Terzo Incontro di Fisica con Ioni Pesanti alle Alte Energie

Collectivity from small to large systems

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Large hadronizing systems: the reign of statistics and viscous hydro

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Collisions of heavy nuclei:

- Study collective phenomena

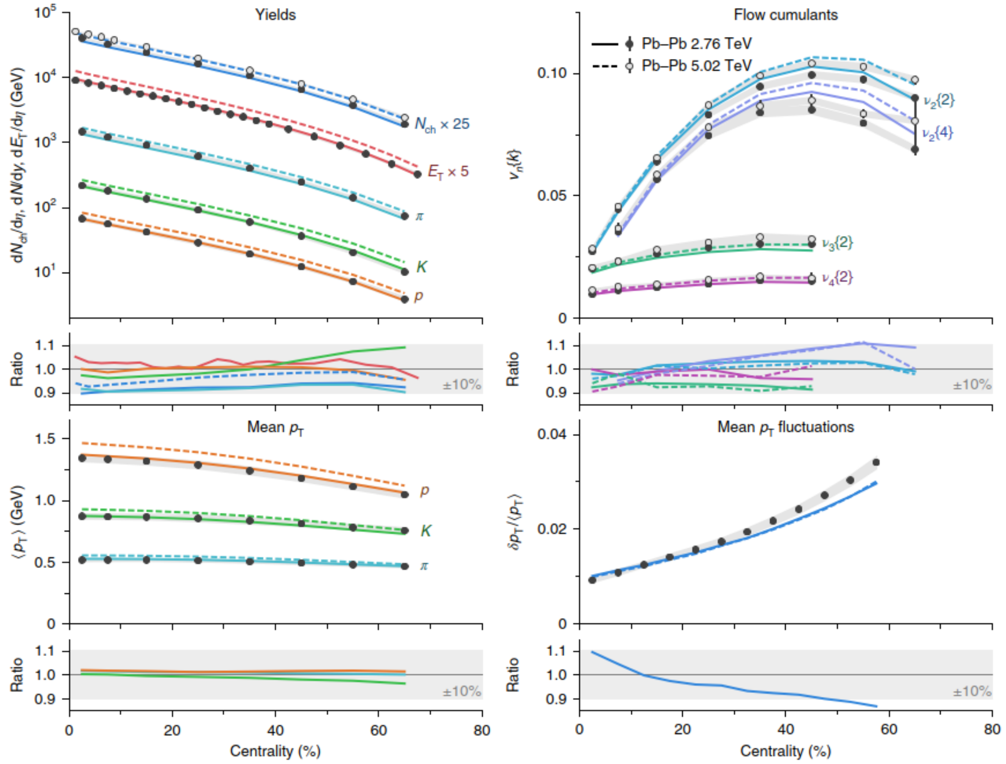
  ↪ High energy density, large medium → radial and anisotropic flow

- Test statistical limit of particle production

  ↪ Large multiplicities → Grand Canonical statistical treatment applicable

- Disentangle hadronic phase effects

  ↪ Large system → nuclei formation at kinetic freeze-out (coalescence)?
  Short-living resonance disappearance (re-scattering)?



Efficient way to describe experimental results:
VISCOUS HYDRO + STATISTICAL HADRONIZATION

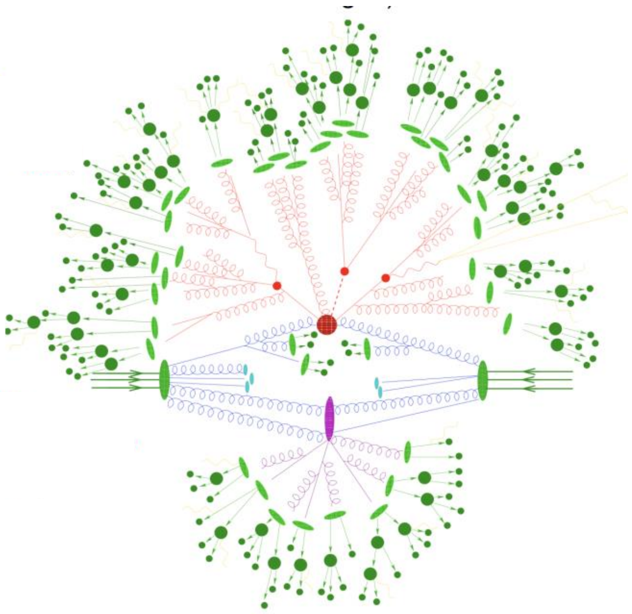
Initial entropy-density anisotropies → Hydro (VISH2+1) + EoS (lattice) → At T_{switch}: transition → Afterburner (UrQMD) →

THE MODEL

J. E. Bernhard at al., Phys. Rev. C 94, 024907 (2016)
J. E. Bernhard at al., Nat. Phys. 15, 1113–1117(2019)
J. E. Bernhard at al., Phys. Rev. C 101, 024911 (2020)

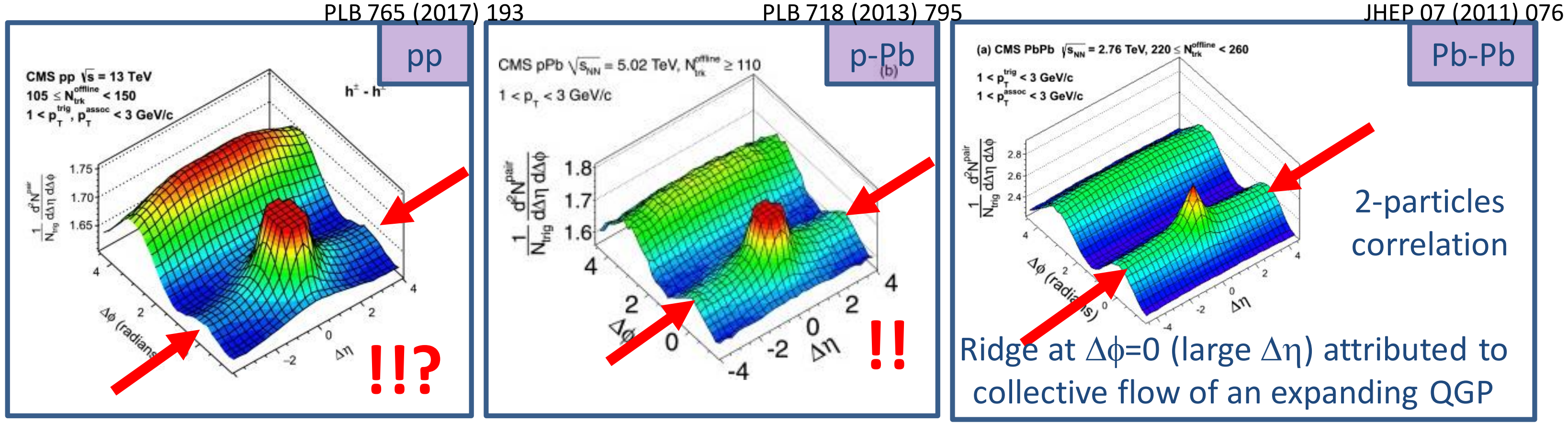
High energy **hadronic interactions** are **far from** being «**elementary**»:

- Multi Parton Interactions (MPI) needed to explain multiplicity
- MPI cross-talk needed to explain p_T spectra at LHC (e.g. Color Reconnection)
- Initial state parton density fluctuations can lead to final-state phenomena



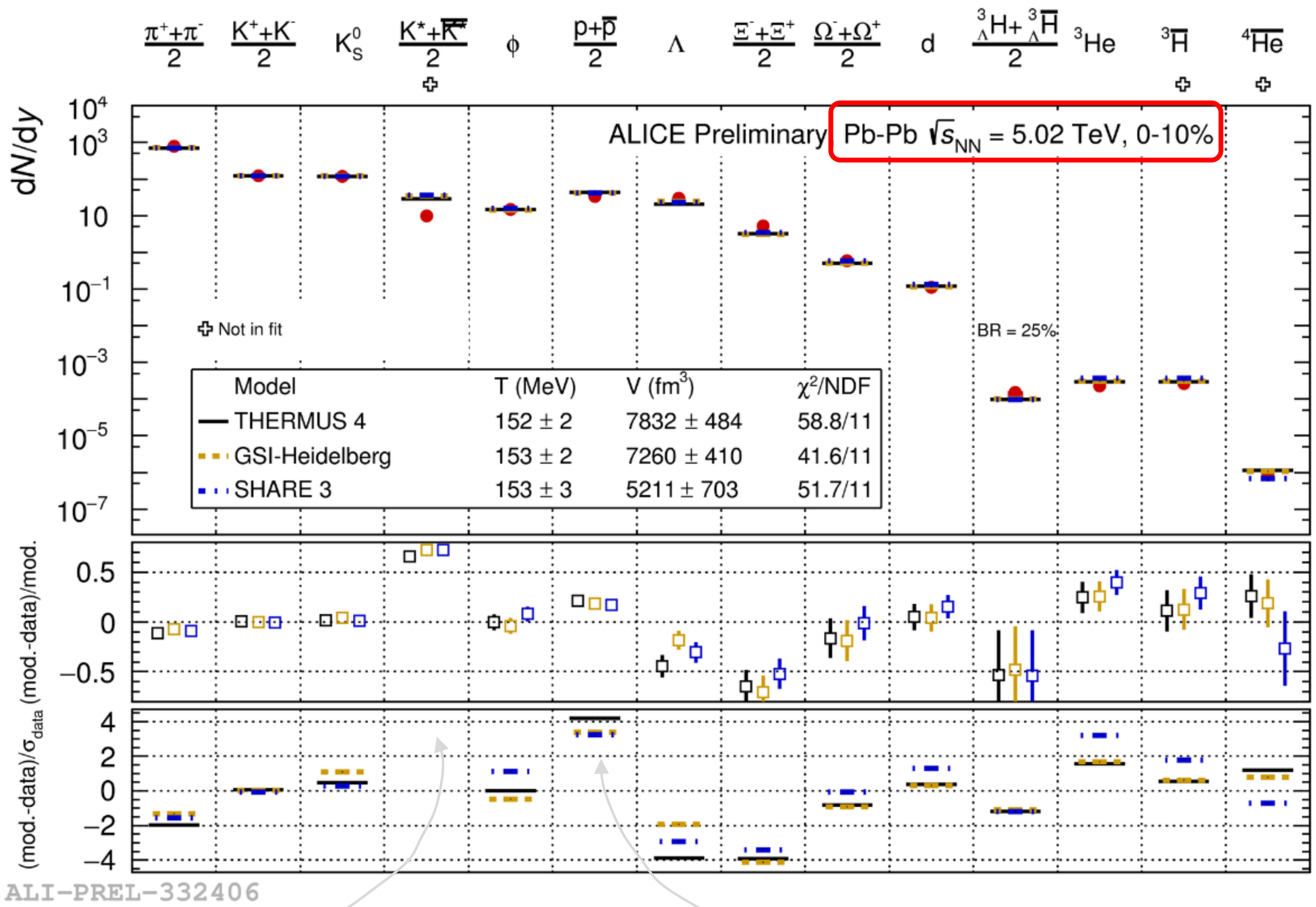
Questions:

- How can we use small systems to better interpret large systems observations?
- Do the observations in small colliding systems imply QGP formation there?



Hadron abundancies

Hadrochemistry in central A-A collisions at the LHC



Production of light flavor hadrons fit over 9 orders of magnitude by Statistical Hadronization Model (SHM) in its Grand Canonical Ensemble (GCE) formulation

Hadron abundancies can be described as emerging from a hot Hadron-Resonance Gas in thermal equilibrium

At LHC: **$\mu_B \sim 0$ $T_{ch} \sim 153$ MeV**

How do these yields compare to those measured in smaller colliding systems?

Short-living resonances not described (influence of hadronic phase)*

Friction with p being addressed through S-matrix approach / re-scattering

Other approaches try to solve p & Ξ issues with flavor-dependent T_{ch}

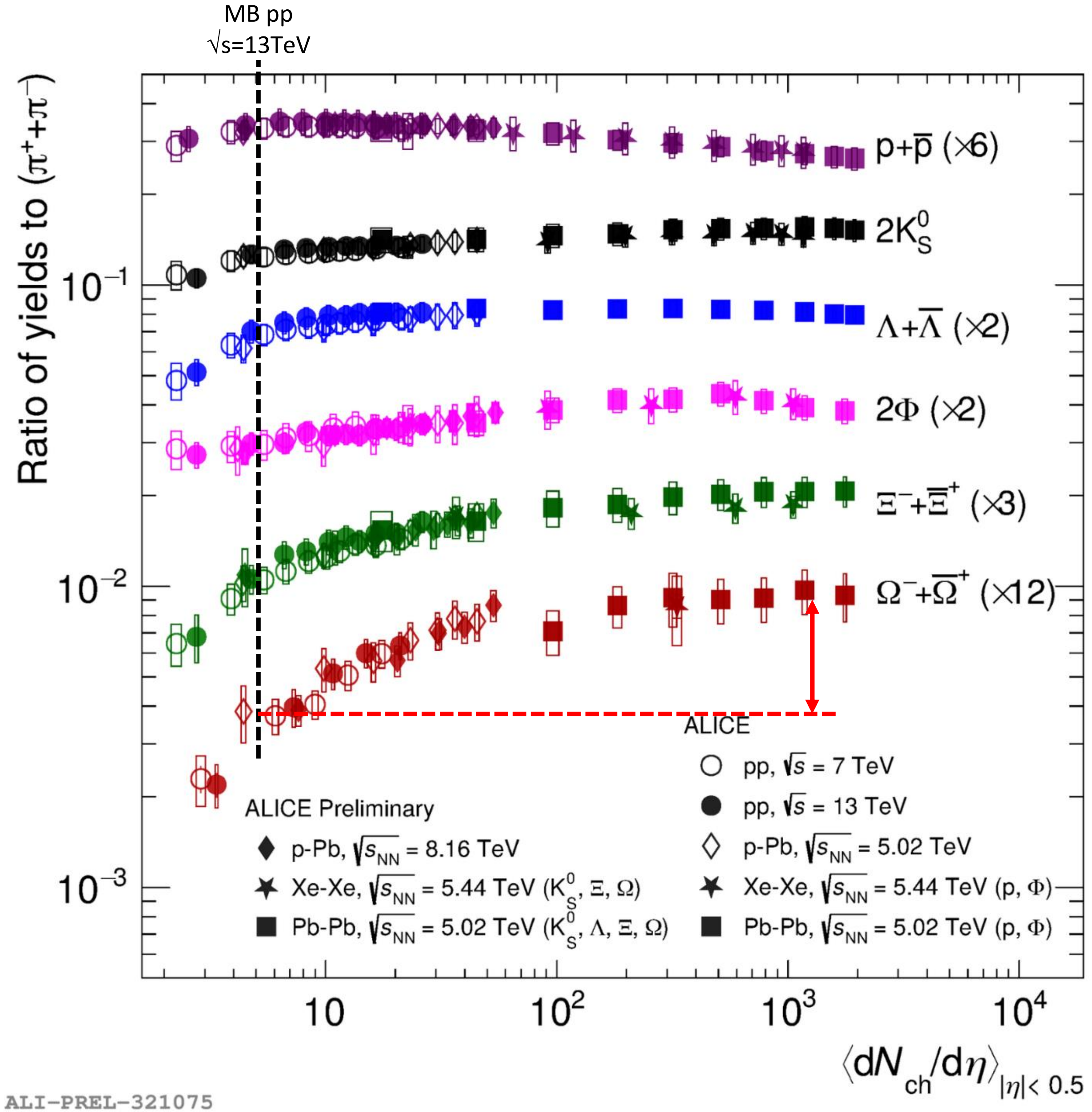
Loosely bound (anti-)nuclei reproduced by SHM (snowballs in hell)

