Strangeness enhancement: from heavy-ions to the observation in high-multiplicity pp collisions

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OUTLINE

- Strangeness production in QGP
- Strangeness enhancement in heavy-ion collisions from SPS to LHC
  - Few selected results

- Strange hadron reconstruction in the ALICE detector
- Multiplicity in ALICE

- Observation of the enhancement of strangeness production in high-multiplicity pp and p-Pb collisions
- Discussion
- A personal outlook

WHAT IS STRANGENESS ENHANCEMENT?

WHAT IS SO SPECIAL ABOUT THE STRANGE QUARK

Strange quarks are created during the collision

The hadronic cross section of (multi)strange hadrons is small → carry information about production stages

The ***s*** quark is "light" (current mass), even if not as light as the *u* and *d* quarks

$m_u \approx 2.3$ MeV
$m_d \approx 4.8$ MeV
$m_s \approx 96$ MeV

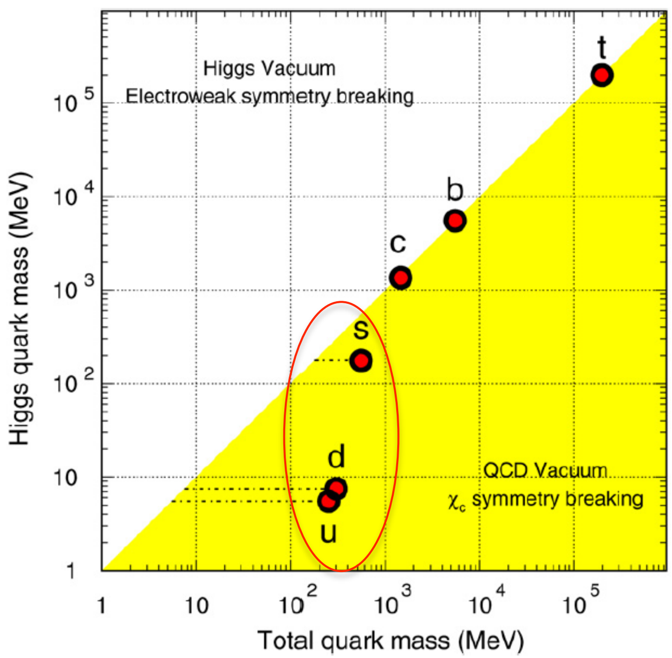
$< \Lambda_{QCD} << m_c \approx 1.3$ GeV

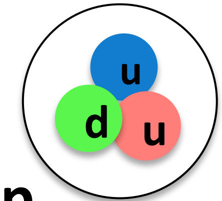
K.A. Olive et al. (PDG), Chin. Phys. C38, 090001 (2014)

- constituent light quarks masses are dominated by spontaneous breaking of chiral symmetry in QCD
  → hadron mass generated "dynamically"

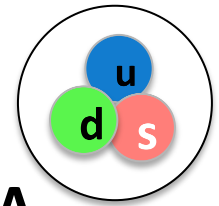
- light quarks can recover their bare current masses if chiral symmetry is (partially) restored
  → near the QCD phase-transition boundary

arXiv:nucl-ex/0610043





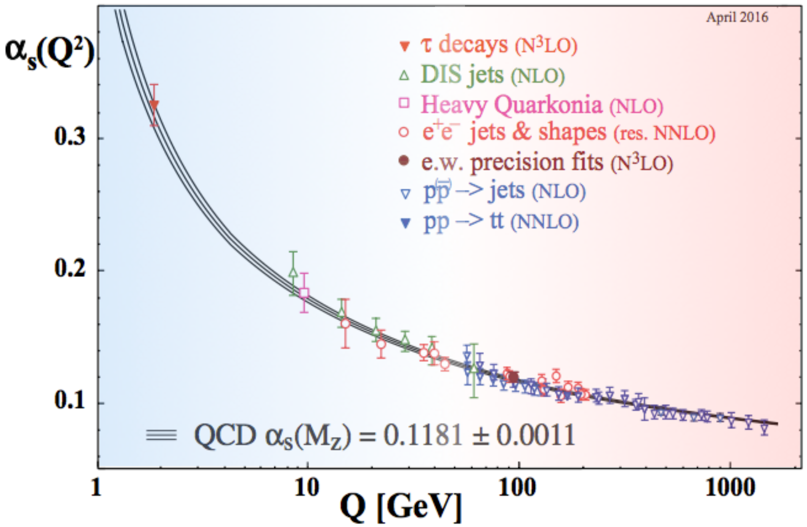
p
M = 938 MeV



Λ
M = 1115 MeV

The QCD phase transition (a very simplified picture)

C. Patrignani et al. (PDG), Chin. Phys. C, 40, 100001 (2016)



Cabibbo and Parisi, Phys. Lett. B 59, 67 (1975)

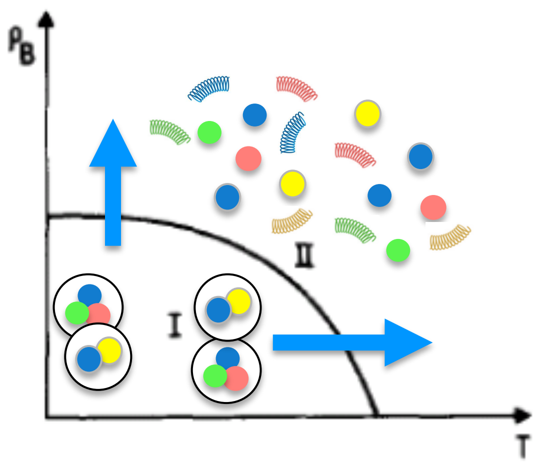


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Quarks and gluons exist in nature as confined in colorless hadrons
→ **confining property of QCD**

The strong coupling becomes weak for processes involving large momentum transfers
→ **asymptotic freedom**

A **deconfined state** of matter (QGP) can be reached by compressing the system to a high-density (ρ_B) and/or heating it up to a high-temperature (T)
→ **ultra-relativistic heavy-ion collisions**

A **phase transition** is expected to occur around **T_c ~ 145 – 164 MeV** (from lattice QCD, *PRD 90 (2014) 094503*)

u, d and **s** quarks **thermally produced in QGP**, as $m_{u,d,s} < T_c$

STRANGENESS PRODUCTION IN QGP

- ~300 MeV are enough to create an s-sbar pair (even less if $m_s^{QCD} \rightarrow m_s^{Higgs}$ by restoration of chiral symmetry)

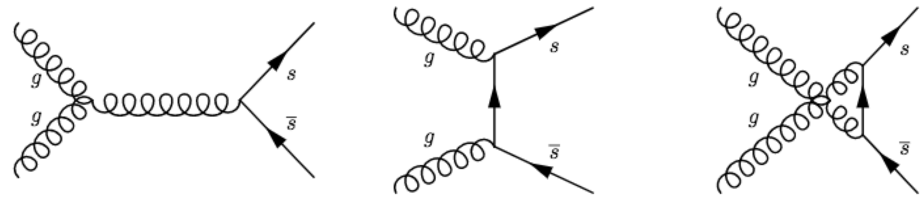
- gluon fusion (a) is the dominant mechanism for strangeness production over quark annihilation (b)
  - Gluons quickly thermalise in t < 1 fm/*c*

  [E. Shuryak, Phys. Rev. Lett. 68 (1992) 3270]

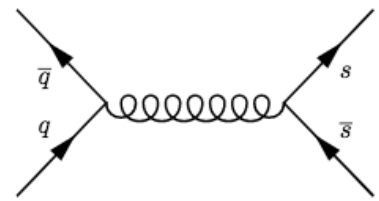
- The backward reaction of (b) depends on the s quark density, thus on the QGP lifetime → saturation of strangeness abundance

- After hadronisation, the abundance c (multi)strange hadrons reflects that c strangeness in the partonic phase
  - If the hadronic phase is short enough to avoid re-diffusion
  - For small hadronic cross sections

(a) $gg \rightarrow s\bar{s}$



(b) $q\bar{q} \rightarrow s\bar{s}$



J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066

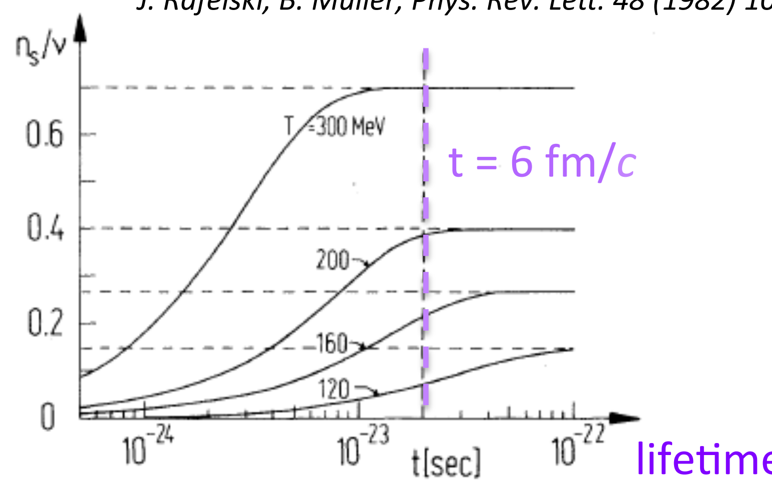


FIG. 3. Time evolution of the relative strange-quark to baryon-number abundance in the plasma for various

Johann Rafelski and Berndt Müller
Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany
(Received 11 January 1982)

Given the present knowledge about the interactions between constituents (quarks and gluons), it appears almost unavoidable that, at sufficiently high energy density caused by compression and/or excitation, the individual hadrons dissolve in a new phase consisting of almost-free quarks and gluons.[1] This quark-gluon plasma is a highly excited state of hadronic matter that occupies a volume large as compared with all characteristic length scales. Within this volume individual color charges exist and propagate in the same manner as they do inside elementary particles as described, e.g., within the Massachusetts Institute of Technology (MIT) bag model.[2]

It is generally agreed that the best way to create a quark-gluon plasma in the laboratory is with collisions of heavy nuclei at sufficiently high energy. We investigate the abundance of strangeness as function of the lifetime and excitation of the plasma state. This investigation was motivated by the observation that significant changes in relative and absolute abundance of strange particles, such as $\overline{\Lambda}$,[3] could serve as a probe for quark-gluon plasma formation.

We thus conclude that strangeness abundance saturates in sufficiently excited quark-gluon plasma ($T > 160$ MeV, $E > 1$ GeV/fm^3), allowing us to utilize enhanced abundances of rare, strange hadrons ($\overline{\Lambda}$, $\overline{\Omega}$, etc.) as indicators for the formation of the plasma state in nuclear collisions.

J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066

Strangeness production in Hadron Gas

In a HG at high temperature (e.g. $T = 150$ MeV, $< T_c$), (multi)strange hadron production is an energy threshold problem:

- by multi-step hadronic processes

  e.g. $\pi + n \rightarrow K + \Lambda$, $E_{th} \sim 540$ MeV

  $\pi + \Lambda \rightarrow K + \Xi$, $E_{th} \sim 560$ MeV

  → Requires longer medium lifetime

  → under-saturation of strangeness

- by direct production

  e.g. $\pi + \pi \rightarrow \pi + \pi + \Lambda + \Lambda$-bar, $E_{th} \sim 2200$ MeV

  $\pi + \pi \rightarrow \pi + \pi + \Xi^- + \Xi^+$-bar, $E_{th} \sim 2600$ MeV

  → have to happen very early by non-thermalised hadrons

- Less efficient than production in QGP
- Harder to reach equilibrium

STATISTICAL HADRONISATION APPROACH(ES) FOR AA

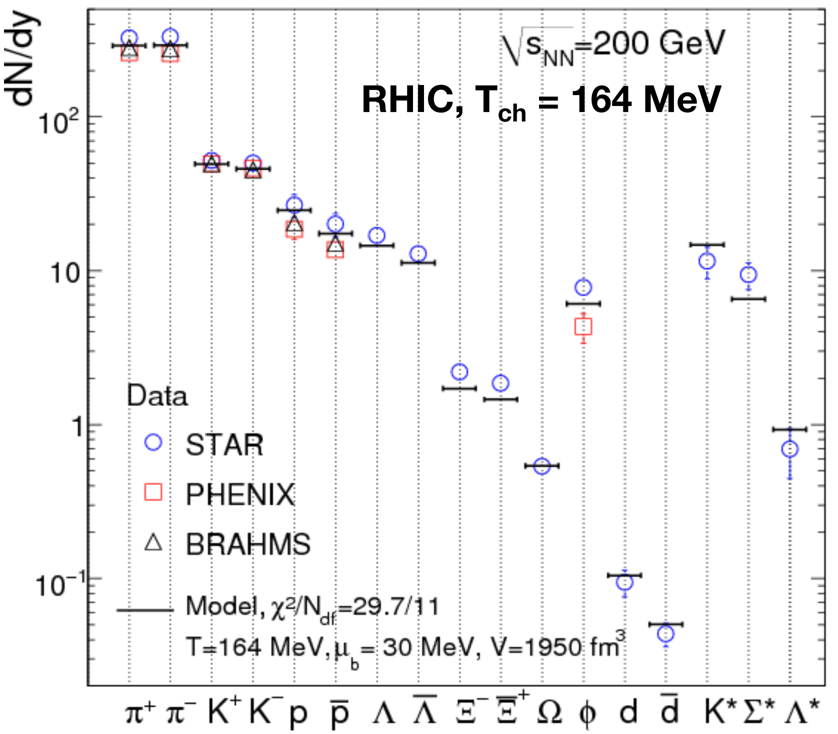
Hadron yields measured in AA collisions at SPS and RHIC (fig. below), have been successfully described by thermal models supporting the idea of matter in **local thermal and chemical equilibrium**

- Caveat: strangeness content, resonances

Several implementations of the **statistical hadronization model (SHM)**, with common features:

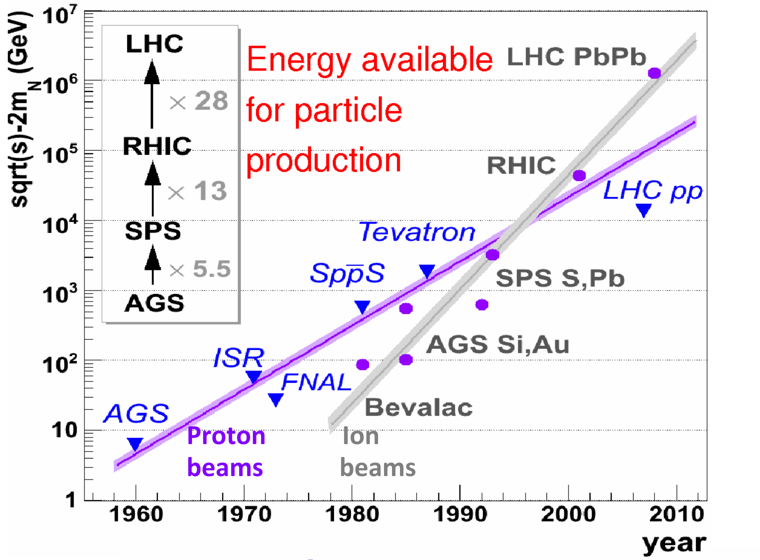
- **grand-canonical** (GC) partition function for a relativistic ideal quantum gas of hadrons
- main parameters: T_{ch}, μ_B, V (volume cancels out if particle ratios are calculated)
- **deviations from (GC) equilibrium** through empirical under(over)-saturation parameters* for strange, charm or light quarks (γ_s, γ_c and γ_q)
- **Measured particle yields (or ratios) are the input to the fits**

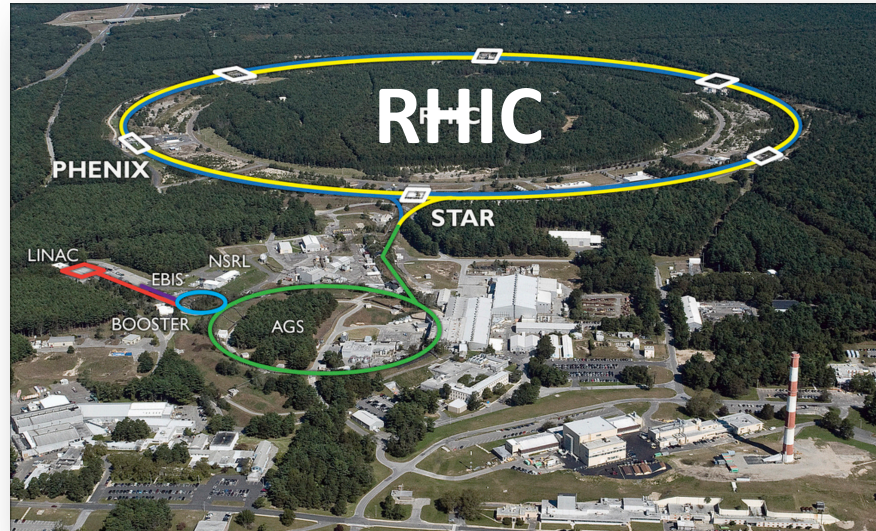
A. Andronic et al., Phys.Lett.B 673:142-145(2009)



Experimental evidence of strangeness enhancement in heavy-ion collisions

30 YEARS OF HEAVY-ION COLLISION EXPERIMENTS



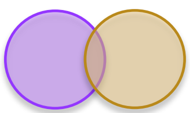


Fixed target experiments:
Bevalac @ LBL (1975-1986) √s <2.4 GeV
SIS @ GSI (1989-) √s <2.7 GeV
AGS @ BNL (1986-1998) √s <5 GeV
SPS @ CERN (1986-2003) √s <20 GeV
FAIR @ GSI (u.c.) √s <9 GeV

Collider experiments:
RHIC @ BNL (2000-) $\sqrt{s_{NN}}$ <200 GeV
[beam energy scan $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, and 62.4 GeV]
LHC @ CERN (Run I, 2009-2013) √s <2.76 TeV
LHC @ CERN (Run II, 2015-2018) √s <5.5 TeV

CENTRALITY

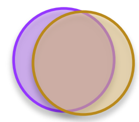
Centrality is defined as the fraction of the total hadronic cross section of nucleus-nucleus (A-A) collisions → can be quantified by the impact parameter (**b**)



Peripheral collisions

→ Large impact parameter

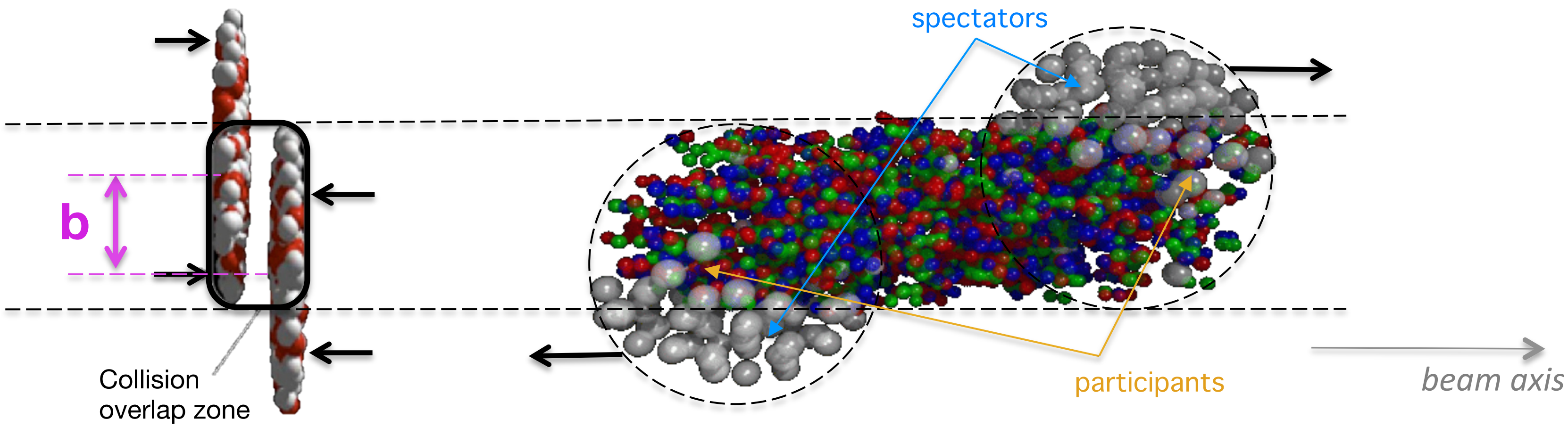
→ Low particle multiplicity



Central collisions

→ Small impact parameter

→ High particle multiplicity



Centrality variables:

- N_{part} (N_{wound}), **number of participating (wounded) nucleons:** determines the energy available for particle production in the collision
- N_{coll}, number of **binary nucleon-nucleon collisions**

GLAUBER MODEL

Glauber model: nucleus-nucleus interaction as incoherent superposition of nucleon-nucleon collisions calculated in a probabilistic approach

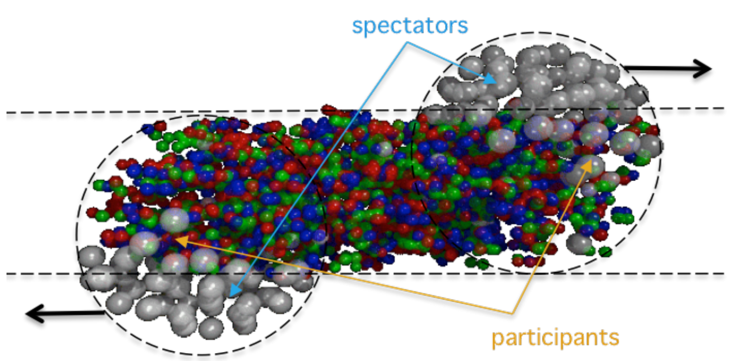
- nucleons in nuclei considered are point-like and non-interacting
- nuclei (and nucleons) have straight-line trajectories (no deflection)

Input:

- Nucleon-nucleon inelastic cross section
- Nuclear density distribution (for Pb, use Woods-Saxon for spherical nuclei)

Allows to extract:

- Interaction probability
- **Number of elementary nucleon-nucleon collisions (N_{coll})**
- **Number of participant nucleons (N_{part})**
- **Number of spectator nucleons**
- Size of the nuclei overlap region

