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Enhanced strangeness production in high-multiplicity pp collisions

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- physics motivation
- experimental apparatus
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Introduction



ALICE

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, thermal/chemical equilibrium, energy loss

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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, however no sign of parton energy loss

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Open questions for small systems:

- are there unusual trends also in strangeness production in high-multiplicity pp?
- is there thermal and / or chemical equilibrium ? (p_T spectra, hadrochemistry)
- is the event multiplicity the steering variable ? (energy dependence)
- what are the microscopic processes at play ? (model comparison)

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***

Physics motivation

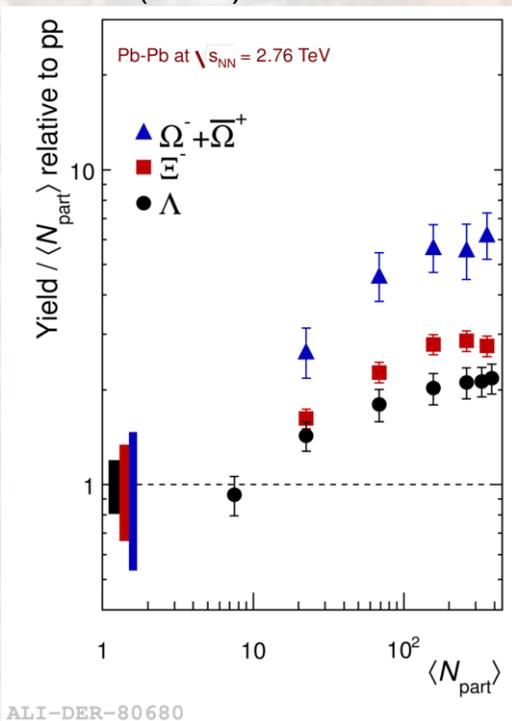


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PLB 728 (2014) 216-227



S=3
S=2
S=1

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



Physics motivation

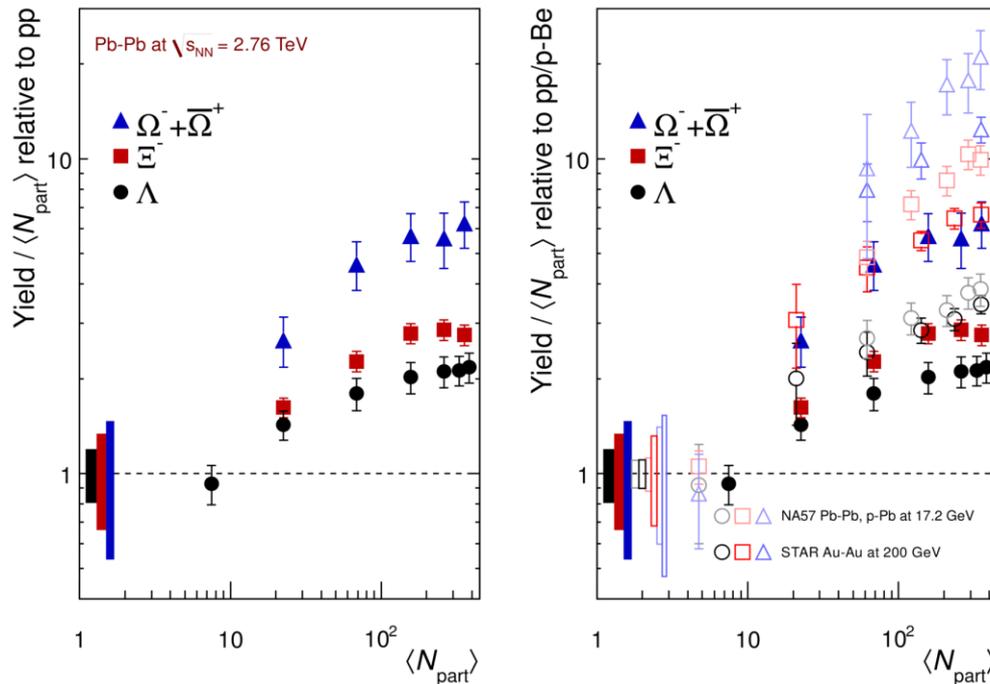


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Hierarchy based on strangeness content:
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RHIC

LHC

Decreasing trend with increasing energy:
 $E(\text{SPS}) > E(\text{RHIC}) > E(\text{LHC})$

ALI-DER-80680



Physics motivation

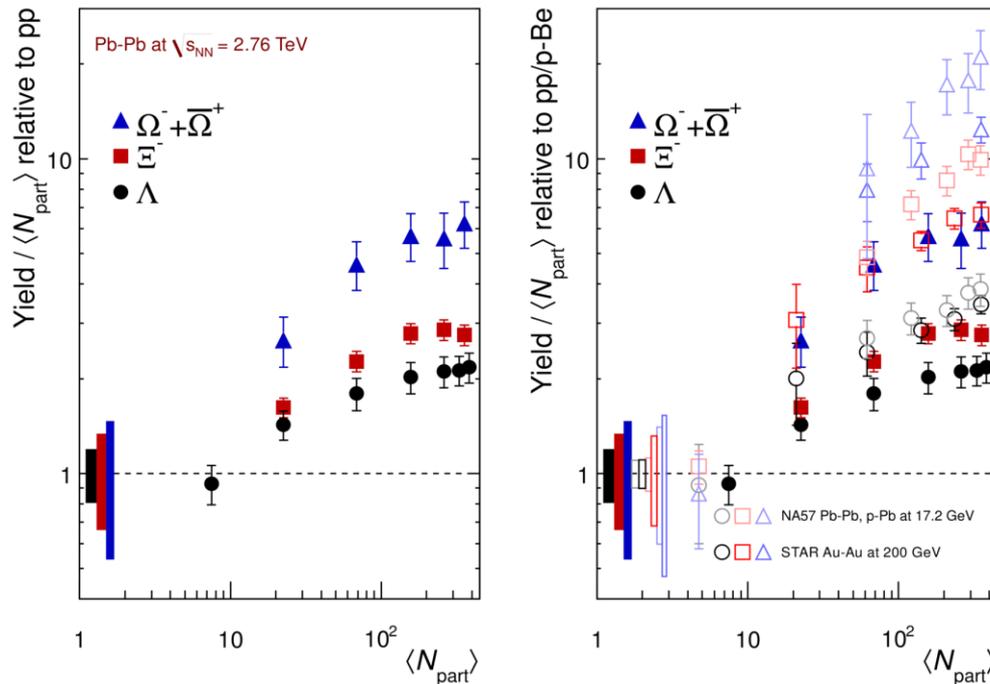


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Possible explanation:

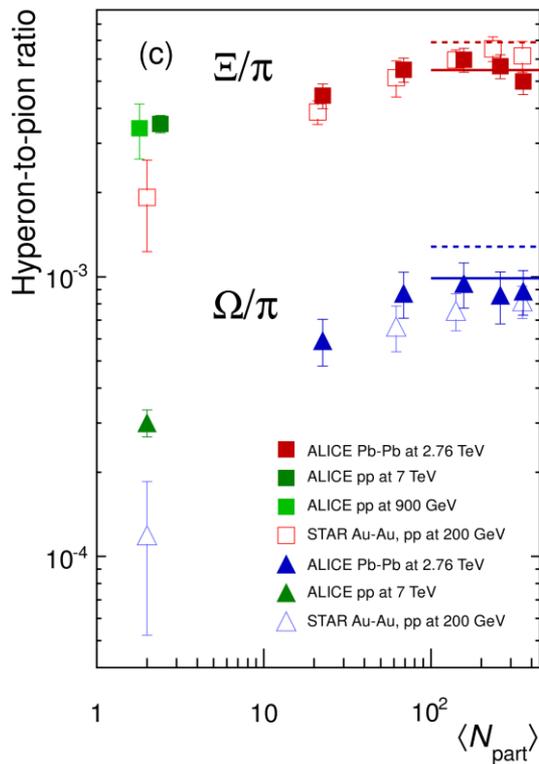
enhancement in the A-A to pp ratio originates from (canonical) suppression in pp



