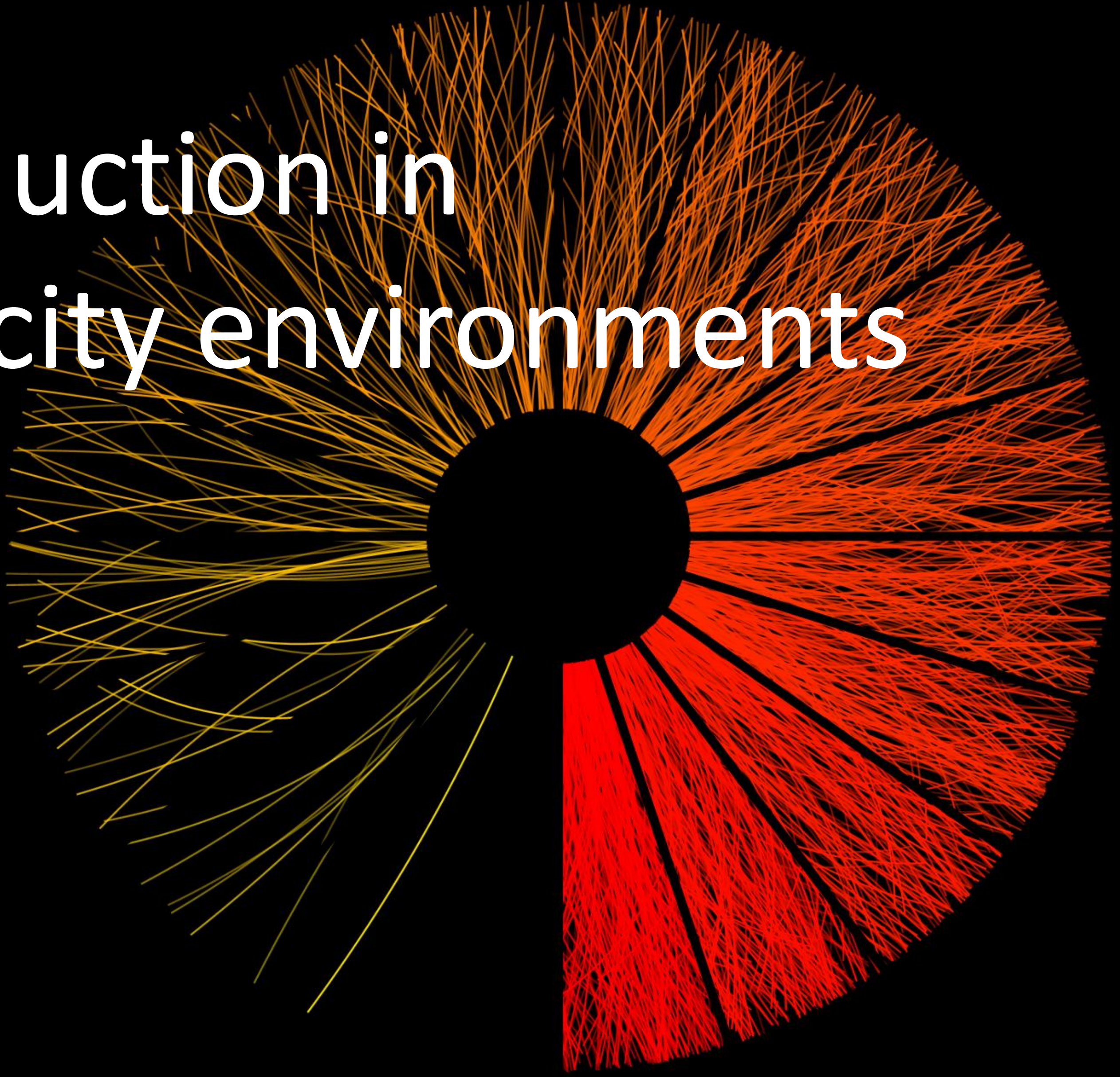
Soft particle production in different multiplicity environments



Livio Bianchi

'Hard-Soft correlations in hadronic collisions' workshop

Clermont-Ferrand

Livio.Bianchi@cern.ch

Overview

Light Flavours: why and how

Small/large/medium/whatsoever system

Results from RHIC and LHC

Interpretation: are we there ‘already’?

Conclusions, Outlook, Positivity, Criticalities

Your turn: shoot!

Introduction

Particles production: an (as much as possible) unbiased perspective (I)

Livio Bianchi
GDR-QCD wshop
24 July 2018

QCD: perturbative regime calculable up to the NNNLO level, non-perturbative regime much less known.
LQCD addresses static hadron properties, models try to describe dynamical processes

Microsopic models

- Solidly QCD-grounded
- Implement several sub-mechanisms to deal with non-perturbative aspects
- (Relatively) large number of parameters
- Normally better in predicting dynamics rather than chemical composition

EXAMPLES:

- Clusters Models (HERWIG)
- String models (PYTHIA, DIPSY)
- …

To which extent can we use them to describe "small systems" observations?

What have we learnt so far? Can we learn more?

Hybrid Models

- Fuse different "regimes" (vacuum + statistical hadroniz., collectivity, etc.)
- Several purely phenomenological mechanisms (→ parameters) implemented

EXAMPLES:

- EPOS

"collective" Models

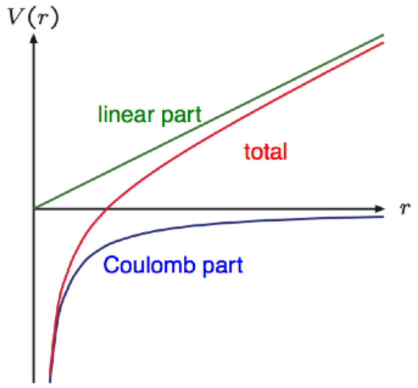
- … as statistical
  - Few parameters
  - Predicts chemical composition
  - Surprisingly ~works from e^+e^- to Pb-Pb
    - EXAMPLES: GSI/Heidelberg, THERMUS, SHARE…
- … or hydro (viscous)
  - Describe collective expansion of hydrodynamic object

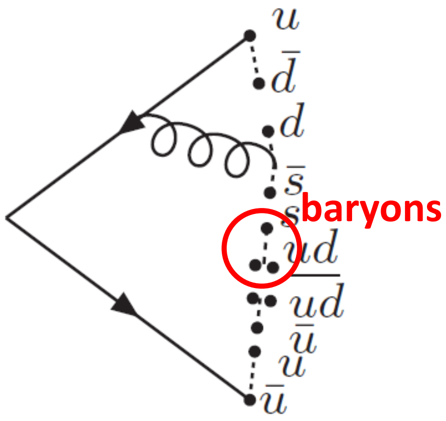
Example of microscopic models: Pythia

- Linear confinement potential for large distances (confirmed by lattice QCD). Short distances: perturbation theory holds
- Confined colour fields: strings with tension κ = 1 GeV/fm
- Breaking of strings (tunneling) give hadrons

$$P \propto e^{-\frac{\pi m_T^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} \cdot e^{-\frac{\pi p_{Tq}^2}{\kappa}}$$

- Flavour determined by gaussian mass suppression term (which mass? current → less s-suppression than observed. constituent → too much s-suppression. s/u tuned on data)





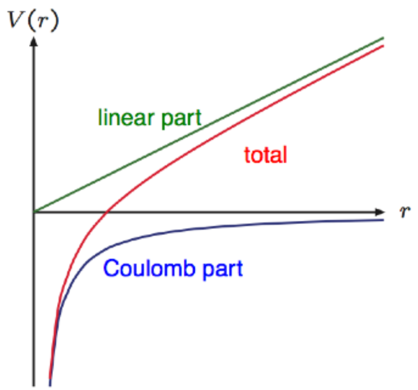
Fischer & Sjostrand, arXiv:1610.09818 (2017)

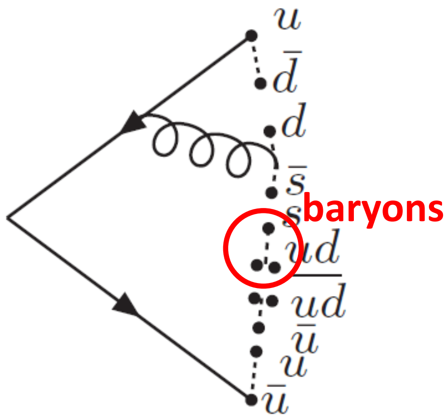
Example of microscopic models: Pythia

- Linear confinement potential for large distances (confirmed by lattice QCD). Short distances: perturbation theory holds
- Confined colour fields: strings with tension κ = 1 GeV/fm
- Breaking of strings (tunneling) give hadrons

$$P \propto e^{-\frac{\pi m_T^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} \cdot e^{-\frac{\pi p_{Tq}^2}{\kappa}}$$

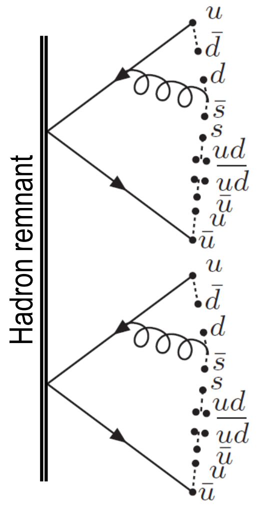
- Flavour determined by gaussian mass suppression term (which mass? current → less s-suppression than observed. constituent → too much s-suppression. s/u tuned on data)

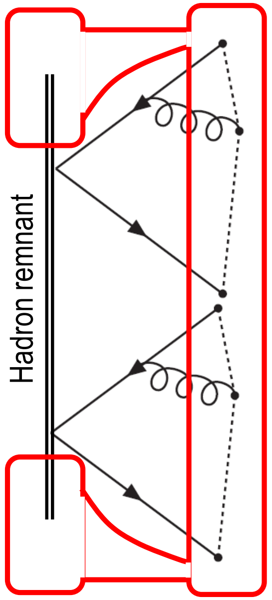




Fischer & Sjostrand, arXiv:1610.09818 (2017)

- **hadronic collisions**: multiple strings needed to describe multiplicity distribution (**MPI**)
- In the LC Lund model each string is hadronizing separately with respect to the others
- The multiplicity increases, but not the $\langle p_T \rangle$ nor the relative flavor abundancies!





- Multiple strings are close in space-time. Dynamical interaction not implemented, but **Colour Reconnection** (CR) can happen
- Takes place after parton shower and considers all SU(3) permitted configurations.
  Selection parameter: total string length
- After re-arrangement, hadronization takes place
- Takes into account colour reconnection in remnant

Christiansen & Skands, arXiv:1505.01681 (2015)

Example of macroscopic models: SHM

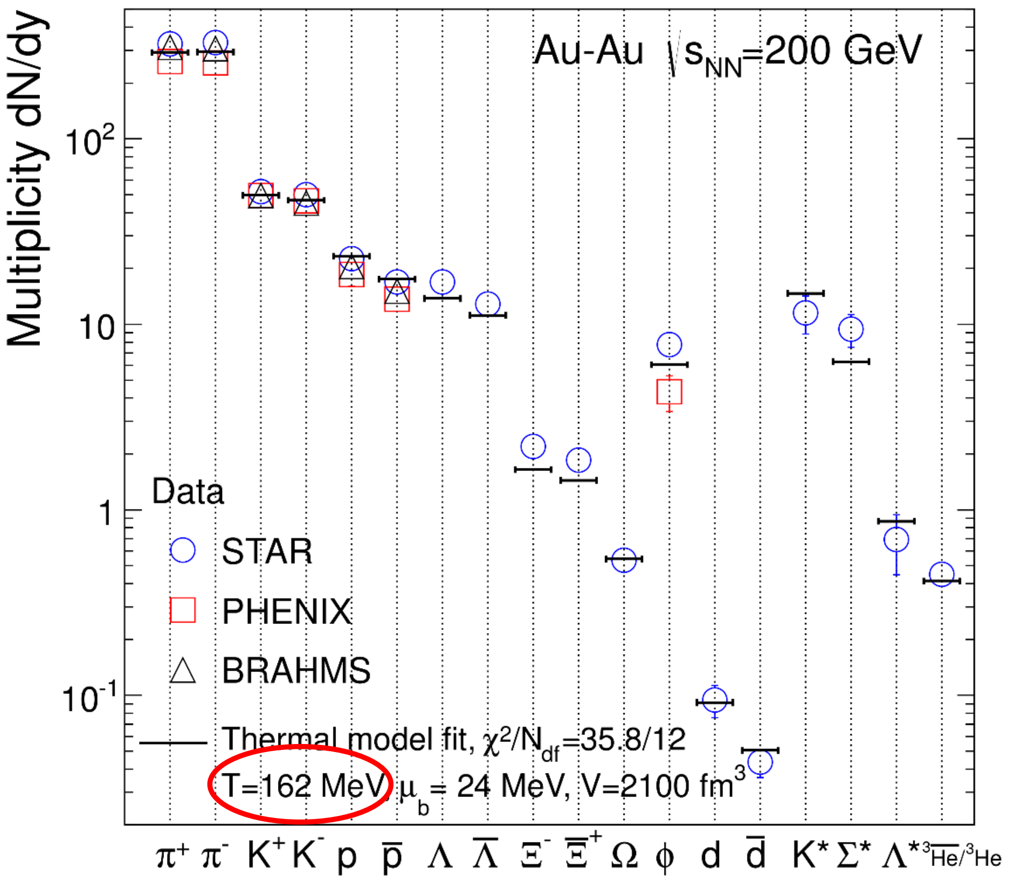
SHM – class of models which predict chemical composition of the final state:

- see hadronization as particles spilling from an excited state (e.g. hadron resonance gas, …) following pure statistical laws.
- have few parameters at play:
  - T : the temperature of the source at chemical freeze-out
  - V : the volume of the source
  - μ_B : baryochemical potential (0 at LHC)
  - μ_S : under-equilibration scale for strangeness
  - …

in some flavour of the model

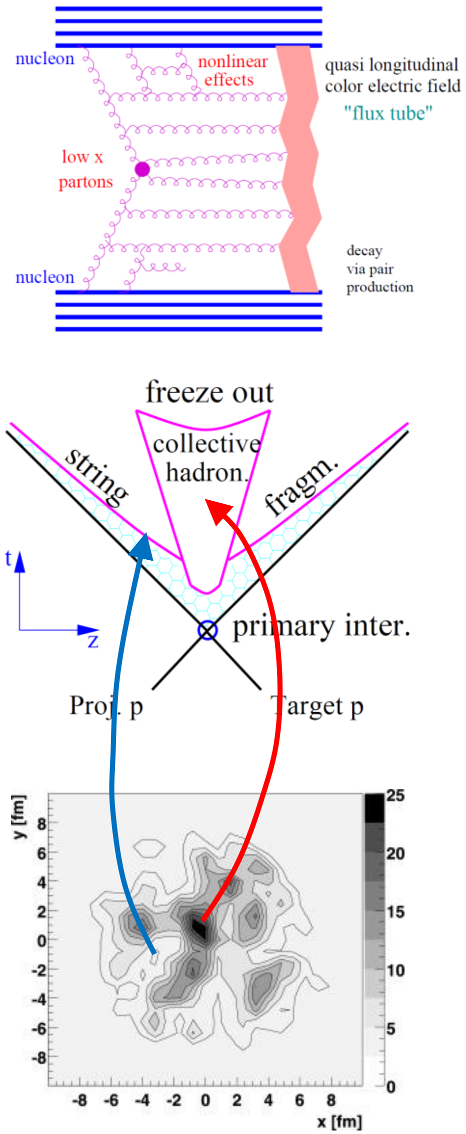
Generally successful in heavy ion collisions, making use of a gran-canonical ensamble

Nucl. Phys. A 904 (2013) 535-538



Andronic & Braun-Munzinger & Redlich & Stachel, arXiv:1710.09425 (2017)

Example of hybrid models: EPOS



- Hard scattering treated with the addition of several DGLAP parton "ladders" (pomerons) + a CGC-inspired saturation scale
- Parton ladders are then considered as relativistic strings, conveniently treated in a string fragmentation approach (a-la Lund)
- At time τ_0 (well before hadronization) strings are divided into: fluid (CORE) and escaping (CORONA) according to their momenta and density of the string segments
  - **CORONA**: strings can hadronize as in the Lund approach
  - **CORE**: from the time τ_0 evolves as a viscous hydrodynamic system. Hadronization happens statistically at a common T_H
- After hadronization hadron-hadron rescattering can be considered, making use of an afterburner (e.g. UrQMD)

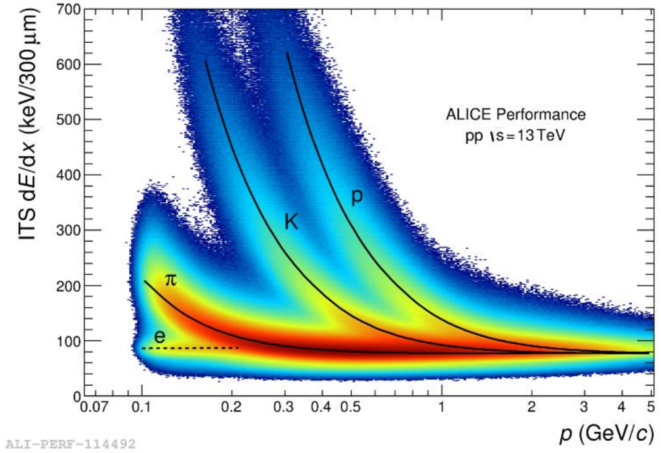
NOTE: parameters governing the core-only part are 6 (τ_0, ρ_0, ε_{FO}, y_{rad}, f_{ecc}, γ_s), to be tuned on data!

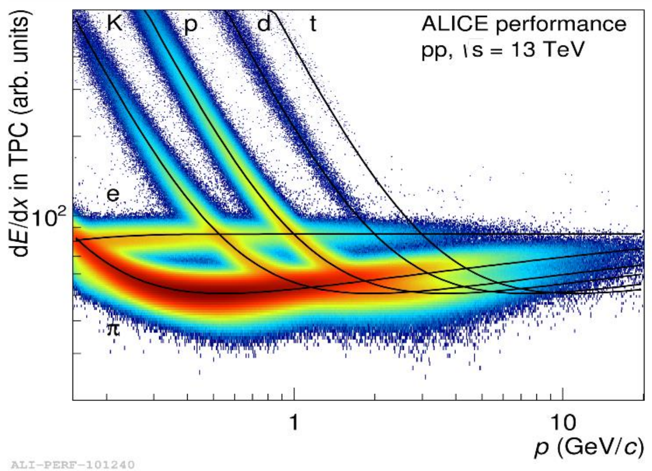
Werner, PRL 98, 152301 (2007)

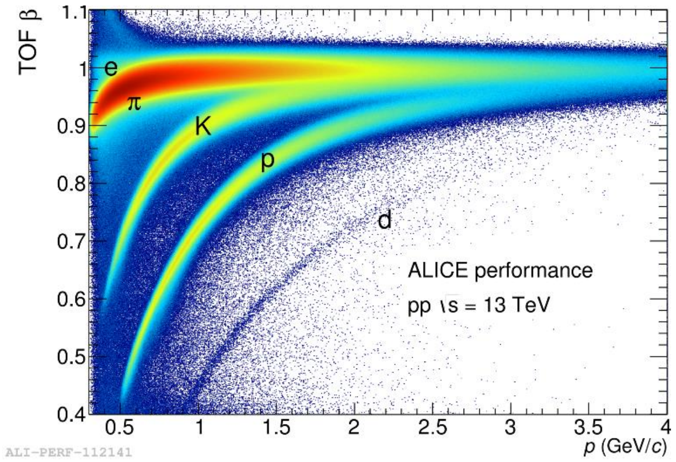
Particles production: measurement techniques (I)

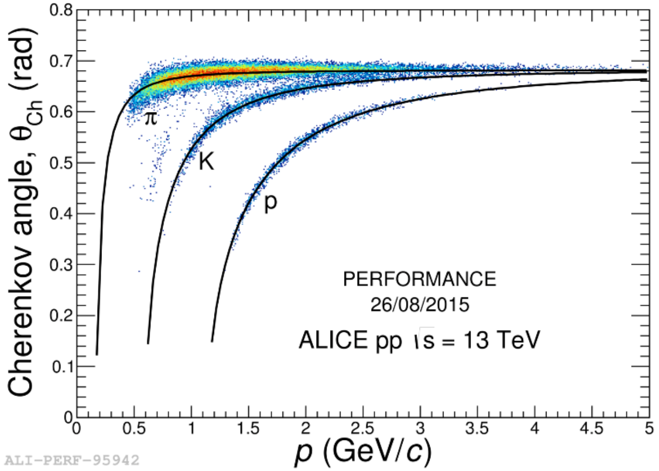
Livio Bianchi
GDR-QCD wshop
24 July 2018

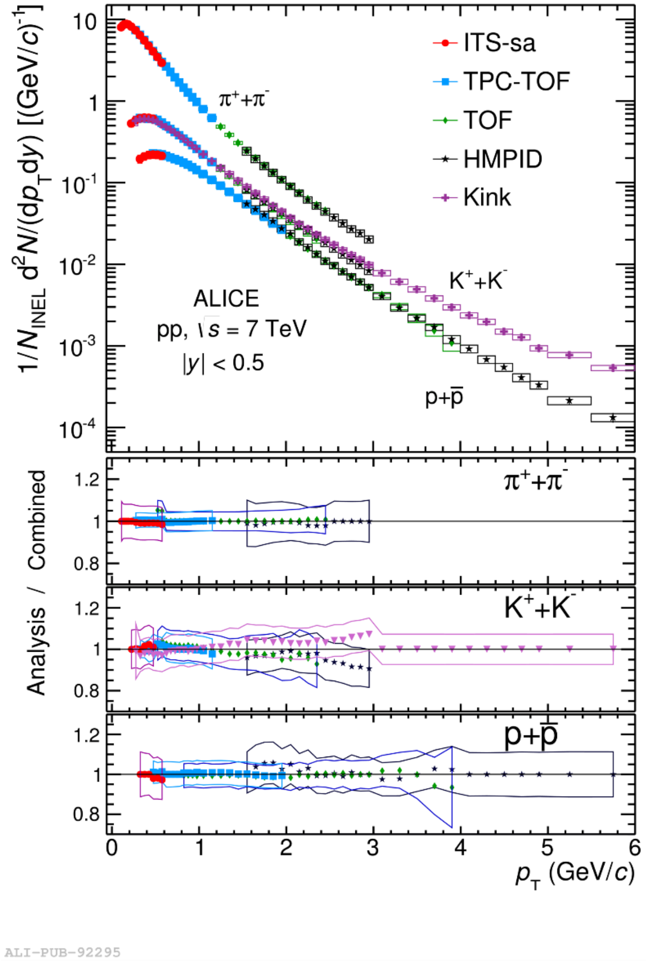
Charged stable light particles (π,$K^{\pm}$,p) are detected through their energy loss. Several PID techniques are useful to cover the largest p_T range









