XIII Quark Confinement and the Hadron Spectrum Conference
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Recent results on Strangeness production at the LHC with ALICE

Domenico Elia
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on behalf of the ALICE Collaboration

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  - physics motivation
  - experimental apparatus
  - strange particle detection with ALICE
- **Results in pp, p-Pb and Pb-Pb (Xe-Xe)**:
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  - baryon-to-meson ratios
  - strange-to-pion ratios: strangeness enhancements
  - comparison with statistical hadronization (thermal) models
- **Conclusions and Outlook**

Physics motivation

- Main goal of the ALICE experiment:
  - study nucleus-nucleus (A-A) collisions
    - investigate deconfined phase of matter (Quark Gluon Plasma, **QGP**):
      - hydrodynamical evolution, energy loss, thermal/chemical equilibrium

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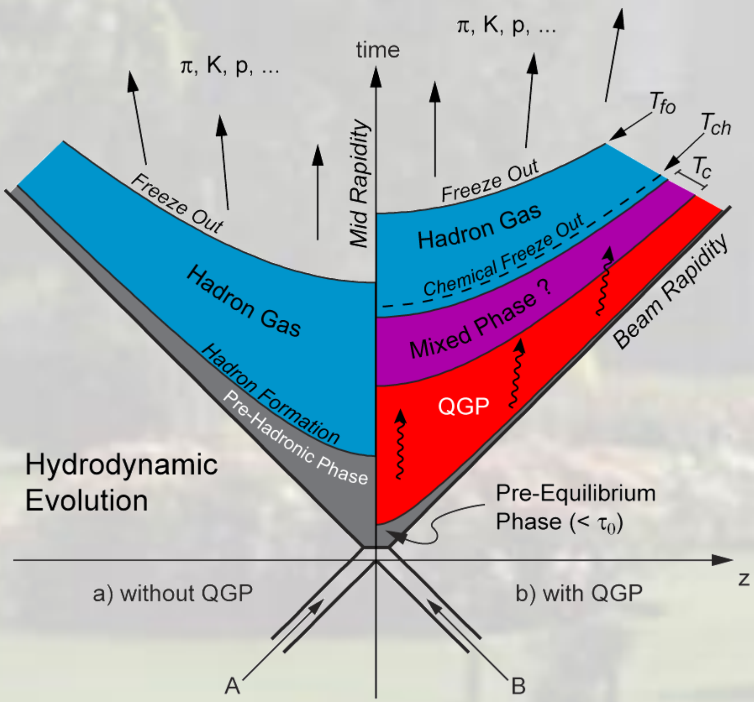

Fireball evolution:

- starts with a "**pre-equilibrium state**"
- forms a "**QGP phase**" (if $T > T_C$)
- "**chemical freeze-out**" (T_{ch}):
  → hadrons stop being produced
- "**kinetic freeze-out**" (T_{kin}):
  → hadrons stop scattering

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  - use pp (and p-Pb) collisions as baseline / control experiments
    - intriguing observations from multiplicity dependent studies:
      - small collisions systems show **remarkable commonalities with A-A**
      - strong hints of collectivity

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Studying strangeness in pp, p-Pb and Pb-Pb (Xe-Xe):

Collectivity (spectra):

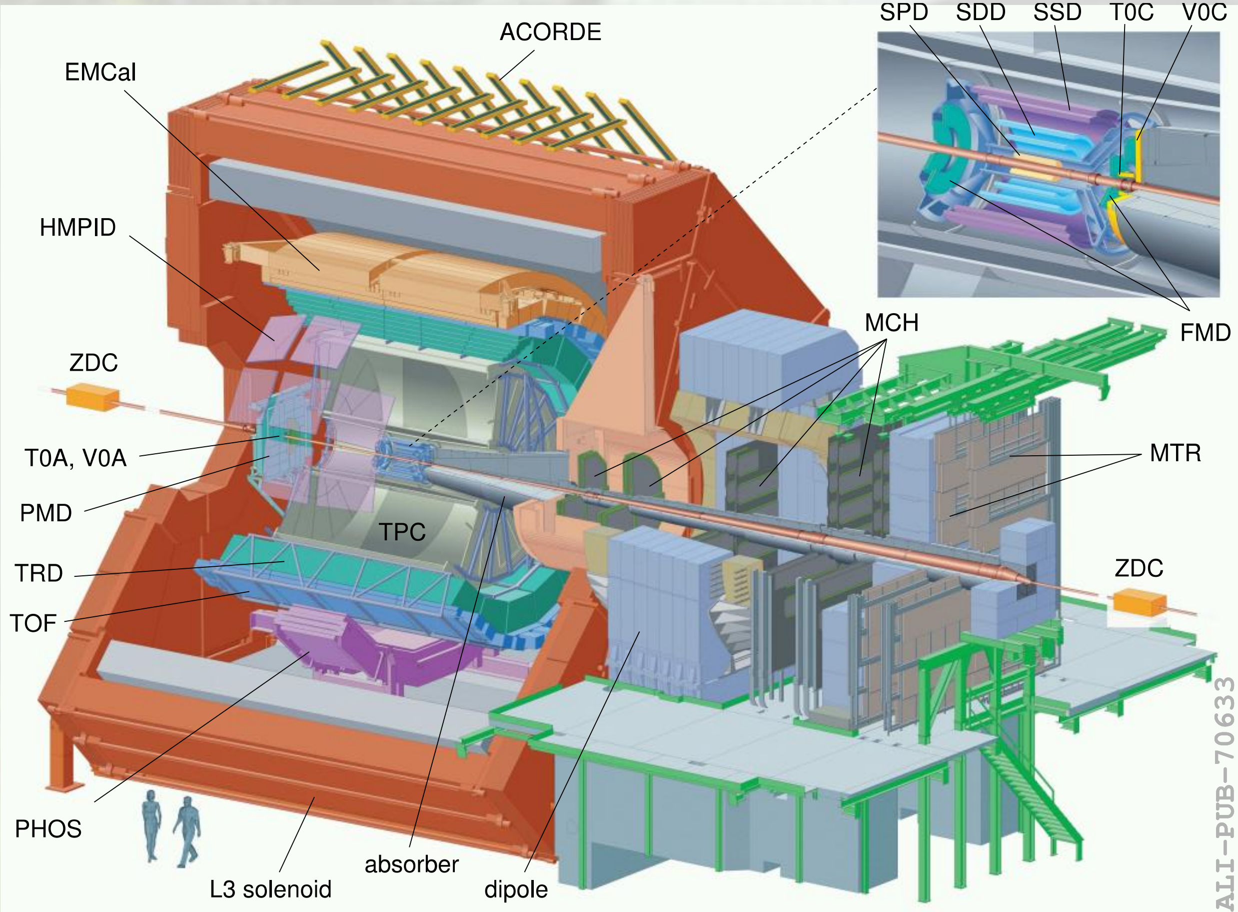
- transverse momentum distributions, baryon-to-meson ratios

Hadrochemistry (yields and ratios):

- strangeness enhancement, multiplicity and energy dependence
- comparison with thermal model predictions

Experimental apparatus

A Large Ion Collider Experiment at the LHC



Low material budget in the central region
good momentum resolution (~1-5%) @ p_T = 0.1-20 GeV/c

ITS, TPC:
tracking, vertexing

V0A(C):
triggering,
beam-gas rejection,
centrality (Pb-Pb, Xe-Xe) and multiplicity (pp, p-Pb)
class definition

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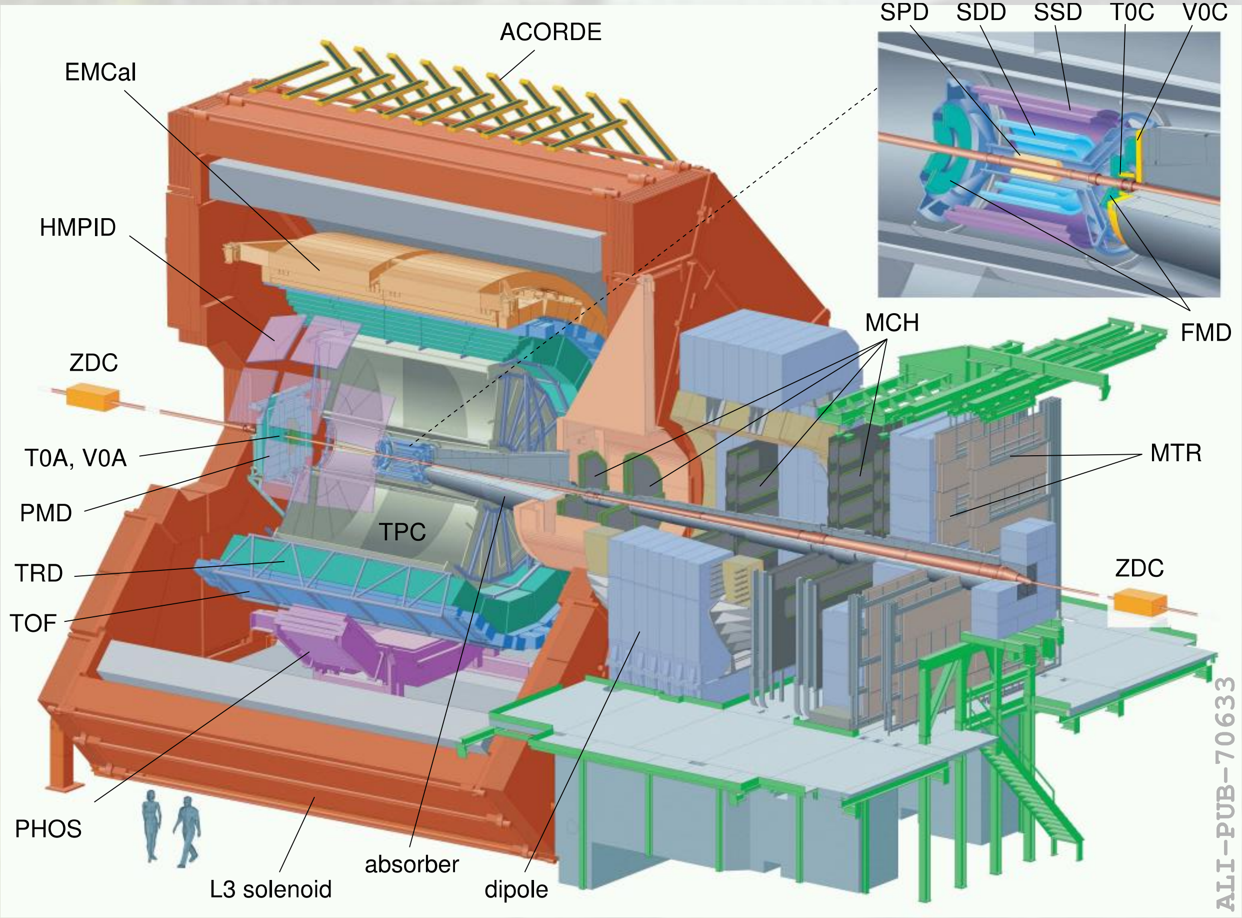

Complementary particle identification techniques

excellent PID capability in a wide p_T range:

- energy loss (**ITS, TPC**)
- time-of-flight (**TOF**)
- Cherenkov (**HMPID**)
- topological decays

Data samples:

- **pp** @ 2.76, 5.02, **7**, 8, **13** TeV
- p-Pb @ 5.02, 8.16 TeV
- **Pb-Pb** @ 2.76, **5.02** TeV
- **Xe-Xe** @ **5.44** TeV

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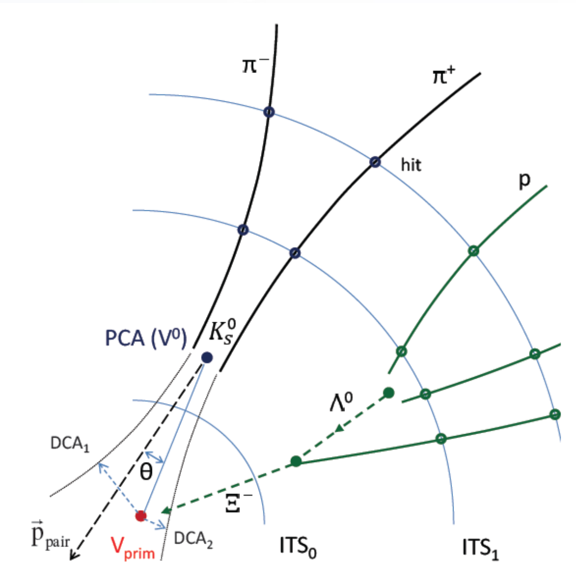
Strange particle detection

