Light flavour particle production from pp to Pb-Pb collisions with ALICE

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Outline

- Introduction
- Experimental details
- Collectivity in large and small systems
- Hadrochemistry
- Hadronic phase
- Nuclear modification factor of light-flavour hadrons
- Conclusions

Light flavour hadrons

Light flavour hadrons are composed by **u, d** and **s** quarks

$m_u \approx 2.2$ MeV
$m_d \approx 4.7$ MeV
$m_s \approx 96$ MeV

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

→ Most of the light-flavour hadron mass is **generated dynamically**

B. Muller, NPA 750 (2005) 84-97

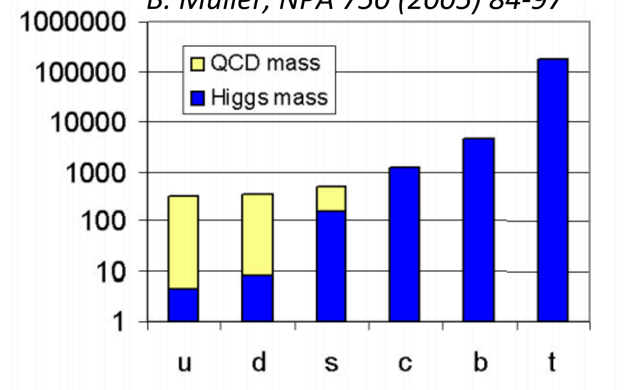


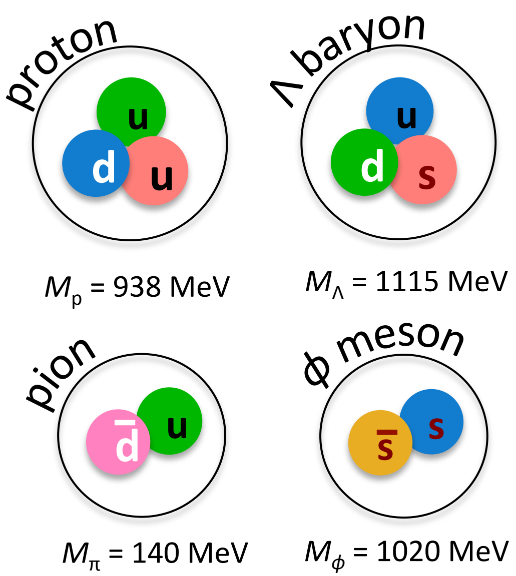
FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale.

A comprehensive set of measurements of identified particles production in all collision systems:

$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, Λ, Ξ, Ω,

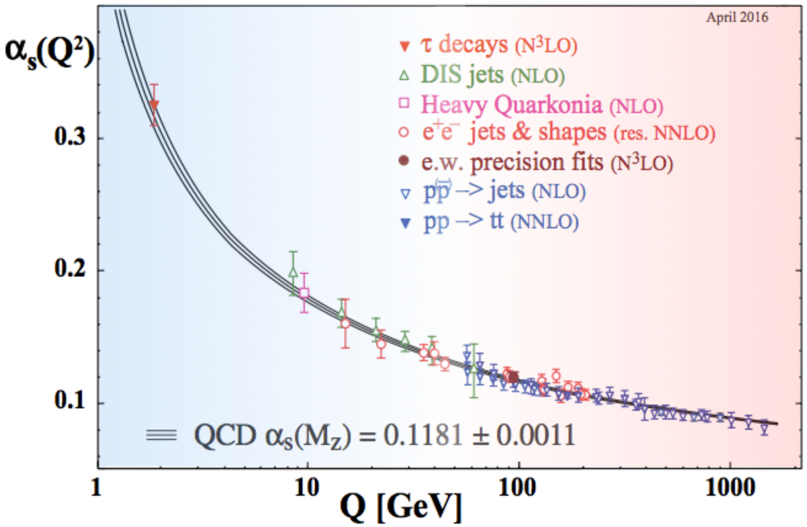
ρ^0, K^{*0}, ϕ, Σ^0, $\Sigma^{*\pm}$, Λ^*, Ξ^{*0}

…plus light nuclei and exotica (anti)d, (anti)^{3}H, (anti)^{3}He, (anti)^{4}He, (anti)$^3_\Lambda$H



QCD and its phase diagram

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



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

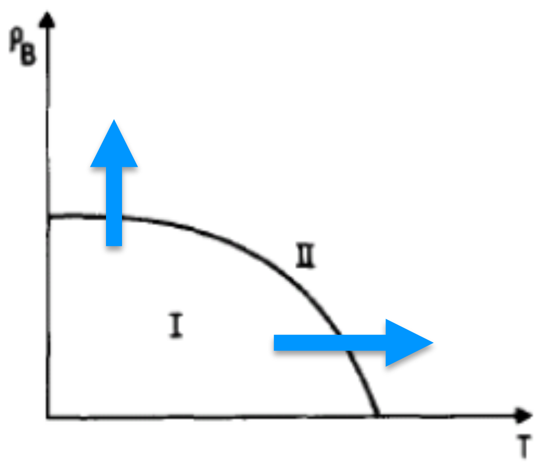


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

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)

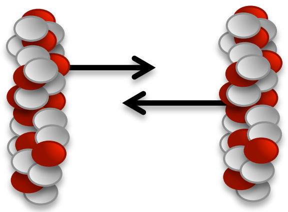
A **phase transition** is expected to occur around **T_c ~ 145 – 164 MeV** (from lattice QCD, *PRD 90 (2014) 094503*)

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

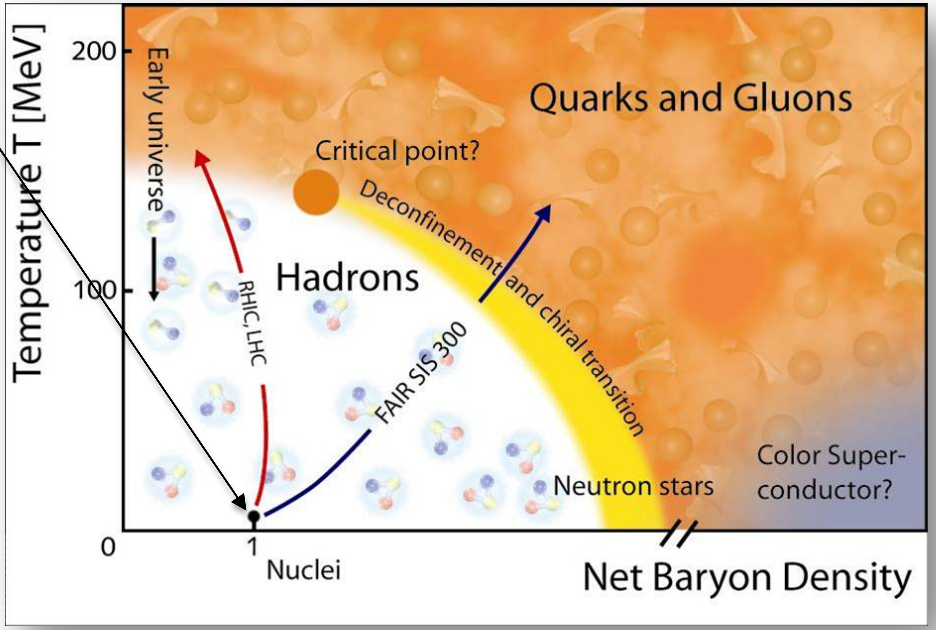
→ **study of light-flavour hadron production**

From nuclear matter to QGP

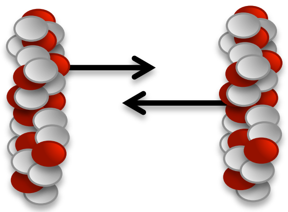
A - A



Nuclear initial state

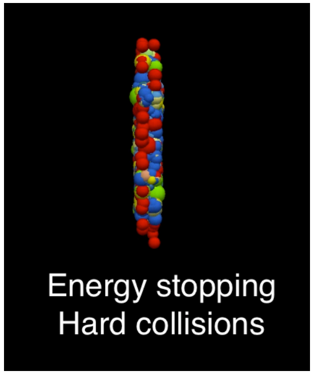


From nuclear matter to QGP



Nuclear initial state
Hot matter in final state

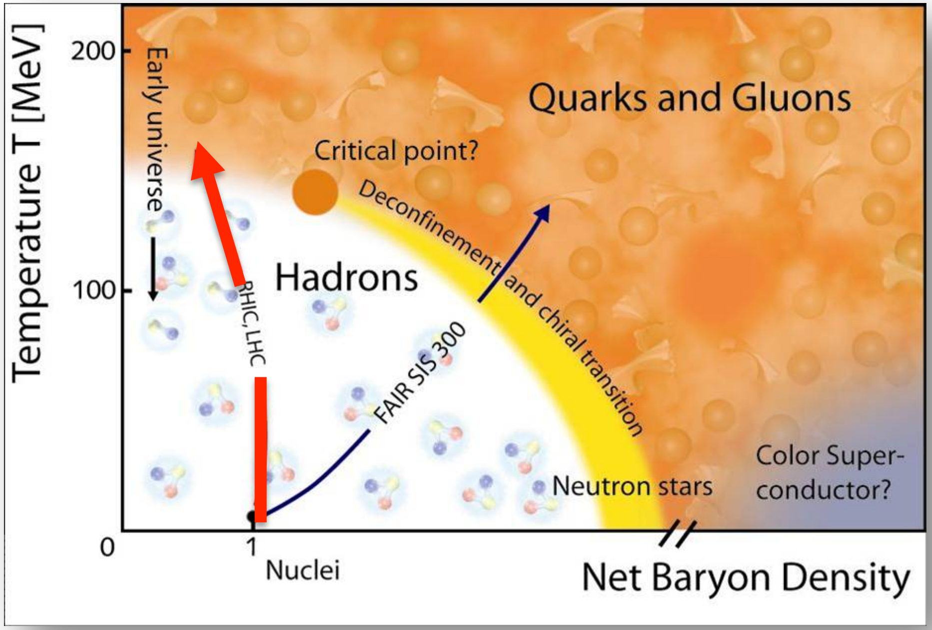
https://madai-public.cs.unc.edu/



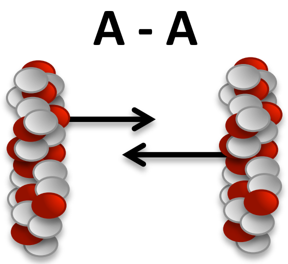
Phase transition: confined → deconfined

At the LHC $\mu_B \sim 0$

$\varepsilon \sim 16$ GeV/fm^3
based on 0-5% Pb-Pb data at 2.76 TeV by ALICE



From nuclear matter to QGP



Nuclear initial state
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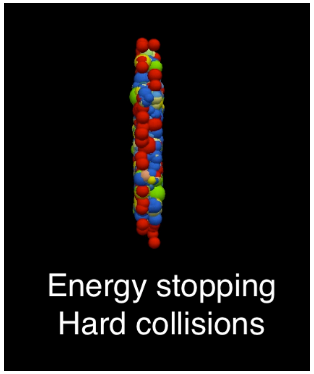
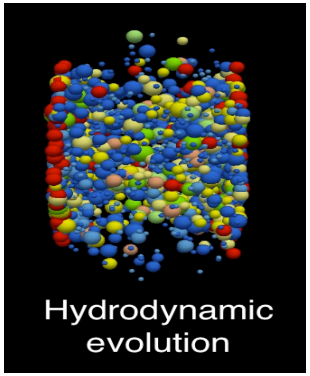
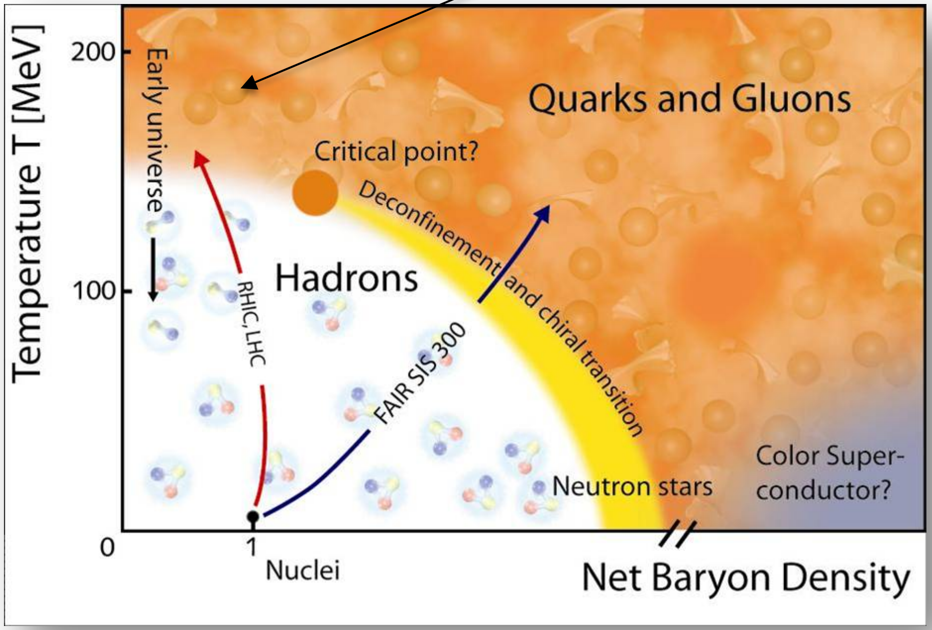
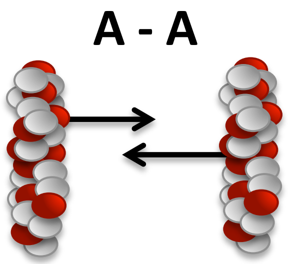




Collectivity (flow) develops

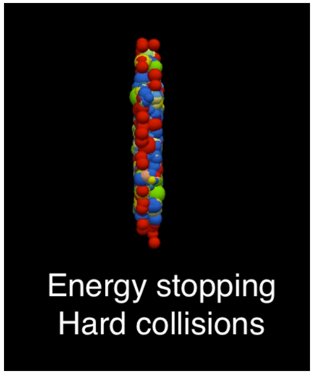


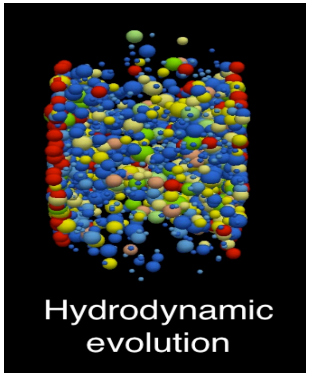
From QGP to hadronic matter



Nuclear initial state
Hot matter in final state

https://madai-public.cs.unc.edu/

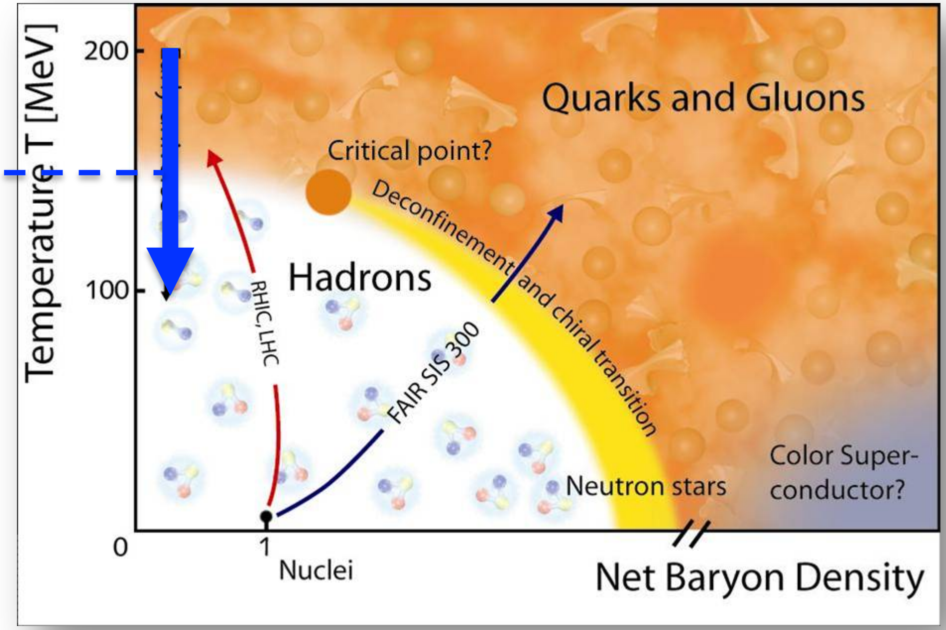




Phase transition: deconfined → confined

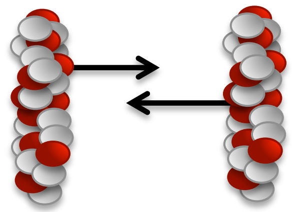
T_c = (154 ± 9) MeV

from Lattice-QCD calculation by HotQCD collaboration
PRD 90 (2014) 094503



From QGP to hadronic matter

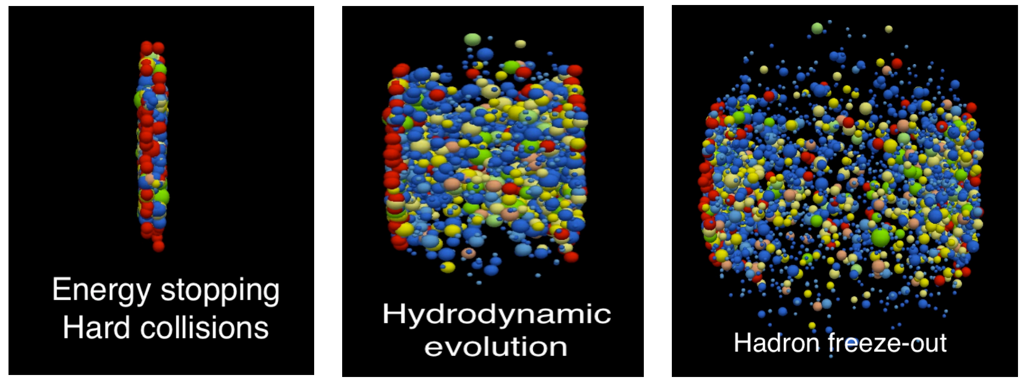
A - A



Nuclear initial state

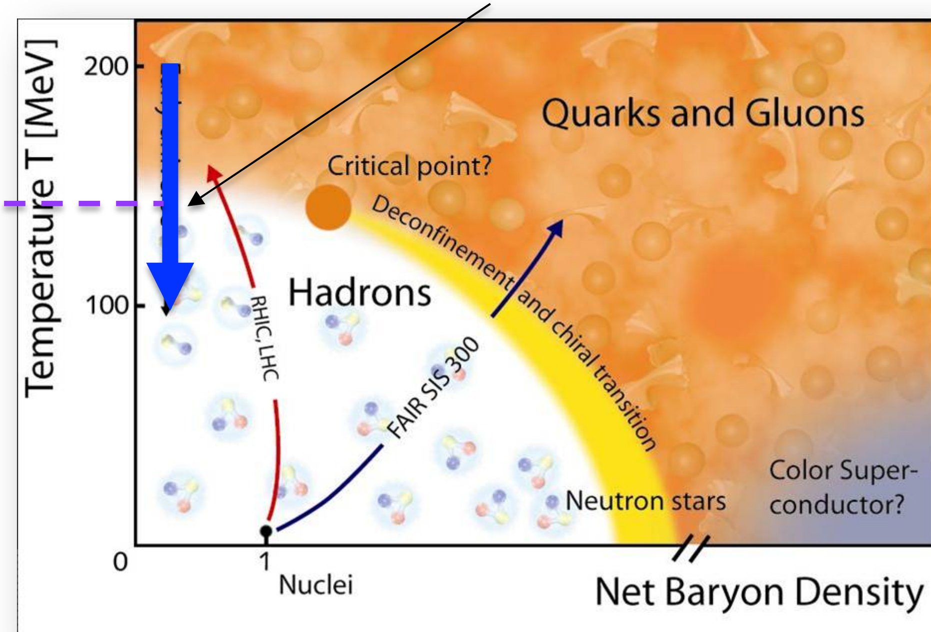
Hot matter in final state

https://madai-public.cs.unc.edu/



Chemical freeze-out: inelastic interactions stop

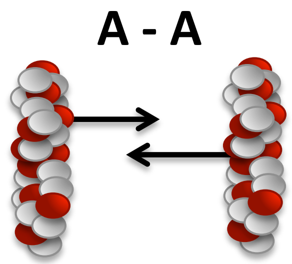
T_{ch} ~ 156 MeV
from thermal model fits of the measured relative particle abundances at the LHC



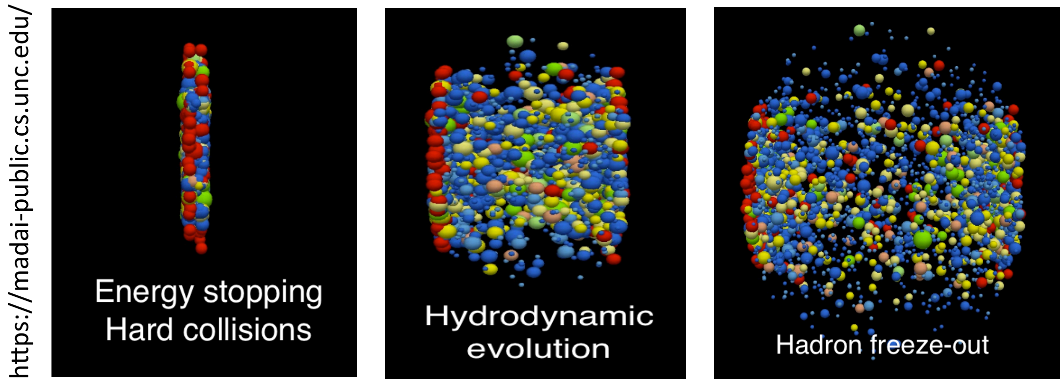
Note: it must be
$T_c \geq T_{ch}$

At the LHC, they are very close to each other → chemical equilibrium reached at or very close to hadronisation!

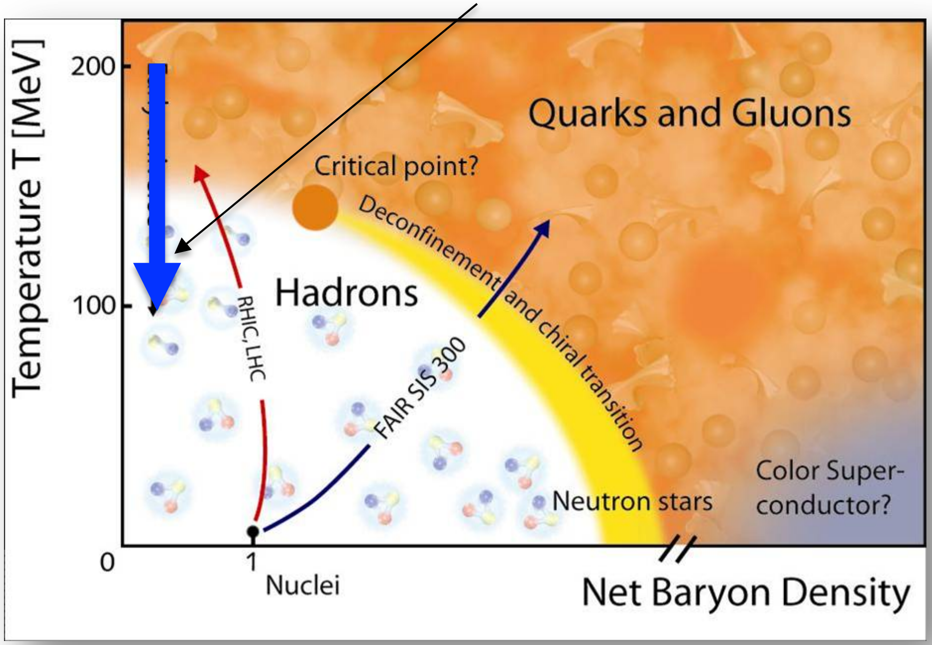
From QGP to hadronic matter



Nuclear initial state
Hot matter in final state



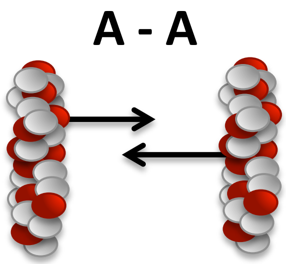
Hadronic phase: (pseudo-)elastic interactions



τ_{HP} ~ 10 fm/c

Short-lived resonances decay and undergo re-scattering and regeneration
→ Yields established at T_{ch} can be modified

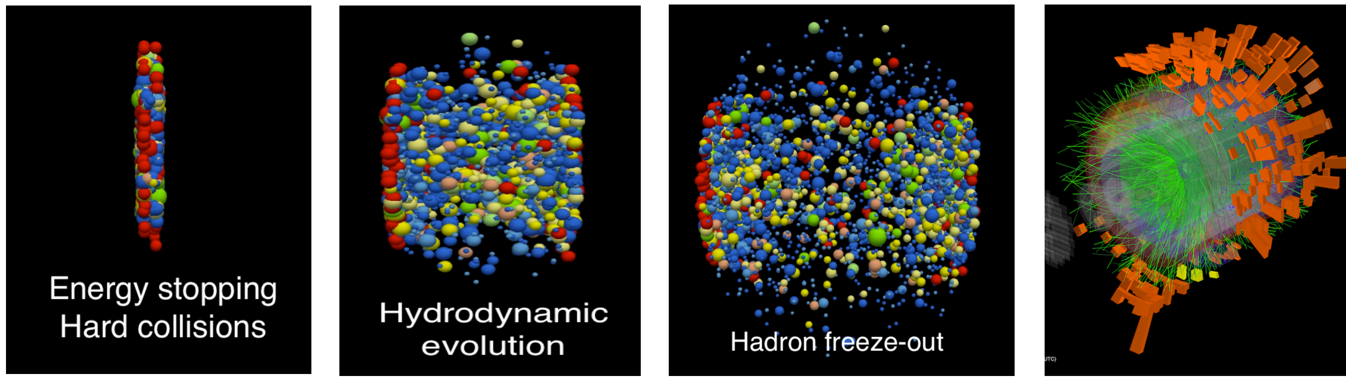
From QGP to hadronic matter



Nuclear initial state

Hot matter in final state

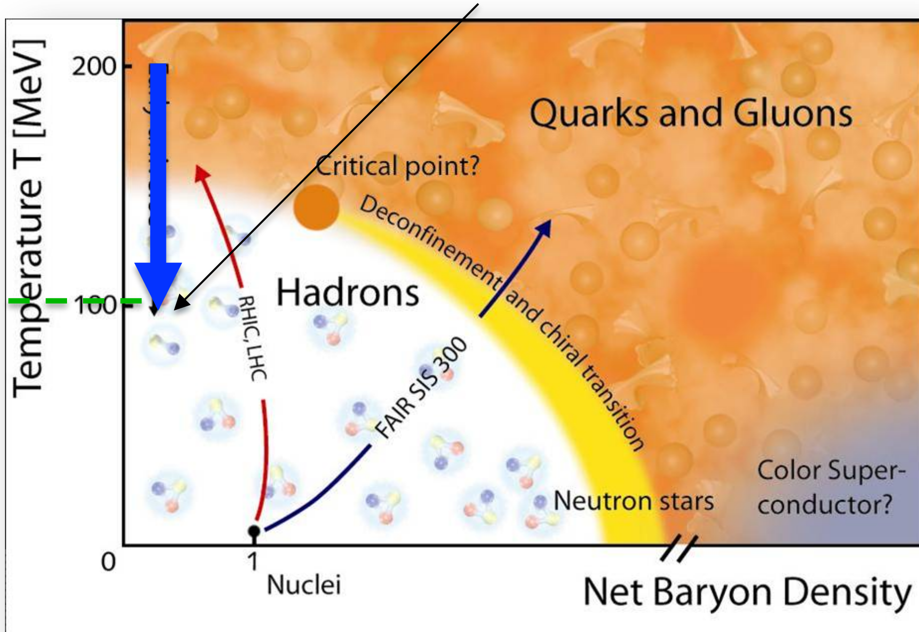
https://madai-public.cs.unc.edu/



Kinetic freeze-out: elastic interactions stop

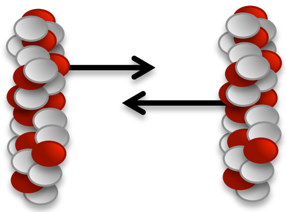
T_{kin} ~ 90-110 MeV

from Blast-Wave model fits of the measured p_T-dependent particle yields at the LHC



"Small" systems as reference for "large" systems

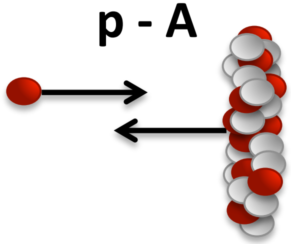
A - A



Nuclear initial state
Hot matter in final state

Pb-Pb collisions
- Particle production mechanisms
- Strangeness enhancement
- In-medium energy loss
- Collectivity
- Properties of the hadronic phase

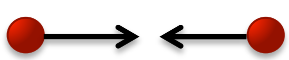
p - A



Nuclear initial state
Cold matter in the final state

p-Pb collisions
- Disentangle final from initial-state effects
- Collectivity in small systems?

p - p

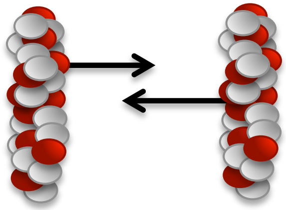


Hadronic initial state
Hadronic final state

pp collisions
- No deconfinement expected
- No collectivity expected
- Reference for "larger" system

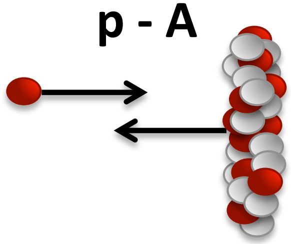
… but more than a reference!

A - A



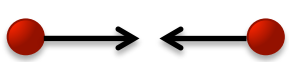
Nuclear initial state
Hot matter in final state

p - A



Nuclear initial state
Cold matter in the final state

p - p



Hadronic initial state
Hadronic final state

Recent measurements have revealed **striking similarities across different systems**

- Hints for **collectivity in small systems**
  → What is its origin (radial flow, color reconnection, …)?

- Smooth **evolution of particle production as a function of multiplicity** across different systems
  → What drives particle composition in different systems?

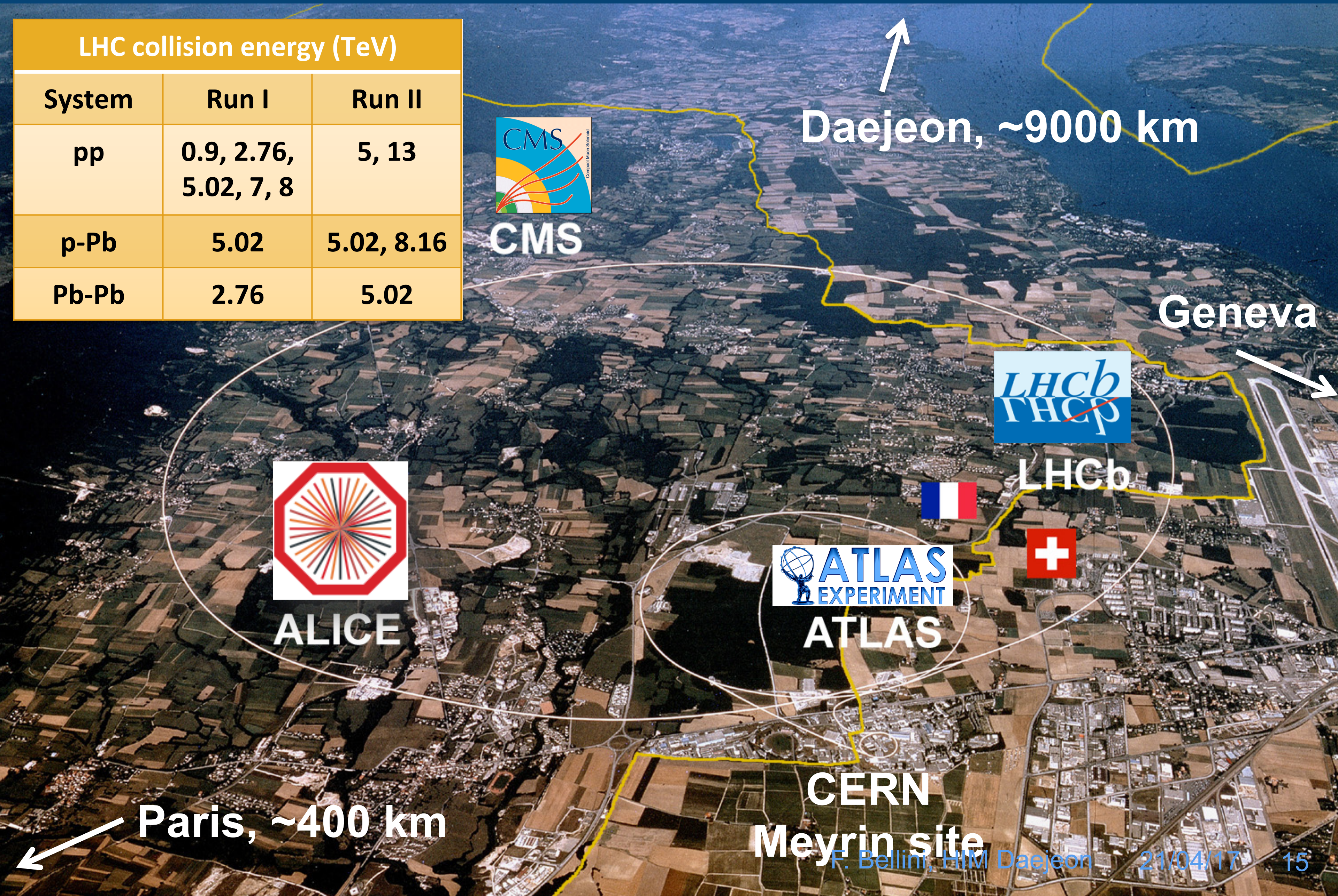
- **Enhancement of strangeness production** from low to high-multiplicity pp and p-Pb

Experimental Details

What particles and momenta are accessible to ALICE?
How are centrality and multiplicity defined in ALICE?