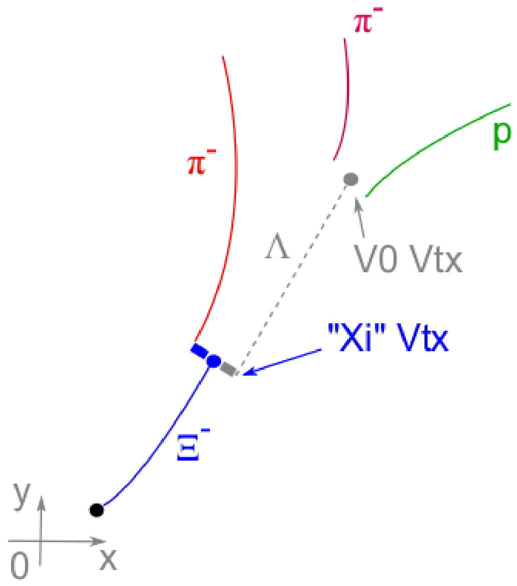


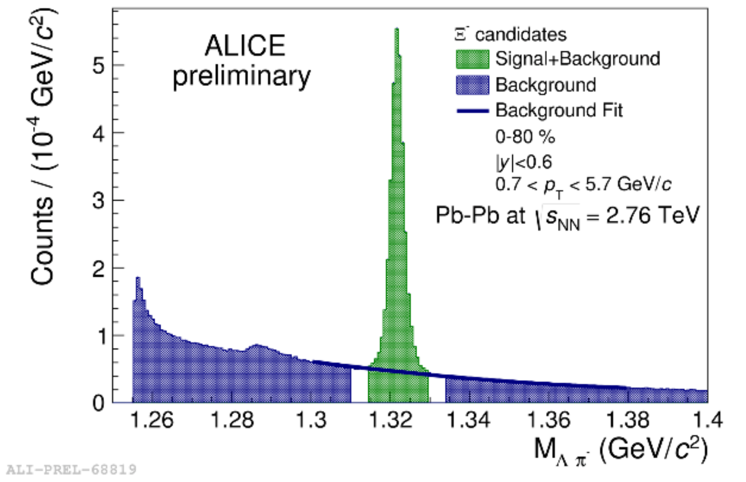
Integration of different techniques is the most delicate point in these analyses

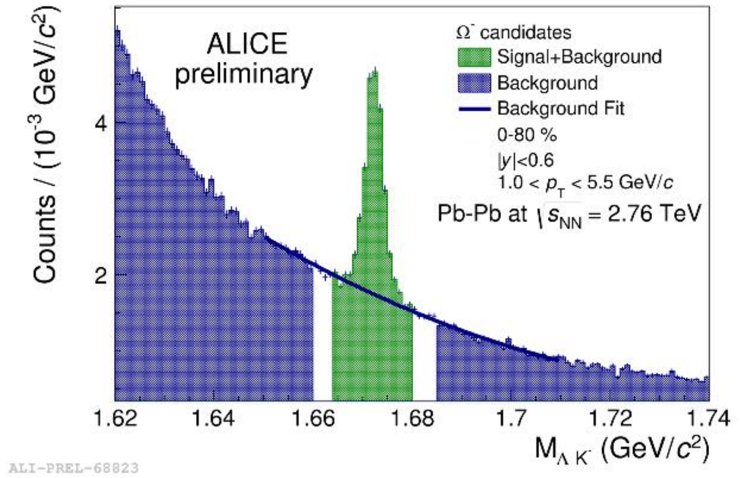
Particles production: measurement techniques (II)

Weak-decaying particles detected exploiting:

- reconstruction of the topological decay
- PID for daughter candidates
- Signal extraction through invariant mass integration





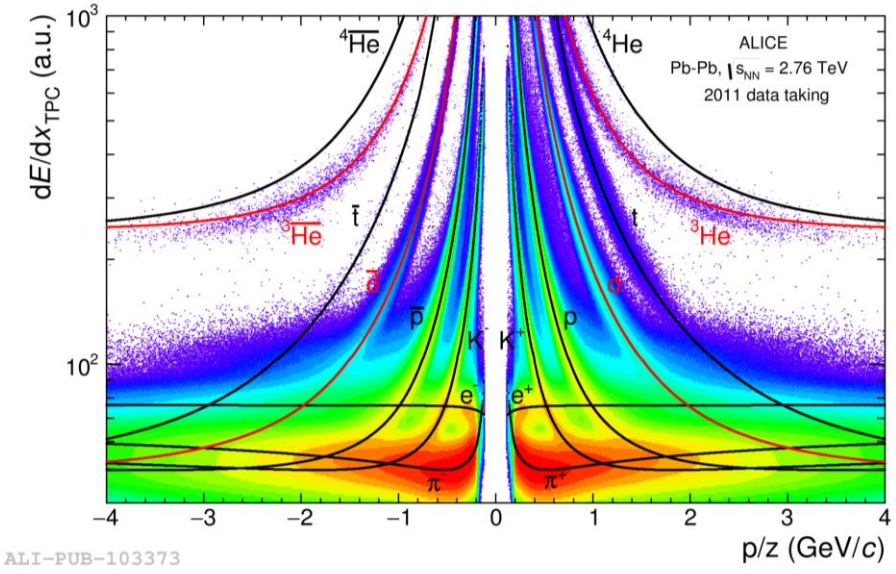


Particle	Mass (MeV/c^2)	Decay channel	cτ (cm)
K^0_S	498	$\pi^+ + \pi^-$ (BR=69%)	2.68
Λ	1116	$p + \pi^-$ (BR=64%)	7.89
Ξ	1322	$\Lambda + \pi^-$ (BR=99.9%)	4.91
Ω	1672	$\Lambda + K^-$ (BR=68%)	2.46

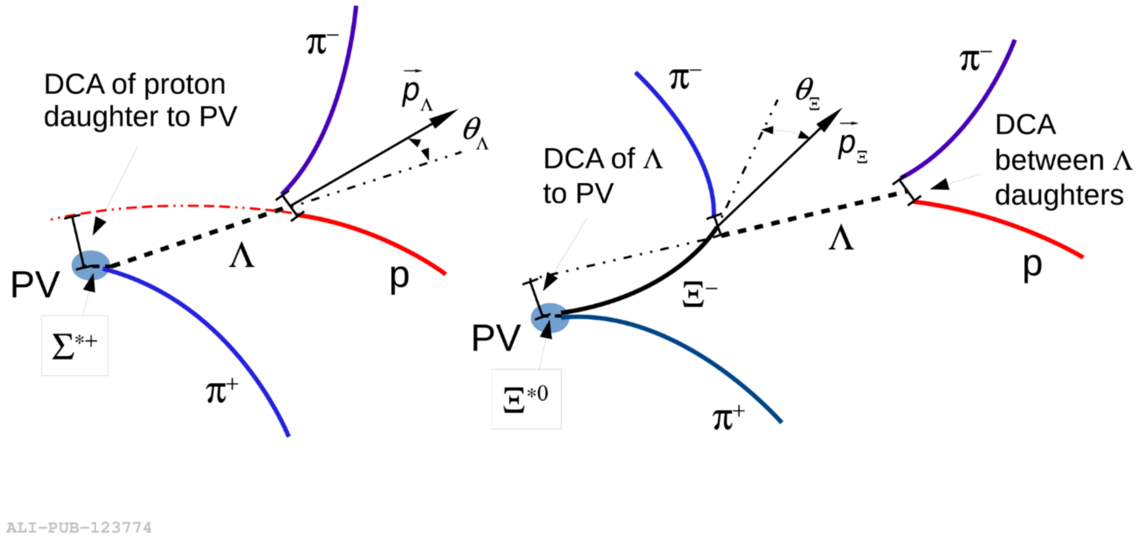
Particles production: measurement techniques (II)

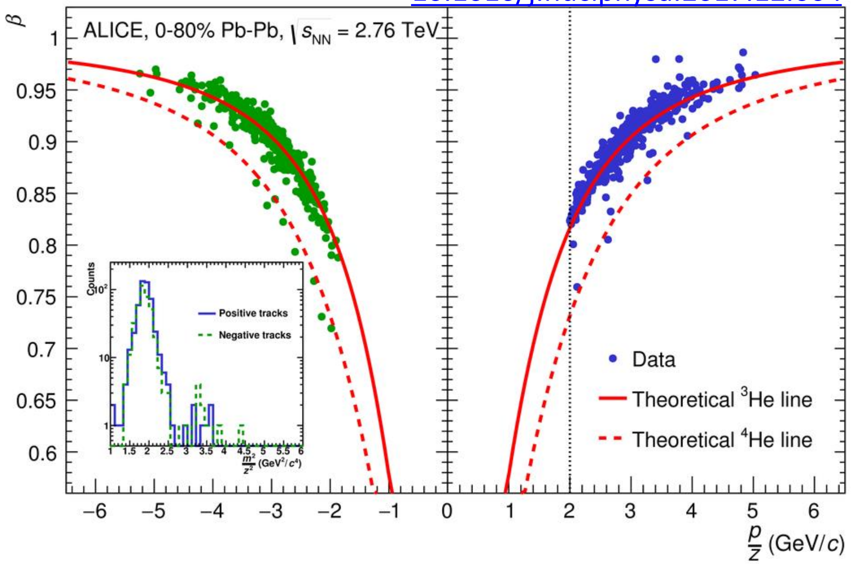
Resonances can be studied through the cascade decay with PID assignment (large combinatorial background)

(Anti-)Nuclei can be detected through their energy loss in the material.



[10.1016/j.nuclphysa.2017.12.004](https://doi.org/10.1016/j.nuclphysa.2017.12.004)

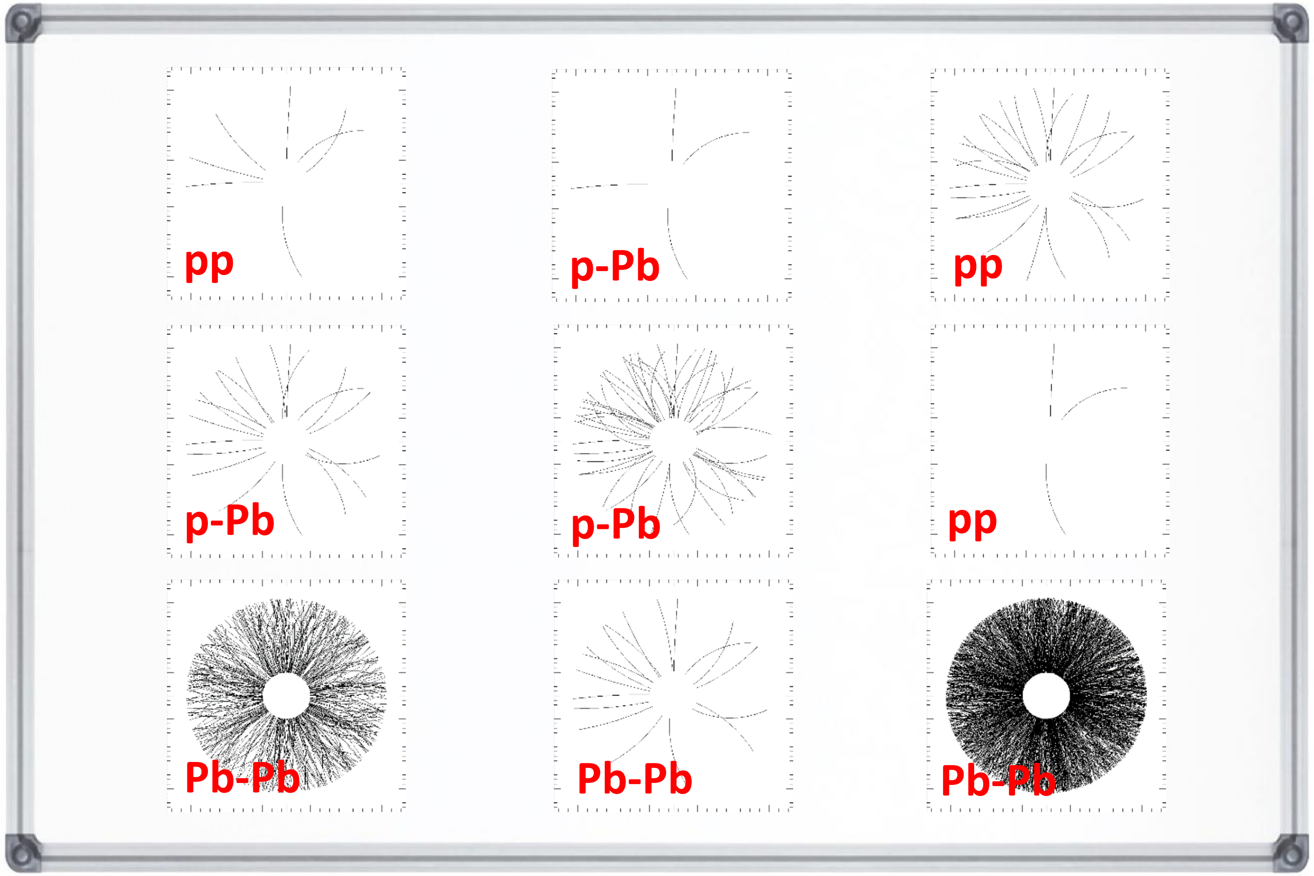




Colliding systems' size: (non-)definition

With small(large)-systems we can normally refer to two different things:

- Size of colliding objects
  - Common way of thinking
  - (ee <) pp < p-A < A-A
- Size of created medium
  - The correspondence to the previous is ~ true only on average
  - N_{part} , N_{coll}
  - Multiplicity



Multiplicity measurement

Multiplicity is a very simple concept:

- Number of particles produced in a defined kinematic region
- HEP experiments have very good performance in reconstructing tracks

But:

- We are mostly interested in primary particles! Need to remove secondaries
- Important concept of MULTIPLICITY ESTIMATOR

Multiplicity measurement

Multiplicity is a very simple concept:

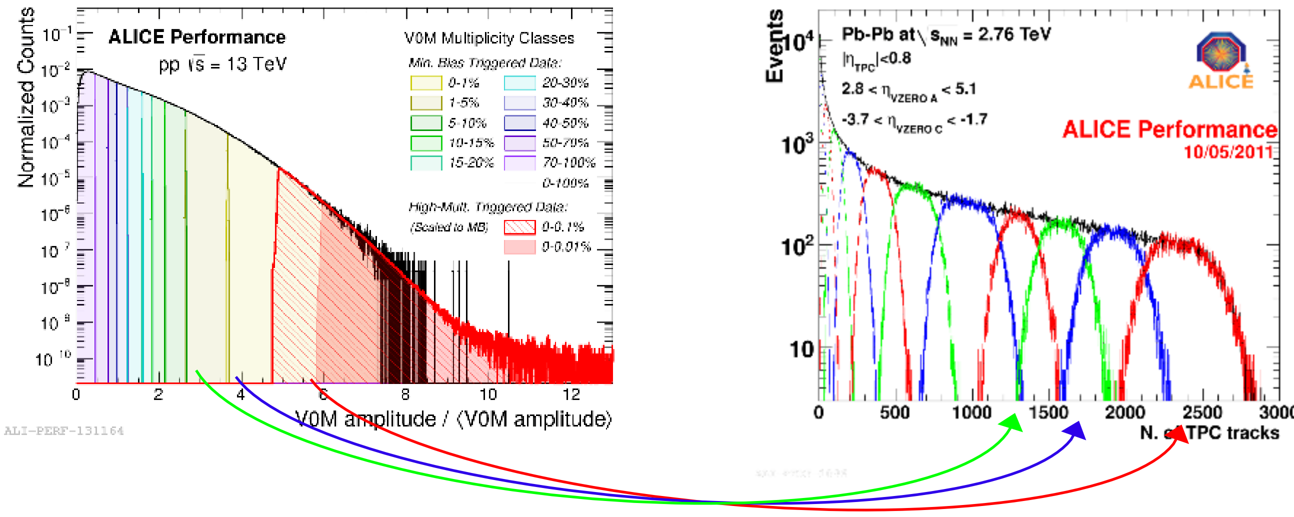
- Number of particles produced in a defined kinematic region
- HEP experiments have very good performance in reconstructing tracks

But:

- We are mostly interested in primary particles! Need to remove secondaries
- Important concept of MULTIPLICITY ESTIMATOR

Multiplicity estimator:

- Tool to categorize each event according to its multiplicity
- η gap: important trick to avoid bias in the multiplicity estimation!*
- Comparison among different colliding systems should always be done using unbiased multiplicity estimators

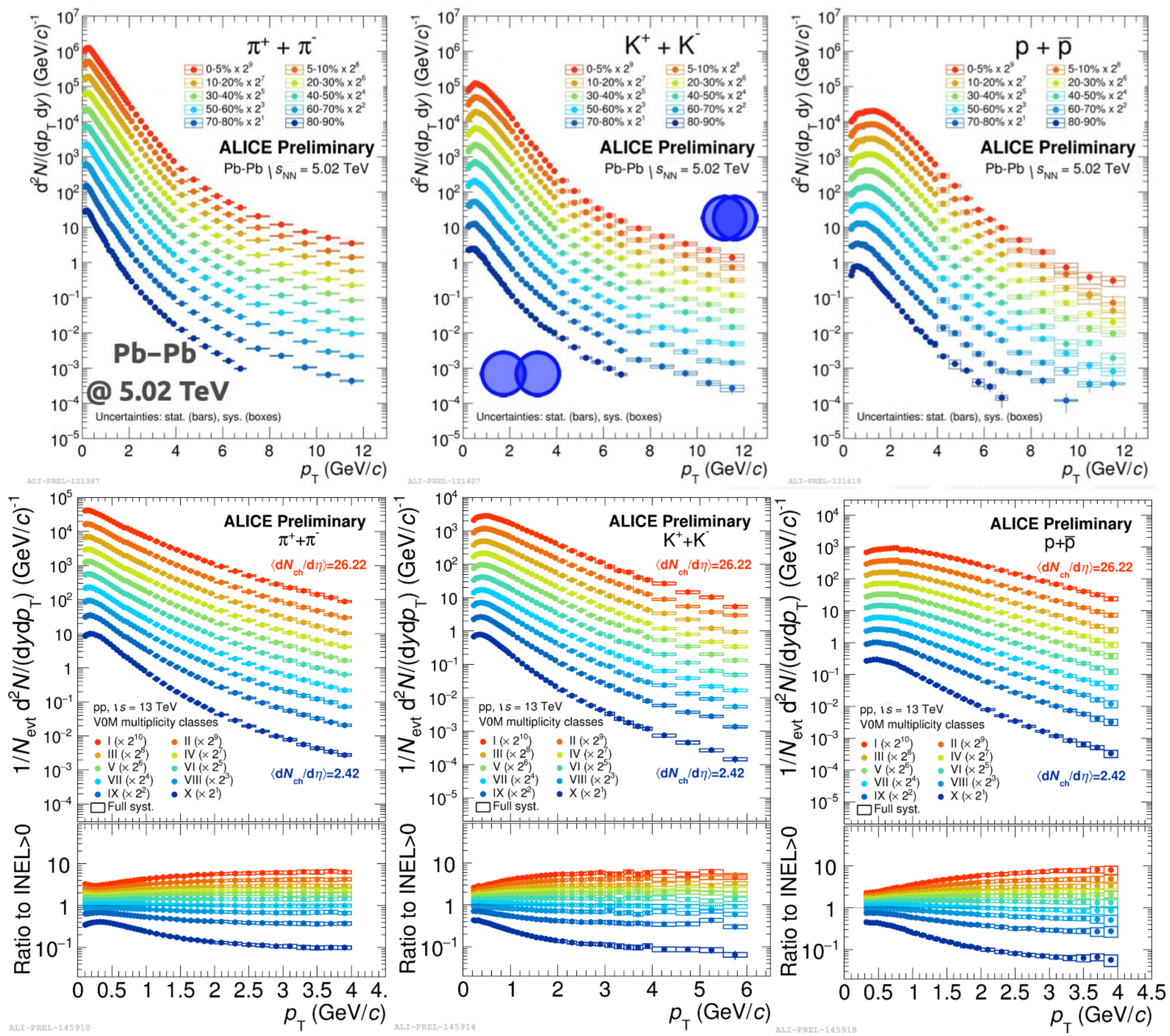


* if you are interested in this technical but KEY detail, just ask ☺

Results: particle spectra and collectivity

Transverse momentum spectra

Livio Bianchi
GDR-QCD wshop
24 July 2018



Detailed study of multiplicity (centrality) evolution of p_T spectra brought-up in all collision systems and at all energies.

