Highlights from ALICE

F. Noferini (INFN Bologna)
On behalf of the ALICE Collaboration

7th International Conference on New
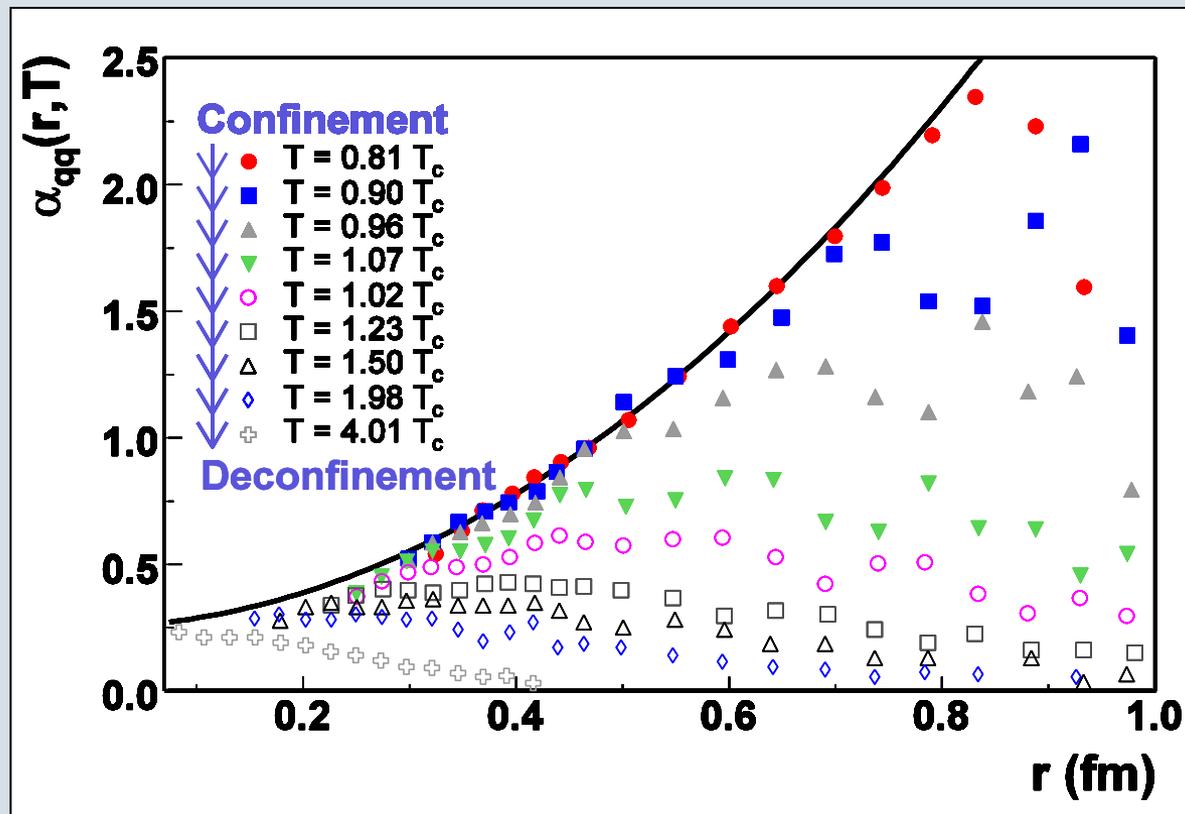Frontiers in Physics (ICNFP2018)
F. Noferini - 6/7/18

Deconfinament as predicted from lattice QCD

Deconfinament is expected for high density and above a critical temperature of ~*170 MeV* (T_c)

The strong coupling between two quarks is expected to vanish for $T > T_c$

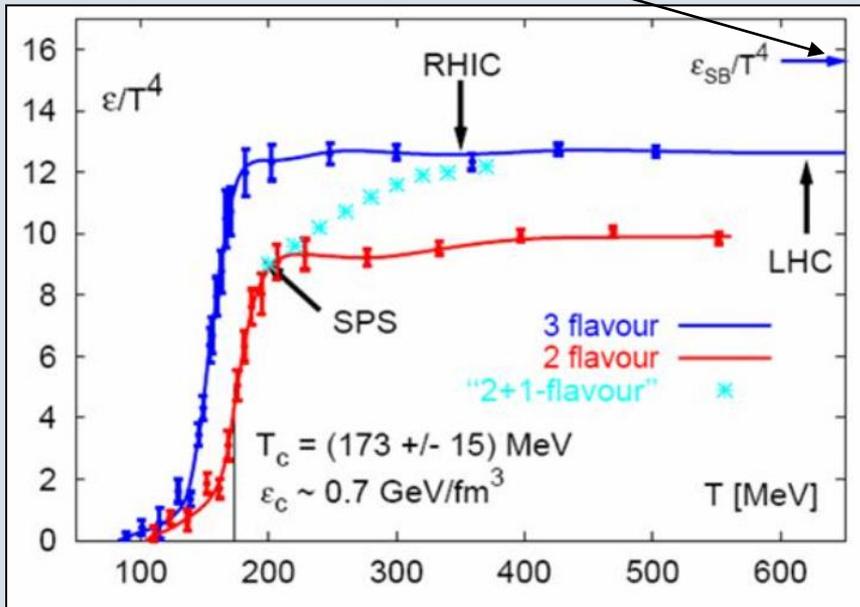Heavy ion collisions are the suitable environment to probe it

Lattice calculations taken by:

O. Kaczmarek and F. Zantow, Phys. Rev. D 71 (2005) 114510

The Quark Gluon Plasma (QGP)
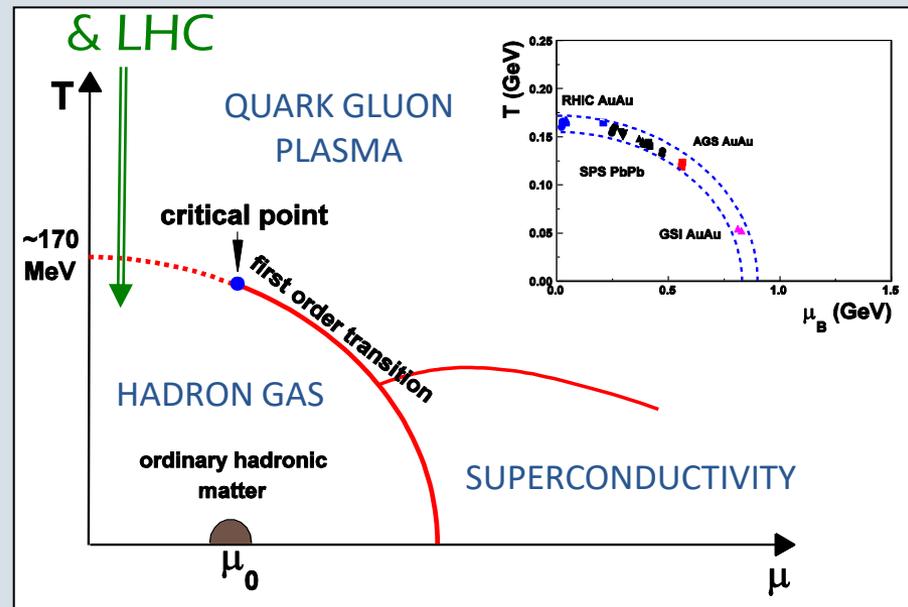
Stephan-Boltzmann limit

Phase transition occurs at very high density and temperature.
Chemical potential vanishes when the centre-of-mass energy of the colliding system increases.

Lattic QCD: energy density increases sharply at $T = T_c$.
ε/T^4 (Stephan-Boltzmann) expected to be proportional to the number of degrees of freedom of the system.

RHIC & LHC

Heavy-ion collisions
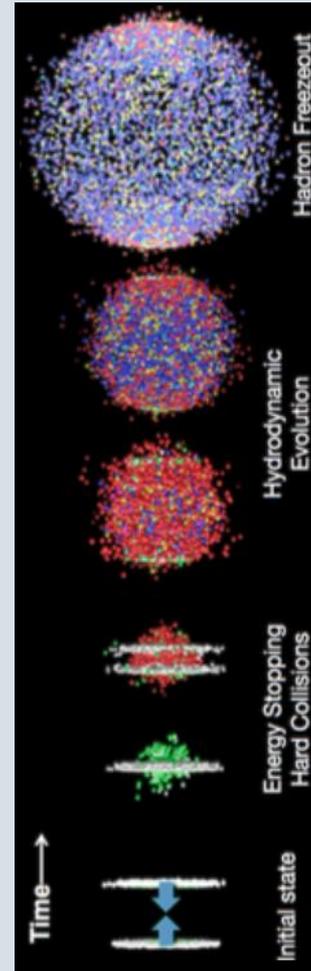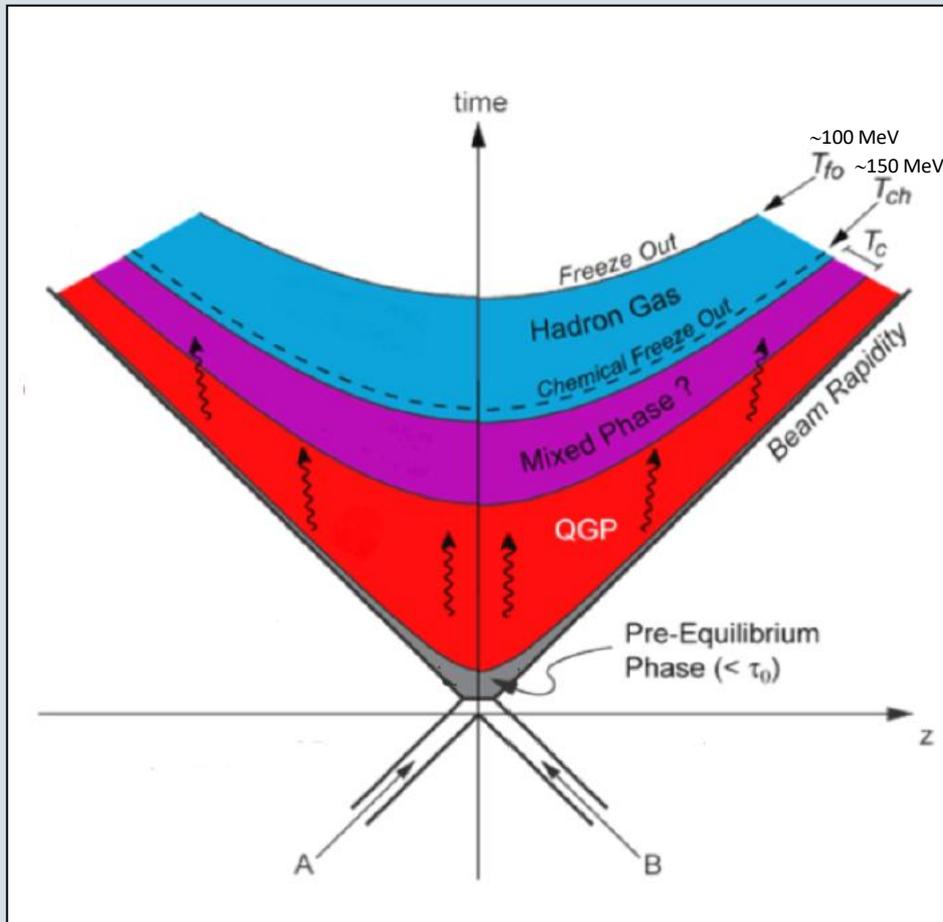
Thermal freeze-out: no elastic interactions
→ **Momentum spectra** "fixed"

Chemical freeze-out
→ **Particle abundances** "fixed"

**Bulk of matter** produced in the collision can be **described in terms of hydrodynamics**:
• Strongly interacting matter
• Rapid expansion & cool down
• Collective flow develops

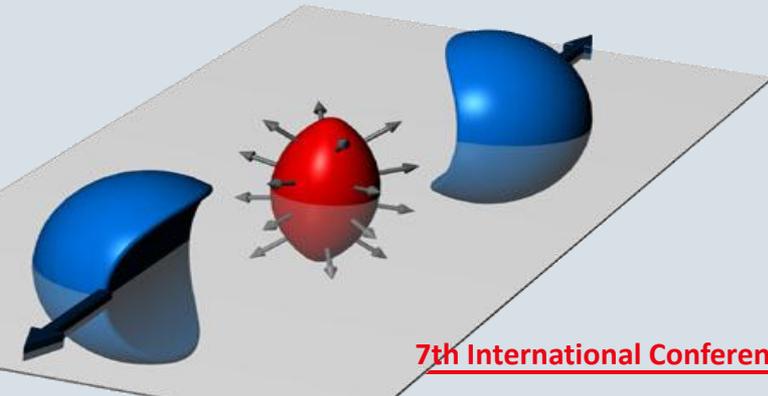**High p_T particles and heavy quarks produced** → they interact with the medium as external probes