- From charged tracks to yields:
  - topological decay reconstruction
  - geometrical and kinematical selections
  - decay product invariant mass analysis



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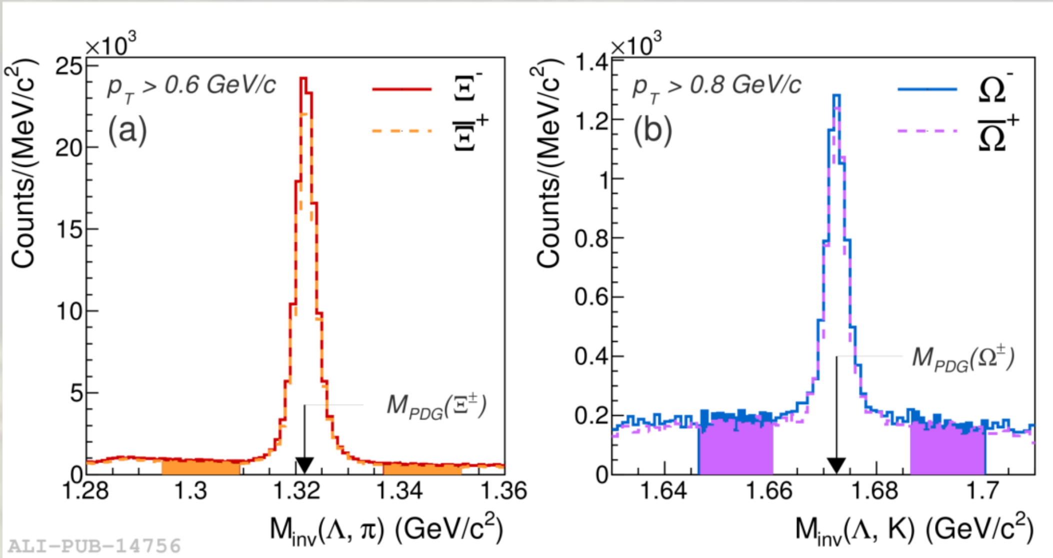

$$K_S^0 \rightarrow \pi^+ + \pi^- \text{ (B.R. 69.2\%)}$$
$$\Lambda \rightarrow p + \pi^- \text{ (B.R. 63.9\%)}$$
$$\overline{\Lambda} \rightarrow \overline{p} + \pi^+ \text{ (B.R. 63.9\%)}$$

$$\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^- + \pi^- \text{ (B.R. 63.9\%)}$$
$$\overline{\Xi}^+ \rightarrow \overline{\Lambda} + \pi^+ \rightarrow \overline{p} + \pi^+ + \pi^+ \text{ (B.R. 63.9\%)}$$
$$\Omega^- \rightarrow \Lambda + K^- \rightarrow p + \pi^- + K^- \text{ (B.R. 43.3\%)}$$
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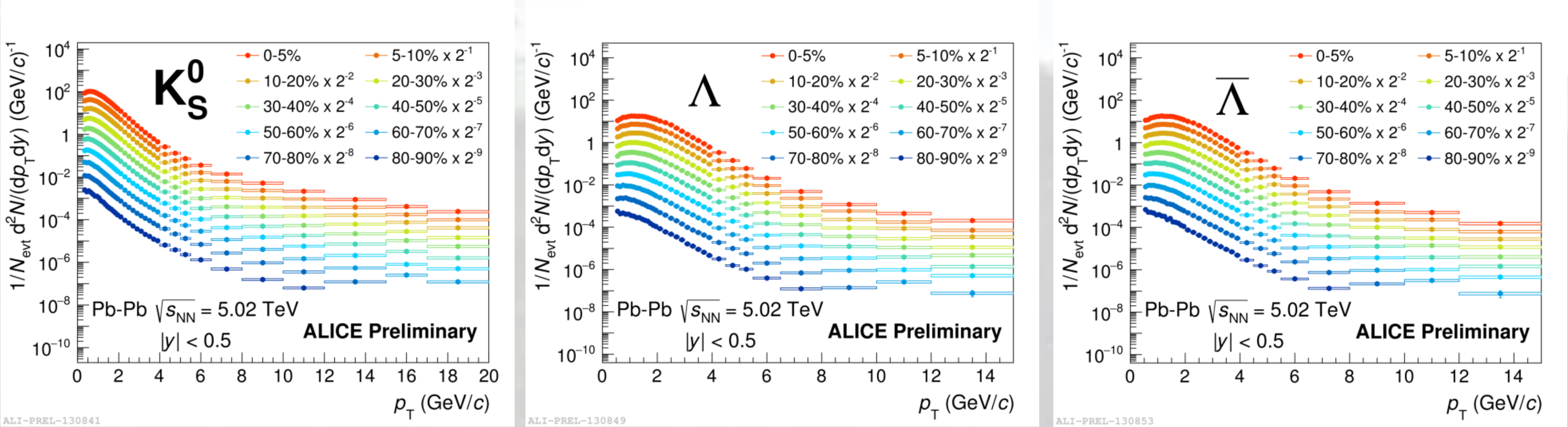
Transverse momentum spectra



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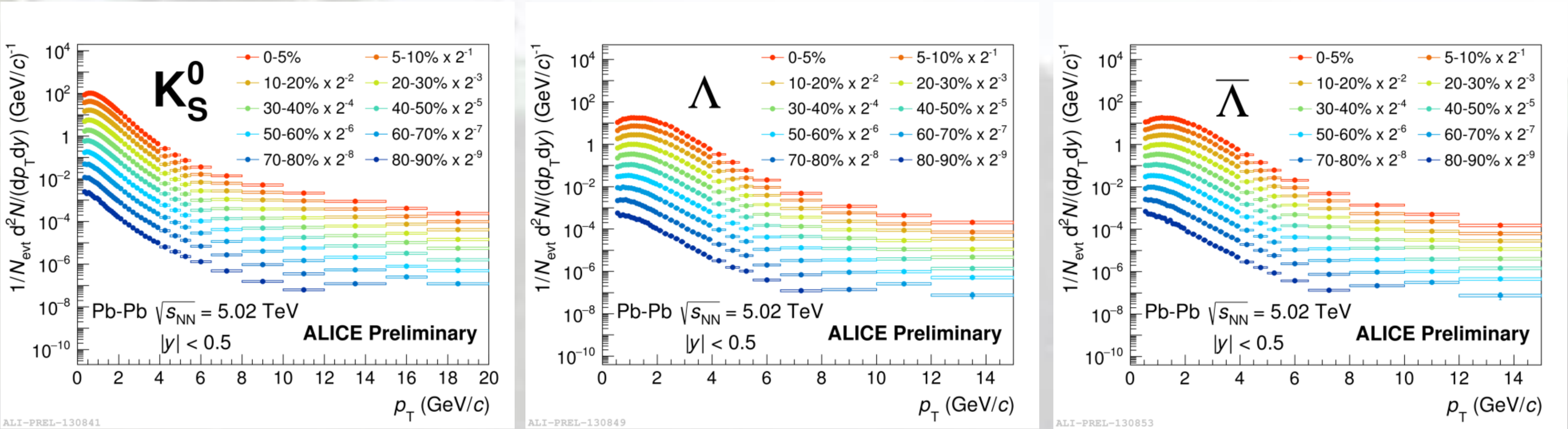


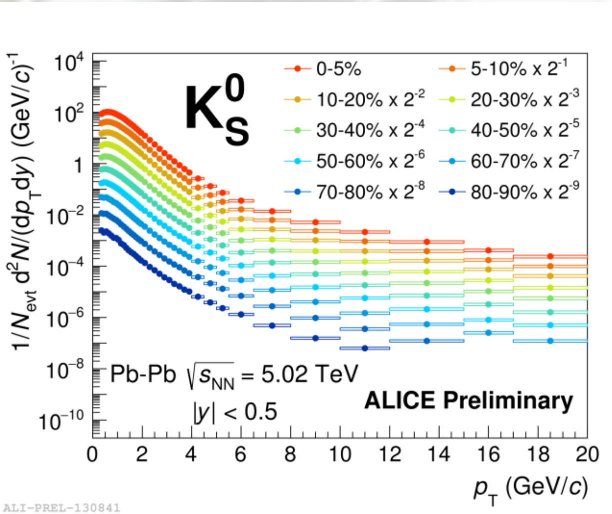
Hardening of the spectra with increasing centrality of the collision

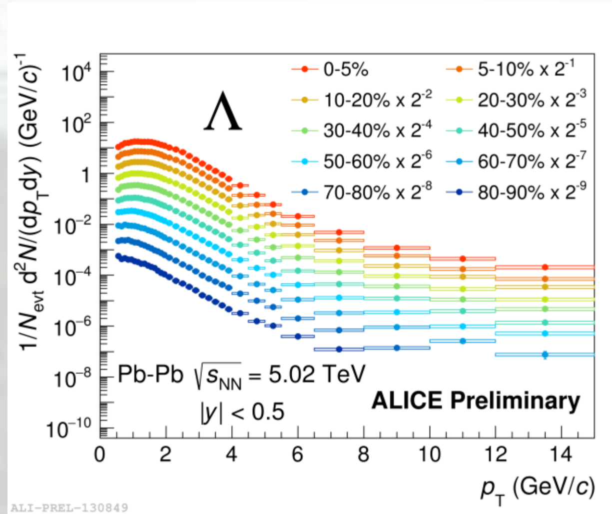
Spectra hardening more pronounced for heavier than for lighter particles (expected as effect of the radial flow)

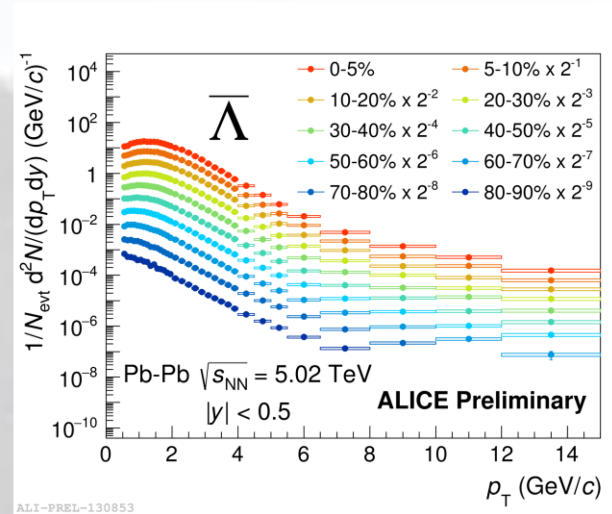
Same pattern for multi-strange hadrons →

