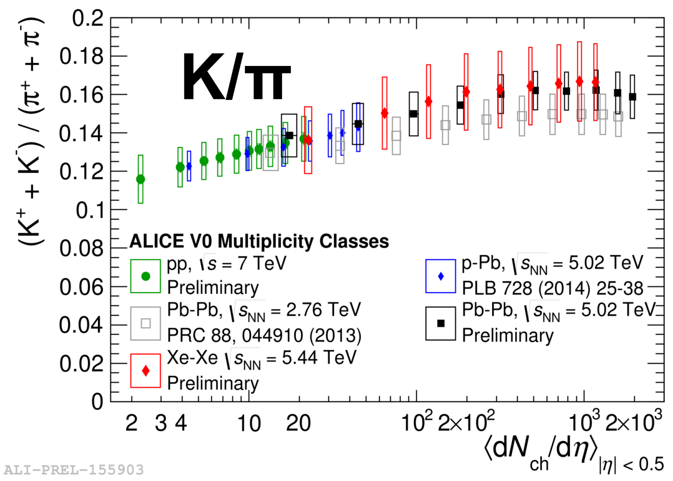
Increasing multiplicity

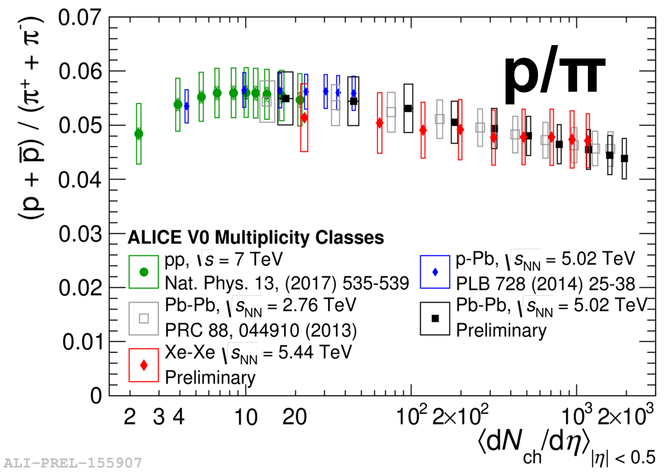


- Does this imply that the trend in different systems is driven by the same type of collectivity (e.g. radial flow)?!

- No!! QCD effects such as **color reconnection** (CR) can **mimic the effects of radial flow.**

Hadron yields: integrated particle ratios





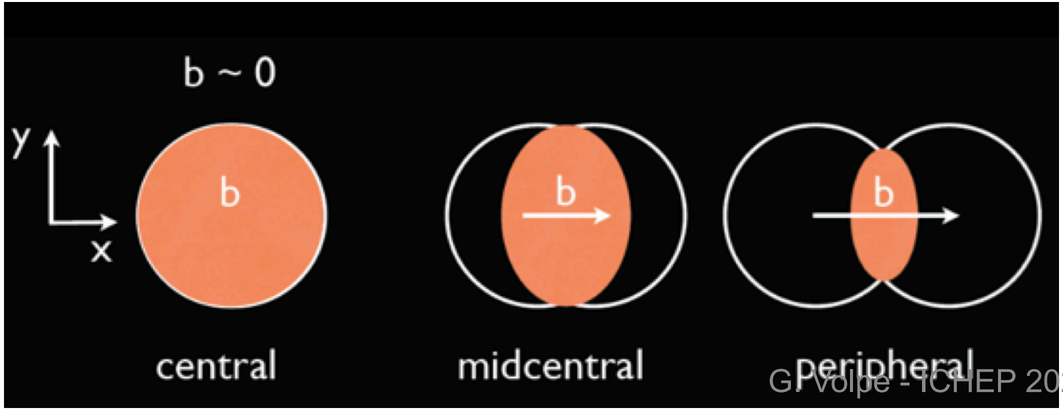
- p_T- integrated particle ratios in Pb-Pb at 5.02 TeV and Xe-Xe at 5.44 TeV are consistent within uncertainties with ratios measured in Pb-Pb at 2.76 TeV.
- The p/π ratio suggests a small decrease with centrality. The centrality dependent behavior is consistent with the hypothesis of the antibaryon-baryon annhilation in the hadronic phase (Phys. Rev Lett. 110, 042501). The effect is expected to be less important for the more dilute system created in peripheral collisions.
- Chemistry is driven by charged particle multiplicity, i.e. the size of the system (regardless of its type and center of mass energy)
- The lower temperature in thermal fit to Pb-Pb at 5.02 TeV data is driven by the increase in size of the system (a further test will be the thermal model fit to the Xe-Xe data).

