Particles and Nuclei International Conference
Beijing (China) – 1 to 5 September 2017

ALICE

Strangeness production in pp, p–Pb and Pb–Pb collisions at LHC energies measured with ALICE

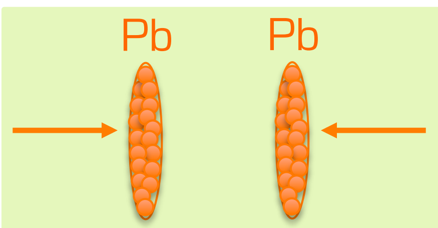
Domenico Colella
Istituto Nazionale di Fisica Nulceare, Sezione di Bari
on behalf of the ALICE Collaboration

INFN
Istituto Nazionale di Fisica Nucleare

Introduction

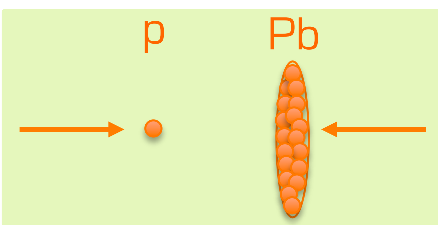
Physics motivation

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**



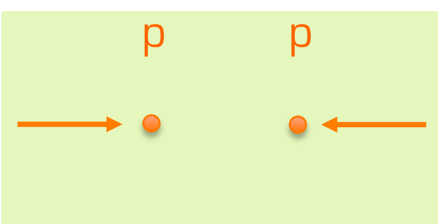
Pb–Pb

- ✓ QGP study
- ○ collected data at $\sqrt{s}$ = 2.76, 5.02 TeV



p–Pb *(intermediate reference between pp and Pb–Pb)*

- ✓ Initial state effects (shadowing/gluon saturation)
- ○ collected data at $\sqrt{s}$ = 5.02, 8.16 TeV



pp *(benchmark for heavy-ion physics)*

- ✓ Particle production mechanisms at low (soft QCD) and high (pQCD) transverse momentum
- ○ collected data at $\sqrt{s}$ = 0.9, 2.76, 5.02, 7, 8.16, 13 TeV

Introduction

Physics motivation

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**

Several phenomena (e.g. common $\langle \beta_T \rangle$ and T_{kin} in blast-wave fit to identified spectra[1], mass ordering of v_2 in p—Pb[2]) attributed to the presence of a QCD medium in local thermodynamic equilibrium in the final state of a Pb—Pb collision are also observed in pp and p—Pb collisions

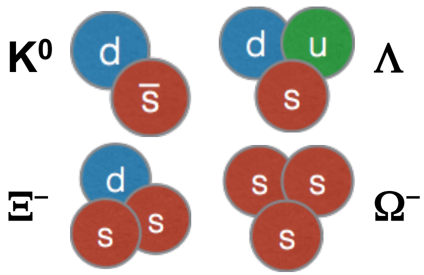
Strangeness production in pp, p—Pb and Pb—Pb collisions

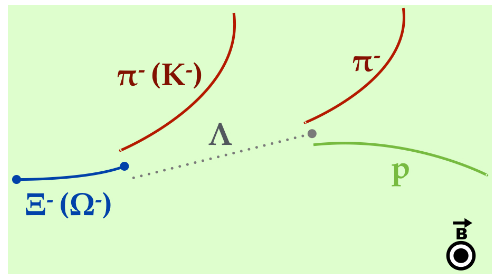
- **Collectivity**
  - ✓ Baryon anomaly (Λ/K^0_S ratio)
- **Hadrochemistry**
  - ✓ Strangeness enhancement

[1] preliminary, Backup
[2] PLB 726 (2013) 164

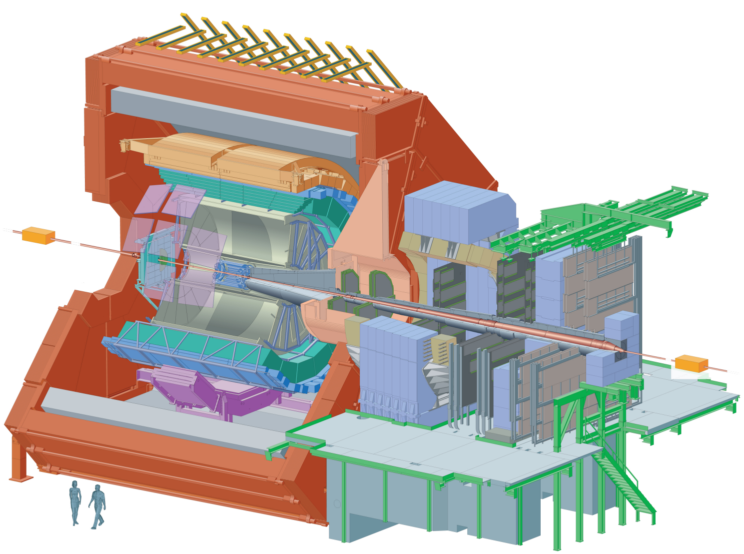
Introduction

(Multi-)Strange hadrons detection in ALICE



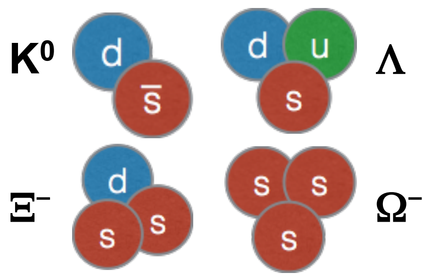


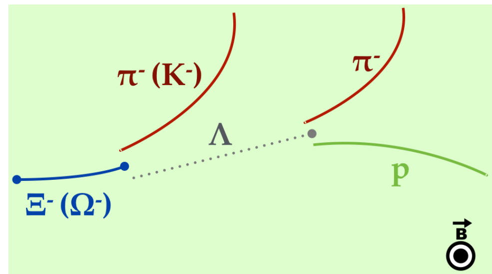
$K^0_S \rightarrow \pi^-\pi^+$ (B.R. 69.2%)
$\Lambda \rightarrow p\pi^-$ (B.R. 63.9%)
$\Xi \rightarrow \Lambda\pi^-$ (B.R. 99.9%)
$\Omega \rightarrow \Lambda K^-$ (B.R. 67.8%)



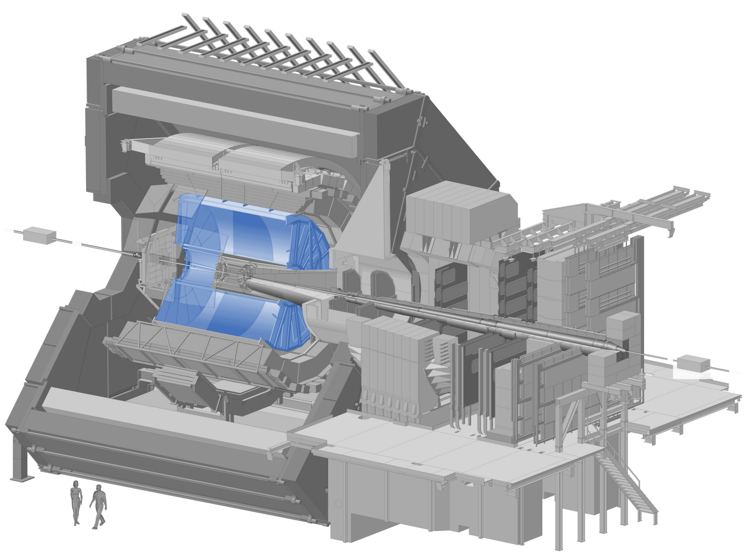
Introduction

(Multi-)Strange hadrons detection in ALICE



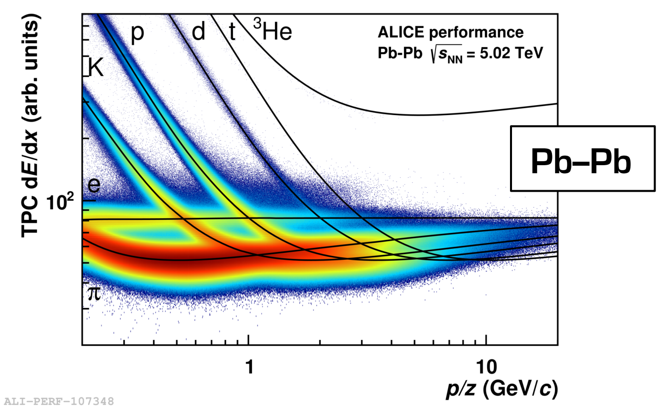


$K^0_S \rightarrow \pi^-\pi^+$ (B.R. 69.2%)
$\Lambda \rightarrow p\pi^-$ (B.R. 63.9%)
$\Xi \rightarrow \Lambda\pi^-$ (B.R. 99.9%)
$\Omega \rightarrow \Lambda K^-$ (B.R. 67.8%)



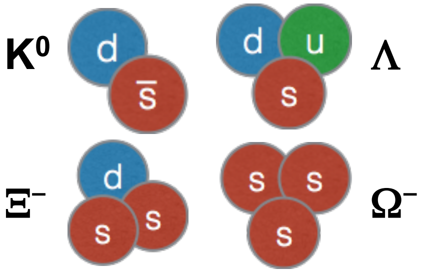
Detectors used in this study:

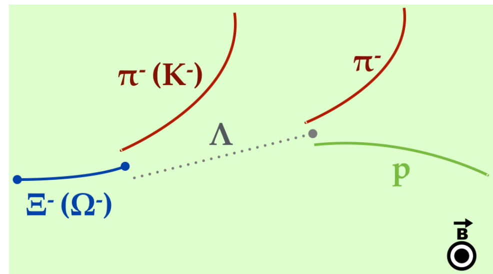
i. **TPC:** Tracking, Vertexing, PID (dE/dx)
ii. **ITS:** Tracking, Vertexing
iii. **V0:** Trigger, Multiplicity/Centrality classes



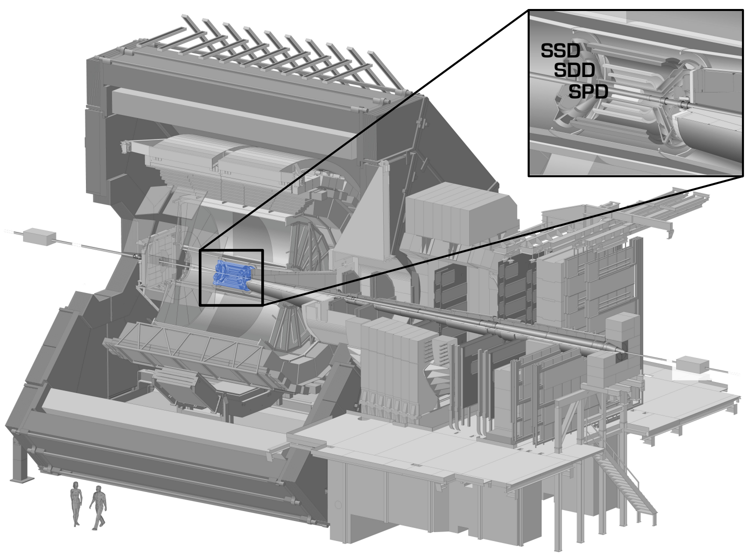
Introduction

(Multi-)Strange hadrons detection in ALICE



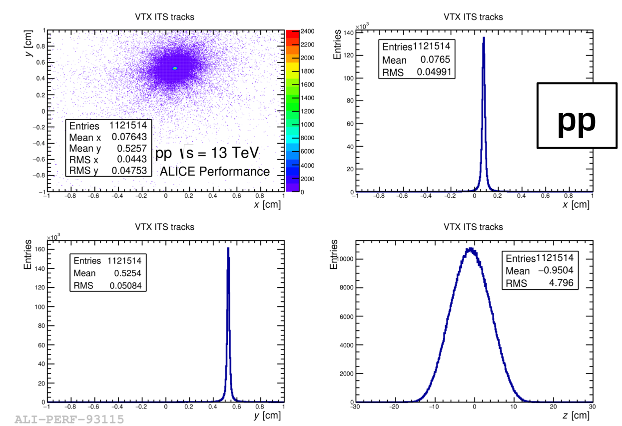


$K^0_S \rightarrow \pi^-\pi^+$ (B.R. 69.2%)
$\Lambda \rightarrow p\pi^-$ (B.R. 63.9%)
$\Xi \rightarrow \Lambda\pi^-$ (B.R. 99.9%)
$\Omega \rightarrow \Lambda K^-$ (B.R. 67.8%)