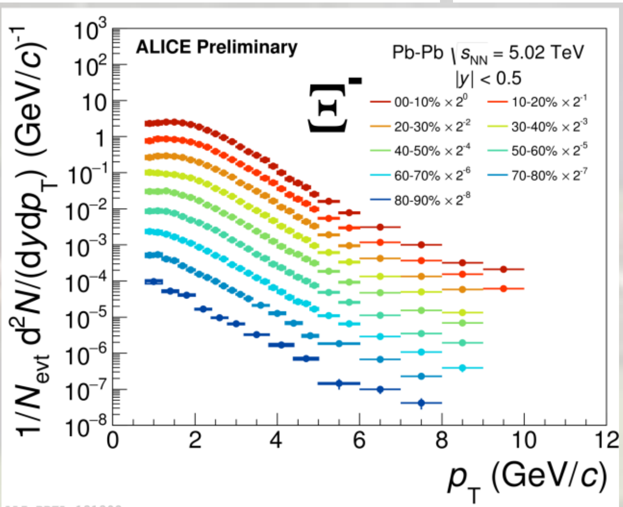
Results in Pb-Pb @ 5.02 TeV

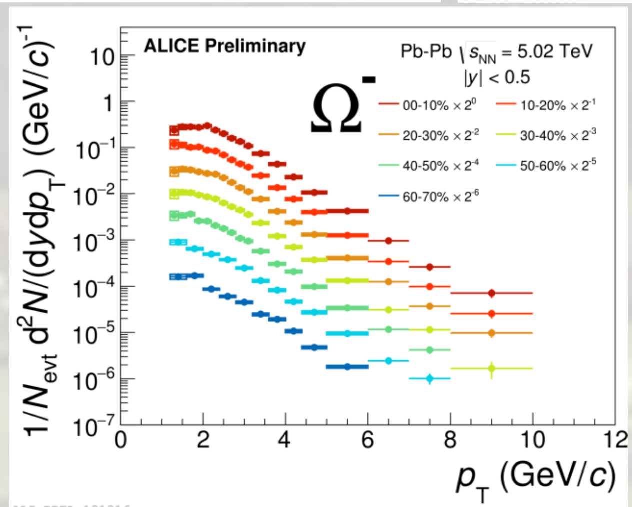
Transverse momentum spectra











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Transverse momentum spectra

- Multiplicity classes based on V0 detector:
  - $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$
  - 10 multiplicity classes (I → X)
    - I: $\langle dN_{ch}/d\eta \rangle \approx 3.5 \langle dN_{ch}/d\eta \rangle^{INEL>0}$

    ...
    - X: $\langle dN_{ch}/d\eta \rangle \approx 0.4 \langle dN_{ch}/d\eta \rangle^{INEL>0}$

  with $\langle dN_{ch}/d\eta \rangle^{INEL>0} \approx 6.0$

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    with $\langle dN_{ch}/d\eta \rangle^{INEL>0} \approx 6.0$

- Shape evolution similar to A-A:
  - harder with increasing multiplicity
  - hardening more pronounced for heavier than for lighter particles

In A-A collisions such behaviour could be explained by models based on relativistic hydrodynamics

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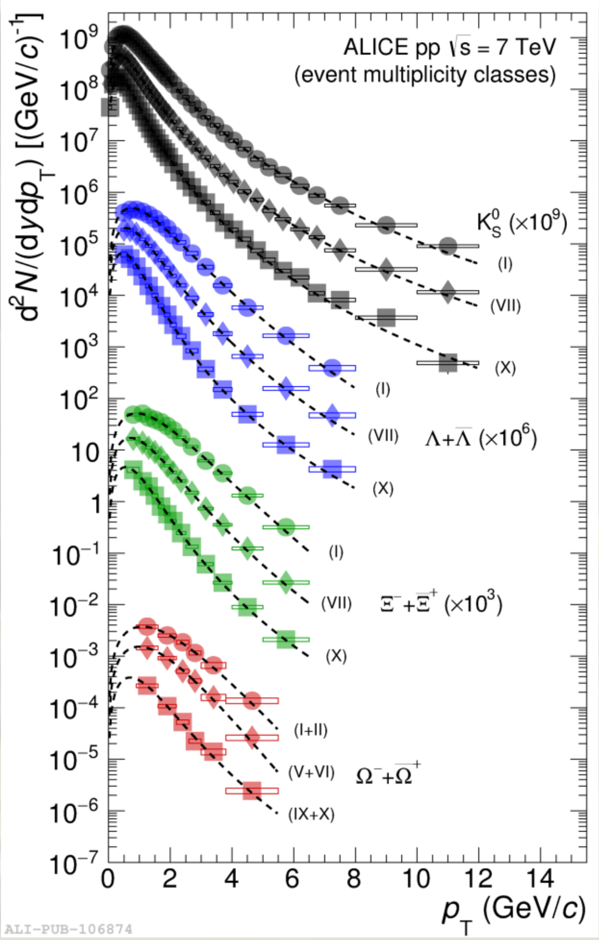
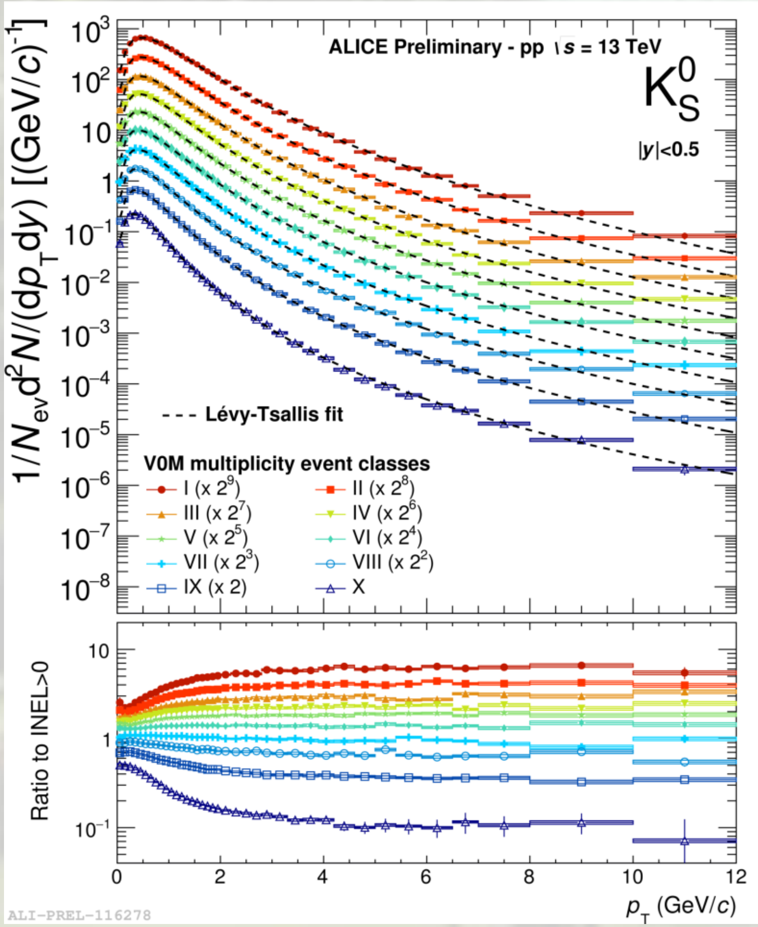
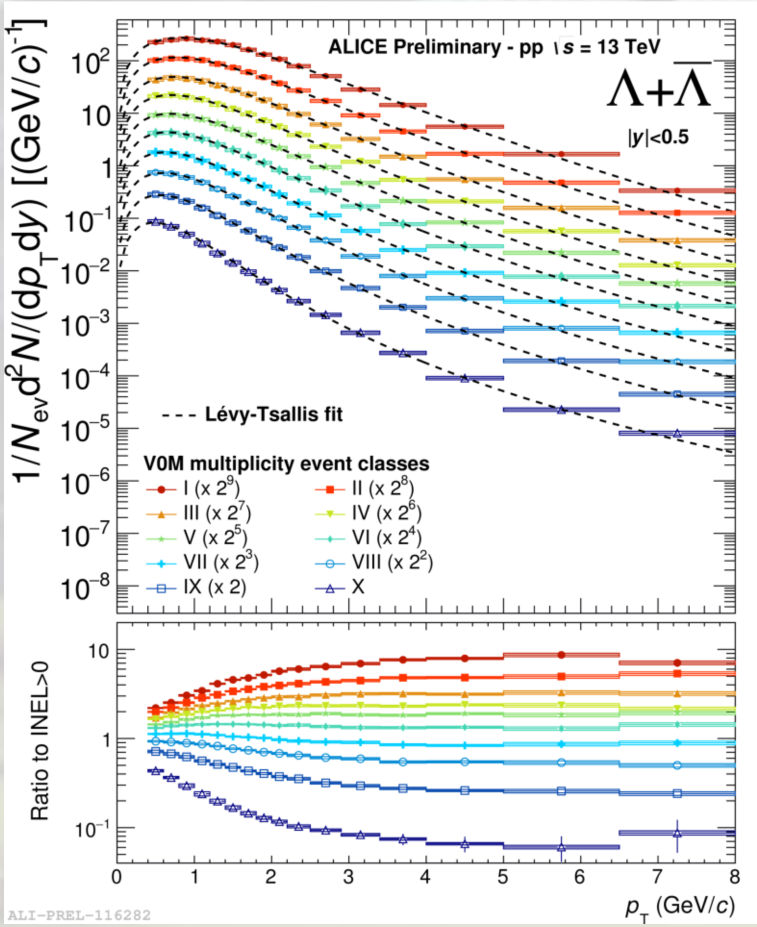


Transverse momentum spectra

Same pattern as observed in pp @ 7 TeV





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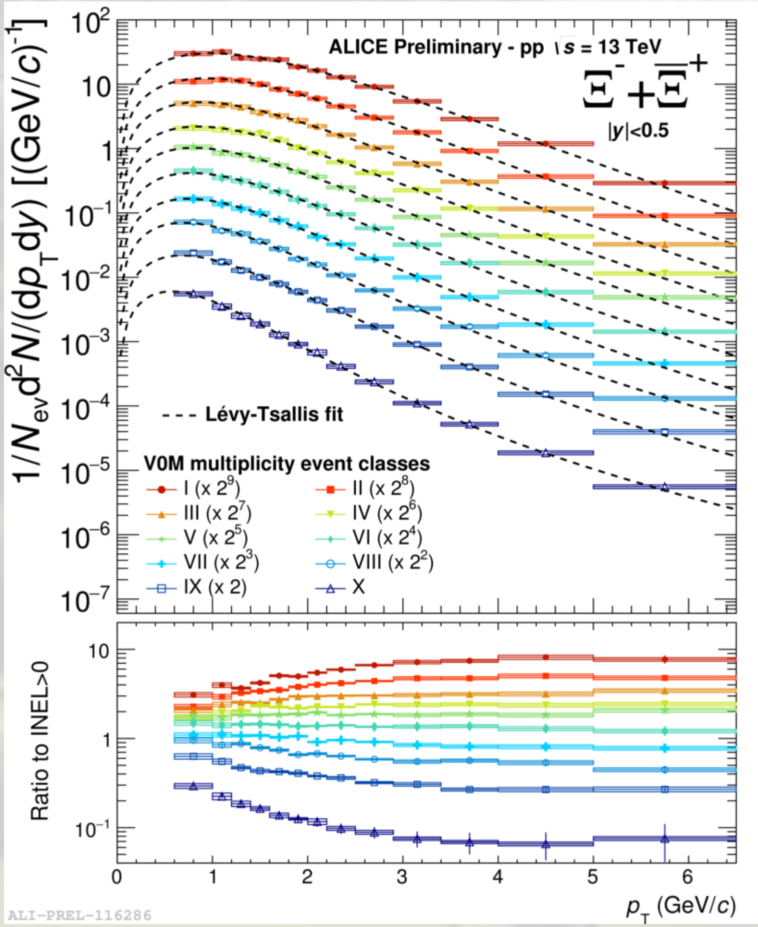

