Soft probes at the LHC: medium properties and hadronization

Livio Bianchi *
Università & INFN Torino

LHCP2020

* livio.bianchi@cern.ch

Why soft probes in HI collisions?

1st OBJECTIVE OF THIS TALK	Demonstrate that the study of soft probes allows to characterize with high precision the hot and dense medium (QGP) produced in heavy-ion collisions

Soft probes in heavy-ion collisions useful to:

- Study collective phenomena

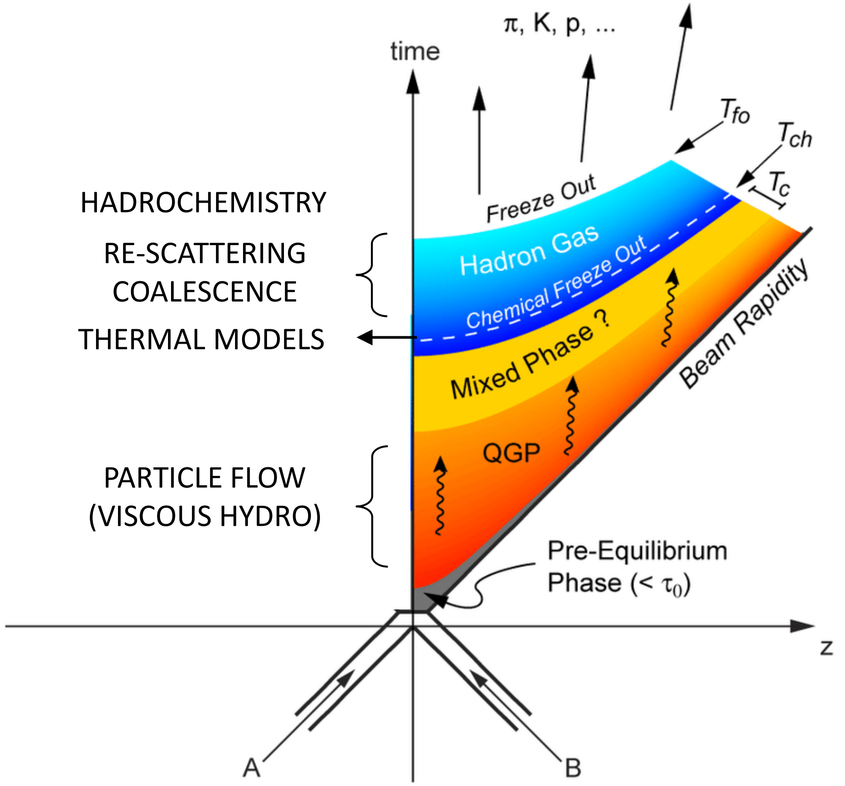
  ↪ High energy density, large medium developing radial and anisotropic flow

- Test statistical limit of particle production

  ↪ Large multiplicities → statistical treatment applicable in Grand Canonical formulation

- Disentangle hadronic phase effects

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



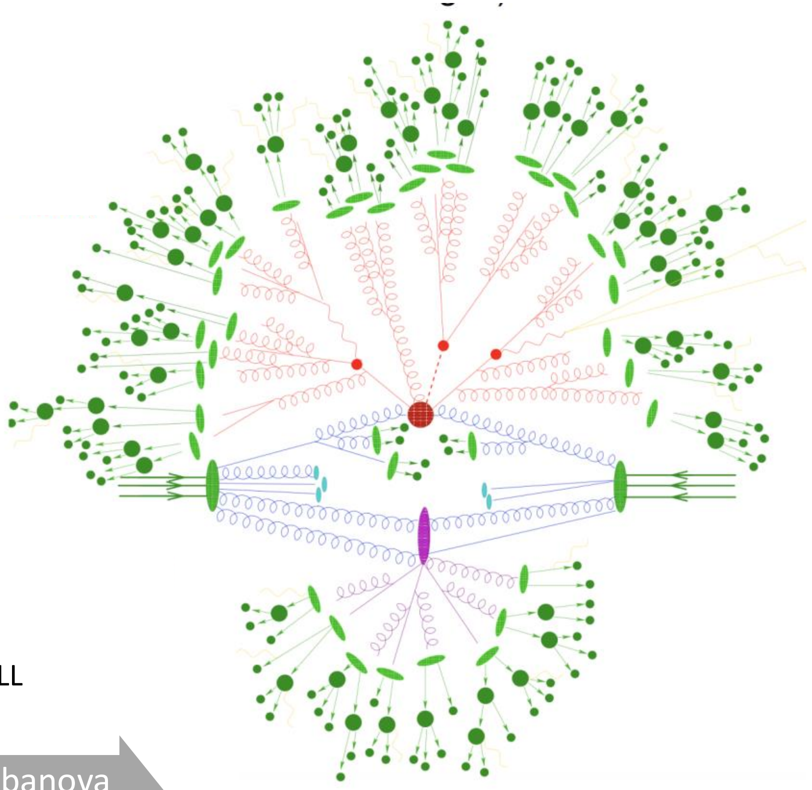
…and extension to small colliding systems

2nd OBJECTIVE OF THIS TALK	Show how exploiting small colliding systems we can have deeper insight on collective effects observed in A-A collisions

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

V. Zaccolo
26 May, 18:00

- 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



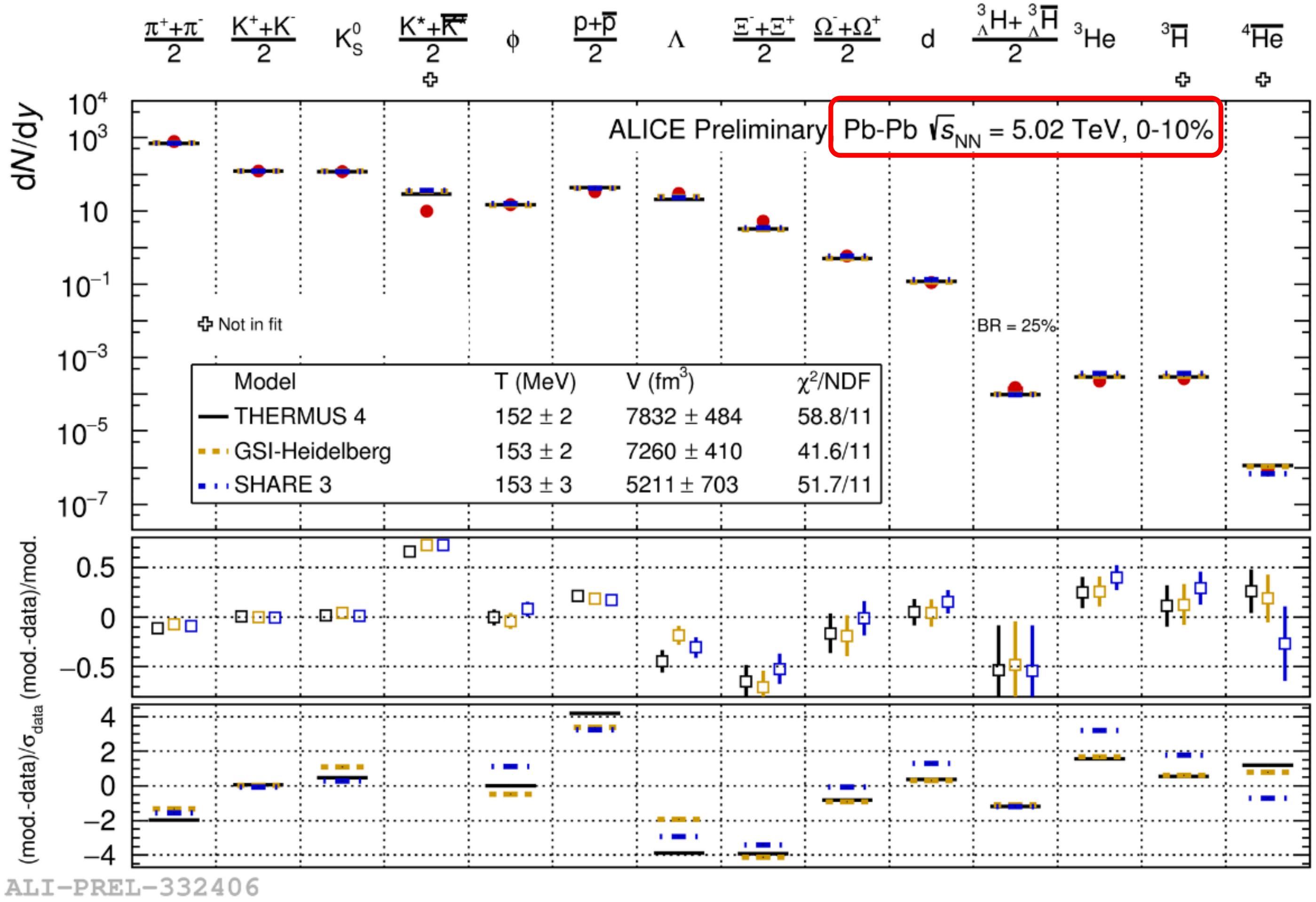
Questions:

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

THIS IS NOT A "SMALL SYSTEMS" TALK

Z. Khabanova
28 May, 15:03

Hadron abundancies in the search for T_{ch}



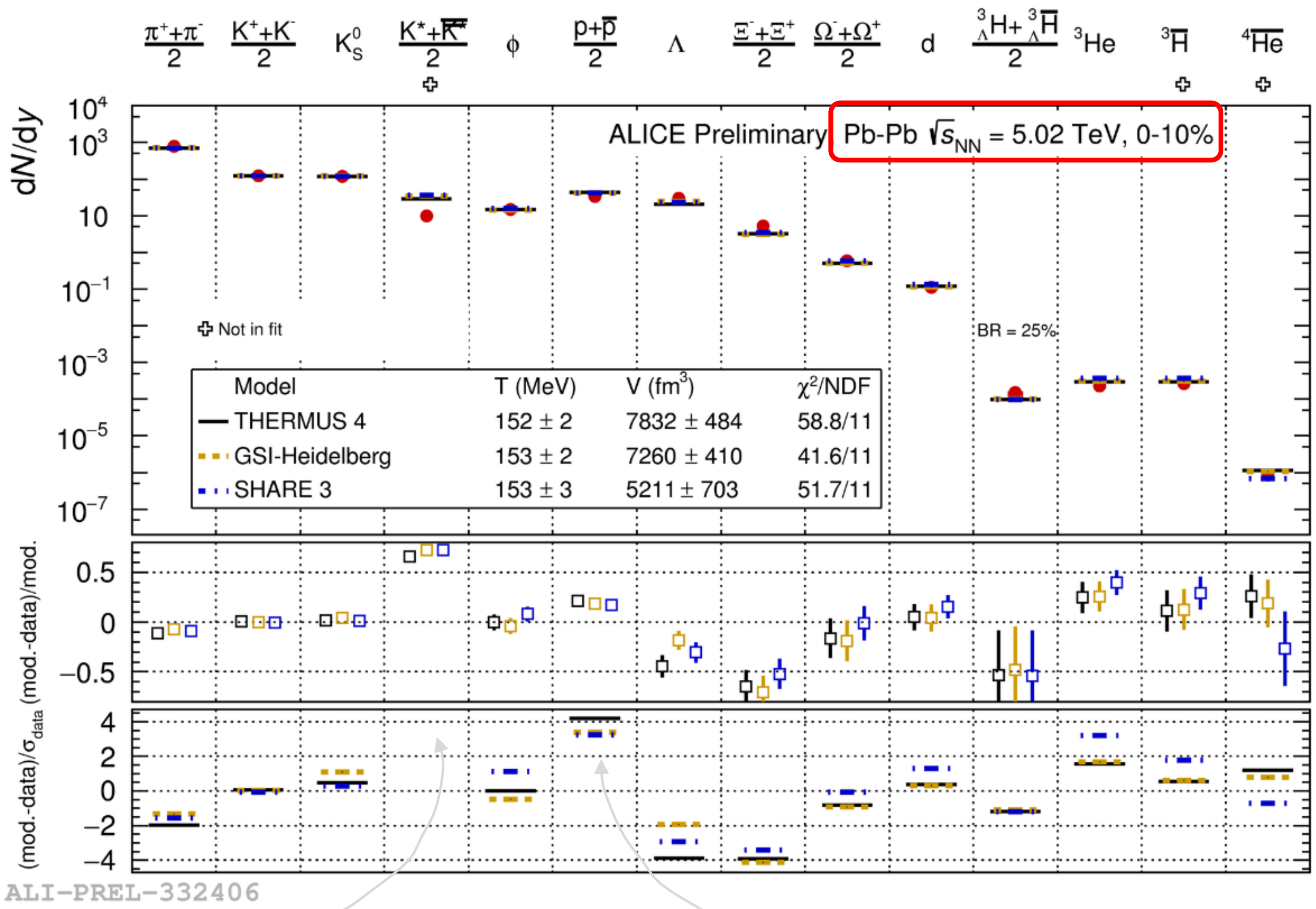
Production of light flavor hadrons fit over 9 orders of magnitude by Statistical Hadronization Model (SHM) in its Grand Canonical Ensemble (GCE) formulation

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

COMPATIBLE WITH CHIRAL CROSSOVER TRANSITION TEMPERATURE FROM LQCD

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

COMPATIBLE WITH CHIRAL CROSSOVER TRANSITION TEMPERATURE FROM LQCD

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

Friction with p being addressed through S-matrix approach (π-N interactions)

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

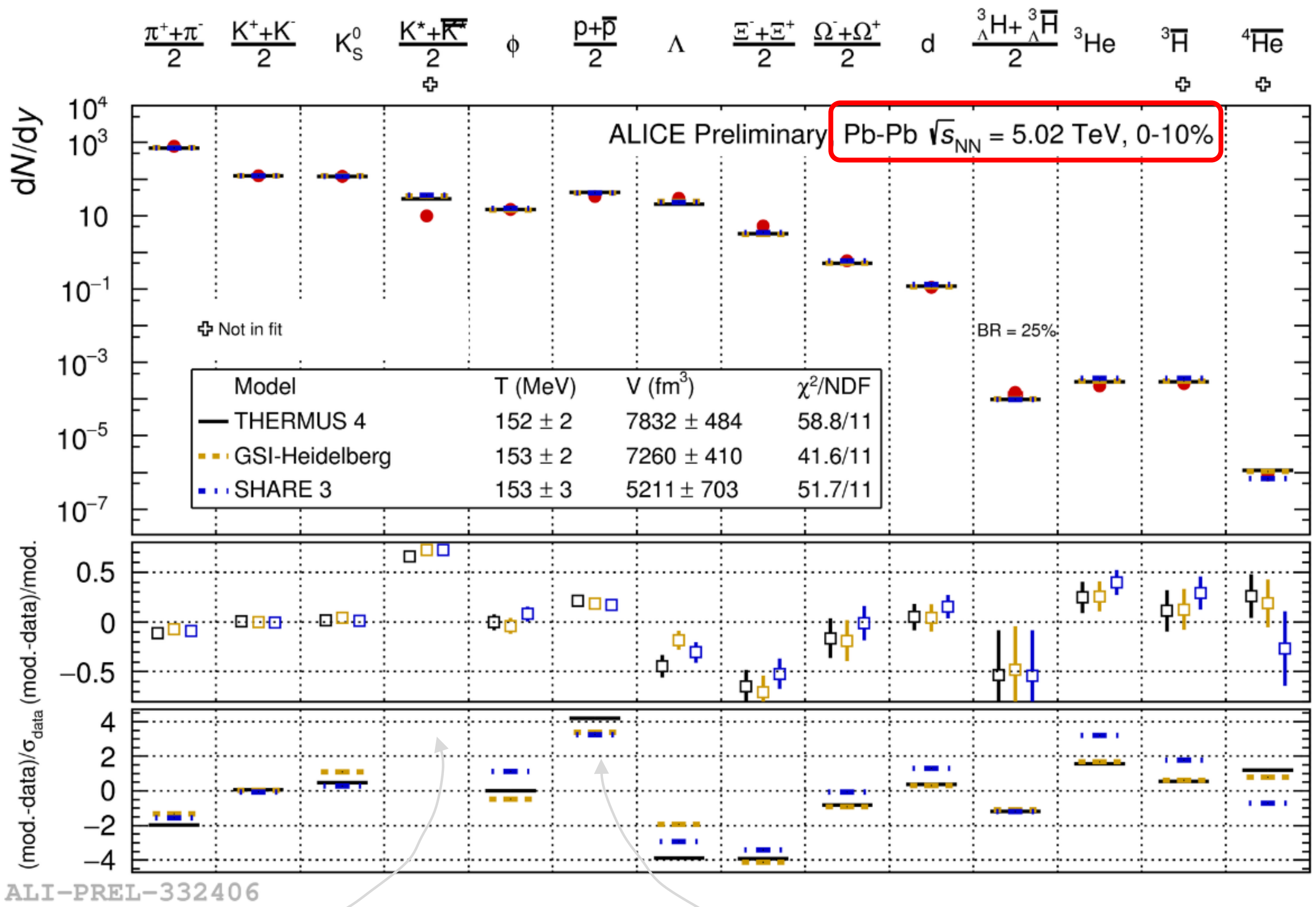
Loosely bound (anti-)nuclei reproduced by SHM (snowballs in hell)

*Not included in fit

A. Andronic et al., Phys. Lett. B 792, 304-309 (2019)

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

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

COMPATIBLE WITH CHIRAL CROSSOVER TRANSITION TEMPERATURE FROM LQCD

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 (π-N interactions)

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

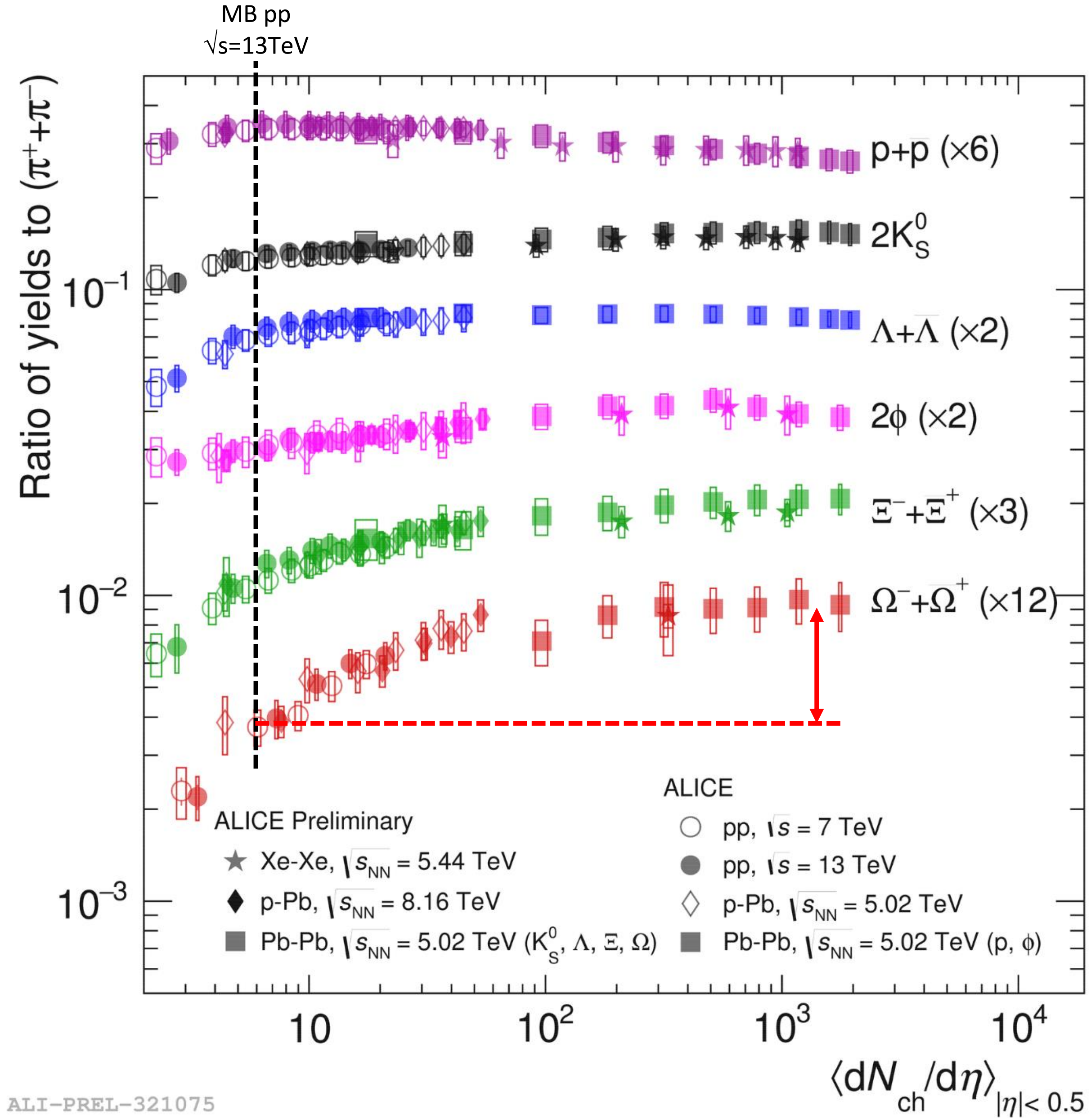
Loosely bound (anti-)nuclei reproduced by SHM (snowballs in hell)