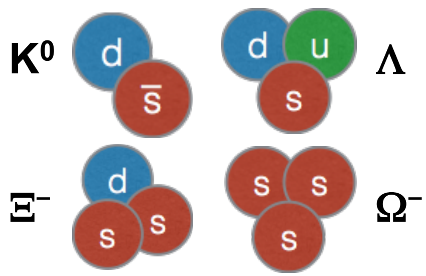
Detectors used in this study:

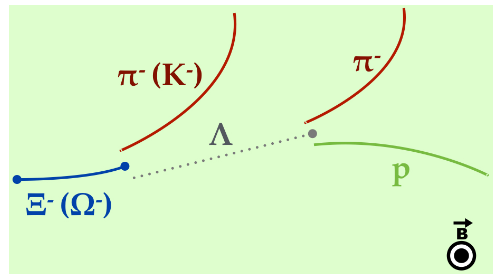
i. **TPC:** Tracking, Vertexing, PID (dE/dx)
ii. **ITS:** Tracking, Vertexing
iii. **V0:** Trigger, Multiplicity/Centrality classes



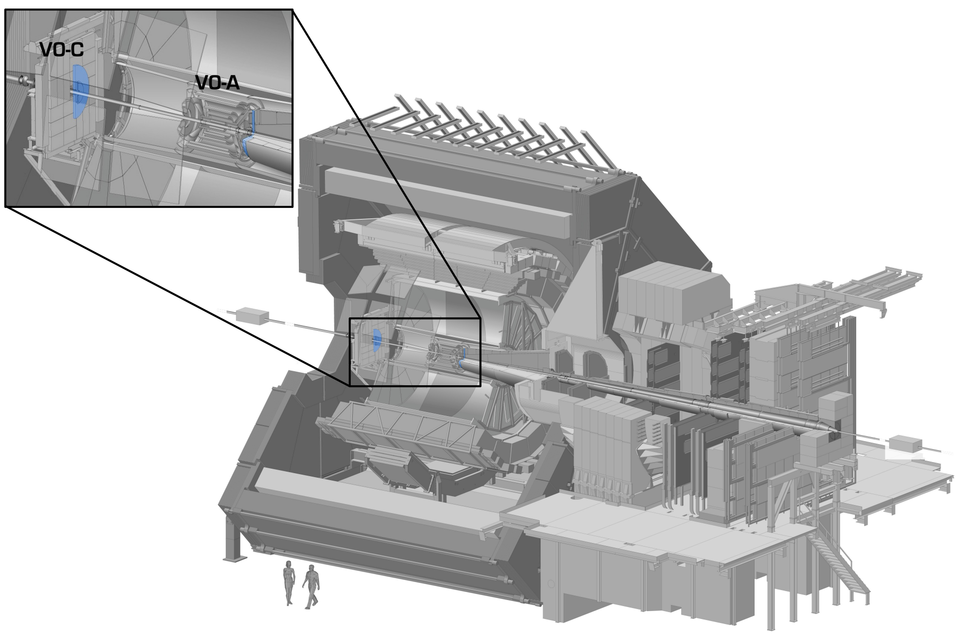
Introduction

(Multi-)Strange hadrons detection in ALICE



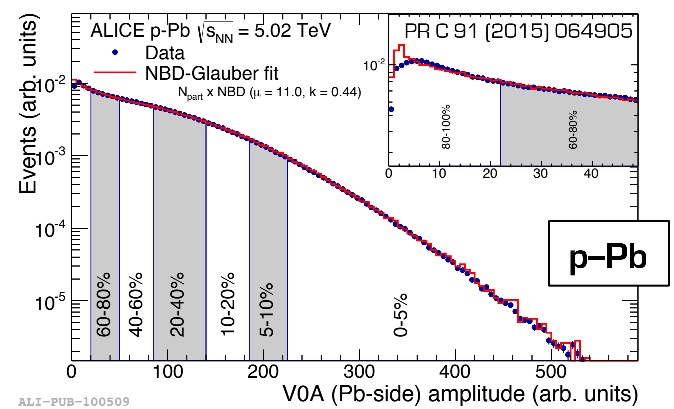


$K^0_S \rightarrow \pi^-\pi^+$ (B.R. 69.2%)
$\Lambda \rightarrow p\pi^-$ (B.R. 63.9%)
$\Xi \rightarrow \Lambda\pi^-$ (B.R. 99.9%)
$\Omega \rightarrow \Lambda K^-$ (B.R. 67.8%)



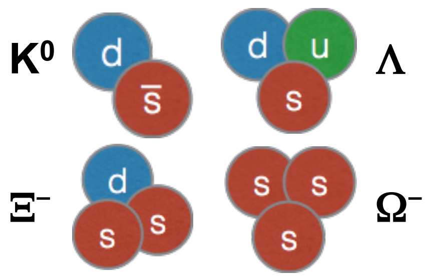
Detectors used in this study:

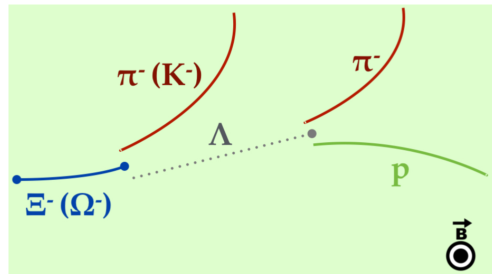
i. **TPC:** Tracking, Vertexing, PID (dE/dx)
ii. **ITS:** Tracking, Vertexing
iii. **V0:** Trigger, Multiplicity/Centrality classes



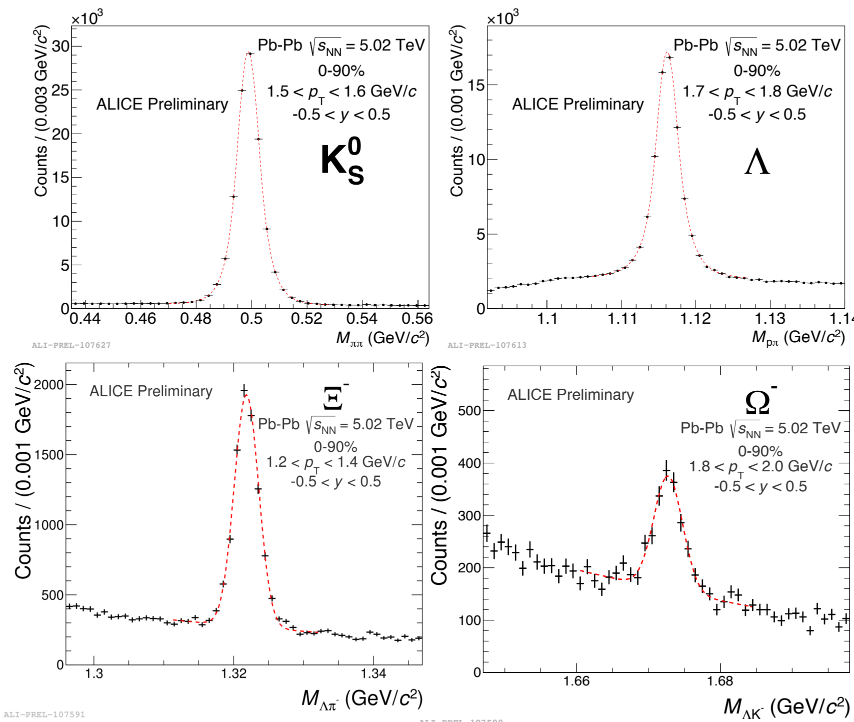
Introduction

(Multi-)Strange hadrons detection in ALICE





$K^0_S \rightarrow \pi^-\pi^+$ (B.R. 69.2%)
$\Lambda \rightarrow p\pi^-$ (B.R. 63.9%)
$\Xi \rightarrow \Lambda\pi^-$ (B.R. 99.9%)
$\Omega \rightarrow \Lambda K^-$ (B.R. 67.8%)



Strange and multi-strange hadrons in ALICE are reconstructed via their weak decay topology:

① charged tracks reconstructed in the tracking system (ITS + TPC)

② specific ionization (in the TPC) used to identify daughters

③ particle candidates obtained by combining reconstructed tracks and applying cuts on geometry and kinematics

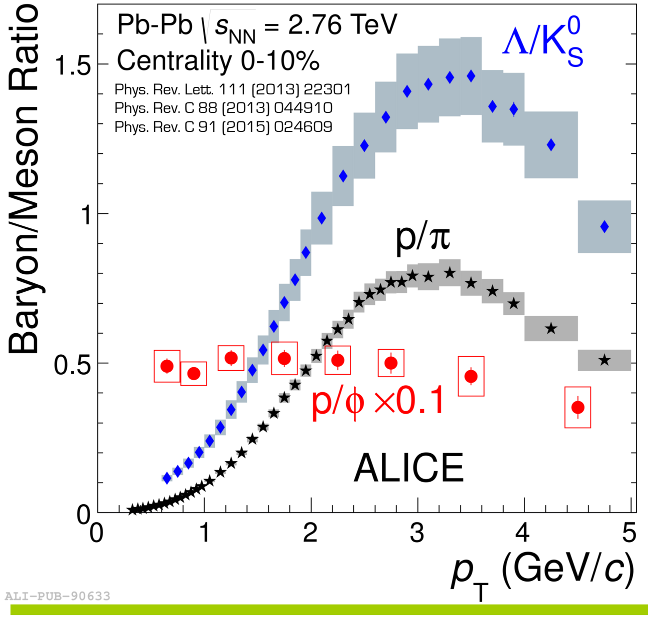
Yields extracted in different transverse momentum bins via invariant mass analysis.

Results

Results

Baryon-to-meson ratio

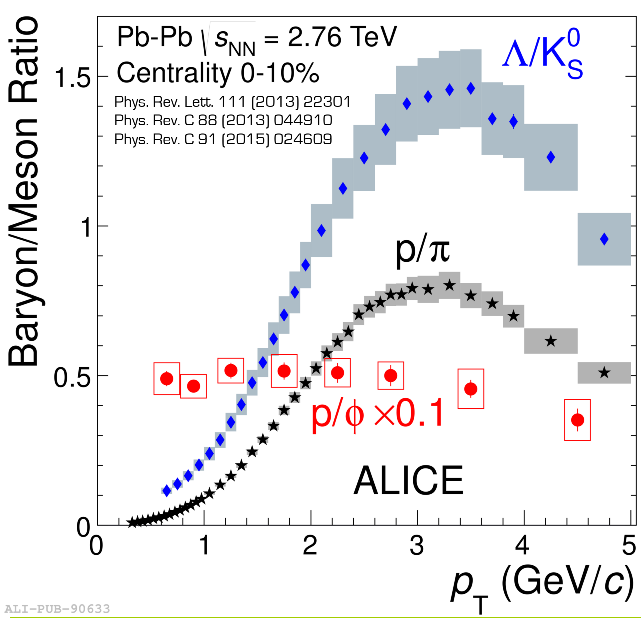
- In central Pb–Pb collisions
  - ✓ p/π, Λ/K^0_S enhancement at intermediate p_T