Partons interact within the nuclei (at zero time)
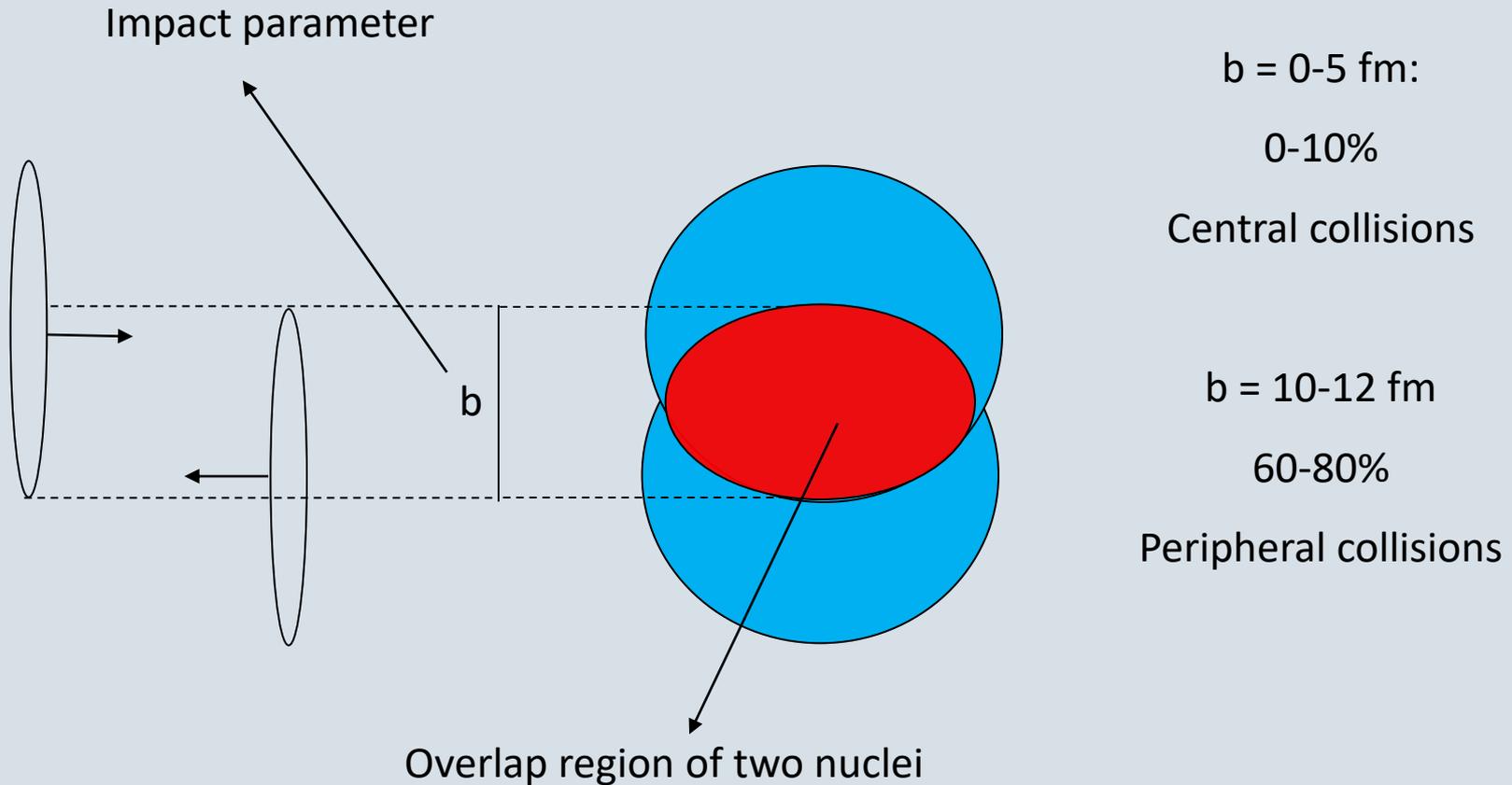
Global properties
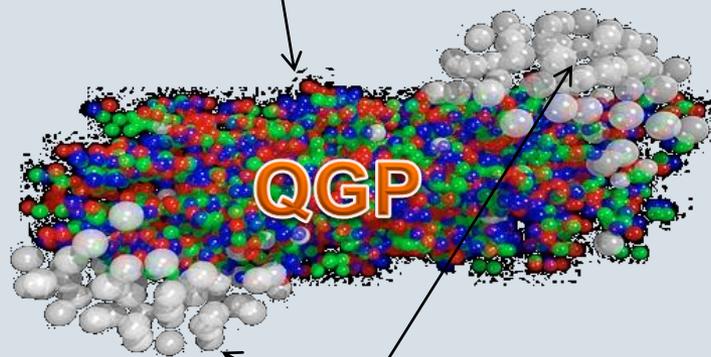
Impact parameter

b

Overlap region of two nuclei

Global properties

Impact parameter

b = 0-5 fm:

0-10%

Central collisions

b
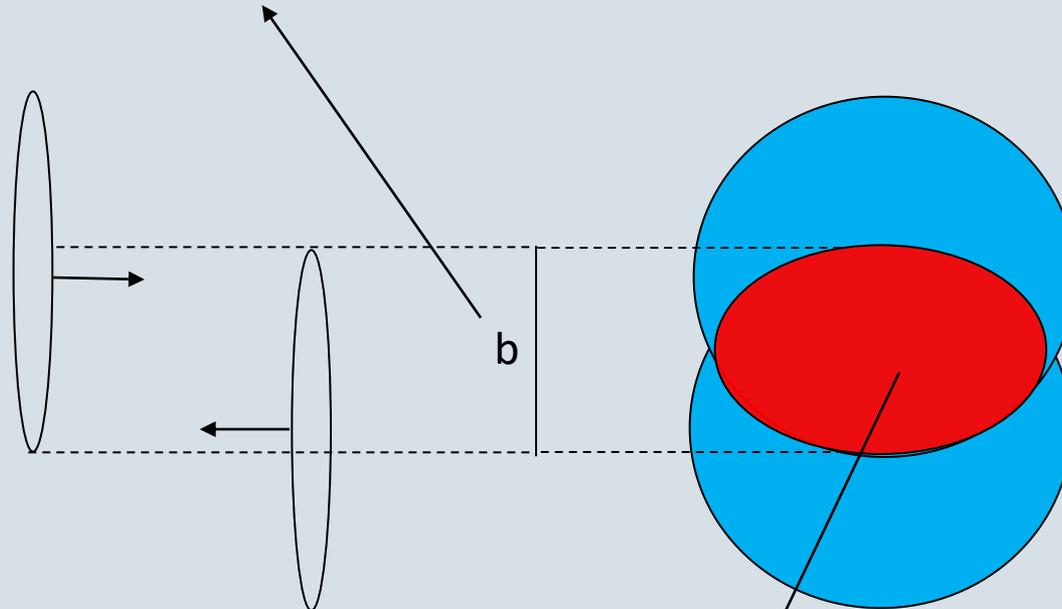
b = 10-12 fm

60-80%

Peripheral collisions

Overlap region of two nuclei

Global properties

Quarks and gluons produced in binary collisions

QGP

Non interacting nucleons (n,p)

b = 0-5 fm:

0-10%

Central collisions

b = 10-12 fm

60-80%

Peripheral collisions

The centrality of the collisions can be also expressed in terms of the number of nucleons which participate to the collision, N_{part}, while N_{coll} represents the number of binary nucleon-nucleon collisions which occur

A Large Ion Collider Experiment:
the detector

B = 0.5 T

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

Central barrel
$|\eta|<0.9$
Tracking+PID

Muon spectrometer
$-4 < \eta < 2.5$

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
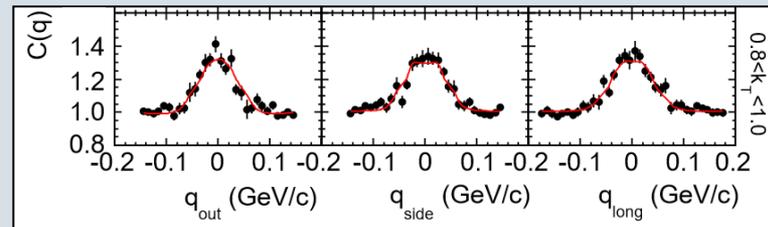15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

Charged particles tracked
starting from hundreds MeV/c

Particle Identification:
150 MeV/c → 20 GeV/c
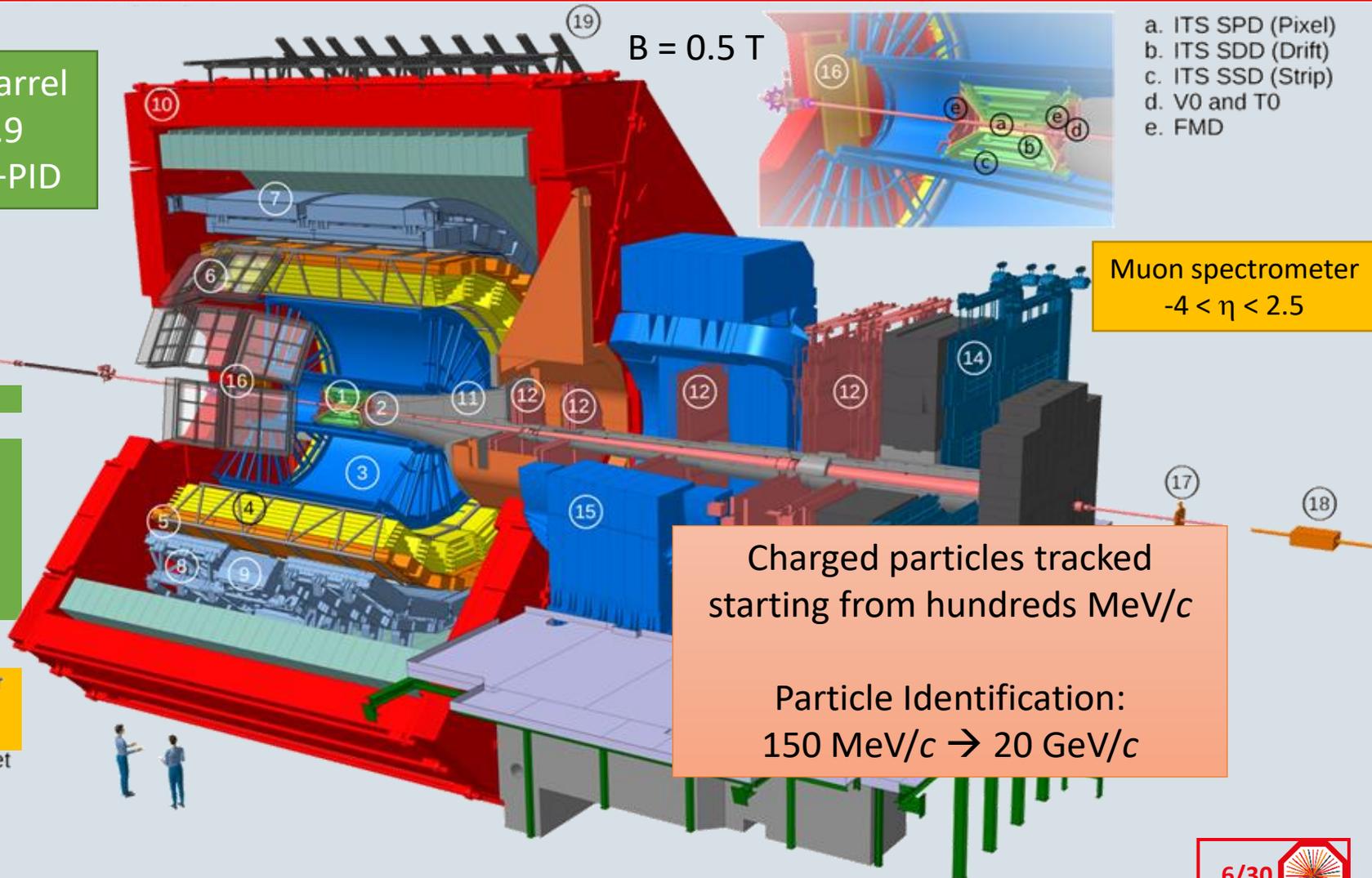
The size of the system

The spatial extent of the fireball is measured via interferometry by exploiting the Bose-Einstein enhancement of identical bosons close in phase space.