Why does it flow?

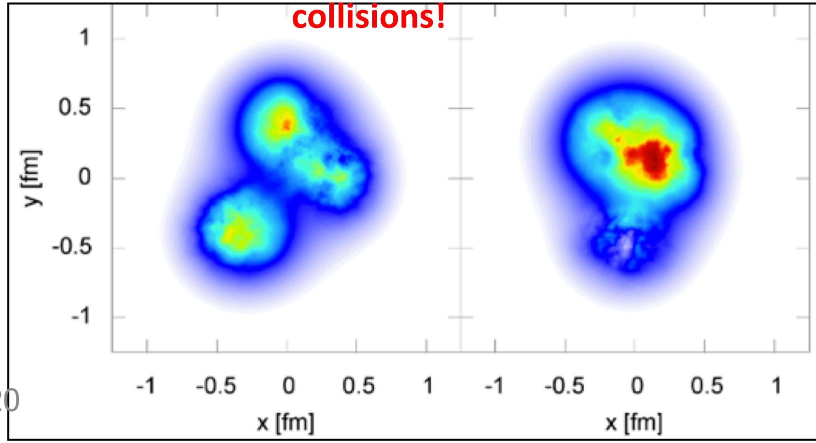
- At low p_T (< 10 GeV/c), it is commonly interpreted as the result of the hydrodynamic behaviour of strongly-interacting QCD matter:
  - strongly-interacting non-spherical system →anisotropic pressure → anisotropic flow

- Spatial anisotropies of the initial system are due to:
  - event-by-event fluctuations
  - impact parameter

In heavy-ion collisions, strong elliptical anisotropy, depending on centrality / impact parameter.

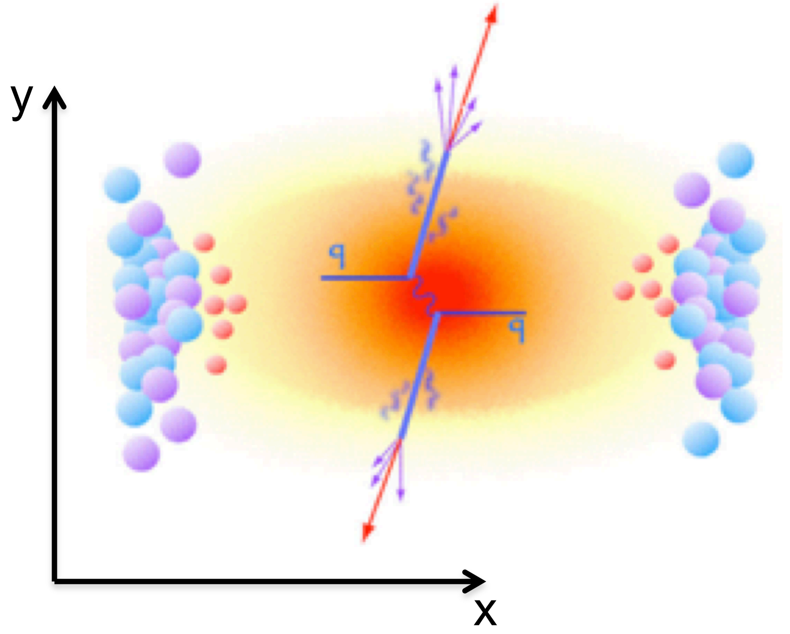


Spatial anisotropies also in p-p collisions!