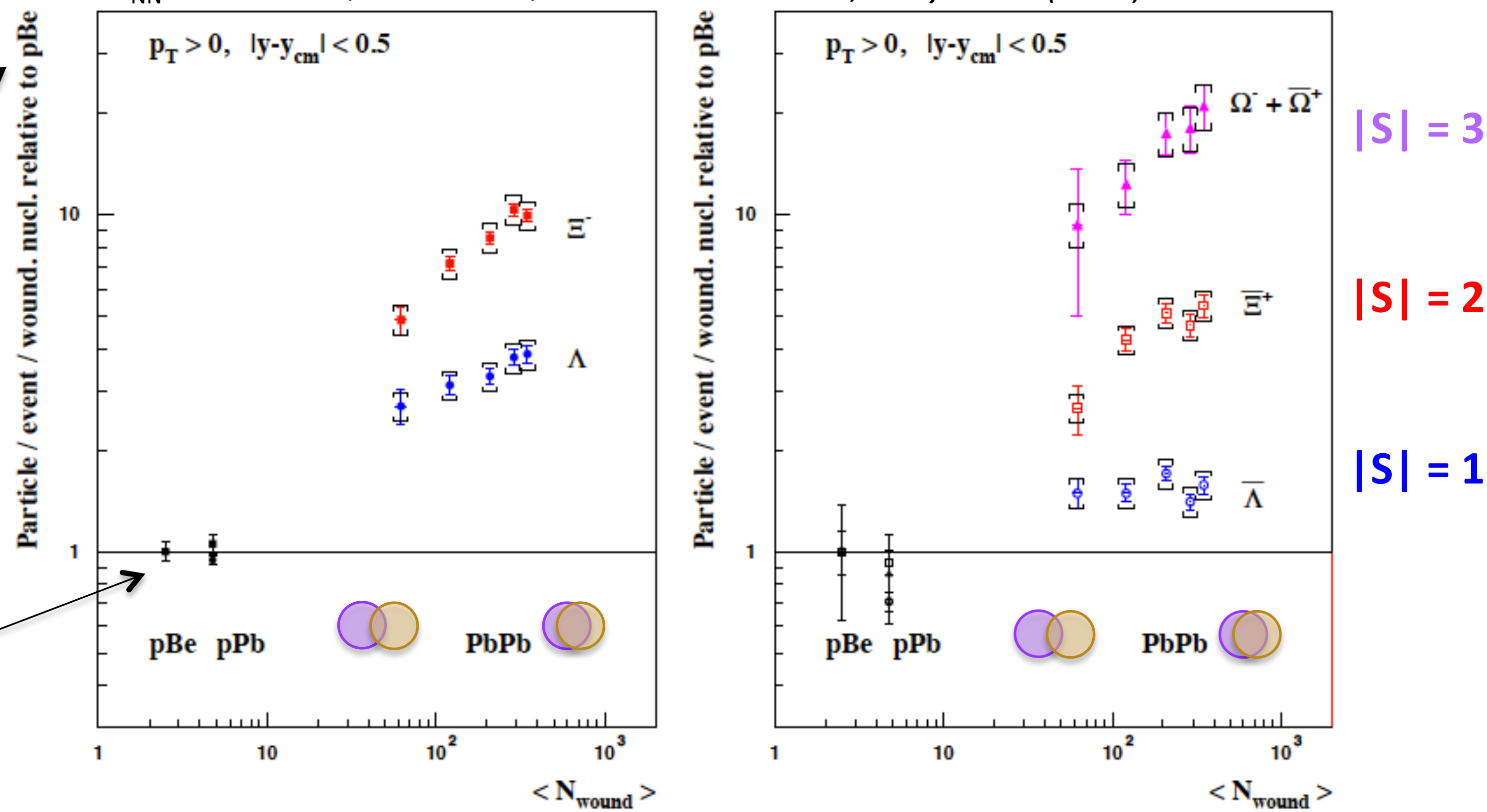


STRANGENESS ENHANCEMENT AT SPS

$\sqrt{s_{NN}}$ = 17.3 GeV (= 158A GeV)

NA57, J.Phys. G32 (2006) 427-442

Not just an effect of having more participants in Pb-Pb → Yields normalised to N_{wound} relative to p-Be



p-Be used as a proxy for pp since N_{wound} is close to 2 (as in pp)

- **Enhancement observed in Pb-Pb** collisions wrt p-Pb, p-Pb for all (multi)strange (anti)baryons
- Anti-baryon less enhanced than baryons → quarks (not anti-quarks!) in the initial stage
- **Hierarchy** of the enhancement with the strangeness content
- **Increase** of the enhancement **with the centrality** of the collision

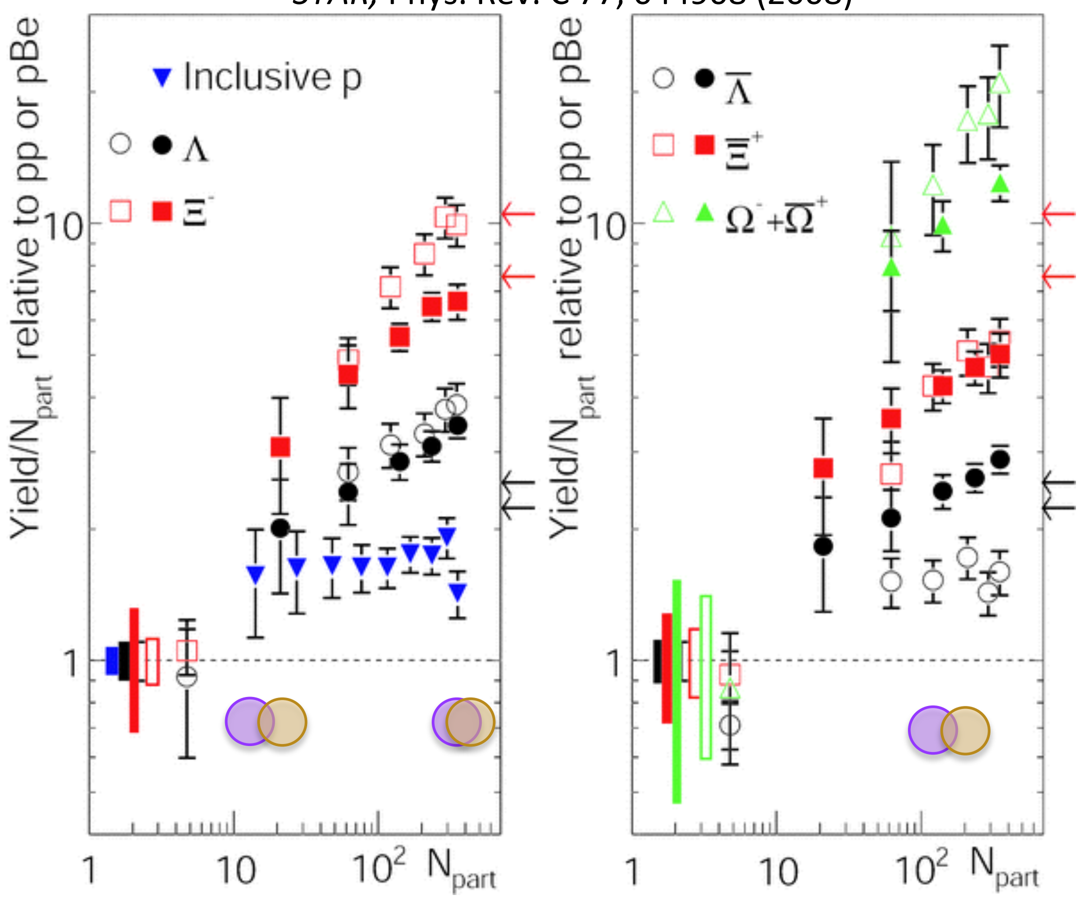
From SPS to RHIC

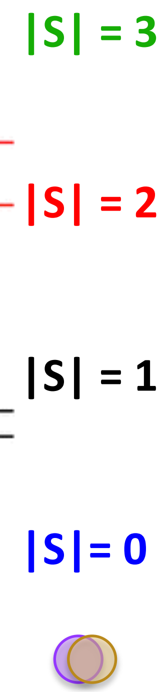
NA57, J.Phys. G32 (2006) 427-442

Open symbols:
NA57, $\sqrt{s_{NN}}$ = 17.3 GeV

Full symbols:
STAR, $\sqrt{s_{NN}}$ = 130 GeV

STAR, Phys. Rev. C 77, 044908 (2008)





- **Enhancement observed also at RHIC**
- **Increase** of the enhancement **with the centrality** of the collision
- Lower enhancement for higher collision energy
  - Multiplicity per N_{part} saturates earlier in AA than in pp

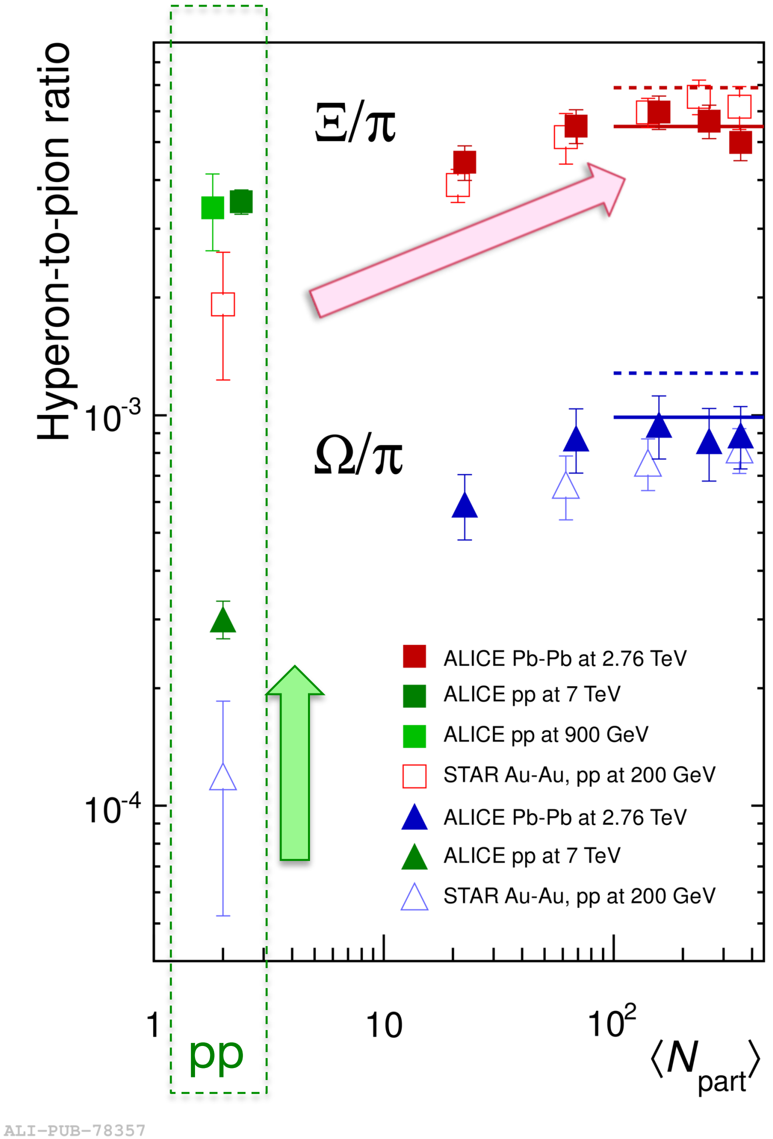
STRANGENESS ENHANCEMENT

Strange quarks are more abundantly produced
in nucleus-nucleus than in pp/pA collisions

Strangeness enhancement
proposed as a first signature of the presence of a deconfined Quark Gluon Plasma *[J. Rafelski and B. Muller, PRL 48 (1982) 1066]*, where strangeness is produced thermally (mainly) by equilibrated gluons

vs. canonical suppression
[K. Redlich, A. Tounsi, Eur. Phys. J. C 24, 589–594 (2002)]
suppression of production due to canonical quantum number conservation law
i.e. strangeness has to be conserved locally in a finite system
Reduced phase space available for particle production
→ Relaxation of canonical suppression with increasing √s (and number of particles)

FROM RHIC TO LHC



RHIC: $\sqrt{s_{NN}}$ = 200 GeV
LHC: $\sqrt{s_{NN}}$ = 2.76 TeV

In **pp collisions** the production of strangeness relative to π at LHC is larger than at RHIC
→ understand the small system "reference"!

From **pp to Pb-Pb** strangeness production increases

For N_{part} >150 the ratios saturate and match predictions from the grand-canonical statistical hadronisation models.

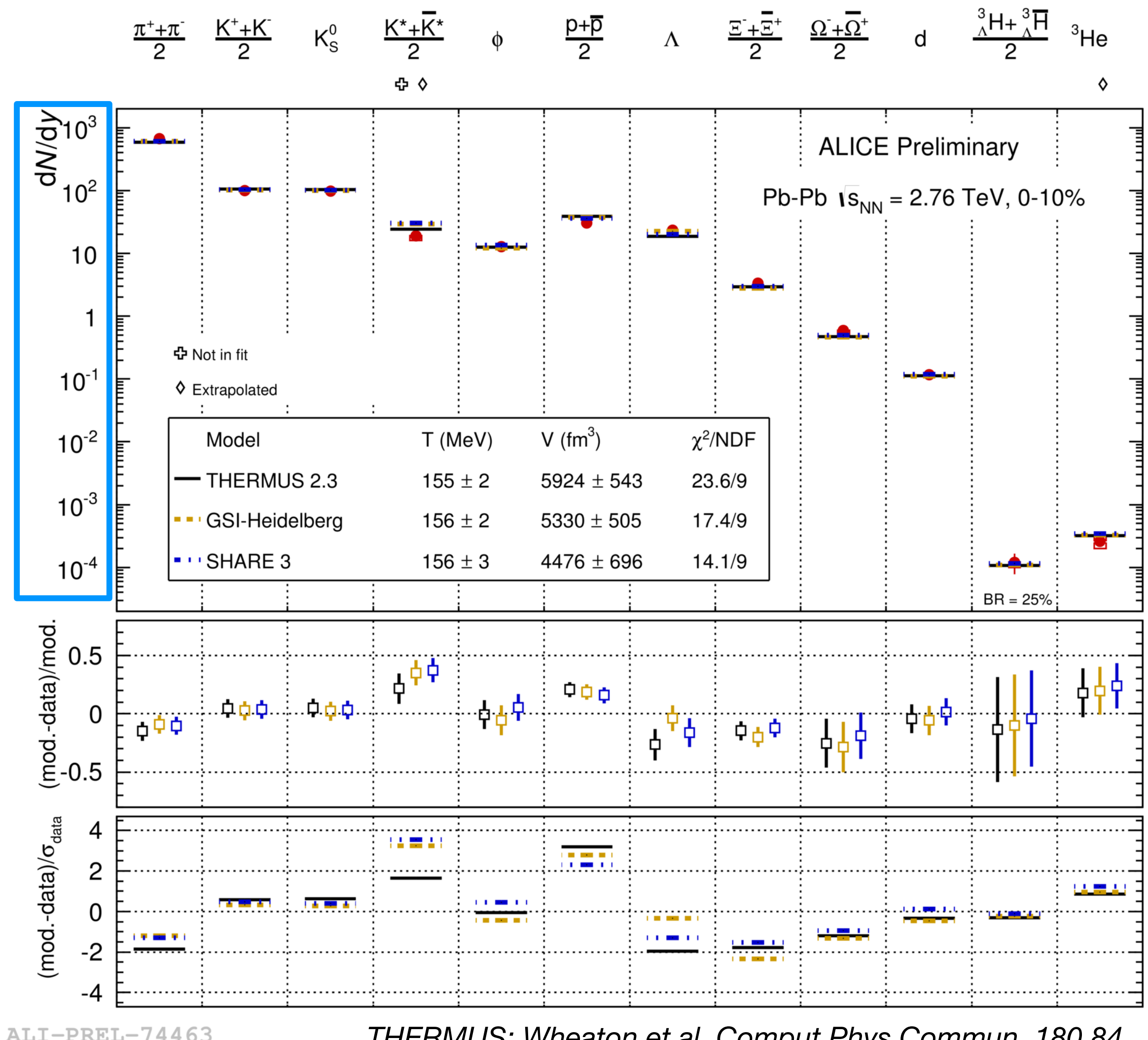
For instance, models at equilibrium

- GSI-Heidelberg: T_{ch} = 164 MeV [*Andronic et al, PLB 673 (2009) 142*]
- THERMUS: T_{ch} = 170 MeV [*Cleymans et al, PRC 74 (2006) 034903*]

In addition, a more recent fit with T_{ch} = 156 MeV…

Thermal model fit at LHC

M. Floris at QM 2014, arXiv:1408.6403



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

Describes hadron production assuming **chemical equilibrium**

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

THERMAL MODEL FIT AT LHC

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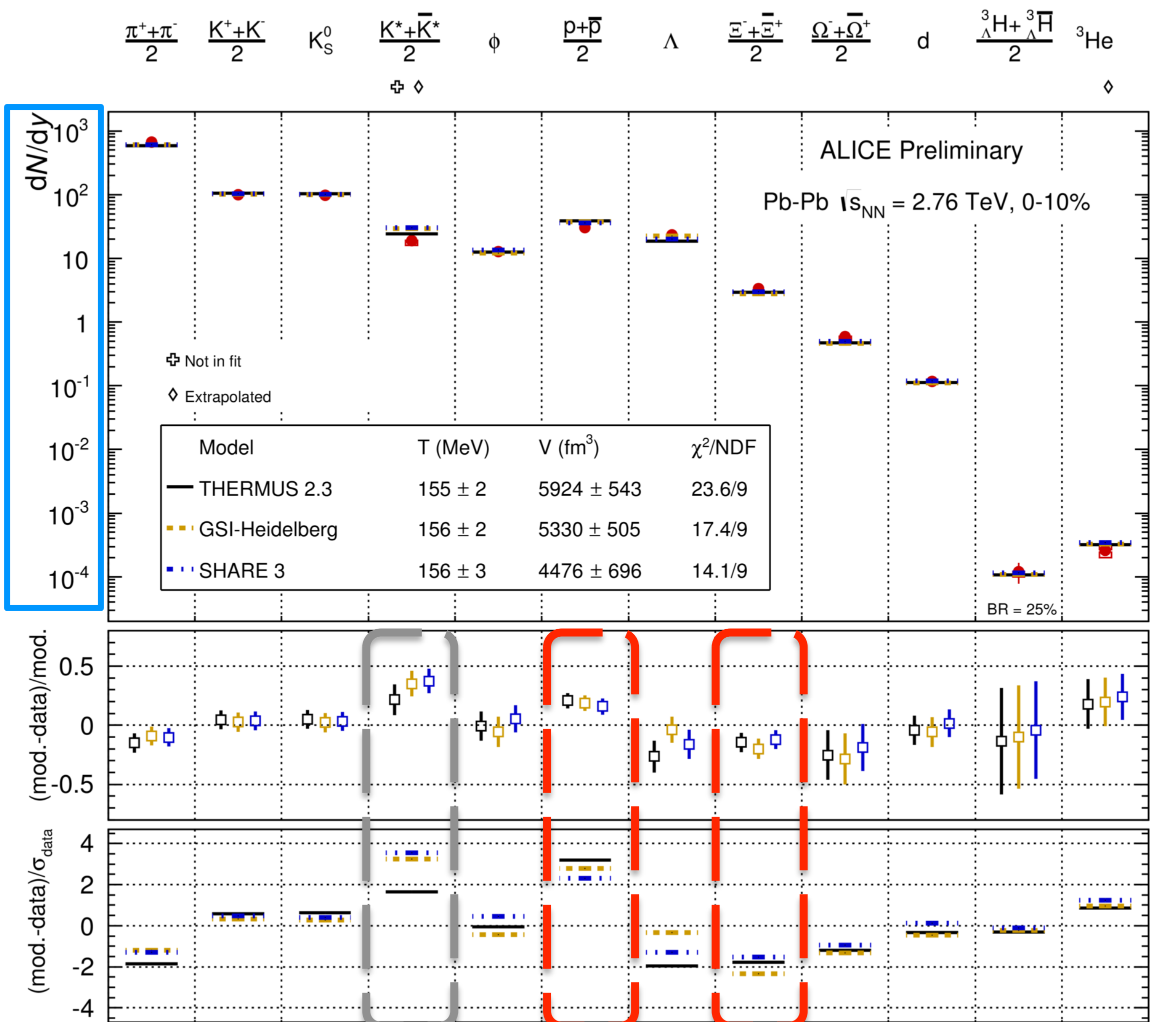

ALI-PREL-74463

THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
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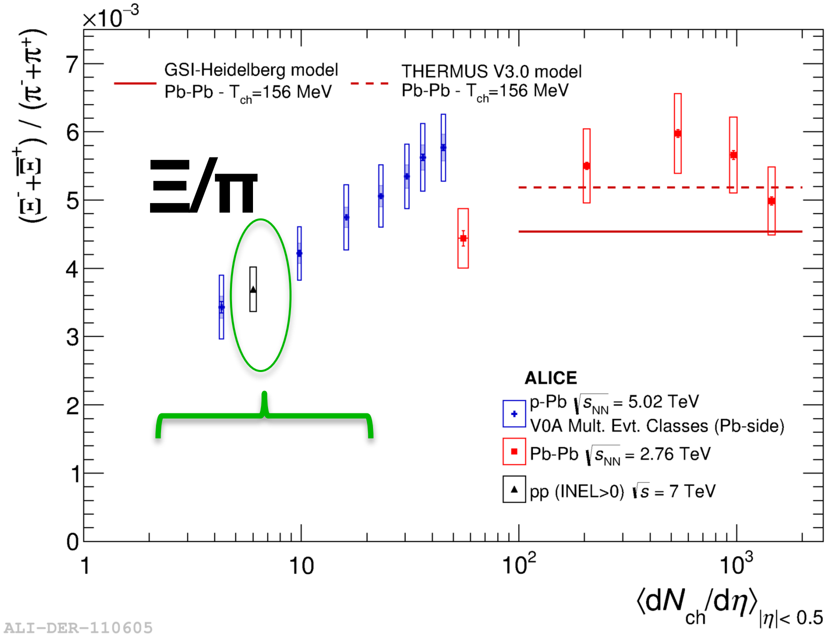
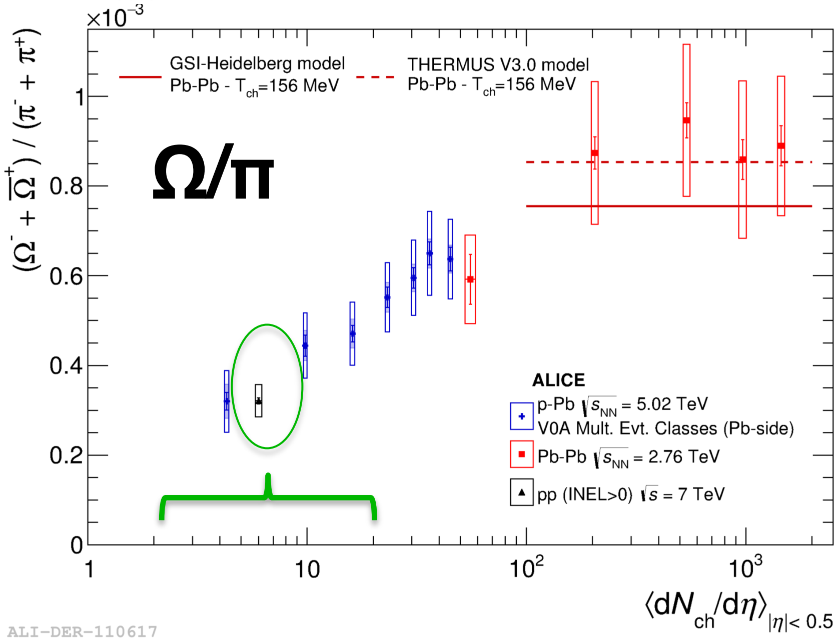
Deviation for **K^{*0} resonance**: re-scattering in the late hadronic phase

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

Small systems at the LHC

ALICE, PLB 728 (2014) 216
ALICE, PLB 759 (2016) 389-401





In **p-Pb** collisions

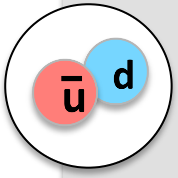
- Ξ/π reaches values seen in Pb-Pb
- Ω/π exhibits a strong rise (~2x) and reaches 60-80% Pb-Pb
- Low-multiplicity p-Pb consistent with minimum bias pp

→ What about in **pp vs multiplicity**?