Hardening of spectra going to higher-multiplicity collisions

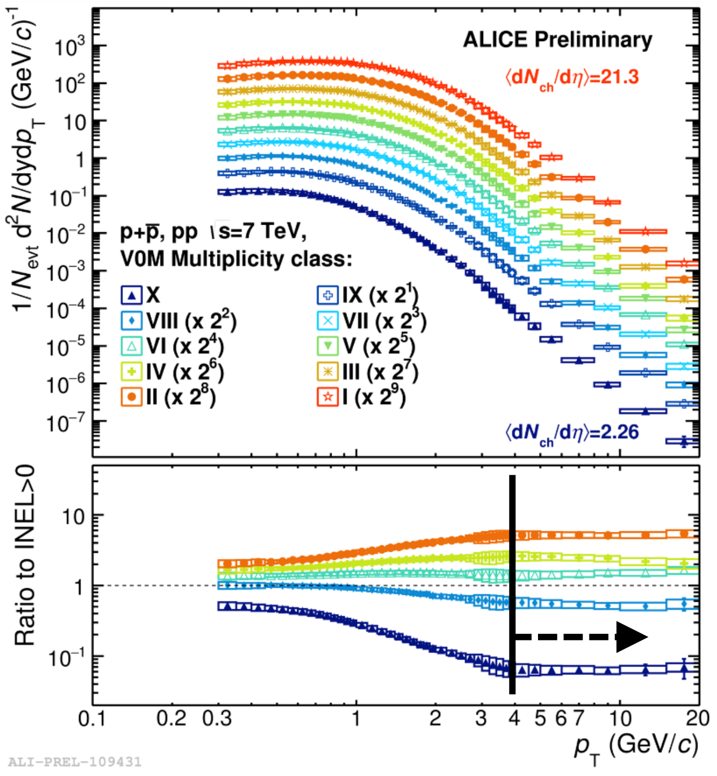
Traditionally attributed to radial flow in large collision systems. Same mechanism in small collision systems?

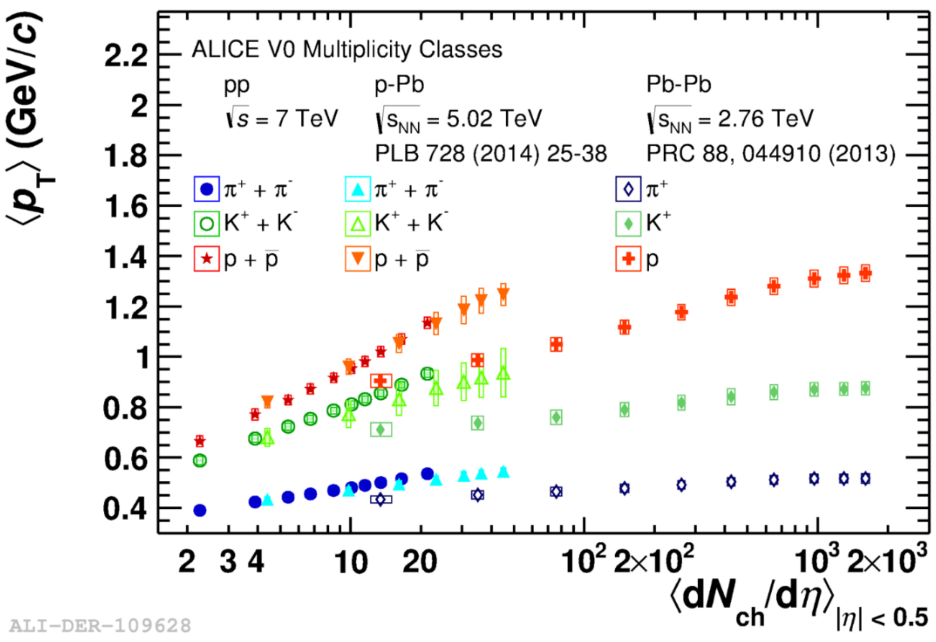
What is the behavior at higher p_T?

Can we learn something from the first moment of the distribution?

↓

Transverse momentum spectra: hardening





Evolution of spectra is over from ~4GeV/c onwards. True for all particles!

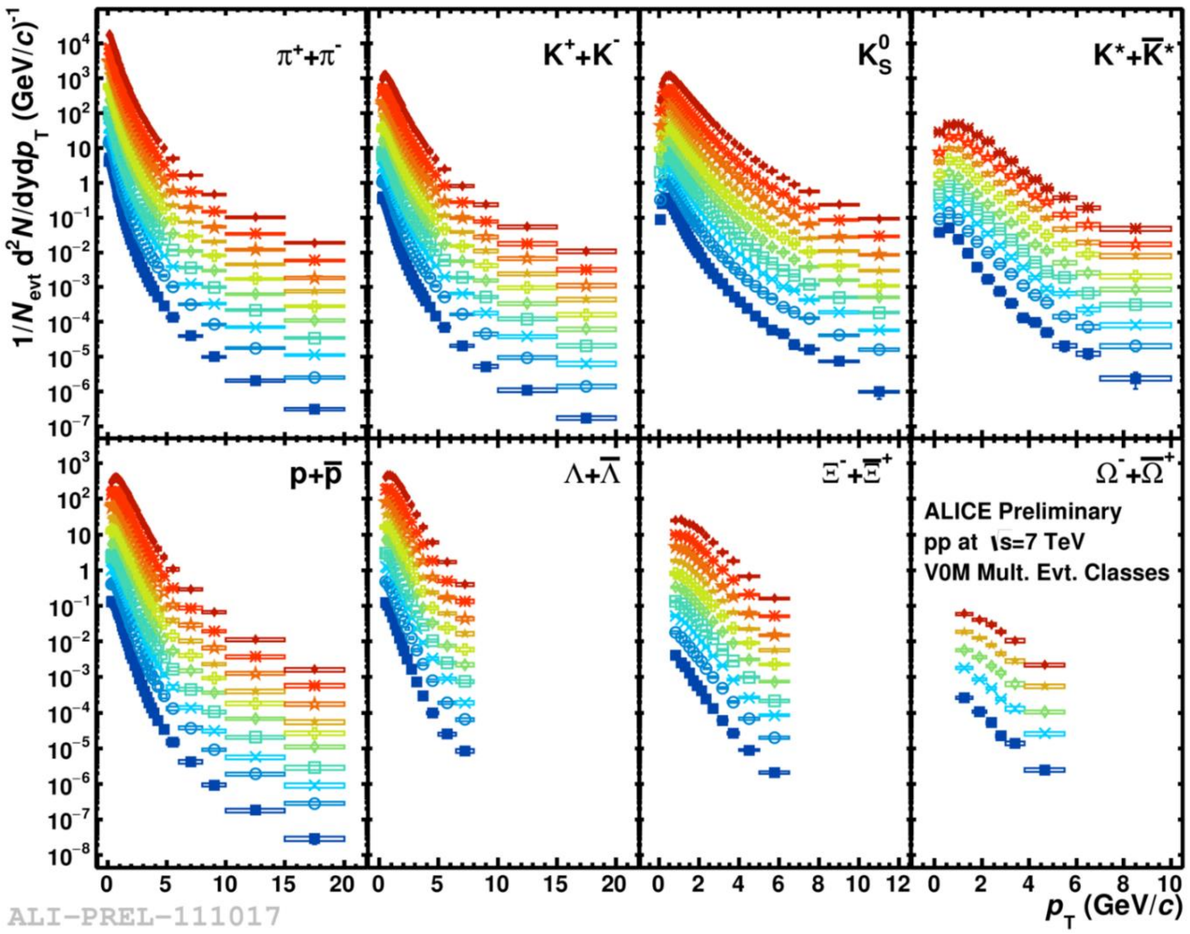
N_{coll}-like scaling in pp collisions?

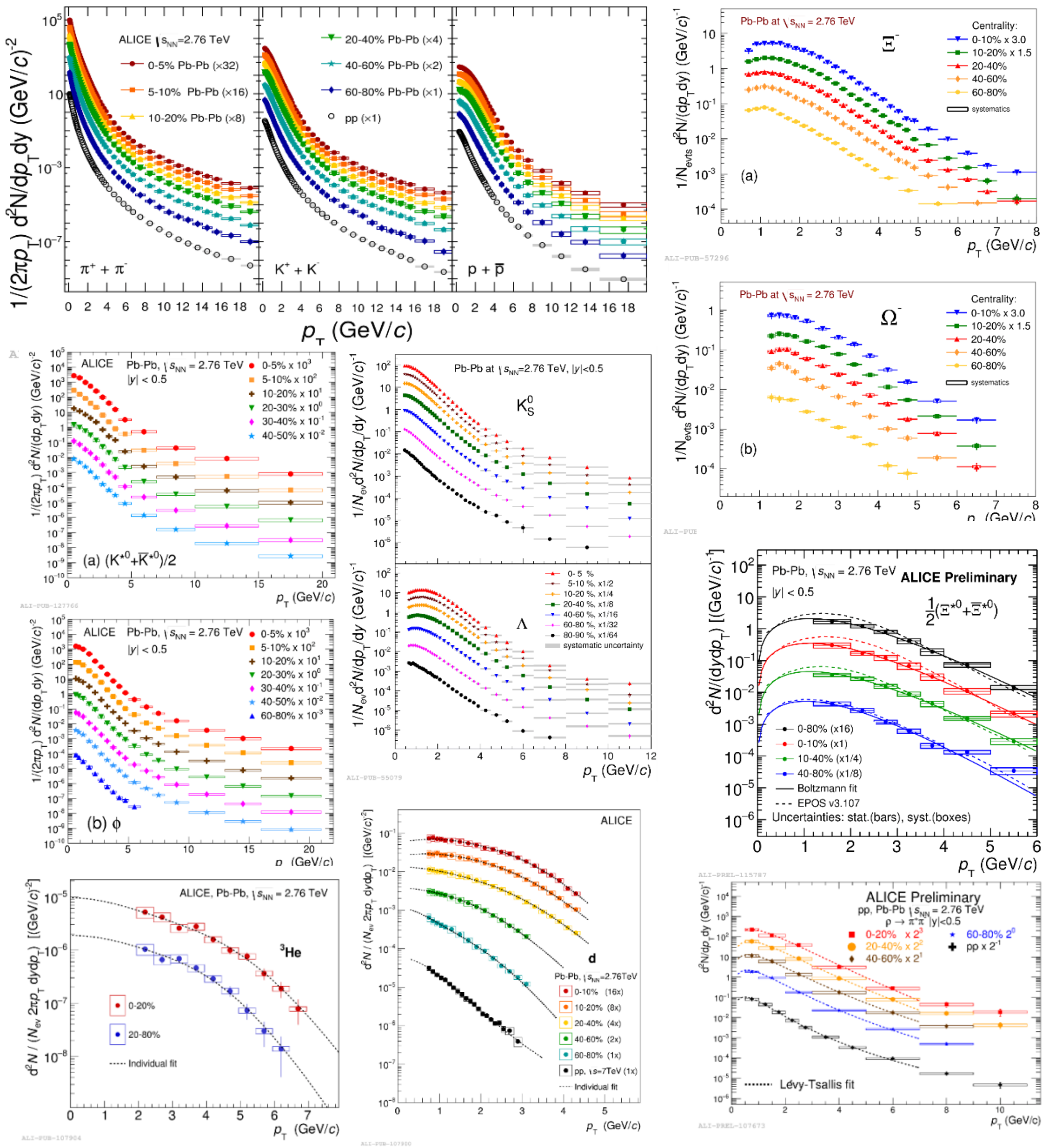
Shows increase in all collision systems.

Very similar in pp and p-Pb, but milder in Pb-Pb. More violently-expanding medium in small systems?

Need to check spectra evolution in a more differential way and compare to models!

Transverse momentum spectra: huge harvest at LHC

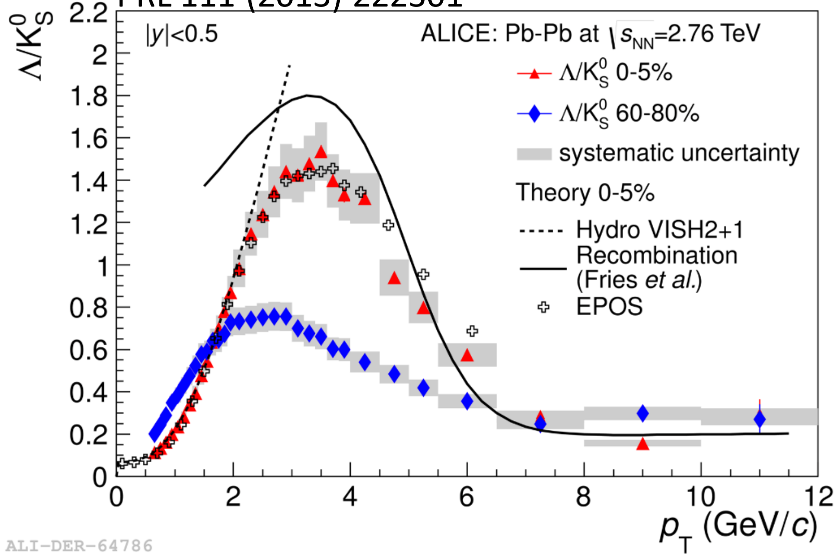


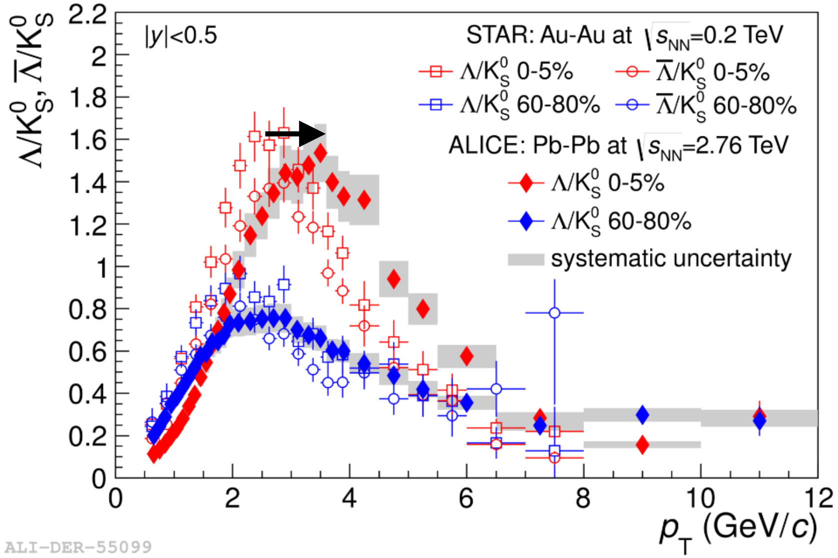


Large variety of particles considered for all collision systems exploited

Transverse momentum spectra: huge harvest at LHC

PRL 111 (2013) 222301





Hydro expansion can describe raising trend.

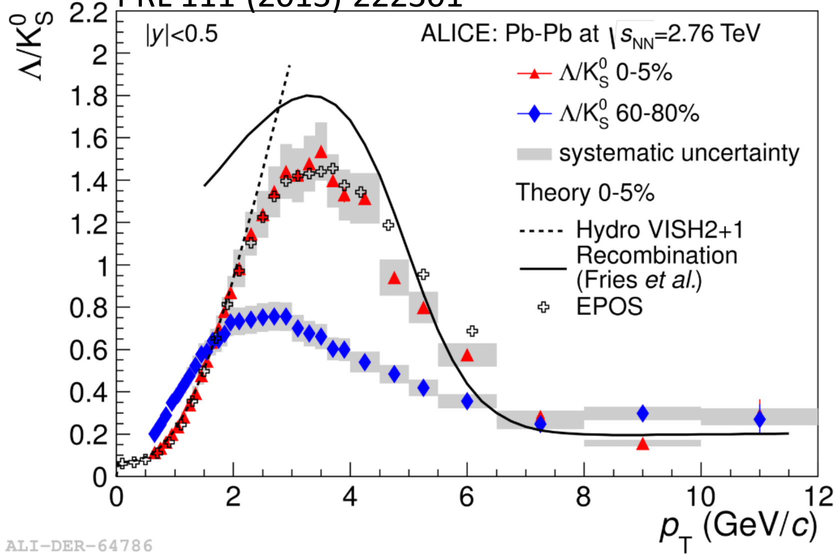
Coalescence and recombination give qualitative explanation of the falling at higher p_T.

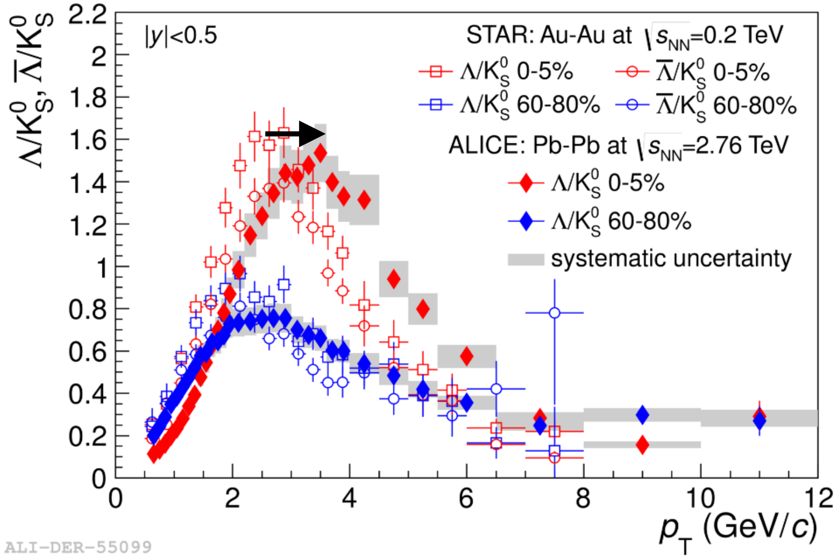
EPOS (hydro+jets) can describe the baryon anomaly in a satisfactory way, when tuning its free parameters on other observables

Higher radial boost at LHC $\xrightarrow{?}$ peak at higher p_T

Transverse momentum spectra: huge harvest at LHC

PRL 111 (2013) 222301



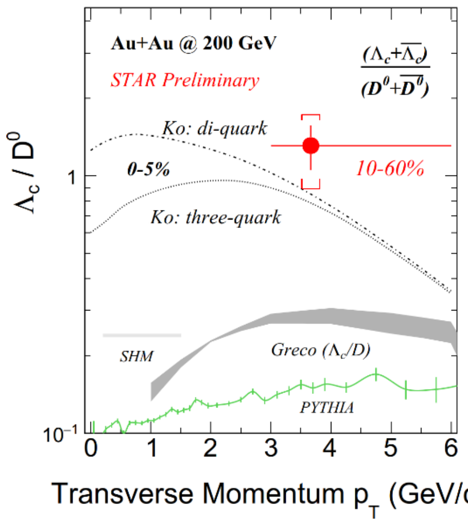


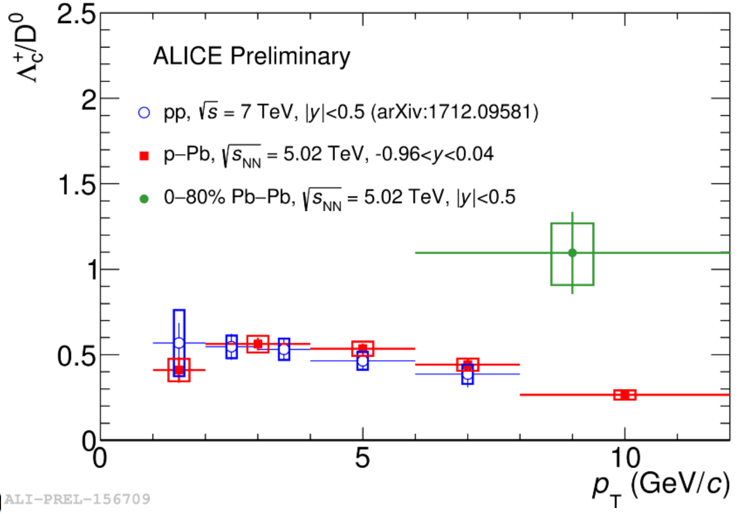
Hydro expansion can describe raising trend.

Coalescence and recombination give qualitative explanation of the falling at higher p_T.

EPOS (hydro+jets) can describe the baryon anomaly in a satisfactory way, when tuning its free parameters on other observables

Higher radial boost at LHC $\xrightarrow{?}$ peak at higher p_T



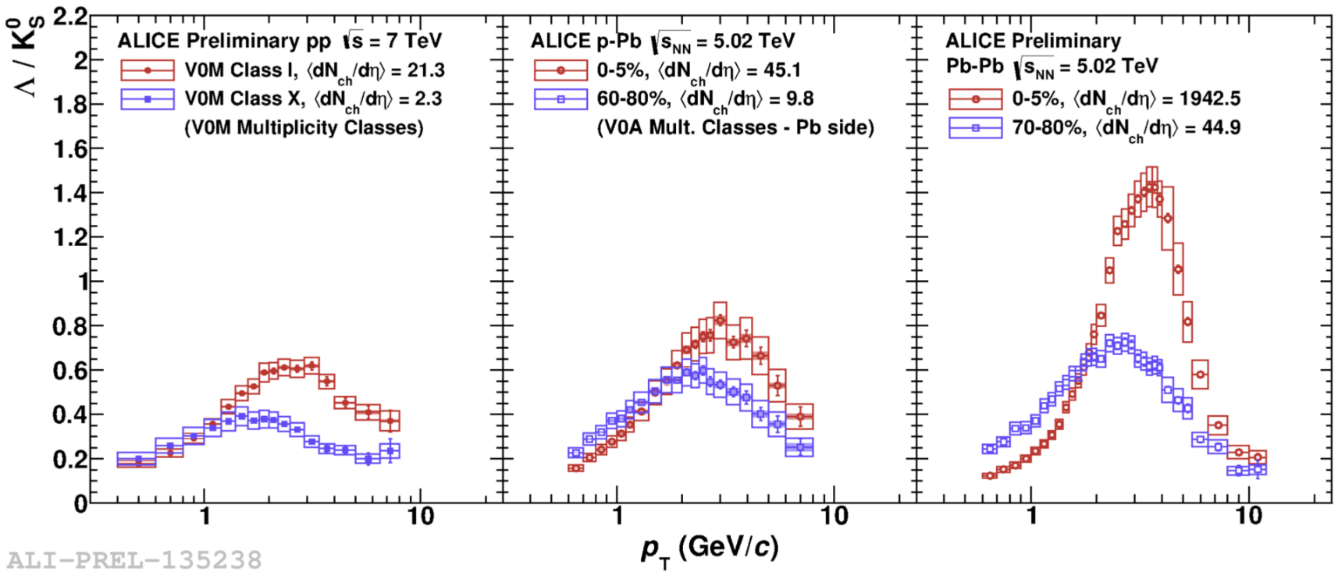


Is this feature present in the charm sector as well?