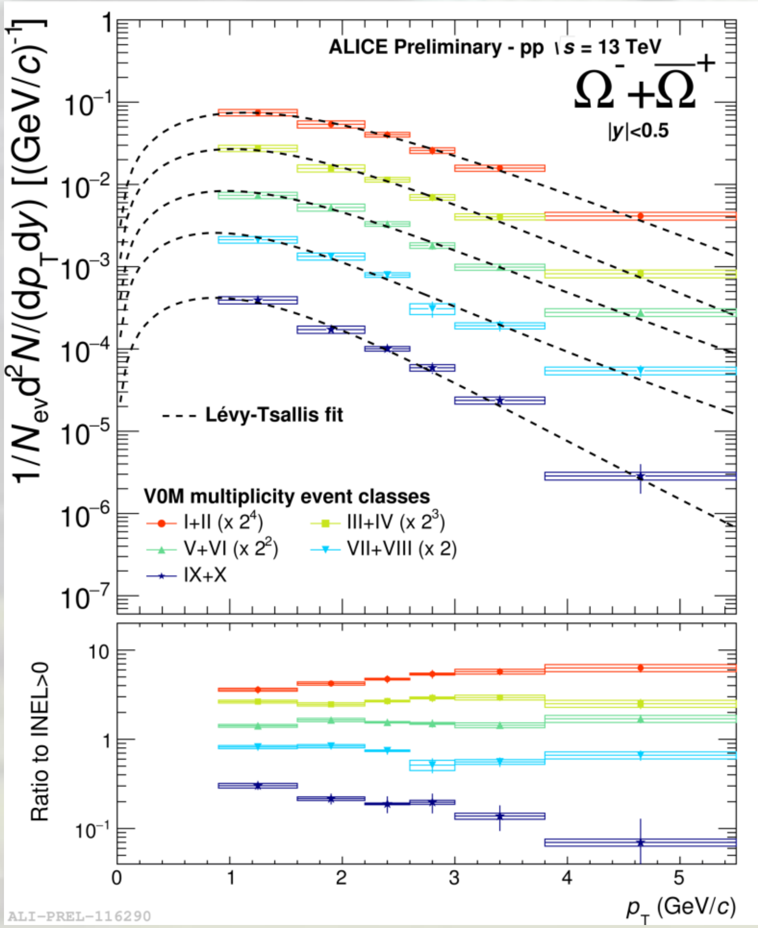

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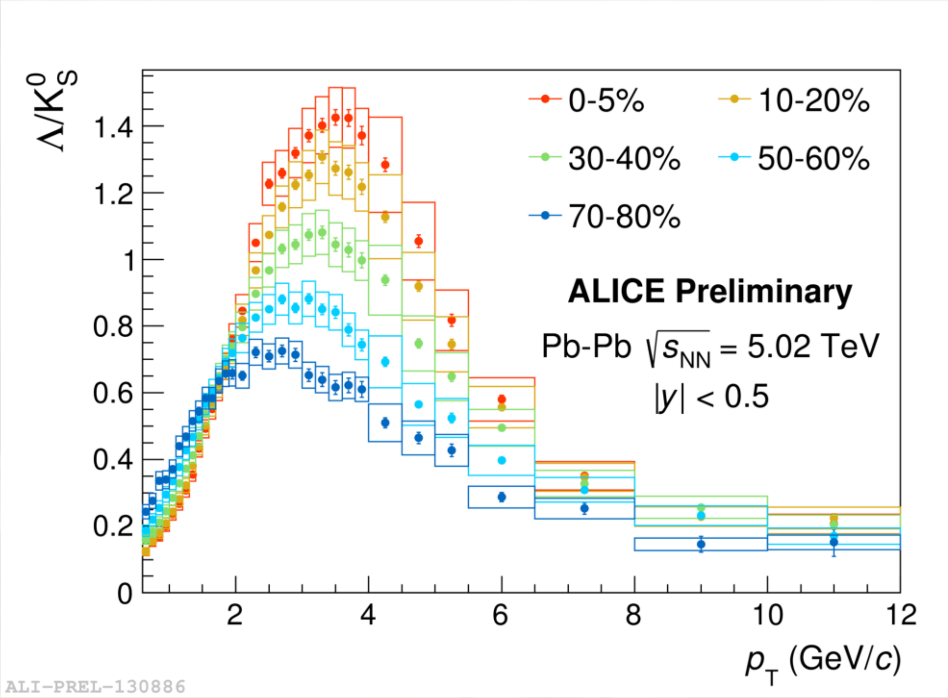
Baryon-to-meson ratios

- Same behaviour as in Pb-Pb @ 2.76 TeV:
  - maximum increasing with centrality
  - peak position shifts to higher p_T (radial flow, quark recombination)
  - high-p_T region: no medium effect on particle composition



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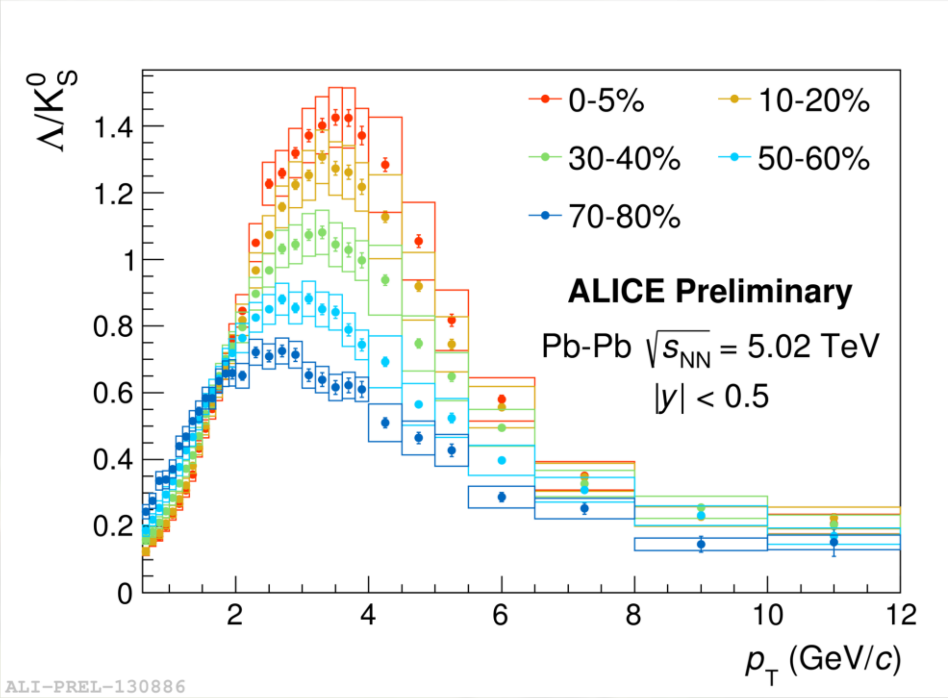
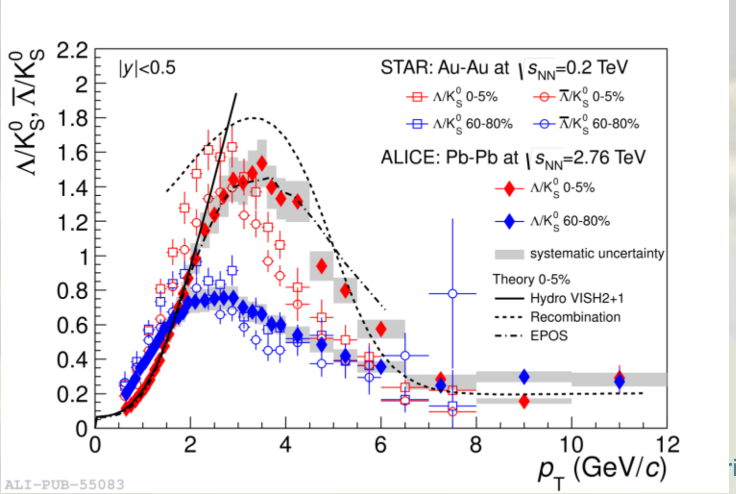


@2.76 TeV:
Intermediate-p_T region: described by hydro and recombination model



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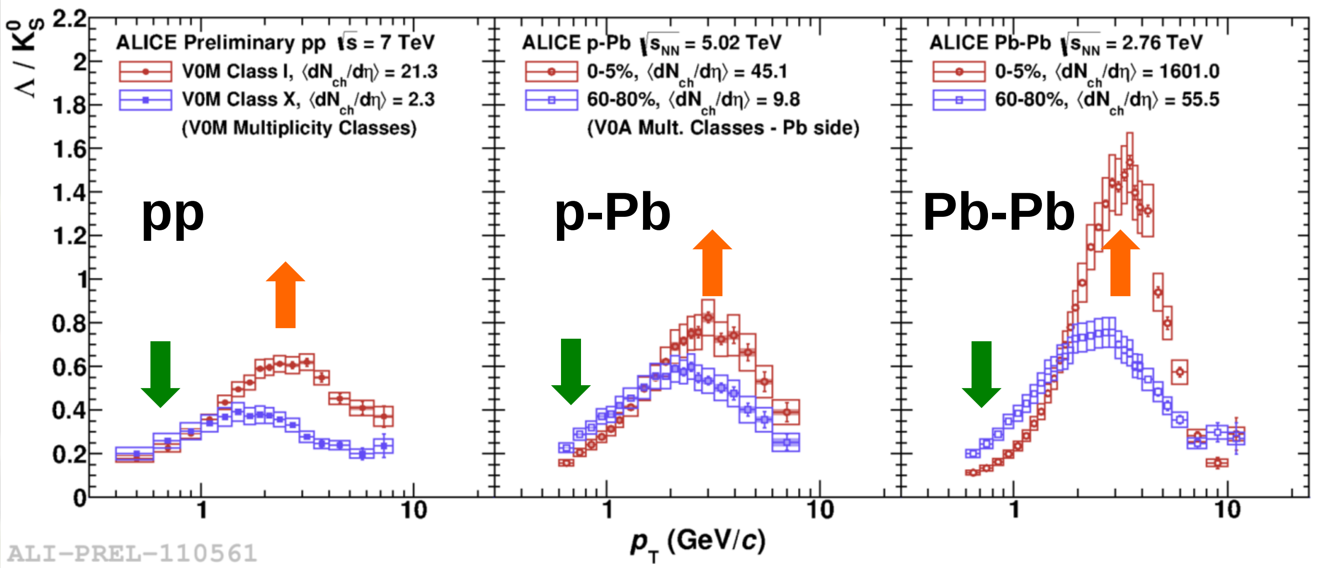
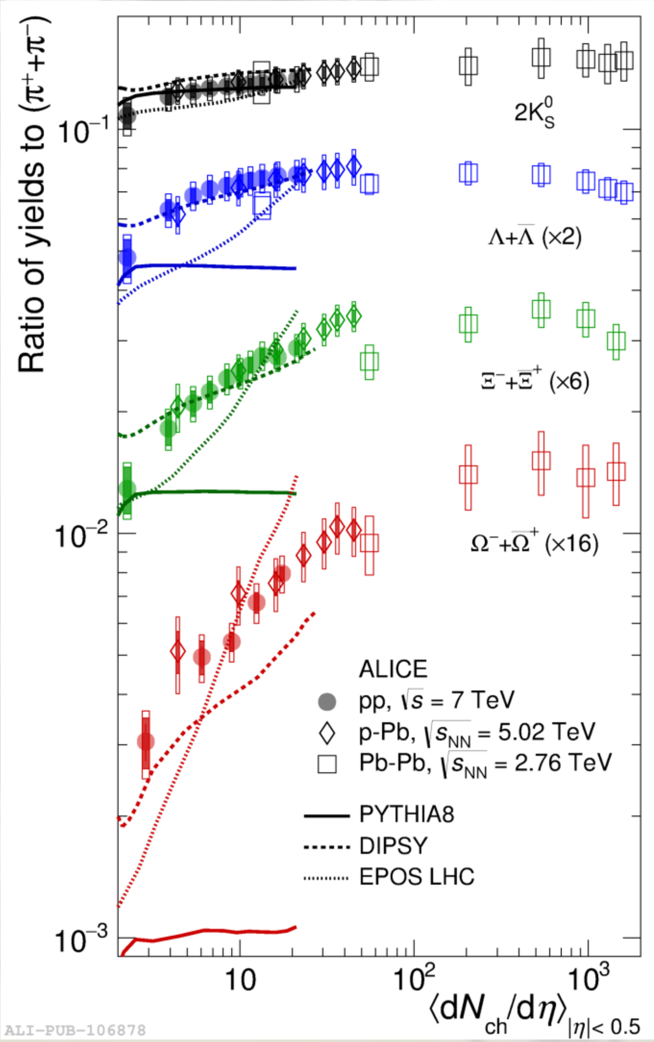
Similarities in the evolution across different systems:

with increasing multiplicity:

- **depletion @ low p_T**
- **enhancement @ intermediate p_T**



Strange-to-pion yields



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Significant enhancement of strange to non-strange particle yields visible for high-multiplicity pp