*Not included in fit

A. Andronic et al., Phys. Lett. B 792, 304-309 (2019)

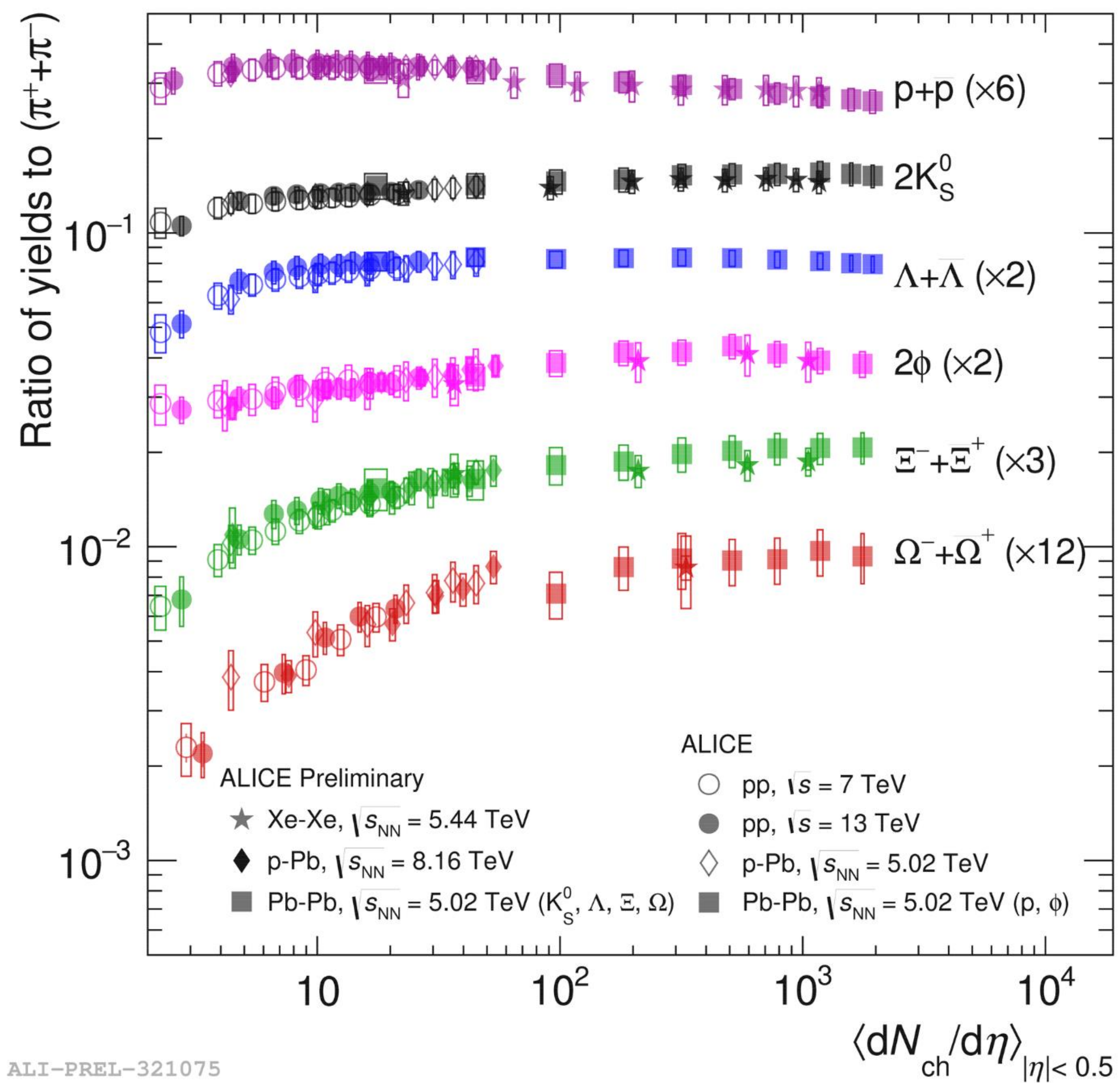
P. Alba et al., Phys. Rev. C 101, 054905 (2020)

Hadrochemistry modification



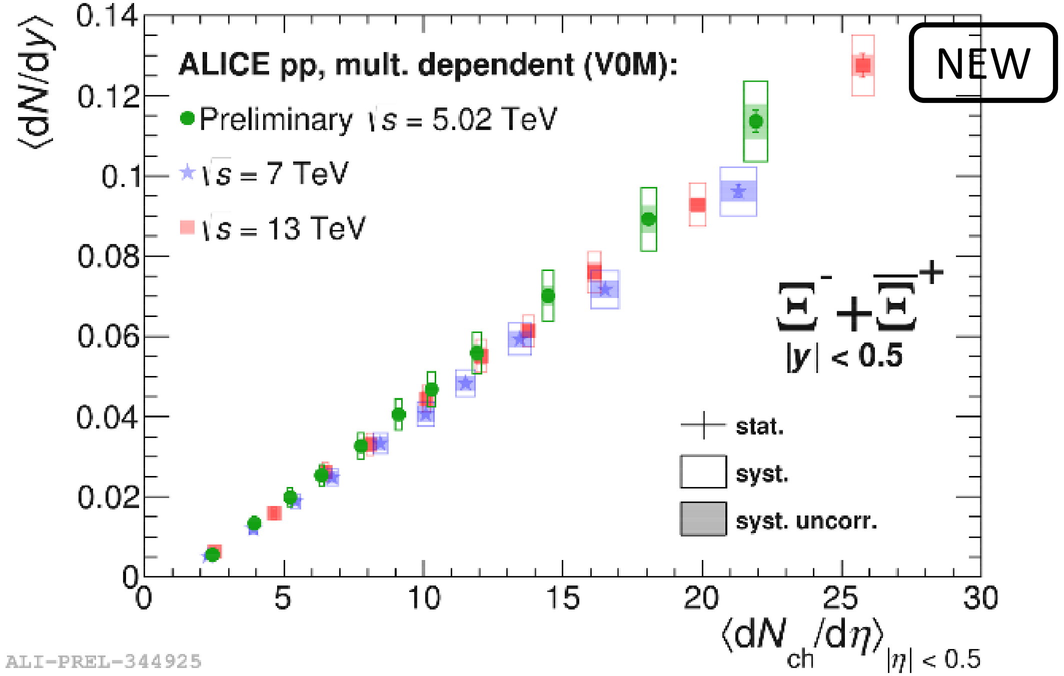
h/π smoothly evolves across multiplicity reaching thermal values in Pb-Pb at the LHC

Hadrochemistry modification

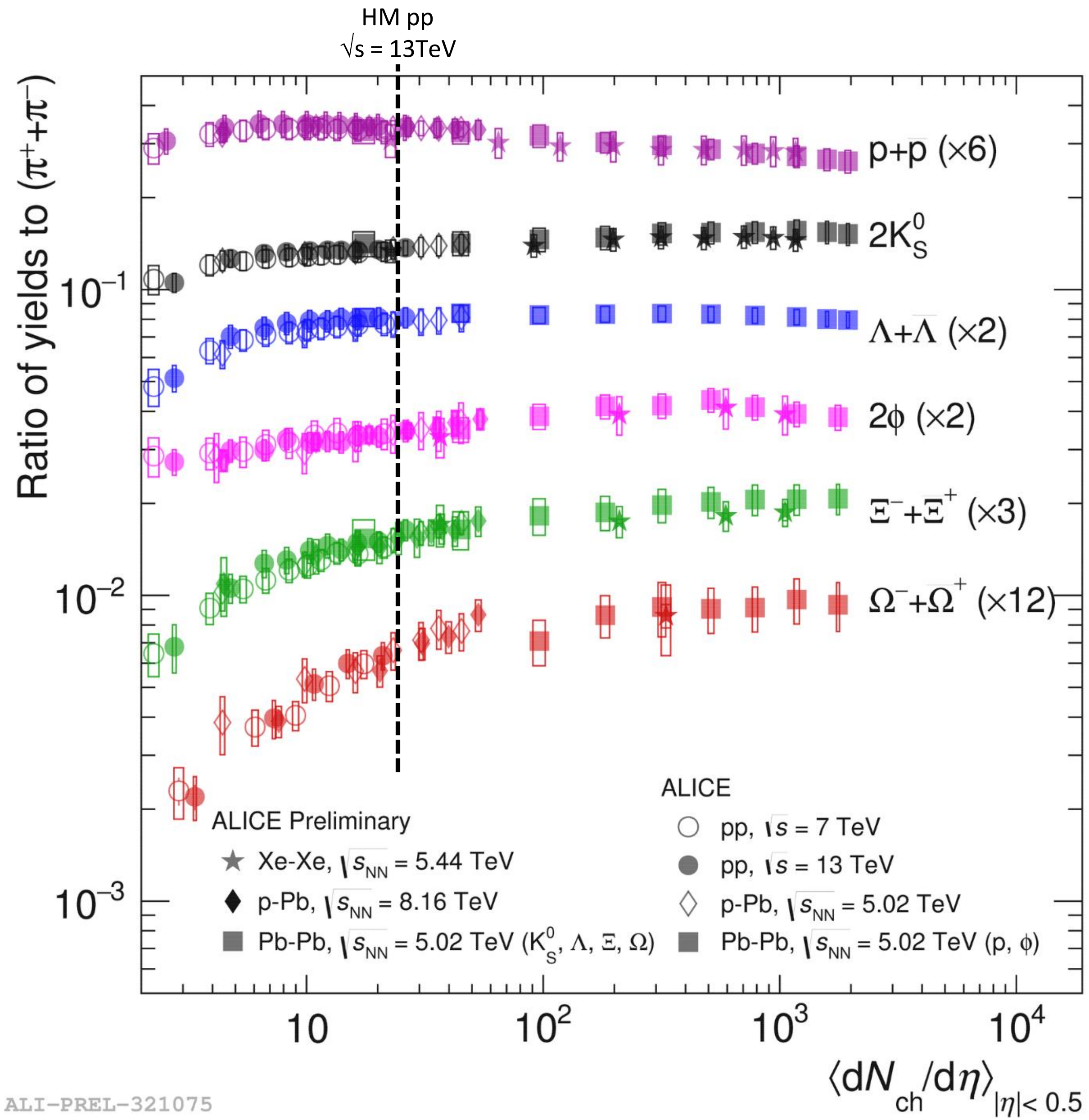


h/π smoothly evolves across multiplicity reaching thermal values in Pb-Pb at the LHC

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



Hadrochemistry modification



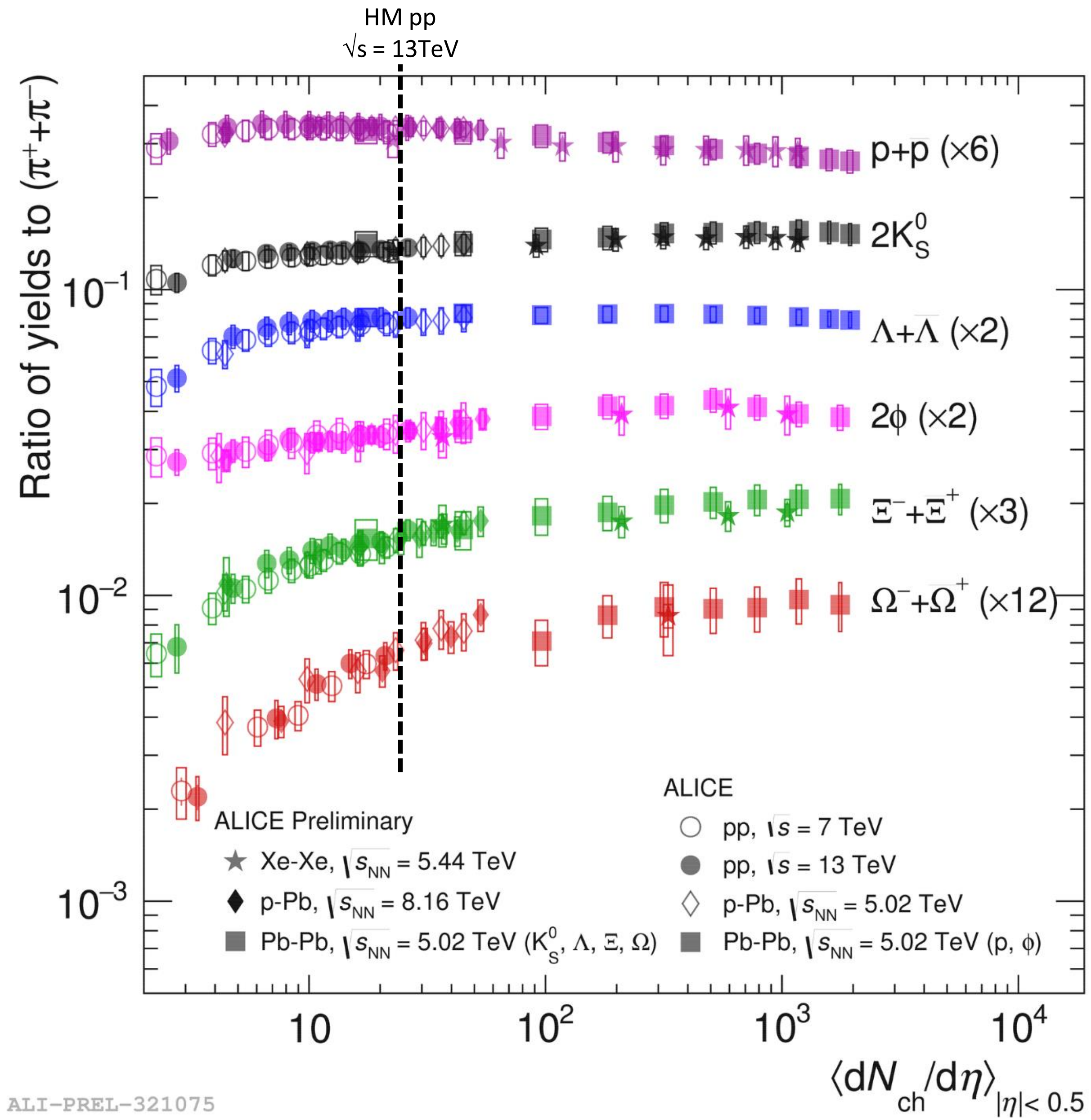
h/π smoothly evolves across multiplicity reaching thermal values in Pb-Pb at the LHC

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

Hadrochemistry modification



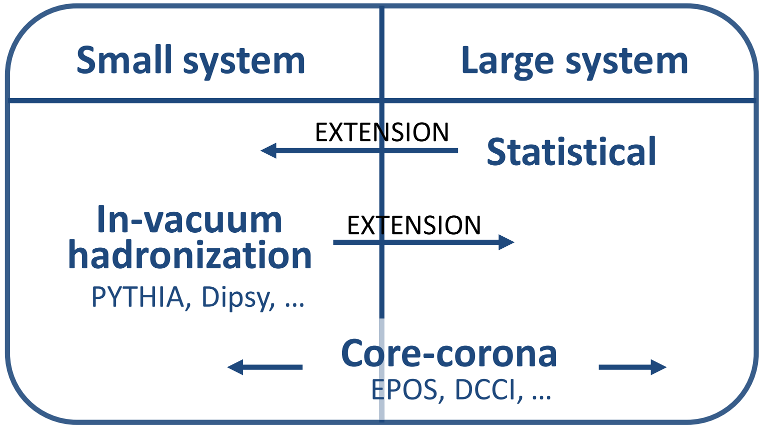
h/π smoothly evolves across multiplicity reaching thermal values in Pb-Pb at the LHC

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

Evolution depends on the hadron:
the stranger the steeper

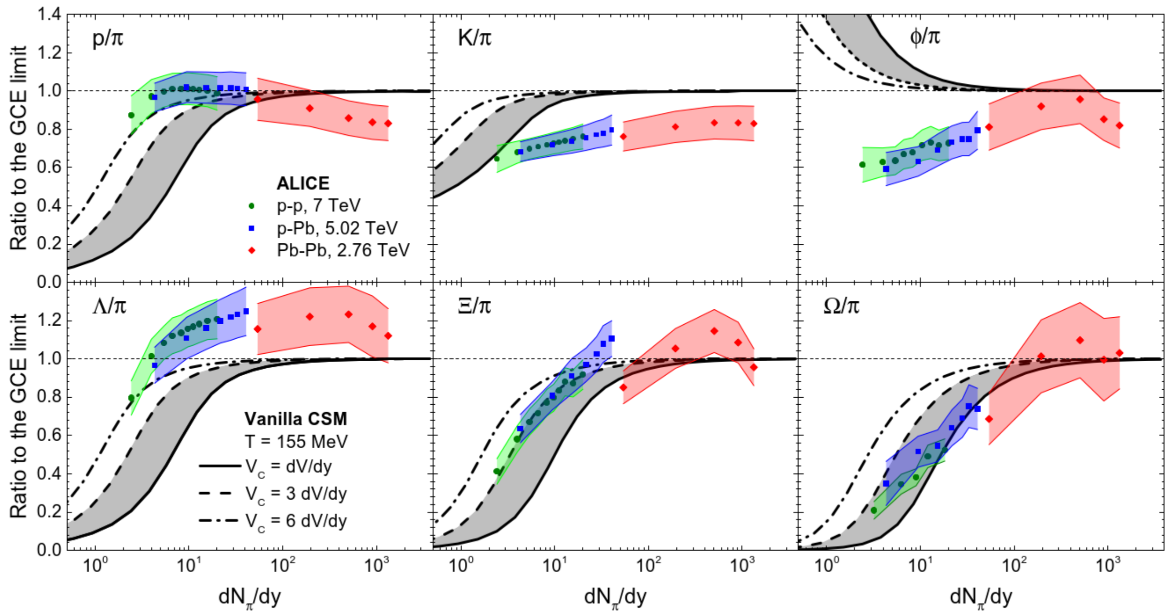
High-multiplicity pp: ~ same hadrochemistry as in a fully thermalized system

How can this trend be interpreted?



