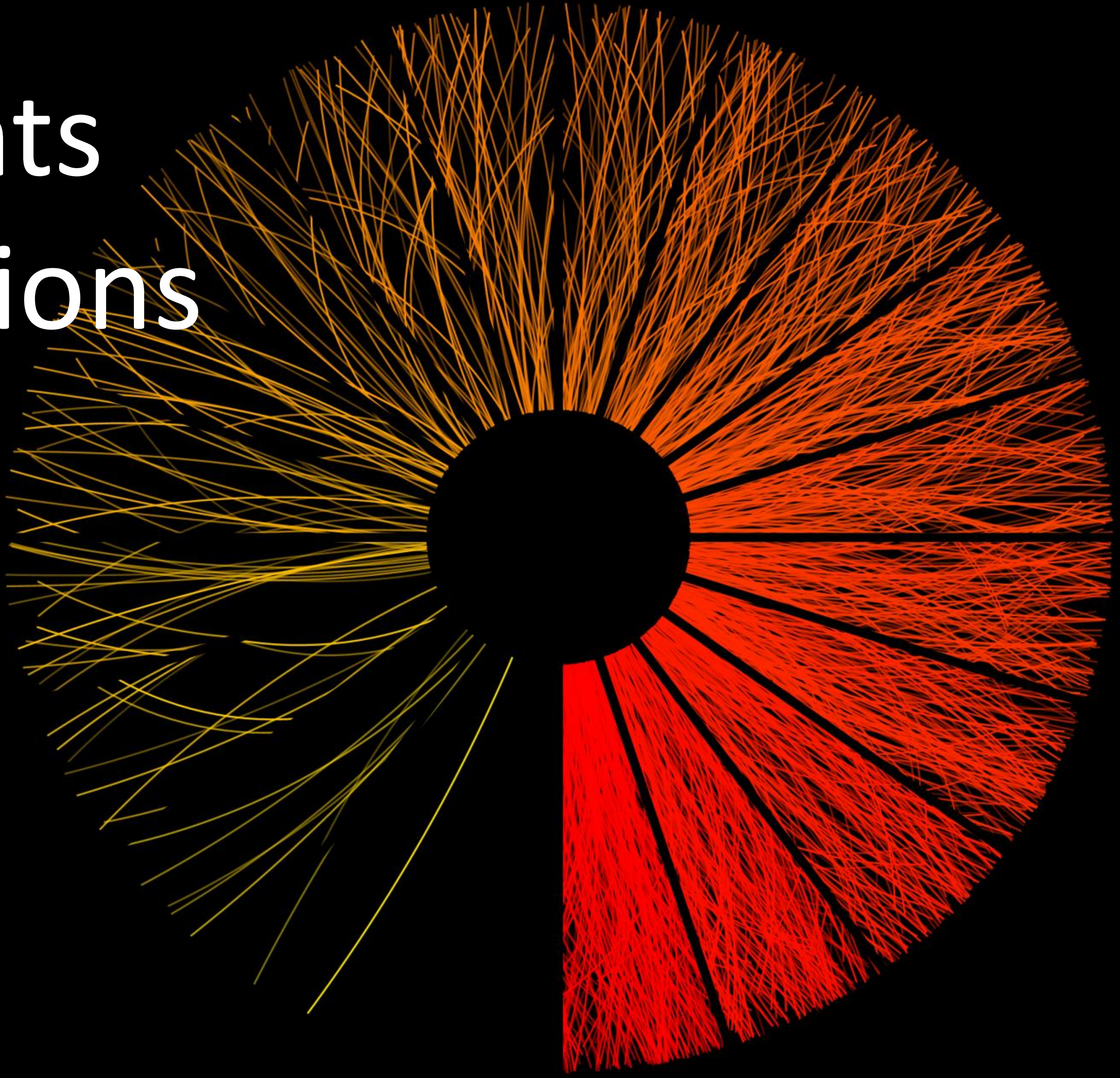
QCD measurements in heavy-ion collisions



Livio Bianchi
QCD@LHC 2018
TU Dresden

Livio.Bianchi@cern.ch

Overview

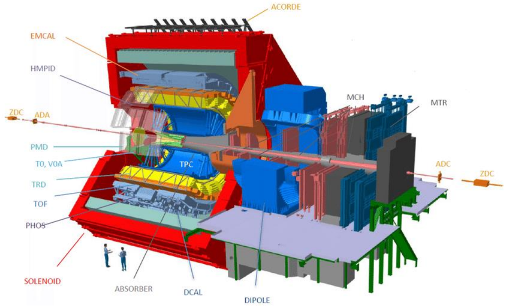
Introduction

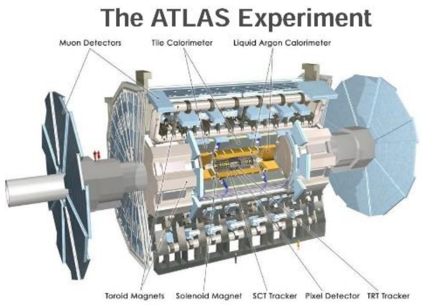
- Why?
- How?

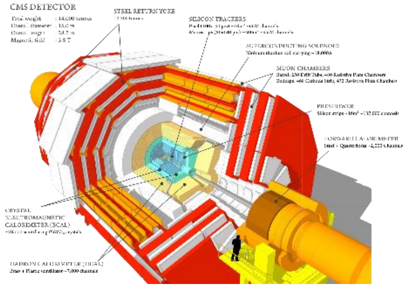
Selected results

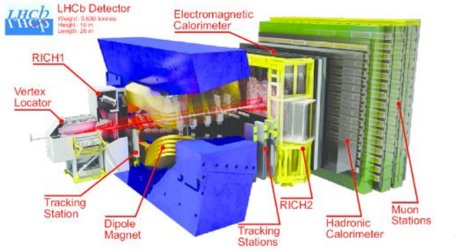
- Hadrochemistry
- Collectivity
- Hard Probes

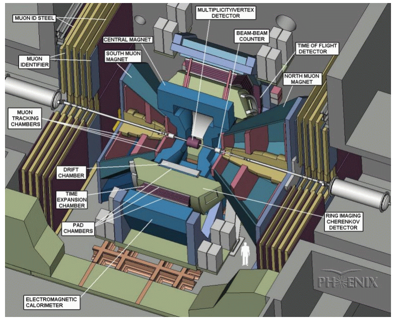
Conclusions

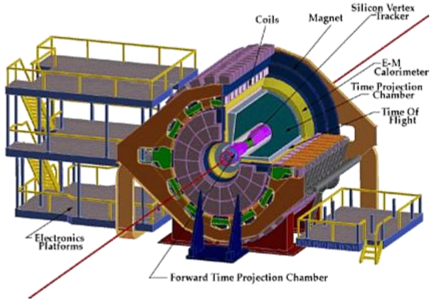






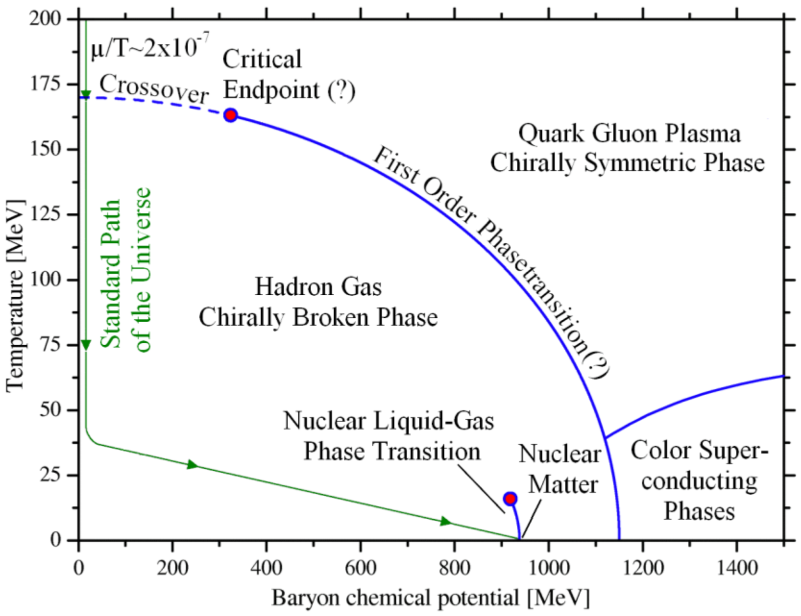






Introduction

Study Q$_{\mathrm{uark}}$G$_{\mathrm{luon}}$P$_{\mathrm{lasma}}$ with heavy ion collisions



Study strongly interacting matter under extreme conditions:

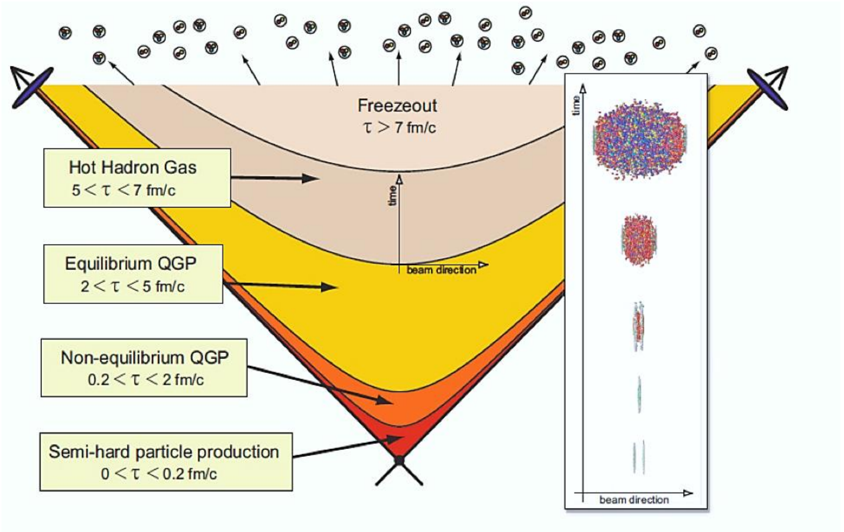
- high temperature and/or
- high density

QCD predicts transition from ordinary hadronic matter to deconfined partonic medium (Quark-Gluon-Plasma)

Need large volume of hot and dense matter
→ Ultra Relativistic Heavy Ion collisions

Many observables to probe different characteristics of the medium. e.g.:

- Soft particles p_T spectra and anisotropies → collectivity
- Soft particle yields → chemical composition
- Jet quenching, heavy flavours, quarkonia → density and temperature
- etc.



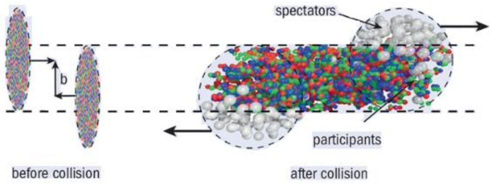
*1 fm/c $\simeq 3 \times 10^{-24}$ seconds

What do we control

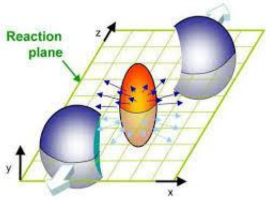
- Collision system: Pb-Pb, Au-Au, Xe-Xe, Cu-Cu, …, p-Pb, …, pp

- $\sqrt{s_{NN}}$ per nucleon pair: ~1-13 TeV for LHC, ~10-200 GeV for RHIC

- Impact parameter *b* (“centrality”)
    - N_{coll}: binary collisions
    - N_{part}: participants



- Reaction plane azimuthal angle



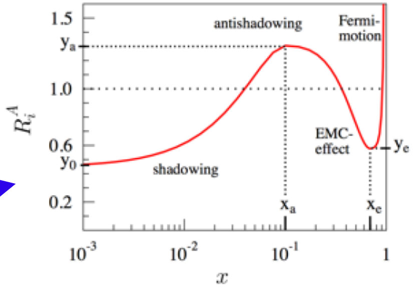
- Initial rate of hard processes above any scale involved ($Q >> \Lambda_{QCD}$, T , …):

$$\frac{d\sigma^{AA\to X}}{dp_T} \propto \underbrace{A^2 f_i^A\left(x_1,Q^2\right)\circ f_j^A\left(x_1,Q^2\right)}\circ\sigma^{ii\to k}\left(x_1,x_2,p_T/z,Q^2\right)\circ D_{k\to X}(z,Q^2)\otimes FS\ \text{Effects}$$

ACCESSIBLE THROUGH p-A COLLISIONS

nuclear mod. of *pdf*

$$f_i^A(x_i,Q^2)=R_i^A(x,Q^2)f_i^p(x,Q^2)$$



Observable considered for hard processes:

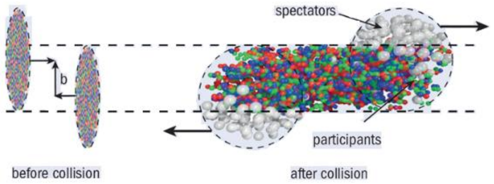
$$\boxed{R_{AA}=\frac{dN/dp_T|_{AA}}{N_{coll}\cdot dN/dp_T|_{pp(pA)}}}$$

What we would measure in AA if it was a incoherent superposition of N_{coll} pp(pA) interactions

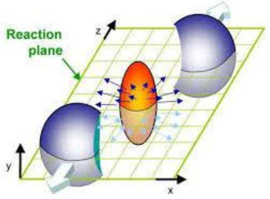
What we actually measure in AA

What do we control

- Collision system: Pb-Pb, Au-Au, Xe-Xe, Cu-Cu, …, p-Pb, …, pp
- $\sqrt{s_{NN}}$ per nucleon pair: ~1-13 TeV for LHC, ~10-200 GeV for RHIC
- Impact parameter *b* (“centrality”)
  - N_{coll}: binary collisions
  - N_{part}: participants



- Reaction plane azimuthal angle



“Small collision systems” (pp, p-A) traditionally used as control-experiments to isolate QGP-like effects in A-A

Recently, several observations point to the onset of similar effects in elementary and A-A collisions

QGP in small systems?

Very much debated, more on this later…

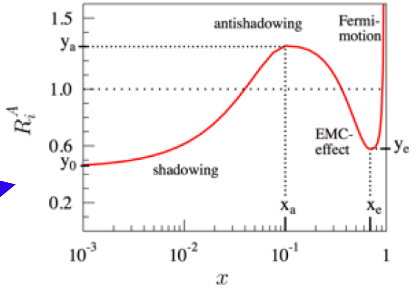
- Initial rate of hard processes above any scale involved (Q >> Λ_{QCD} , T , …):

$$\frac{d\sigma^{AA\to X}}{dp_T} \propto \underbrace{A^2 f_i^A\left(x_1,Q^2\right)\circ f_j^A\left(x_1,Q^2\right)}\circ\sigma^{ii\to k}\left(x_1,x_2,p_T/z,Q^2\right)\circ D_{k\to X}(z,Q^2)\otimes FS\ \text{Effects}$$

ACCESSIBLE THROUGH p-A COLLISIONS

nuclear mod. of *pdf*

$$f_i^A(x_i,Q^2)=R_i^A(x,Q^2)f_i^p(x,Q^2)$$



Observable considered for hard processes:

$$\boxed{R_{AA} = \frac{dN/dp_T|_{AA}}{N_{coll}\cdot dN/dp_T|_{pp(pA)}}}$$

What we would measure in AA if it was a incoherent superposition of N_{coll} pp(pA) interactions

What we actually measure in AA

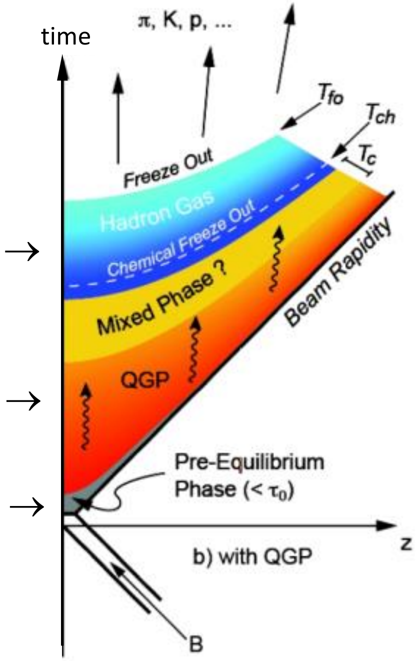
Selected results

…from latest to earlier stages of the evolution:

Hadrochemistry →

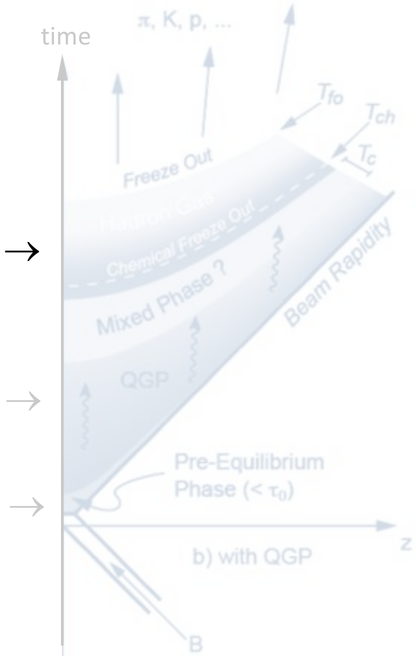
Collectivity →

Hard probes →



Selected results

…from latest to earlier stages of the evolution:



Hadrochemistry →

Collectivity →

Hard probes →

Hadrochemistry: a probe for QGP?

Measurement of **relative abundances of** produced particle **species**

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

Is this suppression still observed at high energy densities?

Hadrochemistry: a probe for QGP?

Measurement of **relative abundances of** produced particle **species**

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

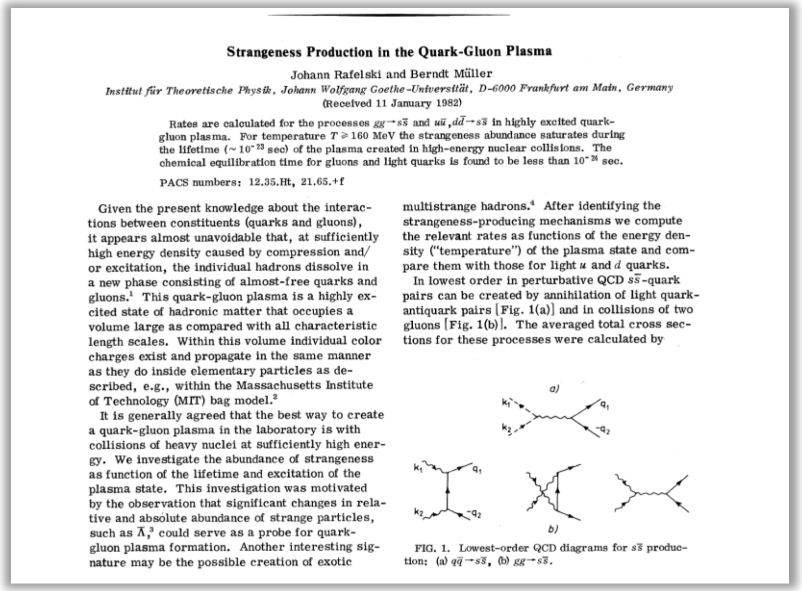
Is this suppression still observed at high energy densities?

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

Statistical Hadronization Model (SHM): all hadrons formed from excited state following 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 $T \geqslant 160$ 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^{-24} 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 $s\bar{s}$ production: (a) $q\bar{q}\to s\bar{s}$, (b) $gg\to s\bar{s}$.

Hadrochemistry: a probe for QGP?

Measurement of **relative abundances of** produced particle **species**

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

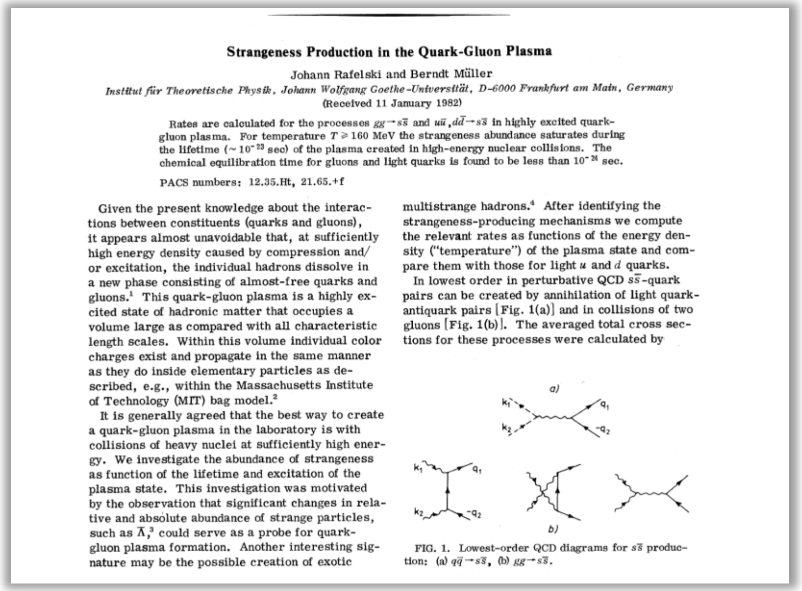
Is this suppression still observed at high energy densities?

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

Statistical Hadronization Model (SHM): all hadrons formed from excited state following 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 $T \geqslant 160$ 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^{-24} 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

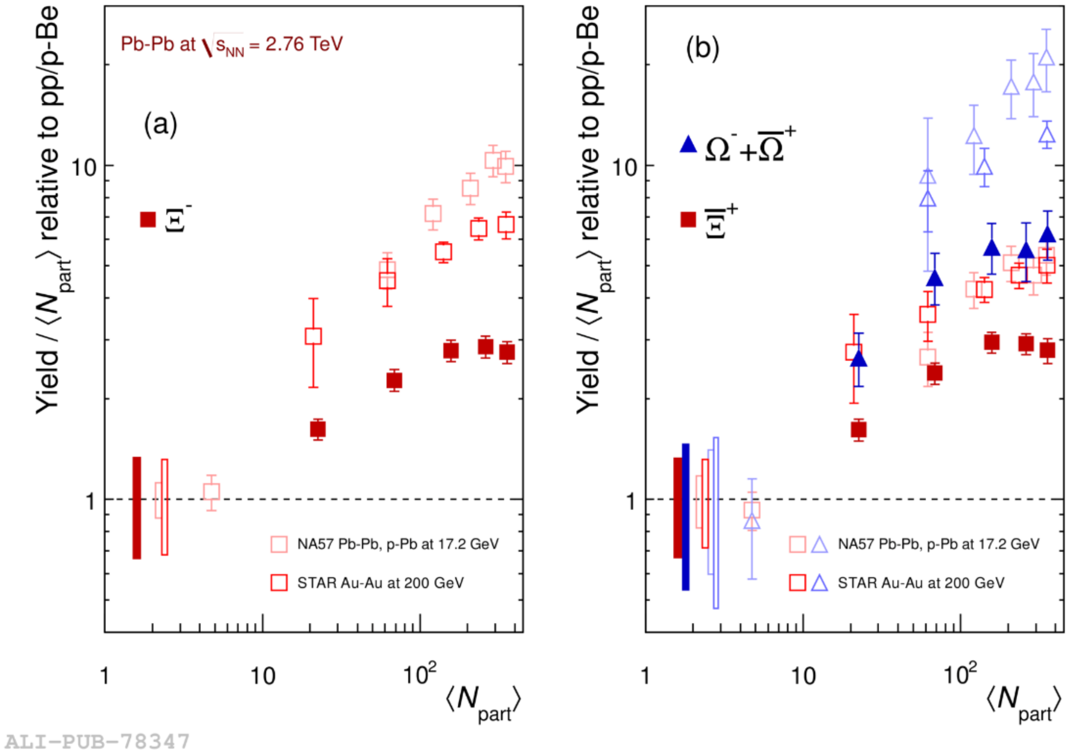
FIG. 1. Lowest-order QCD diagrams for $s\bar{s}$ production: (a) $q\bar{q} \to s\bar{s}$, (b) $gg \to s\bar{s}$.

More in general: is the relative rate of soft particles production affected by the presence of a QGP in the earlier stage?

Control experiment: soft particles production in QCD vacuum (pp?)

Strangeness enhancement: experimental evidence

Phys. Lett. B 728 (2014) 216–227



First observed at SPS (NA57, J.Phys.G37:045105,2010) ...

..then confirmed at RHIC (STAR, Phys. Rev. Lett. 108, 072301) ...

