Strangeness in Quark Matter
Berkeley (California, U.S.A) – June 27 to July 1, 2016

Strangeness production in p–Pb and Pb–Pb collisions with ALICE at LHC

Domenico Colella
Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
European Organization for Nuclear Research (CERN), Geneva, Switzerland
on behalf of the ALICE Collaboration

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  - Transverse momentum spectra
  - Baryon-to-meson ratio
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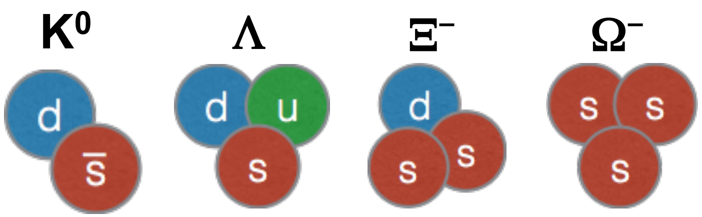
  - Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

Introduction

Strange and multi-strange hadrons detection

ALICE



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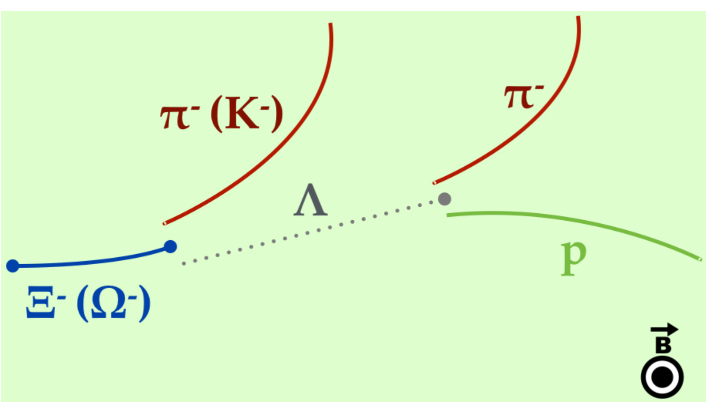

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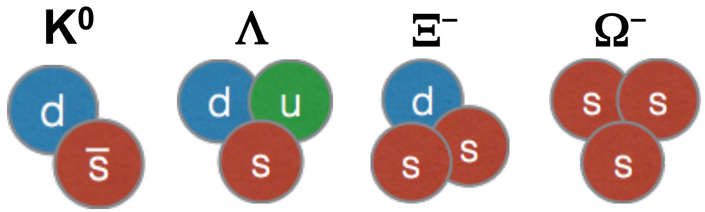

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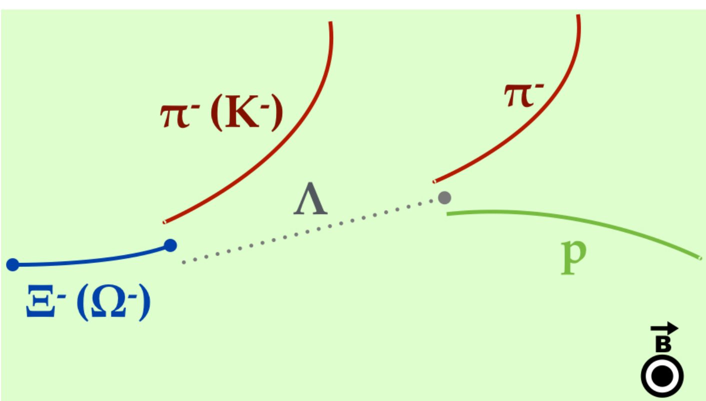

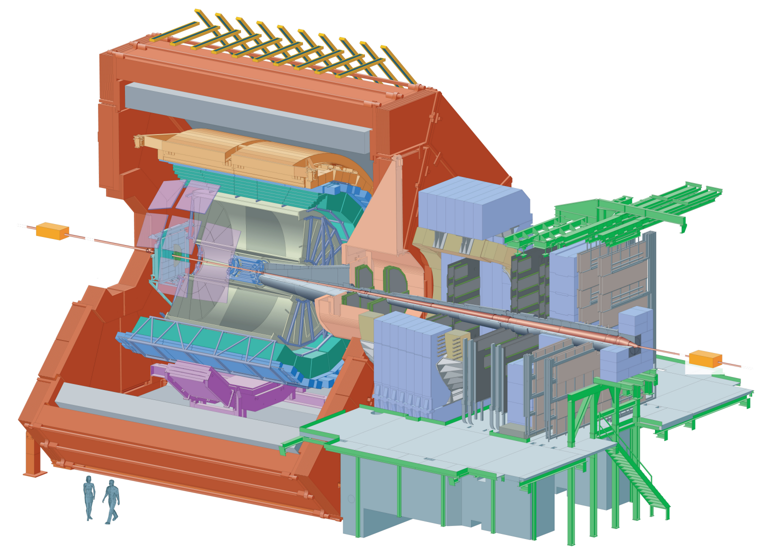

Detectors used in this study:

i. **TPC:** Tracking, Vertexing, PID (dE/dx)
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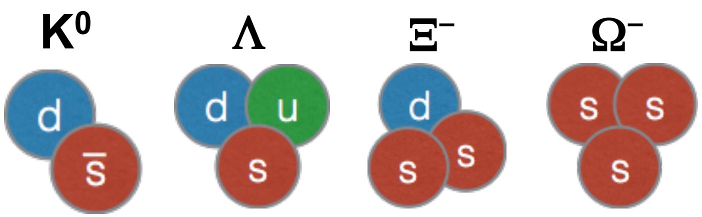

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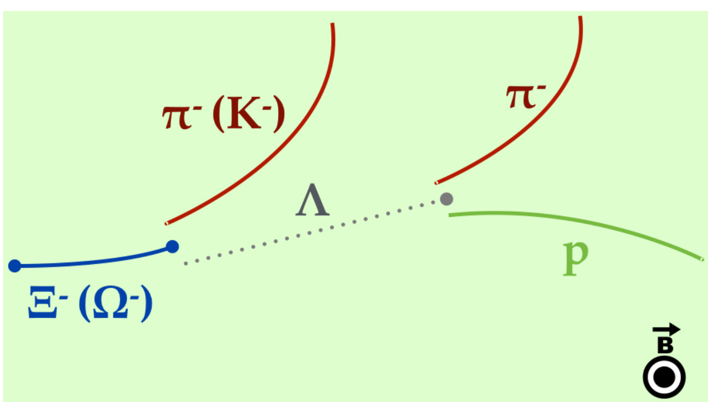

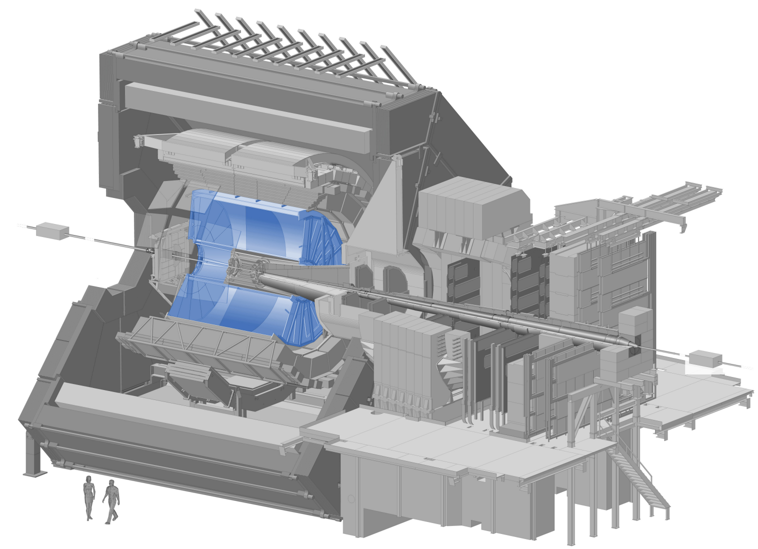

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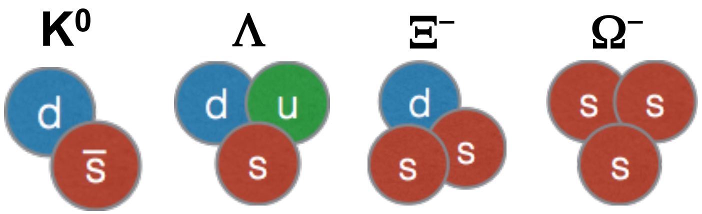

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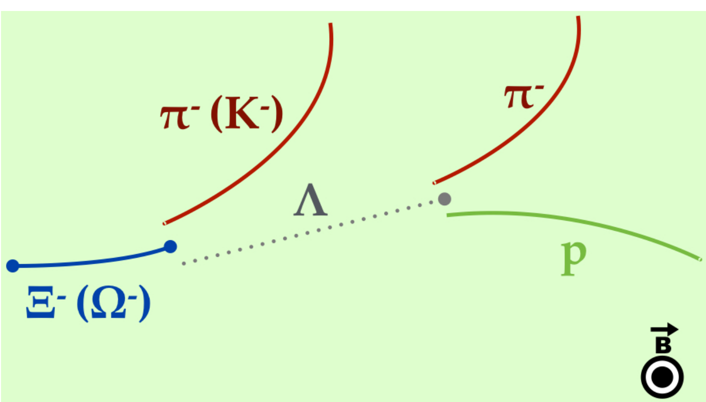

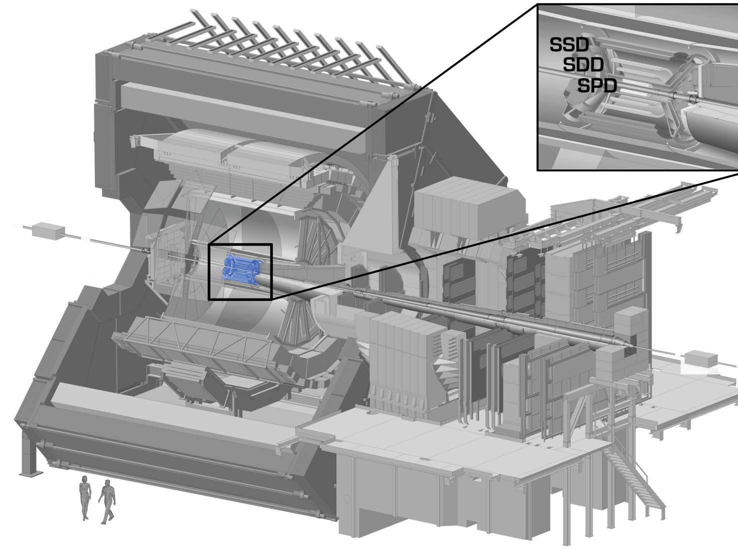

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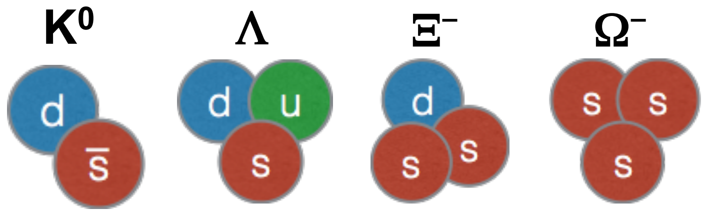

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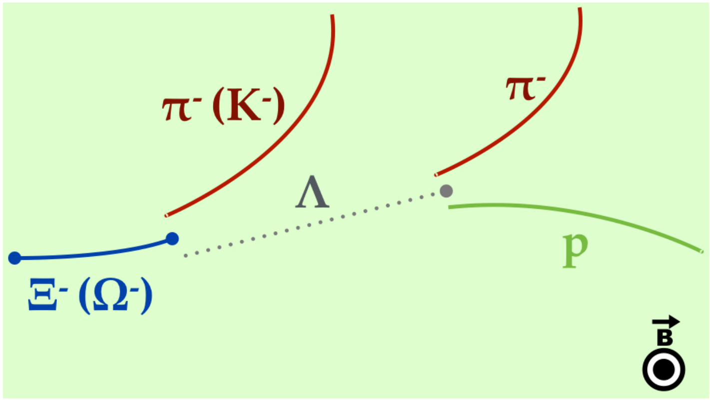

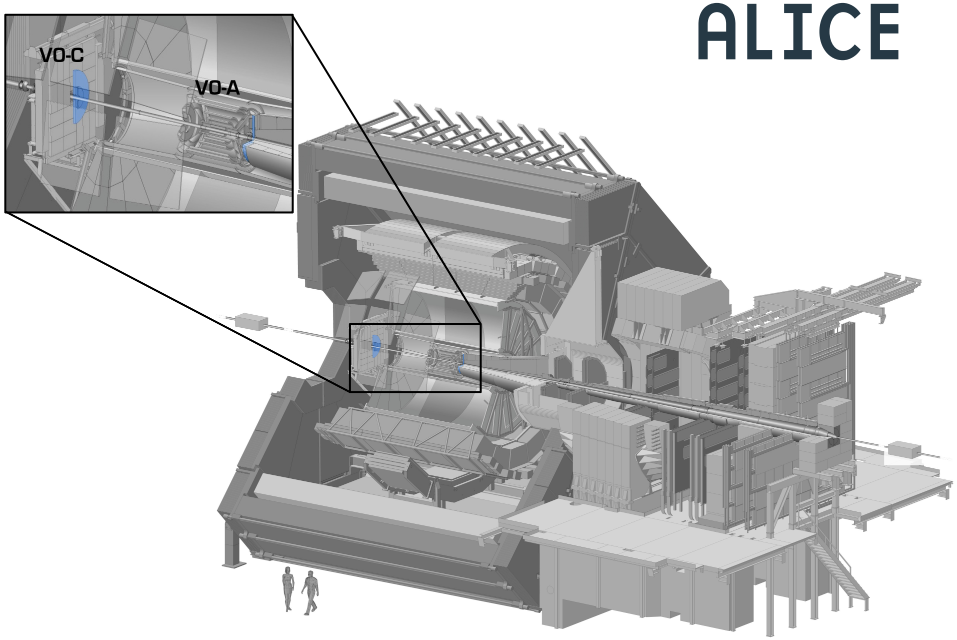

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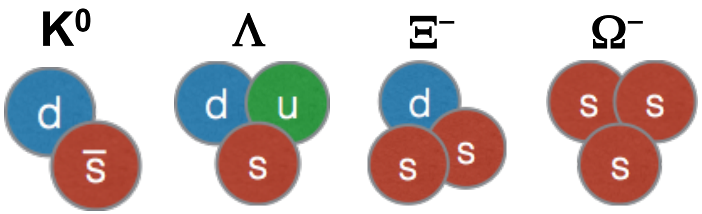

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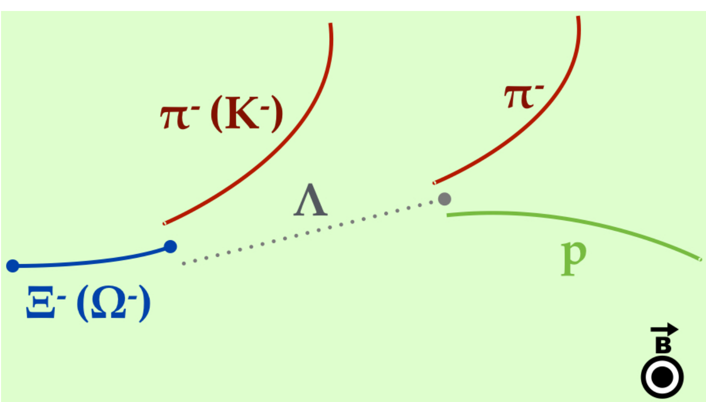