Adapting SHM: canonical suppression, γ_s , …

CSM



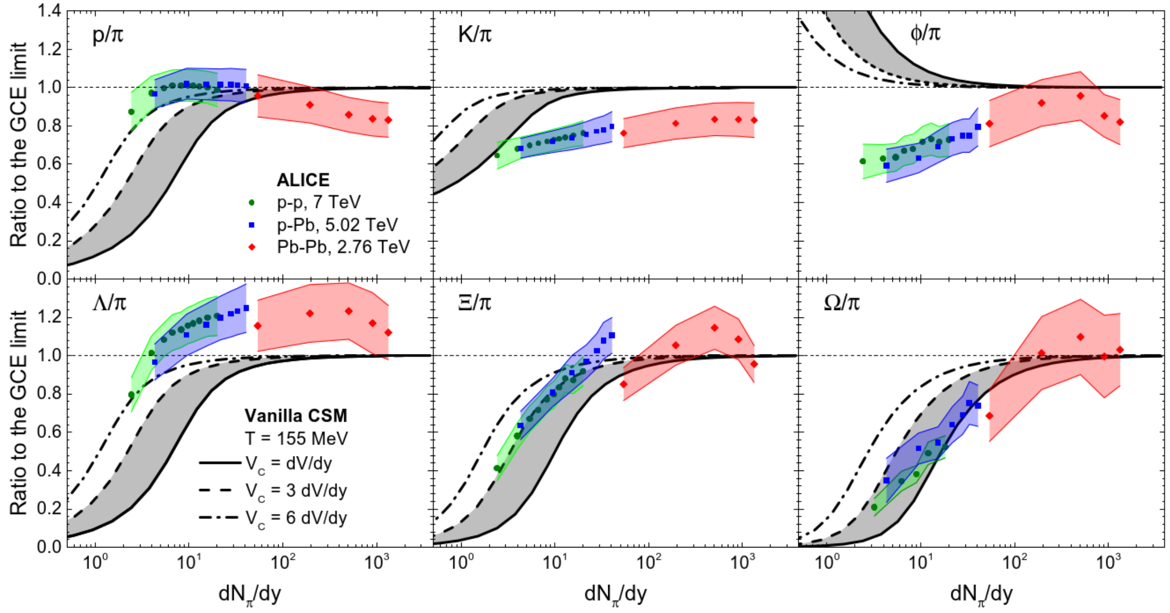
Canonical Statistical Model:
as multiplicity decreases quantum numbers (Q,B,S) are forced to be conserved in smaller and smaller volumes

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

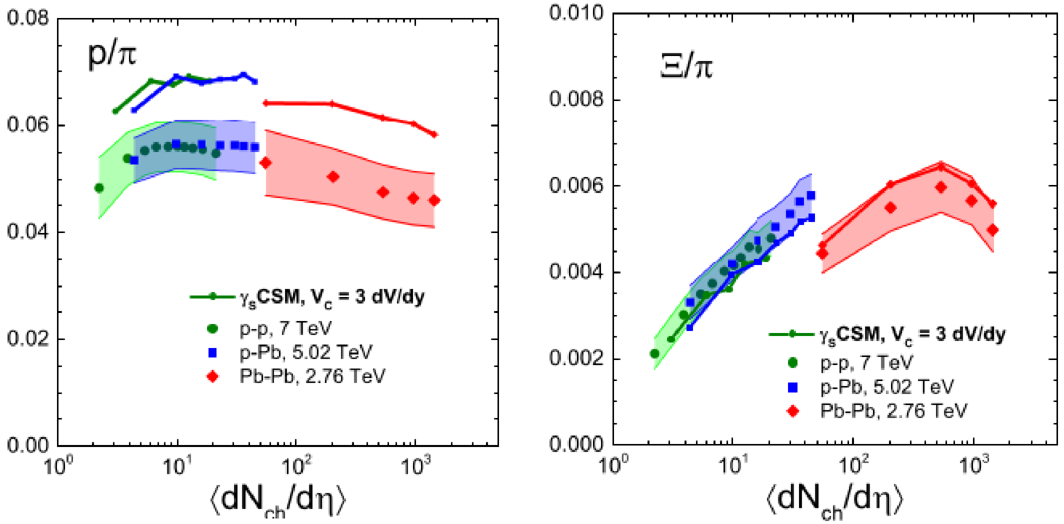
V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

Adapting SHM: canonical suppression, γ_s , …

CSM



CSM + γ_s



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

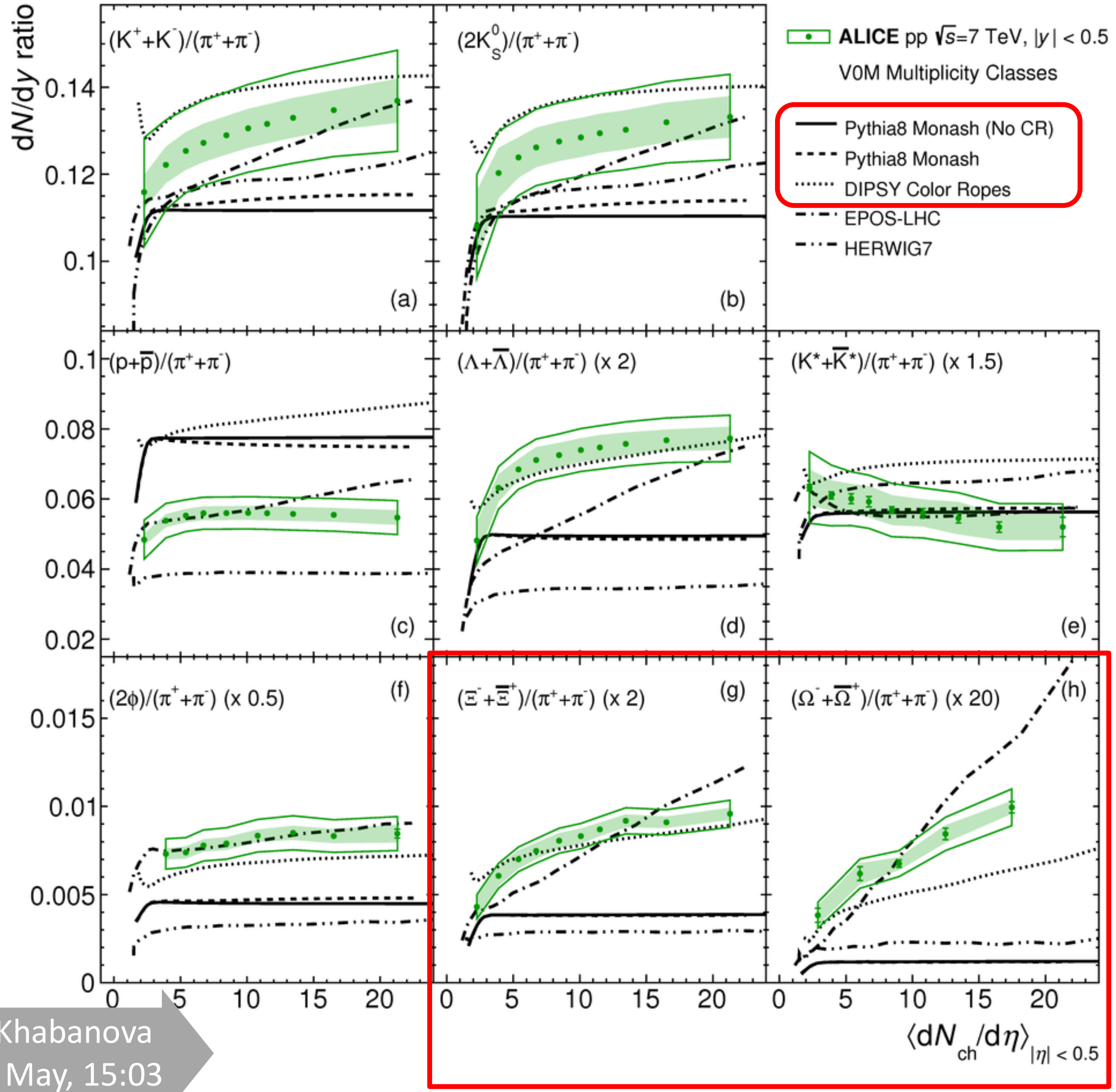
Qualitatively describes Ξ and Ω, but big issues with p (B conservation) and ϕ (Q conservation for π)

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)

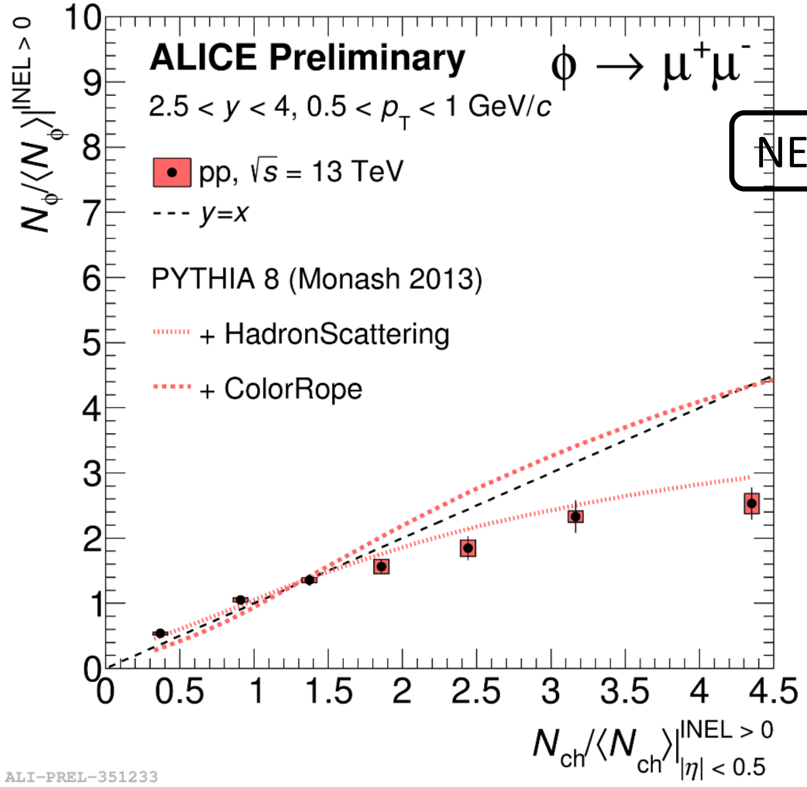
Models starting from small systems

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



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

…but ropes seem not to be the dominant contribution for low-p_T yields at high multiplicity



NEW

Z. Khabanova
28 May, 15:03

Two-component models (core-corona)

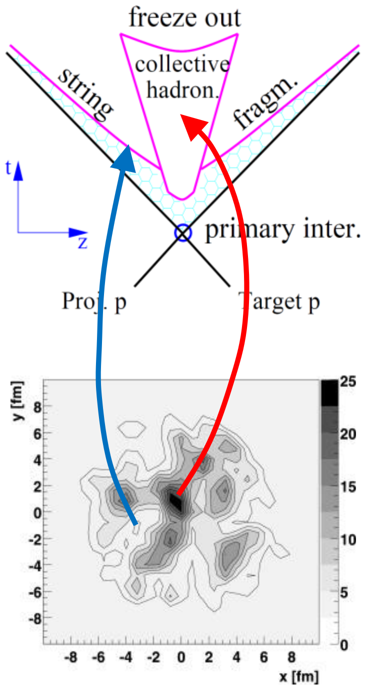
Models implementing a double-regime scenario (EPOS, DCCI, ...):

- **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



Two-component models (core-corona)

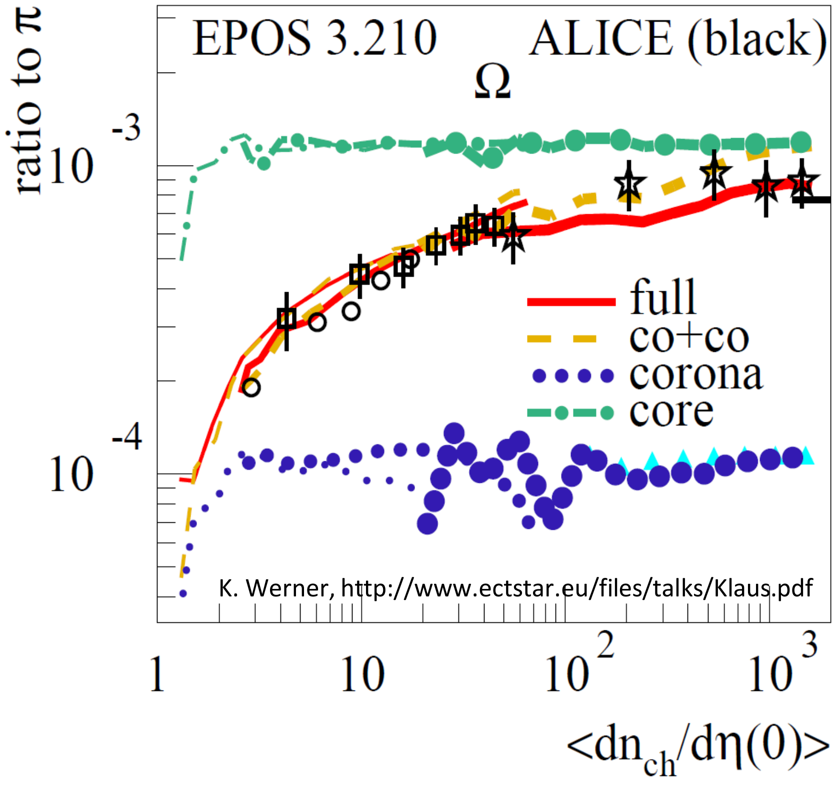
Models implementing a double-regime scenario (EPOS, DCCI, ...):

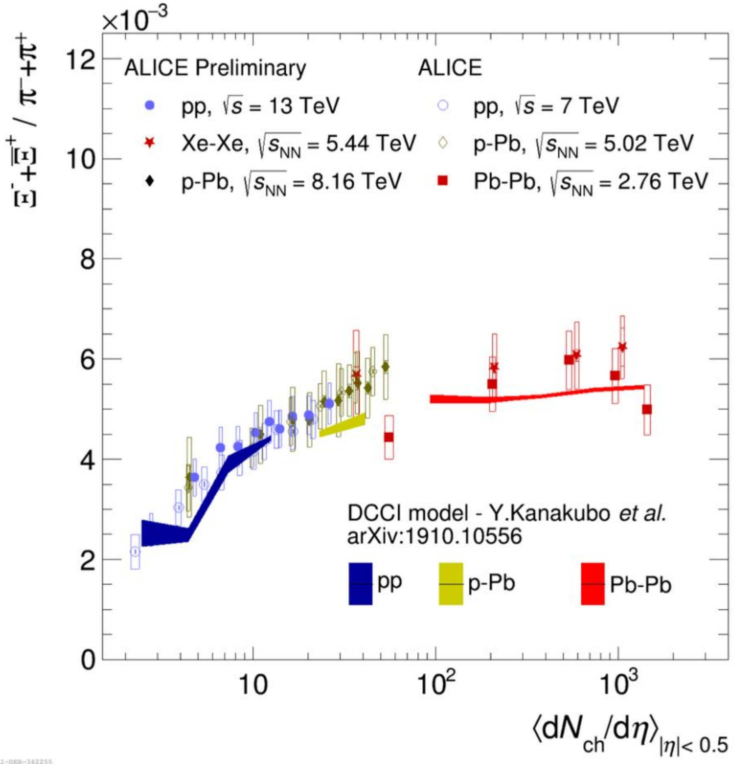
- **Core**: high density, QGP formation, thermal hadronization
- **Corona**: low density, jets, hadronization in vacuum

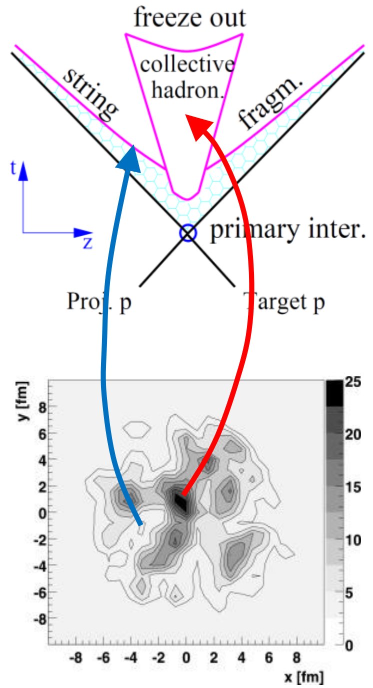
h/π values flat VS $dN_{ch}/d\eta$

Grand-Canonical limit

String fragmentation







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

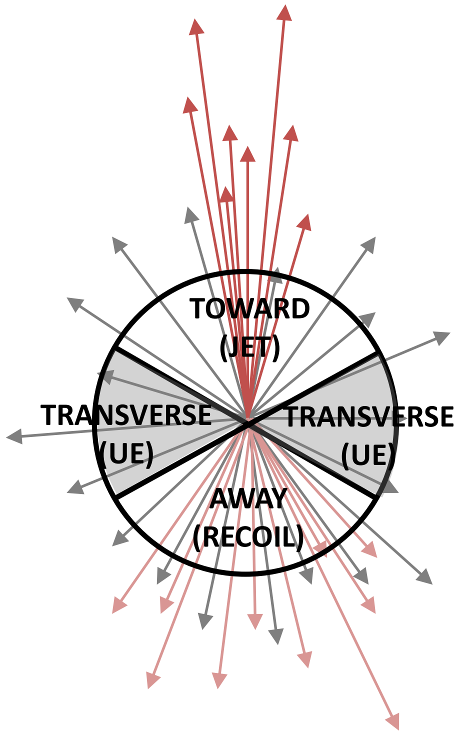
K. Werner, Phys. Rev. Lett. 98, 152301 (2007)
Y. Kanakubo at al., Phys. Rev. C 101, 024912 (2020)

Hadron production VS R_T in small systems (I)

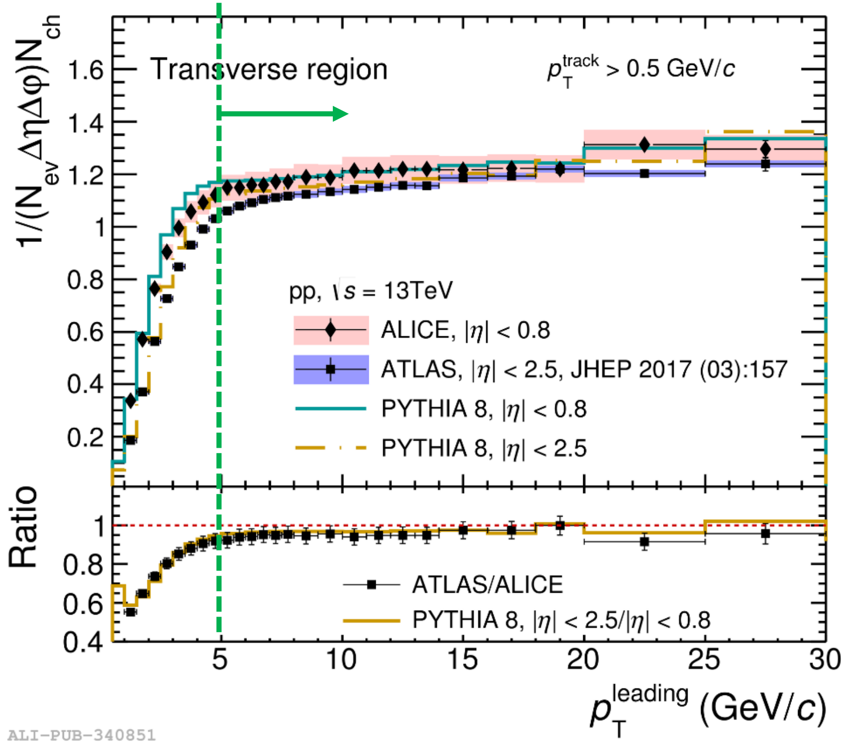
Topological classification of pp events, identifying:

- 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 ($p_T^{leading}$ > 5 GeV/c)



In transverse region the average multiplicity does not change much for $p_T^{leading}$ > 5 GeV/c !