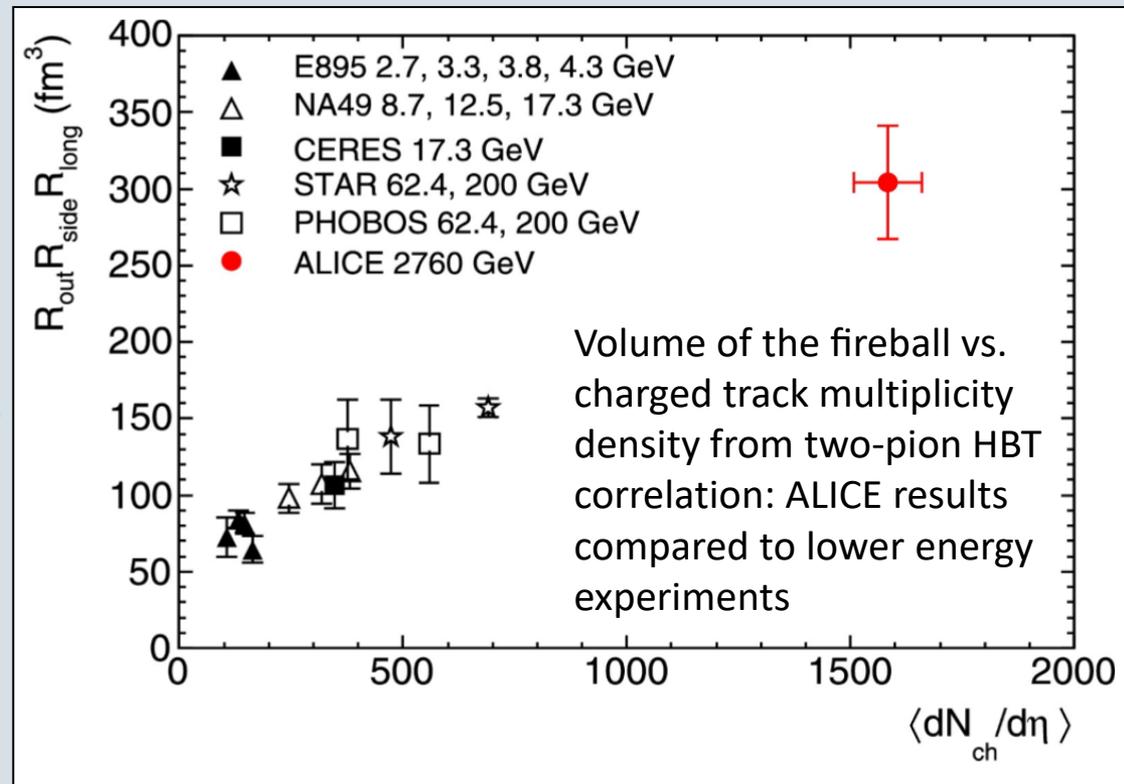$$\vec{q} = \vec{q}_1 - \vec{q}_2$$ momentum difference of identical bosons

$$q_{out,side,long} = \vec{q} \cdot \hat{i}_{out,side,long}$$ proj on the 3 directions

Volume of the fireball vs. charged track multiplicity density from two-pion HBT correlation: ALICE results compared to lower energy experiments

$$C(q) = S(q) / B(q)$$
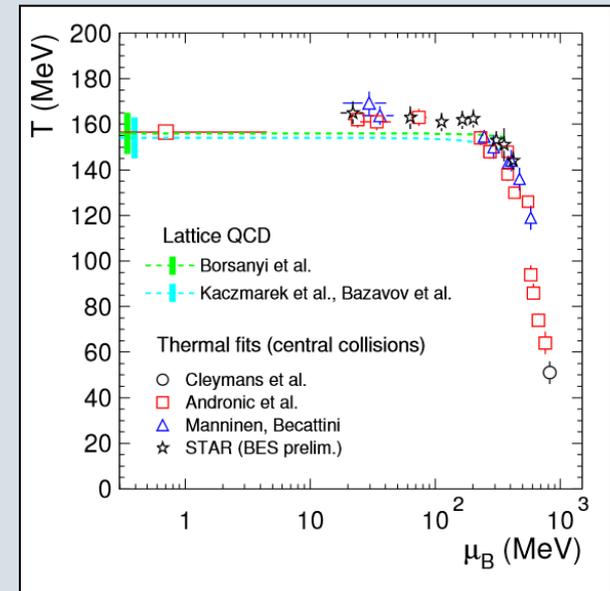
Particles in the same event
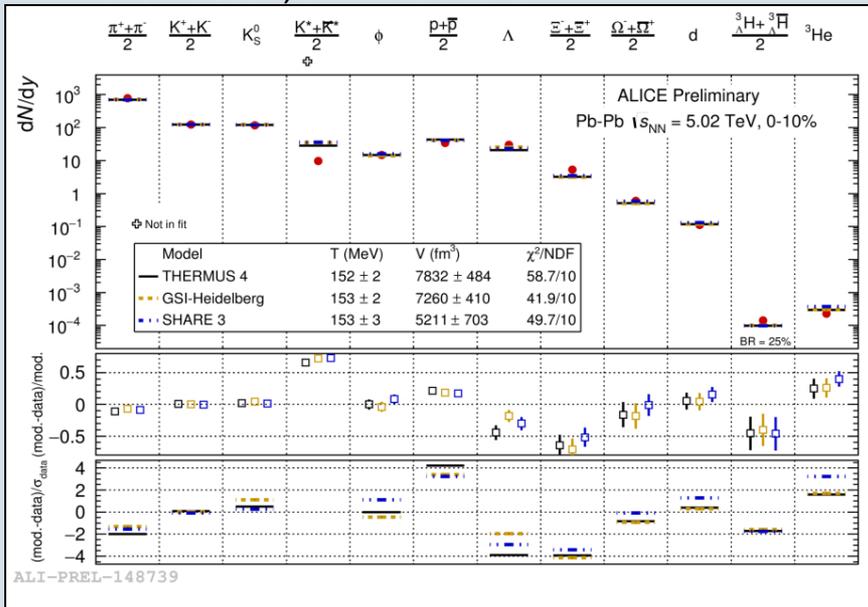
From event mixing

More particles → larger freeze-out volume

The temperature of the system
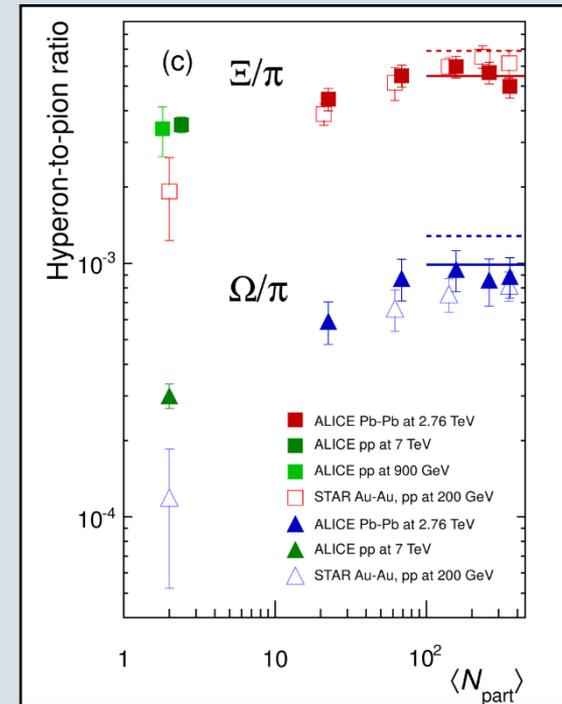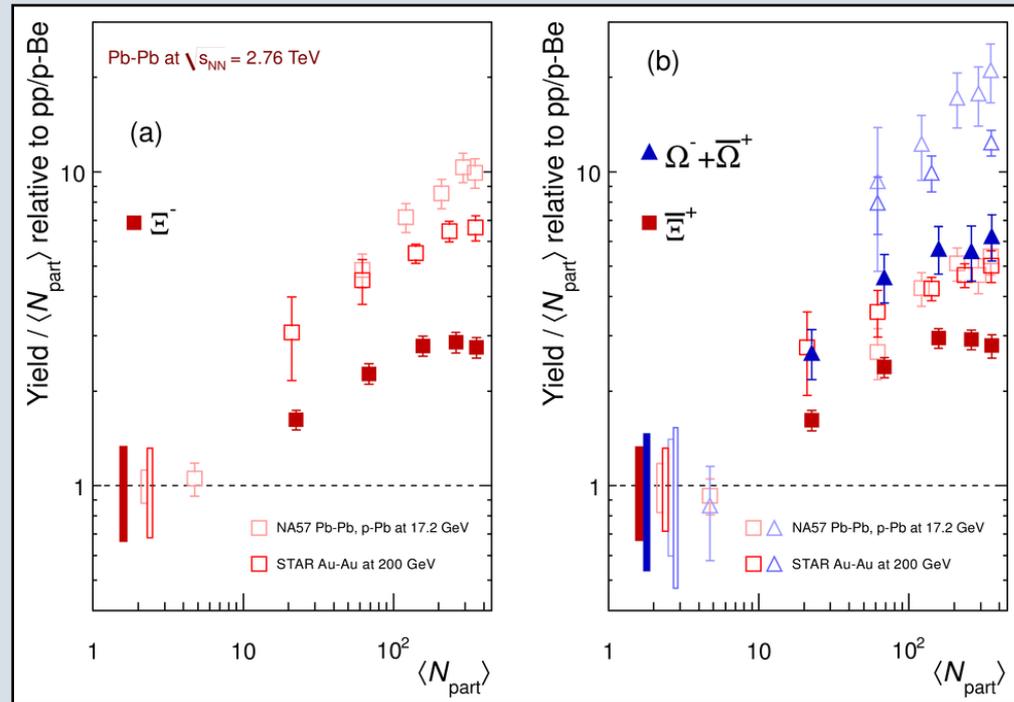
A. Andronic et al., arXiv:1611.01347

ALICE measured the production of many particle species.
Yields were used to extract the system temperature at chemical freeze-out using a thermal model to fit data

Hadron abundances, spanning on several orders of magnitude, in reasonable agreement with a chemically equilibrated system!
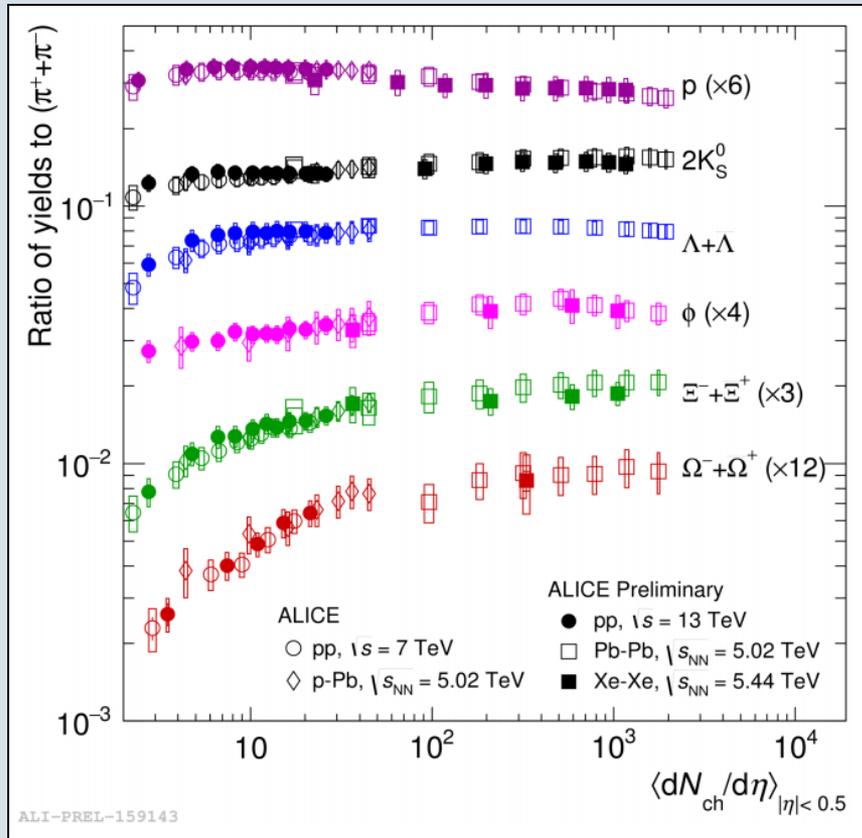
Strangeness enhancement

Strangeness enhancement in AA collisions: natural consequence of QGP formation, thermal production.
Observed at SPS, RHIC and also at the LHC.

Consistent with the prediction of some thermal models which expect a saturation at the grand canonical values

Strangeness and event multiplicity

The plateau in the yield ratio of multistrange hadrons to pions for high multiplicity events consistent with predictions of thermal models expecting a saturation at the grand canonical value.
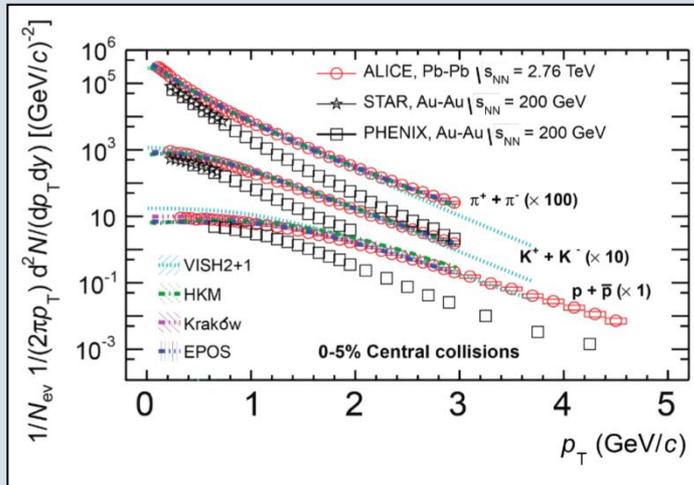
Challenge for pp event generators.
T. Sjostrand at Quark Matter 2018:
"*Conventional pp generator successful, with MPI+CR generating some collectivity but now cracks*".

MORE DETAILS IN THE PRESENTATION OF P. KALINAK ON THE 10th

Medium is expanding → radial flow

Phys. Rev. C 88 044910 (2013)

Hardening of the p_T spectra observed at LHC wrt RHIC consistent with a higher radial flow developing in the medium expansion.