Need for larger statistics!

baryon/meson: different colliding systems

Livio Bianchi
GDR-QCD wshop
24 July 2018



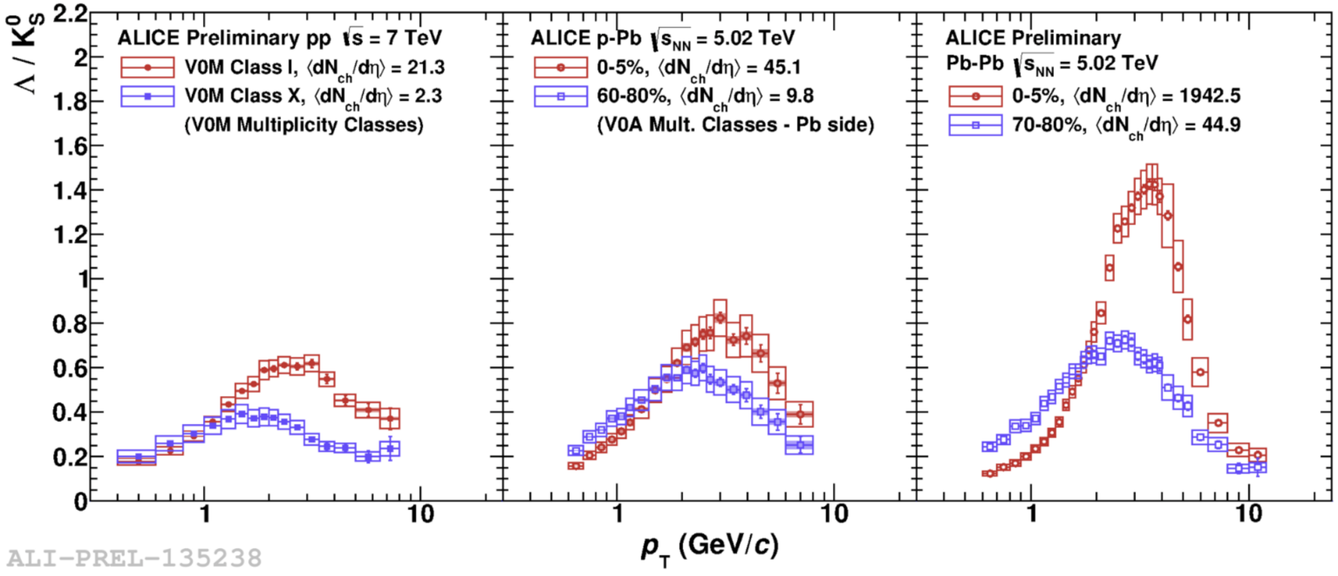
Same pattern in the Λ/K^0_S measured in small systems, with different magnitude…

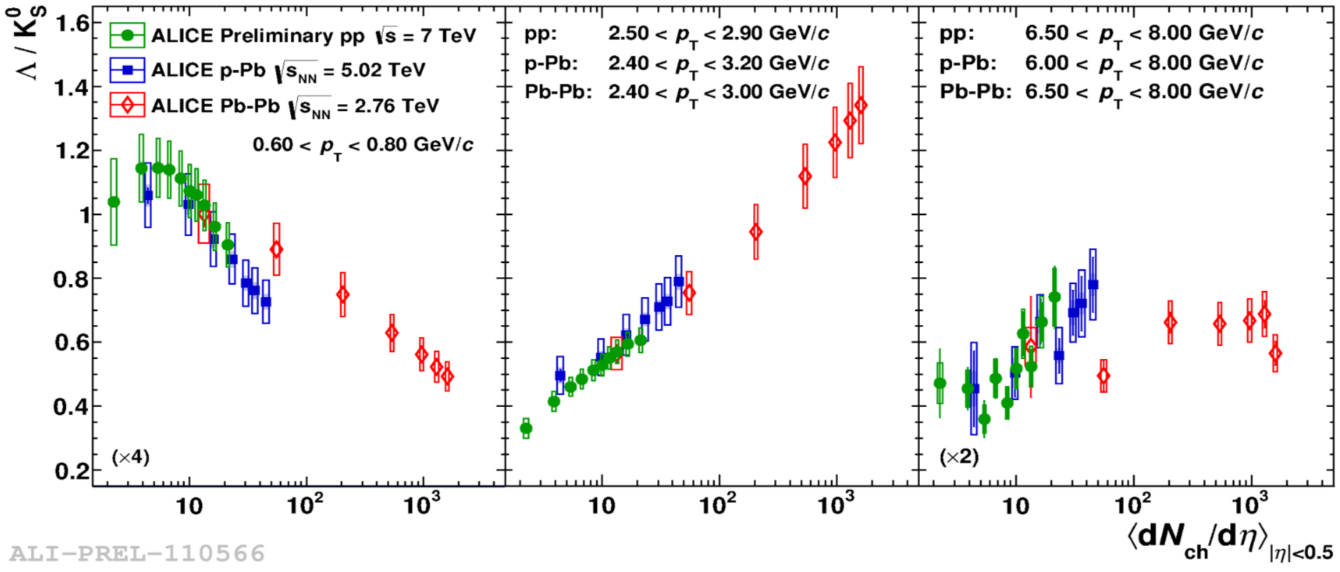
…but…

MIND THE MULTIPLICITY SPAN!

In order to make proper comparison, one can select p_T ranges and look at multiplicity dependence

baryon/meson: different colliding systems





Same pattern in the Λ/K^0_S measured in small systems, with different magnitude…

…but…

MIND THE MULTIPLICITY SPAN!

In order to make proper comparison, one can select p_T ranges and look at multiplicity dependence

Clear continuity among different systems!

Is the underlying mechanism the same here?

Need to compare to hydro

↓

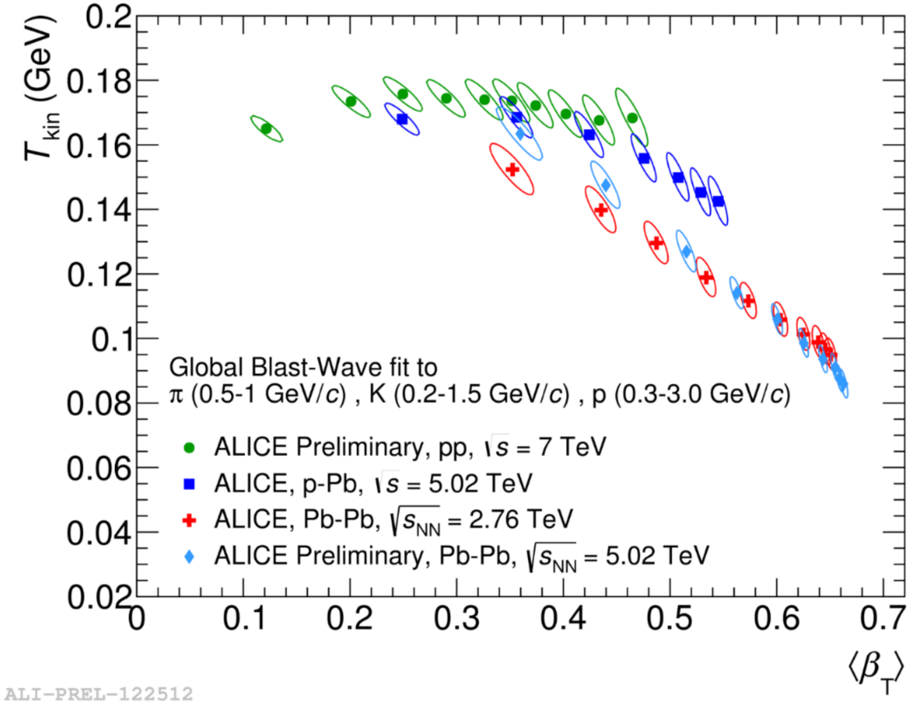
Hydro in pp?

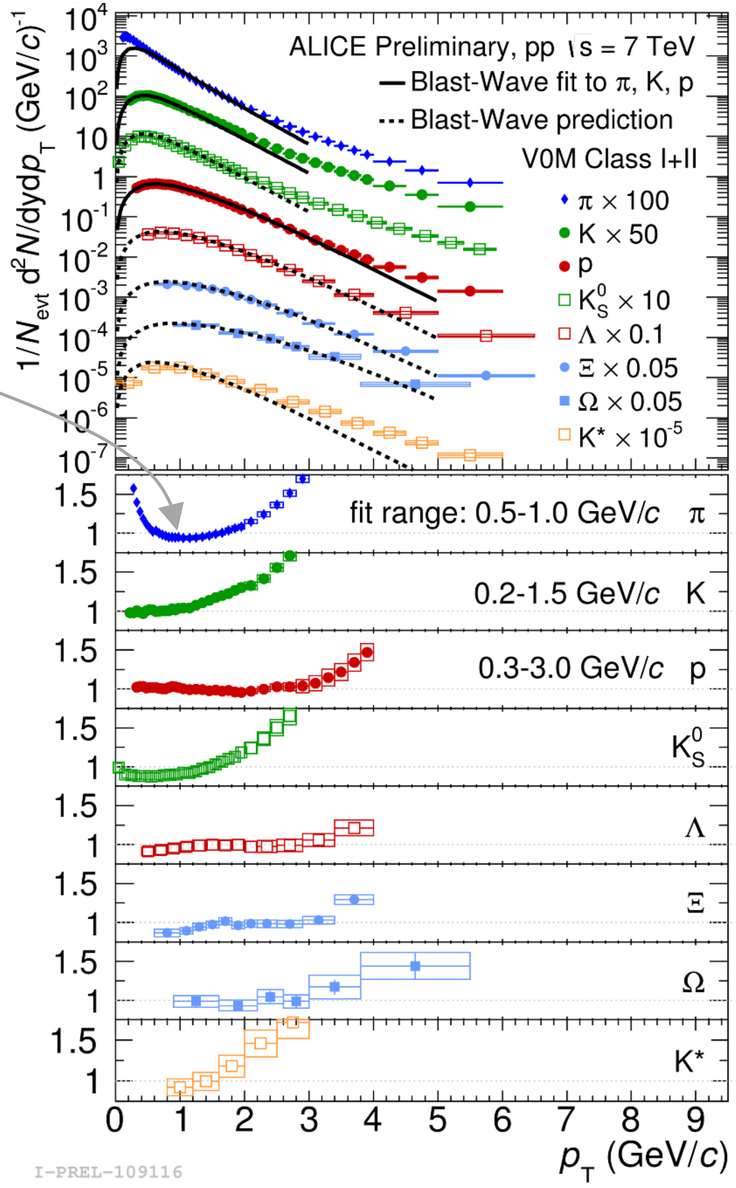
Blast wave: simplified hydro model:

- Assumes common particle expansion with β_T and T_{kin}
- If assumption ok: fit (e.g.) π,K,p $\rightarrow$ predict p_T shape of other particles

- Assumption ~ok for all collision systems
- pp and p-Pb: similar T_{kin}-β_T progression
- Considering corresponding multiplicity: less "violent" expansion in Pb-Pb, but T_{kin} common for all systems

CAVEAT: limited p_T range of validity. Resonance decays at low-p_T, perturbative production at high-p_T





Blast wave: simplified hydro model:

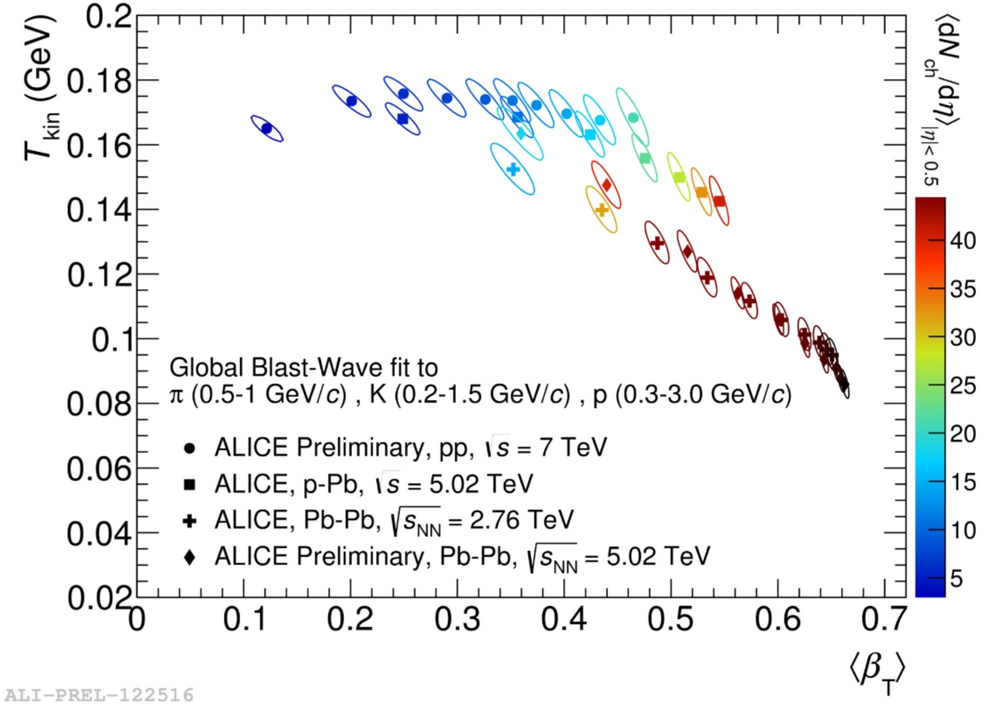
- Assumes common particle expansion with β_T and T_{kin}
- If assumption ok: fit (e.g.) π,K,p → predict p_T shape of other particles

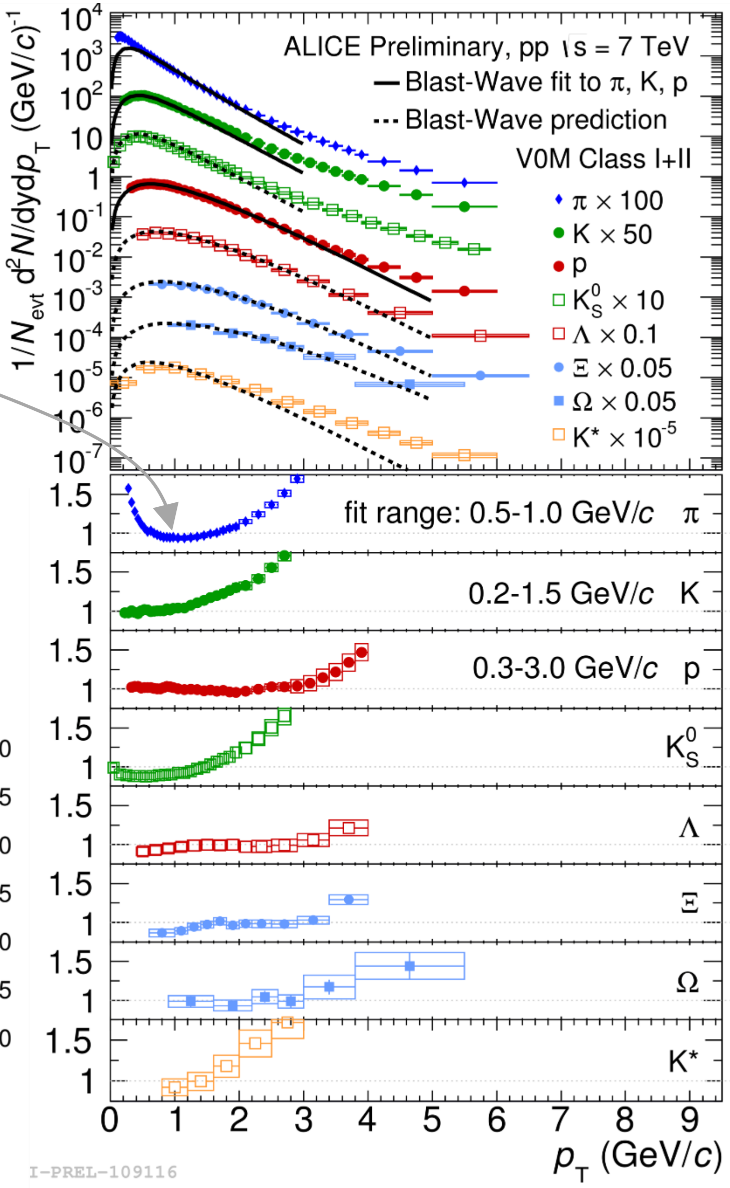
- Assumption ~ok for all collision systems
- pp and p-Pb: similar T_{kin}-β_T progression
- Considering corresponding multiplicity: less "violent" expansion in Pb-Pb, but T_{kin} common for all systems

CAVEAT: limited p_T range of validity. Resonance decays at low-p_T, perturbative production at high-p_T

TAKE HOME

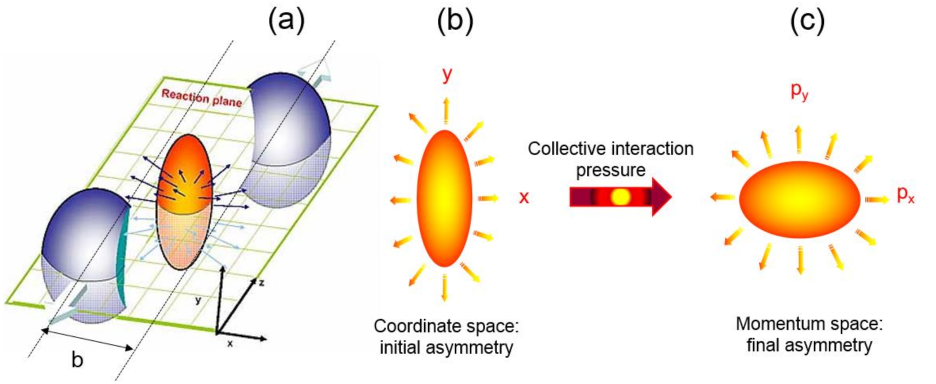
Simple hydro model seems to describe p_T spectra evolution with multiplicity across different collision systems





v_2 in a nutshell

According to the hydro picture, the strongly interacting medium is expected to develop:

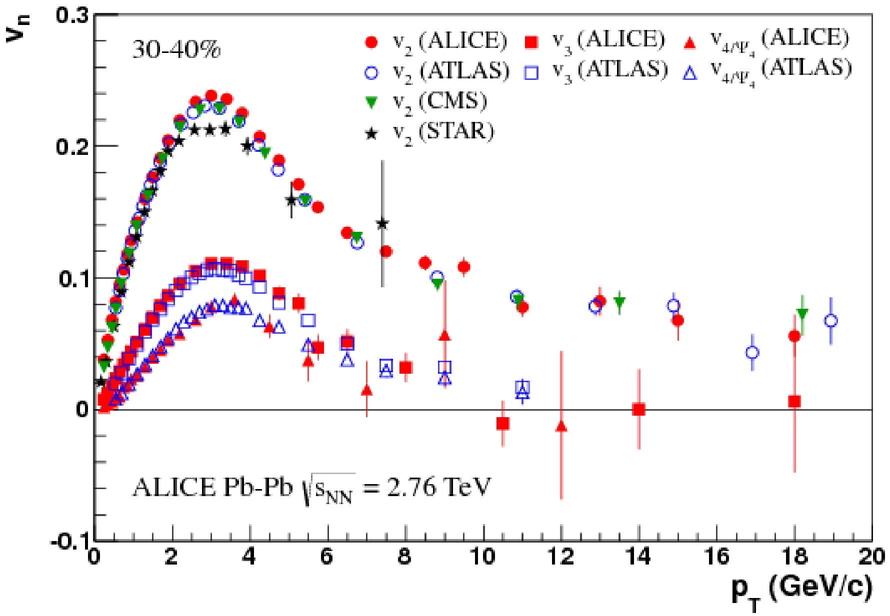


- **Radial flow** (important in central collisions):
  - Common expansion velocity of partons
  - Translates into spectral shape modification
  - Baryon/meson anomaly

- **Anisotropic flow** (important in semi-peripheral collisions):
  - Initial spatial anisotropy translates into final momentum anisotropy (pressure gradients)
  - Measured through angular anisotropies in the momentum distribution

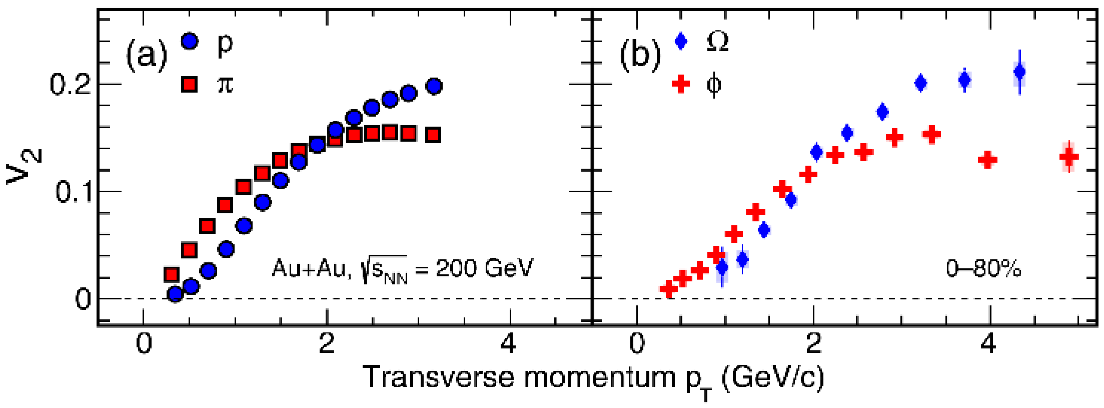
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