*Not included in fit

Phys. Lett. B 792, 304-309 (2019)
Phys. Rev. C 90 (2014) 5, 054907

P. Alba et al., Phys. Rev. C 101, 054905 (2020)

Hadrochemistry modification



h/π smoothly evolves across multiplicity reaching thermal values in Pb-Pb at the LHC

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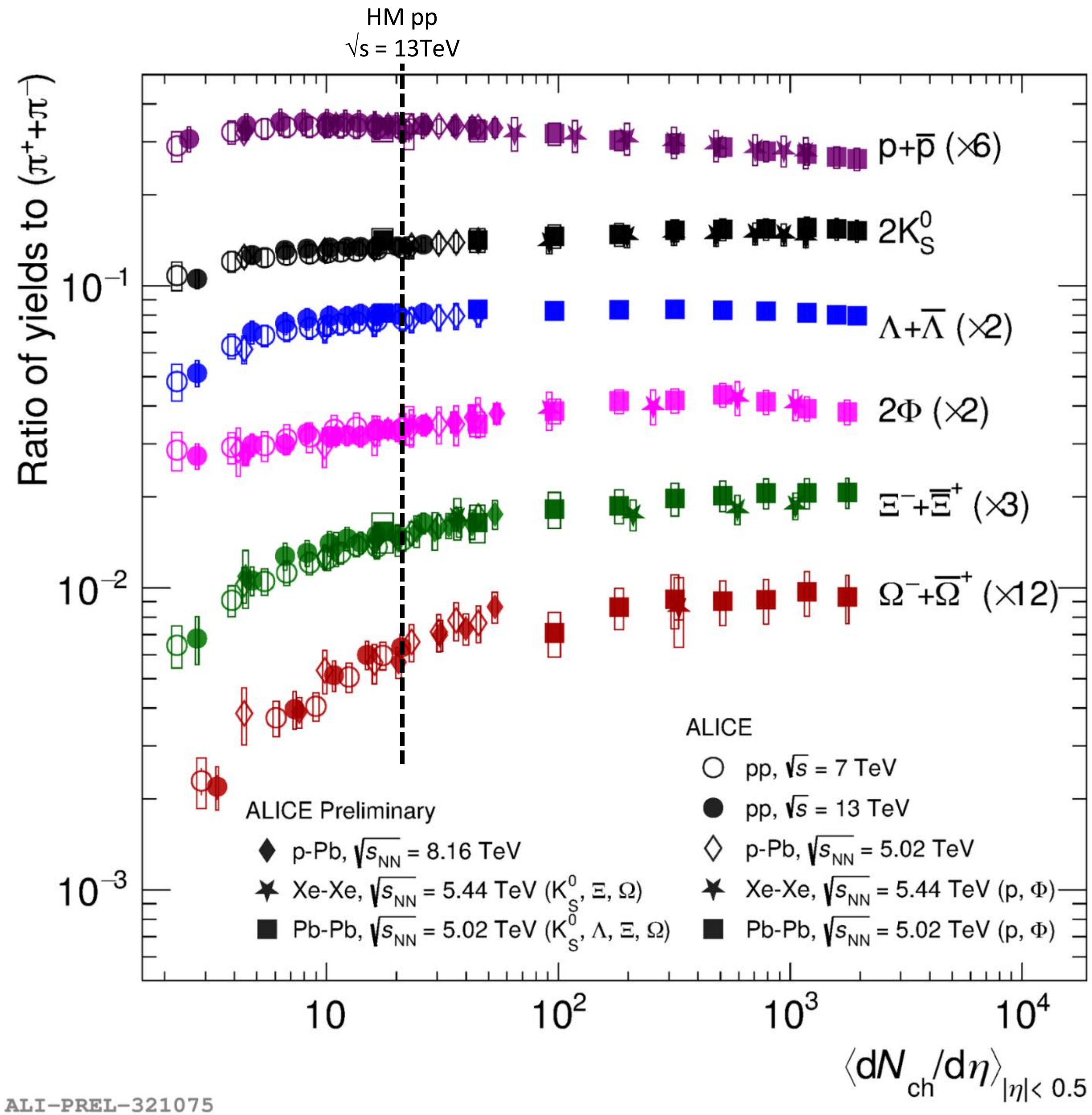


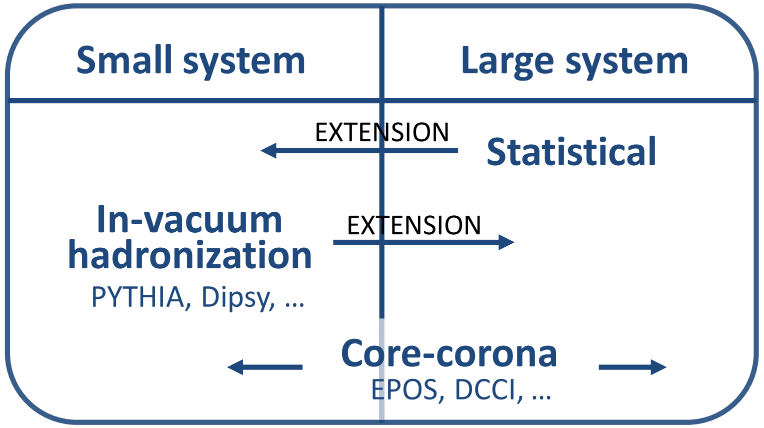
h/π smoothly evolves across multiplicity reaching thermal values in Pb-Pb at the LHC

No √s (down to RHIC) or colliding system dependence

Evolution depends on the hadron:
the stranger the steeper

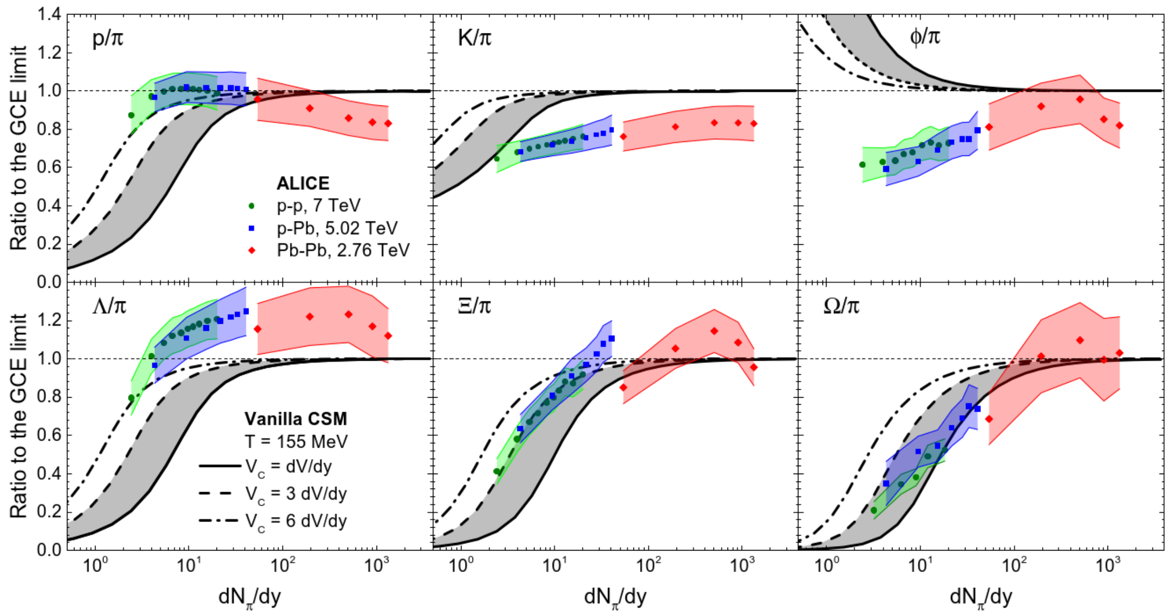
High-multiplicity pp: ~ same hadrochemistry as in a fully thermalized system

How can this trend be interpreted?



Adapting SHM: canonical suppression, γ_s , …

CSM



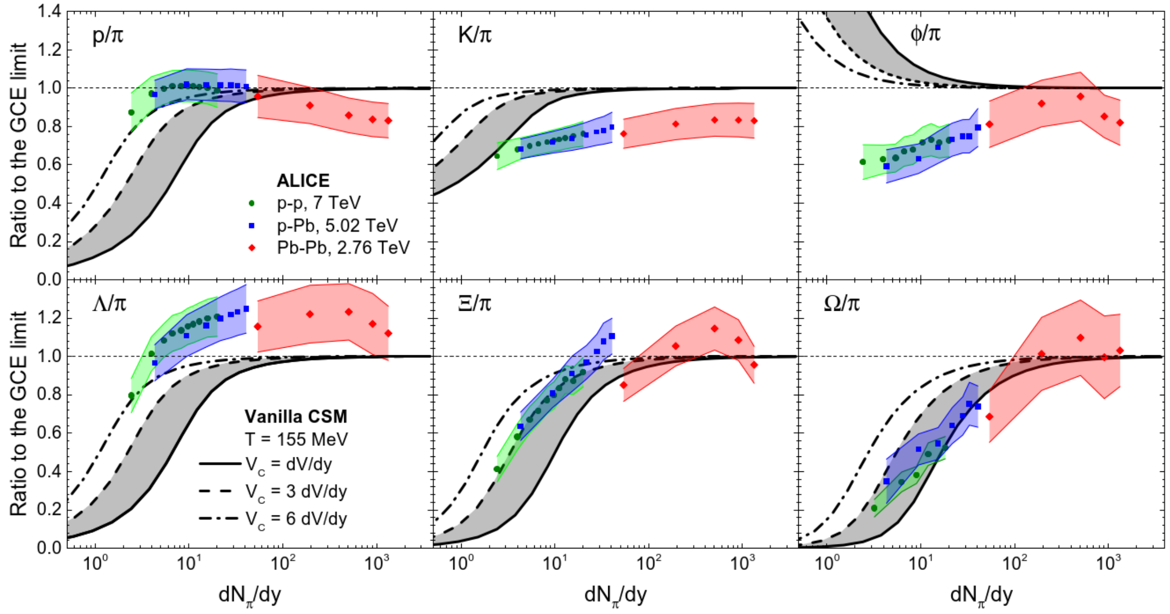
Canonical Statistical Model:
as multiplicity decreases quantum numbers (Q,B,S) are forced to be conserved in smaller and smaller volumes

Qualitatively describes Ξ and Ω, but big issues with p (B conservation) and ϕ (Q conservation for π)

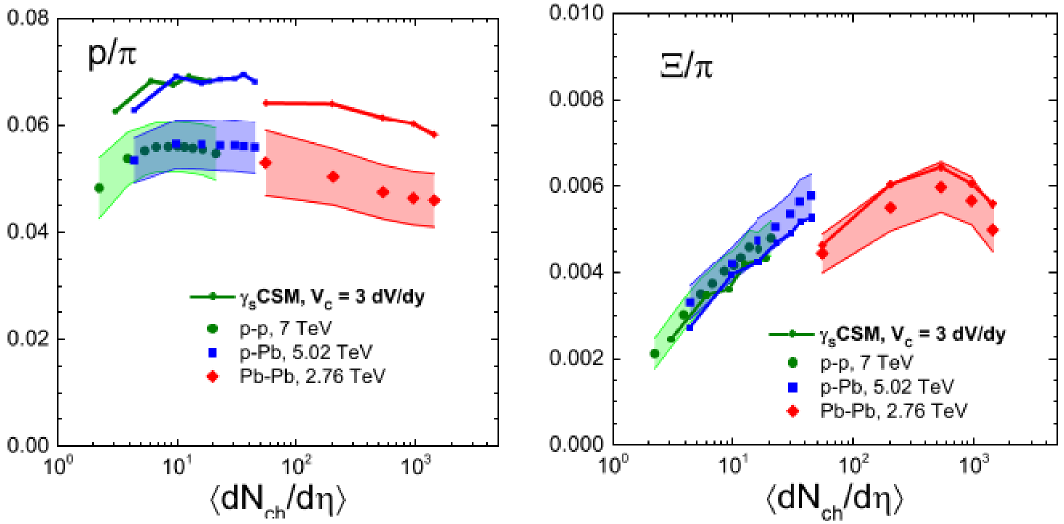
V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

Adapting SHM: canonical suppression, γ_s , …

CSM



CSM + γ_s



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Qualitatively describes Ξ and Ω, but big issues with p (B conservation) and ϕ (Q conservation for π)

Introducing undersaturation parameter γ_s (incomplete equilibration of S) and fitting also T_{ch} and dV/dy in all systems: better agreement, but still problems with p, K and ϕ

V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

Two-component models (core-corona)

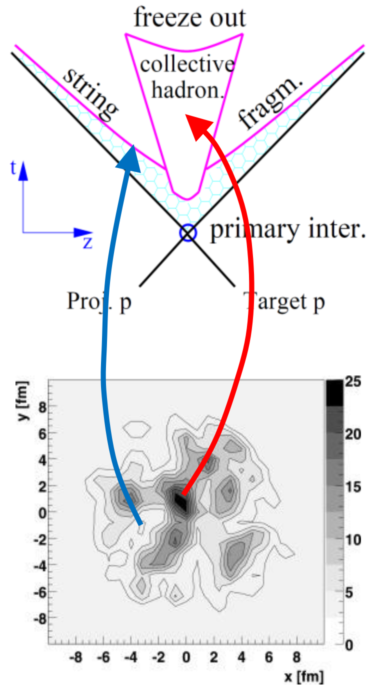
Models implementing a double-regime scenario (EPOS, DCCI, ...):