Mass ordering reproduced by hydro models, larger mass -> larger shift of the p_T distribution Blast-Wave fit (hydro approximation) used to extract radial flow parameters.
CAVEAT: QCD effects such as color reconnection can mimic radial flow!
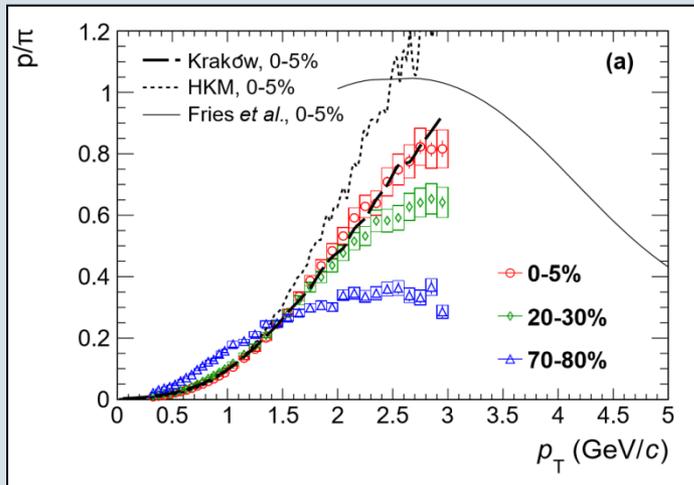
p/π ratio is increasing at low to intermediate p_T (periph. → central)
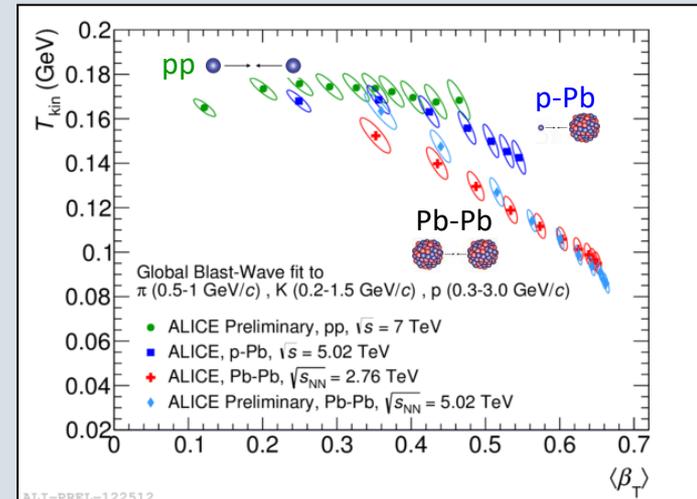
Baryon anomaly

Also a coalescence picture is able to reproduce a hardening of particle spectra at intermediate momenta depending on the quark content (meson/baryon).
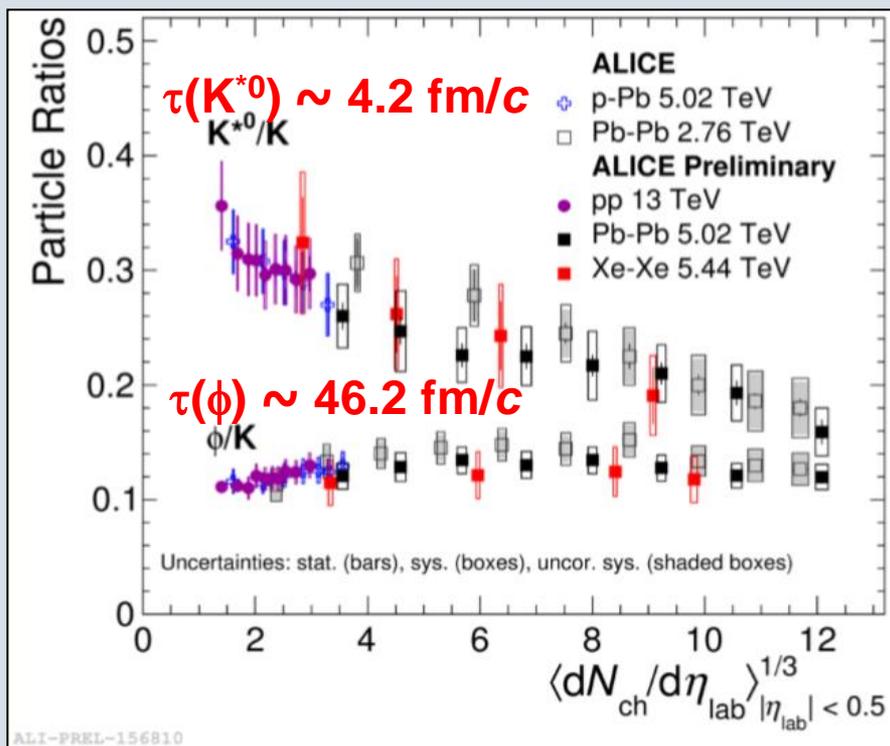**How to distinguish between mass and quark content effects?**
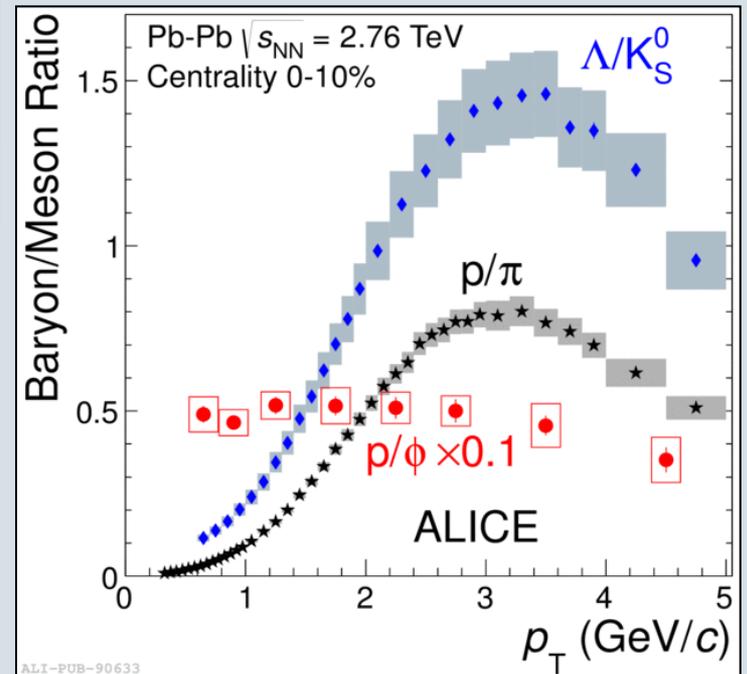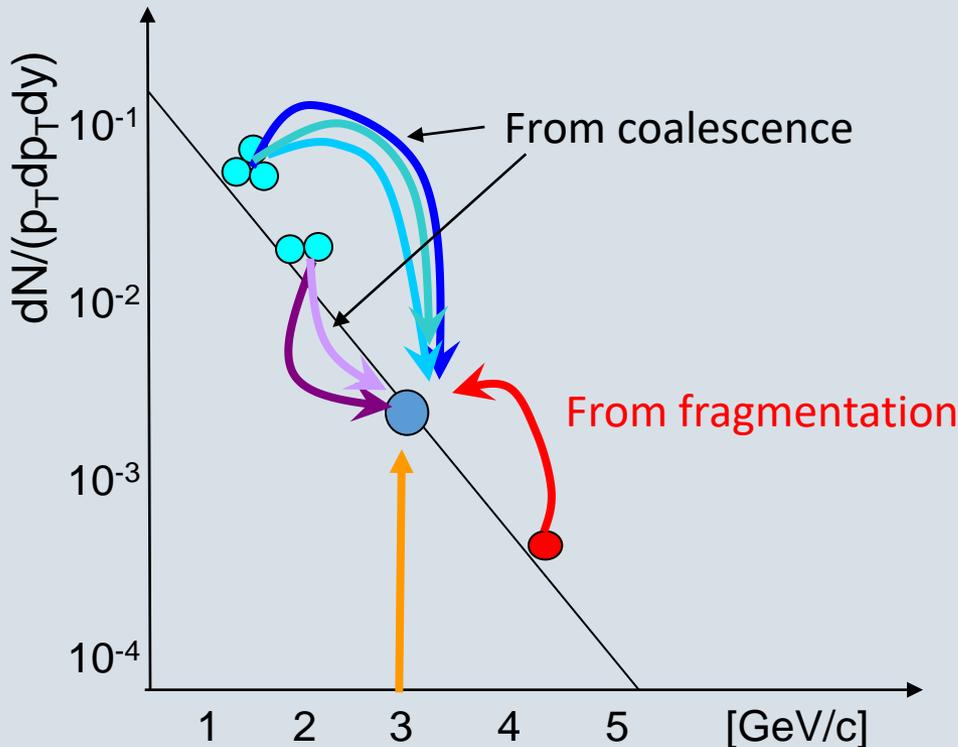
Comparison between ϕ-meson and proton is one key observable to distinguish mass and quark content effects.

Resonances as probe for the time evolution of the medium

$\tau(K^{*0}) \sim 4.2$ fm/*c*

K*⁰/K

ALICE
- p-Pb 5.02 TeV
- Pb-Pb 2.76 TeV

ALICE Preliminary
- pp 13 TeV
- Pb-Pb 5.02 TeV
- Xe-Xe 5.44 TeV

$\tau(\phi) \sim 46.2$ fm/*c*

ϕ/K

Uncertainties: stat. (bars), sys. (boxes), uncor. sys. (shaded boxes)

ALI-PREL-156810

Short living resonances as a probe of the time evolution of the medium (their lifetime is comparable to that).
Suppression of the visible resonances due to daughter particle rescattering (possible mitigation from recombination).
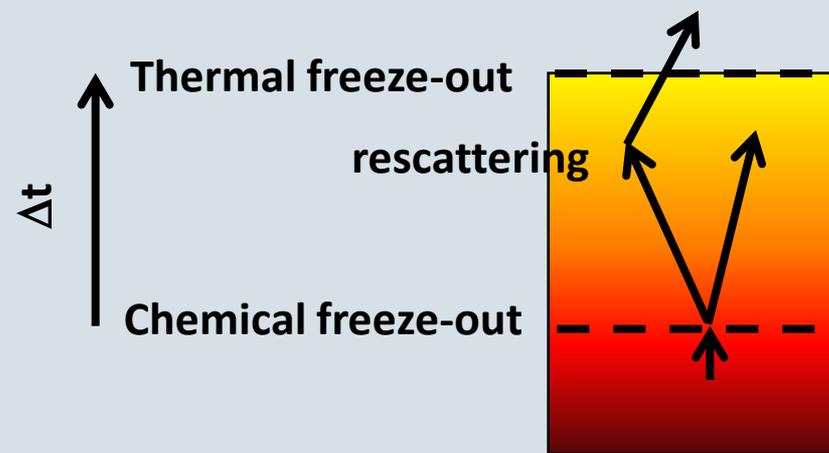
ALICE measured a large sample of such resonances to constrain their production mechanism in the medium.
MORE DETAILS IN THE PRESENTATION OF M. VASILIEIU ON THE 10th

Thermal freeze-out

rescattering

Δt

Chemical freeze-out

Anisotropic flow

Effects due to a spatial asymmetry in the **initial state of the collision** can be used to probe the QGP.

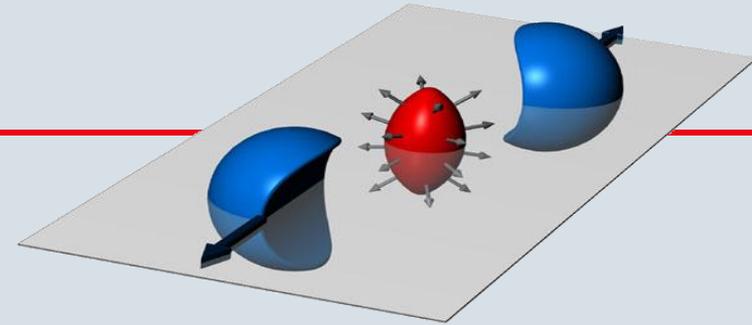→ Coordinate space Eccentricity $\varepsilon_2 = \left\langle \dfrac{y^2 - x^2}{y^2 + x^2} \right\rangle$

a) Overlap of independent coll.

Overlap of all collisions
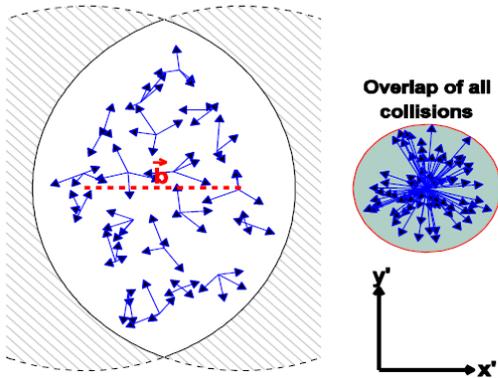
b) Ideal fluid with collective behaviour

Overlap of all collisions
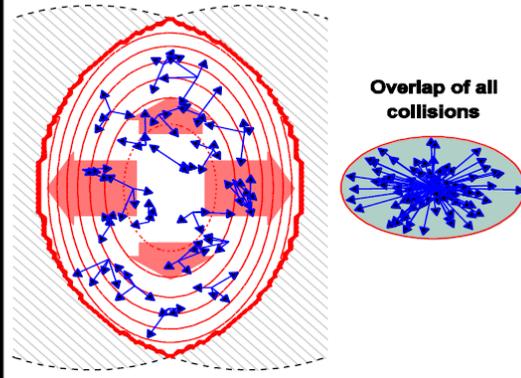
Depending on medium **transport properties**, initial spatial asymmetries produce asymmetries in momentum space → Elliptic flow
**Low shear viscosity value →
high anisotropic coefficients**

$$v_2 = \left\langle \cos\left(2\left(\varphi - \psi_{RP}\right)\right)\right\rangle$$

Elliptic flow

arXiv: 1805.04390 (2018)

Phys. Rev. Lett., 105 252302 (2010)

Mass ordering observed: the larger the mass the larger is the boost in momentum (hydro behavior)