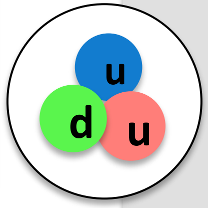
Observation of strangeness enhancement in high multiplicity pp collisions

STRANGE AND IDENTIFIED HADRONS IN ALICE

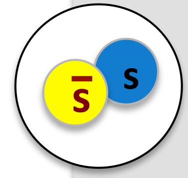
|S| = 0



π^-
M = 140 MeV
Primary*

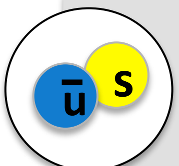


p
M = 938 MeV
Primary*

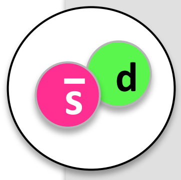


ϕ
M = 1020 MeV
$\phi \rightarrow K^+K^-$ (48.9%)
$c\tau$ = 45 fm

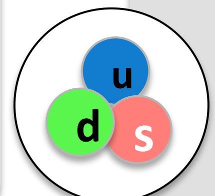
|S| = 1



K^-
M = 494 MeV
Primary*

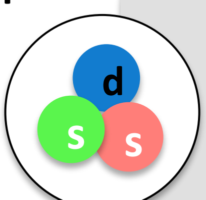


K^0_S
M = 497 MeV
$K^0_S \rightarrow \pi^+\pi^-$ (69.2%)
$c\tau$ = 2.68 cm



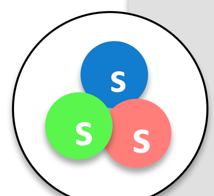
Λ
M = 1115 MeV
$\Lambda \rightarrow p\pi^-$ (63.9%)
$c\tau$ = 7.98 cm

|S| = 2



Ξ^-
M = 1322 MeV
$\Xi^- \rightarrow \Lambda\pi^-$ (99.9%)
$c\tau$ = 4.91 cm

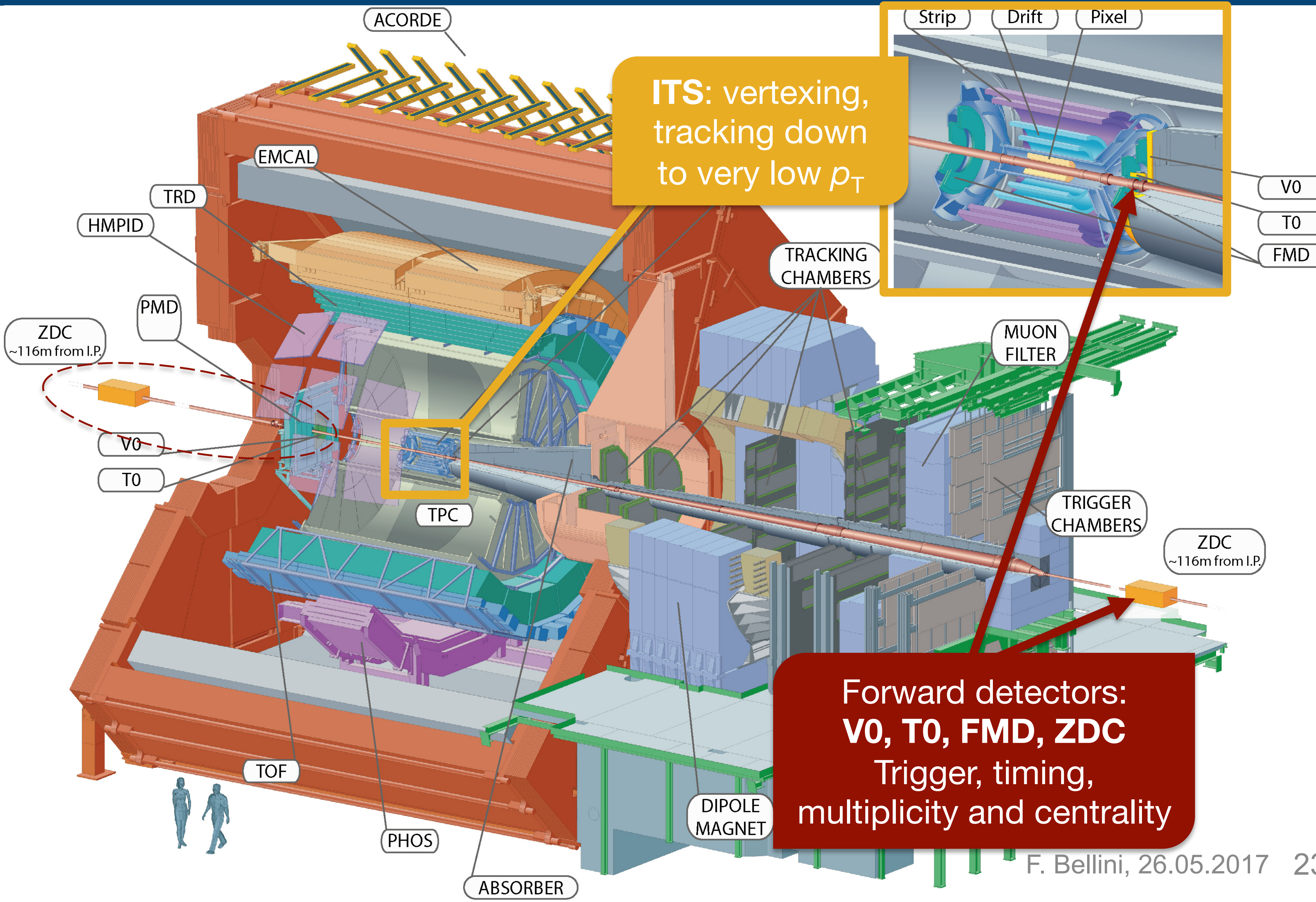
|S| = 3



Ω^-
M = 1672 MeV
$\Omega^- \rightarrow \Lambda K^-$ (67.8%)
$c\tau$ = 2.46 cm

+ antiparticles
+ resonances (not today's topic…)

A Large Ion Collider Experiment at the LHC



ITS: vertexing, tracking down to very low p_T

Forward detectors:
V0, T0, FMD, ZDC
Trigger, timing, multiplicity and centrality

Phys. Rev. Lett. 106 (2011) 032301

EVENT CLASSES IN PB-PB

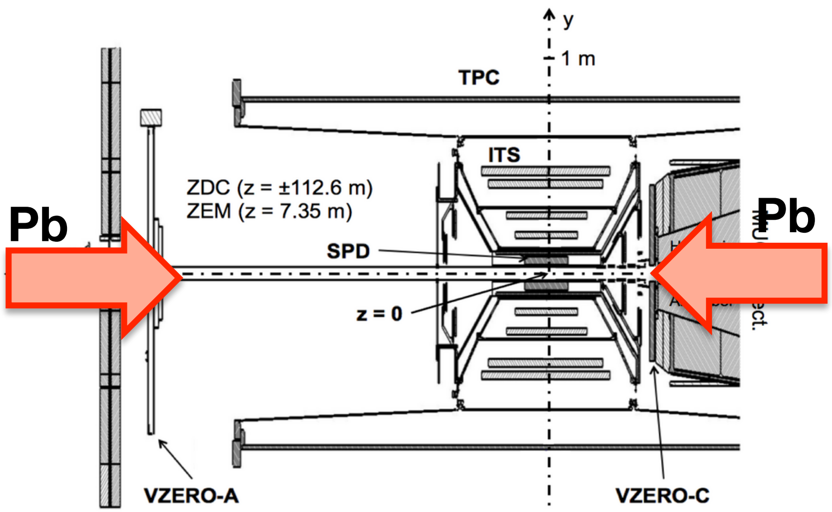
Event **multiplicity/centrality** classes are defined based on the amplitude measured in the **V0 scintillators**, placed at $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C)

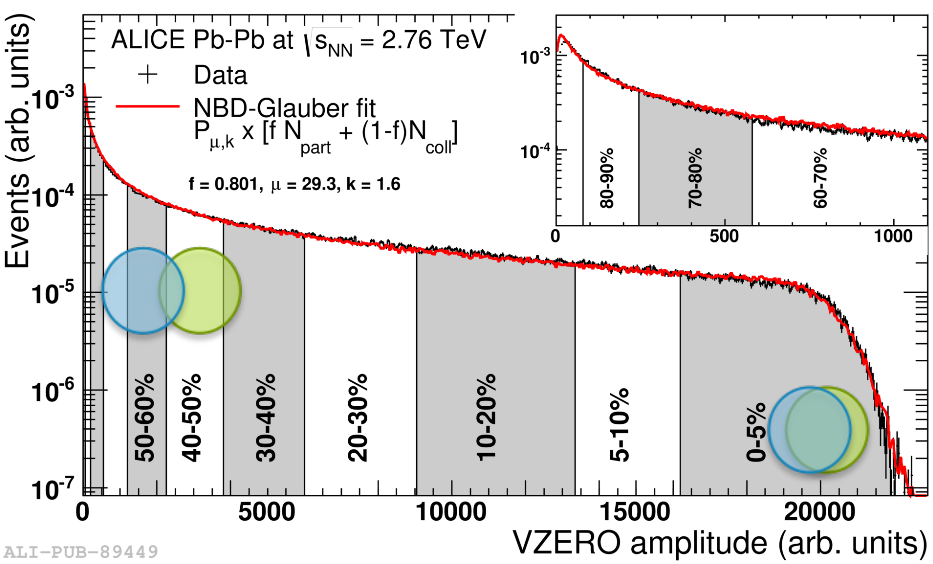
$\langle dN_{ch}/d\eta \rangle$ is measured in $|\eta| < 0.5$
→ avoid "auto-biases" in multiplicity determination

In **Pb-Pb** the Glauber model is used to relate the V0A&V0C ("V0M") amplitude* distribution to the geometry of the collision.

At $\sqrt{s_{NN}} = 2.76$ TeV
0-5%: $\langle dN_{ch}/d\eta \rangle = 1601 \pm 60$
$\langle N_{part} \rangle = 328.8 \pm 3.1$
70-80%: $\langle dN_{ch}/d\eta \rangle = 35 \pm 2$
$\langle N_{part} \rangle = 15.8 \pm 0.6$

(*alternatively, multiplicity of spectators in the Zero Degree Calorimeters or number of tracks in the Silicon Pixel Detector or the Time Projection Chamber)





EVENT CLASSES IN PB-PB, P-PB AND PP

Phys. Rev. Lett. 106 (2011) 032301
Phys. Rev. C 91 (2015) 064905

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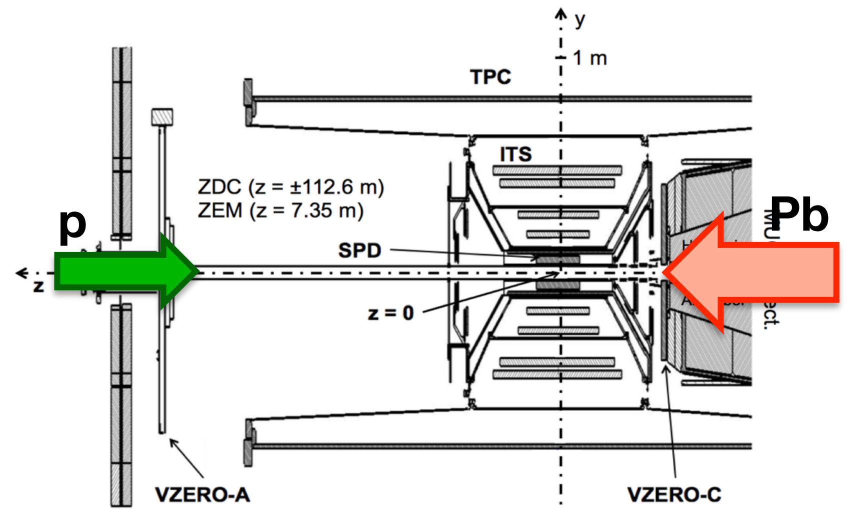
$\langle \mathbf{N_{part}} \rangle$ **= 15.8 ± 0.6**

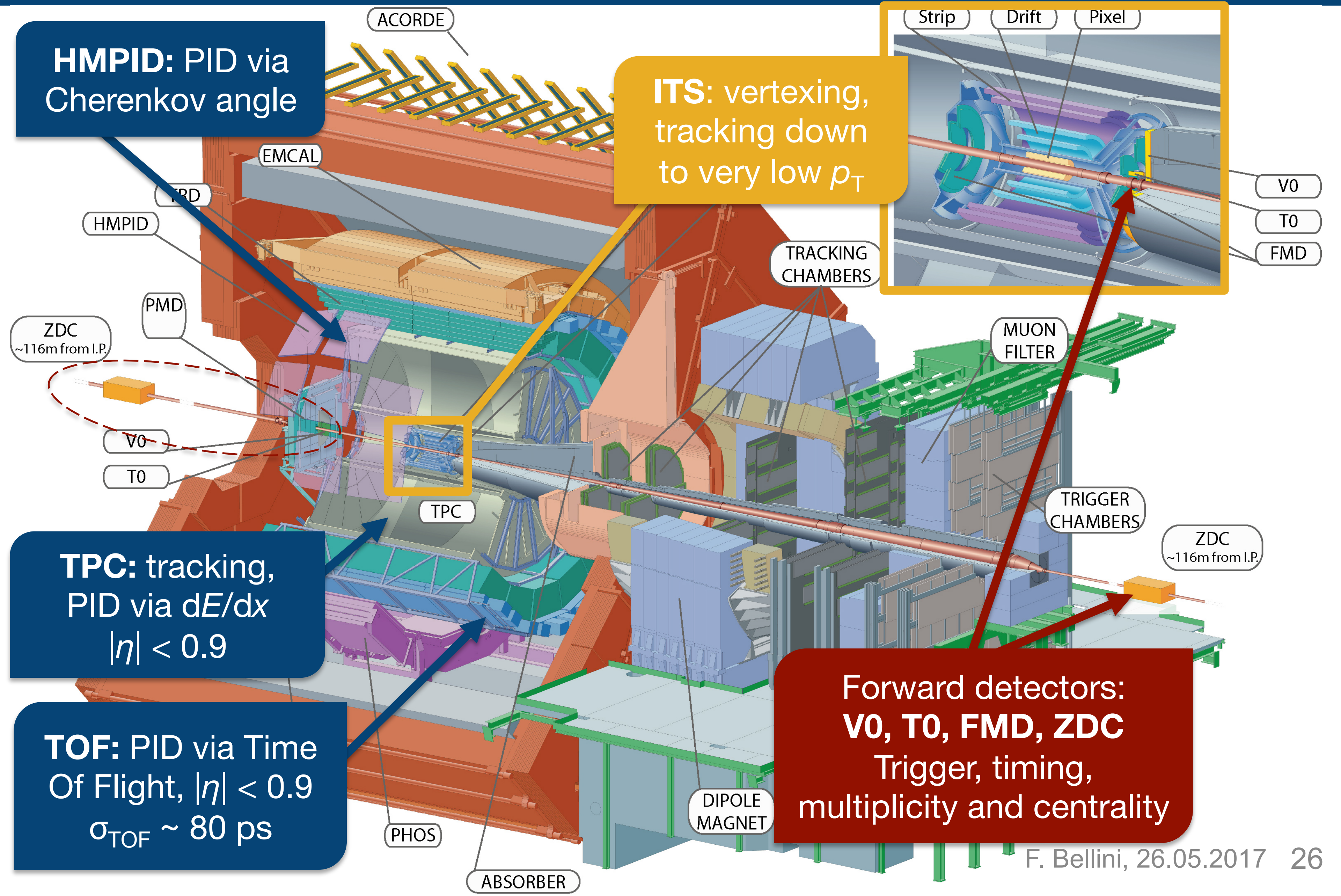
(*alternatively, multiplicity of spectators in the Zero Degree Calorimeters or number of tracks in the Silicon Pixel Detector or the Time Projection Chamber)



In **p-Pb** collisions, V0A (Pb side) is used:
at $\sqrt{s_{NN}}$ = 5.02 TeV
0-5%: $\langle \mathbf{dN_{ch}/d\eta} \rangle$ **= 45 ± 1**
60-80%: $\langle \mathbf{dN_{ch}/d\eta} \rangle$ **= 9.8 ± 0.2**

In **pp** collisions, V0A&V0C ("V0M") us used:
at $\sqrt{s}$ = 7 TeV
0-0.95%: $\langle \mathbf{dN_{ch}/d\eta} \rangle$ **= 21.3 ± 0.6**
48-68%: $\langle \mathbf{dN_{ch}/d\eta} \rangle$ **= 3.90 ± 0.14**

A Large Ion Collider Experiment at the LHC



HMPID: PID via Cherenkov angle

ITS: vertexing, tracking down to very low p_T

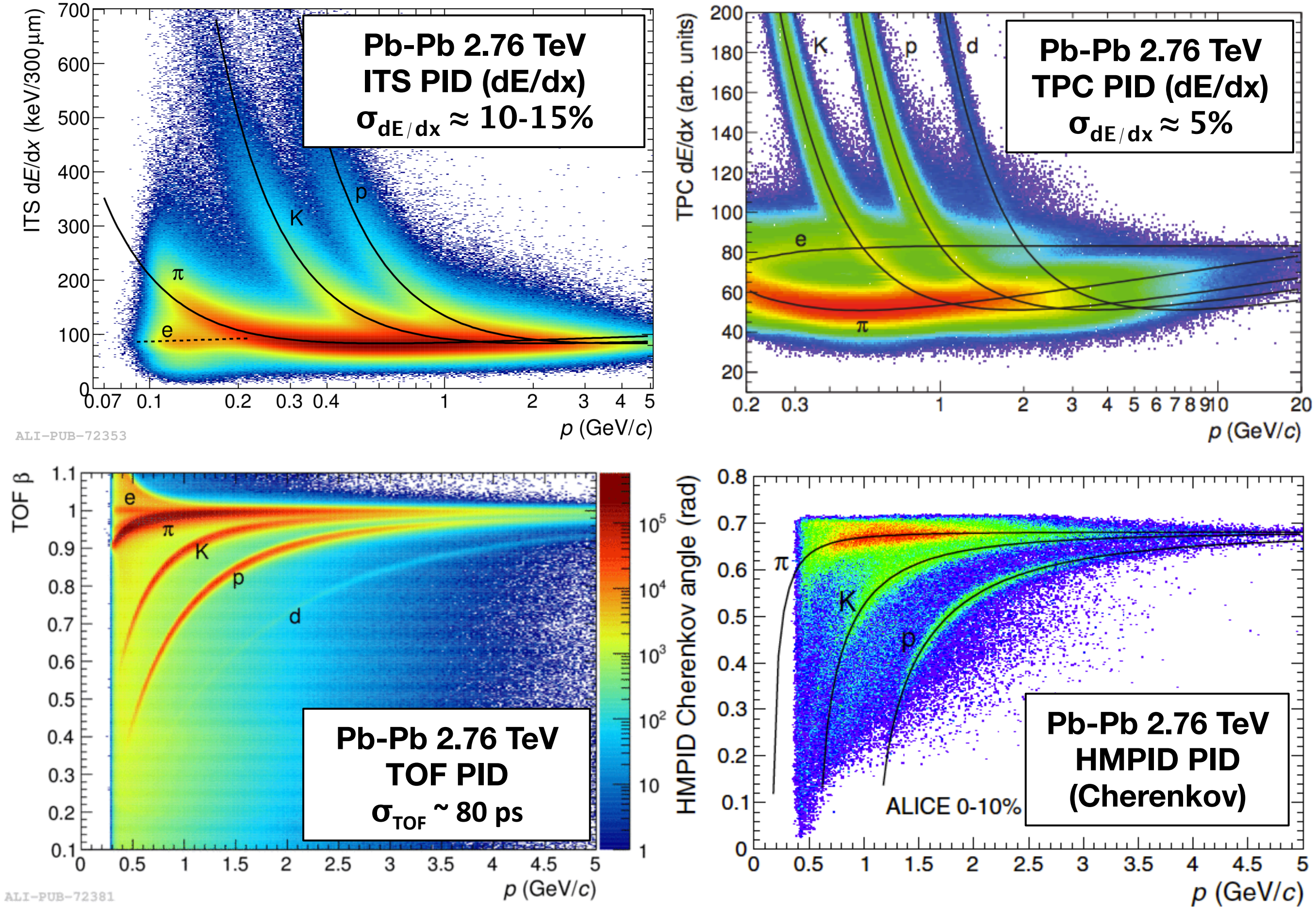
TPC: tracking, PID via dE/dx $|\eta| < 0.9$