Experiments at the Large Hadron Collider

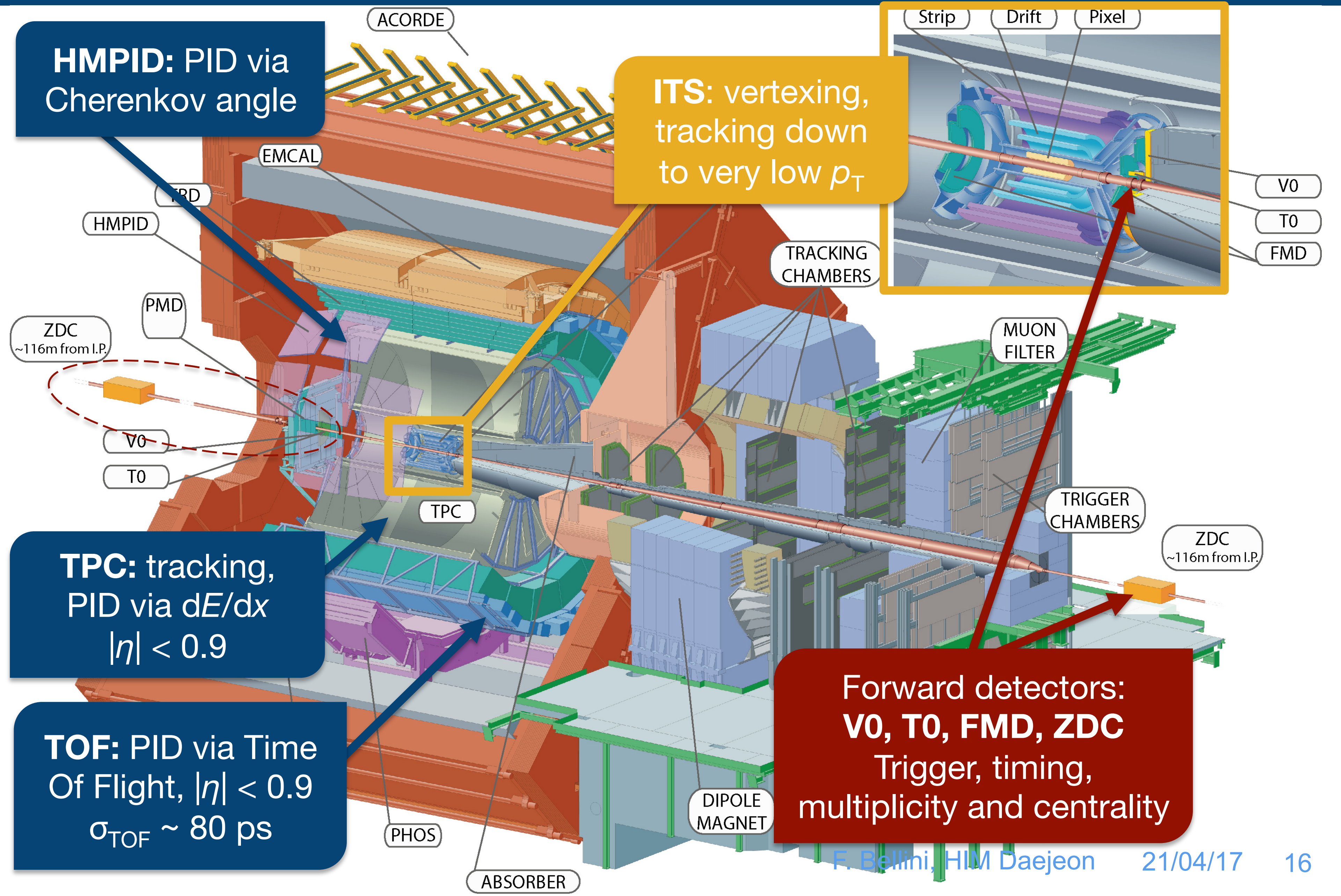
LHC collision energy (TeV)		
System	Run I	Run II
pp	0.9, 2.76, 5.02, 7, 8	5, 13
p-Pb	5.02	5.02, 8.16
Pb-Pb	2.76	5.02



A Large Ion Collider Experiment at the LHC

HMPID: PID via Cherenkov angle

ITS: vertexing, tracking down to very low p_T



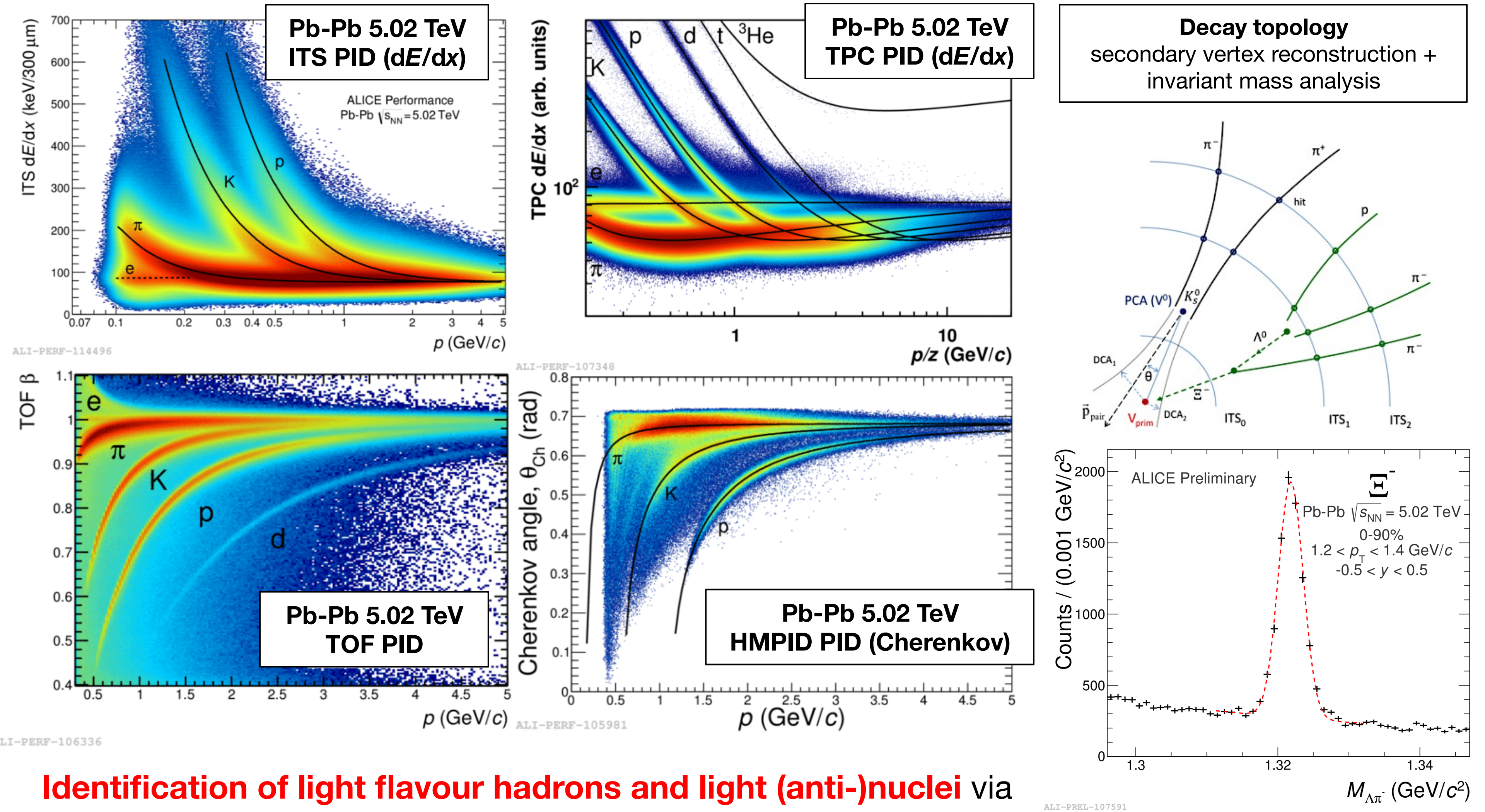
TPC: tracking, PID via dE/dx $|\eta| < 0.9$

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

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

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

Particle identification



Identification of light flavour hadrons and light (anti-)nuclei via practically all known PID techniques in **$0.1\ \mathrm{GeV}/c < p_T < 30\ \mathrm{GeV}/c$**

Phys. Rev. Lett. 106 (2011) 032301

Event classes in Pb-Pb

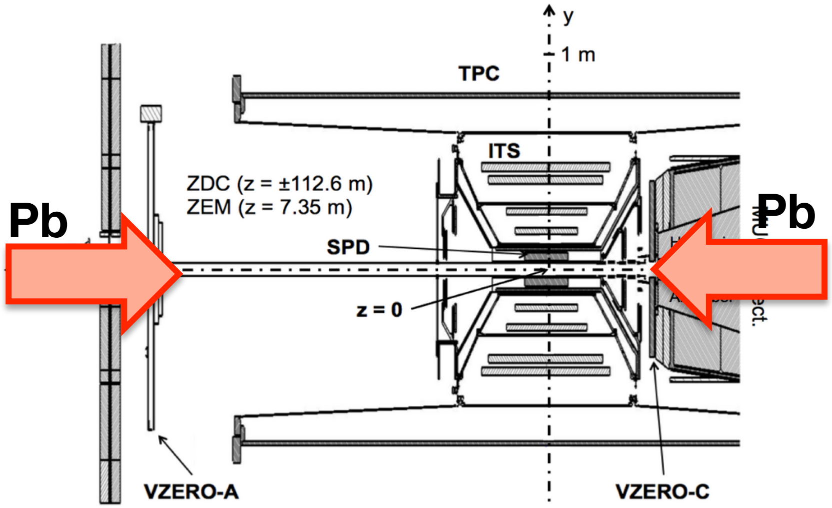
Event **multiplicity/centrality** classes are defined based on the amplitude measured in the **V0 scintillators**, placed at
$2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C)

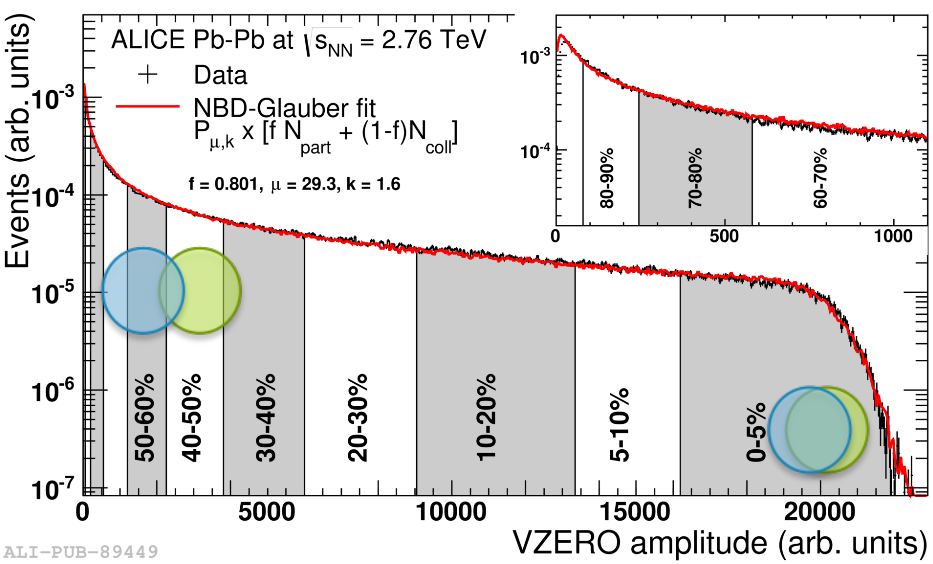
$\langle dN_{ch}/d\eta \rangle$ is measured in $|\eta| < 0.5$
→ avoid "auto-biases" in multiplicity determination

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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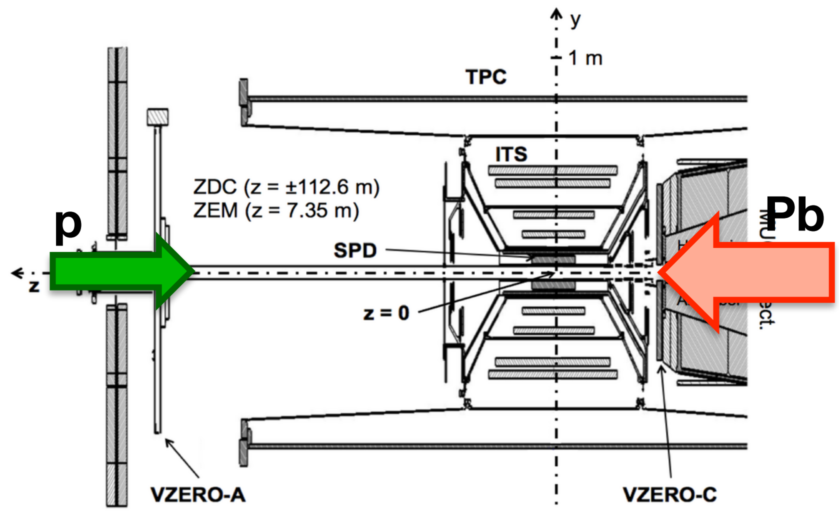

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$\langle \mathbf{N_{part}} \rangle$ **= 15.8 ± 0.6**

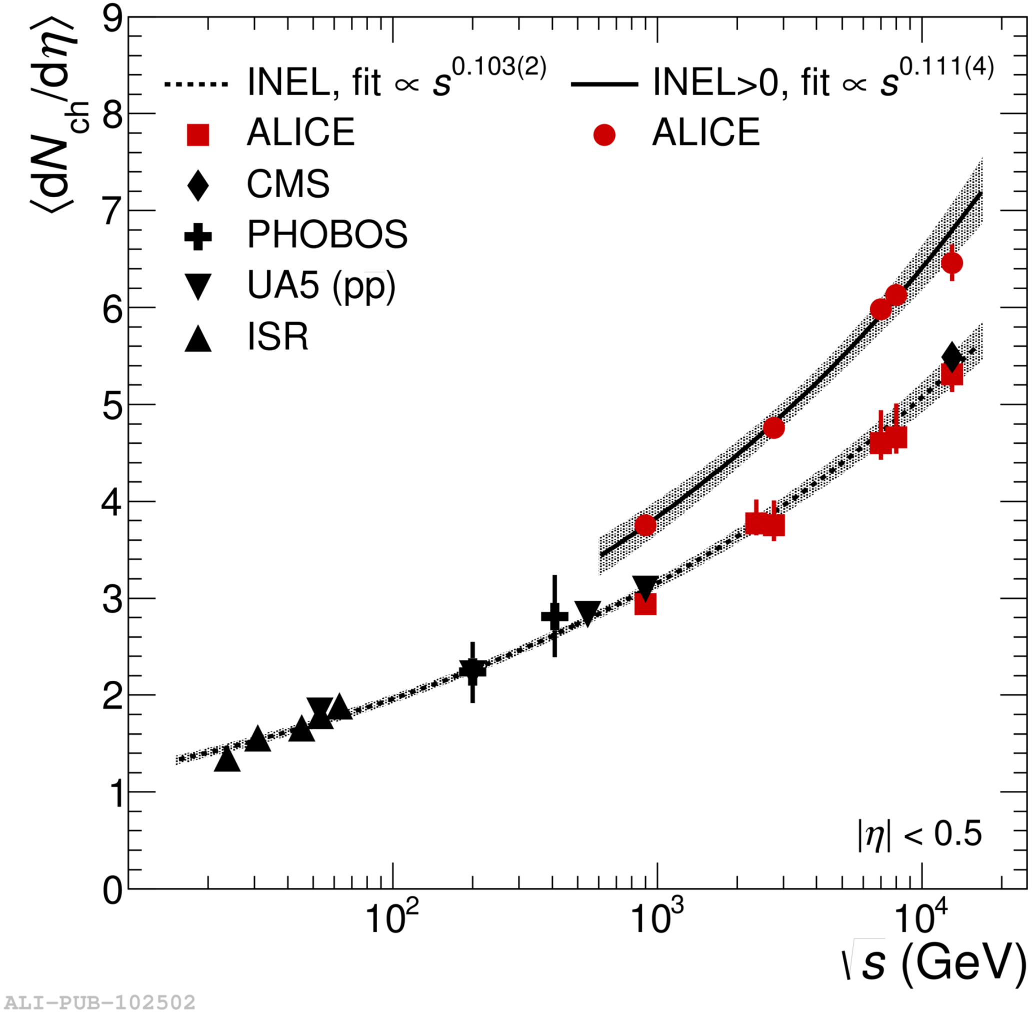
(*alternatively, multiplicity of spectators in the Zero Degree Calorimeters or number of tracks in the Silicon Pixel Detector or the Time Projection Chamber)

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**

Multiplicities in pp at 13 TeV

Phys. Lett. B 753 (2016) 319-329

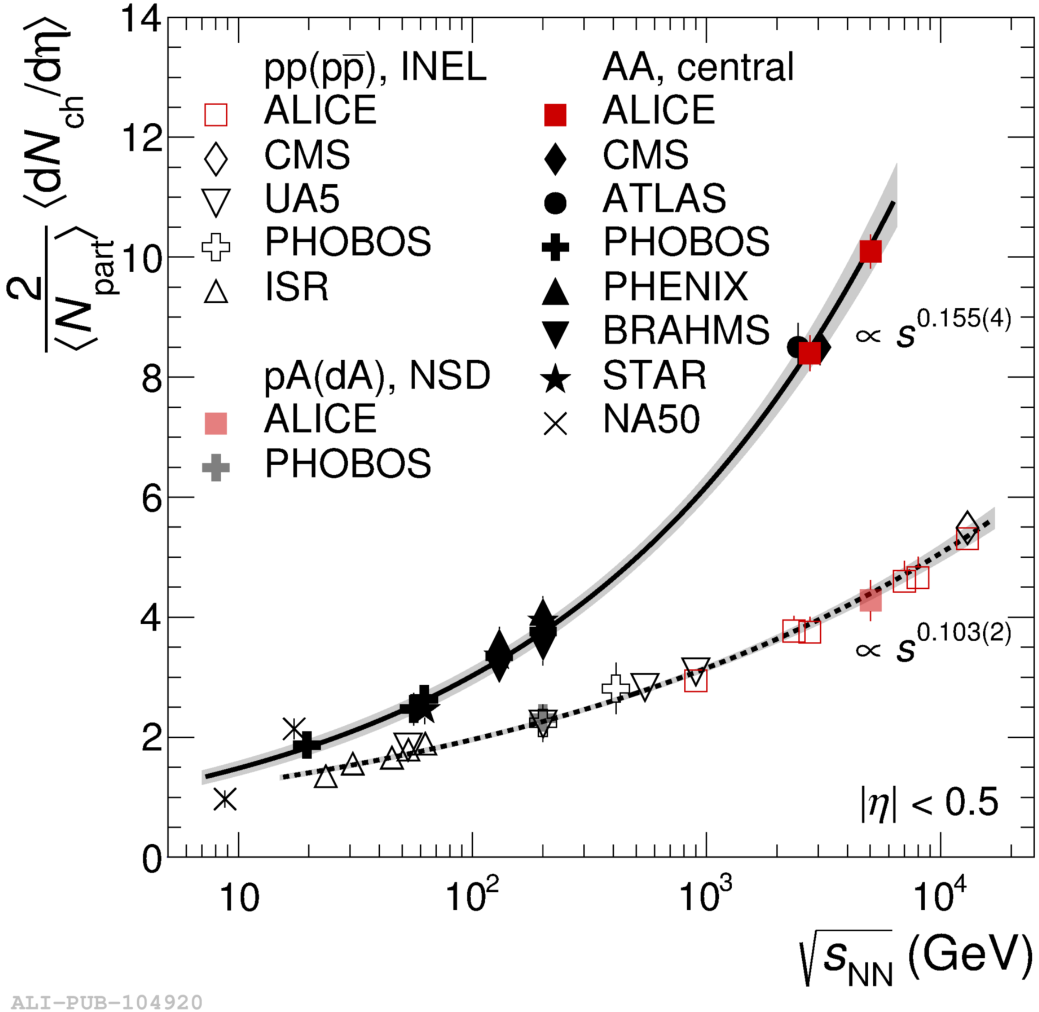


In pp, $\langle dN_{ch}/d\eta \rangle$ increases with $\sqrt{s}$ following a **power law**, along the trend from lower center of mass energies

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

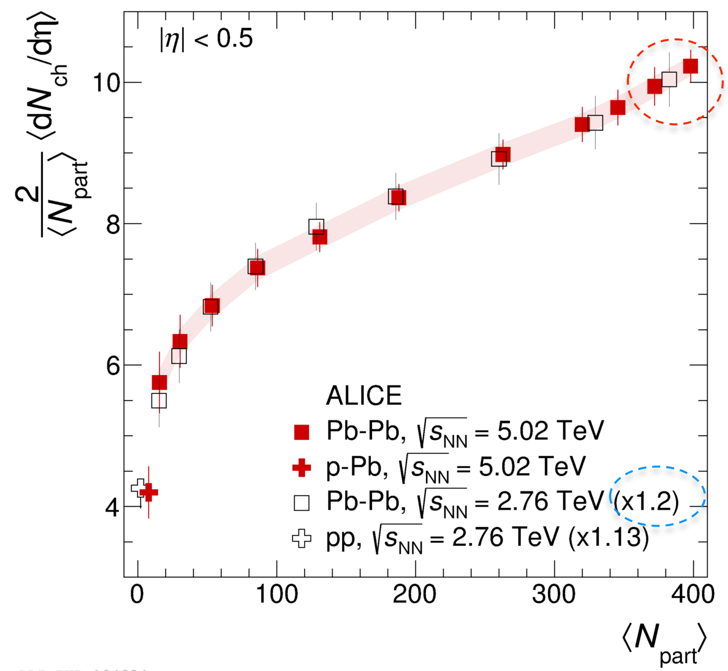
Multiplicities in Pb-Pb at 5.02 TeV

Phys. Rev. Lett. 116 (2016) 222302



In **Pb-Pb** $\langle dN_{ch}/d\eta\rangle/\langle N_{part}\rangle$ increases with $\sqrt{s}$ following a **steeper power law** than pp collisions

→ About **20% increase from 2.76 TeV to 5.02 TeV** (similar $\langle N_{part}\rangle$)



A comprehensive set of results on identified particles production in all collision systems:

$\pi^{\pm}$, $K^{\pm}$, K^0_S, p, Λ, Ξ, Ω, ρ^0, K^{*0}, ϕ, Σ^0, $\Sigma^{*\pm}$, Λ^*, Ξ^{*0}

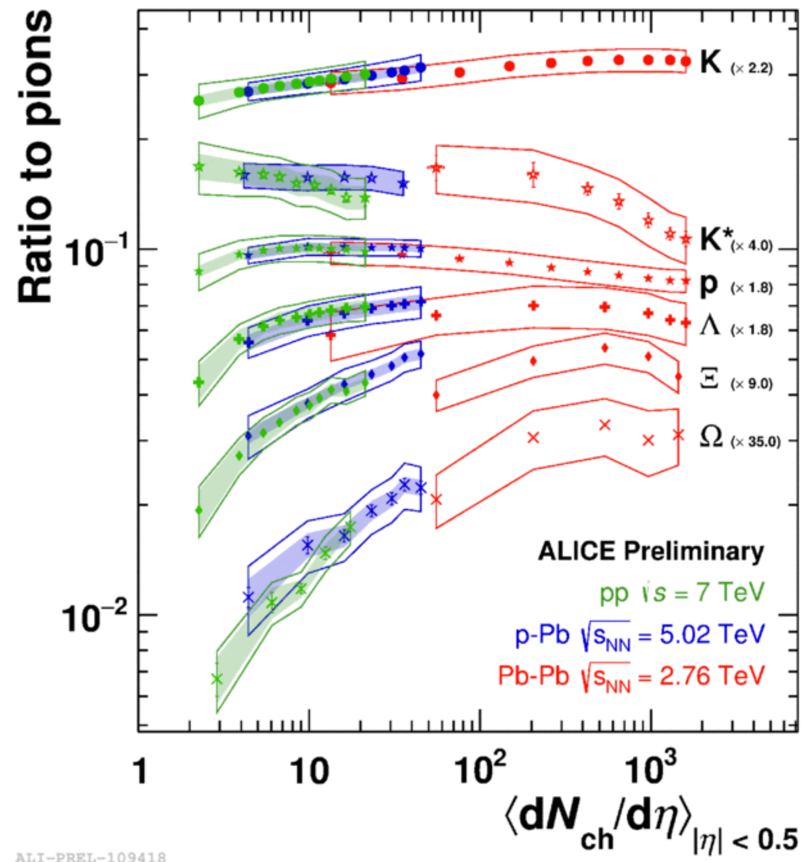
…plus light nuclei and exotica (anti)d, (anti)^{3}H, (anti)^{3}He, (anti)^{4}He, (anti)$^3_\Lambda$H

Run I results:

pp at **$\sqrt{s}$ = 7 TeV** (mb and **vs mult.**)
and $\sqrt{s}$ = 0.9, 2.76, 5.02 TeV
p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

New Run II results (QM 2017):

pp at $\sqrt{s}$ = 5, 13 TeV minimum bias
pp at $\sqrt{s}$ = 13 TeV vs multiplicity
Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

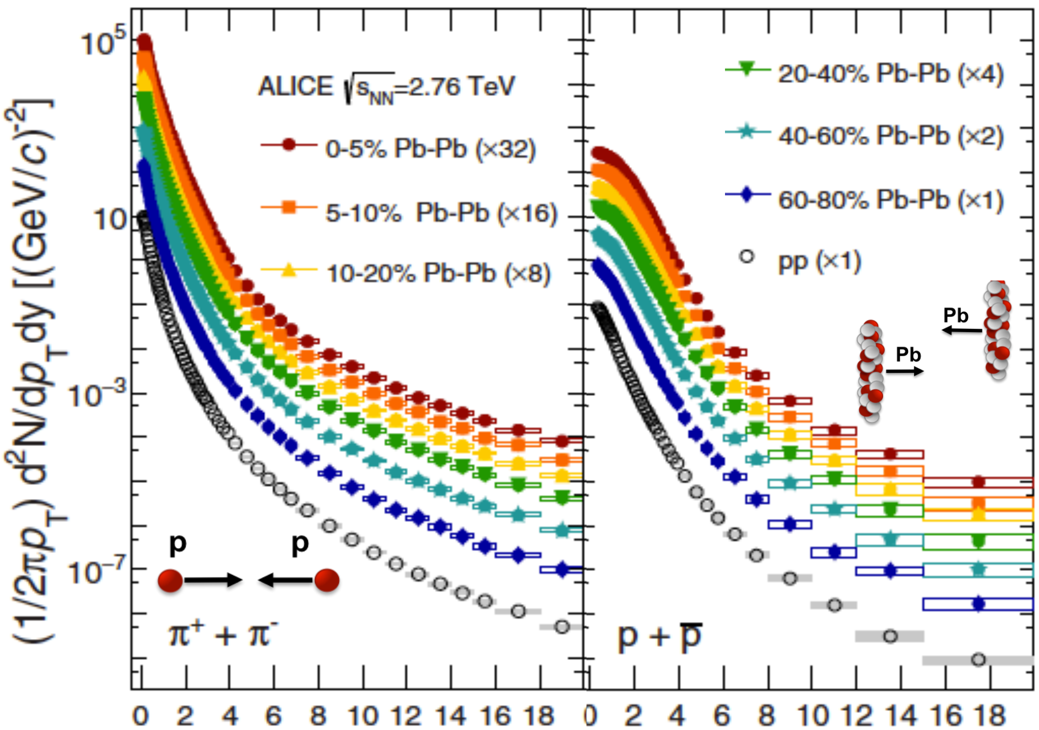


Transverse momentum spectra

Phys. Lett. 88 (2013) 044910
Phys. Rev. C 93 (2016) 034913

A **thermal (soft) part** of the transverse momentum spectra which contains most of the yield and shows roughly an exponential shape

A **hard part** (power-law shape) which is e.g. studied when looking at energy loss in the medium



Low p_T (p_T < 3 GeV/c)
→ Study collective phenomena (radial flow)

Mid-p_T (3 < p_T < 8-10 GeV/c)
→ Study fragmentation vs recombination

High p_T (p_T > 8-10 GeV/c):
→ Study jet quenching and energy loss nuclear via nuclear modification factors

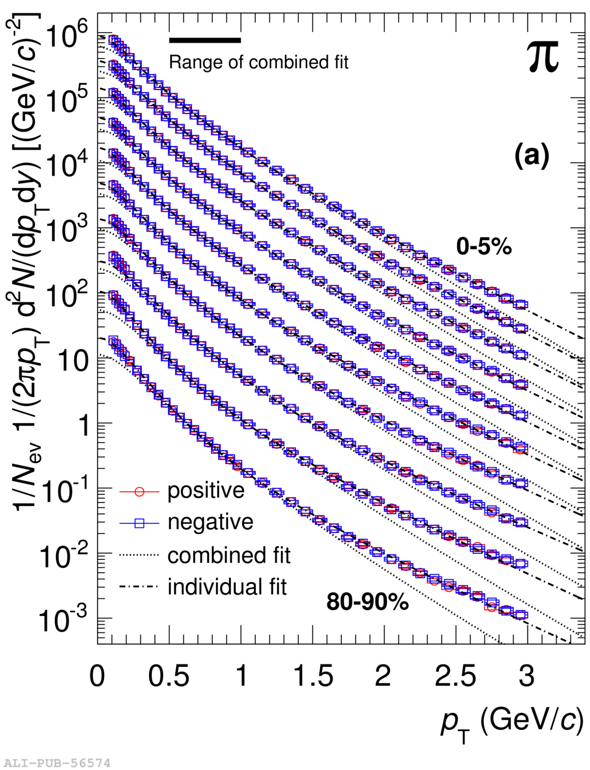
Collectivity

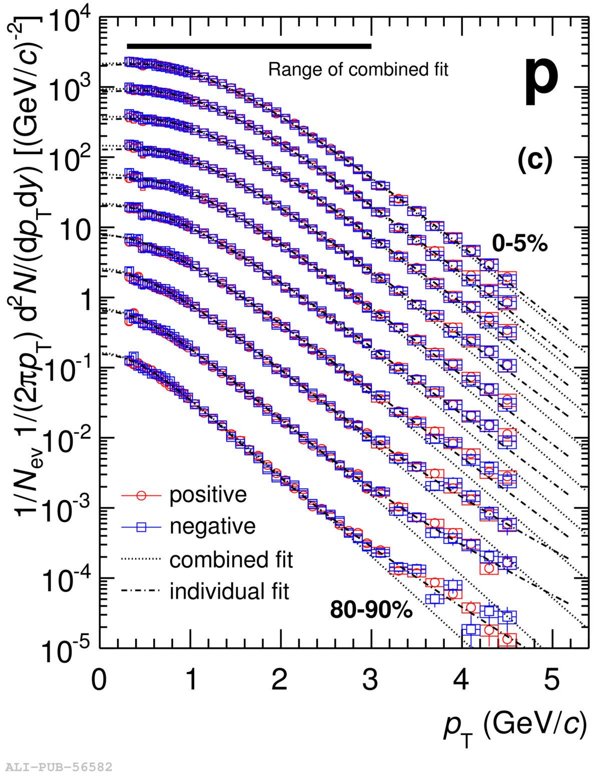
Do we see signs of collective behaviour in small systems?
What is its origin?