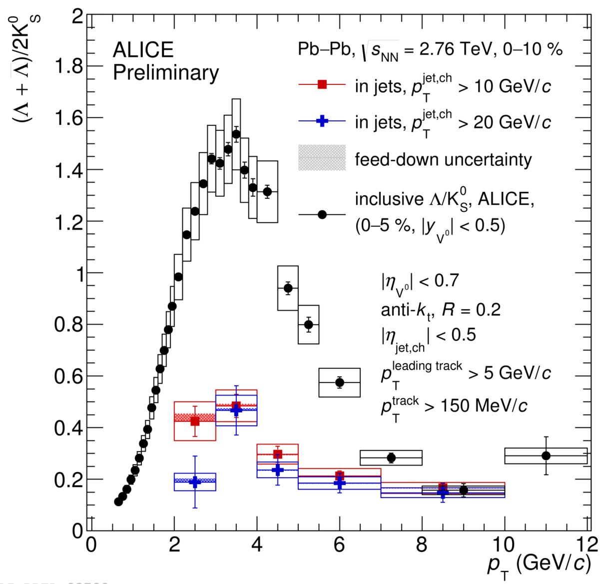


Results

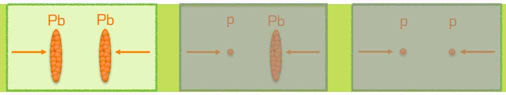
Baryon-to-meson ratio

- 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



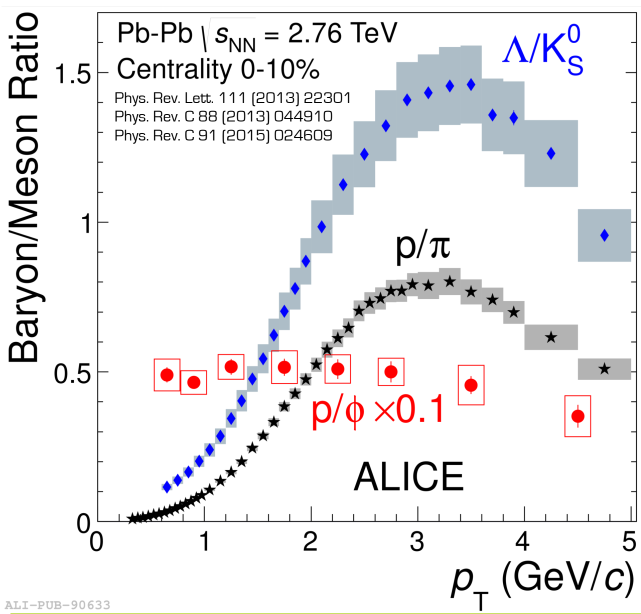


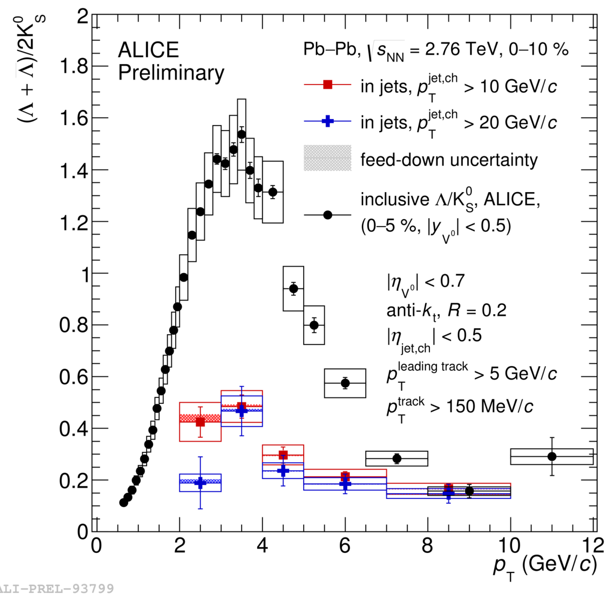
Results

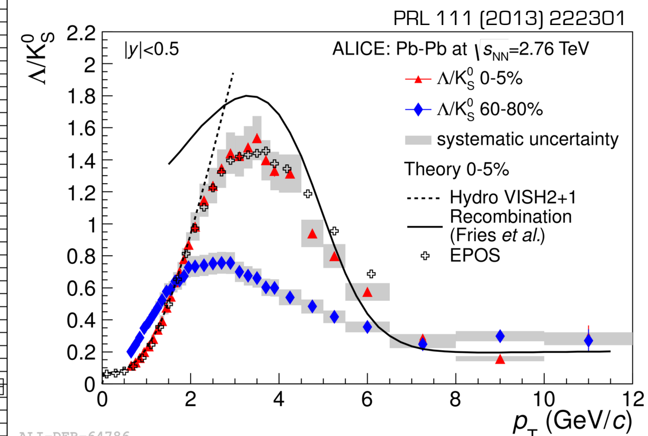


Baryon-to-meson ratio

- 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

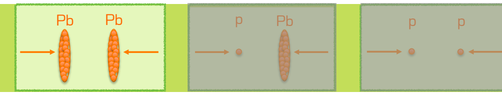






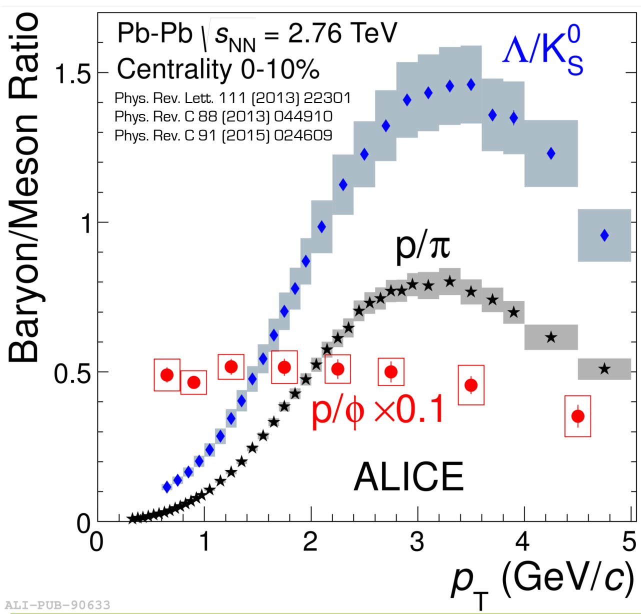
Song, Phys. Lett. B 658 (2008) 279
Fries et al., Ann. Rev. Nucl. Part. Sci. 58 (2008) 177
Werner, Phys. Rev. Lett. 109 (2012) 102301

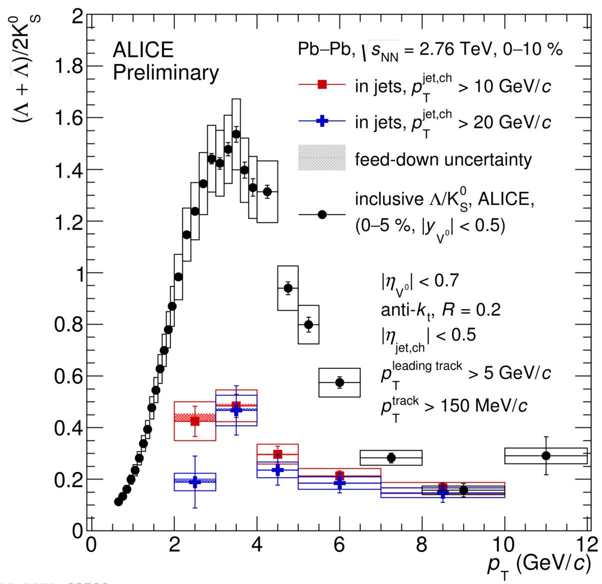
Results

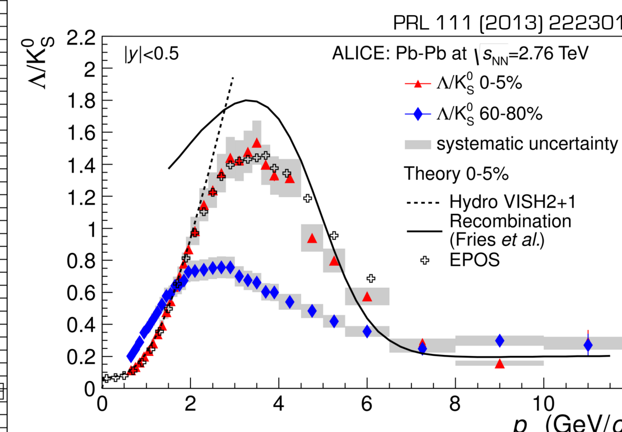


Baryon-to-meson ratio

- 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
  - ✓ 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)



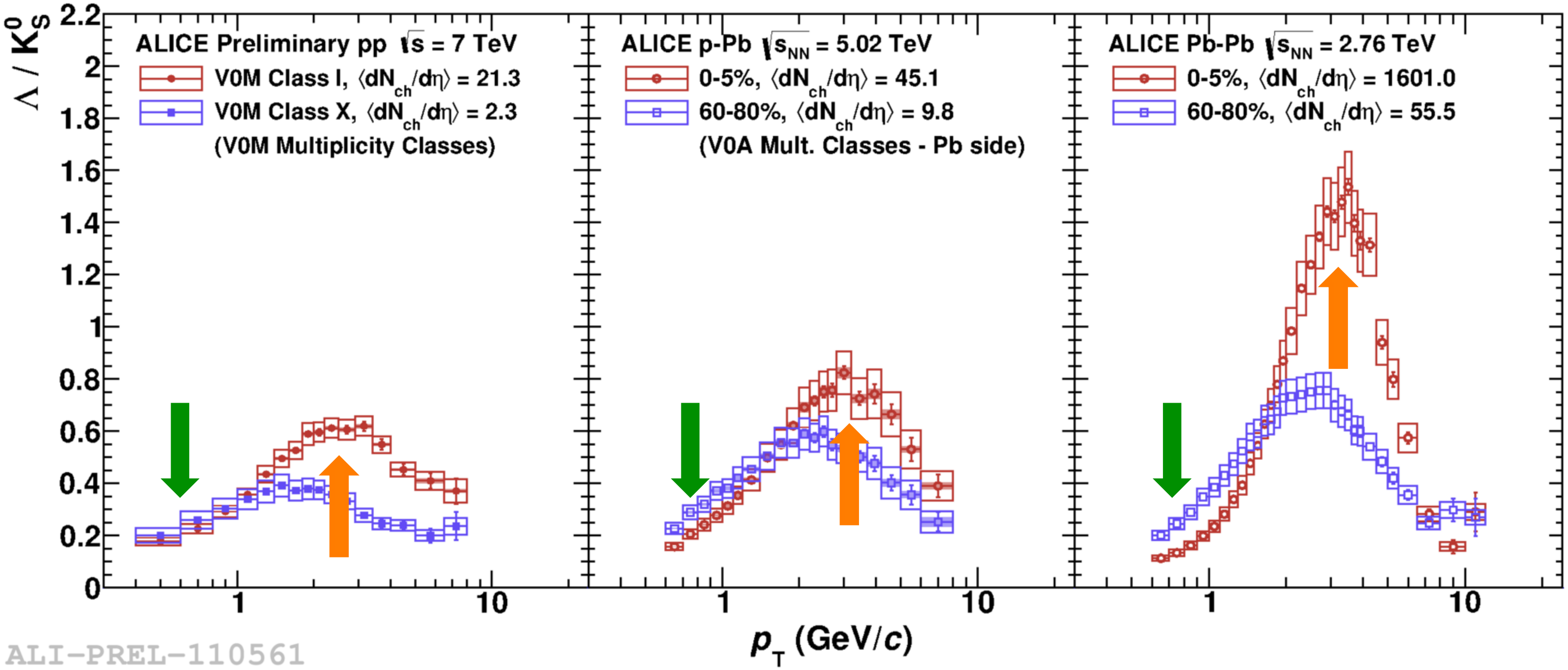




Song, Phys. Lett. B 658 (2008) 279
Fries et al., Ann. Rev. Nucl. Part. Sci. 58 (2008) 177
Werner, Phys. Rev. Lett. 109 (2012) 102301