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1. charged tracks reconstructed in the tracking system (ITS + TPC)
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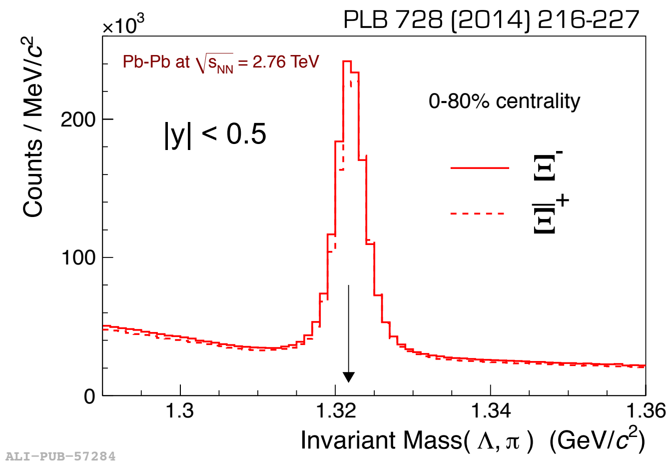

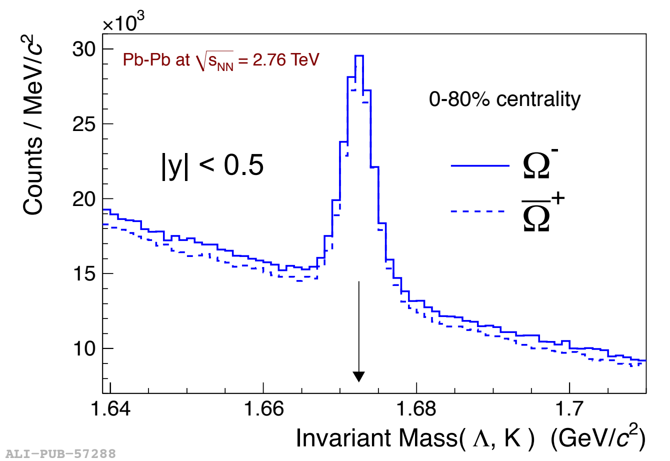

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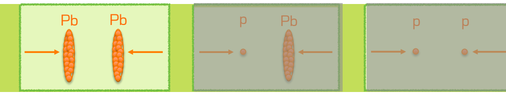
Yields extracted in different transverse momentum bins via invariant mass analysis.

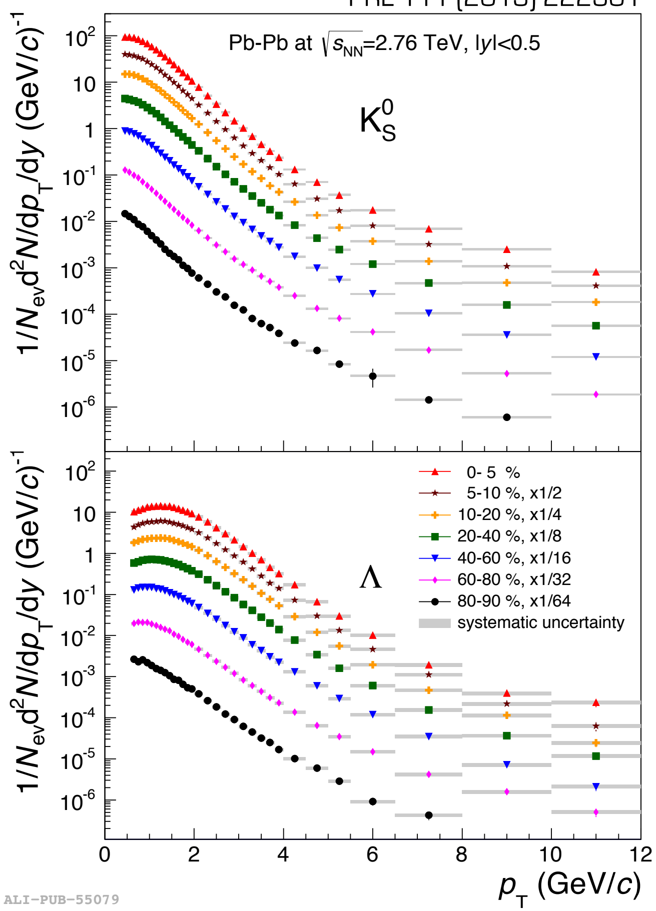
Results

Results

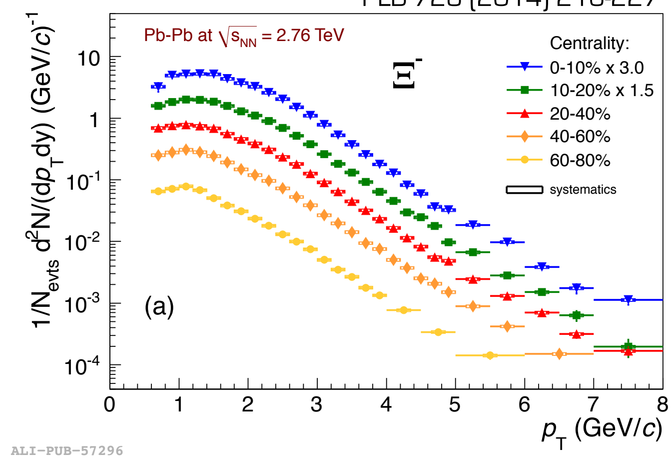


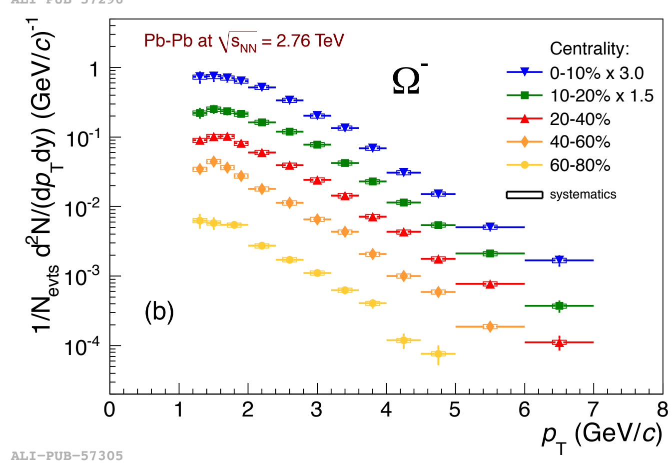
Transverse momentum spectra

PRL 111 (2013) 222301



PLB 728 (2014) 216-227

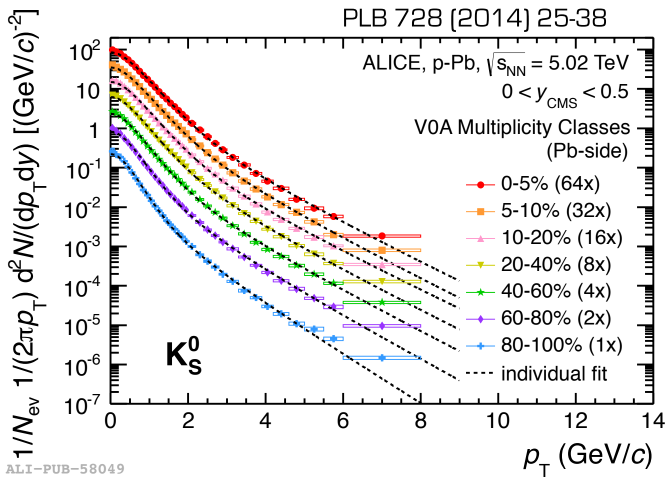


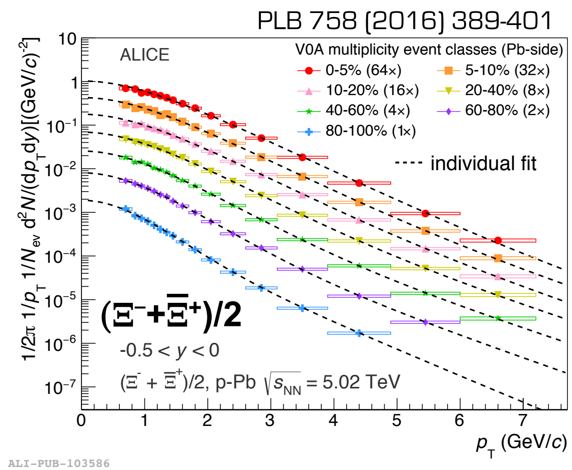


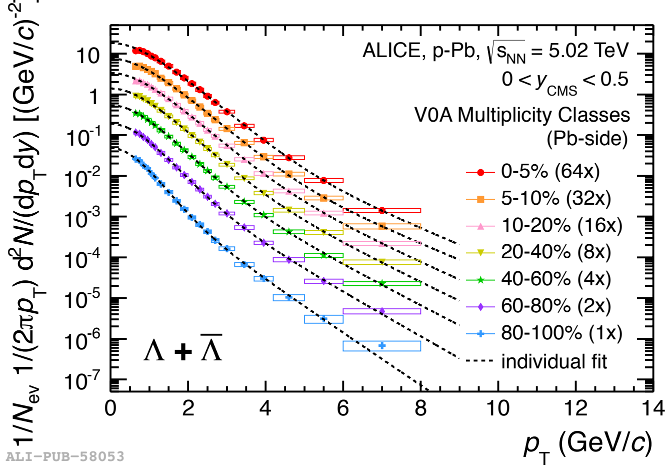
- Particle and antiparticle spectra compatible
- Spectral shape harder in central collisions w.r.t. peripheral collisions

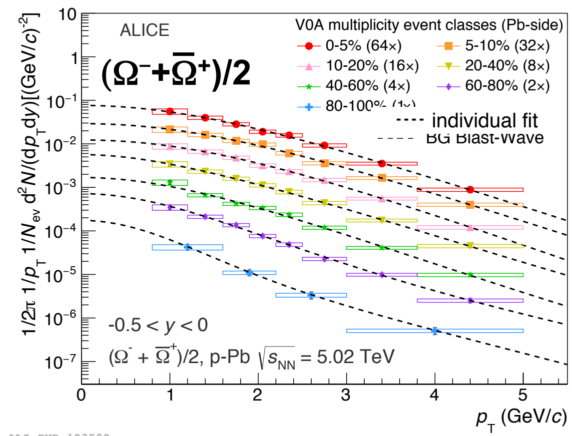
Results

Transverse momentum spectra





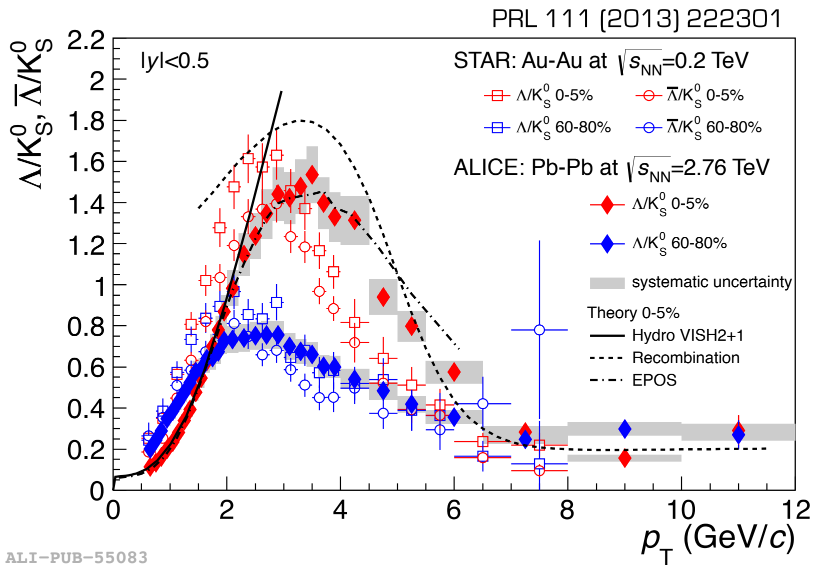




- Particle and antiparticle spectra compatible
- Spectral shape → similar behavior to Pb–Pb collisions

Results

Baryon-to-meson ratio



- Baryon anomaly in Pb–Pb collisions consistent with:
  - ✓ radial flow (p_T < 2 GeV/c) → p/ϕ in central Pb–Pb collisions flat vs p_T (mass dependence)
  - ✓ fragmentation (p_T > 5 GeV/c)

A. Knopse
Tue. 16:00 – Room 102
QCD Phase Diagram: II

Results

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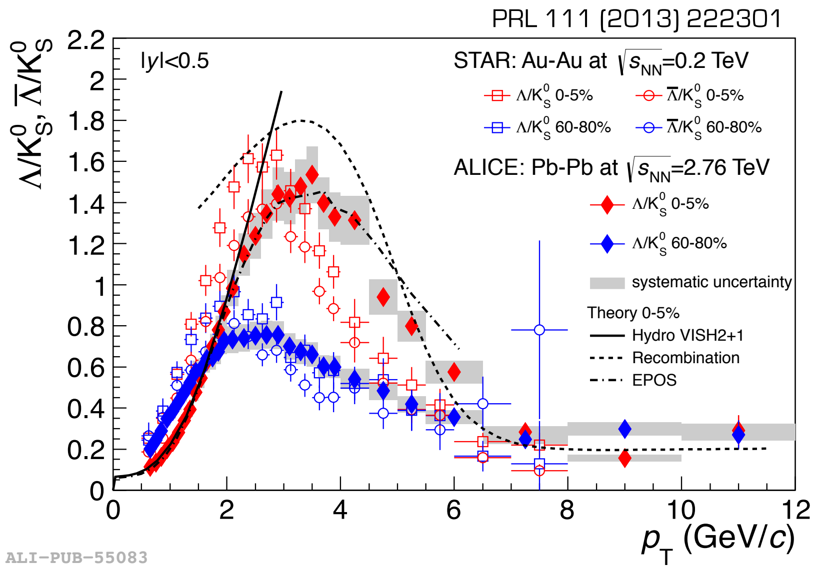

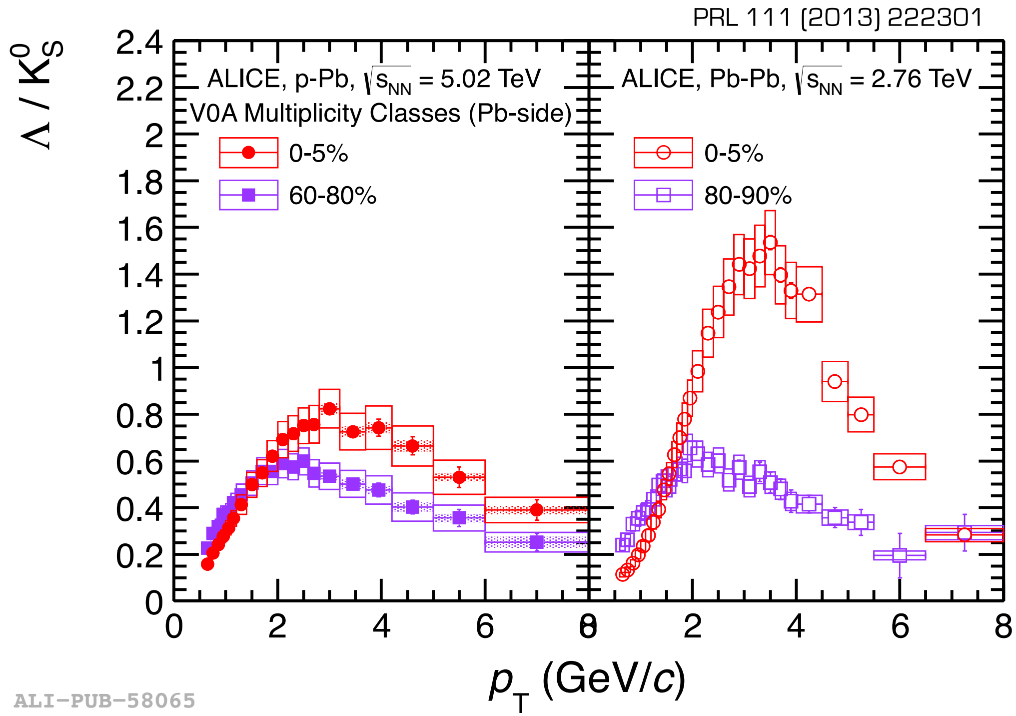

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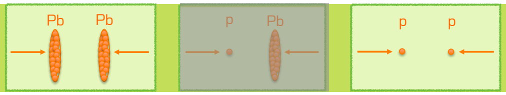
  - ✓ fragmentation (p_T > 5 GeV/c)
- Multiplicity dependence of baryon-to-meson ratio at intermediate p_T also observed in p–Pb collisions