Bulk particle production in Pb-Pb

Phys. Rev. C 88 (2013) 044910
Phys. Rev. C 93 (2016) 034913

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



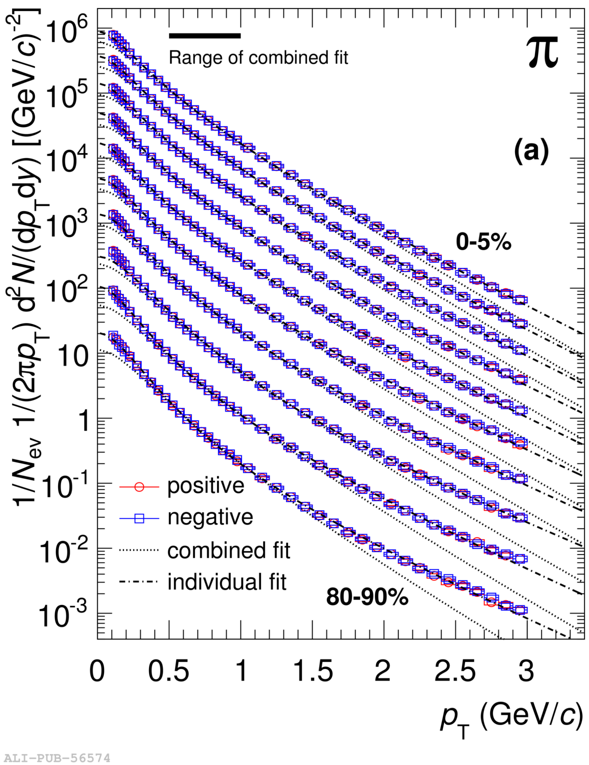


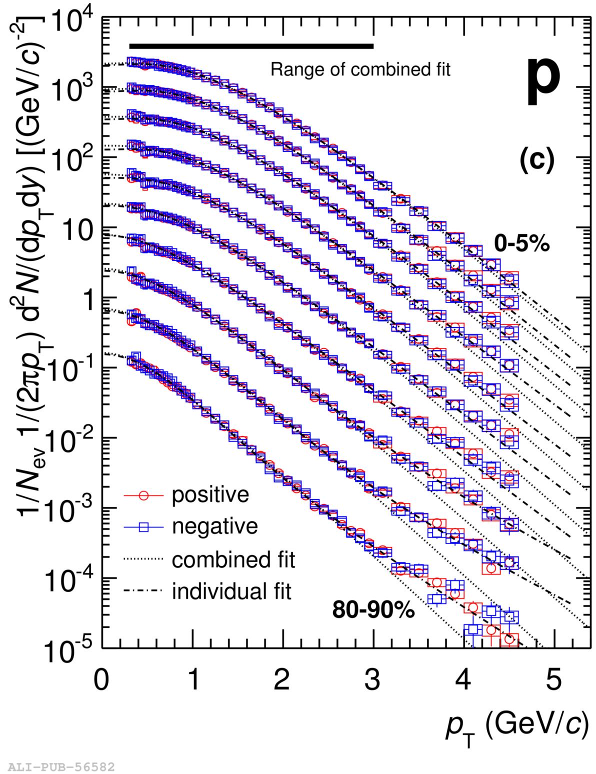
- Spectra get harder with increasing centrality, according to mass ordering

Bulk particle production in Pb-Pb

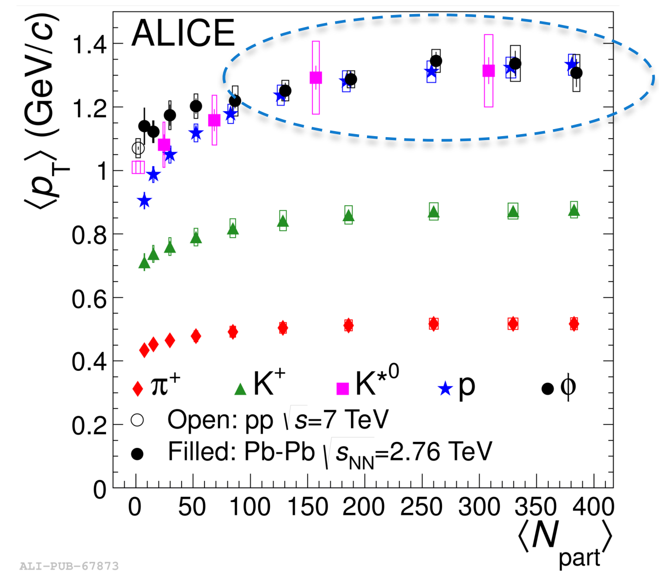
Phys. Rev. C 88 (2013) 044910
Phys. Rev. C 93 (2016) 034913
Phys. Rev. C 91 (2015) 024609

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





m_p ~ 938 MeV/c^2
m_ϕ ~1018 MeV/c^2



- 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**

Behaviour confirmed at 5.02 TeV

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

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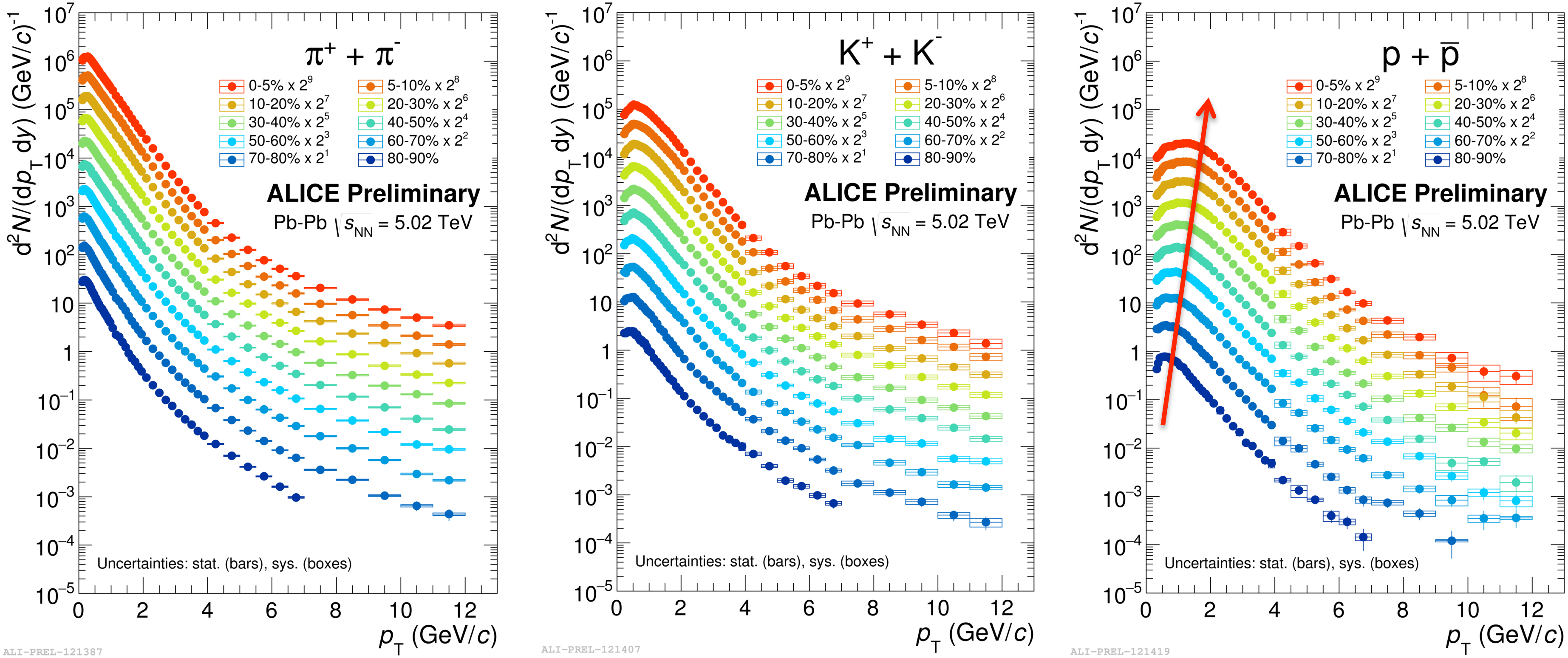

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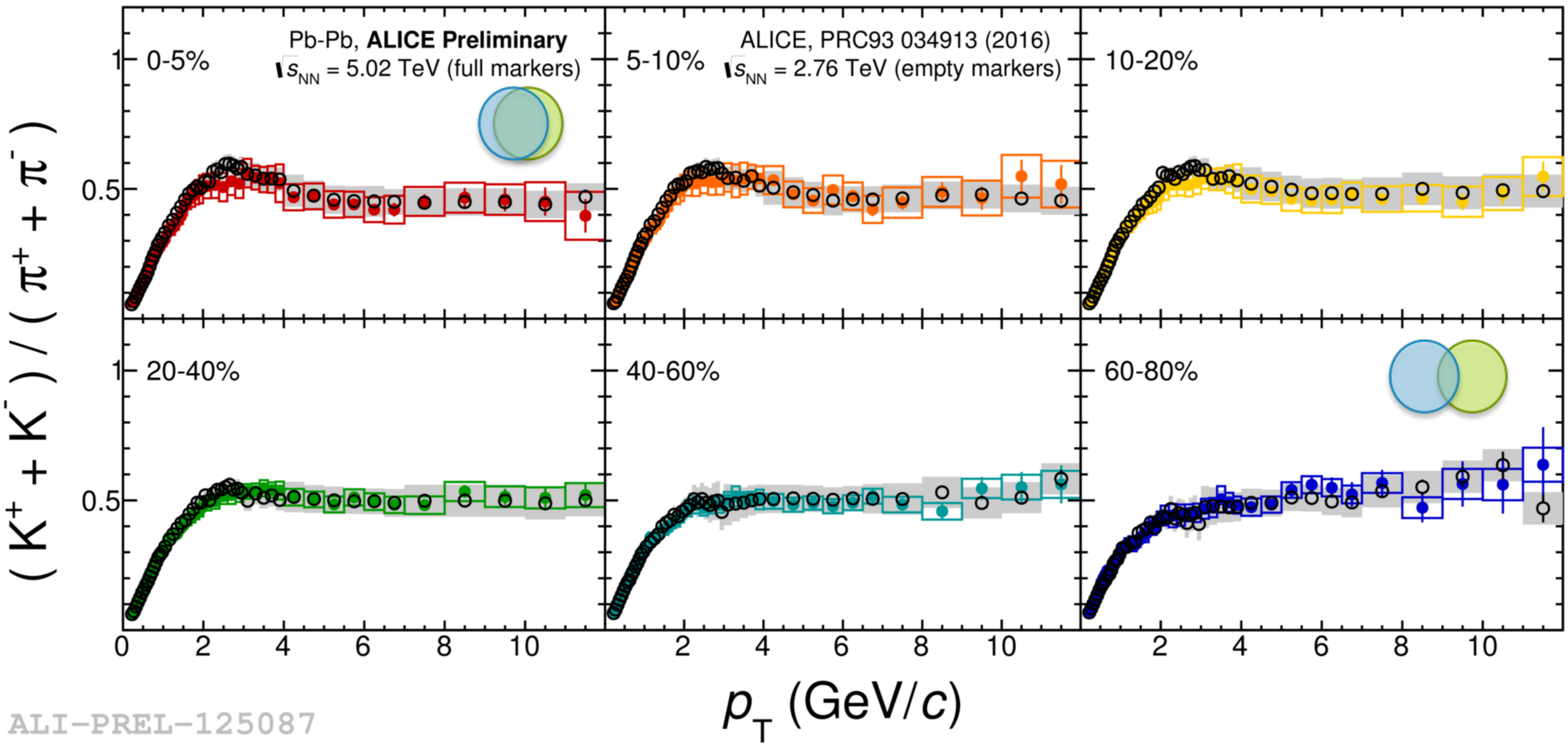
- Particles with similar mass have similar mean p_T in central Pb-Pb

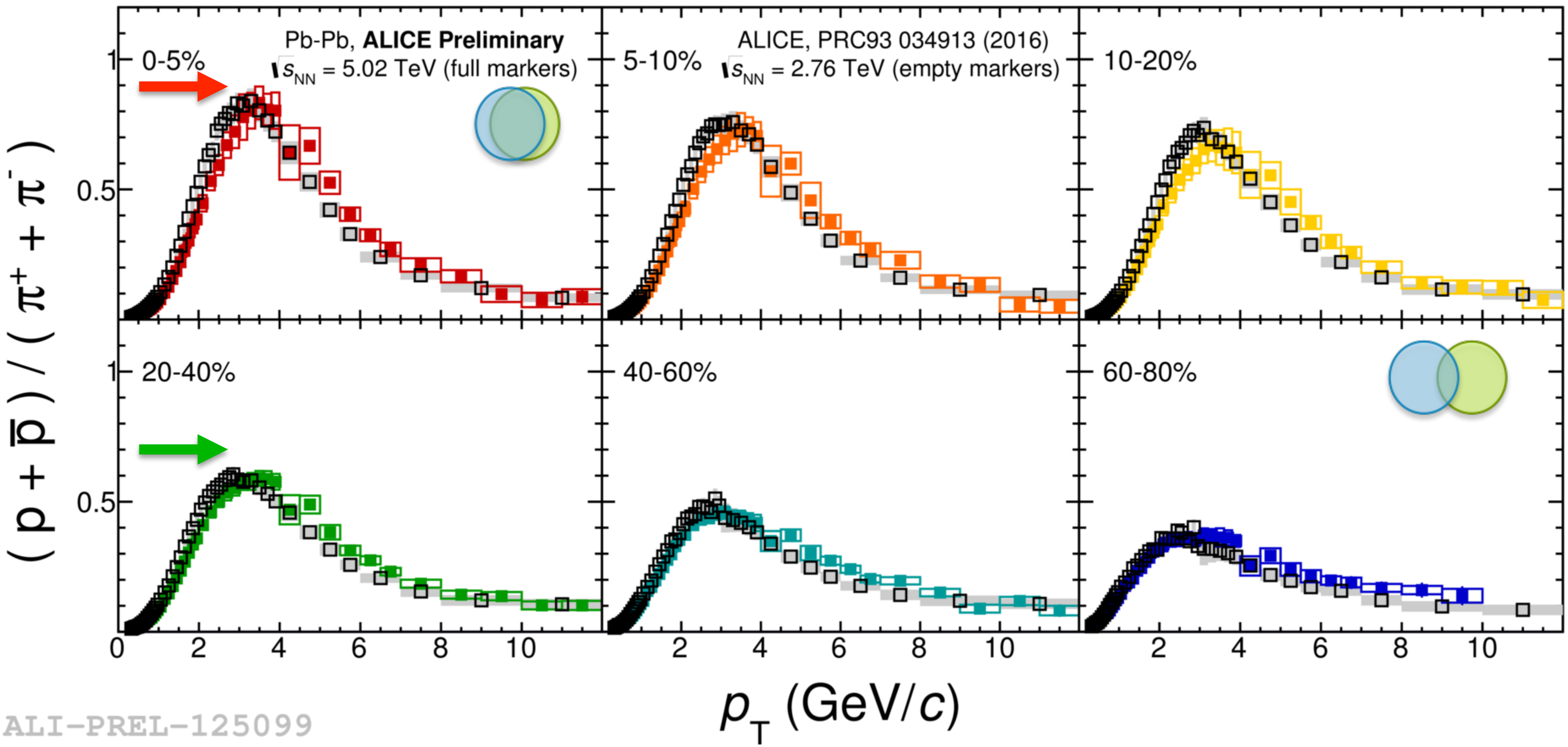
Expected in presence of **collective hydrodynamic expansion** ($p = m{\cdot}\beta\gamma$)
→ Clear signature of **radial flow**, **also at $\sqrt{s_{NN}}$ = 5.02 TeV**

Particle ratios in Pb-Pb from 2.76 to 5.02 TeV



K/π: no significant difference between 2.76 and 5.02 TeV

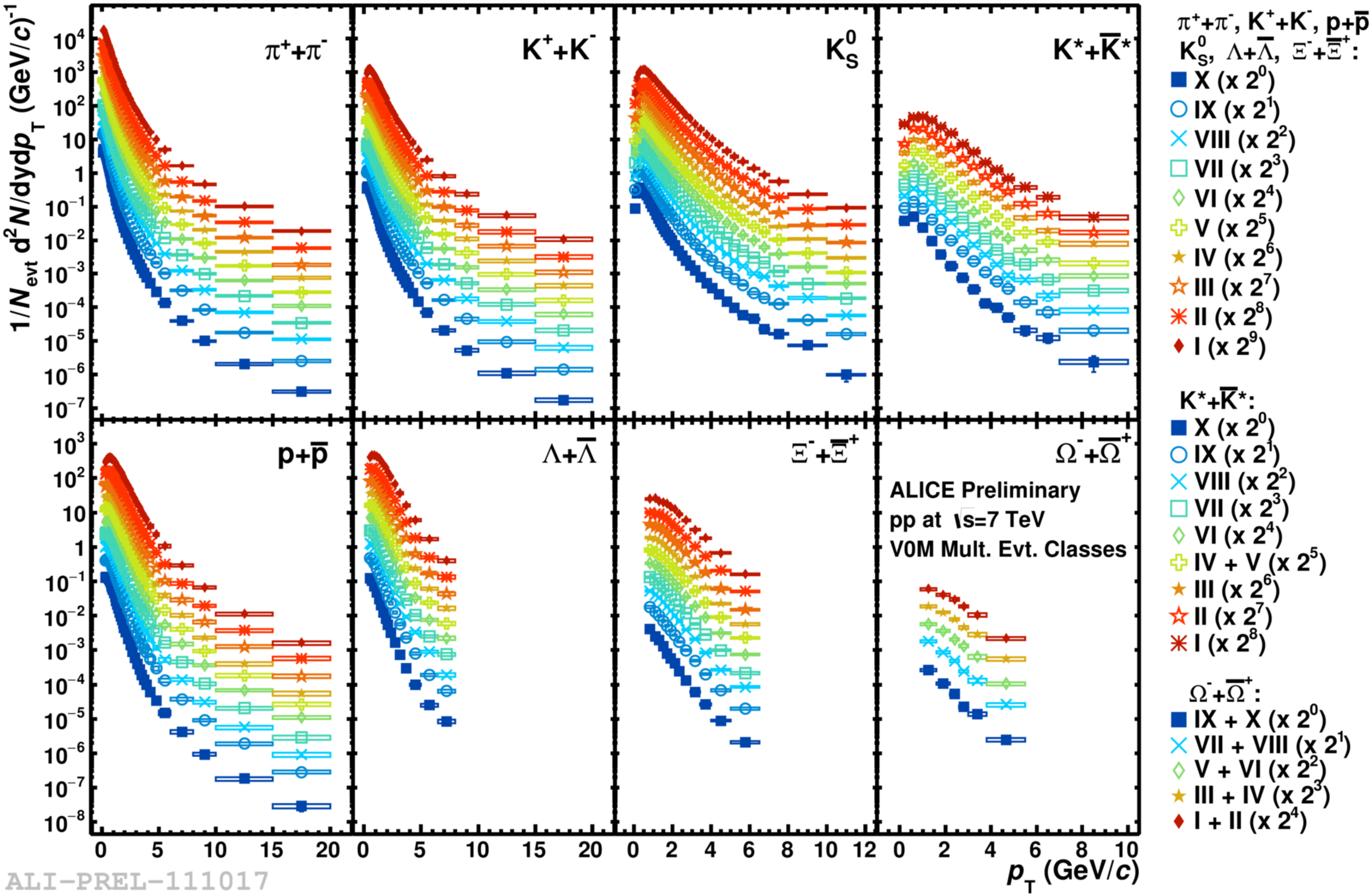
Particle ratios in Pb-Pb from 2.76 to 5.02 TeV



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

Identified hadron spectra in pp collisions

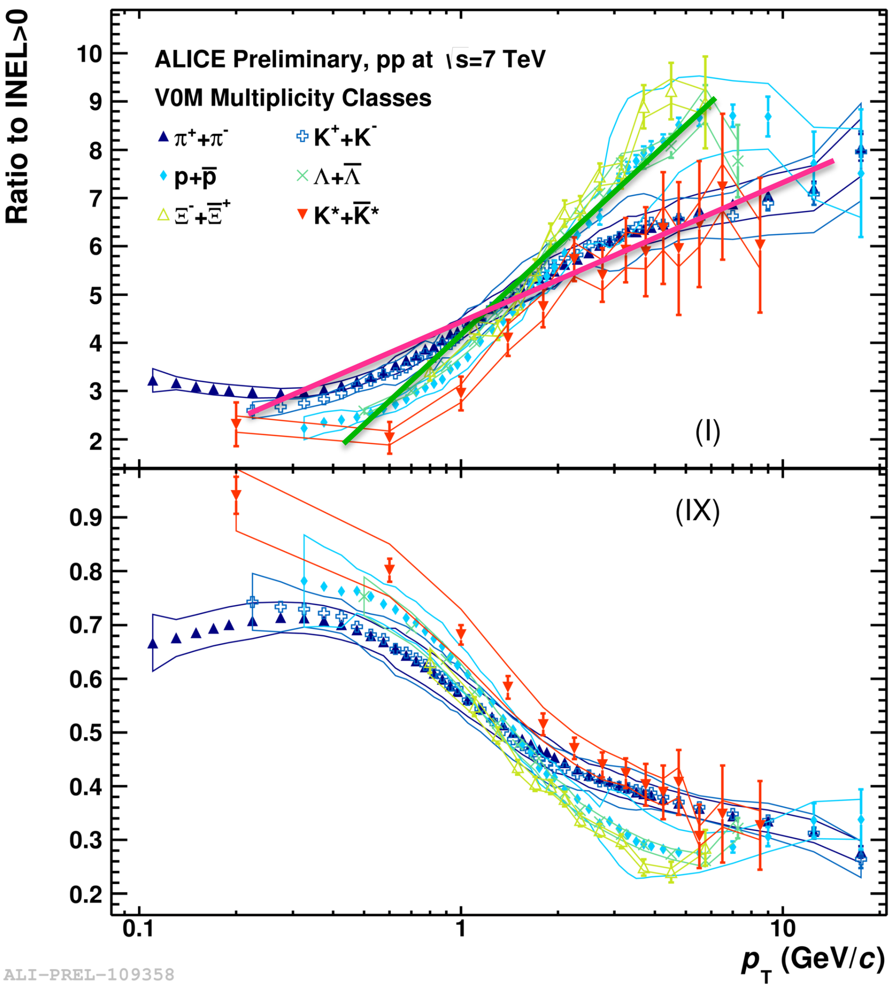


Hardening of spectra in high-multiplicity pp

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

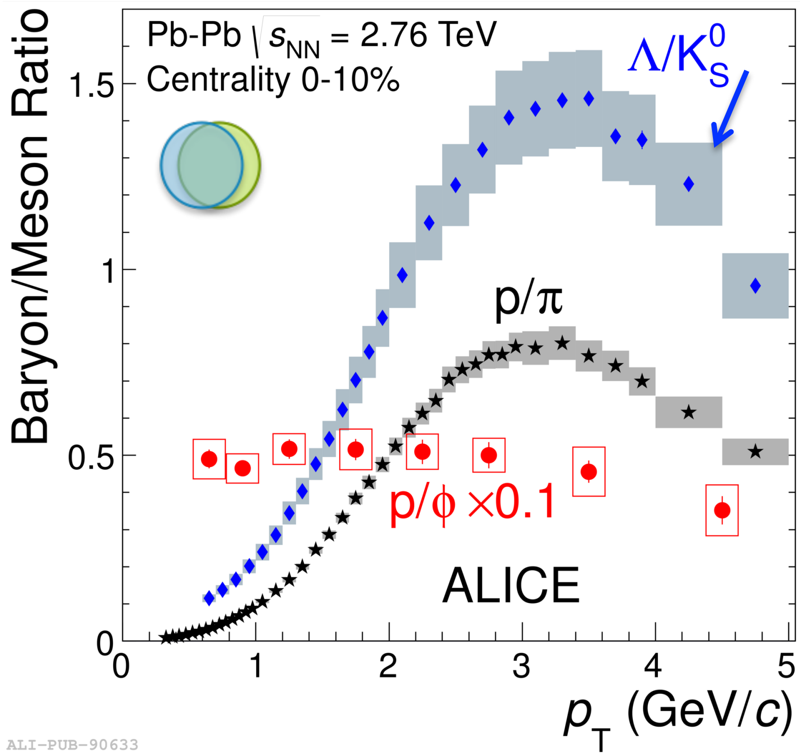
→ Spectra become **harder at higher multiplicities**

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



Baryon-to-meson ratios

Phys. Rev. Lett. 111 (2013) 22301
Phys. Rev. C 88 (2013) 044910
Phys. Rev. C 91 (2015) 024609



In central Pb-Pb collisions

– **p/π, Λ/K^0_S enhancement** at intermediate p_T

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Phys. Rev. Lett. 111 (2013) 22301
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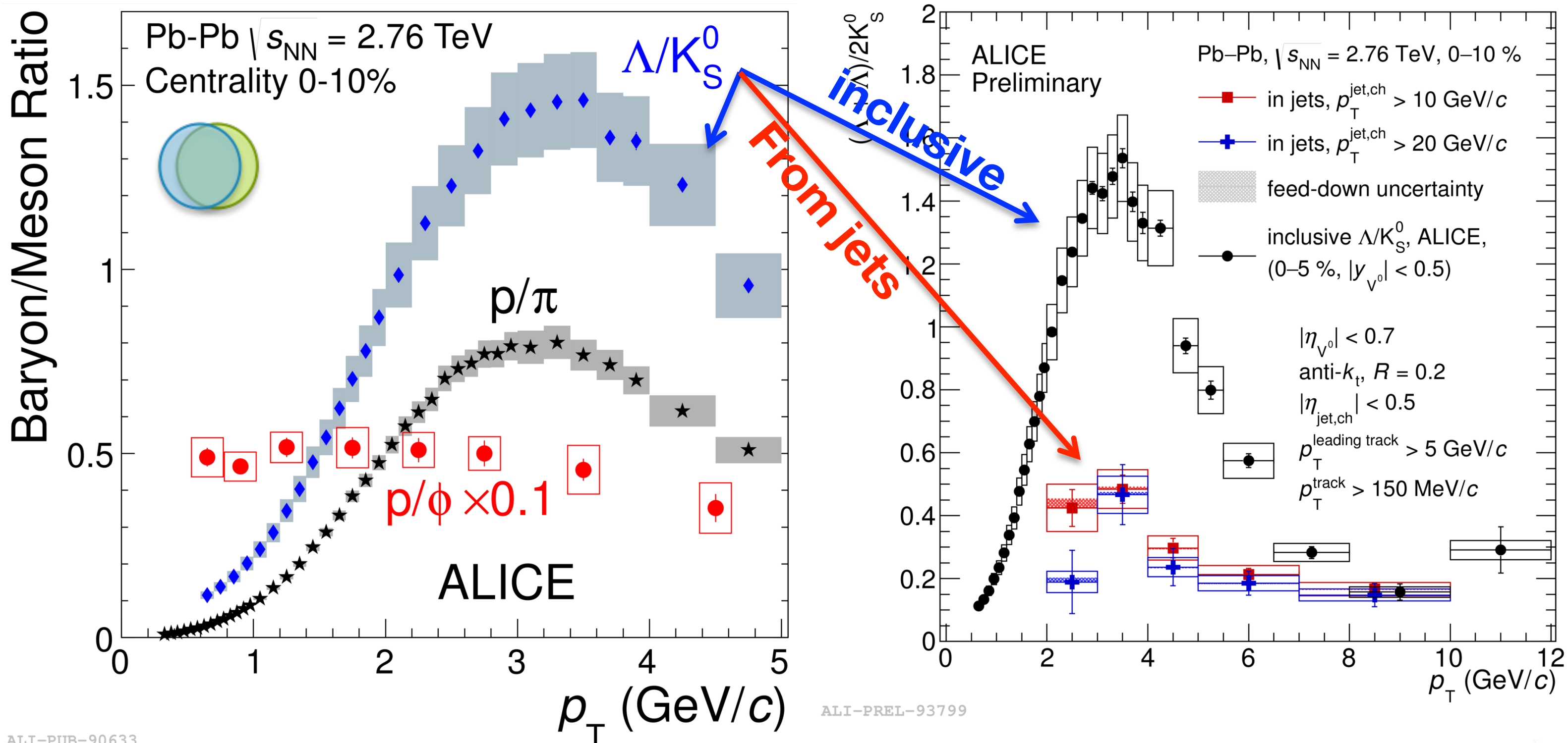
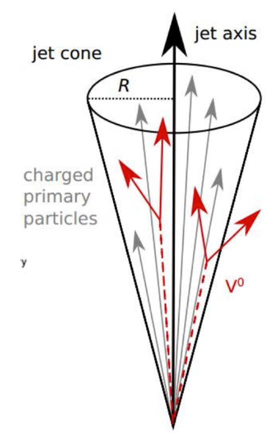
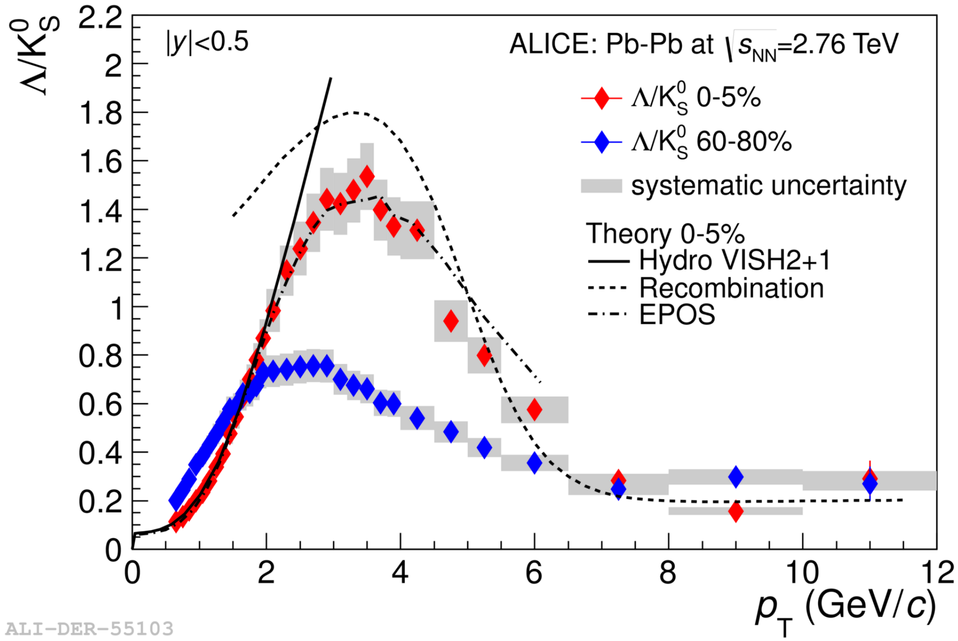


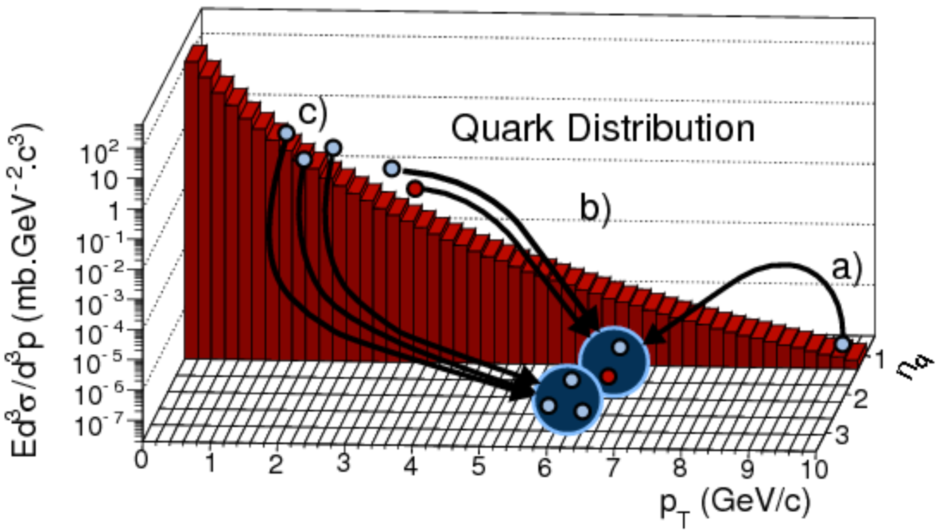


In central Pb-Pb collisions

- **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





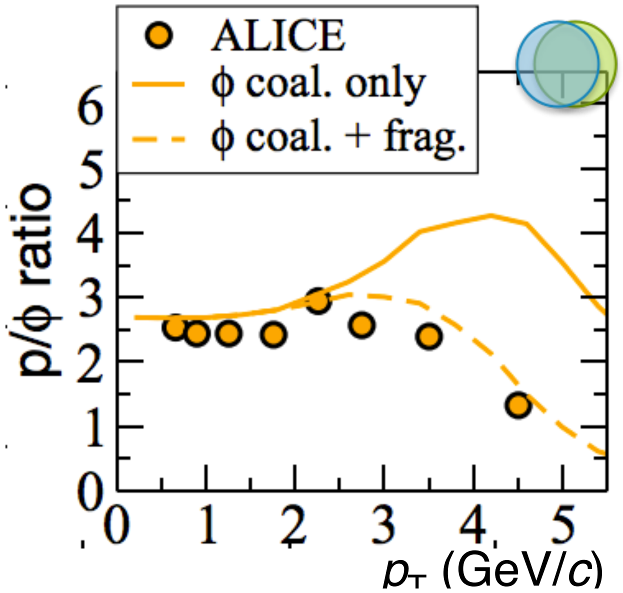
Λ/K^0_S compared with models:

- **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

Phys. Rev. Lett. 111 (2013) 22301

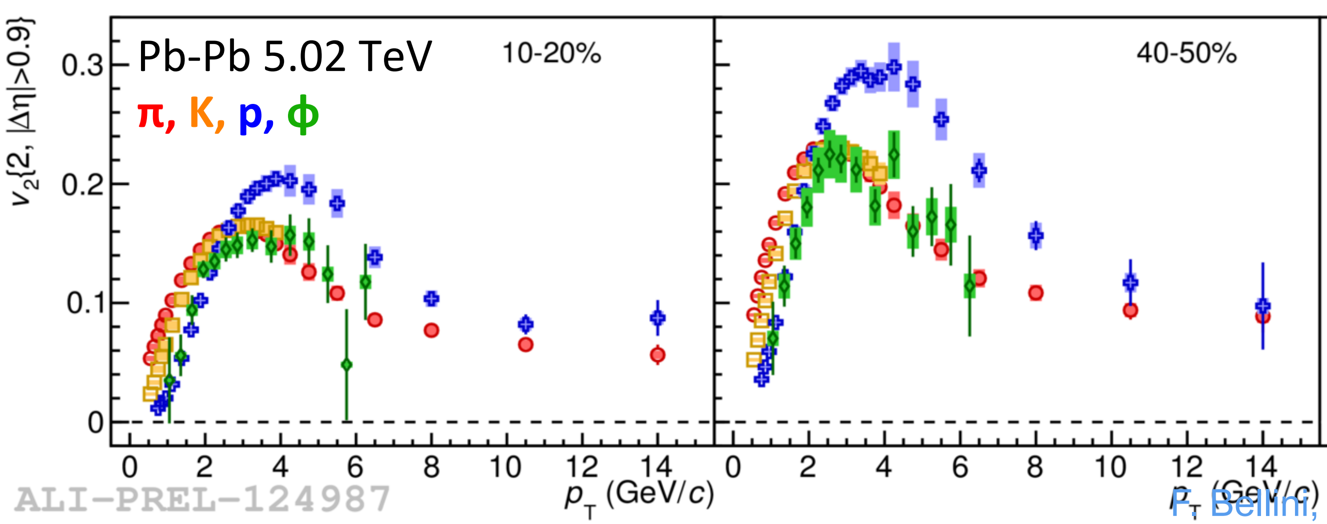
V. Greco at al, Phys.Rev. C 92 (2015) 054904



Flat p/ϕ in Pb-Pb can be explained by

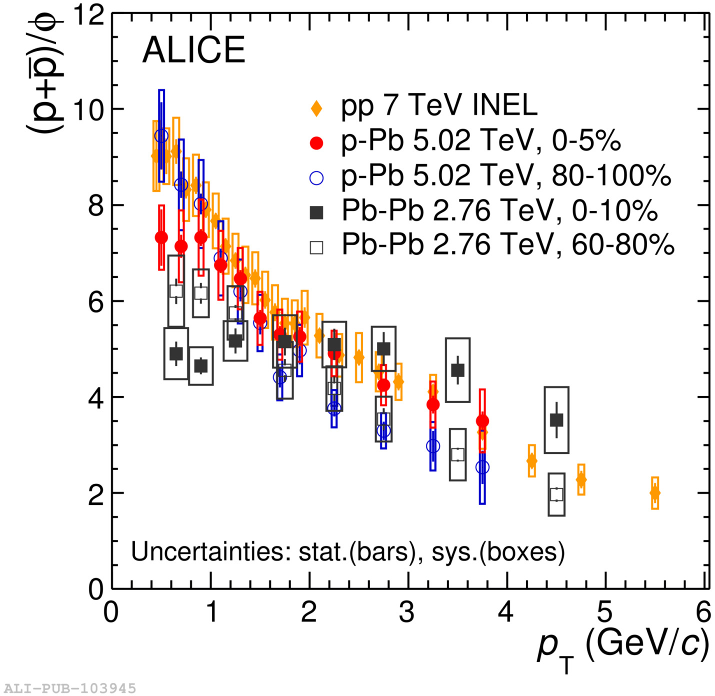
- **by hydro** (radial flow), since similar mass drives similar spectral shapes
- **by models with recombination**

- 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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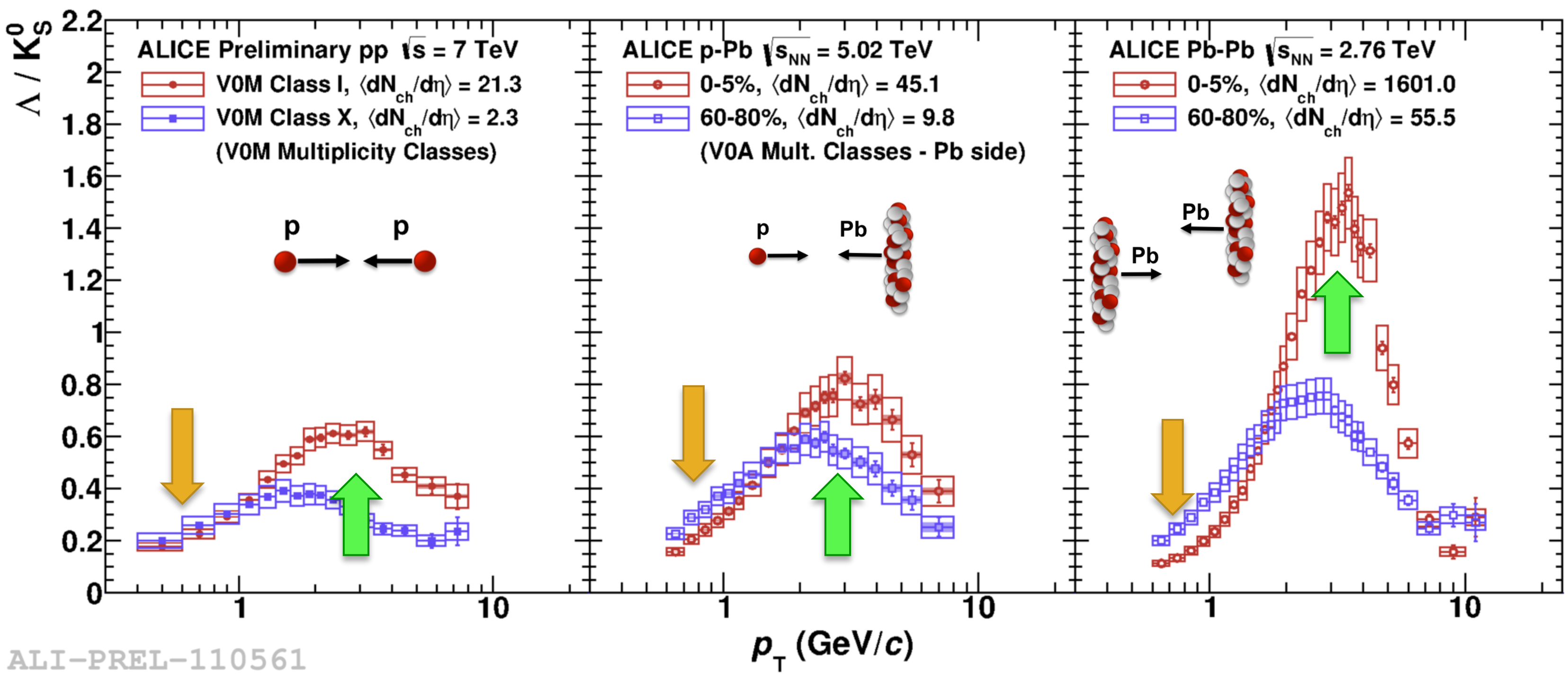
In small systems:

- **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?