Results

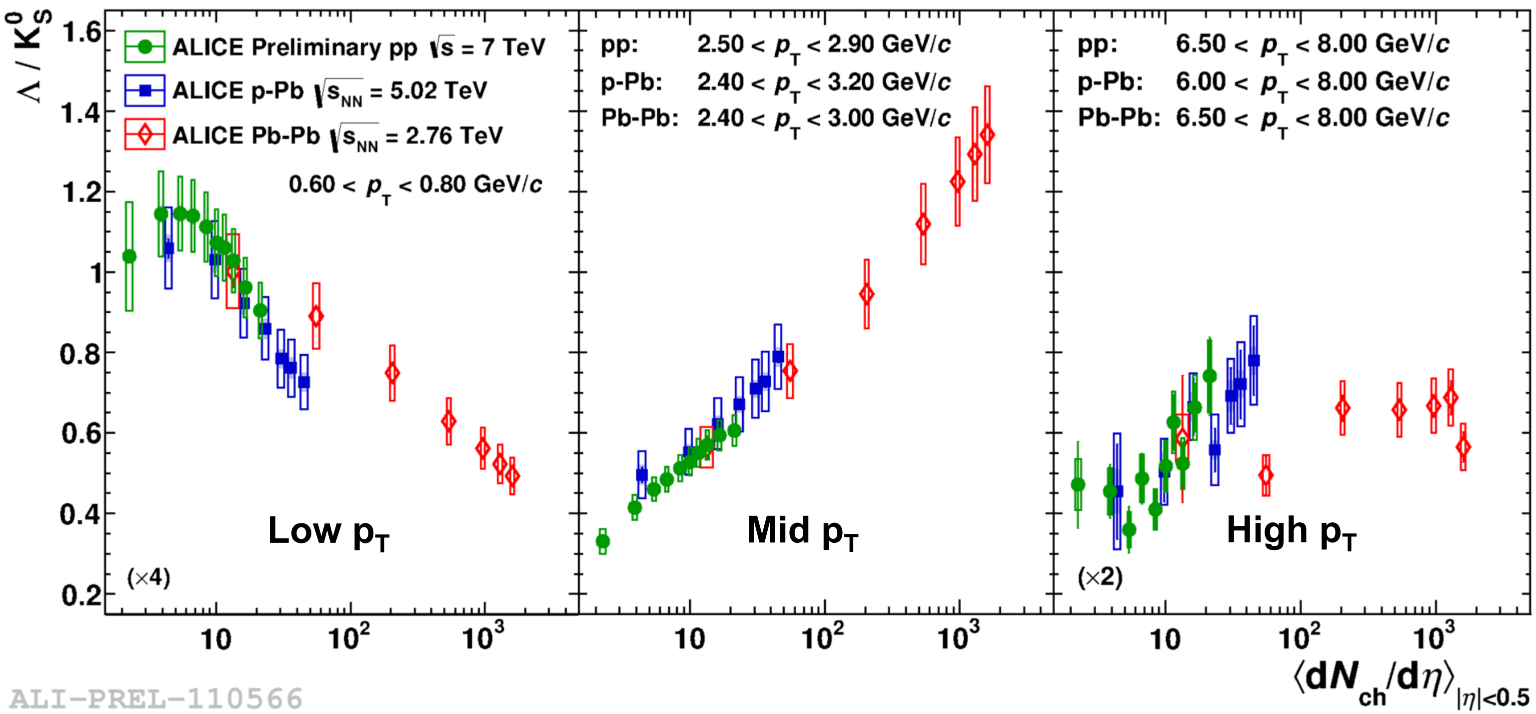
Baryon-to-meson ratio



- 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

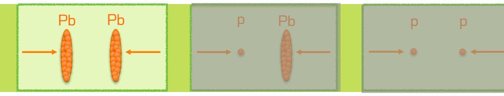
Baryon-to-meson ratio



- 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



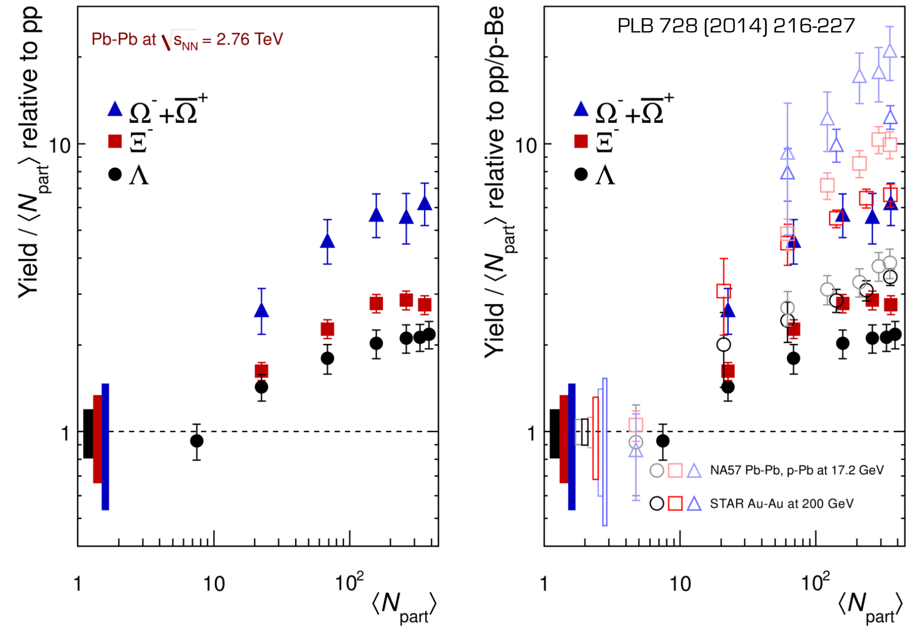
Strangeness enhancement

NA57: J. Phys. G 32, 427 (2006),
J. Phys. G 37, 045105 (2010)
STAR: Phys. Rev. C 77, 044908 (2008)

- Historically among the first suggested probes of Quark Gluon Plasma [Phys. Rev. Lett. 48, 1066 (1982)]

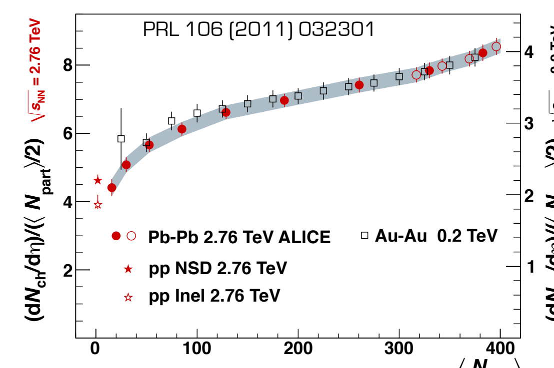
$$E = \frac{Yield_{PbPb} / < N_{part} >}{Yield_{pp} / 2}$$

- Measured at SPS, RHIC and LHC and found to:
  - ✓ increase with strangeness content of the particle
  - ✓ increase with collision centrality
  - ✓ decrease with increasing center-of-mass energy (contrary to the initial expectation)
  - ✓ be in agreement with grand-canonical statistical-thermal model for central Pb–Pb collisions

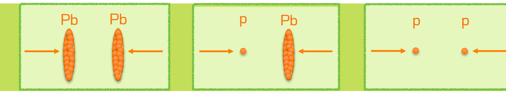


ALI-DER-80680

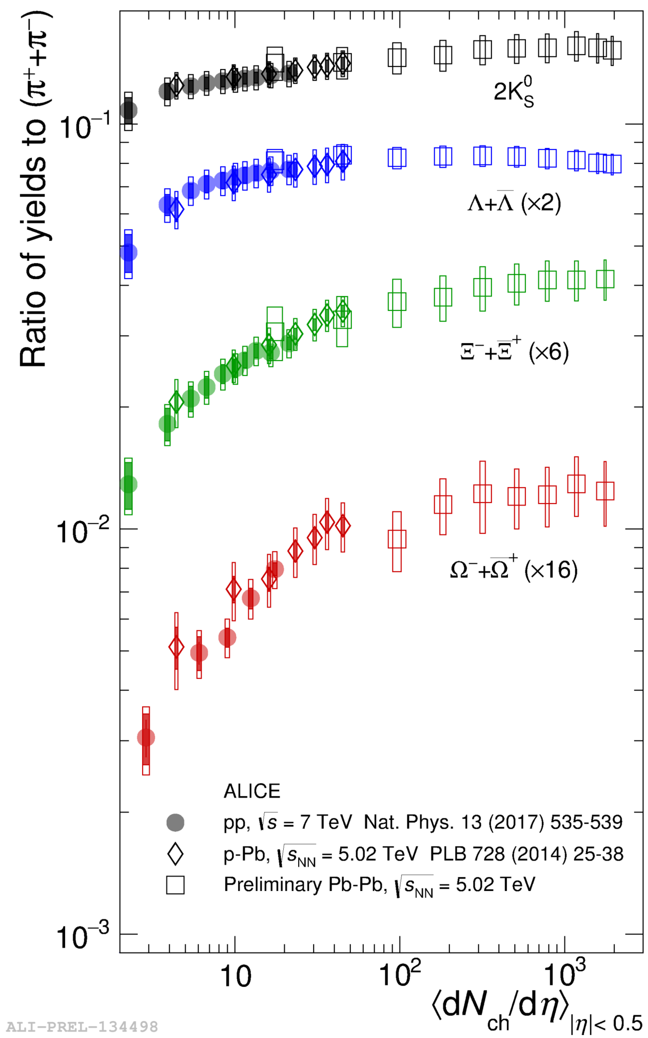
- Is the $\langle N_{part} \rangle$ scaling the right assumption?
Charged particle production does not scale linearly with $\langle N_{part} \rangle$ → Look at ratio-to-pion vs $\langle dN_{ch}/d\eta \rangle$



Results



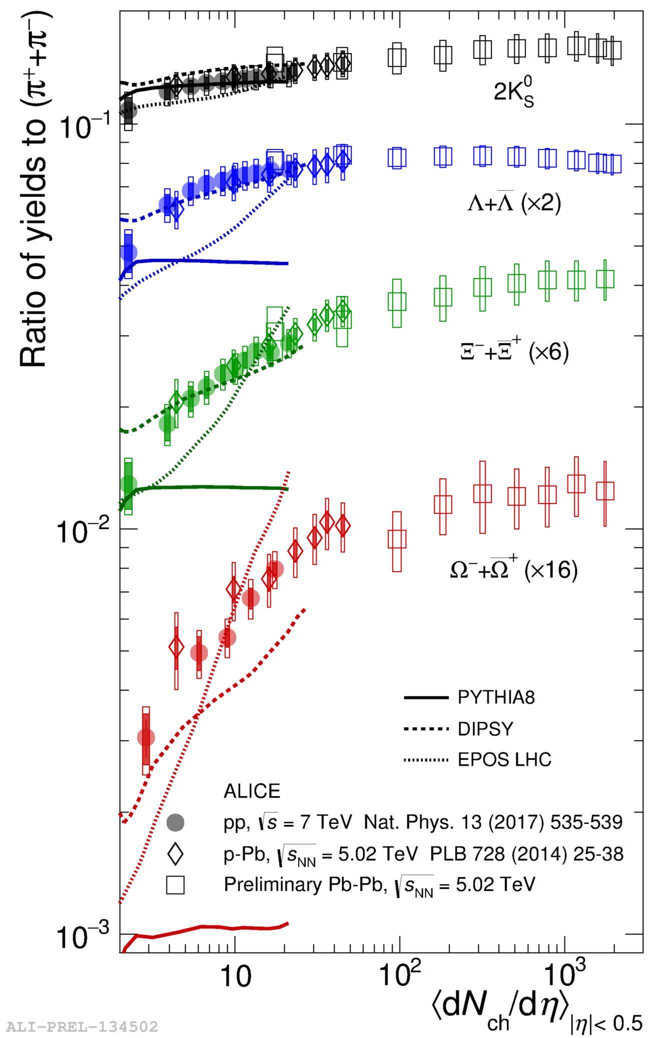
Strangeness enhancement



- Hyperon to pion ratios in the three systems
  - ✓ Significant enhancement of strange to non-strange hadron production from (low multiplicity) pp to most central Pb—Pb collisions (classical Strangeness Enhancement)
  - ✓ Smooth evolution from lower multiplicity pp and p–Pb collisions to most central Pb—Pb collisions
  - ✓ Steeper slope with more strange content
  - ✓ Almost saturated trend in most central Pb—Pb collisions for all particles
  - ✓ Similar behavior for pp and p—Pb both in terms of values and trend with multiplicity