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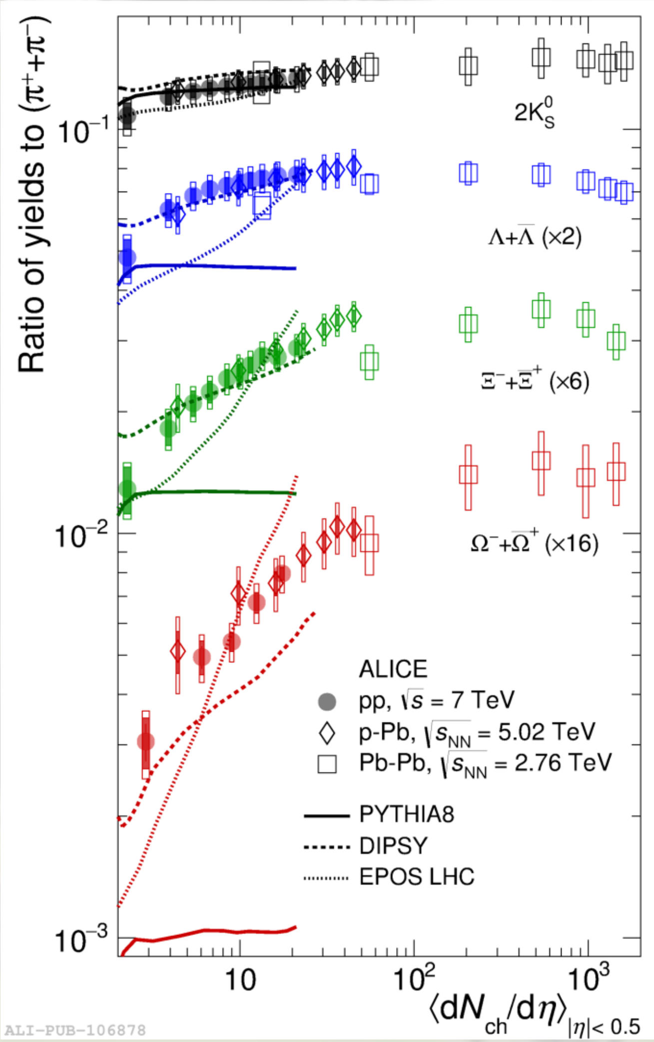

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Significant enhancement of strange to non-strange particle yields visible for high-multiplicity pp

Consistent pattern between pp, pPb and Pb-Pb with nice overlap at fixed final state multiplicity: enhancement observed as a function of <dN_{ch}/dη> independent on the collision type!

Strange to non-strange ratios reach values similar to those observed in PbPb collisions

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Strange-to-pion yields

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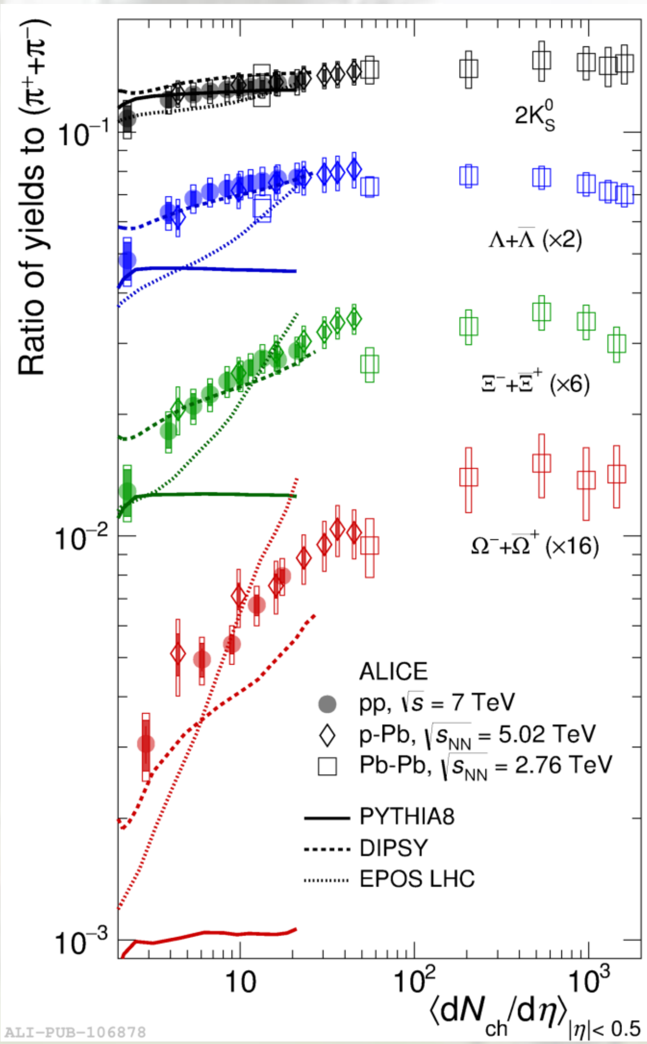

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No MC models describe the data satisfactorily

Question:

- is the enhancement in pp due to mass or some baryon/meson effect or due to strangeness content of the particle?

Strange-to-pion yields

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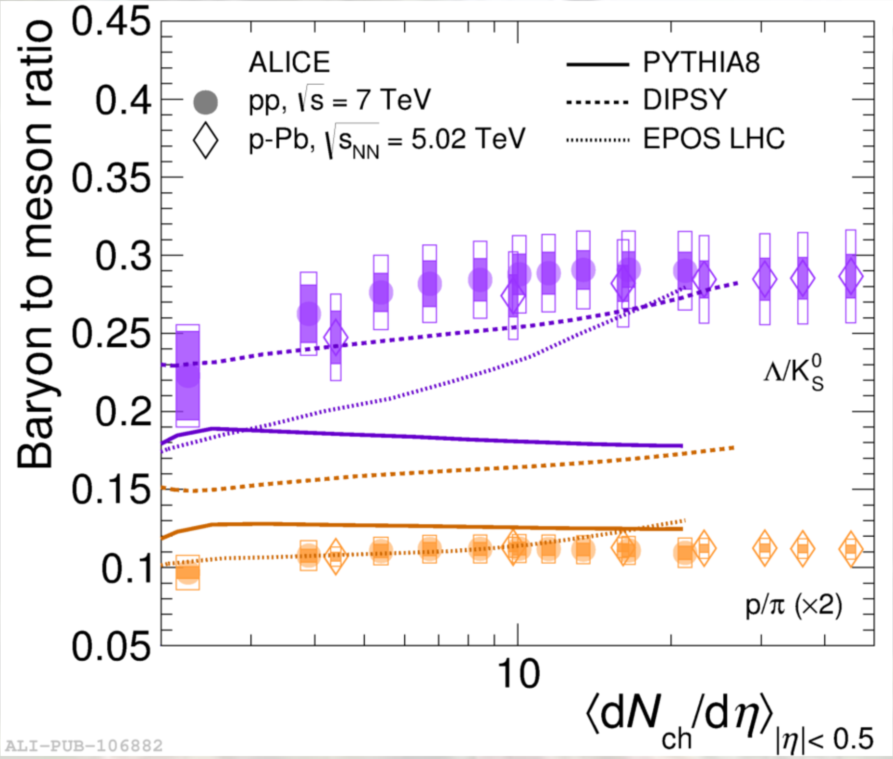

Ratios of yields for particles with large mass difference do not show enhancement as a function of charged multiplicity

No model is able to reproduce the increase of the hyperon to pion ratios and the flatness of baryon to meson ratios simultaneously

➢ enhancement is strangeness rather than mass related

Strangeness enhancement

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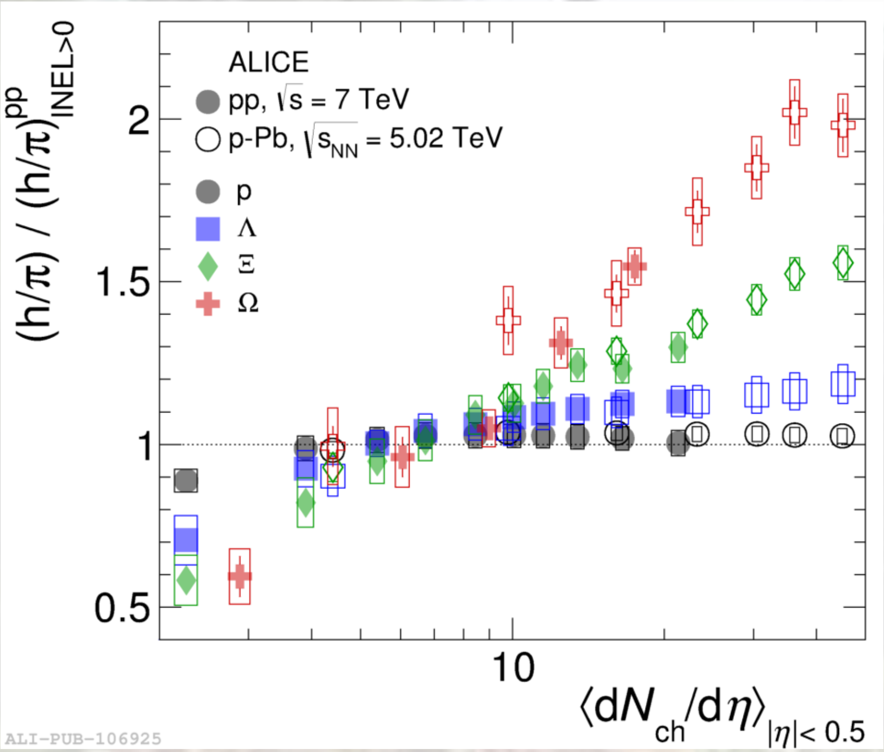

Double-ratio in pp collisions (and in p-Pb) evolves smoothly with multiplicity density

Protons (S=0) is consistent with unity up to the highest <dN_{ch}/dη> probed

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

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Strangeness enhancement

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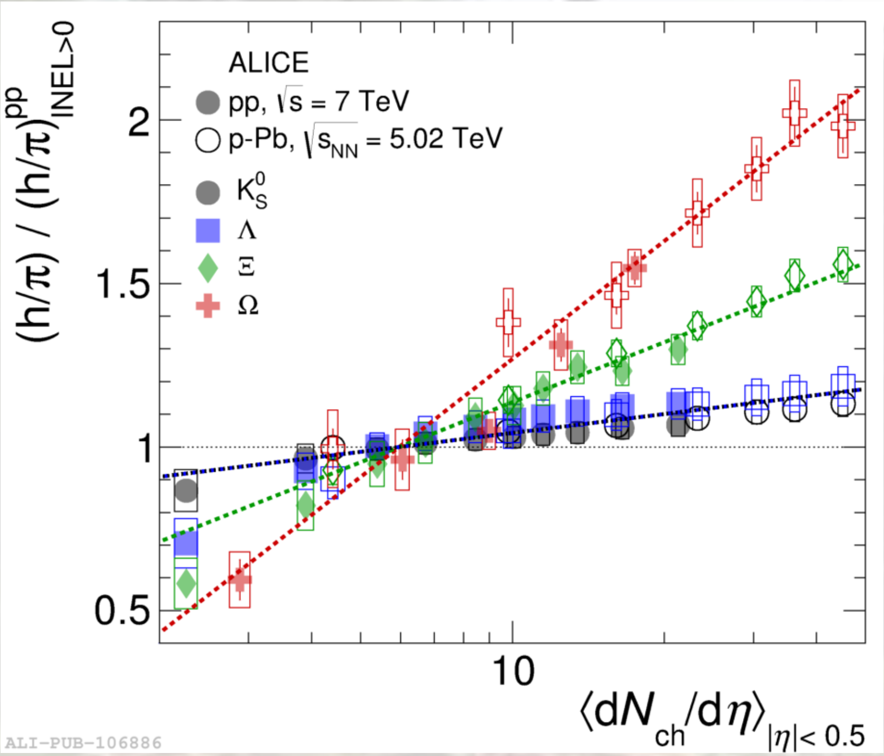

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The larger the valence strange quark content, the steeper the slope: (dashed line fit to guide the eye)

- enhancement is strangeness rather than mass related
- hierarchy determined by the strangeness content of the hadron

Strangeness enhancement

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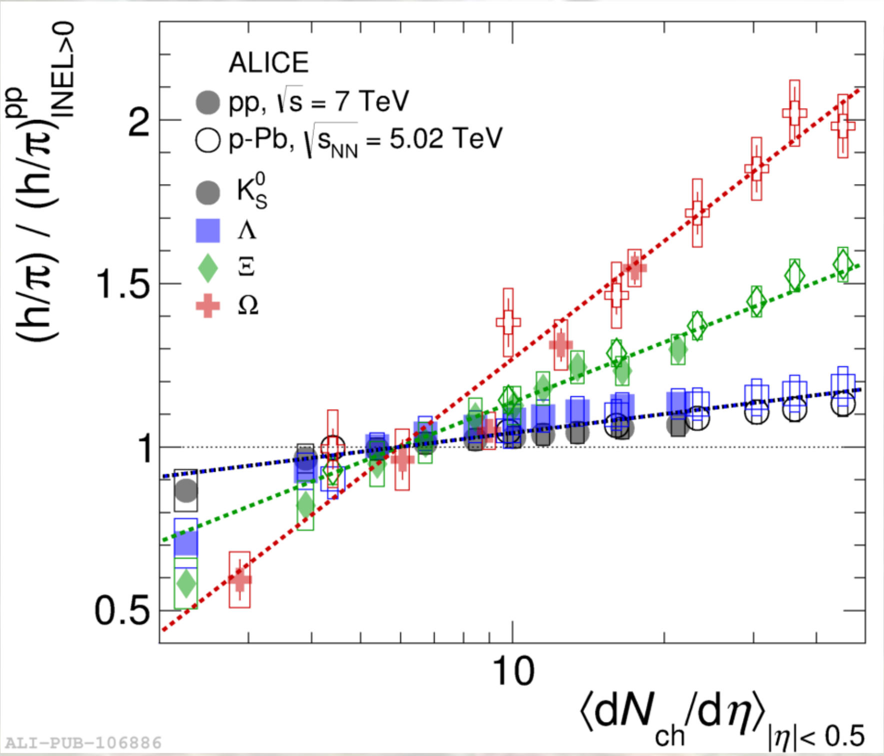

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Further questions:

- is the same enhancement present at higher energy (pp @ 13 TeV)?
- is the enhancement collision-energy dependent or multiplicity driven?

