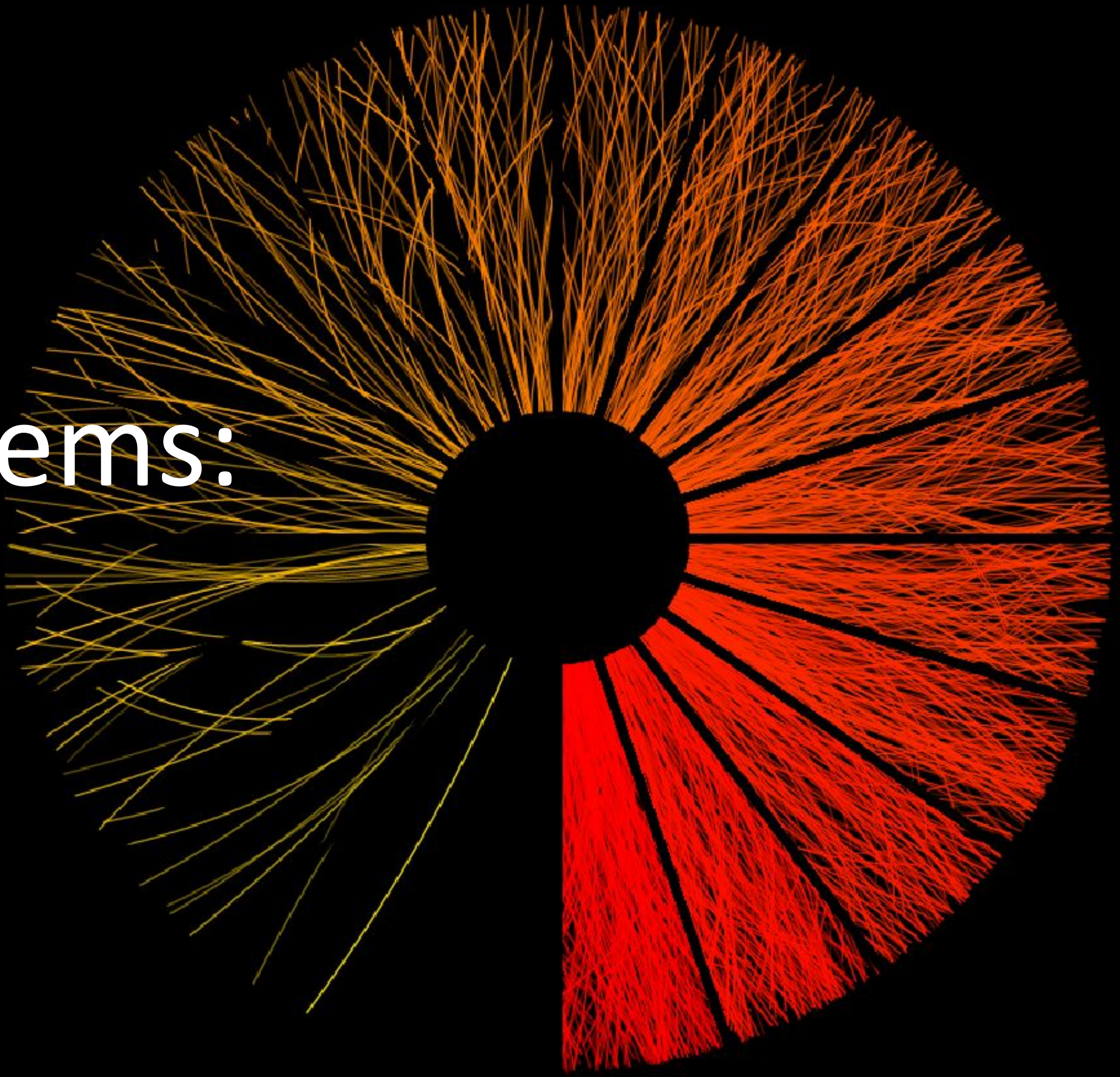
Livio Bianchi *
Università & INFN Torino

QGP in small systems: overview



XVIII Mexican Workshop on Particles and Fields

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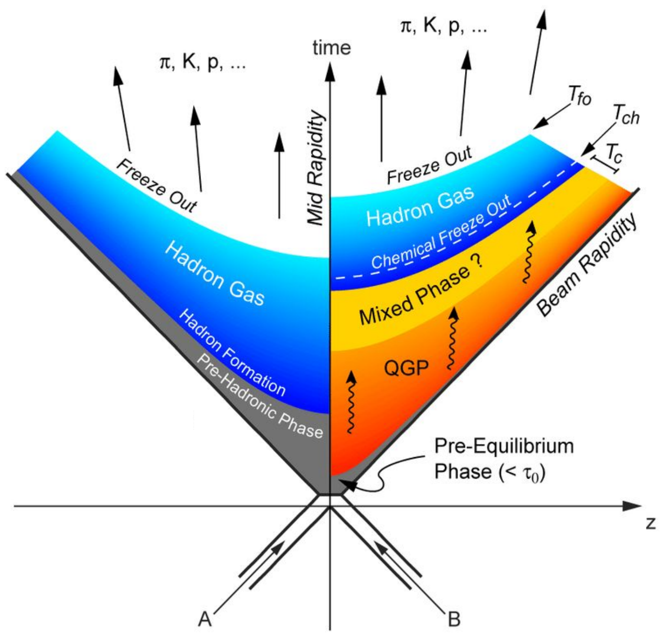
Large VS small systems

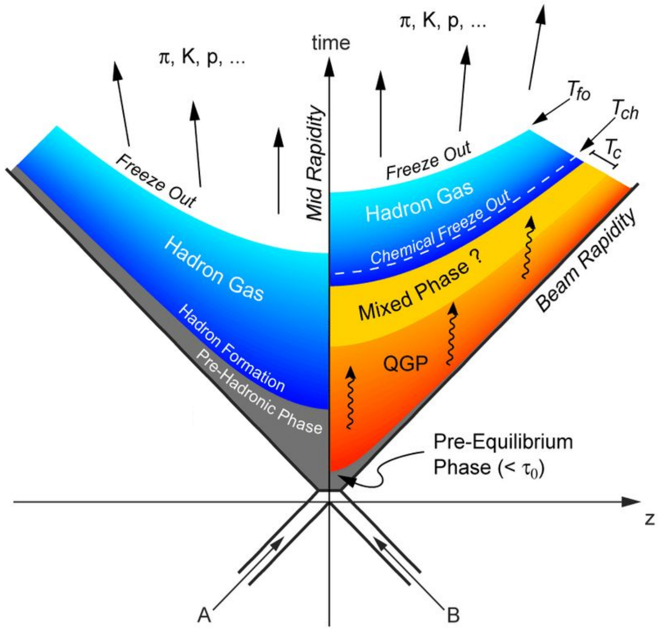


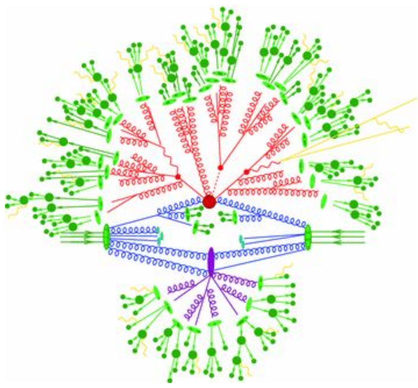
Large colliding systems:

- Huge number of partonic collisions, softening through time →collective partonic motion →Viscous hydro
- hadronization when temperature drops T_{ch} →statistical approach to particle production
- ~100 fm dense partonic medium → parton energy loss and quarkonia melting

Small colliding systems:

- Early times dominated by hard jets
- Presence of several partonic primary collisions (MPI) set a semi-hard scale
- UE ⟶ soft scale
- hadronization described through effective description of QCD potential
- cross-talk among (mini-)jets (and UE?) necessary to explain dynamics (normally introduced ad-hoc)





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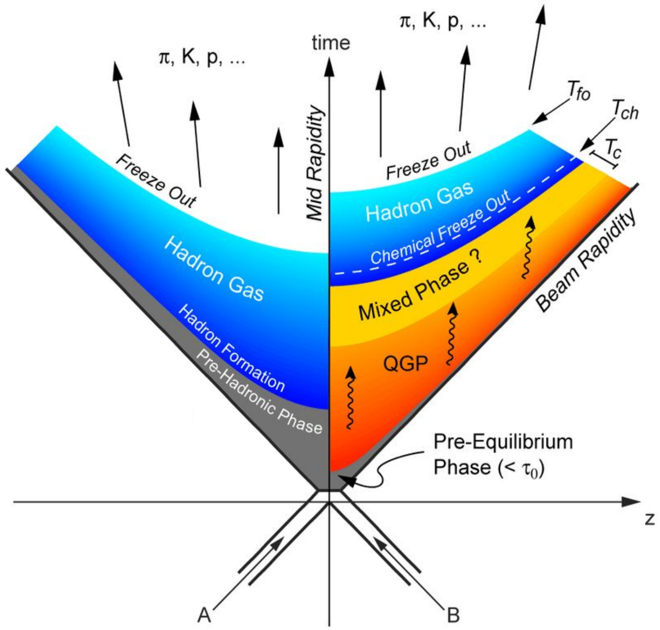

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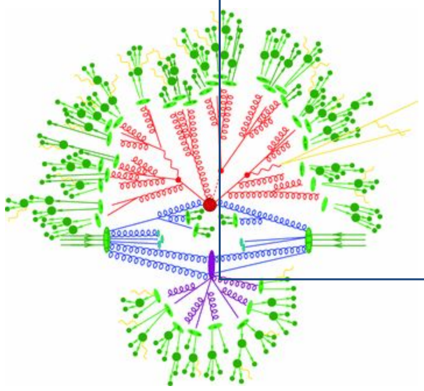


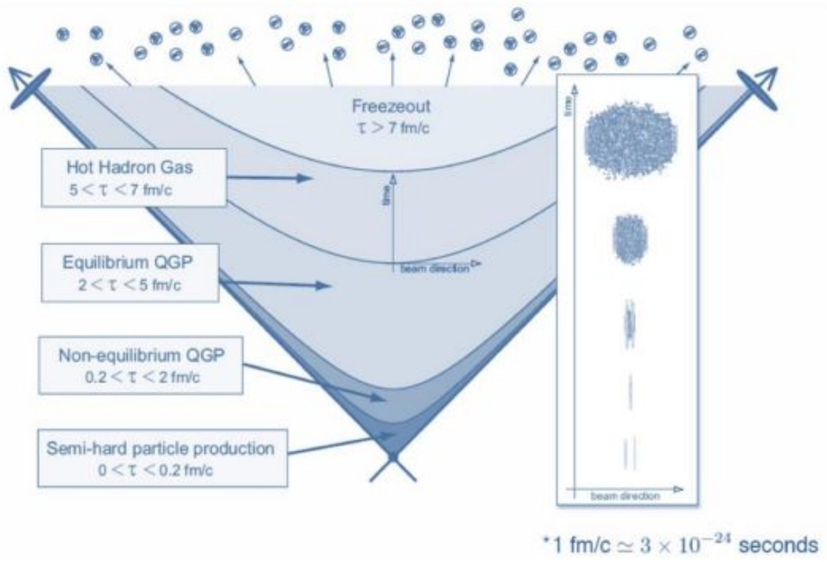
Large systems as an extension of in-vacuum hadronization with large #MPI?

can small system be described by statistical hadronization and far-from-equilibrium hydro?

The Standard Model of Heavy-Ion Collisions (HISM)

Collectivity:

- flow: correlation between space and momentum (particles close in space → similar velocity in magnitude and direction)
- In contrast to random thermal motion
- Radial and anisotropic flow
- Model: hydro



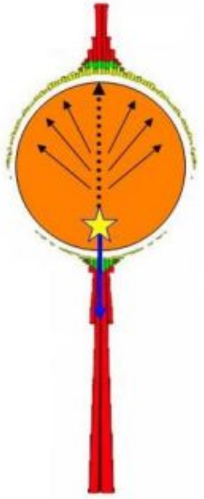
Hadrochemistry:

- Significantly modified when comparing to elementary collisions
- Relative yields of particles studied
- Model: Statistical (thermal)

Compelling evidence of QGP formation putting together SPS, RHIC and LHC results

Partonic energy loss:

- Opaque fluid: absorbs energy of partons travelling through it
- Jet quenching
- Can be exploited to measure physical properties (e.g. density)



Quarkonium suppression:

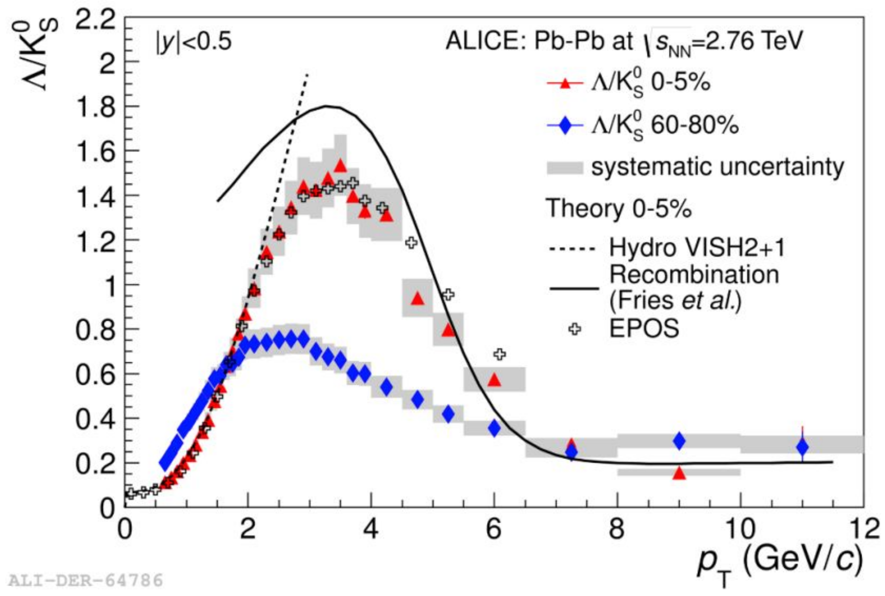
- Debye screening of colour brakes-up qq states
- Sequential suppression of progressively tighter-bound states
- Measures medium's temperature

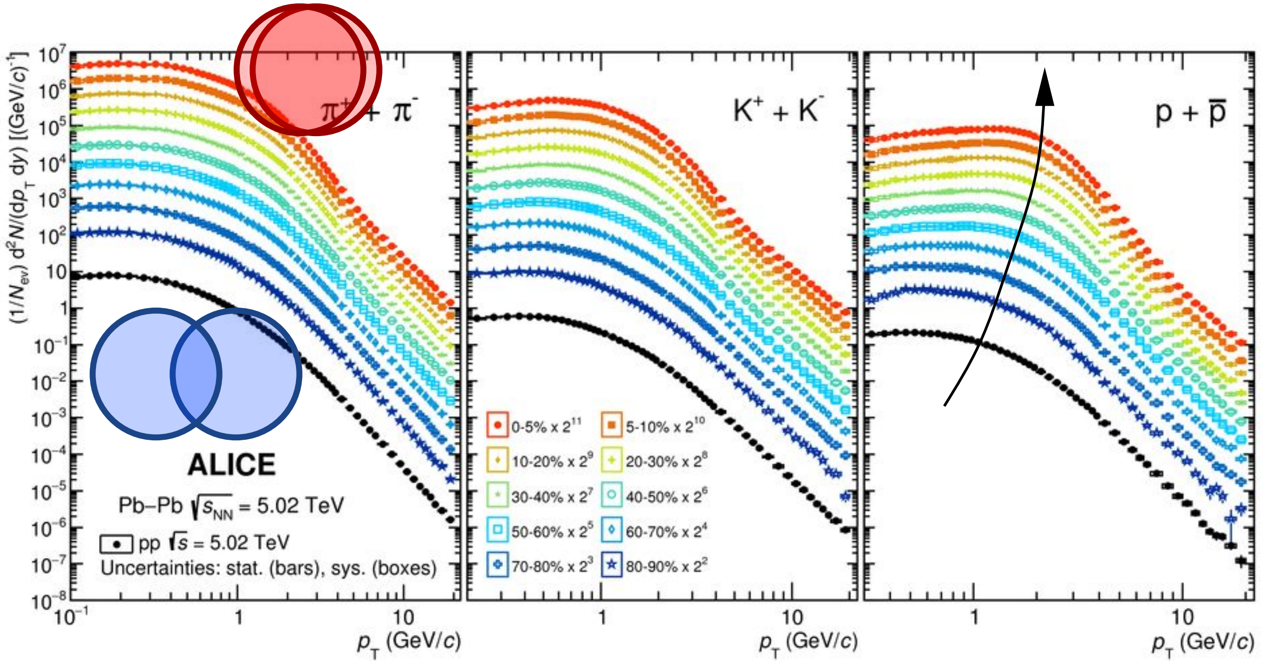
Collectivity

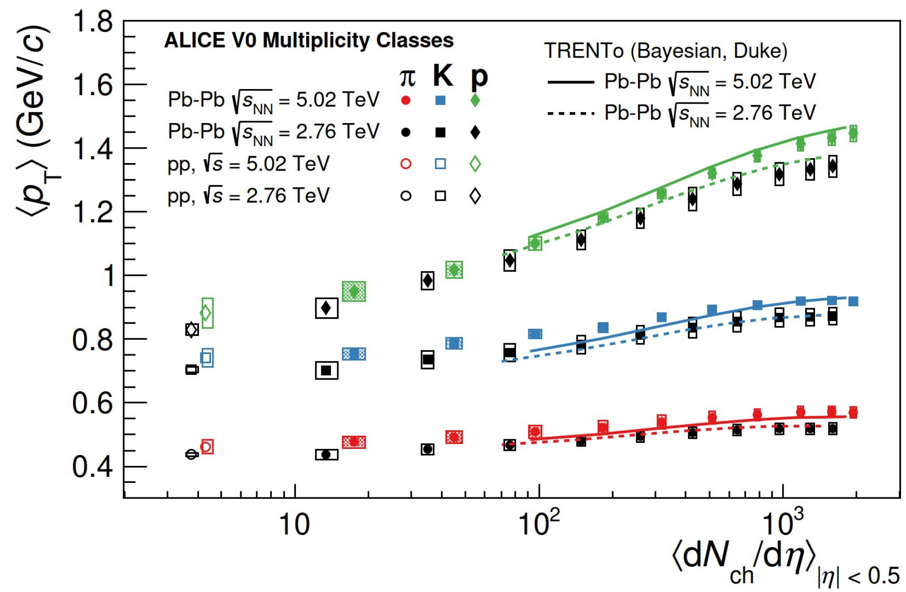
Collectivity in a nutshell (I)

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







Collectivity in a nutshell (II)

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

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

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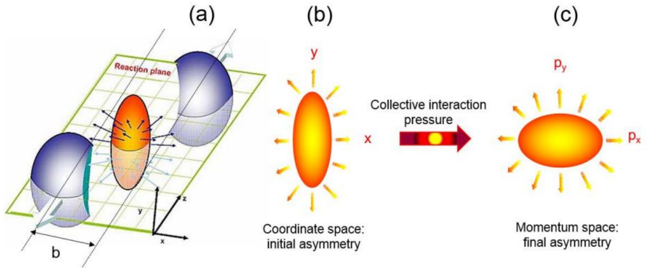
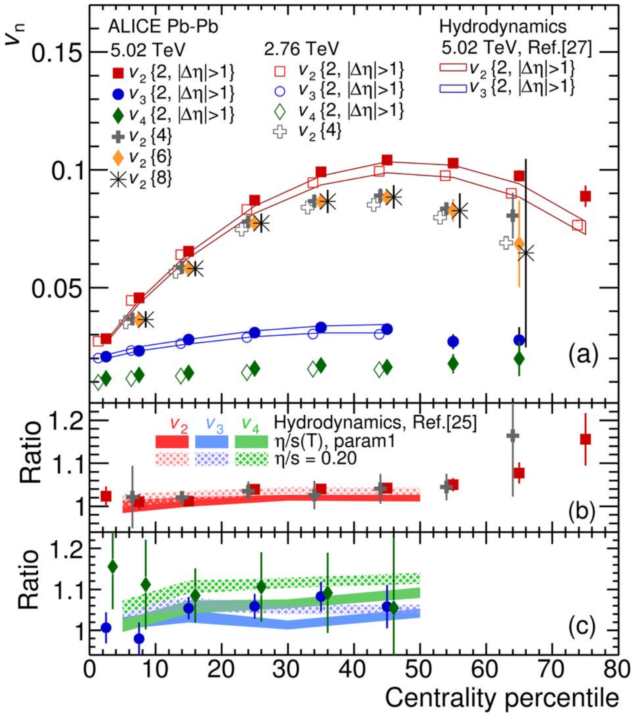
- **Anisotropic flow** (important in semi-central collisions)
  - initial spatial anisotropy translates into final momentum anisotropy (pressure gradients)
  - measured through angular anisotropies in the momentum distribution





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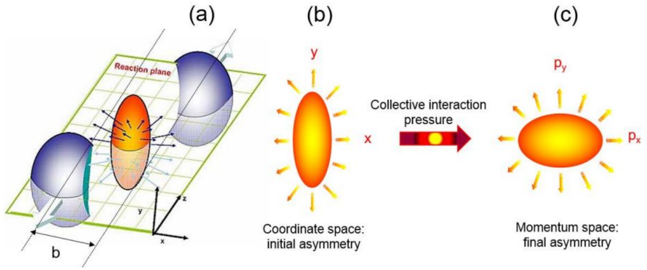
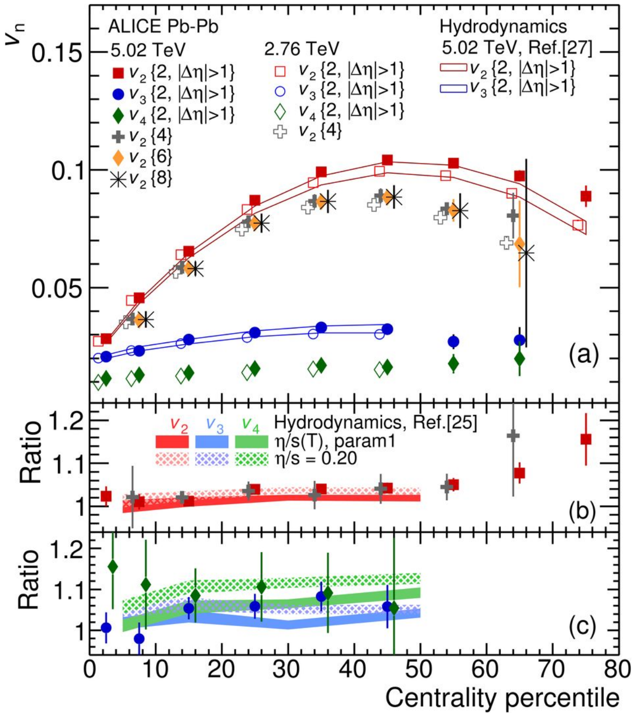
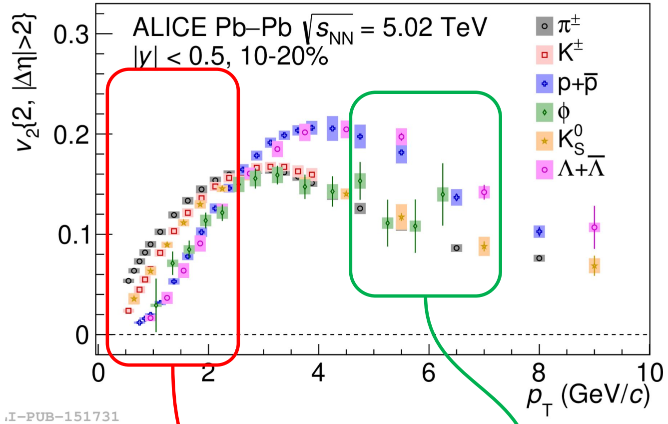