- **Core**: high density, QGP formation, thermal hadronization
- **Corona**: low density, jets, hadronization in vacuum

h/π values flat VS $dN_{ch}/d\eta$

Grand-Canonical limit

String fragmentation



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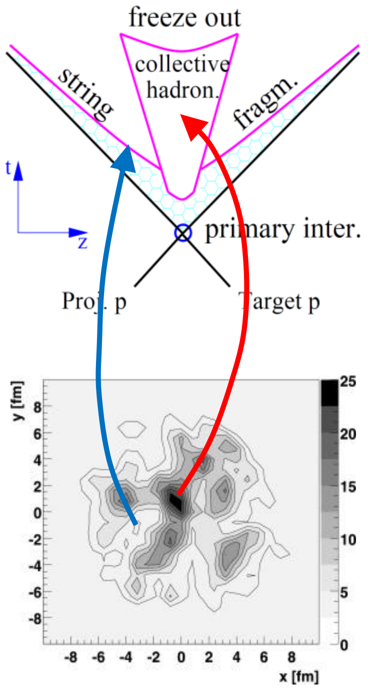
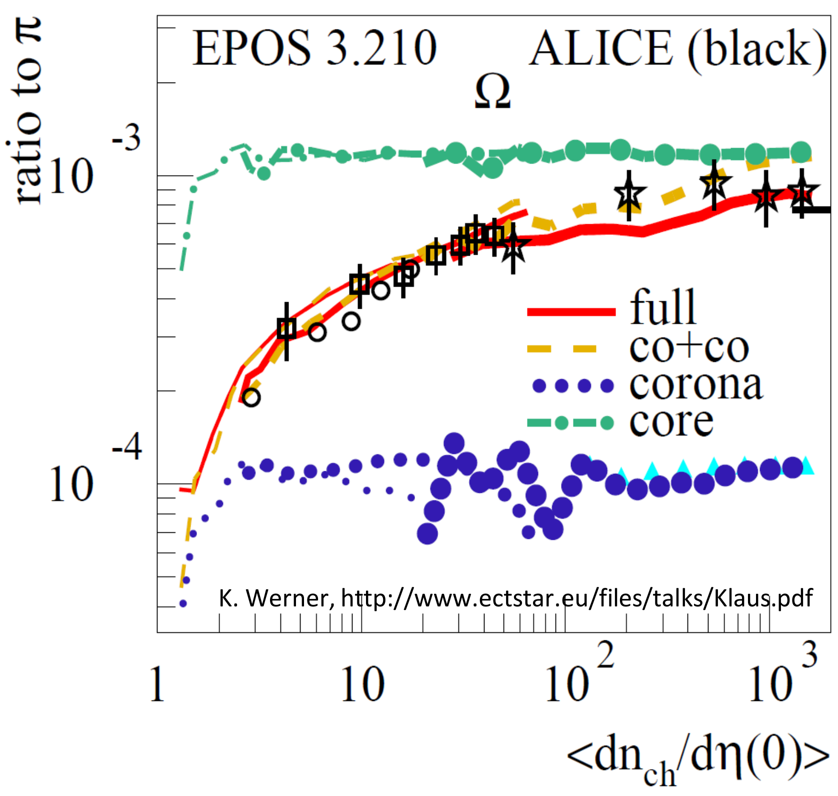
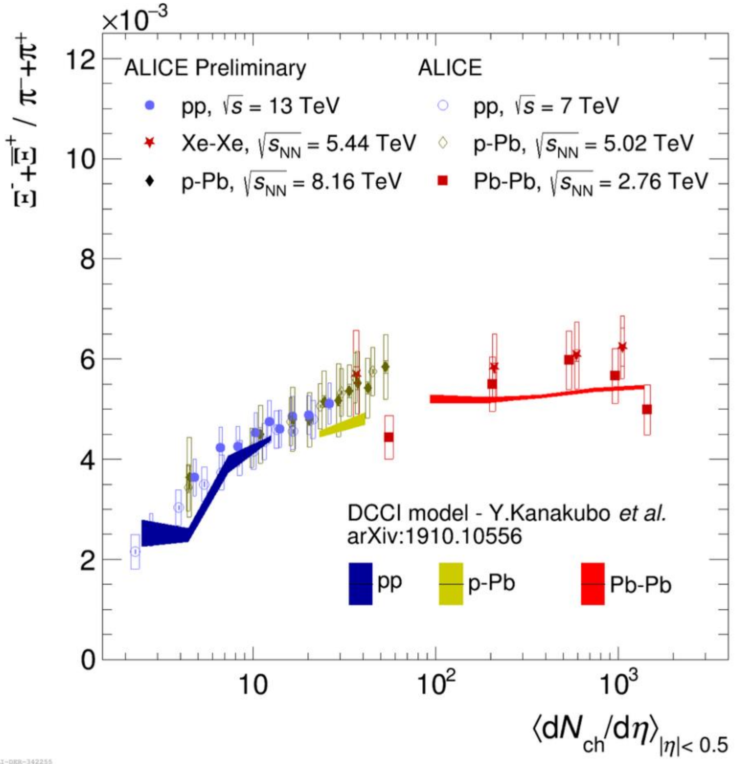


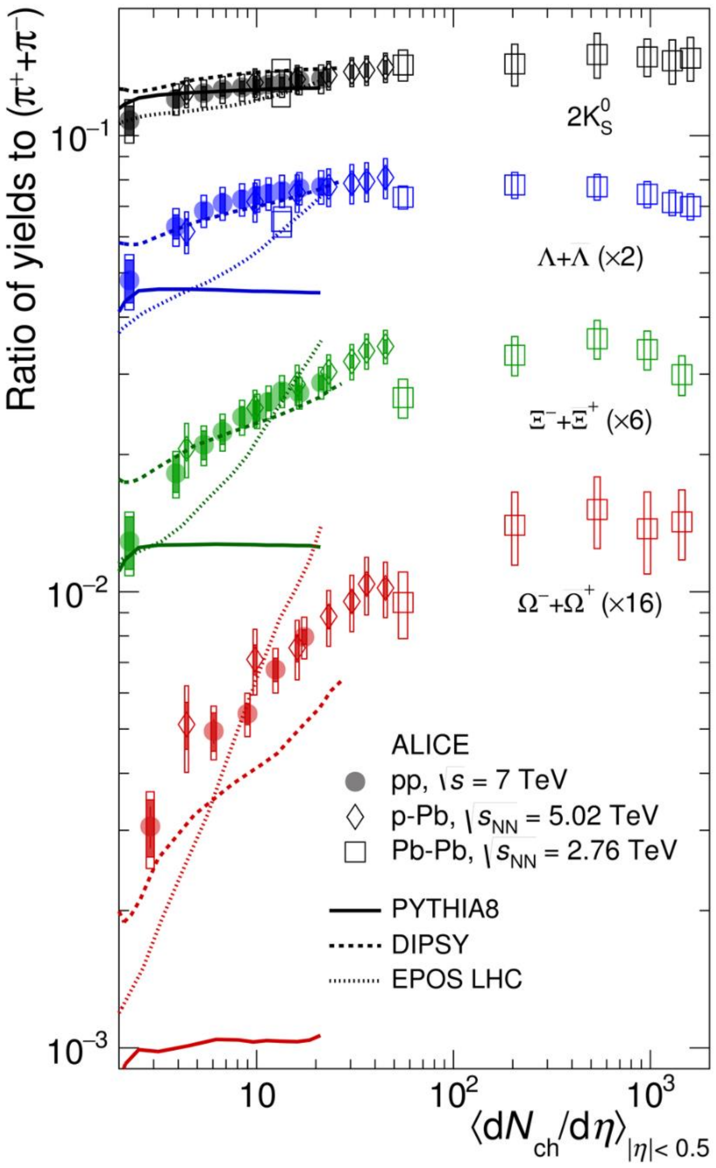




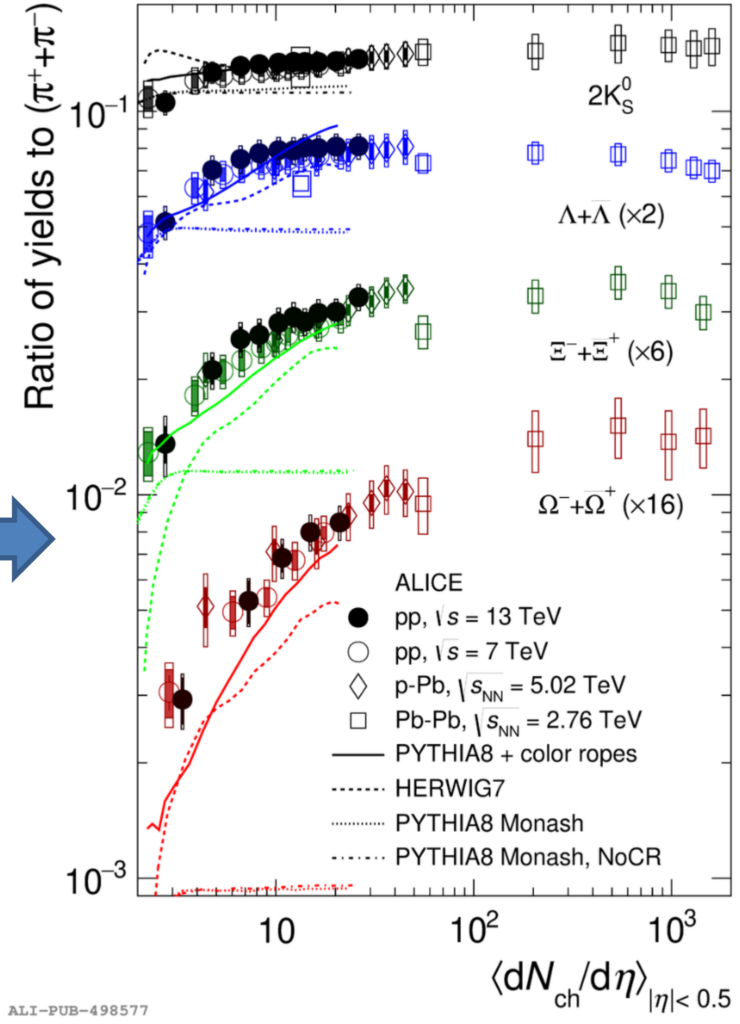
h/π evolution explained by **core-to-corona ratio changing** in events **with** different final-state **multiplicity**

K. Werner, Phys. Rev. Lett. 98, 152301 (2007)
Y. Kanakubo at al., Phys. Rev. C 101, 024912 (2020)

Models starting from small systems



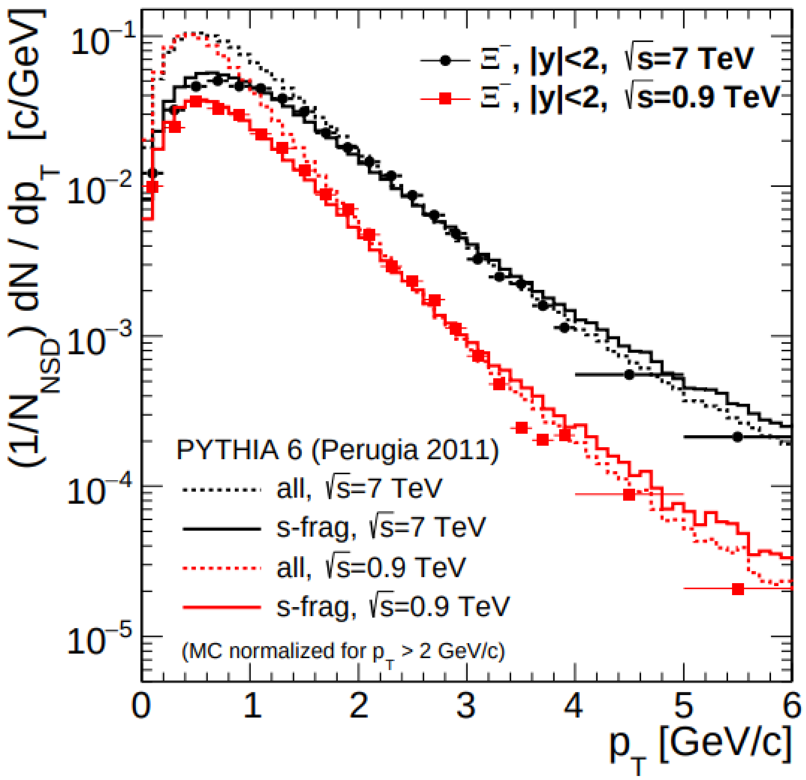
ALICE Collaboration, Eur. Phys. J. C 80 (2020) 693



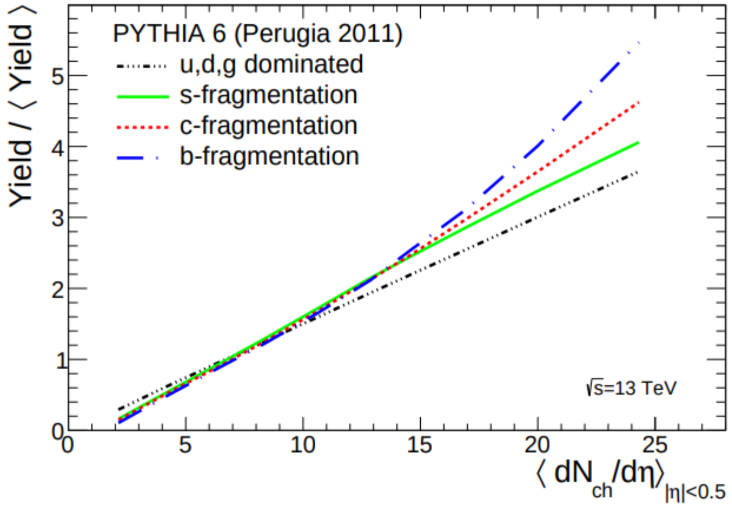
Models traditionally applied in pp can qualitatively reproduce the data if they introduce **color ropes** *
(densely-packed strings → higher string tension)

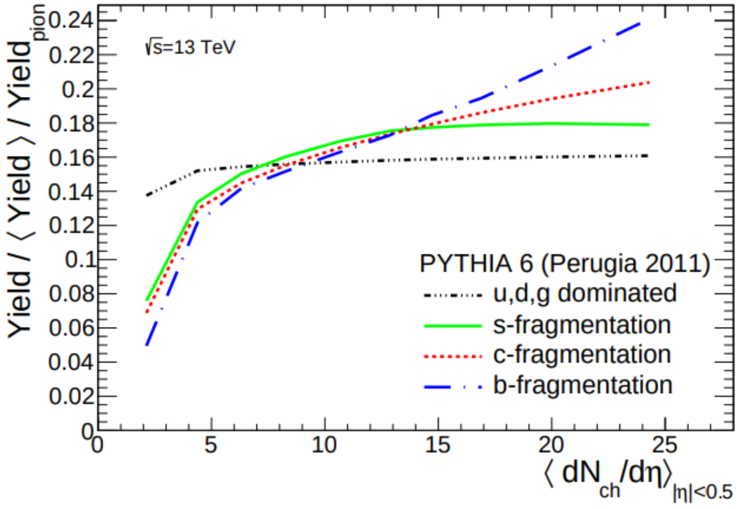
* Still problems with protons

Pythia with no ropes. MPI and s-fragmentation



Ξ coming from s-fragmentation better describe measured spectral shape (even VS multiplicity)*





Ξ from s-fragmentation $\propto N_{MPI}$, while multiplicity is not proportional for lowest values ($N_{MPI} \rightarrow 0$, N_{ch} finite)

→ Strangeness enhancement

Very well reproduces the data with no need for final state effects (except CR, which anyway contributes at highest multiplicity)

No need for final state?