Results

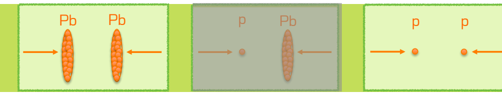


Nuclear modification factor

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{(d^2N / dydp_T)_{A-A}}{(d^2\sigma_{INEL} / dydp_T)_{pp}}$$

no nuclear modification → R_{AA} = 1

Results



Nuclear modification factor

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- K
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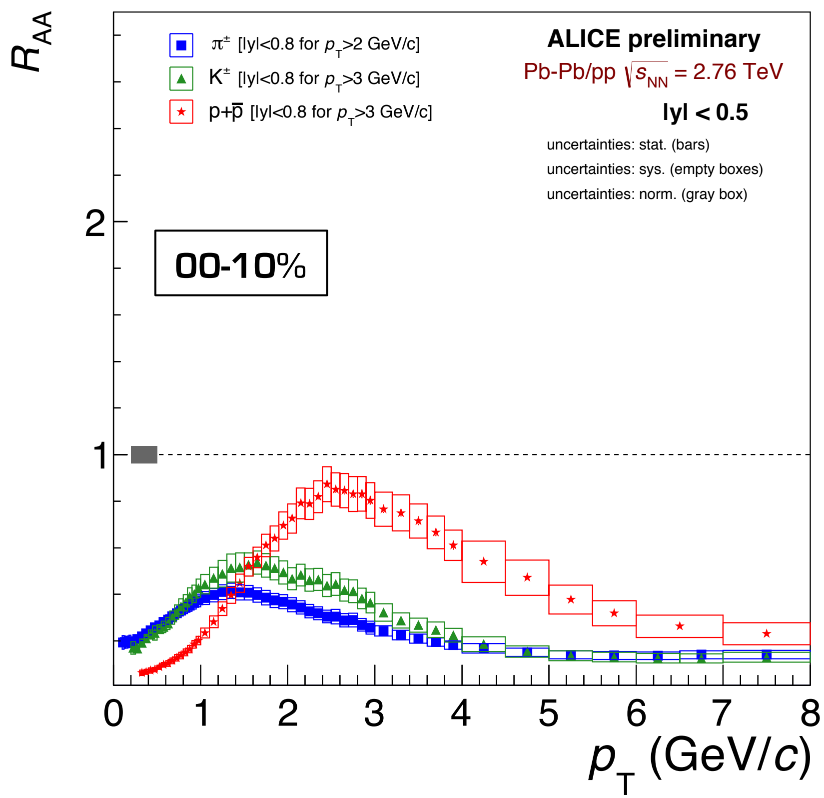

- Large suppression for π, K and p that at high p_T does not depend on the mass of the particle

Results

Nuclear modification factor

■ π ■ Ξ
■ K
■ p

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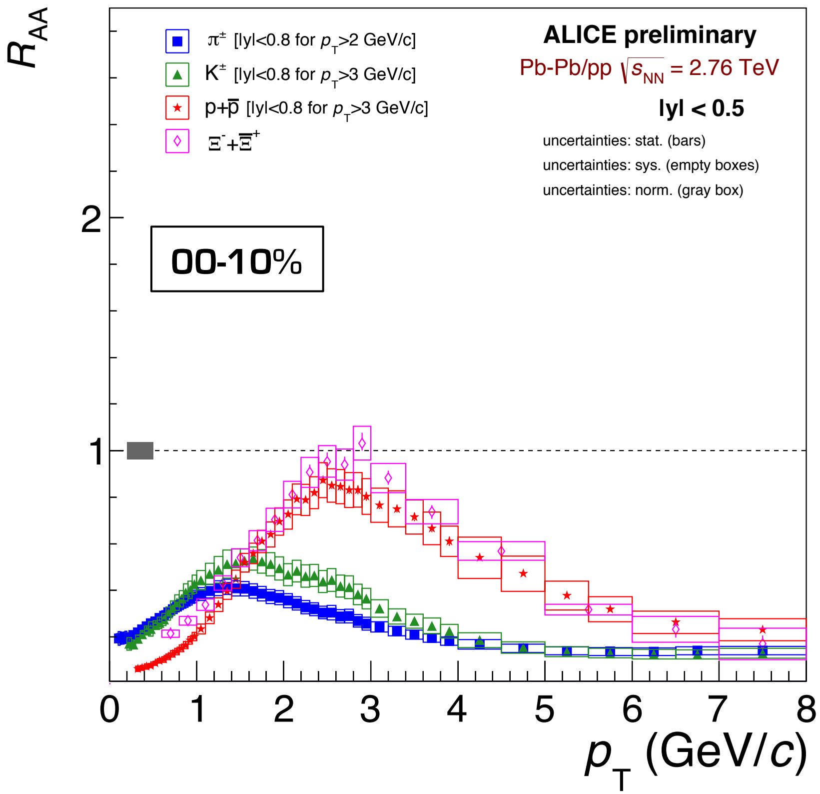

- Large suppression for π, K and p that at high p_T does not depend on the mass of the particle
- Behavior of Ξ similar to that of p

Results

Nuclear modification factor

π K p Ξ Ω

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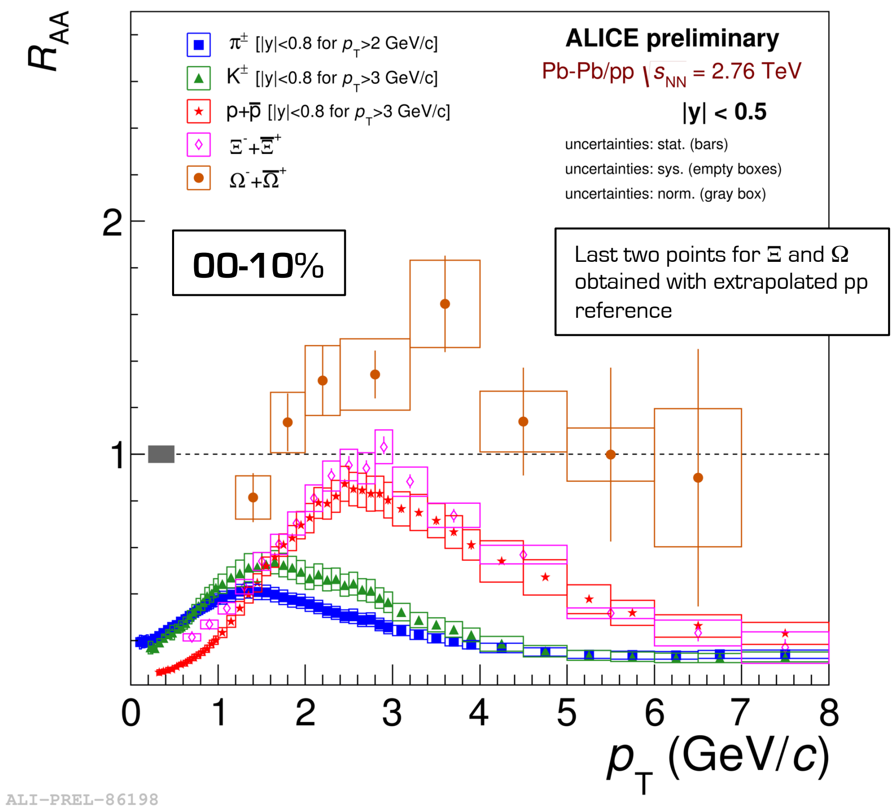

- Large suppression for π, K and p that at high p_T does not depend on the mass of the particle
- Behavior of Ξ similar to that of p
- Mass ordering at mid-p_T (N_{part})
  - ✓ p mass = 0.94 GeV/c²
  - ✓ Ξ mass = 1.32 GeV/c²
  - ✓ Ω mass = 1.67 GeV/c²
- Greater effect of the strangeness enhancement for the Ω?

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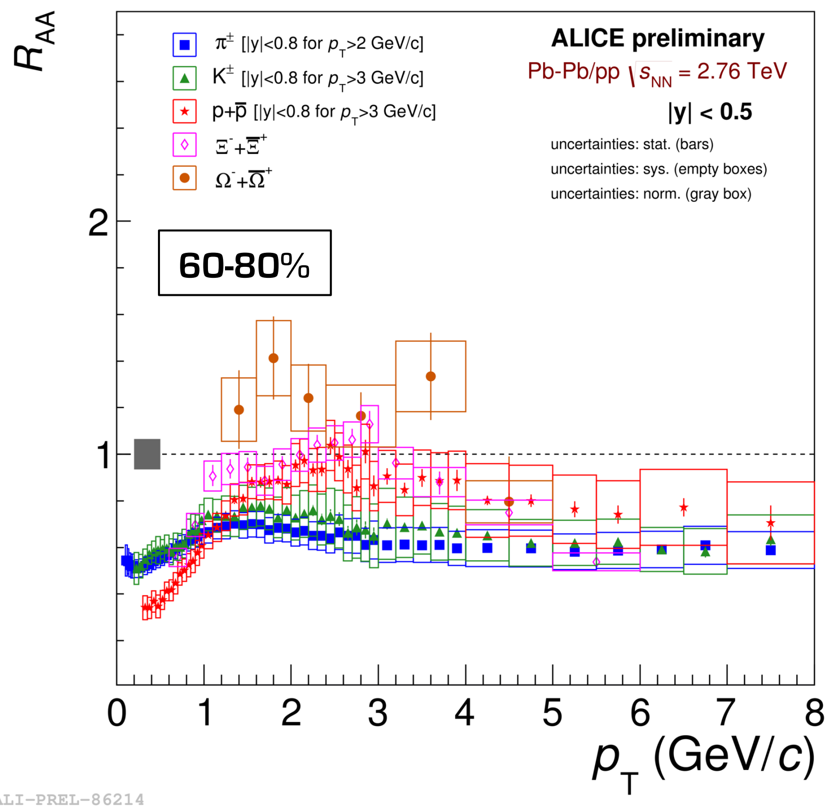

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- Greater effect of the strangeness enhancement for the Ω?
- R_{AA} vs centrality: similar trend than for other particles

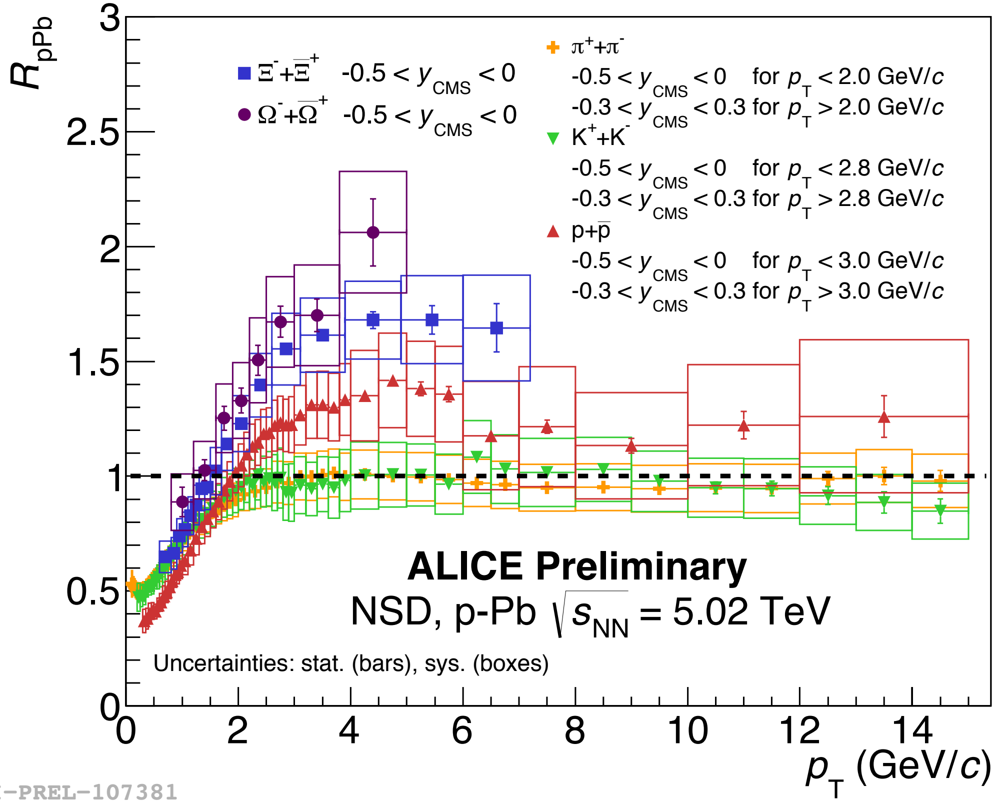
Results

Nuclear modification factor

■	π	■	Ξ
■	K	■	Ω
■	p		

$$R_{pA} = \frac{1}{\langle N_{coll} \rangle} \frac{(d^2N/dydp_T)_{p-A}}{(d^2\sigma_{INEL}/dydp_T)_{pp}}$$

no nuclear modification → $R_{AA} = 1$



- Comparing π, K, p to Ξ and Ω:
  - ✓ π and K flat
  - ✓ π, K, p, Ξ and Ω mass ordering in Cronin-region (2-8 GeV/c)
  - ✓ Strong enhancement for p, Ξ and Ω
- R_{pPb} consistent with unity at large p_T for π, K and p → Suppression in Pb–Pb collisions is a hot matter effect

Results

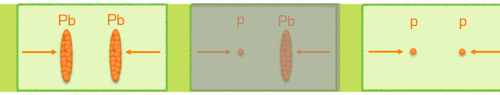
Strangeness enhancement

- 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 and RHIC and found to:
  - ✓ Increasing with strangeness content of the particle
  - ✓ Increasing with collision centrality
  - ✓ Decreasing with increasing center-of-mass energy