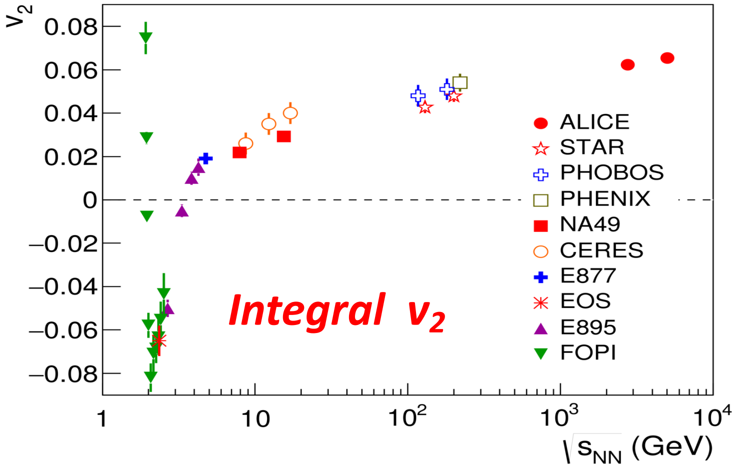


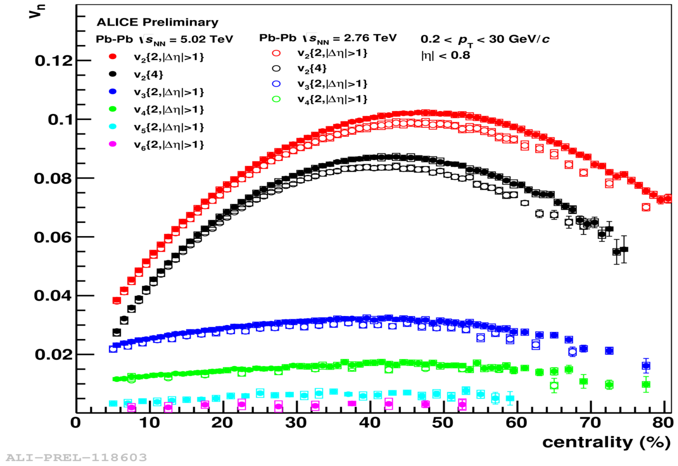
Why does it flow?

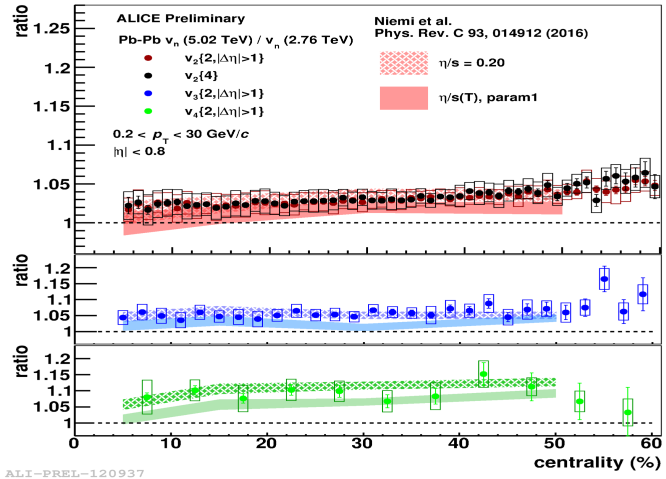
- At high p_T (> 10 GeV/c), mostly set by path length dependent **parton energy loss**