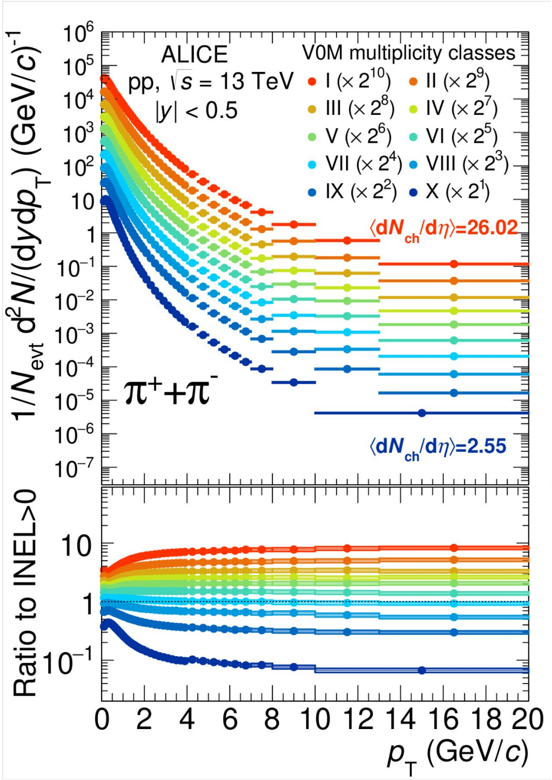


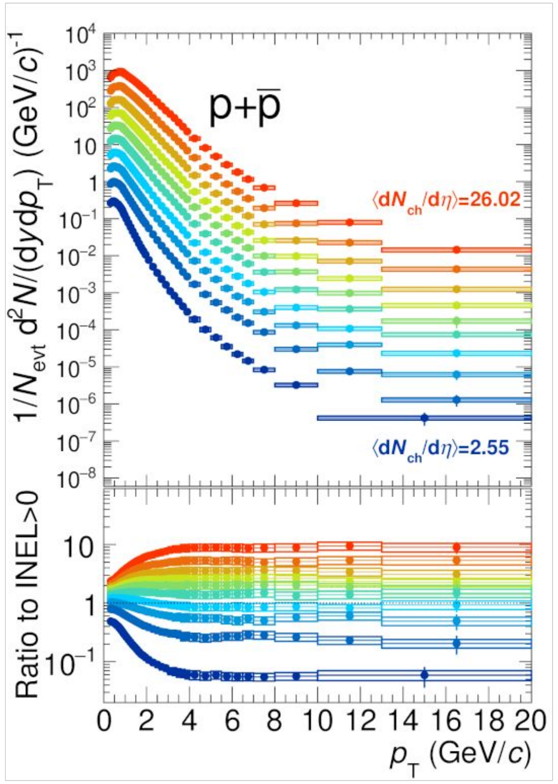


Mass ordering: interplay of radial and anisotropic flow

(approximate) particle type grouping: quark coalescence as dominant production mechanism

Spectra modification in pp and p-Pb





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(valid for all identified particles studied)

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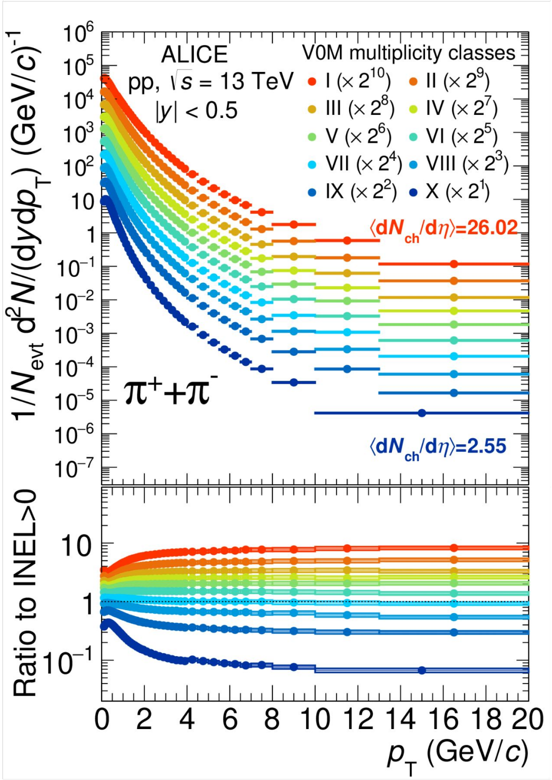

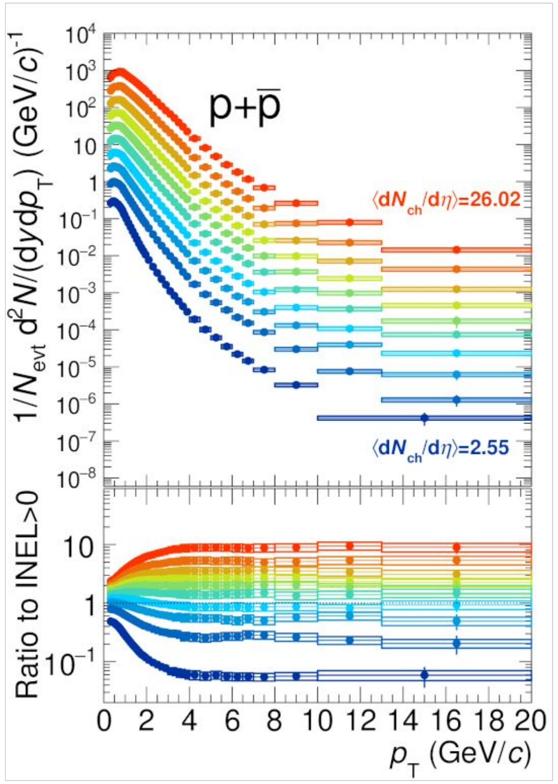

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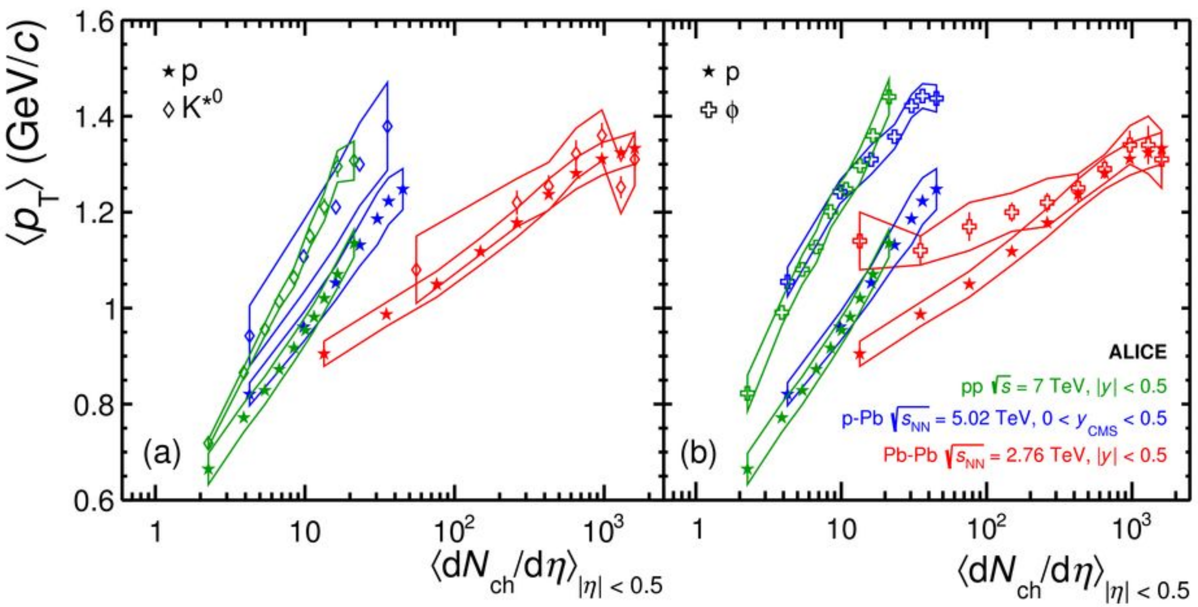
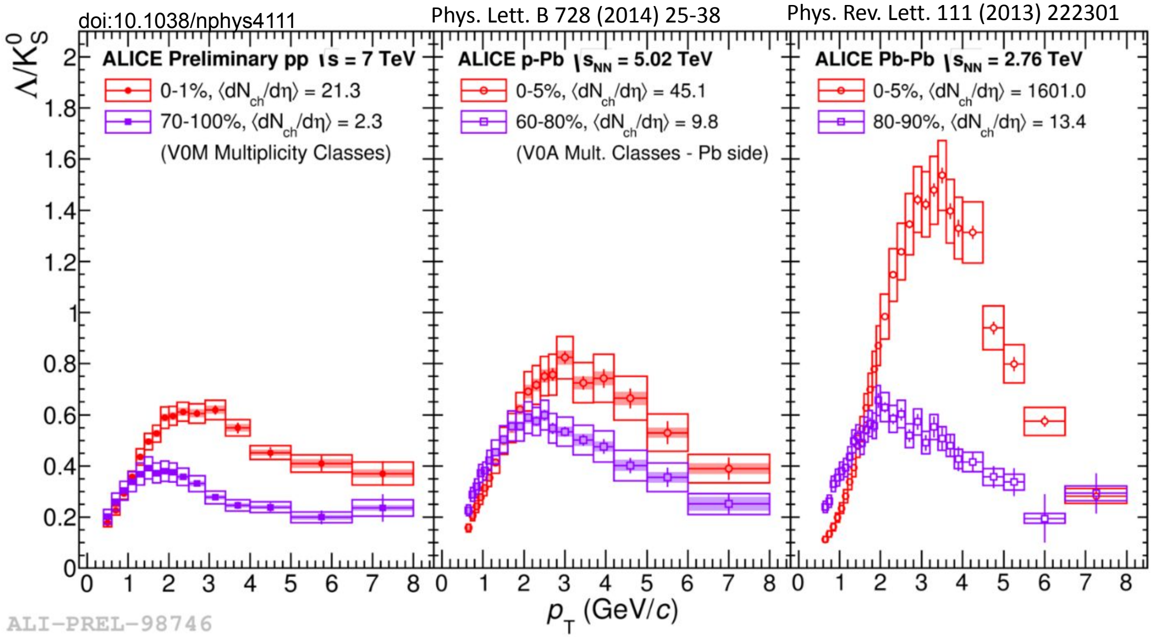


We can quantify with⟨p_T⟩which shows a similar trend VS multiplicity in small systems, but deviates for heavy ion collisions

baryon/meson anomaly in different colliding systems



The ratio depends on the event multiplicity in a **qualitatively similar** way **in pp, p-Pb and Pb-Pb**

The magnitude is smaller in pp with respect to p-Pb and Pb-Pb, but note that for similar percentiles $\langle dN_{ch}/d\eta \rangle$ is dramatically different among the three systems

How to be more quantitative in the comparison?

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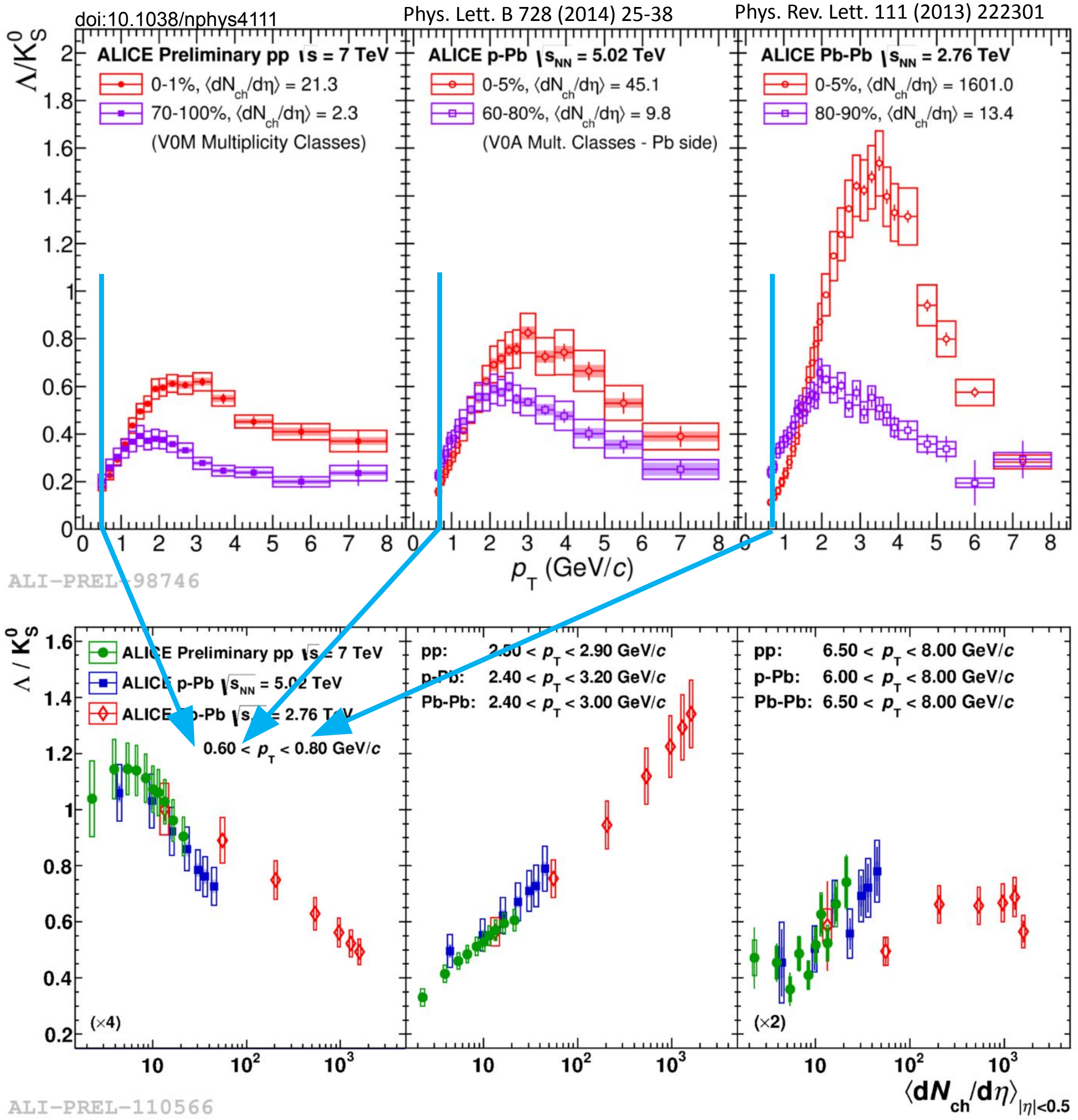

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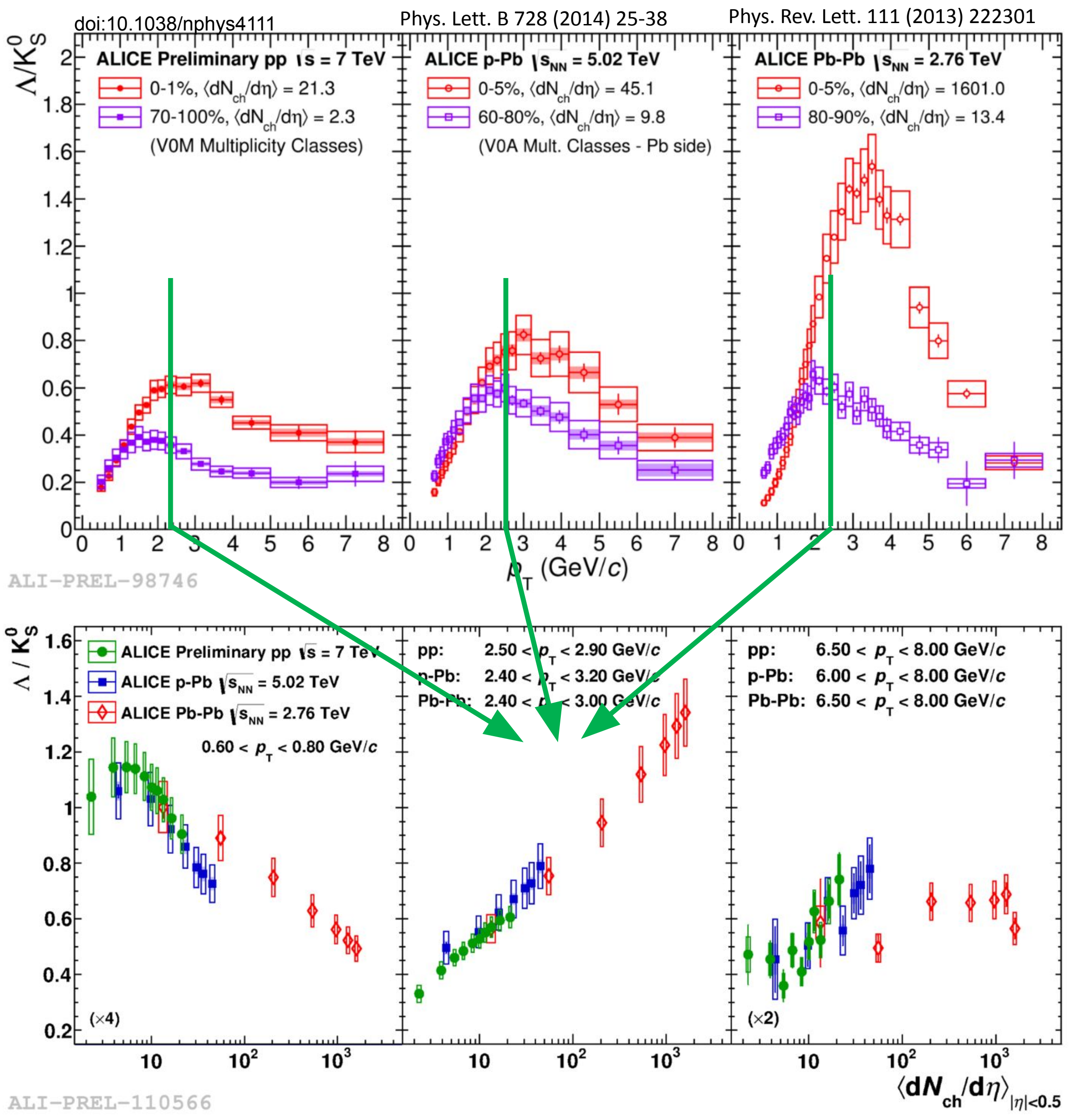

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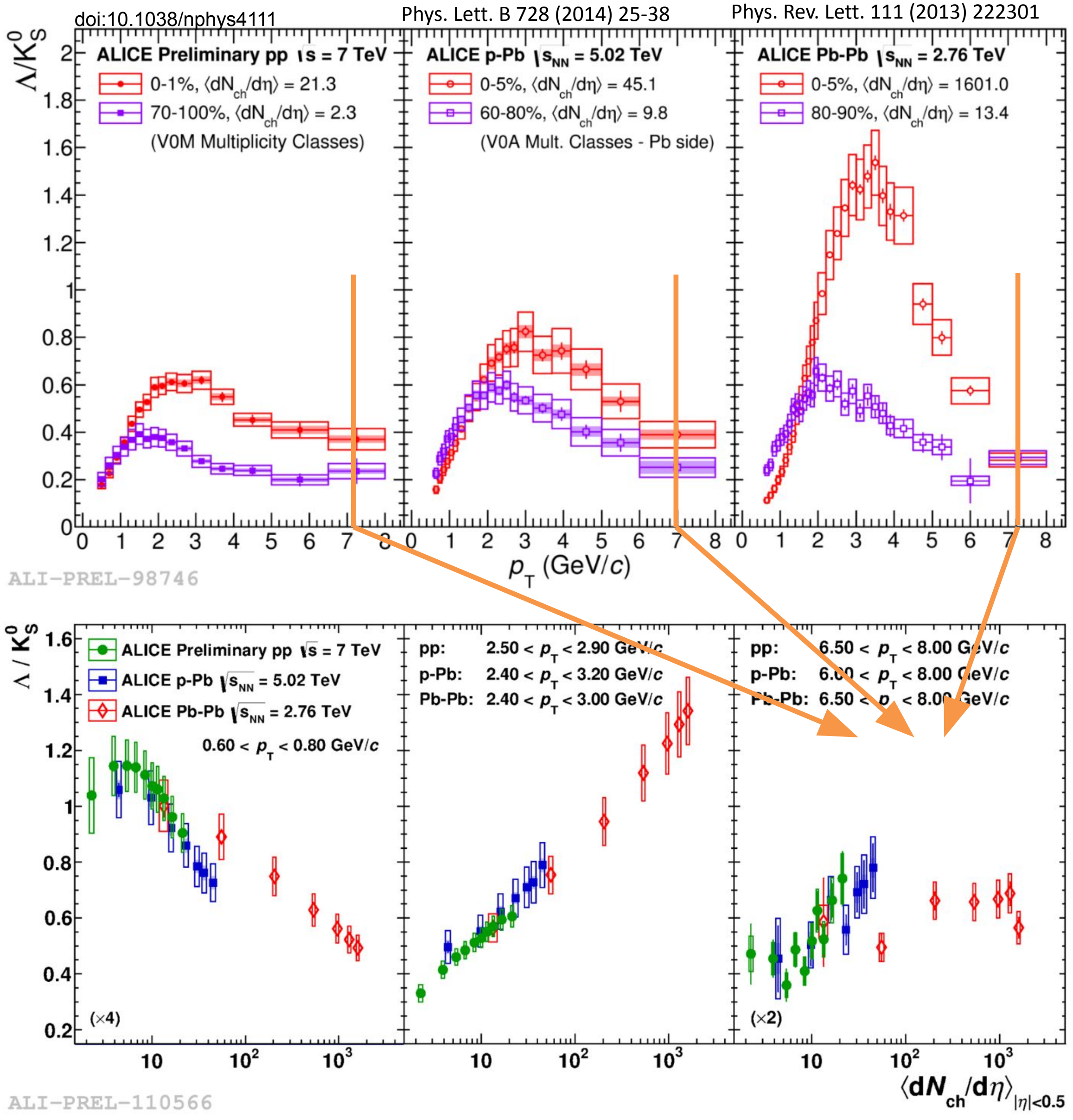