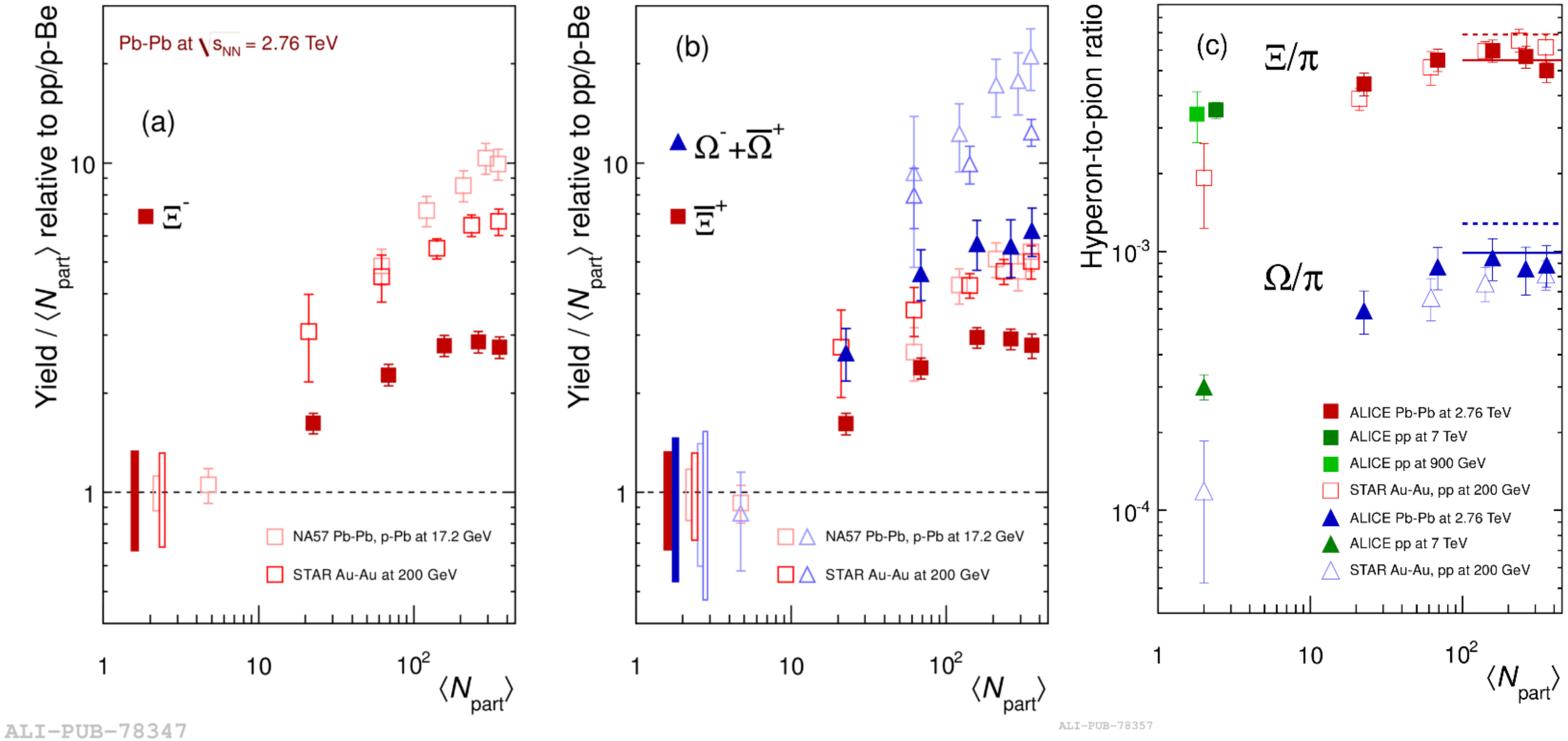
...and at the LHC (Phys. Lett. B 728 (2014) 216–227)

Strangeness production **enhanced** in heavy-ion collisions wrt smaller collision systems. Enhancement larger for particles with higher strangeness content…

…but **less important at higher energy…!?!?**

Strangeness enhancement: experimental evidence

Phys. Lett. B 728 (2014) 216–227



When considering ratio to pions, for high N_{part} strangeness production rate is constant…

…and higher than in small collision systems

Strangeness production **enhanced** in heavy-ion collisions wrt smaller collision systems.
Enhancement larger for particles with higher strangeness content…

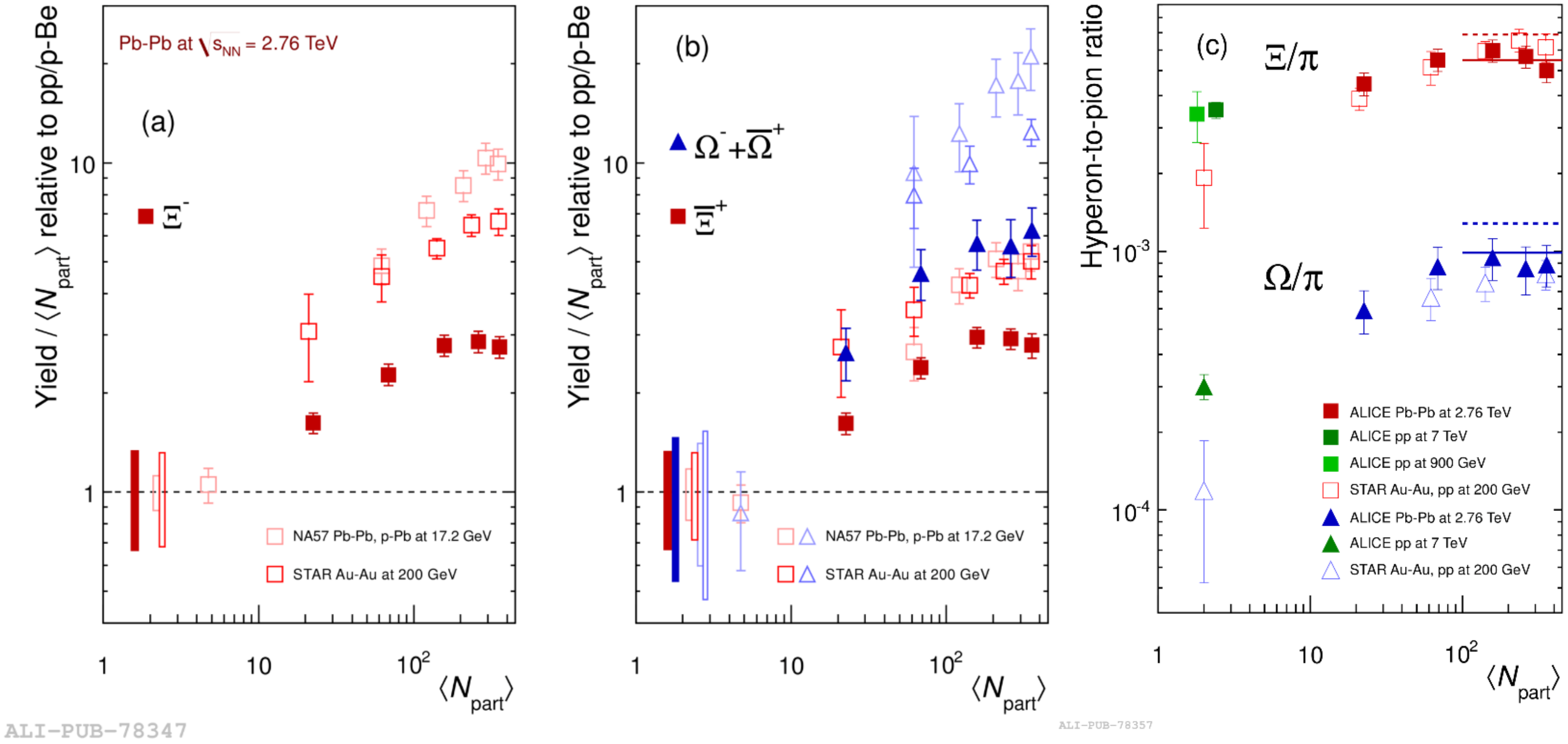
…but **less important at higher energy…!?!?**

…of course!

Because strangeness production in small systems depends on **energy!**

Strangeness enhancement: experimental evidence

Phys. Lett. B 728 (2014) 216–227



When considering ratio to pions, for high N_{part} strangeness production rate is constant…

…and higher than in small collision systems

Is there an evolution of this ratio in small systems?

Difficult to plot against N_{part}. What if we use multiplicity?

Strangeness production **enhanced** in heavy-ion collisions wrt smaller collision systems. Enhancement larger for particles with higher strangeness content…

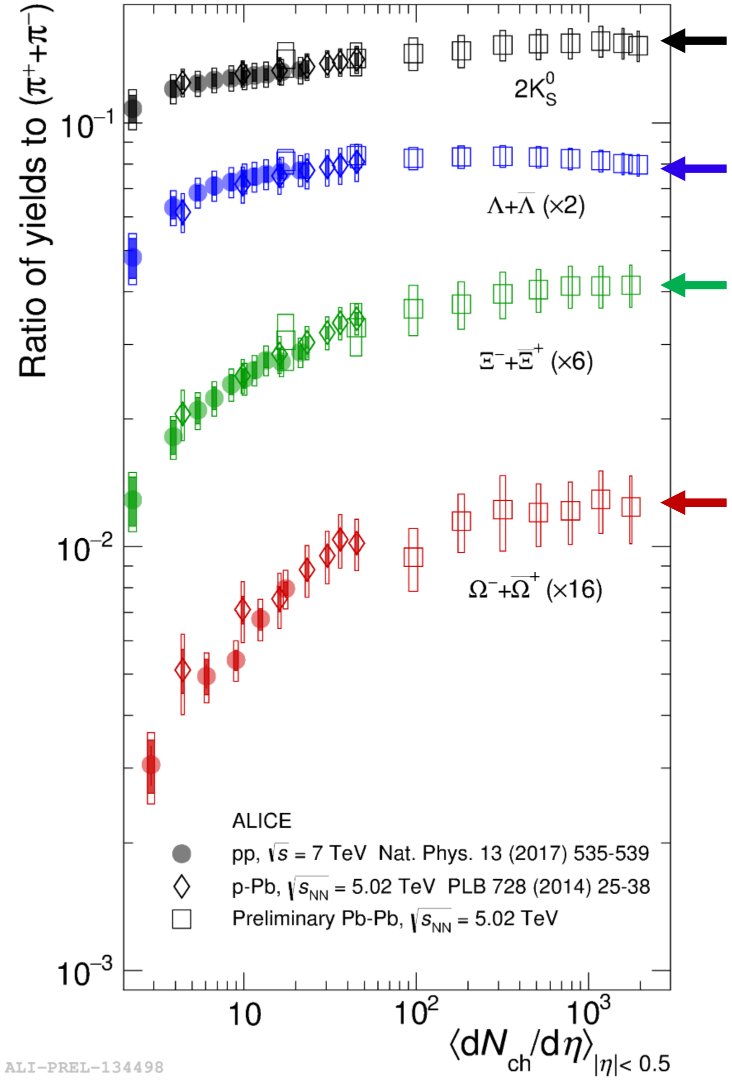
…but **less important at higher energy…!?!?**

…of course!

Because strangeness production in small systems depends on **energy!**

Is this really a dependence on energy itself?

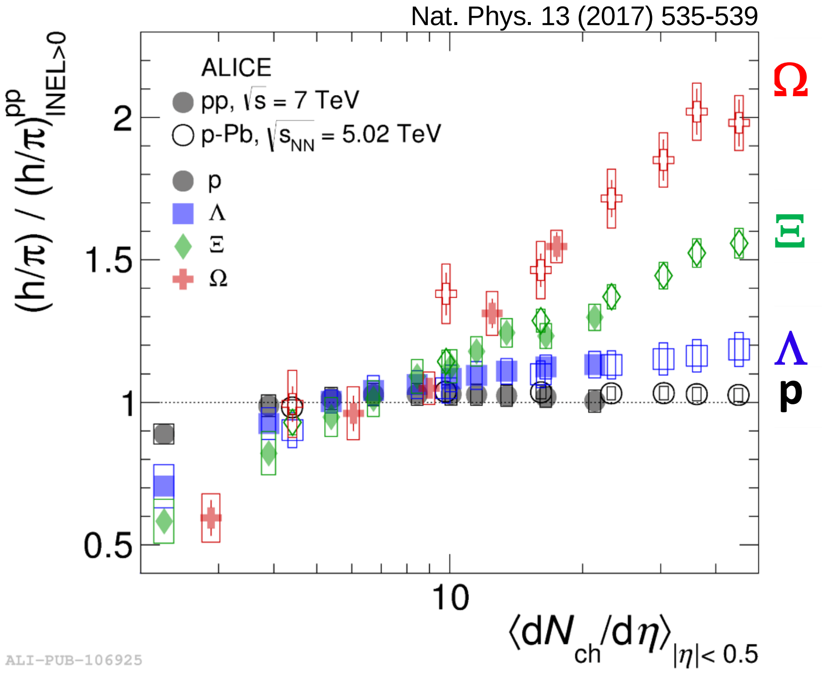
Strangeness enhancement: exploring the “origin”



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

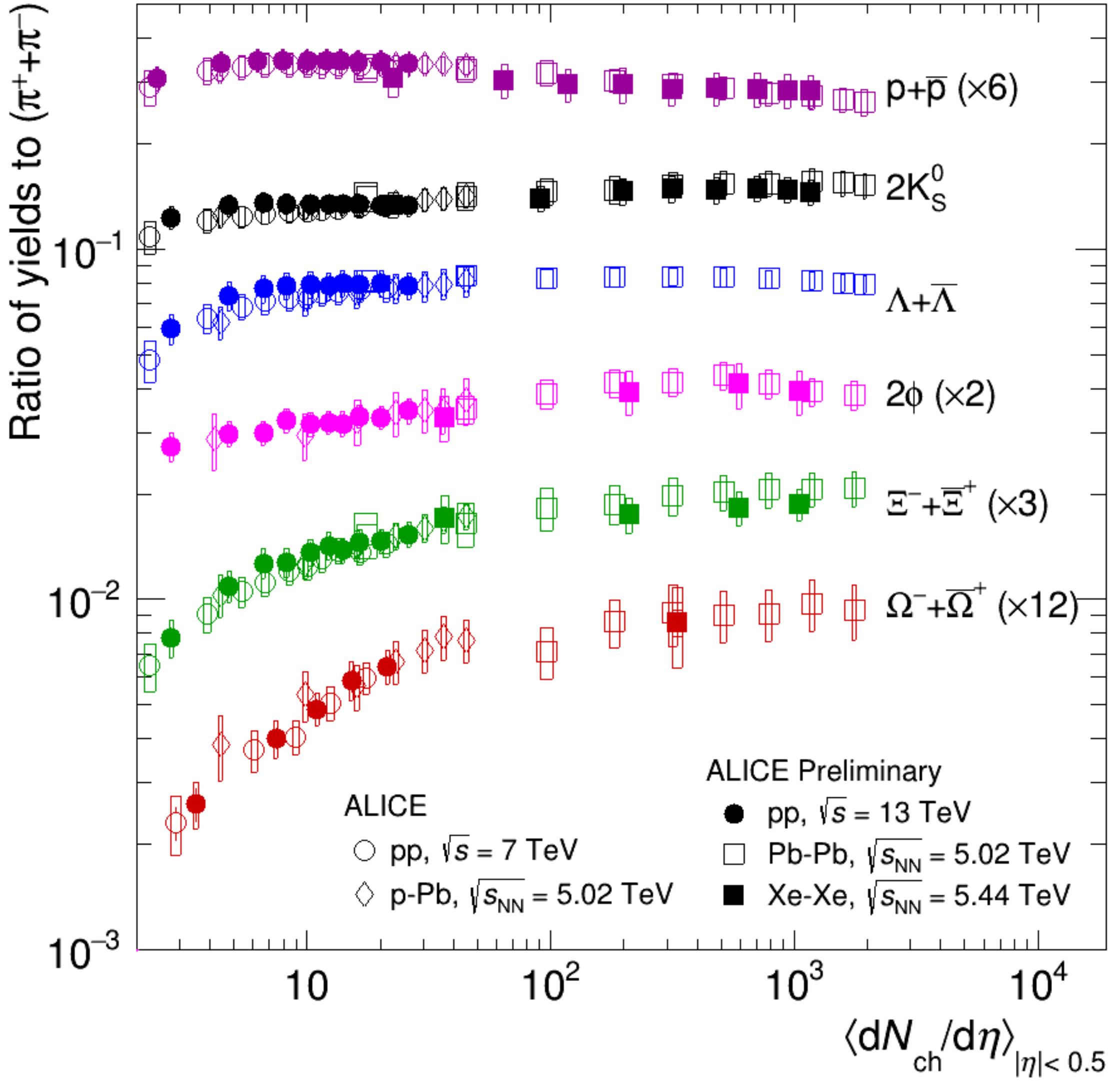
The larger the content in strangeness of the hadron, the steeper the increase is:

Strangeness production saturates at high multiplicity



No matter what the system/energy is!
Tell me the multiplicity of the event and I’ll tell you how many strange hadrons will be produced

Hadrochemistry: multiplicity evolution



Adding different colliding systems the outcome remains the same

Hadrochemistry: thermal emission in heavy ions?

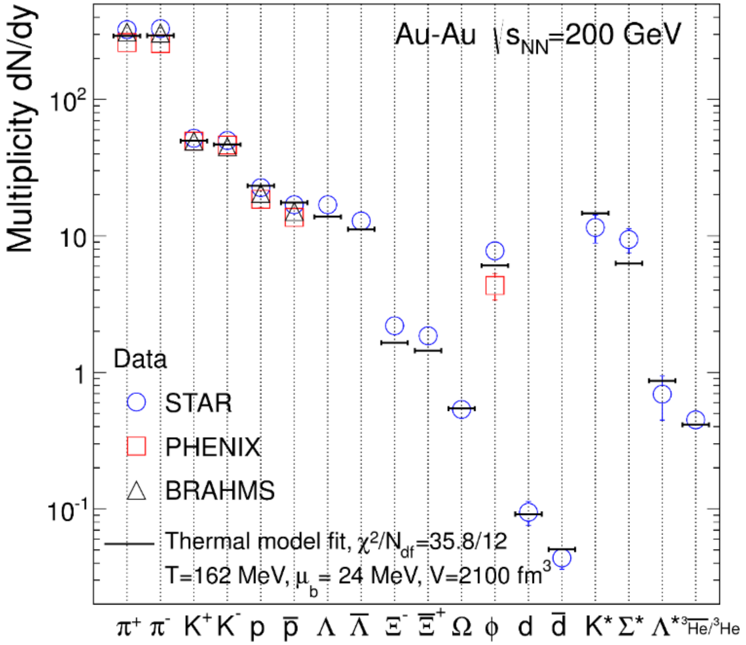
SHM – data fit with few free parameters:

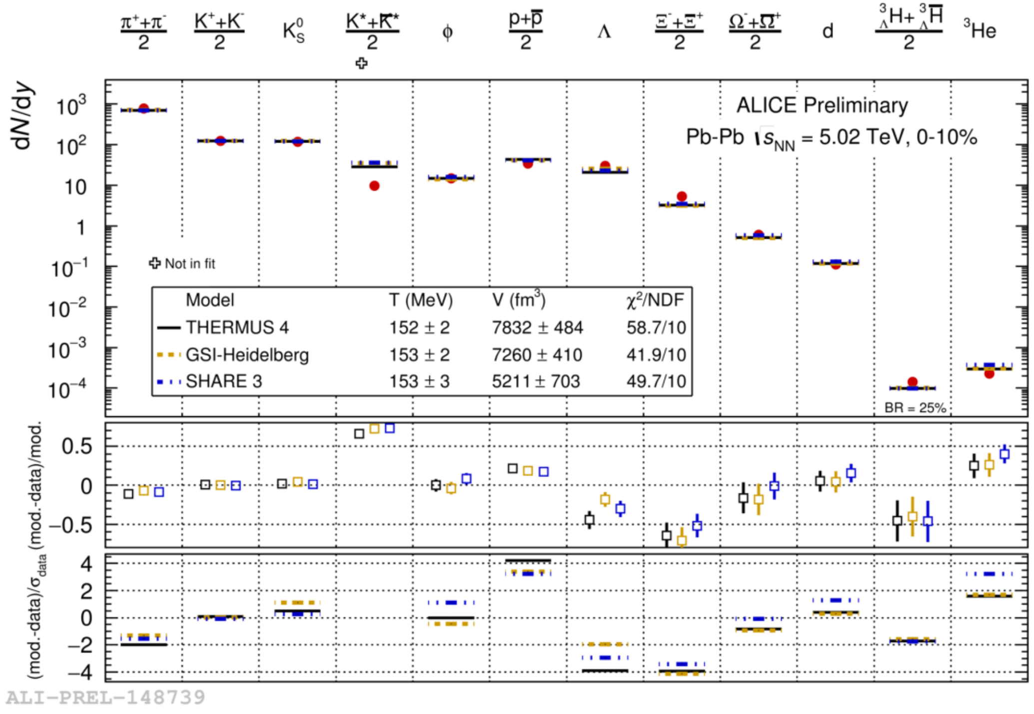
- **T** : the temperature of the source at chemical freeze-out
- **V** : the volume of the source
- μ_B : baryochemical potential (0 at LHC)
- μ_S : under-equilibration scale for strangeness
- …

in some flavours of the model

“good” description of yields over 9 orders of magnitude

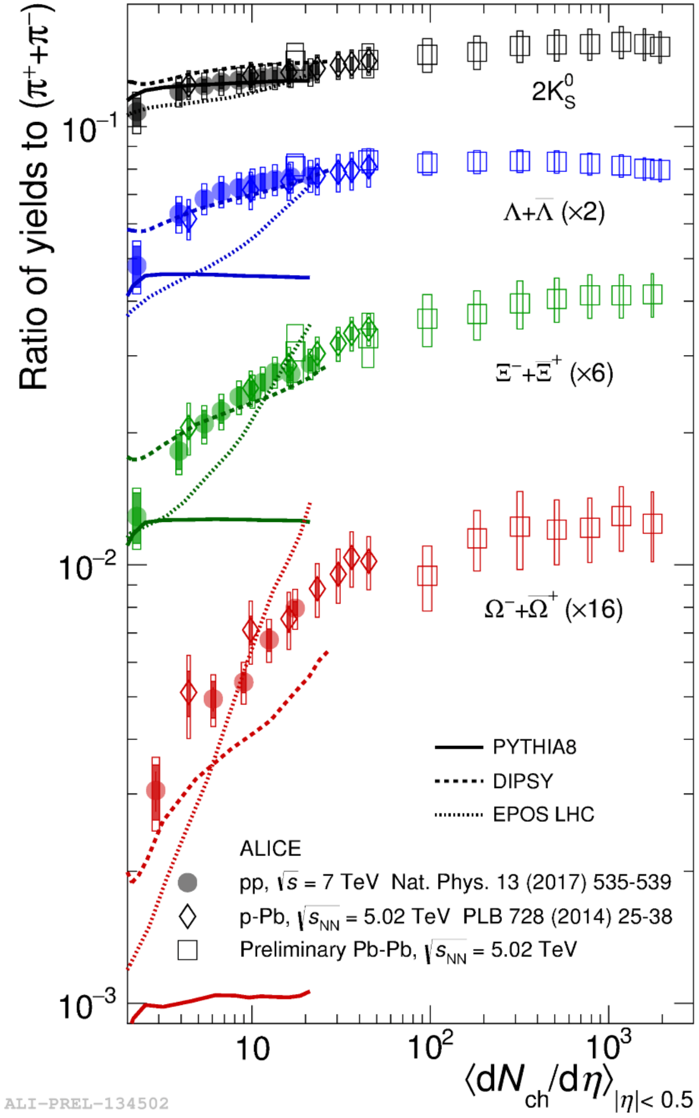
Discrepancies and extension of the SHM to smaller collision systems are under study





Resonances must be treated differently, if interested check backup!

Hadrochemistry as seen by microscopic models

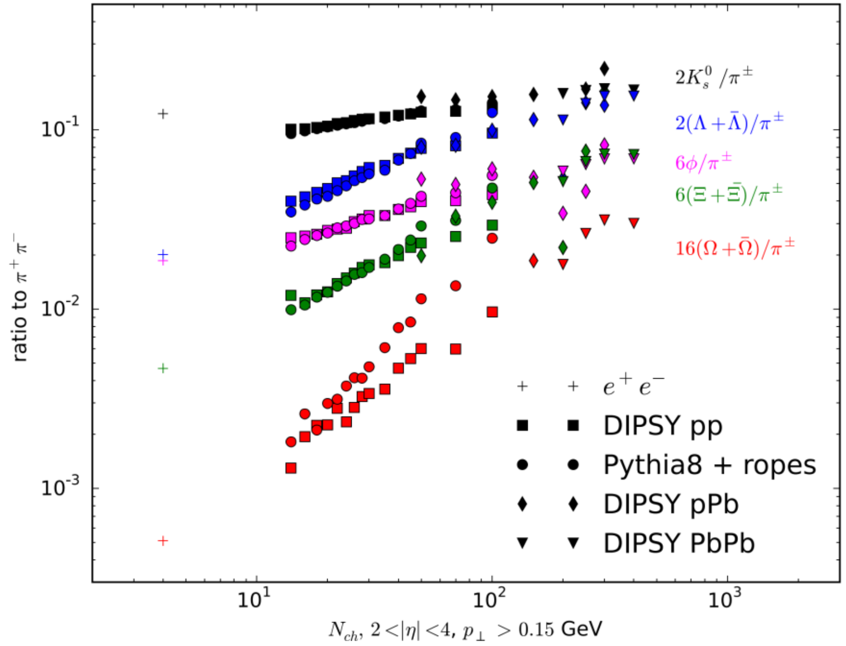


- **PYTHIA** (Lund string model):
  - Linear confinement potential at large distances →strings with tension κ = 1 GeV/fm
  - Hadrons come from string breaking. s/u fit on data
  - At high energies need MPI to describe multiplicity…
  - …and re-connection of colour strings to describe $<p_T>$ VS multiplicity
  - Recently intruduced:
    - Colour **ropes**: packing of strings increase κ
    - Shoving: flow-like push due to colour

dramatically fails

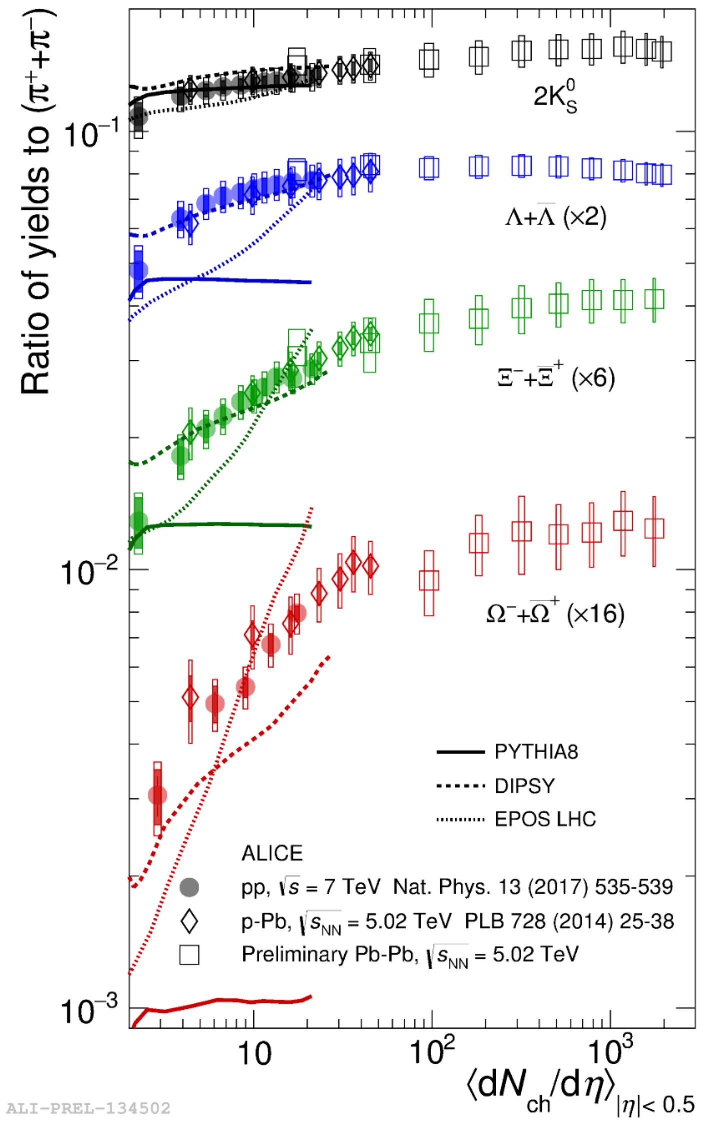
- **DIPSY** (Dipole evolution in Impact Parameter Space and rapiditY)
  - Proton/Nucleus structure built-up dynamically from dipole splitting
  - Evolution of initial state and collision followed in impact parameter space. Naturally treats saturation and MPI
  - Strings which overlap in impact parameter space form **ropes**

C. Bierlich, arXiv:1807.05271



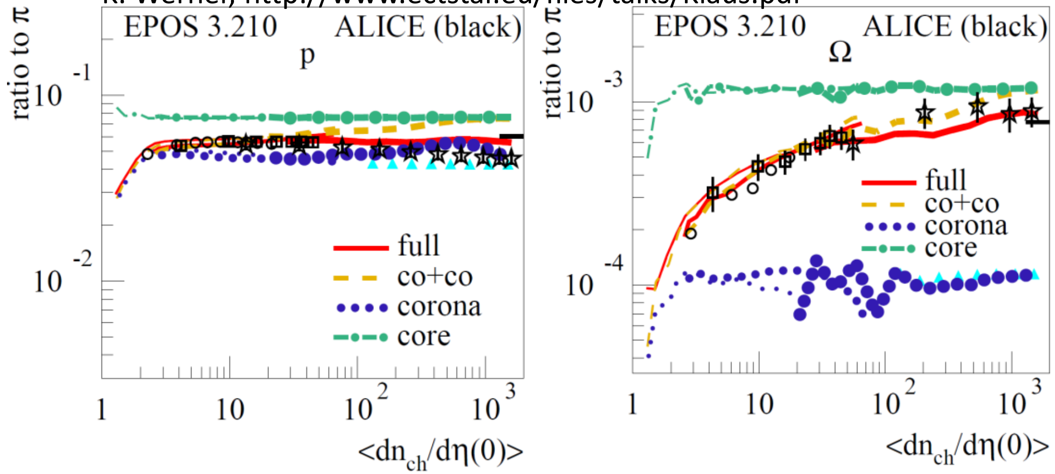
CAVEAT: ropes favor baryons wrt mesons. No flavour preference!