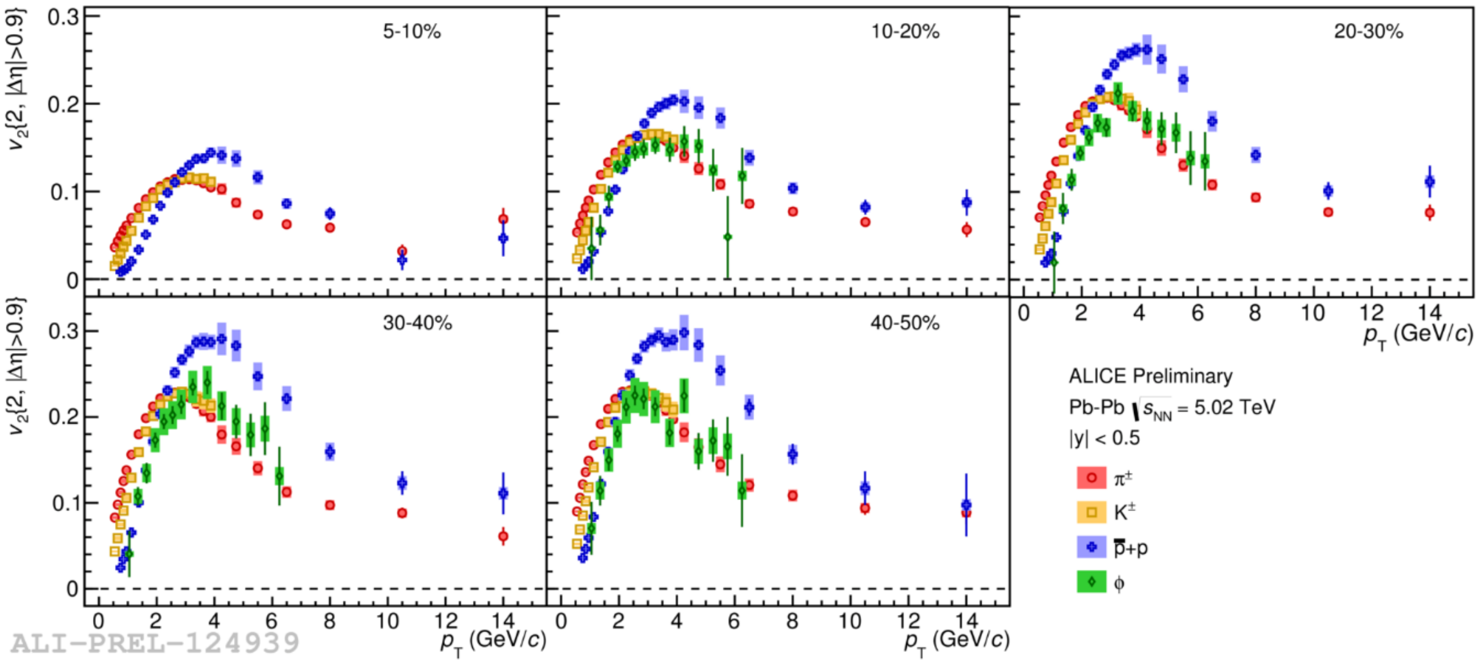
$$E\frac{d^3N}{dp^3} \approx \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,d\eta}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]\right]$$



v_2 in heavy ions

PRL 116, 062301 (2016)





Mass ordering & baryon/meson splitting **equal for strange and non-strange** hadrons at RHIC

Hadronic cross-section: Ω and ϕ << p

⇓

observed v_2 driven by initial spatial anisotropy

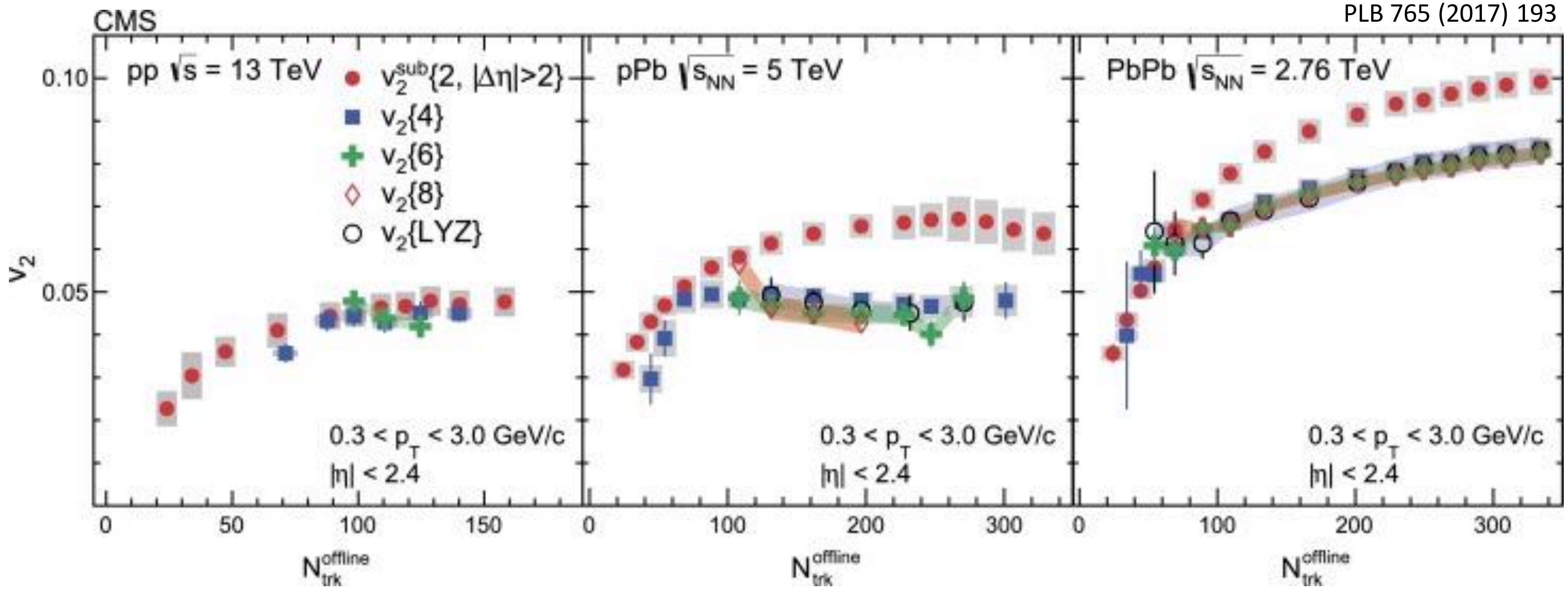
Run1 + Run2 at the LHC confirm the same observation

TAKE HOME

Strangenss flows with the bulk

v_2 in small systems (I)

PLB 765 (2017) 193

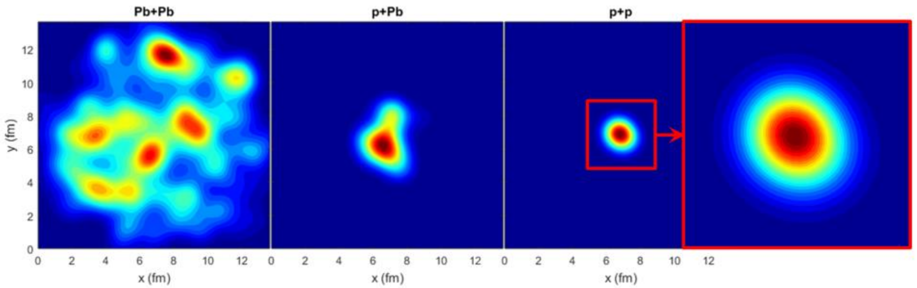


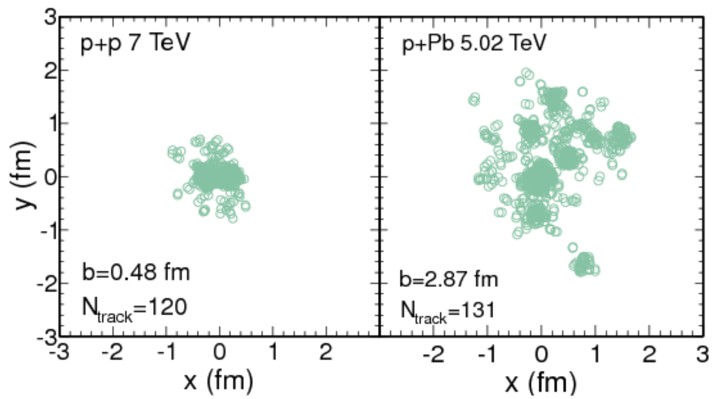
v_2 different from zero observed in all collision systems

NOTE: contribution of non-flow not easy to estimate in pp (and p-Pb)

…but does this make sense at all? Can hydro develop in so small systems? Moreover.. starting from which spatial asymmetry?

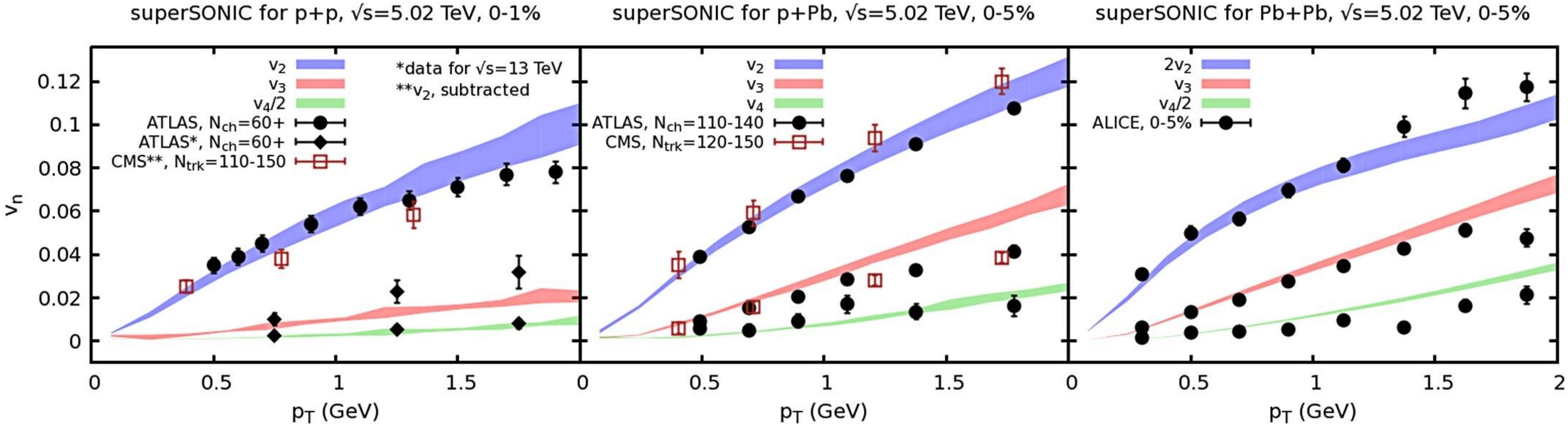
v_2 in small systems (II)





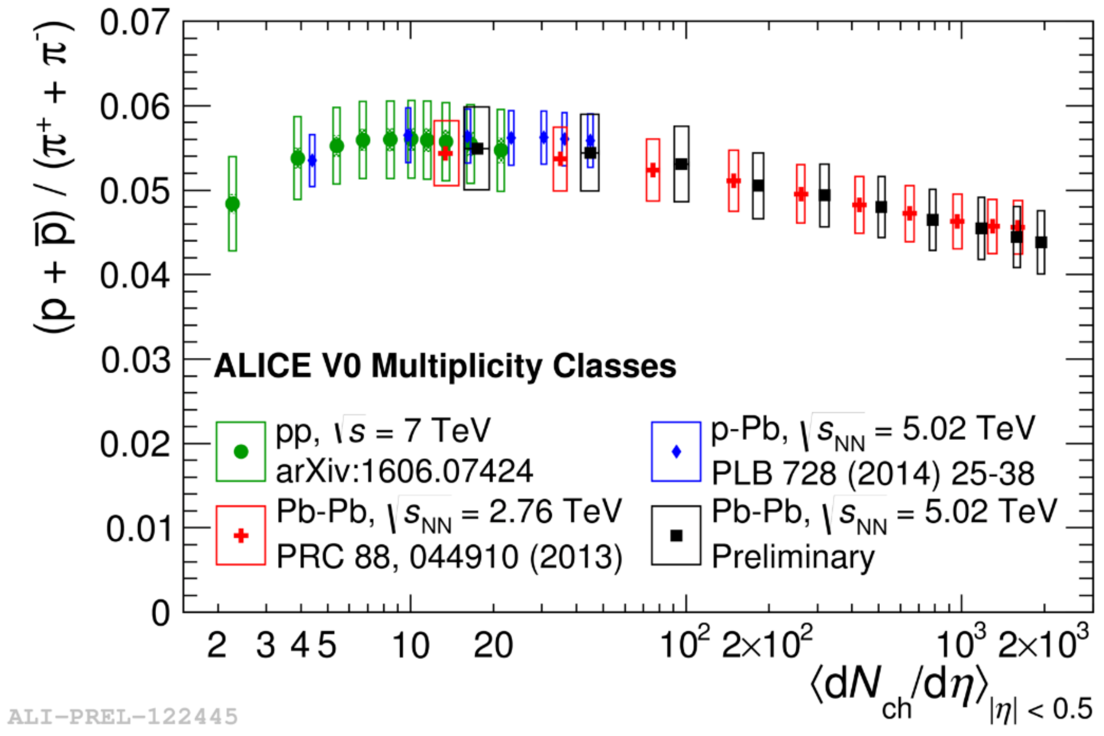
One fluid to rule them all: viscous hydrodynamic description of event-by-event central p+p, p+Pb and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV

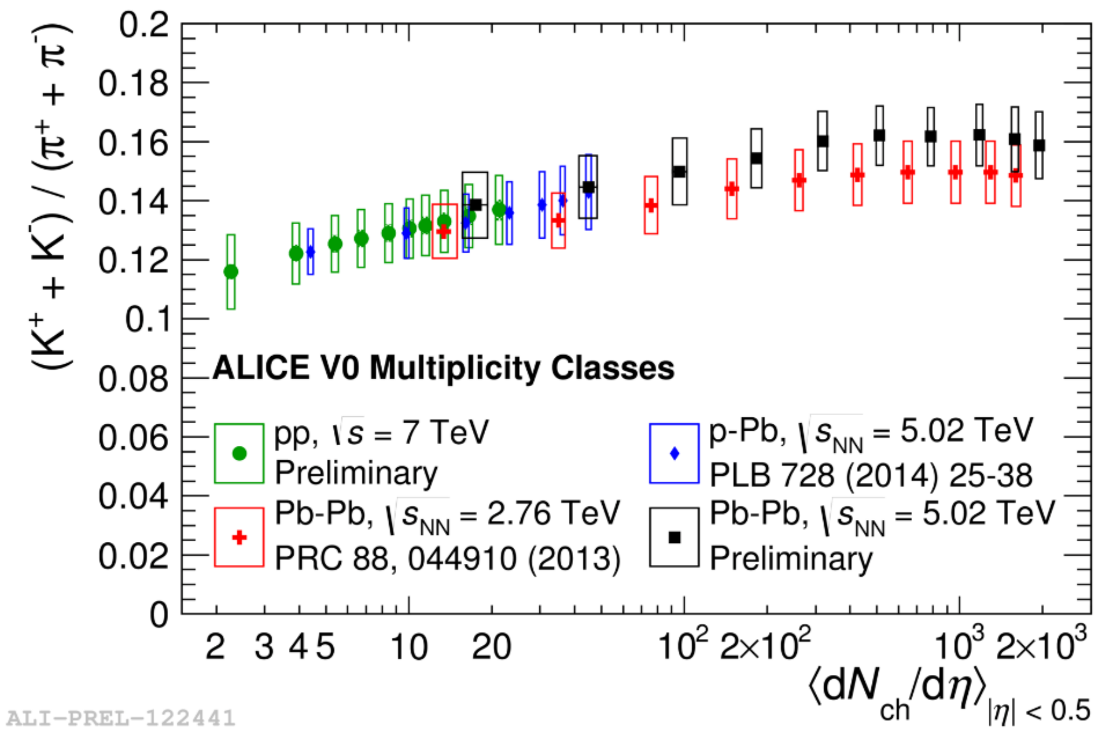
Ryan D. Weller[1] and Paul Romatschke[1,2]



Results: hadrochemistry

Particle yields: ratio to pions (I)

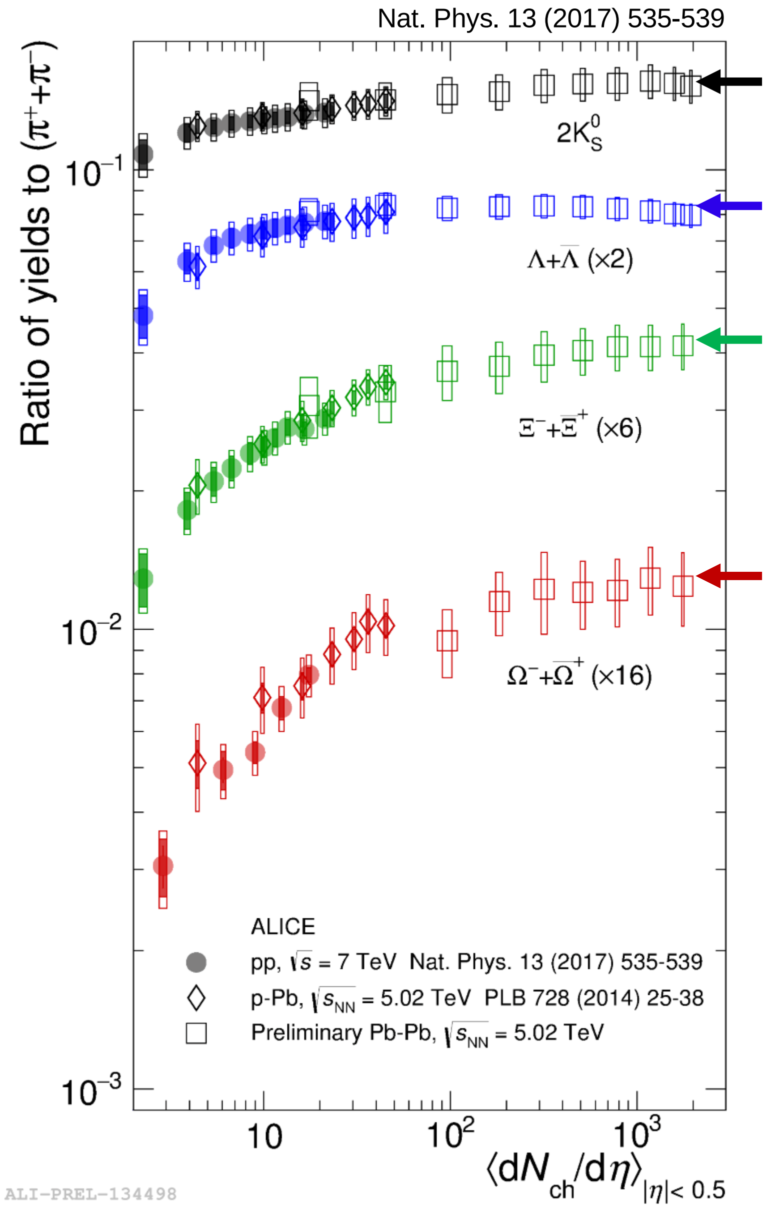




Ratio to pions: relative abundance of particles of a given specie with respect to a common reference

Smooth (mild) evolution of p/π and K/π across different systems when plotting as a function of multiplicity

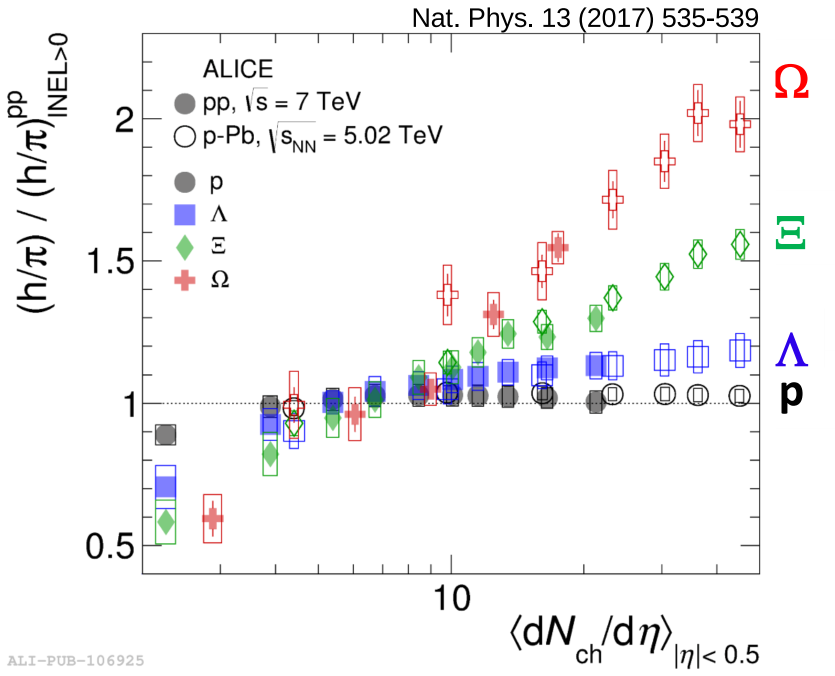
Particle yields: ratio to pions (II)