TOF: PID via Time Of Flight, $|\eta| < 0.9$ $\sigma_{TOF} \sim 80$ ps

Forward detectors: **V0, T0, FMD, ZDC** Trigger, timing, multiplicity and centrality

π, K, p IDENTIFICATION

Int. J. Mod. Phys. A 29 (2014) 1430044



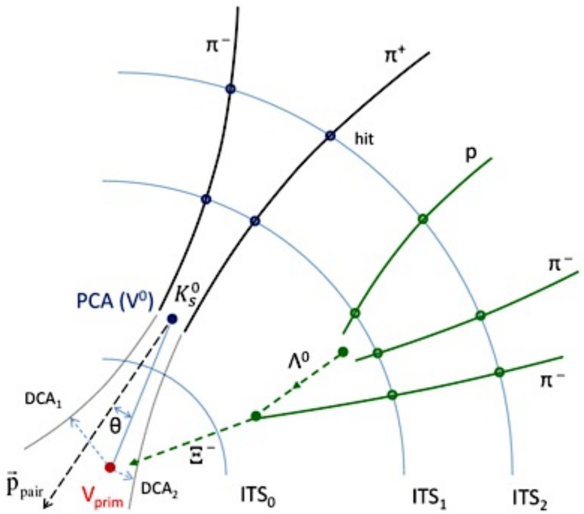
Charged π,K,p are identified by combining several PID techniques in **0.1 GeV/*c* < p_T < 20 GeV/*c***

The yields of identified π and p are corrected for feeddown from secondary particles produced

- in the interaction with the detector material
- in weak decays of strange particles

- Kaons also identified using "kink" topology, $K^{\pm} \rightarrow \mu^{\pm}\nu$
- Statistical identification at high-p_T via relativistic rise of the Bethe-Bloch in the TPC

(MULTI)STRANGE HADRON RECONSTRUCTION

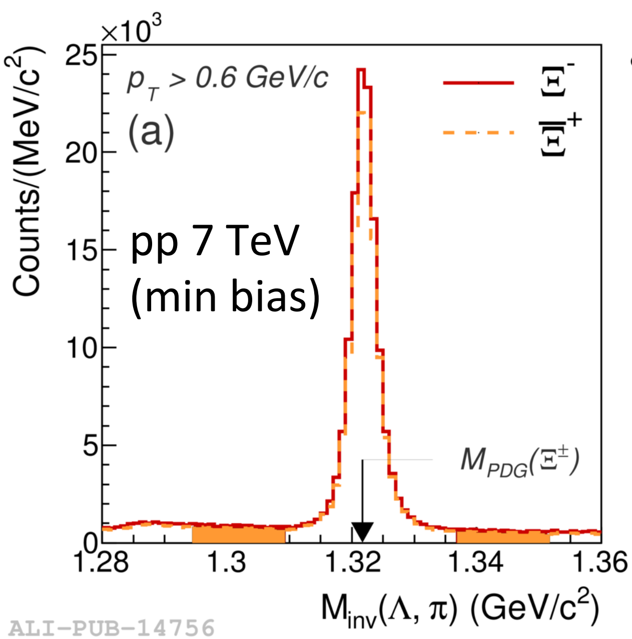


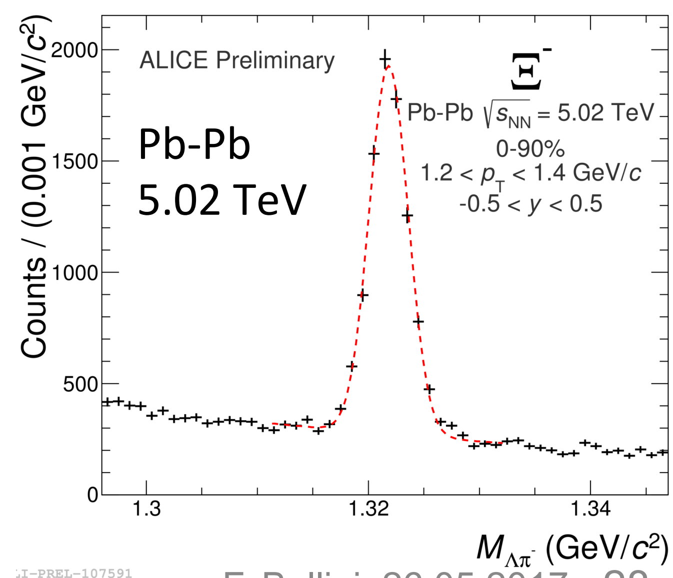
Reconstruction of the weak decay topology

Yield extraction in each p_T bin:

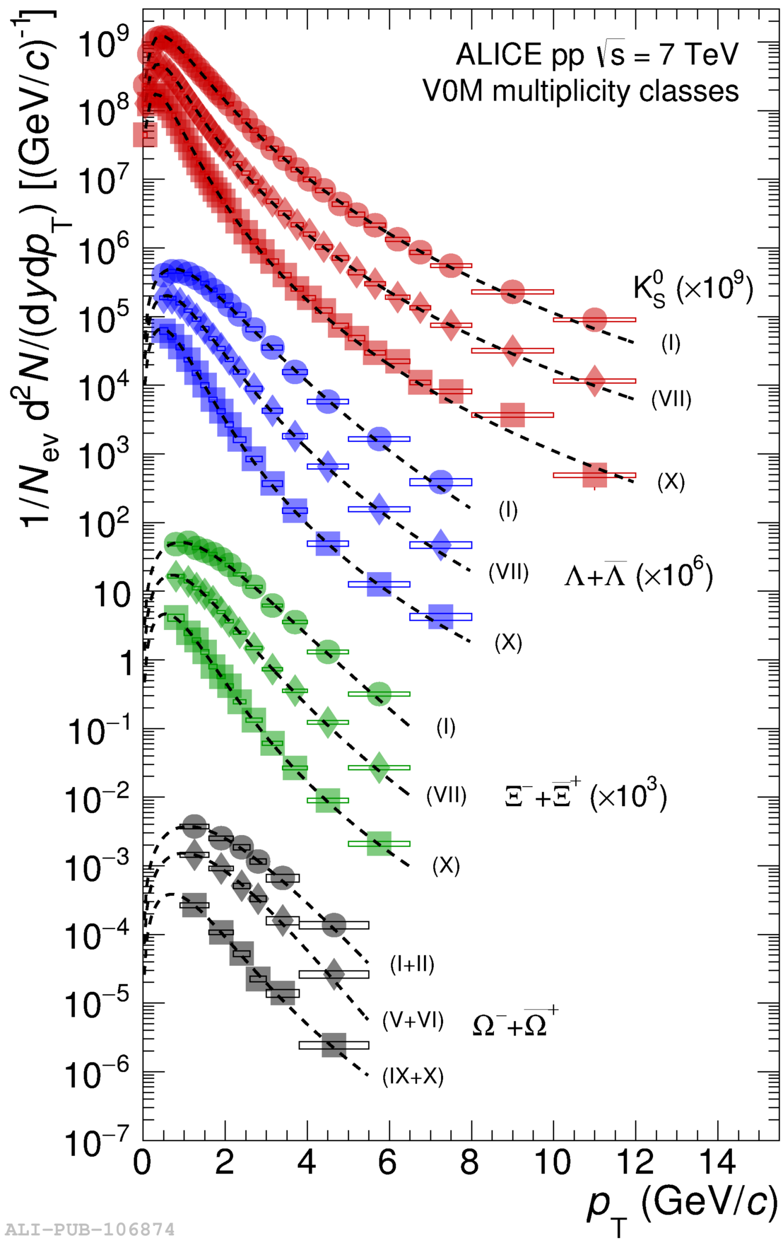
- Fit polynomial + gaussian to get signal mean, σ
- Bin counting in the signal region (3σ)
- Fit background on side-bands
- Integral of background fit
- function in the signal region

→ Signal = Bin counting - Integral





(MULTI)STRANGE HADRON YIELDS IN PP 7 TEV



Nature Physics, DOI: 10.1038/nphys4111

p_T differential yields of strange and multi-strange measured in 10 multiplicity bins

$$\begin{cases} I \rightarrow \langle dN_{ch}/d\eta \rangle \approx 3.5 \times \langle dN_{ch}/d\eta \rangle^{INEL>0} \\ \vdots \\ X \rightarrow \langle dN_{ch}/d\eta \rangle \approx 0.4 \times \langle dN_{ch}/d\eta \rangle^{INEL>0} \end{cases}$$

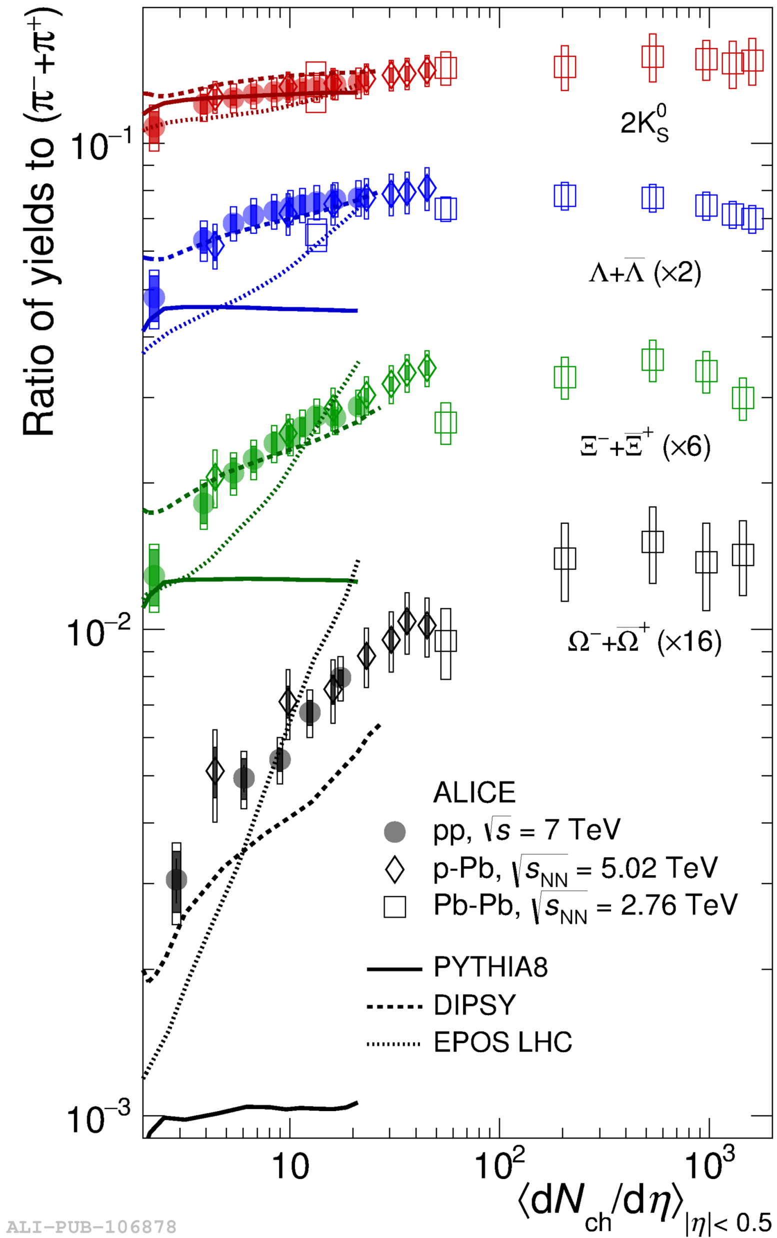
$$\left(\langle dN_{ch}/d\eta \rangle^{INEL>0} \approx 6.0 \right)$$

- **Spectra harden towards higher multiplicity** (as observed in p-Pb and Pb-Pb)

- p_T integrated yields extracted from measured points and extrapolation function at low p_T (Lévy-Tsallis, dashed line)

STRANGE-TO-PION RATIOS

Nature Physics, DOI: 10.1038/nphys4111



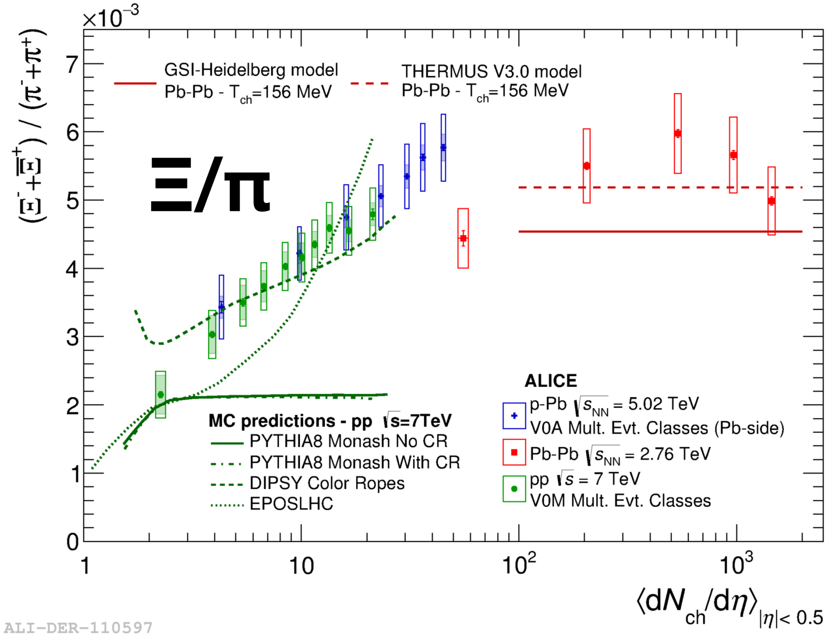
(Multi)strange to non-strange yield ratios **increase significantly and smoothly with multiplicity** in **pp** and **p-Pb** collisions

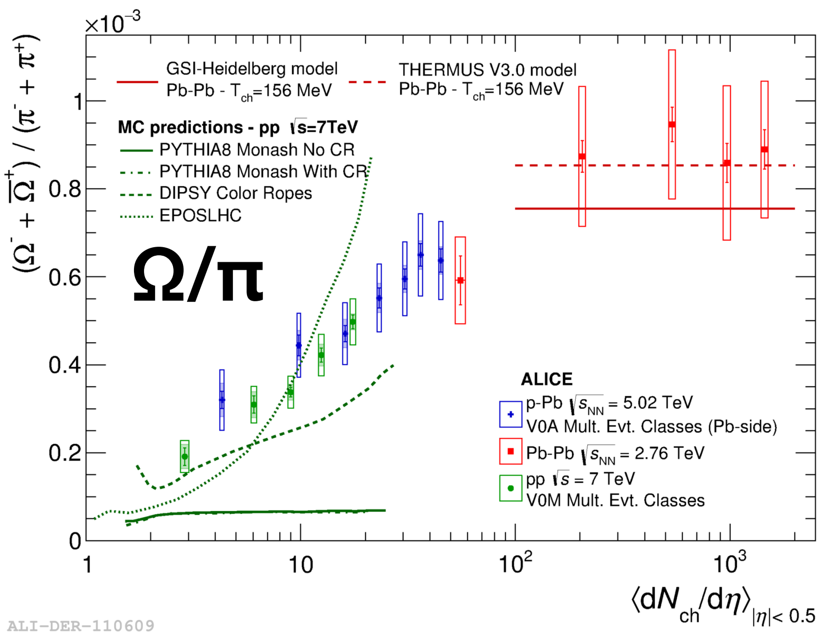
- Ξ/π reaches values seen in Pb-Pb
- Ω/π exhibits a strong rise (~2x) and reaches peripheral Pb-Pb

pp and p-Pb trends are consistent
→ **Final state effect!**

STRANGE-TO-PION RATIOS

Nature Physics, DOI: 10.1038/nphys4111





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Nature Physics, DOI: 10.1038/nphys4111

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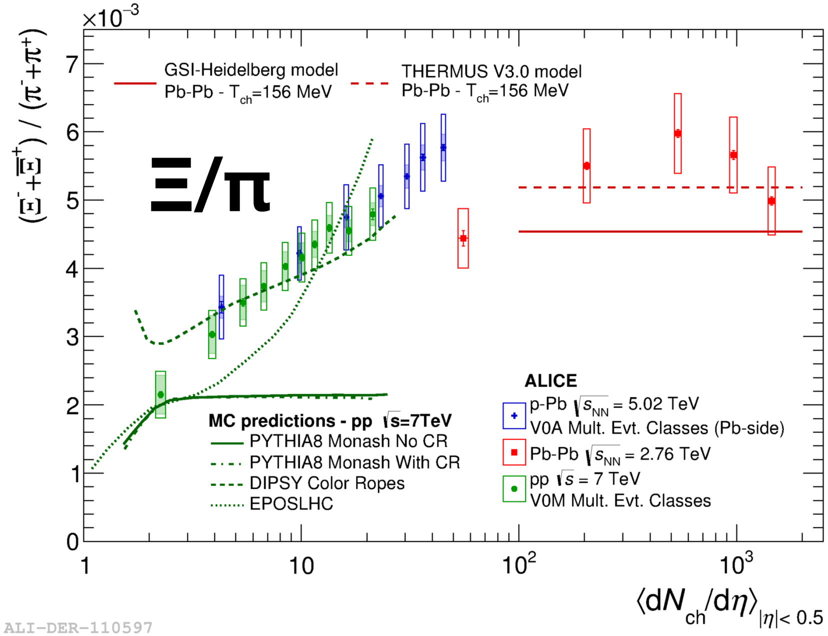

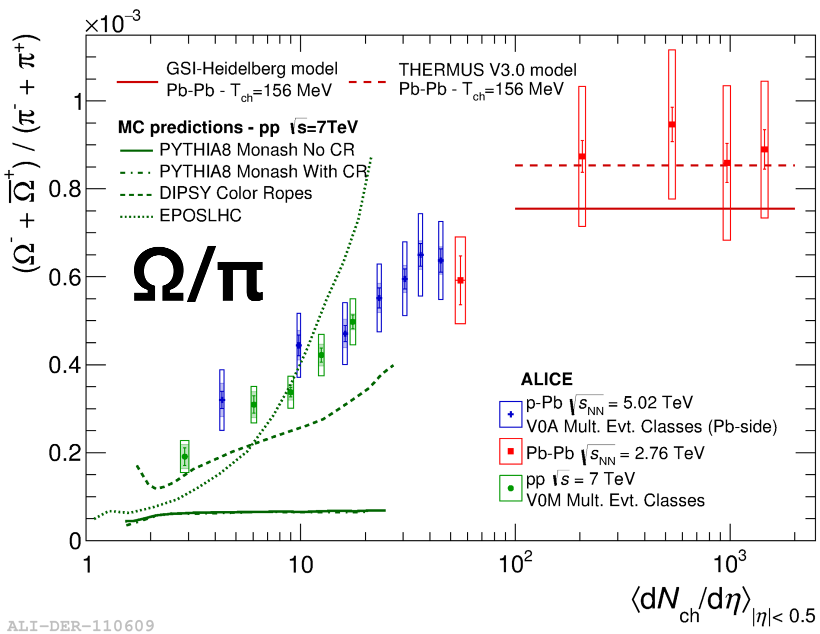

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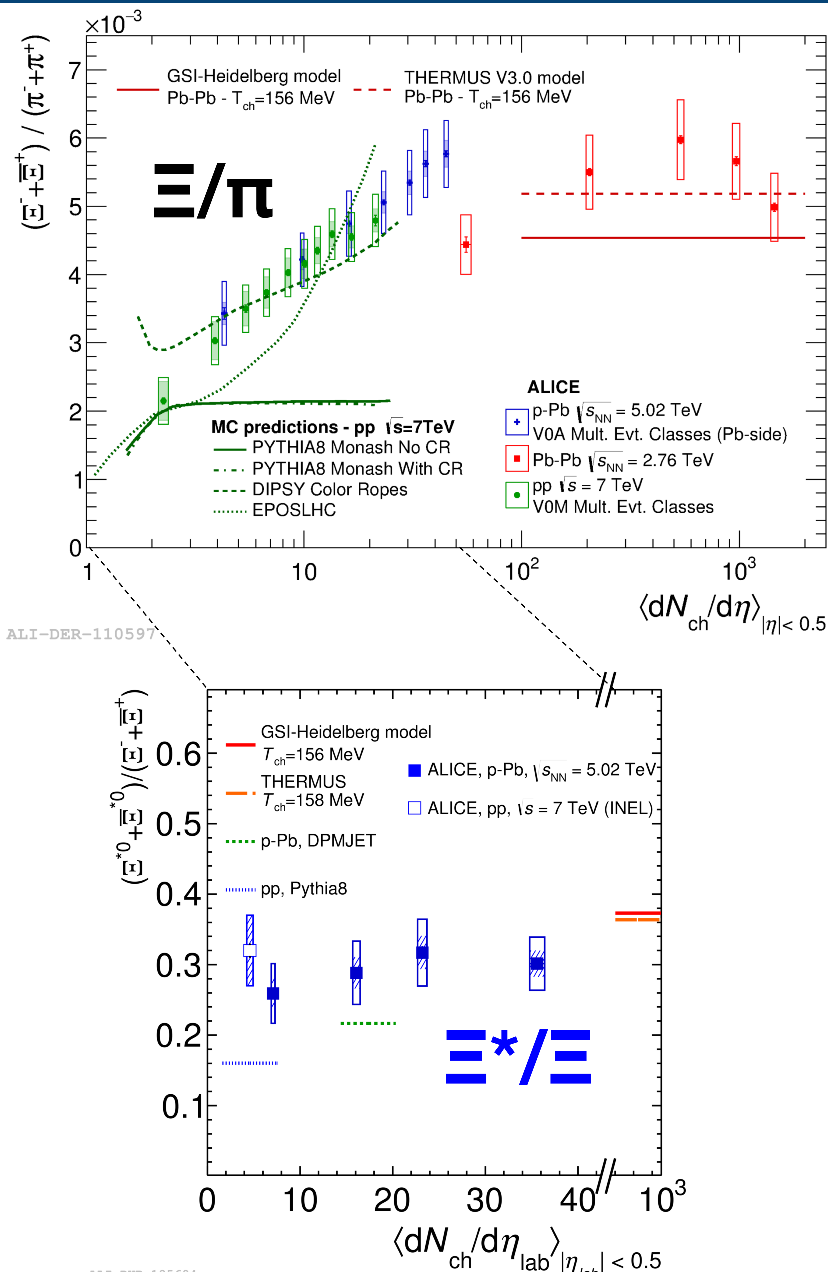
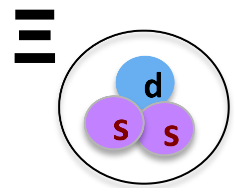
What is driving the increase in small systems?
- ❑ Mass of the hadrons?
- ❑ Baryon/meson effect?
- ❑ Strangeness content?