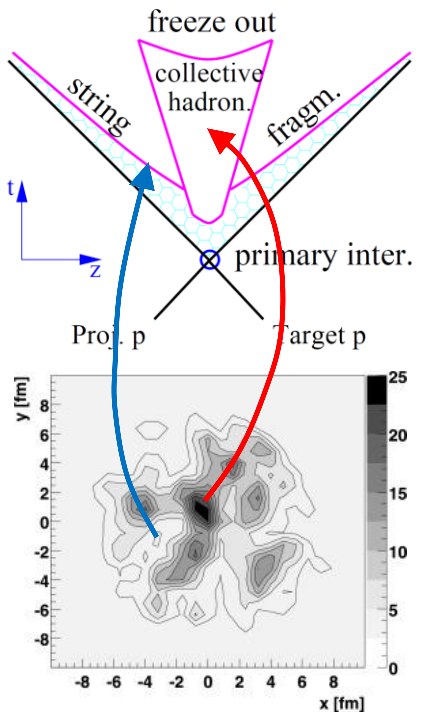
Hadrochemistry as seen by EPOS



- EPOS:
  - Hard scattering: parton “ladders” + CGC-inspired saturation scale
  - At time τ_0 (before hadronization) strings divided into fluid (CORE) and escaping (CORONA) according to momenta and local density
    - ☐ **CORONA**: strings can hadronize as in the Lund approach
    - ☐ **CORE**: from 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)

K. Werner, http://www.ectstar.eu/files/talks/Klaus.pdf



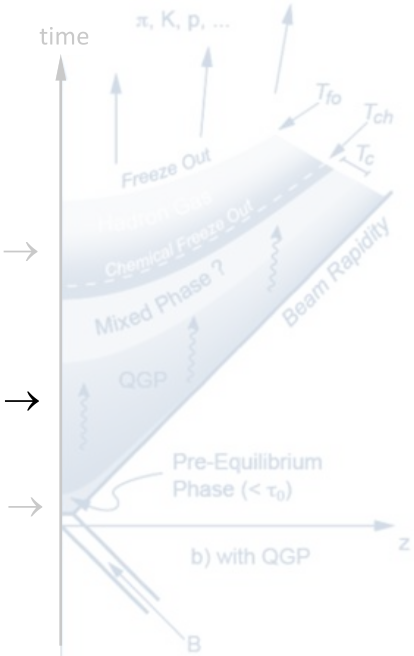


Good job with version 3 of the generator! Hints to the need of hydro in pp collisions..

CAVEAT: 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!!

Selected results

…from latest to earlier stages of the evolution:



Hadrochemistry →

Collectivity →

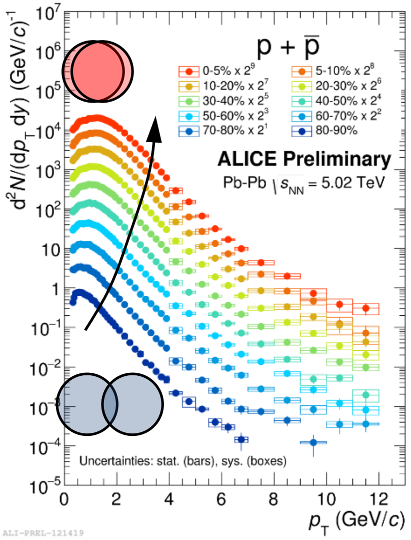
Hard probes →

Collectivity in a nutshell

At large energy density QCD matter expected to behave like a fluid
→ hydrodynamical model.

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 p_T spectra modification
  - Baryon/meson anomaly



p_T spectrum gets harder as the collision gets more central

Common β → larger p-boost to higher-mass particles (p=mγβ)

Collectivity in a nutshell

At large energy density QCD matter expected to behave like a fluid → hydrodynamical model.

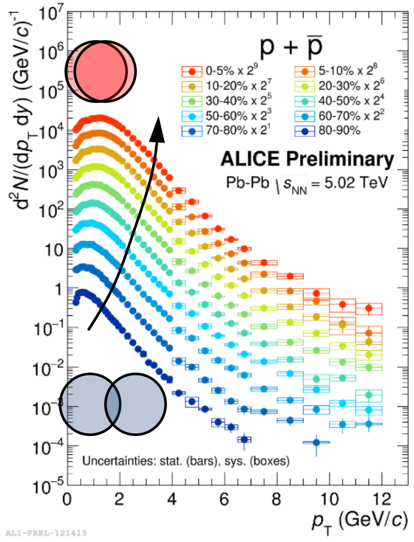
According to the hydro picture, the strongly interacting medium is expected to develop:

- **Radial flow** (important in central collisions):
  - Common expansion velocity of partons
  - Translates into p_T spectra 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

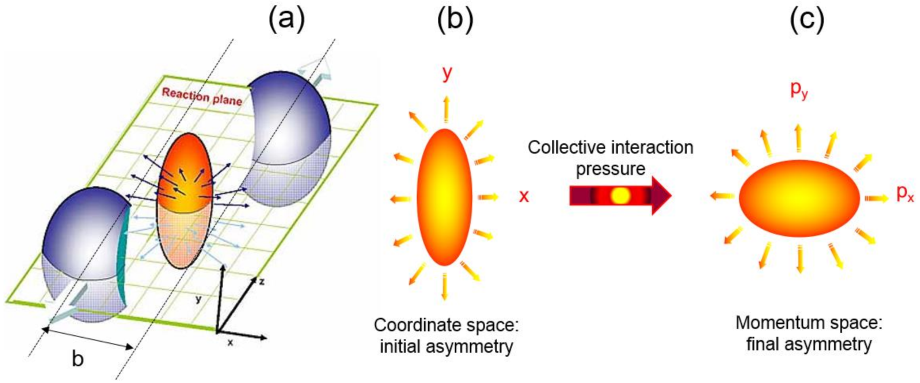
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

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

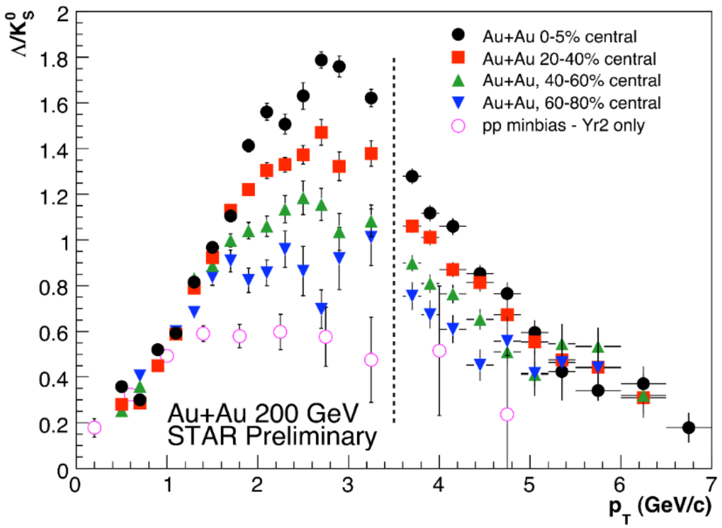


p_T spectrum gets harder as the collision gets more central

Common β → larger p-boost to higher-mass particles ($p=m\gamma\beta$)



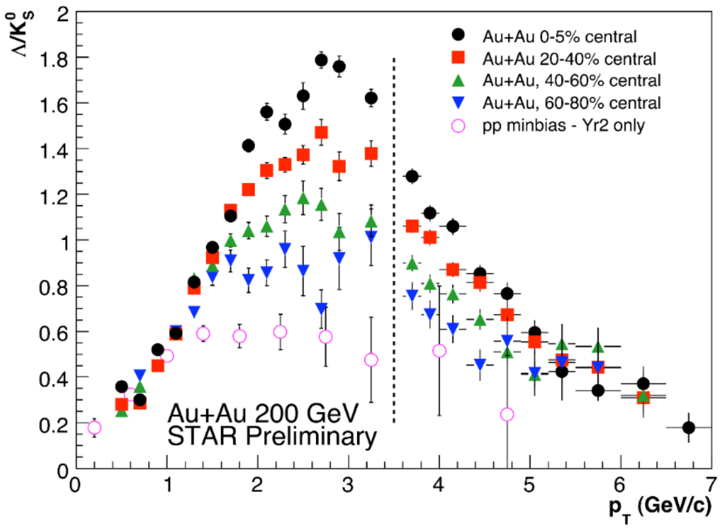
Spectra modification: baryon/meson ratio (HI)

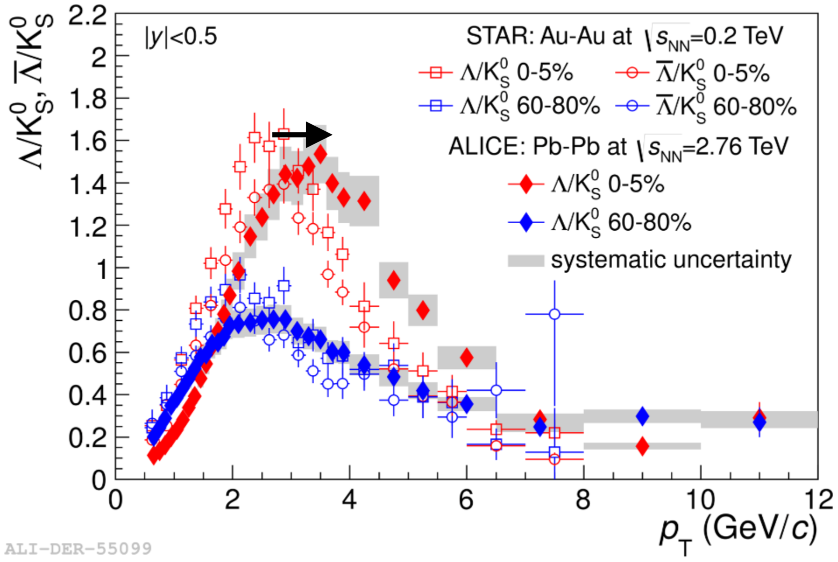


Increase at intermediate p_T in all centrality classes observed by STAR in Au-Au collisions:

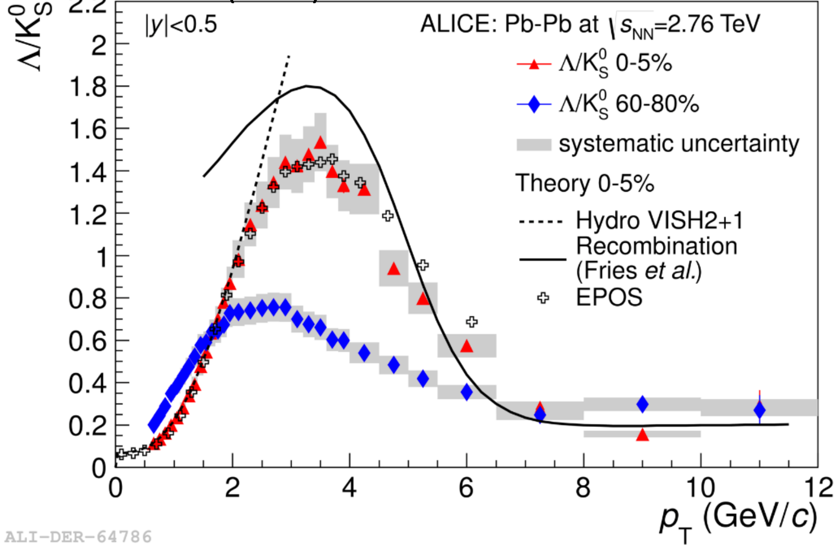
different positions of the peak at different centralities?

Spectra modification: baryon/meson ratio (HI)





PRL 111 (2013) 222301



Increase at intermediate p_T in all centrality classes observed by STAR in Au-Au collisions:

different positions of the peak at different centralities?

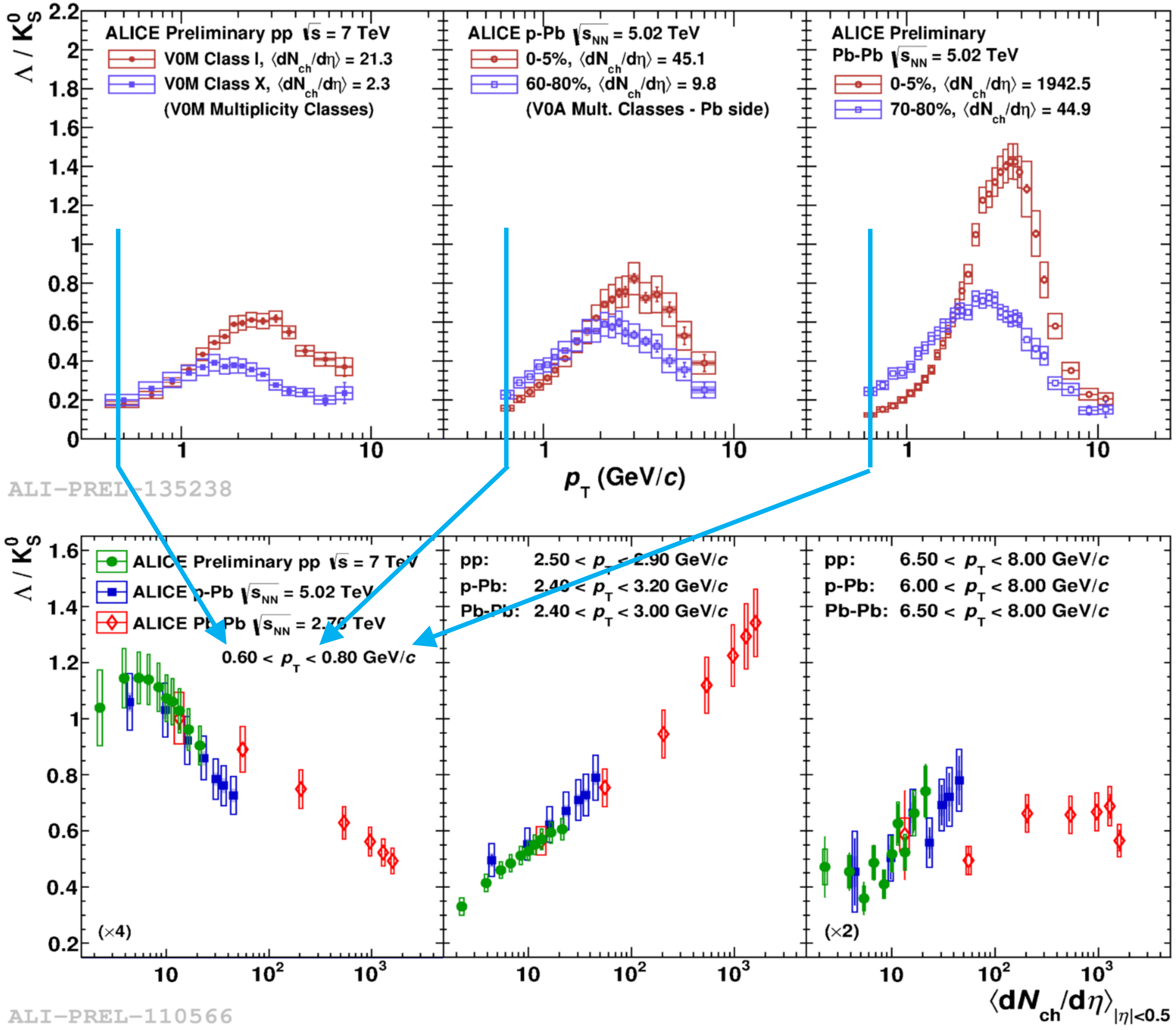
Confirmed at the LHC, with peak position situated at slightly higher p_T

Evolution can be described by hydro models at low-p_T

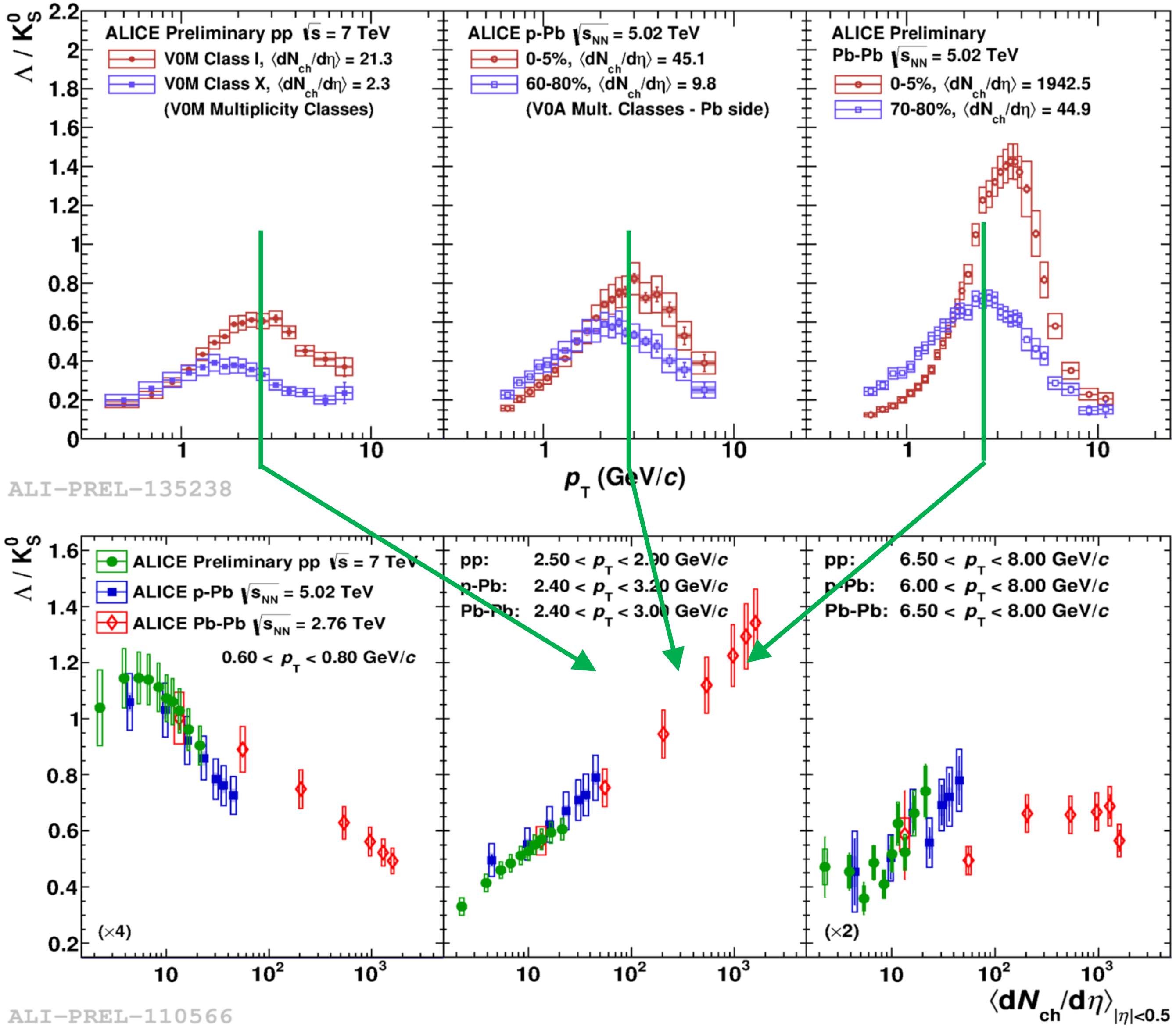
At high p_T the ratio is ~0.2 (as in pp from STAR) at all centralities.

Is there an evolution in pp?

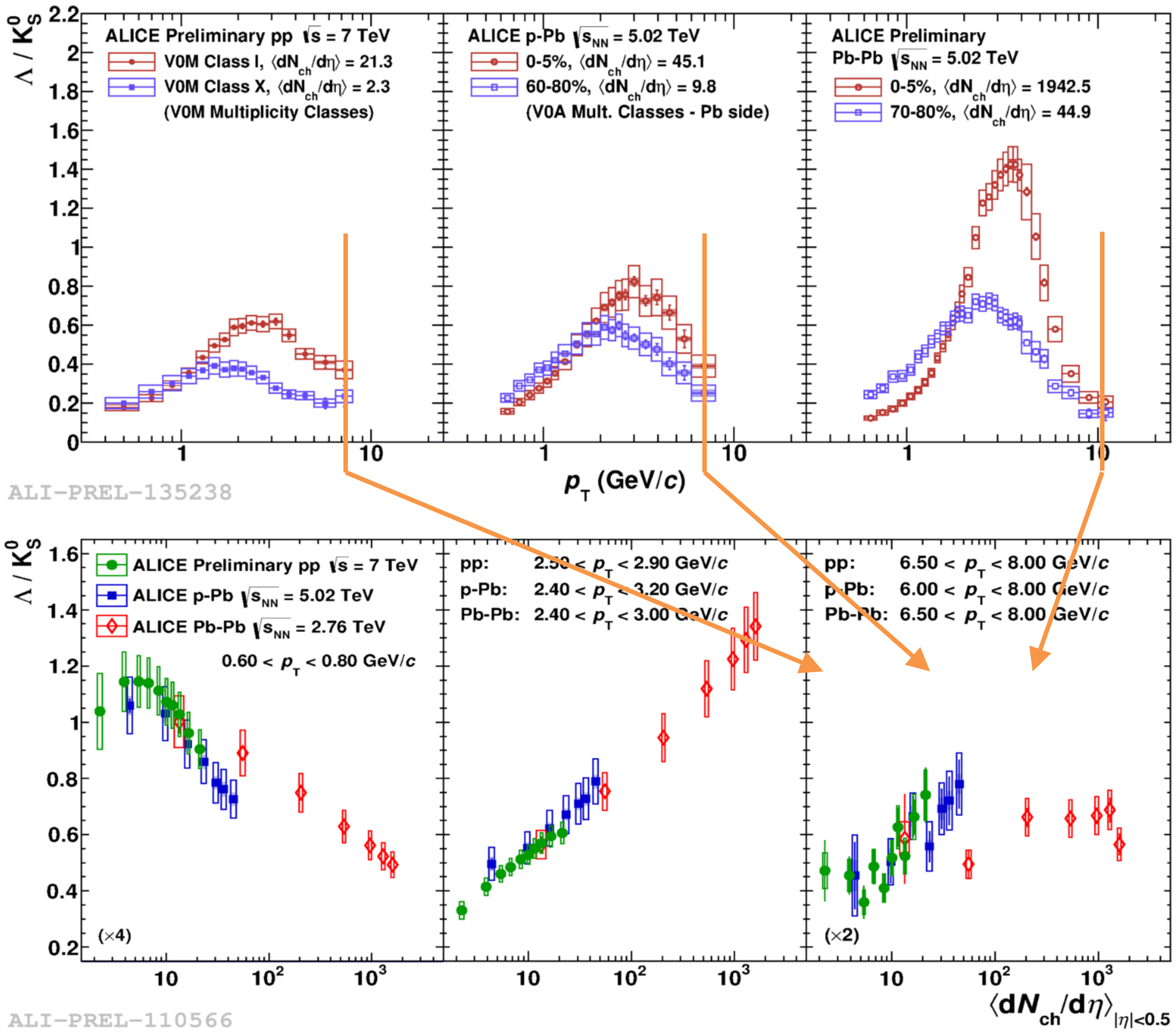
Spectra modification: baryon/meson ratio (small systems)



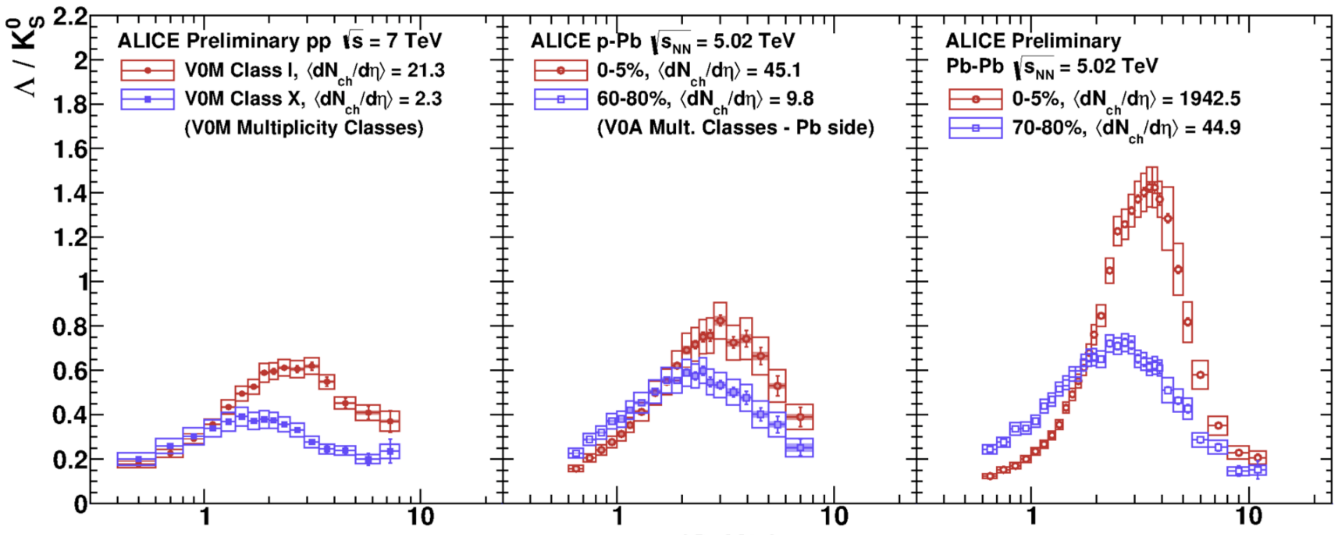
Spectra modification: baryon/meson ratio (small systems)



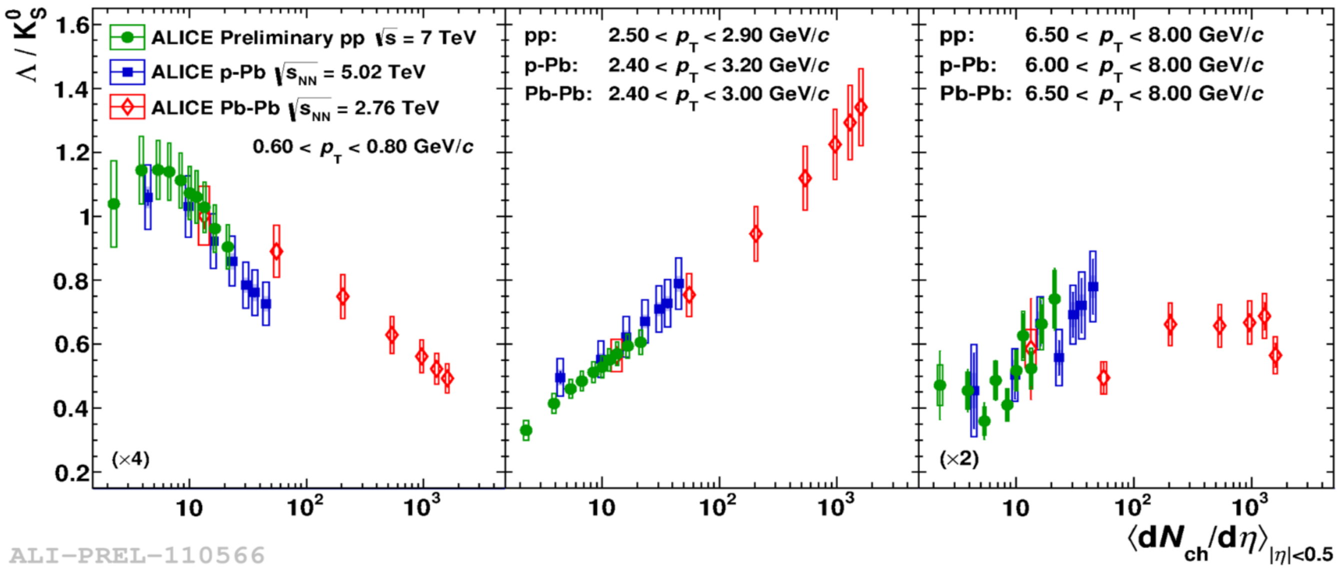
Spectra modification: baryon/meson ratio (small systems)



Spectra modification: baryon/meson ratio (small systems)



ALI-PREL-135238



ALI-PREL-110566

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?