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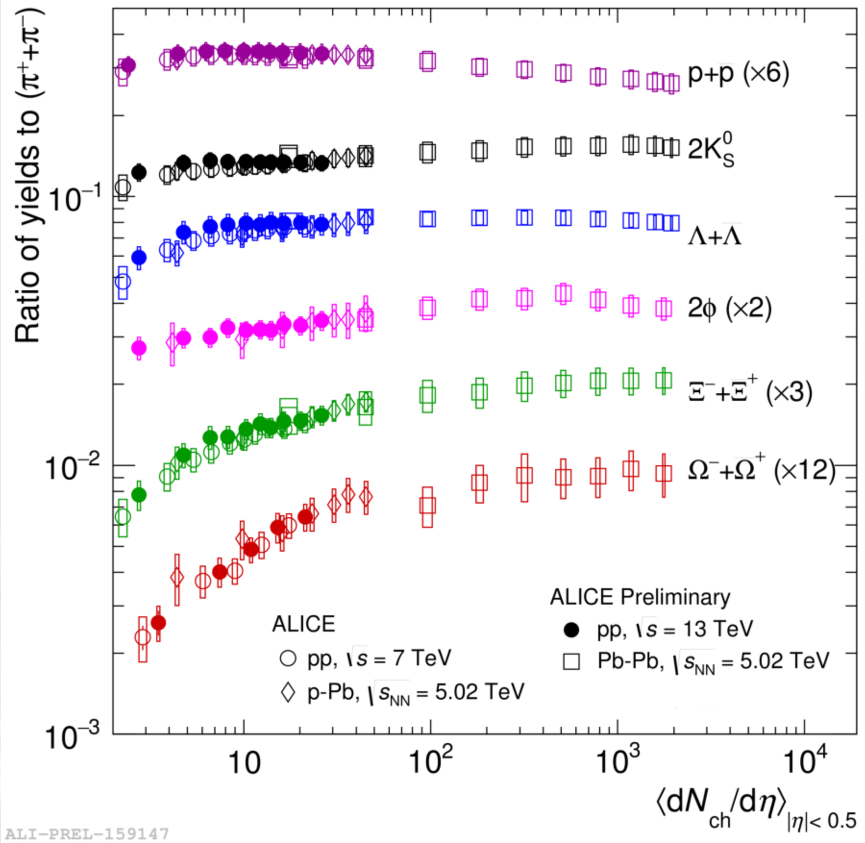
Strangeness enhancement

- Results in pp @ 13 TeV (and Pb-Pb @ 5 TeV):
  - no signs of energy dependence

Similar scaling with multiplicity observed for strangeness production in pp @ 7 and 13 TeV

Most peripheral Pb-Pb @ 5 TeV results bridge p-Pb and high-multiplicity pp, in agreement with Pb-Pb @ 2.76 TeV (also with STAR Au-Au, Cu-Cu @ 200 GeV)

Event activity (system size) drives particle production:
strange particle production is collision energy independent at similar multiplicity



Strangeness enhancement

- Results in Xe-Xe @ 5.44 TeV:
  - system size/geometry dependence: confirm same behaviour

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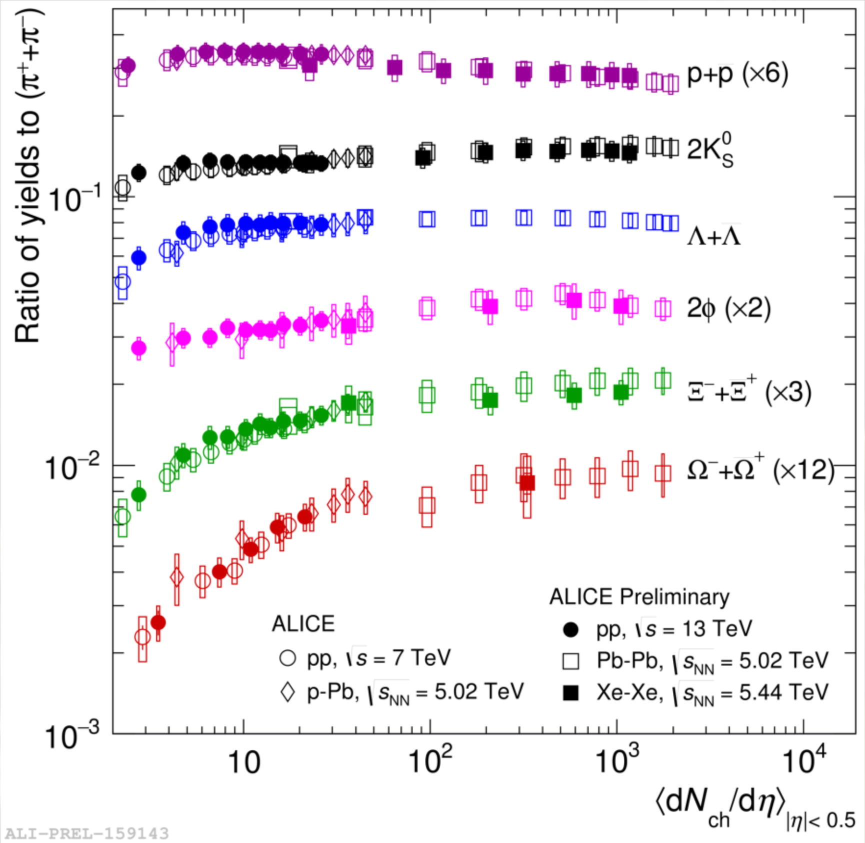
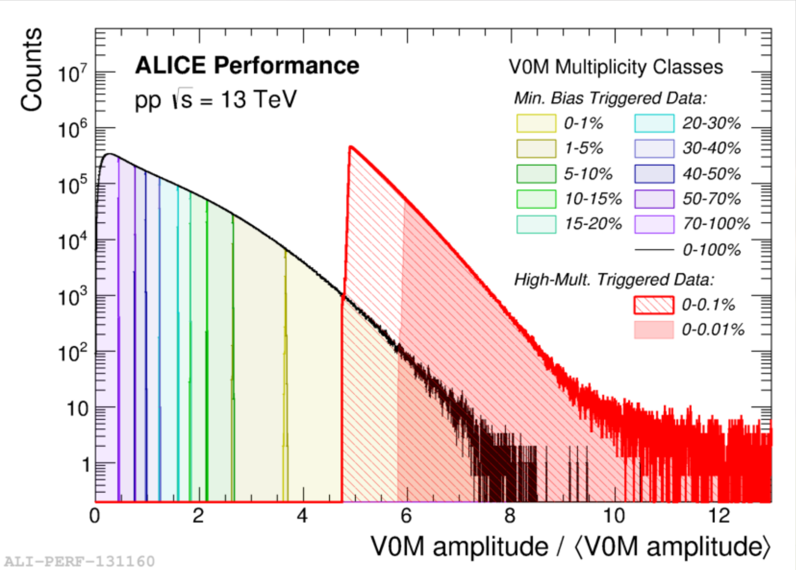


Strangeness enhancement

- Near-term prospects with higher energy pp:
  - special high-multiplicity trigger used for pp @ 13 TeV data taking
  - enough statistics to study 0-0.1% and 0-0.01% multiplicity samples



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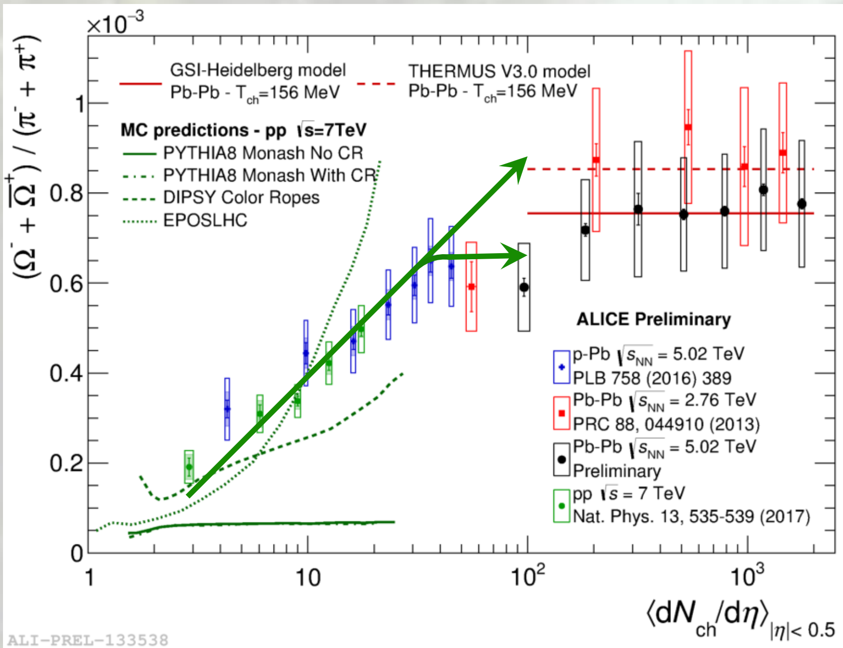

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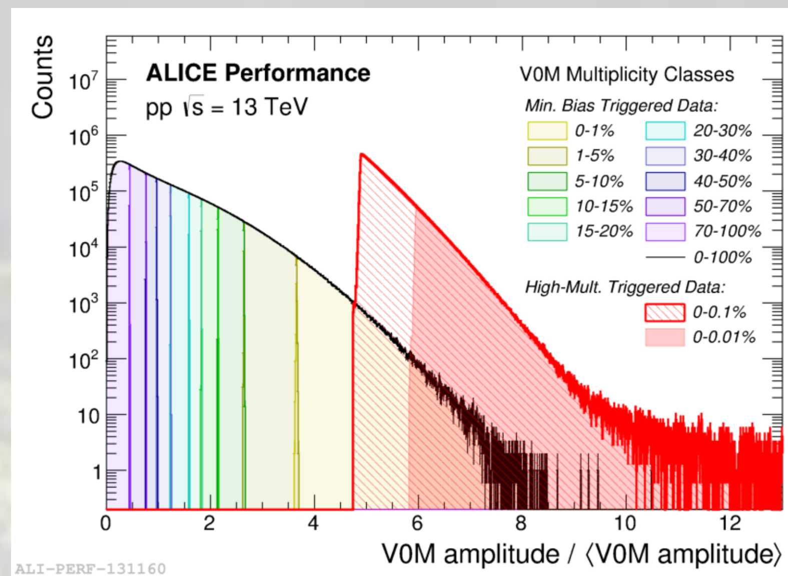

Aim to answer next question: is there any hint of a saturation of the strangeness production for higher-multiplicity pp?