Three systems compared: Λ/K^0_S

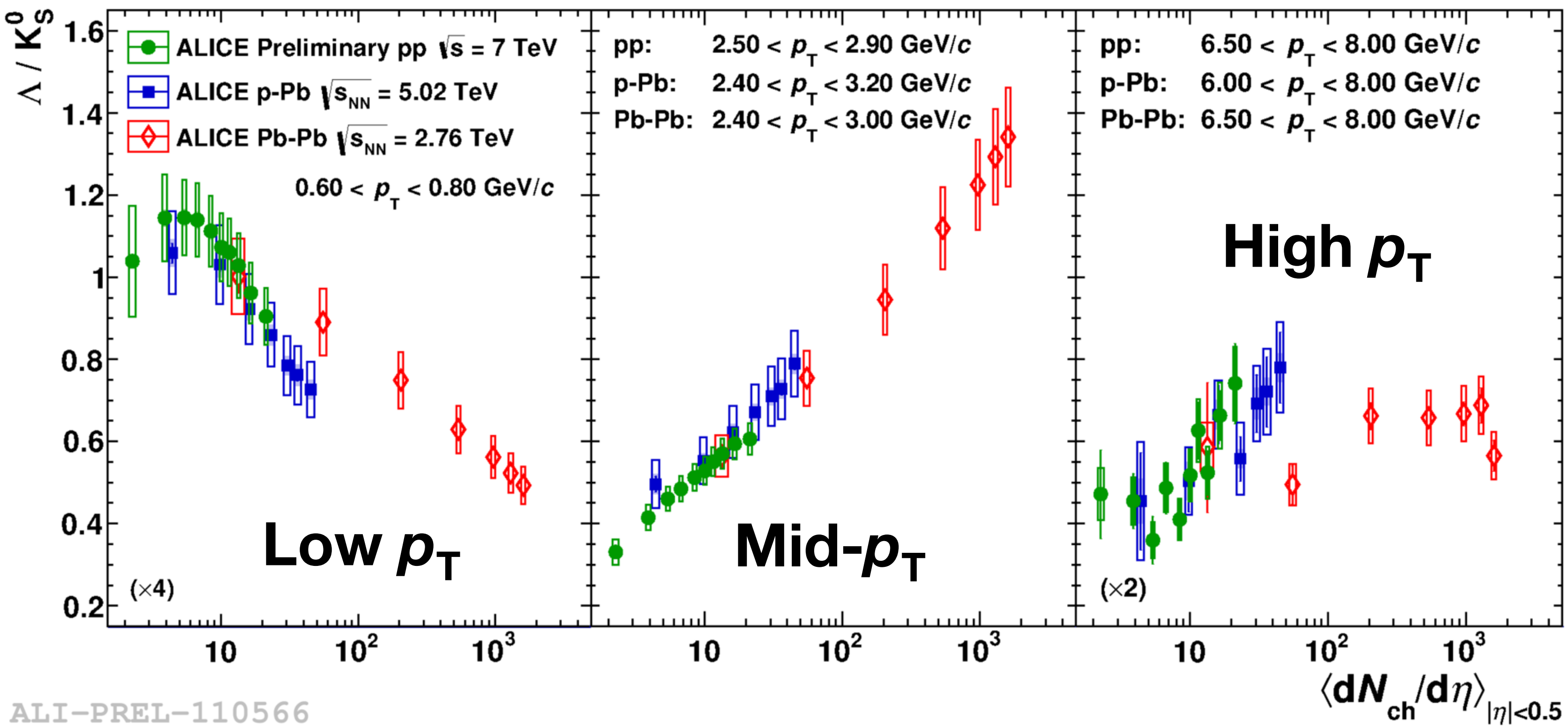
Phys. Rev. Lett. 111 (2013) 22301
Phys. Rev. C 93 (2016) 034913
Phys. Lett. B 728 (2014) 25-38
arXiv:1606.07424



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



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- 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

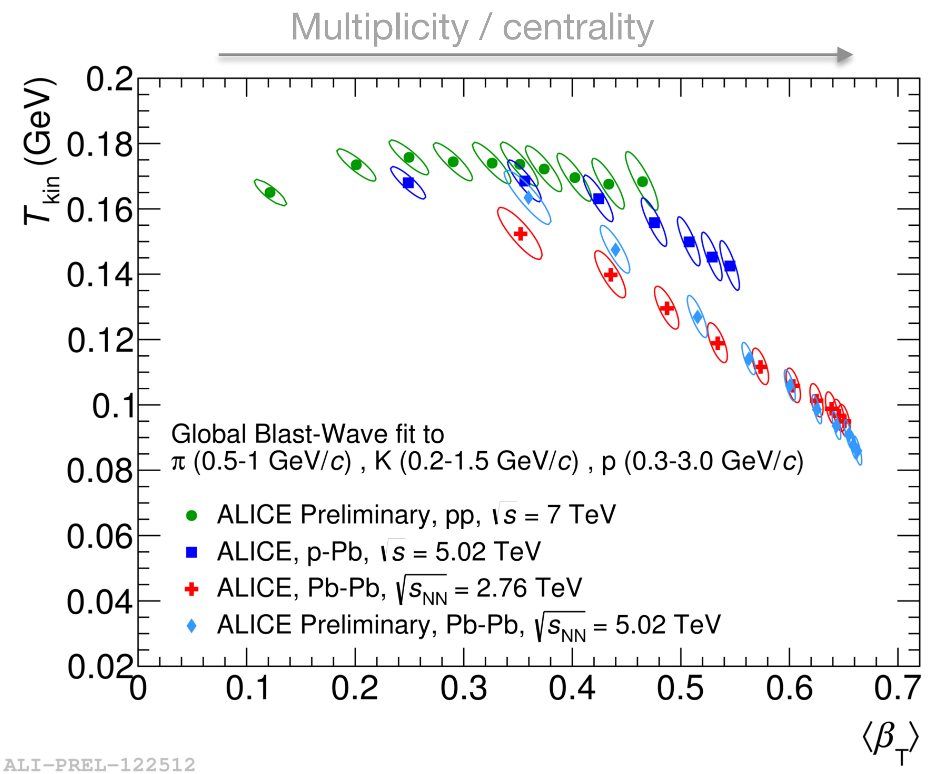
A simplified hydrodynamic model with 3 free fit parameters:

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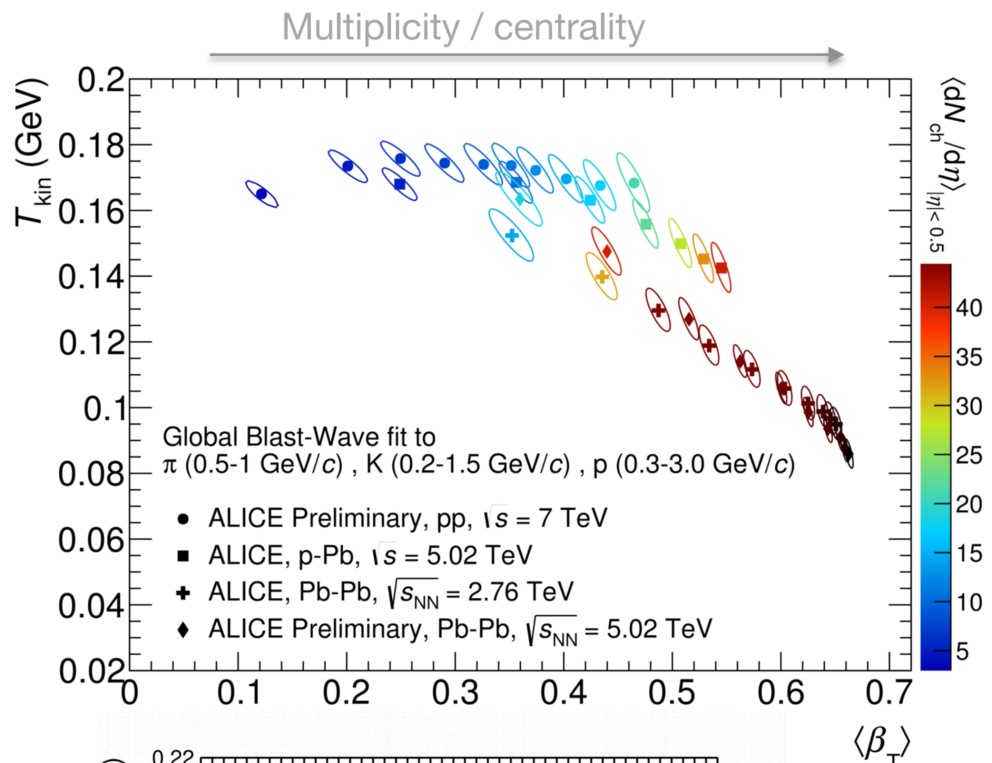
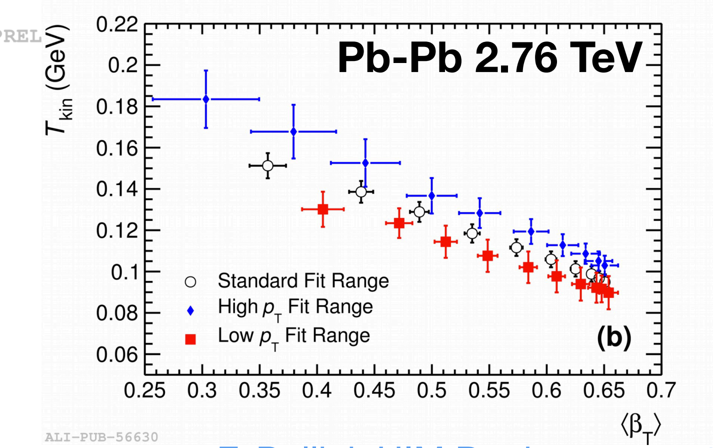
In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity

At similar multiplicity, $\langle\beta_T\rangle$ is larger for smaller systems

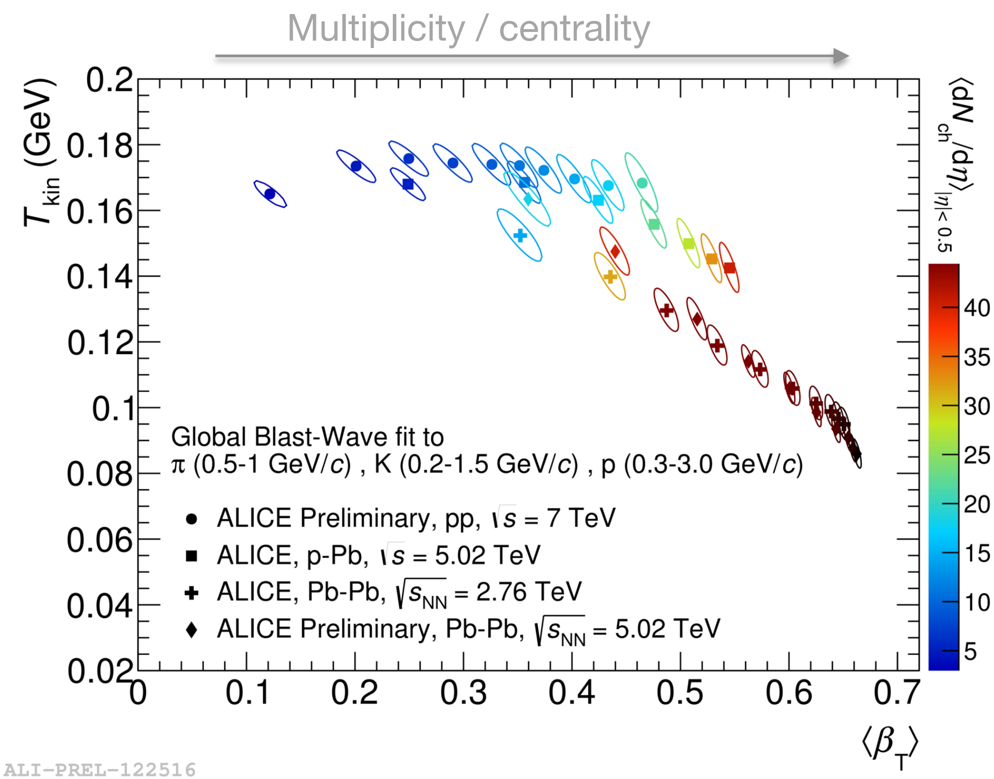
CAVEAT: sensitivity to **fit range** and the set of **particles included in the fit**





Radial flow?

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



Radial flow vs Color Reconnection

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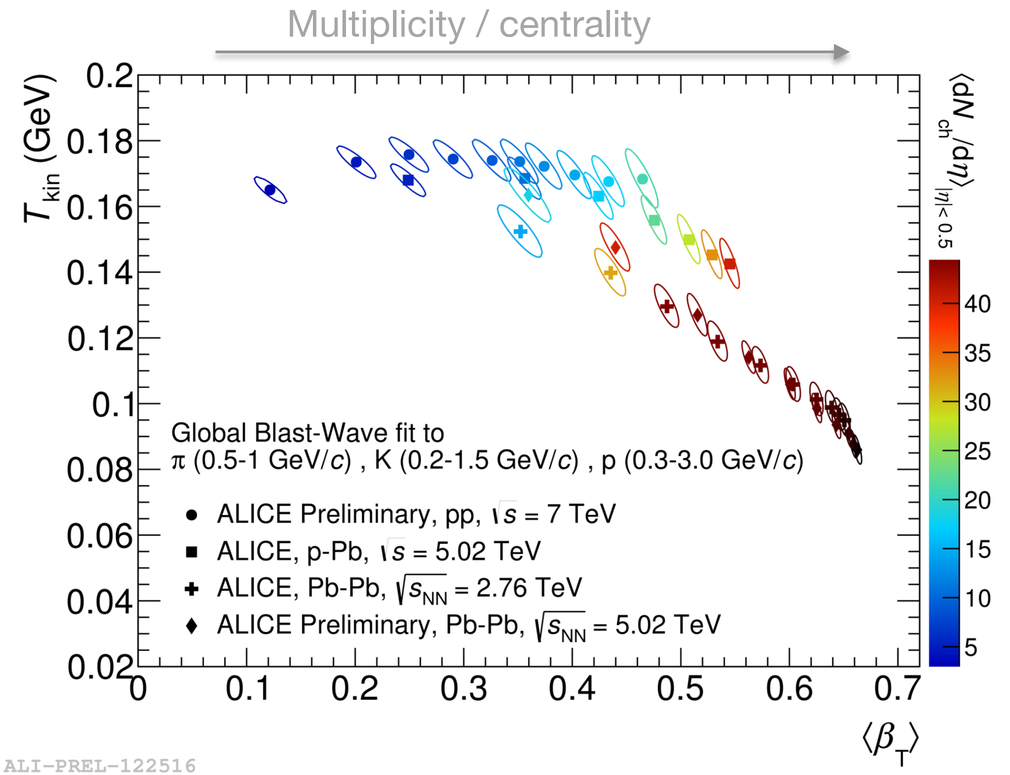
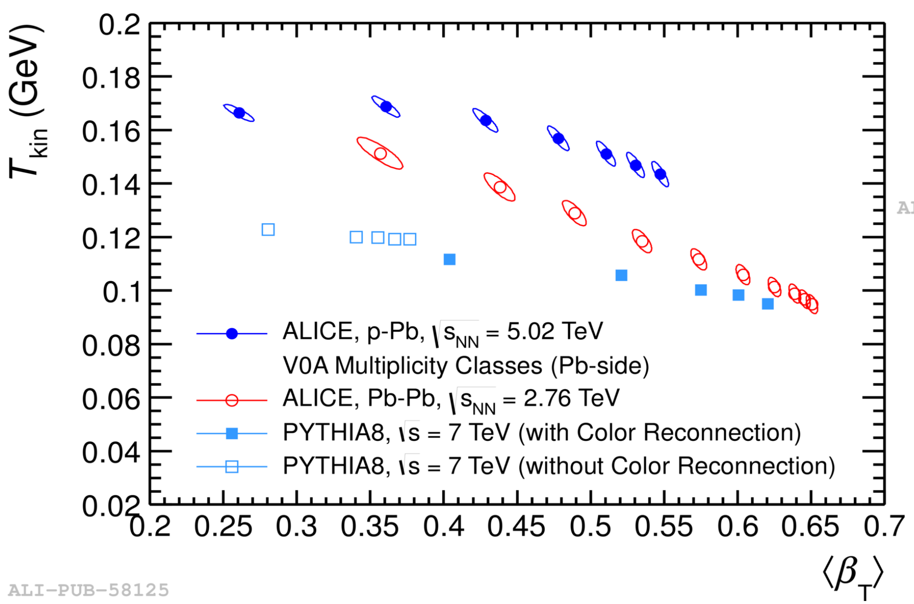
No, QCD effects such as **color reconnection** (CR) can **mimic the effects of radial flow**





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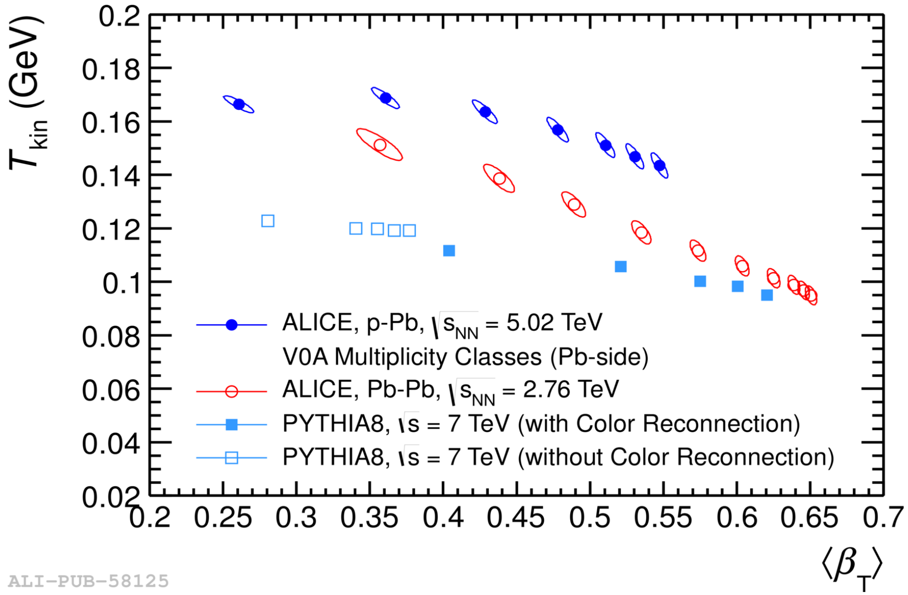

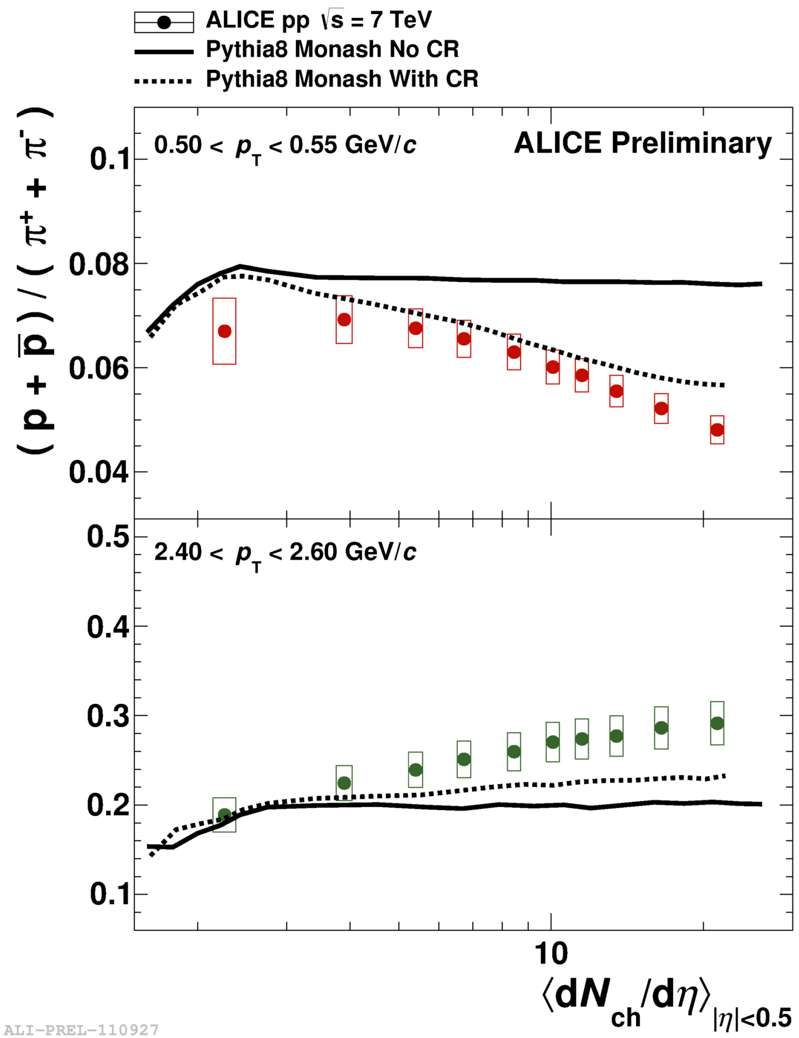

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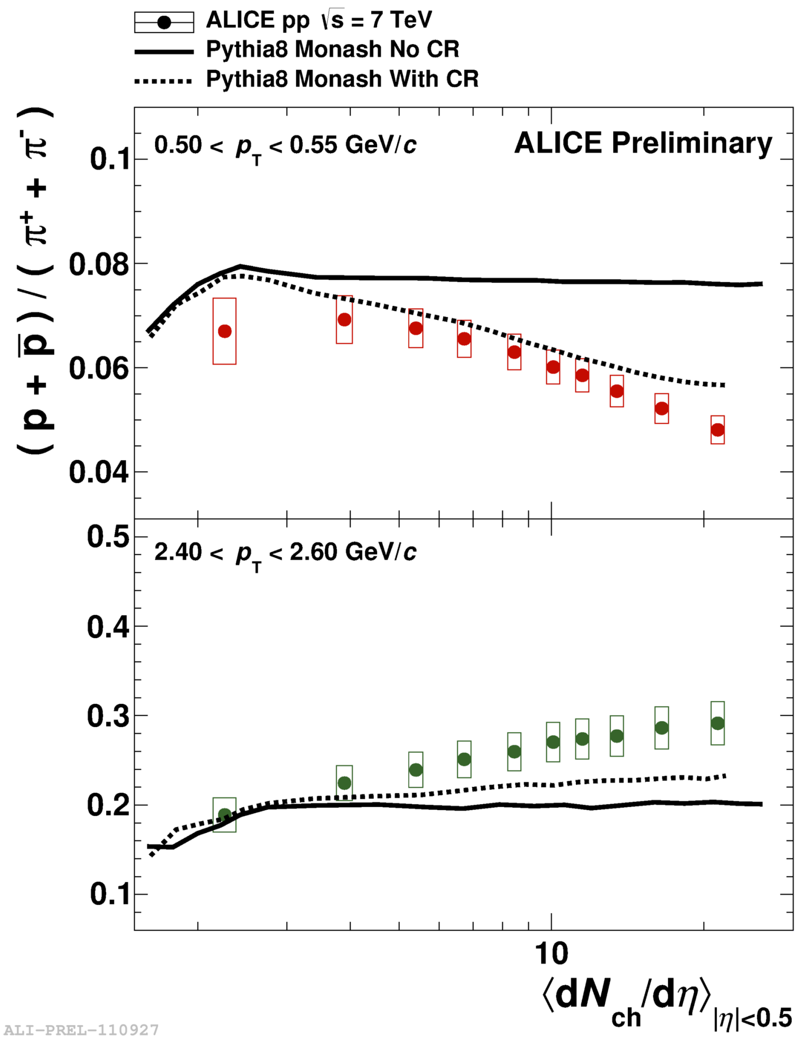
Hydrodynamical (radial) flow is present in a system in **local thermodynamical equilibrium**, which would lead also to **chemical equilibrium**

→ Look at the relative particle abundances!



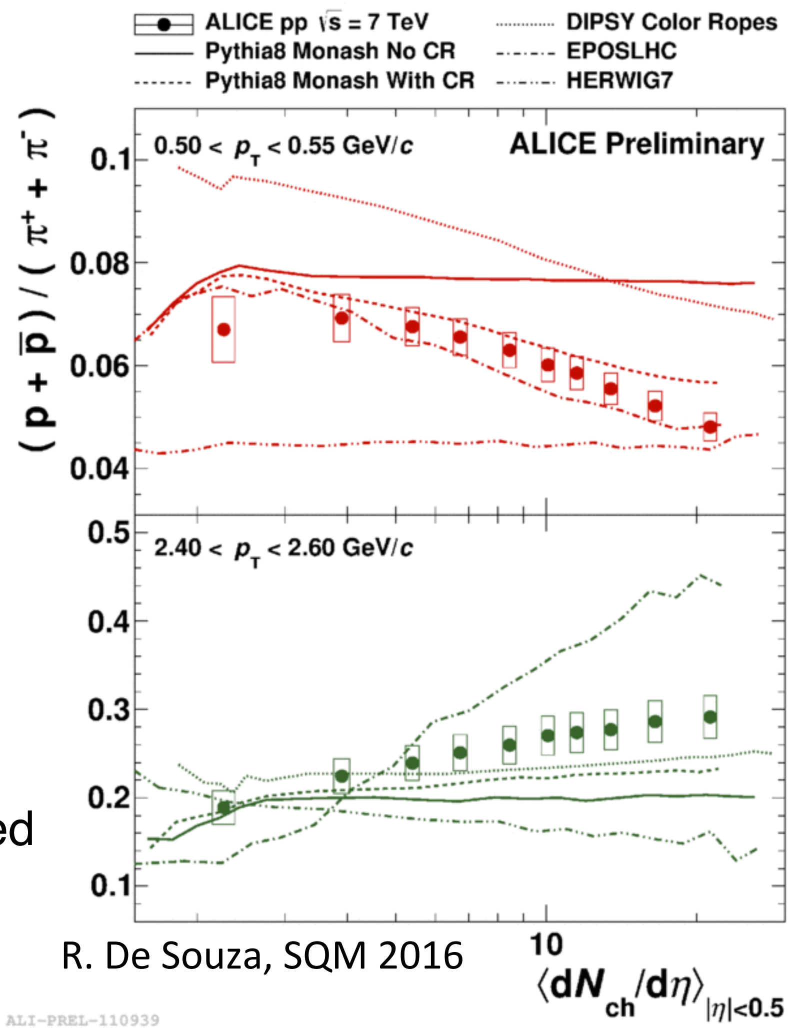
More model comparisons

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

Hadrochemistry

Are particles produced in thermal equilibration?
What drives particle composition in different systems?

Thermal production of hadrons

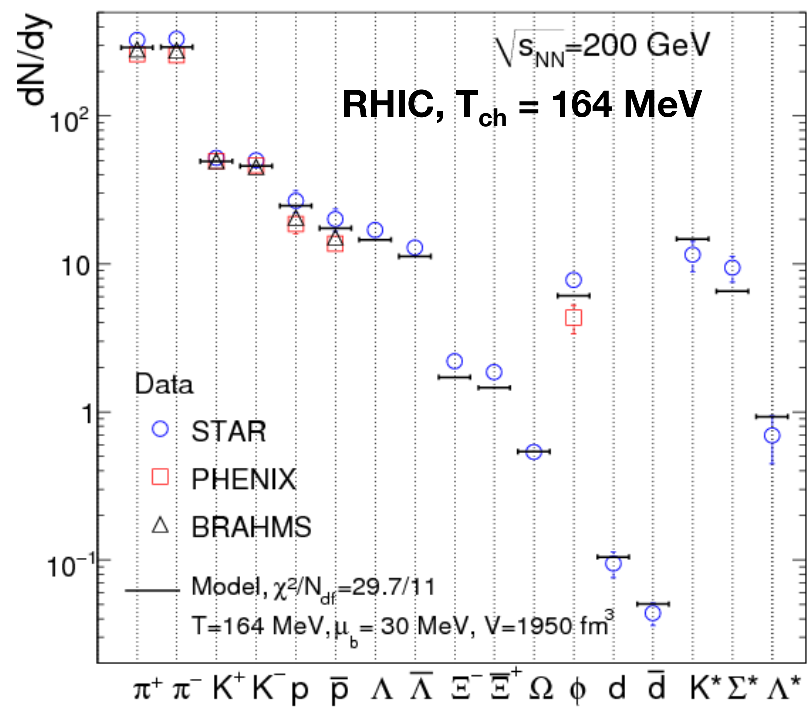
The thermal models described successfully hadron yields measured in AA collisions at SPS and RHIC, supporting the idea of matter in **local thermal and chemical equilibrium**

- Caveat: strangeness content, resonances

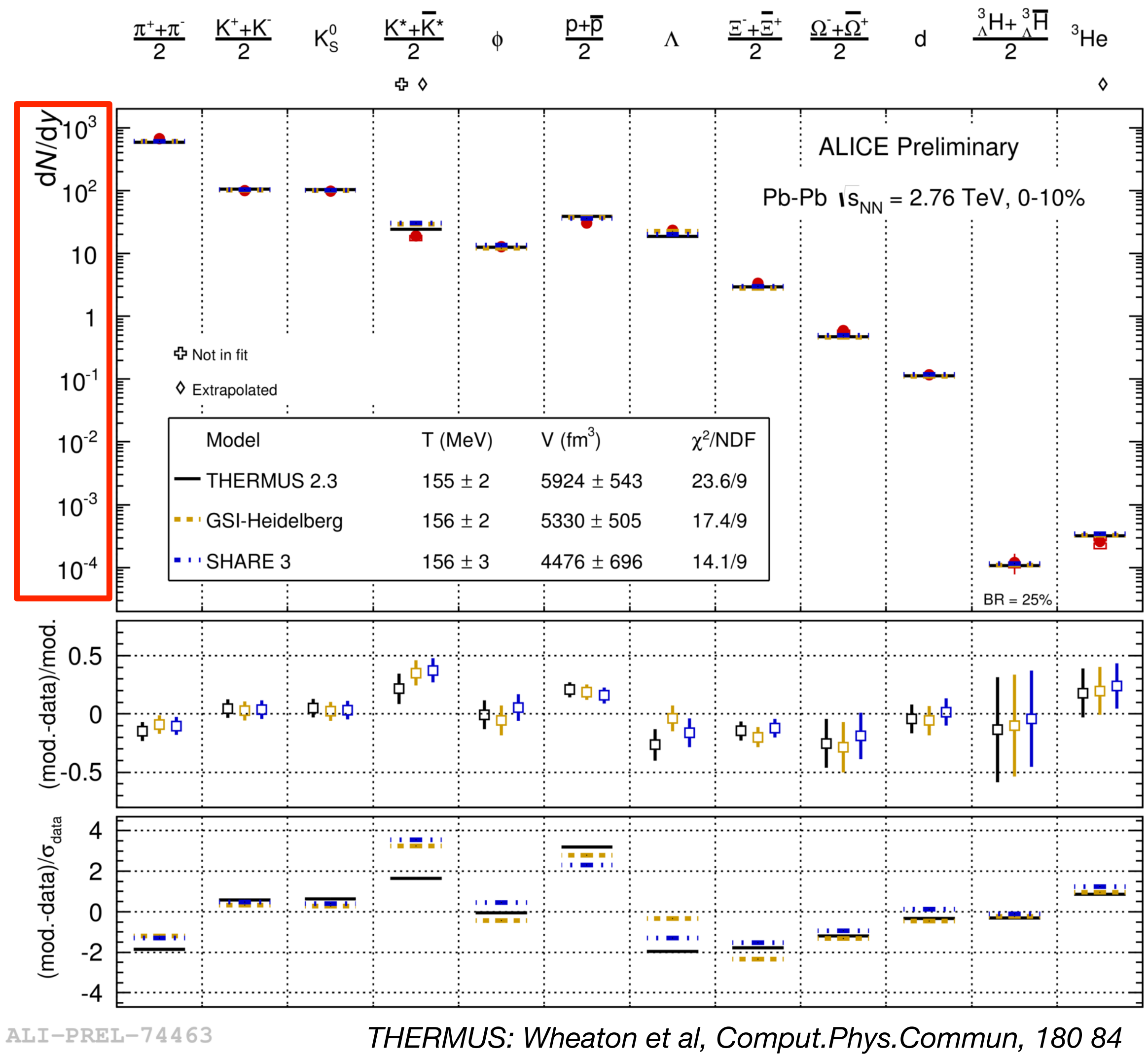
Several implementations of the **statistical hadronization model (SHM)**, with common features:

- **grand-canonical** (GC) partition function for a relativistic ideal quantum gas of hadrons
- main parameters: T_{ch}, μ_B, V, but 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**