V. Zaccolo
26 May, 18:00

A. Caliva
28 May, 15:03

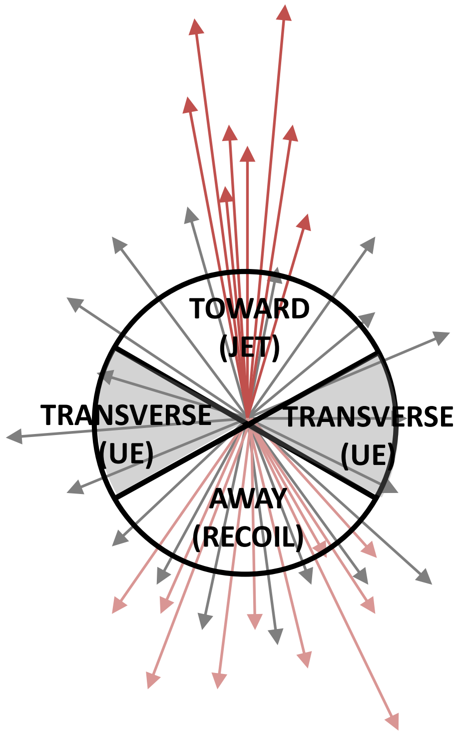
ATLAS Collaboration, JHEP 03 (2017) 157
ALICE Collaboration, arXiv:1910.14400 [nucl-ex]

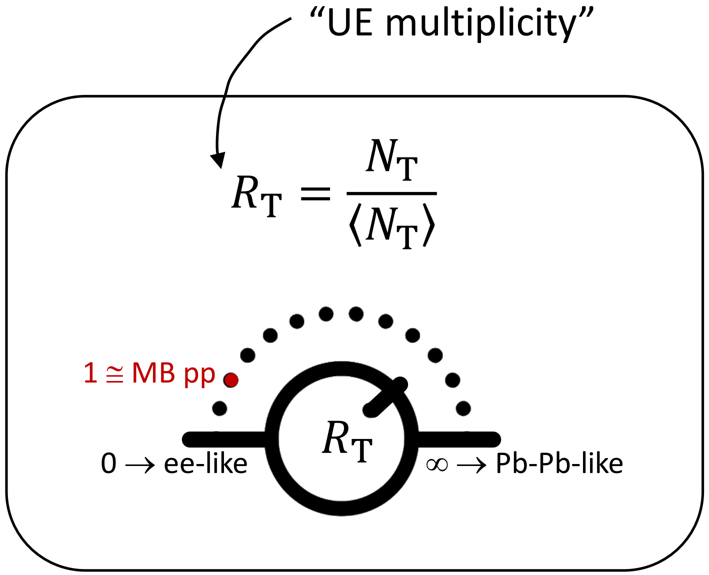
Hadron production VS R_{T} in small systems (I)

Topological classification of pp events, identifying:

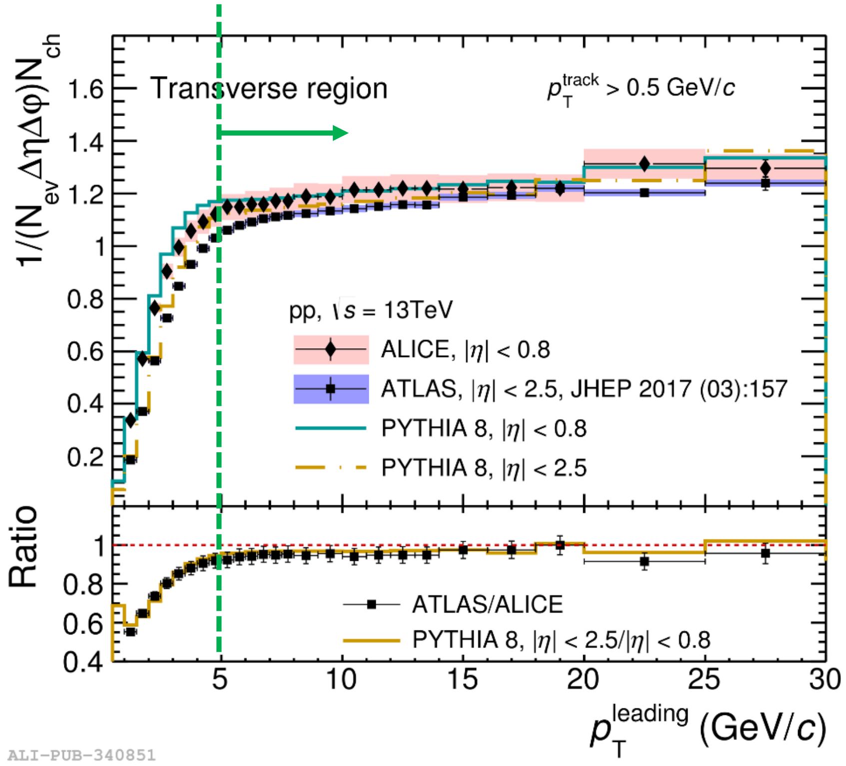
- Toward region (triggering jet) + Away region (recoiling jet)
- Transverse region (Underlying Event - UE)

The jet direction is the direction of the highest-p_{T} hadron ($p_{\mathrm{T}}^{\mathrm{leading}}$ > 5 GeV/c)





In transverse region the average multiplicity does not change much for $p_{\mathrm{T}}^{\mathrm{leading}}$ > 5 GeV/c !



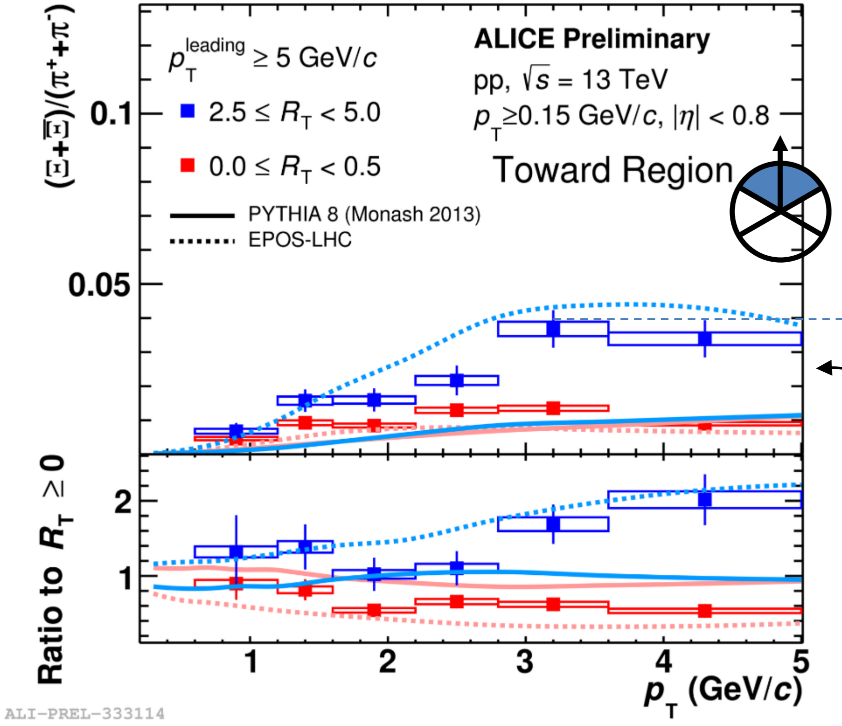
Measurement of hadron production in the three regions, as a function of R_T:

- Is the ratio-to-pion similar in all topological regions?
- How does this ratio evolve with R_T?

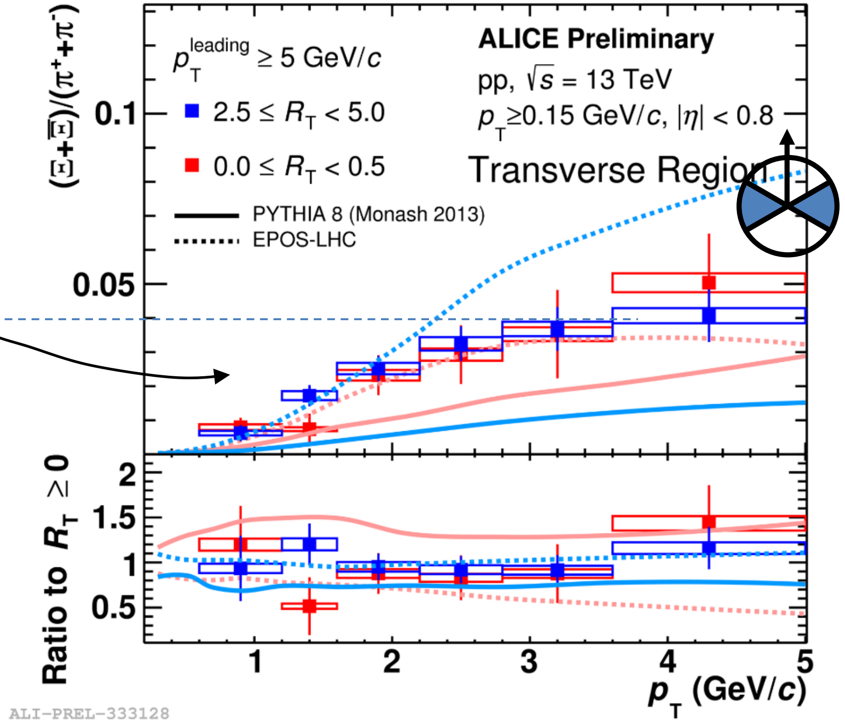
ATLAS Collaboration, JHEP 03 (2017) 157
ALICE Collaboration, arXiv:1910.14400 [nucl-ex]

Hadron production VS R_T in small systems (II)

UE + JET



UE



No evolution of the Ξ/π ratio VS multiplicity in the UE!

NO strangeness enhancement in the UE

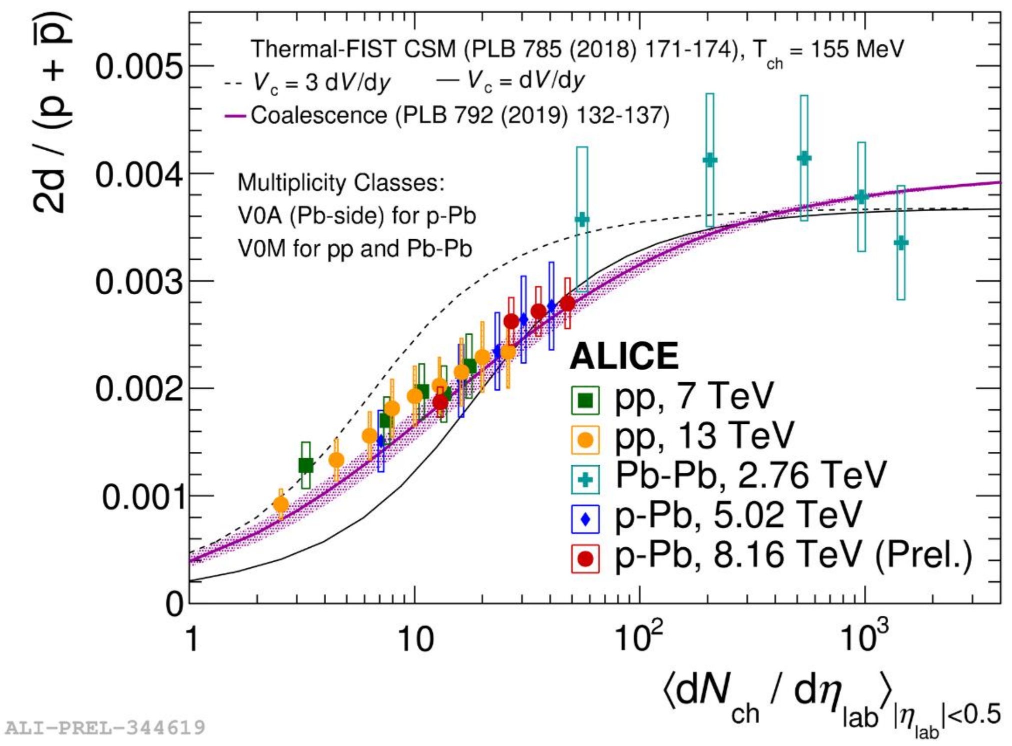
Strangeness enhancement in the toward region (**UE+JET**).

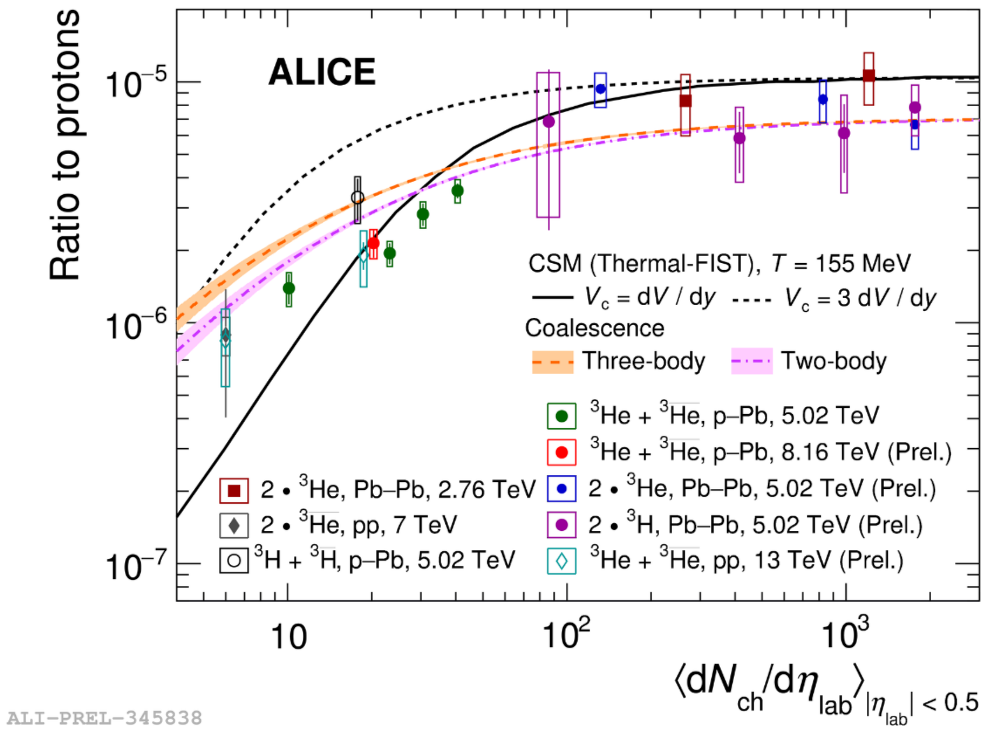
For high R_T we reach values as in the UE-alone

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.

Nuclei production from small to large systems





d, ^{3}He and ^{3}H significantly enhanced throughout multiplicity!

What causes this enhancement? Lifting of canonical suppression? Coalescence probability at kinetic freeze-out?

Qualitative agreement with Thermal Canonical Statistical Model and coalescence model.

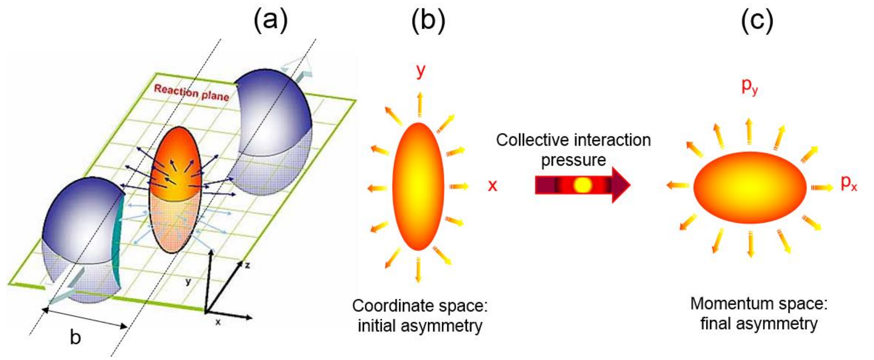
C. Pinto
Poster Session

Collective flow

Collectivity in a nutshell

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

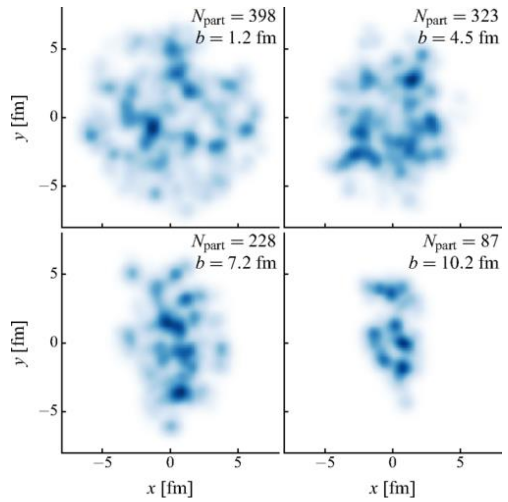
- **Radial flow**
  - Common expansion velocity of partons
  - Translates into p_T spectra modification
- **Anisotropic flow**
  - Initial spatial anisotropy $\rightarrow$ final momentum anisotropy
  - Measured through Fourier expansion coefficients of the p_T distribution



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

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

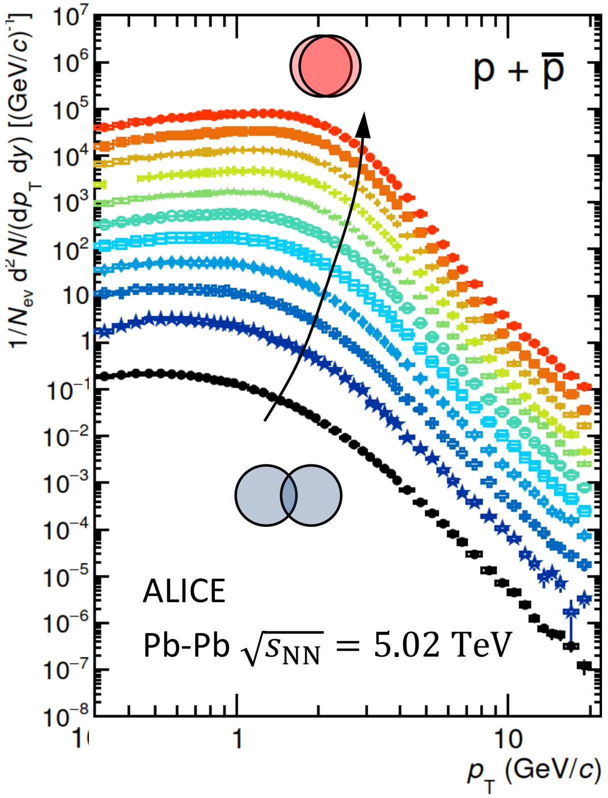
NOTE:
initial anisotropies come from:
- geometry
- parton density fluctuations in the initial state

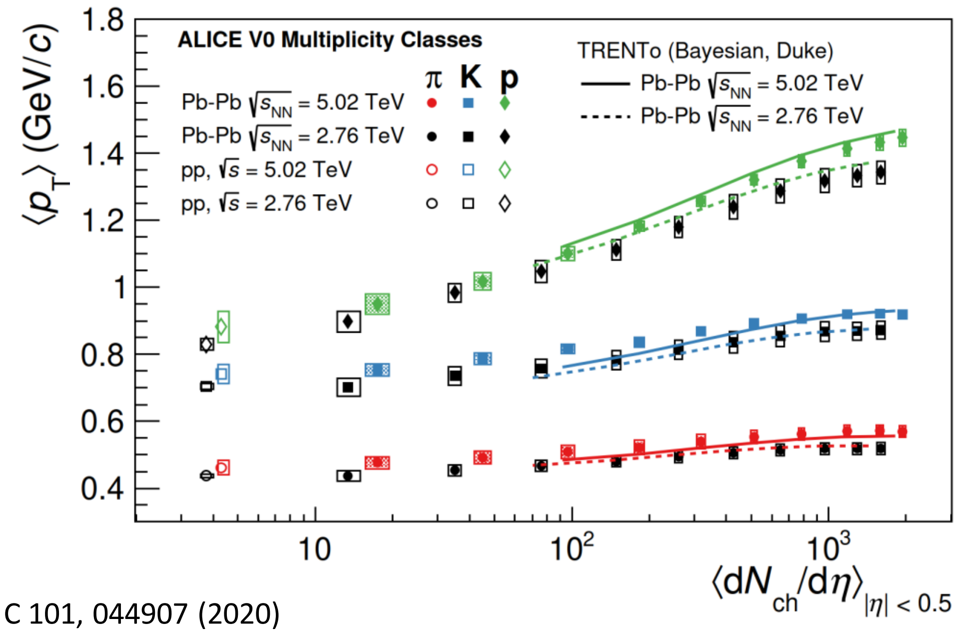


Spectral modification from large …

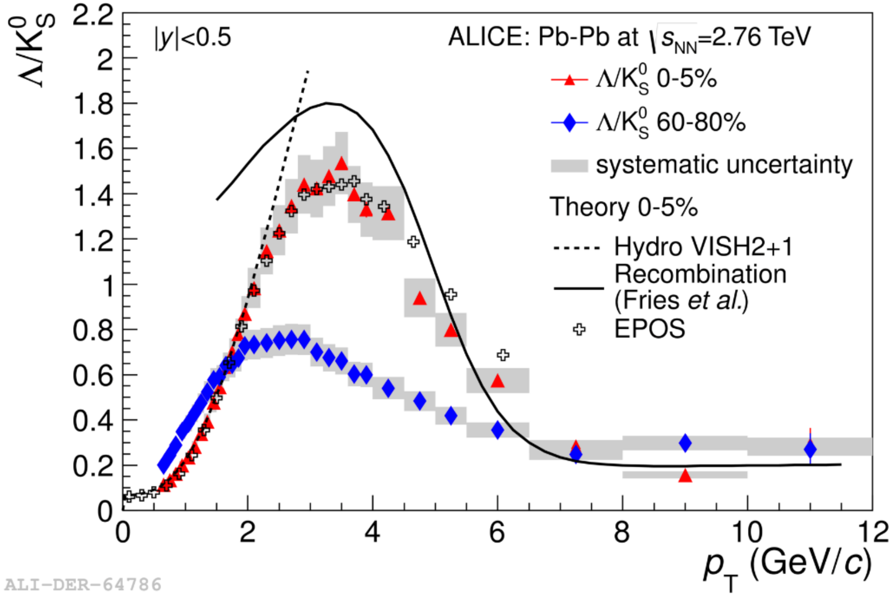
Spectra get harder
going to central A-A collisions