Physics motivation



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



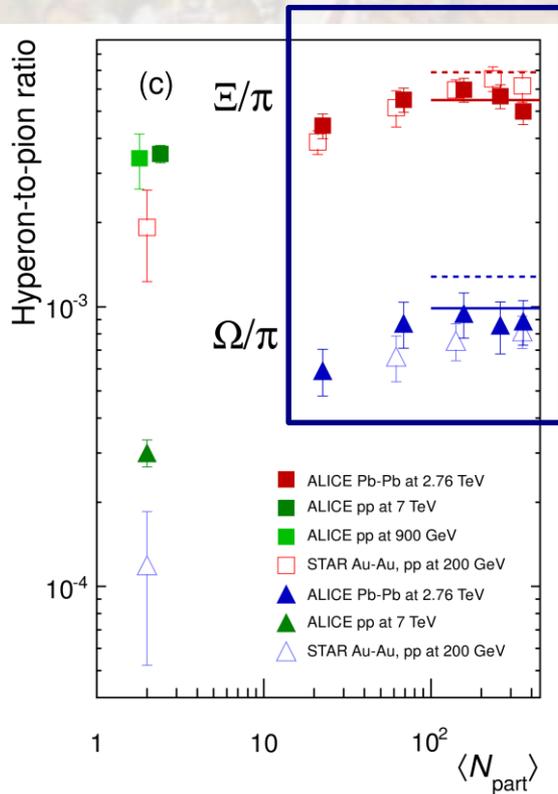
ALI-PUB-78357

Physics motivation



□ Strangeness enhancement:

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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

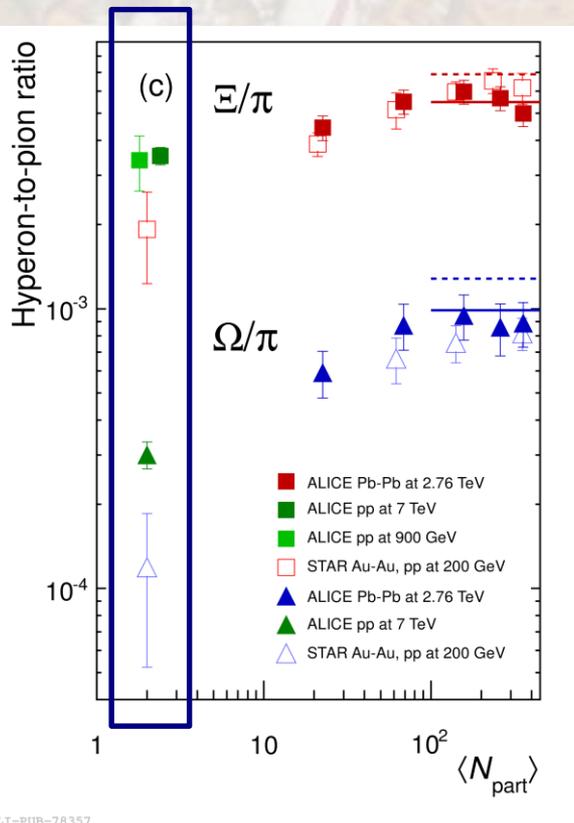
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Relative production of strangeness in pp increases faster with energy than in A-A going from RHIC to LHC (removal of canonical suppression)

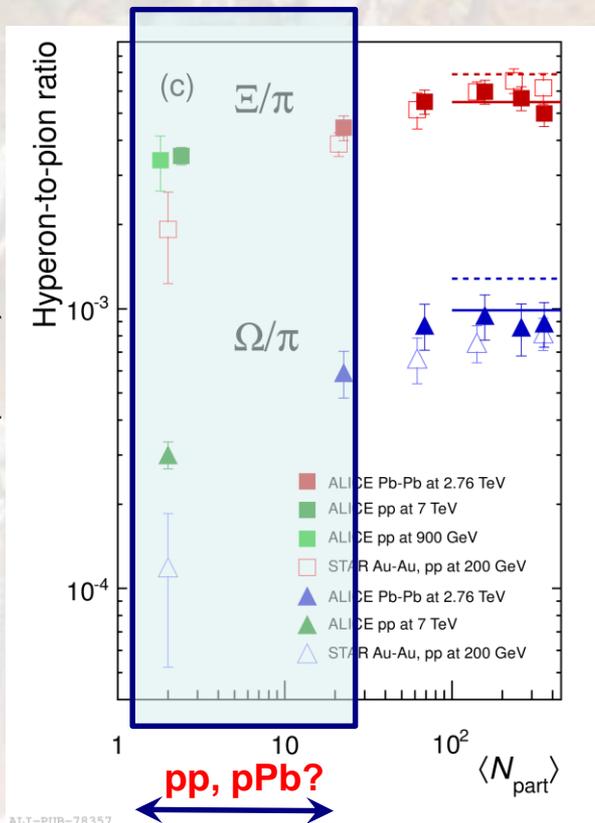
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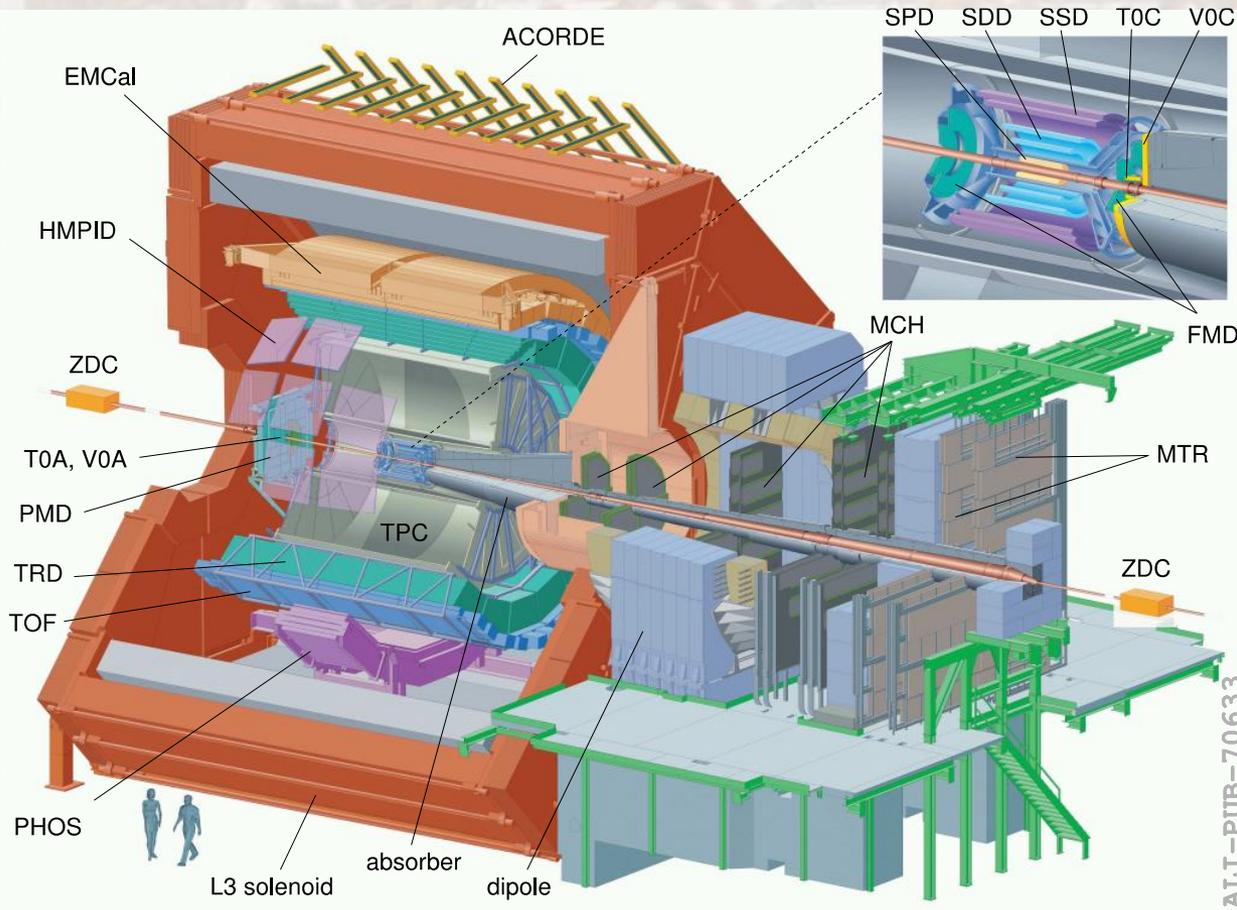
Unprecedented pp/p-Pb statistics at the LHC