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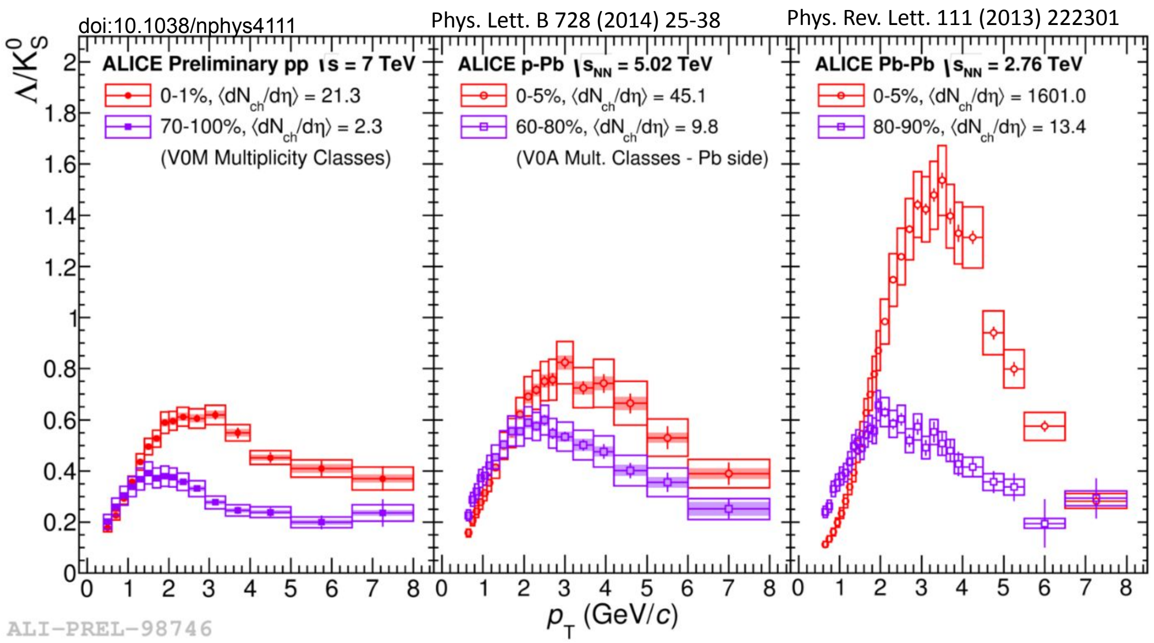
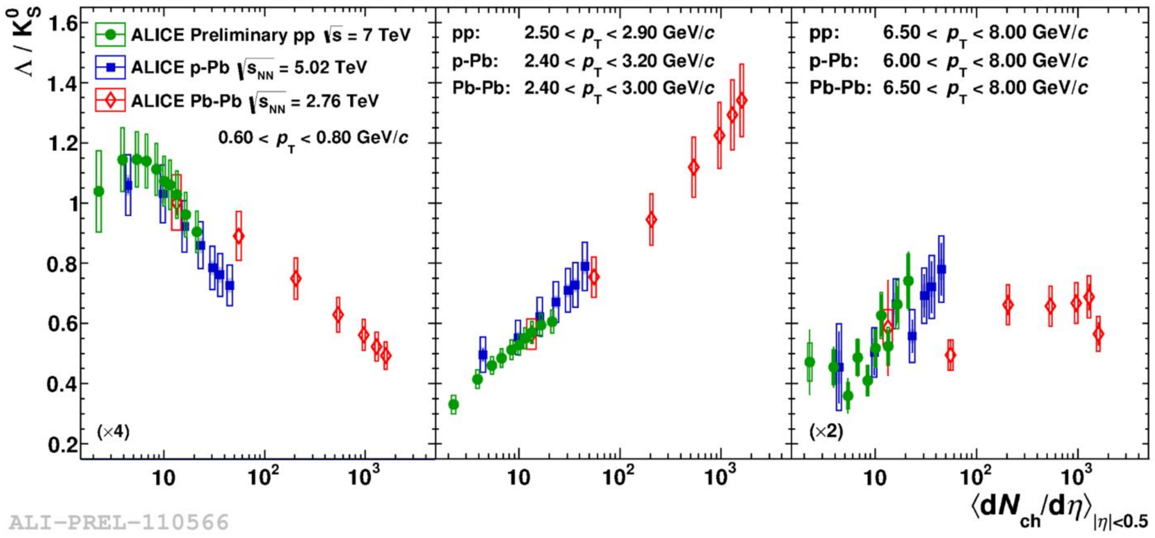
Livio Bianchi
XVII MW on PF
23 Nov 2022





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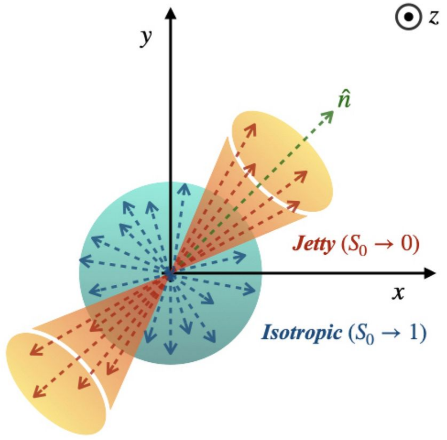
Common trend in the three systems!

Is the observed effect coming from the same mechanism at play?

Are spectra modified in the same way in- and out-of-the jet?



pp collisions feature complicated topologies. Jets and Underlying Event (UE) coexist

Expect QGP-like features to emerge in UE rather than in boosted jets

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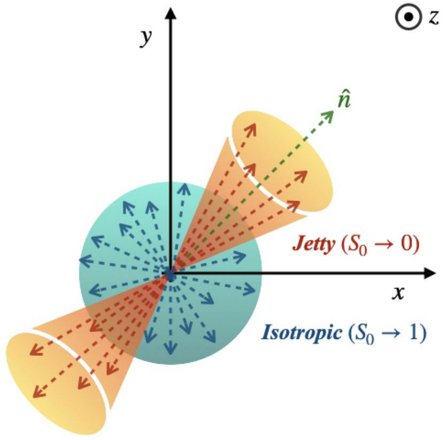

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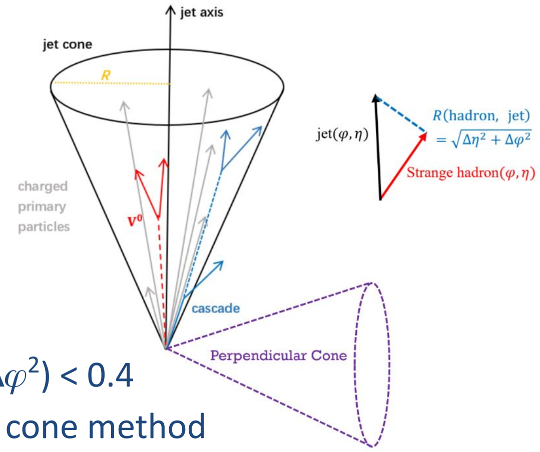
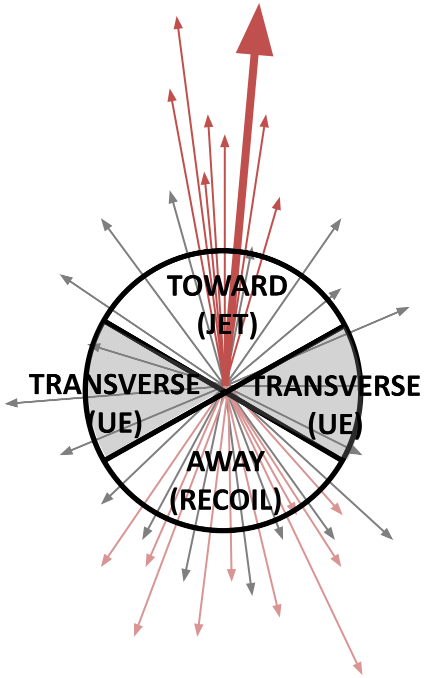
Leading hadron method:

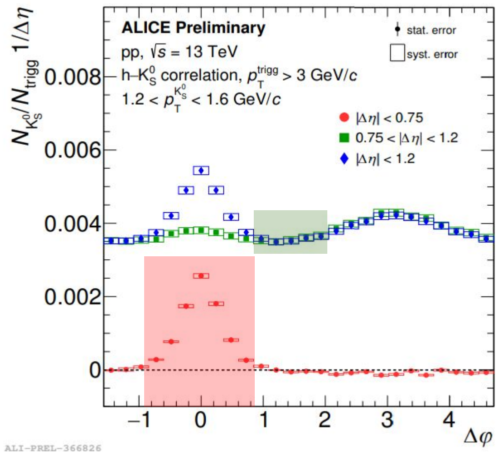
- jet direction: the one of the highest p_T hadron
- $p_T^{leading}$ > 4-5 GeV/c
- hadron-strange correlation method to extract particle yields in- and out-of-the jet

Jet finding:

- Charged track selection:
  $|\eta| < 0.9$, $p_T > 0.15$ GeV/c
- Jet finder: anti-k_T, $R = 0.4$,
  $|\eta_{jet}| < 0.35$, $p_{T,jet} > 10$ GeV/c
- Strange particles found in:
  - Jet Cone →
    $R_{\text{Strange hadron, jet}} = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)} < 0.4$
  - Underlying Event → perp. cone method
  - Jet fragmentation → JE = JC - UE

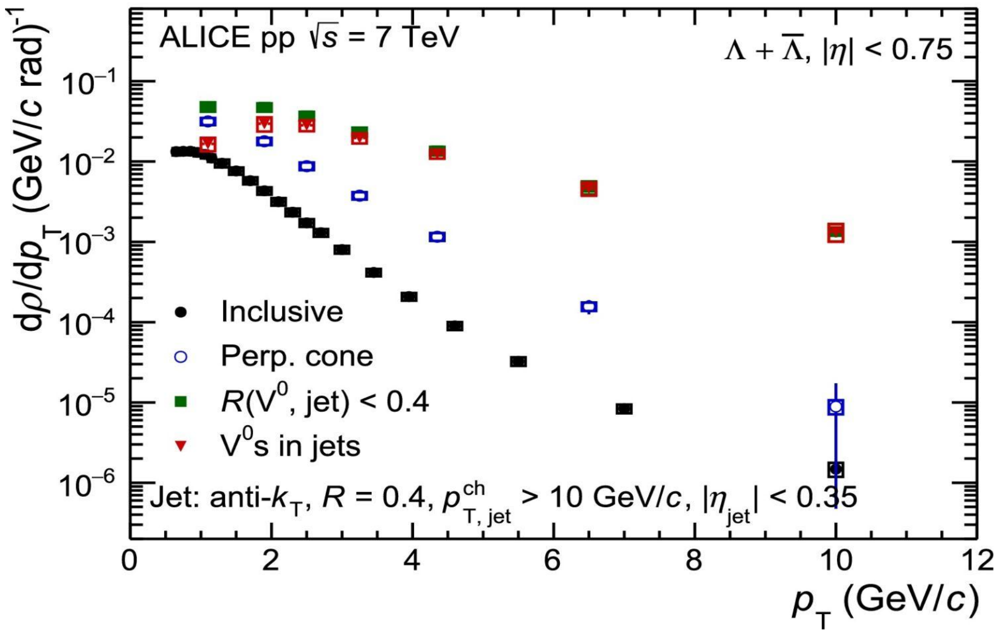


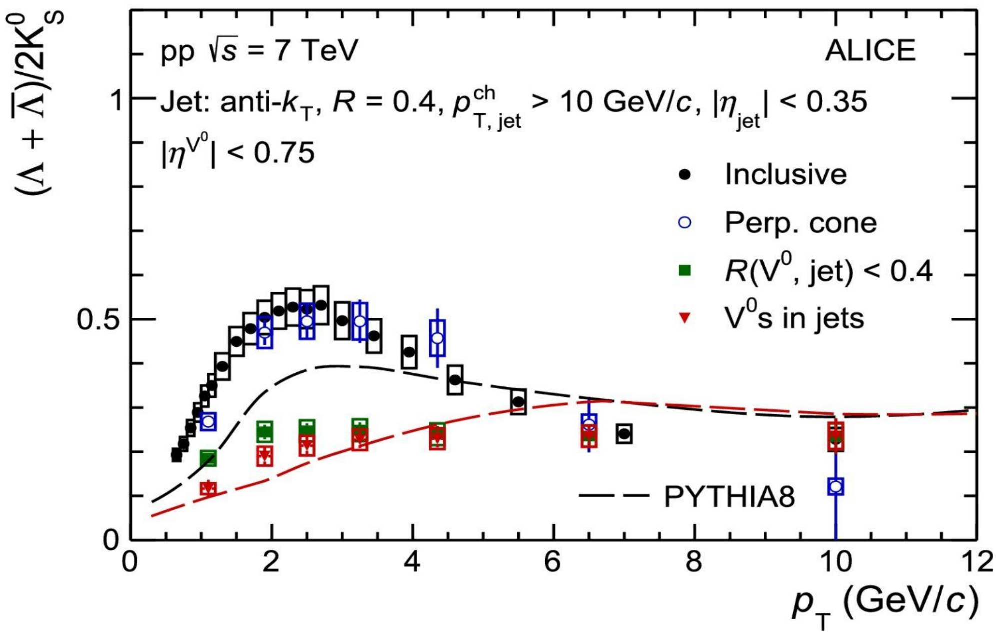




baryon/meson anomaly in- and out-of-jet in pp

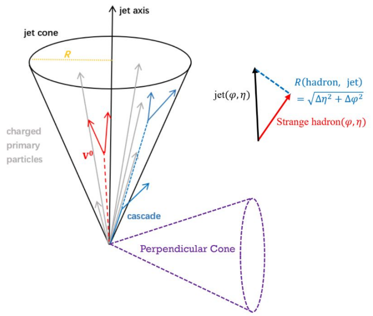
ALICE, Phys. Lett. B 827 (2022) 136984





Spectra are harder in the jet than in the perpendicular cone (UE)

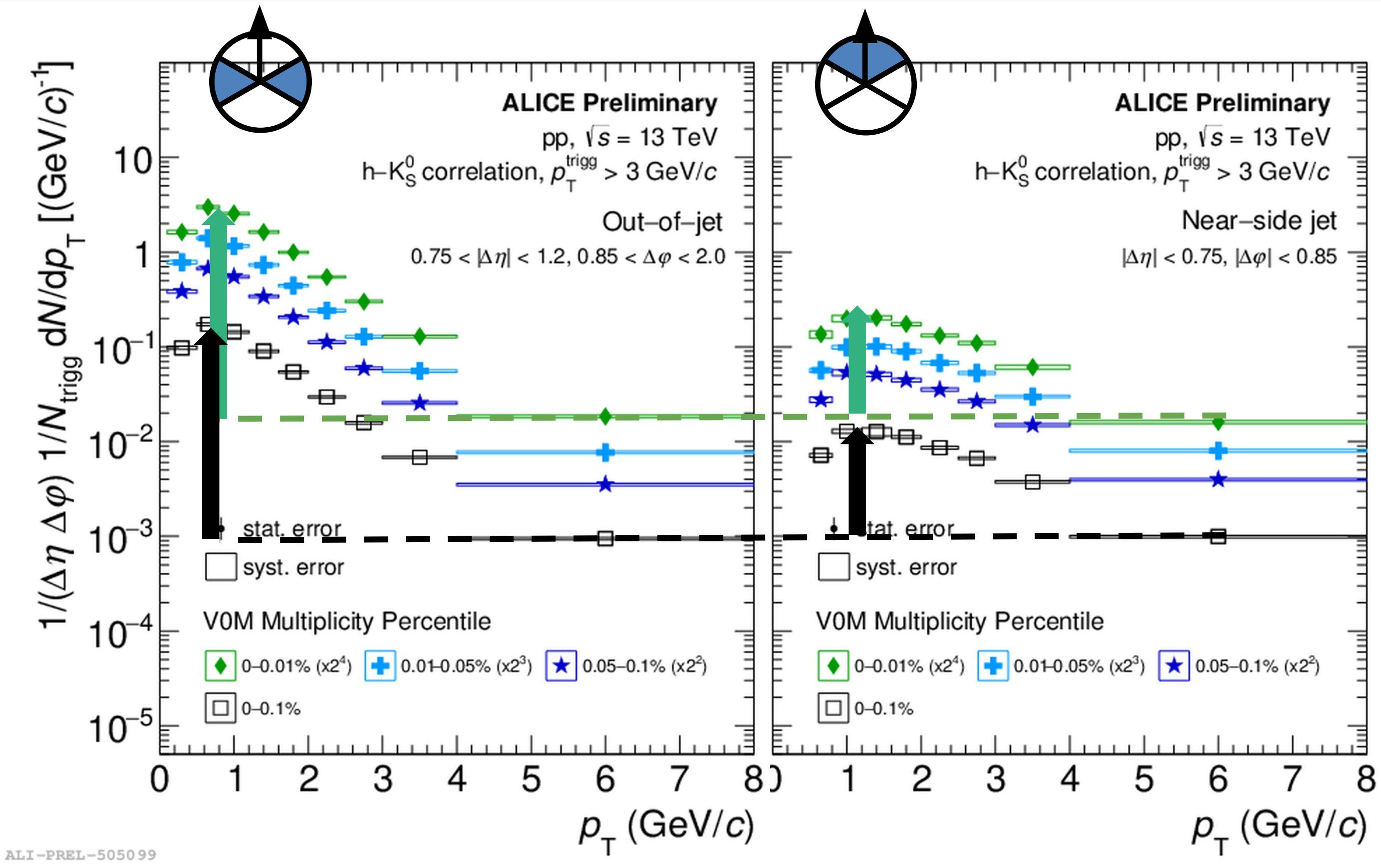
Dynamics in the baryon/meson are dominated by what observed in the UE

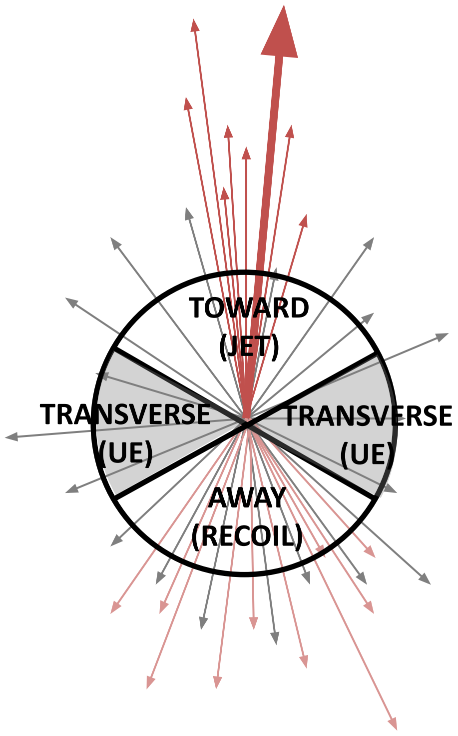


Statistics-hungry analysis, but missing the multiplicity dependence we miss part of the fun!

Need to change our “definition” of jet

baryon/meson anomaly in- and out-of-jet in pp

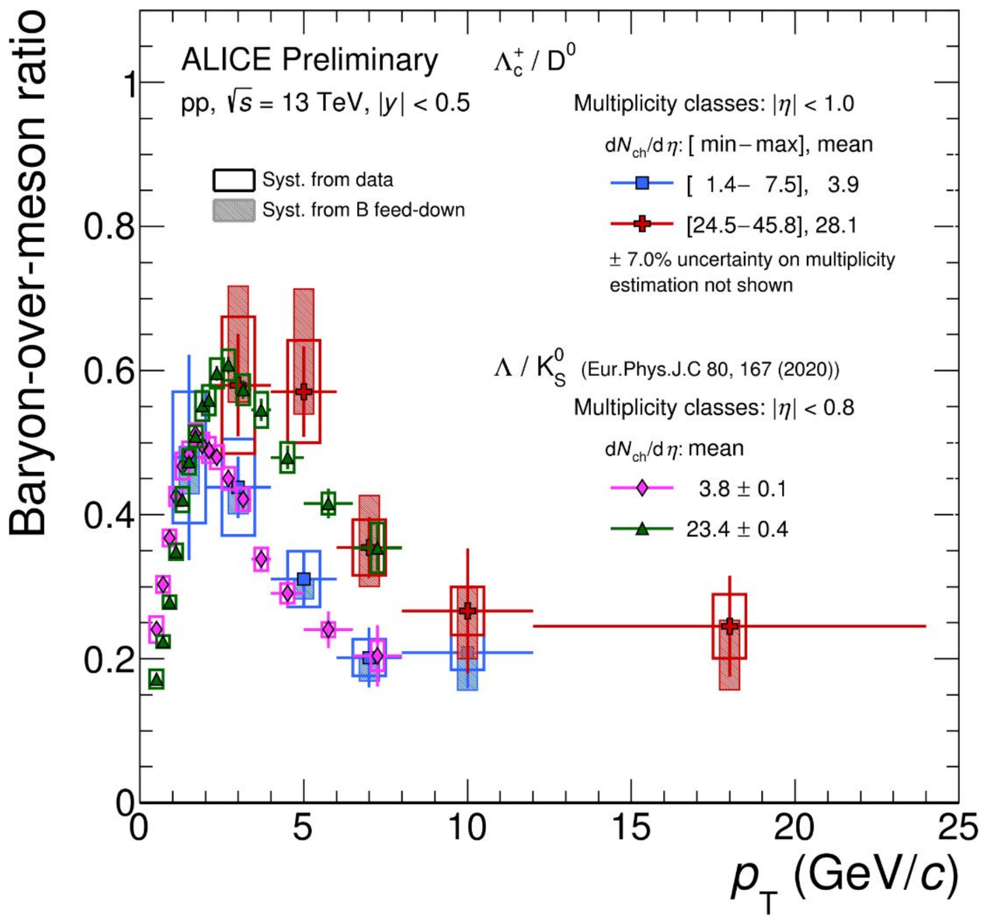




Difference in spectra in- and out-of-jet consistent with what observed with the anti-k_T algorithm

Evolution of the spectra with multiplicity not appreciable when looking at the two components separately.
Huge evolution in the inclusive spectra comes from relative contribution of jets and UE across multiplicities?

excursus: baryon/meson anomaly for hard probes



ALI-PREL-348097

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?