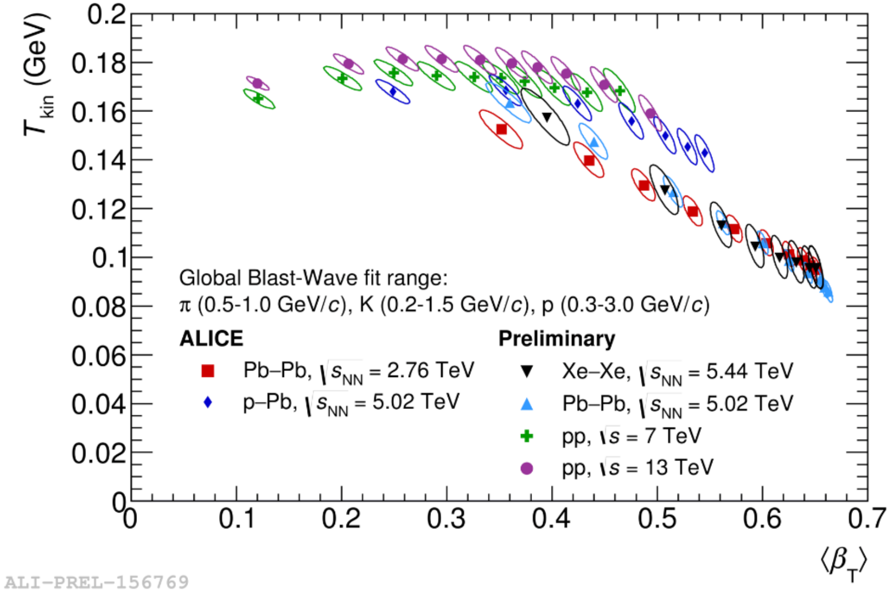
Need to compare p_T spectra to hydro

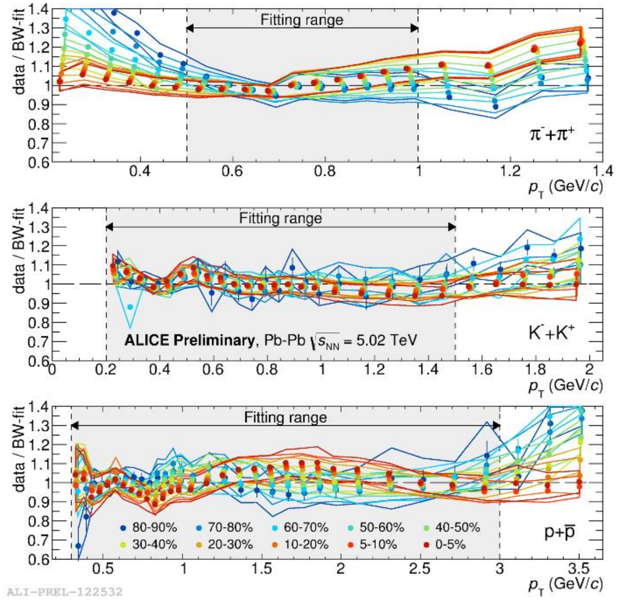
↓

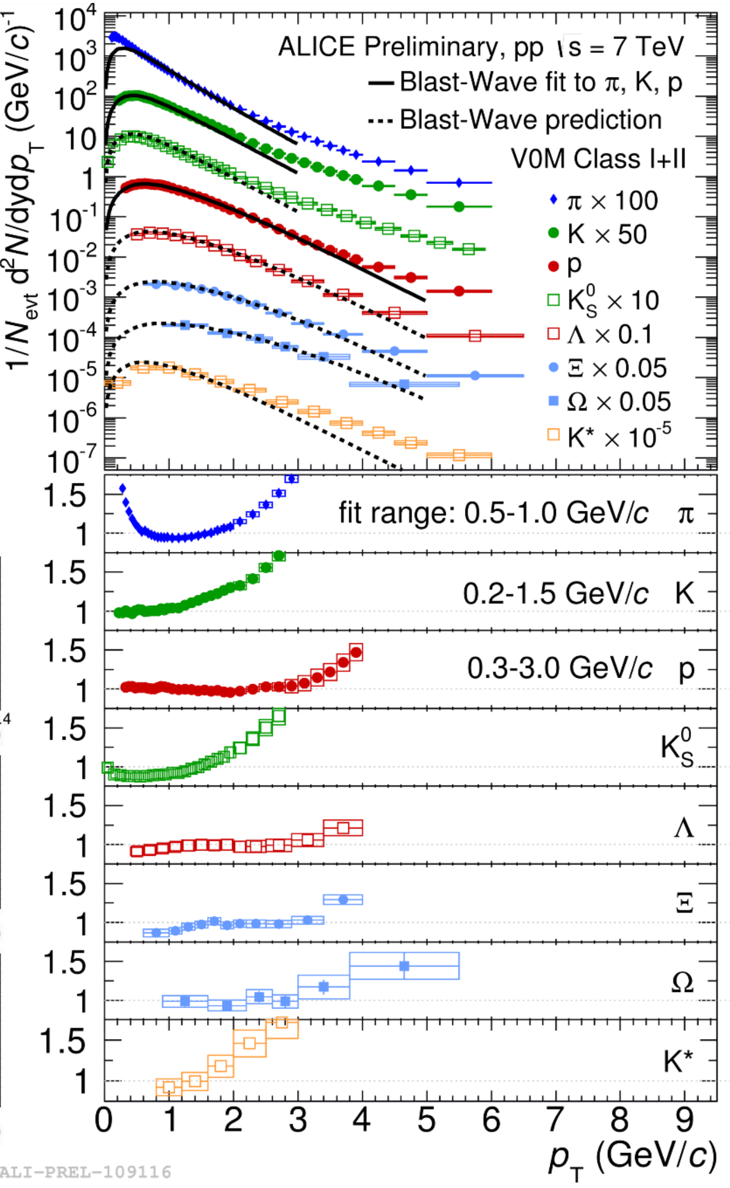
Radial flow: does hydro fit the picture?

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





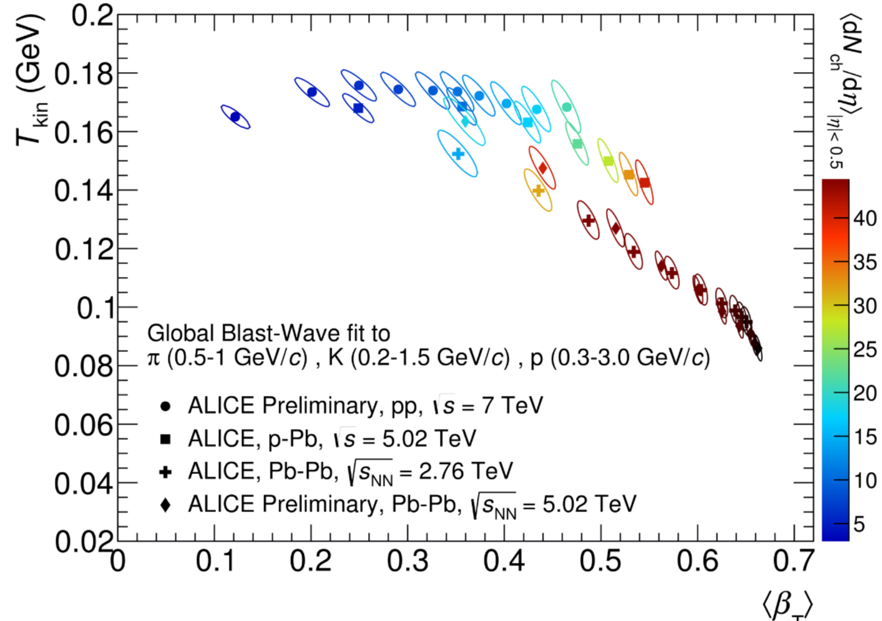


Radial flow: does hydro fit the picture?

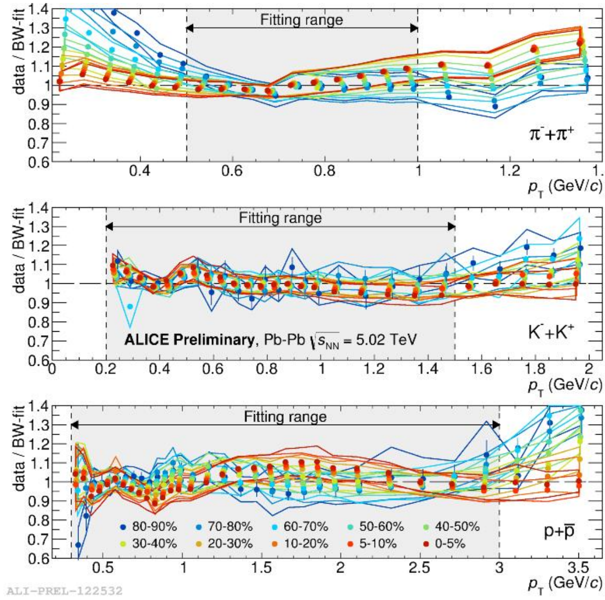
Blast wave: simplified hydro model:

- 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

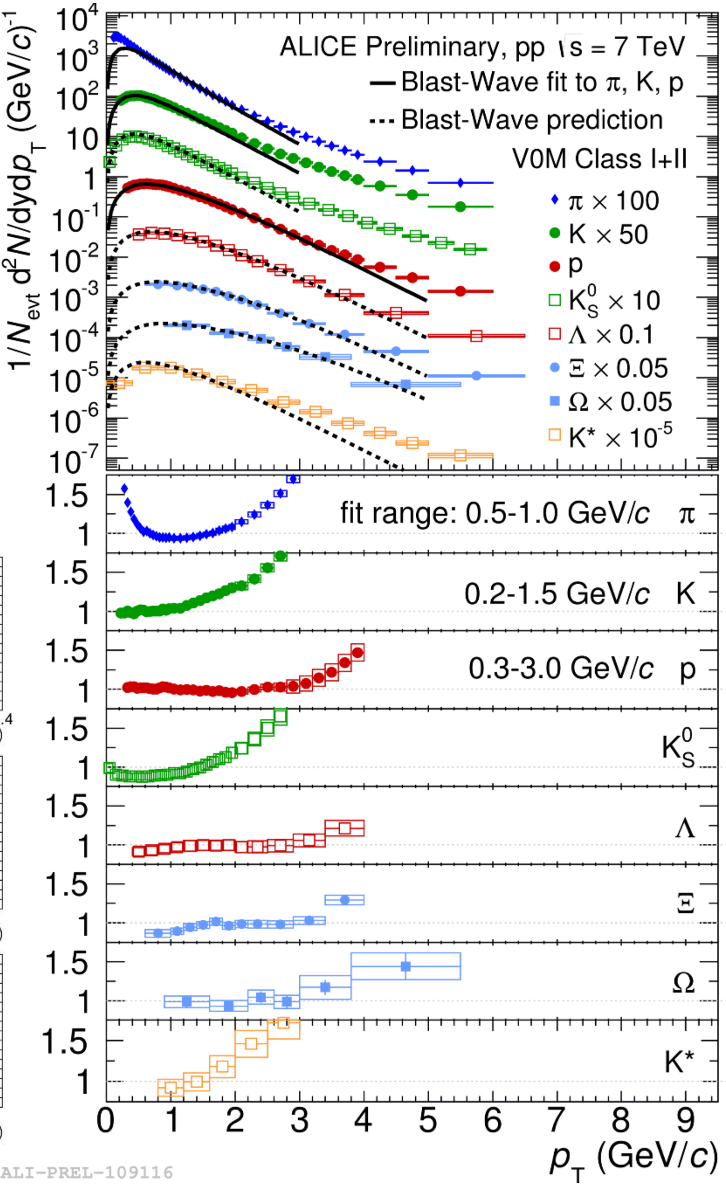
Soft particles p_T spectra in HI support the radial flow hydro picture. Same mechanism at play in high-multiplicity pp collisions?



ALI-PREL-122516

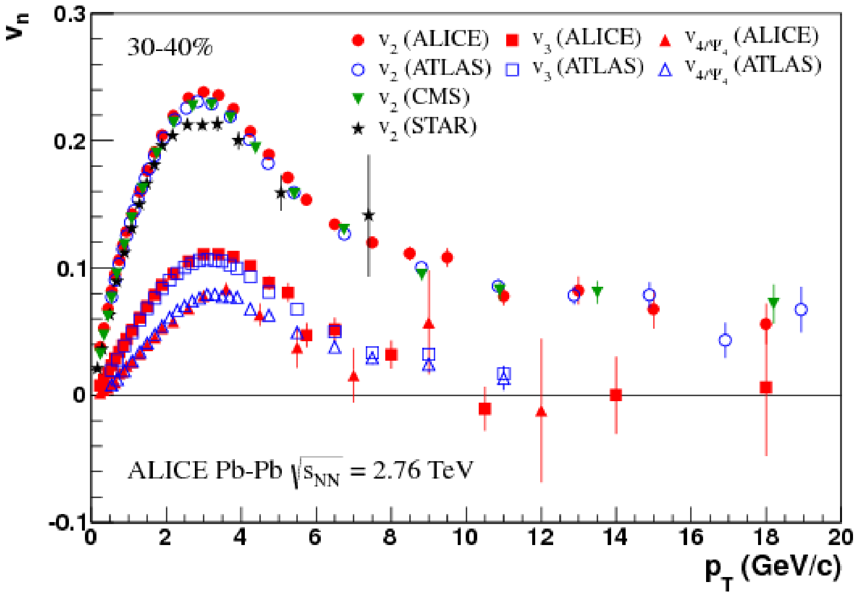


ALI-PREL-122532



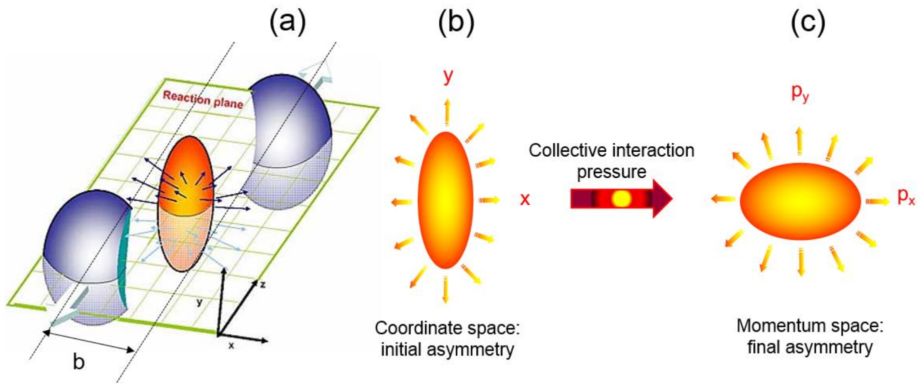
ALI-PREL-109116

Anisotropic flow in heavy ions



$v_n \neq 0$ observed at RHIC and LHC: means that in semi-central collisions the p_T distribution of particles is anisotropic wrt the event plane…

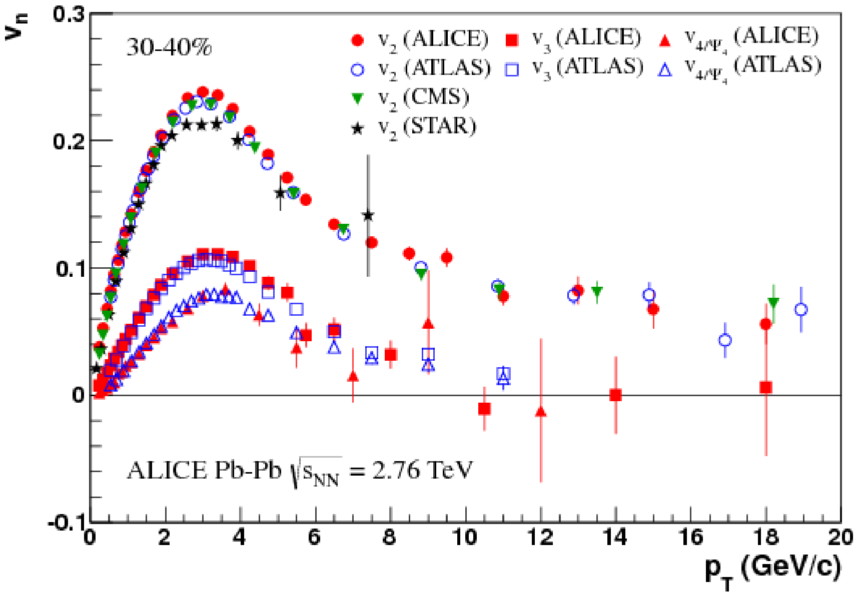
does this mean we have flow?



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

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

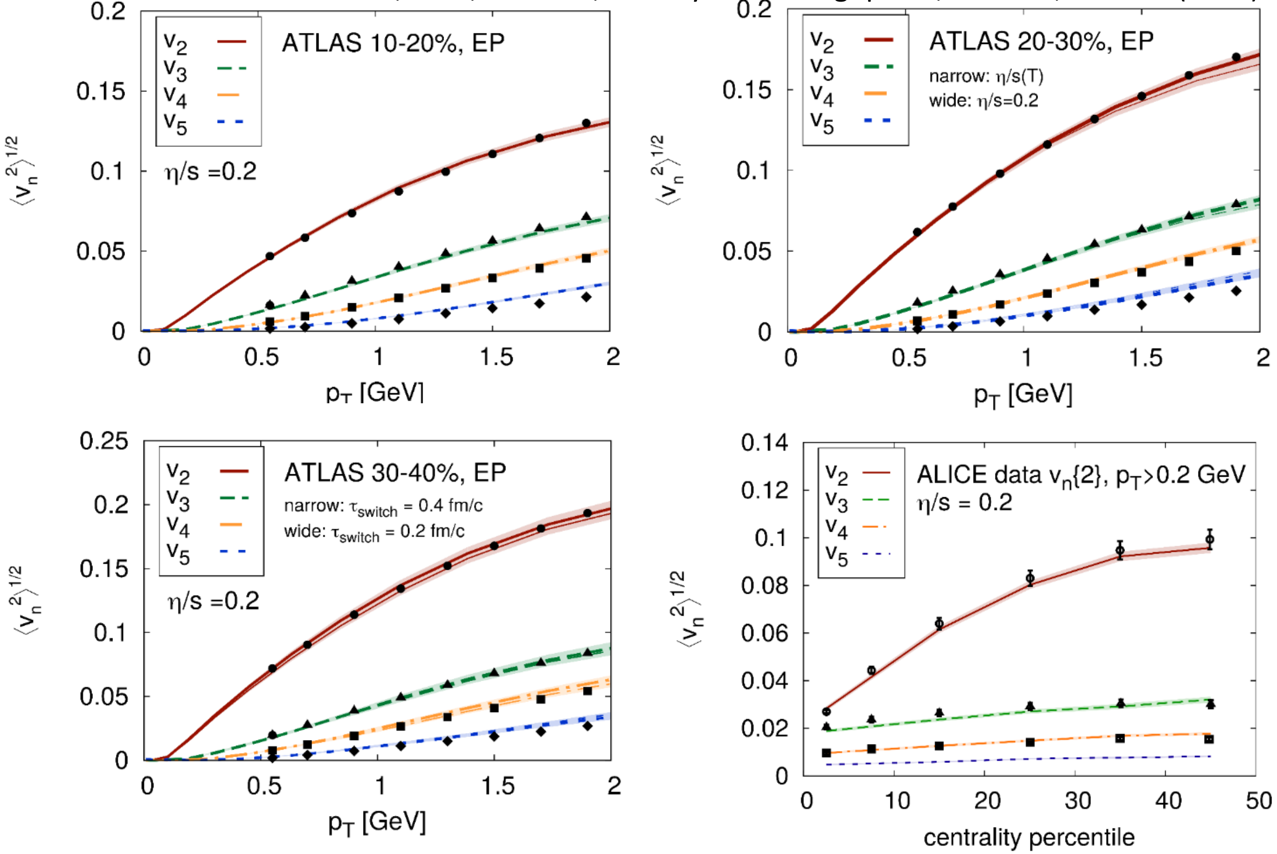
Anisotropic flow in heavy ions



$v_n \neq 0$ observed at RHIC and LHC: means that in semi-central collisions the p_T distribution of particles is anisotropic wrt the event plane…

does this mean we have flow?

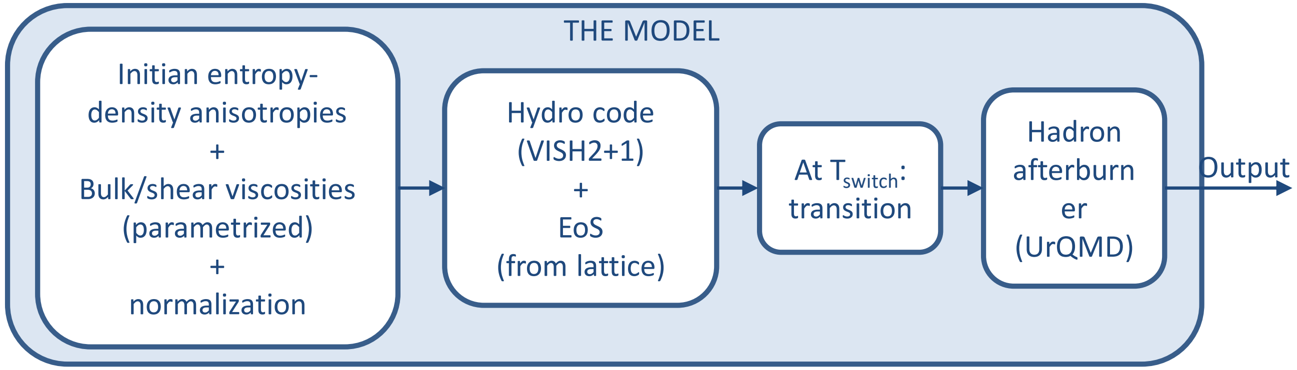
Gale, Jeon, Schenke, Tribedy and Venugopalan, PRL 110, 012302 (2013)



Hydrodynamic models reproduce v_n in all centralities by means of an “almost” perfect fluid: η/s=0.2

Global fits to extract model’s parameters

J. E. Bernhard at al., Phys. Rev. C 94, 024907 (2016)


THE MODEL

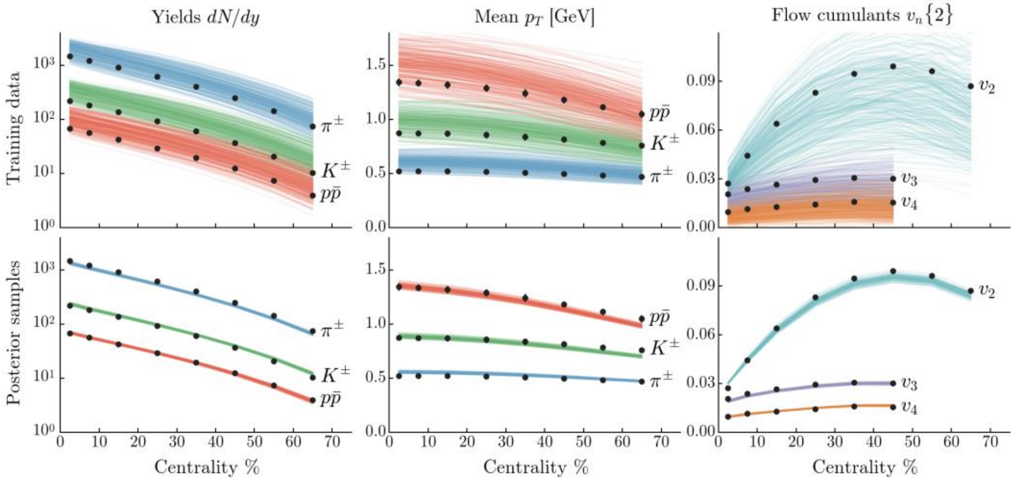
Initian entropy-density anisotropies
+
Bulk/shear viscosities (parametrized)
+
normalization

Hydro code (VISH2+1)
+
EoS
(from lattice)

At T_{switch}: transition

Hadron afterburner (UrQMD)

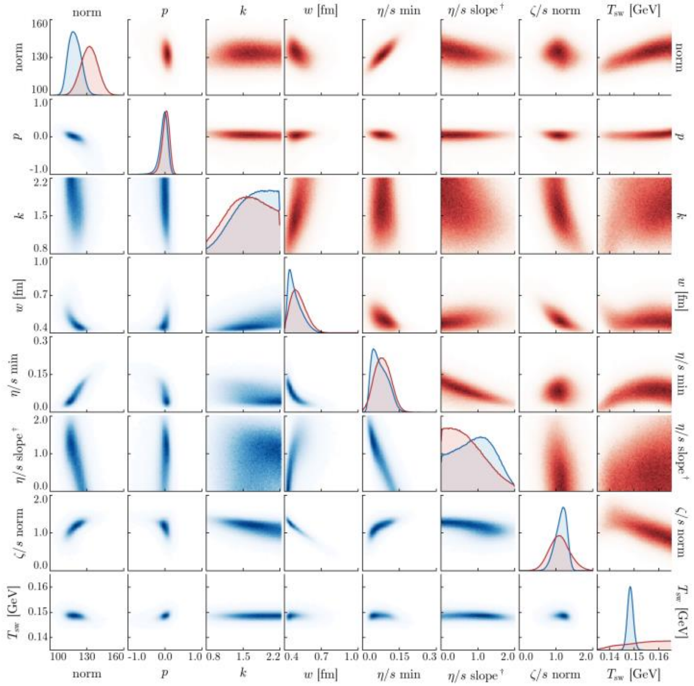
Output

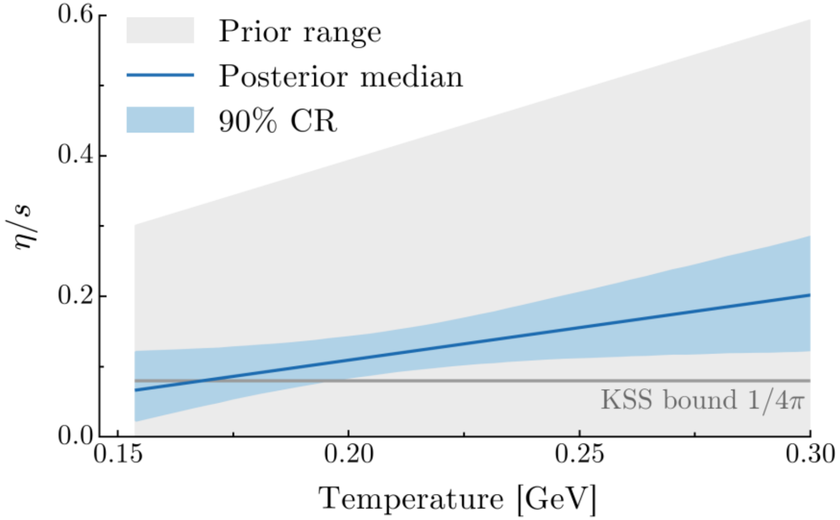


Training

Posterior

9 parameters: bayesian fit to yields, mean-p_T and v_2, v_3, v_4.
Posterior distributions and correlations estimated





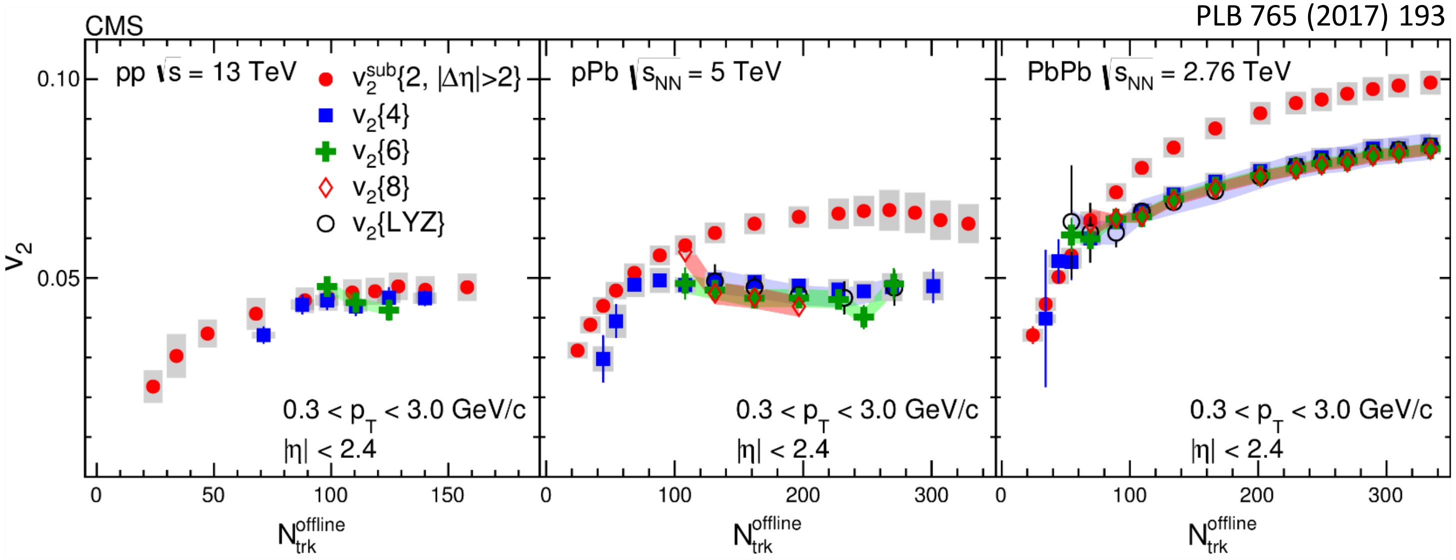
Very mild η/s dependence on temperature

Anisotropic flow: small systems?