Results

Strangeness enhancement – QCD inspired model

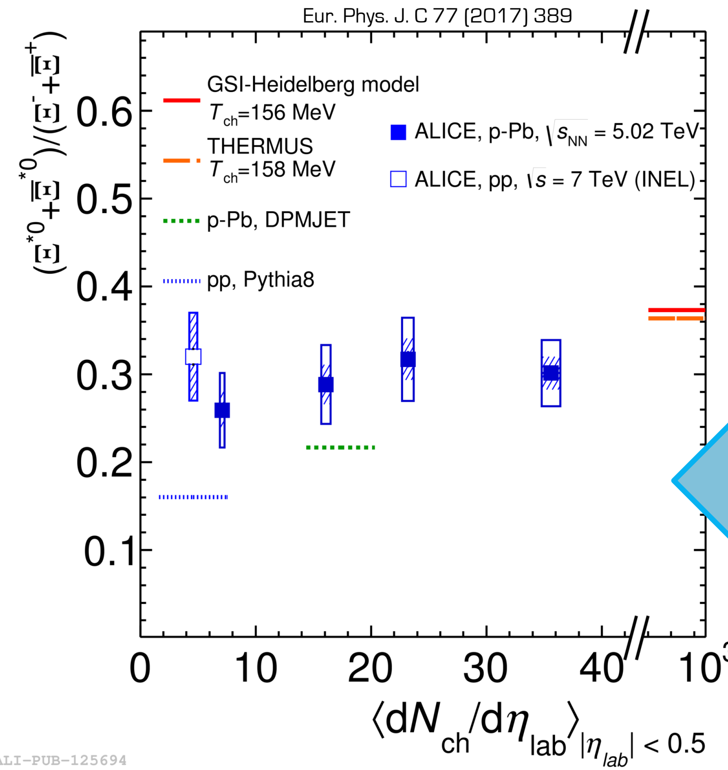


- QCD inspired models fail to describe the data
  - ✓ **PYTHIA8** (Color Reconnection) completely misses the behavior of the data
  - ✓ **DIPSY** (Color Ropes) cannot simultaneously reproduce the observed enhancement for all four strange hadrons
  - ✓ **EPOS LHC** (Core-corona approach) only qualitatively describes the trend

Results

Strangeness enhancement – Multiplicity dependence

- What is driving the increase with increasing multiplicity?
  - ① The mass of the hadrons → No



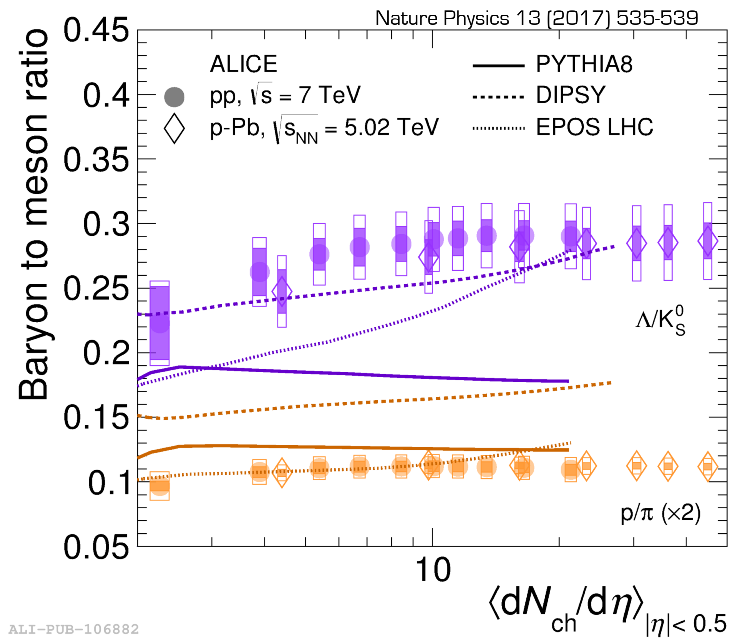
see talk
by E. Fragiacomo
Sun. 14:25
"Hot and dense matter physics" session

Ξ(1530)⁰ resonance:
- same strangeness content as Ξ
- intermediate in mass between Ξ and Ω

In p–Pb collisions, Ξ^{*}/Ξ flat versus multiplicity

Strangeness enhancement – Multiplicity dependence

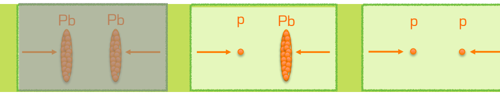
- What is driving the increase with increasing multiplicity?
  1. The mass of the hadrons → No
  2. A baryon/meson effect → No



Baryon-to-meson ratios (with same strangeness content) but different masses:

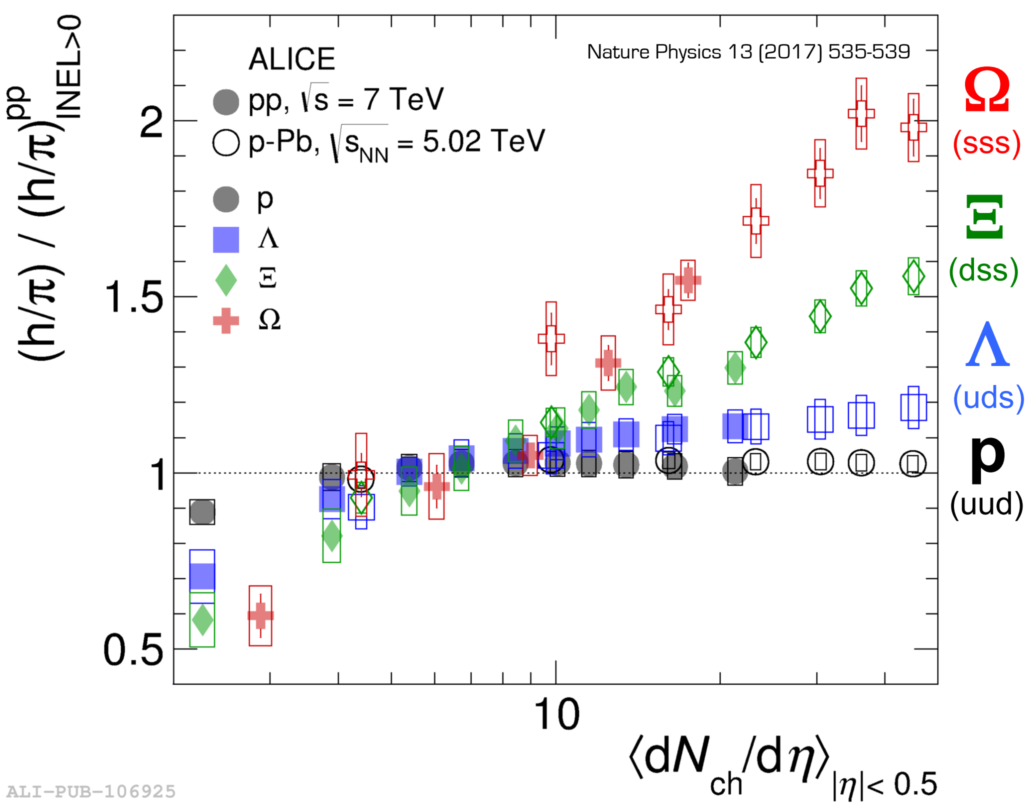
- no significant change with multiplicity

Results



Strangeness enhancement – Multiplicity dependence

- What is driving the increase with increasing multiplicity?
  1. The mass of the hadrons → No
  2. A baryon/meson effect → No
  3. Strangeness content → **Yes**



Results

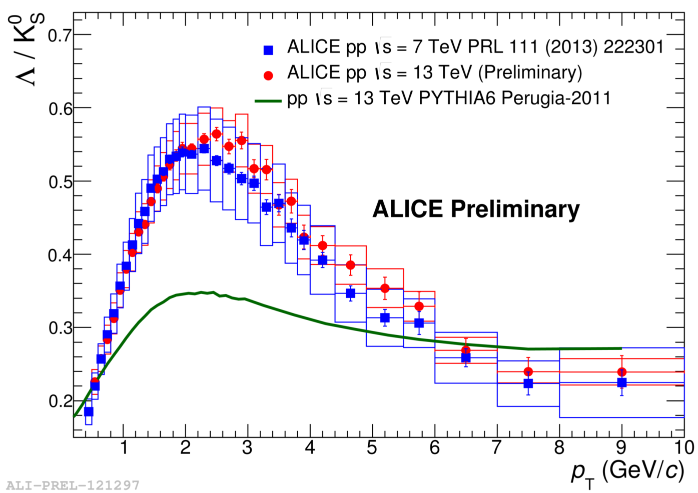
Strangeness enhancement – Collision energy dependence

New measurements in pp at 13 TeV can be used to **disentangle multiplicity and energy dependence of particle production**

- $\langle dN_{ch}/d\eta \rangle$ increases by ~20% from 7 to 13 TeV

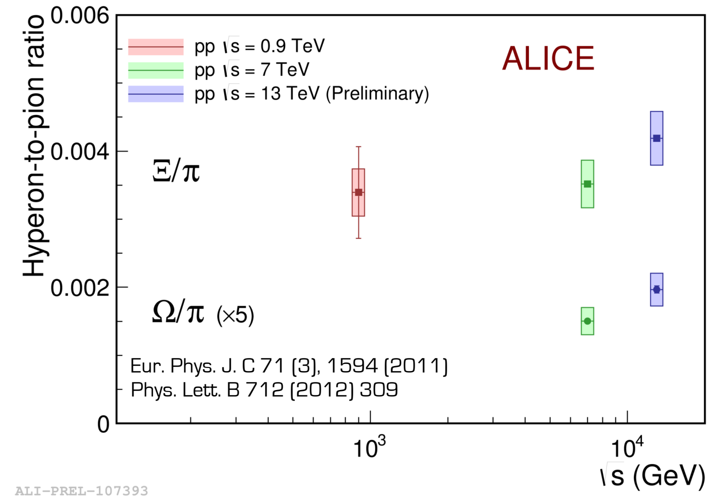
Ratios of spectra in minimum bias pp:

- Hint for a **blueshift of the Λ/K^0_S maxima**



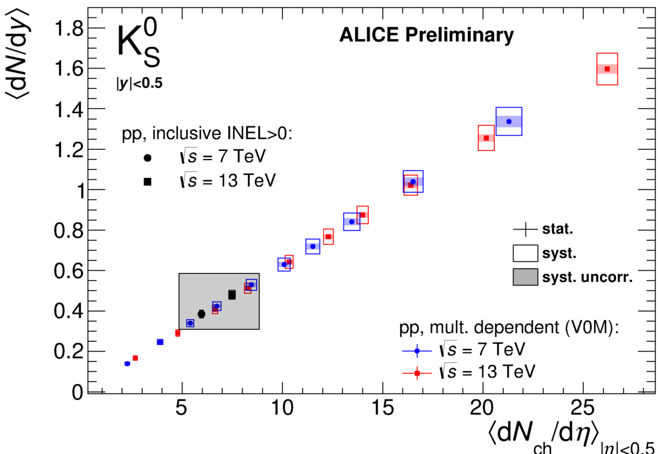
p_T-integrated ratios in minimum bias pp:

- Hint for **increase of hyperon-to-pion** ratio

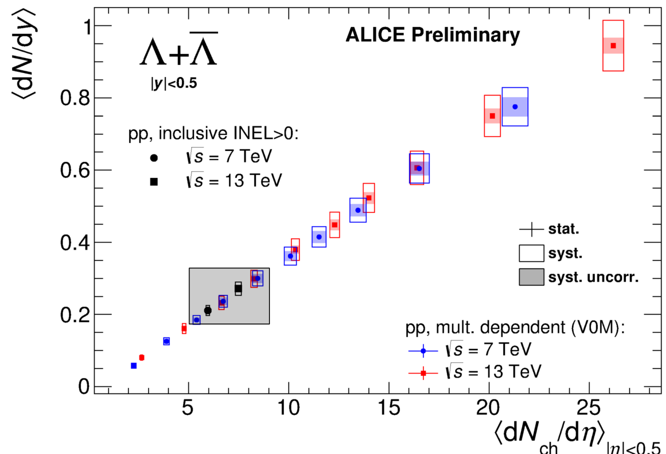


Results

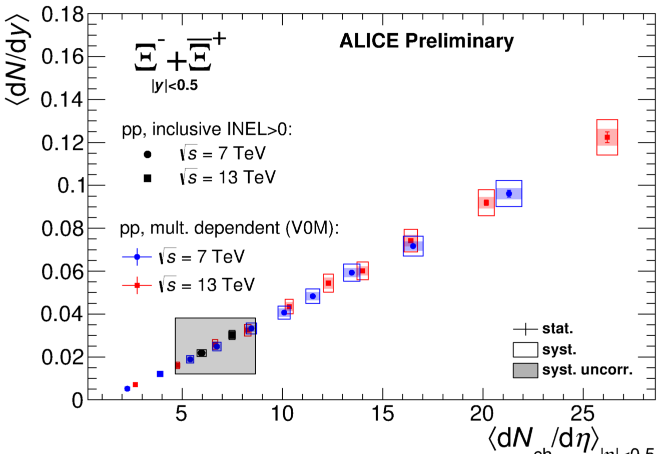
Strangeness enhancement – Collision energy dependence



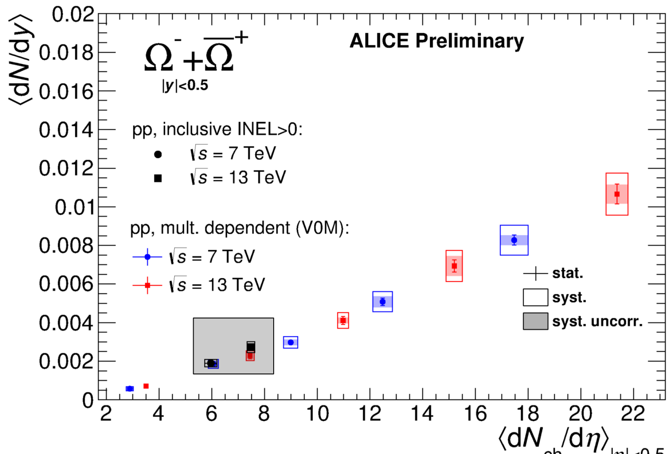
ALI-PREL-116294



ALI-PREL-116298



ALI-PREL-116302

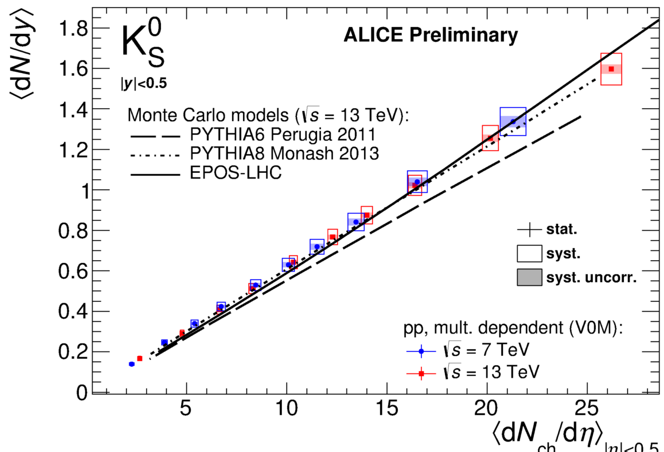


ALI-PREL-116306

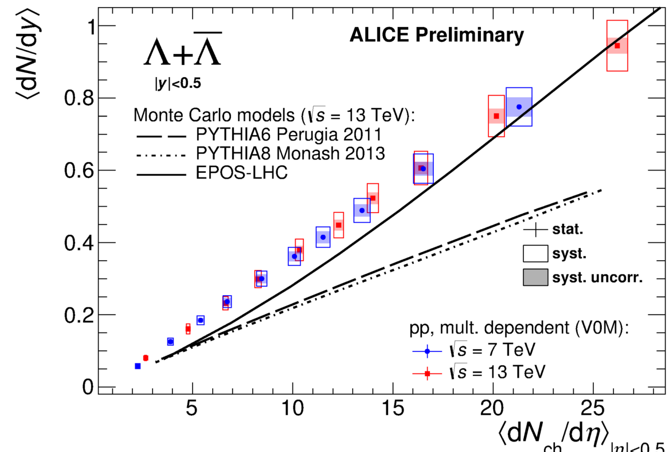
- Yields of (multi-)strange particles measured in pp 13 TeV **as a function of multiplicity** lie on the **same trend as the 7 TeV data**
  - ✓ Inclusive (**INEL>0**) yields at different energies follow the same trend
- The event activity drives particle production, irrespective of the collision energy

Results

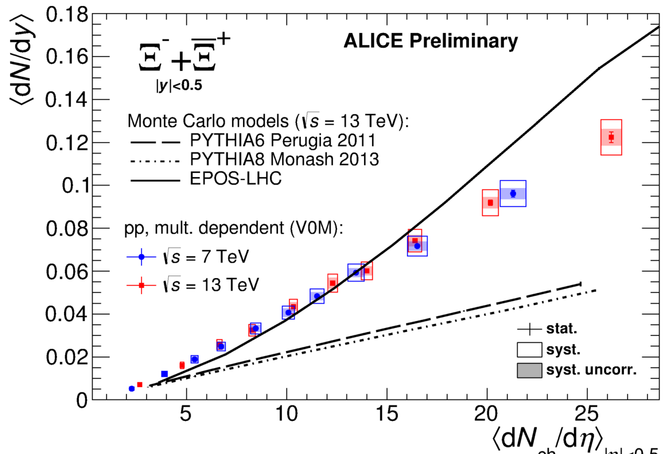
Strangeness enhancement – Collision energy dependence



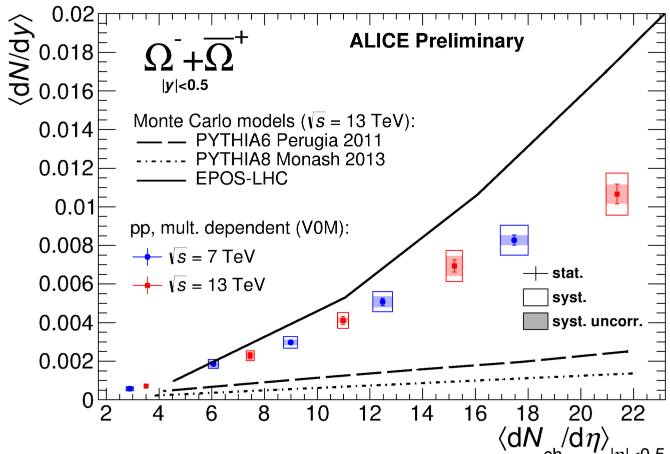
ALI-PREL-116310



ALI-PREL-116318



ALI-PREL-116322

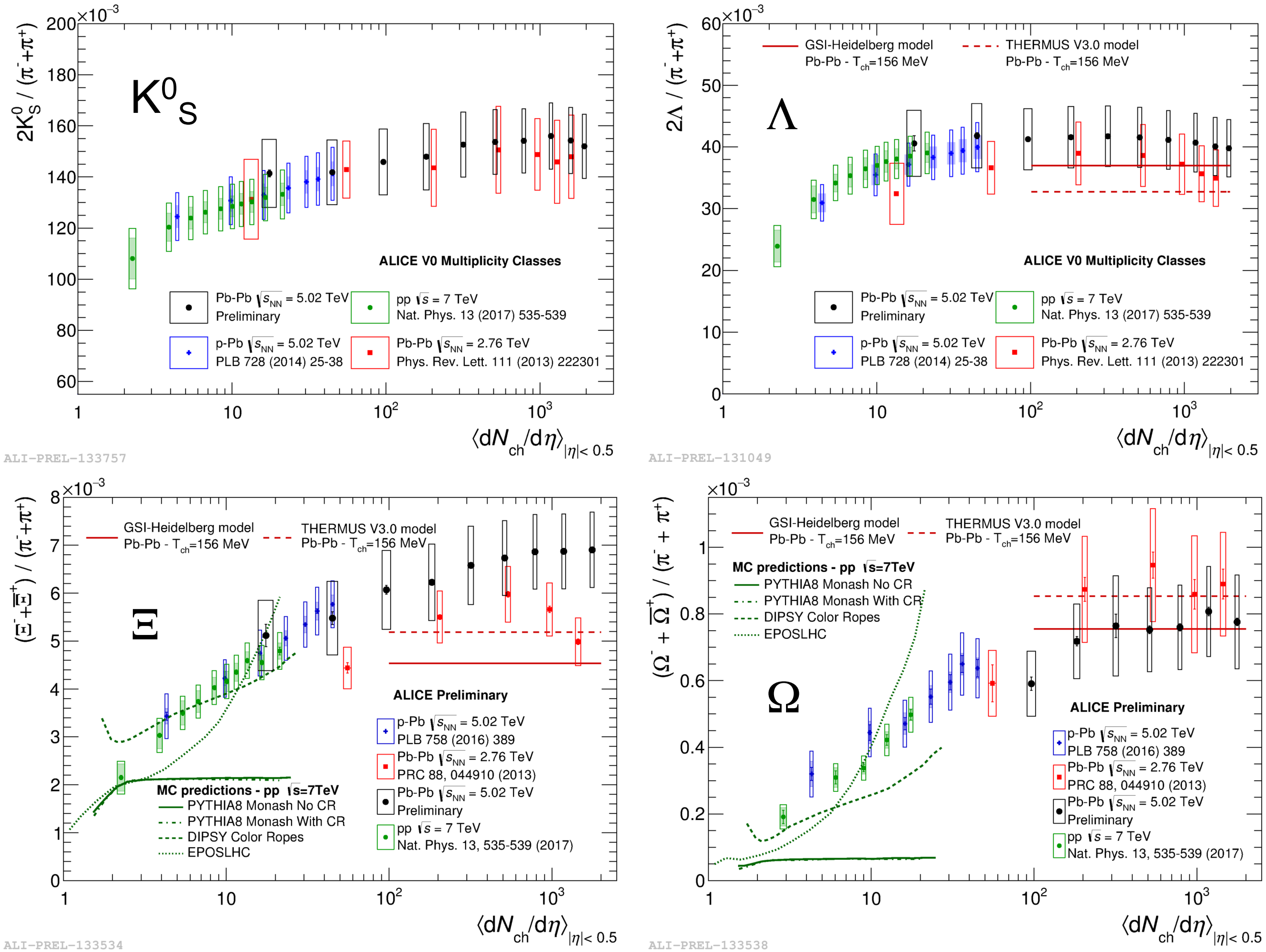


ALI-PREL-116326

- Yields of (multi-)strange particles measured in pp 13 TeV **as a function of multiplicity** lie on the **same trend as the 7 TeV data**
  - ✓ Inclusive (**INEL>0**) yields at different energies follow the same trend
- The event activity drives particle production, irrespective of the collision energy
- Models
  - ✓ EPOS reproduces only qualitatively the trend with multiplicity
  - ✓ PYTHIA fails in describing (multi-)strange baryon production → Some tuning needed from the models side

Results

Strangeness enhancement – Collision energy dependence



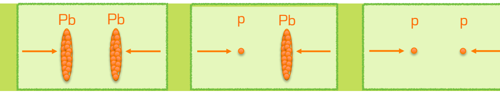
Pb—Pb at $\sqrt{s}$ = 2.76 TeV (PUB)

Pb—Pb at $\sqrt{s}$ = 5.02 TeV (PREL)