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

v_n from pp to Pb-Pb

$v_2 > v_3 > v_4 \neq 0$ 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)

…but does this make sense at all?
Can hydro develop in so small systems?

Naïve expectation: need "large" and "live-long" enough medium to reach thermal equilibrium and apply hydro (several interactions needed)

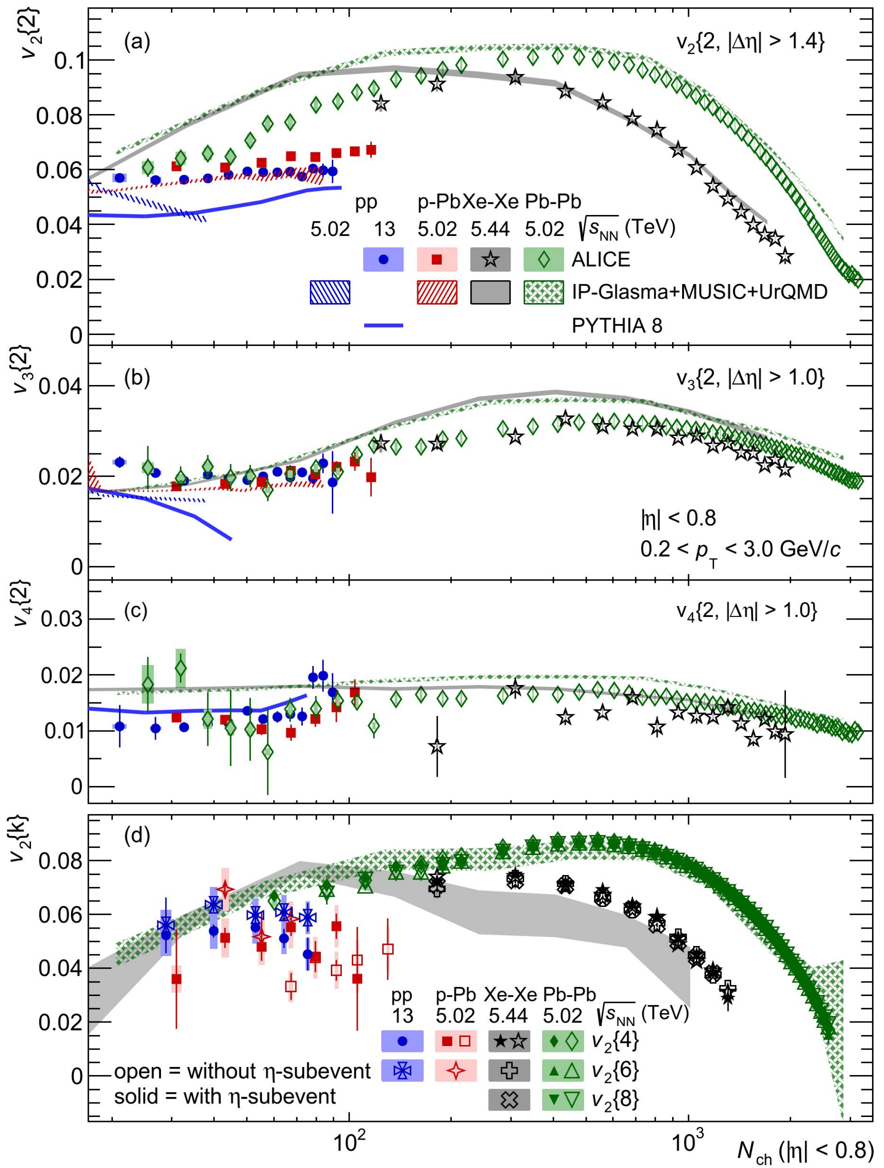
- ~~$R > \lambda$~~
- ~~$\tau > \lambda/v$~~

Too restrictive → far from equilibrium hydro

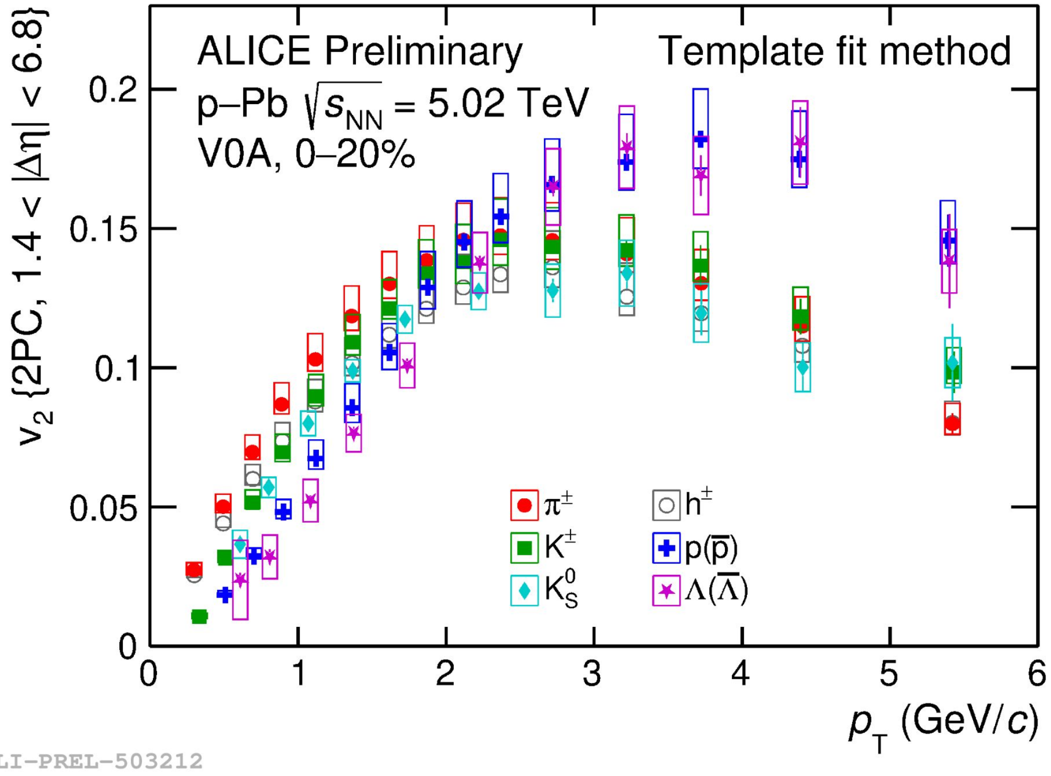
W. Li, arXiv: 1704.03576

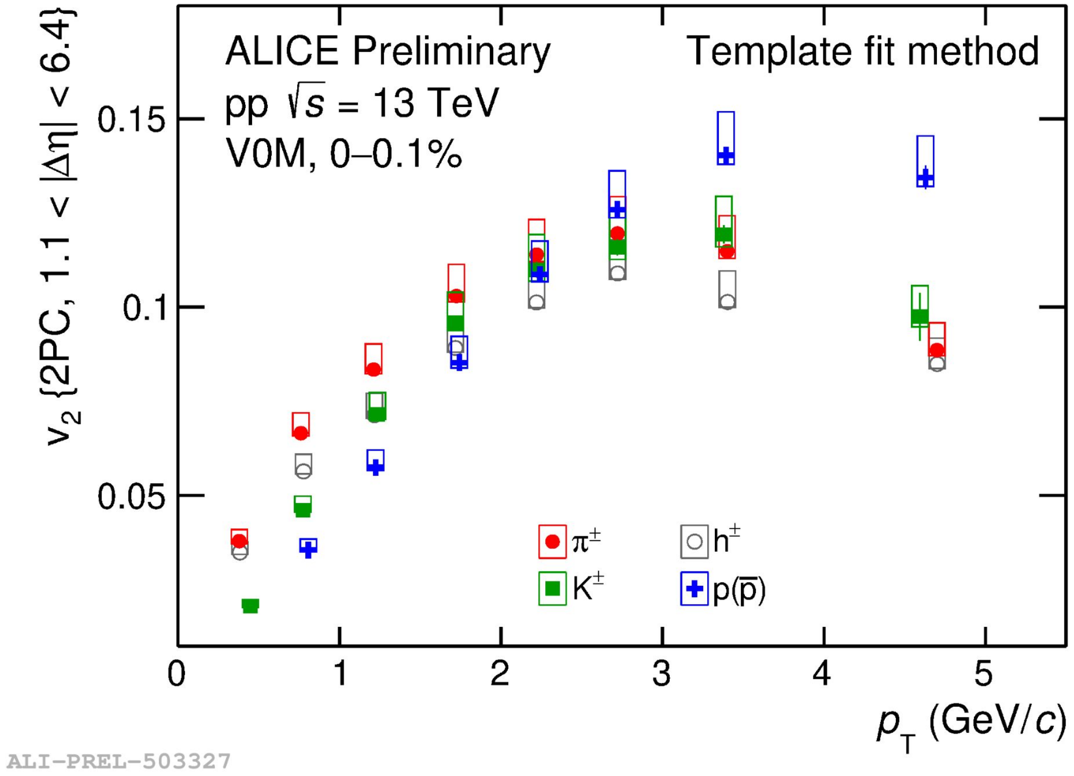
No model can quantitatively describe the data over the full multiplicity range

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



v_2 of identified hadrons in pp and p-Pb





Not only we observe v_2 in small systems, but the **particle hierarchy** (in different p_T regions) is the one that we **expect from hydro** and observe in Pb-Pb collisions

Hadrochemistry

Strangeness enhancement as probe of QGP?

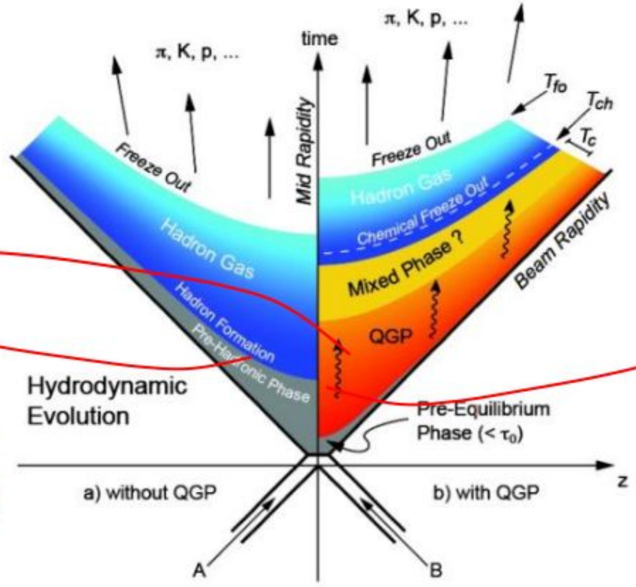
Hadrochemistry: measurement of **relative abundancies of** produced particle **species**

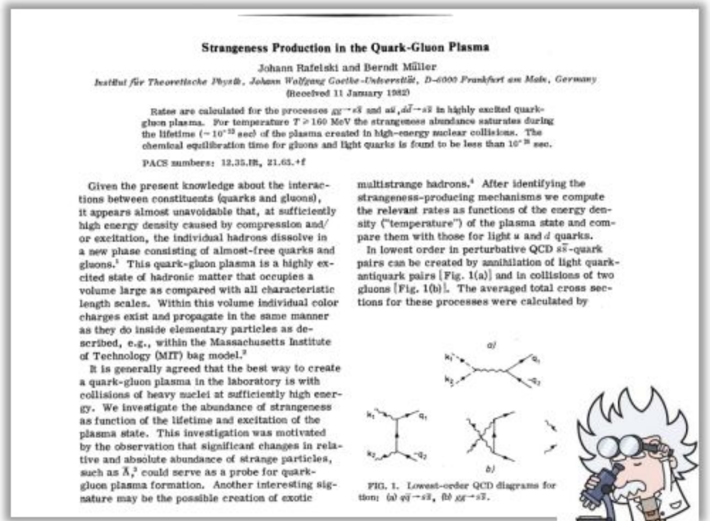
Light hadrons (composed by *u* and *d*) abundantly produced in **elementary collisions**, but **strange hadrons** are **suppressed**!

What happens at high energy densities?

Statistical Hadronization Model (SHM): all hadrons formed from an excited state following pure statistical laws. **Strangeness enhancement** can come from:

- **Canonical suppression** in pp
- **Incomplete equilibration** of strangeness
- ??





Strangeness Production in the Quark-Gluon Plasma

Johann Rafelski and Berndt Müller

Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, D-6000 Frankfurt am Main, Germany

(Received 11 January 1982)

Rates are calculated for the processes $gg \to s\bar{s}$ and $u\bar{u}, d\bar{d} \to s\bar{s}$ in highly excited quark-gluon plasma. For temperature $T \geq 160$ MeV the strangeness abundance saturates during the lifetime ($\sim 10^{-23}$ sec) of the plasma created in high-energy nuclear collisions. The chemical equilibration time for gluons and light quarks is found to be less than 10^{-23} sec.

PACS numbers: 12.35.Ht, 21.65.+f

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

It is generally agreed that the best way to create a quark-gluon plasma in the laboratory is with collisions of heavy nuclei at sufficiently high energy. We investigate the abundance of strangeness as function of the lifetime and excitation of the plasma state. This investigation was motivated by the observation that significant changes in relative and absolute abundance of strange particles, such as $\bar{\Lambda}$,[3] could serve as a probe for quark-gluon plasma formation. Another interesting signature may be the possible creation of exotic multistrange hadrons.[4] After identifying the strangeness-producing mechanisms we compute the relevant rates as functions of the energy density ("temperature") of the plasma state and compare them with those for light *u* and *d* quarks.

In lowest order in perturbative QCD $s\bar{s}$-quark pairs can be created by annihilation of light quark-antiquark pairs [Fig. 1(a)] and in collisions of two gluons [Fig. 1(b)]. The averaged total cross sections for these processes were calculated by

FIG. 1. Lowest-order QCD diagrams for ...tion: (a) $q\bar{q} \to s\bar{s}$, (b) $gg \to s\bar{s}$.

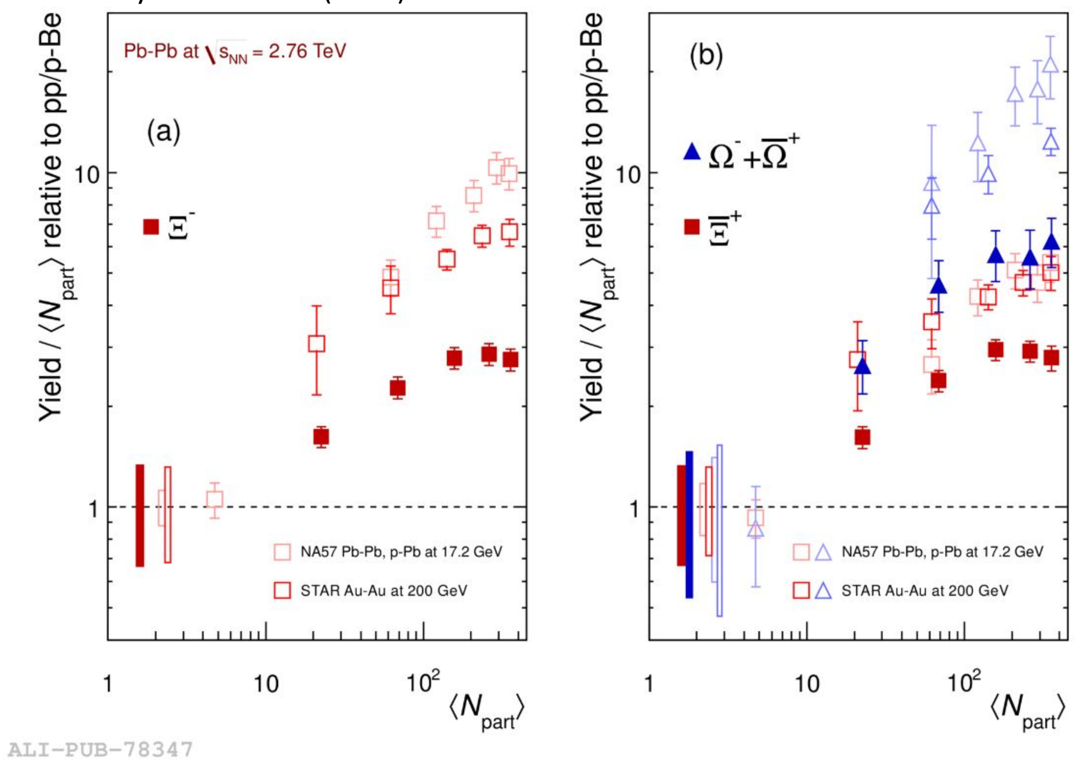
1982 (Rafelski, Muller): **Strangeness enhancement** relative to elementary collisions proposed as smoking gun for **QGP formation**:

- Lower Q-value for $s\bar{s}$ relative to $H_s H_{\bar{s}}$ formation
- Faster equilibration in partonic medium

Strangeness enhancement in large systems

Strangeness enhancement in A-A observed from SPS up to LHC.
More important for lower energy experiments! Why?

Phys. Lett. B 728 (2014) 216–227



The enhancement of strangeness in AA actually comes from a suppression in pp, which is more important for lower energies: **canonical suppression in pp**!!

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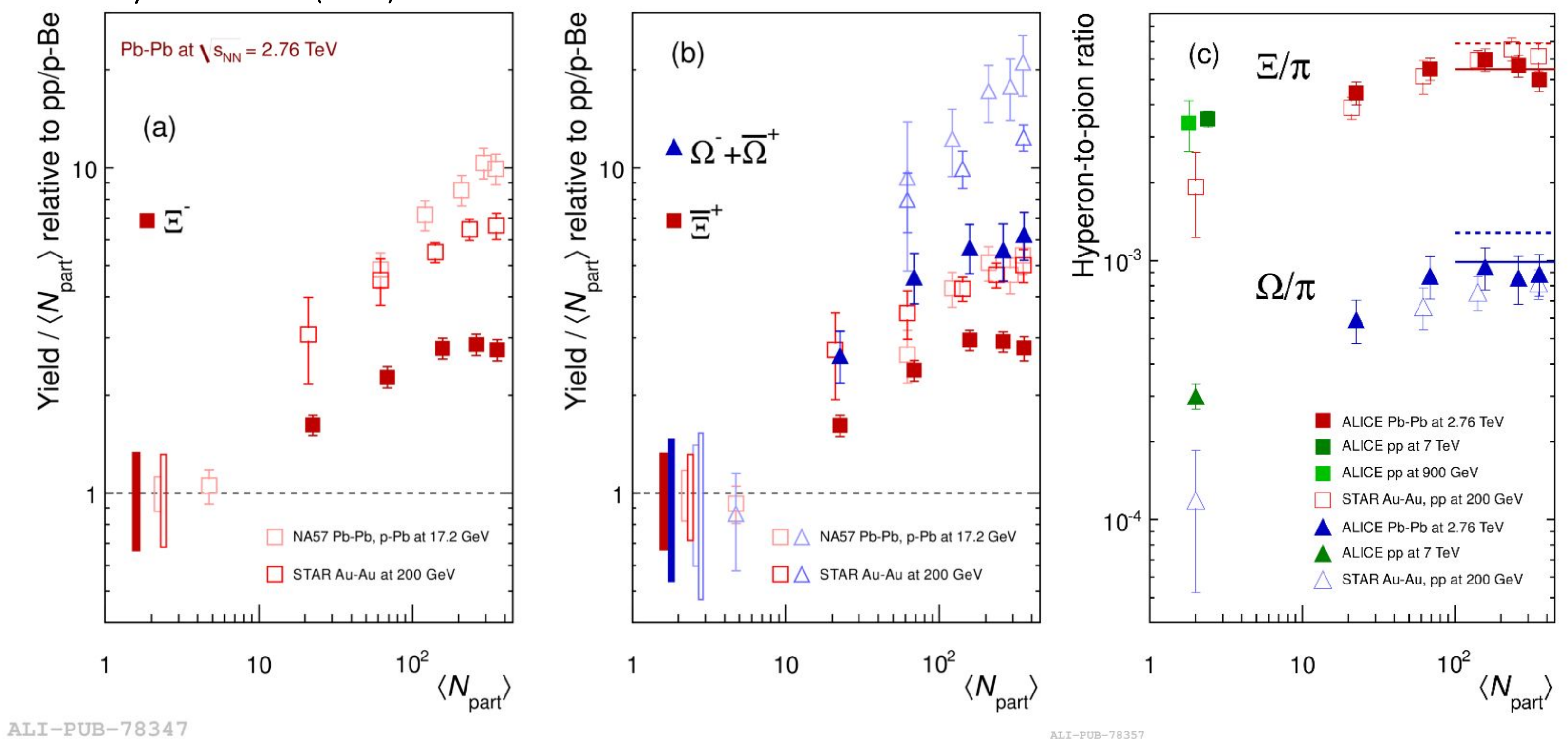