Elliptic flow

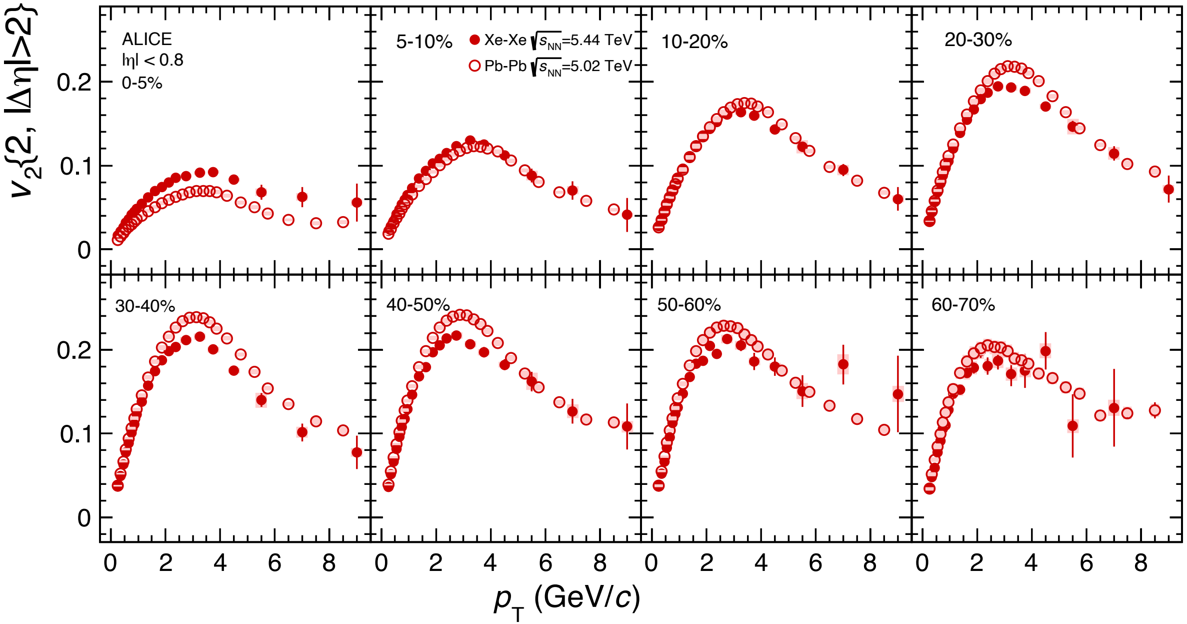






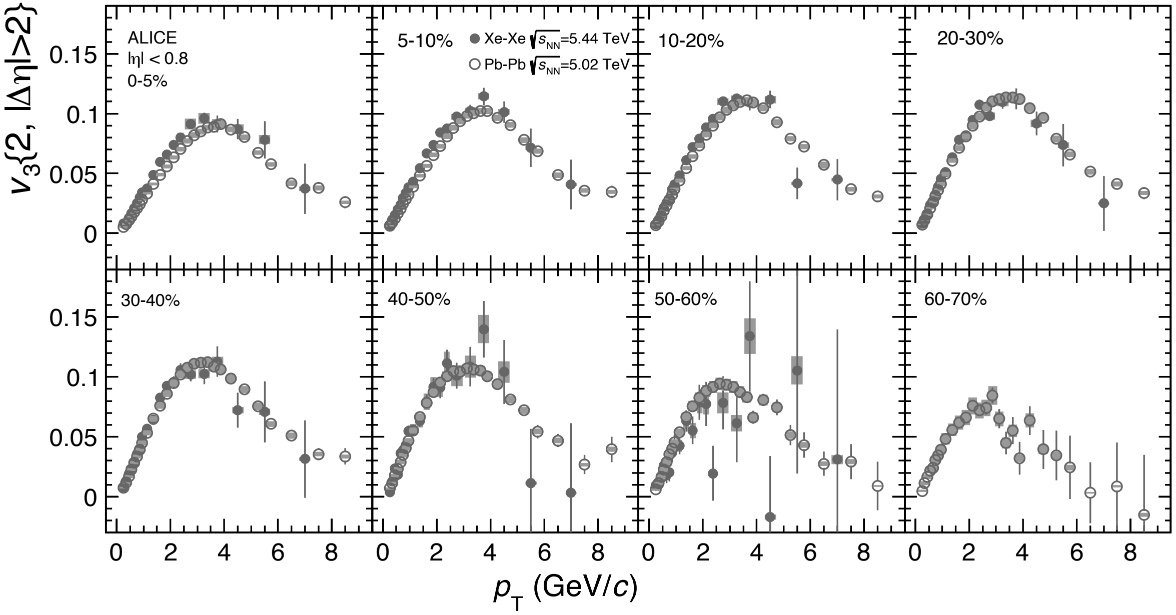
- Elliptic flow at LHC ≈ 30% larger than at RHIC
- The transfer of the spatial coordinate anisotropy to the momentum space brings information about the viscosity of the fluid, η.
  - η/s is the relevant parameter of the hydrodynamic theory (s = entropy density).
  - The system created at LHC has a very low viscosity $\eta/s = 0.2$ (perfect fluid).