The integrated elliptic flow at the LHC is larger than at RHIC.
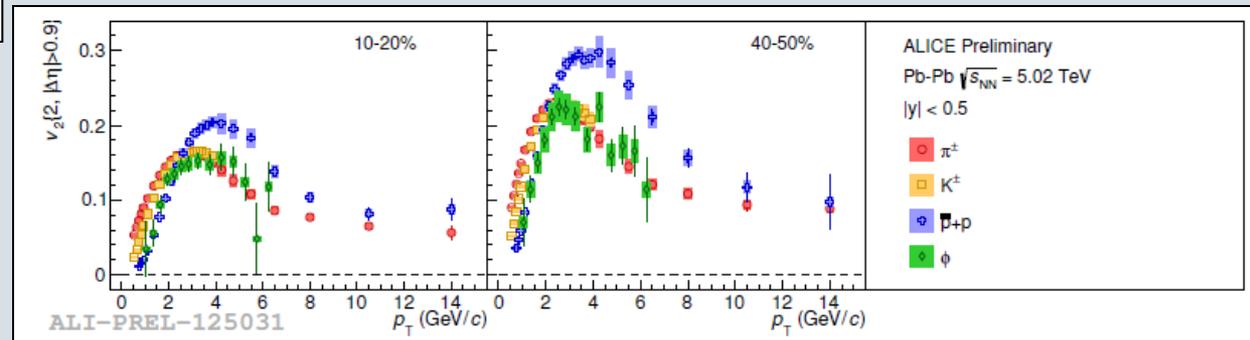
At low momentum φ has a similar behavior as the proton (same mass ← hydro) but at intermediate p_T it "stays" with mesons (← coalescence)

Higher harmonics

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left(1 + \sum_{n=1} 2v_n \cos(n[\varphi - \Psi_n])\right)$$

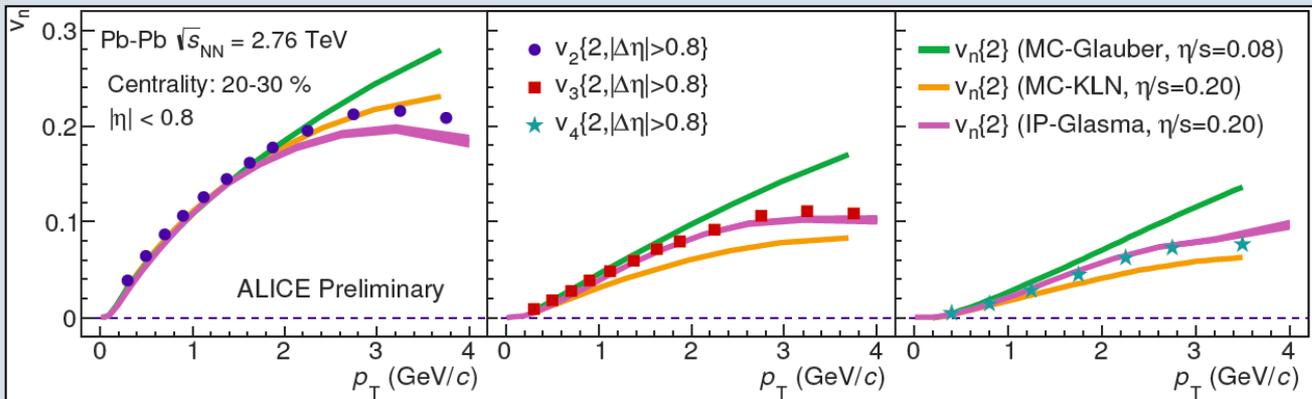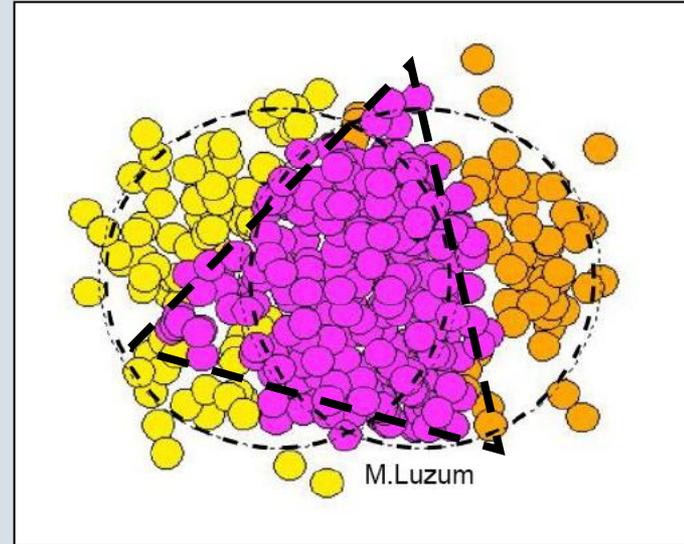Event-by-event fluctuations may produce other changes in the shape of the energy density profile in the interacting region affecting the measured value of v_2 and leading to non-zero values for v_3, v_4, ... , v_n. Therefore, **we need to measure higher order harmonics** too in order to constrain (inputs in the) models: →**Geometry properties** and **fluctuations**

M.Luzum

The best description was achieved with the IP-Glasma initial conditions and shear viscosity $\eta/s = 0.2$

IP-GLASMA: PRL 110, 012302

Pb-Pb $\sqrt{s}_{NN}$ = 2.76 TeV
Centrality: 20-30 %
$|\eta| < 0.8$

ALICE Preliminary

- $v_2\{2,|\Delta\eta|>0.8\}$
- $v_3\{2,|\Delta\eta|>0.8\}$
- $v_4\{2,|\Delta\eta|>0.8\}$

— $v_n\{2\}$ (MC-Glauber, η/s=0.08)
— $v_n\{2\}$ (MC-KLN, η/s=0.20)
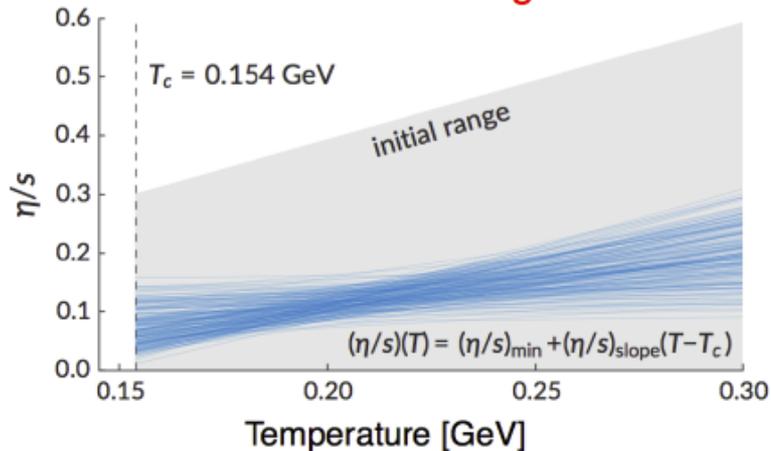— $v_n\{2\}$ (IP-Glasma, η/s=0.20)

p_T (GeV/c)

High precision constraints from ALICE

High data quality enables quantitative extraction of medium parameters
- e.g.: Bayesian parameter estimation from **ALICE data** (Duke+OSU) [v_n, PID, mean p_T]
- strong constraints on initial conditions (eccentricity, parton saturation, …)
→ extraction of temperature dependence of medium bulk and shear viscosity

temperature dependent shear viscosity:
- analysis favors small value and shallow rise
- need RHIC data to disambiguate

$T_c = 0.154$ GeV

initial range

$(\eta/s)(T) = (\eta/s)_{min} + (\eta/s)_{slope}(T - T_c)$

magnitude of (temp. dep.) bulk viscosity:
- significant non-zero value at T_C favored

initial range

$(\zeta/s)(T)$ from Denicol et. al.
vary overall normalization
black line: norm = 1
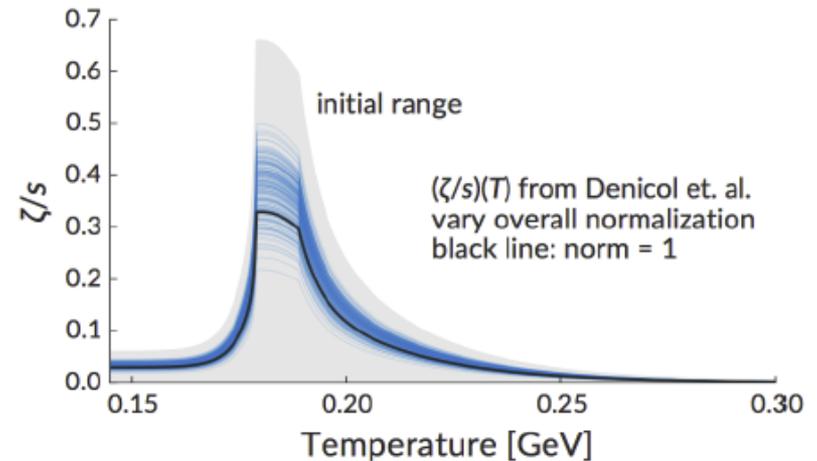
J Bernhard et al.: Phys Rev C 94 (2016) 024907

A coloured world → Jet quenching

path length L
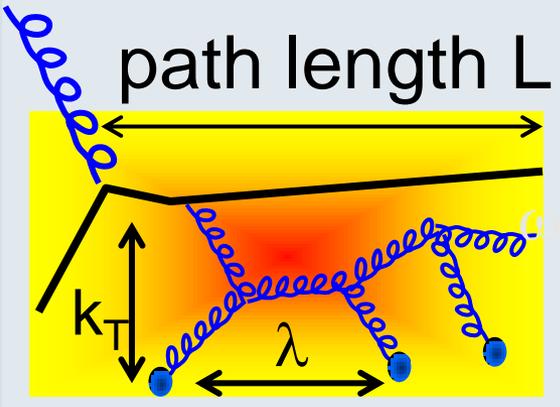
$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291
Salgado, Wiedemann, PRD 68(2003) 014008
Dokshitzer and Kharzeev, PLB 519 (2001) 199
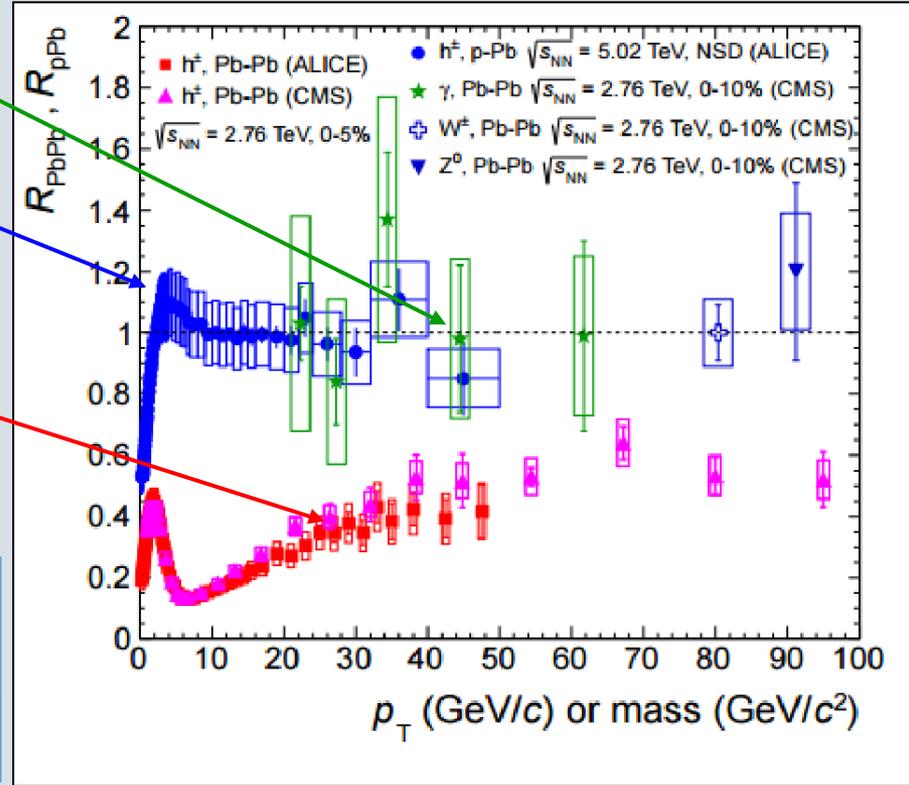Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003

High p_T partons are expected to loose energy in a colored medium via induced gluon radiation → **hard QCD probes are expected to be suppressed in AA collisions** (electroweak probes are not affected!)