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



Thermal model of particle production

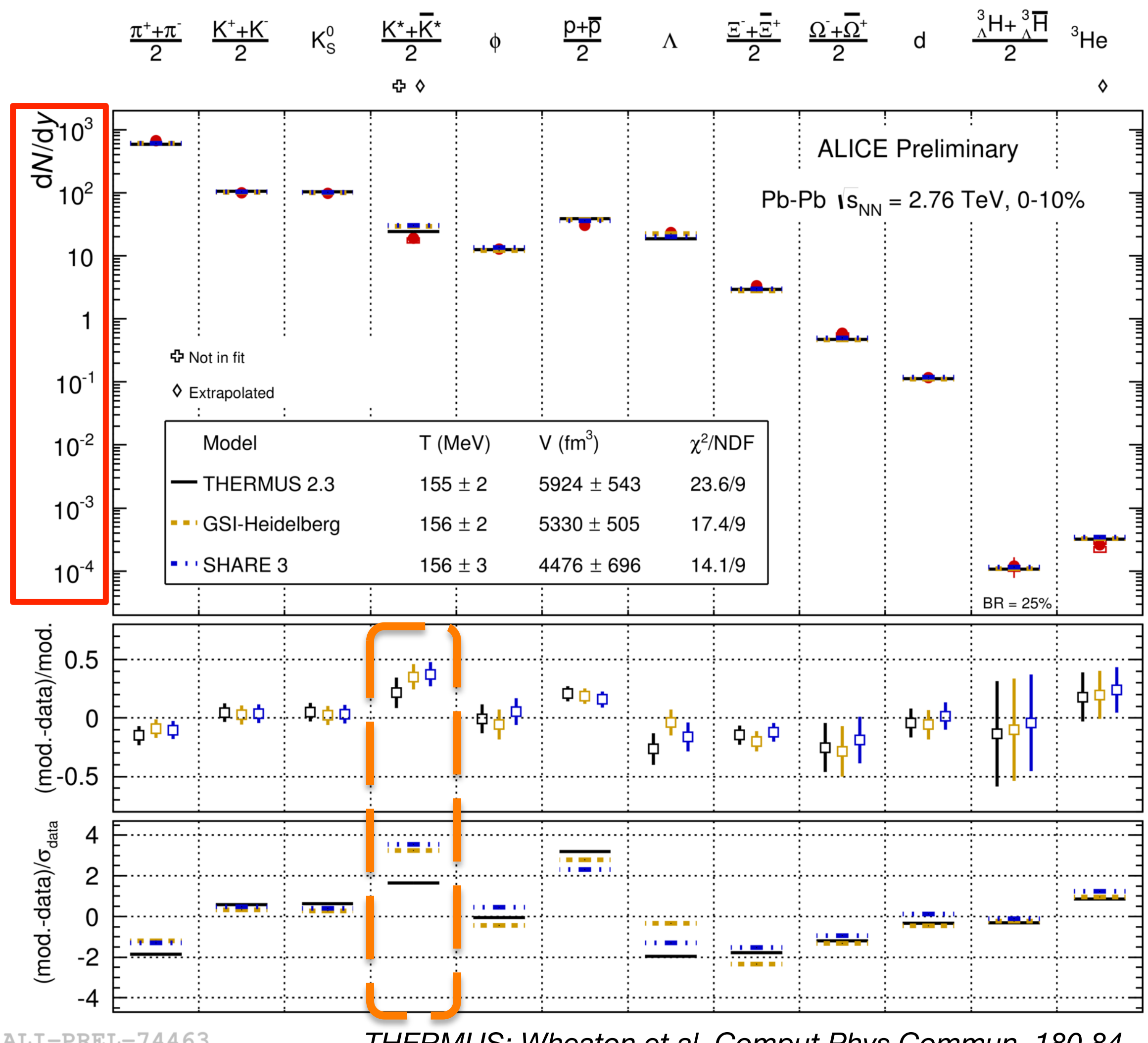


THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

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 of particle production



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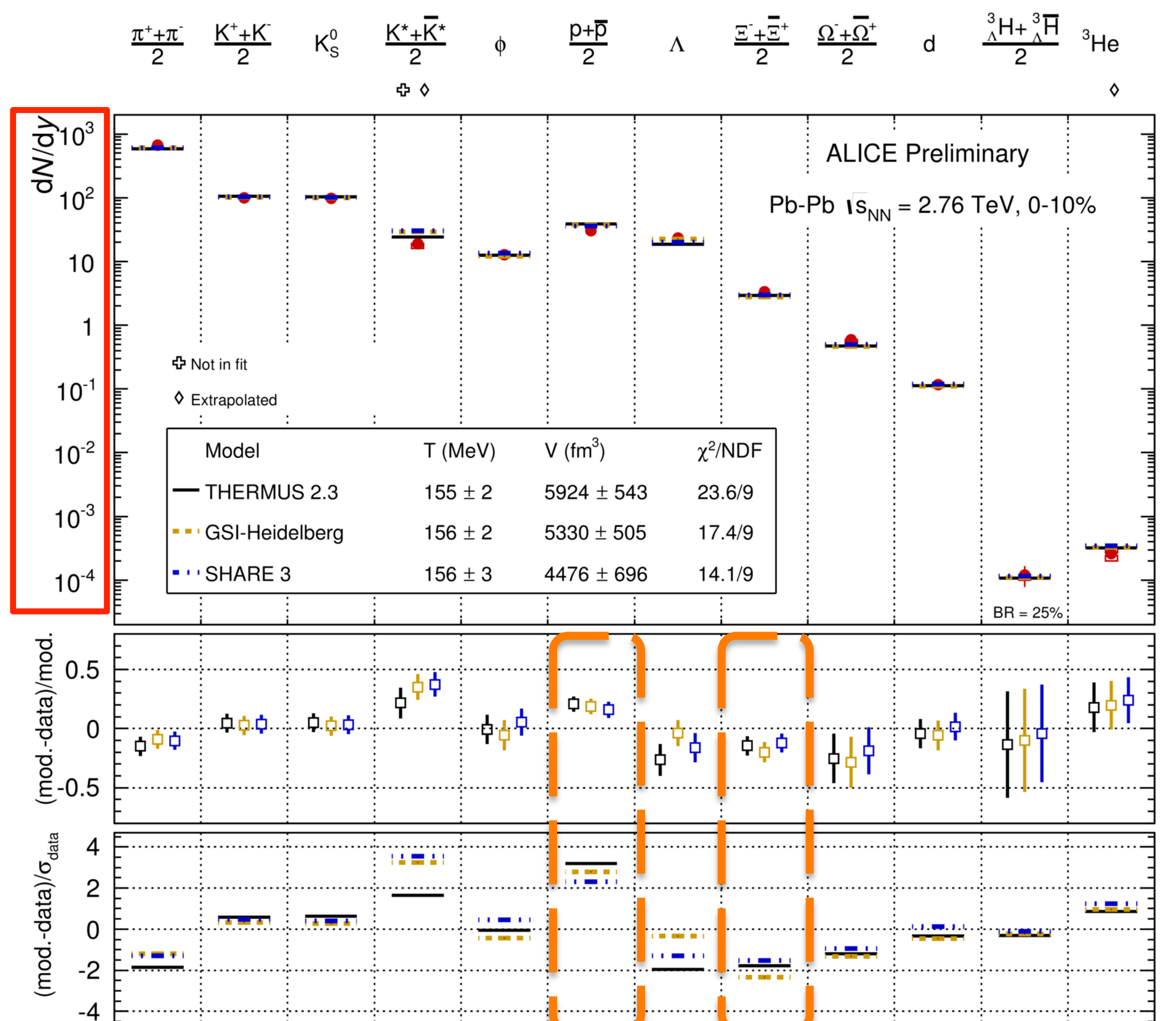
Deviation for **K^{*0} resonance**: re-scattering in the late hadronic phase?

Thermal model of particle production



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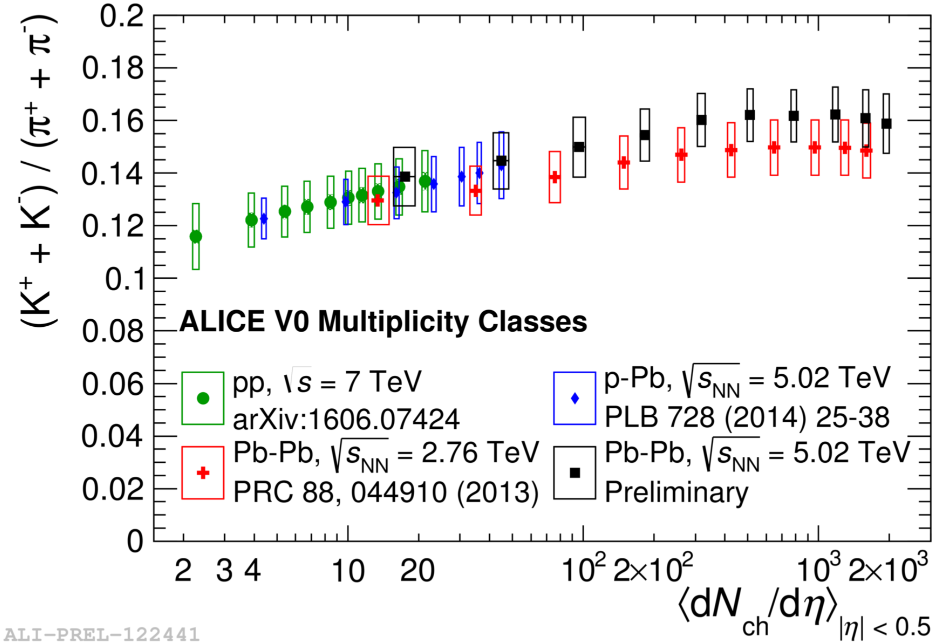
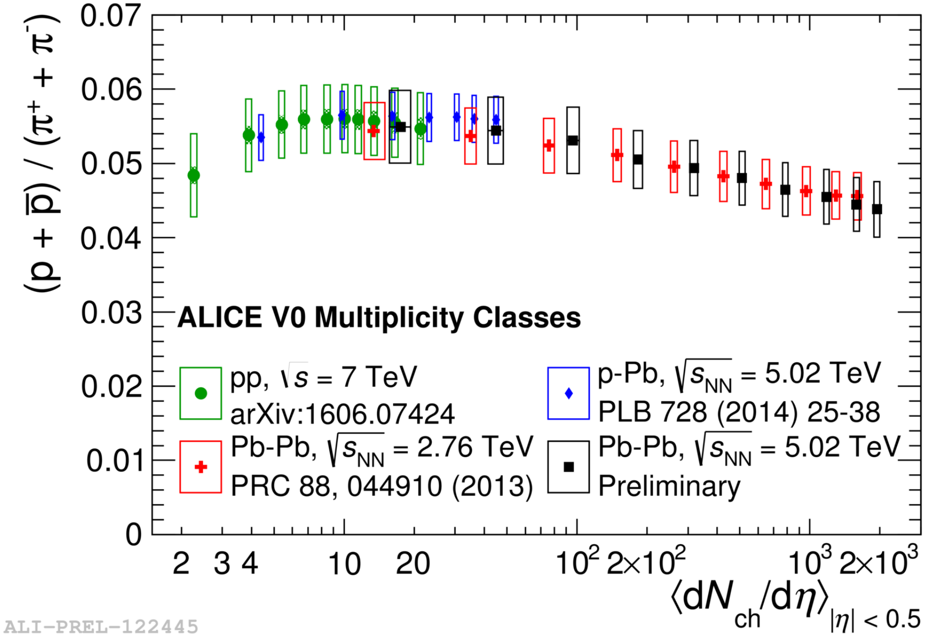
Deviation for **K*⁰ resonance**: re-scattering in the late hadronic phase?

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

p_T-integrated K/π, p/π ratios





Smooth evolution of the p/π and K/π ratios across different systems

- High multiplicity pp at 7 TeV and peripheral Pb-Pb at 2.76 and 5.02 TeV are consistent

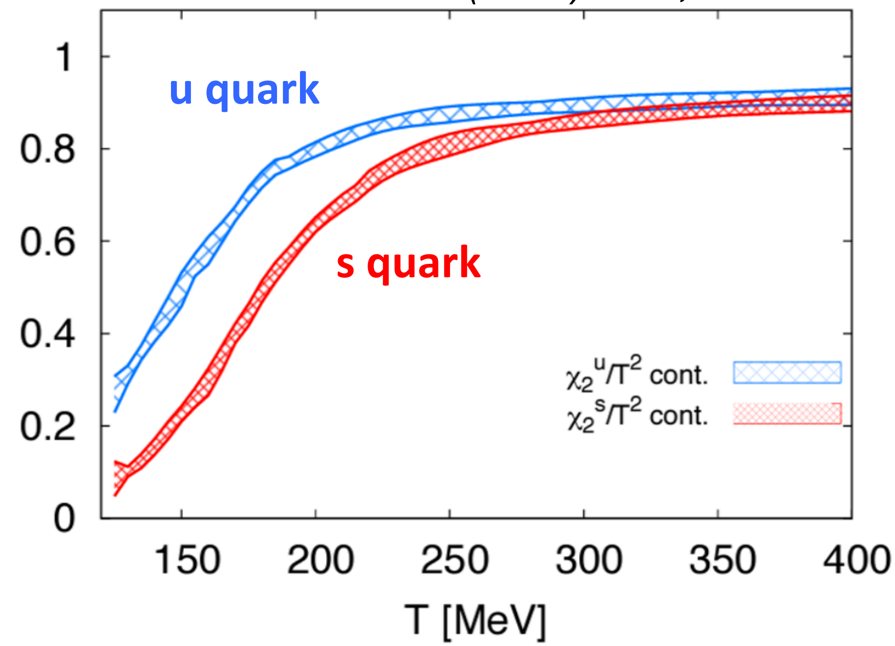
No significant evolution in Pb-Pb collisions **from 2.76 to 5.02 TeV**

Strangeness production

s quark can be **thermally** produced in QGP as u and d quarks. However,

- Strange quarks are more abundantly produced in Pb-Pb than in pp collisions: *strangeness enhancement vs. canonical suppression*
- *Do strange hadrons in Pb-Pb form at a different temperature wrt non-strange (e.g. the proton)?*
  → indications from one of the two major LQCD groups

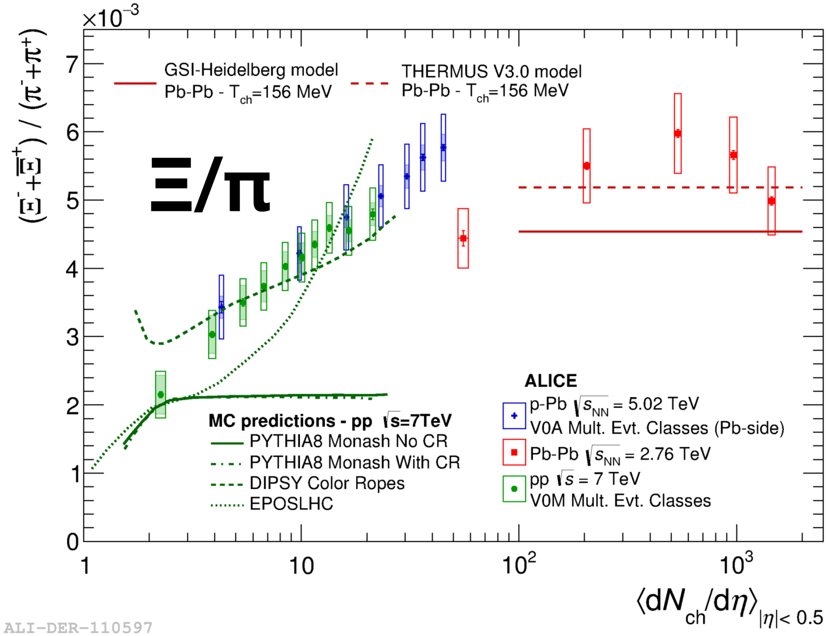
JPCS 736 (2016) no.1, 012018



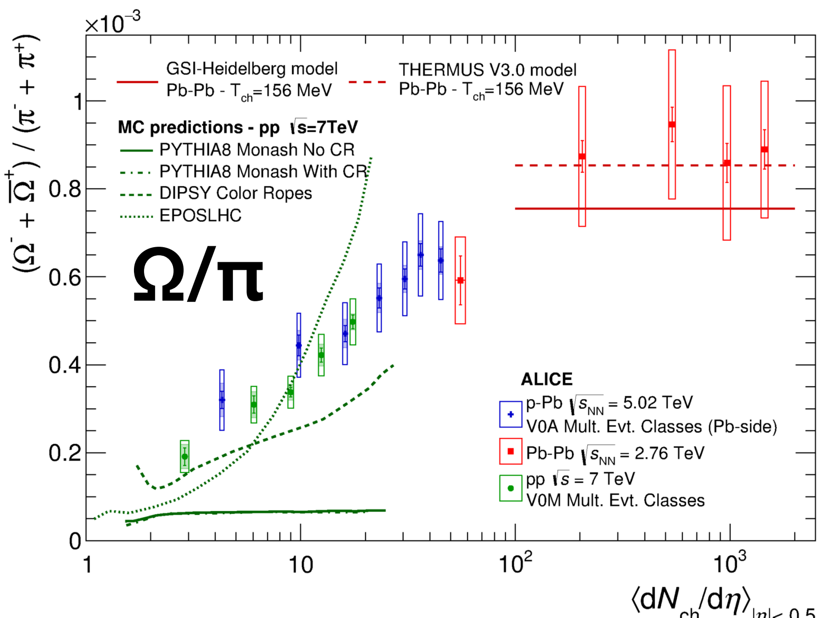
Wuppertal-Budapest-Houston Lattice QCD

Strangeness production

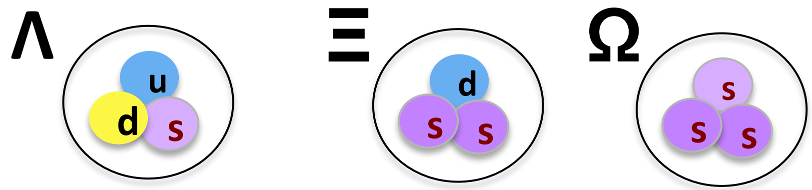
C. Bierlich et al., PRD 92 (2015) 094010
T. Pierog et al., arXiv:1306.0121
arXiv:1606.07424



ALI-DER-110597



ALI-DER-110609



In **Pb-Pb** collisions strangeness production reaches values consistent with predictions from the thermal model

In **pp** and **p-Pb** collisions (multi)strange to non-strange production smoothly increases with multiplicity

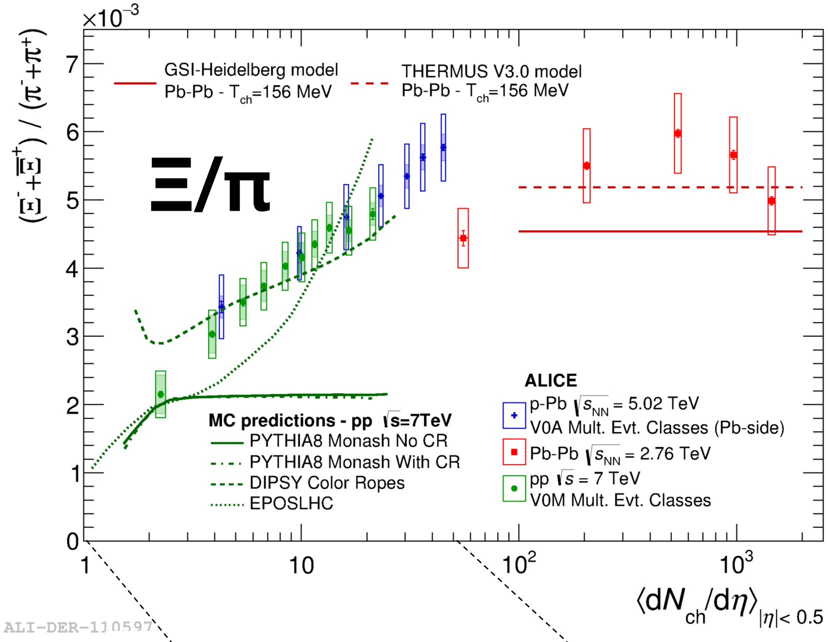
- Ξ/π reaches values seen in Pb-Pb
- Ω/π exhibits a strong rise (~2x) and reaches peripheral Pb-Pb

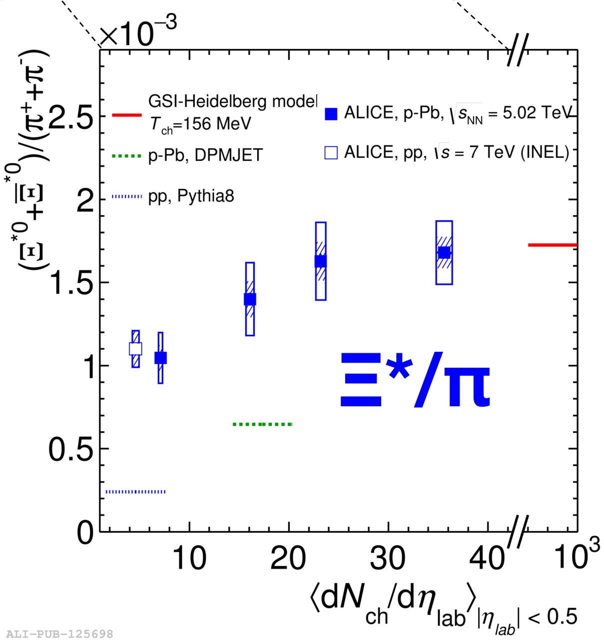
What is driving the increase in small systems?

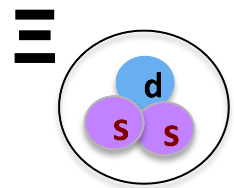
- ❑ Mass of the hadrons?
- ❑ Baryon/meson effect?
- ❑ Strangeness content?

Andronic et al, PLB 673 (2009) 142
Cleymans et al, PRC 74 (2006) 034903
Phys. Lett. B 728 (2014) 216
arXiv:1701.07797

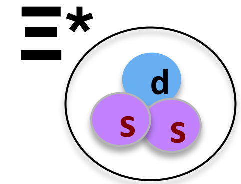
Strangeness production







M ~ 1300 MeV



M ~ 1500 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

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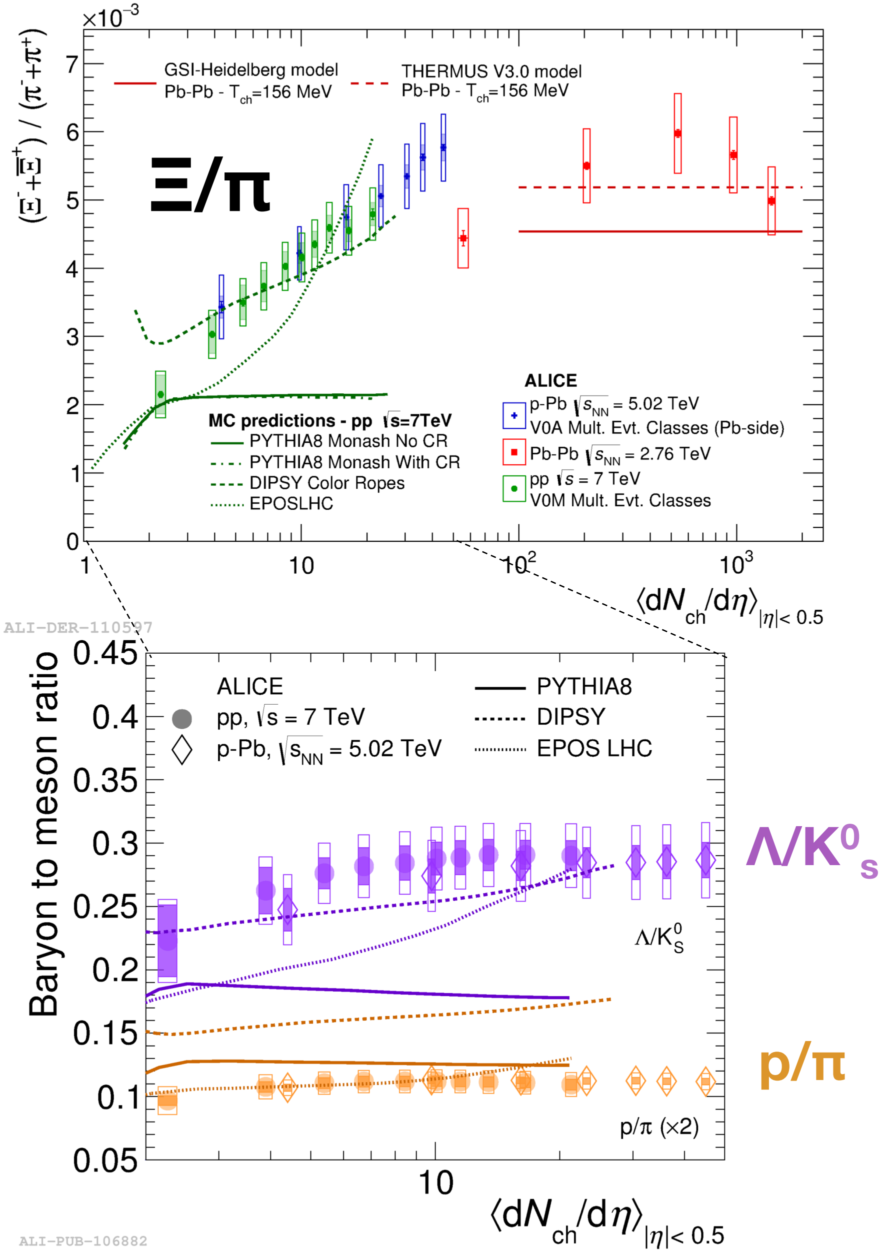


Baryon-to-meson ratios where the net strangeness content is zero, as **p/π** and **Λ/K^0_S**, are flat with multiplicity

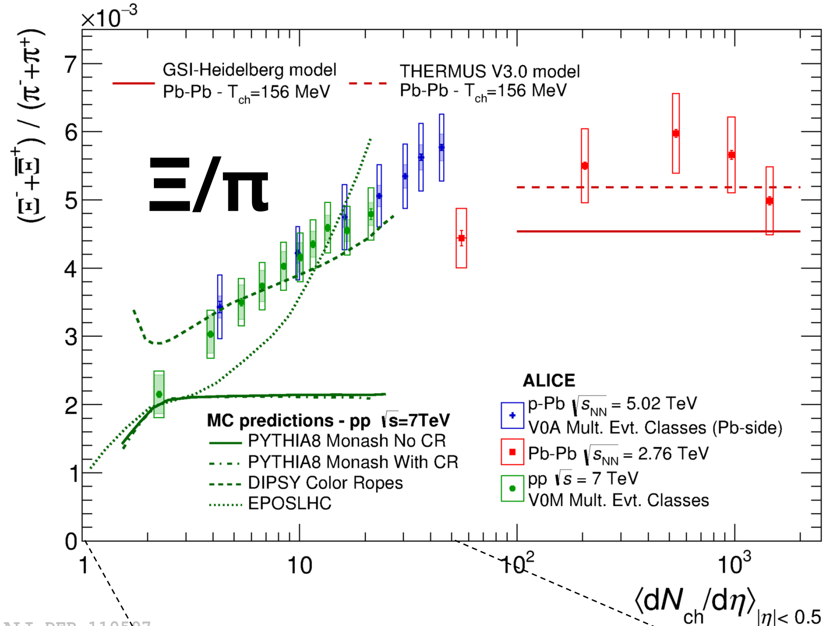
Models as DIPSY (color ropes) and EPOS LHC exhibit a trend with multiplicity but may still **need tuning**…

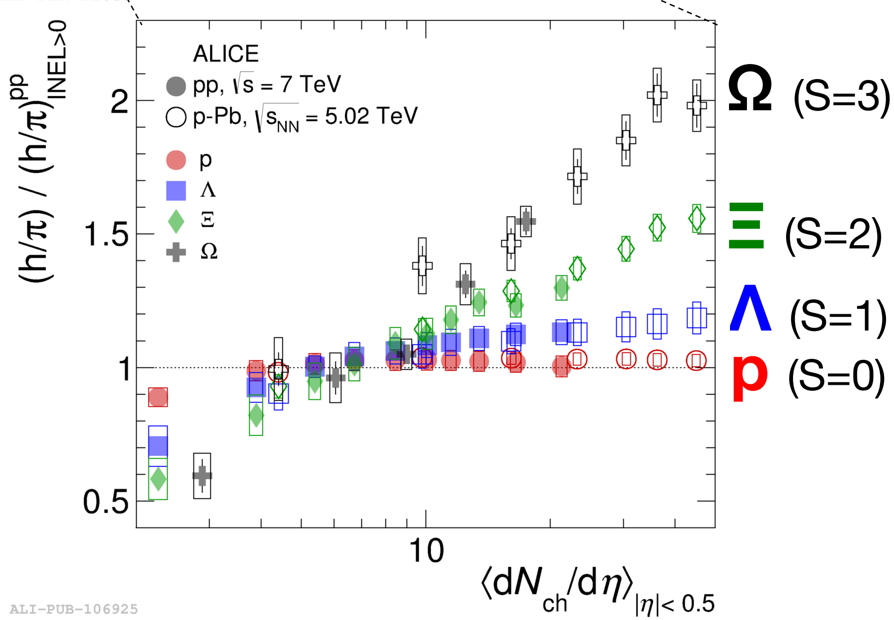
What is driving the increase in small systems?

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

Strangeness production

Andronic et al, PLB 673 (2009) 142
Cleymans et al, PRC 74 (2006) 034903
Phys. Lett. B 728 (2014) 216
arXiv:1701.07797





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?

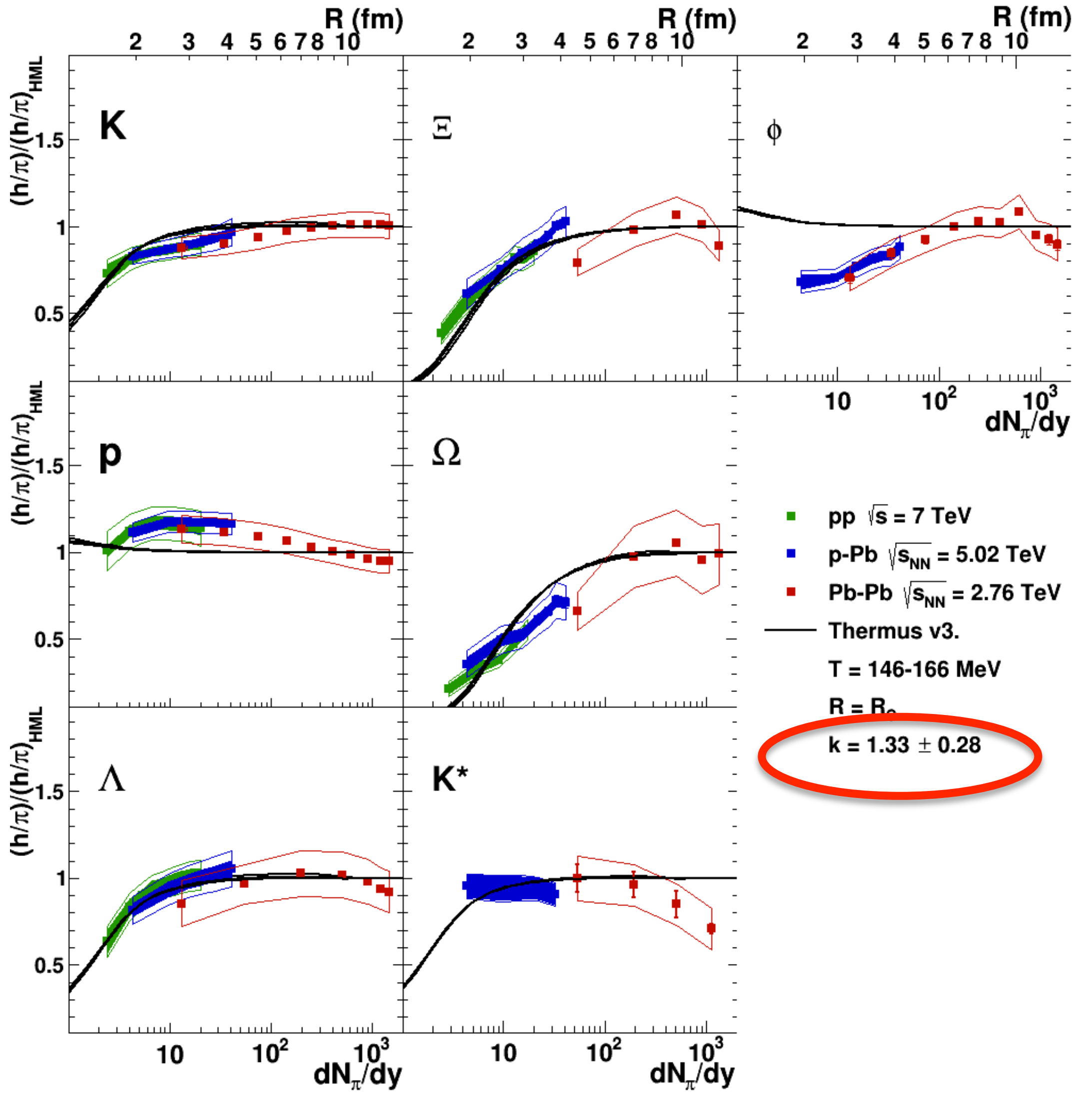
Strangeness production in the SHM

V. Vislavicius, A. Kalweit, arXiv:1610.03001

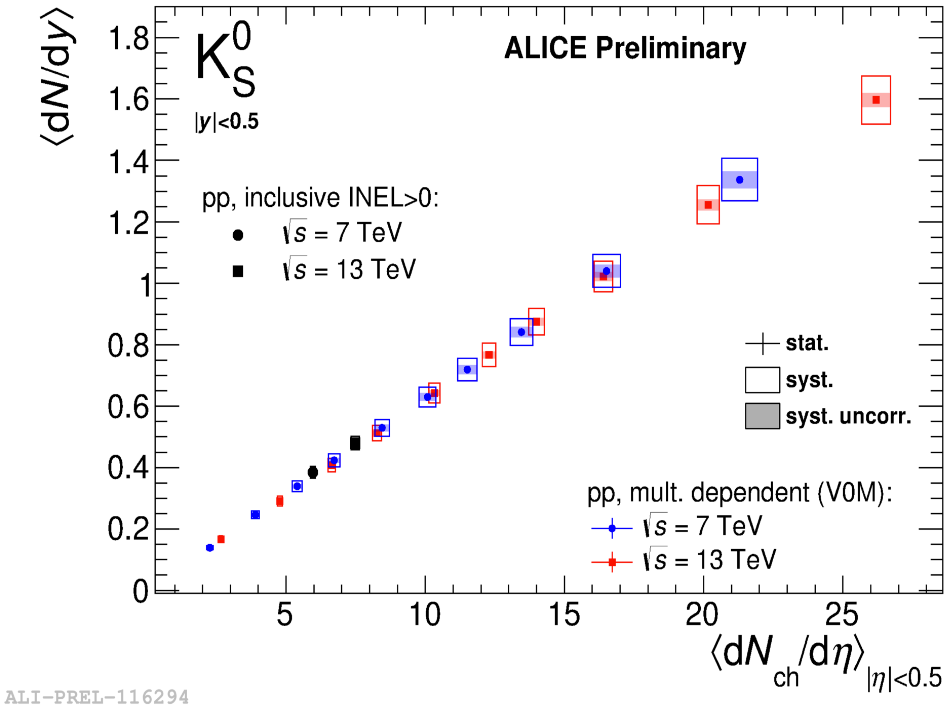
In equilibrium statistical (thermal) hadronisation (SHM) models, strangeness enhancement is a result of the **suppression of strange hadron production in small systems** due to the explicit **conservation of the strangeness** quantum number