* Mind the huge normalization

A. Morsch, C. Loizides, arxiv.org/abs/2109.05181

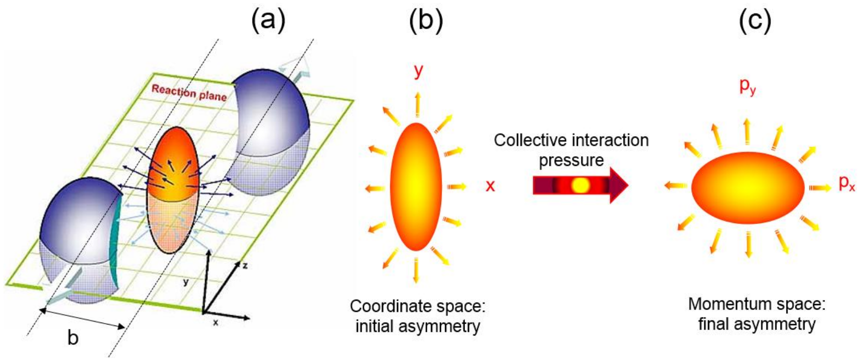
Collective flow

Collectivity in a nutshell

According to hydro picture, the QGP is expected to develop:

- **Radial flow**
  - Common expansion velocity of partons
  - Translates into p_T spectra modification

- **Anisotropic flow**
  - Initial spatial anisotropy $\rightarrow$ final momentum anisotropy
  - Measured through Fourier expansion coefficients of the p_T distribution

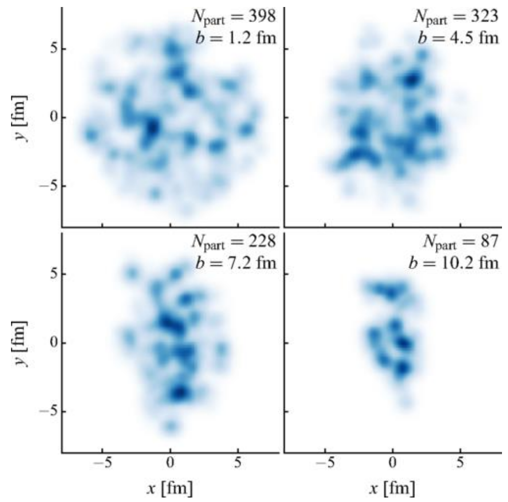


$$E\frac{d^3N}{dp^3} \approx \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,d\eta}\left[1+2\sum_{n=1}^{\infty} v_n \cos[n(\phi-\Psi_n)]\right]$$

Medium properties affect the values of flow coefficients:
low bulk and shear viscosities $\rightarrow$ large radial and anisotropic flows

NOTE:
initial anisotropies come from:

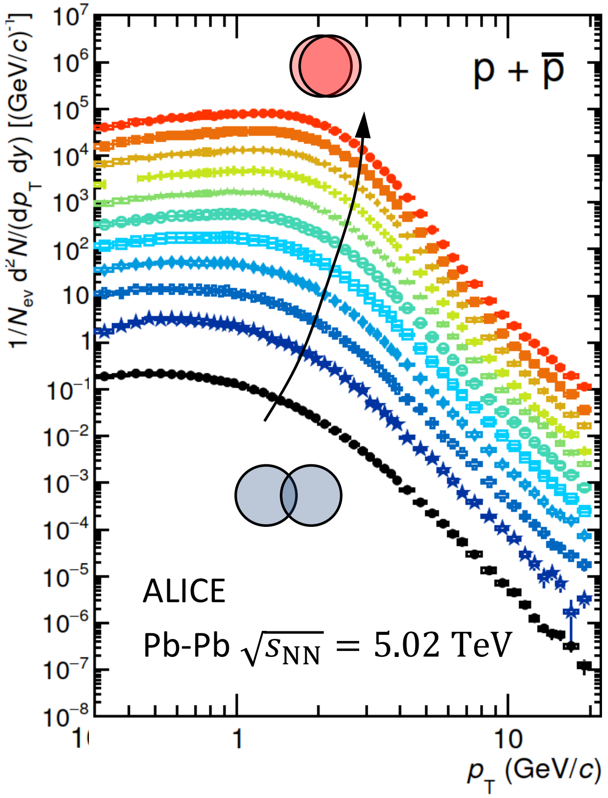
- geometry
- parton density fluctuations in the initial state

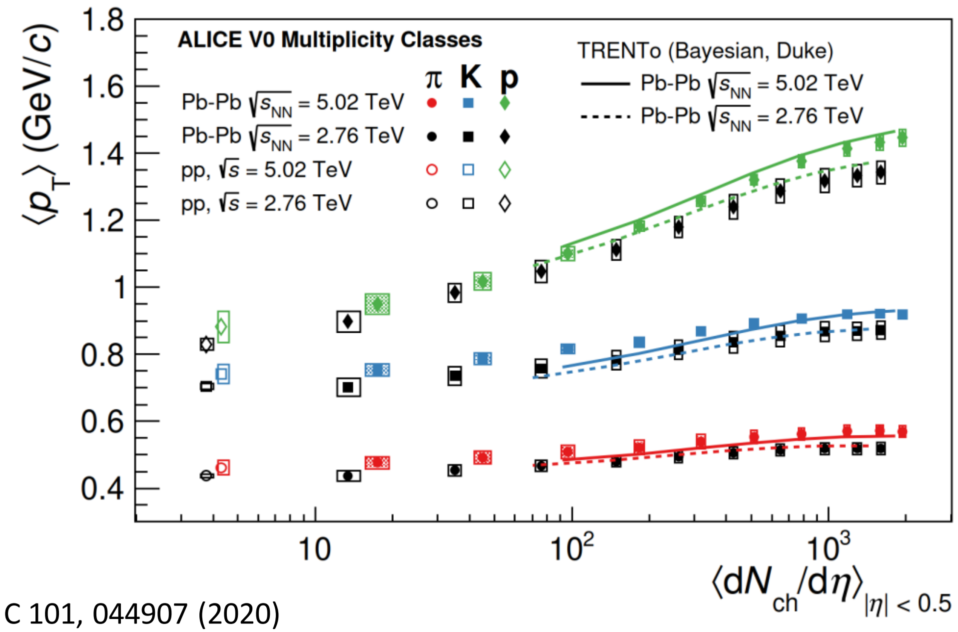


Spectral modification from large …

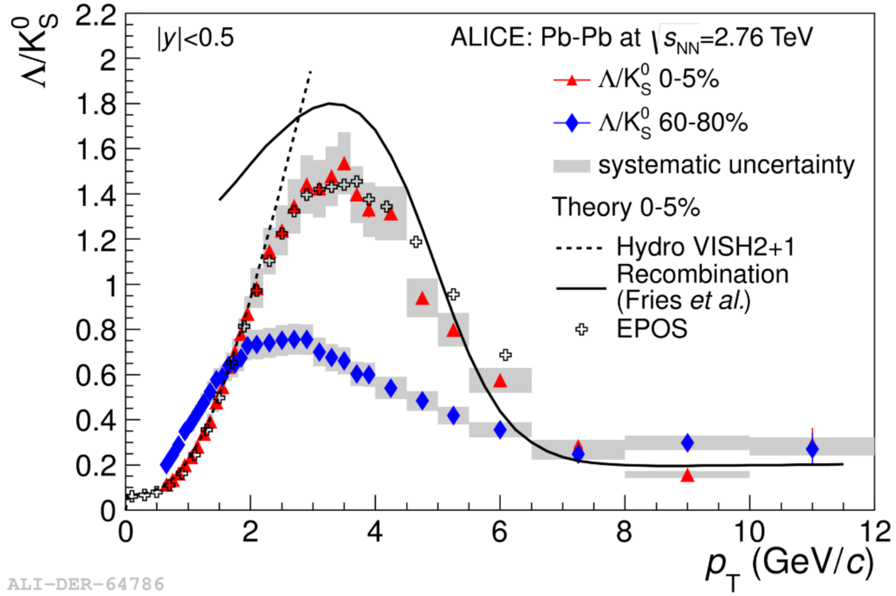
Spectra get harder
going to central A-A collisions

- $\langle p_T \rangle$ increases (higher particle mass → steeper increase)
- Can be seen in «baryon/meson» ratios (e.g. Λ/K^0_S)
- Interpreted as radial flow: higher mass → higher p_T boost
- Well reproduced by hydro calculations at low-p_T



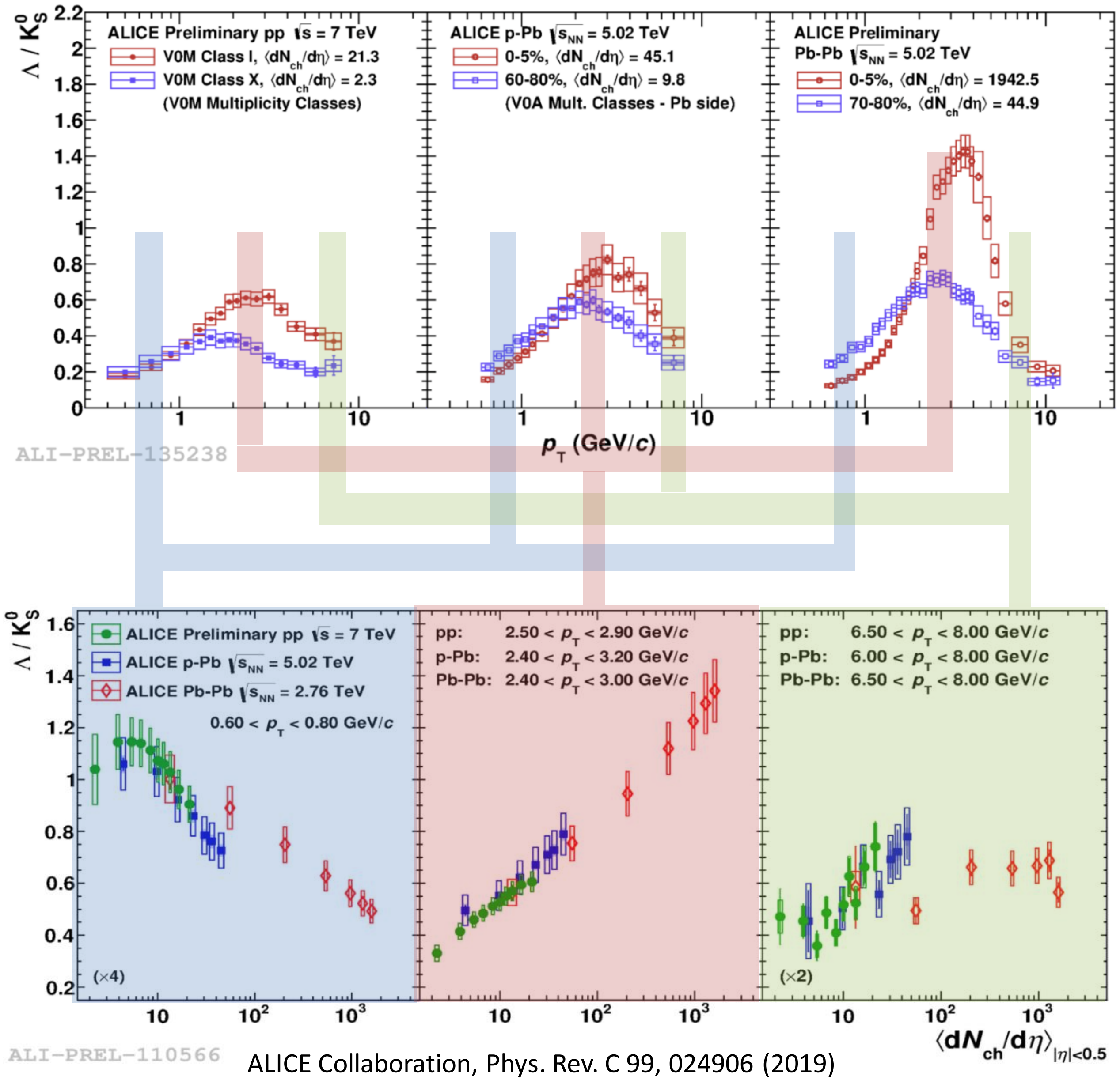


ALICE Collaboration, Phys. Rev. C 101, 044907 (2020)



ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 222301

… to small systems



ALICE Collaboration, Phys. Rev. C 99, 024906 (2019)

Λ/K_S^0 enhancement present in all collision systems at the LHC:

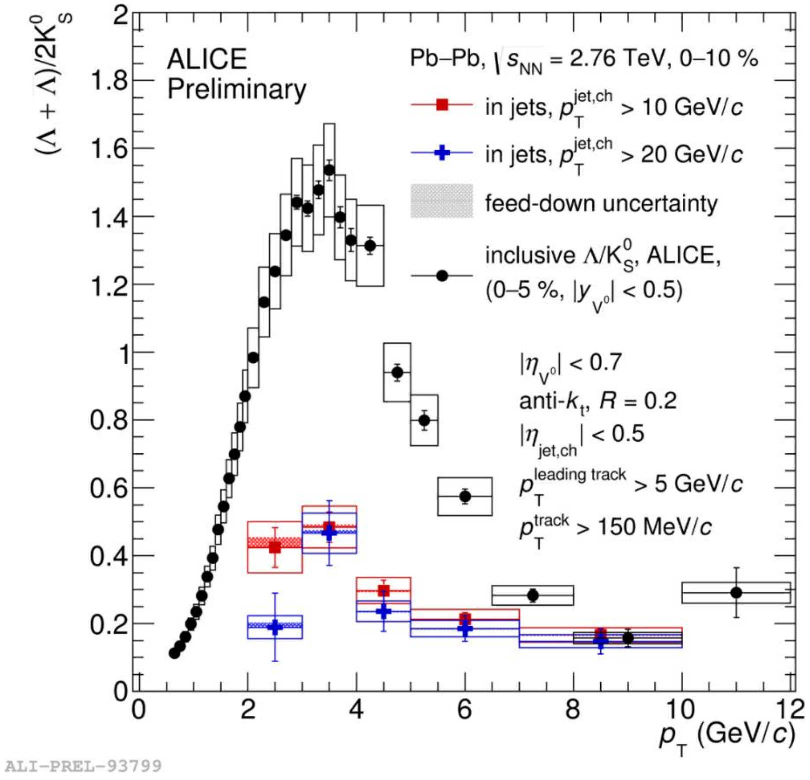
- The larger the colliding system, the larger the effect
- Smooth evolution with multiplicity when selecting specific p_T intervals
- Radial flow in small systems?