Thermal model fits

- Working fairly well in Pb-Pb @ 2.76 TeV:
  - most light-flavour yields described with single T_{fo} (156±3 MeV)
  - some tension for protons and (multi-)strange hadrons

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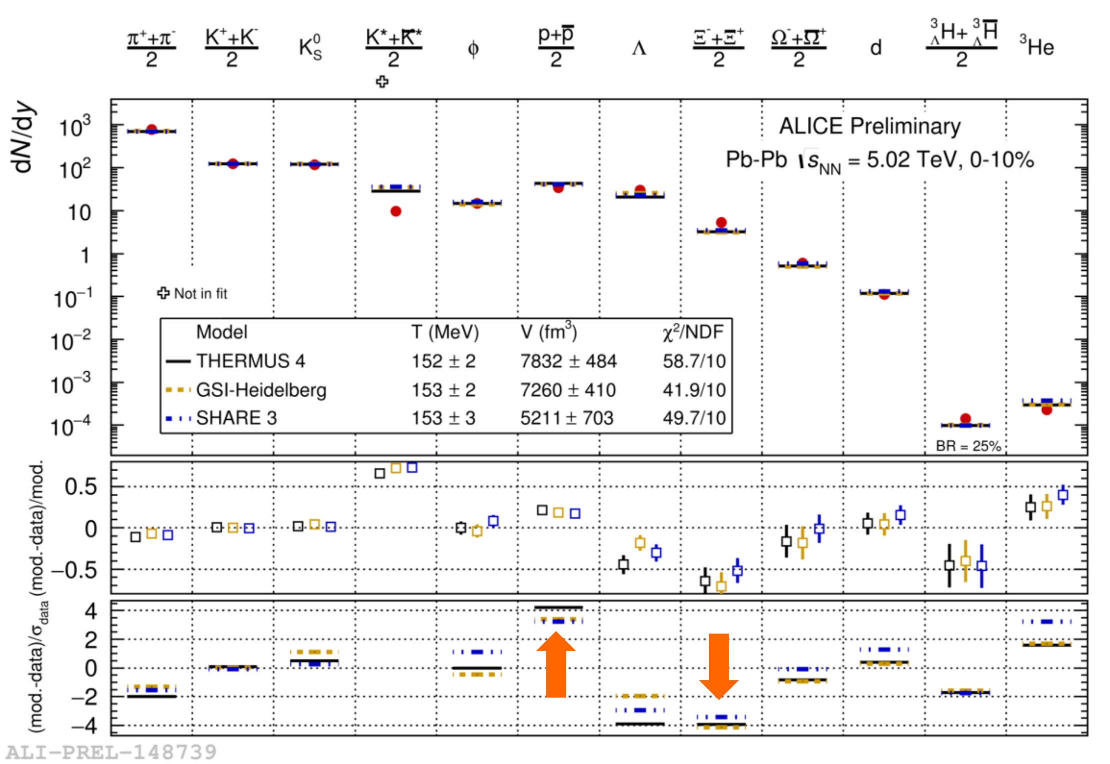

In Pb-Pb @ 5.02 TeV similar behaviour:
T_{fo} = 153±3 MeV
lower temperature, consistent with that for Pb-Pb @ 2.76 TeV within uncertainties

THERMUS: Wheaton et al., *Comput. Phys. Commun.* **180** 84 (2009)
GSI-Heidelberg: Andronic et al., PLB **673** 142 (2009)
SHARE: Petran et al., *Comput. Phys. Commun.* **185** 2056 (2014)

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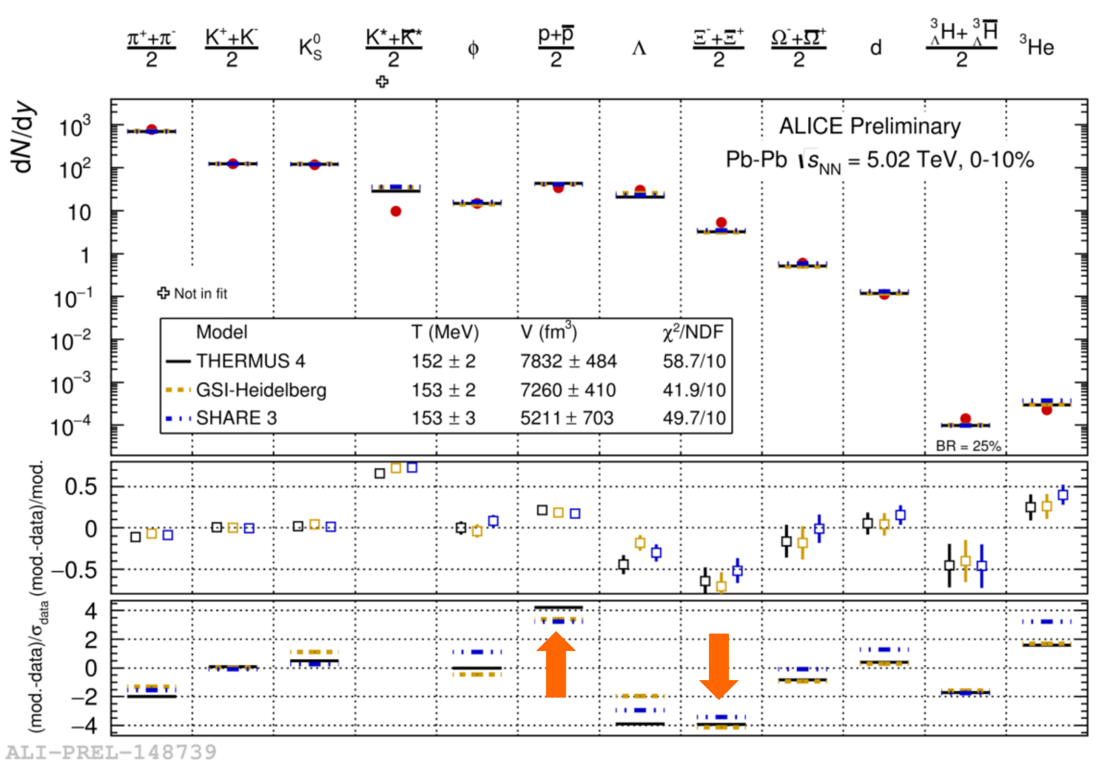

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lower temperature, consistent with that for Pb-Pb @ 2.76 TeV within uncertainties

Additional effects needed?
Baryon annihilation, interacting hadron gas, incomplete hadron spectrum

Conclusions

- Strange hadron spectra:
  - hardening of transverse momentum spectra with increasing centrality in Pb-Pb collisions (as expected from radial flow)
  - similar effect observed in pp @ 7, 13 TeV, with increasing multiplicity
- Baryon-to-meson ratios:
  - results in Pb-Pb @ 5 TeV (and pp @ 7, 13 TeV) confirm enhancement at intermediate p_T seen in Pb-Pb at 2.76 TeV
- Strangeness enhancement:
  - strangeness enhancement observed in high-multiplicity pp collisions (possible consequence of canonical suppression)
  - strange-to-pion ratios evolve smoothly and universally with event multiplicity, regardless collision system and energy
- Thermal model fit to the yields:
  - confirmed good description in Pb-Pb @ 5 TeV (few caveats)

... and Outlook

- Among the most intriguing open questions:
  - will the relative strangeness production in pp saturate?
    - stay tuned for results from high-multiplicity trigger in pp @ 13 TeV!

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Strangeness in Quark Matter Conference

Bari, Italy
June 10 – 15, **2019**

We look forward to welcoming you in Bari!

Backup slides

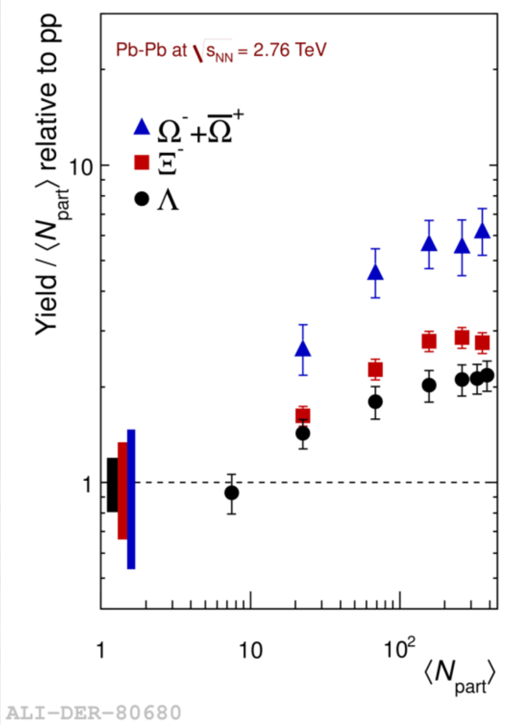
Physics motivation

- Strangeness enhancement:

J. Rafelski and B. Müller, PRL 48, 1066 (1982)

  - enhanced production of strange particles in A-A wrt pp
    - one of the first proposed signatures of QGP formation in A-A collisions*

PLB 728 (2014) 216-227



S=3

S=2

S=1

Hierarchy based on strangeness content:
E(S=3) > E(S=2) > E(S=1)

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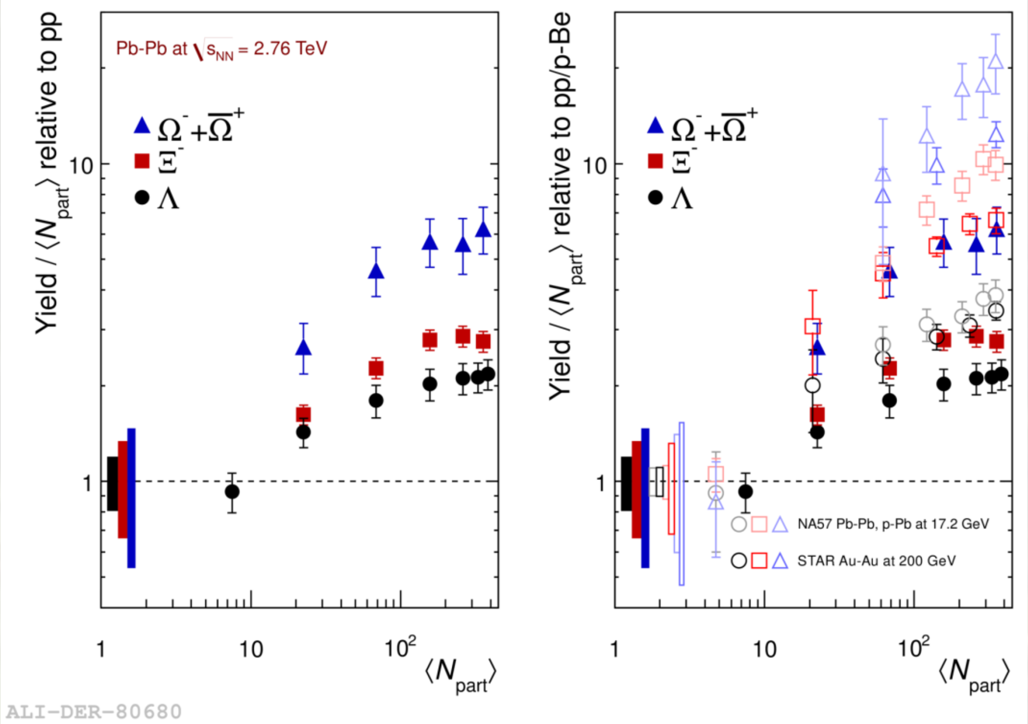
    - one of the first proposed signatures of QGP formation in A-A collisions*

PLB 728 (2014) 216-227



SPS
RHIC
LHC

Hierarchy based on strangeness content:
E(S=3) > E(S=2) > E(S=1)

Decreasing trend with increasing energy:
E(SPS) > E(RHIC) > E(LHC)