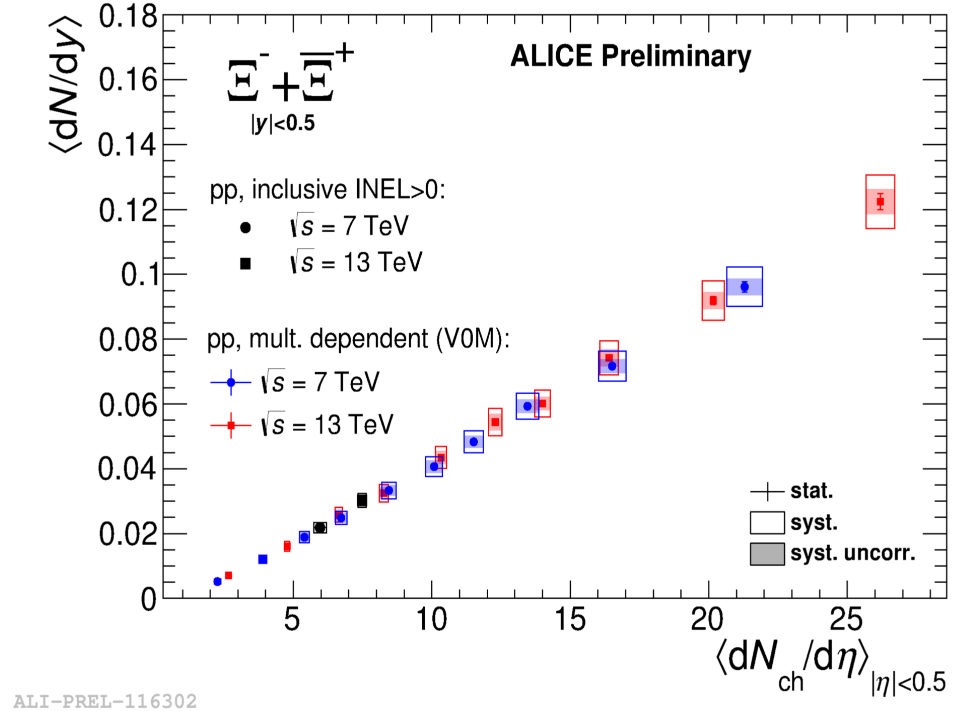
→ First comparisons to model calculations based on THERMUS code show agreement with data within uncertainties, except for φ

→ More studies ongoing on comparisons with alternative models, such as core-corona



√s- vs multiplicity- dependence

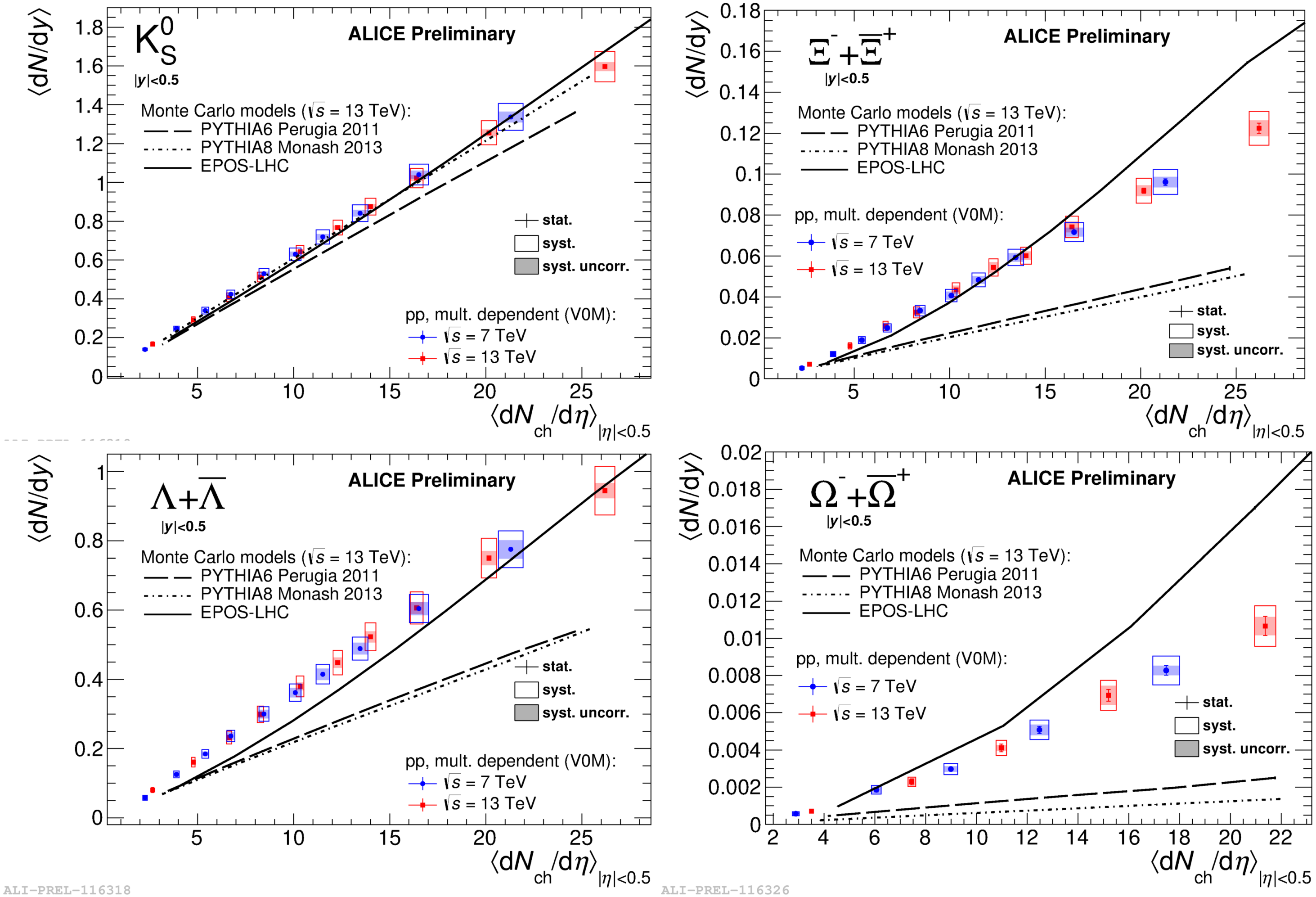




New measurements in pp at 13 TeV can be used to **disentangle multiplicity and energy dependence of particle production**

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**

Model comparison – Yields vs multiplicity and √s

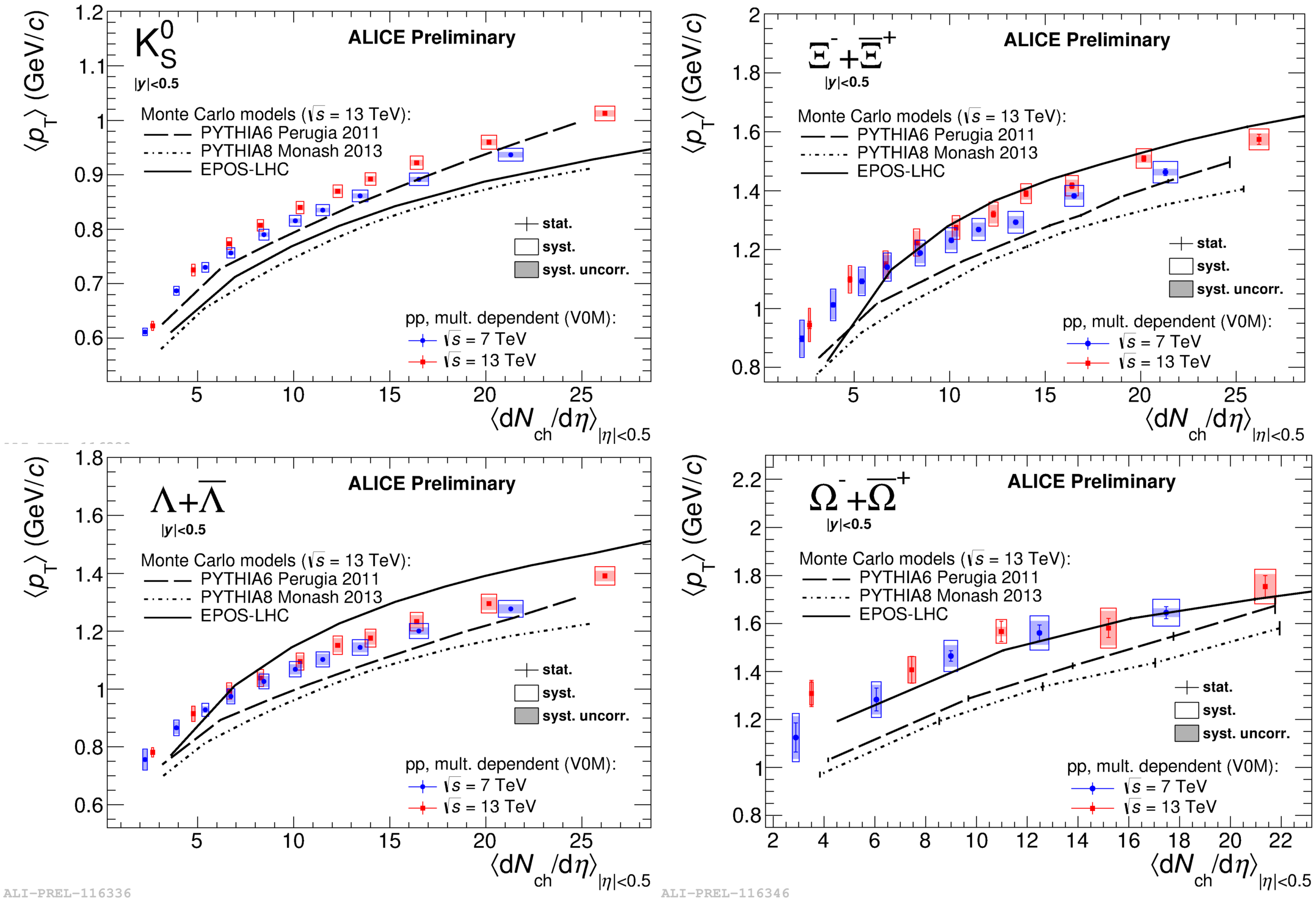


EPOS reproduces only qualitatively the trend with multiplicity

Pythia fails in describing (multi)strange baryon production

→ Some tuning (or new approaches) needed from the models side

Model comparison – Mean p_T vs multiplicity and $\sqrt{s}$



Average p_T for K^0_S higher at higher energy for similar multiplicities
Models reproduces only qualitatively the trend with multiplicity

Hadronic phase

How do the processes occurring in hadronic phase
affect the final state hadron distributions?

Probing the hadronic phase with resonances

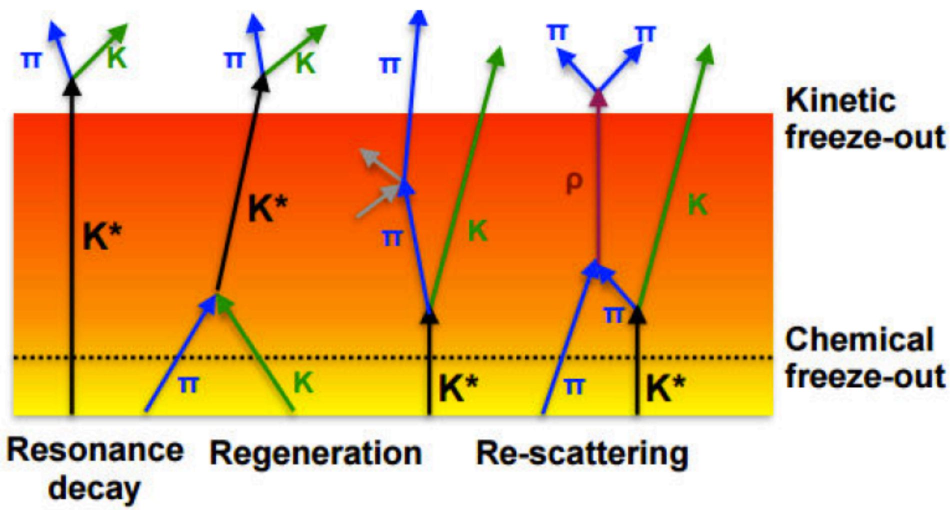
Resonances contribute to the study of **particle production mechanisms**
→ compare particles that differ by mass, baryon number, strangeness content

Hadronic resonances decay under the strong interaction with **lifetimes** (~10^{-23}s) of the same order of magnitude **as that of the fireball.**

Yields are fixed at chemical freeze-out

In the hadronic phase, resonances **decay** their decay products undergo **(pseudo)elastic processes** (re-scattering vs regeneration) depending on

- **duration** of the hadronic phase
- **lifetime** of resonances
- scattering **cross-section** of the decay products



Probing the hadronic phase with resonances

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- **duration** of the hadronic phase
- **lifetime** of resonances
- scattering **cross-section** of the decay products

→ **Compare resonances with different lifetimes**

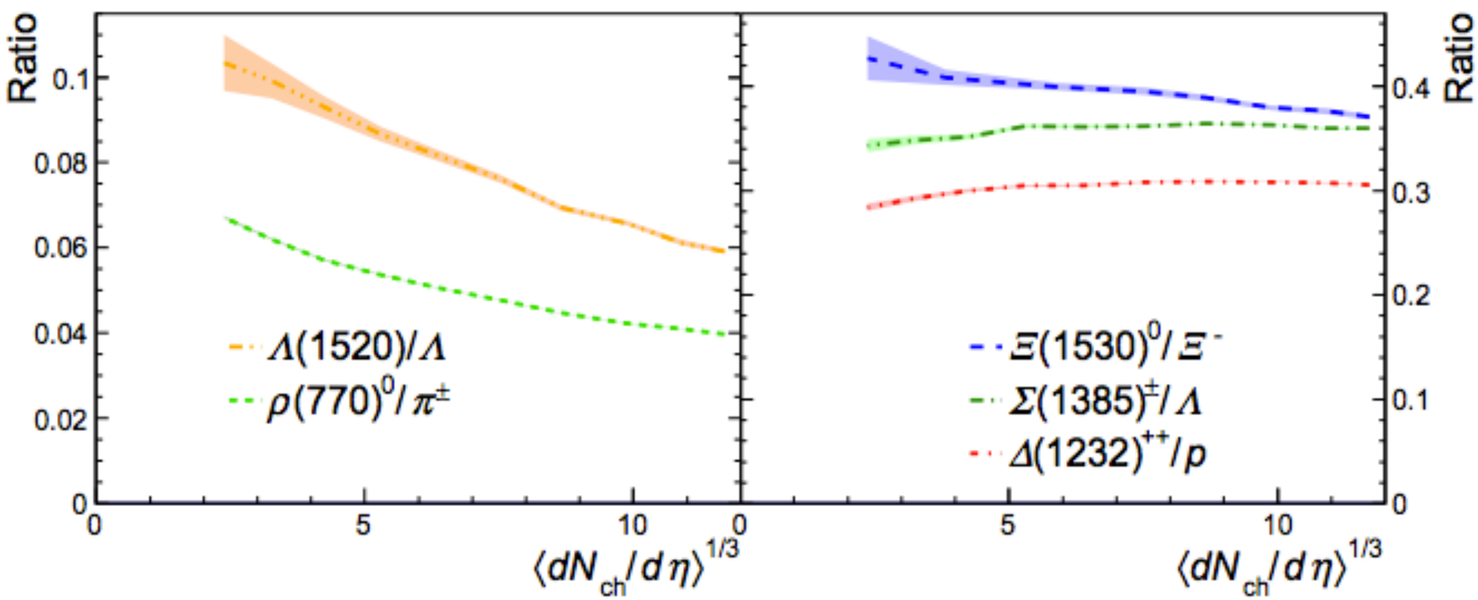
$\rho(770)^0$	$K(892)^0$	$\Sigma(1385)^{\pm}$	$\Lambda(1520)$	$\Xi(1530)^0$	$\Phi(1020)$
cτ ~ 1.3 fm	4 fm	5.5 fm	12.5 fm	22 fm	46 fm
S = 0	S = 1	S = 1	S = 1	S = 2	S = 0

Probing the hadronic phase with resonances

Key measurements:

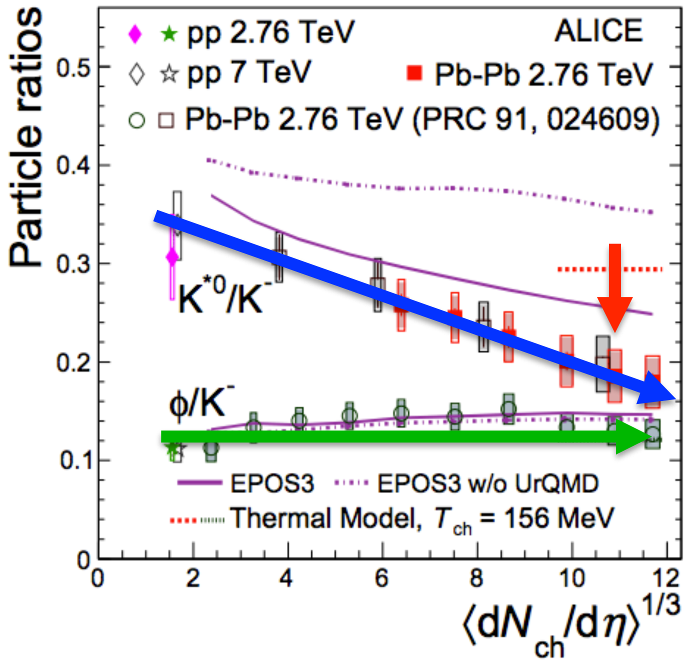
- Resonance yields and **ratios to long-lived particles vs. centrality**
  - Re-scattering effects expected to be stronger in central collisions, as the medium is denser and lasts longer
  - Depending on the species, regeneration effects might be dominant (e.g. Σ*)
- Spectra **down to low p_T**
  - Improve precision on the yields by minimising the extrapolated fraction
  - UrQMD predicts the largest effects for $p_T < 2$ GeV/c

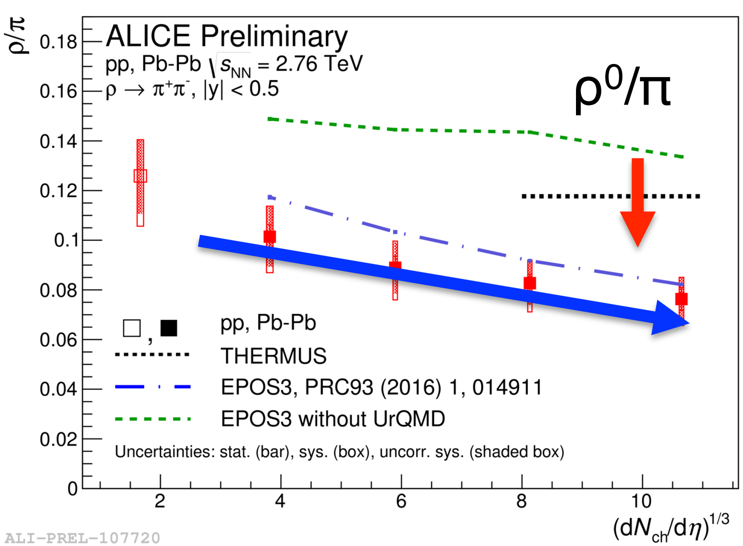
A. Knospe et al. Phys. Rev. C 93 (2016) 014911



Suppression in Pb-Pb collisions

A. Knospe et al., Phys. Rev. C 93 (2015) 014911
Phys. Rev. C 91 (2015) 024609
arXiv:1702.00555





lifetime →

	ρ^0	K^{*0}	$\Sigma^{*\pm}$	Λ^*	Ξ^{*0}	Φ
cτ (fm)	1.3	4	5.5	12.5	22	46
S	0	1	1	1	2	0

ρ^0/π, K^{*0}/K suppressed in central Pb-Pb
with respect to peripheral Pb-Pb and pp
and wrt the Grand-Canonical thermal model (**GCTM**)

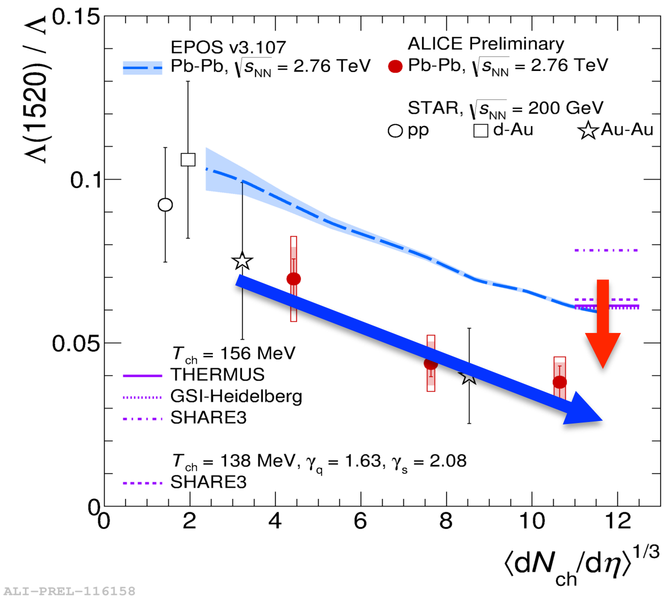
ϕ/K not suppressed (longer lived)

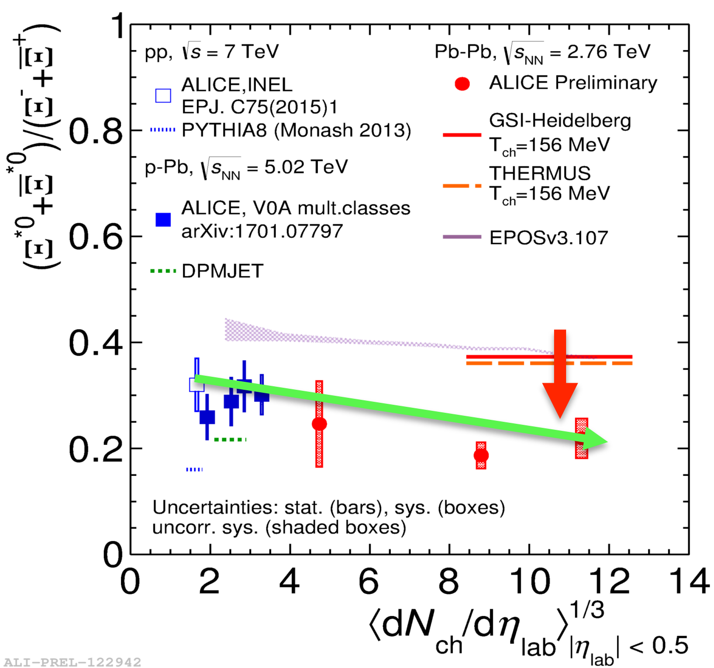
Trends qualitatively reproduced by **EPOS3 with** the hadronic cascade modeled by **UrQMD** (includes rescattering and regeneration)

→ K^{*0}, ρ^0 suppression understood as due to
dominant rescattering effects

Suppression in Pb-Pb collisions

A. Knospe et al., Phys. Rev. C 93 (2015) 014911
arXiv:1701.07797





lifetime →

	ρ^0	K^{*0}	$\Sigma^{*\pm}$	Λ^*	Ξ^{*0}	Φ
cτ (fm)	1.3	4	5.5	12.5	22	46
S	0	1	1	1	2	0

Λ*/Λ suppressed in central wrt peripheral and **wrt GCTM**

Ξ*/Ξ⁻ suppressed wrt pp, p-Pb and **GCTM**, despite the 5x longer lifetime wrt K*

→ The set of results are suggestive of the existence of an hadronic phase lasting long enough for the yields of short-lived resonance to be affected by **re-scattering**

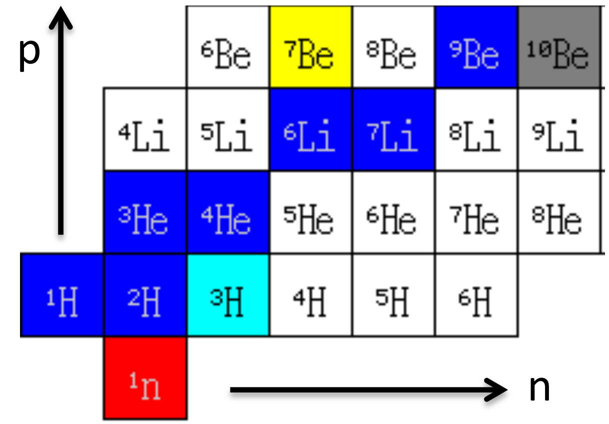
Light (anti-)nuclei production

S. T. Butler, C. A. Pearson. Phys. Rev. 129, 836 (1963)

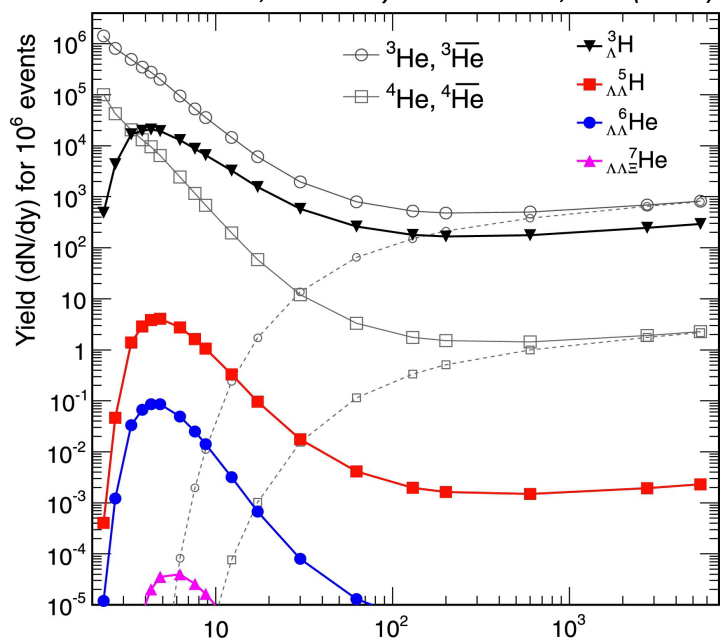
At the LHC energies, light nuclei and anti-nuclei are abundantly produced according to two possible mechanisms:

- **Thermal production**: hadrons emitted from the interaction region at chemical freeze-out (T_{ch})
  → **Abundance ∝ exp (- m / T_{ch})**

- **Coalescence**: (Anti-)baryons close in phase space at the kinetic freeze-out can form a(n) (anti-)nucleus
  - The coalescence parameter (B_A) expresses the formation probability
  - in simple coalescence model, B_A is expected to be independent of p_T and centrality



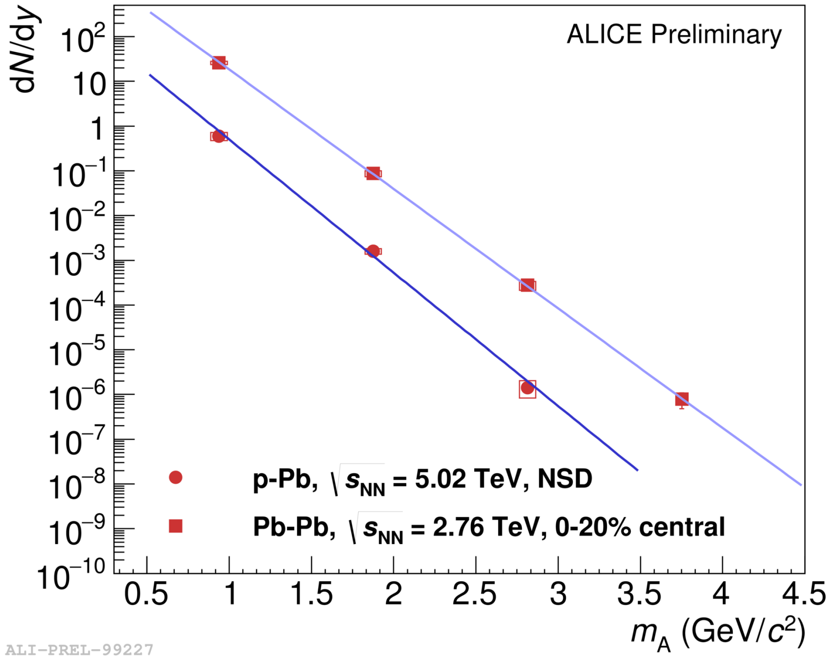
A. Andronic, et al. Phys. Lett. B 697, 203 (2011)

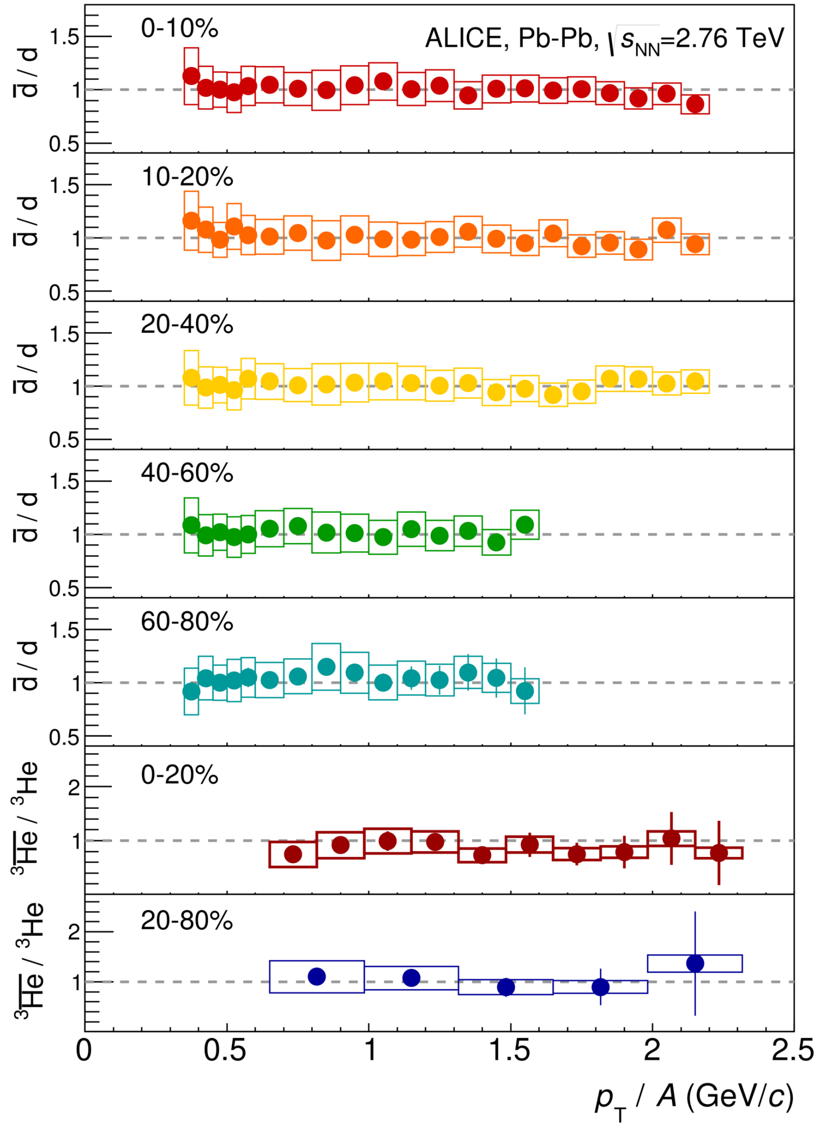


Light (anti-)nuclei production

At the LHC energies, **light nuclei and the corresponding anti-nuclei are produced in equal amounts**

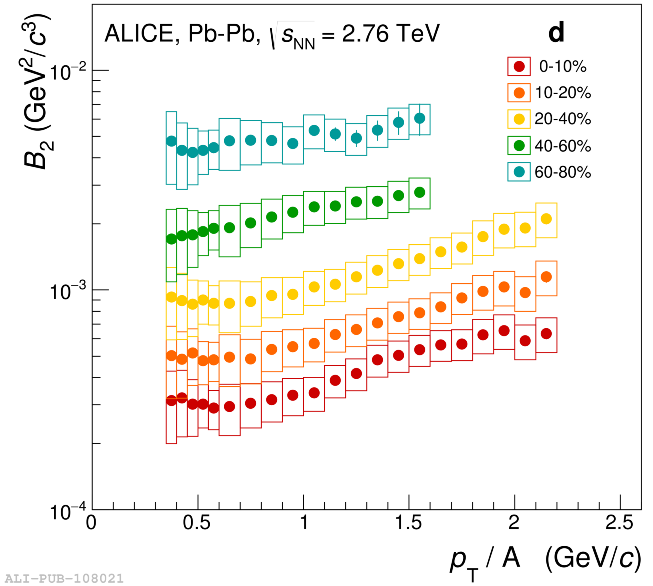
Mass ordering of nuclei: "penalty factor" for adding one nucleon ~300
- thermal production predicts in first order
$dN/dy \propto \exp(-m/T)$

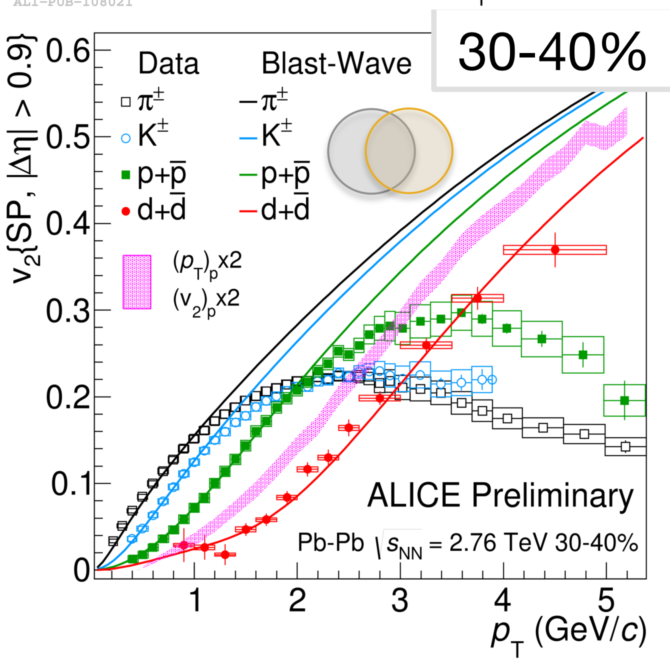




Light (anti-)nuclei production

Phys. Rev. C 93 (2015) 024917





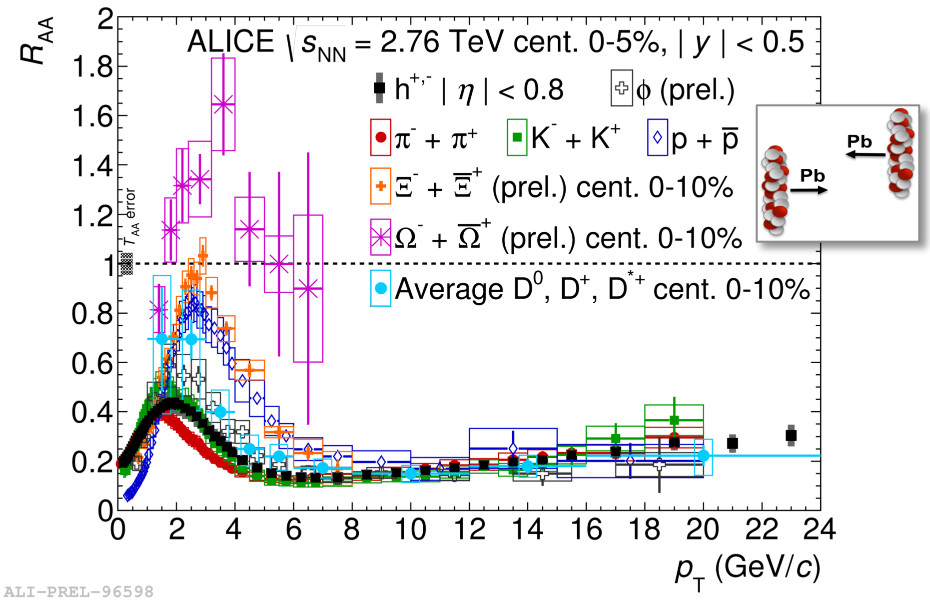
Measurements of d and ^{3}He yields and elliptic flow coefficient v_2 in Pb-Pb at 2.76 TeV show