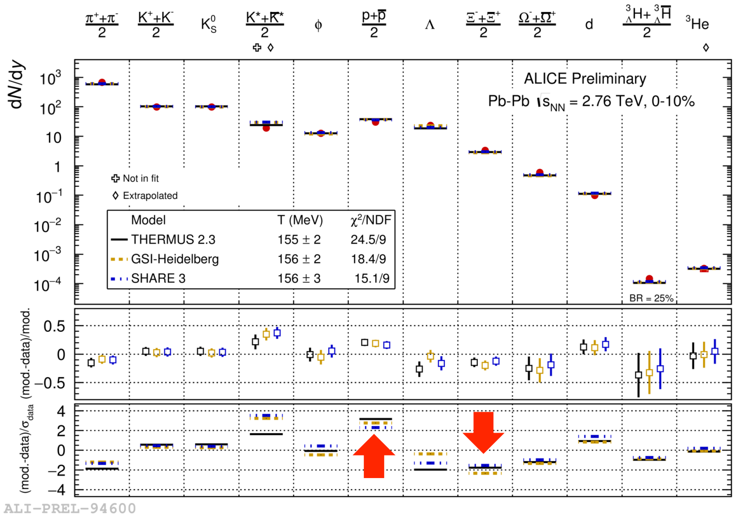
- In Pb—Pb collisions the relative production of strange particles has no significant dependence on collision energy

Ξ measurement in Pb–Pb collisions at $\sqrt{s}$ = 2.76 TeV currently under re-analysis

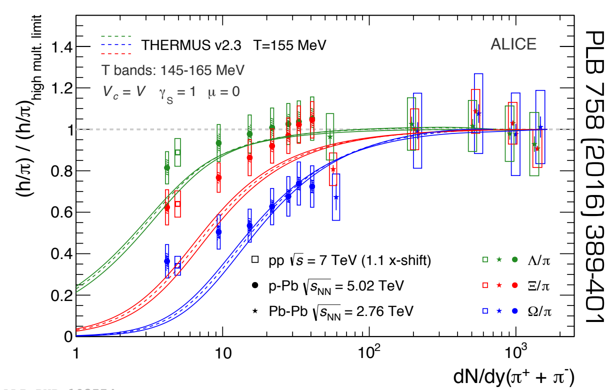
Results



Strangeness enhancement – Statistical hadronization picture

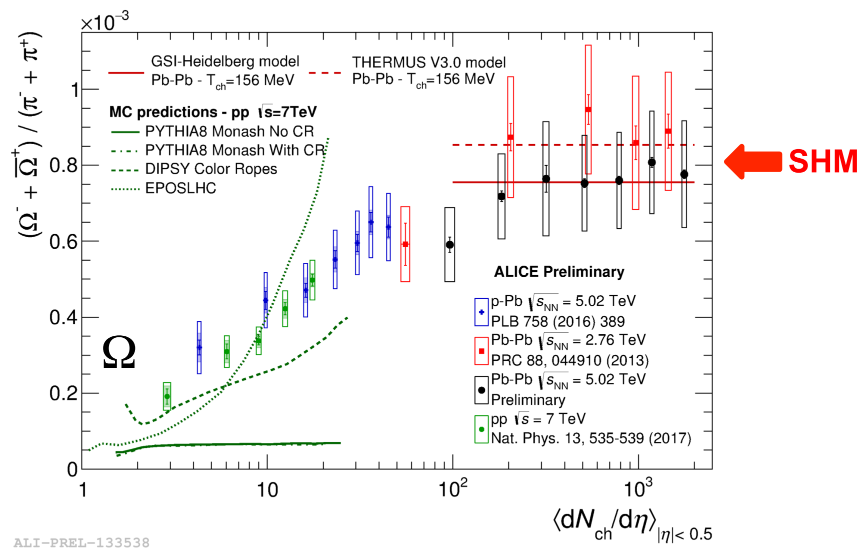


- SHM gives a good description in central Pb—Pb collisions, with some caveats: p/π (prediction too high), Ξ/π (prediction too low)
- The model can be extended to lower multiplicities implementing strangeness canonical suppression
- Data are a "*beautiful demonstration of approach to grand-canonical plateau*" (P.B.M. at SQM17),



High multiplicity limit

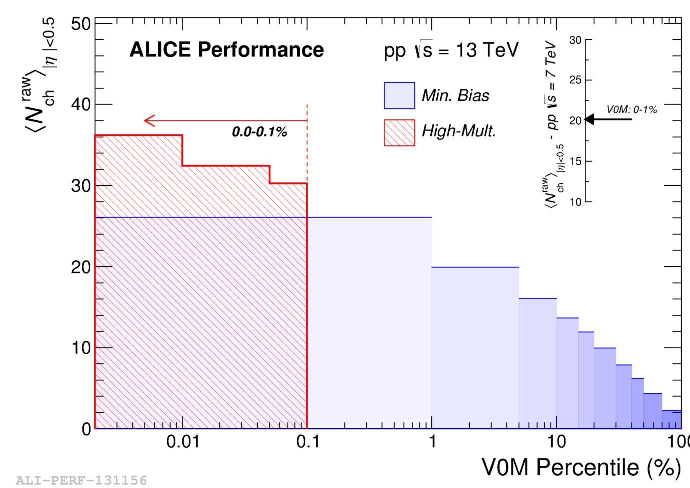
- ✓ Data: h/π in 0-60% most central Pb–Pb events
- ✓ Model: GC limit



Conclusions and outlook

- Baryon-to-meson ratio Pb—Pb like behavior observed in pp and p–Pb collisions
  → example of potential collective phenomena in small systems ("kinetic equilibrium")
- Enhancement of strange hadron production observed towards high multiplicity pp events
  → example of collective behavior observed in small system ("chemical equilibrium")
- Relative production of strange particle is driven by event activity (not by collision energy)
- Statistical thermal model gives a good description of the hadronic abundances with few caveats (p/π and Ξ/π)
  → significance of these differences to be precisely quantified in future

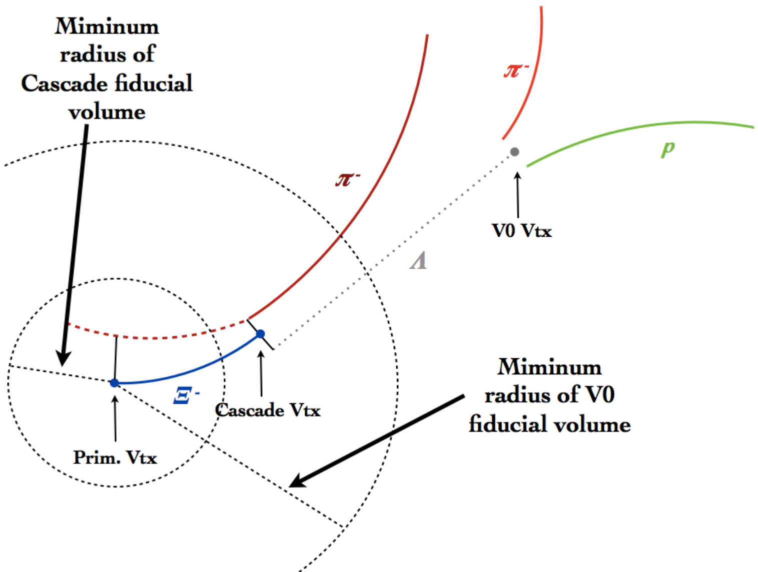
➢ Next interesting question: what happen in very high multiplicity pp events? ALICE is already working on it…

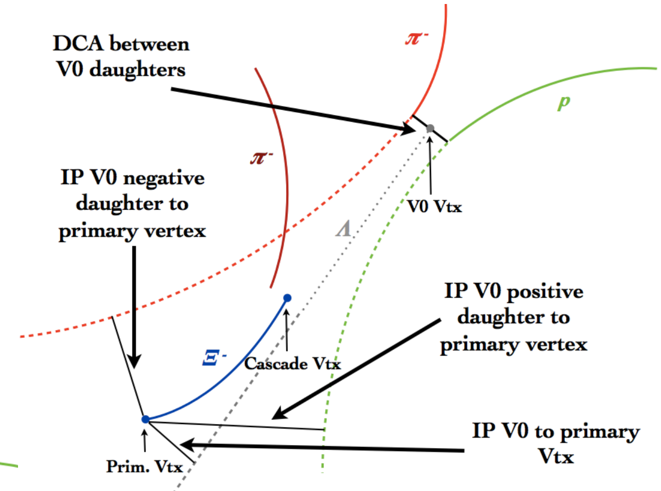


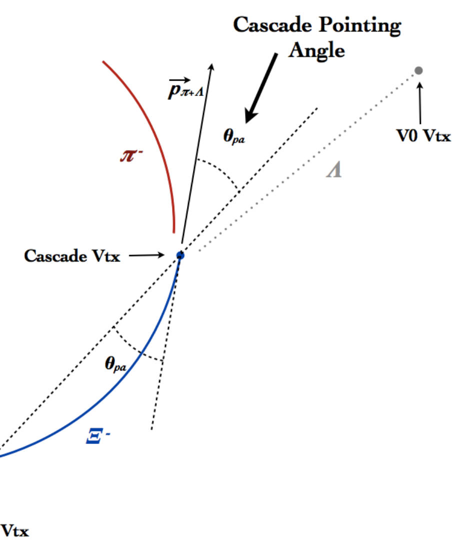
Backup

Backup

Topological cuts in Pb–Pb and pp analysis



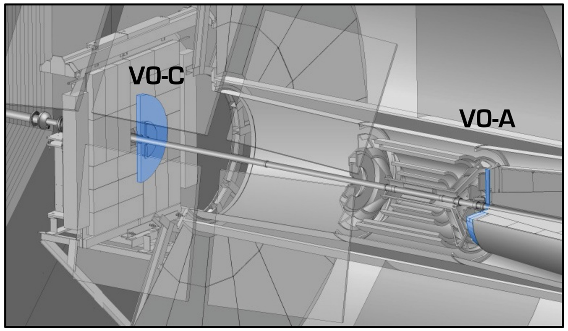




Backup

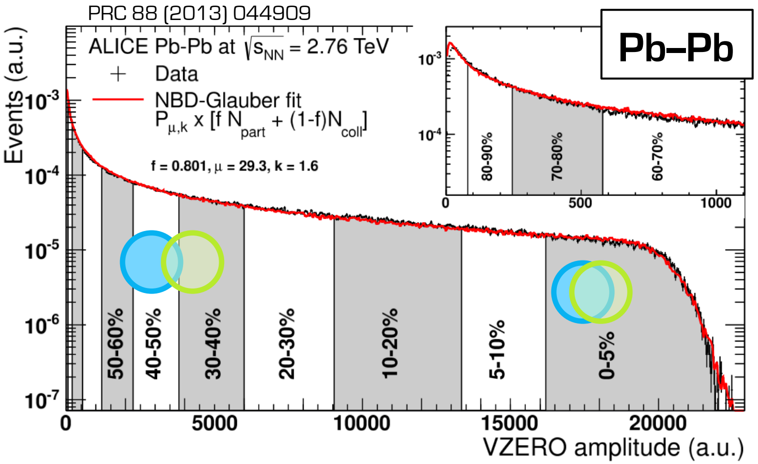
Centrality/Multiplicity determination

- 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
- 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



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)

$\langle dN_{ch}/d\eta \rangle$			
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