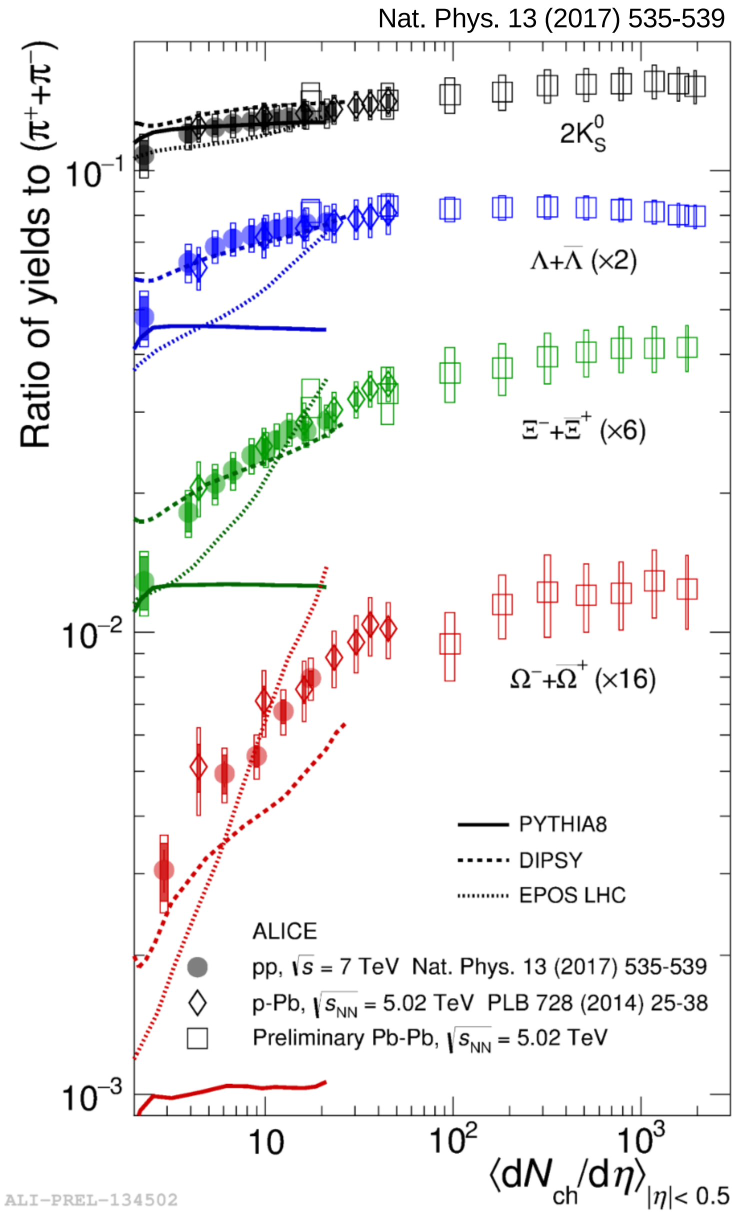
Strangeness enhancement in small collision systems (pp and p-Pb)

Strangeness production saturates at high multiplicity

The larger the content in strangeness of the hadron, the steeper the increase is:

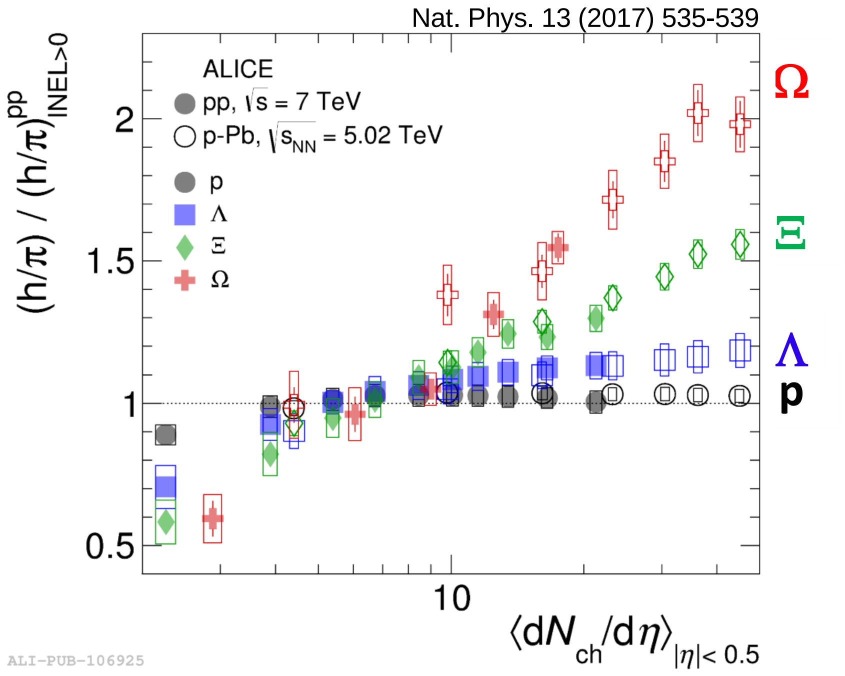


Particle yields: ratio to pions (II)



Strangeness enhancement in small collision systems (pp and p-Pb)

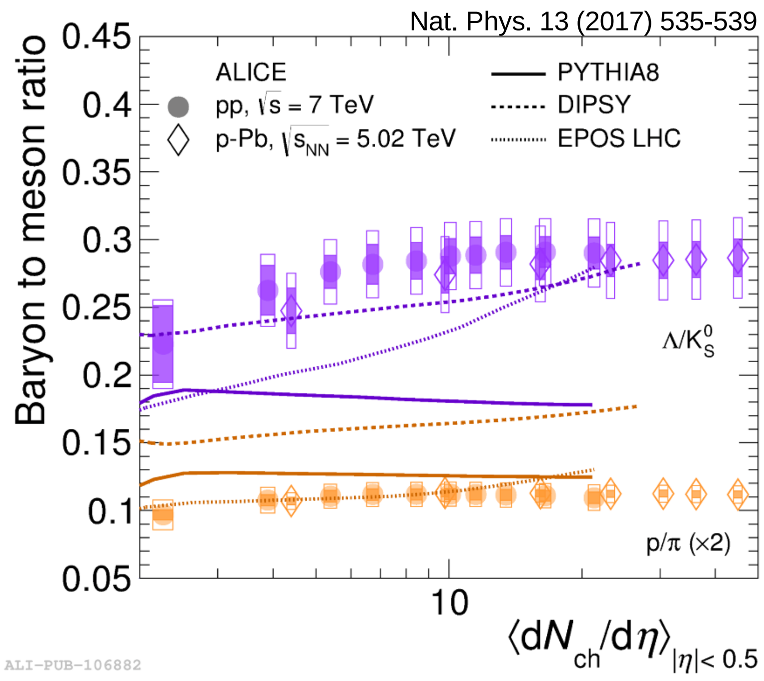
The larger the content in strangeness of the hadron, the steeper the increase is:



Strangeness production saturates at high multiplicity

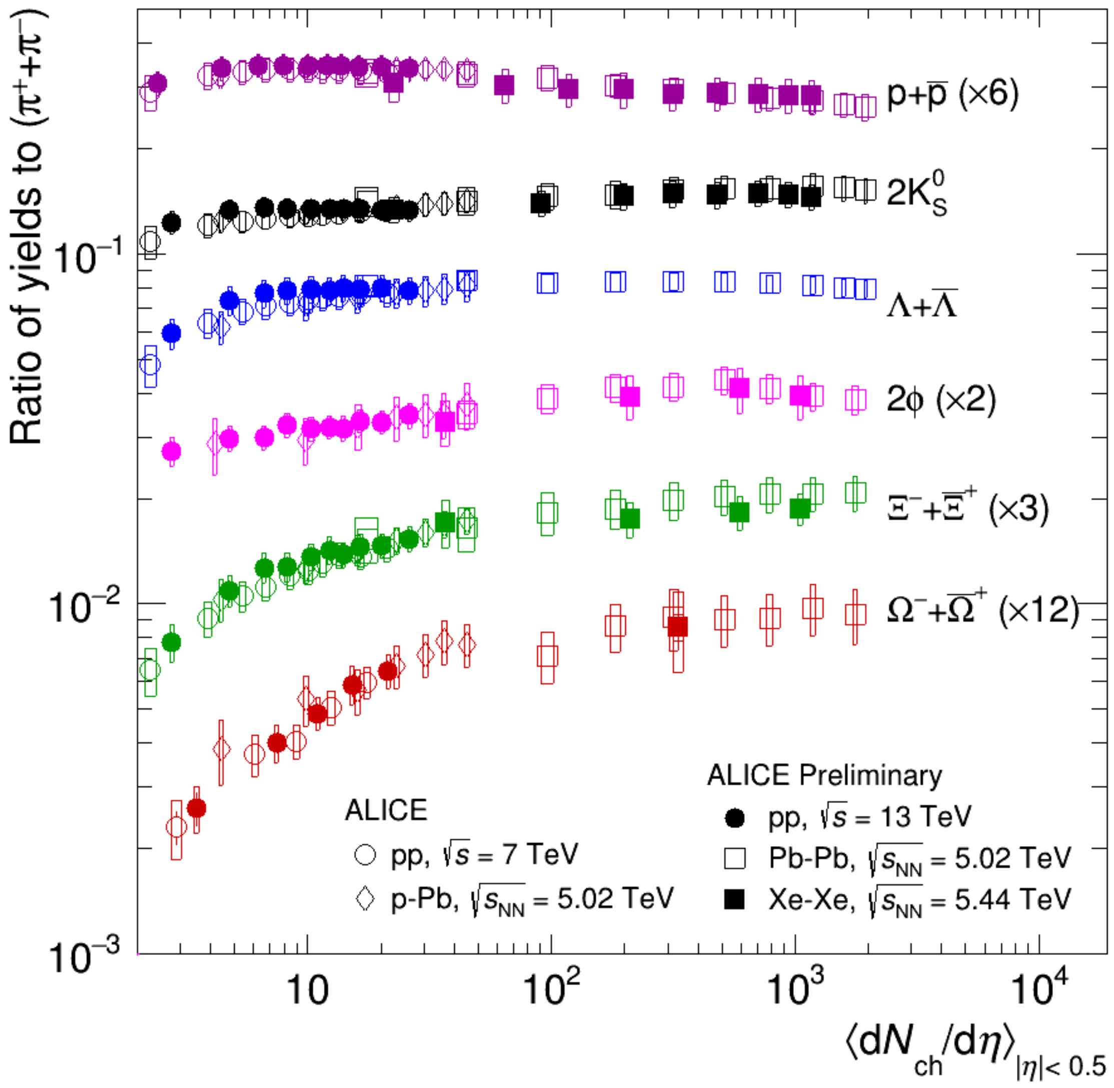
Enhancement is a strangeness-related effect!

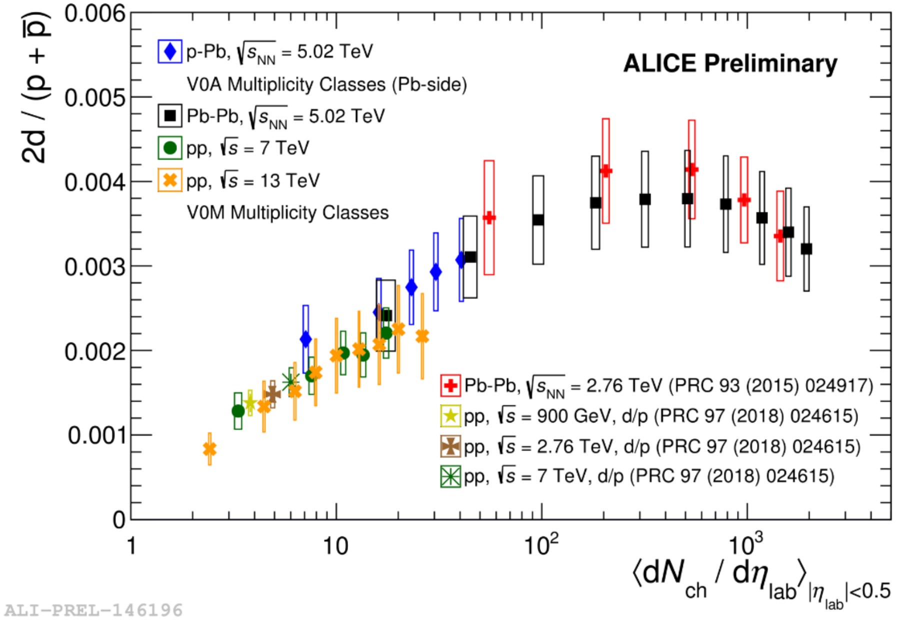
↓



Particle yields: ratio to pions (III)

Livio Bianchi
GDR-QCD wshop
24 July 2018





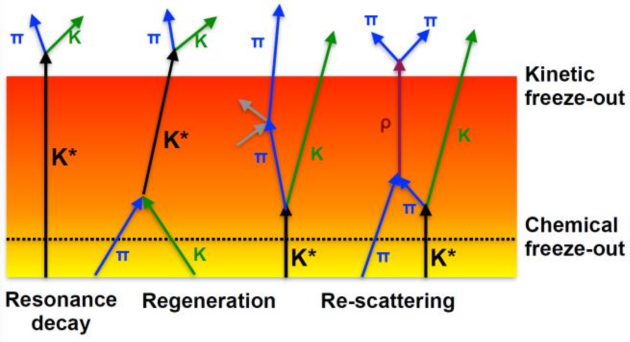
Adding different colliding systems the outcome remains the same

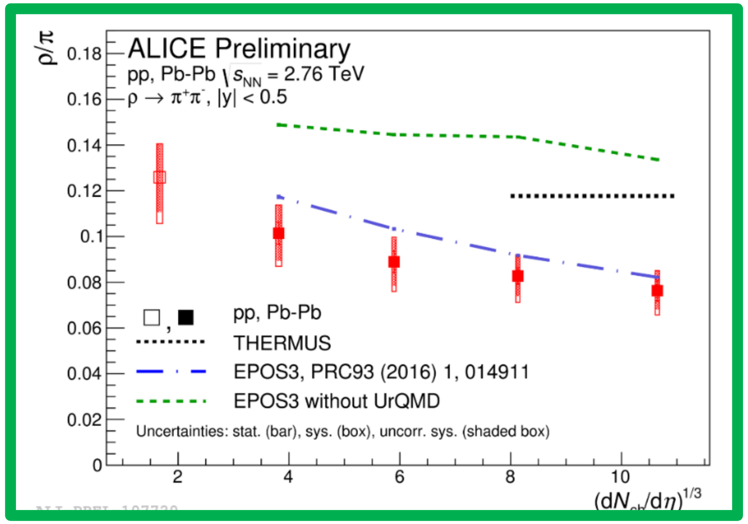
Even deuteron shows a smooth evolution across multiplicity

Particle yields: ratio to pions (IV)

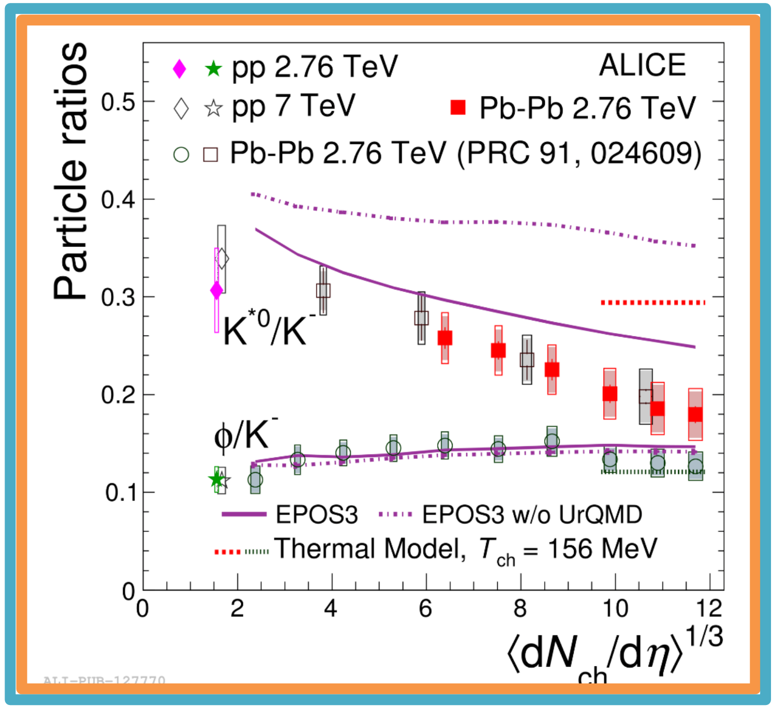
Livio Bianchi
GDR-QCD wshop
24 July 2018

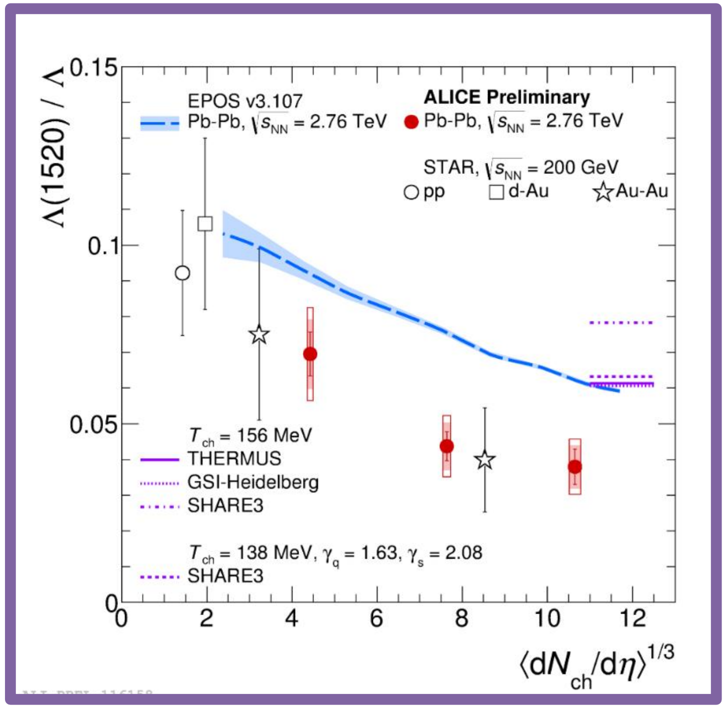
Resonances are powerful tools to probe the hadronic phase after chemical freeze-out

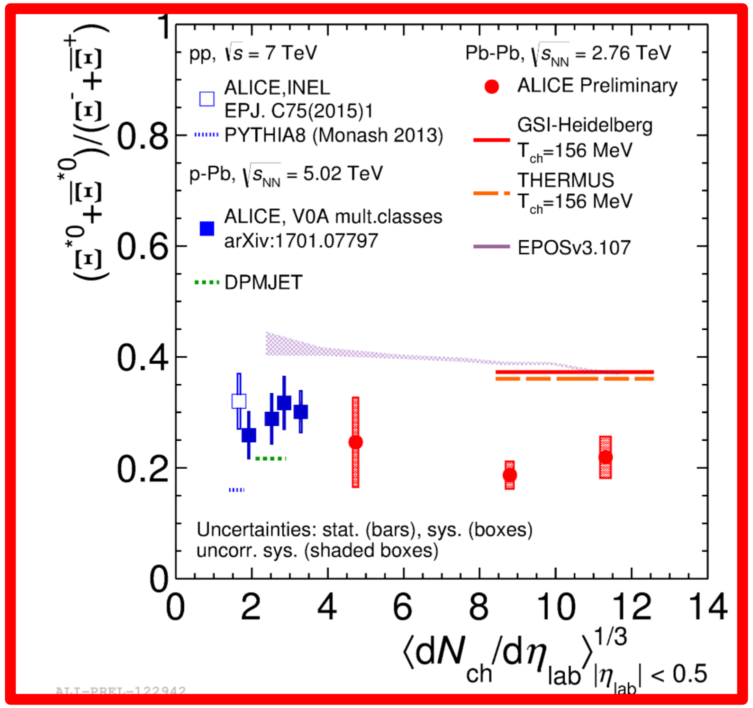




Lifetime [fm/c] : ρ [1.3] < K* [4.2] < Λ* [12.6] < Ξ^{0*} [21.7] < ϕ [46.2]

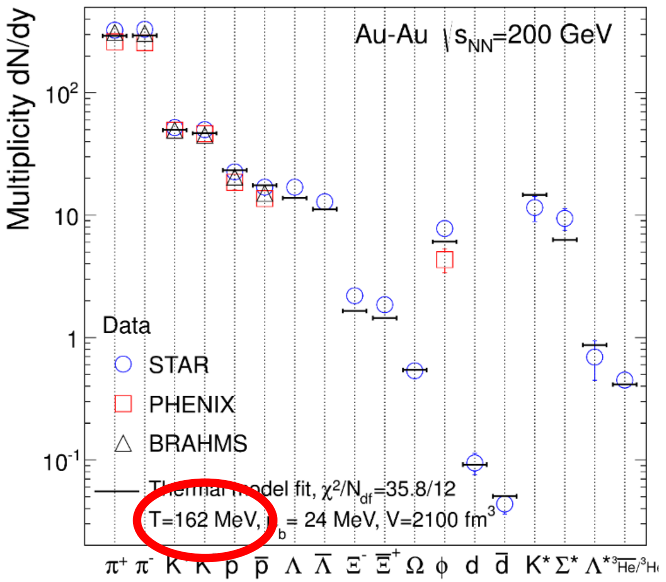


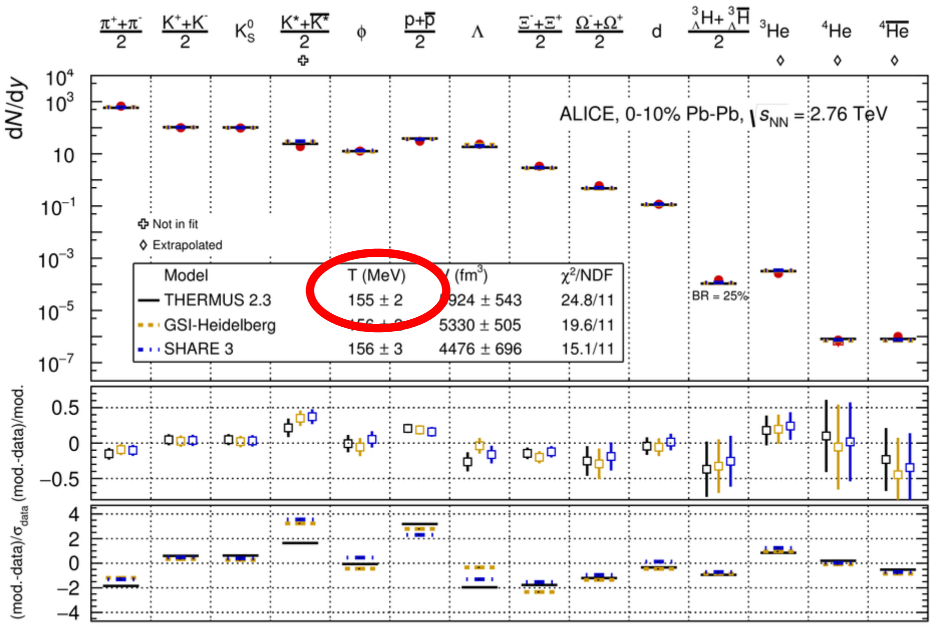


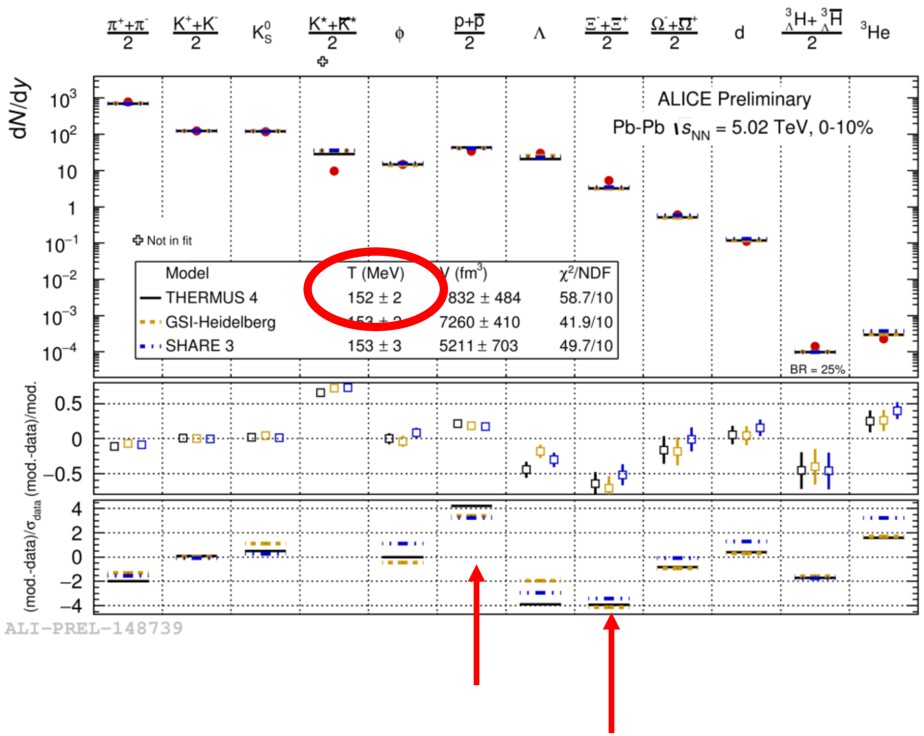


Interpretation: are we there ‘already’?