Possible explanation:

enhancement in the A-A to pp ratio originates from (canonical) suppression in pp

Physics motivation

- Strangeness enhancement:
  - compare A-A to pp normalising to pions

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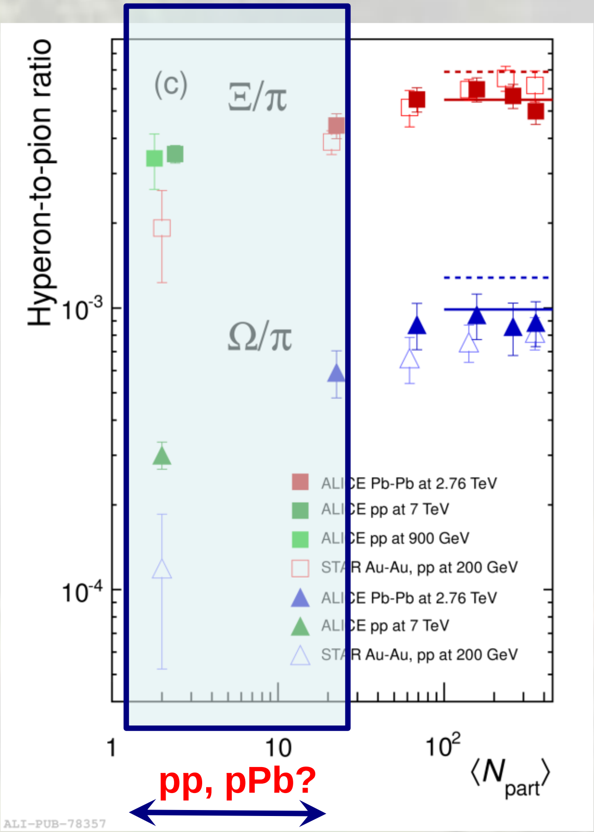


Ratios in Pb-Pb at LHC increase with centrality and saturate towards central collisions (larger system) matching predictions from thermal models based on a Grand-Canonical (GC) formulation

Relative production of strangeness in pp increases faster with energy than in A-A going from RHIC to LHC (removal of canonical suppression)

Unprecedented pp/p-Pb statistics at the LHC allows extensive multiplicity study of reference samples: suitable to **explore transition between pp and A-A**

Multiplicity definition

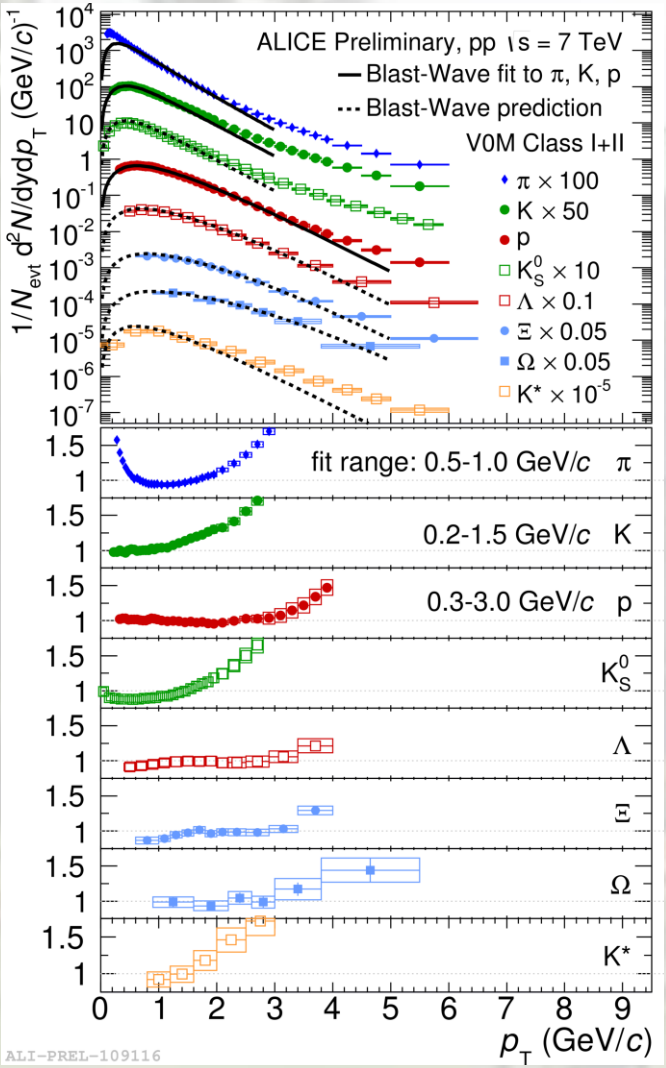
- Based on the measurements in the V0:
  - analyzed events have at least one charged particle in $|\eta| < 1$ (INEL>0)
  - event sample divided into 10 classes according to ionisation energy deposited in the V0 detectors ($2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$)

$\langle dN_{ch}/d\eta \rangle$: average pseudorapidity density of primary charged particles in $|\eta| < 0.5$

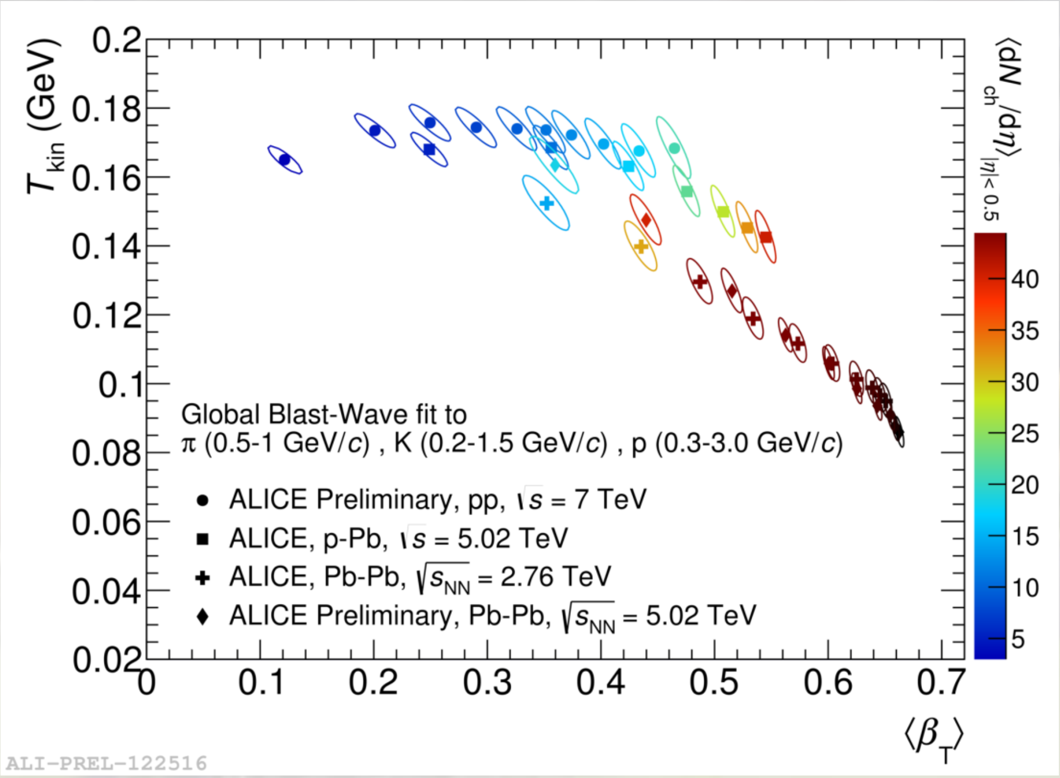
Multiplicity classes used in pp @ 7 TeV analysis

Class name	I	II	III	IV	V
$\sigma/\sigma_{\mathrm{INEL}>0}$	$0 - 0.95\%$	$0.95 - 4.7\%$	$4.7 - 9.5\%$	$9.5 - 14\%$	$14 - 19\%$
$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	21.3 ± 0.6	16.5 ± 0.5	$13.5 \pm 0.4\%$	11.5 ± 0.3	10.1 ± 0.3
Class name	**VI**	**VII**	**VIII**	**IX**	**X**
$\sigma/\sigma_{\mathrm{INEL}>0}$	$19 - 28\%$	$28 - 38\%$	$38 - 48\%$	$48 - 68\%$	$68 - 100\%$
$\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$	8.45 ± 0.25	6.72 ± 0.21	$5.40 \pm 0.17\%$	3.90 ± 0.14	2.26 ± 0.12

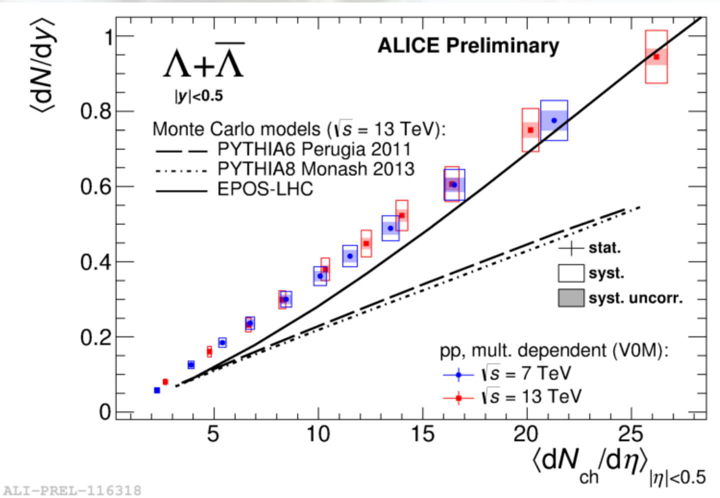
Blast-Wave fit



At similar multiplicity, the kinetic freeze-out temperature and the average transverse velocity are higher in pp than in Pb-Pb collisions



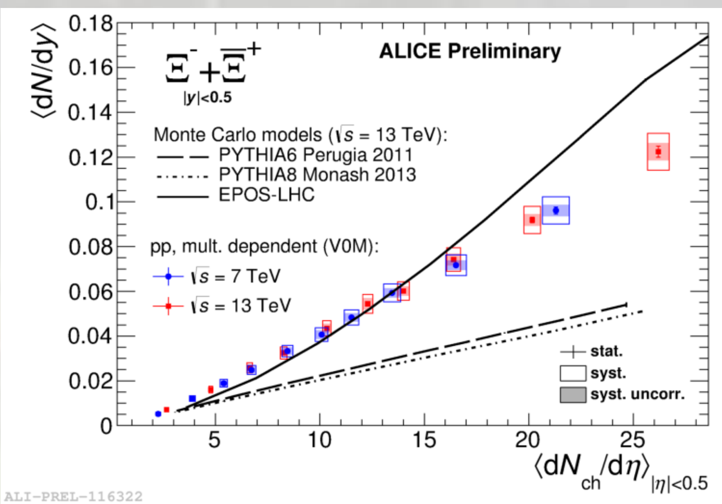
Comparison with pp @ 13 TeV

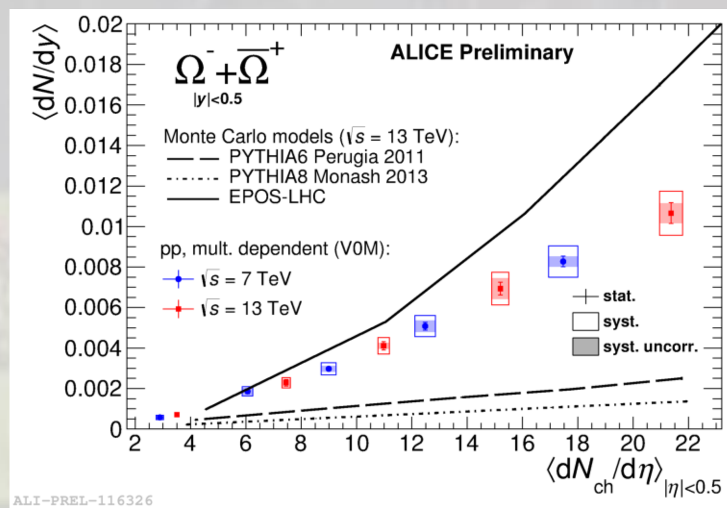


Similar scaling with multiplicity observed for strangeness production in pp @ 7 and 13 TeV

Event activity drives particle production: strange particle production is collision energy independent at similar multiplicity

Models: EPOS reproduces multiplicity trend





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