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





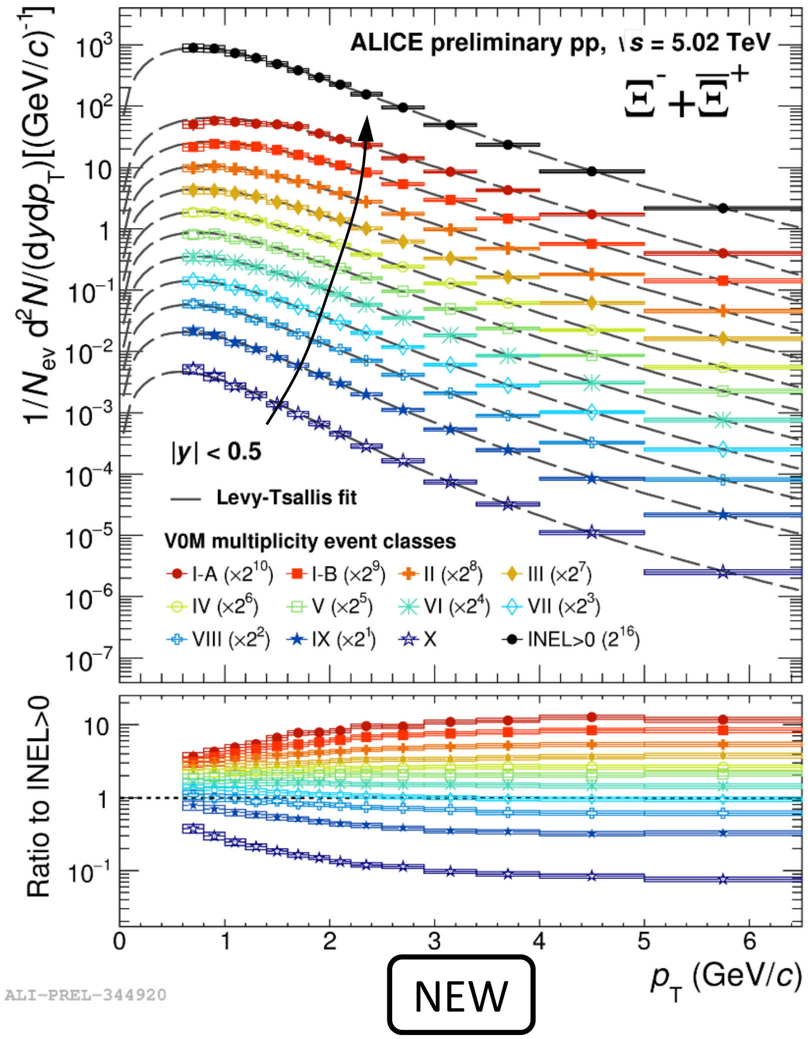
ALICE Collaboration, Phys. Rev. C 101, 044907 (2020)

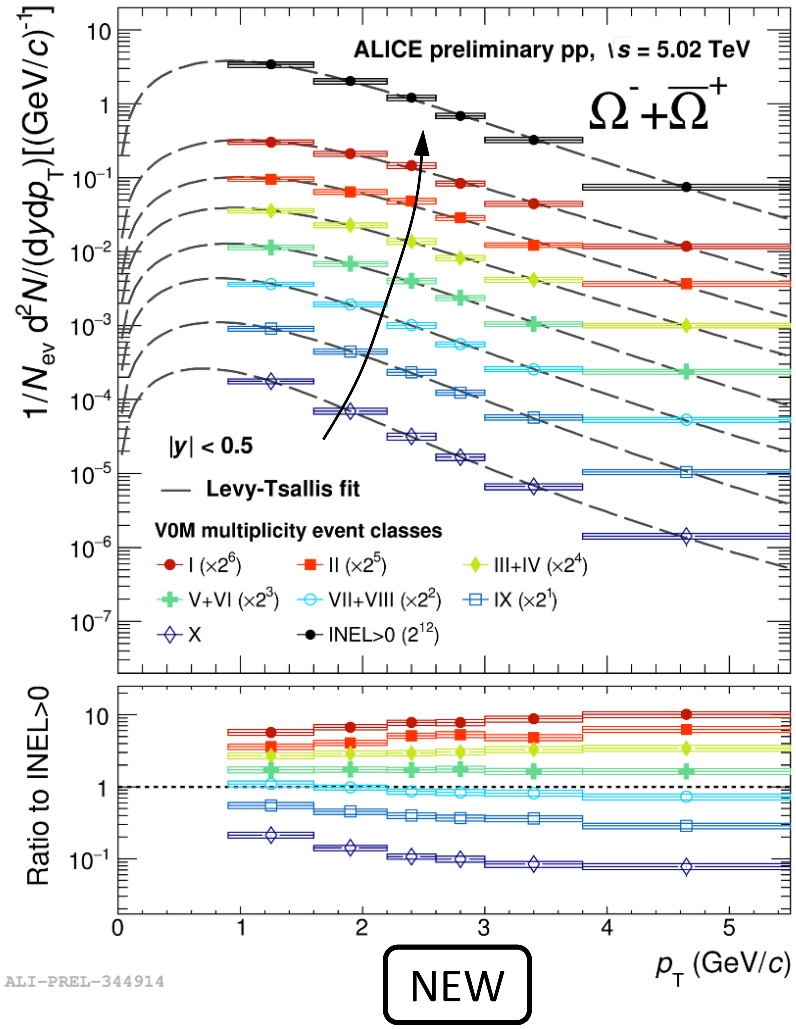


ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 222301

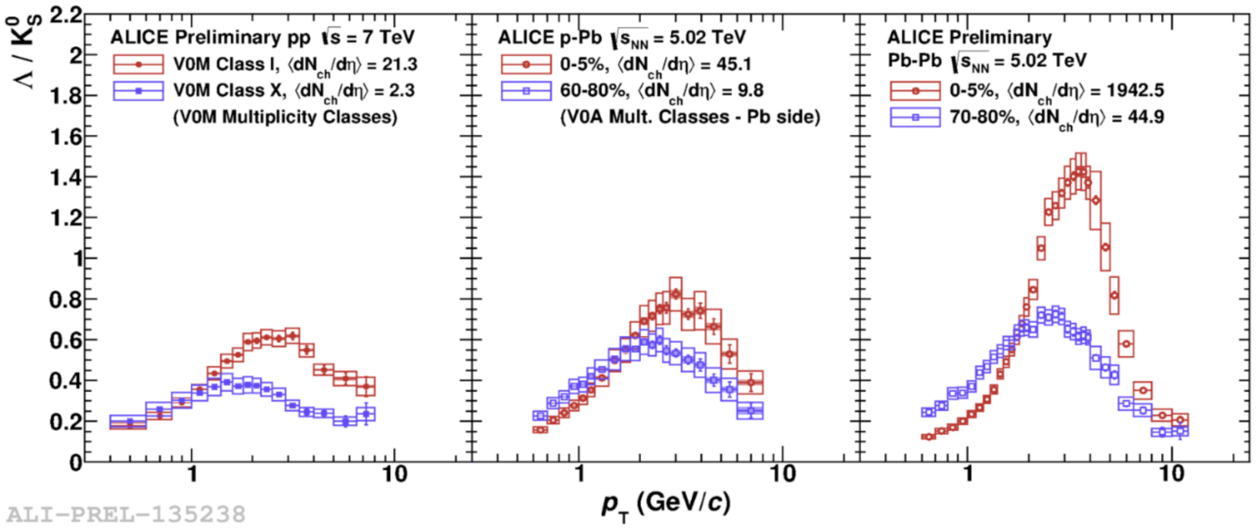
… to small systems (I)

Hardening of spectra observed in small systems as well (e.g. pp)





… to small systems

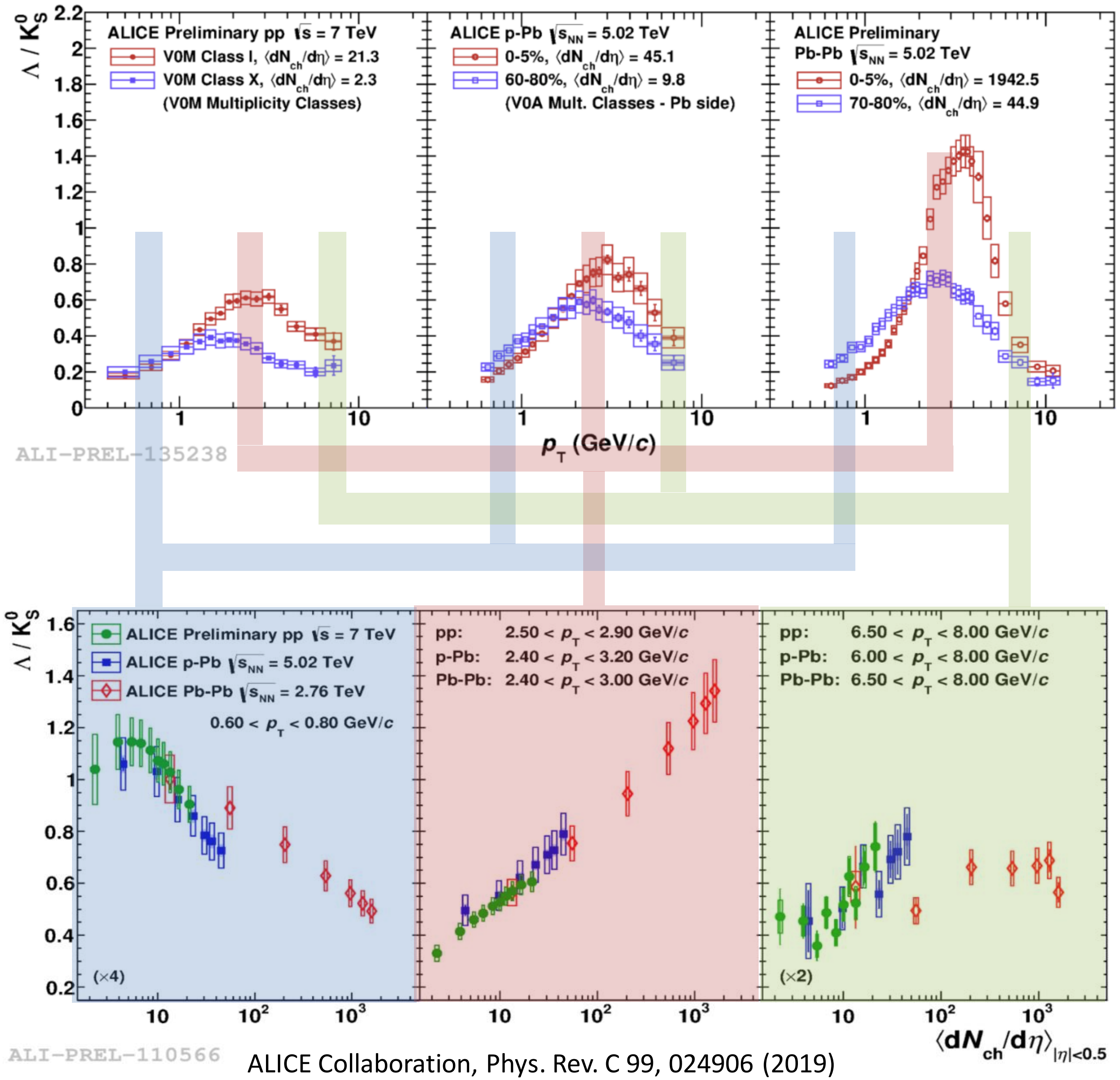


Λ/K^0_S enhancement present in all collision systems at the LHC:

- The larger the colliding system, the larger the effect

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

… to small systems



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

Λ/K^0_S 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?

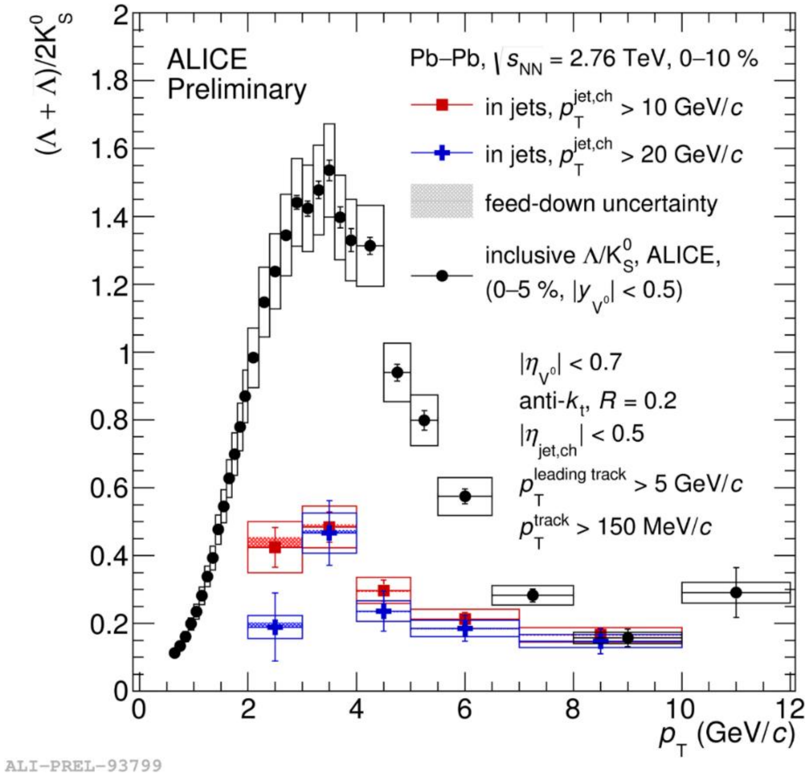
Application of hydro far from equilibrium under study