$v_2 \neq 0$ 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?



PLB 765 (2017) 193

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

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

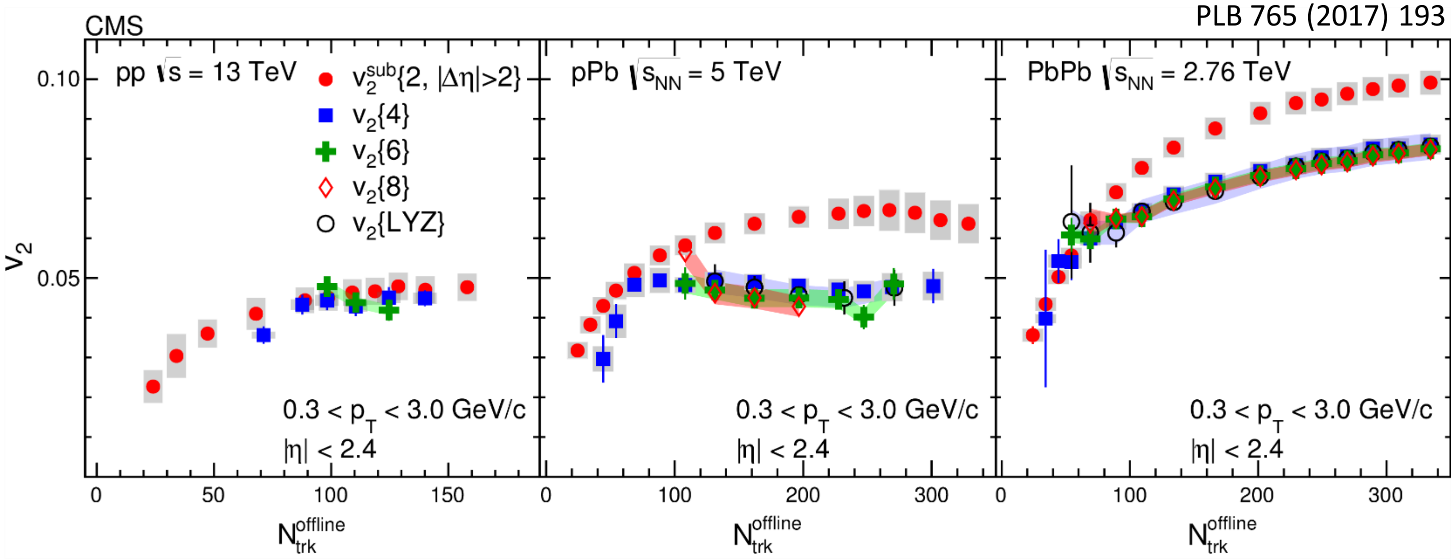
MEAN
FREE
PATH

Anisotropic flow: small systems?

$v_2 \neq 0$ 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?



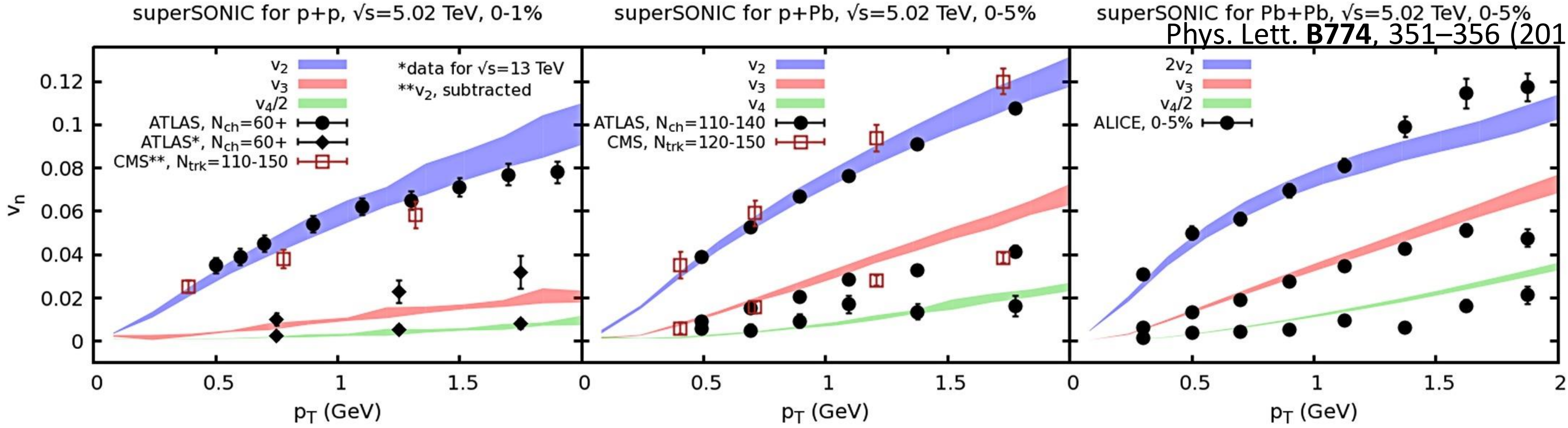
PLB 765 (2017) 193

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

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

Too restrictive: hydro can be applied far from thermalization!

W. Li, arXiv: 1704.03576

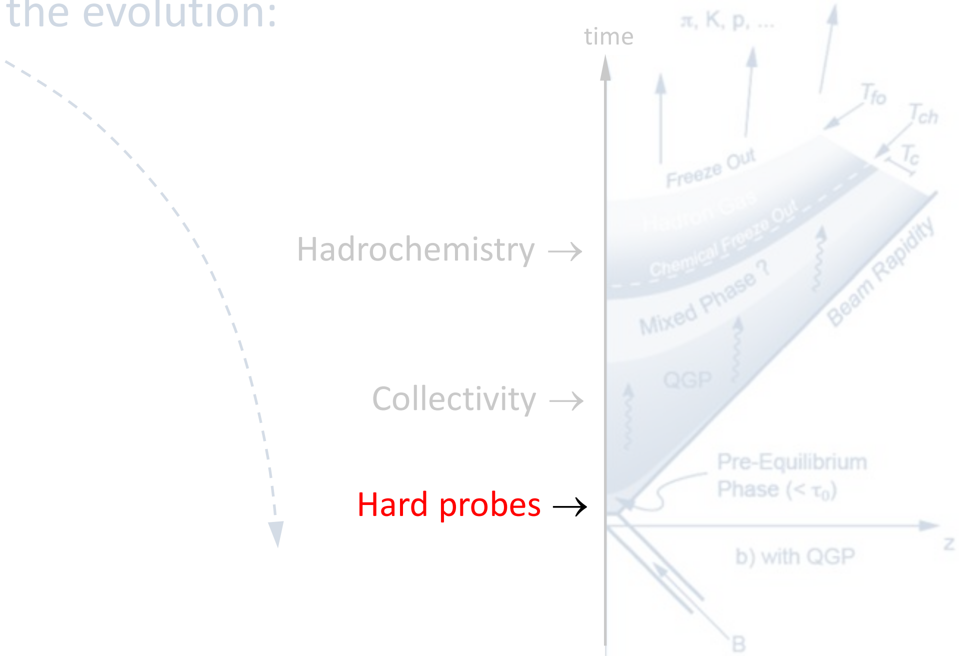


Phys. Lett. **B774**, 351–356 (2017)

First theoretical calculations involving hydro expansion of a single fluid in all collisional systems start appearing.

Selected results

…from latest to earlier stages of the evolution:



Hadrochemistry →

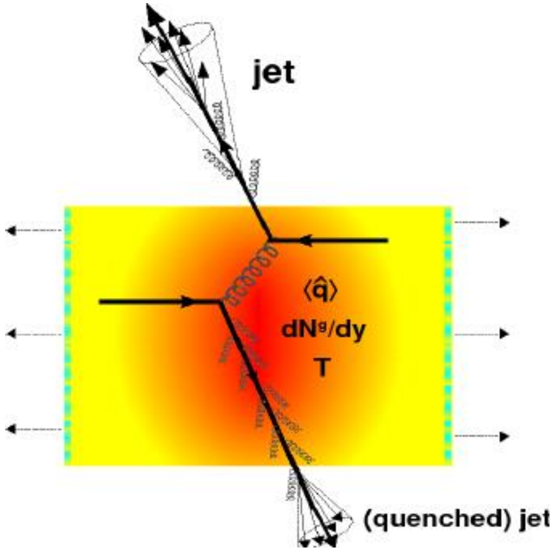
Collectivity →

Hard probes →

High-p_T hadrons and jets

Jets are a self-generated probes of the medium:

- High-p_T partons produced in the early stages of the collisions (τ<<1fm)
- Loose energy in the medium through:
    - elastic scattering
    - Induced gluon radiation (dominant at high-p_T)
- Simple prediction (dead-cone effect): $\Delta E_g > \Delta E_{light-quark} > \Delta E_{heavy-quark}$



BDMPS approach (example): describes parton shower in the medium (similarly to DGLAP in the vacuum)

$$\Delta E_{rad} \sim \alpha_S \, C_R \, \hat{q} \, L^2$$

With transport parameter:

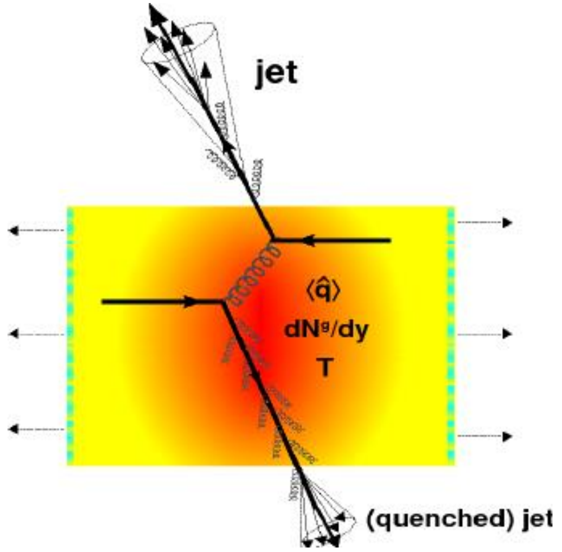
$$\hat{q} = \frac{\langle p_T^2 \rangle}{\lambda}$$

Nucl. Phys. B 484 (1997) 265

High-p_T hadrons and jets

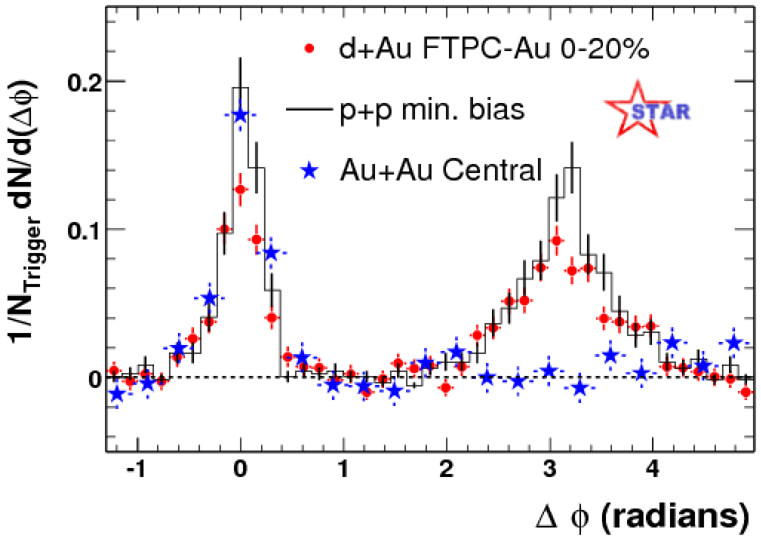
Jets are a self-generated probes of the medium:

- High-p_T partons produced in the early stages of the collisions (τ<<1fm)
- Loose energy in the medium through:
  - elastic scattering
  - Induced gluon radiation (dominant at high-p_T)
- Simple prediction (dead-cone effect): $\Delta E_g > \Delta E_{light-quark} > \Delta E_{heavy-quark}$



First approximation: look at R_{AA} of leading particle or at the central/hard-part of the jet

STAR, PRL 91 (2003) 072304



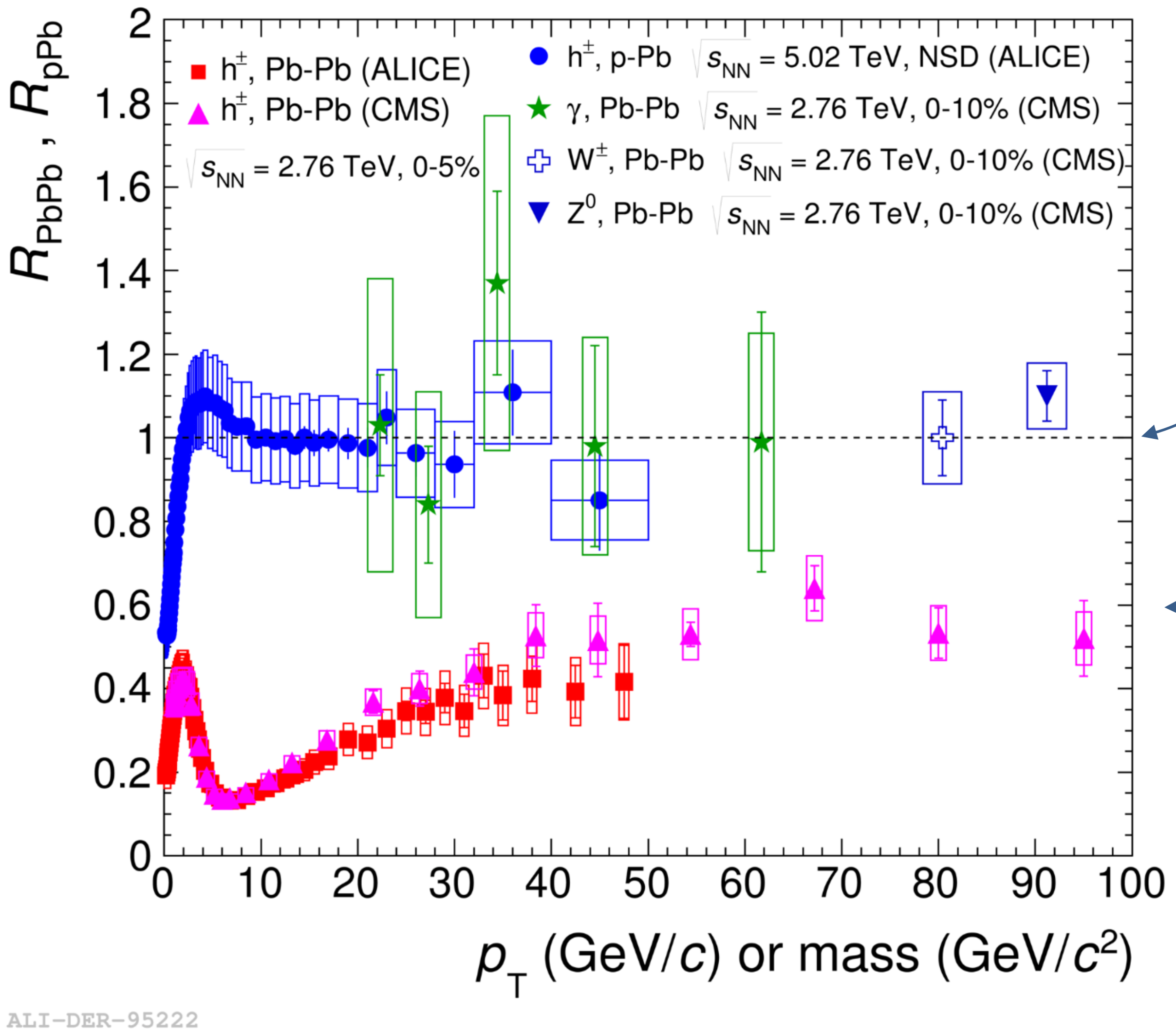
BDMPS approach (example): describes parton shower in the medium (similarly to DGLAP in the vacuum)

$$\Delta E_{rad} \sim \alpha_S \, C_R \, \hat{q} \, L^2$$

With transport parameter:

$$\hat{q} = \frac{\langle p_T^2 \rangle}{\lambda}$$

High-p_T hadrons and jets



Electroweak bosons not affected by QGP ⇒ R_{AA}=1

In p-Pb collisions no evidence for R_{AA}≠1
⇒ no final state effects observed

At high-p_T (~10÷100) charged hadrons suppressed ⇒ final state effect

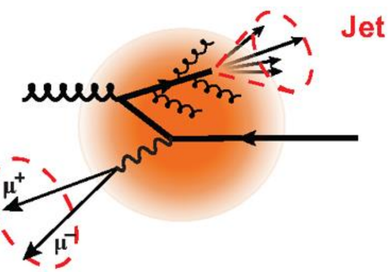
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \text{ at } \begin{array}{l} T = 370\ \mathrm{MeV} \\ T = 470\ \mathrm{MeV} \end{array}$$

JET Collaboration, PHYSICAL REVIEW C 90, 014909 (2014)

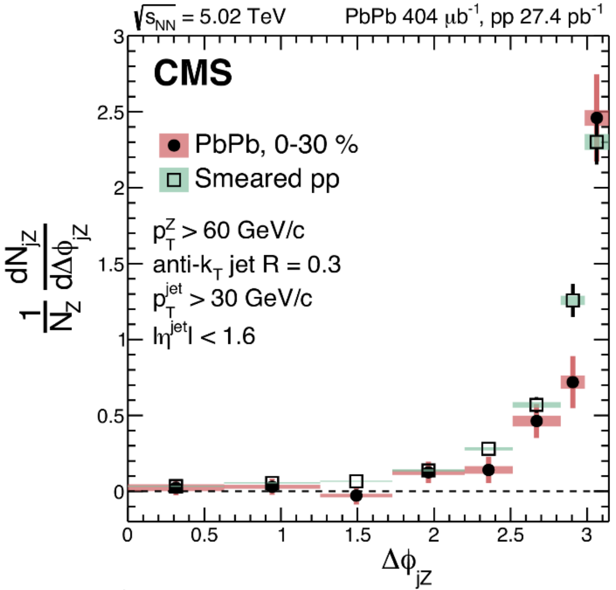
γ+jet & Z+jet

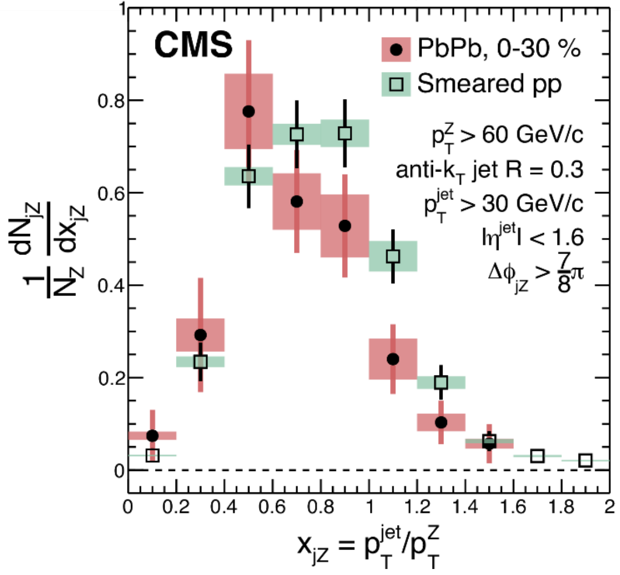
Studies with triggering boson and back-to-back jet give direct access to energy loss

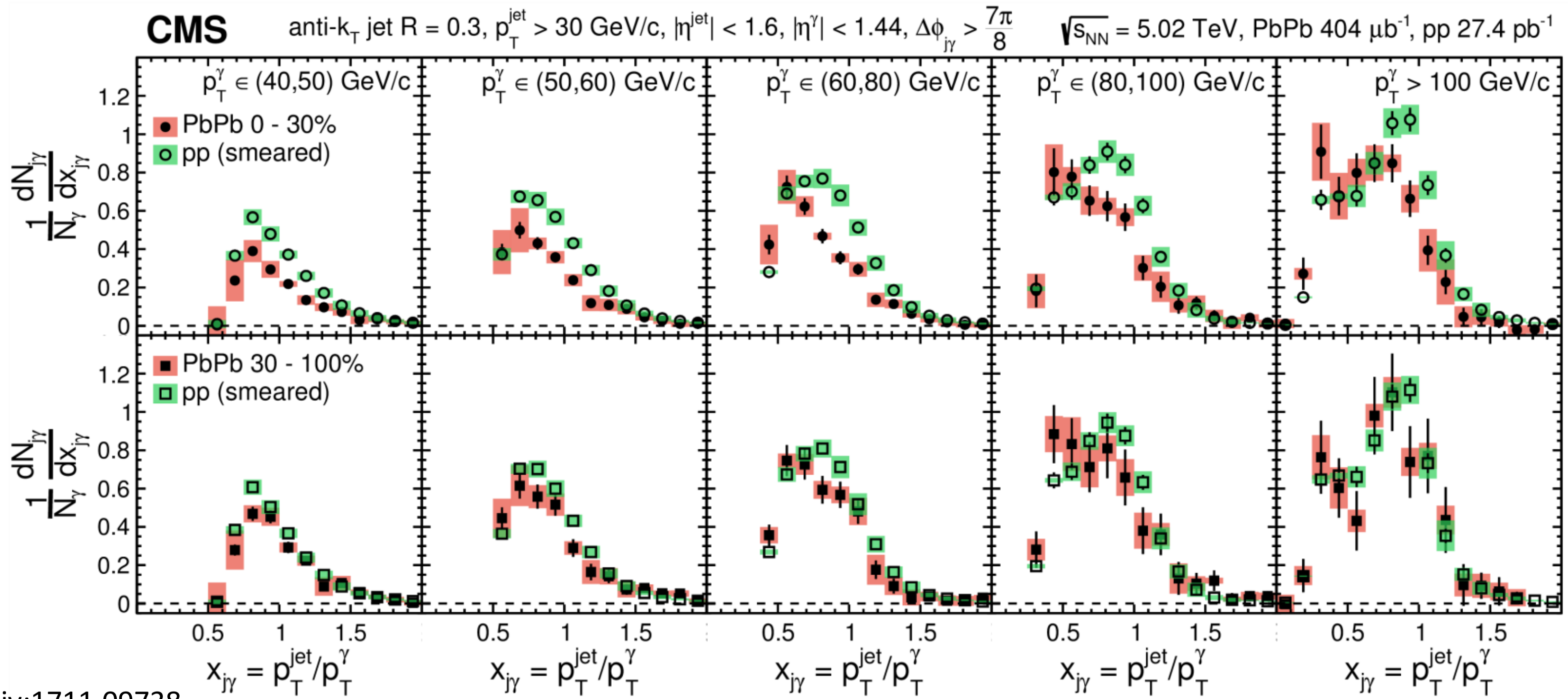
Clear imbalance: ΔE O(10GeV) for high-p_T jets



CMS, PRL 119 (2017) 082301

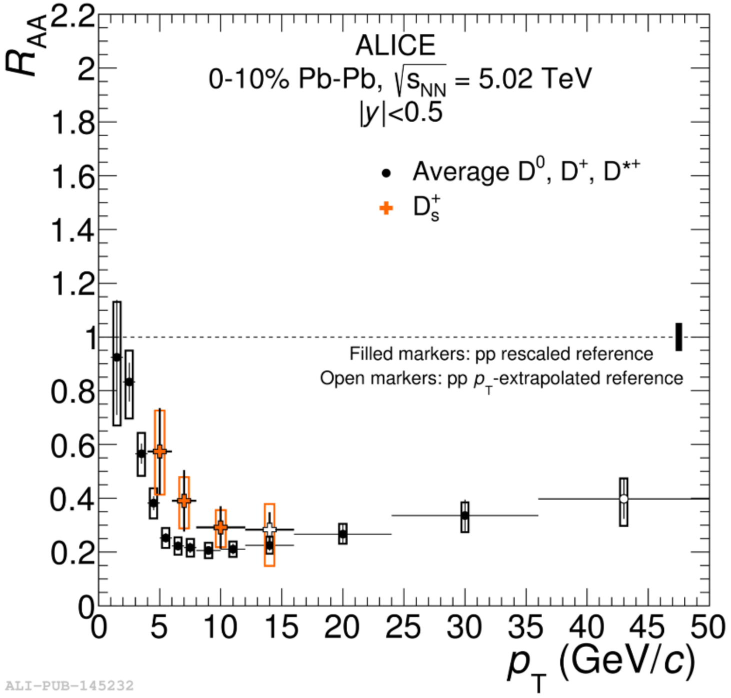






CMS, arXiv:1711.09738

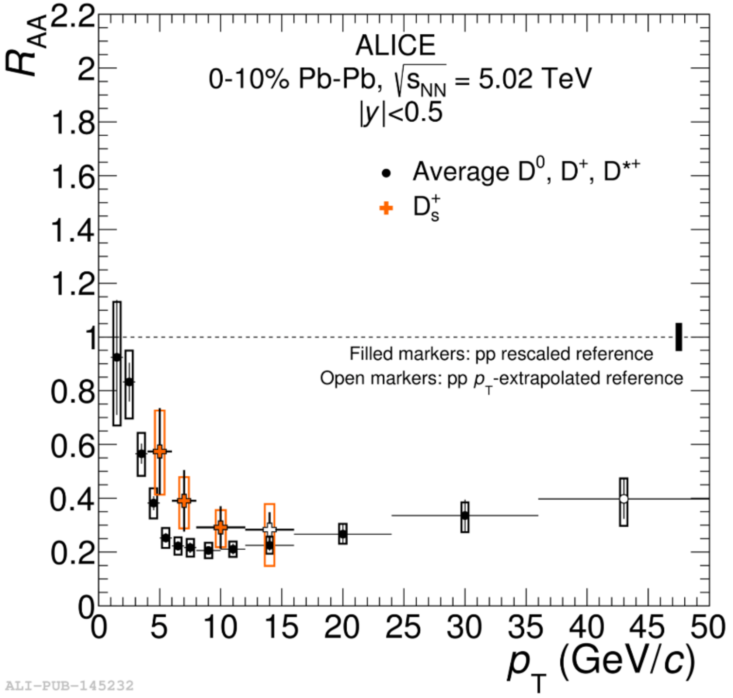
D- and B-mesons

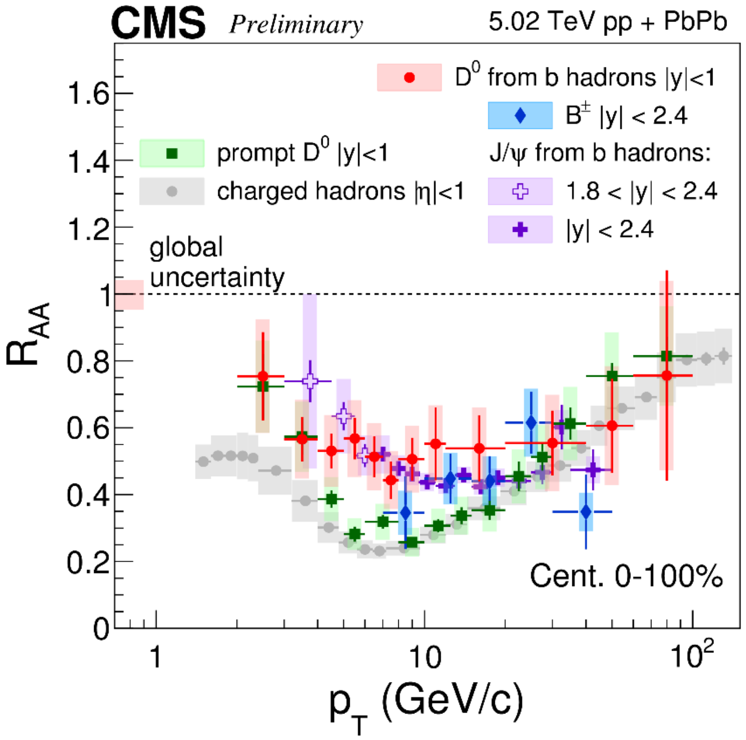


D-mesons R_{AA} shows large suppression (comparable to the one of charged hadrons)

Hint for higher R_{AA} in case of strange D-hadrons. Coming from strangeness enhancement in Pb-Pb?