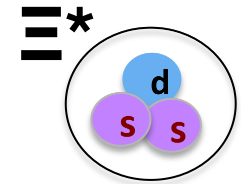
STRANGENESS ENHANCEMENT IN PP

Nature Physics, DOI: 10.1038/nphys4111
arXiv:1701.07797





M ~ 1320 MeV



M ~ 1530 MeV

Ξ(1530)⁰ resonance:

- Same strangeness content as Ξ
- Intermediate in mass between Ξ and Ω

→ In p-Pb collisions, Ξ*/π shows an increase compatible with that of Ξ/π

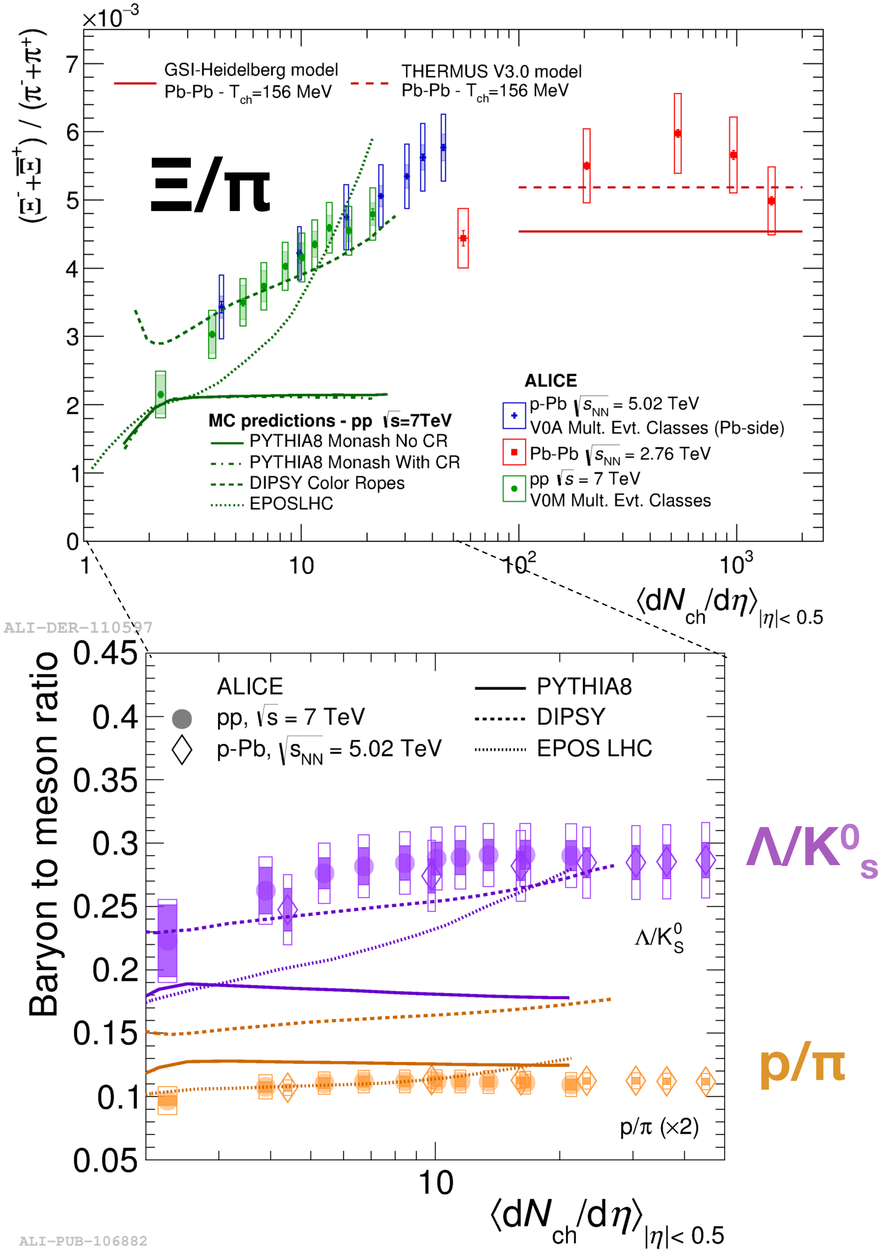
→ Strangeness content more relevant than mass

What is driving the increase in small systems?

- ☒ Mass of the hadrons?
- ☐ Baryon/meson effect?
- ☐ Strangeness content?

Nature Physics, DOI: 10.1038/nphys4111

STRANGENESS ENHANCEMENT IN PP



Baryon-to-meson ratios where the net strangeness content is zero, as **p/π** and **Λ/K^0_S**, are flat with multiplicity

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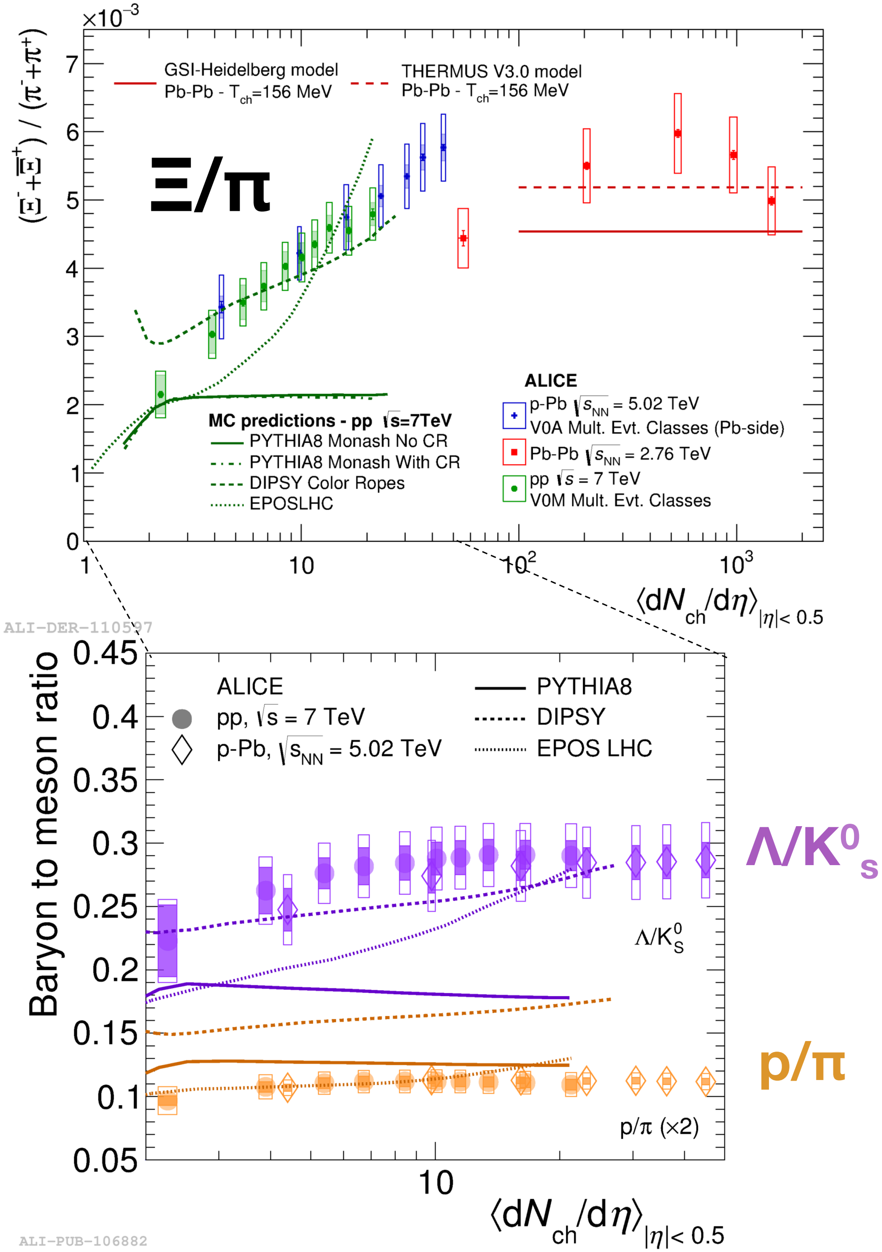

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Models as

- PYTHIA8 (color reconnection)
- DIPSY (color ropes)
- EPOS LHC (collective radial expansion)

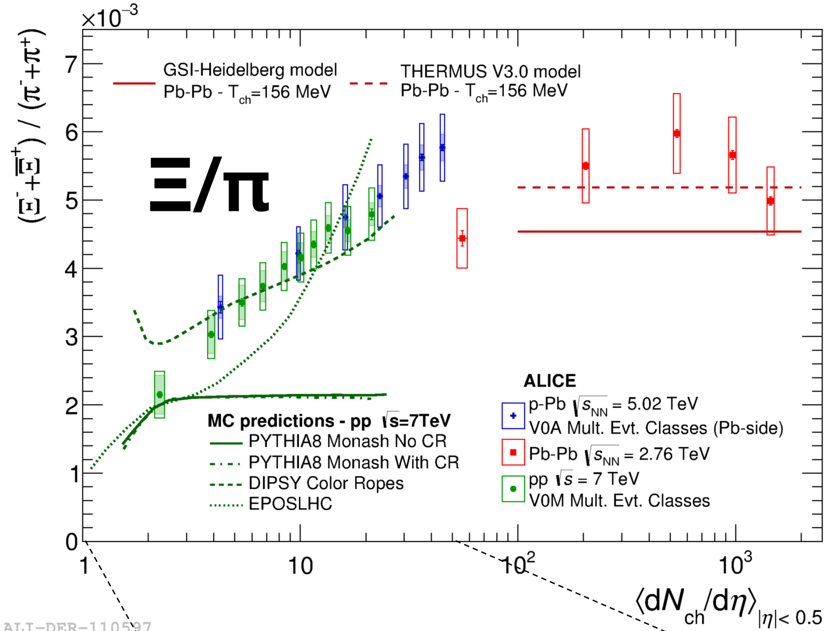
exhibit a trend with multiplicity but may still **need tuning to reproduce all ratios simultaneously**…

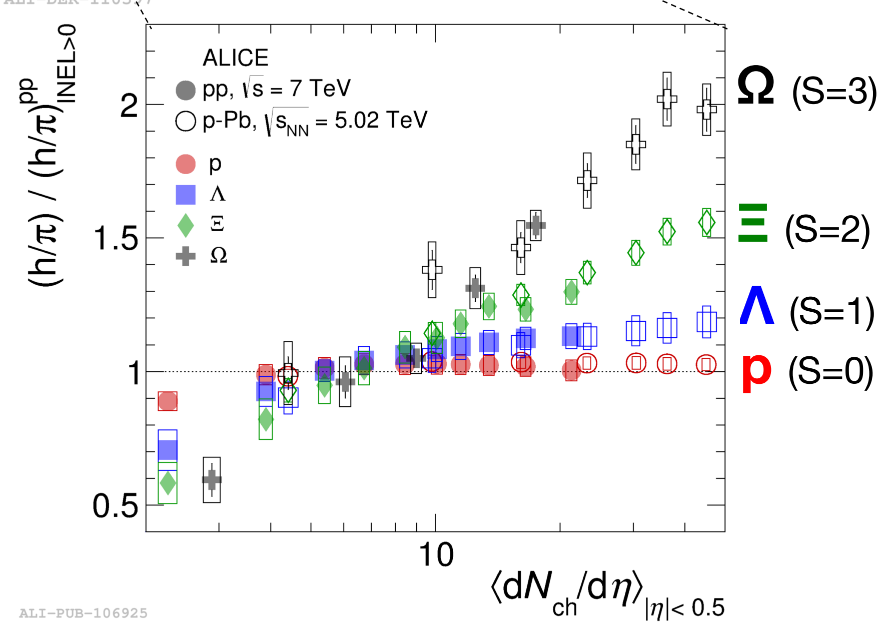
What is driving the increase in small systems?

- ❌ Mass of the hadrons?
- ❌ Baryon/meson effect?
- ❑ Strangeness content?

Nature Physics, DOI: 10.1038/nphys4111

STRANGENESS ENHANCEMENT IN PP





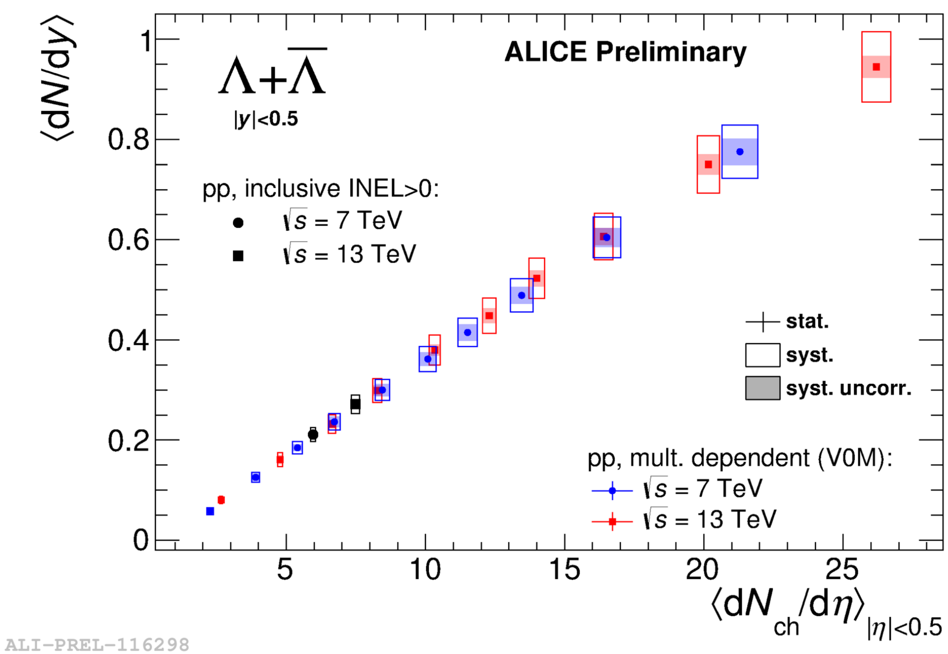
Normalised values to INEL>0 show

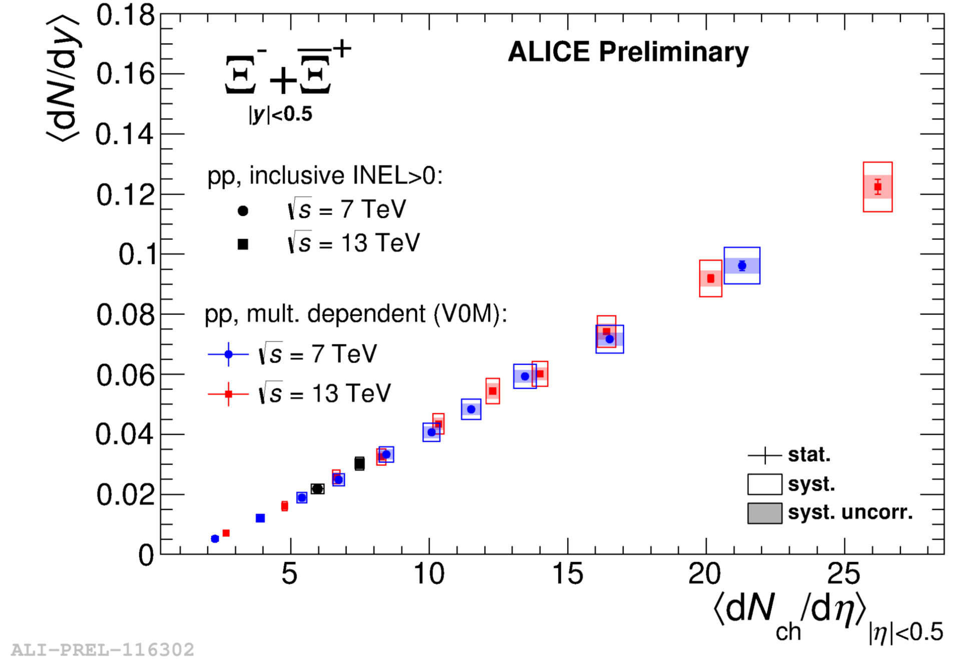
- No increase for p/π
- **Hierarchy** of the increase clearly associated **with the strangeness content**

What is driving the increase in small systems?

- ✘ Mass of the hadrons?
- ✘ Baryon/meson effect?
- ✔ Strangeness content?

√s- VS MULTIPLICITY- DEPENDENCE

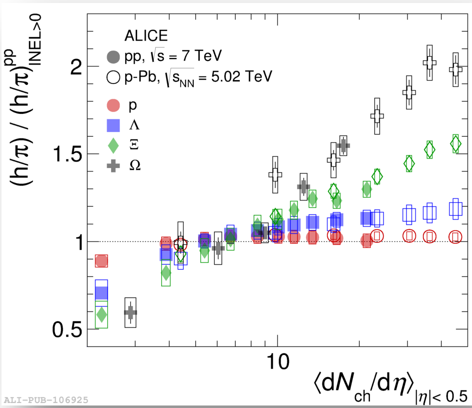


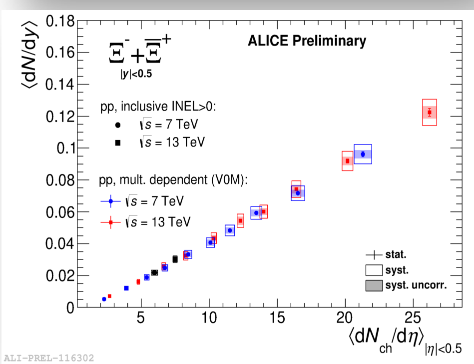


New measurements in pp at 13 TeV can be used to **disentangle multiplicity and energy dependence of particle production**

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**
→ The **event activity** drives particle production, **irrespective of the collision energy**

STRANGENESS ENHANCEMENT IN PP - OUTLOOK



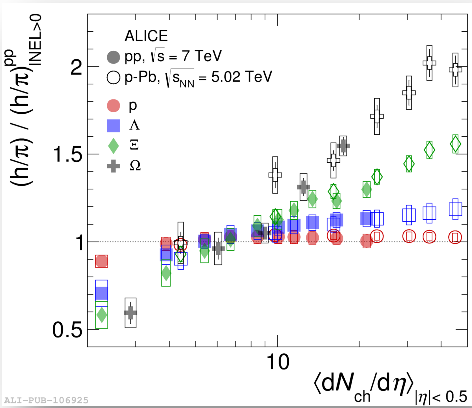


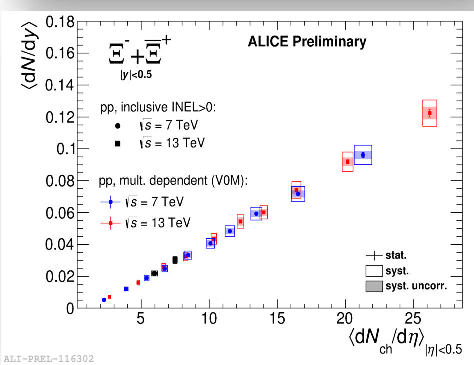
ALICE has observed a **strangeness-related enhancement of hadron production from low- to high-multiplicity** pp events at $\sqrt{s}$ = 7 TeV and p-Pb at 5.02 TeV

Measurements at different energies as a function of multiplicity seem to indicate that the **hadrochemistry** is driven by **event activity** regardless of the collision energy

The full set of observations is poorly described by commonly used MC generators
→ some effort needed from the model/theory side

STRANGENESS ENHANCEMENT IN PP - OUTLOOK





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→ some effort needed from the model/theory side

Is this an indication for QGP in small systems?
If not, what else?