allows extensive multiplicity study of reference samples: suitable to

explore transition between pp and A-A

Experimental apparatus

A Large Ion Collider Experiment at the LHC



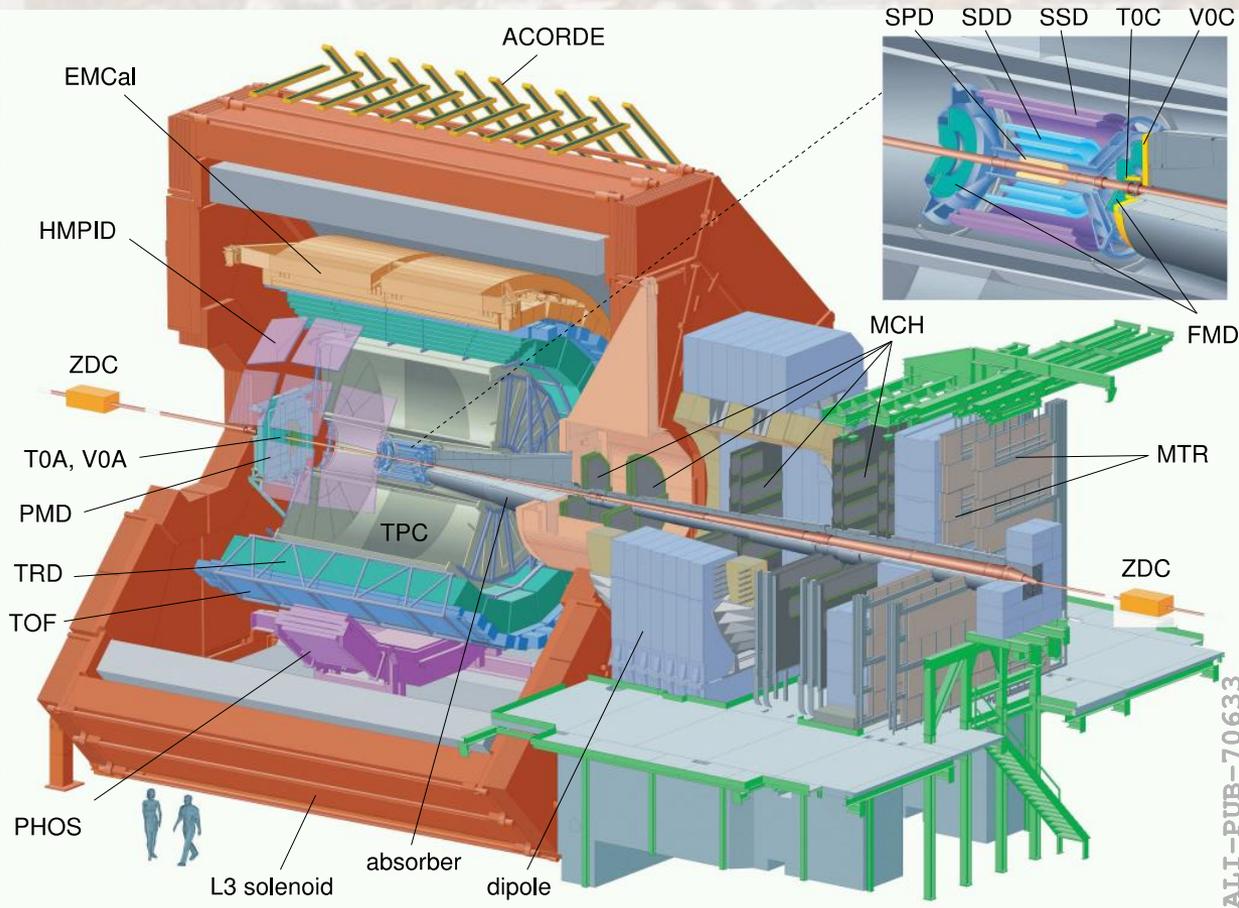
Low material budget in the central region

good momentum resolution ($\sim 1-5\%$) @ $p_T = 0.1-20$ GeV/c

ITS, TPC: tracking, vertexing
VZERO: triggering, beam-gas rejection, centrality (Pb-Pb) and multiplicity (pp, p-Pb) class definition

Experimental apparatus

A Large Ion Collider Experiment at the LHC



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

Analysed data samples:

- pp @ 7 TeV, 100 M (2010)
- pp @ 13 TeV, 50 M (2013)

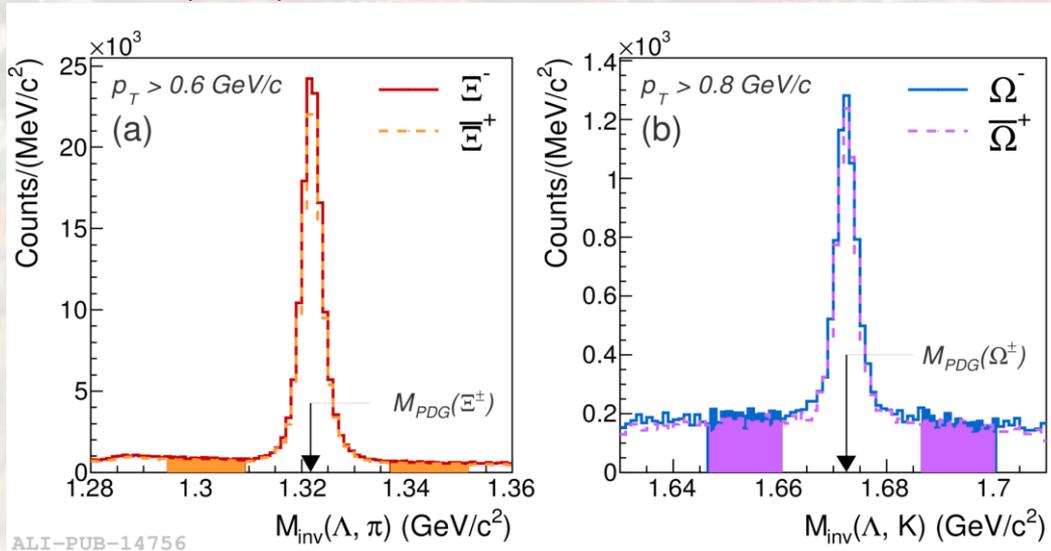
Strange particle detection



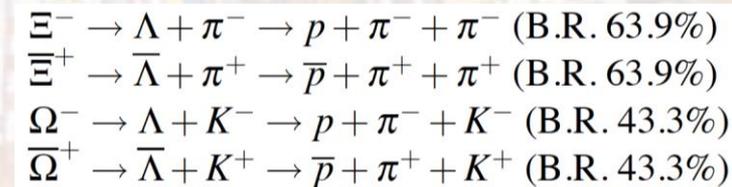
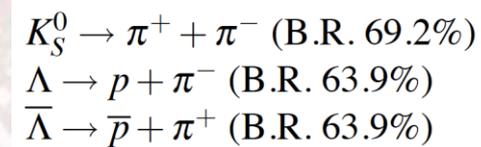
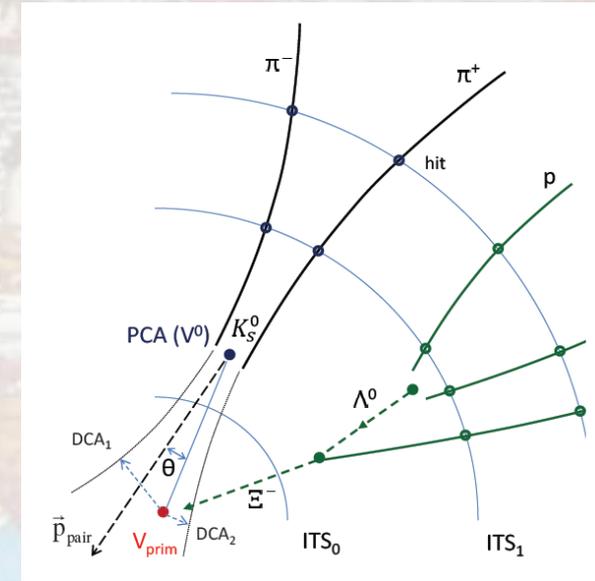
□ From single tracks to yields:

- topological decay reconstruction
- geometrical and kinematical selections
- decay product **invariant mass analysis**

PLB 712 (2012) 309



ALI-PUB-14756



Results in pp @ 7 TeV



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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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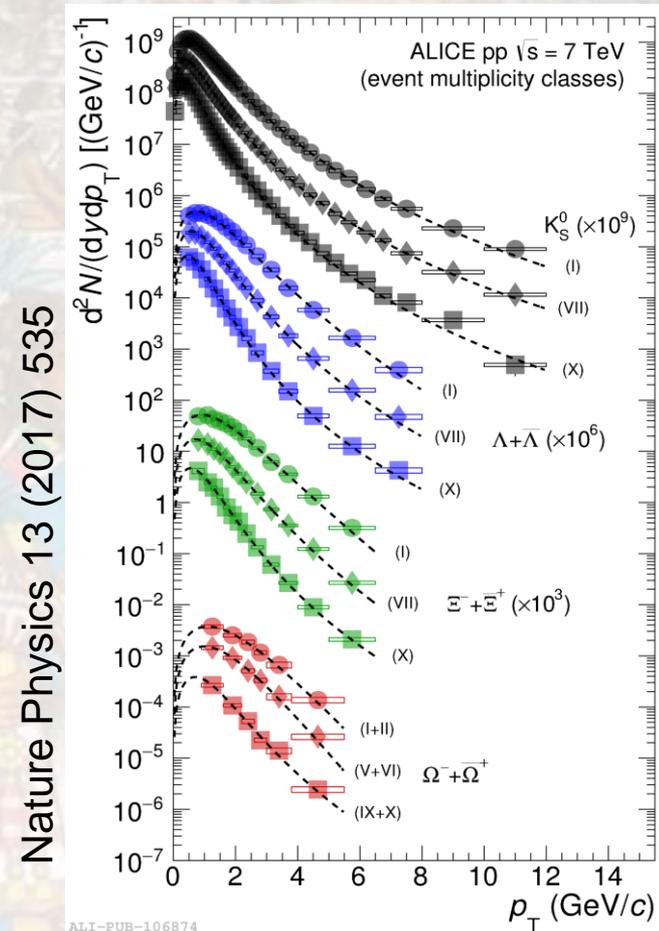
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□ Spectra shape evolution:

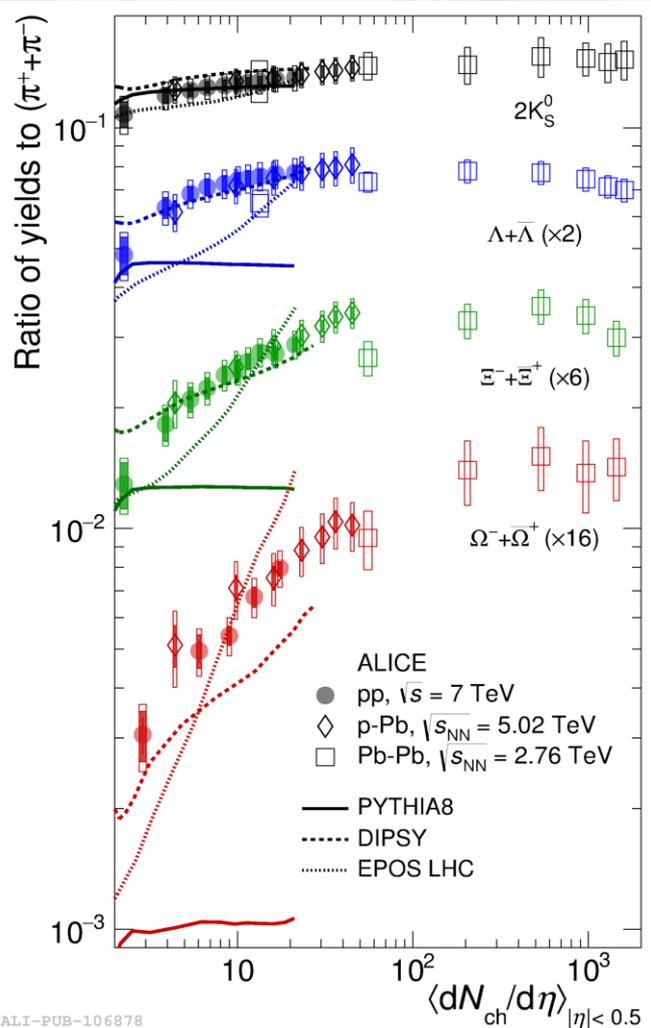
- **harder with increasing multiplicity**
(similar to A-A collisions)

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

Blast-Wave fit to all species for class I points to a thermal source with $T_{kin} \sim 163$ MeV and $\beta_T \sim 0.49$