D- and B-mesons





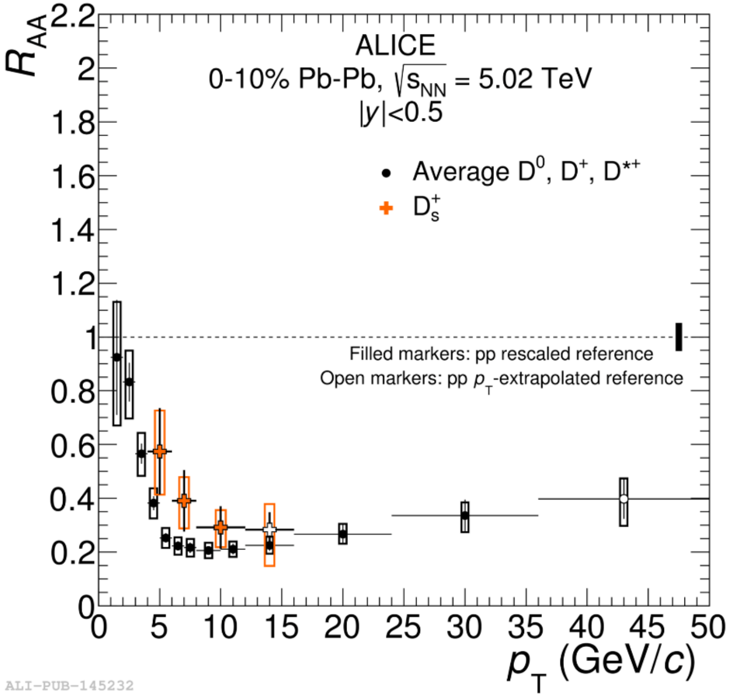
D-mesons R_{AA} shows large suppression (comparable to the one of charged hadrons)

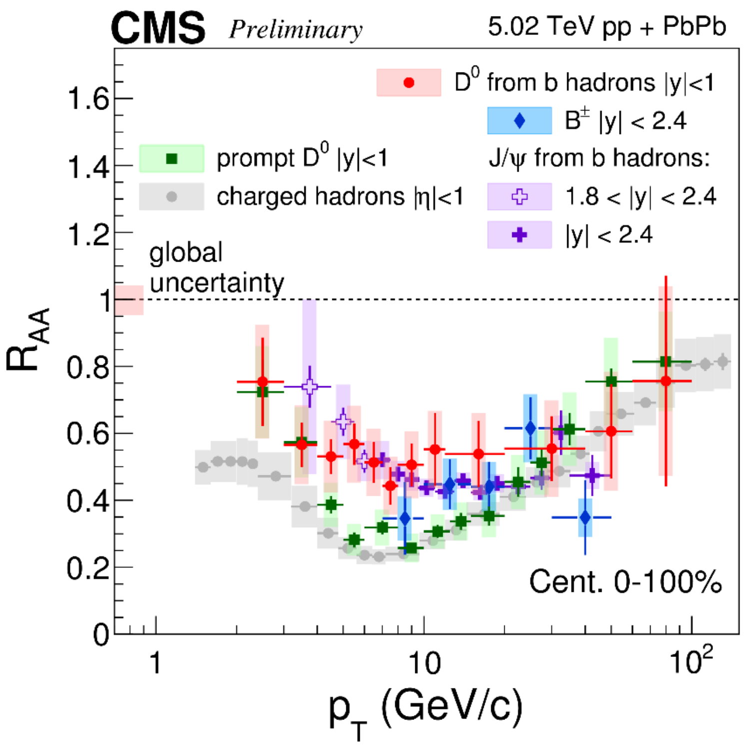
Hint for higher R_{AA} in case of strange D-hadrons. Coming from strangeness enhancement in Pb-Pb?

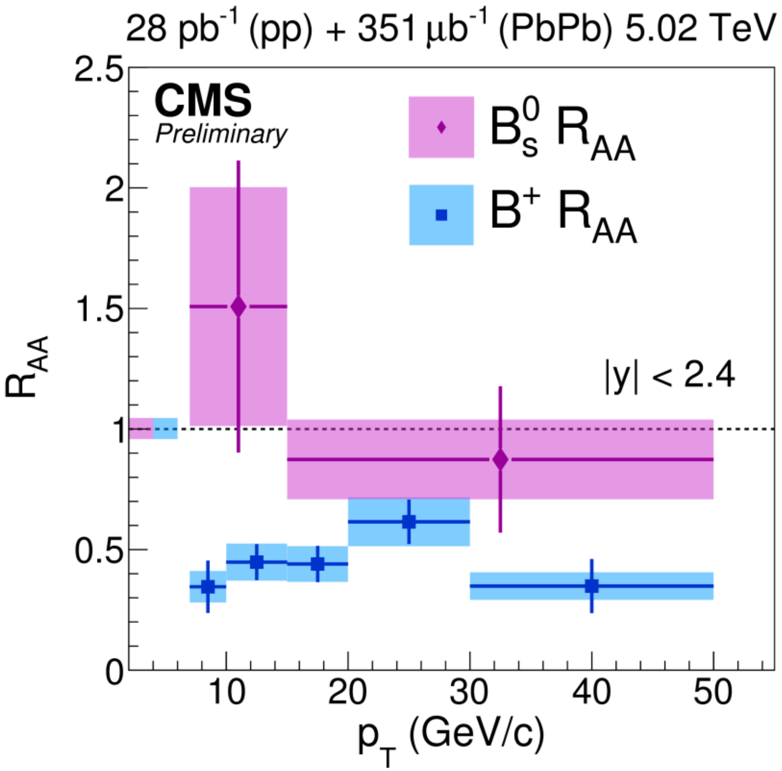
B hadrons less suppressed than D hadrons at ~10 GeV/*c*, as expected by dead-cone effect.

All R_{AA} merging at higher p_T

D- and B-mesons







D-mesons R_{AA} shows large suppression (comparable to the one of charged hadrons)

Hint for higher R_{AA} in case of strange D-hadrons. Coming from strangeness enhancement in Pb-Pb?

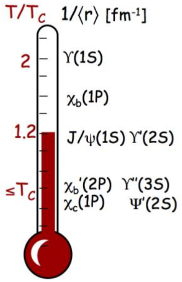
B hadrons less suppressed than D hadrons at ~10 GeV/*c*, as expected by dead-cone effect.

All R_{AA} merging at higher p_T

First results from CMS on B_s production and (mild) hints for larger R_{AA} wrt B^+

Quarkonia

- **the original idea:**
  quarkonium production suppressed via color screening in the QGP
  T.Matsui and H.Satz, Phys.Lett.B178 (1986) 416

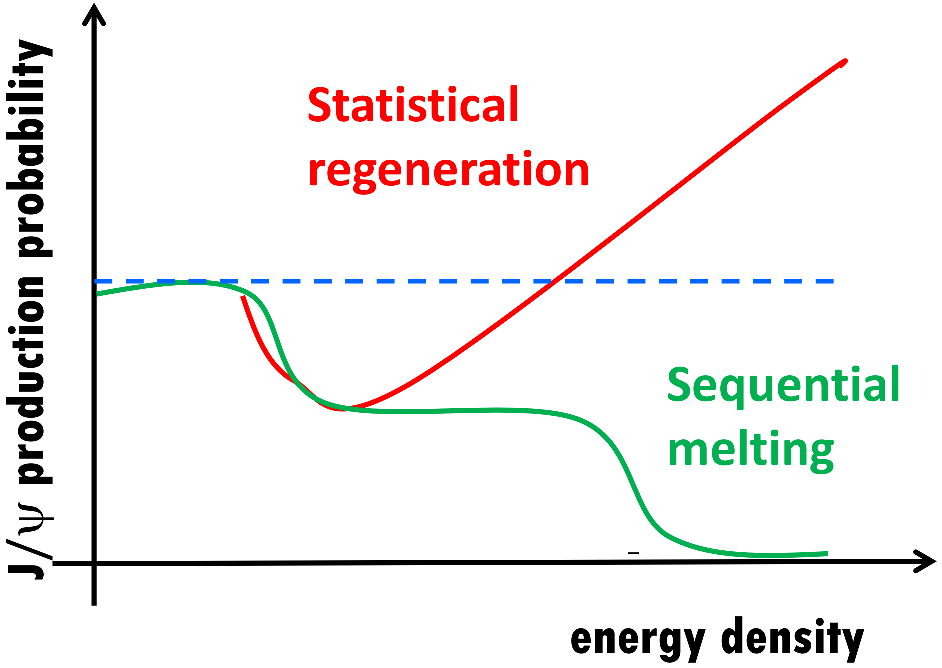


- **sequential melting**
  differences in quarkonium binding energies lead to a sequential melting with increasing temperature

- **(re)combination**
  enhanced quarkonium production via (re)combination during QGP phase or at hadronization

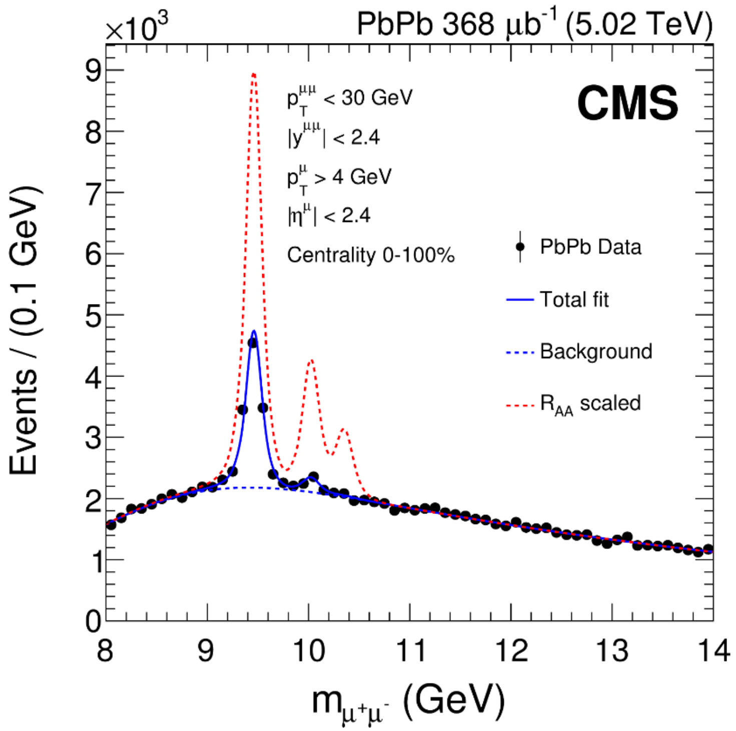
Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76TeV	LHC 5.02TeV
N_{ccbar}/event	~0.2	~10	~85	~115

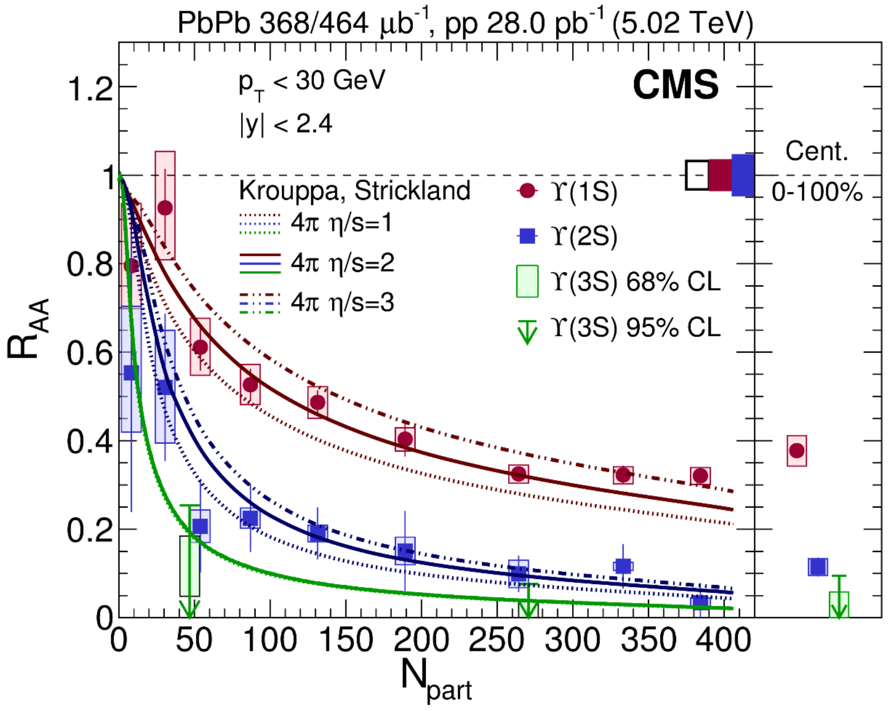
P. Braun-Muzinger,J. Stachel, PLB 490(2000) 196
R. Thews et al, Phys.Rev.C63:054905(2001)



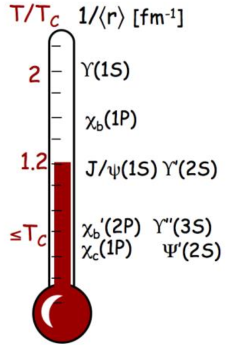
Quarkonia: progressive suppression

CMS, arXiv:1805.09215





Quantitative use of quarkonium as thermometer!!

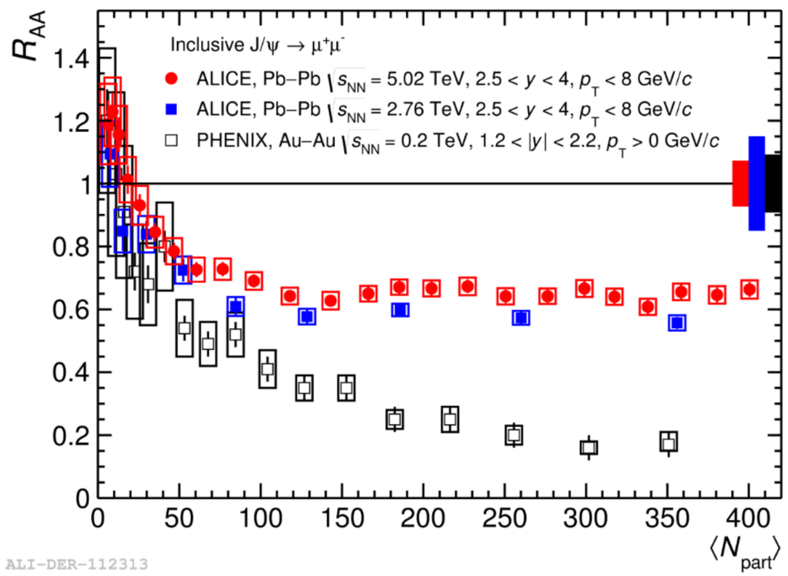


Progressive suppression of Υ(1S), Υ(1S) and Υ(3S)
Compliant with Debye screening picture

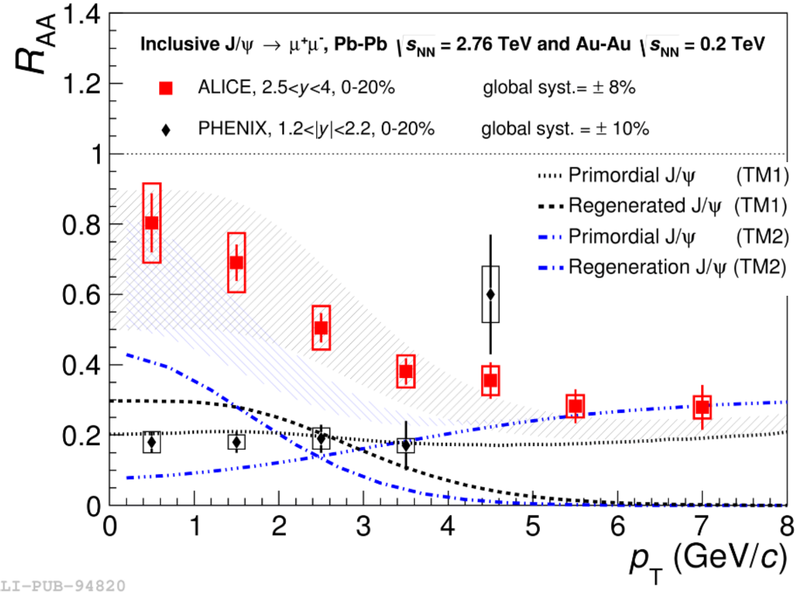
N_{part} dependence very well reproduced by models which include a fluid with $\eta/s = {}^{2}/_{4\pi}$

Krouppa and Strickland, Universe 2016, 2(3), 16

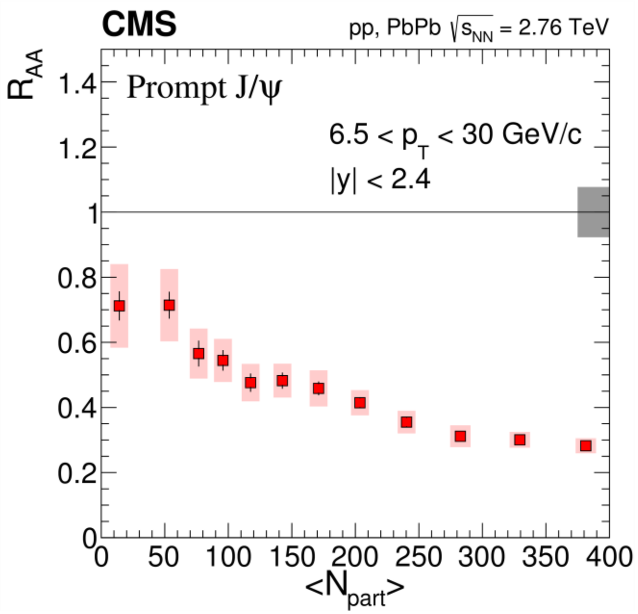
Quarkonia: low-p_T regeneration



ALI-DER-112313



ALI-PUB-94820



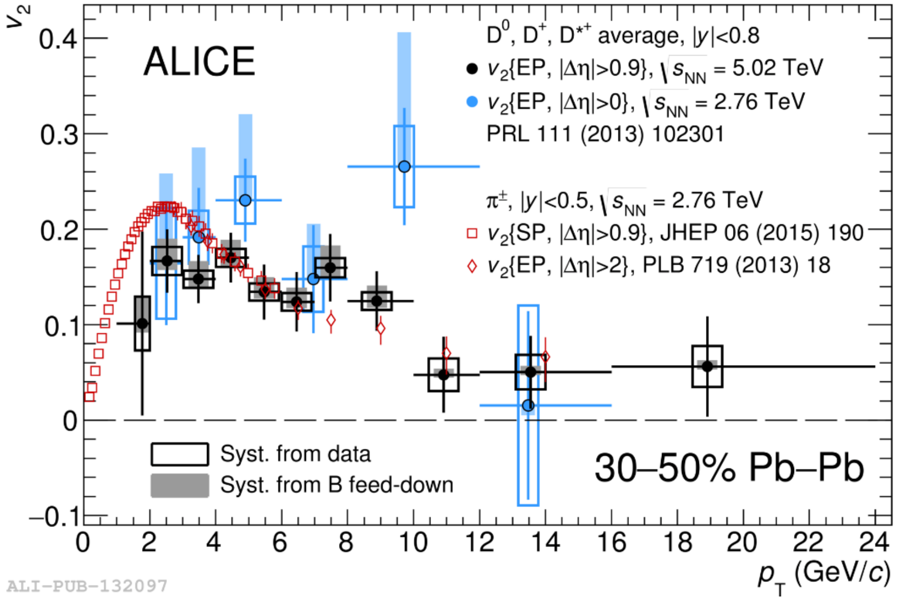
Less suppression at LHC than at RHIC for the J/ψ

Difference located at low-p_T, where regeneration is expected to play an important role

At high p_T: similar suppression at RHIC and LHC

(Re)generated J/ψ come from the combination of random c-c_{bar} from the bulk. Does charm take part to collective motion in the bulk?

Does charm participate to the collective motion?



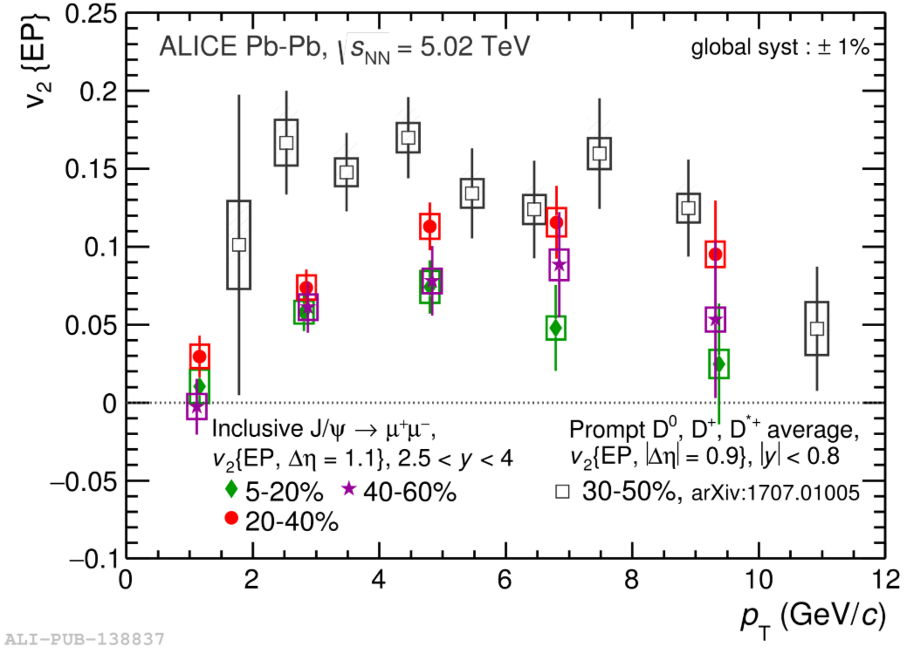
v_2 of D-mesons significantly different from 0
in semi-central Pb-Pb collisions at the LHC.

Magnitude compatible with the one of pions!

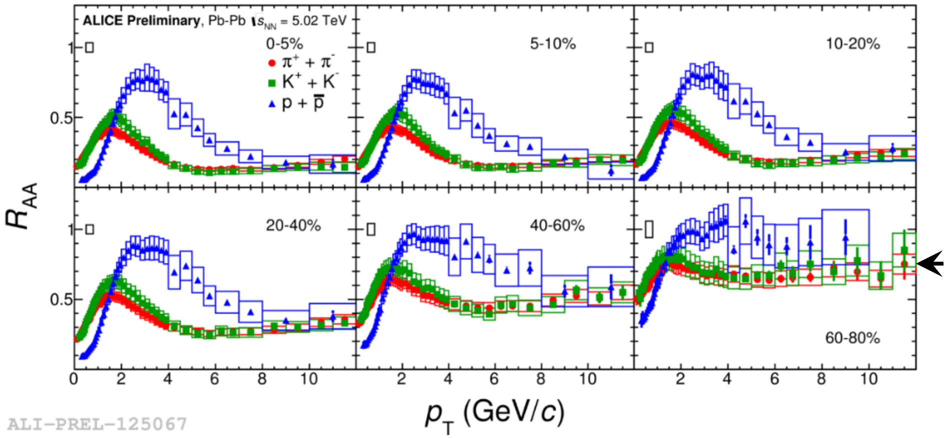
Does this mean that charm
flows with the bulk?