STRANGENESS PRODUCTION IN THE SHM

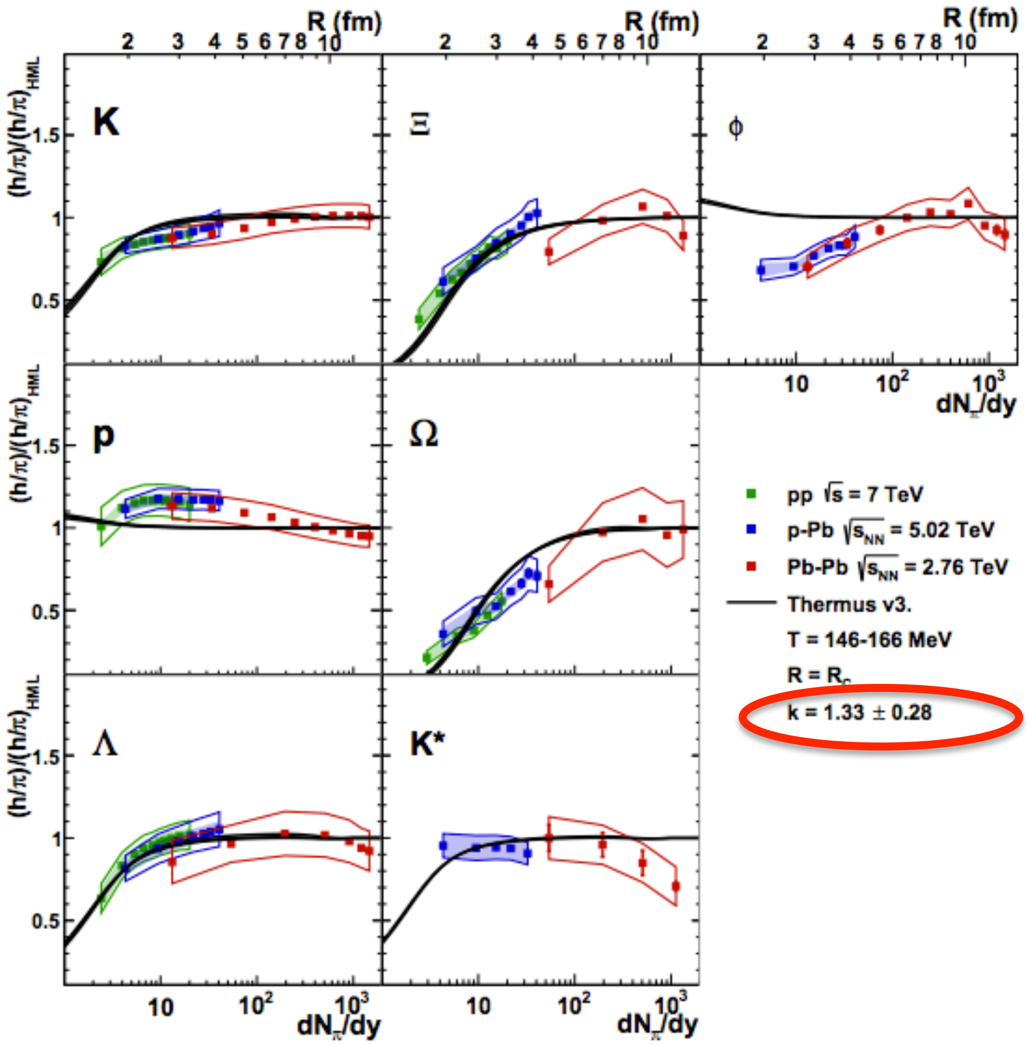
In equilibrium statistical (thermal) hadronisation (SHM) models, strangeness enhancement is a result of the **suppression of strange hadron production in small systems** due to the explicit **conservation of the strangeness** quantum number

First comparisons to model calculations based on THERMUS code:

- Normalisation to ratio in 0-60% Pb-Pb
- the rapidity window where strangeness is to be conserved is a free parameter, resulting in k ~ 1.33 (to be compared to 1 in std calculations)

→ agreement with data within uncertainties, except for ϕ meson (also "immune" to canonical suppression)

V. Vislavicius, A. Kalweit, arXiv:1610.03001



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→ agreement with data within

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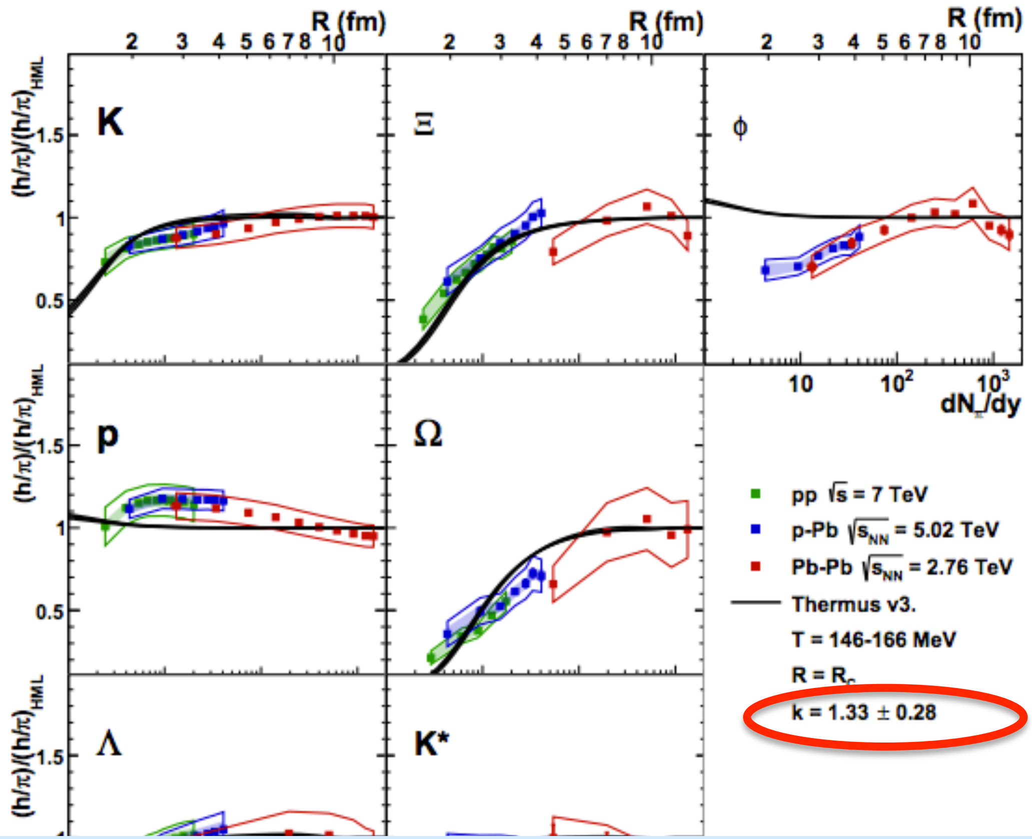
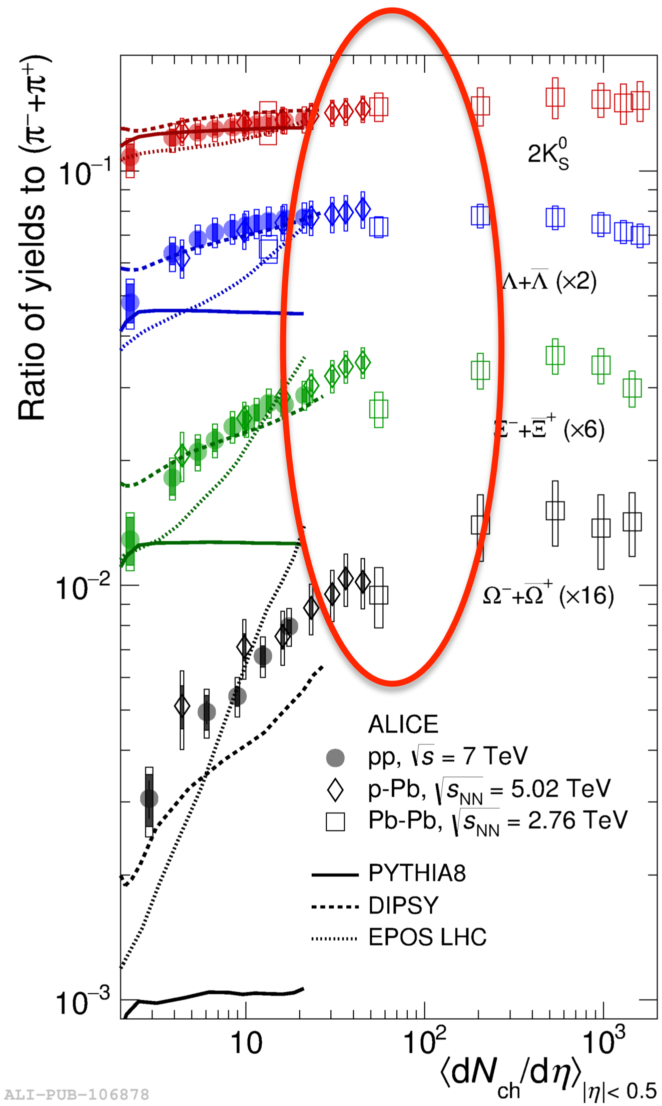


…not yet the end of the story!!!

Also, look for other models e.g. core-corona calculations!

A PERSONAL OUTLOOK…



The intriguing similarities among different systems do not end here but extend to the dynamics:

- Presence of collectivity (flow) is established in Pb-Pb
- we have hints for collectivity in small systems, whose origin and phenomenology is under investigation

[see FB's talk at ECT, Trento 27.02.2017]*

What is next?

Go to **higher multiplicity in pp**

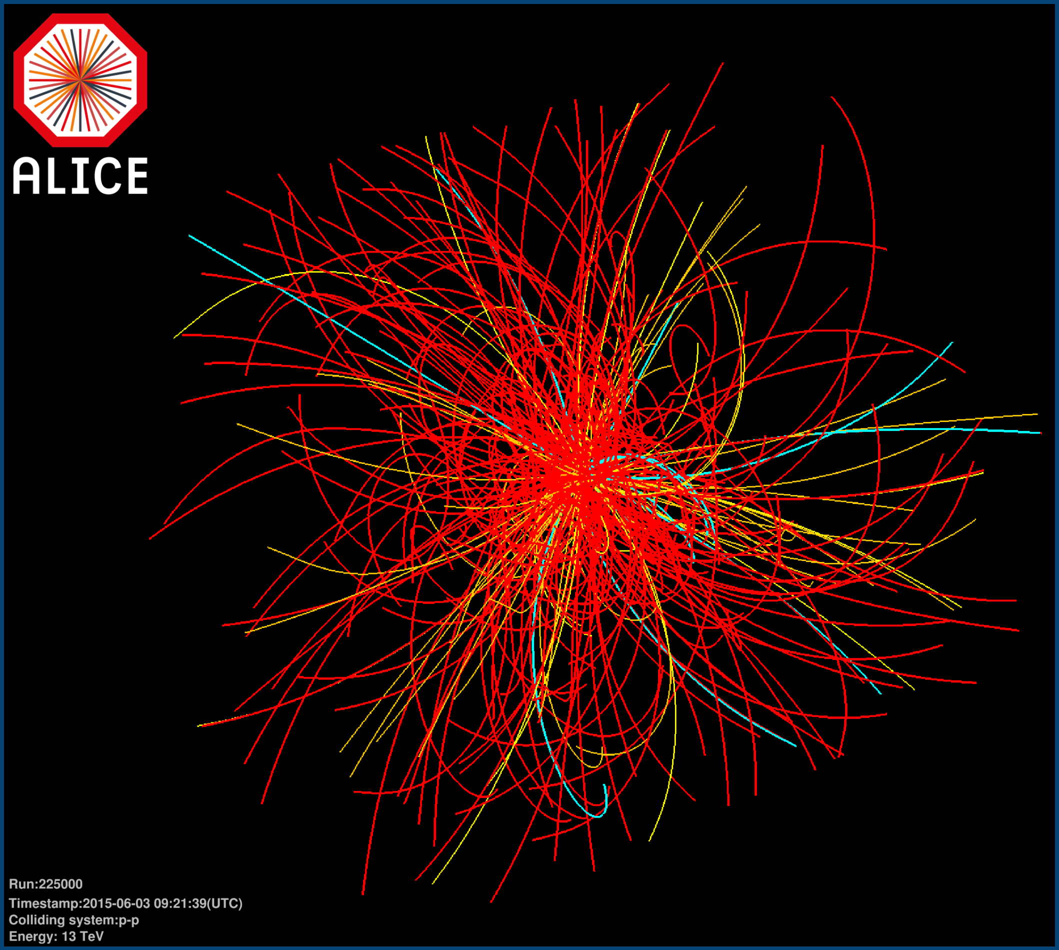
Go **more differential in peripheral** Pb-Pb collisions

→ Can we have an handle on the **onset of deconfinement**?

pp used to be a **reference** for p-Pb and Pb-Pb collisions, now they look more alike than we thought

→ Shall we use a new reference?

→ Or can we describe pp, p-Pb and Pb-Pb with a **common "framework"**?

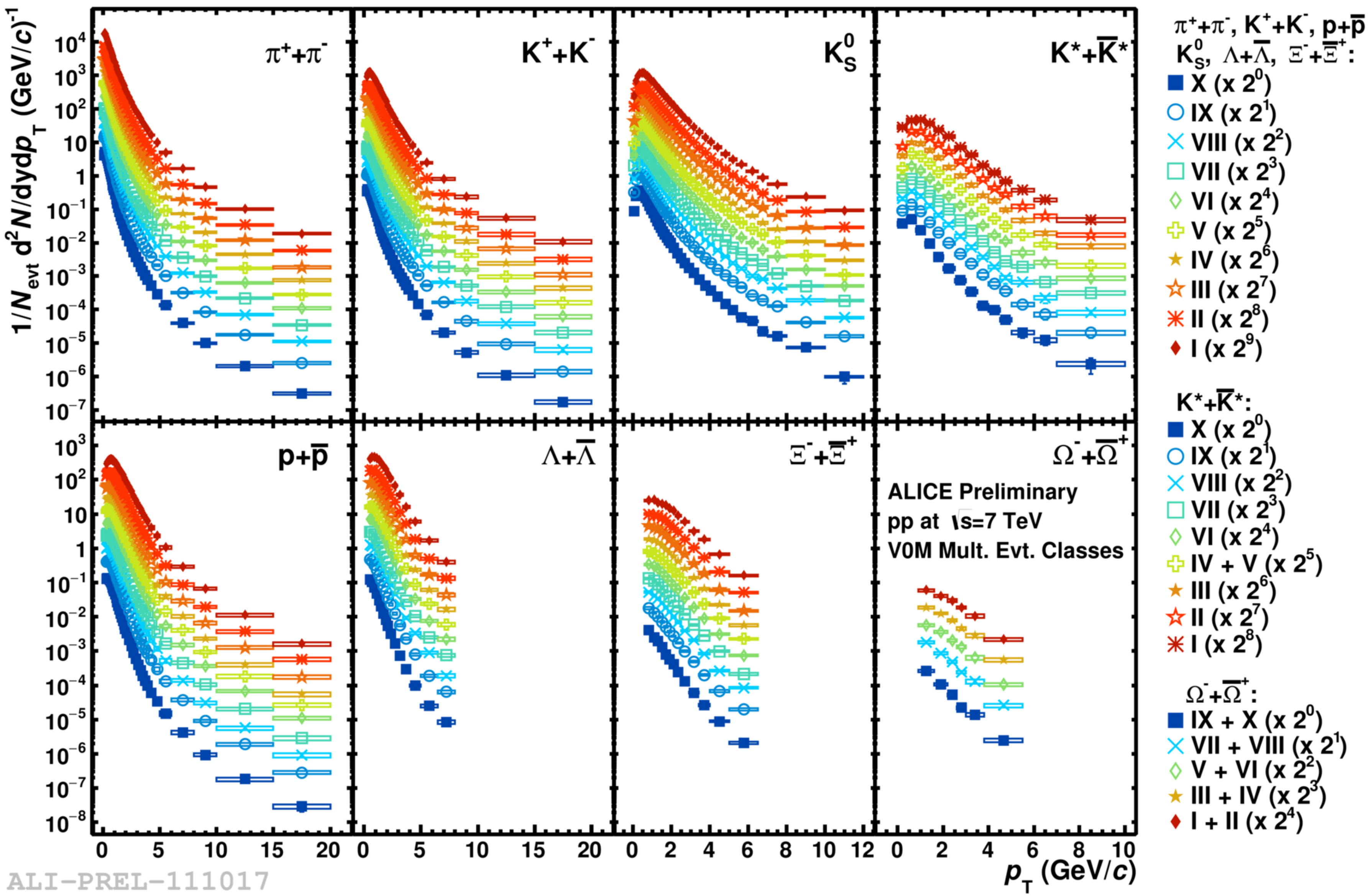


For further discussions:
fbellini@cern.ch

thank you!

APPENDIX

IDENTIFIED HADRON SPECTRA IN PP COLLISIONS

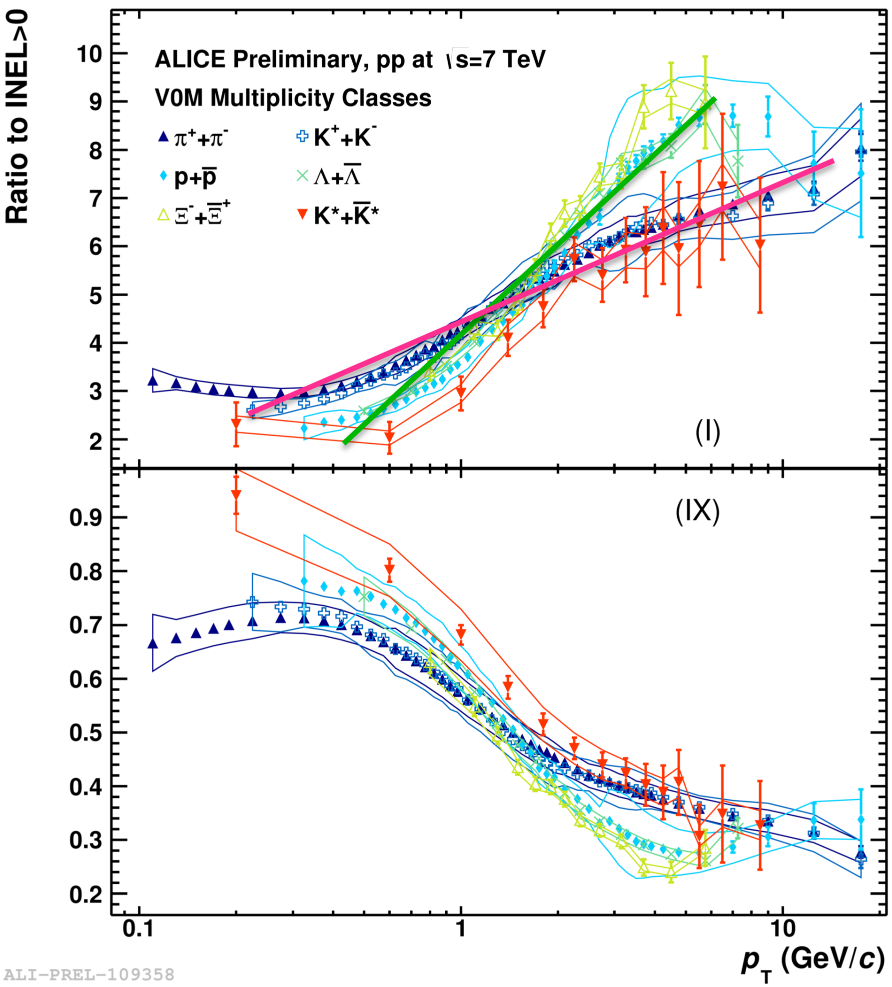


HARDENING OF SPECTRA IN HIGH-MULTIPLICITY PP

Ratio to minimum bias spectra show spectral modification as a function of multiplicity:

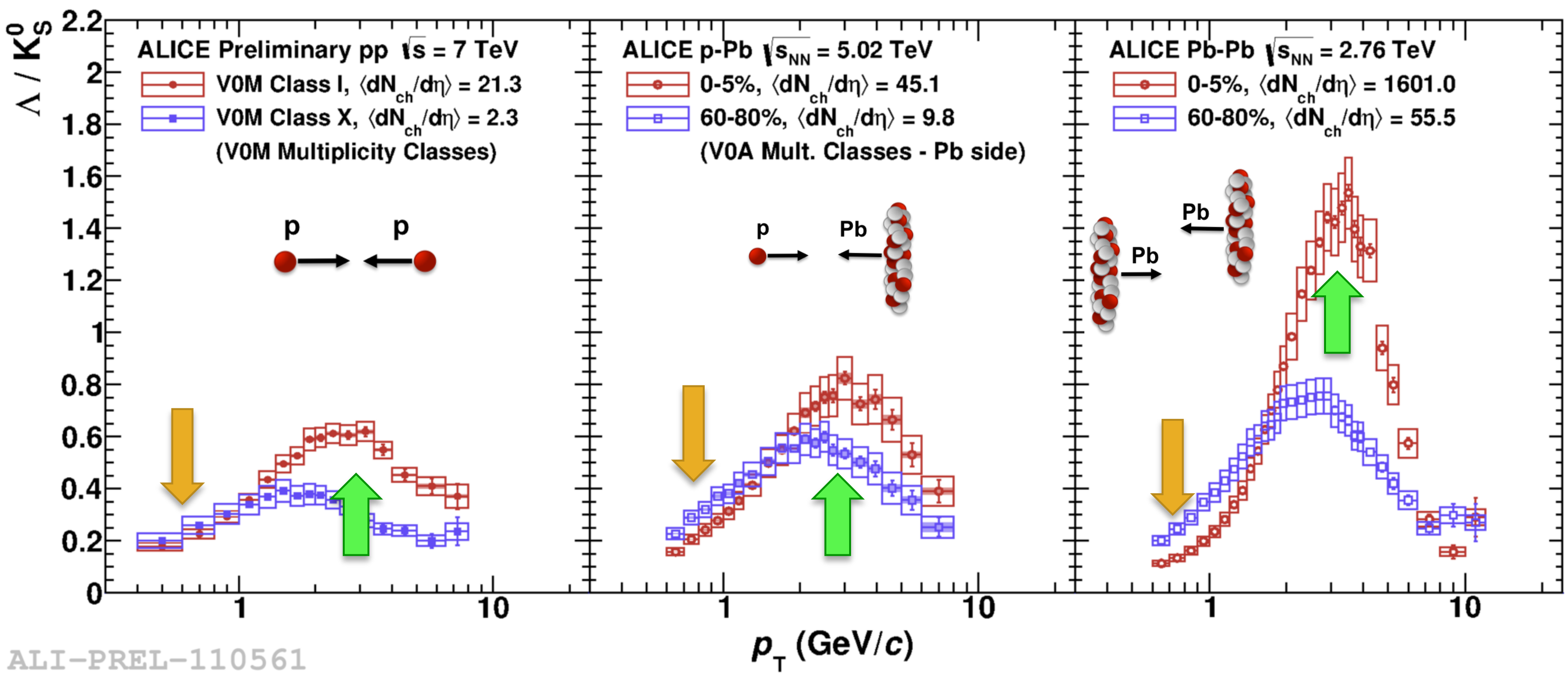
→ Spectra become **harder at higher multiplicities**