Charged hadron flow in Pb-Pb and Xe-Xe collisions



- For the most central collisions, where the overlap geometry is expected to play a minimal role for both systems, v_2 is larger for Xe–Xe collisions.
- In terms of the initial state, this is expected for two reasons.
  - The first relates to the fact that the ^{129}Xe nucleus is deformed while the ^{208}Pb nucleus is not;
  - the second relates to the role of initial state fluctuations and the number of sources that contribute.

Charged hadron flow in Pb-Pb and Xe-Xe collisions



- For the most central collisions, where the overlap geometry is expected to play a minimal role for both systems, v_3 is larger for Xe–Xe collisions.
- In terms of the initial state, this is expected for two reasons.
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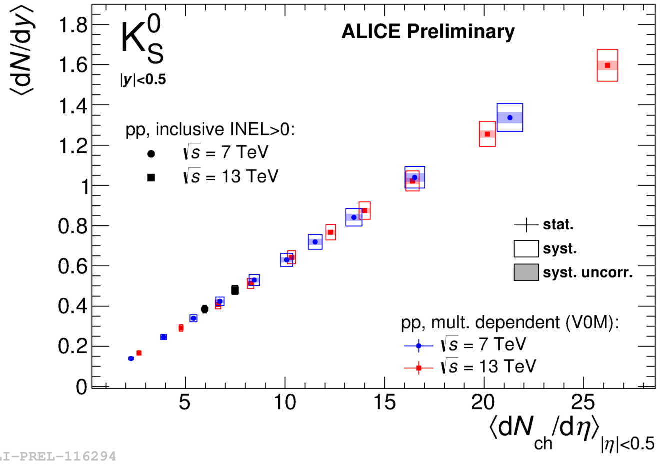
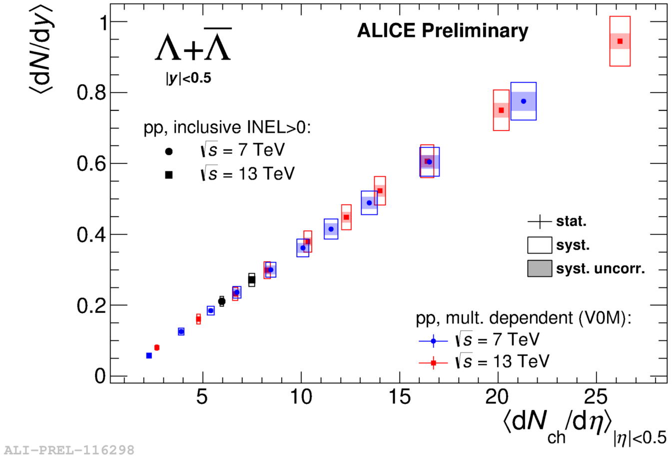
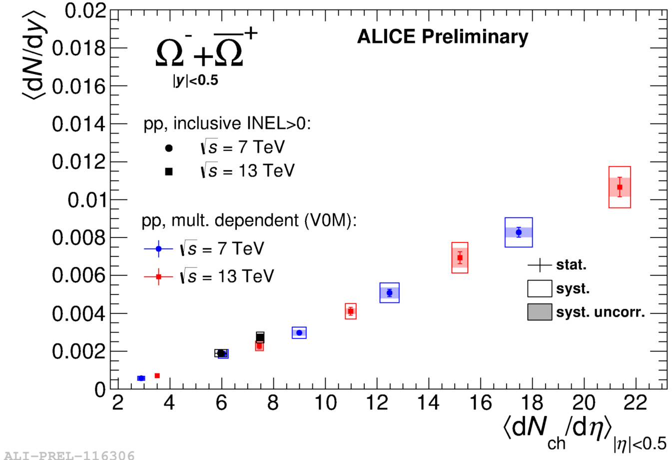
  - the second relates to the role of initial state fluctuations and the number of sources that contribute.