Pb-Pb
Electroweak

p-Pb
(cold matter)

Pb-Pb
hadrons

ALICE, Phys. Rev. Lett., 110 (2013) 082302
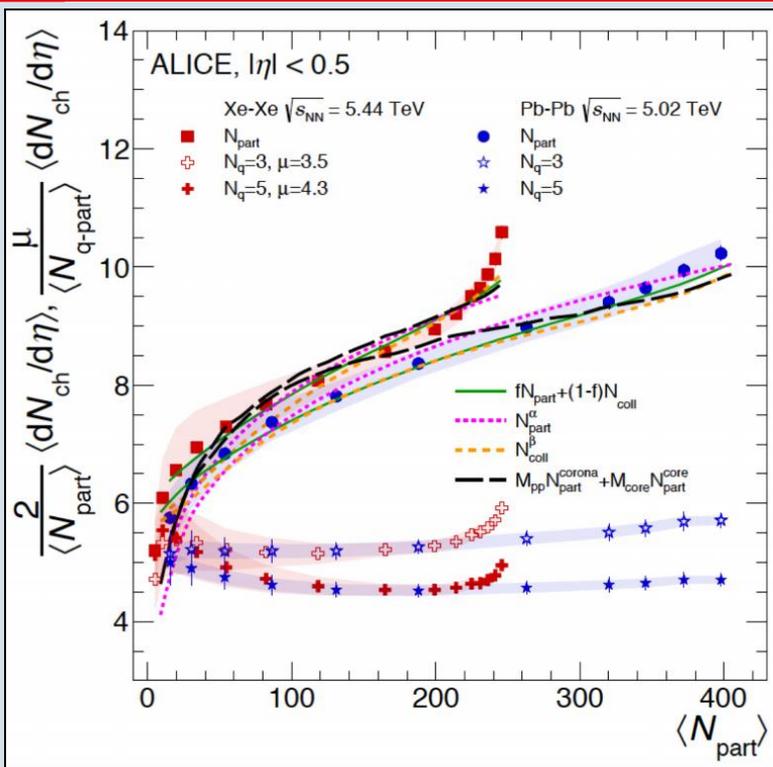CMS, *JHEP*, 03 (2015) 022

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{N_{coll}(dN/dp_T)_{pp}}$$

Number of binary nucleon-nucleon collisions in AA/pA interactions (Glauber)

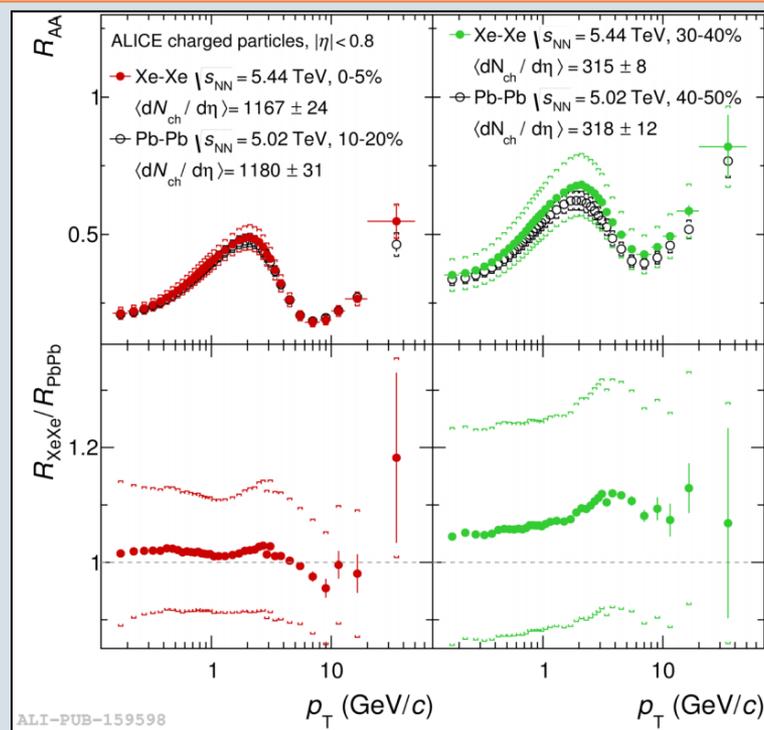# Particle production in AA collisions

ALICE recently collected 6 hours of data in Xe-Xe collisions.

Strong increase of N_{ch}/N_{part} for central Xe-Xe...

... but similar trends vs multiplicity →

Some deviations for peripheral collisions, different geometry for same multiplicity?

Charm quarks in the medium

Charm quarks cannot be produced in the medium but only in the initial hard scattering:

- Do they loose the same energy as light quarks?
- Do they flow in the bulk as lighter quarks?

arXiv: 1804.09083 (2018)

Dokshitzer, Kharzeev (PLB519(01)199) predicted a lower energy loss due to dead cone effect (massive particles cannot radiate along the direction of propagation)
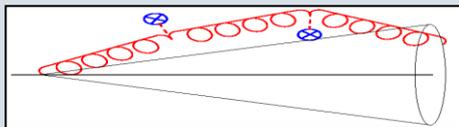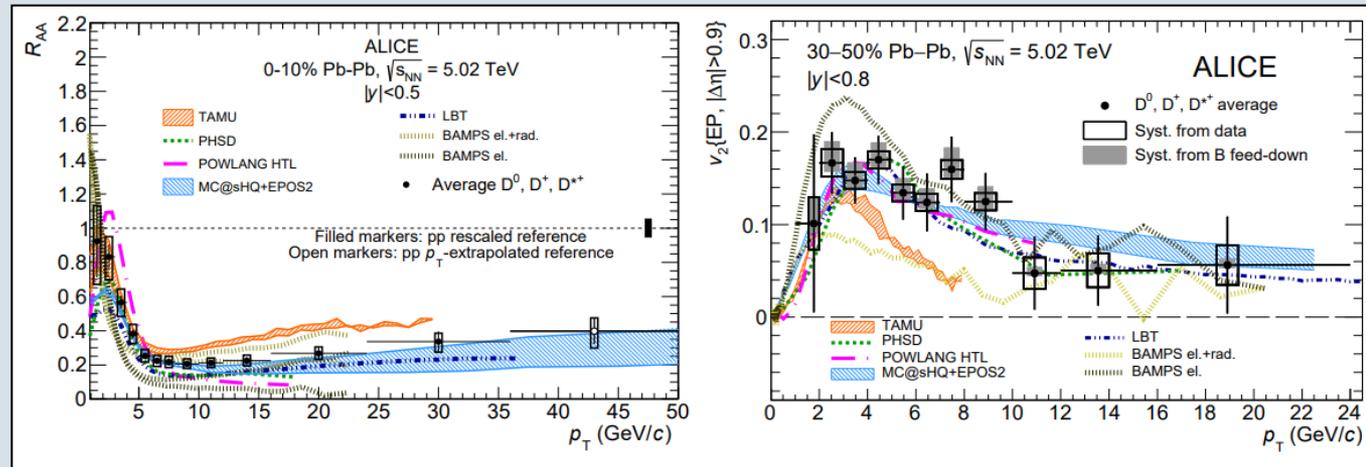

The strength of R_{AA} suppression is almost as large as that observed for charged particles ($p_T > 8$ GeV/c).
No large cold nuclear effects by p-Pb results (JHEP 1603 081 (2016))
→suppression in Pb–Pb collisions is genuine and indicates strong interactions of charm quarks with QGP

v_2 of D mesons in semi-central collisions is comparable in magnitude to that of light flavor hadrons

J/ψ: quarkonia in the medium

J/ψ suppression was one of the signature predicted for QGP formation (due to Debye screening of cc in medium) → SPS and RHIC **Statistical recombination expected at the LHC.**
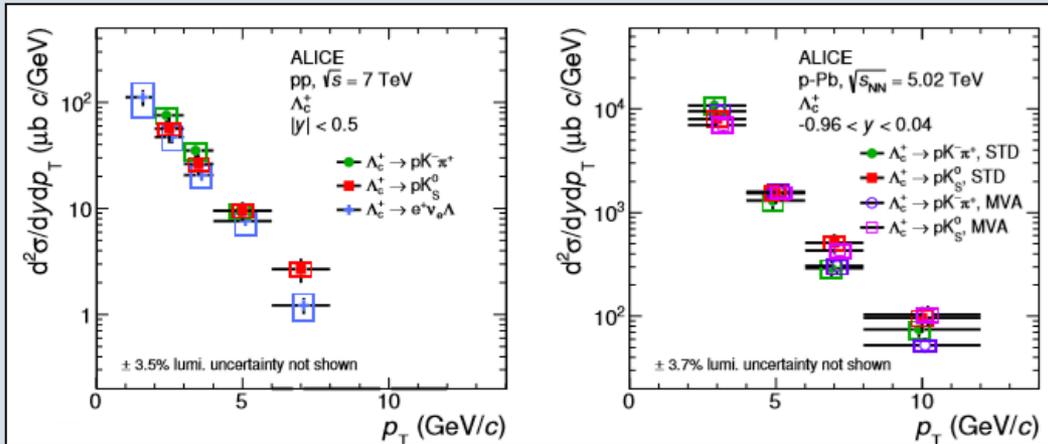

ALI−PREL−148496
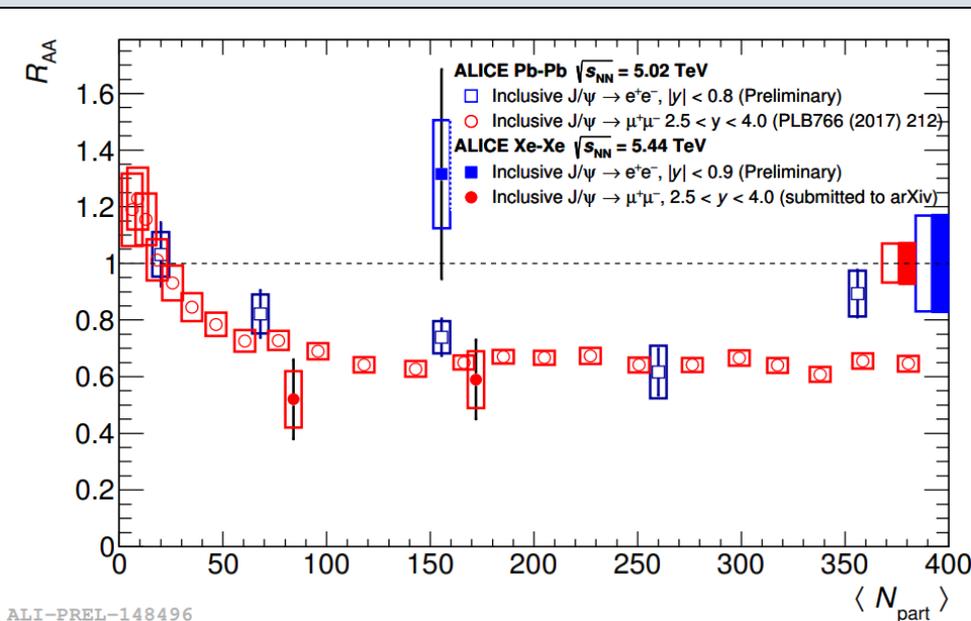
A lower suppression at LHC wrt RHIC consistent with a production of J/Ψ via recombination at the LHC → also confirmed by the latest Xe-Xe measurement.

MORE DETAILS IN THE PRESENTATION OF A. LARDEUX ON THE 10th

Charmed baryon production

PLB 781 (2018) 8
First Ξ_c^0 production measured at the LHC
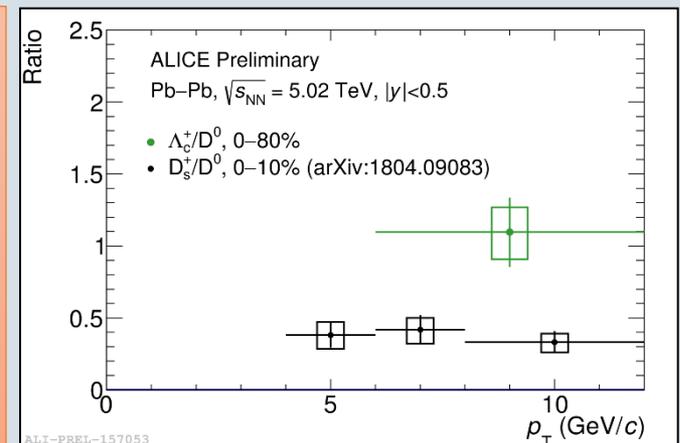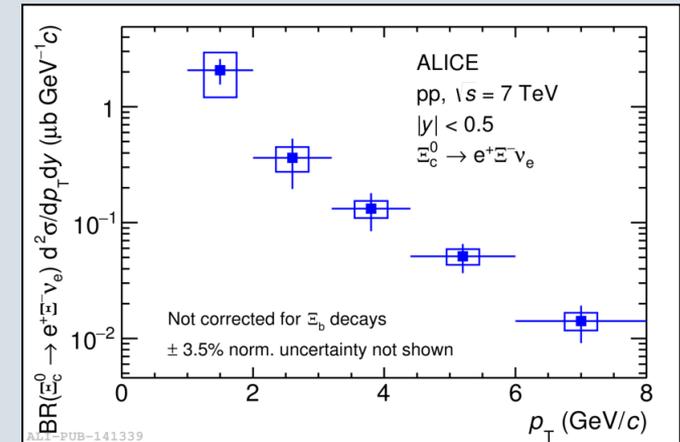

Reconstruction of Λ_c
JHEP 1804 (2018) 108

Charmed baryon cross sections are measured in pp and p-Pb collisions → relative production wrt open charm mesons directly assesses charm baryon formation mechanism.
Preliminary data now available also for Pb-Pb →
MORE DETAILS IN THE PRESENTATION OF A. ALICI ON THE 5th

Collectivity in small system?