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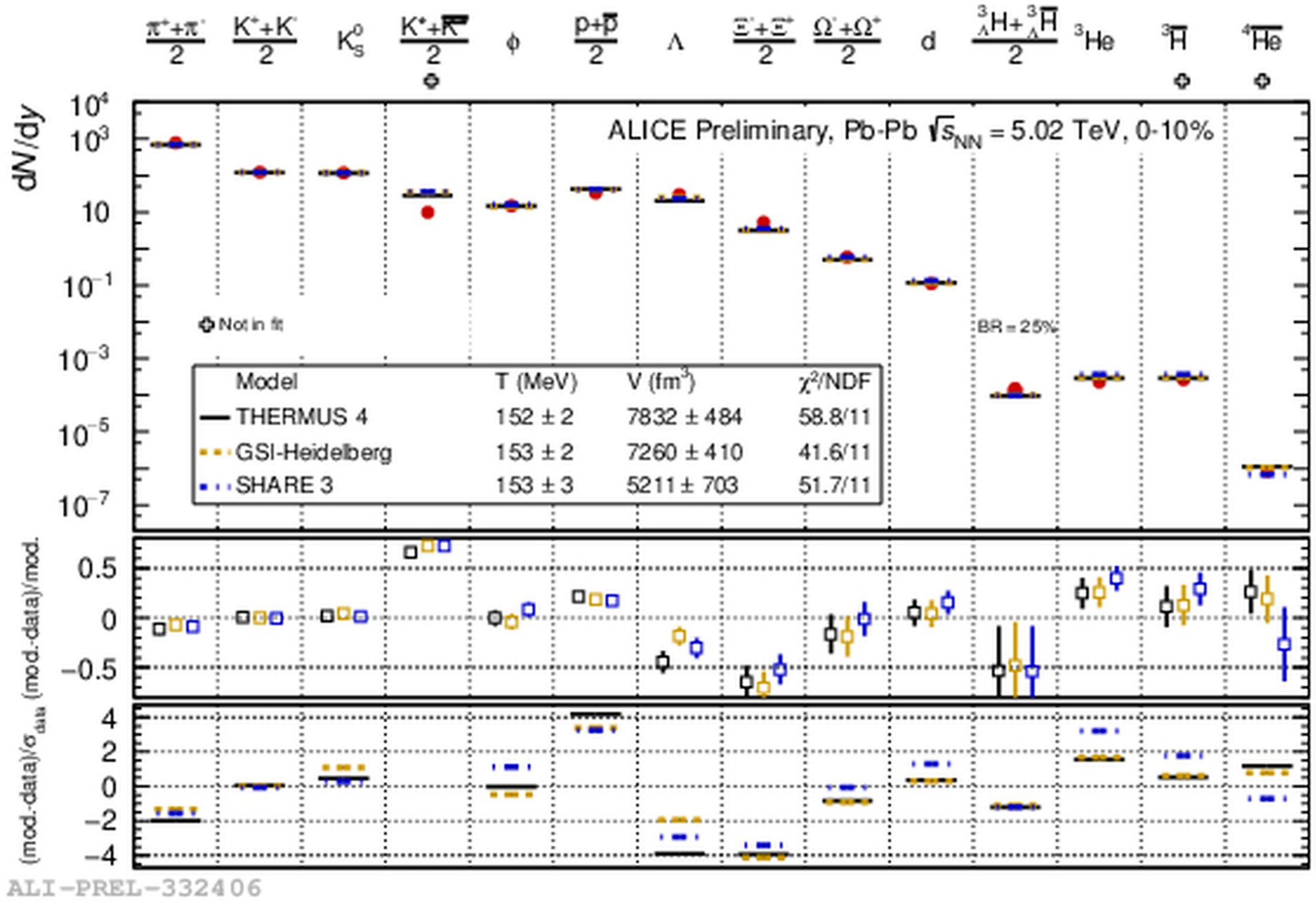
Large systems: the reign of statistical hadronization



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

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

At LHC: μ_B~0 , T_{ch}~ 153 MeV

Nature 561 (2018) 7723, 321-330

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

Phys. Lett. B 792, 304-309 (2019)

Phys. Rev. C 90 (2014) 5, 054907

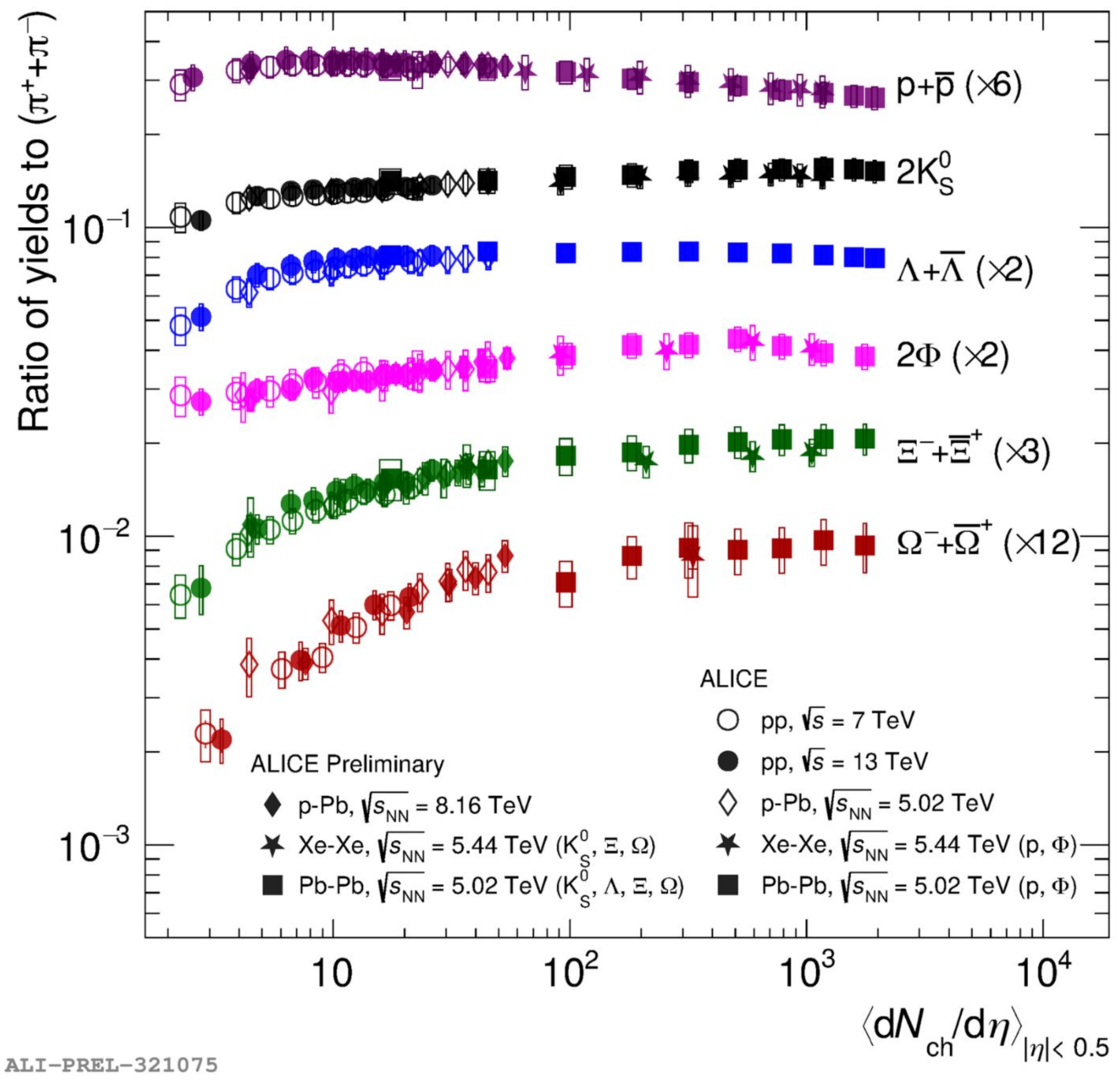
Other approaches try to solve p & *Ξ* issues with flavor-dependent T_{ch}

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

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

Strange hadron evolution from small to large systems

ALICE, Nature Physics 13, 535–539 (2017)



Iconic figure at the LHC:

- smooth strangeness enhancement (SE) VS final state multiplicity
- Strange content hierarchy: **SE(Ω) > SE(Ξ) > SE(Λ,K^0_S)**
- strangeness- and not baryon-related
- peculiar role of ϕ meson

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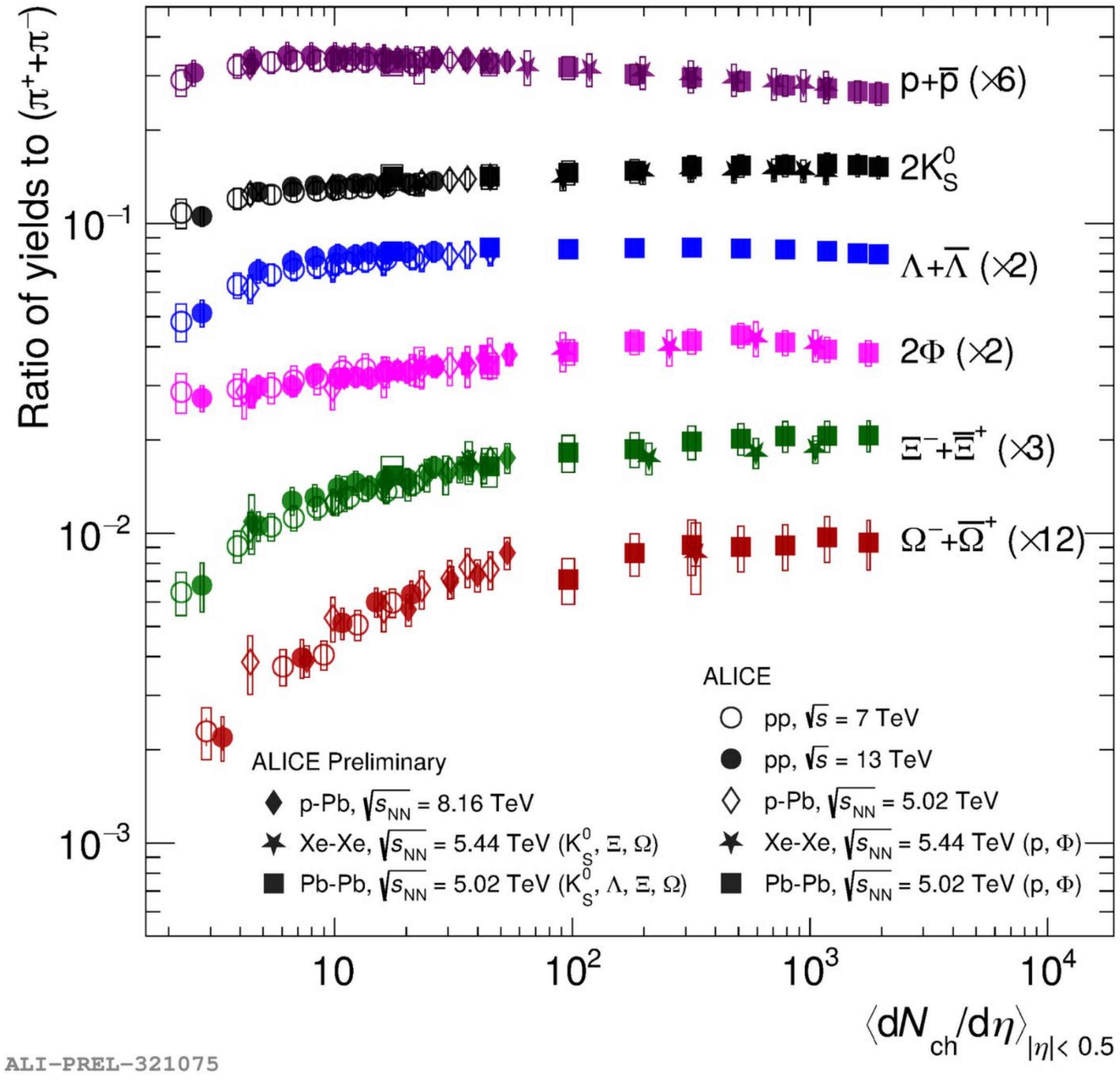

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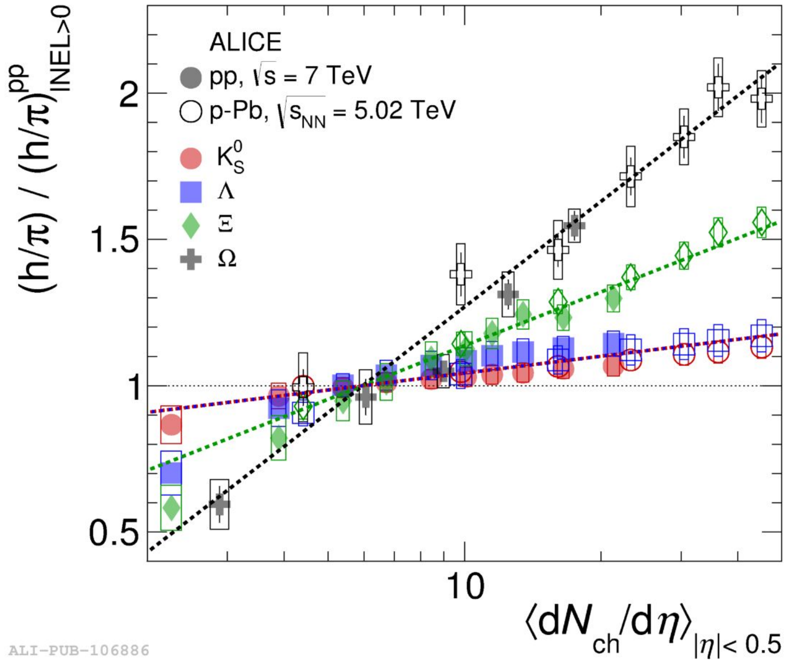

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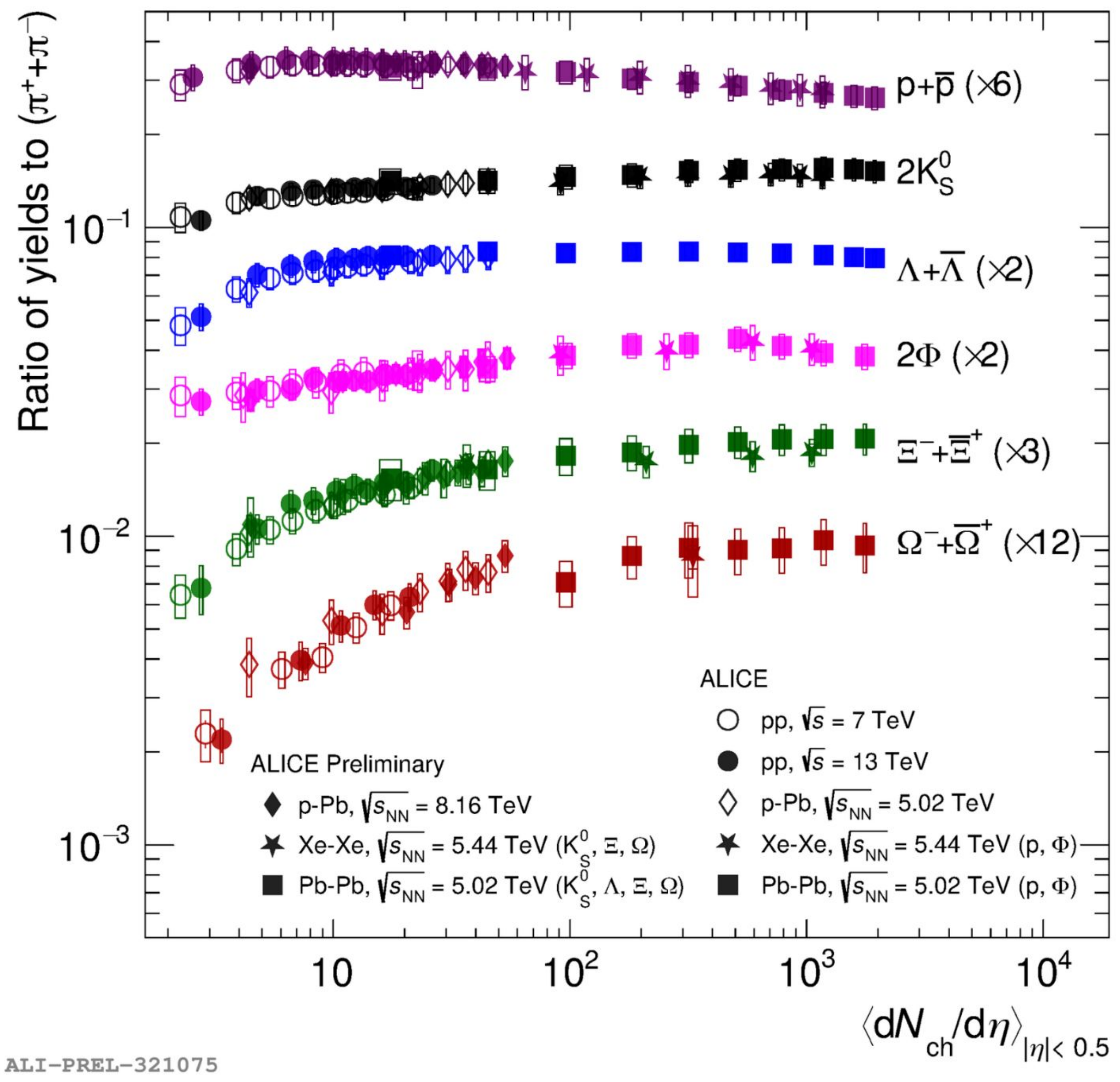

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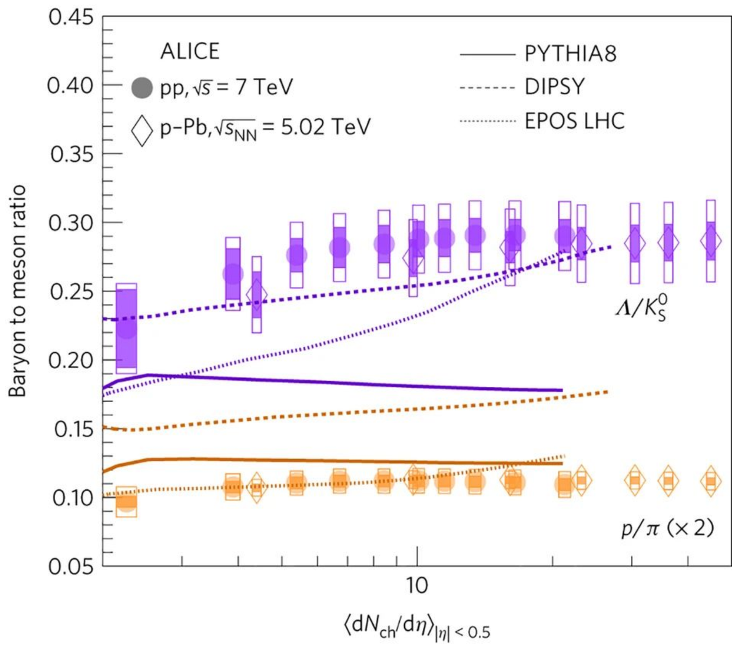
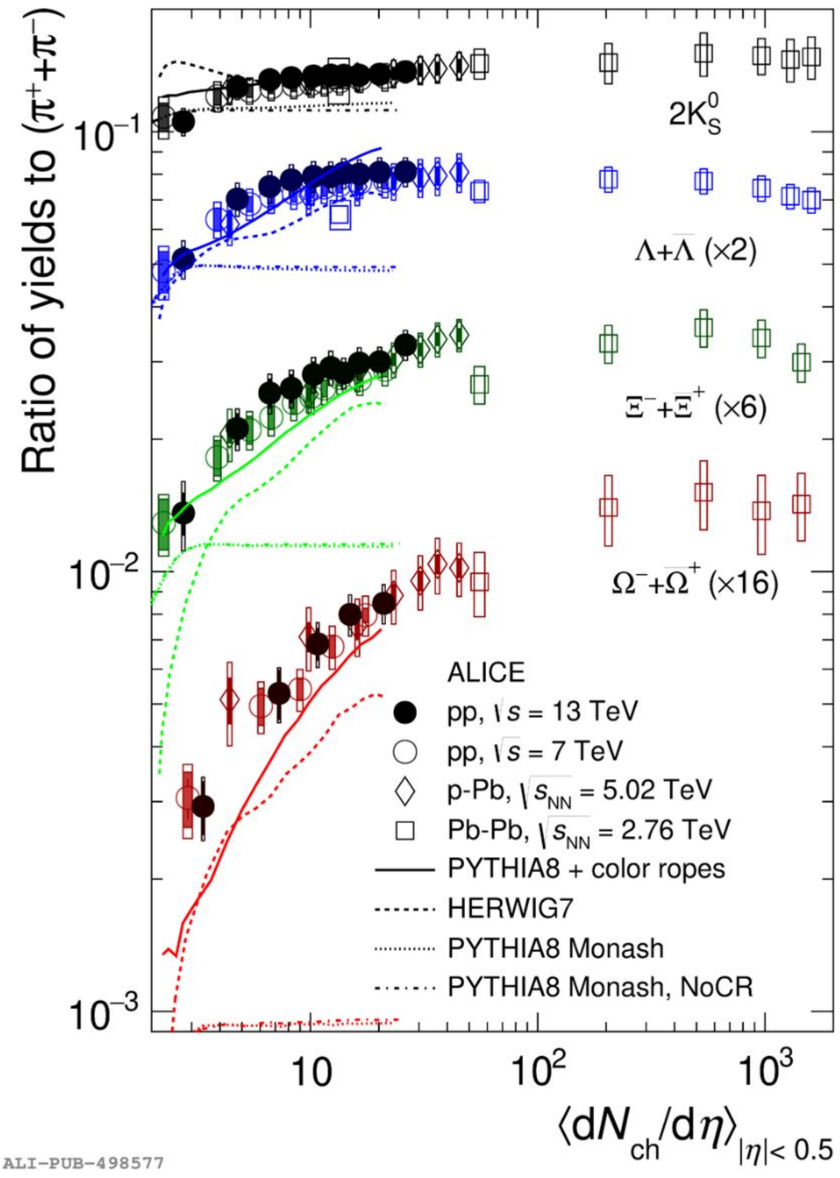
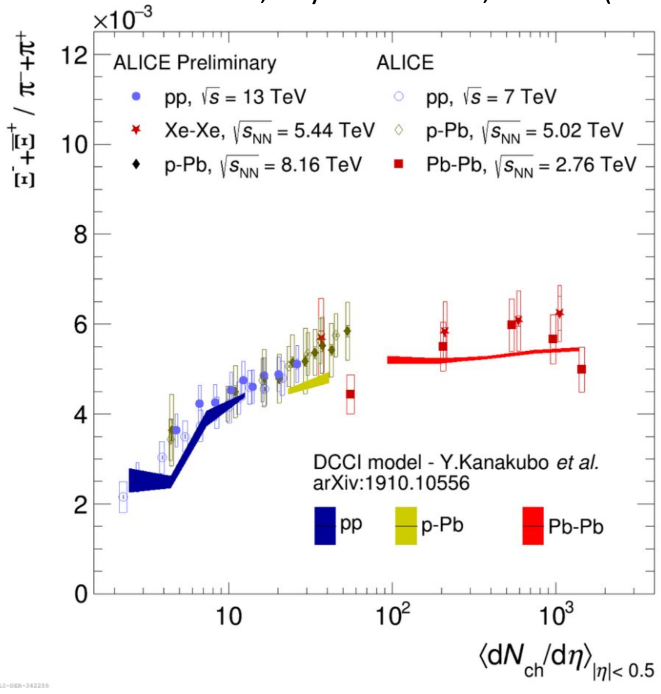