Results



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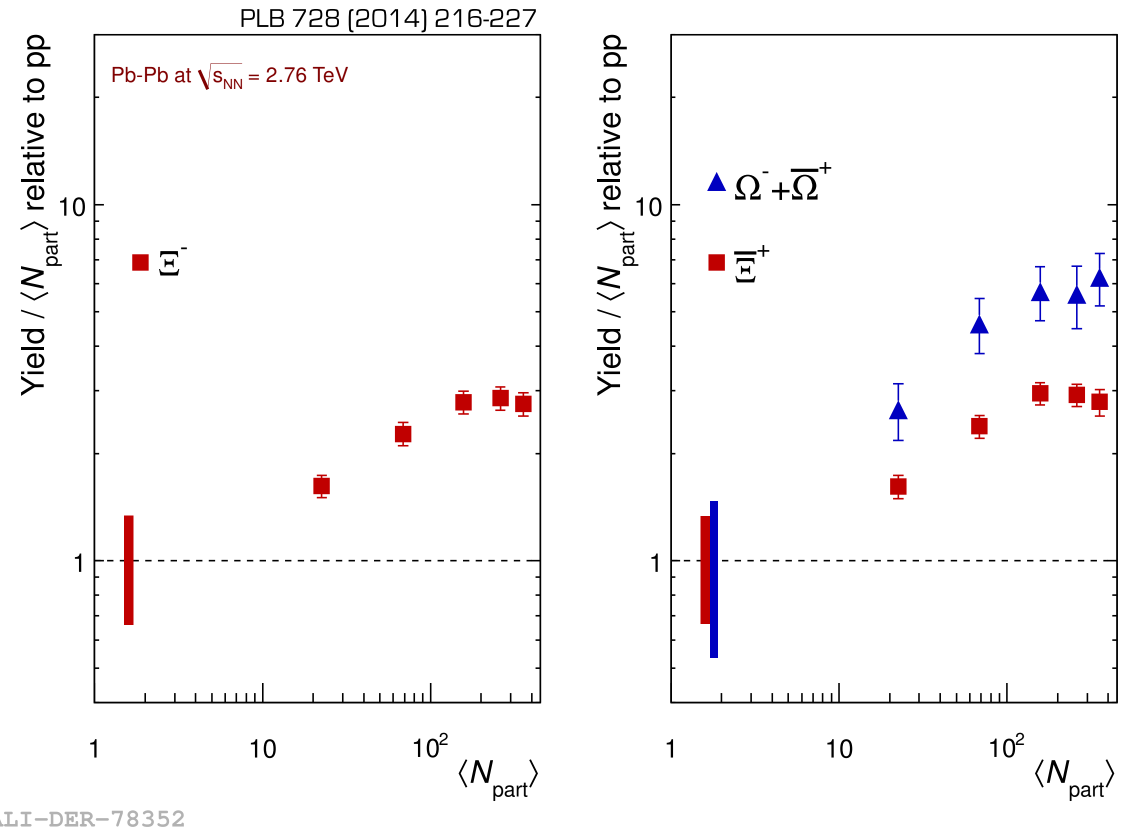

- Hierarchy based on strangeness content

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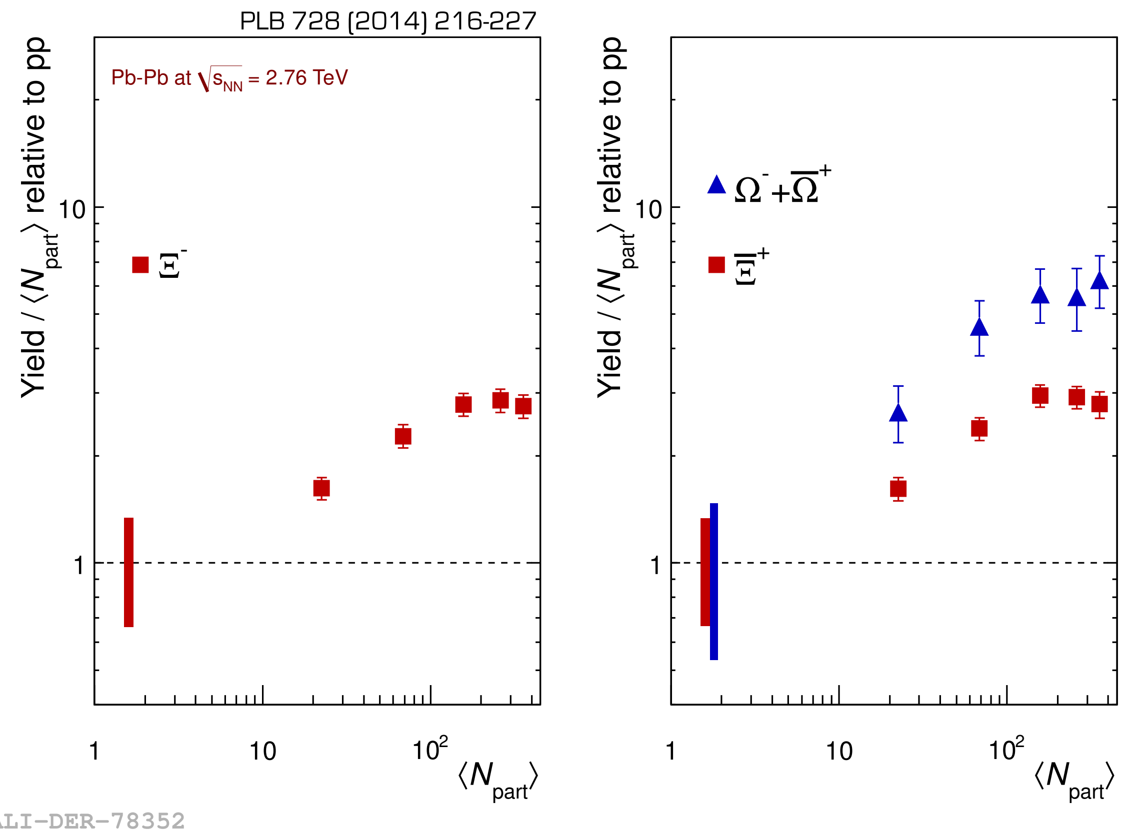

- Hierarchy based on strangeness content
- Magnitude increases when going from peripheral to most central collisions

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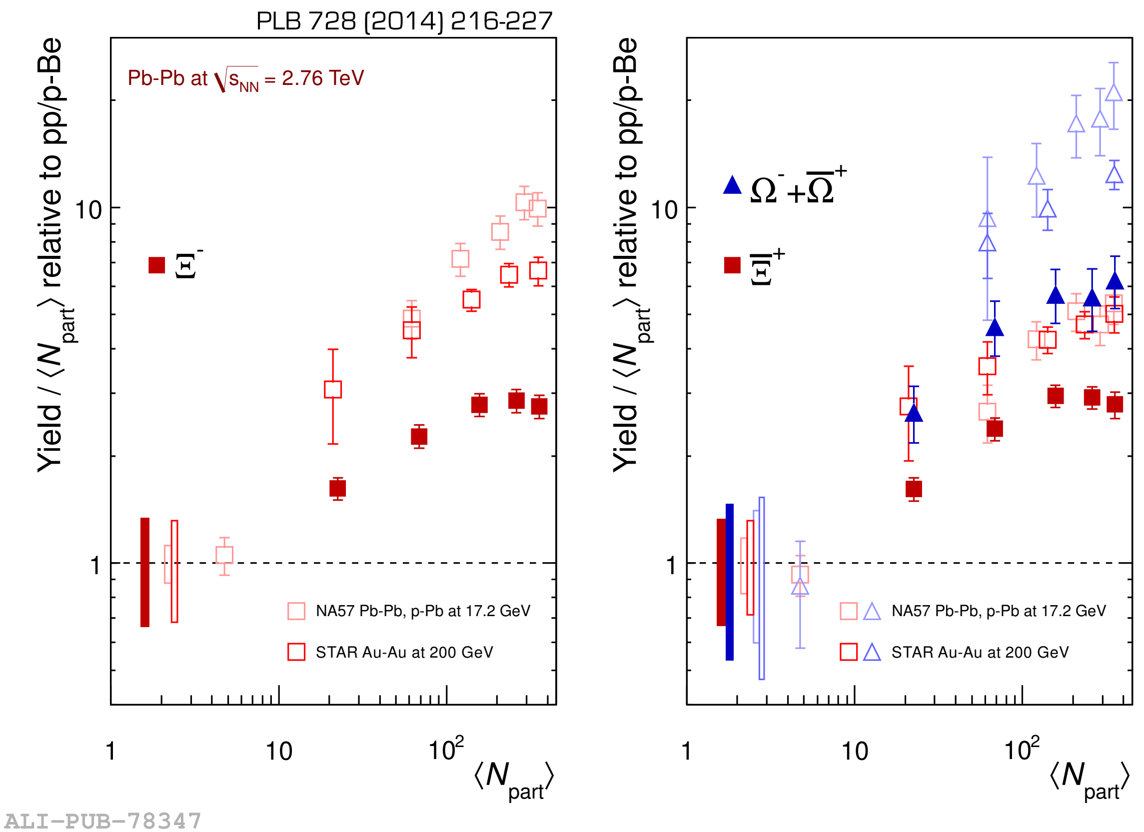

- Hierarchy based on strangeness content
- Magnitude increases when going from peripheral to most central collisions
- Results from SPS, RHIC and LHC show a decreasing enhancement with energy

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

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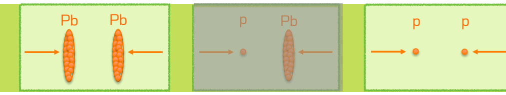

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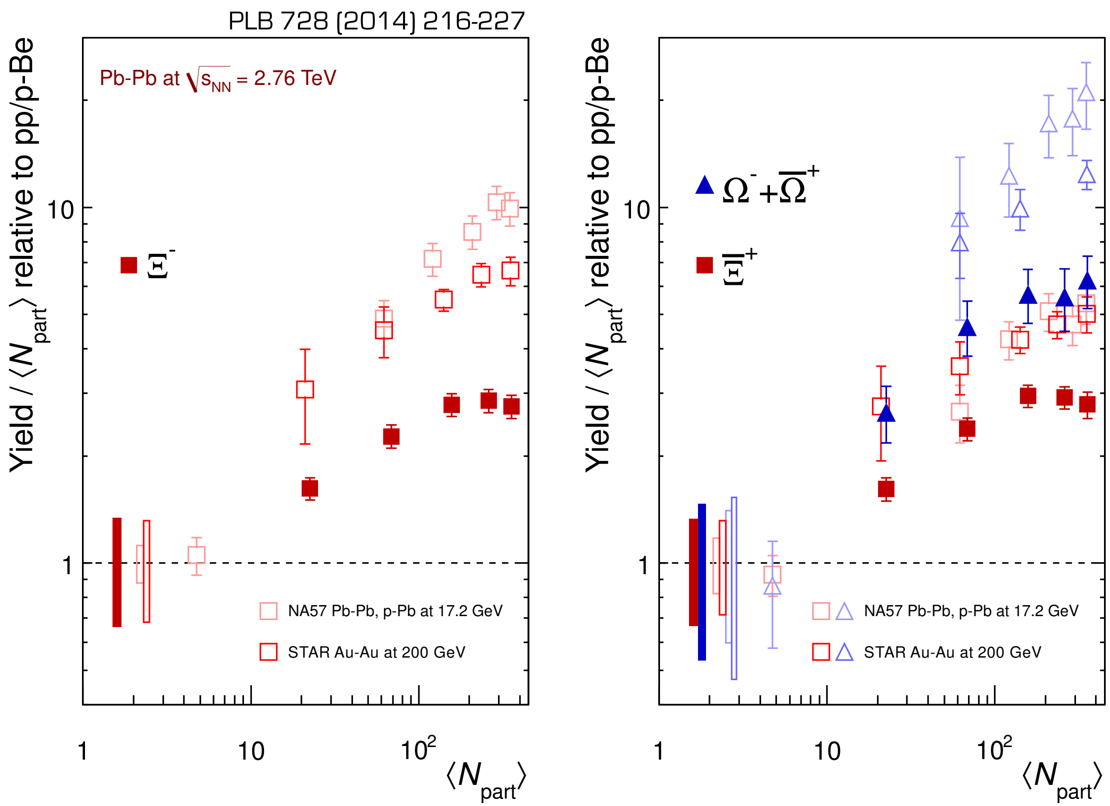

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Question

Is the N_{part} scaling the right assumption?

Charged particle production is not proportional to N_{part}

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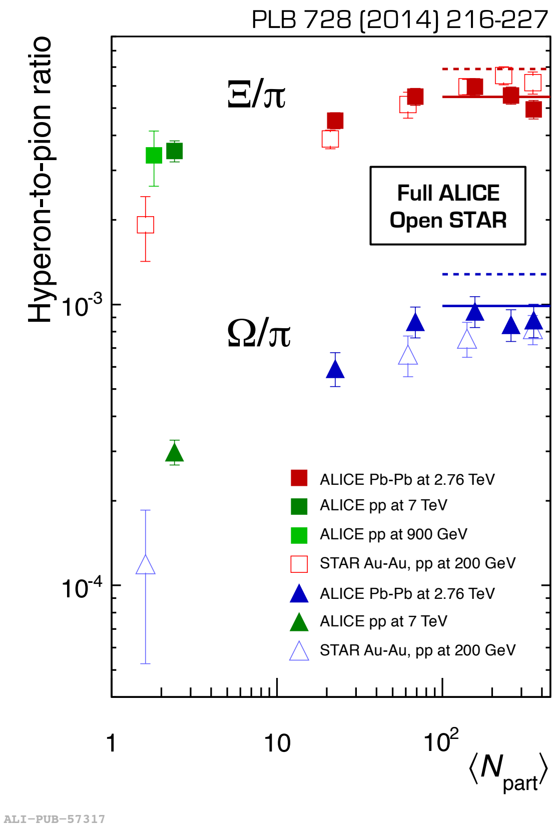

- Hyperon to pion ratios in Pb–Pb:

STAR: Phys. Rev. C 75, 064901 (2007)
Phys. Rev. Lett. 98, 62301 (2007)
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ALICE: Phys. Lett. B 712, 309 (2012)
1303.0737v1 [hep-ex]
Eur. Phys. J. C 71, 1594 (2011)
Eur. Phys. J. C 71, 1655 (2011)

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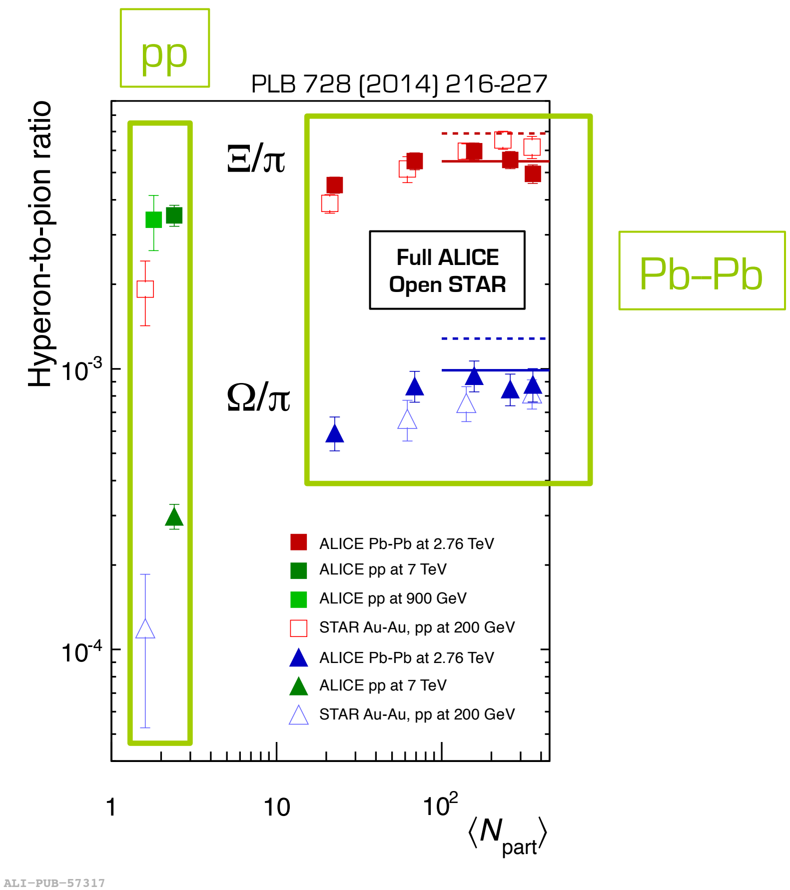