Strangeness production: pp at 7 and 13 TeV



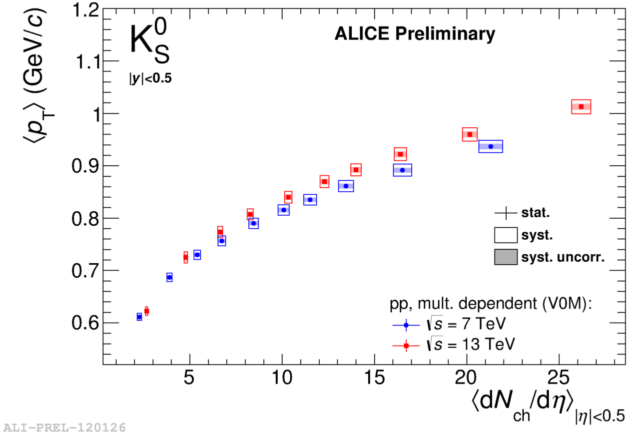


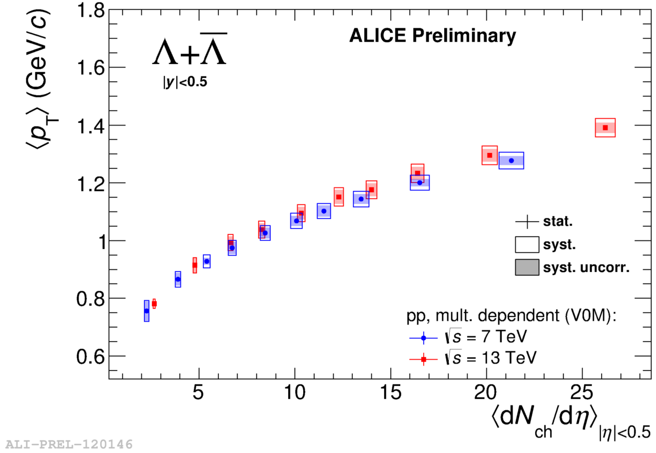


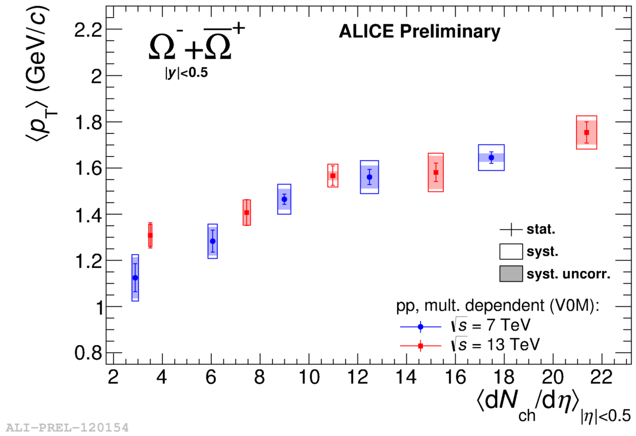
- Similar scaling is observed for strangeness production with $\langle dN_{ch}/d\eta \rangle$ in pp collisions at $\sqrt{s}$ = 7 TeV and 13 TeV.

- **Strange hadron production is collision energy independent at similar multiplicity.**

Strangeness production: pp at 7 and 13 TeV







- $\langle p_T \rangle$ of K^0_s at 13 TeV $\gtrsim \langle p_T \rangle$ of K^0_s at 7 TeV at similar charged particle multiplicity densities.
- Λ and Ω: $\langle p_T \rangle$ are similar within systematic uncertainties.
- **Yields scale well with √s, while $\langle p_T \rangle$ not!**

PYTHIA and DIPSY

PYTHIA Lund string model:

- Confined color fields→ "string" with tension ~ 1 GeV/fm
- String breaking → hadron formation
- MPI + Color Reconnection mechanisms at play in high energy hadronic interactions