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

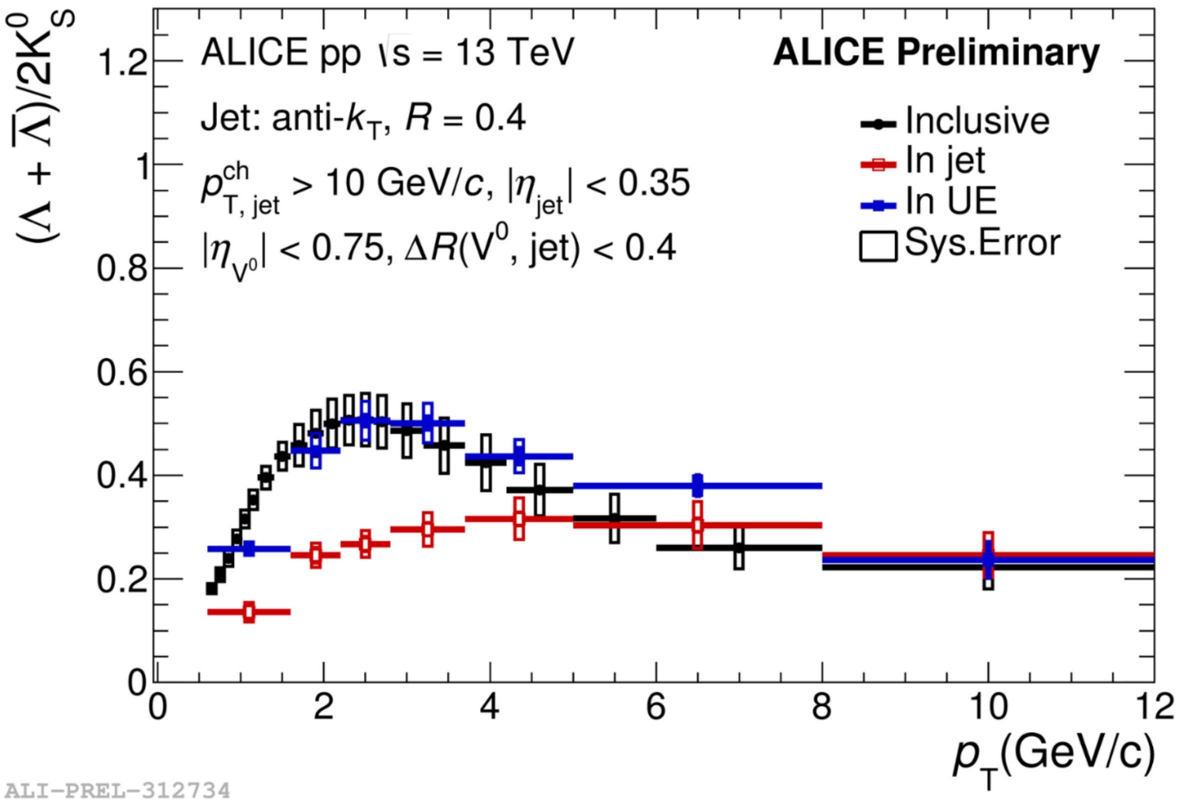
Z. Khabanova
28 May, 15:03

Spectral modification in- and out-of-jets

Pb-Pb



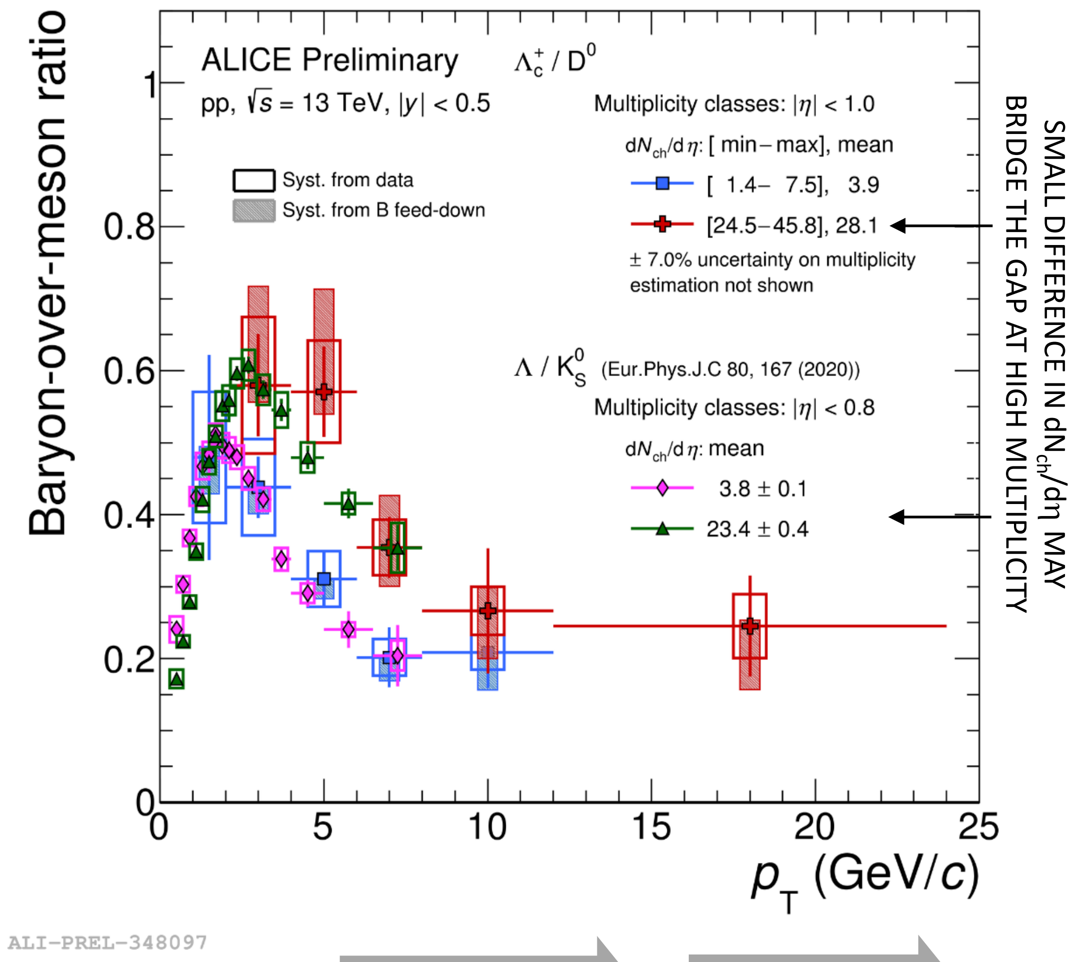
pp



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

Spectral modification: light and heavy flavors



G. M. Innocenti earlier today

V. Zaccolo 26 May, 18:00

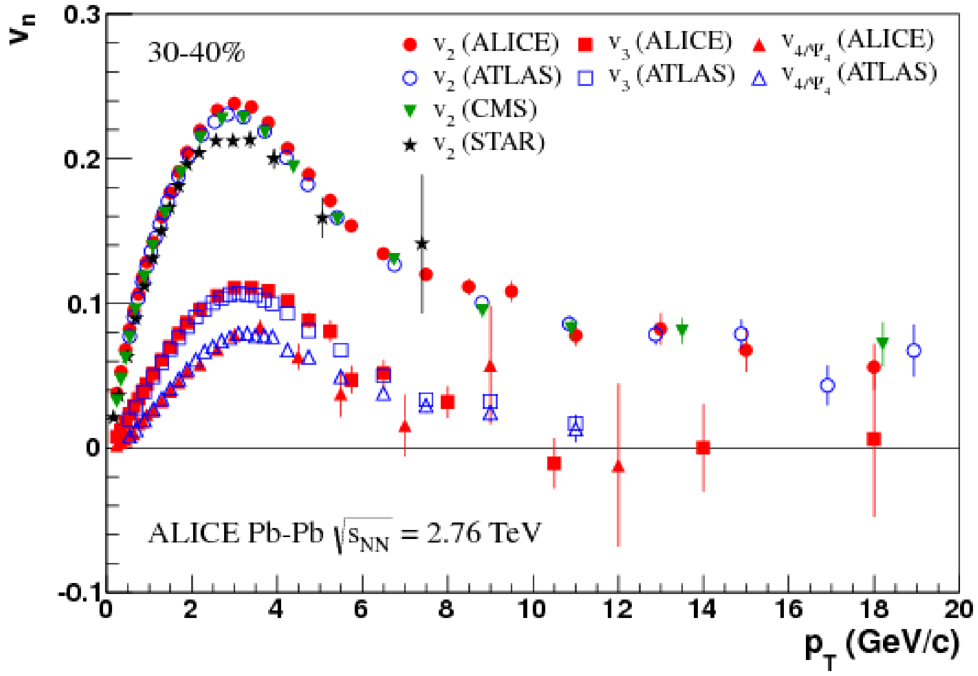
Striking similarities between light and heavy flavors in small systems

Intriguing observation:

- Hydro for charm? Hard to believe! Not supported by A-A observations:
  ↪ low-p_T hierarchy $v_2^h > v_2^c > v_2^{cc}$
  ↪ $\Lambda/K_S^0 > \Lambda_c/D_0$
  ⇒ Challenges hydro hypothesis for light flavors in pp
- 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

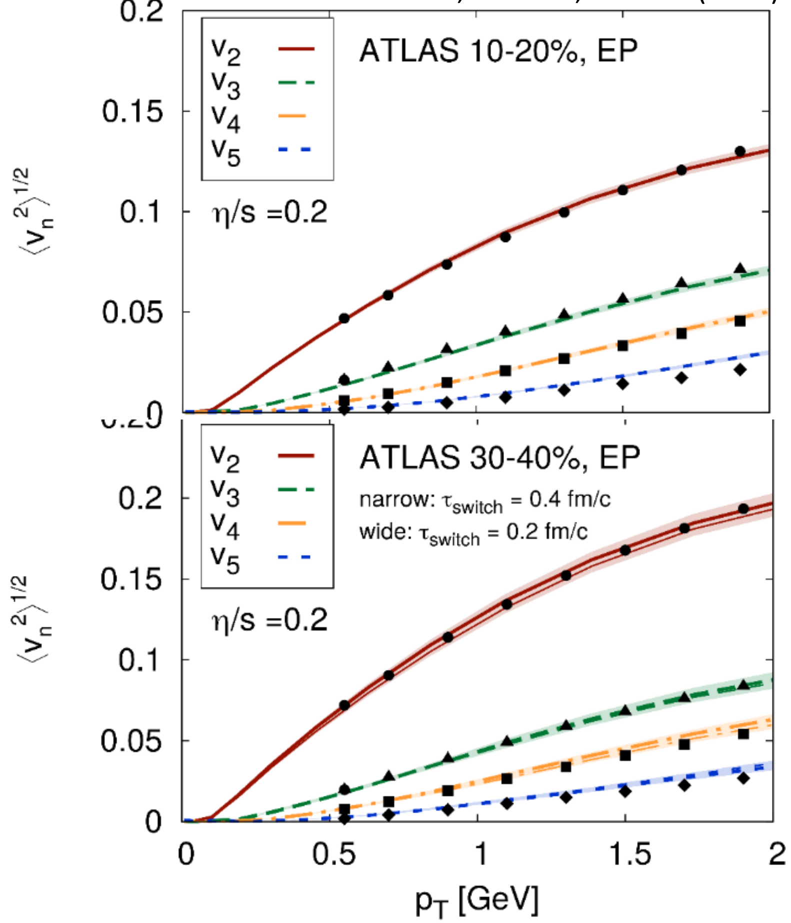
Anisotropic flow and hydro calculations



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

More important in semi-peripheral collisions (large eccentricity)

Gale et al., PRL 110, 012302 (2013)



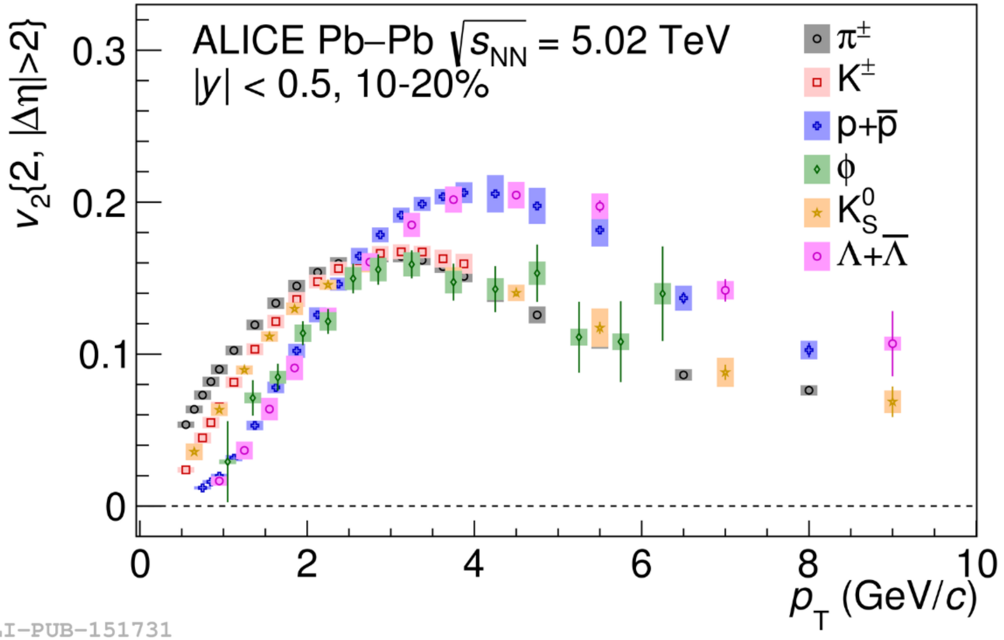
Hydrodynamic models reproduce v_n at low-p_T in all centralities by means of an "almost" perfect fluid: **η/s=0.2**

J. Hansen
Poster Session

E. G. Nielsen
Poster Session

v_2 for identified particles at LHC

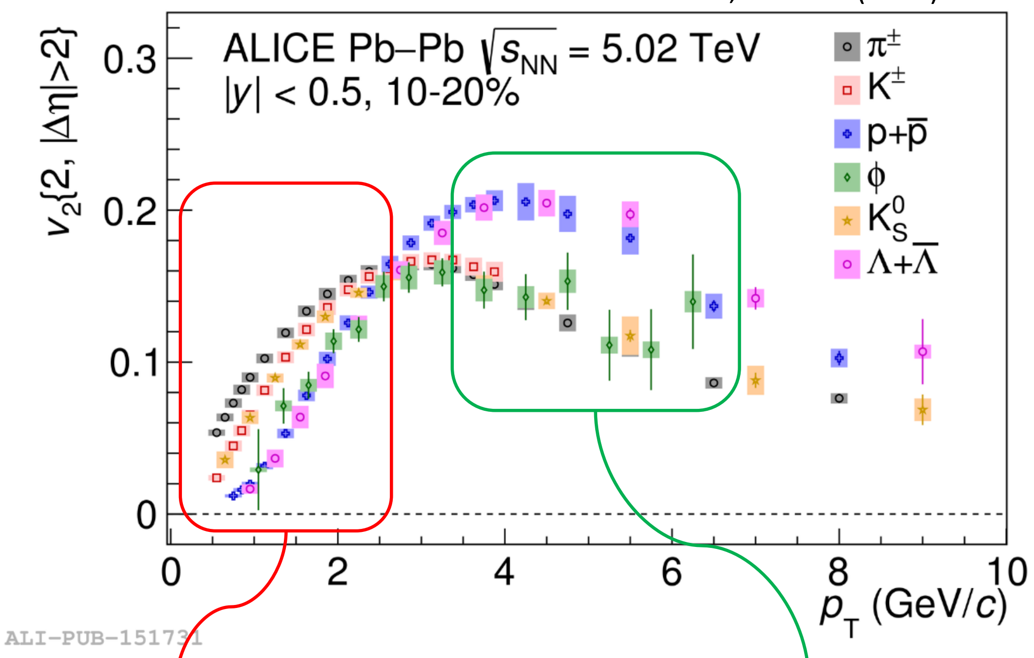
ALICE Collaboration, JHEP 09 (2018) 006



ALI-PUB-151731

v_2 for identified particles at LHC

ALICE Collaboration, JHEP 09 (2018) 006



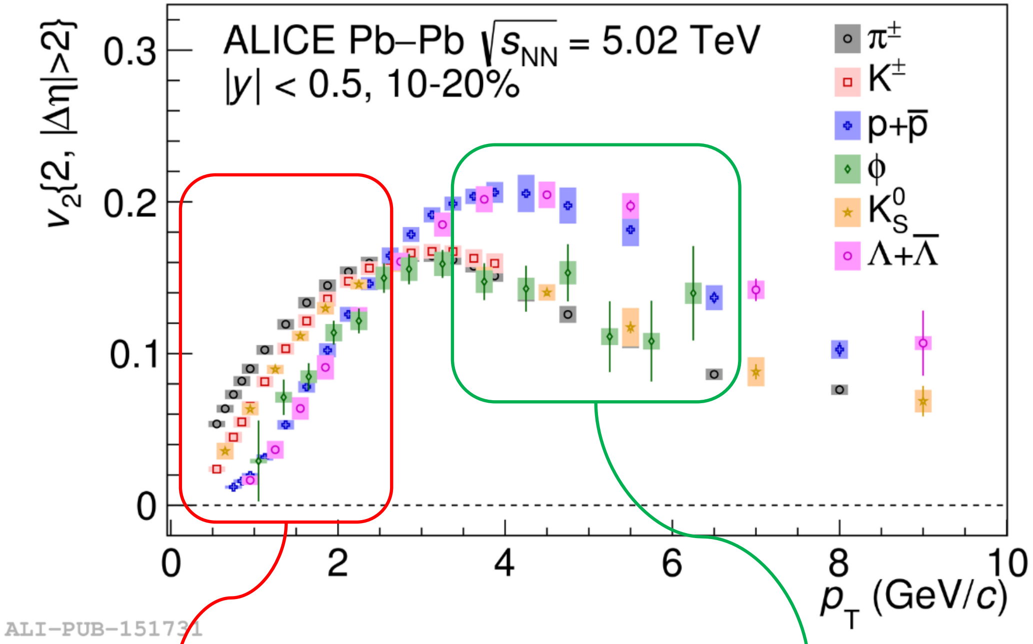
Mass ordering (higher mass → lower v_2): interplay between radial and elliptic flow

(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)

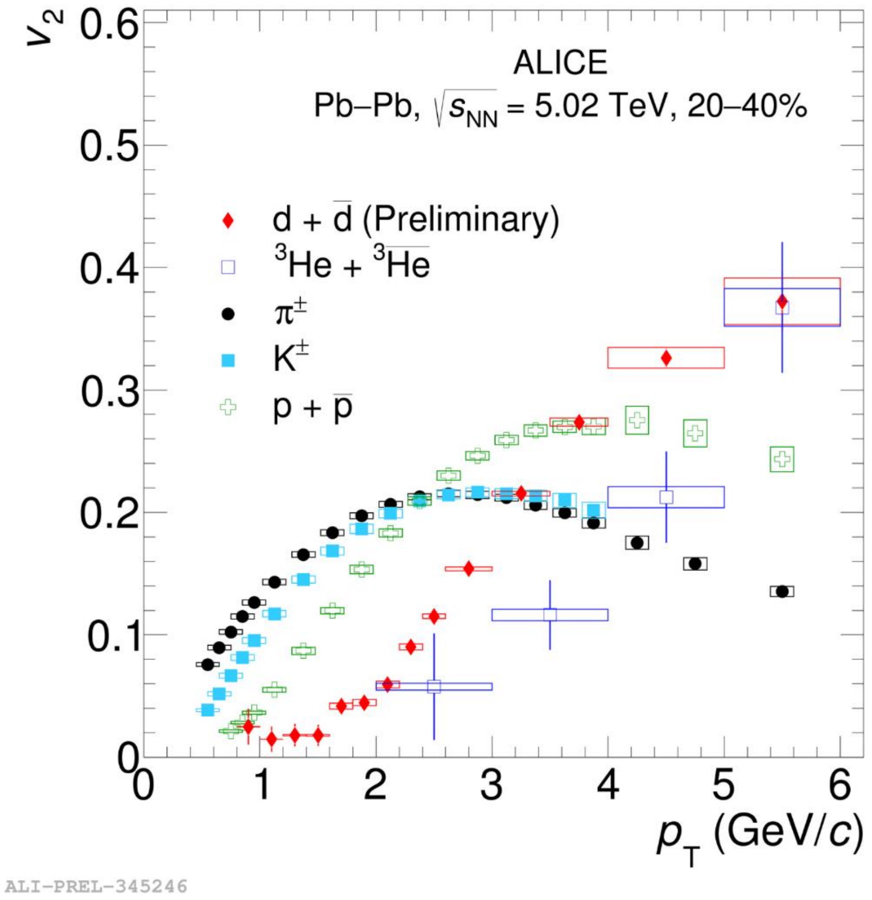
v_2 for identified particles at LHC

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

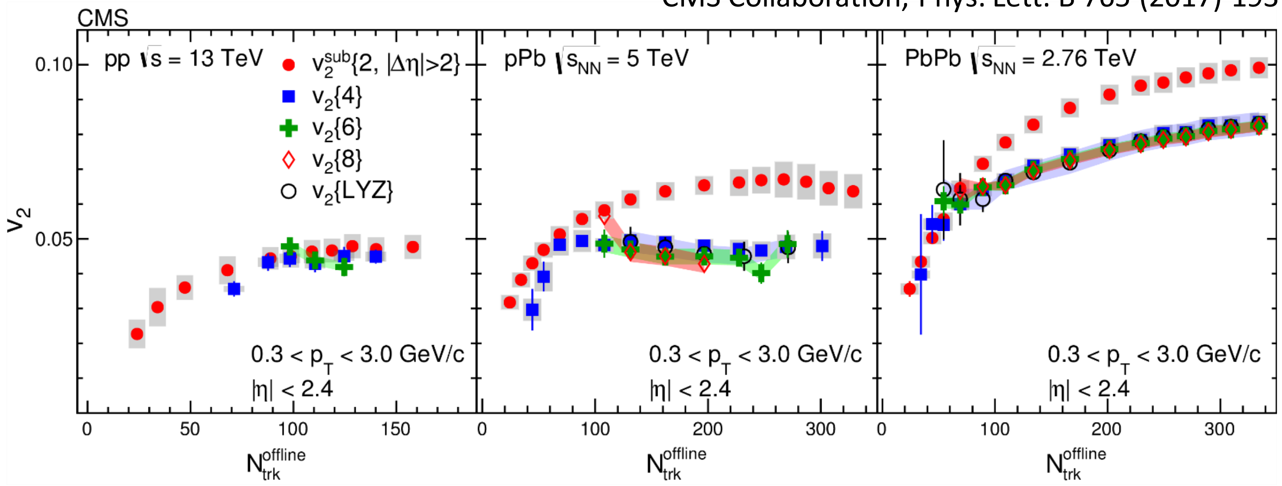


The ϕ meson groups to protons at low-p_T (same mass) and to mesons at intermediate-p_T (same n_q)

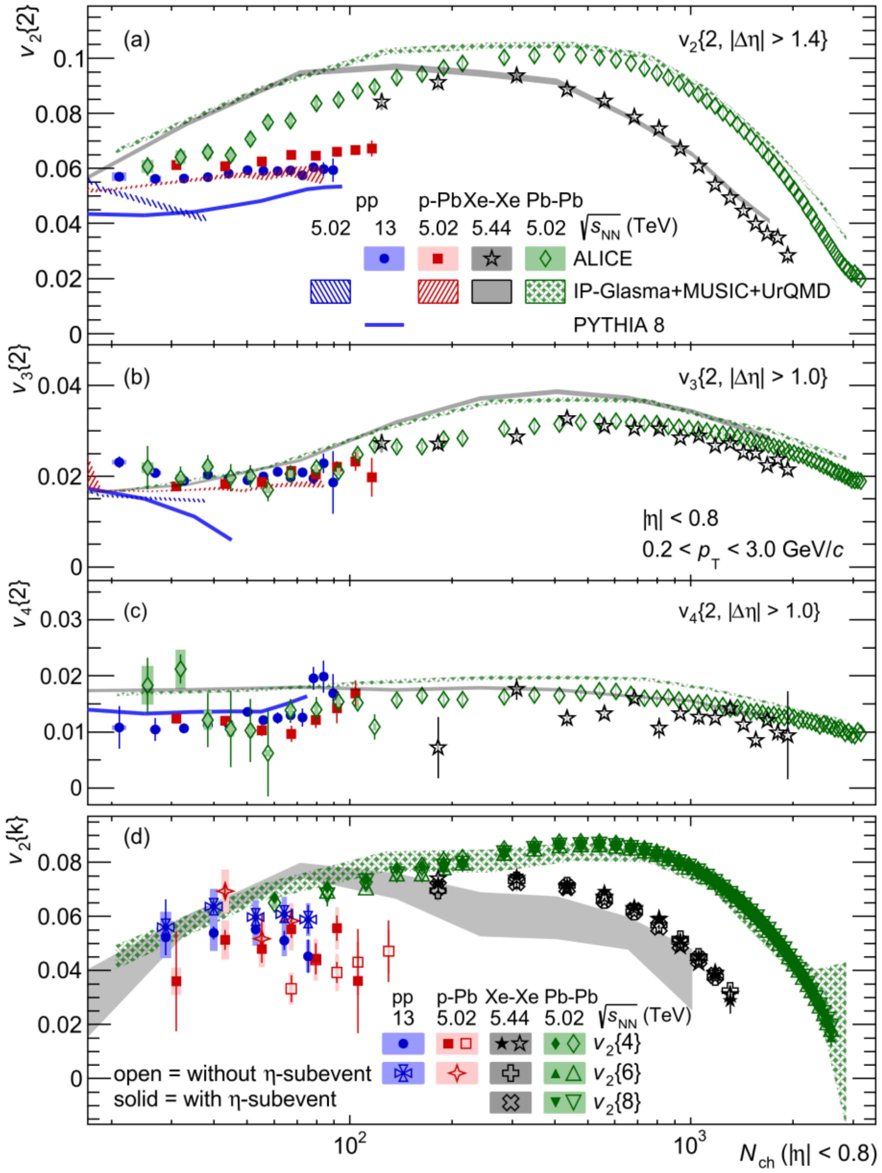
Observation confirmed up to ^{3}He at the LHC!