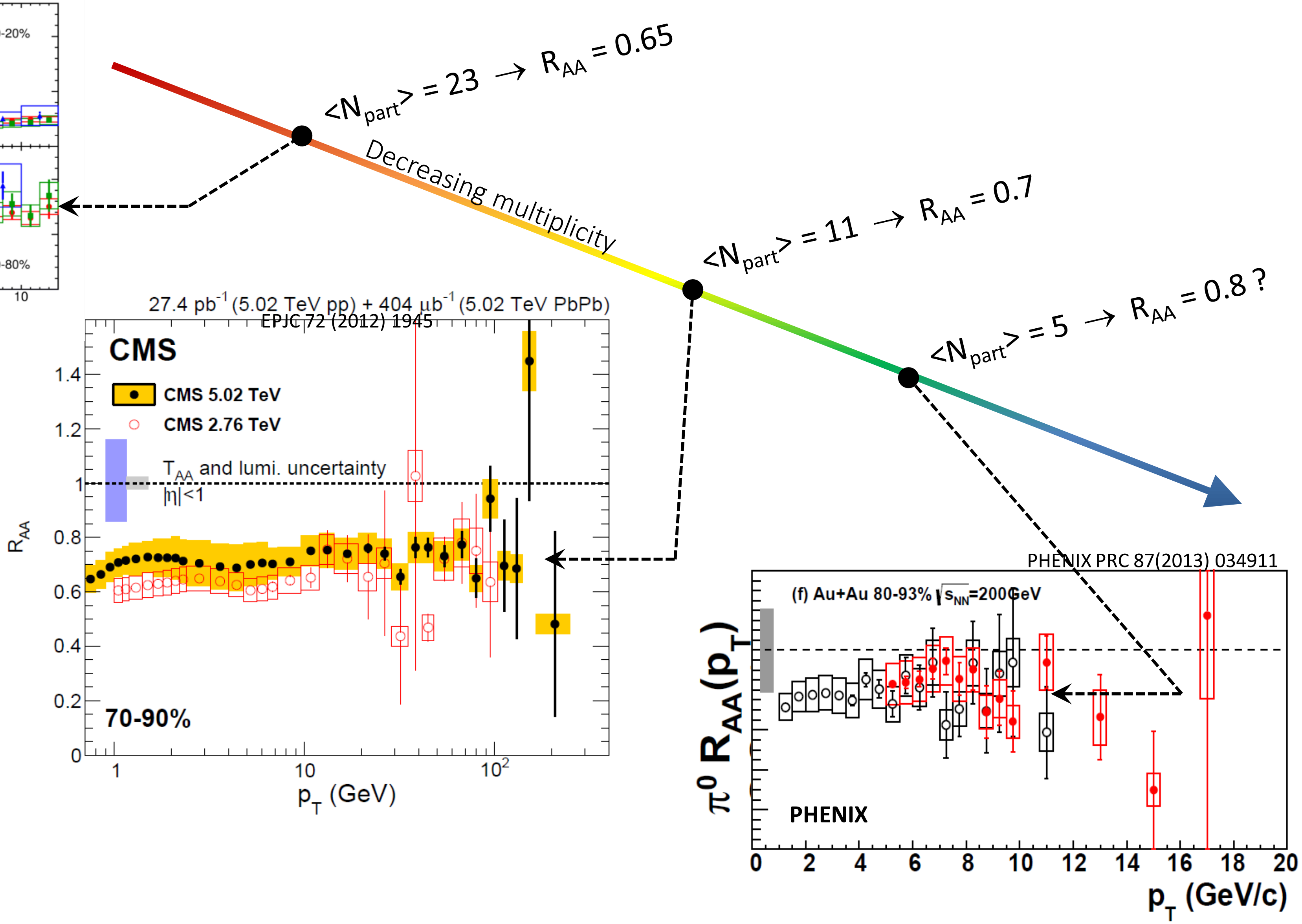
D-mesons are composed by charm and light quarks.
Can it be that v_2 of D comes from collective motion of light quarks?

J/ψ v_2 significantly different from 0!
…and this is solely charm!



Hard probes: going “smaller”





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

But what happens in small collision systems?

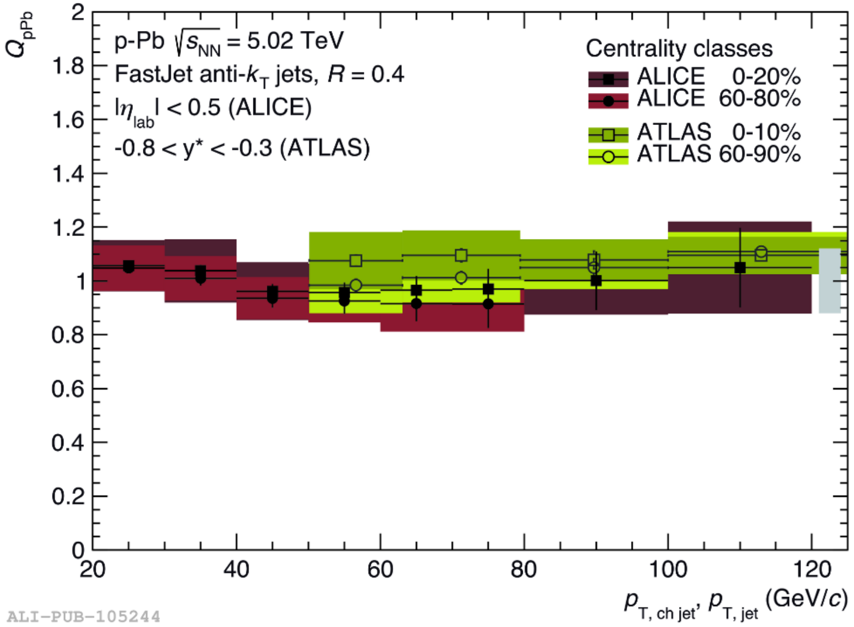
Difficult to define an R_{AA} in pp…!!!

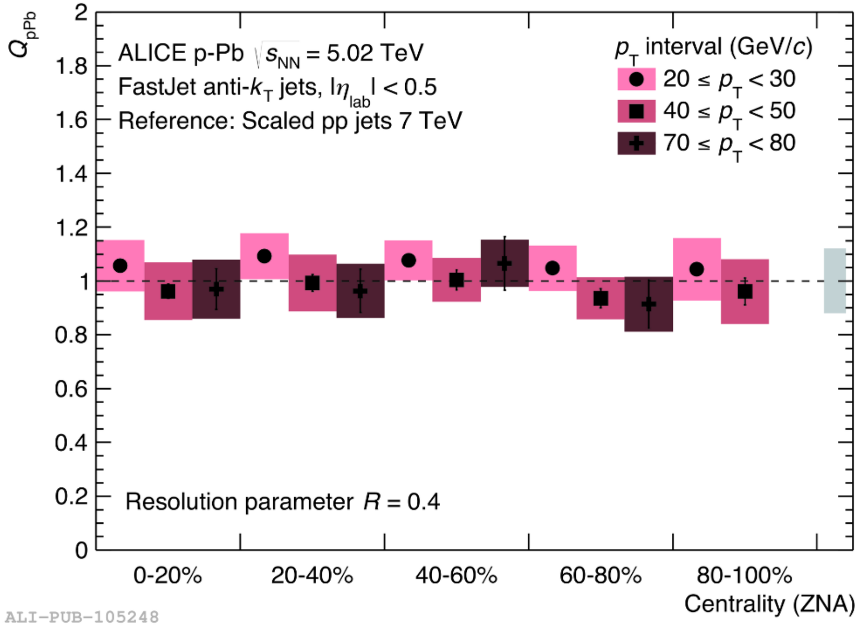
Let’s concentrate on p-Pb

↓

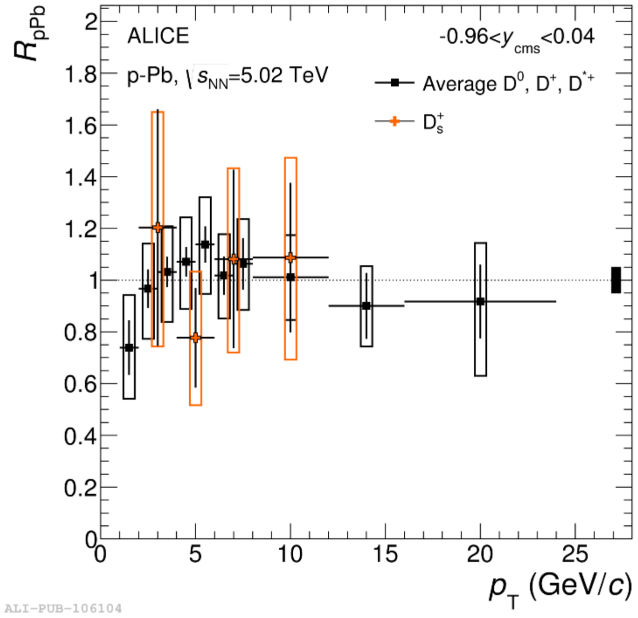
Energy loss in small systems?

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





ALICE, Phys. Rev. C 94 (2016) 054908



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

High-p_T hadrons do also not show any suppression

…but multiplicity in 0-20% p-Pb is higher than in all cases discussed in the previous slide…!

⇨

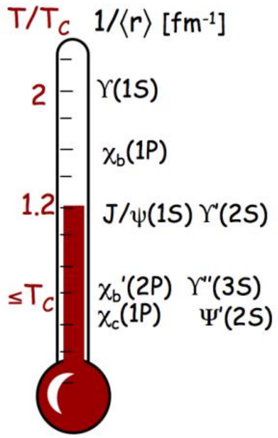
…should we conclude that multiplicity is NOT the driving quantity for “hard” observables?

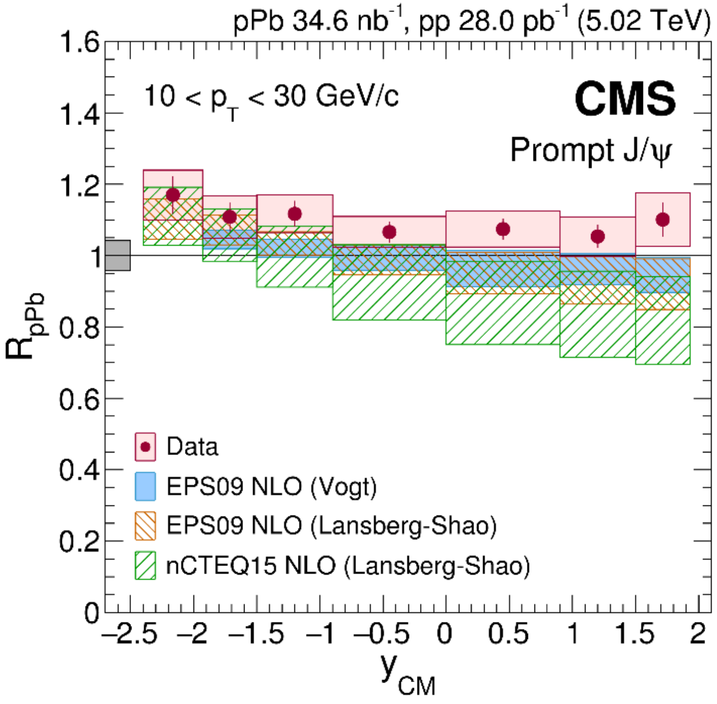
Quarkonia melting in small systems?

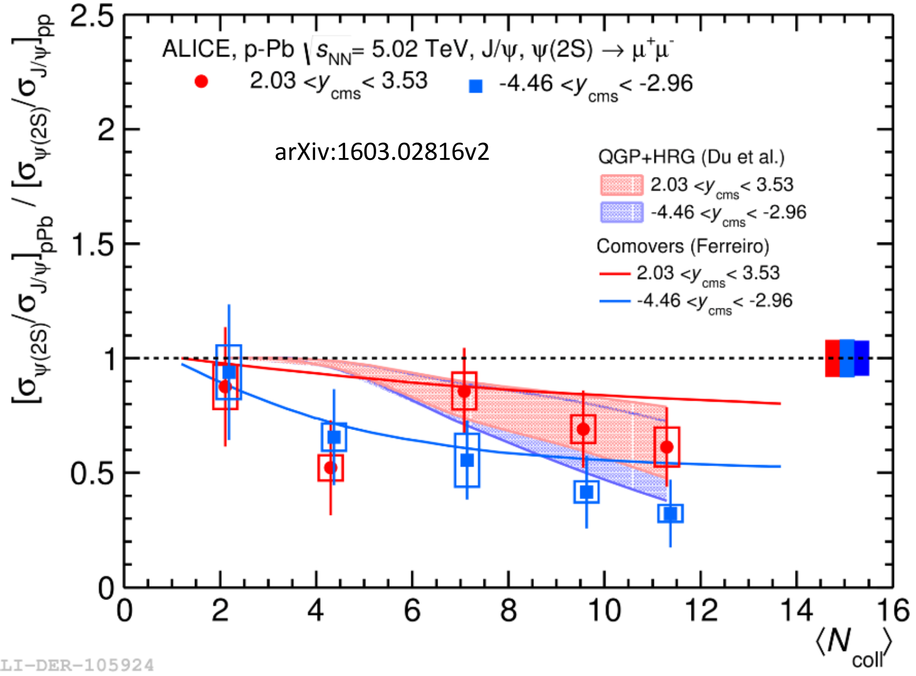
J/ψ not suppressed in p-Pb collisions

…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







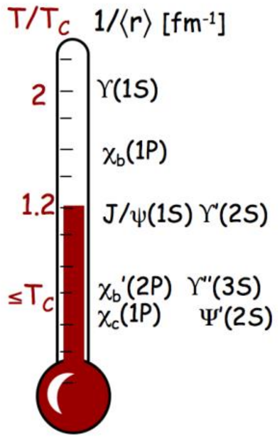
arXiv:1603.02816v2

Quarkonia melting in small systems?

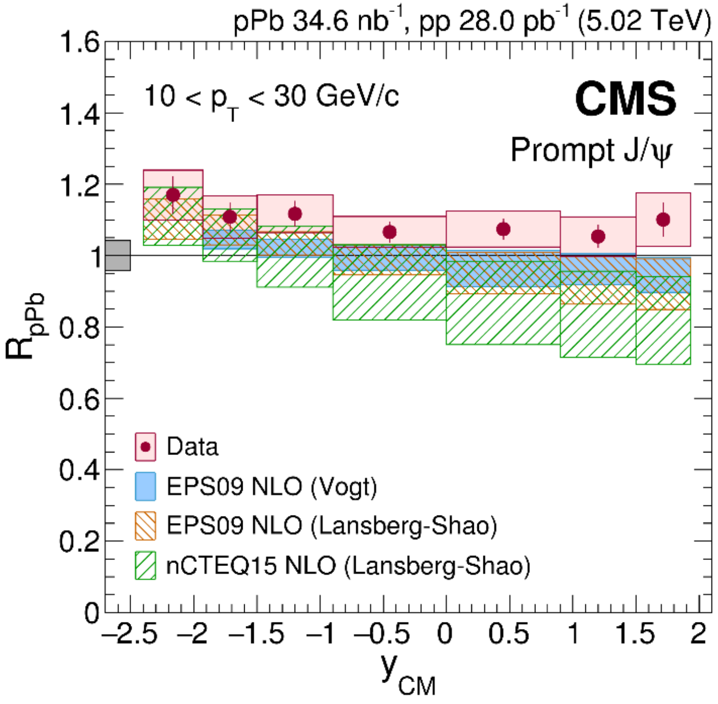
J/ψ not suppressed in p-Pb collisions

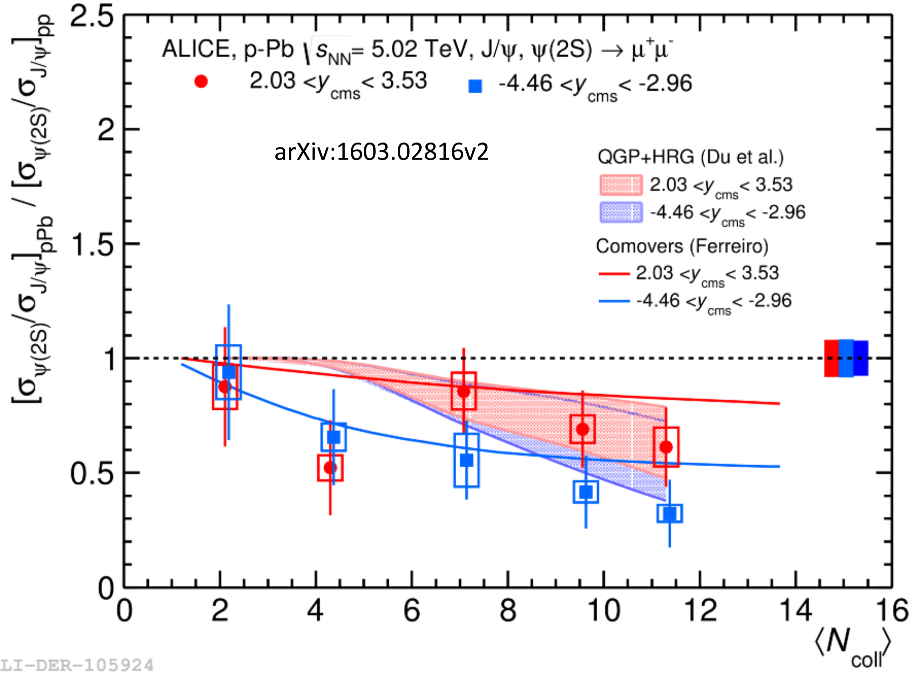
…but ratio ψ(2S)/J/ψ significantly lower than 1 at large N_{coll}!!

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

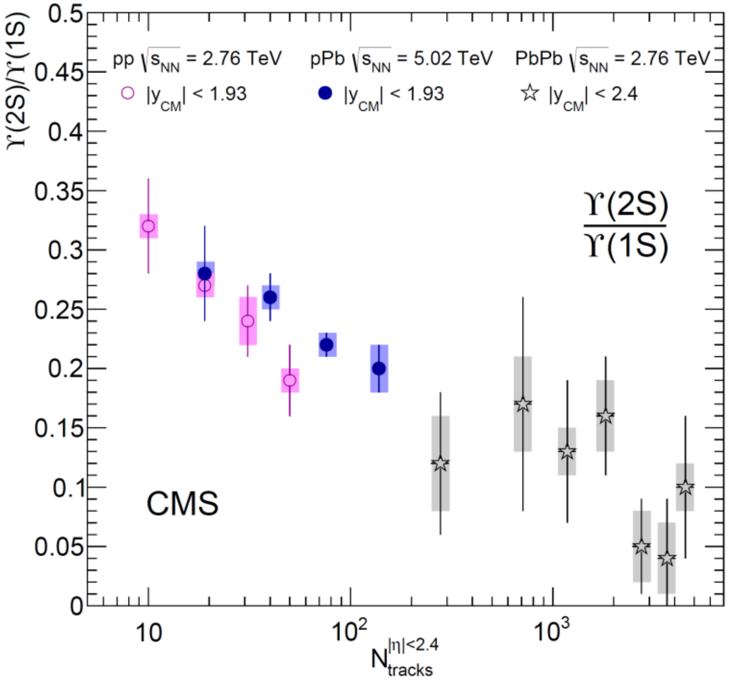


…but then, why ϒ(2S) is suppressed in p-Pb and even pp high-multiplicity events?





ALI-DER-105924



Conclusions

Conclusions

Entering the era of quantitative characterization of the QGP:

- Chemical composition of the fireball is found to be at the saturation level, as predicted by Thermal Models
- Evidence for radial and anisotropic flow developing in the hydro expansion of the fireball → $\eta/s \approx 0.2$
- Jet quenching observed and extensively studied at the LHC, with first estimate of transport parameter → $\hat{q} \approx 2\ \mathrm{GeV}^2/\mathrm{fm}$
- Expectation $\Delta E_{light-quark} > \Delta E_{heavy-quark}$ varified @LHC
- Bottomonium thermometer of the medium finally exploited → $\eta/s \approx {}^{2}/_{4\pi}$ (in agreement with v_2 estimate)

Thank you

Conclusions

Entering the era of quantitative characterization of the QGP:

- Chemical composition of the fireball is found to be at the saturation level, as predicted by Thermal Models
- Evidence for radial and anisotropic flow developing in the hydro expansion of the fireball → $\eta/s \approx 0.2$
- Jet quenching observed and extensively studied at the LHC, with first estimate of transport parameter → $\hat{q} \approx 2\ \mathrm{GeV}^2/\mathrm{fm}$
- Expectation $\Delta E_{light-quark} > \Delta E_{heavy-quark}$ varified @LHC
- Bottomonium thermometer of the medium finally exploited → $\eta/s \approx {}^{2}/_{4\pi}$ (in agreement with v_2 estimate)

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

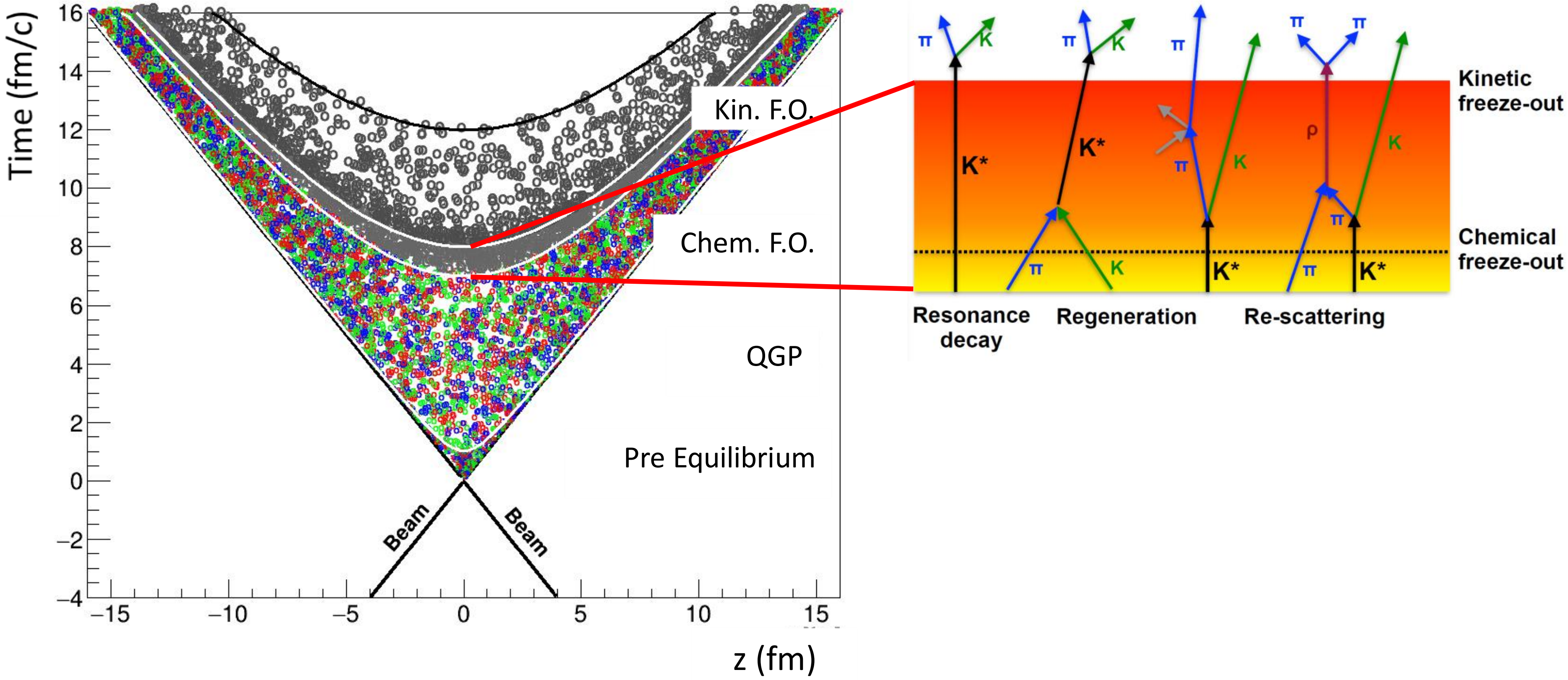
- Final state multiplicity drives light flavours observables across systems and energies.
- Strangeness enhancement in pp collisions. In highest multiplicity, hadrochemistry ≈ to the one in the QGP
- $v_2 \neq 0$ in pp and p-Pb collisions at the LHC.
- No parton energy loss observed in pp and p-A
- Intriguing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

Thank you

Backup

The resonances’ story (I)

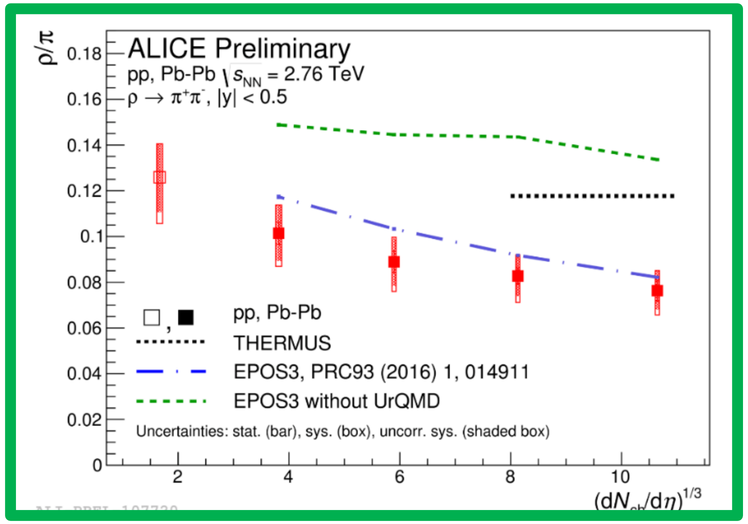
Resonances are powerful tools to probe the hadronic phase after chemical freeze-out

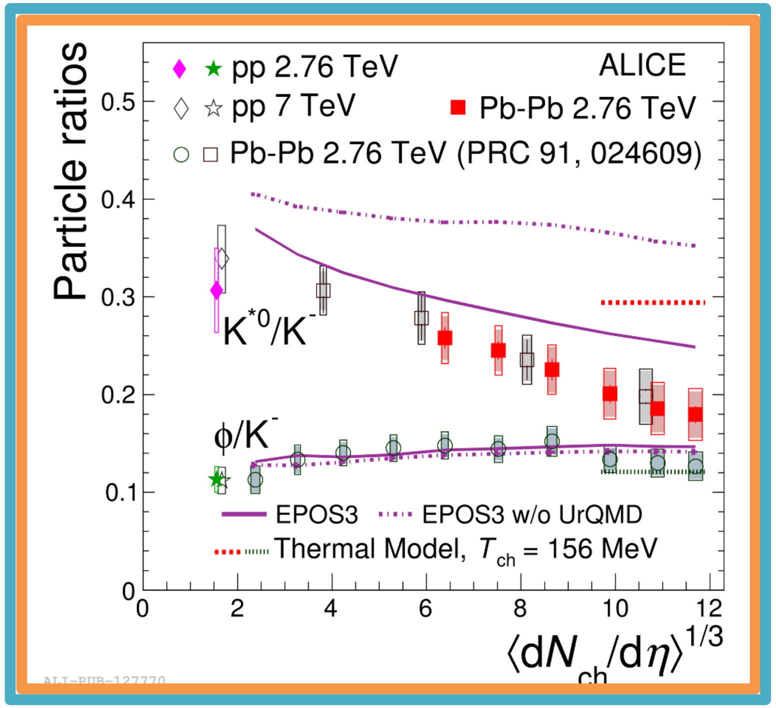


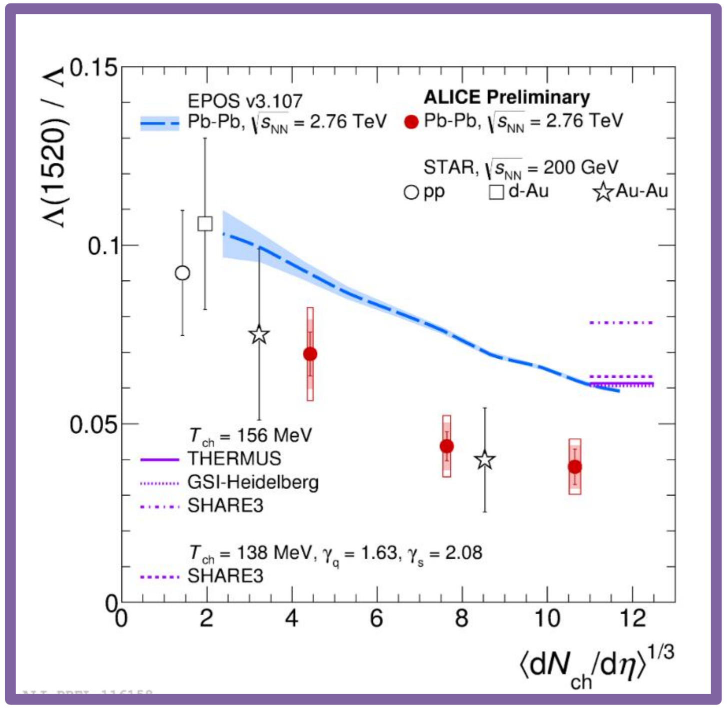
The resonances' story (II)