Application of hydro far from equilibrium under study

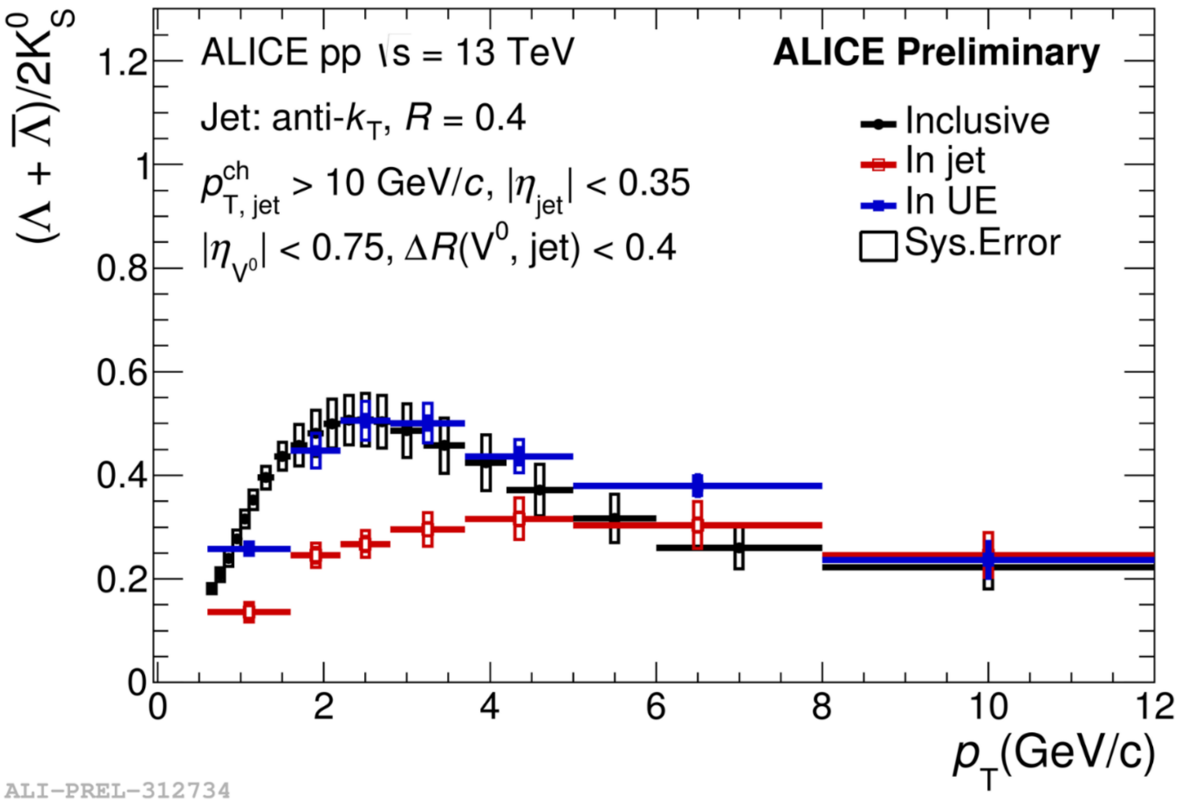
PYTHIA with CR can describe the low-p_T trend observed in pp

Spectral modification in- and out-of-jets

Pb-Pb



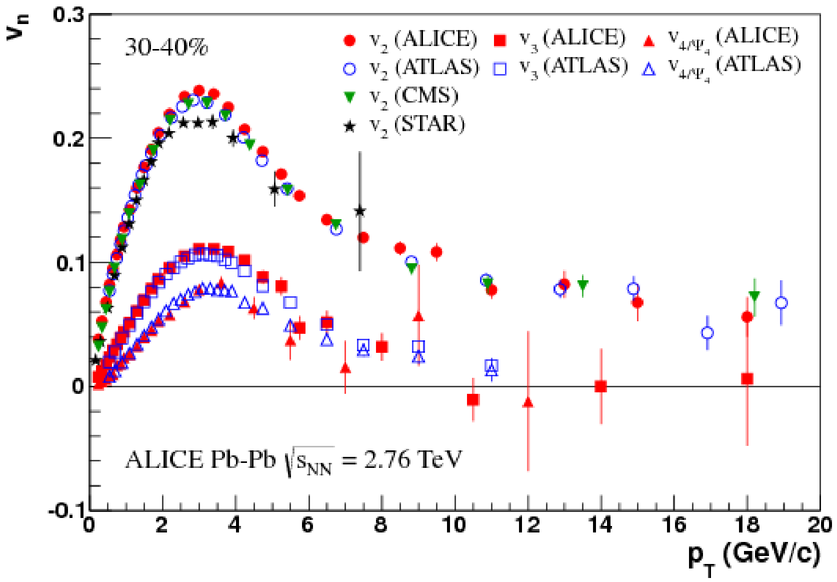
pp



Spectra modification mostly happening **outside the jet**!

In two-component models this would be linked to the presence of radial flow in core (UE?) and of vacuum hadronization in jets

Anisotropic flow and hydro expectations

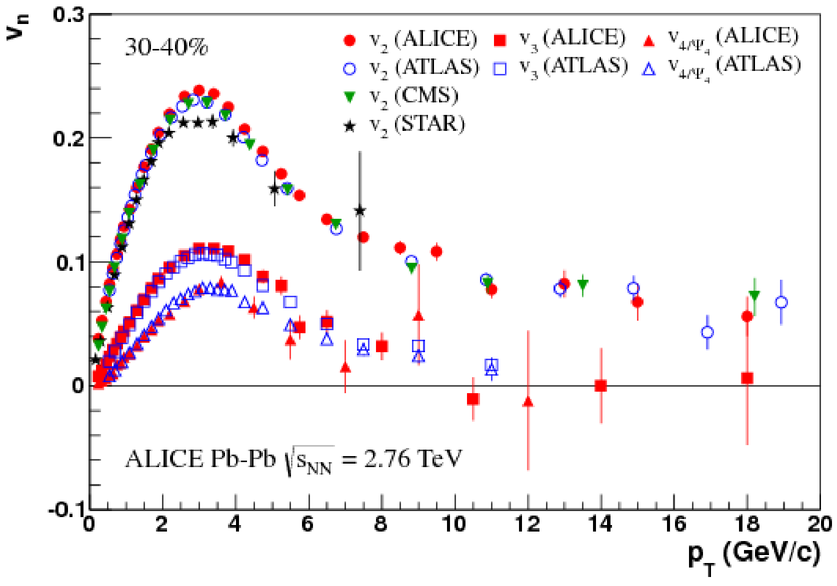


$v_n \neq 0$ observed at RHIC and LHC.

More important in semi-peripheral collisions (large eccentricity)

Hydrodynamic models reproduce v_n at low-p_T in all centralities by means of an "almost" perfect fluid: **$\eta/s=0.2$**

Anisotropic flow and hydro expectations



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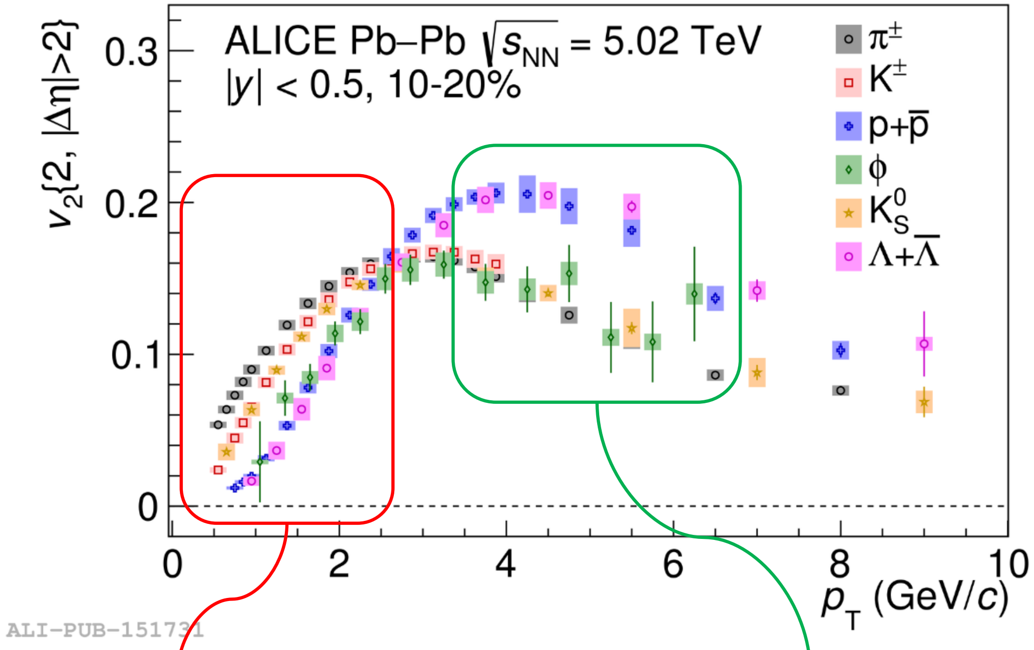
ALICE Collaboration, JHEP 09 (2018) 006



Mass ordering (higher mass → lower v_2): interplay between radial and elliptic flow

(approximate) particle type grouping (higher n_q → higher v_2): quark coalescence as dominant particle production mechanism

The ϕ meson groups to protons at low-p_T (same mass) and to mesons at intermediate-p_T (same n_q)

v_2 in small systems at LHC

$v_2 > v_3 > v_4 \neq 0$ in all colliding systems:

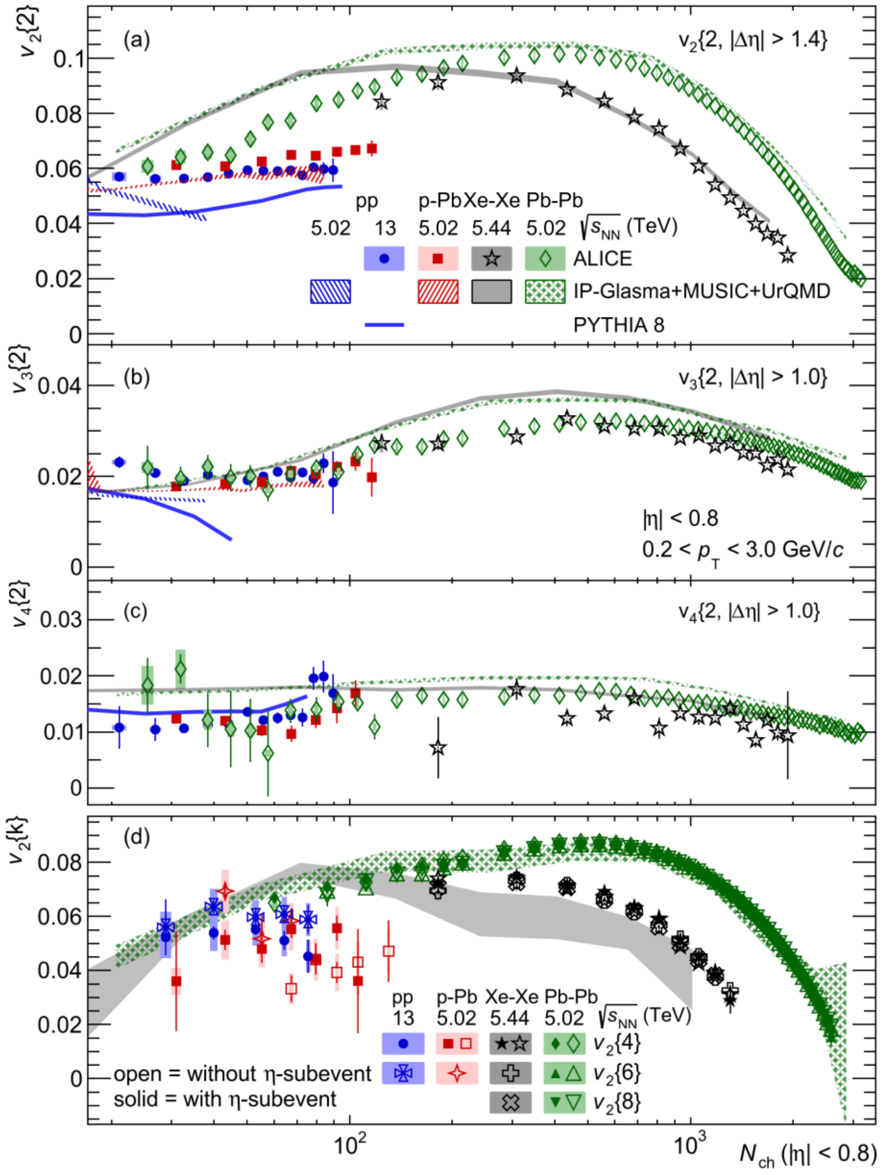
- $v_2\{4\}_{3\text{-sub}} = v_2\{6\}$ in pp: small influence of non-flow
- v_2 higher in A-A (eccentricity evolution), almost flat in pp and p-Pb
- v_3 & v_4 similar across systems (larger sensitivity to parton density anisotropy)

No model can quantitatively describe the data over the full multiplicity range

… but hydro far from equilibrium approaching from the right

And Pythia + shoving approaching from the left..!

ALICE Collaboration, Phys. Rev. Lett. 123, 142301 (2019)



… so?

Status

- **Large colliding systems:**
  - Statistical hadron production
  - Viscous hydro
  - Two-component models successful (large dominance of core)
  - Microscopic models (e.g. Pythia Angantyr) in the game

- **Small colliding systems:**
  - Microscopic models are improving hadrochemistry description (ropes) and achieve non-zero v2 (shoving)
    … but even without final state..!
  - Two component models ok for hadrochemistry (interplay between core and corona) and basic features of hydro-like phenomena (e.g. radial flow)
  - Hydro far from equilibrium (previous talk) in the game

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CHOOSE YOUR WAY!

Need to find FEATURES in the data, cannot play at tuning models ourselves!

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DIFFERENT TIMESCALES INVOLVED

WHAT'S THE ROLE OF HF DECAYS ON STRANGENESS ENHANCEMENT?

CAN WE DISENTANGLE INITIAL FROM FINAL STATE EFFECTES?

HOW IS MULTIPLICITY GENERATED?

CAN WE SEPARATE HARD AND SOFT SCALES?

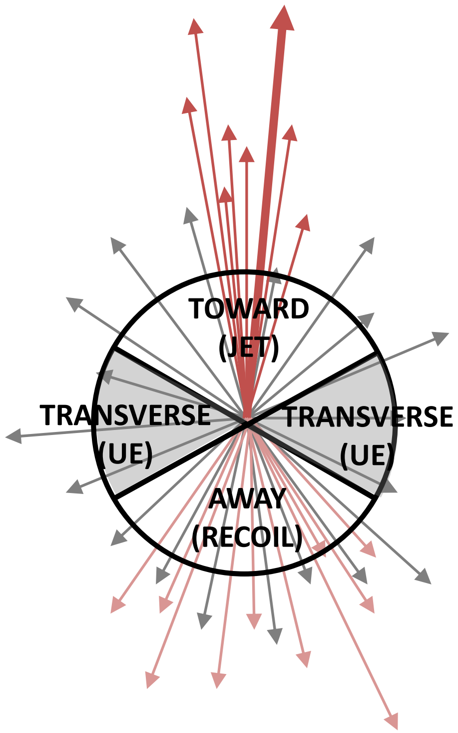
…

Event topology

Topological classification of pp events, identifying:

- Toward region (triggering jet) + Away region (recoiling jet)
- Transverse region (Underlying Event - UE)

The jet direction is the direction of the highest-p_T hadron (p_T^{leading} > X GeV/c)



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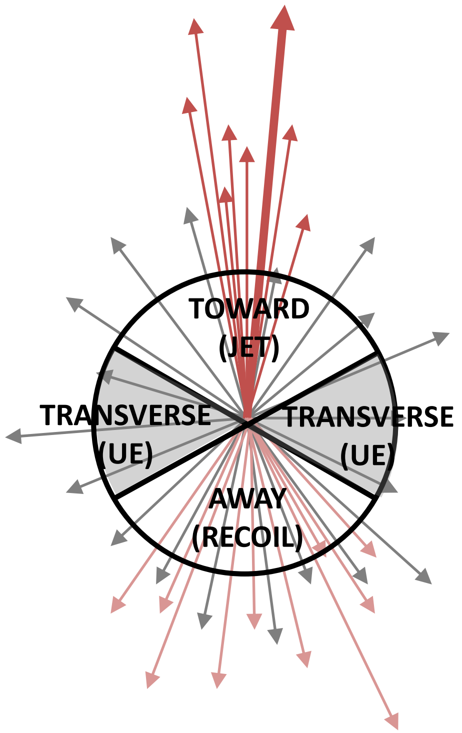
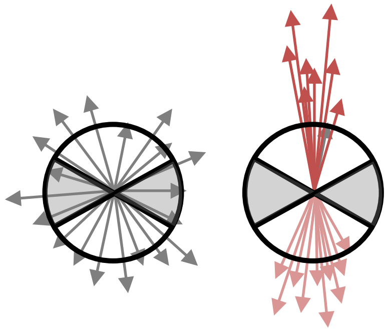
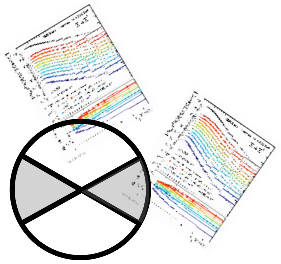