→ The hardening is **more pronounced for baryons than for mesons**



THREE SYSTEMS COMPARED: Λ/K^0_S

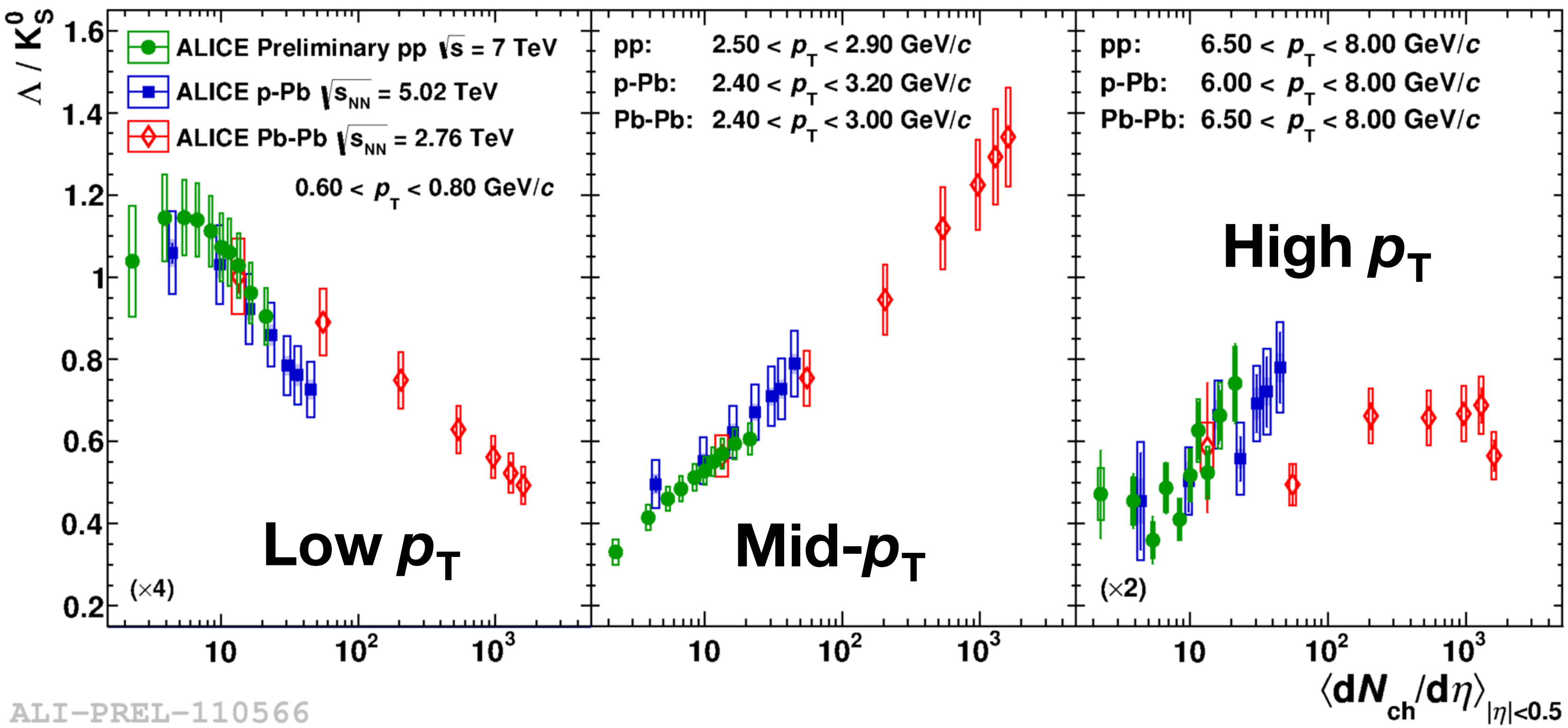
Phys. Rev. Lett. 111 (2013) 22301
Phys. Rev. C 93 (2016) 034913
Phys. Lett. B 728 (2014) 25-38
arXIv:1606.07424



Across the three systems the baryon-to-meson ratios **evolve with multiplicity**

– in qualitatively similar way: **depletion** at low p_T, **enhancement** at intermediate p_T

Three systems compared: p_T slices



Across the three systems the baryon-to-meson ratios **evolve with multiplicity**

- in qualitatively similar way: depletion at low p_T, enhancement at intermediate p_T
- rather **smoothly for given p_T** intervals

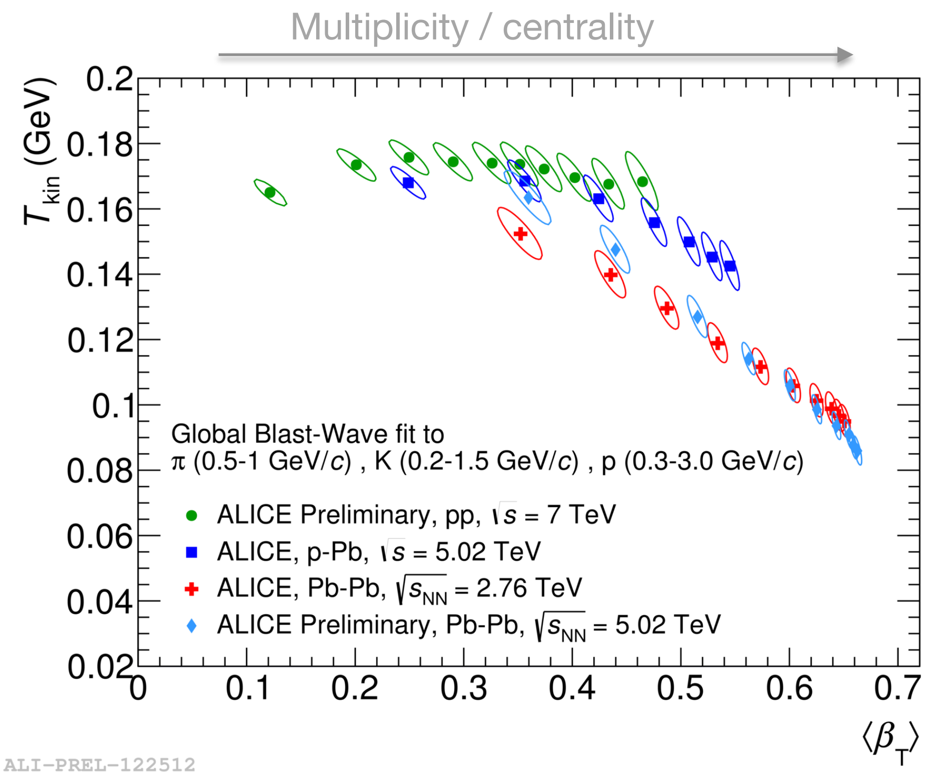
BLAST-WAVE MODEL FIT TO π,K,p

E. Schnedermann et al., Phys. Rev. C48 (1993) 2462
Phys. Rev. C 88 (2013) 044910
Phys. Lett. B 728 (2014) 25-38

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

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



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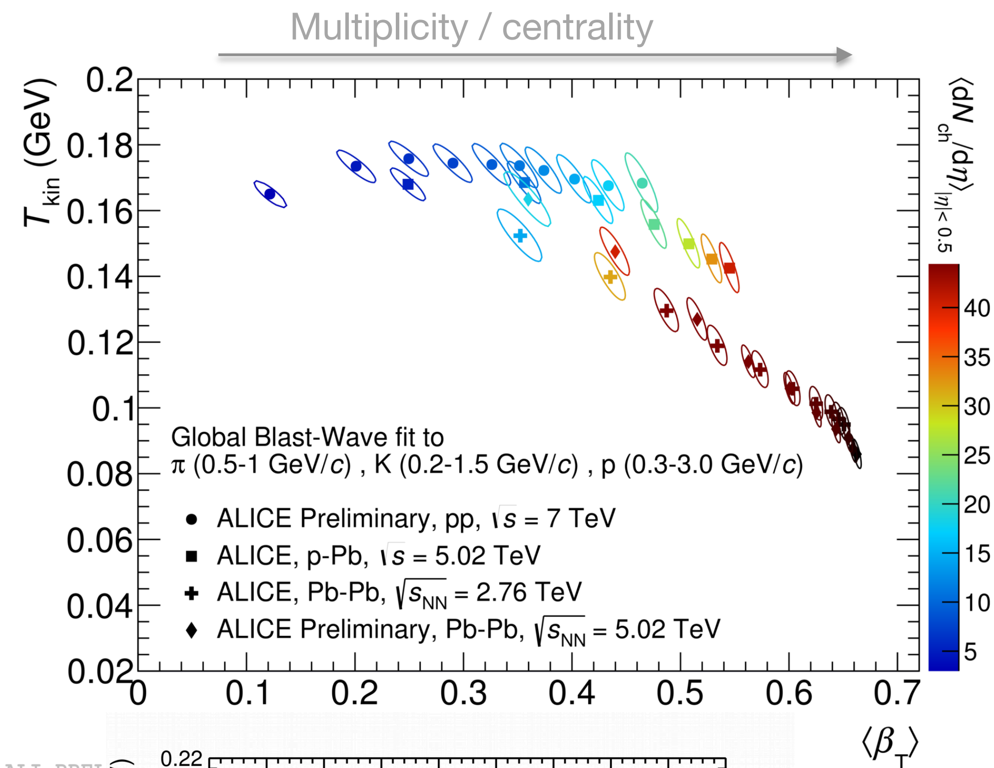
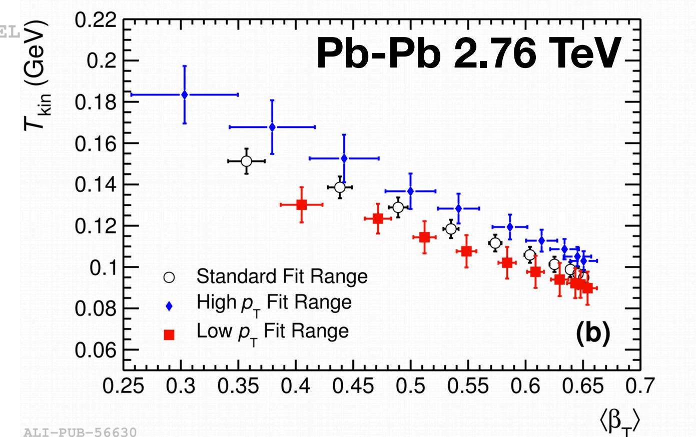
In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity

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**





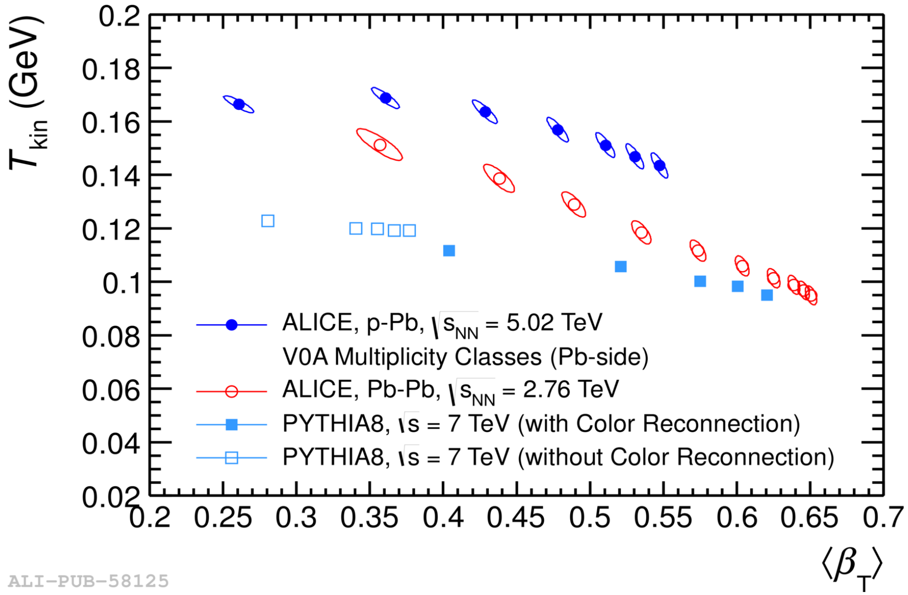
P. Skands, J.R. Christiansen, JHEP 08 (2015) 003

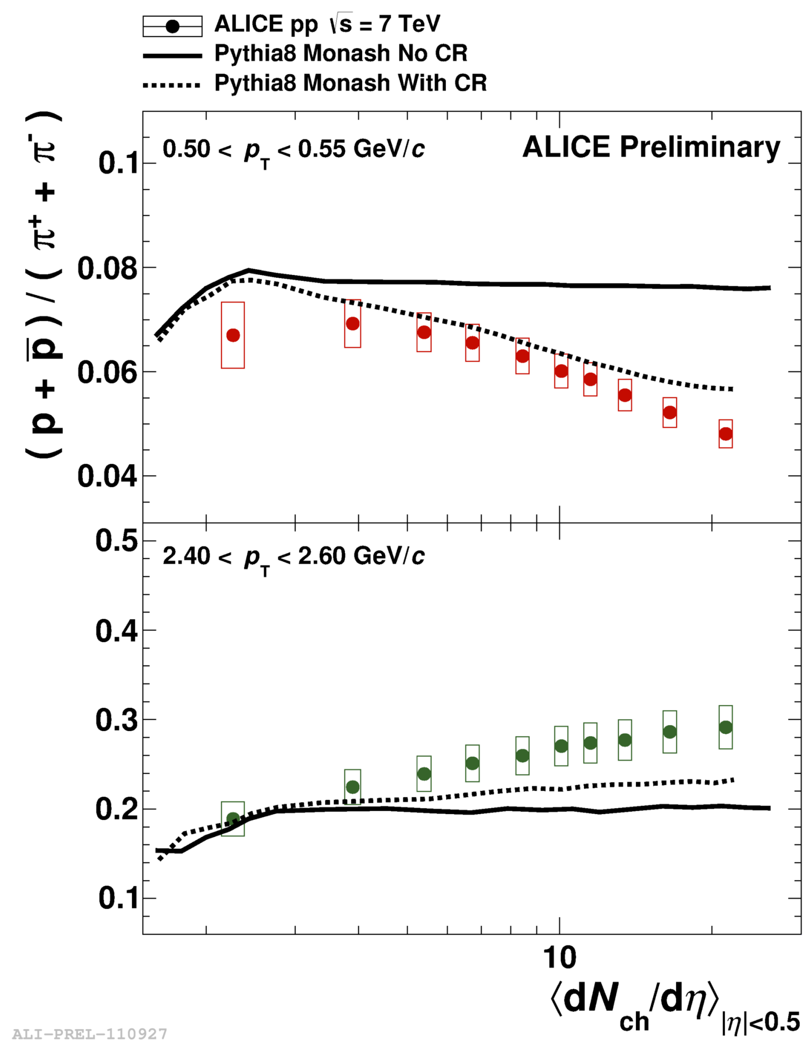
Radial flow vs Color Reconnection

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

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

- p/π vs multiplicity is described better by Pythia8 with CR than w/o CR





RADIAL FLOW VS COLOR RECONNECTION

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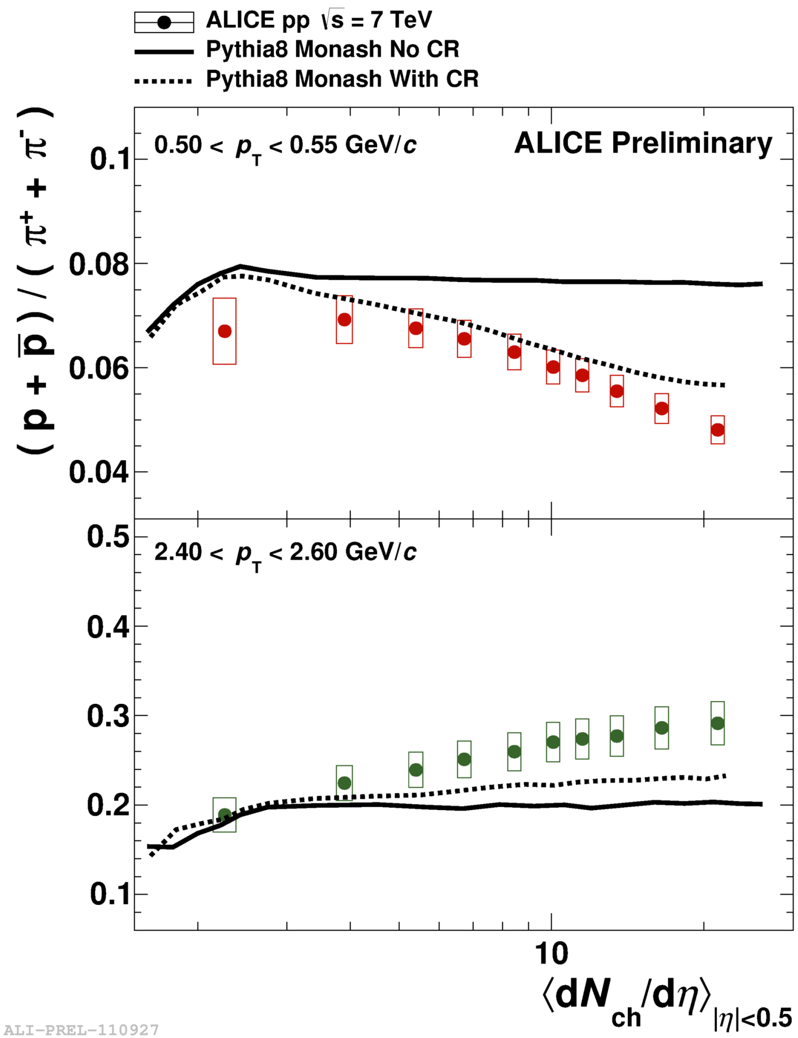
Hydrodynamical (radial) flow is present in a system in **local thermodynamical equilibrium**, which would lead also to **chemical equilibrium**

→ Look at the relative particle abundances!



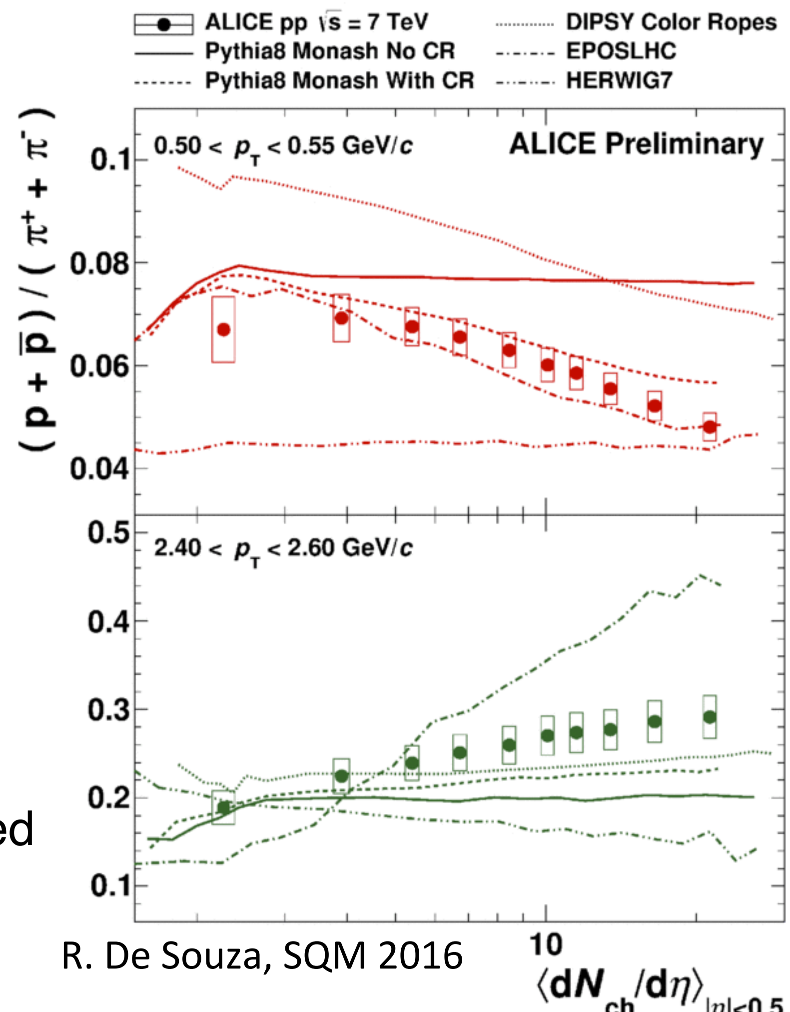
More model comparisons

Comparison with MC predictions in pp:

Color Reconnection:
- Implemented in PYTHIA8 Monash
- Qualitative agreement with the data

Color Ropes:
- Similar mechanism in DIPSY
- also reproduces qualitatively the data

Collective Radial Expansion:
- Present in EPOS LHC
- viable explanation but effect is overestimated



R. De Souza, SQM 2016

PYTHIA8 – T. Sjöstrand et al., Comput. Phys. Commun. 178 (2008) 852-867

DIPSY – C. Flensburg et al., JHEP 08 (2011) 103; C. Bierlich et al., JHEP 03 (2015) 148; C. Bierlich et al., PRD 92 (2015) 094010