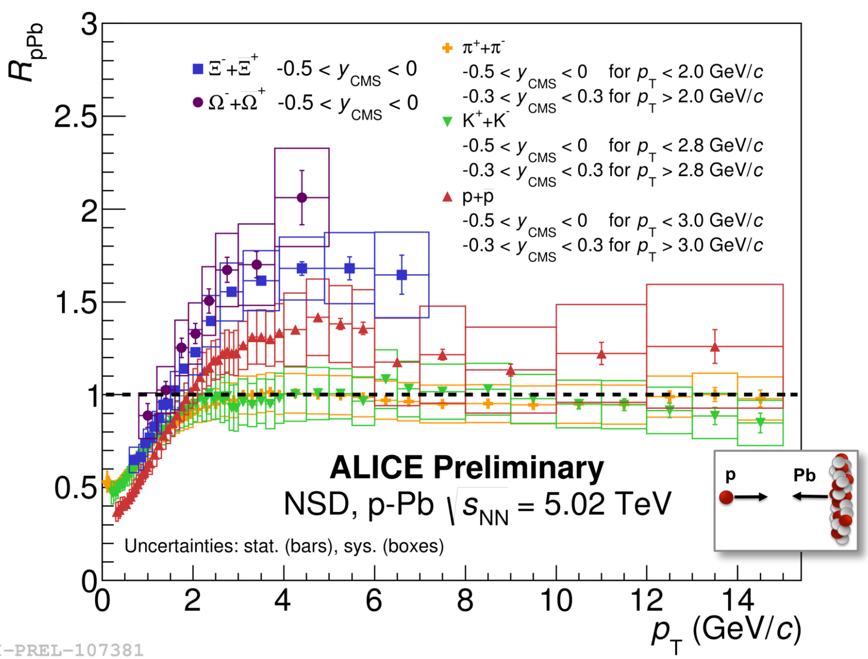
- yields are in **agreement with thermal model**
- **Hydrodynamic** (Blast-Wave) **model** from a simultaneous fit of π,K,p spectra and v_2 describes the deuteron spectra and v_2
  → **common radial expansion** with other light hadrons
- Deuteron v_2 follows mass scaling
- trend of the coalescence parameter with p_T and centrality can be explained by space-momentum correlations caused by radial flow
- **simple coalescence model** from measured proton as $2v_{2,p}(2p_{T,p})$ **fails** in describing v_2

Nuclear modification of light flavour hadrons

ALICE, PRC 93 (2016) 034913

Nuclear modification of spectra





$$R_{xA}(p_T) = \frac{d^2 N_{ch}^{xA} / d\eta dp_T}{\langle T_{xA} \rangle d^2\sigma_{ch}^{pp} / d\eta dp_T}$$

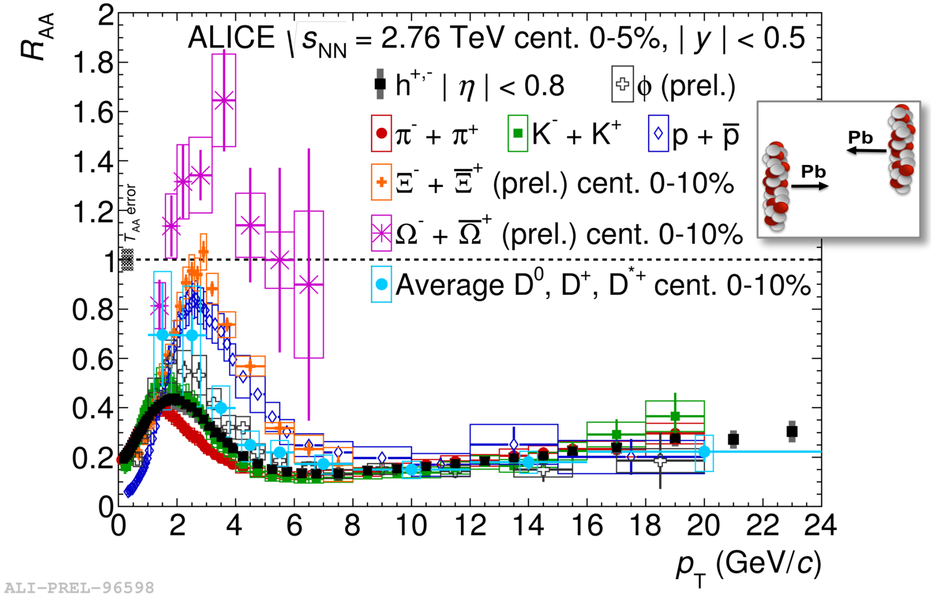
At **high-p_T** (>8-10 GeV/c):

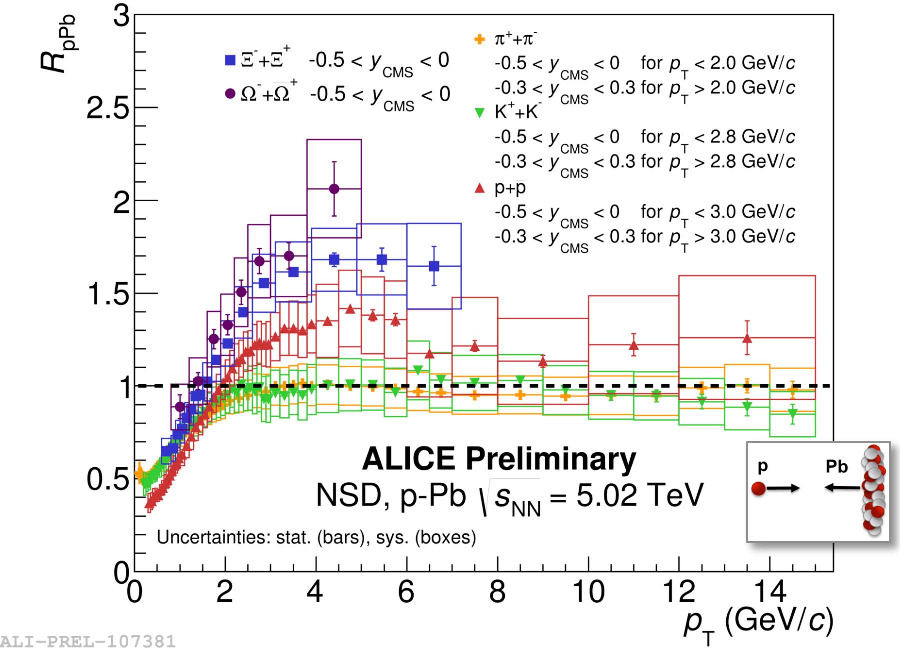
- Strong (light) **flavour-independent suppression** in **central Pb-Pb** with respect to pp
- **no suppression** observed **in p-Pb** for π,K,p above 6-8 GeV/c

→ In Pb-Pb, due to **parton energy loss in the hot nuclear matter**

Nuclear modification of spectra

ALICE, PLB 720 (2013) 52
ALICE, PLB 736 (2014) 196
ALICE, PRC 93 (2016) 034913





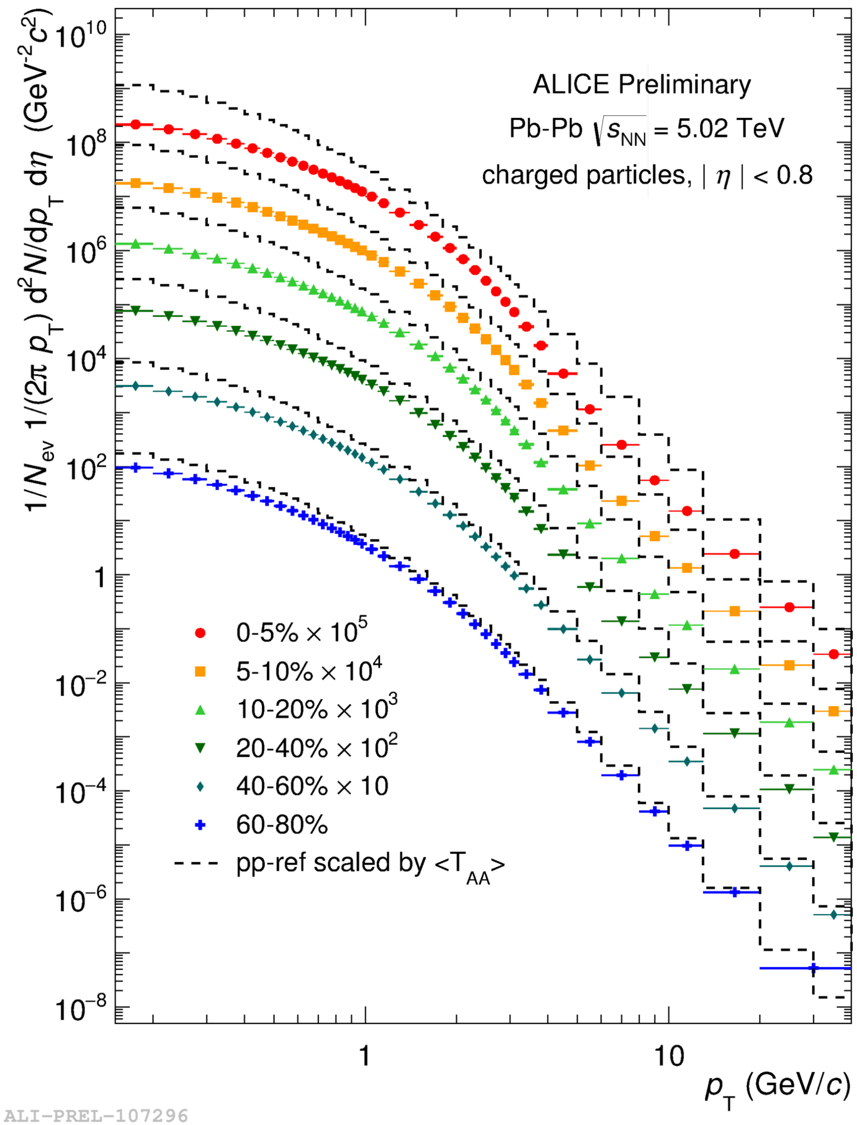
$$R_{xA}(p_T) = \frac{d^2N_{ch}^{xA}/d\eta dp_T}{\langle T_{xA}\rangle d^2\sigma_{ch}^{pp}/d\eta dp_T}$$

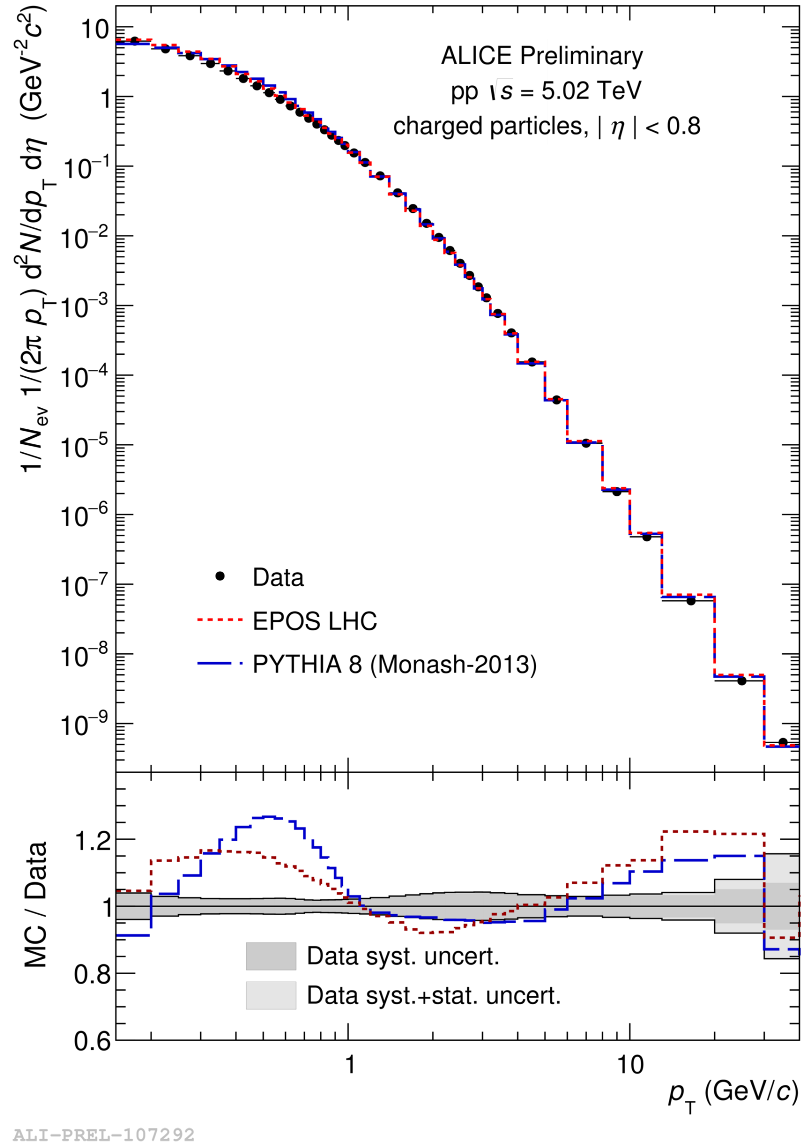
At **intermediate-p_T** ($3 < p_T < 6$ GeV/c):

- **Baryon/meson** difference in central **Pb-Pb**
- **Cronin peak** in **p-Pb** collisions

→ presence of **other final state effects or dynamics** (flow, recombination, …)?

Charged particles spectra in Pb-Pb, pp at 5.02 TeV

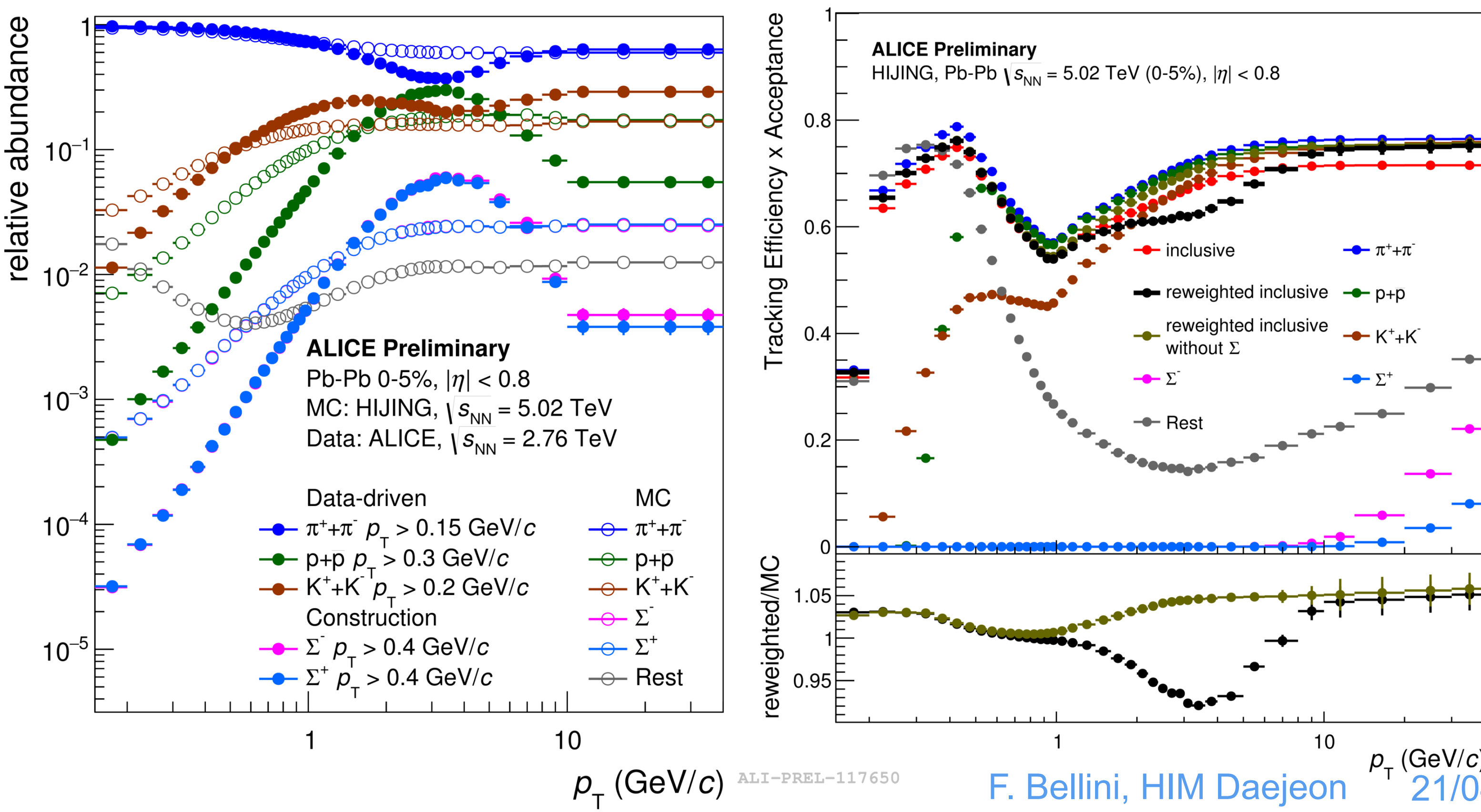




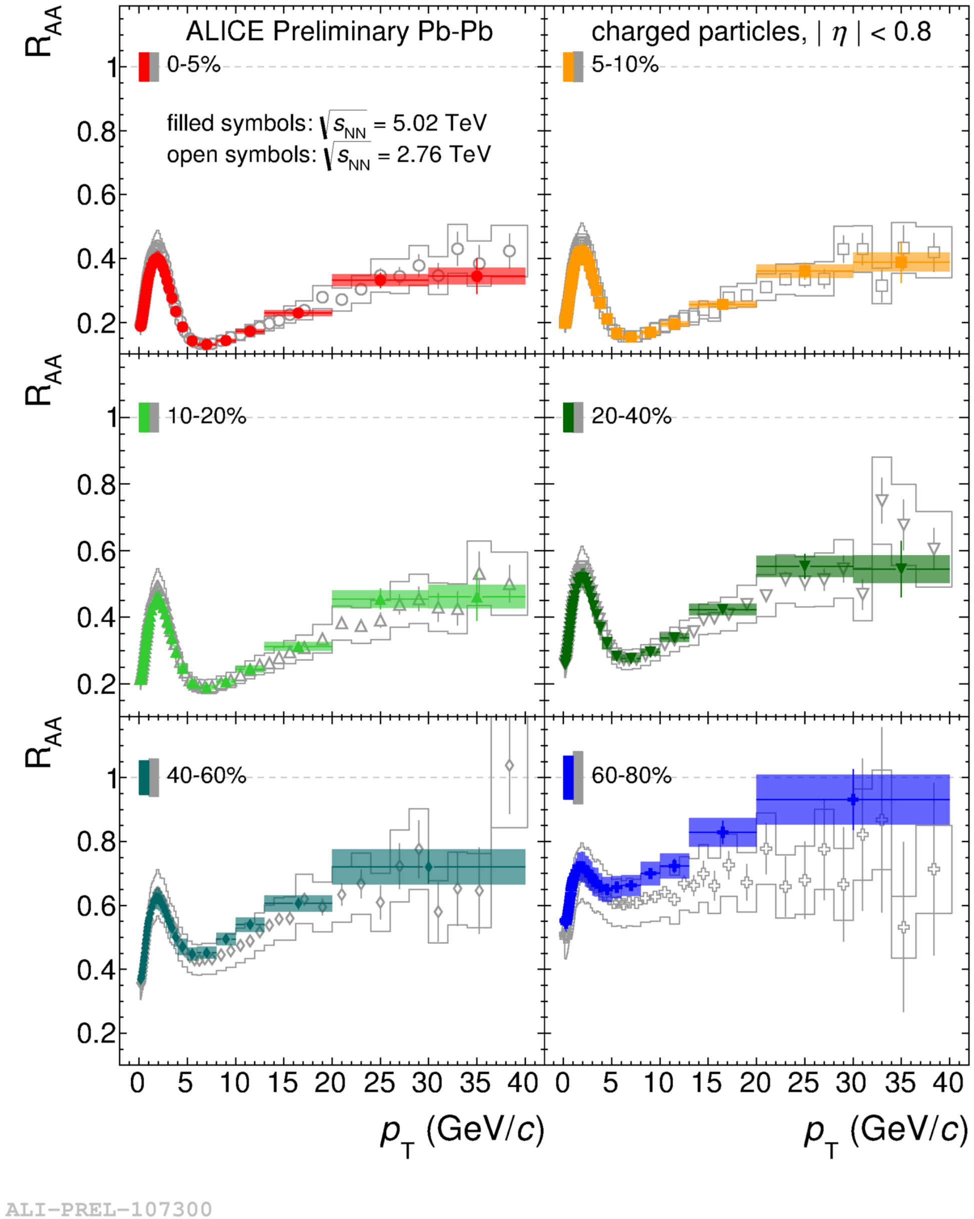
Detail: data driven-particle composition reweighting

Identified particle measurements in pp at 7 TeV and Pb-Pb collisions at 2.76 TeV used as input for a **data-driven correction** of the tracking efficiencies to account for different **particle composition** in data and MC generators

- particle species: $\pi^{+}+\pi^{-}$, p+p, $K^{+}+K^{-}$, Σ^{+}, Σ^{-}
- measurement of Λ-baryons used to approximate charged Σ-baryons
- all others: rest (e, μ, Ξ, Ω)



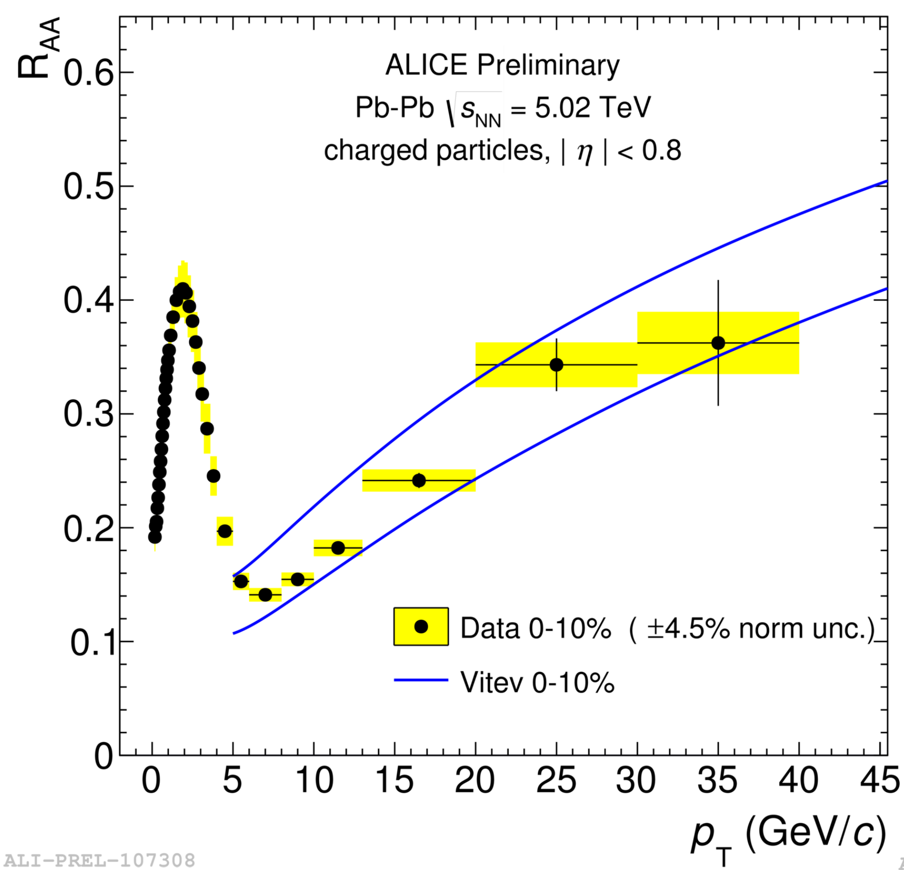
R_{AA} in Pb-Pb at 5.02 TeV

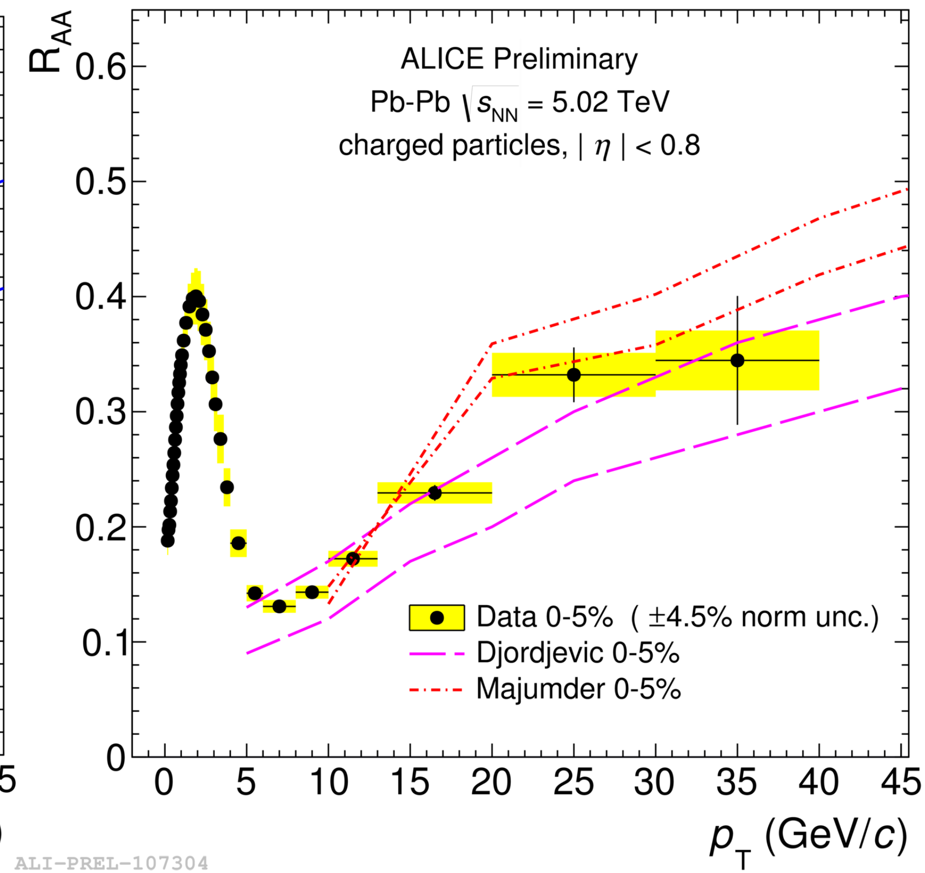


Measurement of nuclear modification factor of inclusive charged particles as a function of centrality

- Data-driven particle composition reweigthing of tracking efficiencies → **Improved systematics** wrt previous 2.76 TeV measurement by a factor of 4
- **R_{AA} compatible with 2.76 TeV**
- hotter/denser medium?

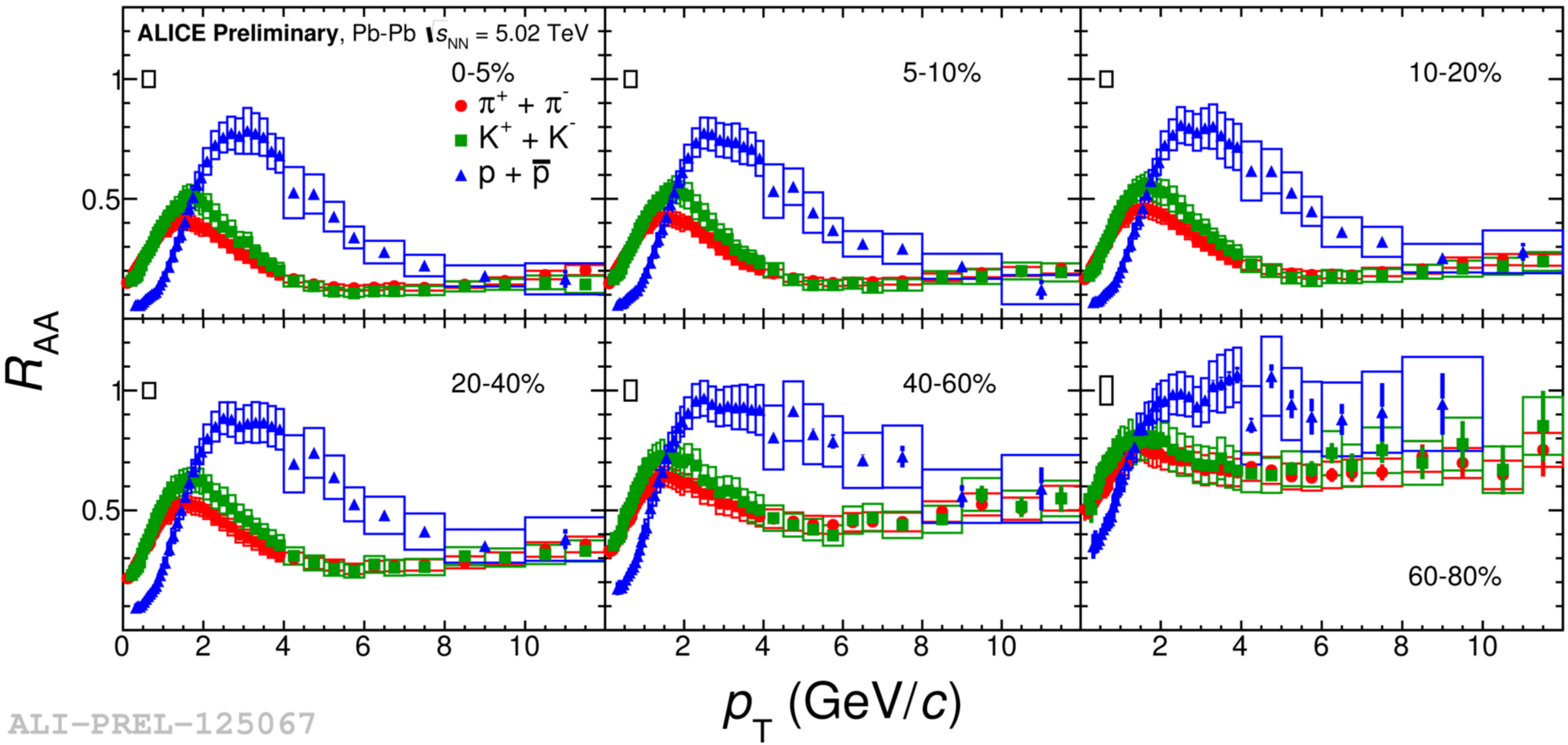
R_{AA} in Pb-Pb at 5.02 TeV – model comparison





Vitev et al., Phys. Rev. D 93 (2016) 7
Djordjevic et al., arXiv:1601.07852
Majumder et al., Phys. Rev. Lett. 109 (2012)

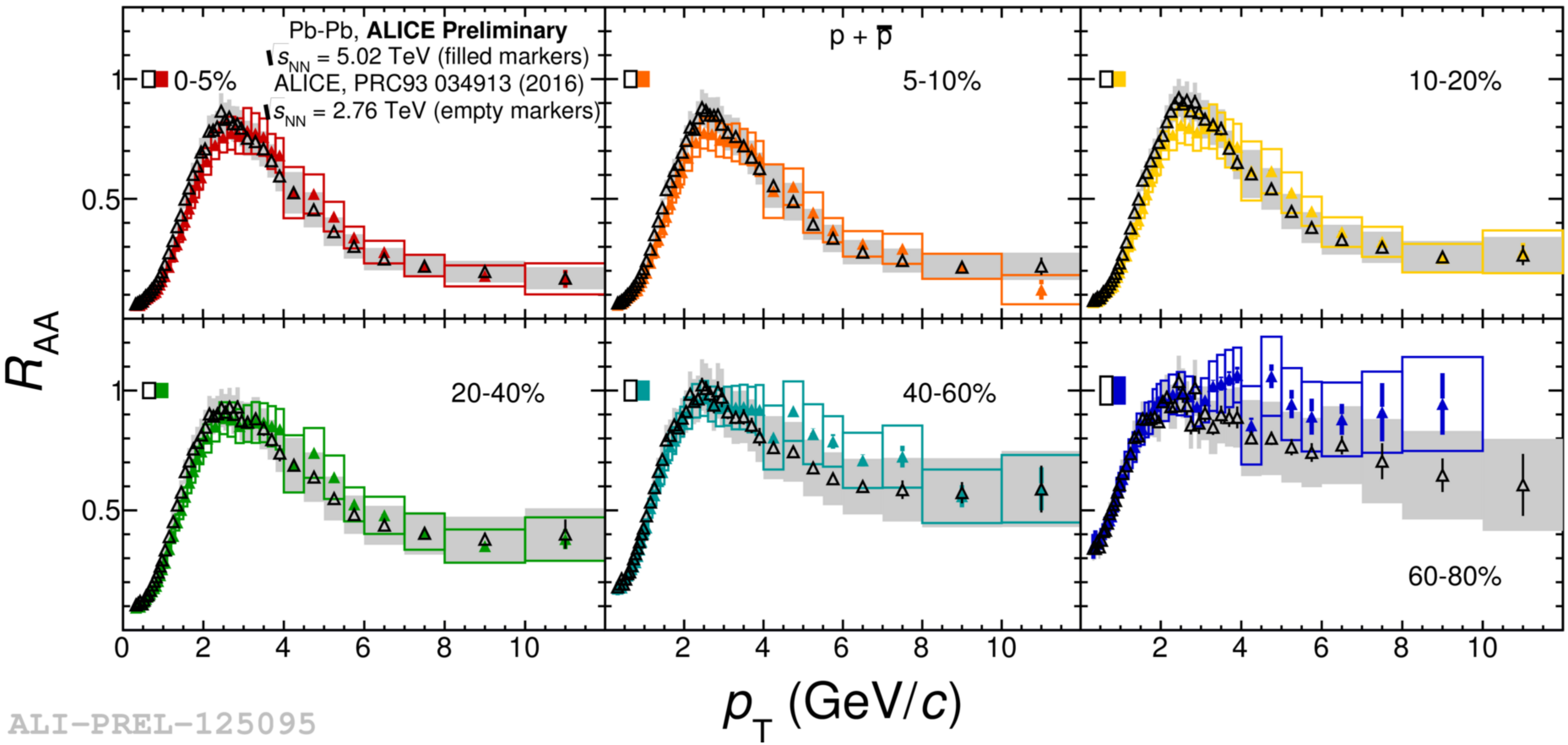
Identified hadrons R_{AA} in Pb-Pb at 5.02 TeV