And then one can:

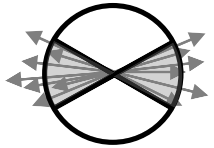
- Select "isotropic" and "pencil-like" events (Spherocity)



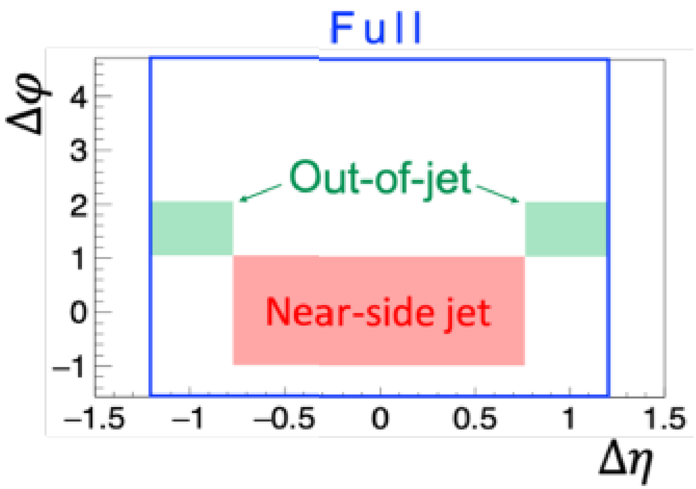
- Measure spectra in "toward", "transverse", "away" (in-/out-of-jet)

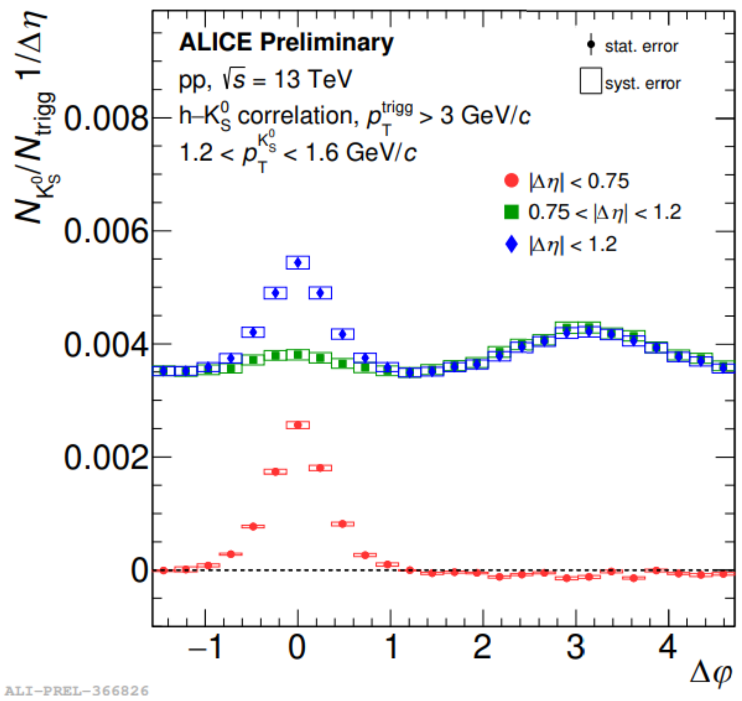


- Express enhancement wrt UE multiplicity (R_T)



Event topology: in- and out-of-jet





C. De Martin, IS 2021

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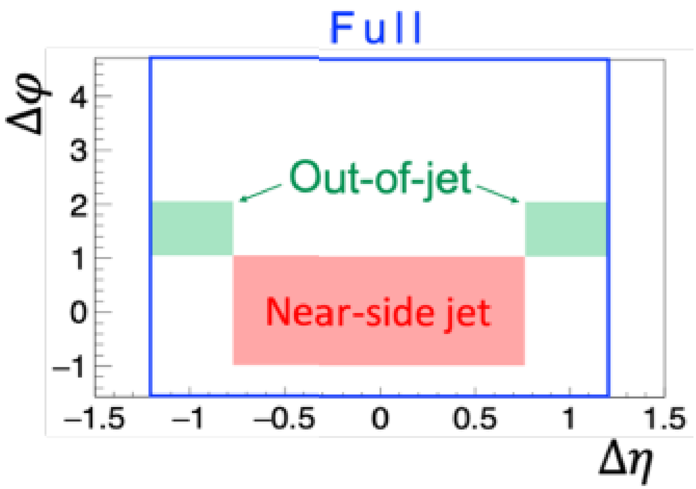
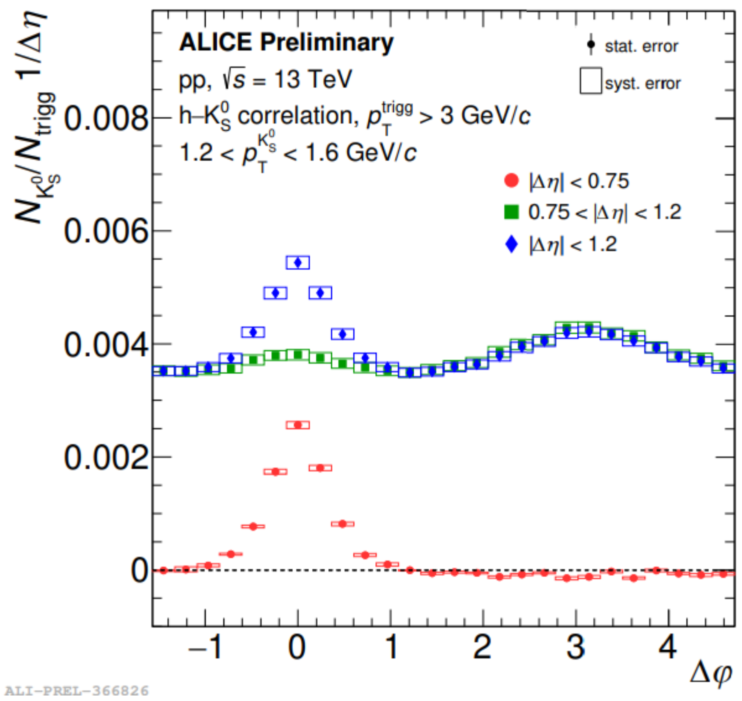
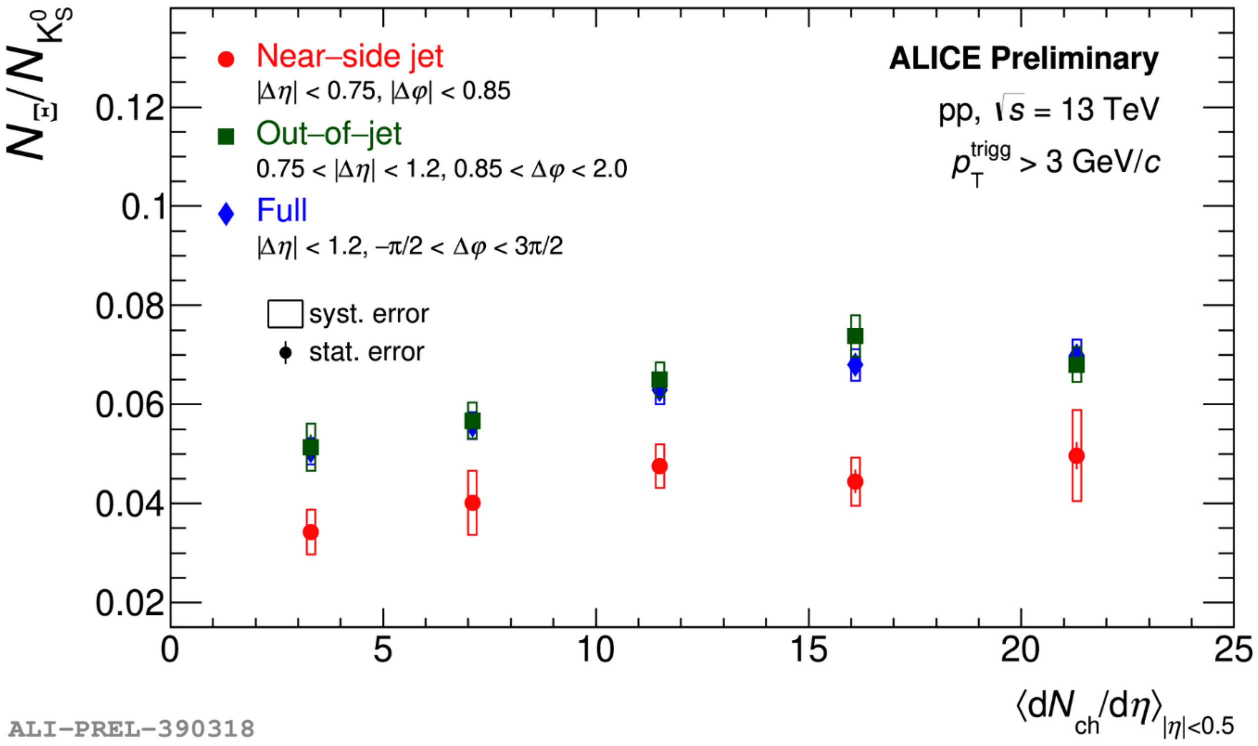






In events with a leading particle with $p_T > 3$ GeV/c

multi-strange hadrons are mostly produced outside the jet (soft part of the event, collectivity?)

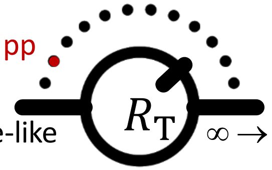
C. De Martin, IS 2021

Event topology: in- and out-of-jet VS R_T

"UE multiplicity"

$$R_T = \frac{N_T}{\langle N_T \rangle}$$

1 ≅ MB pp



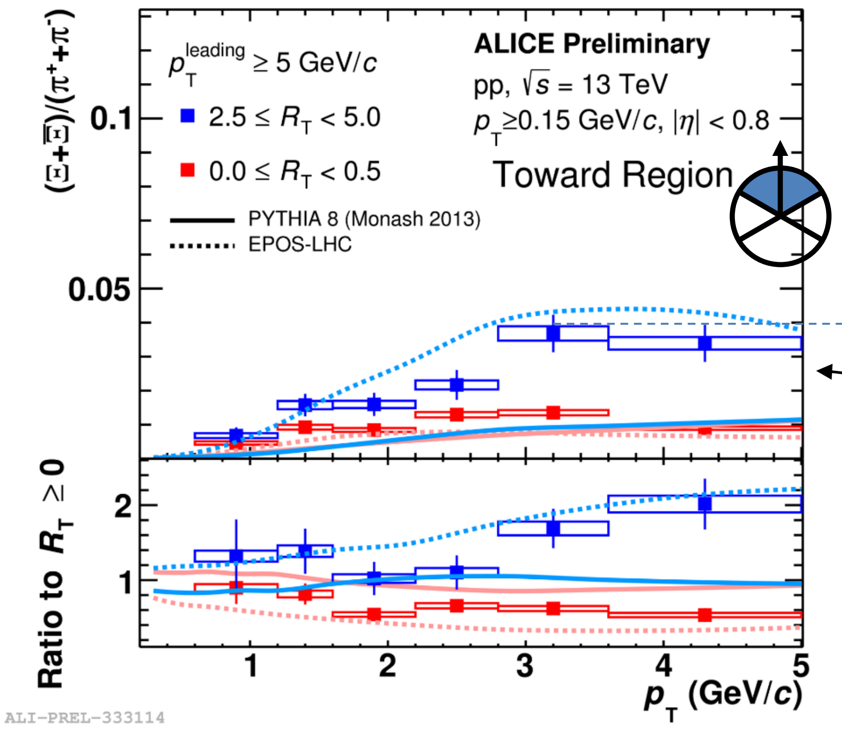
0 → ee-like

∞ → Pb-Pb-like

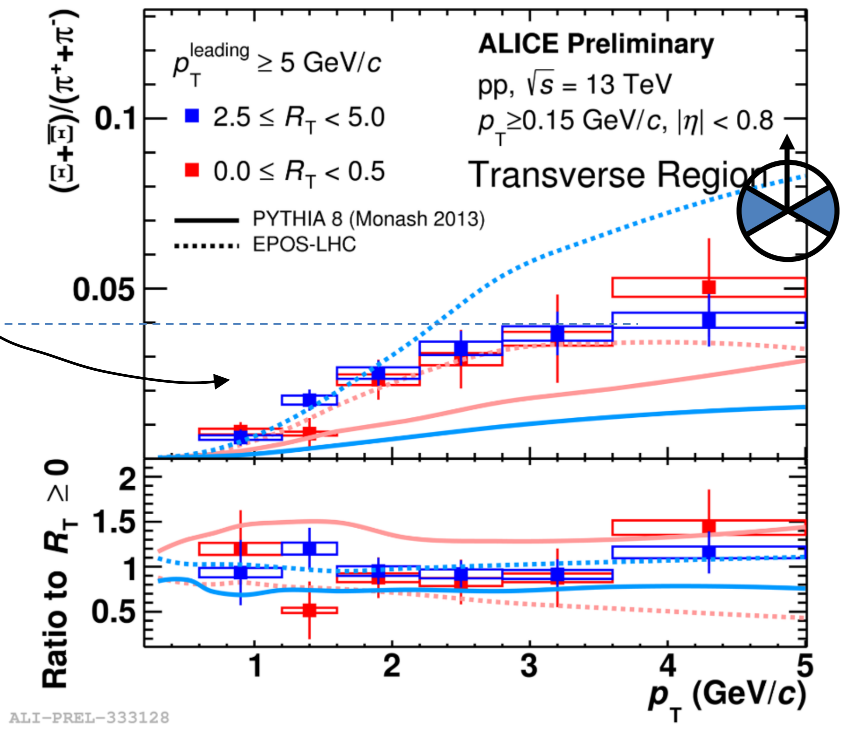
L. Bianchi, LHCP2020

Event topology: in- and out-of-jet VS R_T

UE + JET



UE



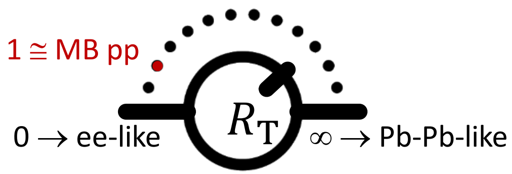
No evolution VS mult. in the UE!