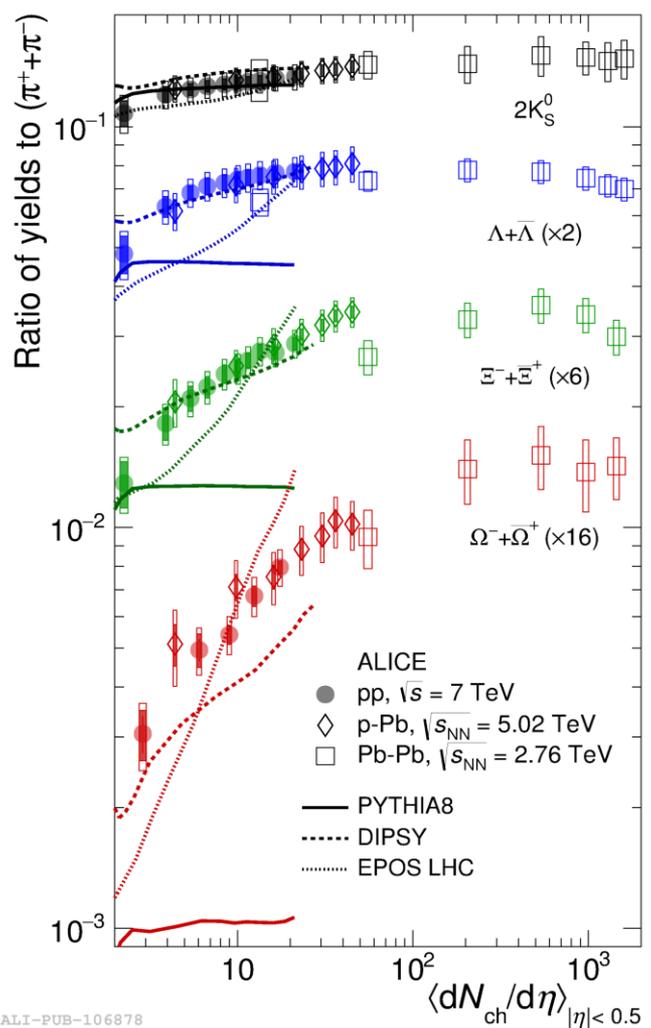


Ratios of integrated yields



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

Ratios of integrated yields



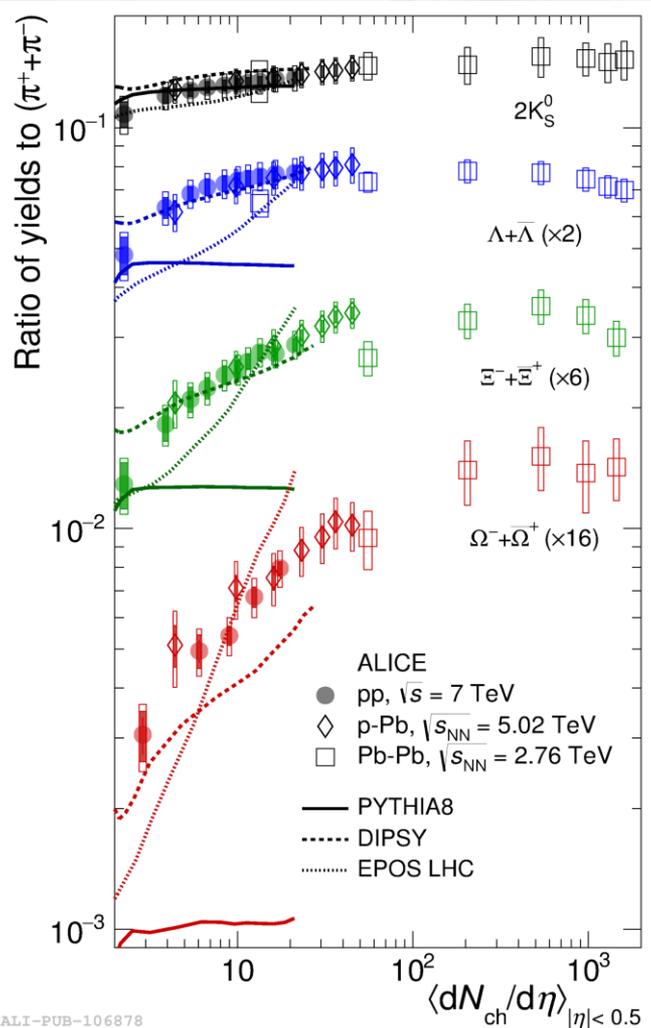
Significant enhancement of strange to non-strange particle yields visible for high-multiplicity pp

Consistent pattern between pp, pPb and Pb-Pb with nice overlap at fixed final state multiplicity:

enhancement observed as a function of $\langle dN_{ch}/d\eta \rangle$ independent on the collision type!

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

Ratios of integrated yields



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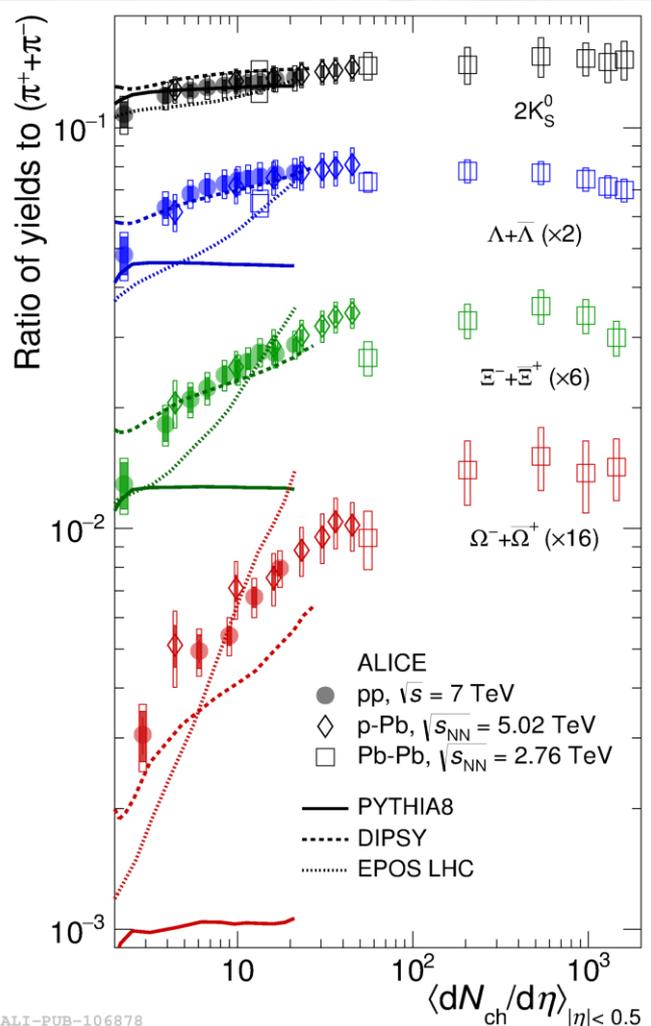
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Strange to non-strange ratios reach values similar to those observed in PbPb collisions

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?