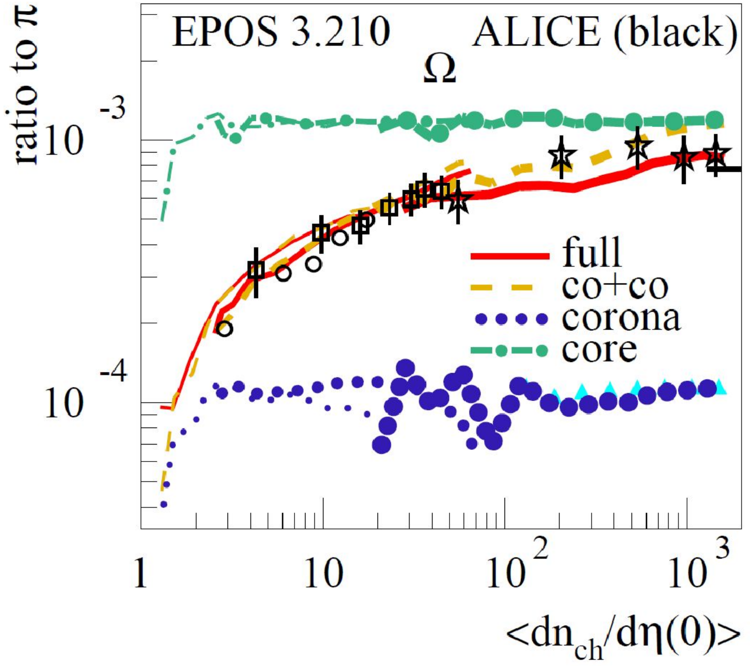
Strangeness enhancement: model comparison

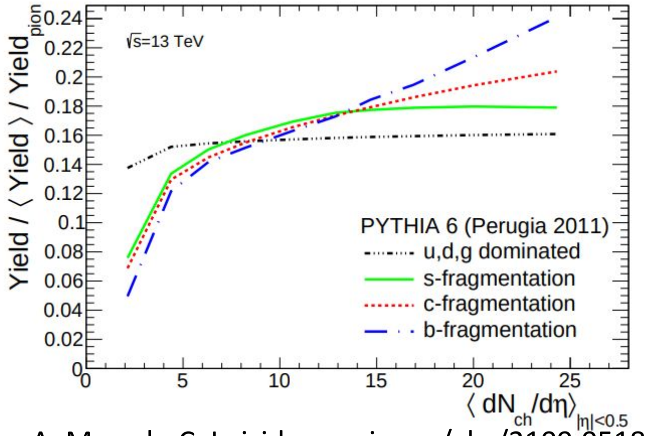
ALICE Collaboration, Eur. Phys. J. C 80 (2020) 693



Y. Kanakubo at al., Phys. Rev. C 101, 024912 (2020)





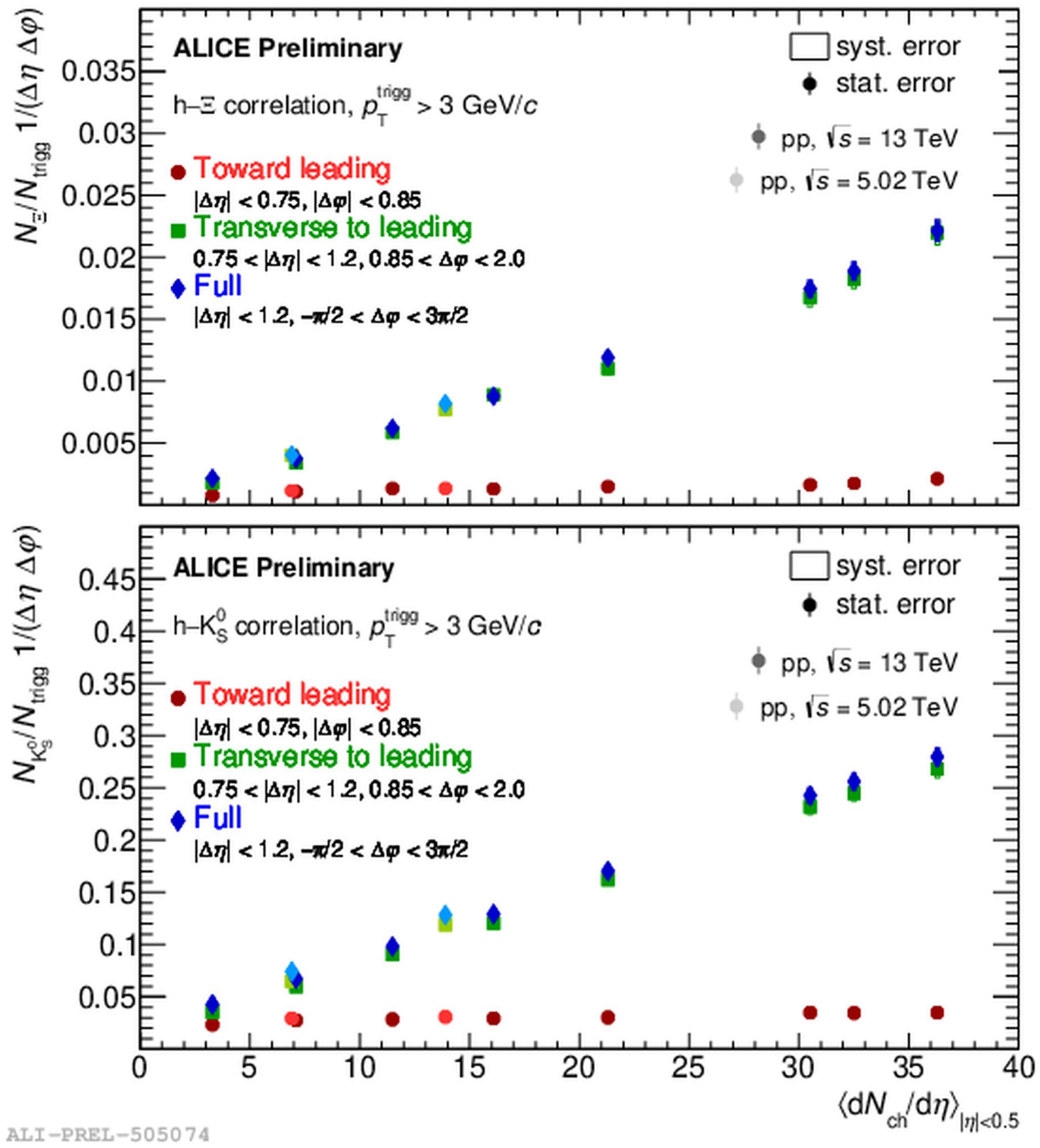


A. Morsch, C. Loizides, arxiv.org/abs/2109.05181

Models have been challenged for many years in trying to describe these observations

Recently: with very different production mechanisms can qualitatively describe the data

Strangeness enhancement in- and out-of-the jet



(multi-)strange hadrons are mostly produced outside the jet [in events with a leading particle with p_T > 3-4 GeV/c]

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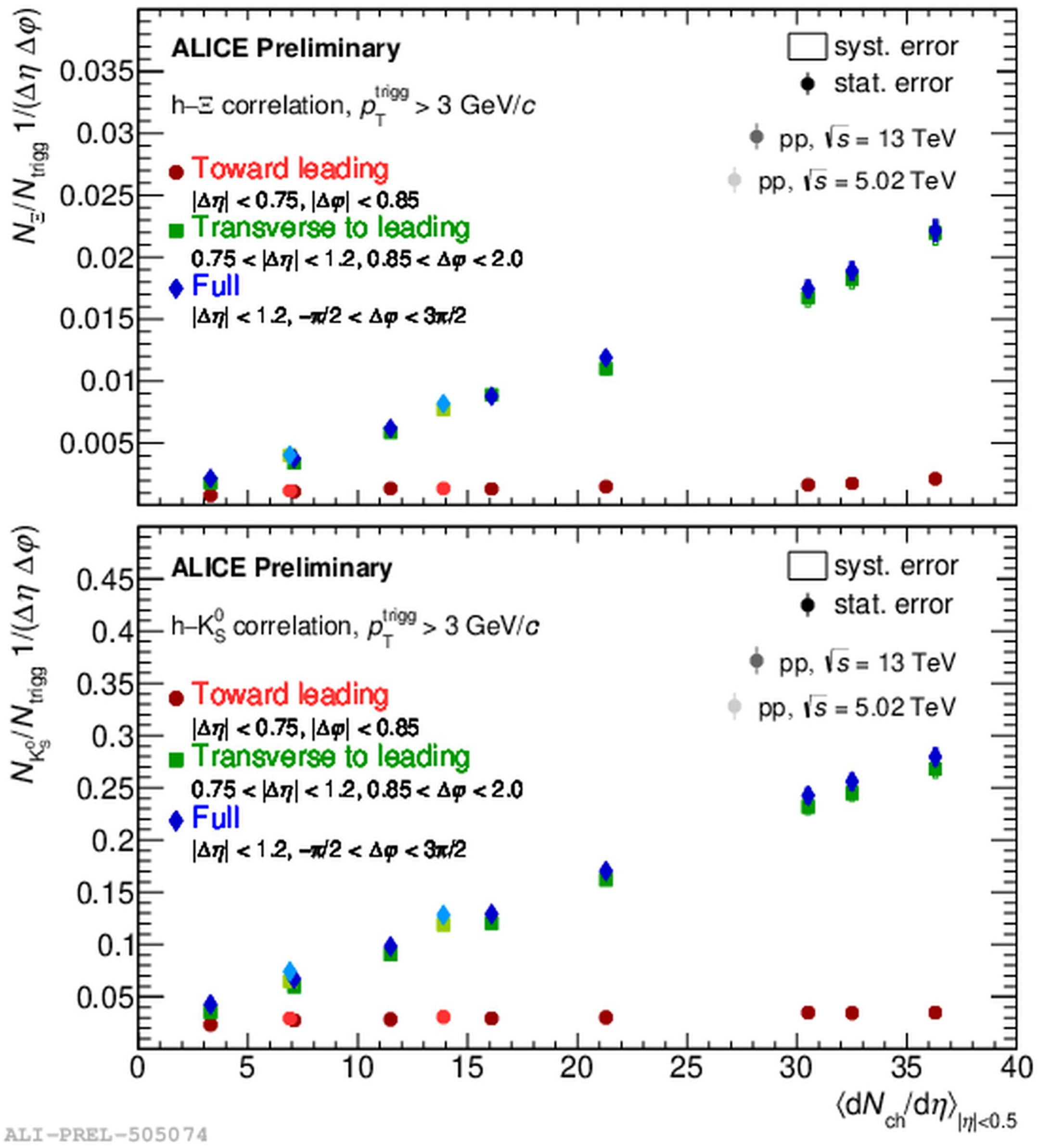
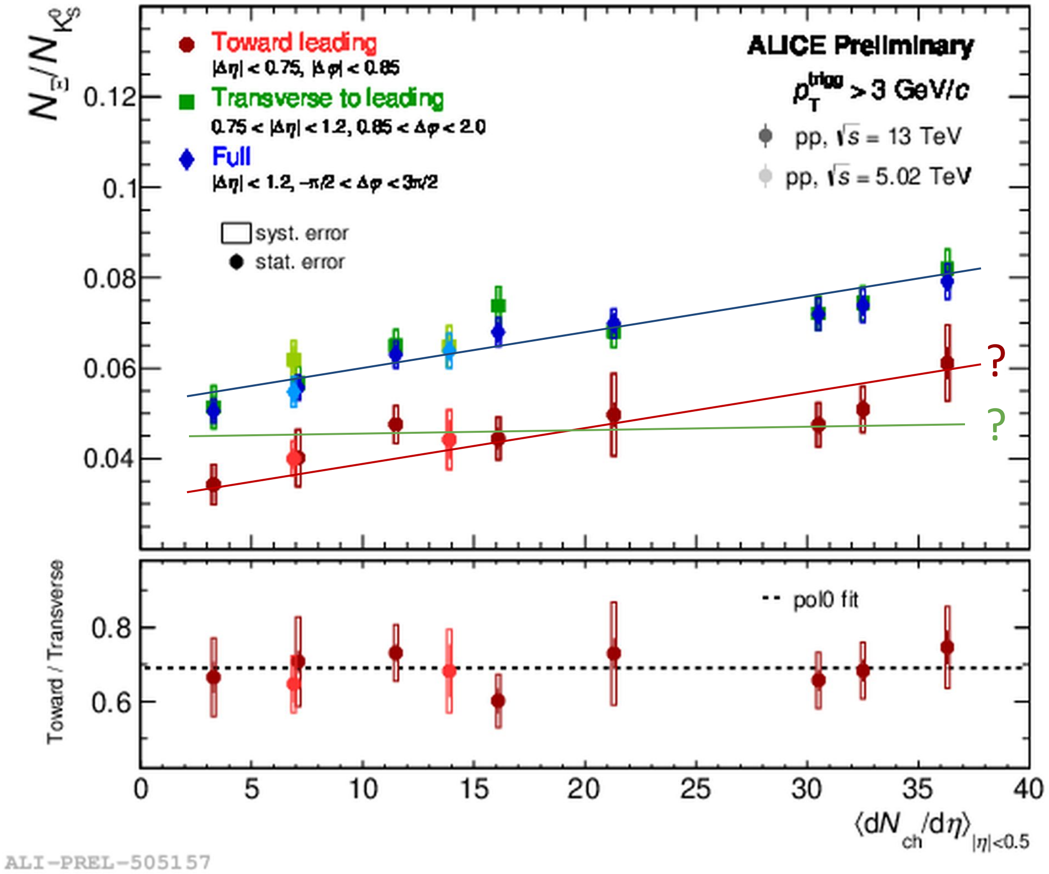
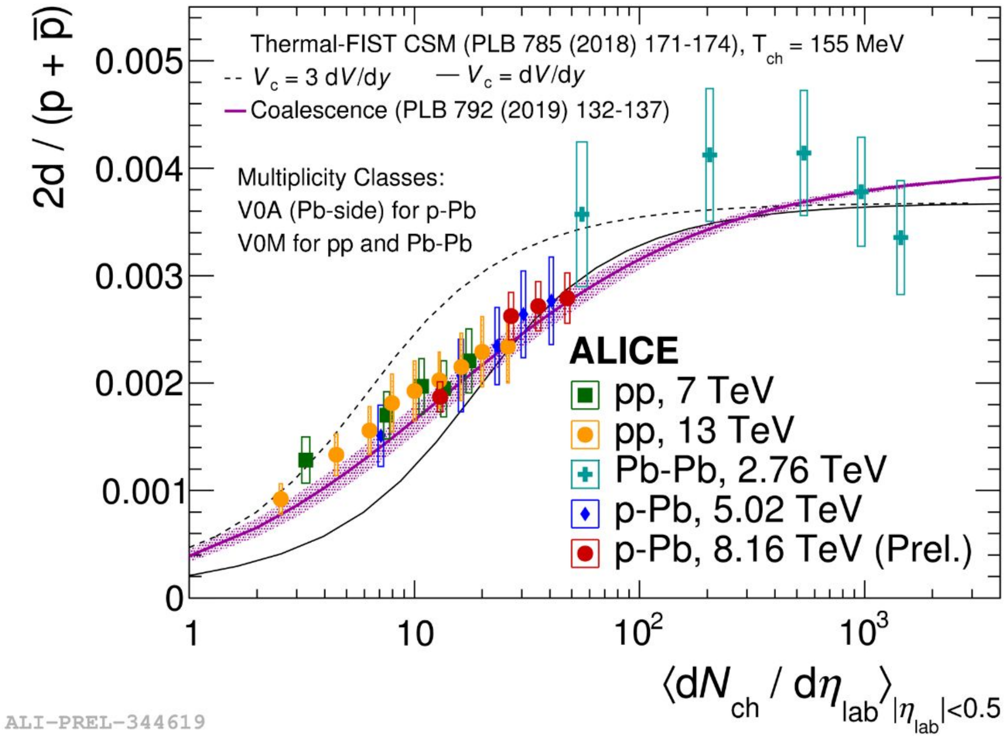


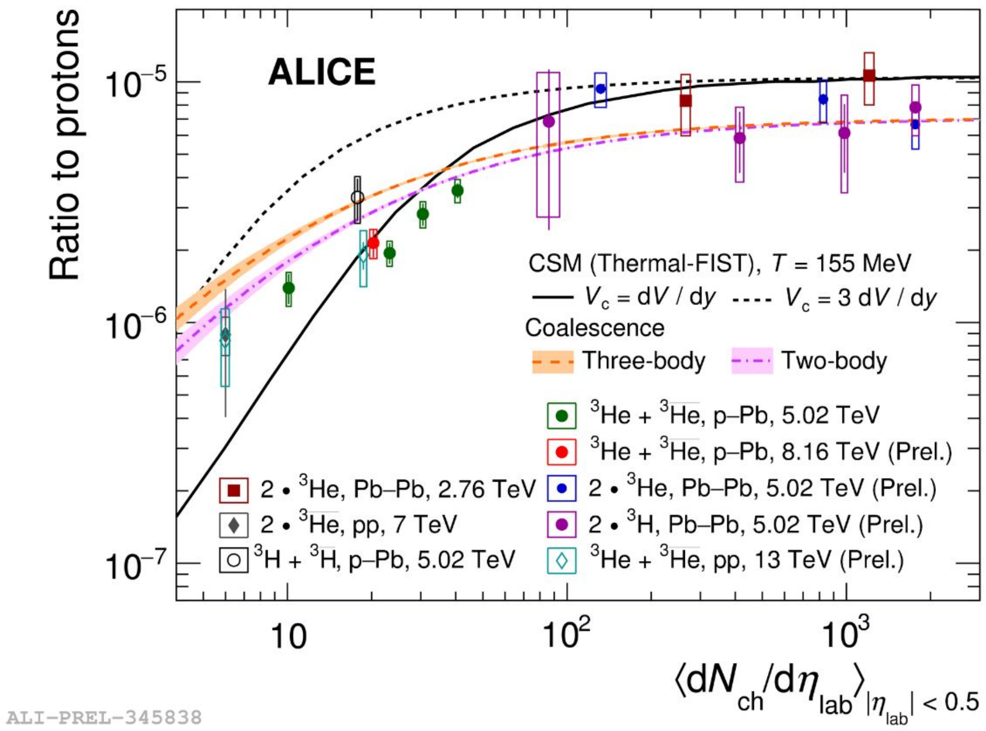
(multi-)strange hadrons are mostly produced outside the jet [in events with a leading particle with p_T > 3-4 GeV/c]

… but (in-) and (out-of-)jet SE looks ~the same…



Not only strangeness: nuclei evolve too!





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

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

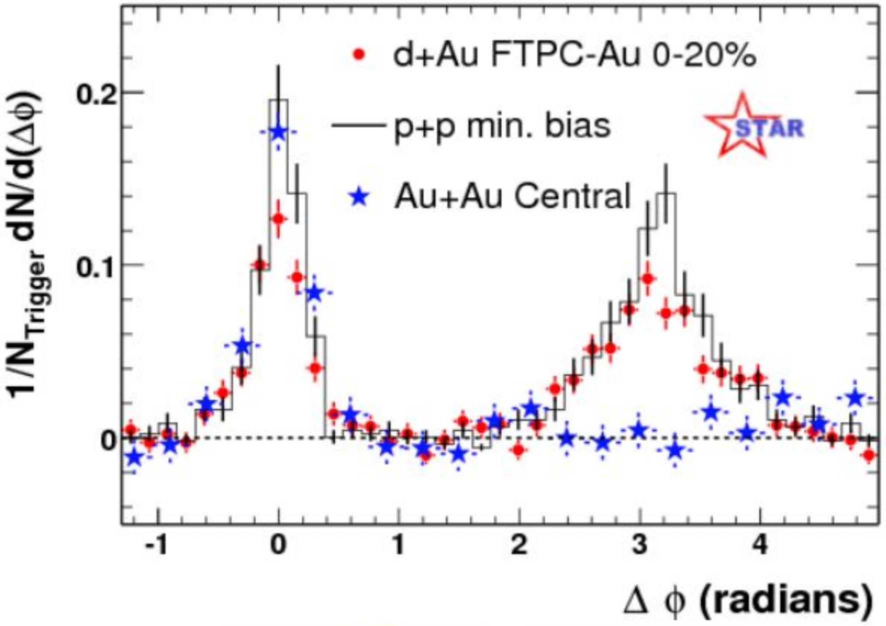
Qualitative agreement with Thermal Canonical Statistical Model and coalescence model.