NO strangeness enhancement in the UE

Strangeness enhancement in the toward region (**UE+JET**)

"UE multiplicity"

$$R_T = \frac{N_T}{\langle N_T \rangle}$$

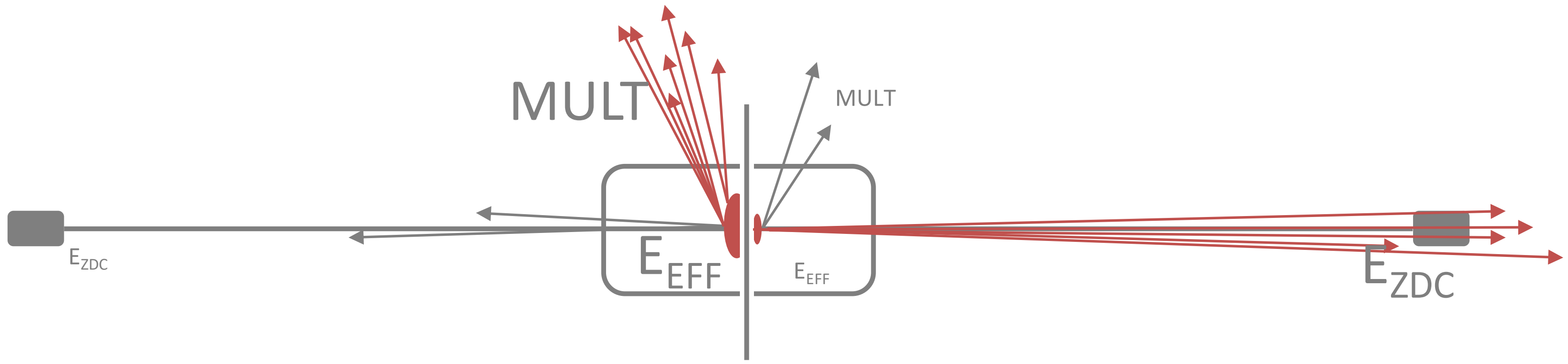


Core-corona models may explain this as different Ξ/π ratios in jets (vacuum hadronization) and in the UE (core, statistical hadronization)

Need more measurements to draw firm conclusions: strange-hadron correlations, in- and out- full-reconstructed jet productions, etc.

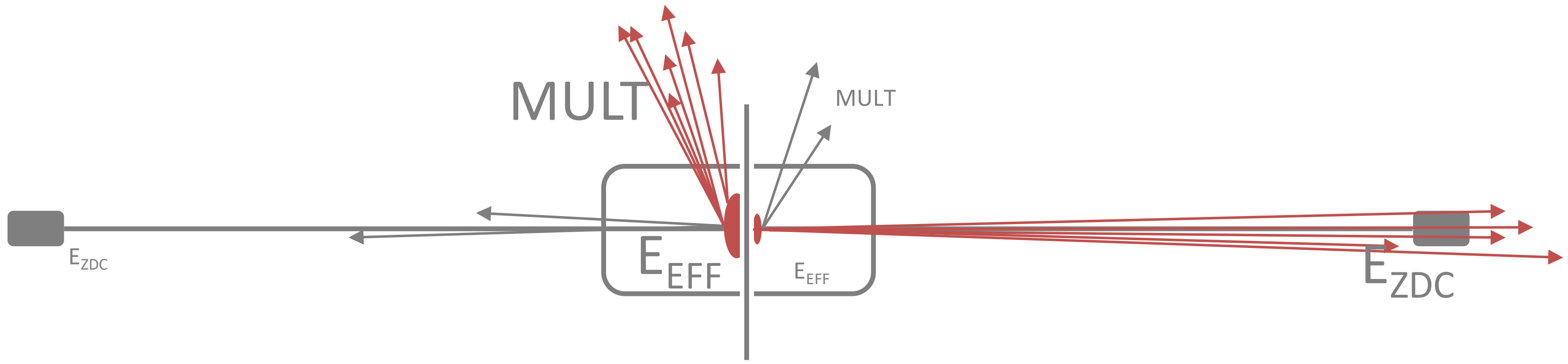
L. Bianchi, LHCP2020

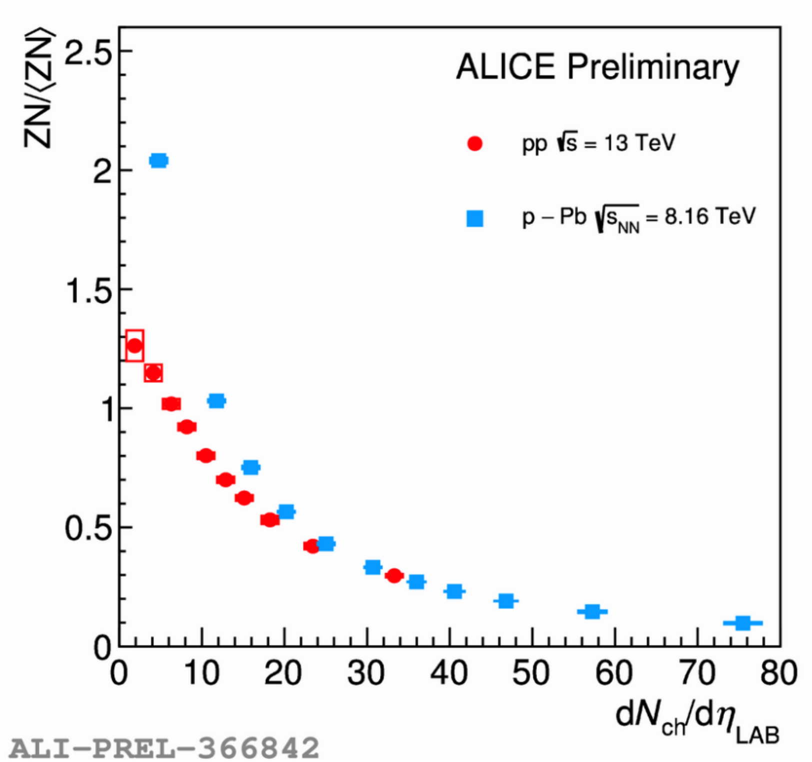
Initial VS final state

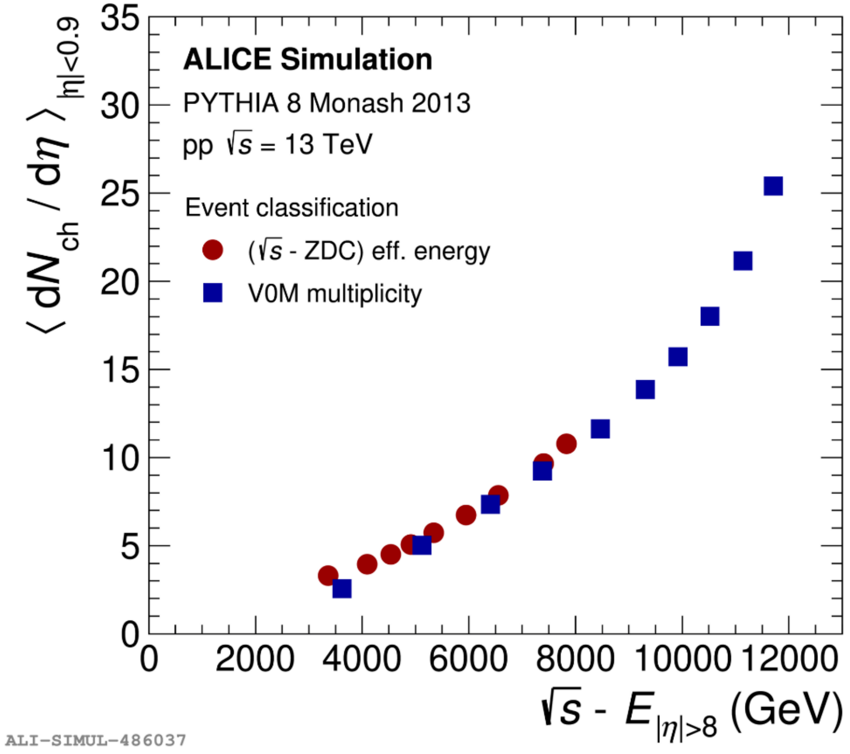


F. Ercolessi, SQM 2021

Initial VS final state

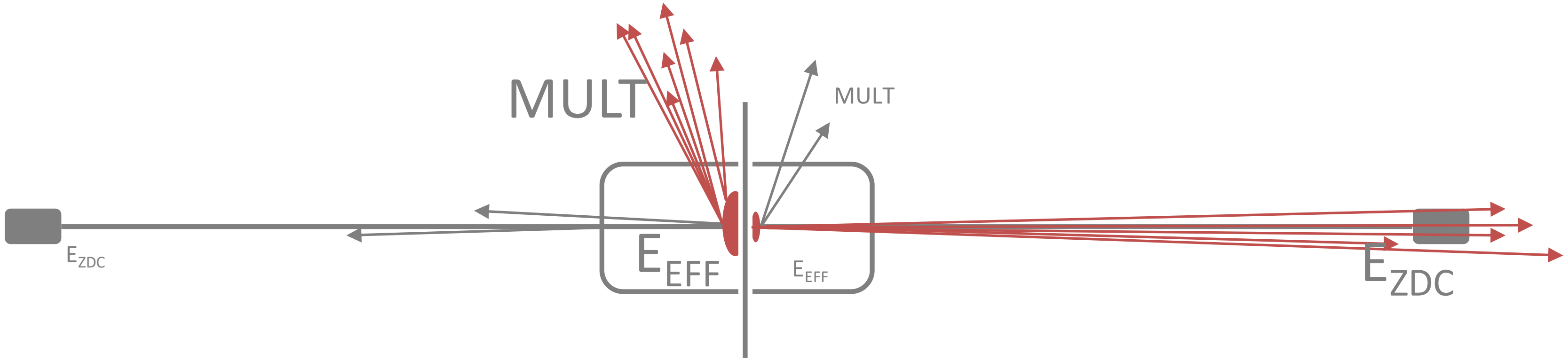


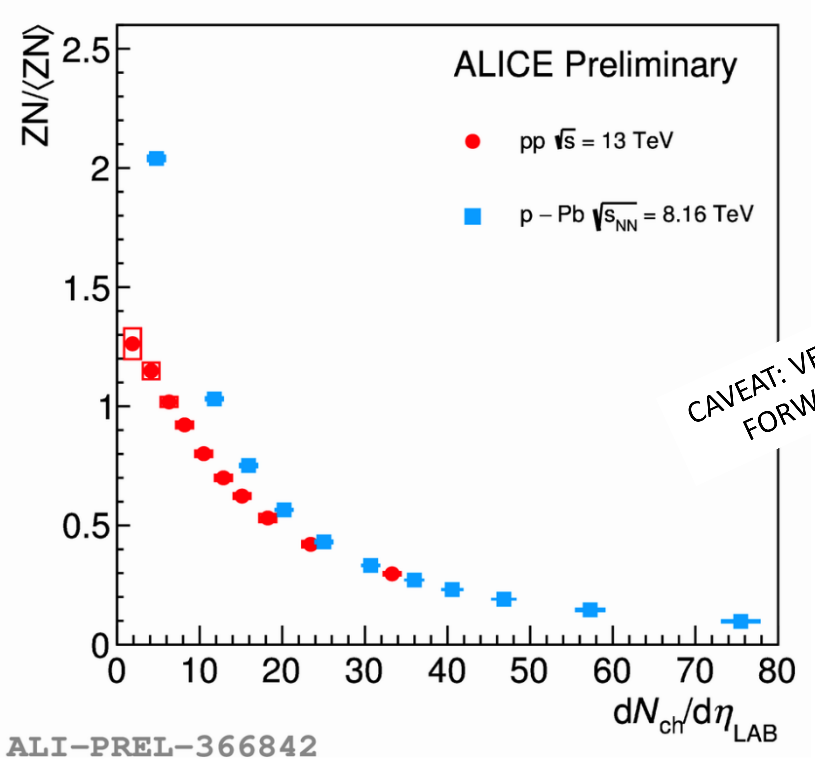




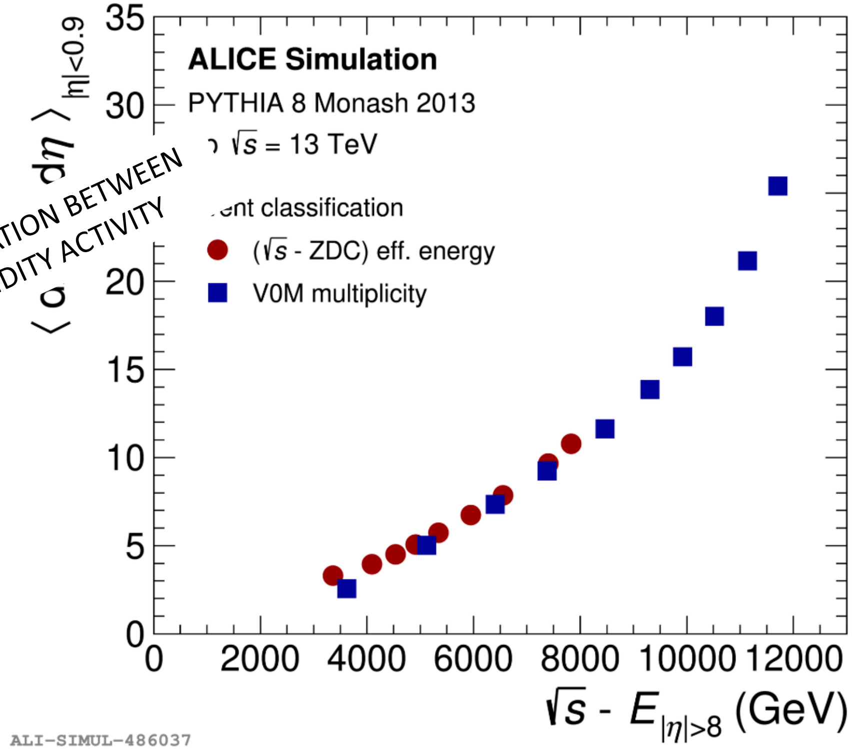
F. Ercolessi, SQM 2021

Initial VS final state





CAVEAT: VERY BROAD CORRELATION BETWEEN FORWARD- AND MID-RAPIDITY ACTIVITY

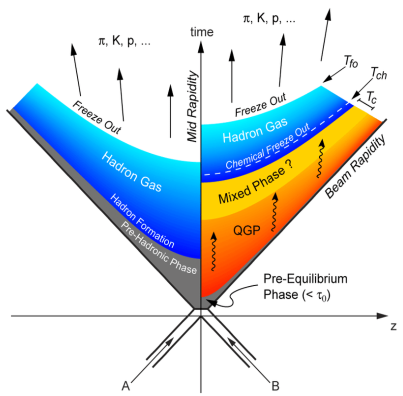


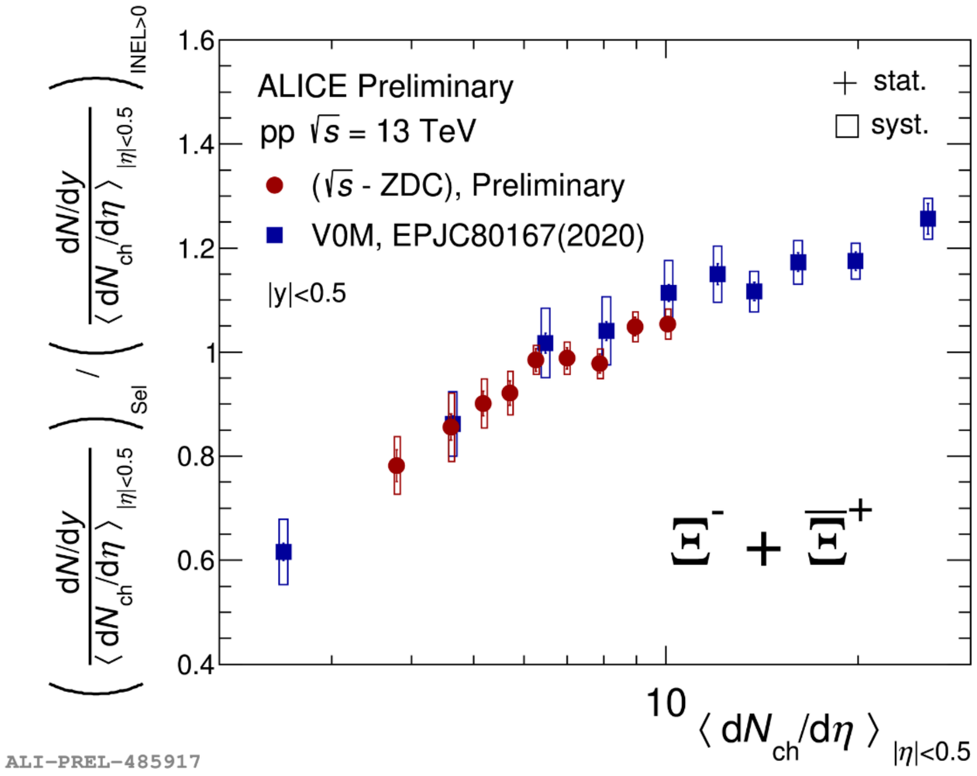
F. Ercolessi, SQM 2021

Initial VS final state

Forward and mid-rapidity activities are causally disconnected right after t_0

If initial state effects play an important role on strangeness production, for a given multiplicity there should be modulation with effective energy