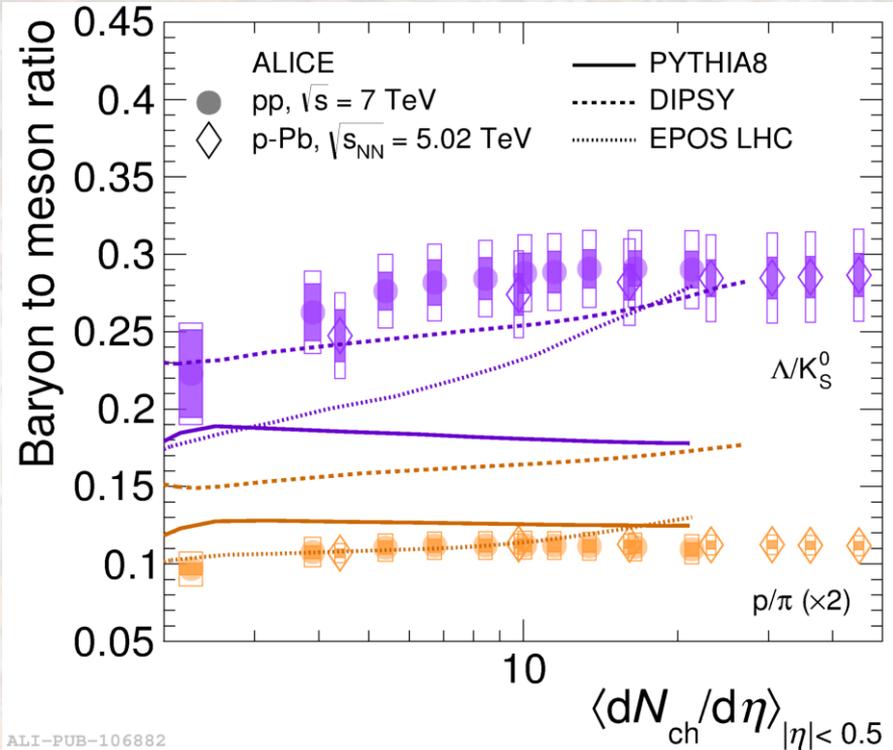


Istituto Nazionale di Fisica Nucleare
Sezione di Bari

Strangeness enhancement



Nature Physics 13 (2017) 535



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

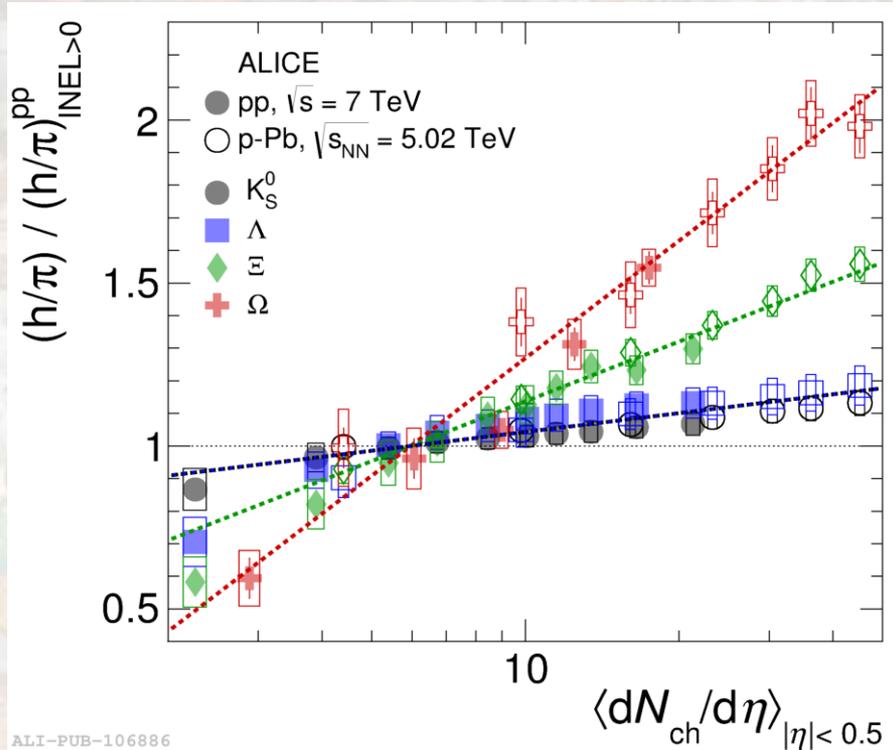
No model is able to reproduce the increase of the hyperon to pion ratios and the flatness of baryon to meson ratios simultaneously

➤ enhancement is strangeness rather than mass related

Strangeness enhancement



Nature Physics 13 (2017) 535



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

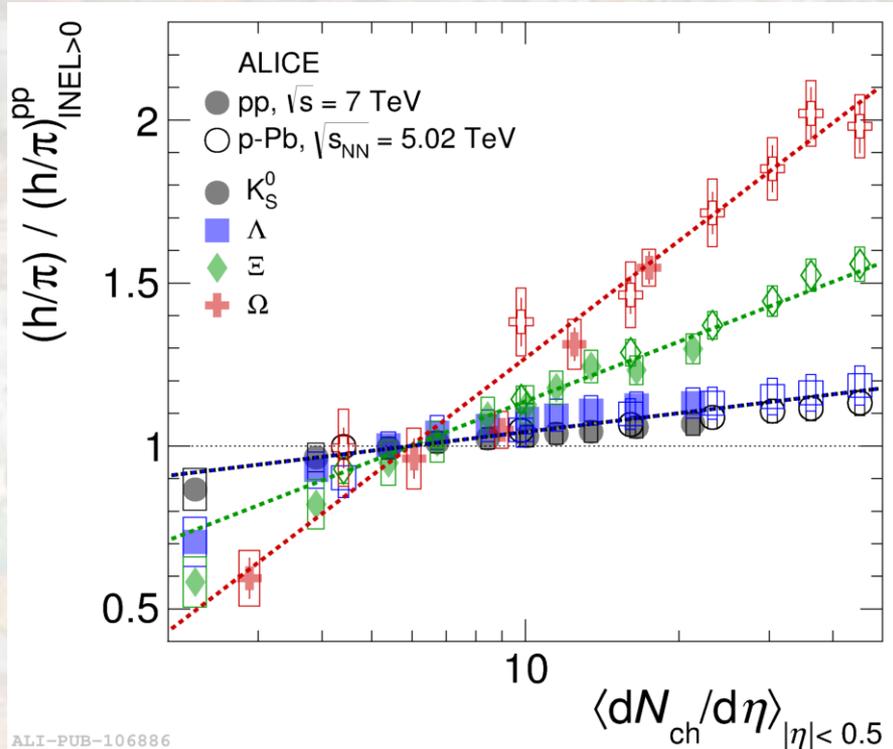
Hyperon production increases from low to high multiplicity in pp and p-Pb

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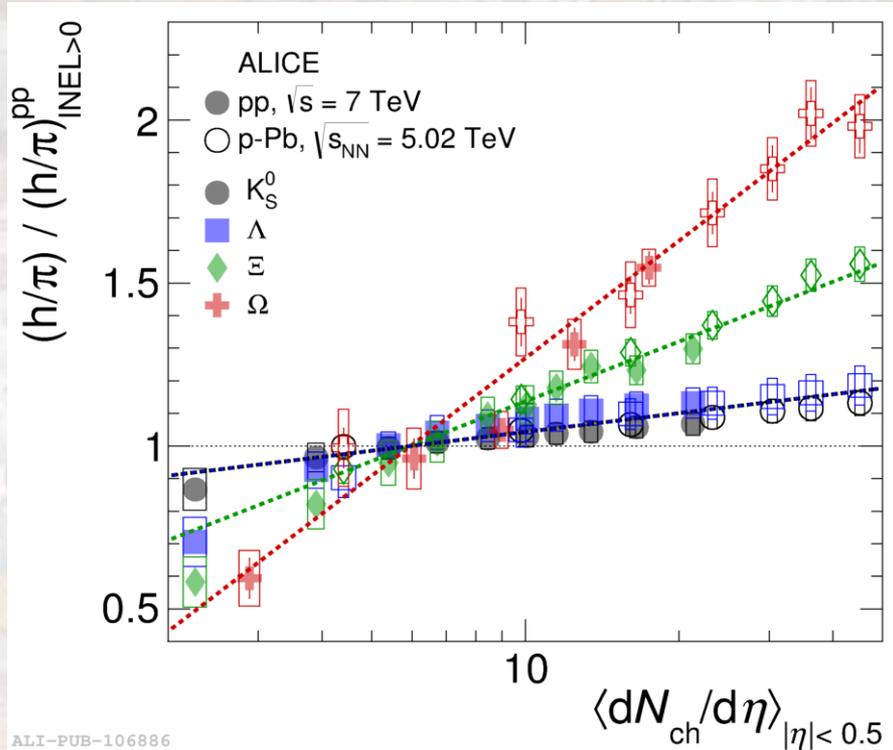
The larger the valence strange quark content, the steeper the slope: (dashed line fit to guide the eye)

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

Strangeness enhancement



Nature Physics 13 (2017) 535



ALI-PUB-106886

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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?

Results in pp @ 7 TeV

Comparison with pp @ 13 TeV



- New measurements at higher energy:
 - multiplicity increases by ~20% going from 7 to 13 TeV
 - preliminary results on strange particle production available
 - possibility to disentangle multiplicity and energy dependence

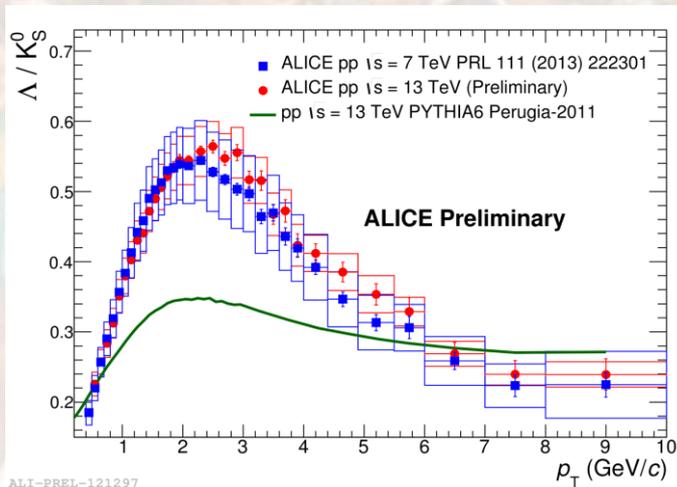
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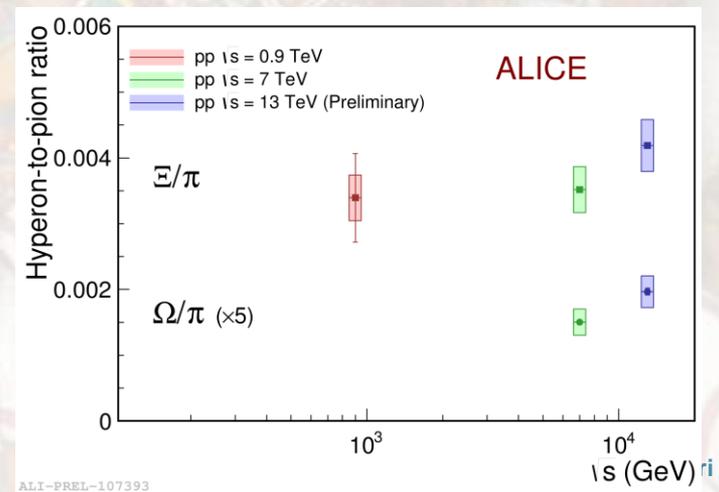
Ratio of spectra in min bias pp:

- hint for a blue shift of the Λ/K^0_S ratio



p_T integrated yields in min bias pp:

- hint for increase of hyperon-to-pion ratios

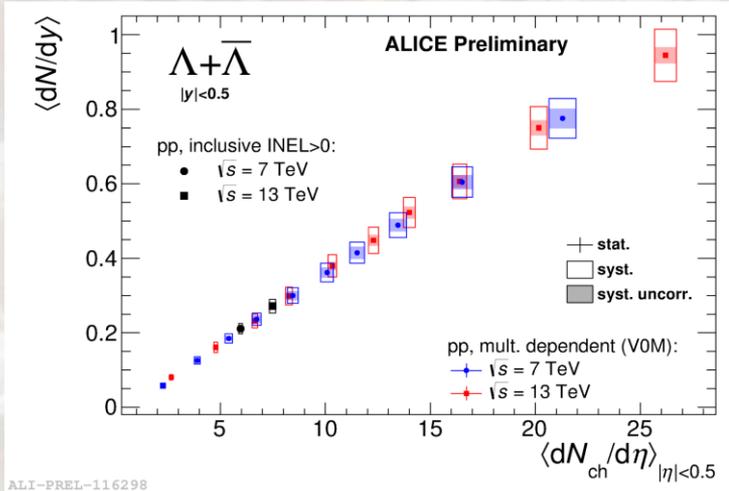


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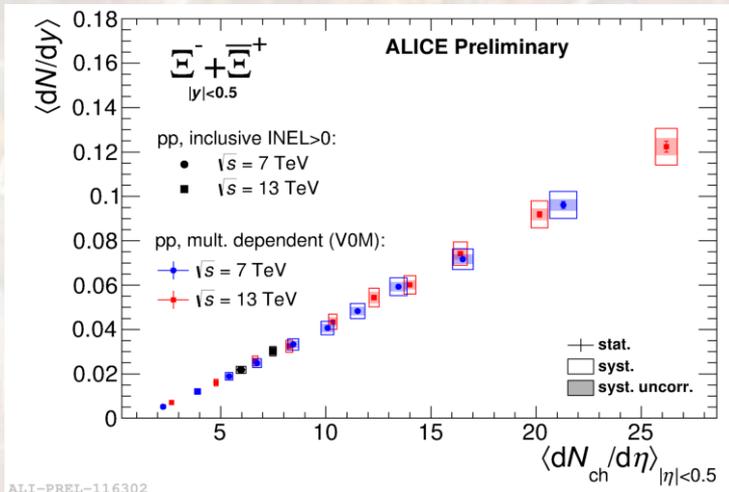


Similar scaling with multiplicity observed for strangeness production in pp @ 7 and 13 TeV

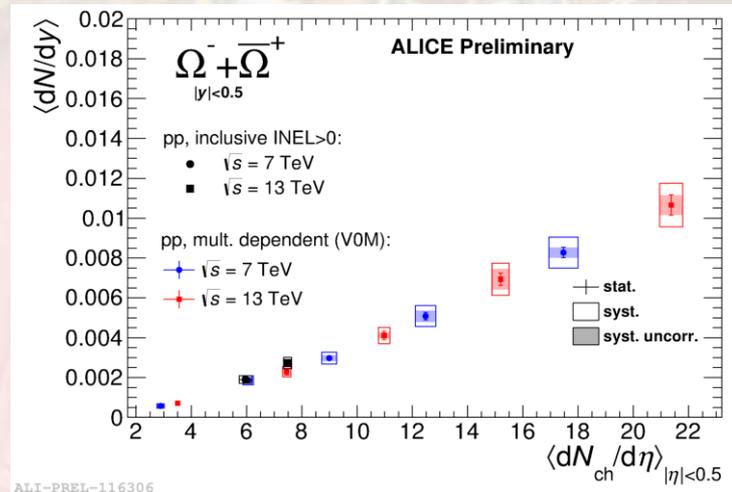
Event activity drives particle production: strange particle production is collision energy independent at similar multiplicity



ALI-PREL-116298



ALI-PREL-116302



ALI-PREL-116306

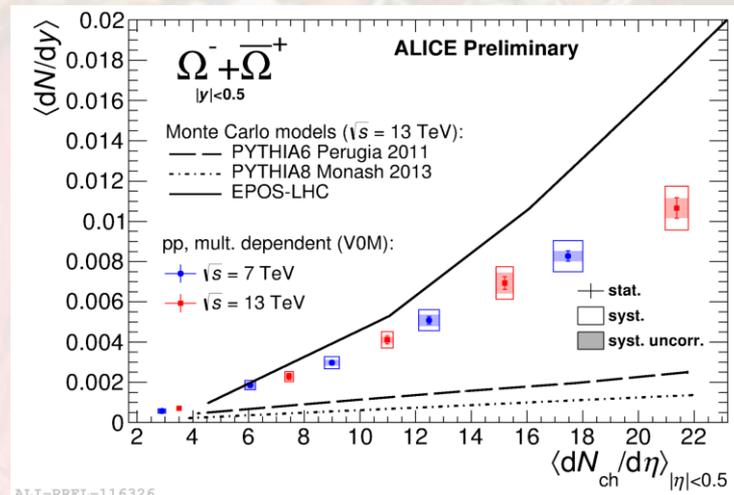
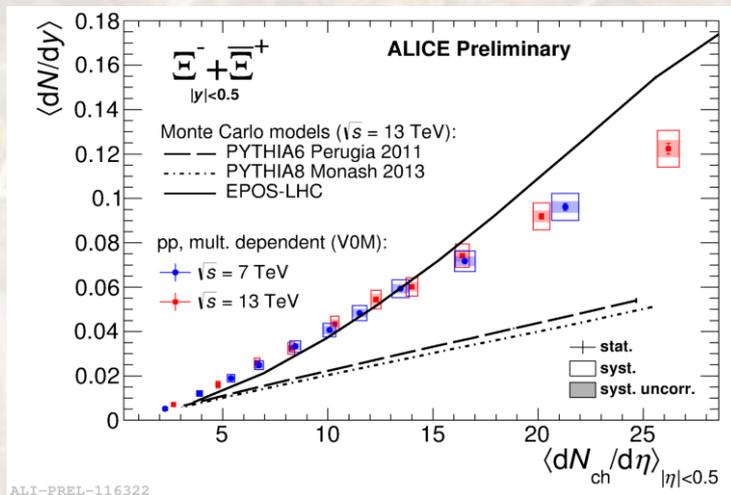
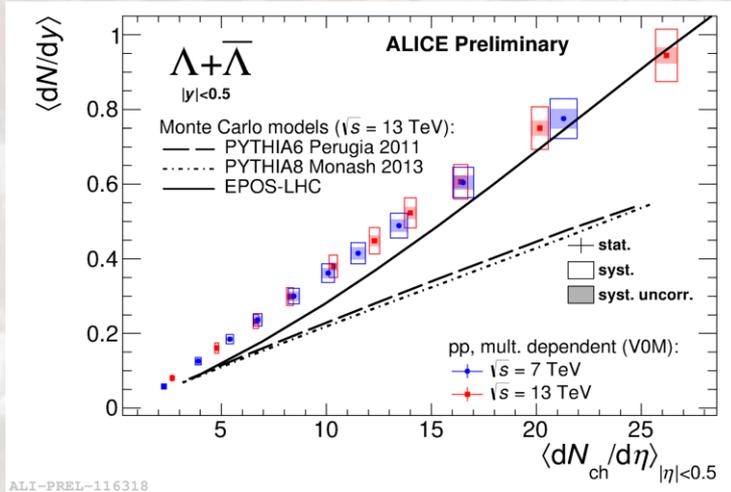
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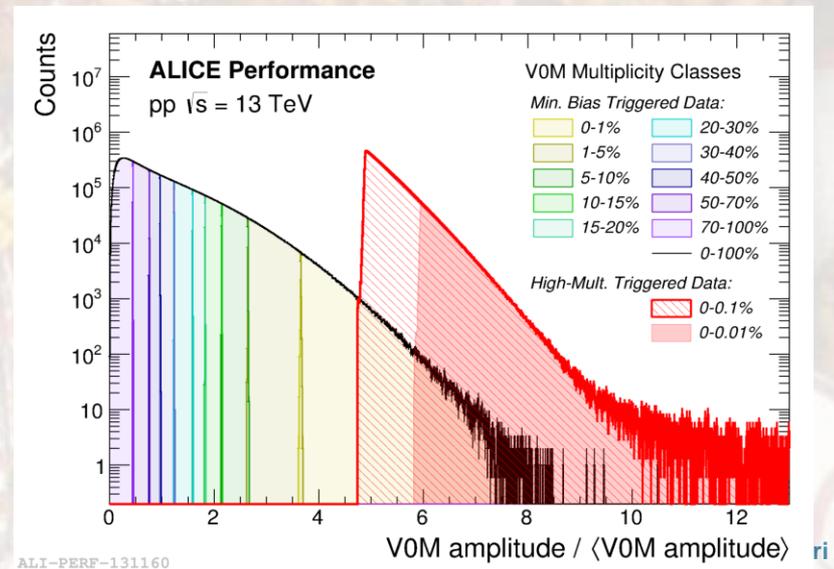
Models: EPOS reproduces multiplicity trend