SHM applied to heavy ions provides a “good” description of particle yields over 9 orders of magnitude!!





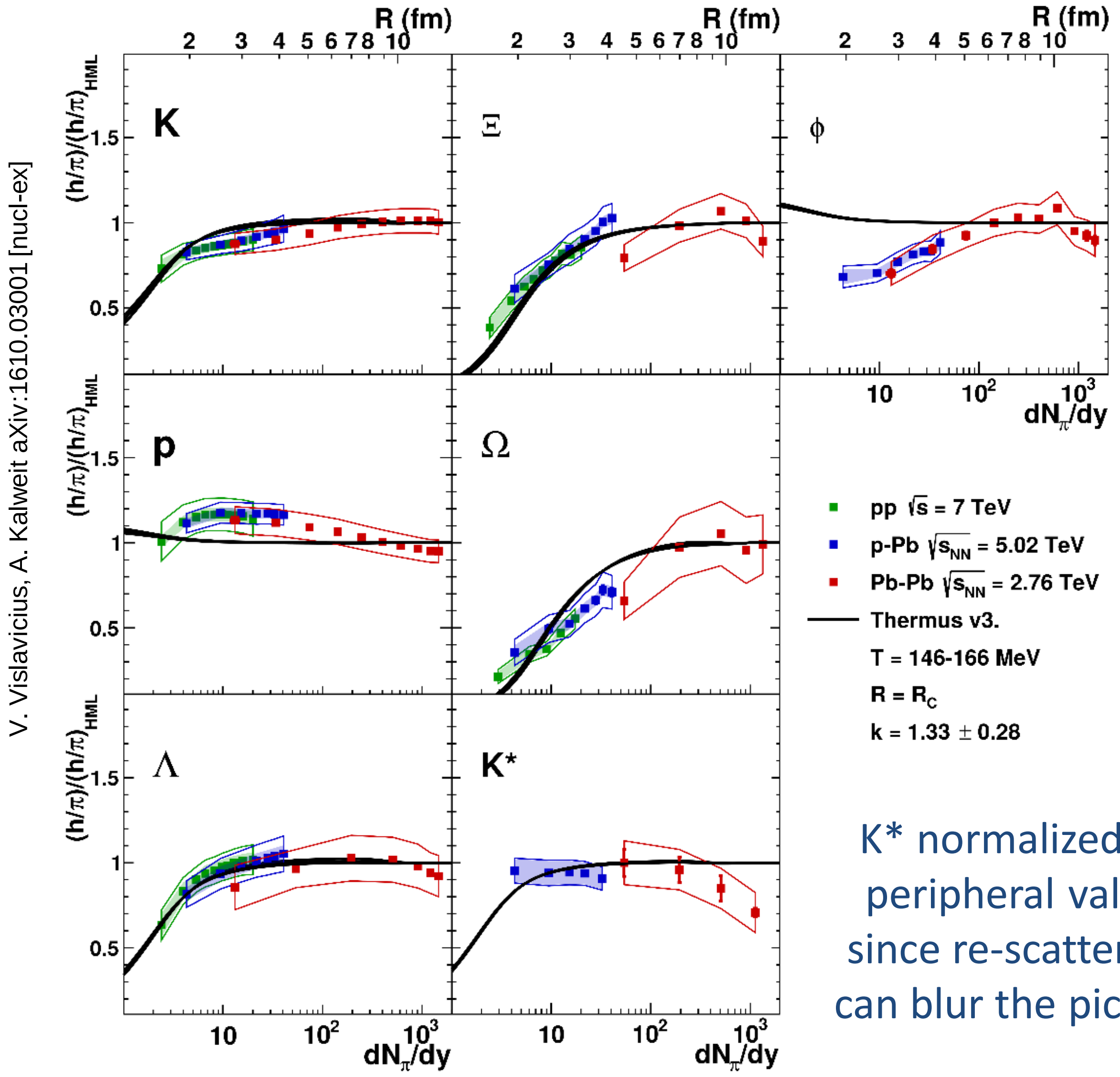


But…

Freeze-out temperature depends on energy?
In principle should not!
Does this come from post-freezeout effects?

Tension for protons and Xi in very central collisions. Hadronic re-scattering? Hierarchical freeze-out? Others?

SHM: pure canonical suppression of strangeness?



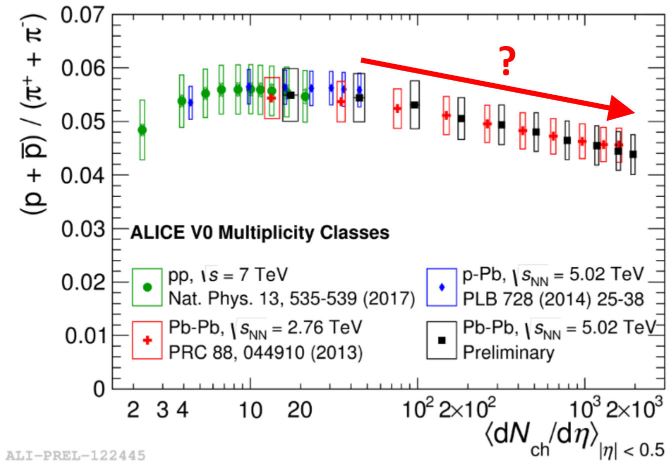
K* normalized to peripheral value since re-scattering can blur the picture

Fix yield's ratio to saturation limit. Check the evolution when decreasing the volume (multiplicity)

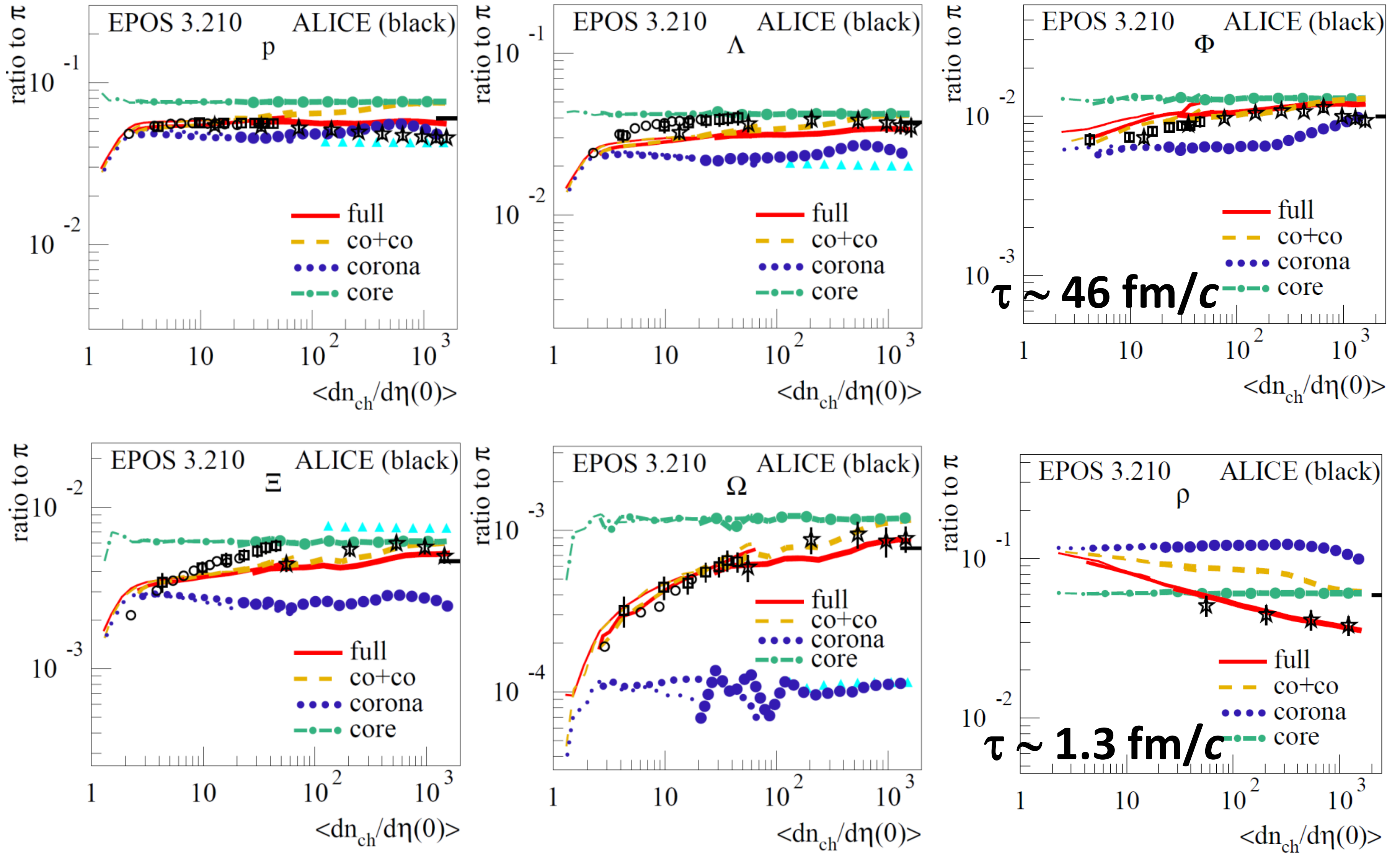
Qualitatively the thermal fit describes K,Λ,Ξ,Ω

Notable exception is the ϕ!

Slightly decreasing protons
Hint for hadronic re-scattering?
Need to evaluate degree of correlation on systematics across multiplicity!



EPOS: core-corona



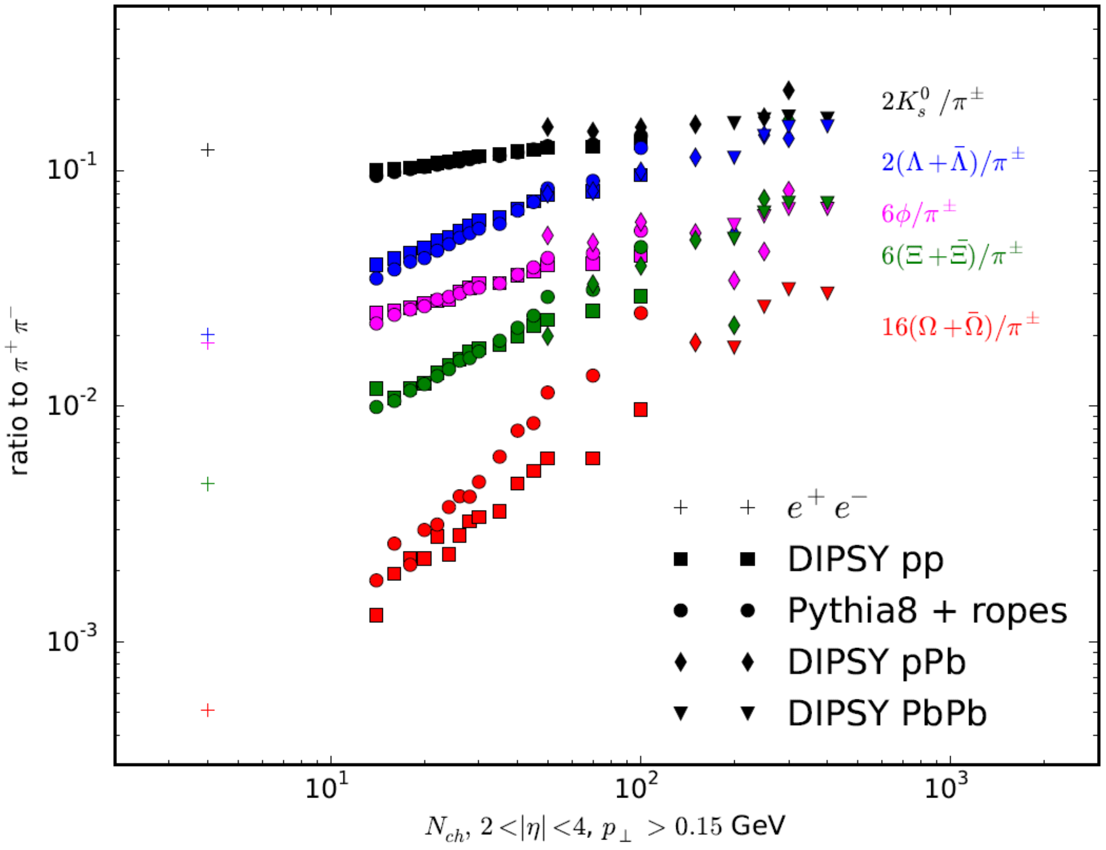
Observed trends of relative particle yields **reproduced** thanks to **interplay** between **core** and **corona** (+ UrQMD)

- Relative importance of CORE/CORONA in the yields for long and short living resonances is strikingly different
- Mild Φ enhancement with multiplicity observed in EPOS

TAKE HOME

Spectra + yields described in EPOS through evolution with multiplicity of relative importance of CORE and CORONA

Pythia + CR + ropes + shoving



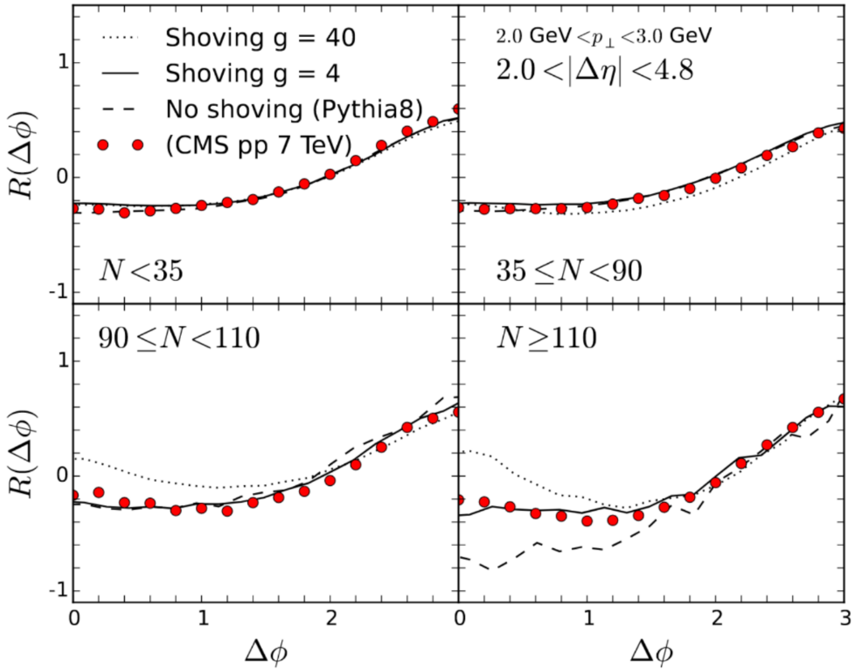
↑

Strangeness enhancement

Two mechanisms introduced in Pythia8:

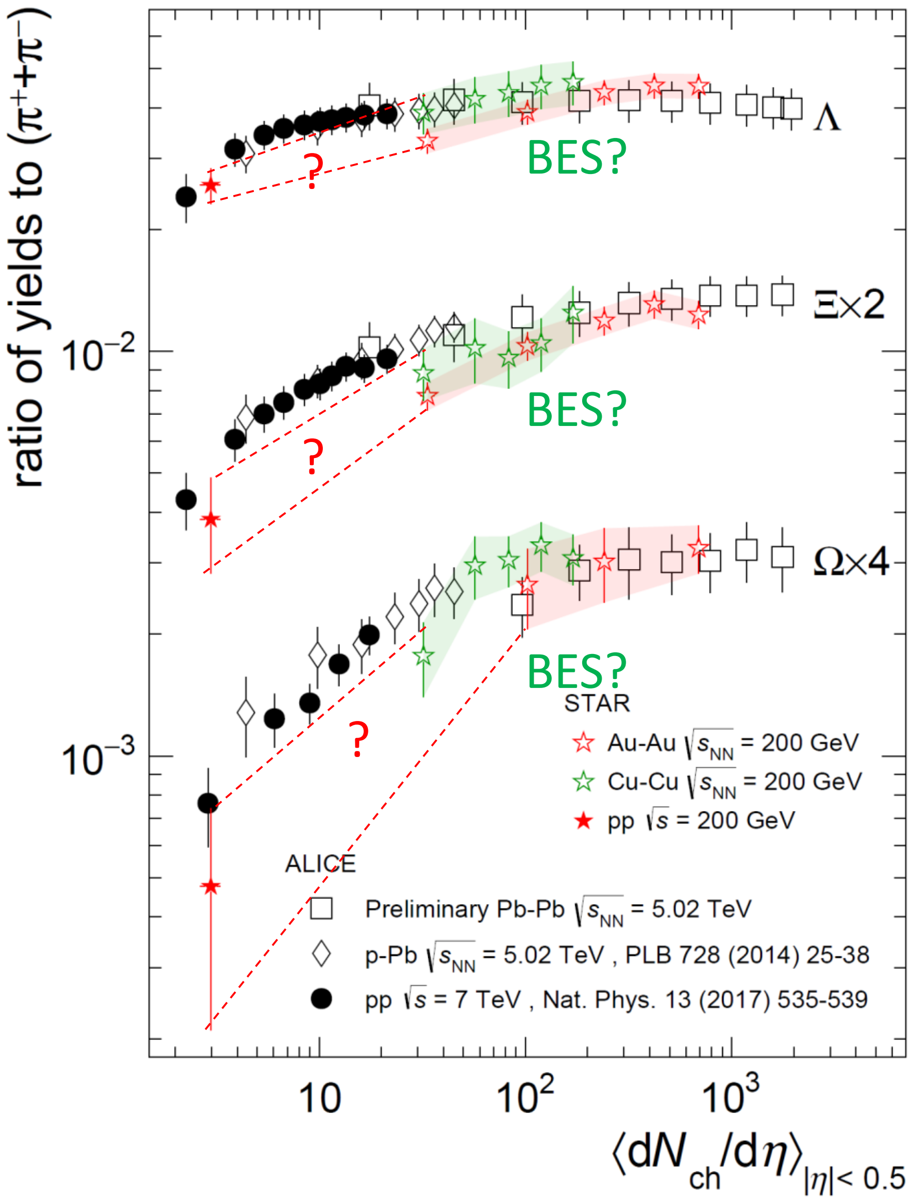
- **COLOR ROPES**: densely packed strings overlap → net effect is increase of string tension (baryon rather than strangeness effect!)
- **STRING SHOVING**: colour re-arrangement leads to transverse pressure which develops flow-like final state patterns

Ridge in high multiplicity pp →



Is it all? What can we expect more?

Particle yields: systems, energy, multiplicity. And then?