v_2 in small systems at LHC

CMS Collaboration, Phys. Lett. B 765 (2017) 193



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



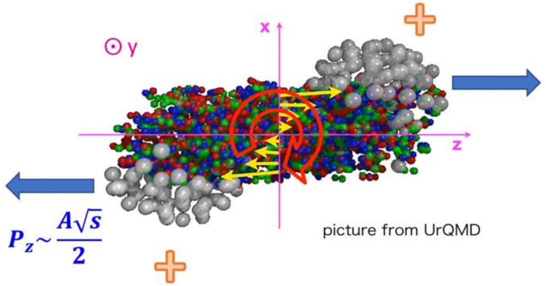
$v_2 > v_3 > v_4 \neq 0$ in all colliding systems:

- $v_2\{4\}_{3\text{-sub}} = v_2\{6\}$ 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

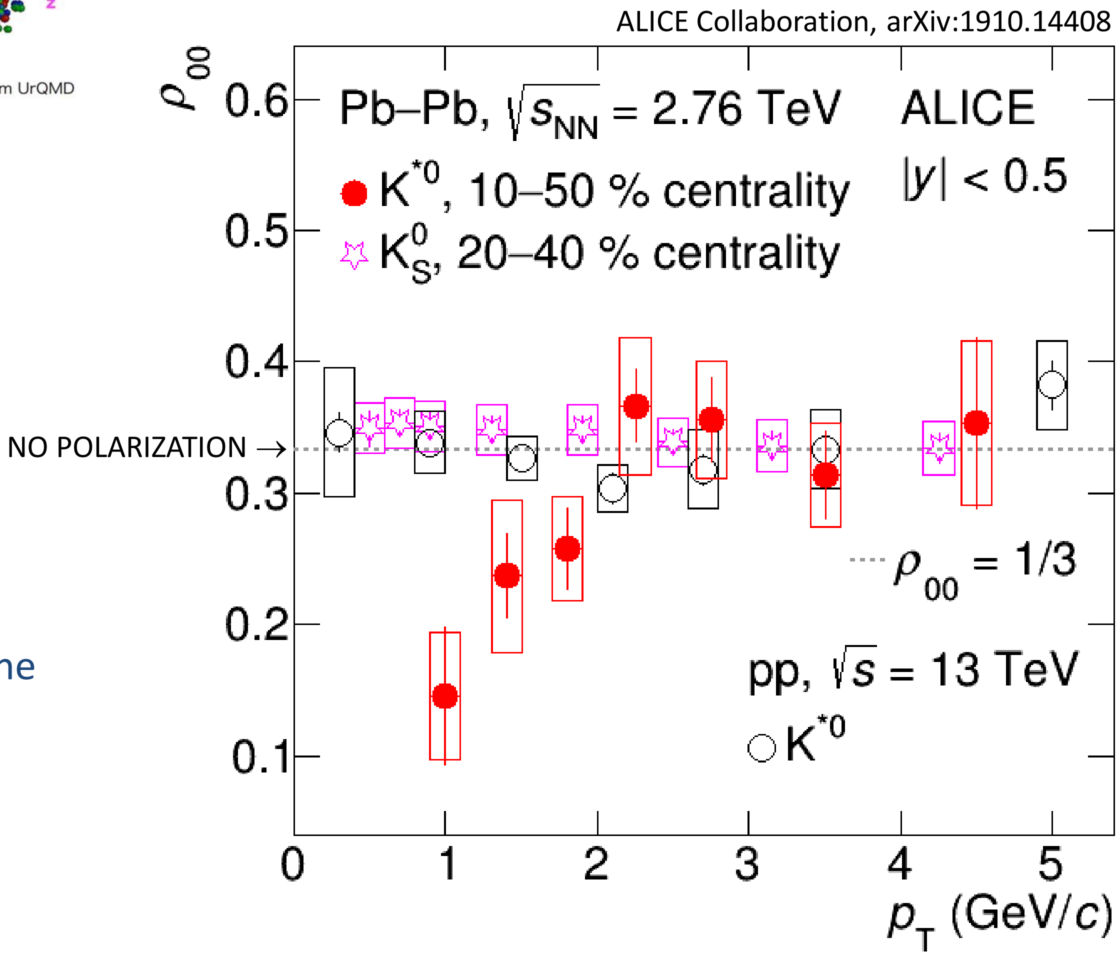
Magnetic fields and polarization

- Semi-central collisions
  ↪ extreme $\vec{B}$ generated by spectator nucleons (10^{21} revolutions/s)



- $\vec{B}$ quickly decays, but $\vec{L}$ conserved

- ρ_{00} : probability of finding a vector meson in $S_z = 0$ with respect to the normal to the event plane (B direction) *



ρ_{00} below 1/3 for low-p_T and mid-central collisions:
3σ(2σ) for K* (ϕ)

Consistent with hadronisation through recombination of q and q̄ from the QGP (Polarized plasma → polarized vector mesons) **

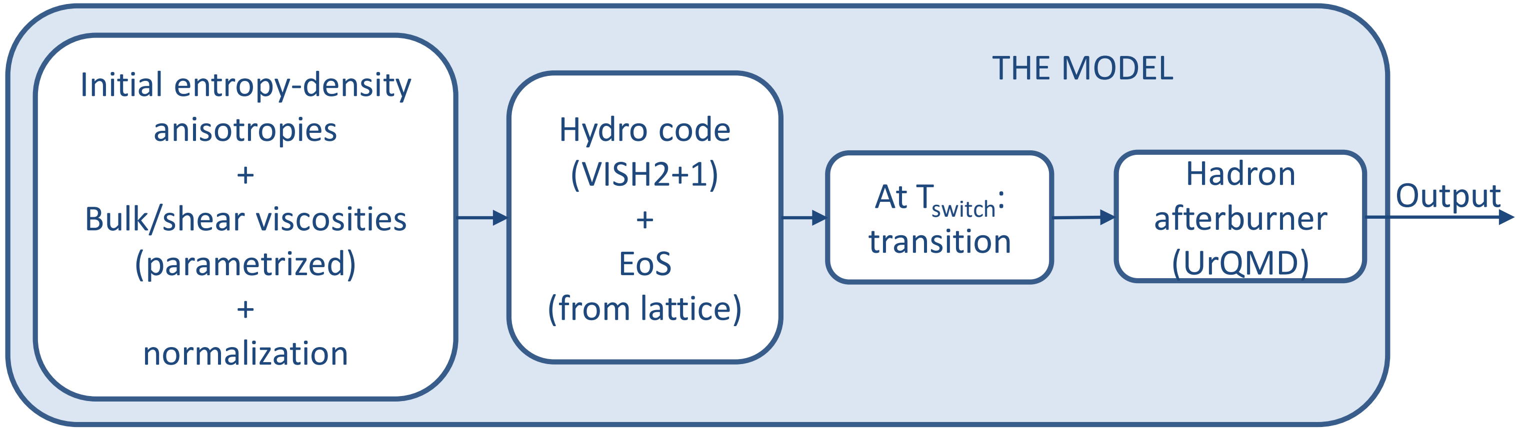
No effect observed for K_S^0 and in pp collisions

* Yang et al., Phys. Rev. C 97, 034917 (2018)
** Liang et al., Phys. Lett. B 629 20-26 (2005)

Determining QGP properties with global fits

Medium properties: from qualitative to quantitative (I)

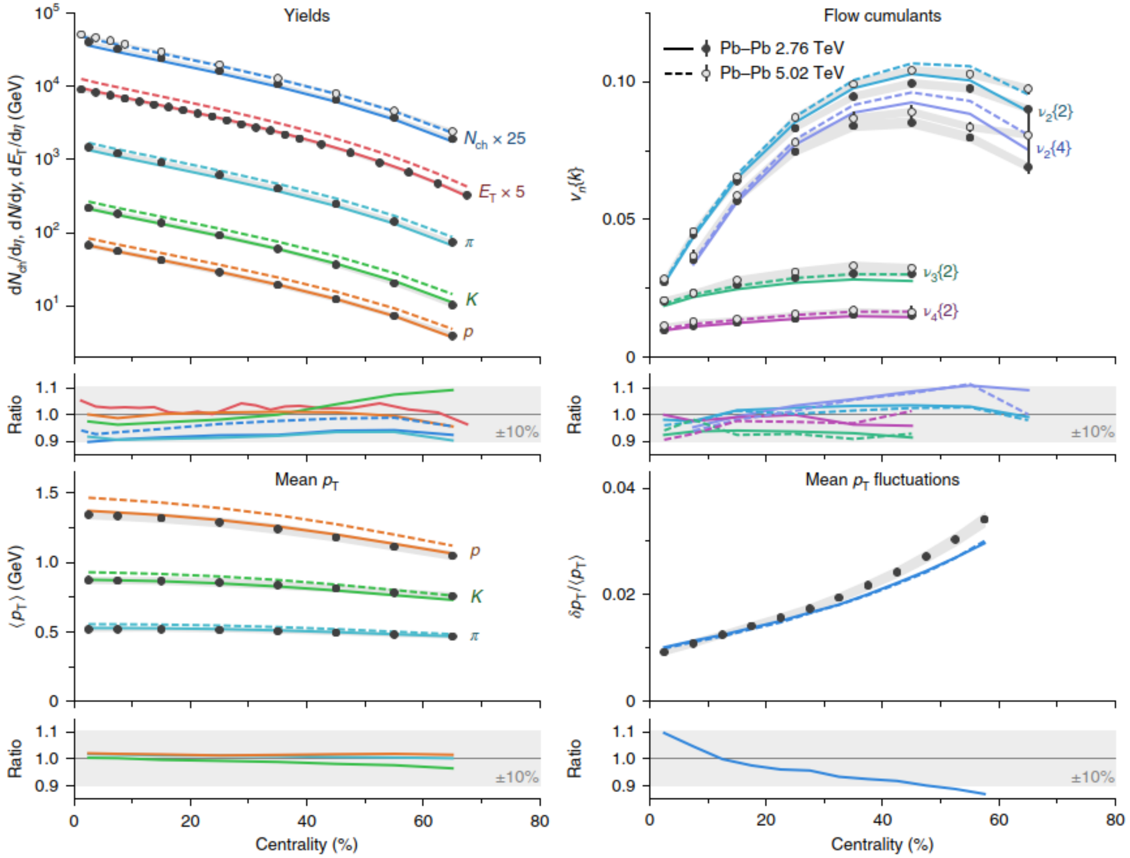
Trying to describe in a unified picture (IC+hydro+Hadronization+afterburner) several measurements from the experiments



- 15 parameters (e.g. parametrization of shear and bulk viscosity, initial conditions, …)
- Bayesian fit to yields, $\langle p_T \rangle$, $\langle p_T \rangle$ fluctuations and v_2, v_3, v_4 from LHC experiments
- Posterior parameter PDFs and correlations estimated

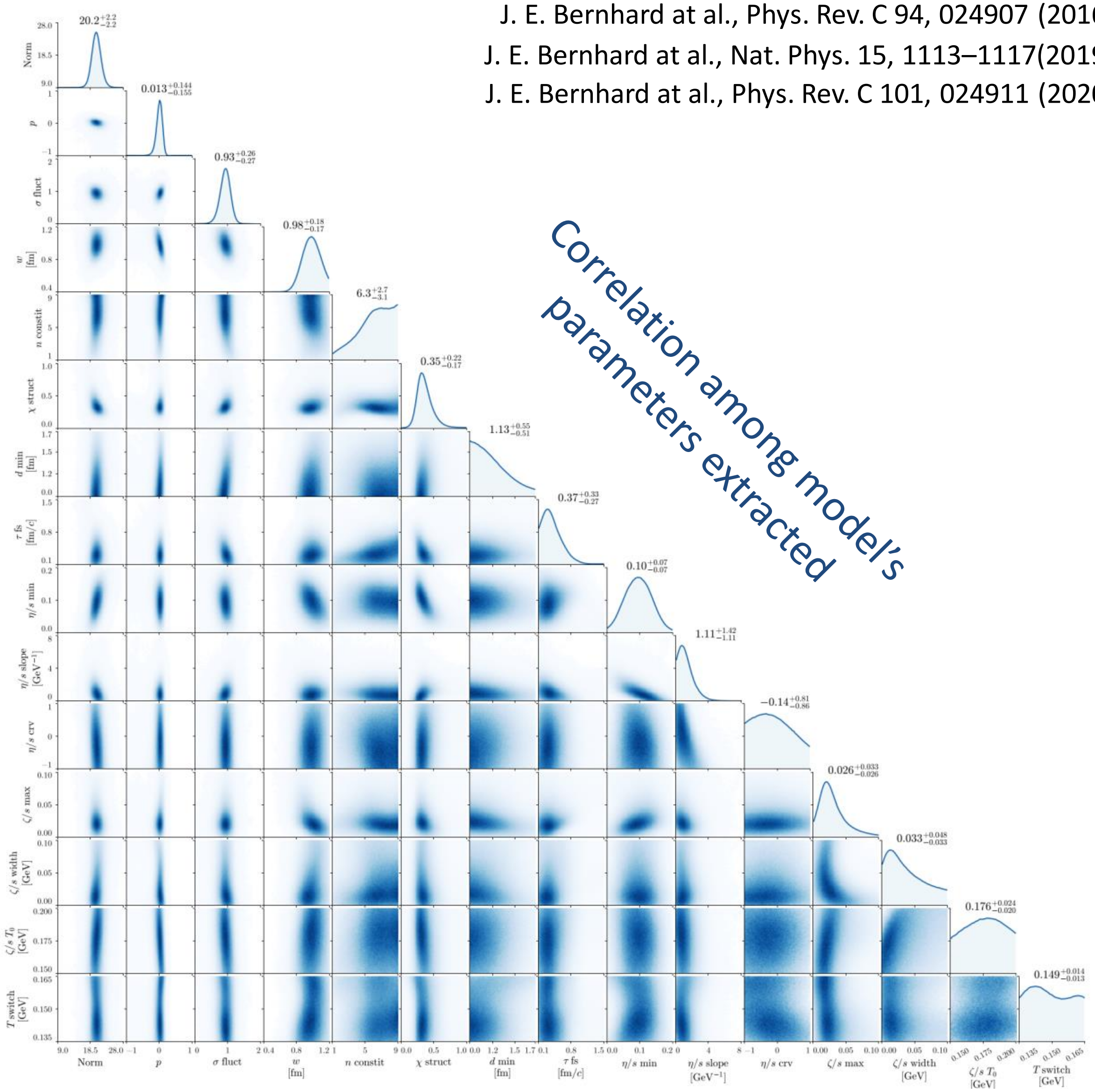
J. E. Bernhard at al., Phys. Rev. C 94, 024907 (2016)
J. E. Bernhard at al., Nat. Phys. 15, 1113–1117(2019)
J. E. Bernhard at al., Phys. Rev. C 101, 024911 (2020)

Medium properties: from qualitative to quantitative (II)



Posterior distributions describe LHC data at the 10% level

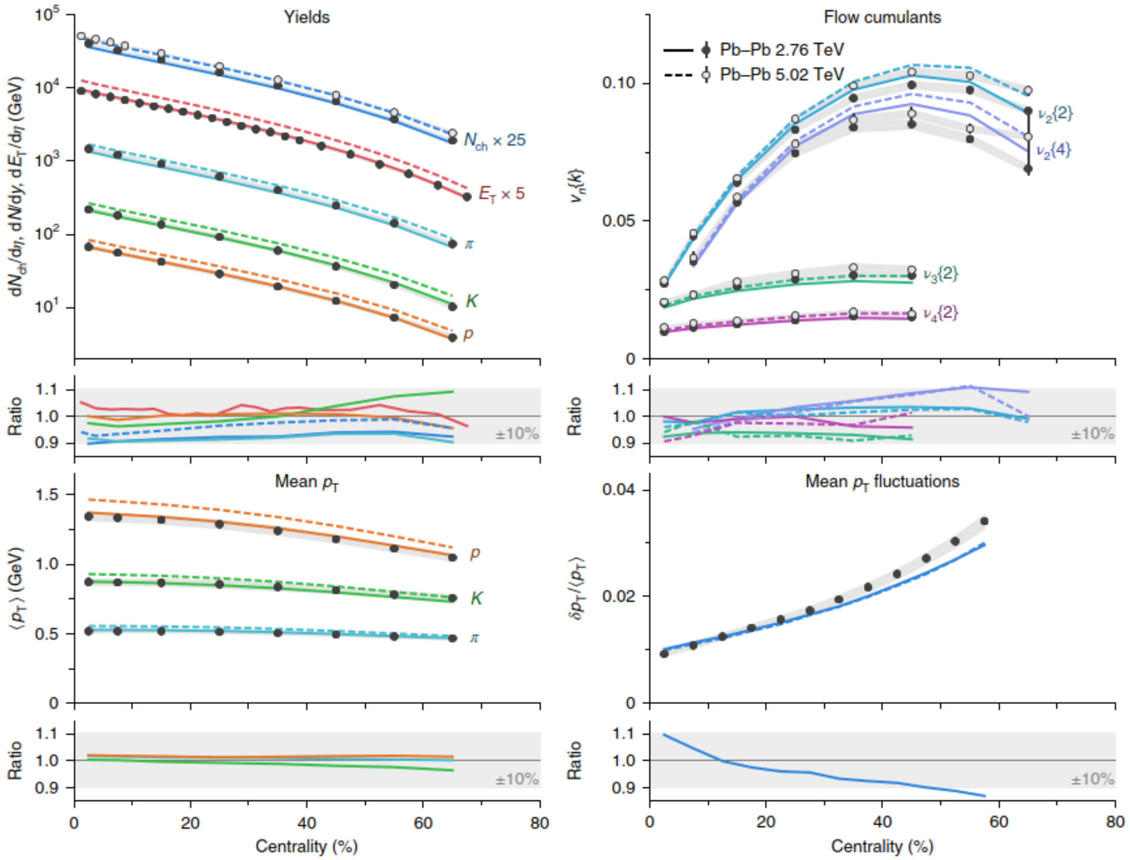
J. E. Bernhard at al., Phys. Rev. C 94, 024907 (2016)
J. E. Bernhard at al., Nat. Phys. 15, 1113–1117(2019)
J. E. Bernhard at al., Phys. Rev. C 101, 024911 (2020)