DIPSY partonic model

- implements color ropes in high density environment:
  - densely packed strings → increase in string tension
  - Higher string tension → more baryons and more flavours ≠ (u,d)

EPOS model

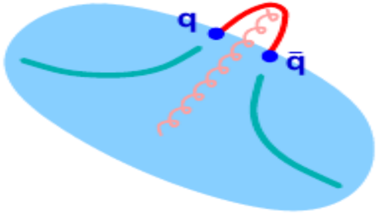
Phys. Rev. C **93** 014911 (2016) "fluid-jet interaction"

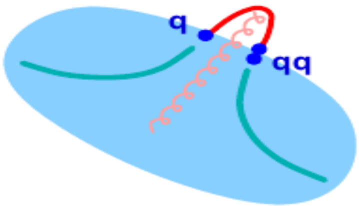
Describes pp, p–A ,and A–A collisions with a common framework

Hydrodynamical phase + hadronization processes at intermediate p_T where the interaction between bulk matter and jets is considered

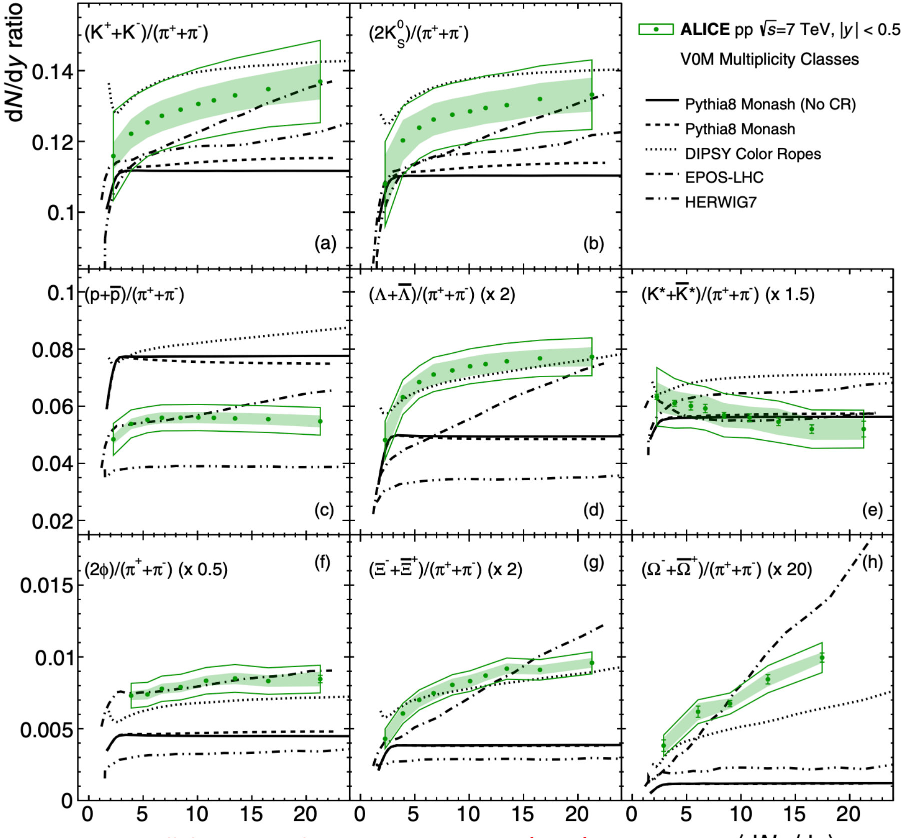
Baryon-meson effect where a quenched jet hadronizes with flowing medium quarks

"Considering transverse fluid velocities up to 0.7*c*, and thermal parton momentum distributions, one may get a "push" of a couple of GeV/c to be added to the transverse momentum of the string segment. This will be a crucial effect for intermediate p_T jet hadrons."





Strangeness - p_T –integrated yield as a function of multiplicity



ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)

PYTHIA underestimates strangeness production in pp and no progression with multiplicity is foreseen

DIPSY in qualitative agreement with measured ratios