ALICE, Phys. Lett. B 719 (2013) 29
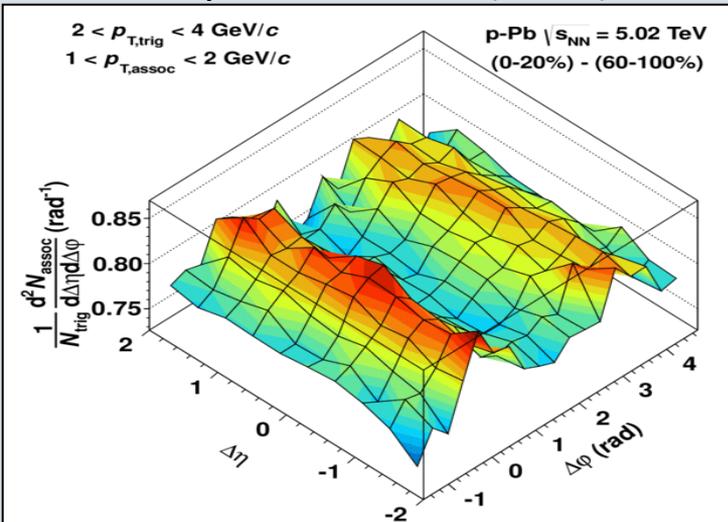
p-Pb (central – pheripheral)
• excess structure in the correlation forms two ridges.
MORE DETAILS IN THE PRESENTATIONS OF I. RAVASENGA ON THE 5th AND L. DE LIMA PIMENTEI ON THE 10th
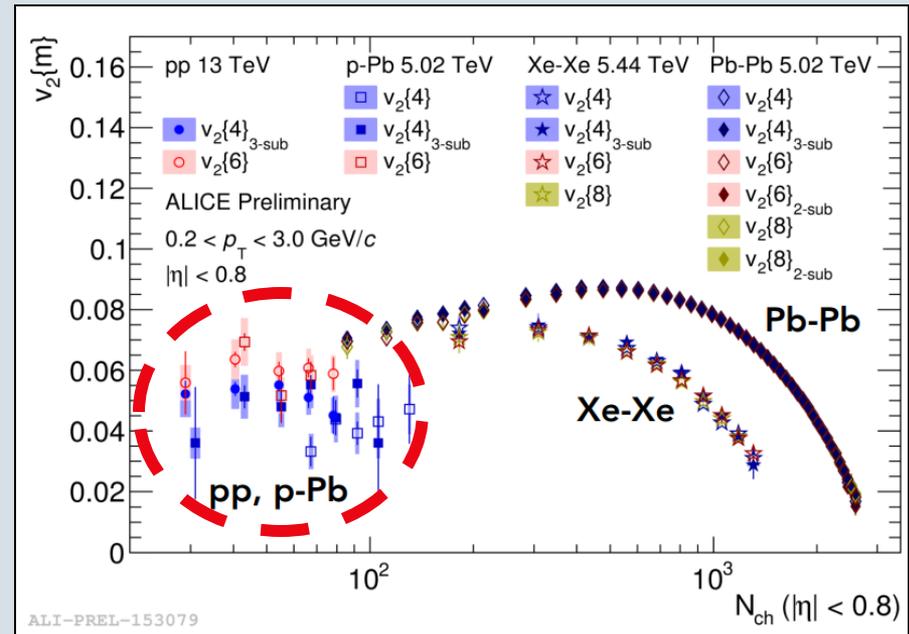
Collective behavior is observed in multi-particle cumulants (where non-flow contributions are suppressed) even in the smallest systems.

Are these hints for collectivity?

Anti-nuclei production in AA collisions

In high energy Pb-Pb collisions at the LHC a large amount of (anti)nuclei is produced.
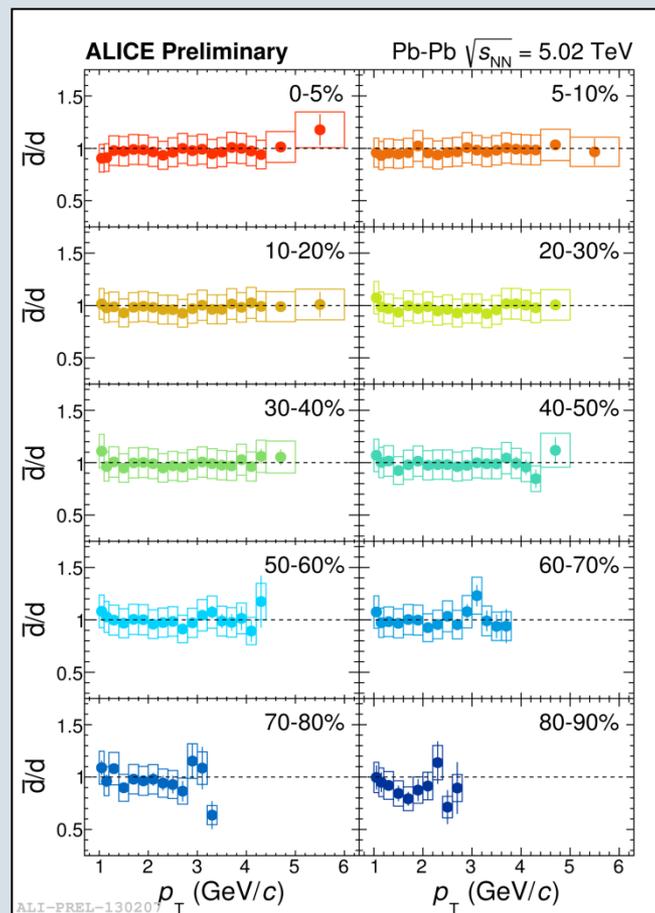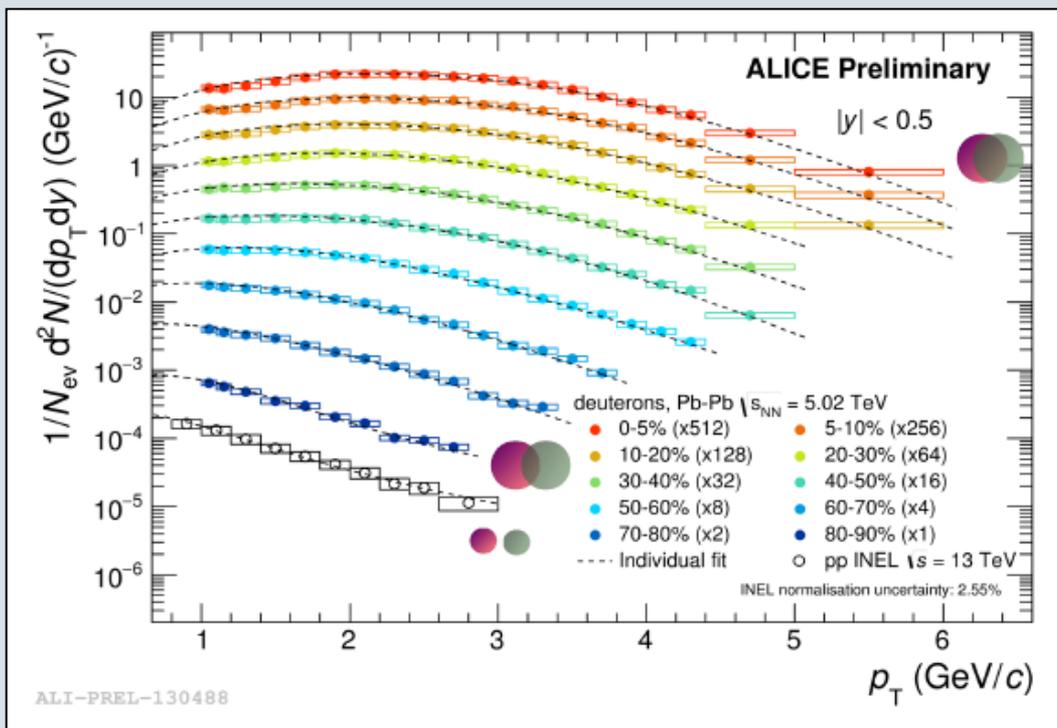
Same amount of nuclei and antinuclei observed!
Volume effect: lower coalescence probability in large systems

Anti-nuclei production in AA collisions

In high ene[...]is produced.

arXiv:1710.07531

ALICE

0-10% Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV

Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
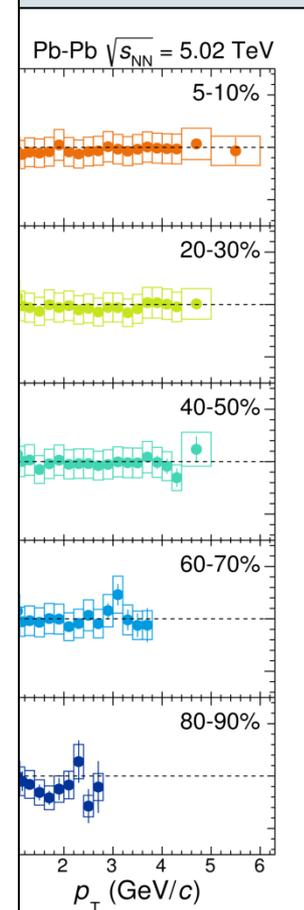
Same

Nuclei production at the LHC

Within the coalescence picture the yield of light (anti)nuclei depends on the (anti)baryon densities. Within the approximation of no effect due to volume (coordinate space neglected in the model):

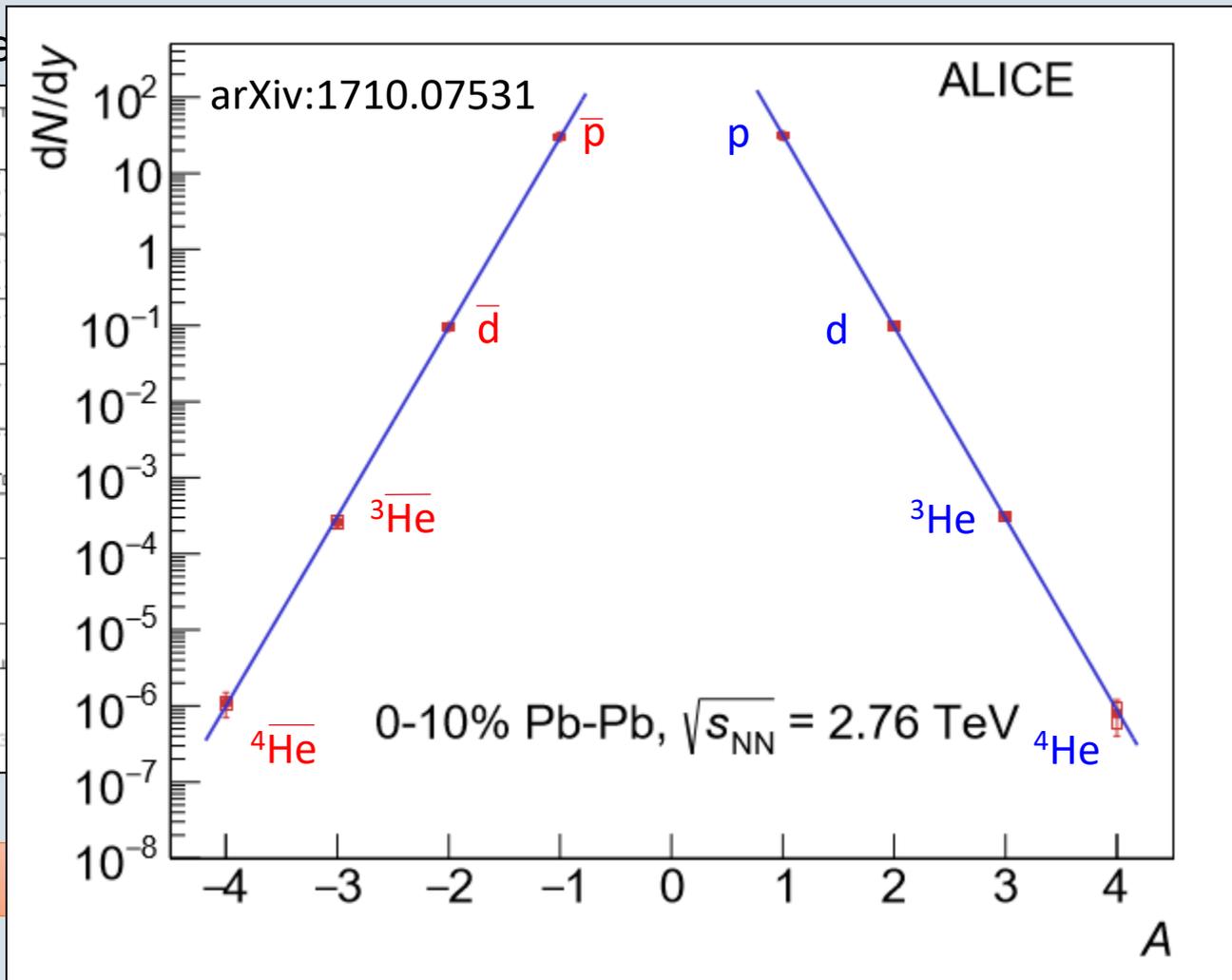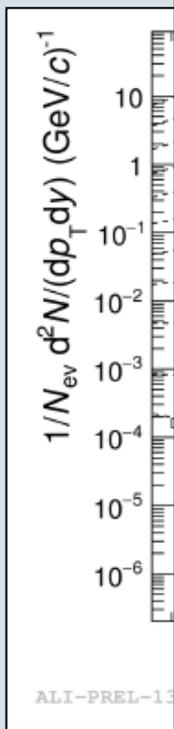$$\gamma_A \frac{d^3 N_A}{dp_A^3} = \left(\frac{2s_A + 1}{2^A}\right) \left(\frac{4\pi}{3} p_0^3\right)^{A-1} \left(\gamma_p \frac{d^3 N_p}{(dp_A^3/A)}\right)^Z \left(\gamma_n \frac{d^3 N_n}{(dp_A^3/A)}\right)^N$$

ALICE Preliminary
$p_T/A = 0.75$ GeV/c

ALICE, d+d, pp, $\sqrt{s} = 7$ TeV
V0M Multiplicity Classes
ALICE, d+d, p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
V0A Multiplicity Classes (Pb-side)
ALICE, d, Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
ALICE, d, Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV (PRC 93 (2015) 024917)