High precision data from the LHC suggest that the production of strangeness is driven by the final-state multiplicity of the collision

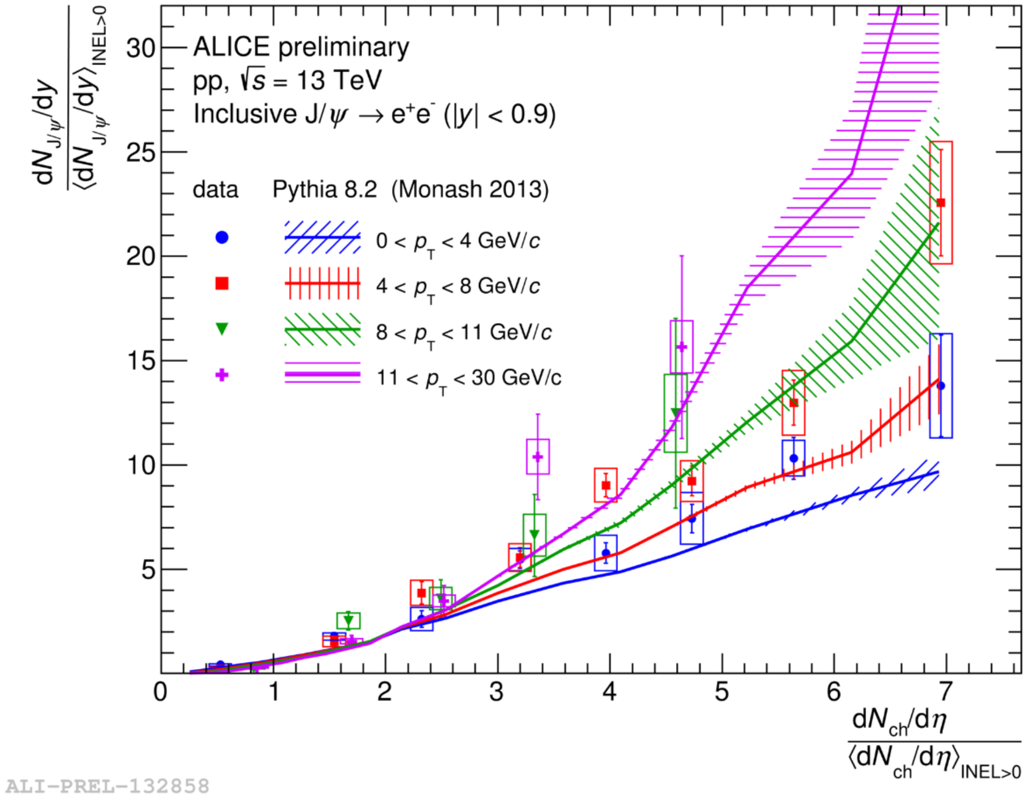
Independence on the collision energy

Can we extend this observation to lower energies?

High multiplicity STAR results superimpose to ALICE's points

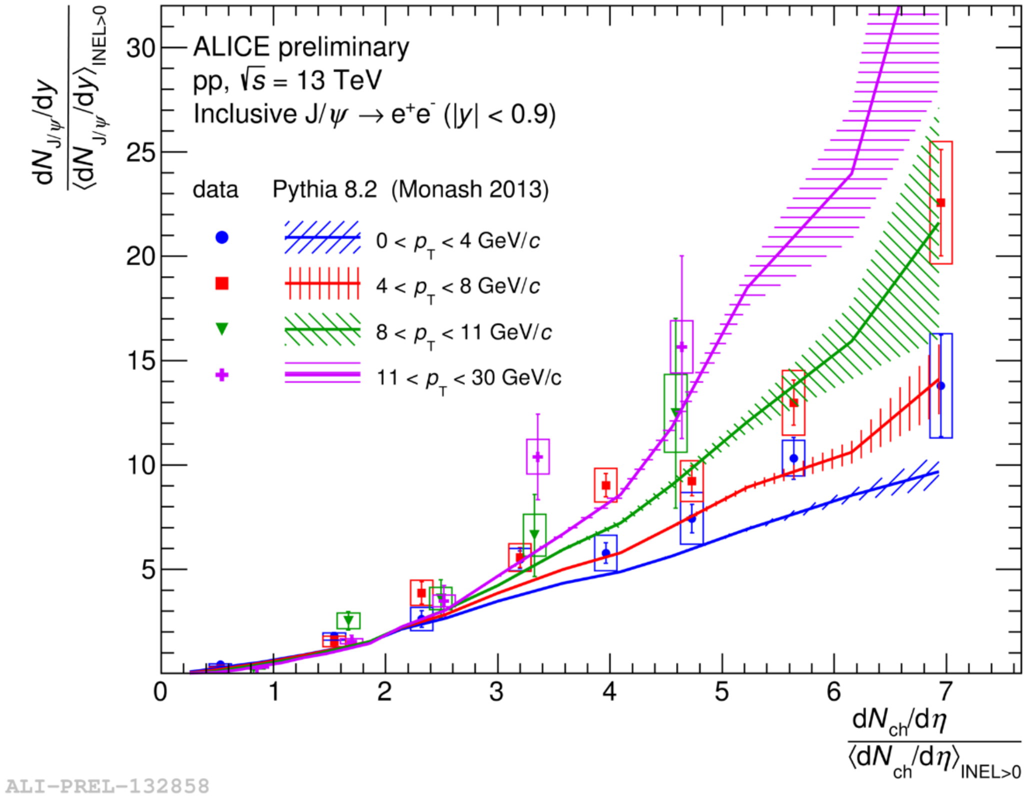
Can we infer something looking at the trend at lower multiplicity?

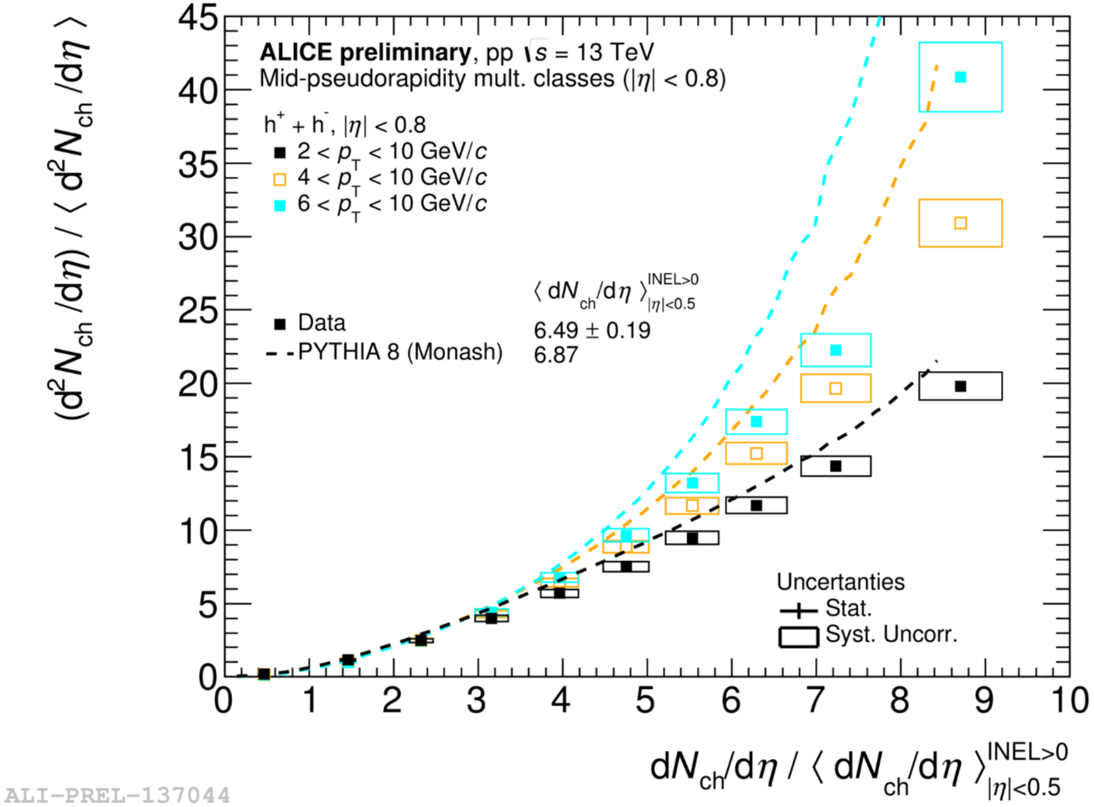
Hint for different evolution with multiplicity? γ_S at play?
Would be interesting to complement with smaller systems results @RHIC!!



More-than-linear trend of self normalized ratios for J/ψ as a function of the multiplicity

Particle yields: light and heavy flavours

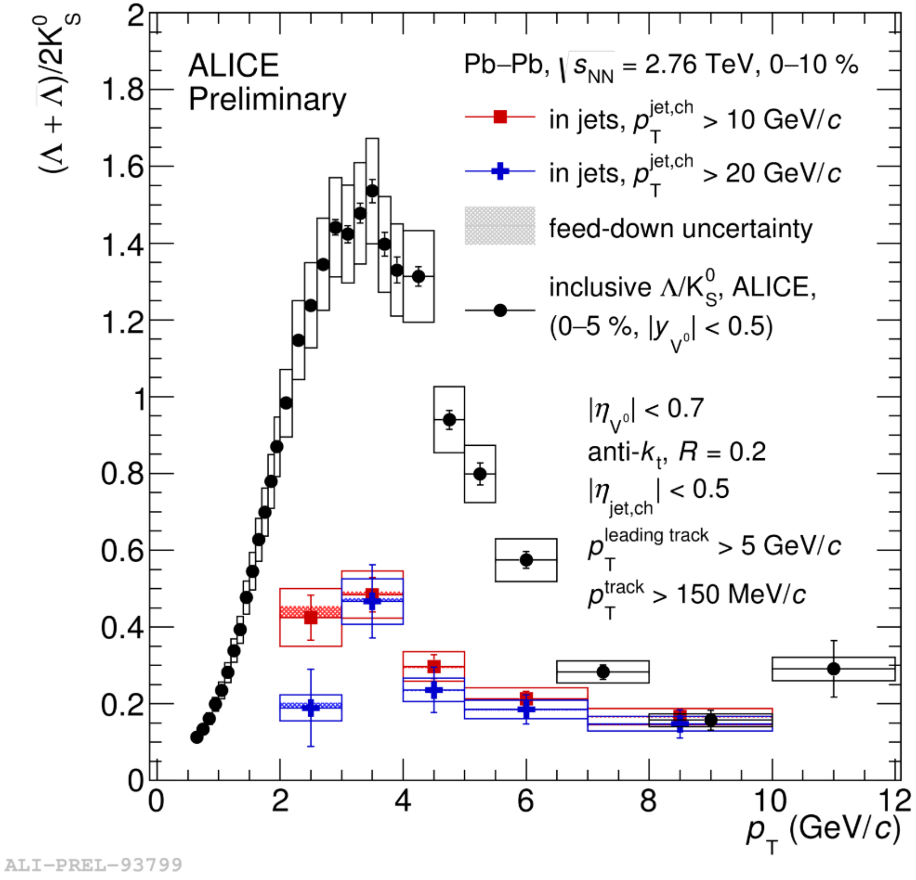




More-than-linear trend of self normalized ratios for J/ψ as a function of the multiplicity

…also observed in charged particles at high-pT. Soon out with PID particles as well

Particle yields: soft-hard cross-talk

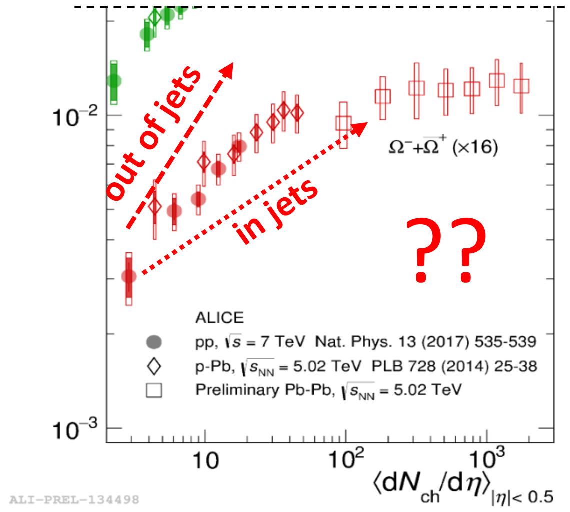


Λ/K^0_S **in jets** in Pb-Pb collisions @LHC: no same dynamical behavior observed in inclusive measurement

Baryon boost only present in underlying event?

What about smaller systems?

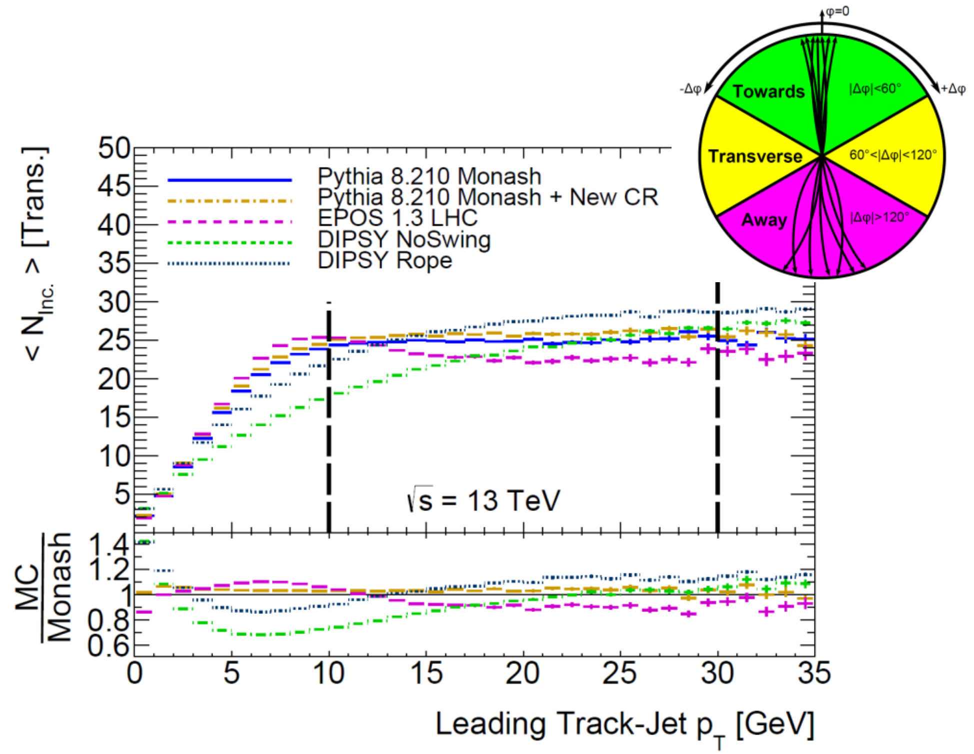
What about hadrochemistry?



Particle yields: soft-hard cross-talk from microscopic theory

- Jet pedestal effect: for 10<p_T^{jet}<30 GeV/c transverse activity is constant (on average!) and > than in MB
- Proposed "new" x-axis:

$$R_T = {N_{inc}}/{\langle N_{inc} \rangle}$$



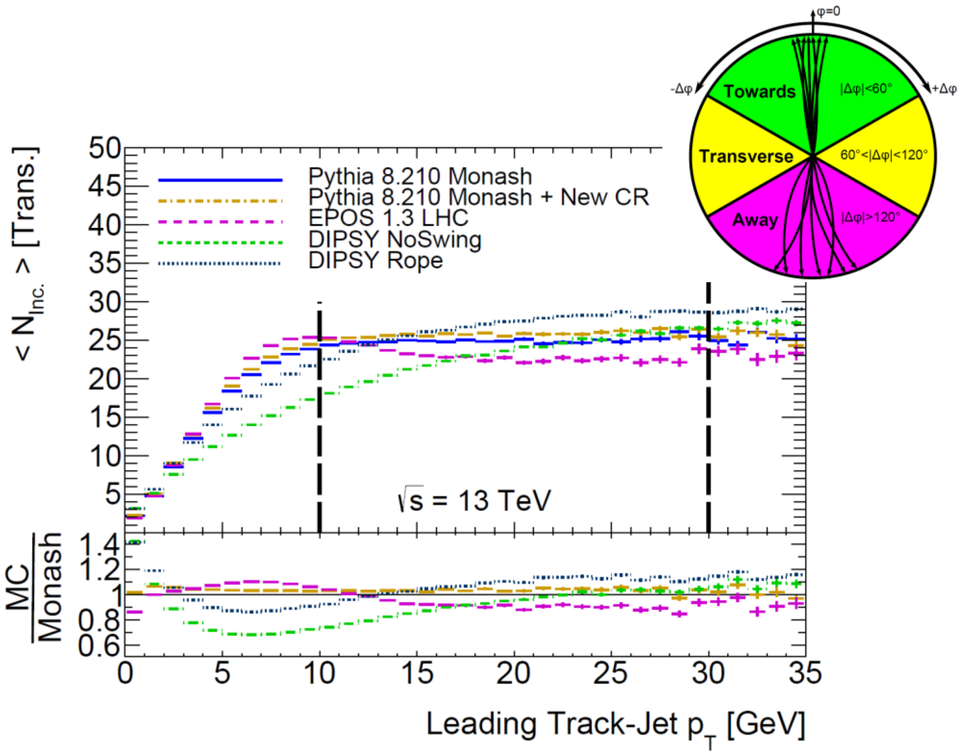
Martin & Skands & Farrington, Eur.Phys.J. C76 (2016) 5, 299

Particle yields: soft-hard cross-talk from microscopic theory

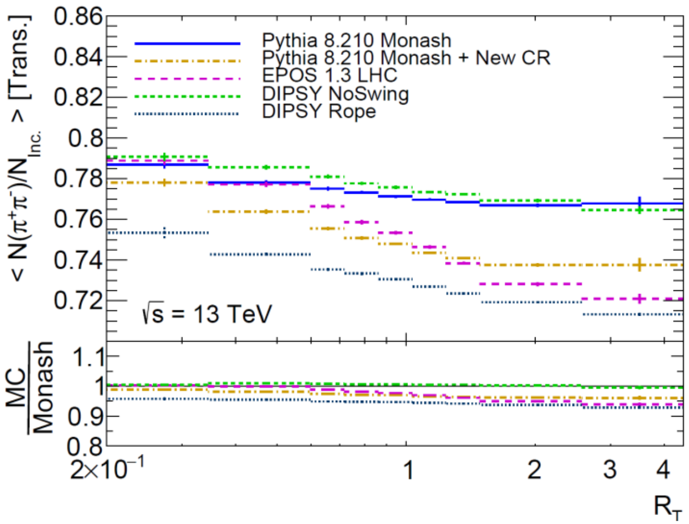
Livio Bianchi
GDR-QCD wshop
24 July 2018

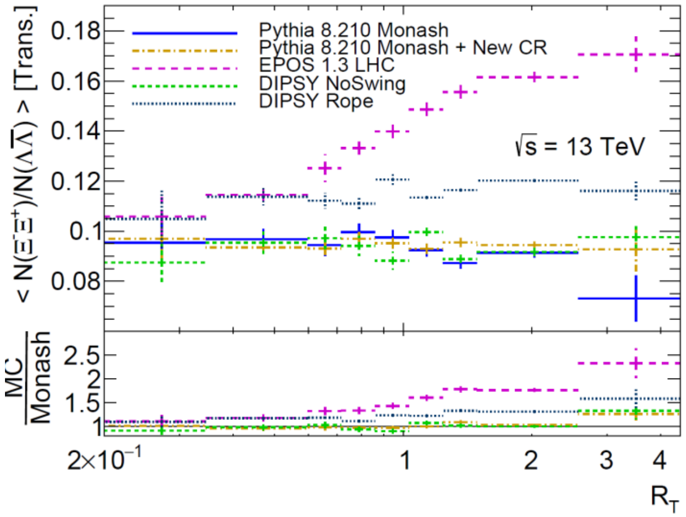
- Jet pedestal effect: for 10<p_T^{jet}<30 GeV/*c* transverse activity is constant (on average!) and > than in MB
- Proposed "new" x-axis:

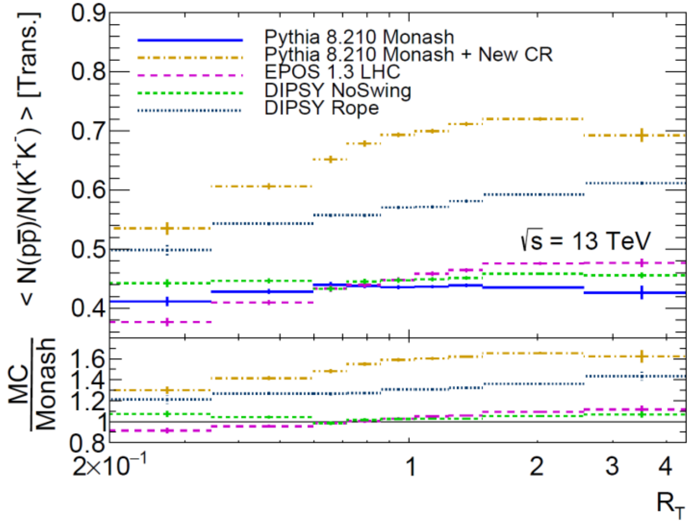
$$R_T = N_{inc} / \langle N_{inc} \rangle$$



Different models predict different trends for strange/baryon hadrons VS R_T







Martin & Skands & Farrington, Eur.Phys.J. C76 (2016) 5, 299

Conclusions

Conclusions, Outlook, Positivity, Criticalities

The study of soft particles production is a key tool in the challenging quest for the understanding of hadronization

LHC and RHIC are providing high precision data which are attracting the attention of theorist from most different backgrounds

Hadrochemistry and dynamical properties of the soft part of the final state seem to be solely driven by multiplicity

Lower energy results from RHIC (and possibly from future experiments) would complement the present observations

More differential studies are needed in order to disentangle soft particle production inside jets and inside the underlying event. First looks in this direction show non-trivial features which need to be solidified with more studies.

Conclusions, Outlook, Positivity, Criticalities

The study of soft particles production is a key tool in the challenging quest for the understanding of hadronization

LHC and RHIC are providing high precision data which are attracting the attention of theorist from most different backgrounds

Hadrochemistry and dynamical properties of the soft part of the final state seem to be solely driven by multiplicity

Lower energy results from RHIC (and possibly from future experiments) would complement the present observations

More differential studies are needed in order to disentangle soft particle production inside jets and inside the underlying event. First looks in this direction show non-trivial features which need to be solidified with more studies.

Thank you