Initial VS final state

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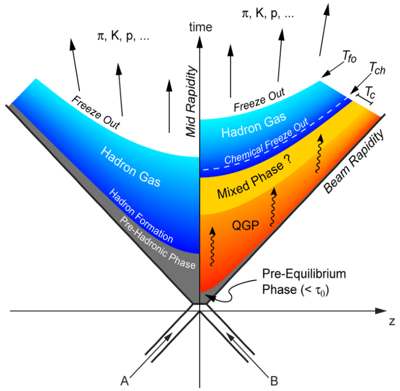
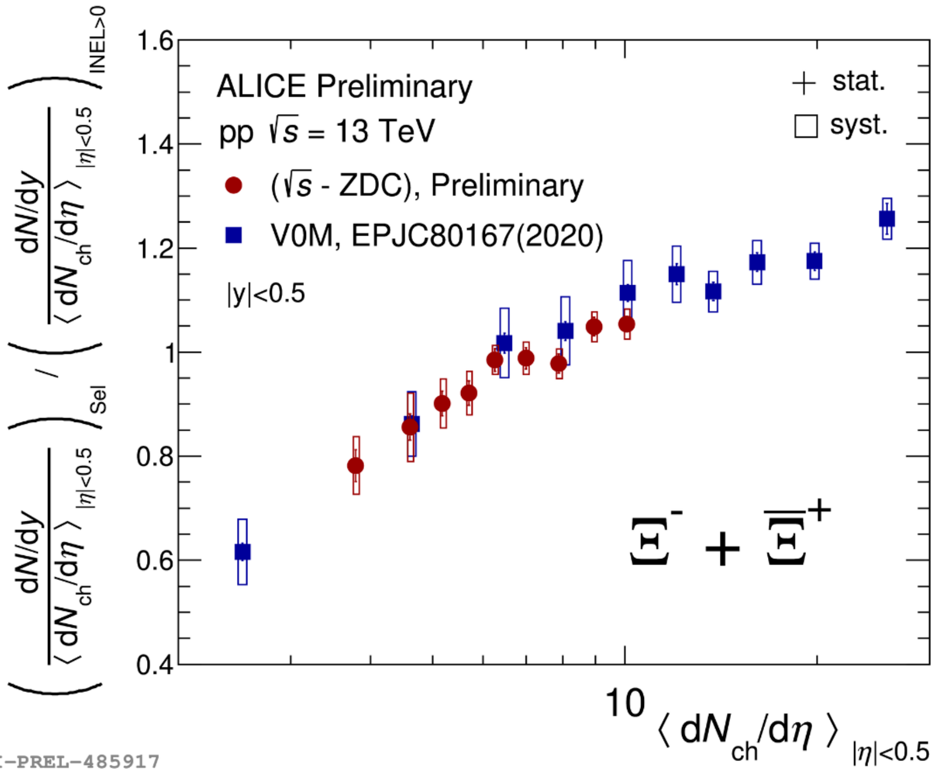
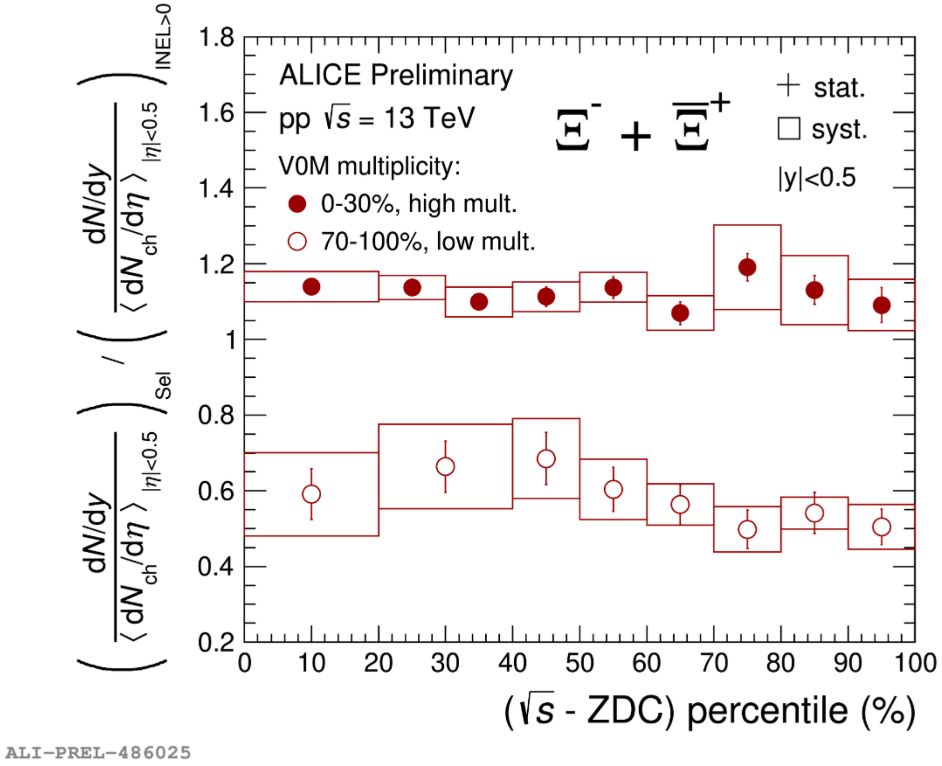
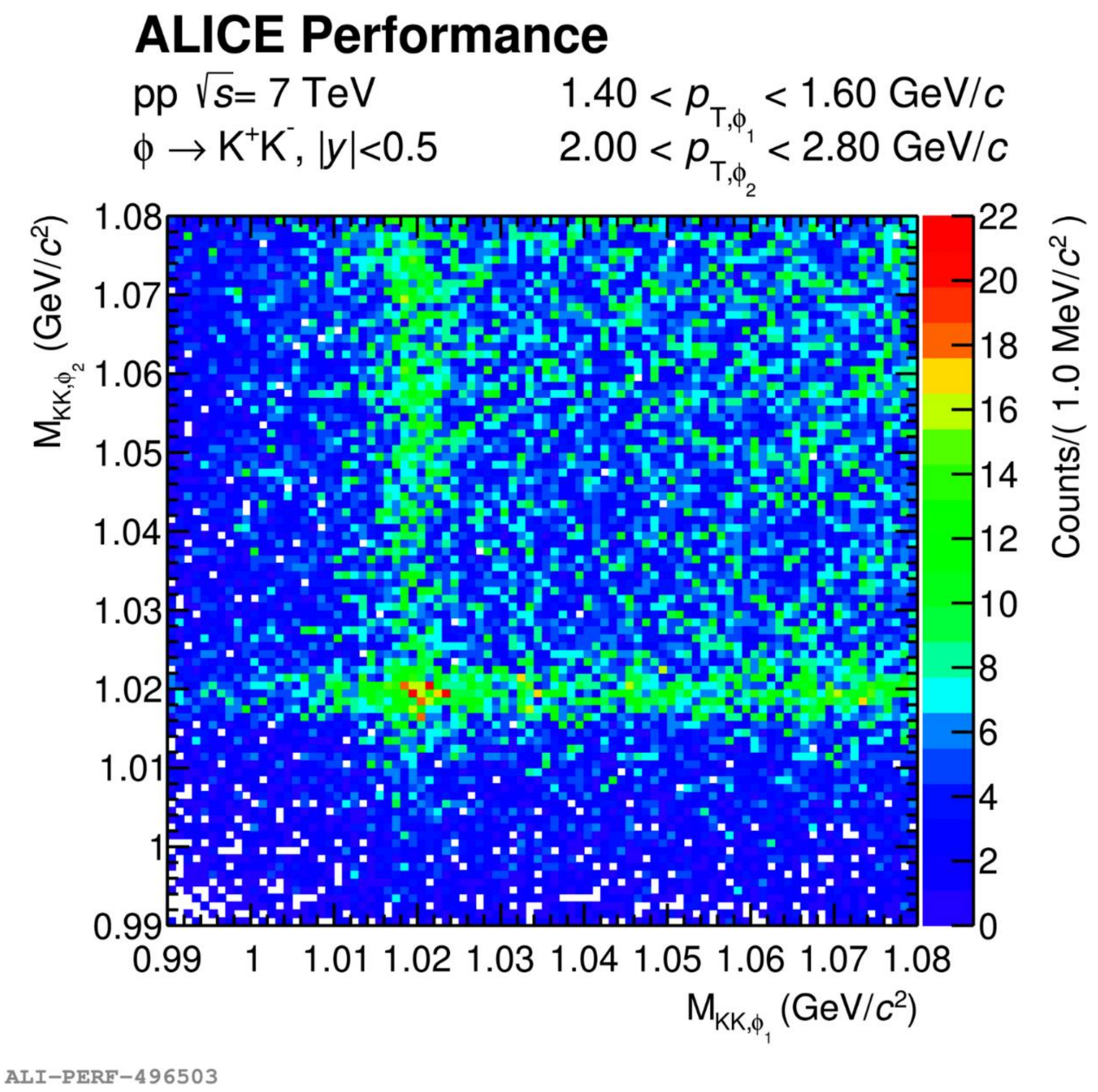






F. Ercolessi, SQM 2021

Multiple strange hadrons / event



Multiplicity distribution of p, ϕ, K0S, Λ, Ξ, Ω per event VS charged particle multiplicity

Multiple strange hadrons per event can add important constraints to the models

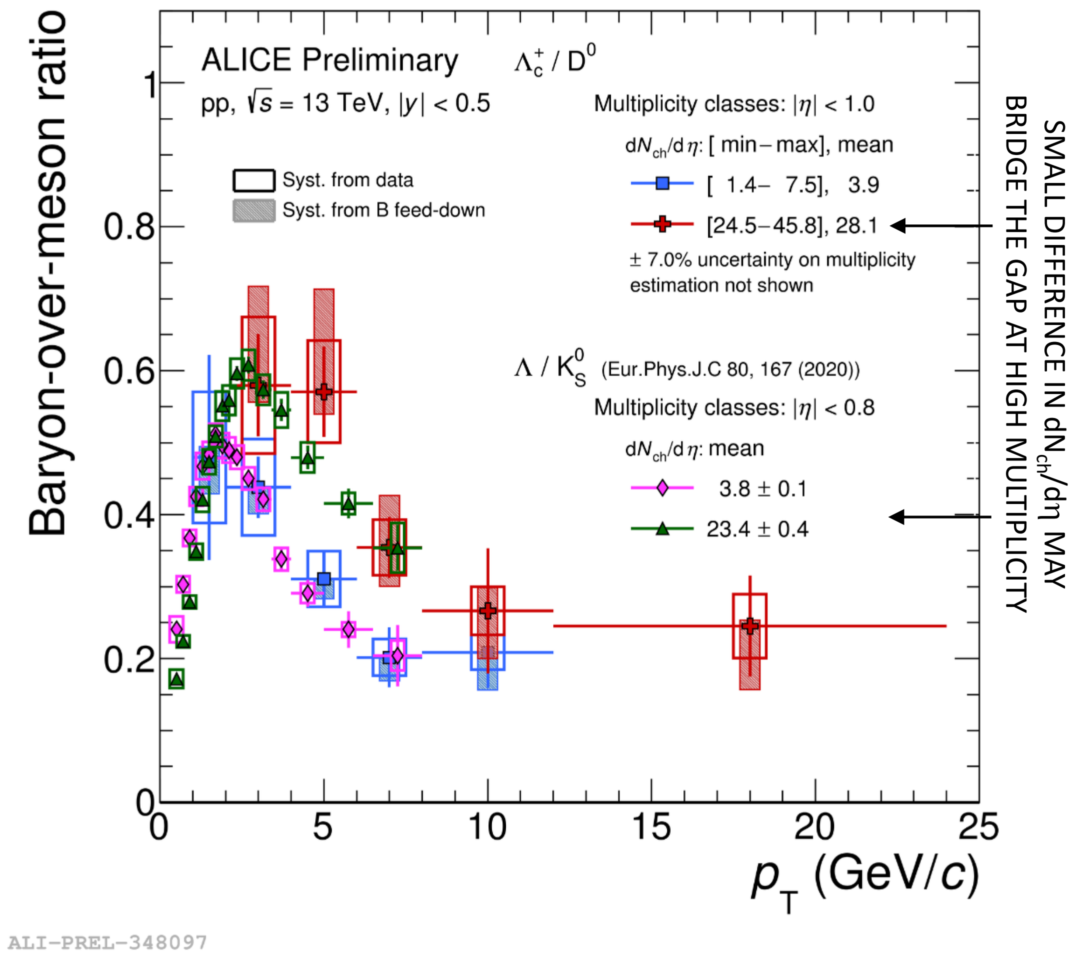
- Trivial Poisson behavior would hint at statistical production
- Deviations could indicate relevant correlated production

N. Rubini, SIF 2021

Conclusions and outlook

- Observations on soft particle production in large systems require some sort of collectivity to be interpreted
  - The nature of this collectivity is debated, with explanations differing for microscopic description and timescale differences
- Small colliding systems are powerful tools to help understanding collectivity.. and yet they introduce more complication
  - Final state effects are often required to describe observations VS multiplicity
  - … but not always
- We can easily imagine that in 5 years from now models differing very much for underlying physics will all describe published data → **Need to explore new features**
- Many new investigations which aim at
  - Fixing timescales
  - Fixing hard scales and looking at soft production
  - Disentangle initial/final state
  - Explore multiple PID production

Spectral modification: light and heavy flavors



Striking similarities between light and heavy flavors in small systems

Intriguing observation:

- Hydro for charm?
- Coalescence at intermediate p_T with same net effect for light and heavy flavors?
- Color Reconnection in the final state?

Need to extend Λ_c/D_0 at lower p_T and with larger statistics