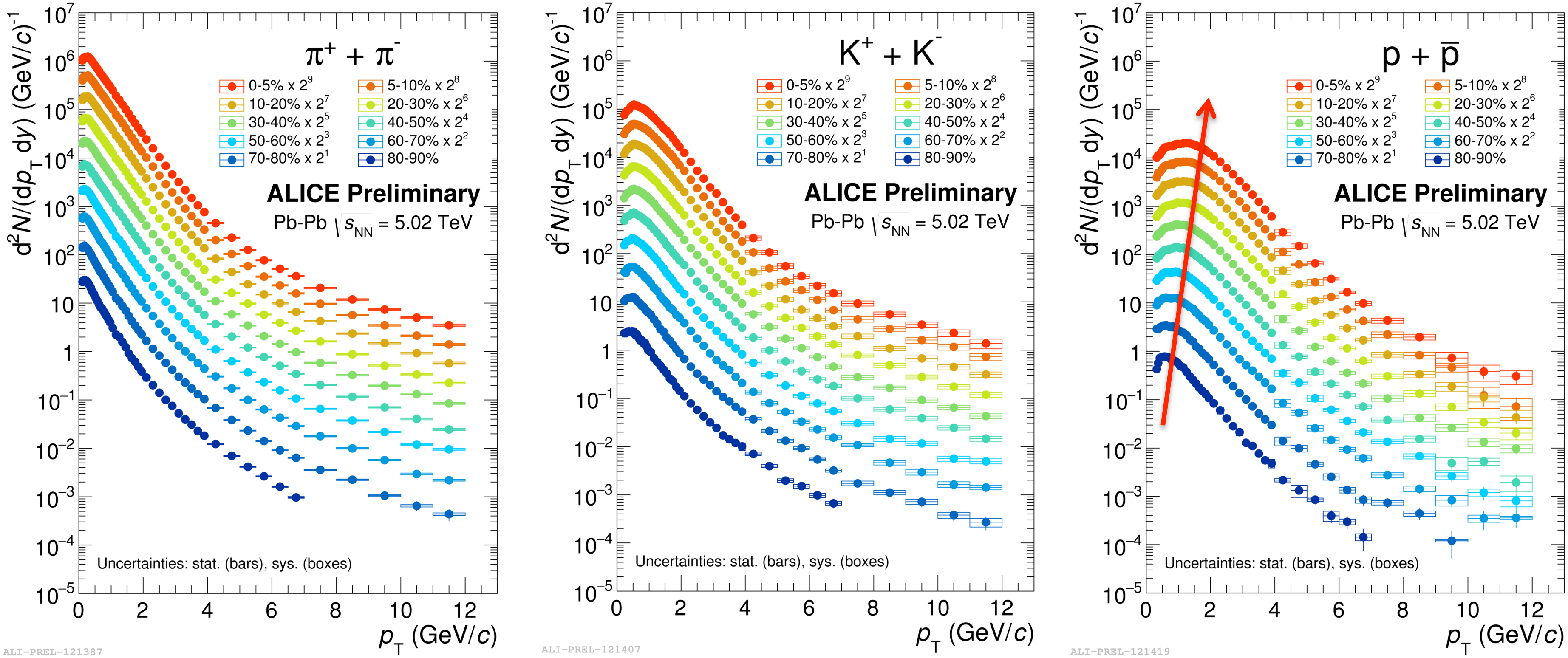
EPOS LHC – T. Pierog et al., arXiv:1306.0121

HERWIG7 – M. Bahr et al., EPJC 58 (2008) 639-707; J. Bellm et al., EPJC 76 no.4 (2016) 196

Bulk particle production in Pb-Pb

Phys. Rev. C 88 (2013) 044910
Phys. Rev. C 91 (2015) 024609

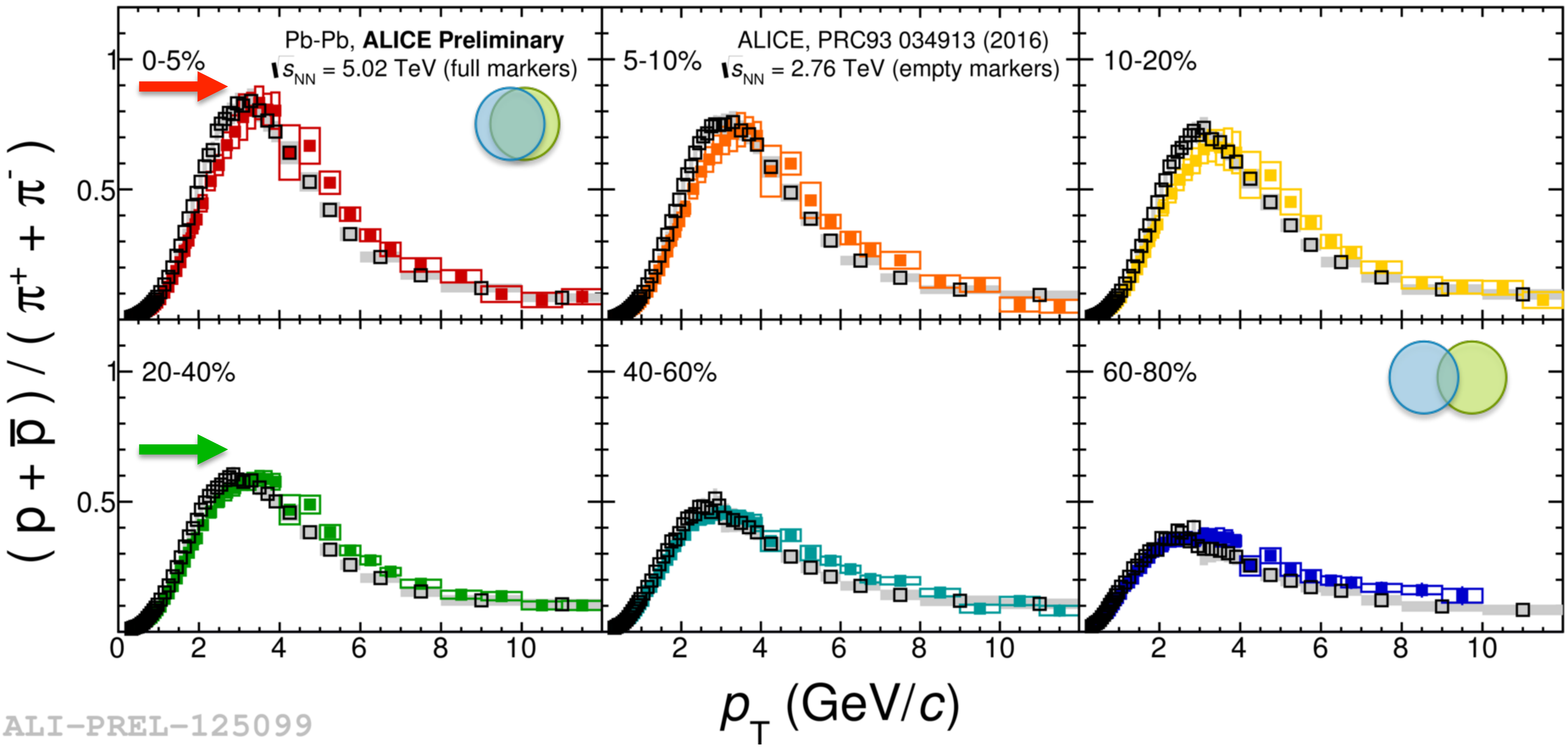
Bulk composition: ~80% of charged particles are π, ~13% are K, ~4% are p



- Spectra get harder with increasing centrality, according to mass ordering
- Particles with similar mass have similar mean p_T in central Pb-Pb

Expected in presence of **collective hydrodynamic expansion** ($p = m \cdot \beta\gamma$)
→ Clear signature of **radial flow**, **at $\sqrt{s_{NN}}$ = 5.02 TeV as at 2.76 TeV**

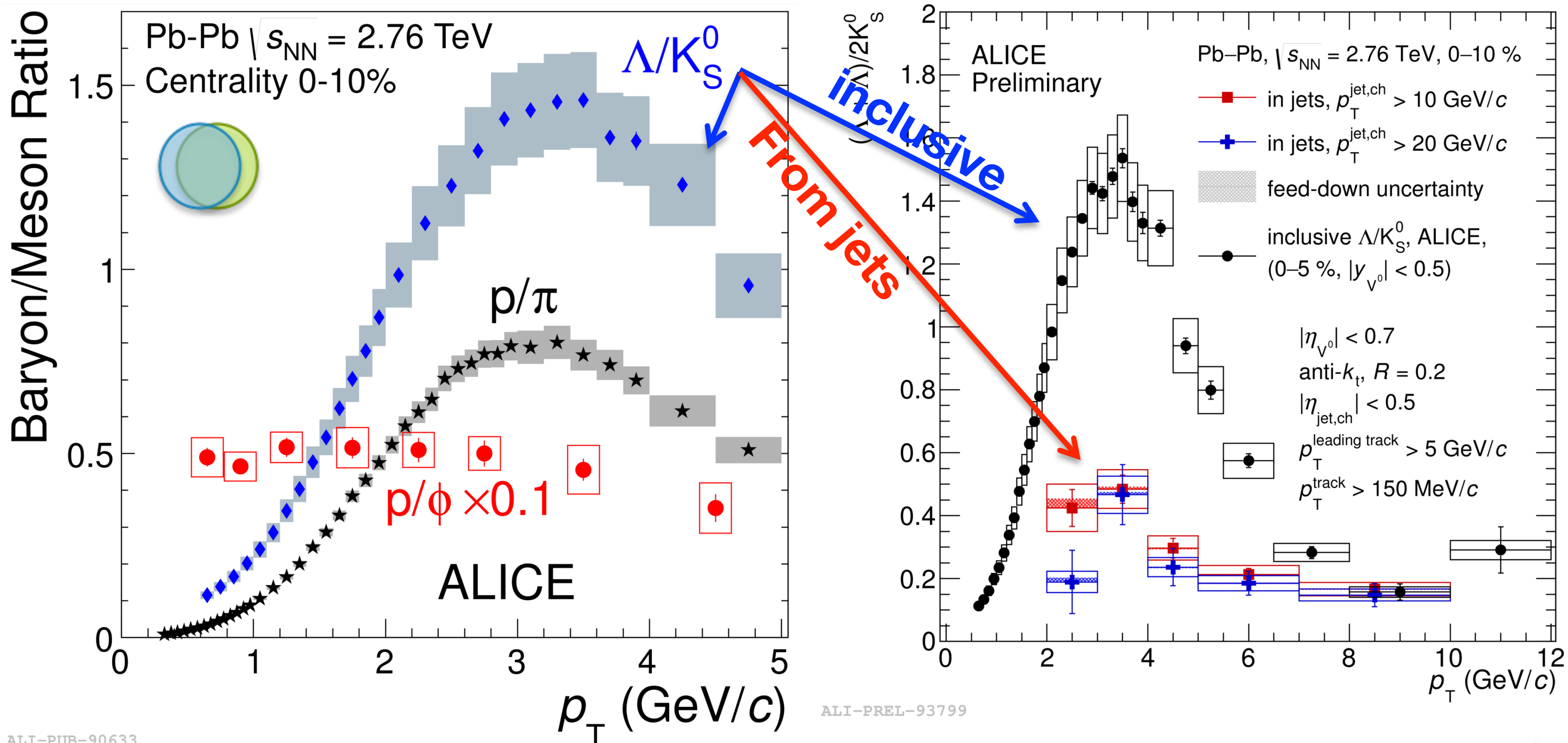
PARTICLE RATIOS IN PB-PB FROM 2.76 TO 5.02 TEV



K/π: no significant difference between 2.76 and 5.02 TeV
p/π: small blueshift of the maxima → (slightly) **larger radial flow at 5.02 TeV**

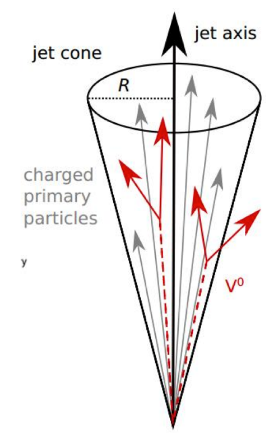
The effect is more evident in p/π than in K/π, due to the larger mass difference

BARYON-TO-MESON RATIOS

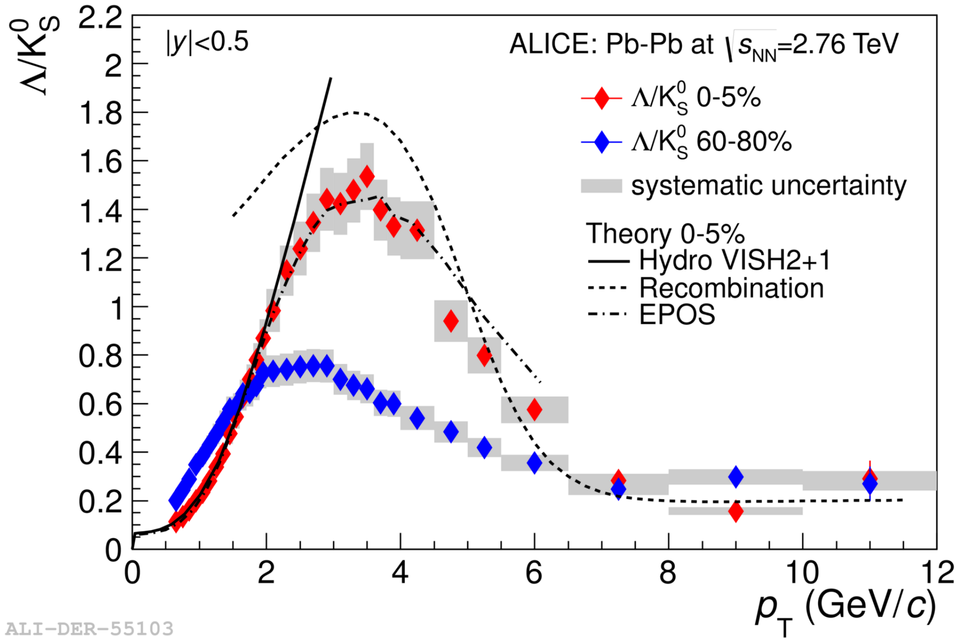


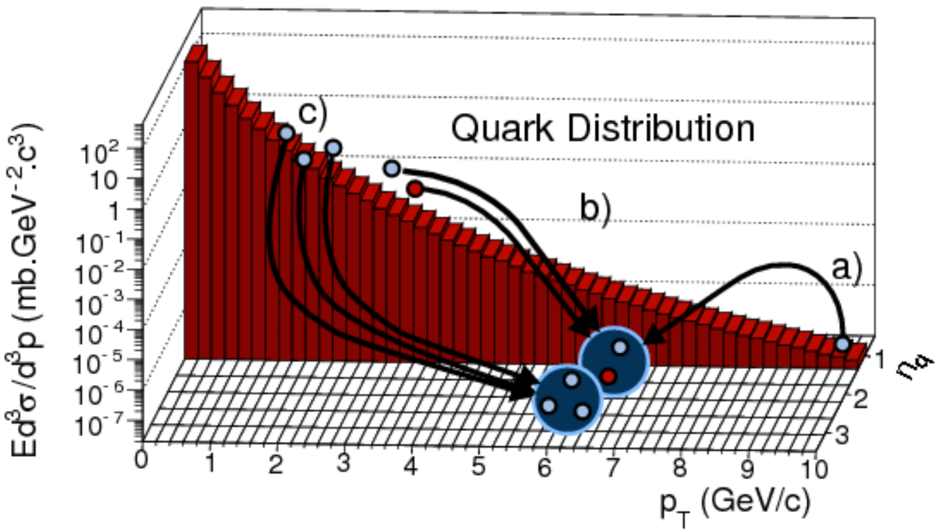
In central Pb-Pb collisions

- **p/π, Λ/K^0_S enhancement** at intermediate p_T
- Effect **arising in the bulk** and not from jets
- **Flat p/ϕ**



Particle production mechanisms



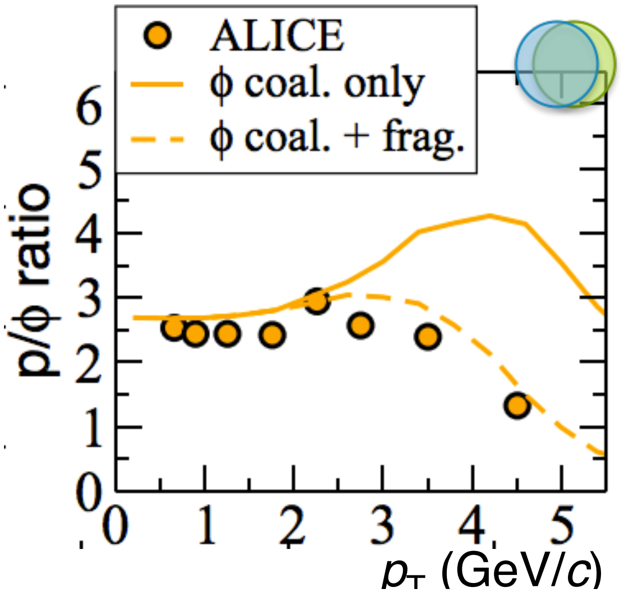


Λ/K^0_S compared with models:

- **Hydro** alone describes only the rise < 2 GeV/*c* *[H. Song, U. Heinz, PLB 658 (2008) 279]*
- **Recombination** alone reproduces effect but overestimates *[Fries et al., ARNPS 58 (2008) 177]*
- **EPOS** (with **flow**) gives good description of the data *[K. Werner, PRL 109 (2012) 102301]*

PARTICLE PRODUCTION MECHANISMS

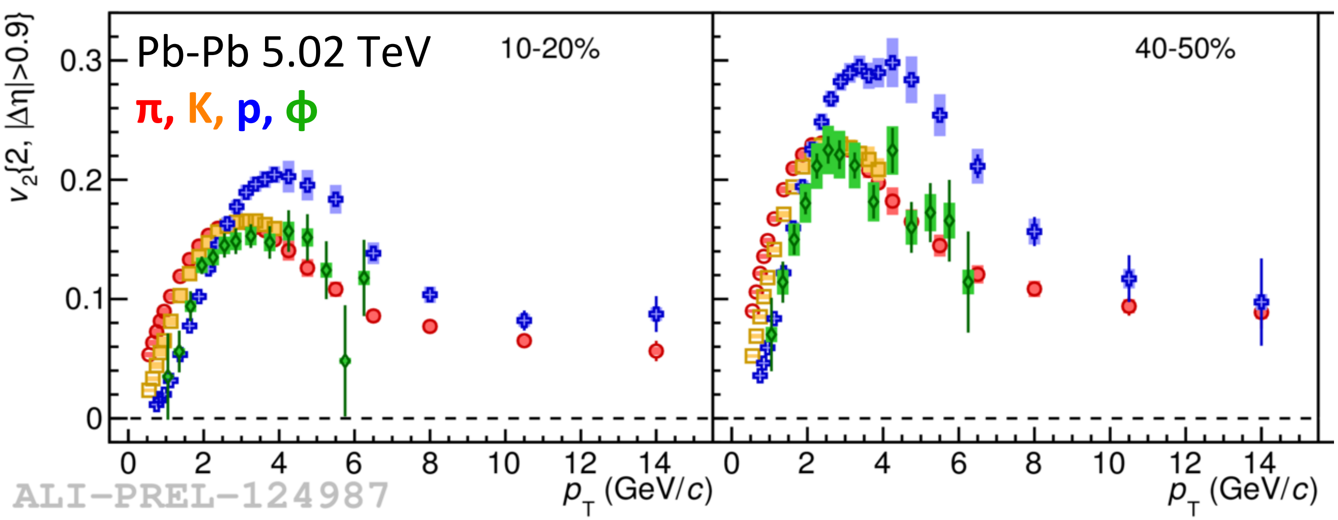
V. Greco at al, Phys.Rev. C 92 (2015) 054904



Flat p/ϕ in Pb-Pb can be explained by

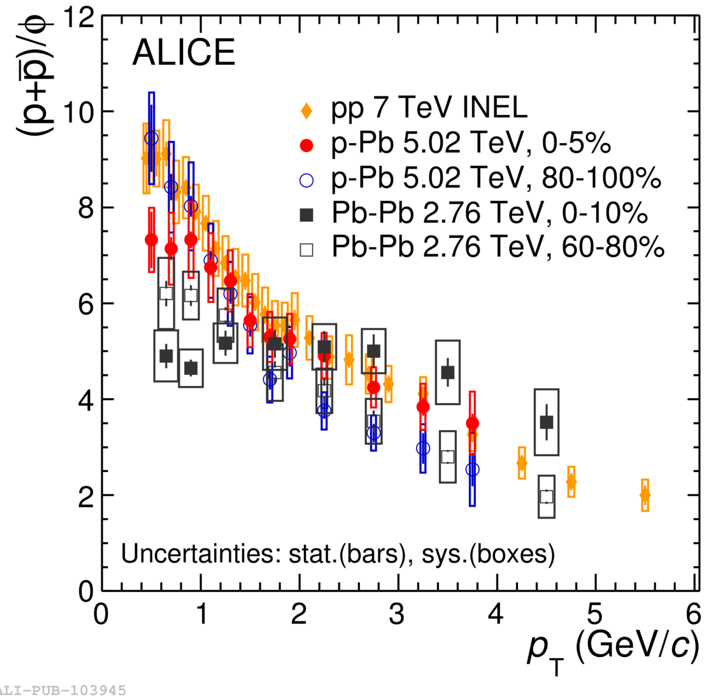
- **by hydro** (radial flow), since similar mass drives similar spectral shapes
- **by models with recombination**

- v_2 results are suggestive of a **transition between production mechanisms** around ~3 GeV/*c*



Eur. Phys. J. C 76 (2016) 245

Particle production mechanisms



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- **by hydro** (radial flow), since similar mass drives similar spectral shapes
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In small systems:

- **steep p_T dependence** of the **p/ϕ ratio**
- Hint for a flattening at very low p_T in central p-Pb → hint of the presence of radial flow?

OUTLINE

- Strangeness production as probe for the QGP and its thermal properties.
  - What is special about the production of strangeness in QGP
  - Need for reference systems (pp, pA)

- Strangeness enhancement in HI collisions
  - What is centrality
  - Selected results from SPS and RHIC
  - From RHIC to LHC
    - → Need to take special care of the "reference"
    - → Intro to the observation of strangeness enhancement in high-multiplicity pp collisions by the ALICE experiment at the CERN Large Hadron Collider
- ALICE details
  - What we measure and how
  - How multiplicity is defined in pp, pA
- Results:
  - From pp, pA to Pb-Pb a smooth trend, Enhancement towards HM
  - Enhancement related to strangeness content

- comparison with model predictions
  - QCD inspired models
  - Thermal production in pp collisions, canonical picture

- Other measurements showing that pp collisions exhibit characteristic features known from high-energy heavy-ion collisions, e.g. collectivity

- Conclusions
- Is it strangeness enhancement not a unique feature of QGP formation?
- Can high-multiplicity pp collisions provide information on the onset of deconfinement?