- Hyperon to pion ratios in Pb–Pb:
  - ✓ Relative production of strangeness in pp increases faster with energy than in A–A going from RHIC to LHC (suggest removal of canonical suppression)

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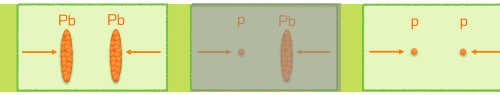

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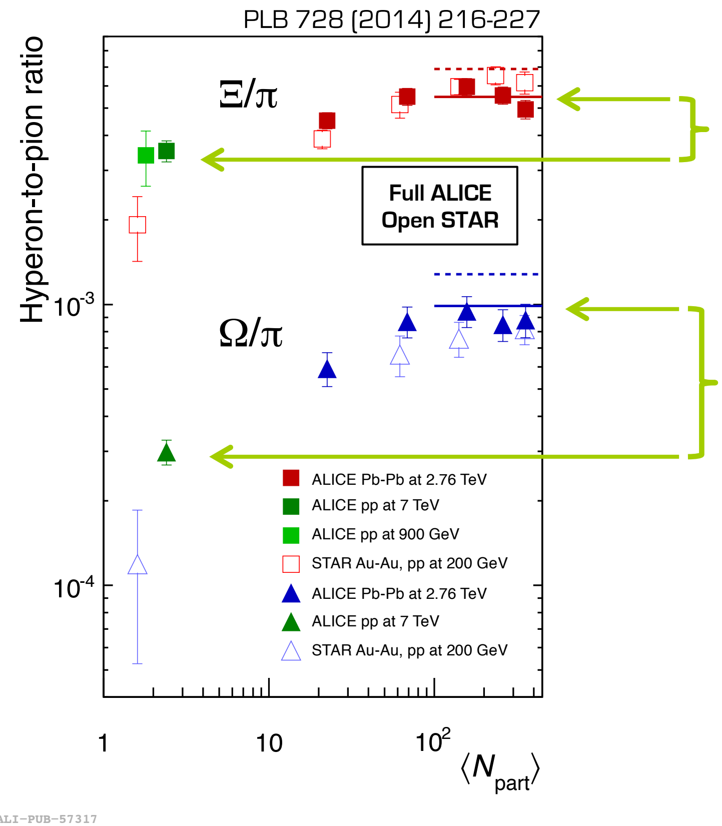

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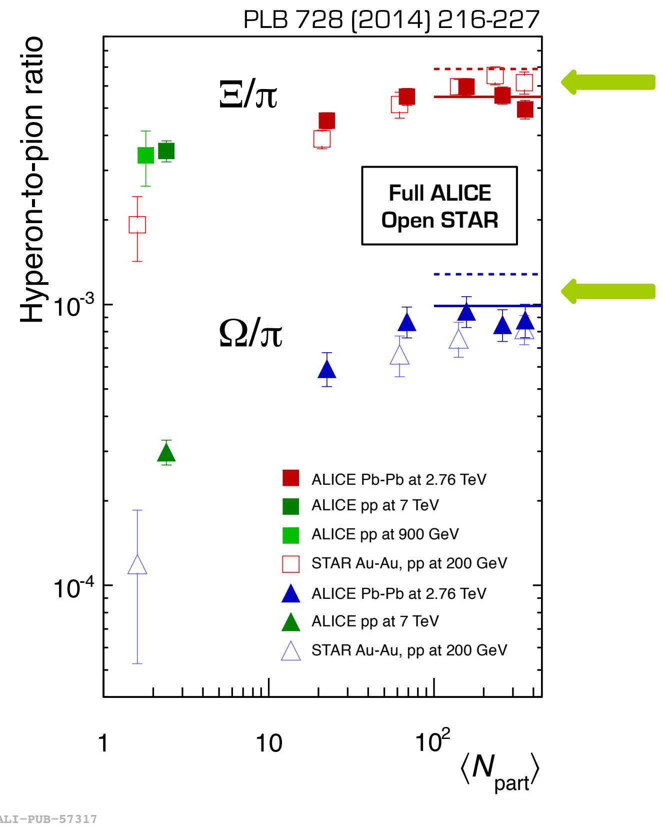
  - ✓ Relative production of strangeness in pp increases faster with energy than in A–A going from RHIC to LHC (suggest removal of canonical suppression)
  - ✓ Increase of Ξ/π and Ω/π from pp to Pb–Pb: almost half of the Ξ and Ω enhancements as defined by the participant-scaled yields

STAR: Phys. Rev. C 75, 064901 (2007)
Phys. Rev. Lett. 98, 62301 (2007)
Phys. Rev. C 79, 034909 (2009)

ALICE: Phys. Lett. B 712, 309 (2012)
1303.0737v1 [hep-ex]
Eur. Phys. J. C 71, 1594 (2011)
Eur. Phys. J. C 71, 1655 (2011)

Results

Strangeness enhancement



- Hyperon to pion ratios in Pb–Pb:
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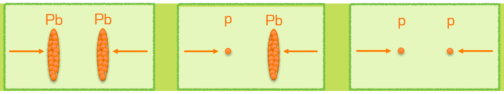
  - ✓ Increase of Ξ/π and Ω/π from pp to Pb–Pb: almost half of the Ξ and Ω enhancements as defined by the participant-scaled yields
  - ✓ Ratios in Pb–Pb at LHC for $N_{part} > 150$ match predictions from thermal models based on a grand canonical approach
    - — GSI model [1]: T_{ch} = 164 MeV
    - ... THERMUS model [2]: T_{ch} = 170 MeV

STAR: Phys. Rev. C 75, 064901 (2007)
Phys. Rev. Lett. 98, 62301 (2007)
Phys. Rev. C 79, 034909 (2009)

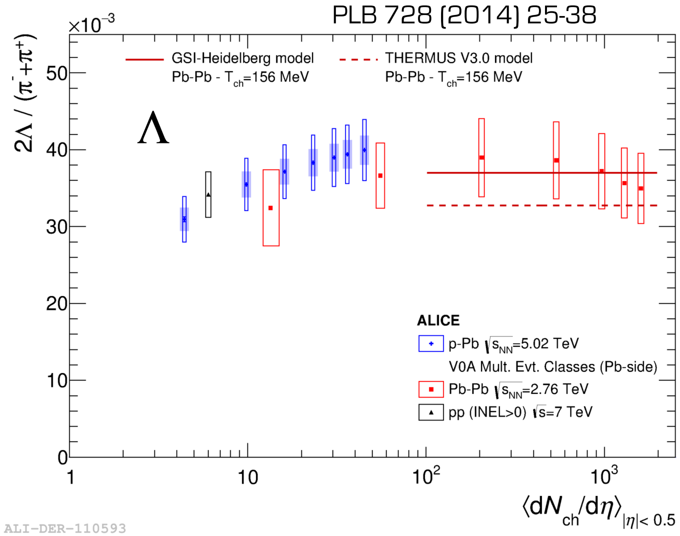
ALICE: Phys. Lett. B 712, 309 (2012)
1303.0737v1 [hep-ex]
Eur. Phys. J. C 71, 1594 (2011)
Eur. Phys. J. C 71, 1655 (2011)

[1]: Andronic, A. et al. Phys.Lett. B673 (2009) 142-145, Erratum-ibid. B678 (2009) 516
[2]: Wheaton, S. et al. Comput.Phys.Commun. 180 (2009) 84-106

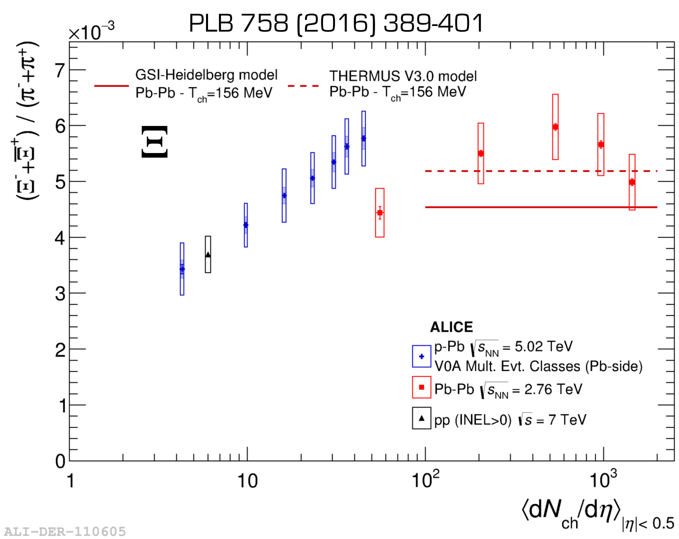
Results

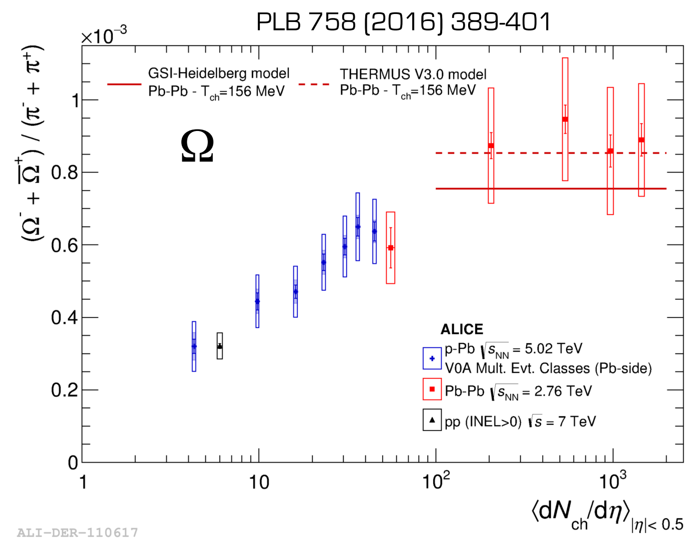


Strangeness enhancement

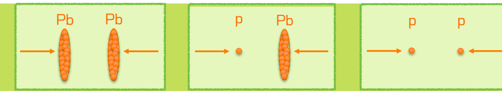


- Hyperon to pion ratios in p–Pb:
  - ✓ Increases for larger $\langle dN_{ch}/d\eta \rangle$
  - ✓ Lowest multiplicity compatible to pp values
  - ✓ Compared to Pb–Pb:
    - Λ/π and Ξ/π comparable to central Pb–Pb
    - Ω/π close to results from peripheral Pb–Pb

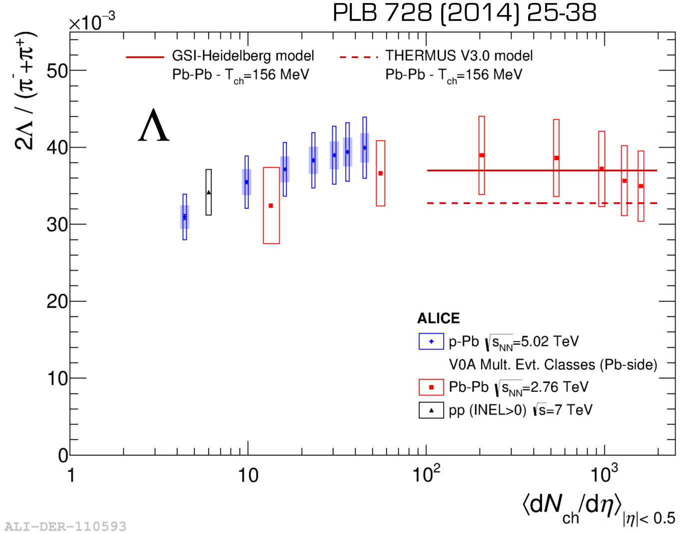




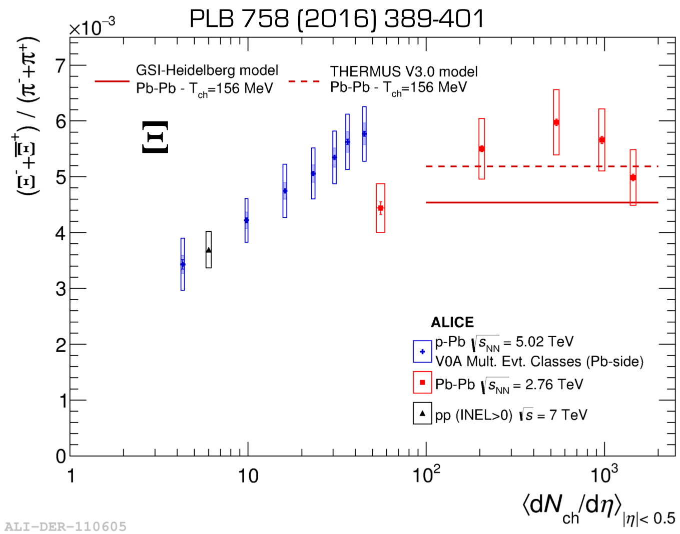
Results

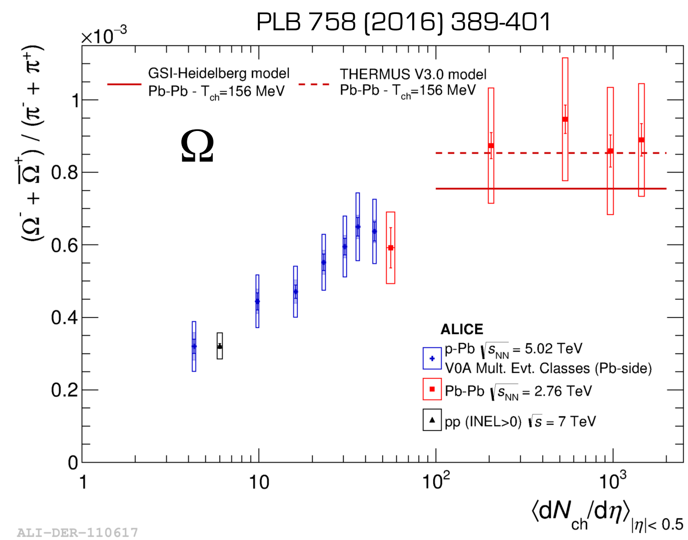


Strangeness enhancement

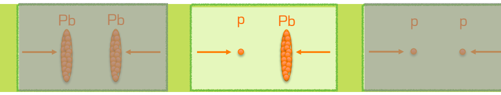


- Hyperon to pion ratios in p–Pb:
  - ✓ Increases for larger $\langle dN_{ch}/d\eta \rangle$
  - ✓ Lowest multiplicity compatible to pp values
  - ✓ Compared to Pb–Pb:
    - Λ/π and Ξ/π comparable to central Pb–Pb
    - Ω/π close to results from peripheral Pb–Pb
  - ✓ Comparison with thermal models:
    - Ξ/π comparable to thermal model predictions
    - Ω/π do not reach the equilibrium limits