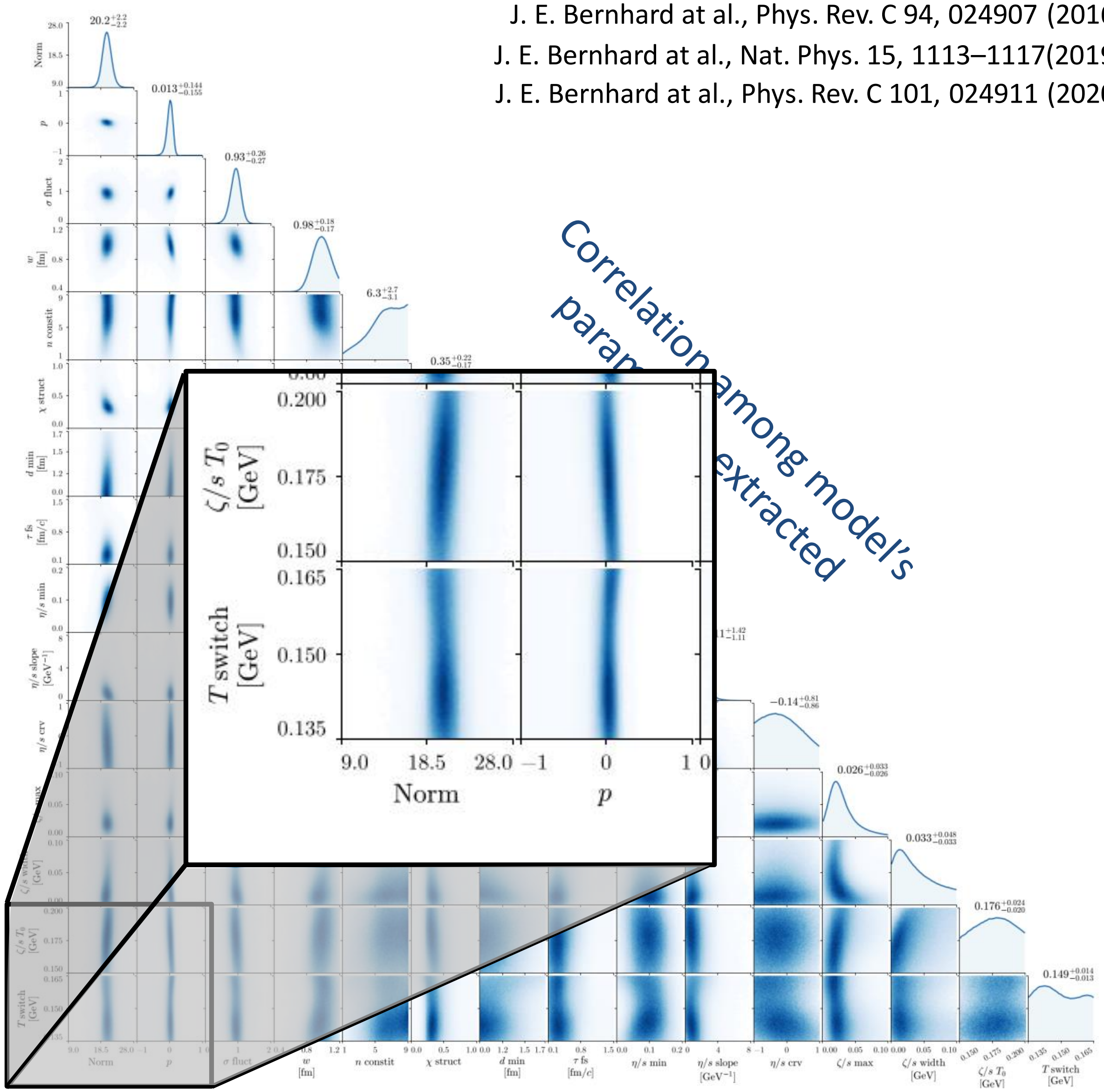
Correlation among model's parameters extracted

Medium properties: from qualitative to quantitative (II)

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)



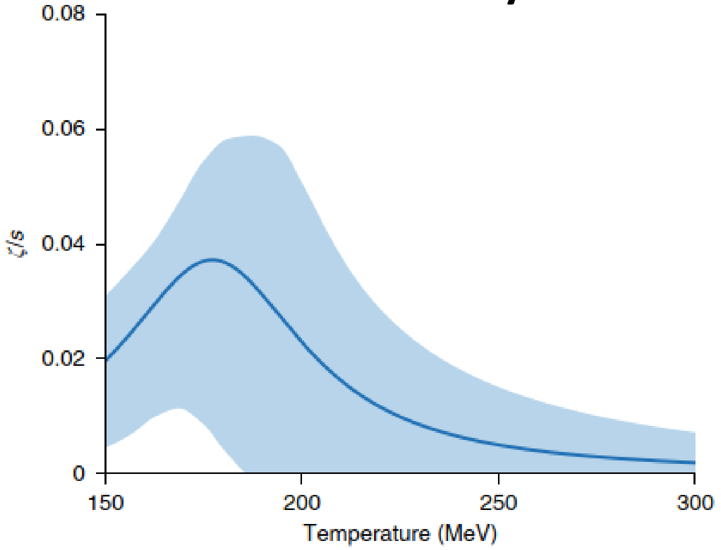
Posterior distributions describe LHC data at the 10% level



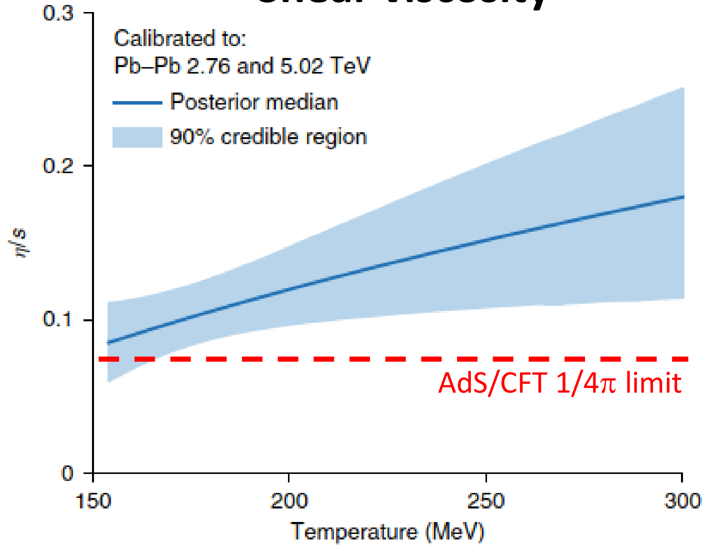
Correlations among model's
param
extracted

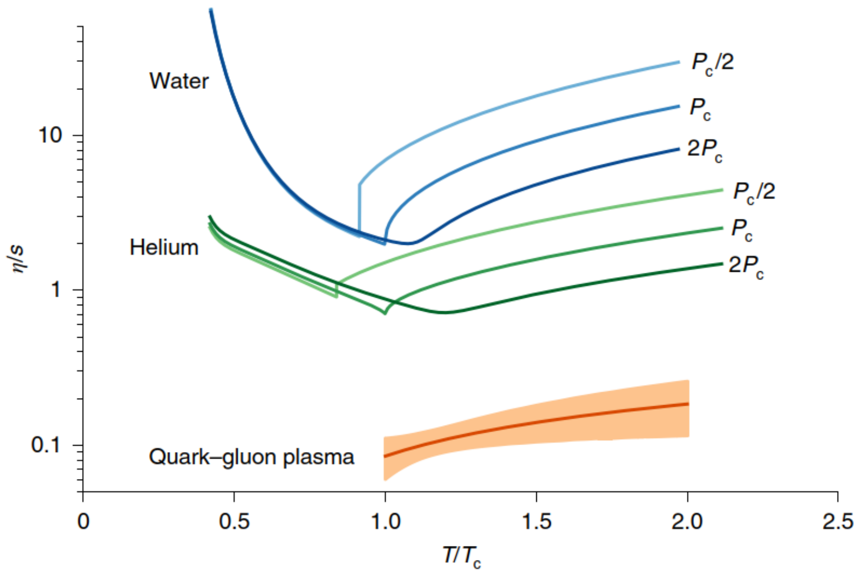
Medium properties: from qualitative to quantitative (III)

Bulk viscosity



Shear viscosity





η/s mildly dependent on the temperature and near to the lowest allowed value (from AdS/CFT):

almost perfect fluid!

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)

Conclusions and outlook

Study of soft probes in heavy-ion collisions:

- system produced at the LHC: **color-deconfined thermalized medium**
- Almost perfect fluid (**$\eta/s \approx 0.2$** mildly dependent on T) which expands hydrodynamically leading to radial and anisotropic flow of the produced particles
- The medium undergoes **chemical freeze out at $T_{ch} \approx$ 150-160 MeV**
- **Nucleosynthesis** from large medium is consistent with **thermal production**

Study of soft probes in small colliding systems:

- Propedeutical to a deeper understanding of QGP phenomena in A-A
- **Hadrochemistry** and **collectivity** at high-multiplicity **match** what observed in **A-A** (for variables not strongly connected to collision geometry)
- Description is **very challenging for** any **theoretical model**. Two-component scenario seems favored

Thank you

Soft probes is much more! Many other results presented at LHCP:

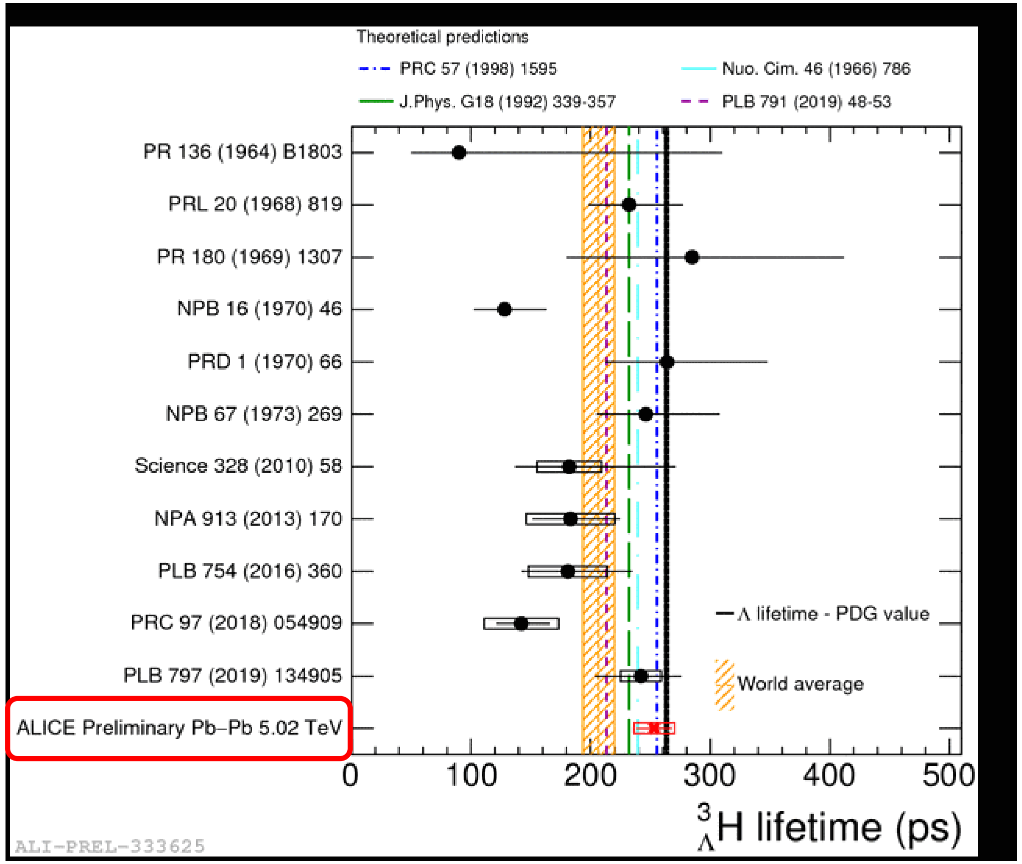
- V. Zaccolo 26 May, 18:00
- A. Caliva 28 May, 15:03
- Z. Khabanova 28 May, 15:03
- C. Pinto Poster Session
- J. Hansen Poster Session
- E. G. Nielsen Poster Session

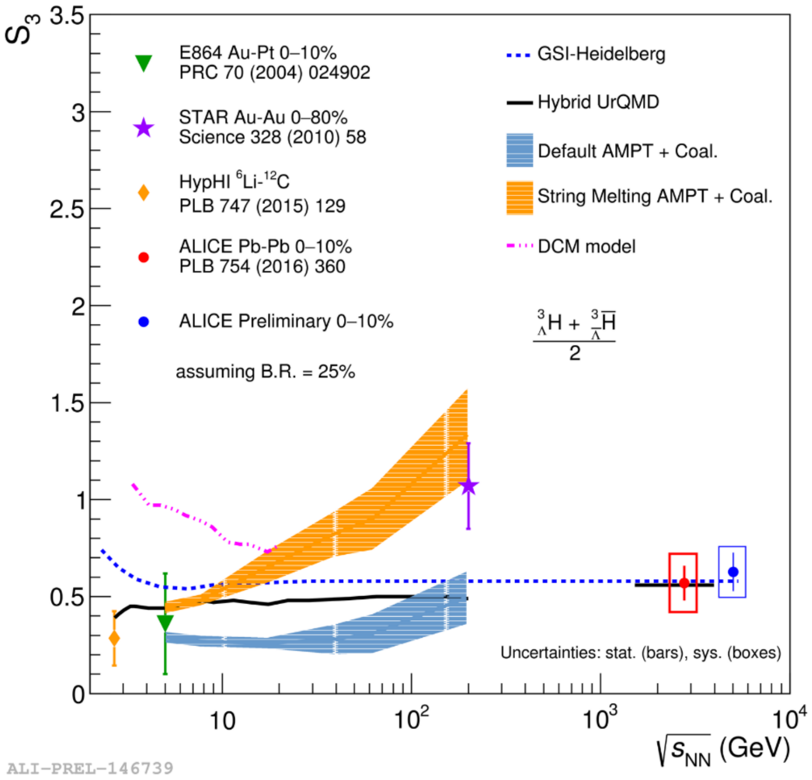
More questions? Private discussion?

Topic: LHCP_HIplenary_SoftProbes
Time: May 27, 2020 02:00 PM Zurich
Join Zoom Meeting: link
Meeting ID: 944 5644 3177
Password: same as this session’s

Backup

$^{3}_{\Lambda}H$ lifetime: the (no) puzzle





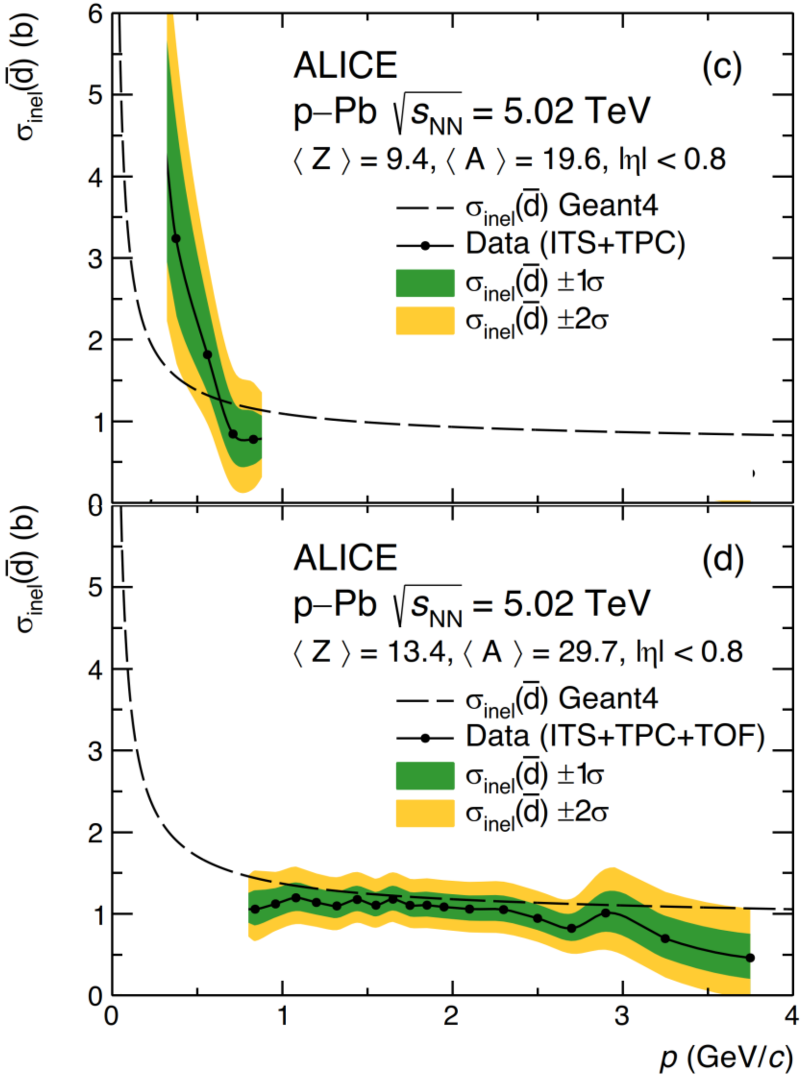
Expectation: $^{3}_{\Lambda}H$ lifetime $\sim \Lambda$ lifetime (loosely bound object)

World average 2 years ago: significantly lower

New results from ALICE: more precise than world average.
Full compatibility with Λ lifetime

… yet loosely bound and compatible with thermal production (at T_{ch}) makes this exotic state pivotal in understanding nucleosythesis

ALICE Collaboration, arXiv:2005.11122



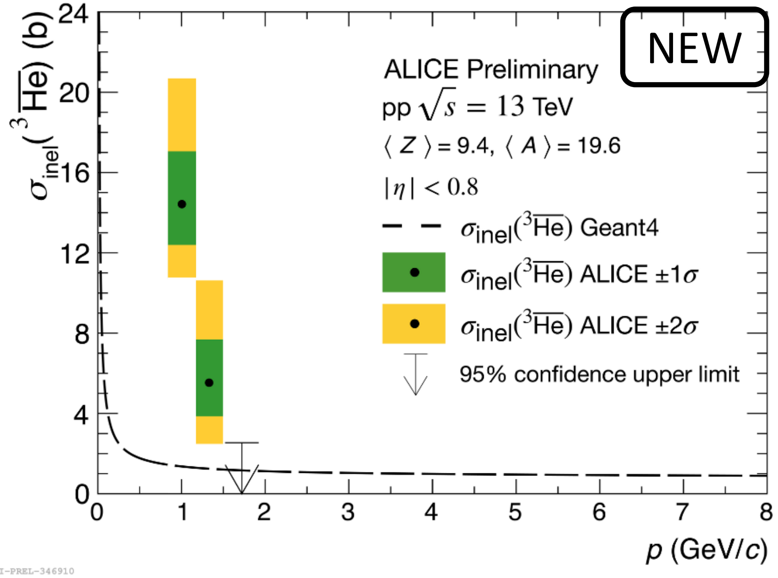
Anti-nuclei production as a probe of dark matter annihilation in the universe*

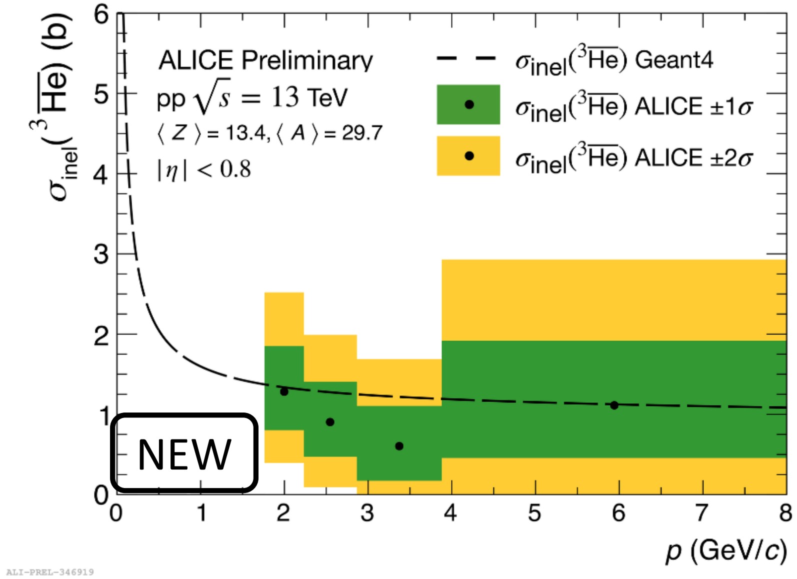
Background: secondary production from ordinary matter collisions (pp, p-A with small Z...)

Anti-nuclei inelastic cross-section in matter known precisely for $\bar{p}$ only

LHC: equal amount of matter and antimatter at mid rapidity

Nuclei and anti-nuclei have different inelastic cross-section in the detector material





* K. Blum et al., 10.1103/PhysRevD.96.103021
F.Donato et al.,10.1103/PhysRevD.62.043003

Resonance production and the hadronic phase

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