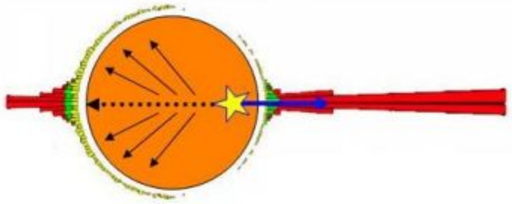
Hard Probes

Jet quenching

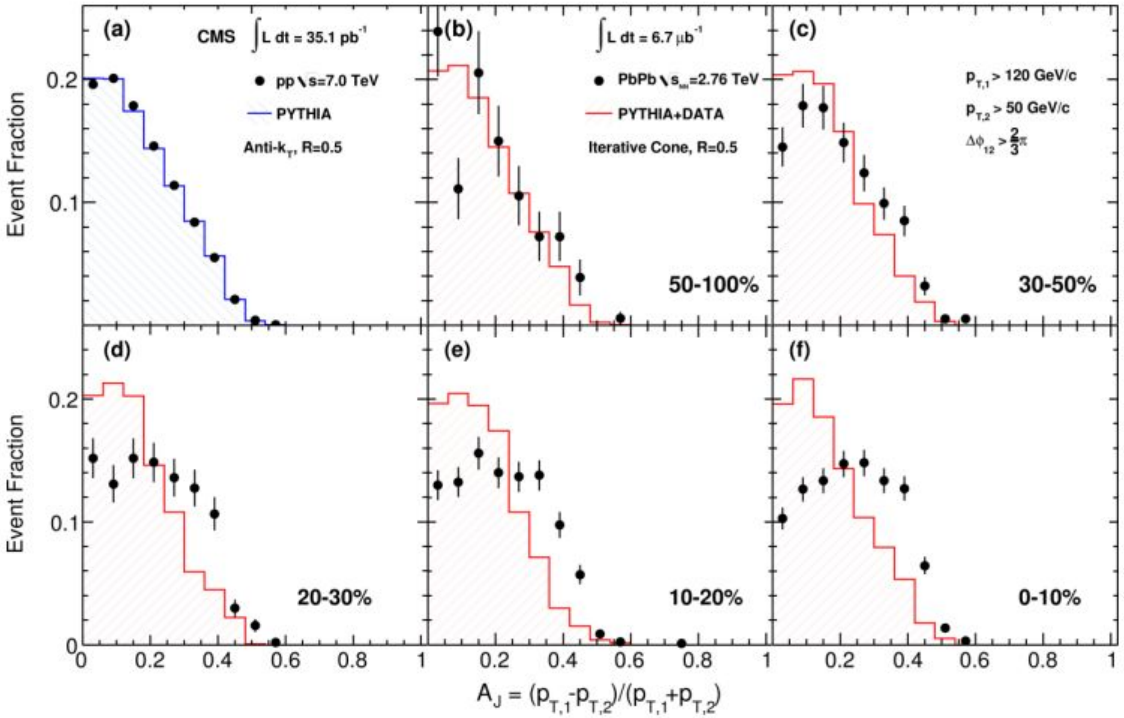
Recoiling jet suppressed by energy loss inside the medium

Clearly observed by STAR at RHIC…





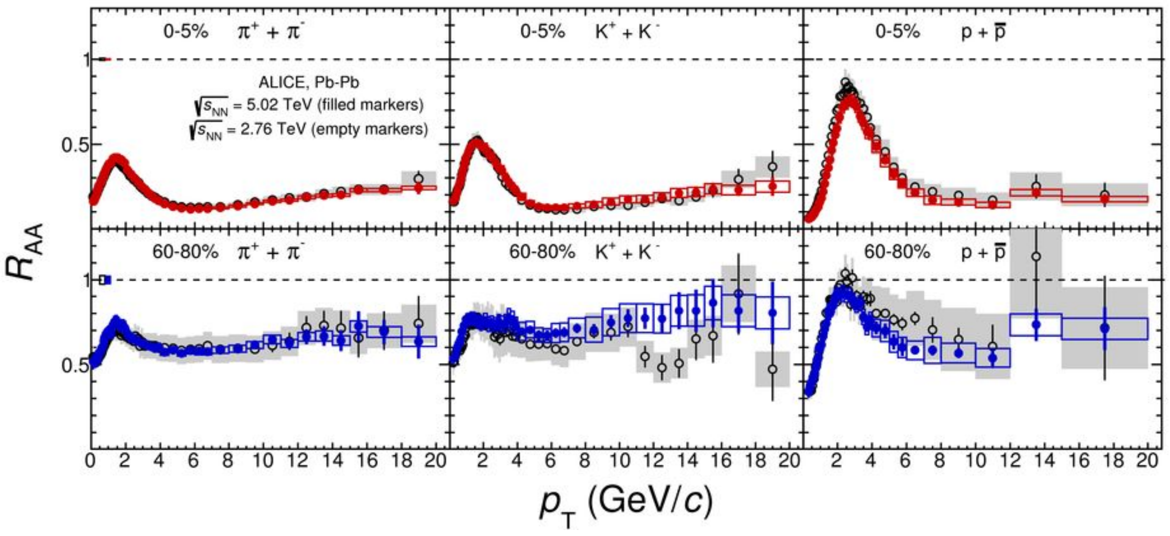
… and extensively studied at the LHC

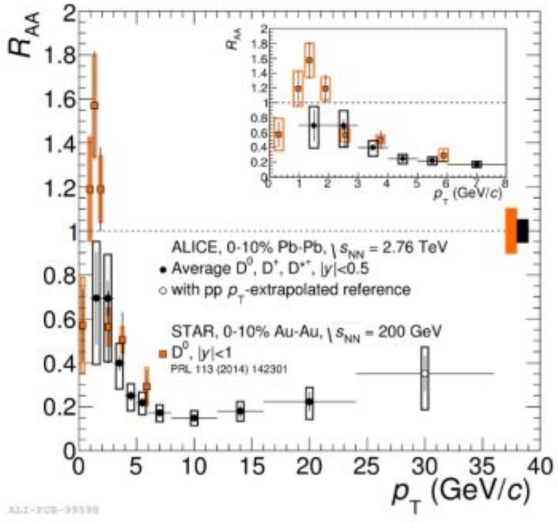


Nuclear modification factor (R_{AA}): heavy ions

Nuclear modification factor, indicates how far A-A observations are from the “normal” pp (binary scaled)

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{<N_{coll}> d^2N^{pp}/dydp_T}$$





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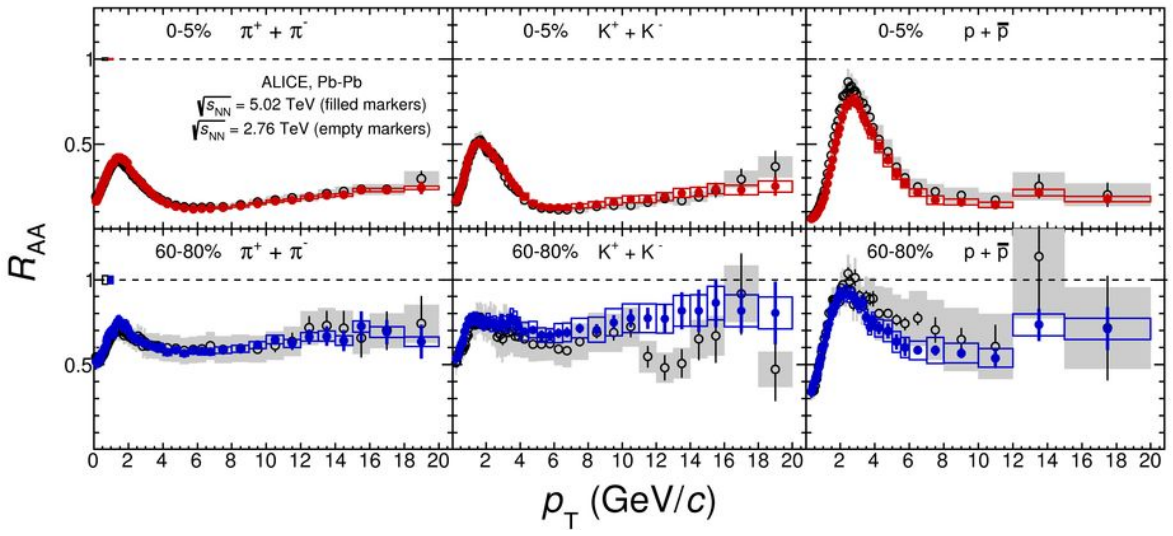
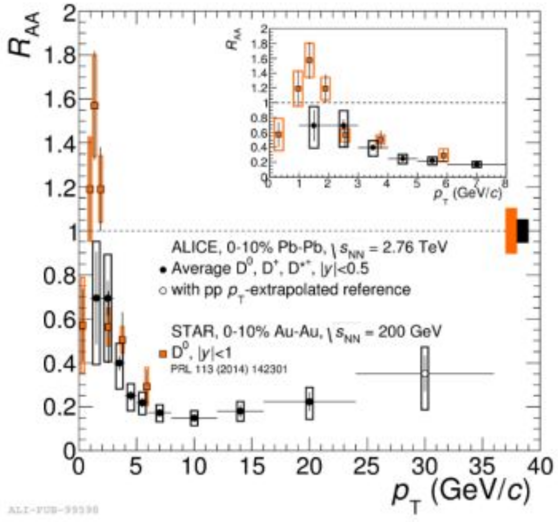
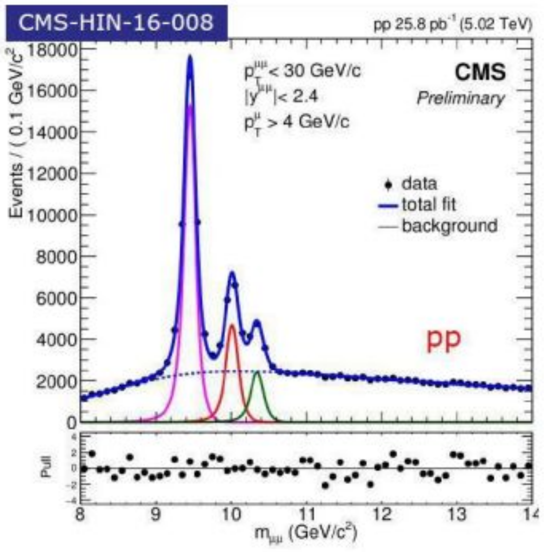
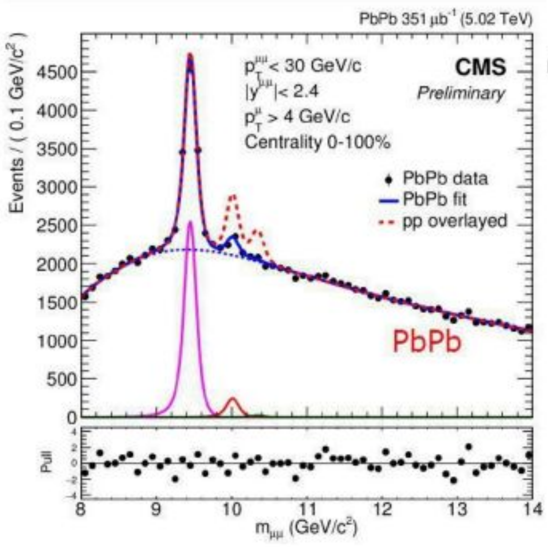
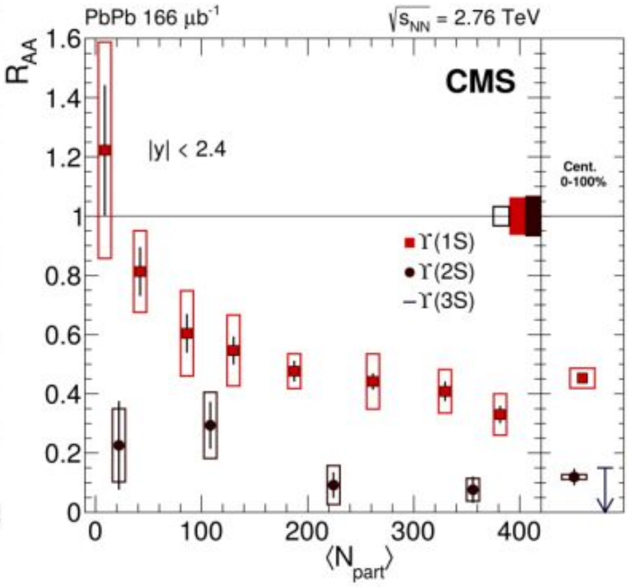


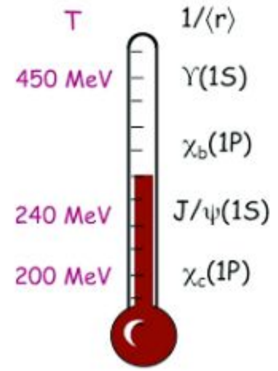




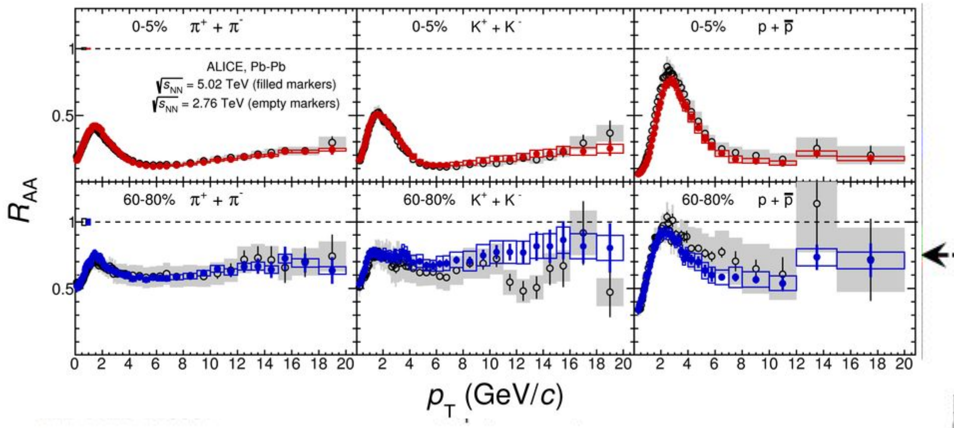


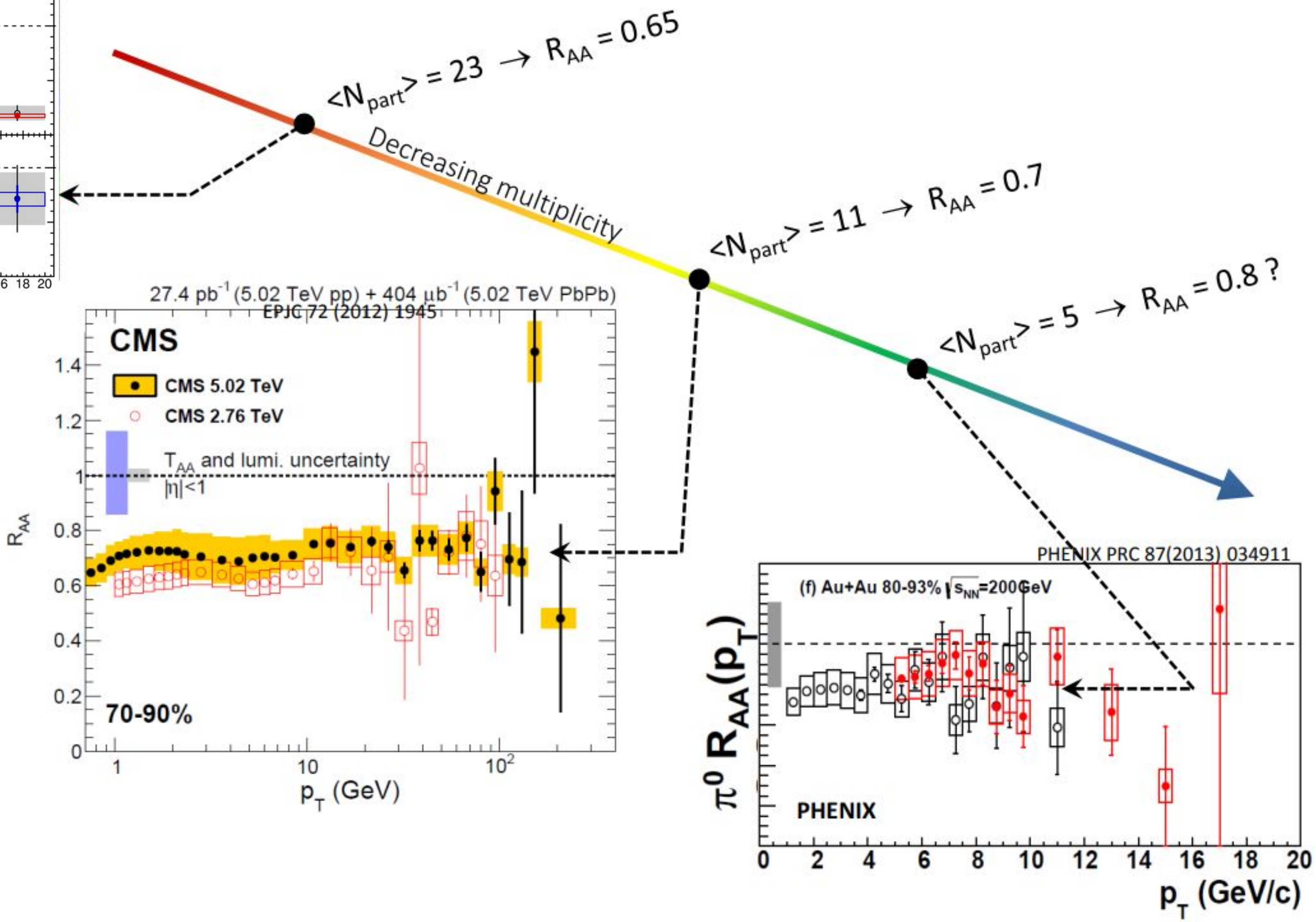


Quarkonia sequential suppression: less-bound states will survive less in a colored medium (Debye screening)



Nuclear modification factor (R_{AA}): heading to smaller systems





$R_{AA} \neq 1$ in A-A down to very low $\langle N_{part} \rangle$ (hence multiplicities)

But what happens in small collision systems?

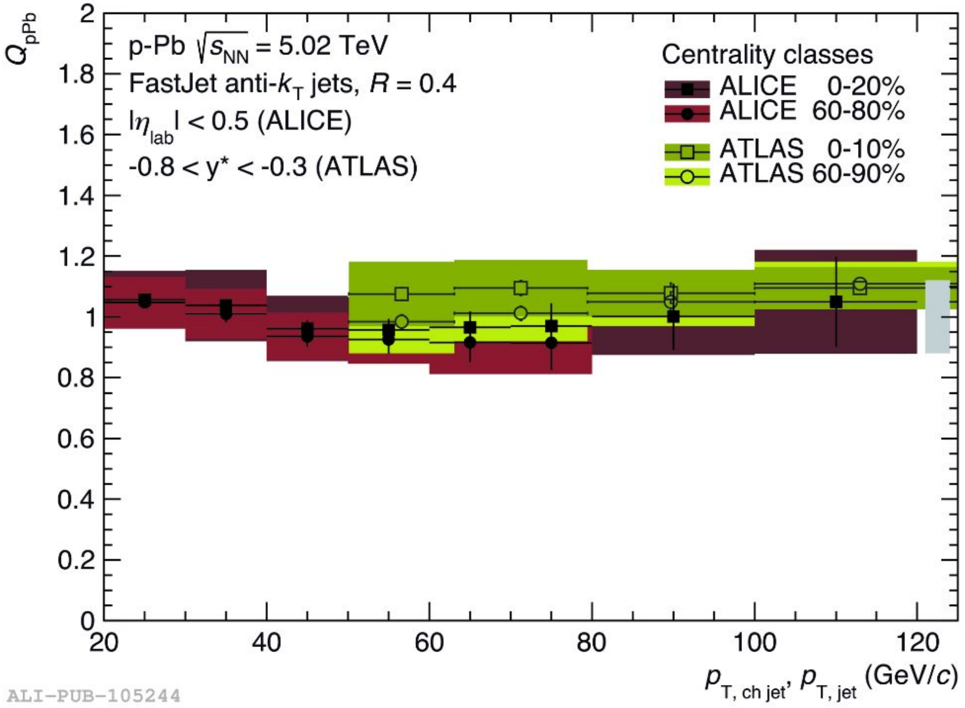
Difficult to define an R_{AA} in pp…!!!