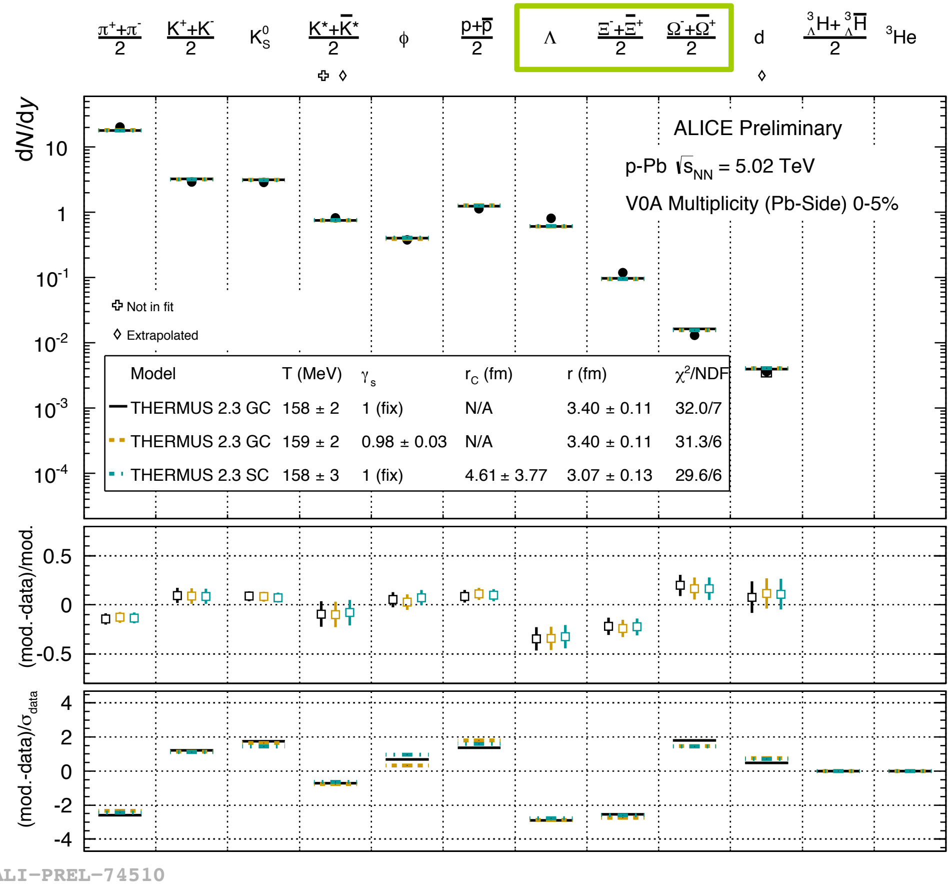


Results



Strangeness enhancement

Statistical hadronization models



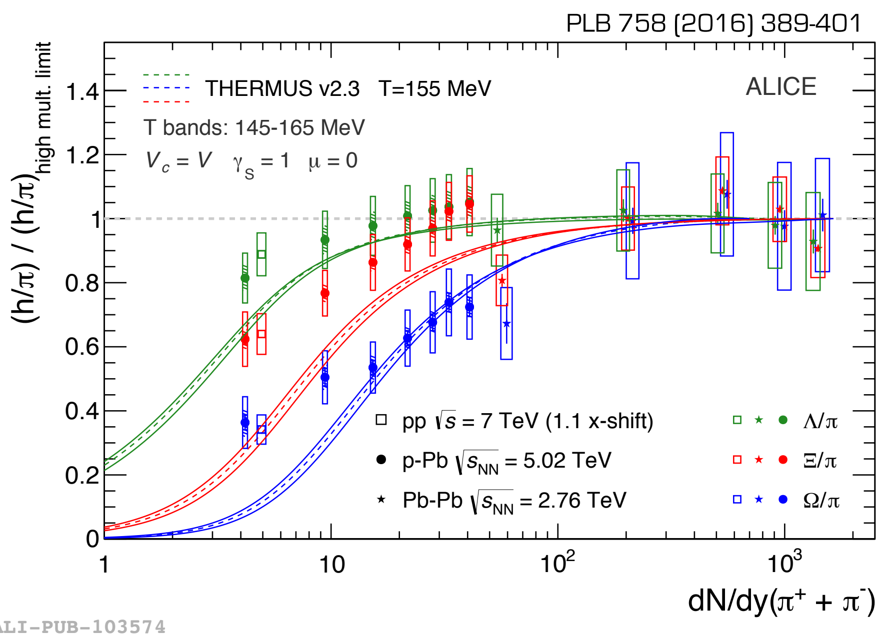
Fit of p–Pb data at high multiplicity with Grand Canonical (GC) and Strangeness Canonical (SC) treatment:

- similar results
  - ✓ the extracted temperature is robust
  - ✓ γ_S is compatible with unity
  - ✓ R_C is compatible with R
- deviations of Λ, Ξ and Ω yields independent of the schema of the fit

Results

Strangeness enhancement

Canonical suppression



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

In p–Pb collisions the trend of the ratio h/π is raising towards the theoretical GC saturation value.
Is this consistent with a canonical suppression scenario?

- h/π ratio normalized to the ratio at high multiplicity limit as a function of charged pion multiplicity
- compared to THERMUS curves for the three species (T=145-165 MeV, R=Rc, γ_S=1, $\mu_B=\mu_Q=\mu_S=0$)

→ The canonical suppression picture is qualitatively in good agreement with the experimental results

Conclusions and outlook

- Spectral p_T shape
  - Particle and antiparticle compatible and hardening of the shape with increasing multiplicity in both systems
  - Baryon-to-meson ratio: qualitatively same behavior in the two systems but stronger in Pb–Pb
  - Nuclear modification factors:
    - ✓ Absence of suppression at high p_T in R_{pPb} implies that in R_{AA} it is due to nuclear matter effect
    - ✓ Mass ordering at mid-p_T (flow) in both systems
    - ✓ Ω R_{AA} strongly affected by strangeness enhancement

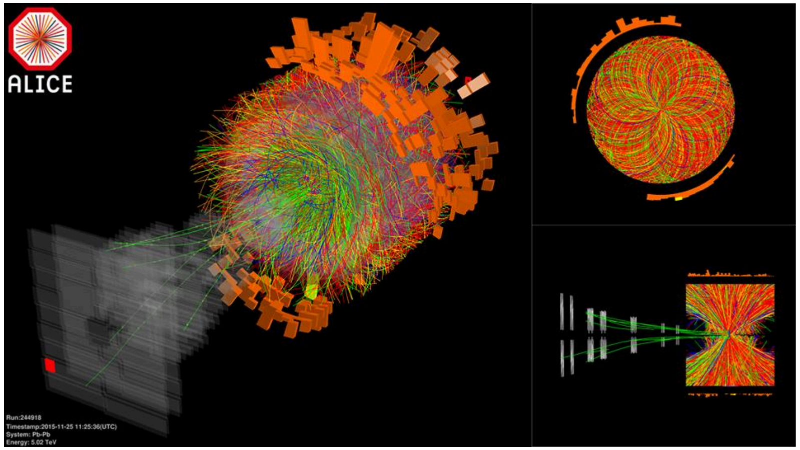
- Strangeness enhancement
  - In Pb–Pb collisions basic features as at lower energies
  - Weaker at LHC than at RHIC, is caused by larger increase of strangeness production in pp
  - Hyperon-to-pion ratios in p–Pb bridge pp and Pb–Pb and increase with charged particle multiplicity
  - The canonical suppression picture is qualitatively in good agreement with the experimental results

- Looking forward for new results
  - pp collisions at $\sqrt{s}$ = 7 and 13 TeV as a function of multiplicity
  - Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV → finer study vs multiplicity

R. D. de Souza
Tue. 17:00 – Room 102
QCD Phase Diagram: II

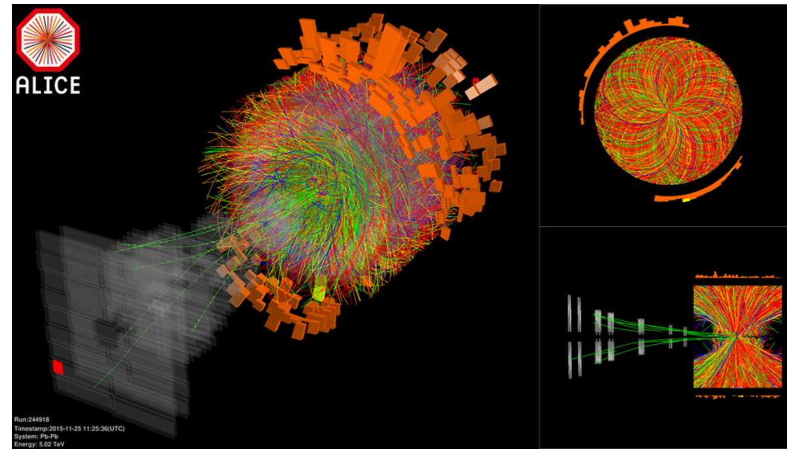
Conclusions and outlook

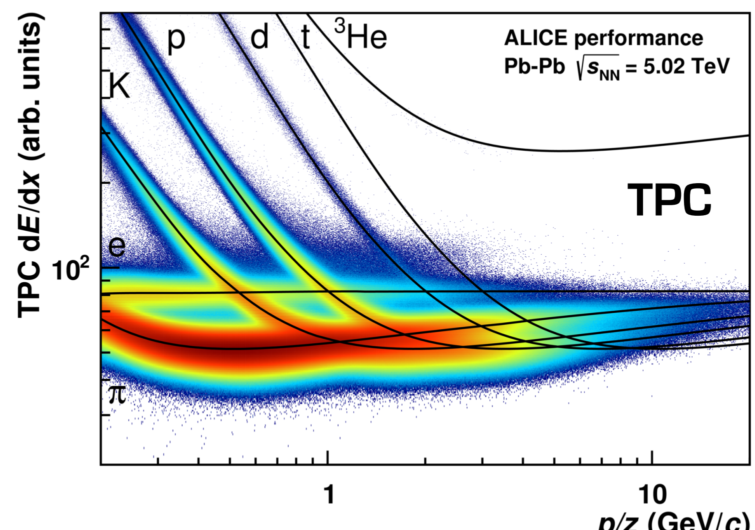
Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



Conclusions and outlook

Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



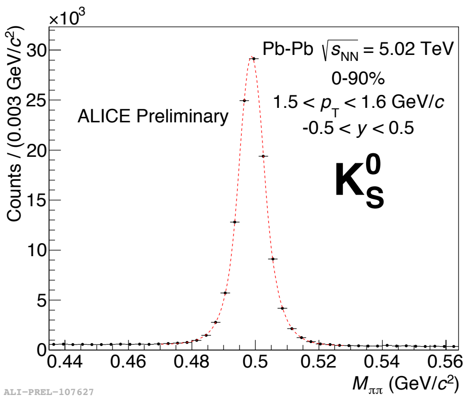


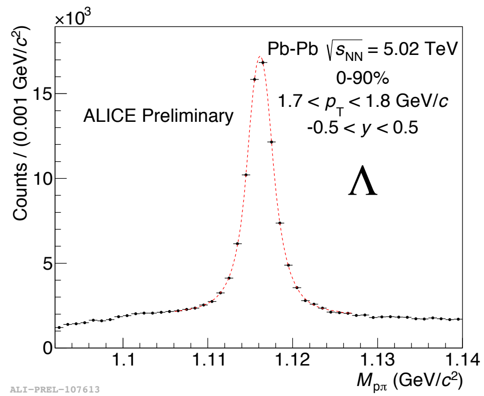
ALI-PERF-107348

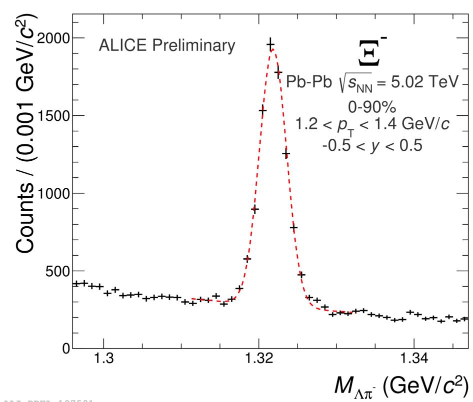
Conclusions and outlook

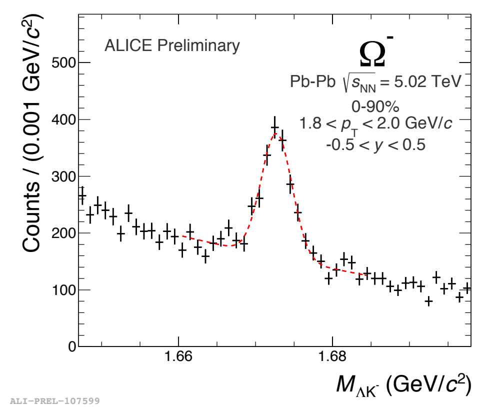
Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

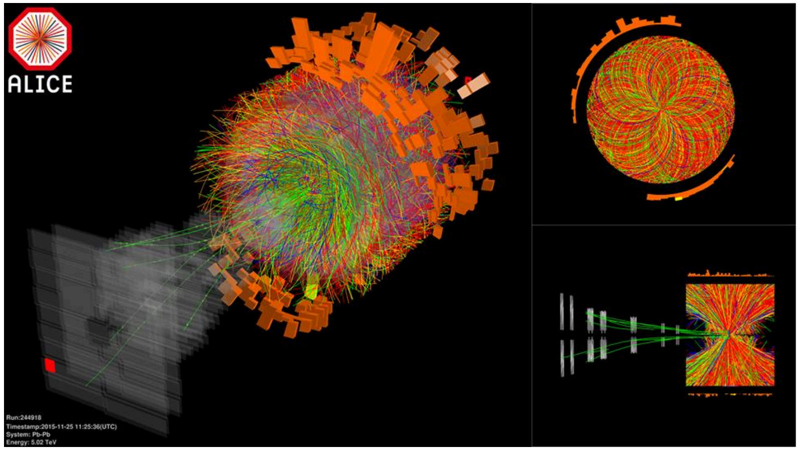
- Reconstruction of the data ongoing
- Analysis performed on minimum bias Pb–Pb collisions from low interaction rate beam fills (about 3×10^6 events)