New preliminary measurement of the nuclear modification factor of identified hadrons at 5.02 TeV

→ Confirms behaviour seen at 2.76 TeV

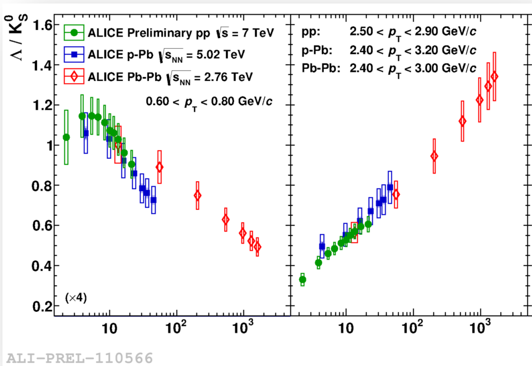
Identified hadrons R_{AA} in Pb-Pb at 5.02 TeV

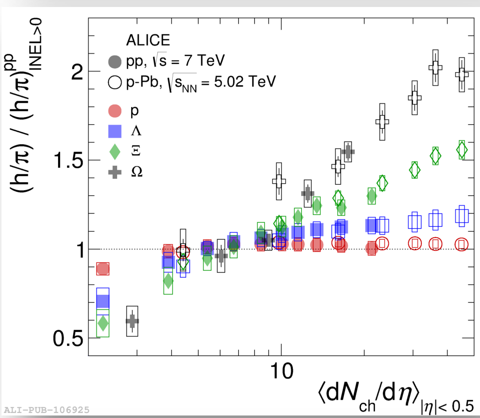


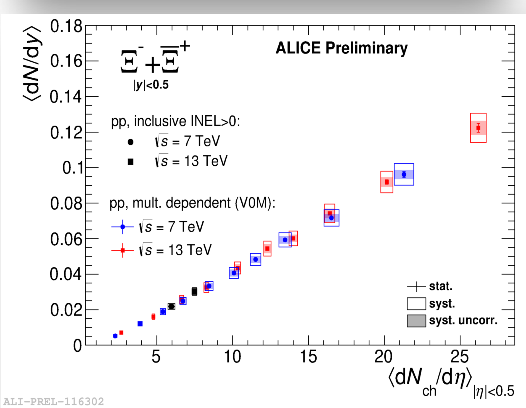
New preliminary measurement of the nuclear modification factor of identified hadrons at 5.02 TeV

→ Confirms behaviour seen at 2.76 TeV, **consistent with lower energy**

Summary







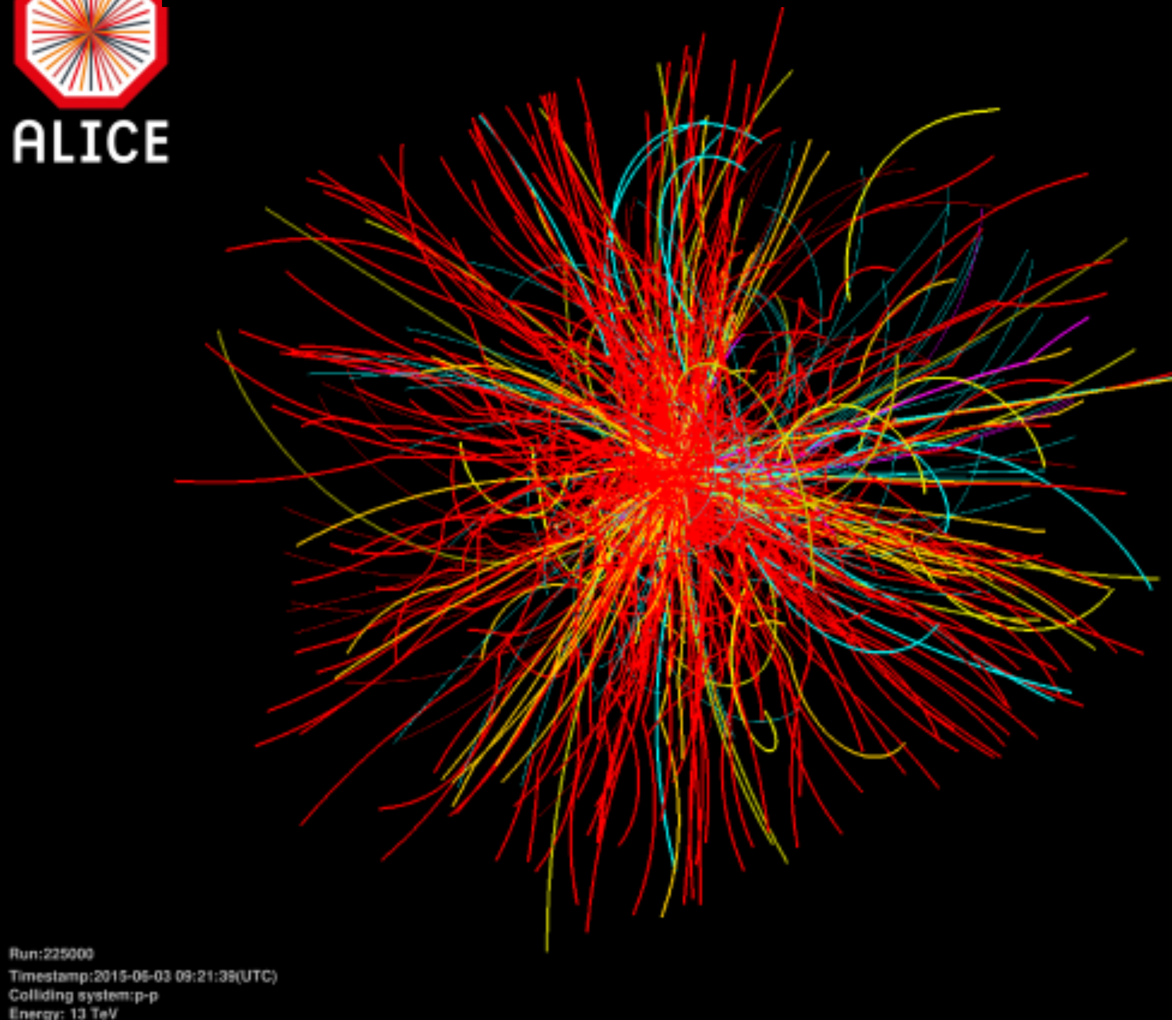
ALICE can perform unique measurements of identified particle production in pp, p-Pb, Pb-Pb collisions at LHC energies

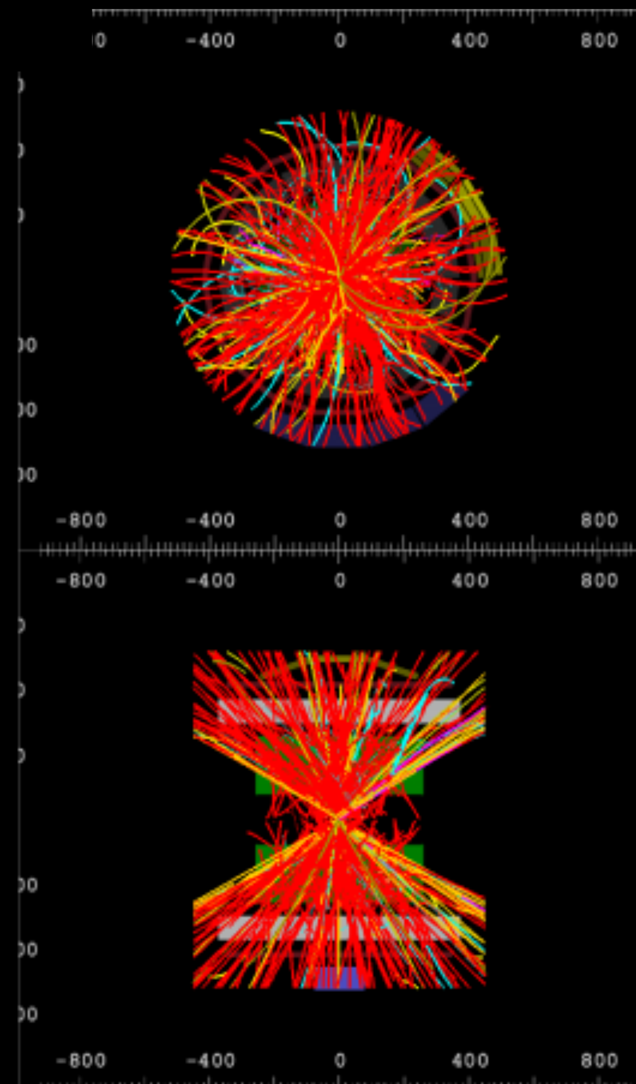
Intriguing similarities among different systems:

- Established collectivity in Pb-Pb + hints for **collectivity in small systems,** whose origin and phenomenology is under investigation
- 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
- **Enhancement of strangeness** production observed from low to high-multiplicity pp events at $\sqrt{s}$ = 7 TeV, poorly described by commonly used MC generators

→ What would happen **at higher multiplicity?**
→ more soon from the high-multiplicity triggered ALICE data in pp collisions
→ more differential measurements in peripheral Pb-Pb collisions

High-multiplicity event, pp at $\sqrt{s}$ = 13 TeV



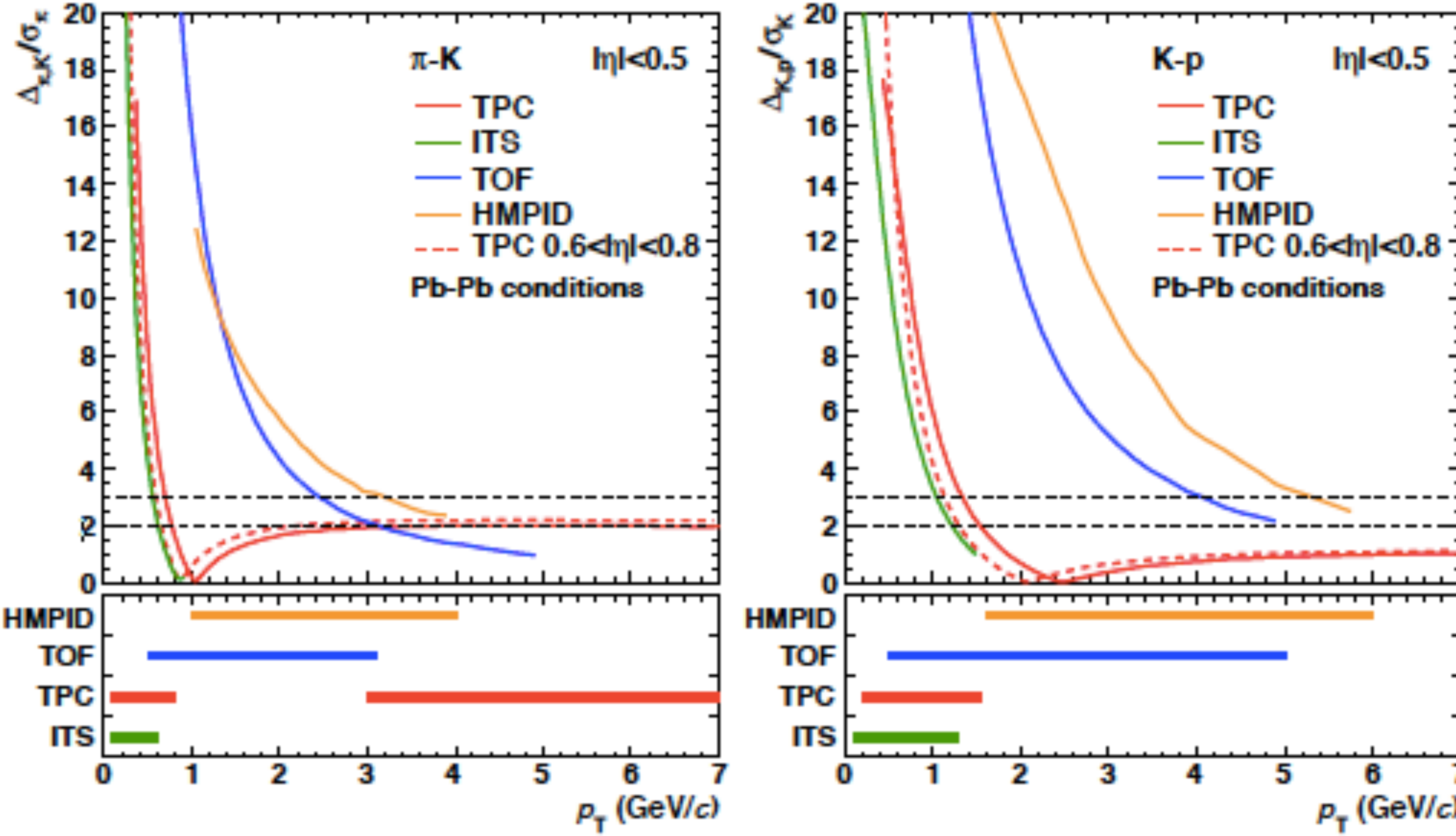


thank you!

Additional slides

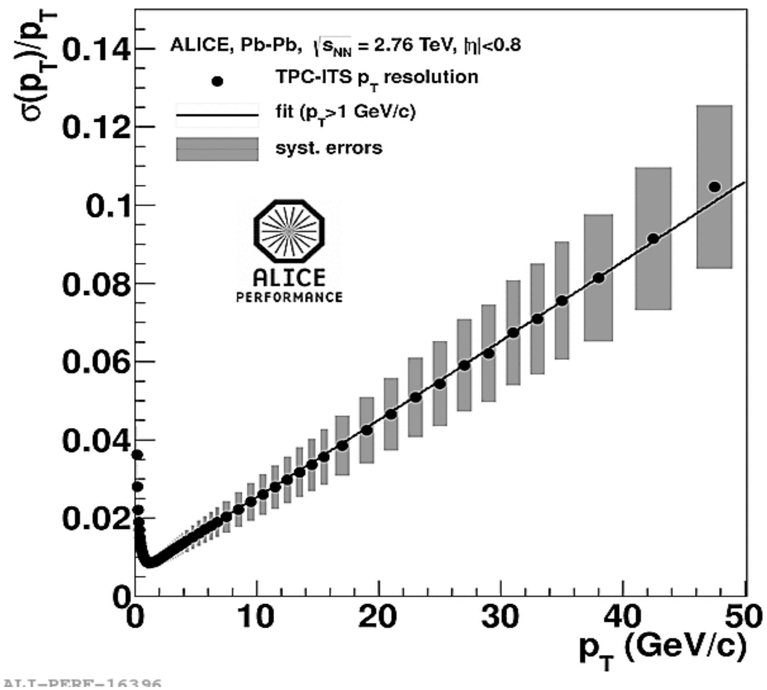
Overview of PID in ALICE

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



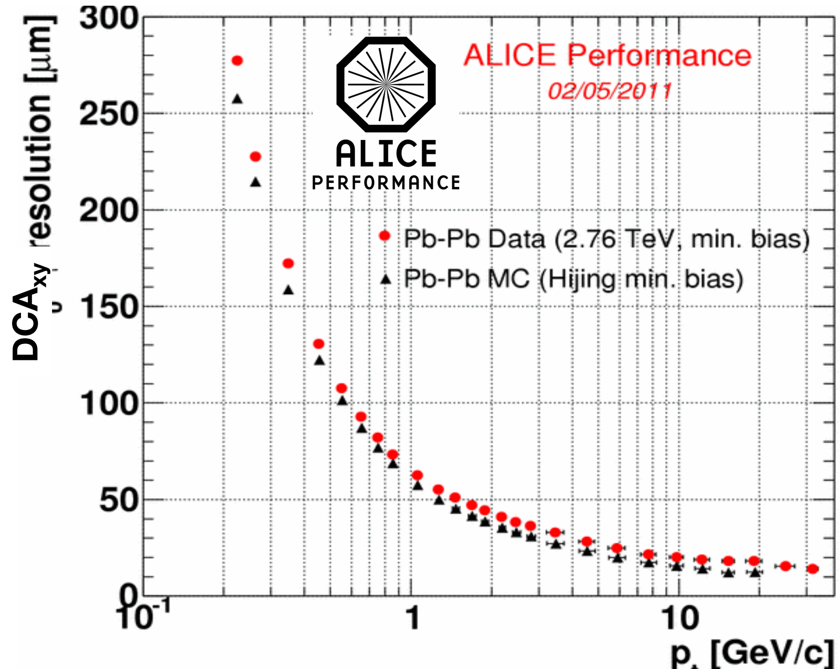
ALICE Tracking performance

p_t resolution



p_t resolution ~10% at 50 GeV/c
- Small multiplicity dependence
- Estimate from track residuals

DCA_{xy}: Transverse distance-of-closest-approach



Good DCA_{xy} resolution

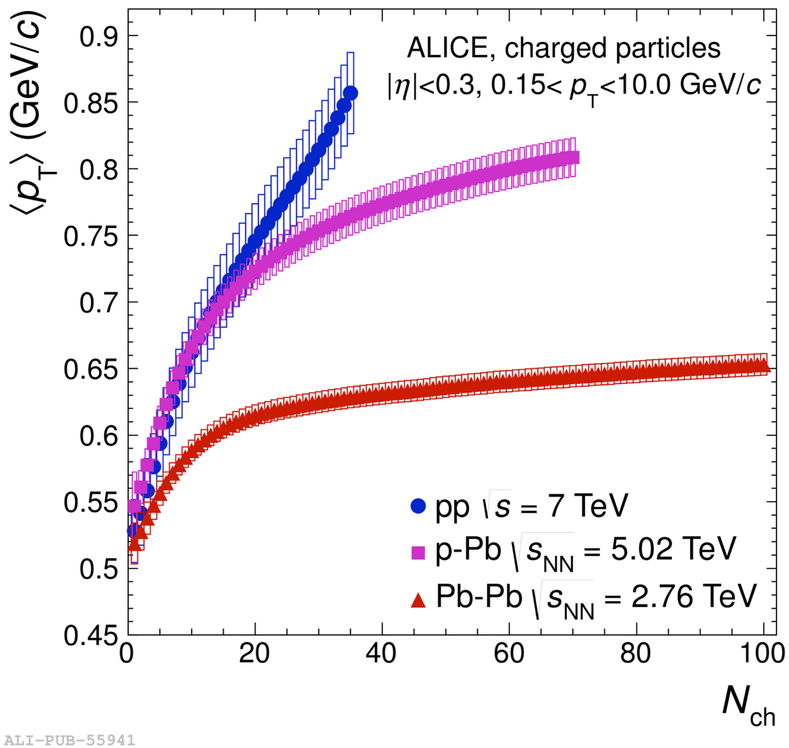
→ control contamination from secondaries

Strict DCA_{xy} cut (< 7σ), small contamination

Residual contamination less than 1% for p_t > 4 GeV/c

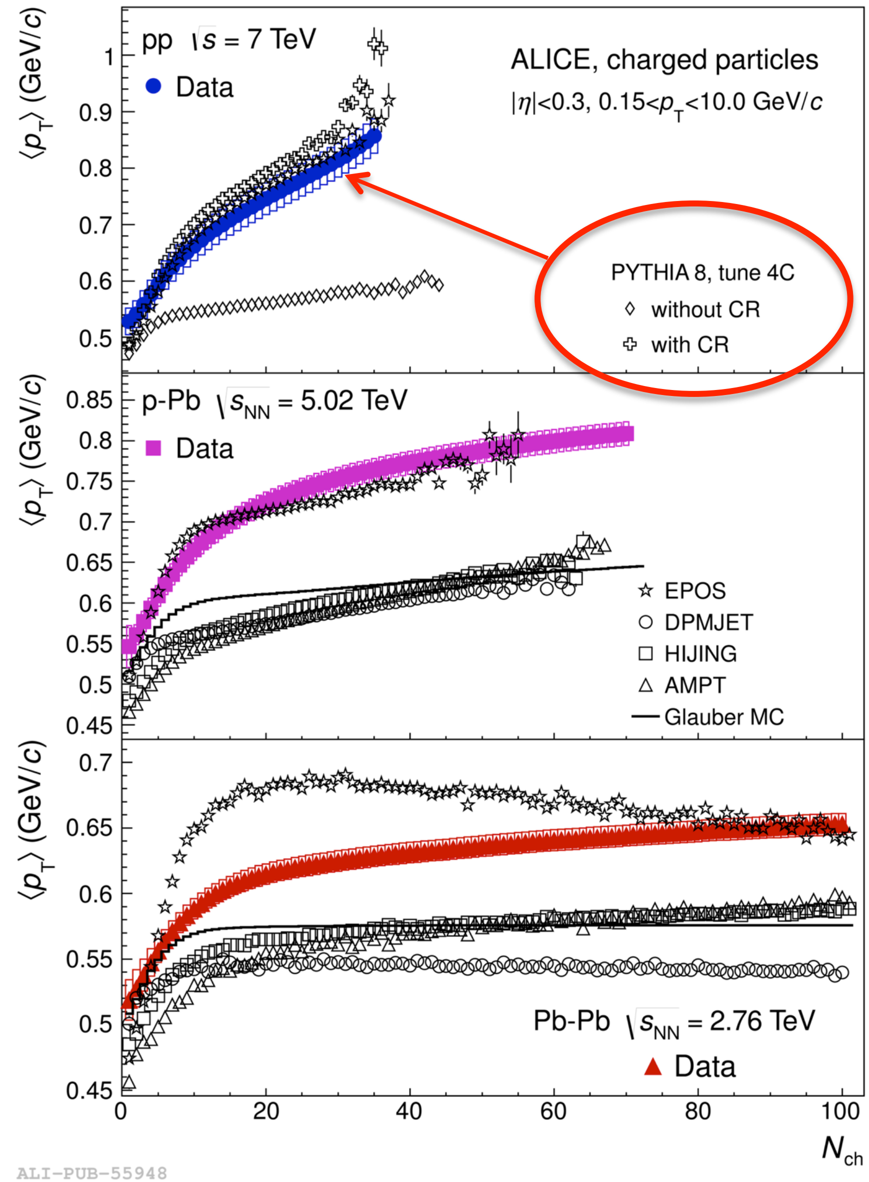
Phys. Lett. B 727, 371–380 (2013)

Multiplicity dependence of <p_T>



In **PYTHIA** the strong increase of ⟨p_T⟩ with N_{ch} is described by an effect of color reconnections between strings produced in MPI.

→ The same mechanism in p–Pb collisions?



$\sqrt{s}$ dependence of particle production

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

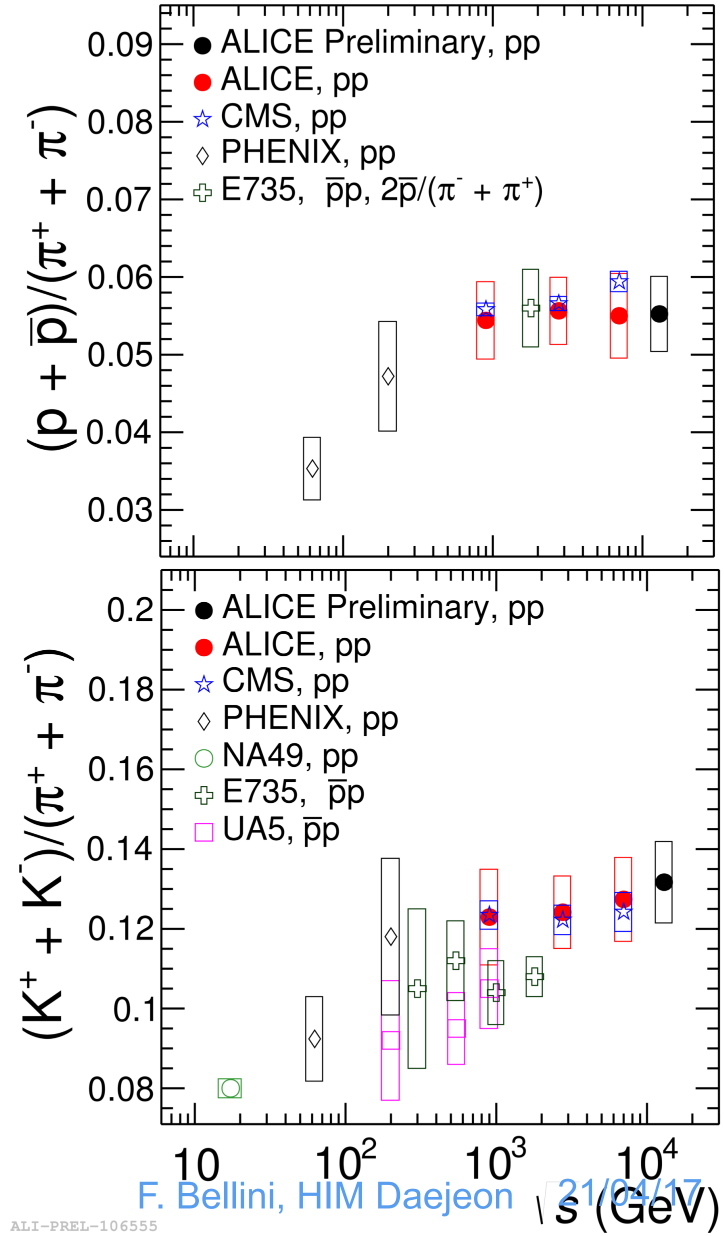
Reminder: <dN_{ch}/dη> increases by ~20% from 7 to 13 TeV

Ratios of spectra in min. bias pp:

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

p_T-integrated ratios in min. bias pp:

- **No significant evolution with energy** for **p/π, K/p**



√*s* dependence of particle production

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

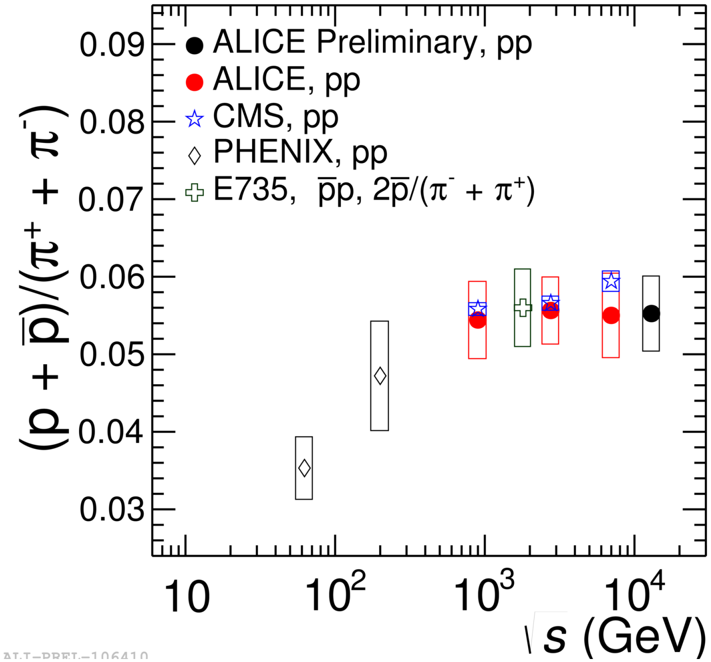
Reminder: <dN_{ch}/dη> increases by ~20% from 7 to 13 TeV

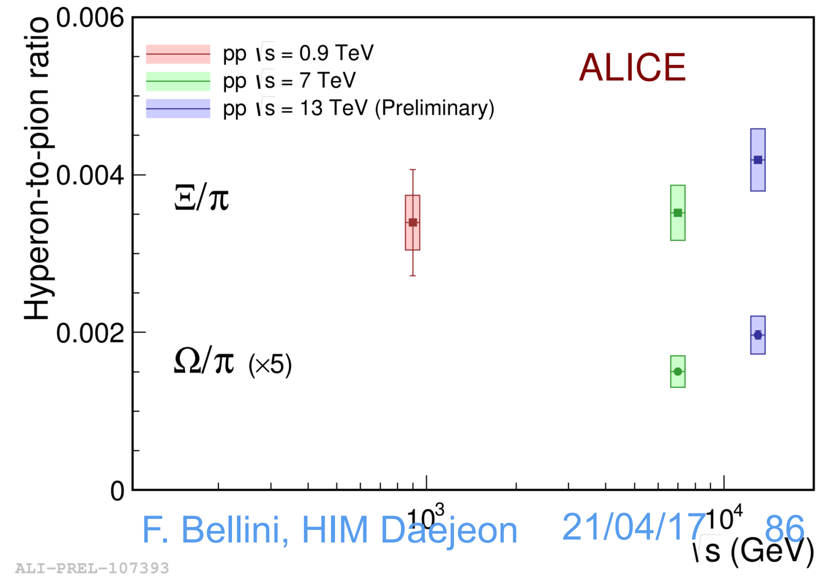
Ratios of spectra in min. bias pp:

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

p_T-integrated ratios in min. bias pp:

- **No significant evolution with energy** for **p/π, K/p, K*/K, φ/π**
- hint for **increase of hyperon-to-pion** ratio





Statistical models

*M. Floris, QM 2014, arXiv:1408.6403

- Implementations of statistical models
  - Original ideas go back to Pomeranchuk (1950s) and Hagedorn (1970s).

Several different implementations (and interpretations):

- K. Redlich, P. Braun-Munzinger, J. Stachel, A. Andronic (GSI)
  - Eigen-volume correction: ideal gas → Van-der-Waals gas
  - emphasis on complete hadron list
- F. Becattini
  - non-equilibrium parameter γ_S^N
- J. Rafelski (SHARE)
  - non-equilibrium parameter γ_S^N and γ_q^N
- J. Cleymans (THERMUS)
  - Allows also canonical suppression in sub-volumes of the fireball
- W. Broniowski, W. Florkowski (THERMINATOR)

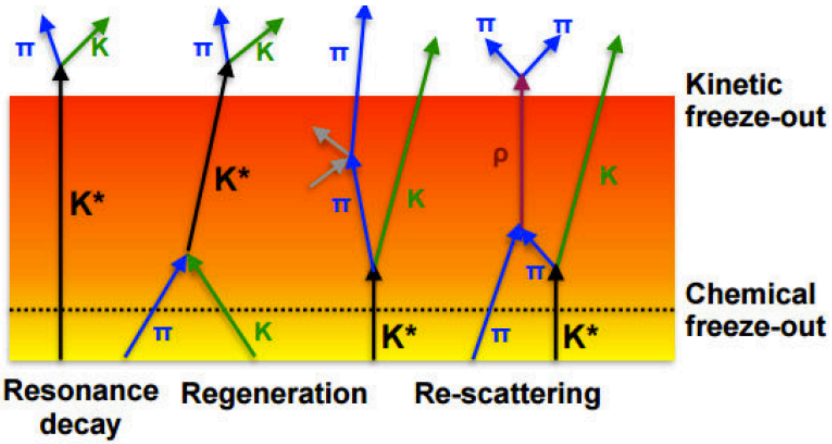
Resonances as probes

Resonances contribute to the study of **particle production mechanisms**
→ compare particles that differ by mass, baryon number, strangeness content

Short-lived resonances decay due to strong interaction ($c\tau$ ~ few fm) during the hadronic phase:

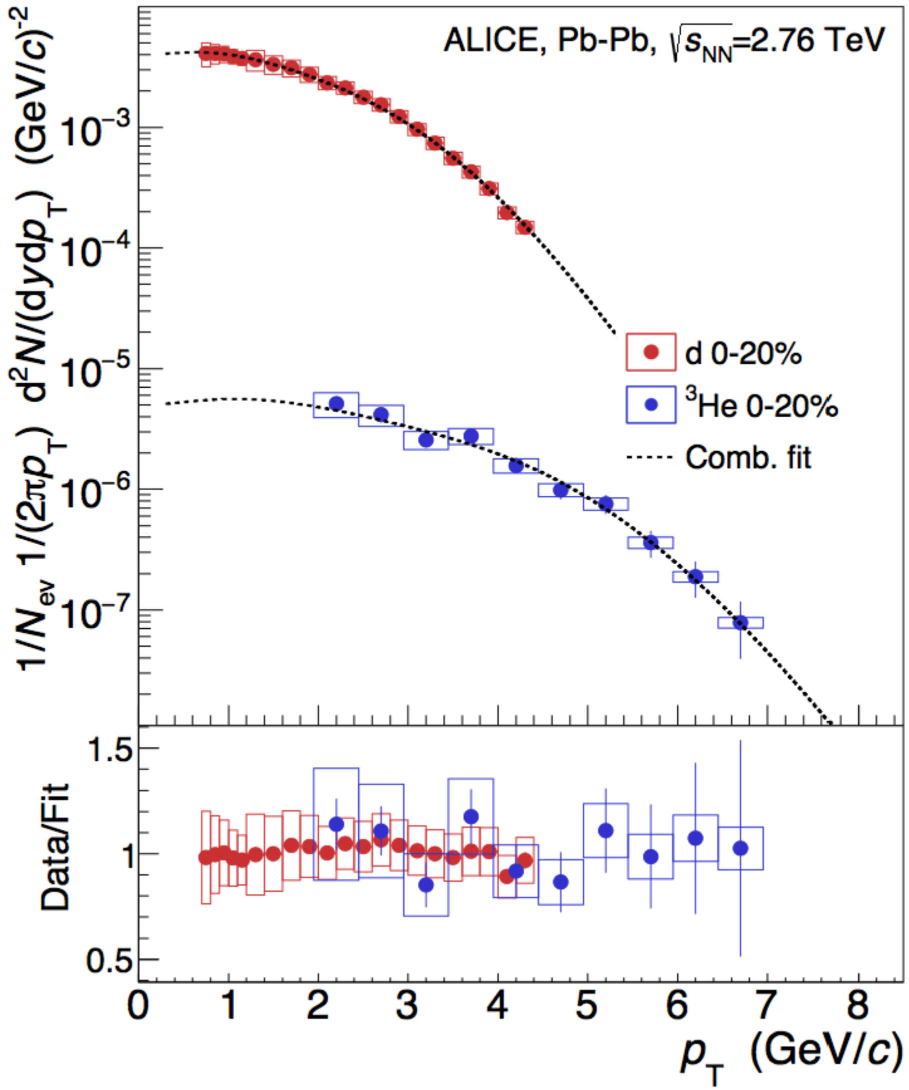
- Collective behaviour (flow), decoupling from medium
- **Rescattering vs. regeneration**: (pseudo-)elastic processes modify the yield established at chemical freeze-out

→ Compare **resonances with different lifetimes**



$\rho(770)^0$	$K(892)^0$	$\Sigma(1385)^{\pm}$	$\Lambda(1520)$	$\Xi(1530)^0$	$\Phi(1020)$
$c\tau$ ~ 1.3 fm	4 fm	5.5 fm	12.5 fm	22 fm	46 fm
S = 0	S = 1	S = 1	S = 1	S = 2	S = 0

Light-nuclei spectra vs. Blast Wave model



The p_T-spectra of deuteron and ^{3}He are well described by the Blast-Wave model fit which describes π, K, p

→ Unique behaviour in Pb-Pb collisions!