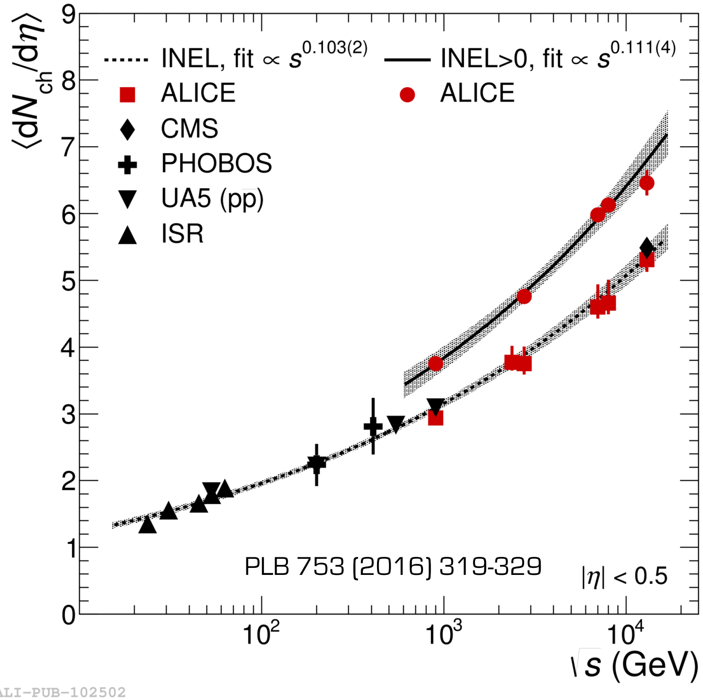


Backup

Charged particle production vs energy

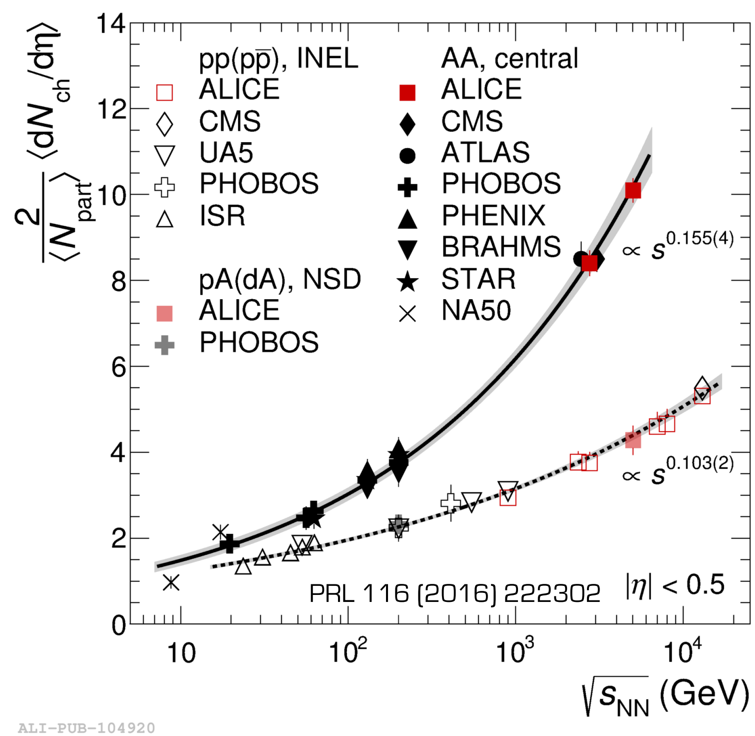
In **pp at 13 TeV** $\langle dN_{ch}/d\eta\rangle$ increases with $\sqrt{s}$ following a power law, along the trend from lower center of mass energies

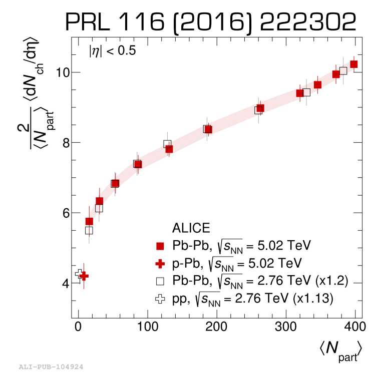
→ About **20% increase** from 7 to 13 TeV



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

Compare strangeness production in hadron gas and QGP

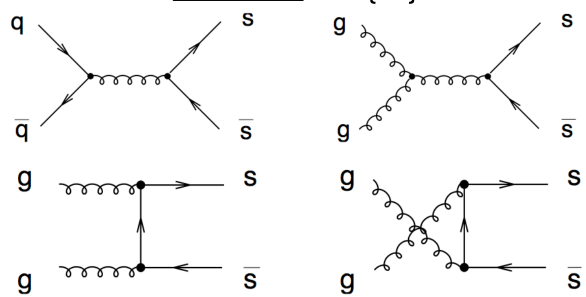
- In the Rafelski-Muller argumentations there are two considerations:

  1. Production mechanisms:
     - ✓ In hadron gas (HG) scenario strange hadron are prouced trough direct (N+N→N+ Λ +K) or indirect reactions.
     - ✓ In QGP scenario basic strange (anti-)quarks production process is the fusion of two gluons.

  ➜ Should be much easier to generate strangeness once a plasma state has been formed.

QGP

$Q(s\bar{s})$=200 MeV



HG

Direct production:

π + π → π + π + strange hadron + antiparticle

$Q(\Xi)$ = 2642 MeV and $Q(\Omega)$ = 3344 MeV

Indirect production:

1) π + N → K + Λ

2) π+ Λ → K + Ξ and π + Ξ → K + Ω

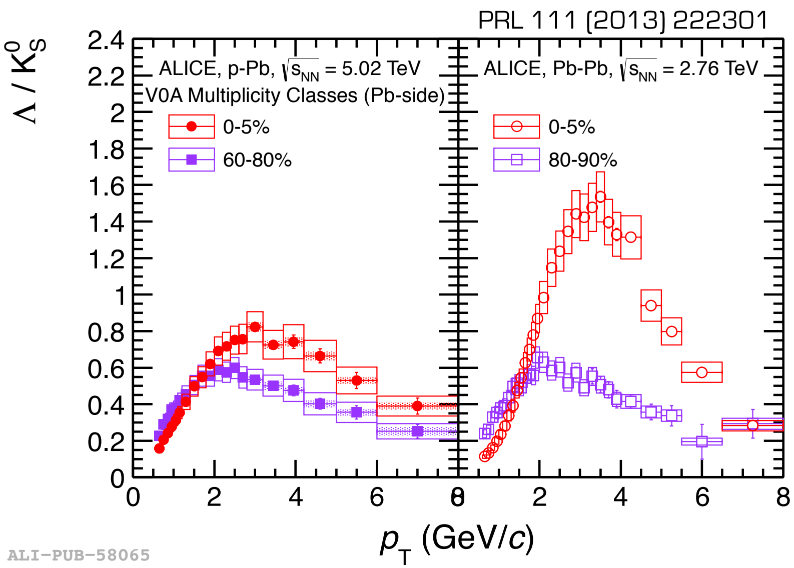
$Q(\Xi)$ = 1100 MeV and $Q(\Omega)$ = 1810MeV

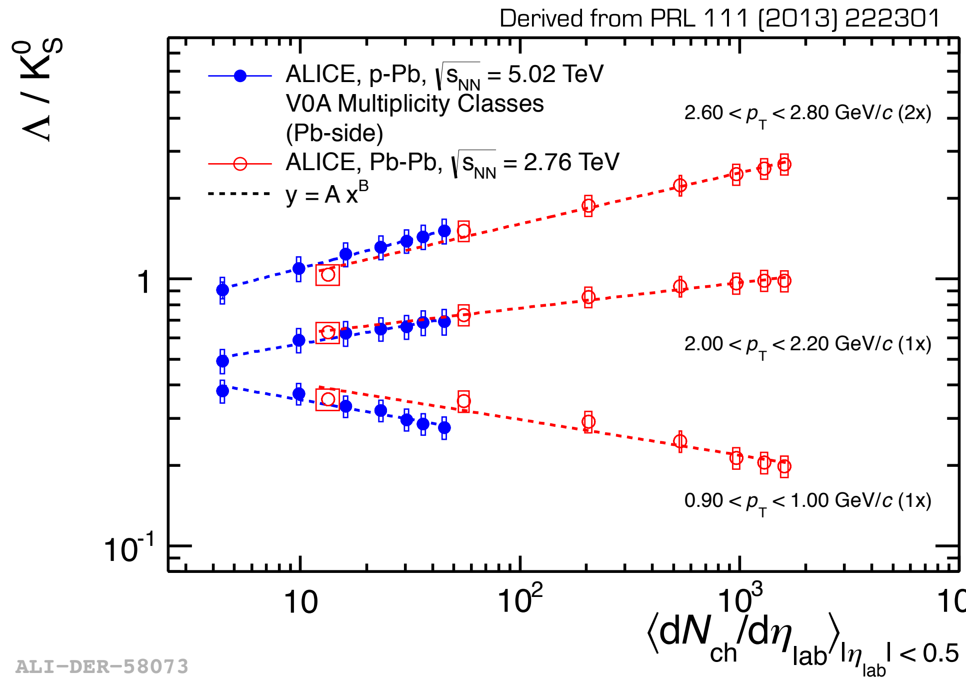
  2. The equilibration time of partonic reactions, expecially due to the gluon fusion process, is much shorter than the one for the hadronic reactions. The difference is especially large, if rare multi-strange (anti-)baryons are considered ($^{eq}\tau_{QGP} \simeq 10$ fm; $^{eq}\tau_{HG} = 30$ fm).

  ➜ Would be very difficult to produce multi-stange particle in large abundances in a hadron resonance gas, while the presence of a QGP would be reflected in much higher production rates of these particles.

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

Backup

Blast-wave fit study

Boltzmann-Gibbs Blast-Wave model

A simplified hydrodynamic model with 3 free fit parameters:

- T_{kin} = kinetic freeze-out temperature
- β_T: transverse radial flow velocity
- n: velocity profile

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T\sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T\cosh\rho}{T_{kin}}\right)$$

$$\rho = \tanh^{-1}\beta_T$$

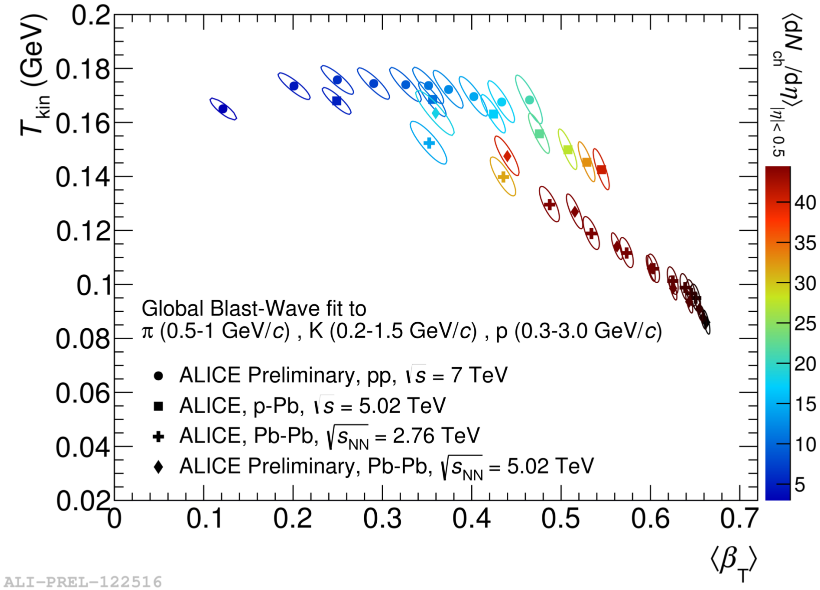
T_{kin} – kinetic freeze-out
β_T – transverse velocity

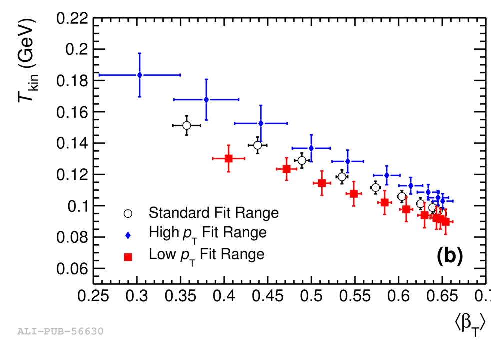
Simultaneous fit to the π, K, p spectra:

– in **Pb–Pb** increase of $\langle\beta_T\rangle$ with centrality
– $\langle\beta_T\rangle$ at **5.02 TeV** is (1.78 0.9)% larger than at 2.76 TeV in central Pb—Pb

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





CAVEAT: sensitivity to fit range and the set of particles included in the fit