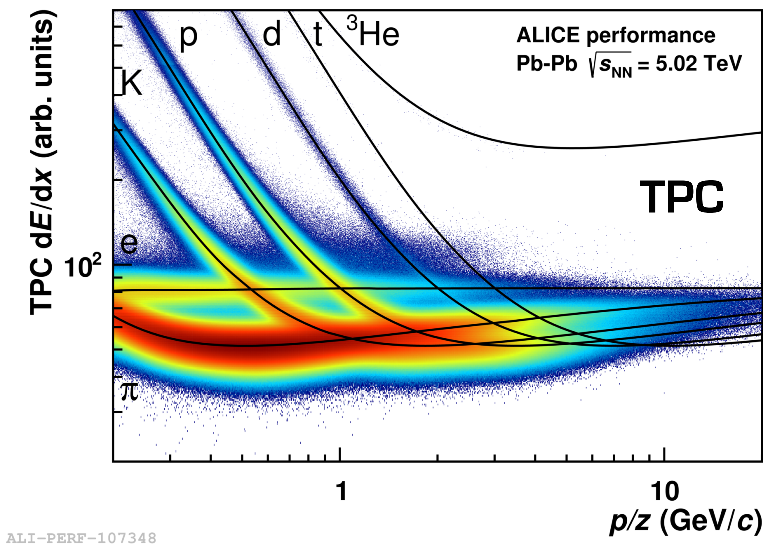












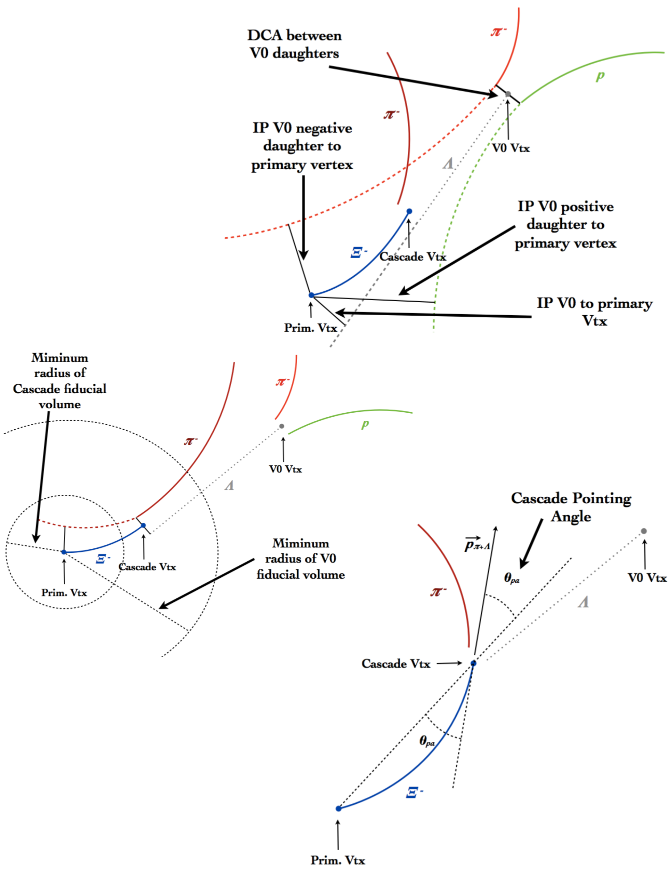
Backup

Backup

Topological cuts in Pb–Pb and pp analysis

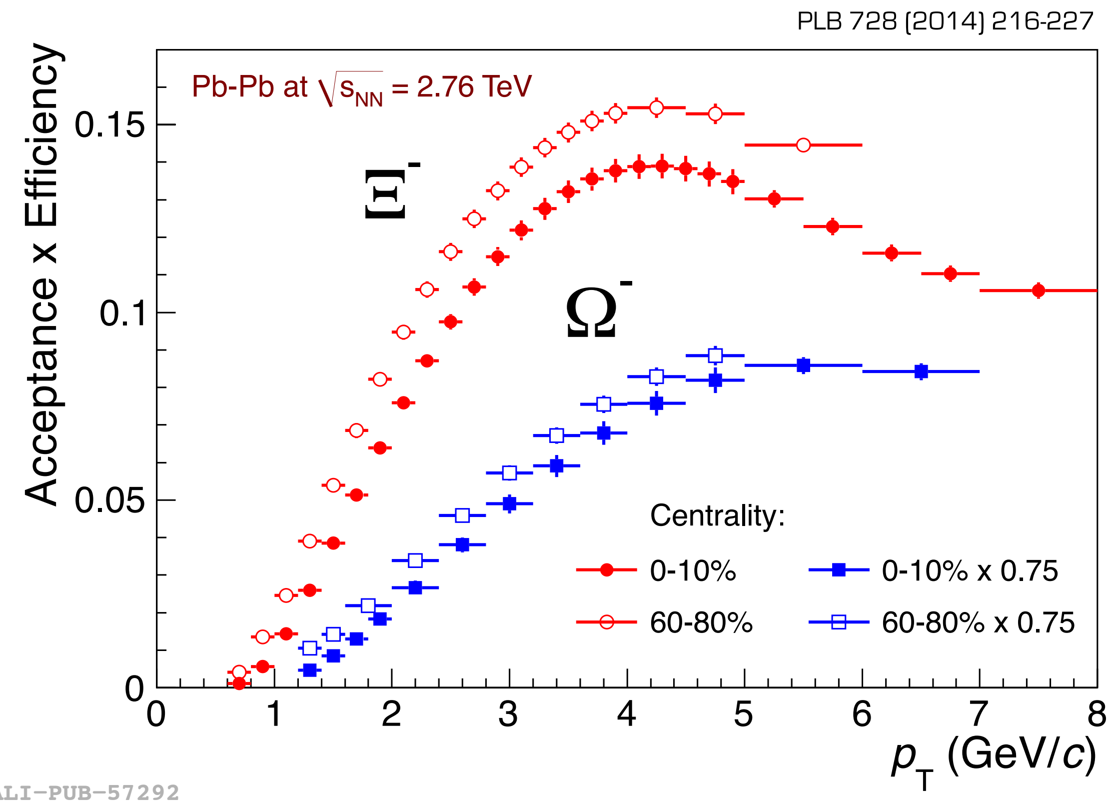
Cuts for cascades	Pb–Pb Ξ (Ω)	pp@2.76TeV Ξ (Ω)	pp@7TeV Ξ(Ω)
Min Allowed V^0 ip (cm)	0.1	0.05(0.01)	0.07
Window around the Λ mass (MeV/c^2)	0.005	0.006(0.008)	1.110 – 1.122
Min allowed bachelor ip (cm)	0.03	0.03(0.01)	0.05
Max allowed DCA cascde daugh (cm)	0.3	1.5(0.5)	1.6 (1.0)
Min allowed cos of cascade PA	0.9992	0.985(0.990)	0.97 (re-set)
Min radius of the fid. vol. (cm)	1.5(1.0)	0.4(0.4)	0.8 (0.6)
Proper length cascade (cm)	15(8)	-	–

Cuts for V^0	Pb–Pb Ξ (Ω)	pp@2.76TeV Ξ (Ω)	pp@7TeV Ξ(Ω)
Min allowed ip for 1° daught (cm)	0.1	0.05(0.05)	0.04 (0.03)
Min allowed ip for 2° daught (cm)	0.1	0.05(0.05)	0.04 (0.03)
Max allowed DCA between daught. tracks (cm)	0.8	1.5(1.5)	1.6 stan. dev.
Min allowed cosine of V^0's PA	0.998	p_T dependent	0.97
Min radius of fiducial volume (cm)	3.0	0.2(0.2)	1.4



Backup

Acceptance-efficiency correction vs p_T



Backup

Blast-wave and Lèvy-Tsallis parametrizations

- To measure the yields in the full p_T range the following parametrization have been used in Pb–Pb and pp analysis:
  - *Blast-wave* [1]: hydrodynamically inspired model which assumes a thermalized, transverse expanding source.
    - Three fit parameters: kinetic freeze-out temperature, transverse velocity and exponential power (T, β_T and n)
    - Gives the best fit to individual particles
    - From PHOBOS evidence that this parametrization gives a good description to very low p_T
  - *Lévy-Tsallis* [2]: the function is grounded in Tsallis statistics and approximates an exponential component (represented by T parameter) as well as a power-law dependence for high-p_T tail.

$$\frac{d^2N}{dydp_T} = \frac{(n-1)(n-2)}{nT[nT+m_0(n-2)]} \times \frac{dN}{dy} \times p_T \times \left(1 + \frac{m_T - m_0}{nT}\right)^{-n}$$

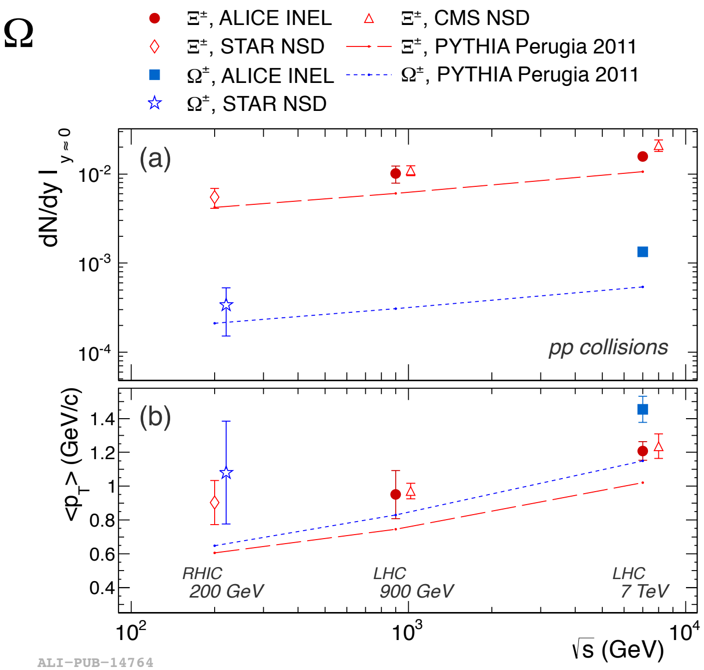
- where T, n and dN/dy (this representing the particle yield per unit rapidity) are fit parameters, $m_T = \sqrt{(m_0^2+p_T^2)}$ and m_0 denotes the particle mass.

[1] E. Schnedermann, J. Sollfrank and U. Heinz, Phys. Rev. C 48, 2462 (1993)
[2] C. Tsallis, J. Stat. Phys. 52 (1988) 479

Backup

Yields for reference pp strangeness enhancement measure

- Reference for enhancements at LHC
  - Interpolate 0.9[1] and 7[2] TeV pp data for Ξ
  - Interpolate 200[3] GeV (STAR) and 7[2] TeV pp data for Ω
  - Use excitation function from PYTHIA Perugia-2011[4]: $s^{0.25}$ ($s^{0.22}$ for charged multiplicity)
  - Checked to match the preliminary measurement in pp collision at $\sqrt{s}$ = 2.76 TeV



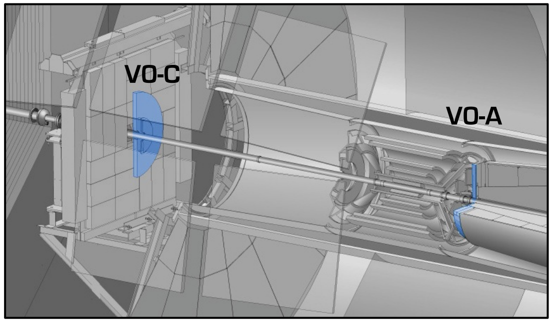
pp@2.76 TeV	Yield Ξ	Yield Ω
Interpolated	(Ξ^-) 0.0068±0.0023 (Ξ^+) 0.0066±0.0022	($\Omega^-+\Omega^+$) 0.00107±0.00050
Measured	(Ξ^-) **0.0059±0.0001** $^{+0.0007}_{-0.0007}$ (Ξ^+) **0.0060±0.0001** $^{+0.0007}_{-0.0007}$	($\Omega^-+\Omega^+$) **0.00092±0.00007** $^{+0.00017}_{-0.00017}$

[1] Phys. Lett. B 712, 309 (2012)
[2] Eur. Phys. J. C 71, 1594 (2011)
[3] Phys. Rev. C 75, 064901 (2007)
[4] Phys. Rev. D 82, 074018 (2010)

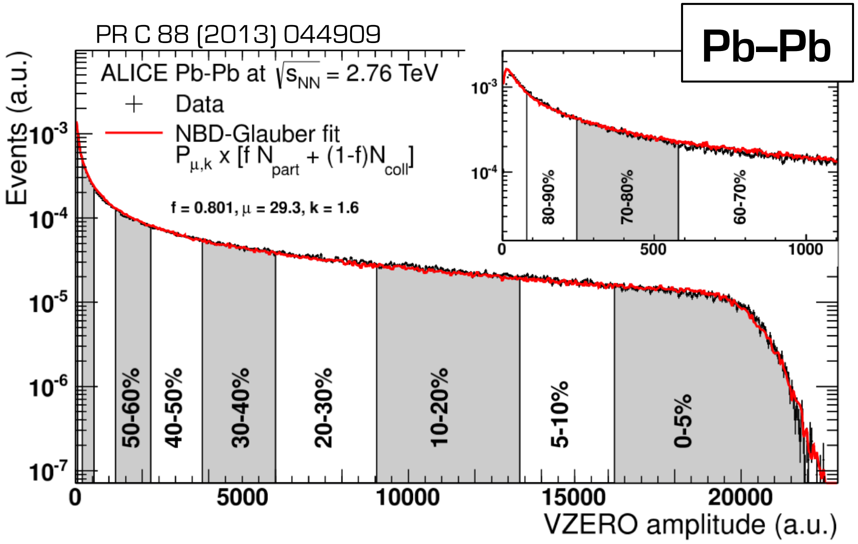
Backup

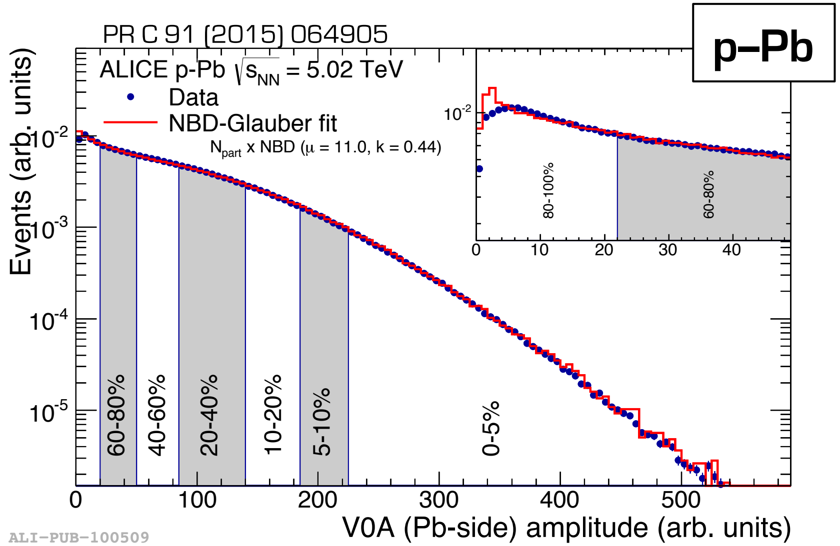
Centrality/Multiplicity determination in Pb–Pb/p–Pb collisions

- 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:** sum of amplitudes in the two V0 scintillators
  - **p–Pb:** amplitude by V0-A (placed on the outgoing Pb side)



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



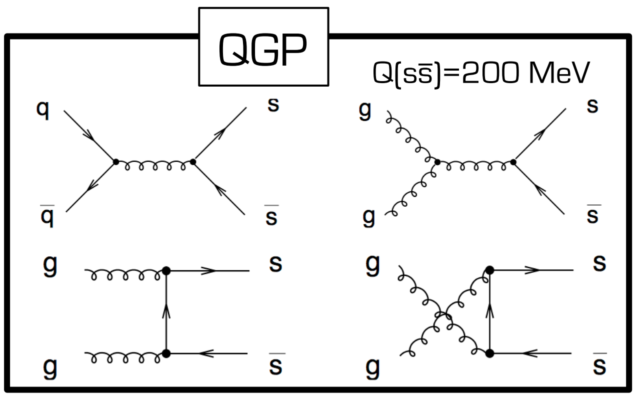


Backup

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 ($N+N \rightarrow N+\Lambda+K$) 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.**



HG

Direct production:

$\pi + \pi \rightarrow \pi + \pi$ + strange hadron + antiparticle

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

Indirect production:

1) $\pi + N \rightarrow K + \Lambda$

2) $\pi + \Lambda \rightarrow K + \Xi$ and $\pi + \Xi \rightarrow K + \Omega$

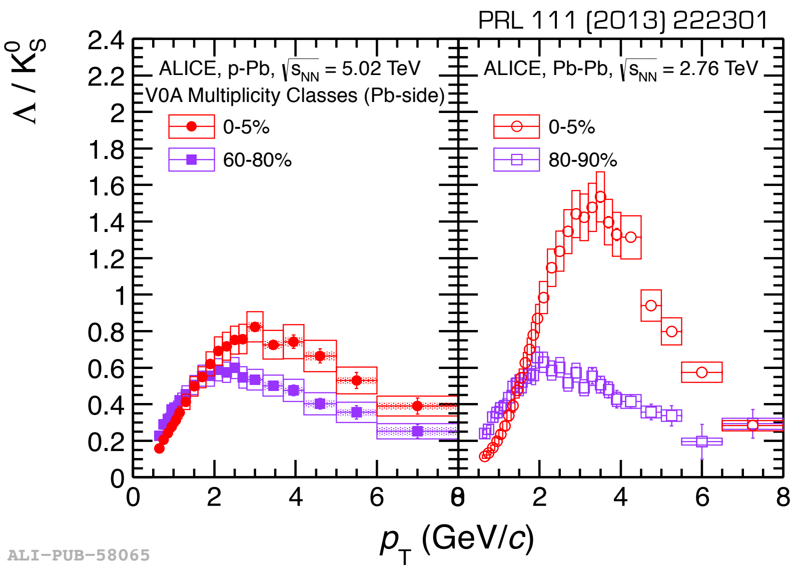
$Q(\Xi) = 1100$ MeV and $Q(\Omega) = 1810$MeV

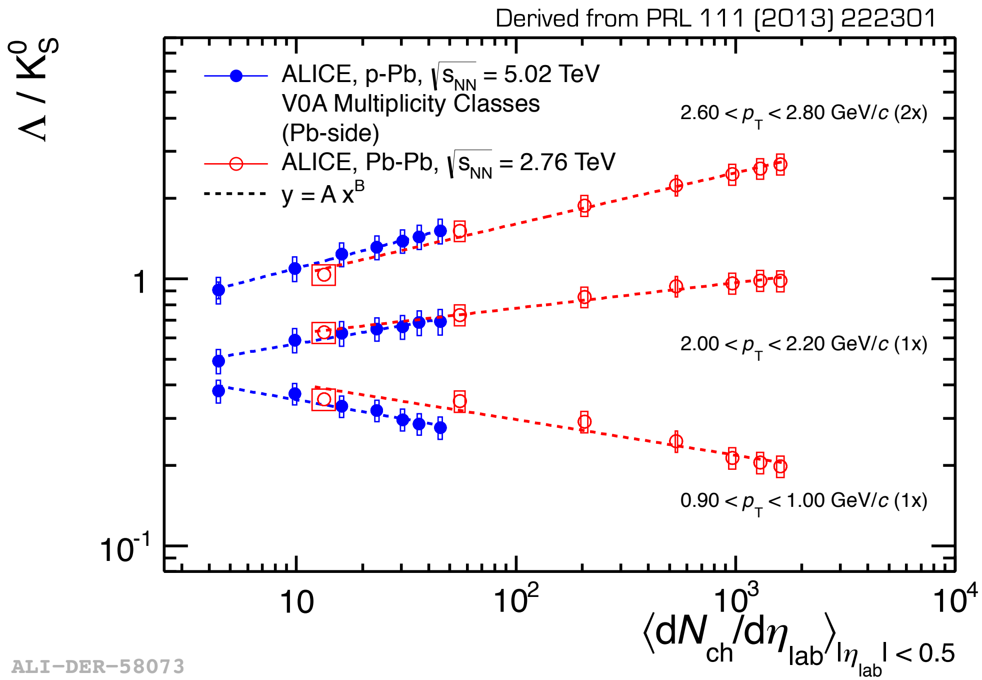
  2. The equilibration time of partonic reactions, expecially due to the gluon fusion process, is much shorter than the one for the hadronic reactions. The difference is especially large, if rare multi-strange (anti-)baryons are considered (${}^{eq}\tau_{QGP} \simeq 10$ fm; ${}^{eq}\tau_{HG} = 30$ fm).

     ➜ **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

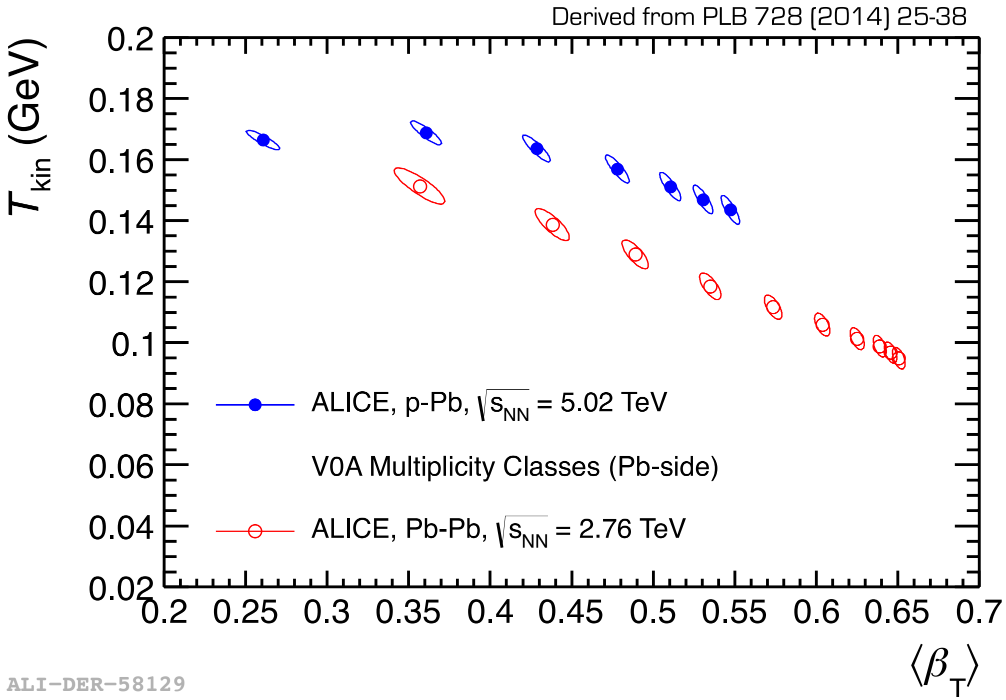
Blast-wave fit study

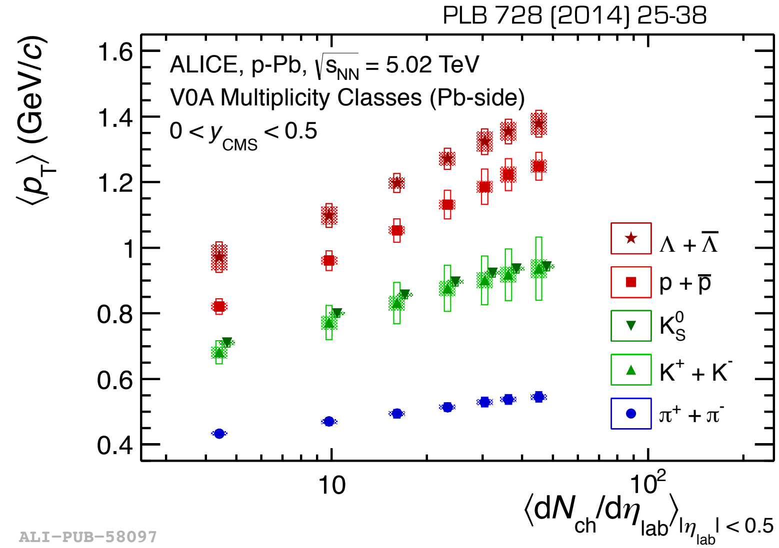
$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\, m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

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

T_{kin} – kinetic freeze-out

β_T – transverse velocity





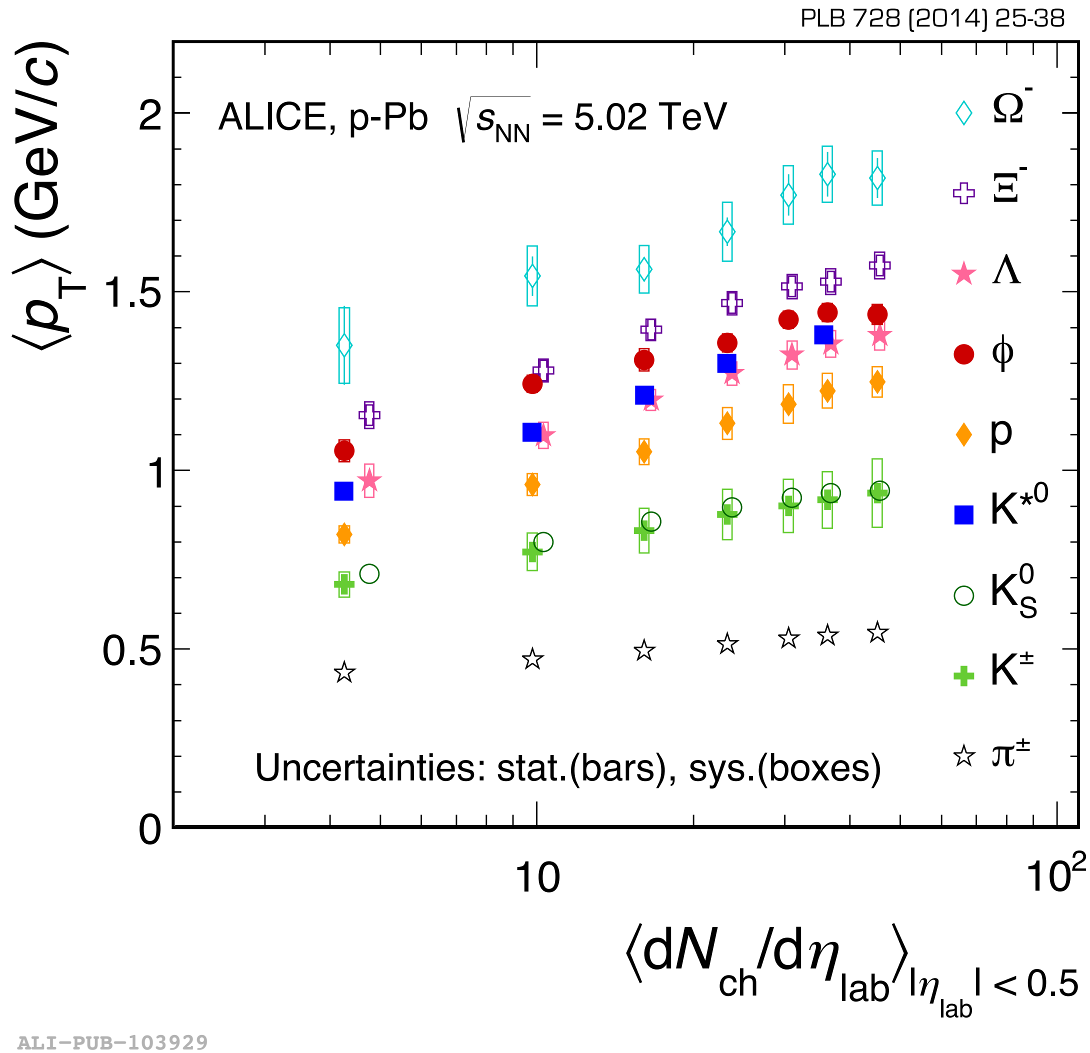
Multiplicity dependence of $\langle p_T\rangle$ for identified particles shows a clear mass ordering → indication for a collective expansion with a common velocity field

- Same kind of mass ordering is also qualitatively expected from color re-connections

Similar evolution of the blast–wave parameters with increasing multiplicity in p–Pb and Pb—Pb.

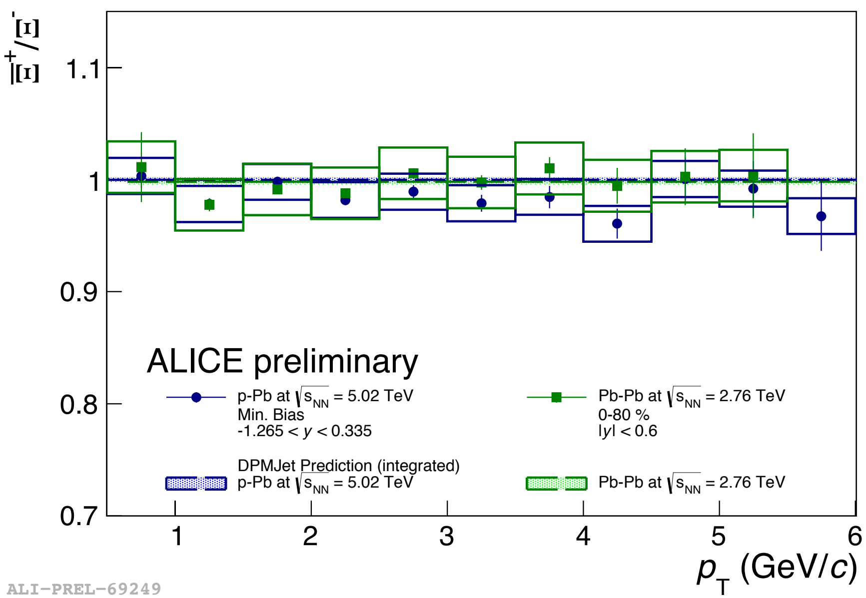
Backup

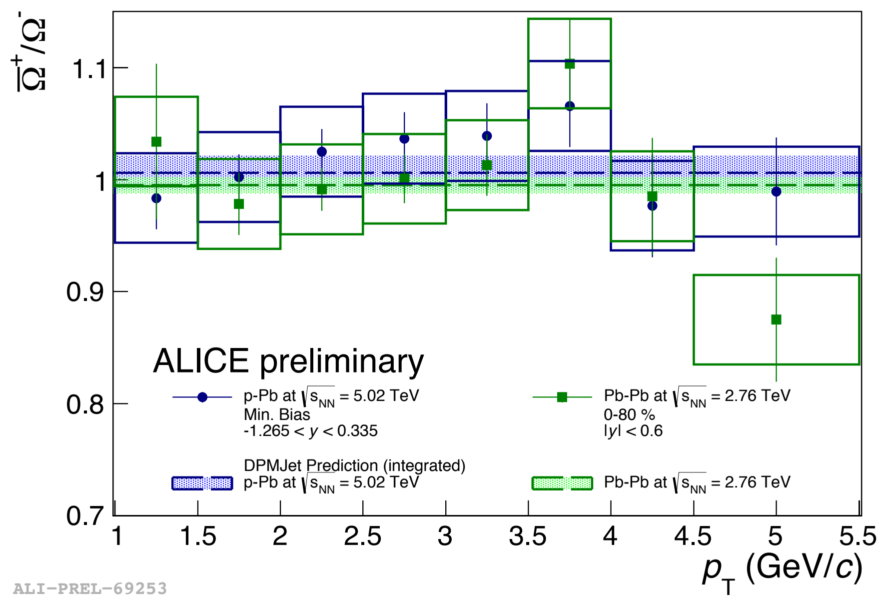
Spectra p_T shape



Backup

Antiparticle over particle ratio





Backup

Charged particle production