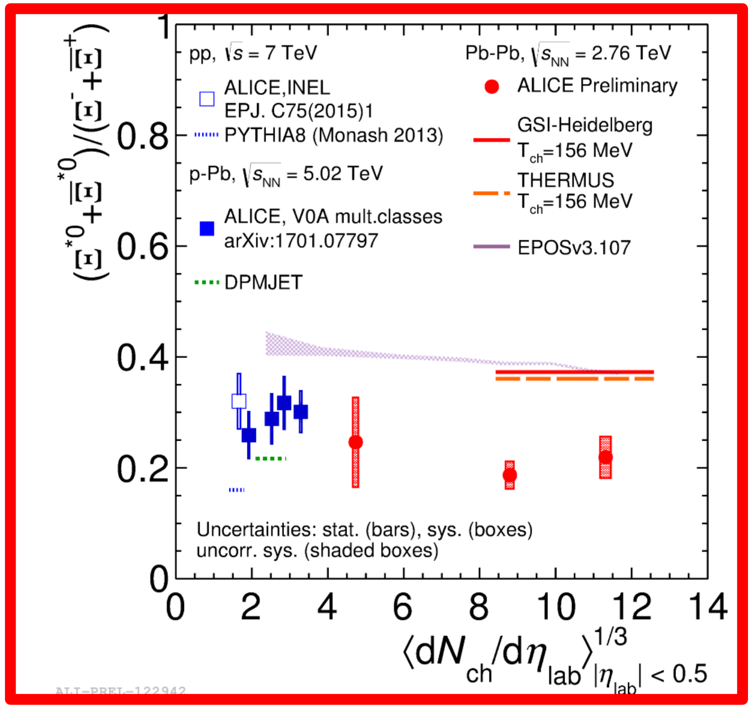
Resonances are powerful tools to probe the hadronic phase after chemical freeze-out

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

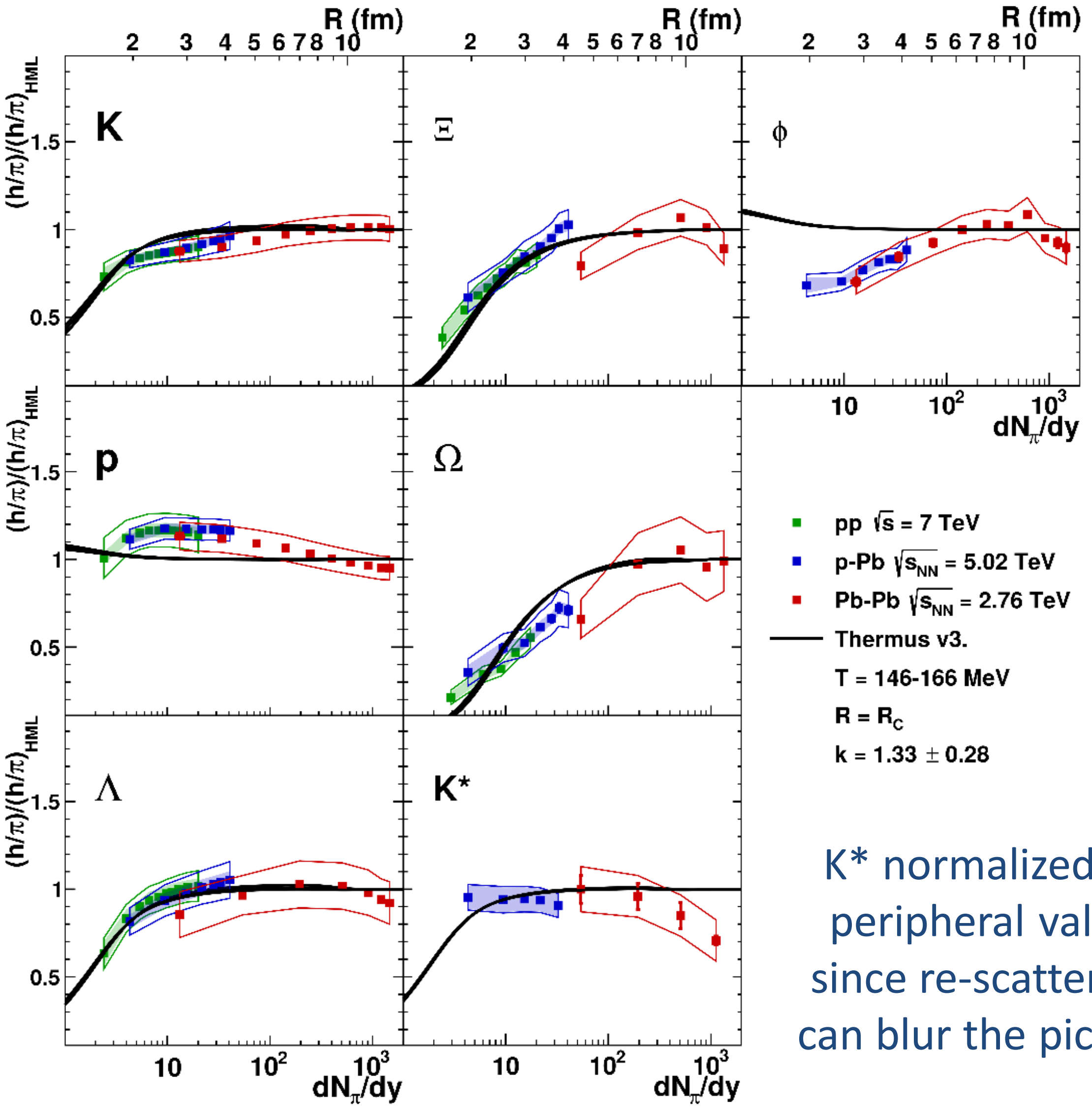








Hadrochemistry: thermal emission in elementary collisions?



V. Vislavicius, A. Kalweit aXiv:1610.03001 [nucl-ex]

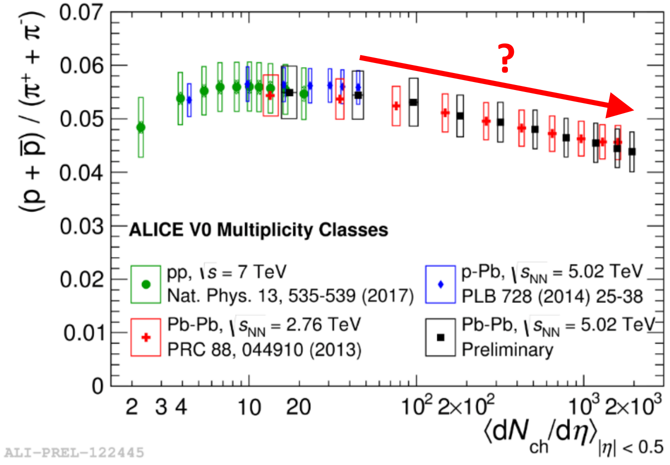
K* normalized to peripheral value since re-scattering can blur the picture

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!



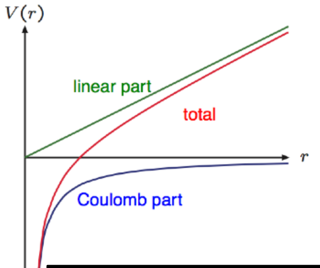
If interested in re-scattering in the hadronic phase, more in the backup!

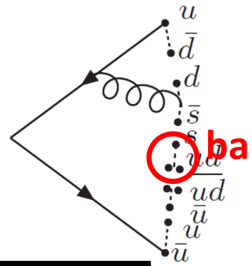
The Lund string model: basics

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

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

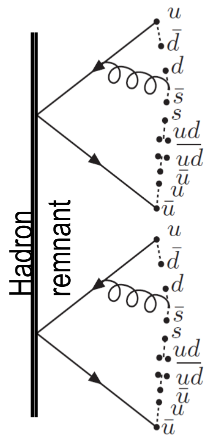
- Flavour of hadrons determined by the Gaussian mass suppression term (which mass to put? If current → less s-suppression than observed. If constituent → too much s-suppression. s/u empirical number to be tuned on data)



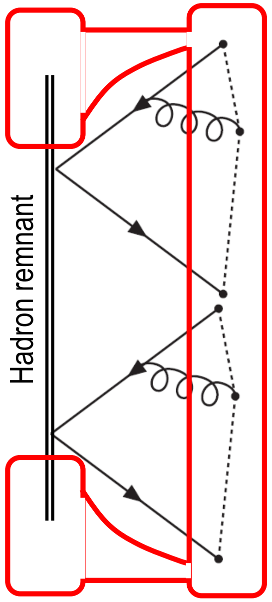


baryons

Fischer & Sjostrand, arXiv:1610.09818 (2017)



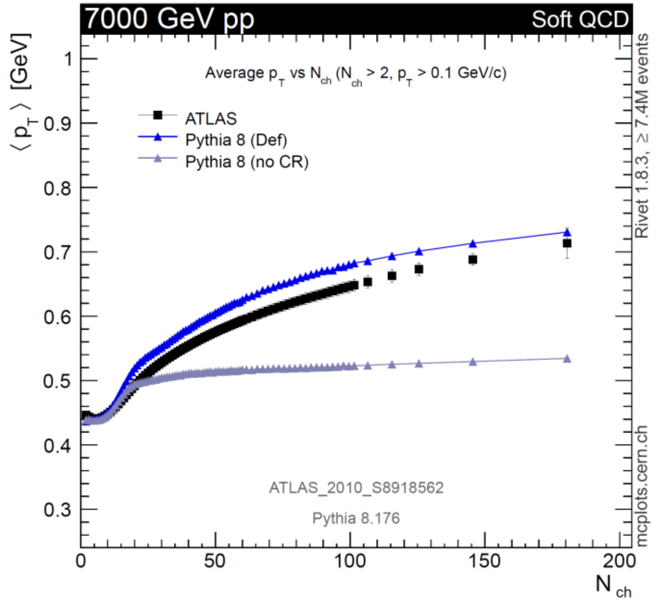
- In **hadronic collisions** multiple strings needed to describe multiplicity distribution (**MPI**)
- In the LC Lund model each string hadronizes separately with respect to the others
- The multiplicity increases, but not the $\langle p_T \rangle$ nor the relative flavor abundancies!



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

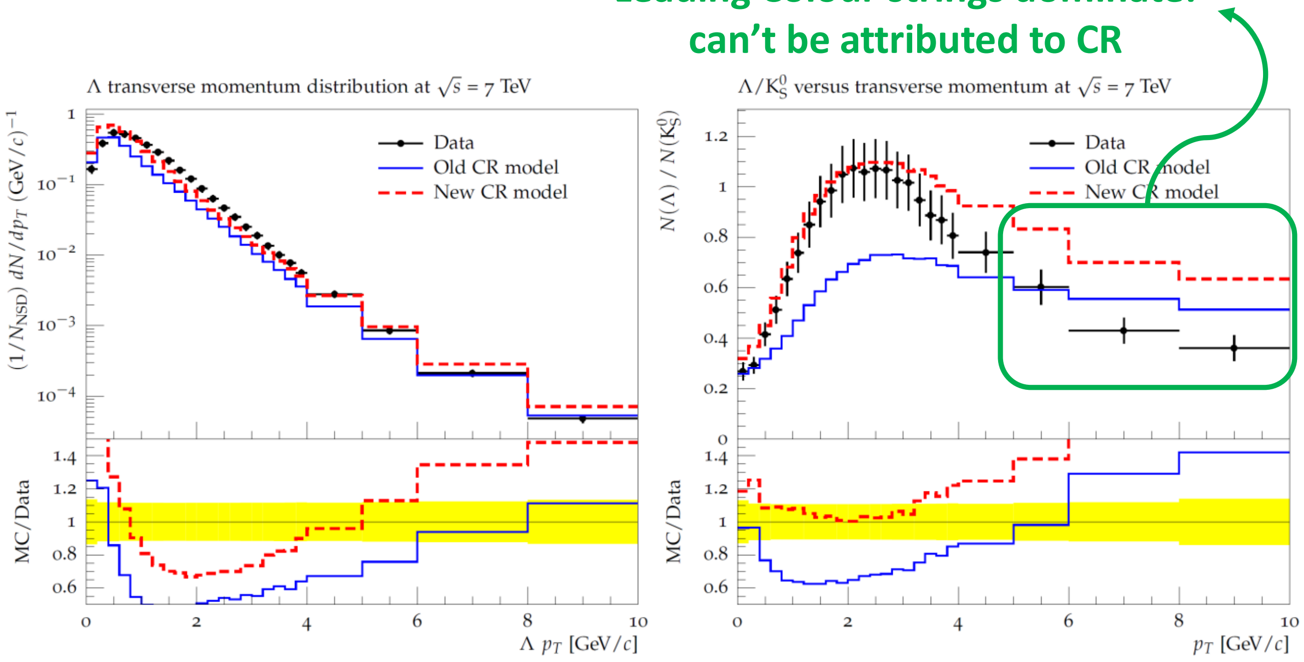
Christiansen & Skands, arXiv:1505.01681 (2015)

PYTHIA: effect of CR



- 3 main parameters tuned on data: c_{time} ($\langle p_T \rangle$), c_j (Λ/K^0_S) and p_T^{ref} ($dN_{ch}/d\eta$).
- The presence of **junctions increases baryon production** at intermediate p_T, but not sufficient to reproduce data
- Λ/K^0_S shape (magnitude is tuned!) reproduces data up to 3 GeV/c → problem in spectra common to baryons and mesons?

Leading Colour strings dominate: can't be attributed to CR



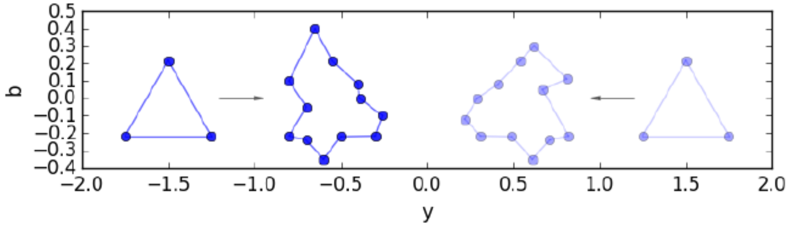
TAKE HOME

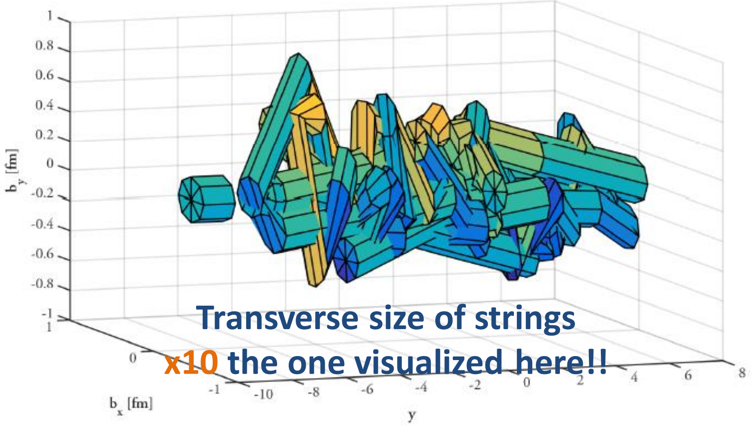
CR mimics features that we traditionally attribute to collective flow, but something more is needed. Tuning?

Christiansen & Skands, arXiv:1505.01681 (2015)

The DIPSY model: basics & ropes

- Partonic model in impact parameter space and rapidity (**D**ipole evolution in **I**mpact **P**arameter **S**pace and rapidit**Y**)
- Mueller dipole model (LL-BFKL)
- Proton/Nucleus structure built up dynamically from dipole splittings
- Builds-up initial state + collision in impact parameter space. Naturally treats saturation and MPI





Transverse size of strings
x10 the one visualized here!!

To the question “Which are the strings that can interact?” the DIPSY model answers following the evolution of colour strings during the whole parton shower

How do strings interact?

Stack of colour strings close in the IP-y space: can form colour singlets or multiplets according to the summing rules of SU(3)
Singlets correspond to simple re-arrangement of single strings,
Multiplets correspond to **ROPES**.

Hadronizing a rope means fragmenting string-by-string
with an **effective string tension $\kappa > \kappa_0$**

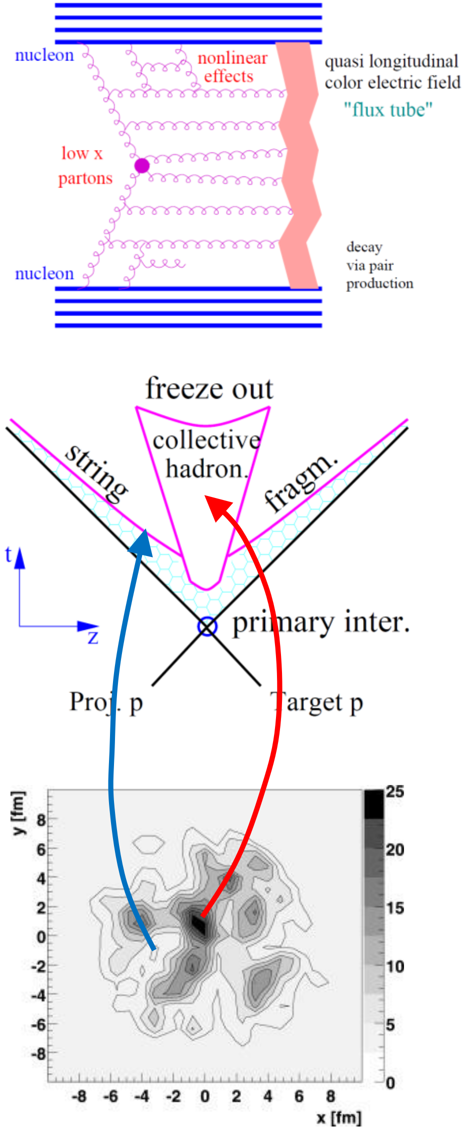
As we know from previous works,
higher string tension ⇒ more baryons and more flavours≠(*u*,*d*)

Before hadronizing a string
a “swing” mechanism further allow colour re-arrangements
(in analogy with colour re-connection)

Flensburg et al. arXiv:1103.4321

Bierlich & Christiansen, arXiv:1507.02091

EPOS: the melting pot

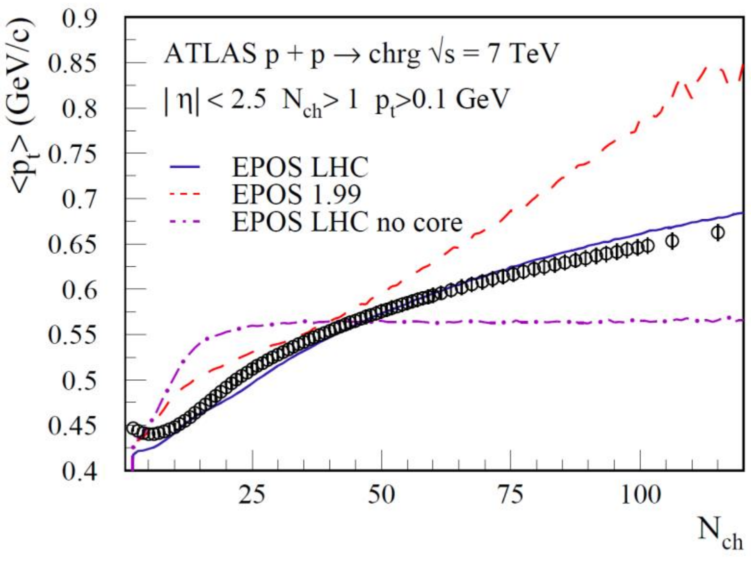


- Hard scattering treated with the addition of several DGLAP parton “ladders” (pomerons) + a CGC-inspired saturation scale
- Parton ladders are then considered as relativistic strings, conveniently treated in a string fragmentation approach (a-la Lund)
- At time τ_0 (well before hadronization) strings 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)

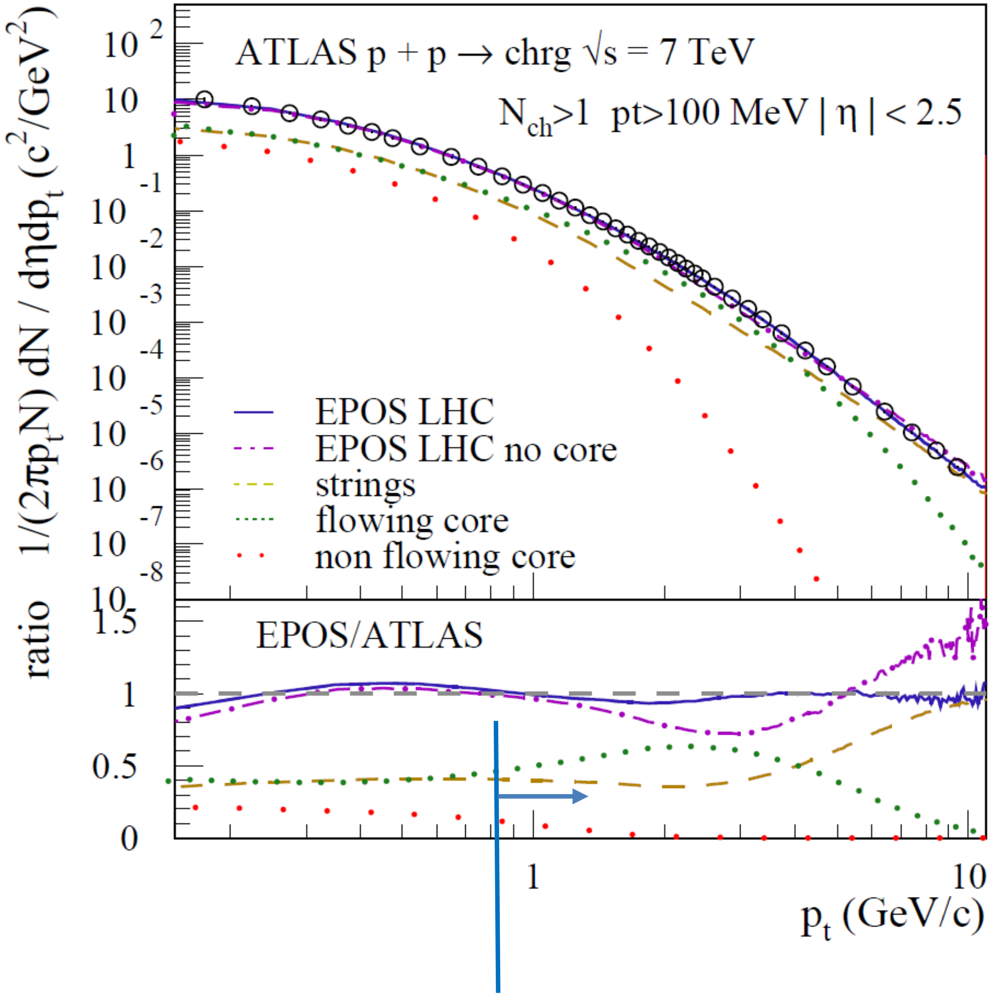
NOTE: parameters governing the core-only part are 6 (τ_0, ρ_0, ε_{FO}, y_{rad}, f_{ecc}, γ_s), to be tuned on data!!

Werner, PRL 98, 152301 (2007)

EPOS: effects of Core-Corona (I)



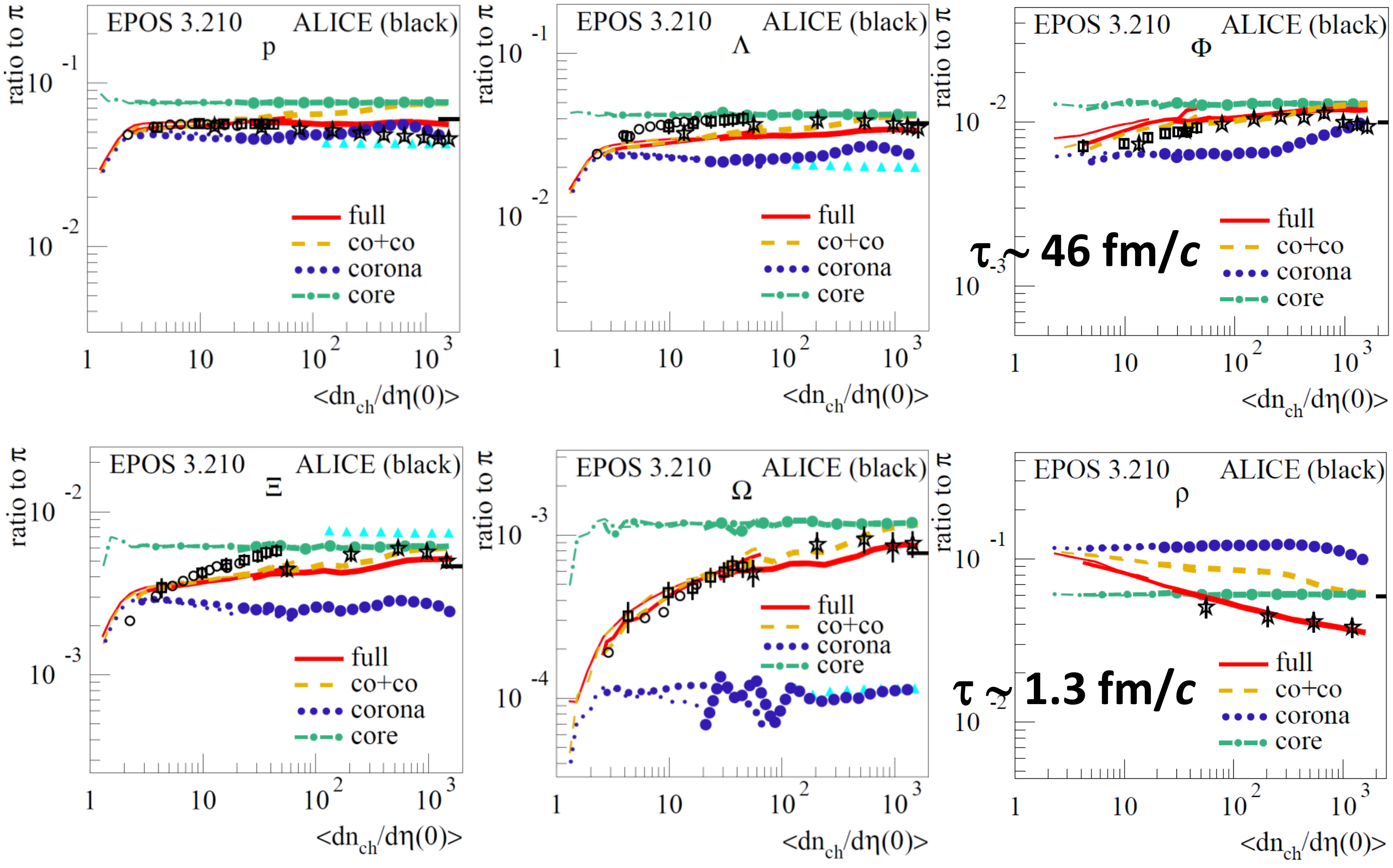
- $\langle p_T \rangle$ increases only when introducing a flowing core
- **Radial flow** of the core also **dominates** the **intermediate** region of the p_T spectrum
- High p_T is dominated by escaping fragmenting strings



NOTE: the exact onset of the effect depends on tuning (p_T cut-off for escaping strings)

Pierog & Karpenko & Katzy & Yatsenko & Werner, arXiv:1306.0121

EPOS: effects of Core-Corona (II)



τ ~ 46 fm/*c*

τ ~ 1.3 fm/*c*

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

TAKE HOME

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

NOTE: Does this imply QGP in small systems? NO! May or may not be.

- 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