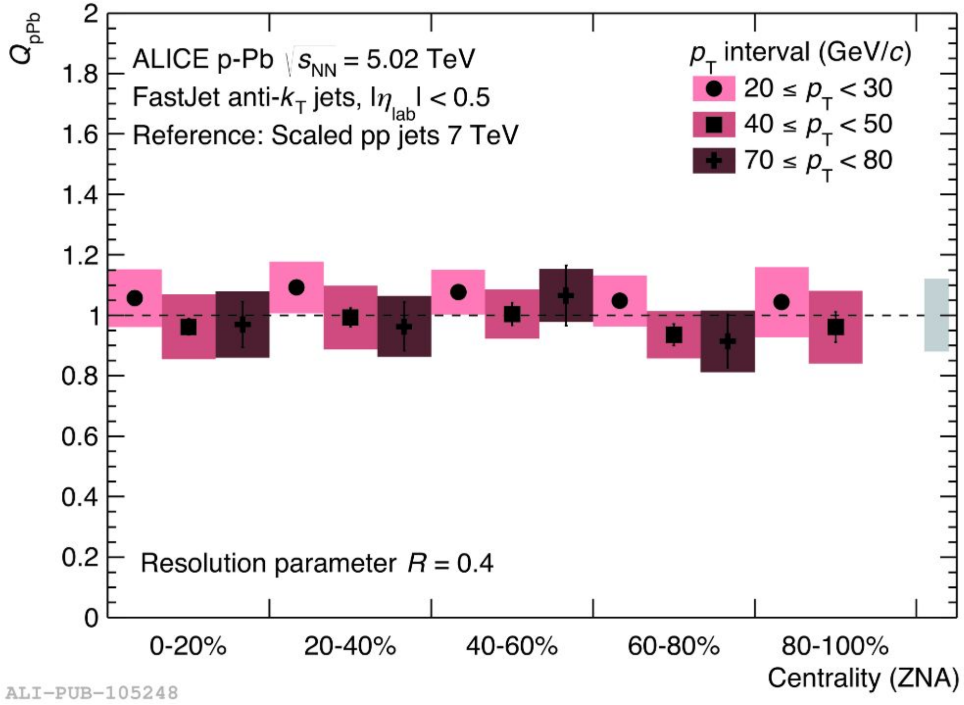
Let's concentrate on p-Pb

↓

…but no jet quenching in small systems…

ALICE, Eur. Phys. J. C76 (2016) 271



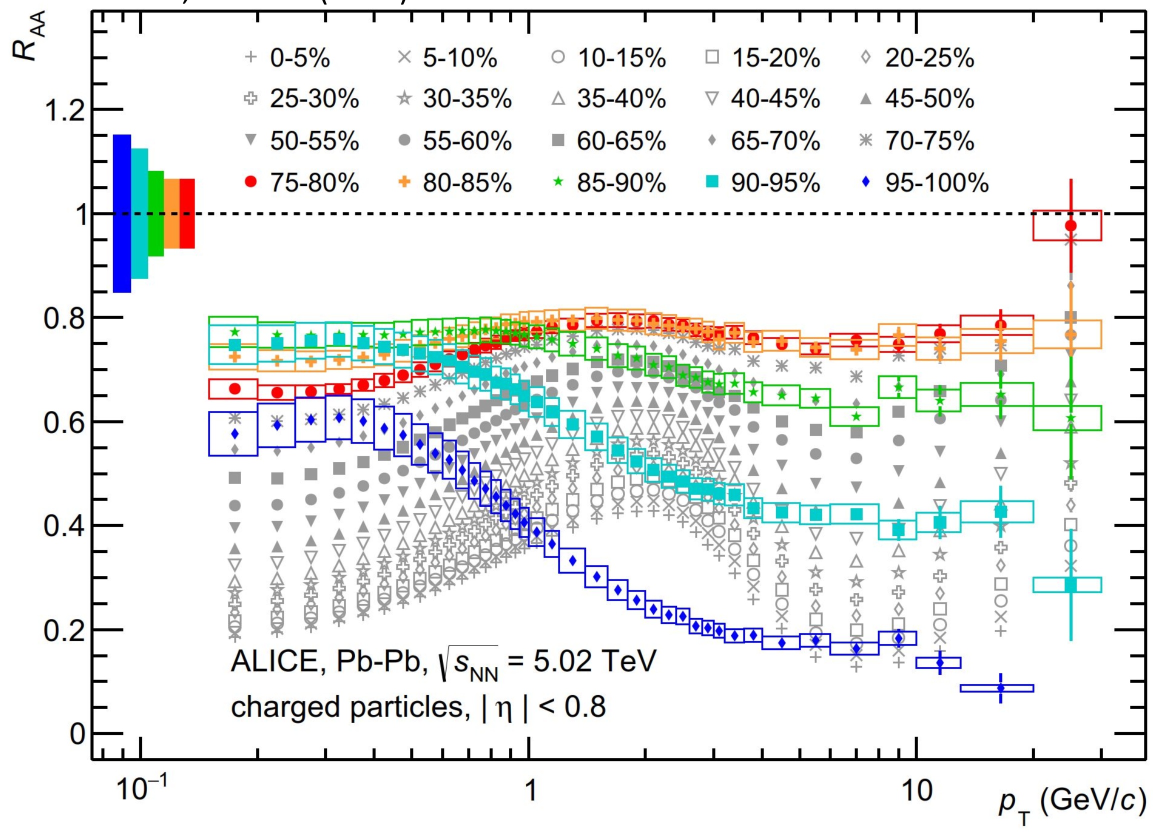


No evidence of **jet quenching in p-Pb** collisions at the LHC

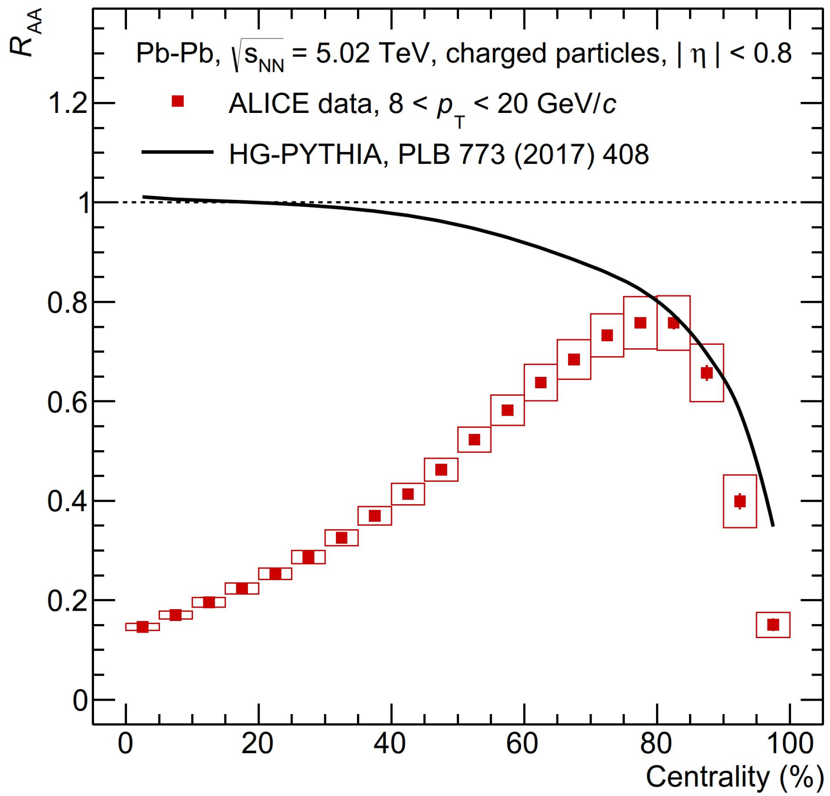
High-p_T hadrons do also not show any suppression

Is it a real problem?

ALICE, PLB 793 (2019) 420-432



arXiv:1705.08856 [nucl-ex]

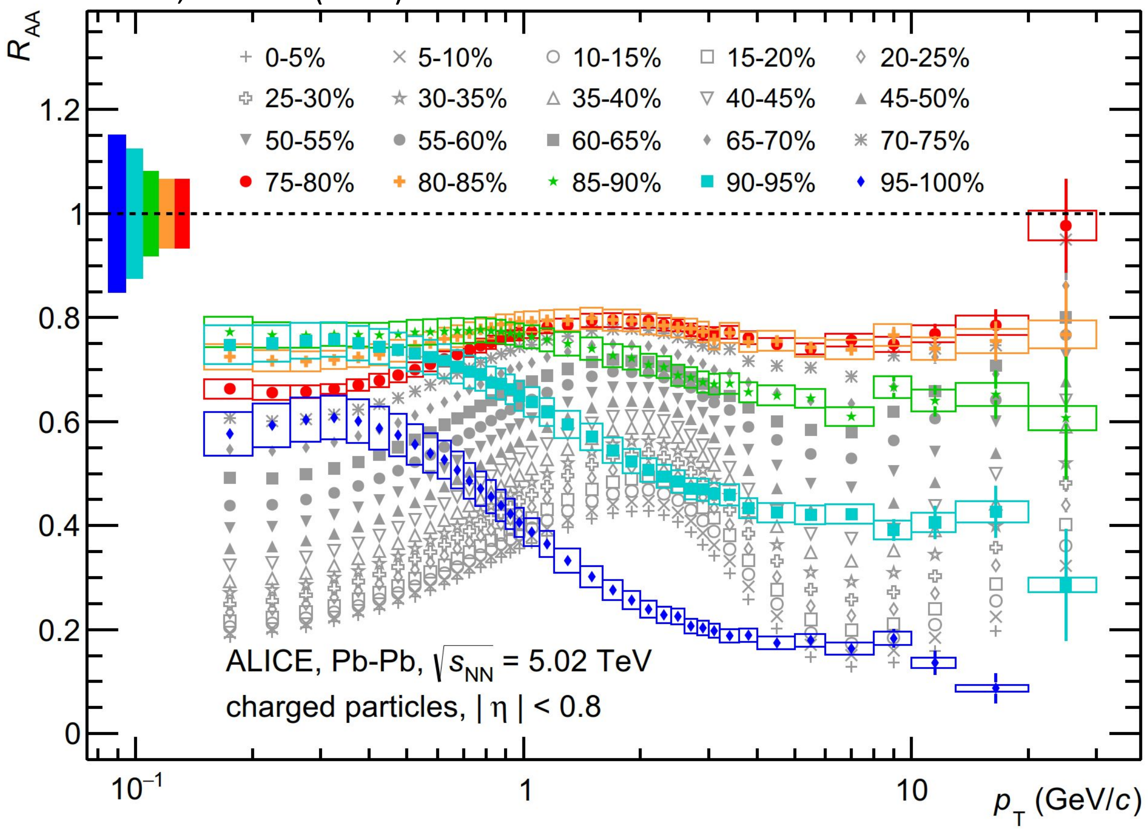


R_{AA} in very peripheral collisions is far from 1
… but it actually decreases from the value it has in semi-peripheral. Why?

The answer is **selection bias**:
PYTHIA (with no energy loss) ~describes R_{AA} in very peripheral Pb-Pb collisions from ALICE!

Is it a real problem? NO

ALICE, PLB 793 (2019) 420-432



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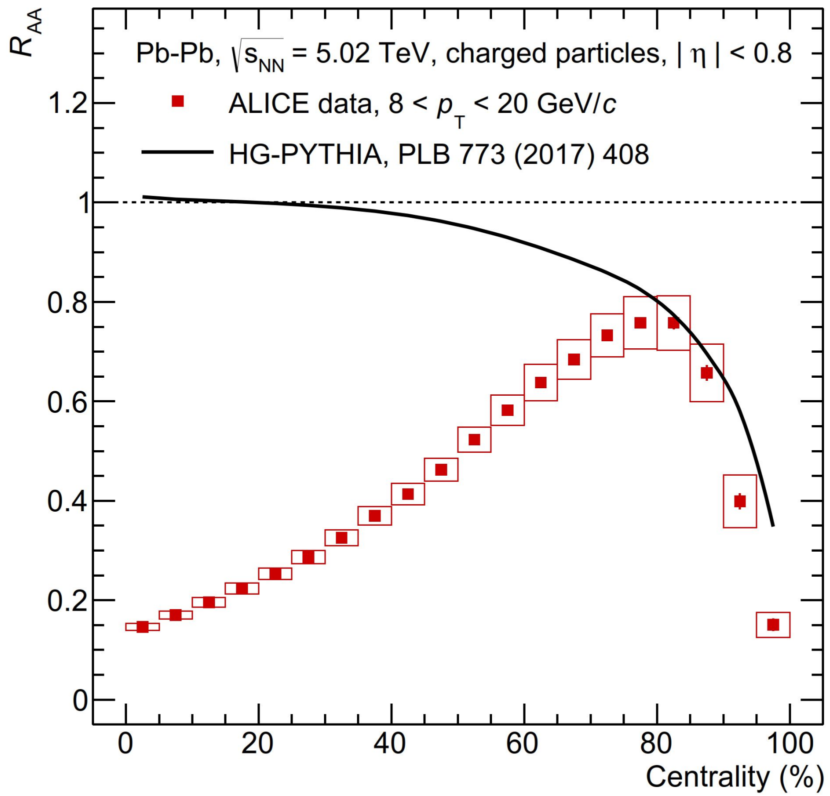

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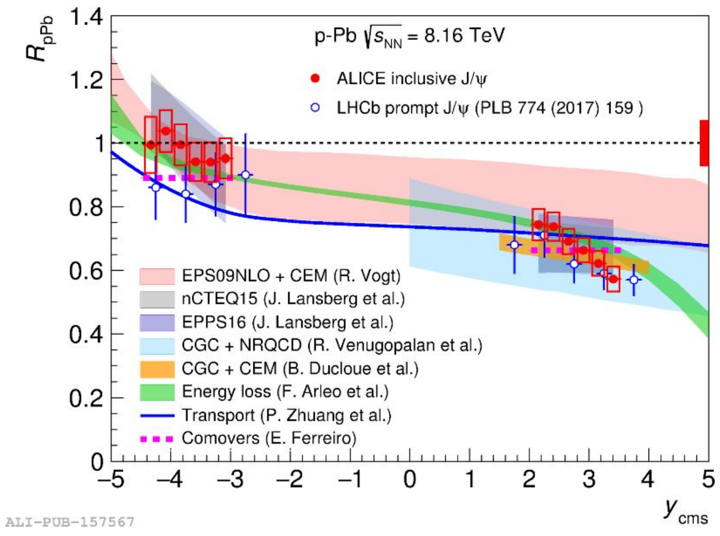
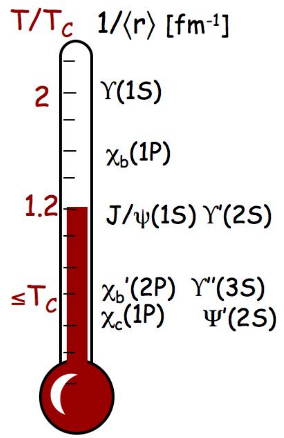
Quarkonia in small systems (I)



No F.S. suppression for J/ψ in p-Pb collisions



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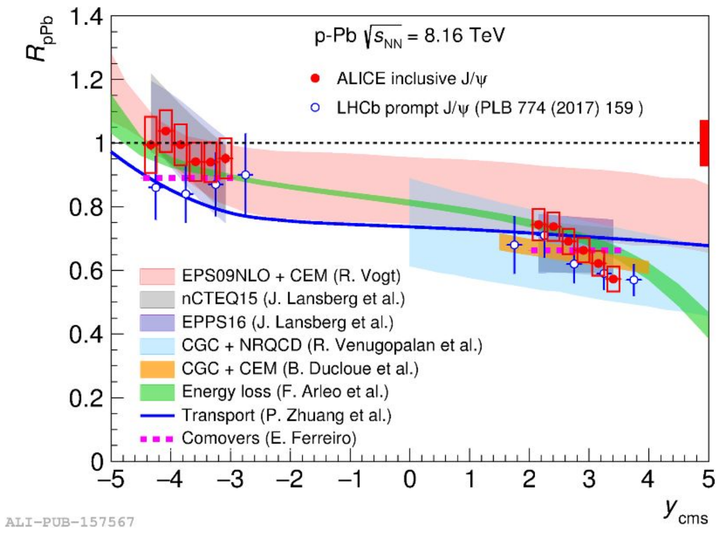
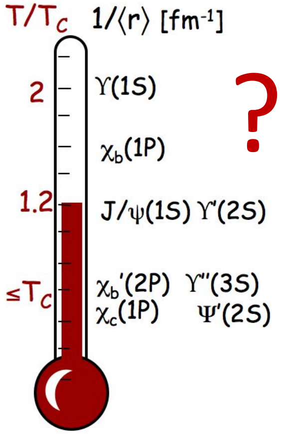
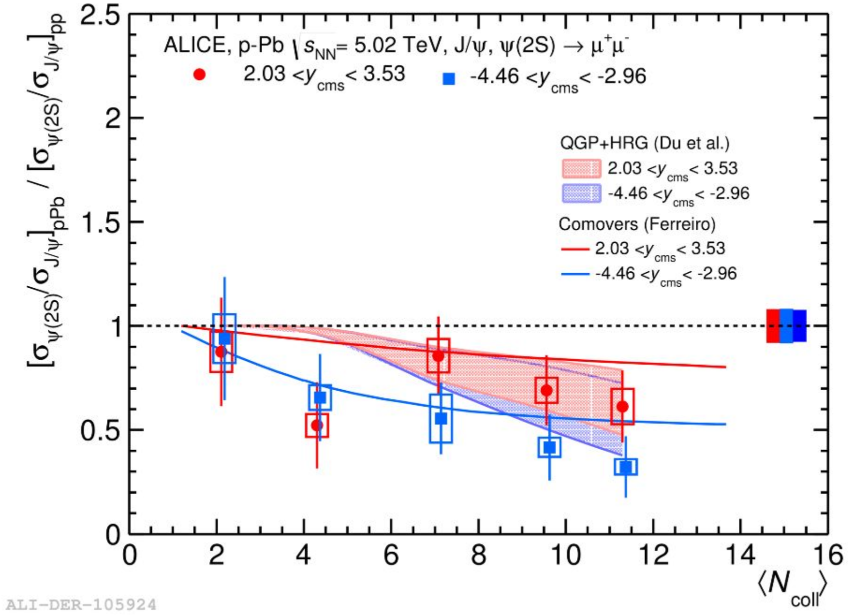


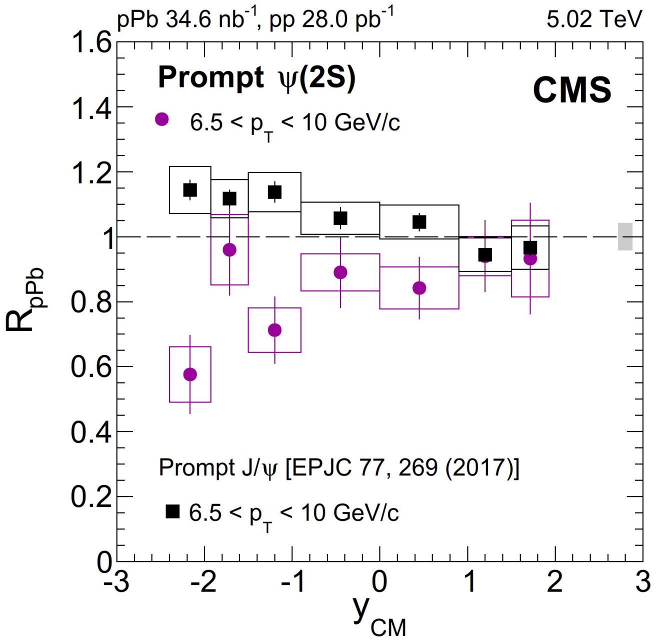
No F.S. suppression for J/ψ in p-Pb collisions

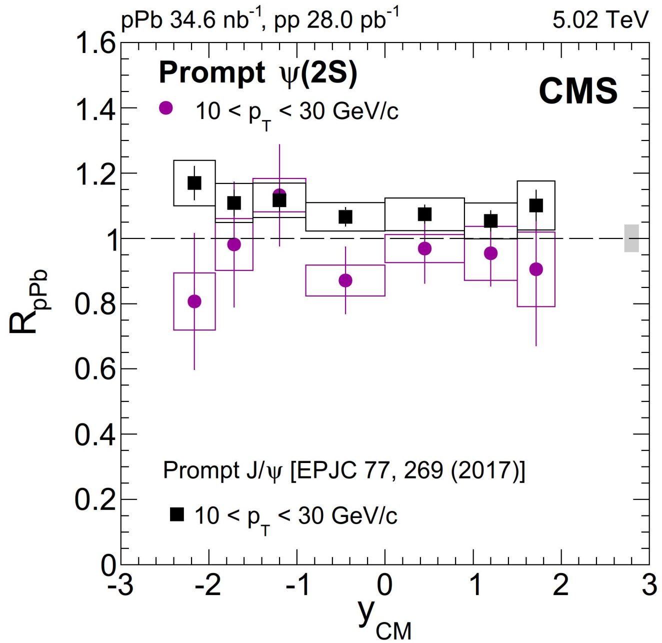
…but ratio ψ(2S)/J/ψ significantly lower than 1 at large N_{coll}!!

Makes sense in the "sequential suppression scenario": ψ(2S) should dissociate at lower T

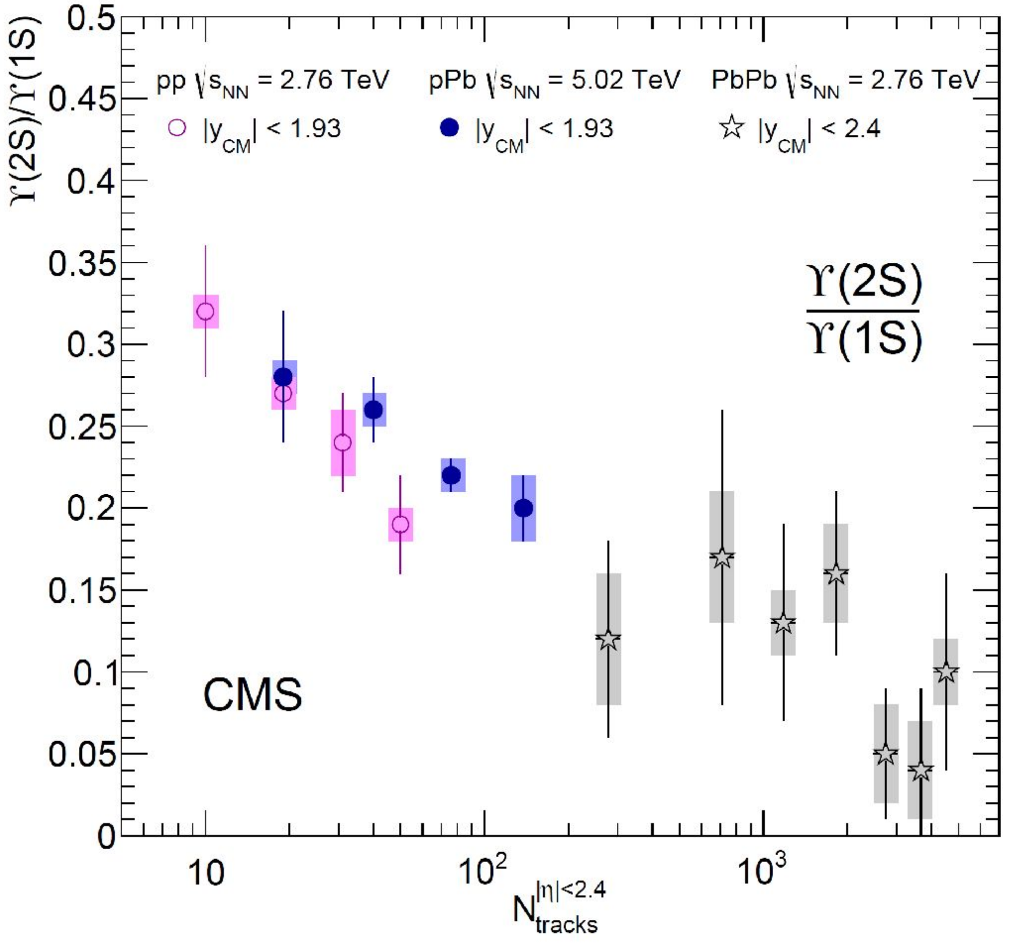


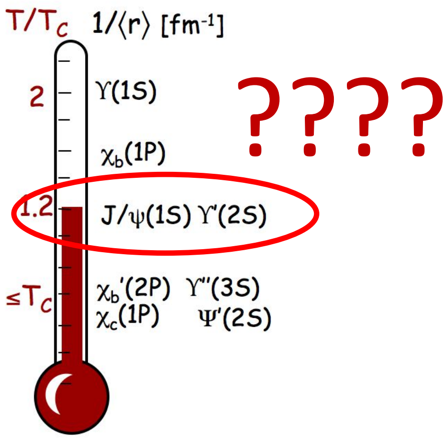






Quarkonia in small systems (II)





...but then, why Υ(2S) is suppressed in p-Pb and even pp high-multiplicity events?

Perspective:

ψ(2S)/J/ψ versus multiplicity in pp collisions?

Wrap-up

Conclusions and outlook

“small systems” path the way to a possibly deeper (microscopic) understanding of QGP phenomena :

- Final state multiplicity drives light flavours observables across systems and energies.
- Strangeness enhancement in pp collisions. In highest multiplicity, hadrochemistry ≈ to the one in the QGP
- $v_2 \neq 0$ in pp and p-Pb collisions at the LHC.
- No parton energy loss observed in pp and p-A
- Intriguing (and unclear) results on quarkonium suppression in p-A (and pp!) collisions