Comparison with pp @ 13 TeV



- Nearest perspective with higher energy pp:
 - special high-multiplicity trigger used for pp @ 13 TeV data taking in 2016
 - enough statistics to study 0-0.1% and 0-0.01% multiplicity samples

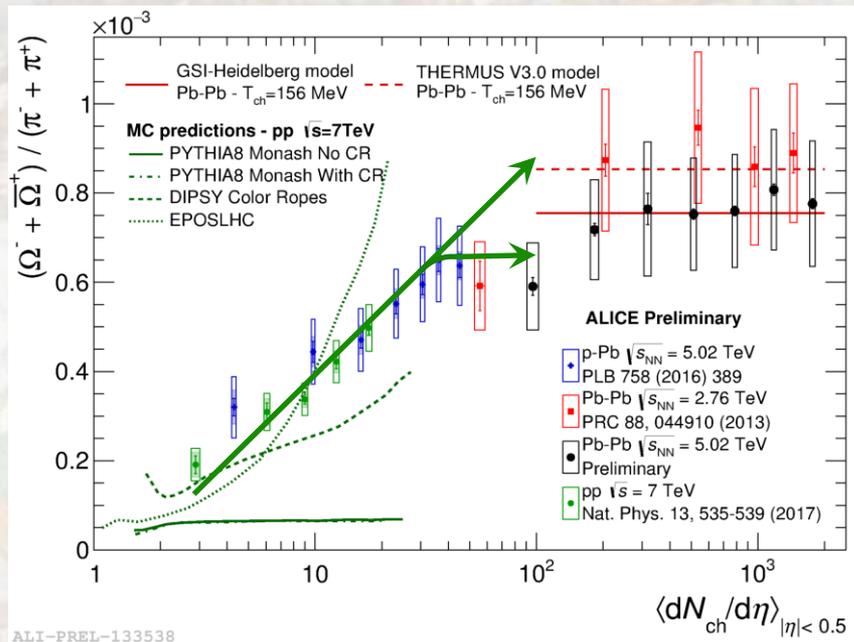


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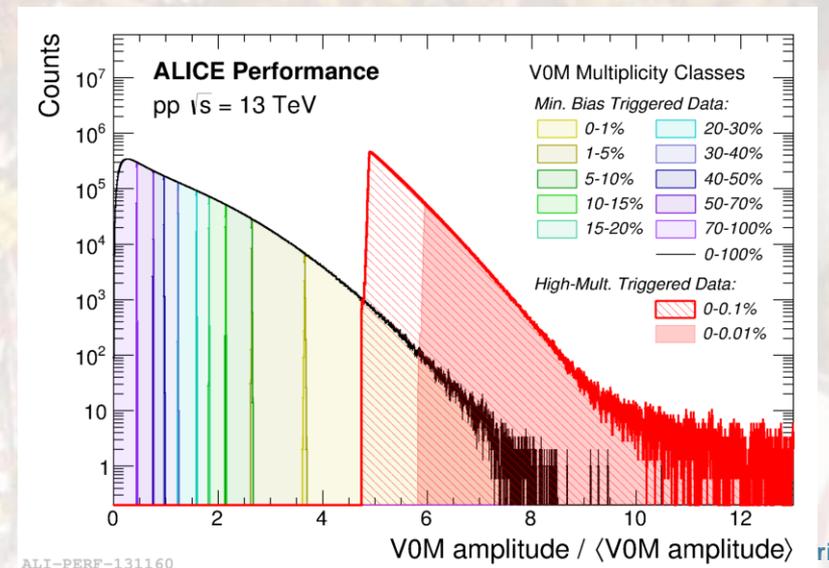


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Aim to answer next question: is there any hint of a saturation of the strangeness production for higher-multiplicity pp?



Conclusions and Outlook



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- Spectra in pp @ 7 TeV:
 - hardening of transverse momentum spectra with increasing multiplicity observed in pp @ 7 TeV (effect similar to A-A)
- Strangeness enhancement:
 - first observation of a multiplicity dependent strangeness enhancement in high-multiplicity pp collisions [*Nature Physics* 13 (2017) 535]
 - enhancement is due to strangeness content and not due to mass
 - multiplicity dependence of the enhancement is strikingly similar in pp and p-Pb, and approaches values similar to those measured in central Pb-Pb
 - QCD inspired MC generators fail to describe these observations
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 - QCD inspired MC generators fail to describe these observations
 - measurements in pp @ 13 TeV seems to indicate that hadrochemistry is driven by event activity regardless of collision energy
- Open question:
 - will the **relative strangeness production in pp saturate**?
 - stay tuned for results from high-multiplicity trigger in pp @ 13 TeV!



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Thanks!

Backup slides



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Multiplicity definition



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- 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 $-3.7 < \eta < -1.7$)

$\langle dN_{\text{ch}}/d\eta \rangle$: 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
$\sigma/\sigma_{\text{INEL}>0}$	0 – 0.95%	0.95 – 4.7%	4.7 – 9.5%	9.5 – 14%	14 – 19%
$\langle dN_{\text{ch}}/d\eta \rangle$	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
$\sigma/\sigma_{\text{INEL}>0}$	19 – 28%	28 – 38%	38 – 48%	48 – 68%	68 – 100%
$\langle dN_{\text{ch}}/d\eta \rangle$	8.45 ± 0.25	6.72 ± 0.21	$5.40 \pm 0.17\%$	3.90 ± 0.14	2.26 ± 0.12

Blast-Wave fit



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