ALI-PREL-136474
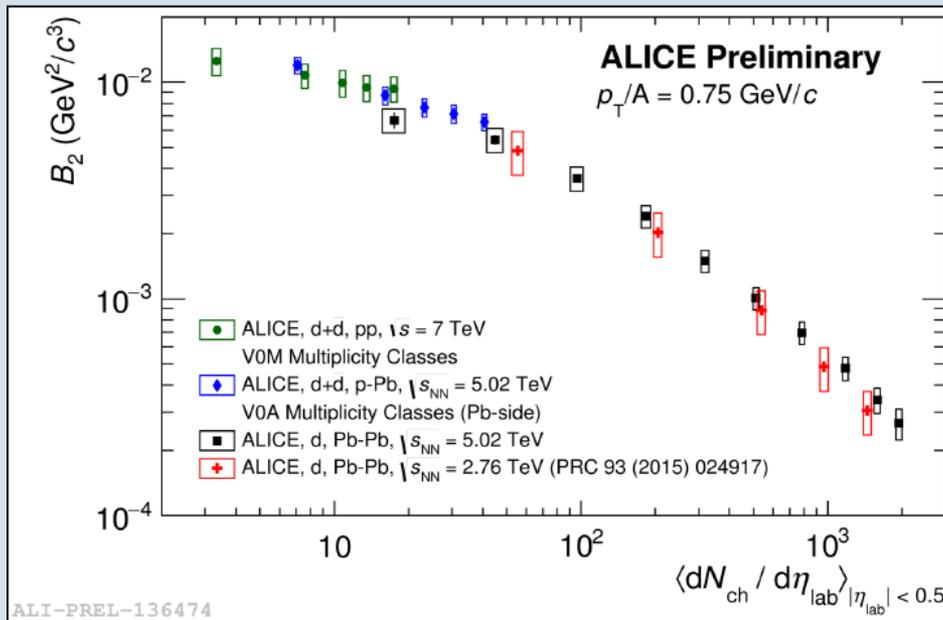
Assuming that p and n have the same mass and have the same p_T spectra:

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3}\right)^A$$

Input for dark matter searches

Light nuclei measurements in high energy physics can be used to estimate the background for the estimation of secondary anti-nuclei in dark matter search

K. Blum et al., arXiv:1704.05431
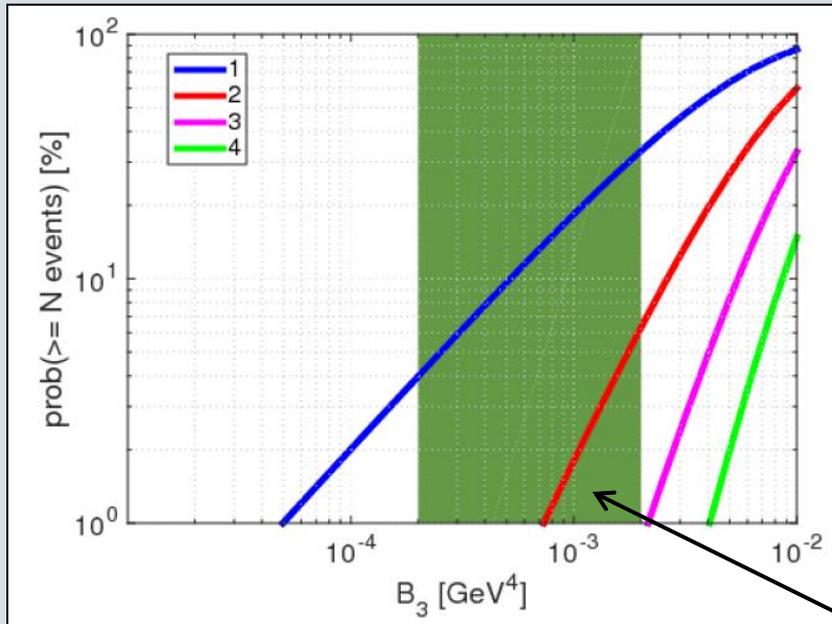
arXiv:1709.08522
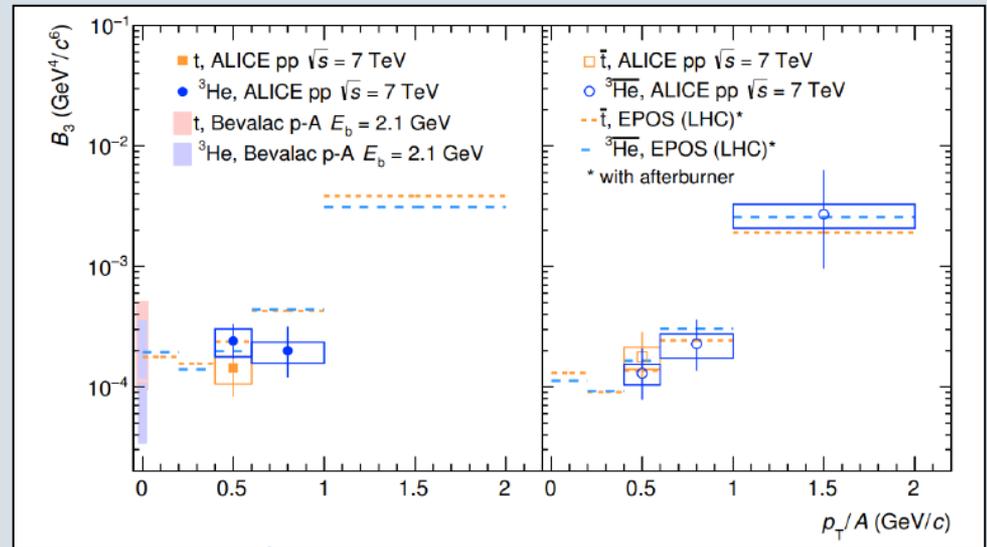
Poisson probability for detecting N≥1, 2, 3, 4 $^3\overline{\text{He}}$ events in a 5-yr analysis of AMS02

ALICE measurement (green box region) allows to reduce uncertainties in the model (AMS02)

Hypernuclei

Main goals of hypernuclear physics:
- Extension of nuclear chart
- Understand the baryon-baryon interaction in strangeness sector
- Study the structure of multi-strange systems
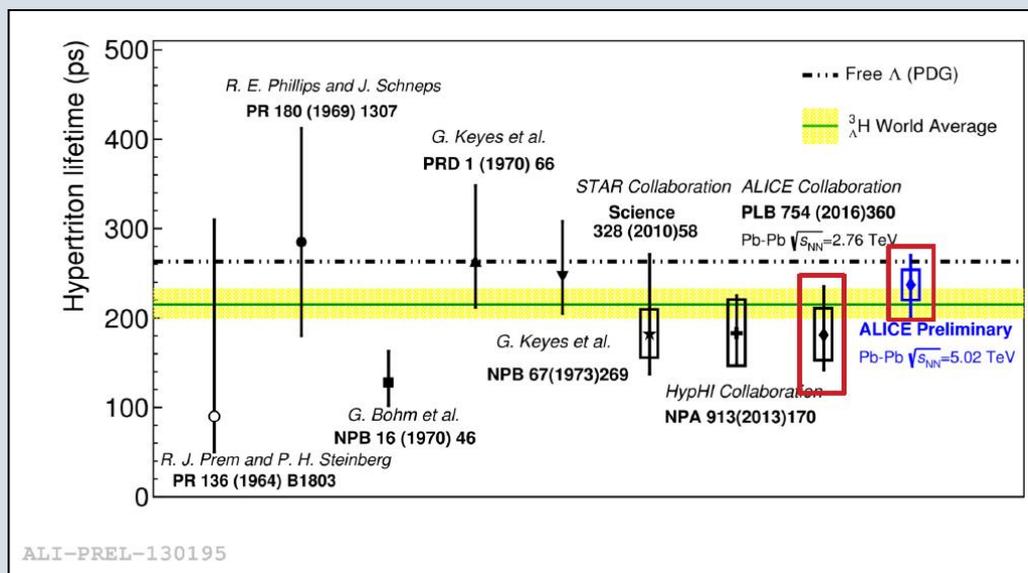
Decay Channels

|		
$^3_\Lambda H \rightarrow \,^3He + \pi^-$	~25%	$^3_\Lambda \overline{H} \rightarrow \,^3\overline{He} + \pi^+$
$^3_\Lambda H \rightarrow H + \pi^0$	~13%	$^3_\Lambda \overline{H} \rightarrow \overline{H} + \pi^0$
$^3_\Lambda H \rightarrow d + p + \pi^-$	~41%	$^3_\Lambda \overline{H} \rightarrow \overline{d} + \overline{p} + \pi^+$
$^3_\Lambda H \rightarrow d + n + \pi^-$	~21%	$^3_\Lambda \overline{H} \rightarrow \overline{d} + \overline{n} + \pi^+$
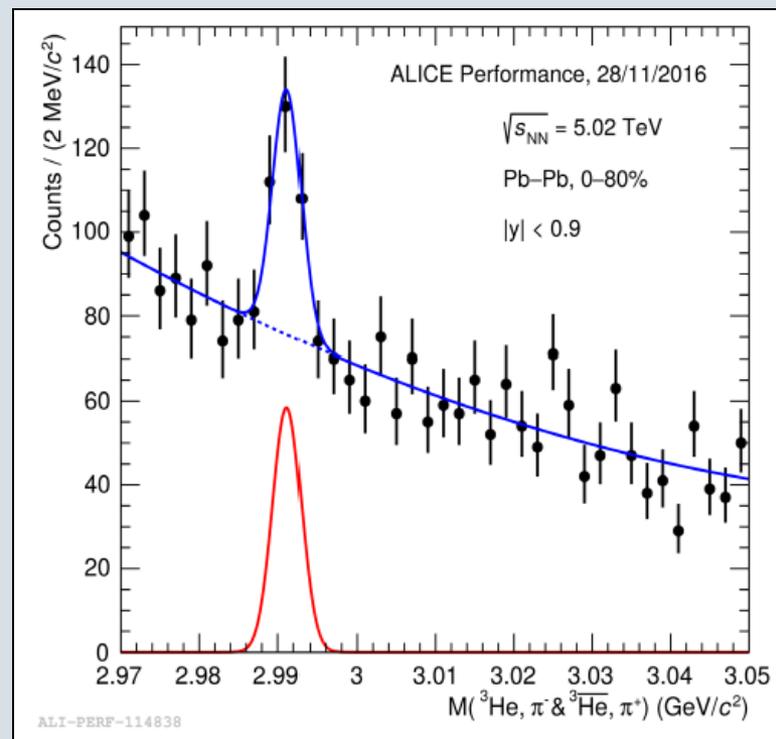
The ALICE upgrade for Run-3

The LHC schedule (for PbPb)

Run-2 (→ 2018) $L^{PbPb}_{\text{integrated}} = 1.0 \, \text{nb}^{-1}$

Run-3 (2021-2023) $L^{PbPb}_{\text{integrated}} = 6.0 \, \text{nb}^{-1}$

Run-4 (2026-2029) $L^{PbPb}_{\text{integrated}} = 7.0 \, \text{nb}^{-1}$

Major upgrade of detector system during Long Shutdown 2 (2019-2020)
→ **faster detectors + continuous readout**
→ higher secondary vertices precision due to **inner tracker upgrade (also lower material budget)**

CERN-LHCC-2013-024 · CERN-LHCC-2012-012 · CERN-LHCC-2015-021 · CERN-LHCC-2013-019 · CERN-LHCC-2015-006

Improvements are expected for many analyses:
- Study the thermalization of partons in the QGP focusued on charm and beauty quarks
- Low-momentum charmonia dissociation (and regeneration?)
- Production of thermal photons and low-mass dileptons emitted by QGP to study initial temperature and equation of state of the medium (**lower B = 0.2 T and lower material**)
- Precision study of light nuclei and hyper-nuclei (**higher statistics, faster DAQ rate due to TPC upgrade**)

Conclusion

The physics of ALICE is very rich allowing to characterize the medium produced in AA collisions in terms of:

SOFT probes: medium was characterized in terms of:

- Hadronization vs. coalescence (hadron spectra, elliptic flow)
- Low viscosity of the medium (anisotropic flow)
- Is the system similar in p-Pb central collisions? (hints from ridge, strangeness production, v_n)

HARD probes: medium was characterized in terms of:

- Jet quenching (R_{AA}, with and w/o PID)
- Recombination (J/ψ suppression/enhancement)
- Heavy vs. light quarks: are heavy quarks thermalized and flowing? (J/ψ and D v_2)
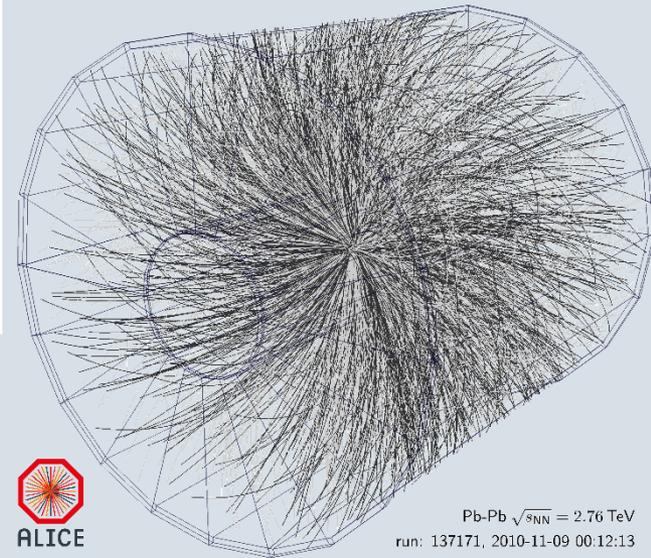
... thanks for your attention!

Backup

Data taking in Run-1 at the LHC

System	Year	$\sqrt{s_{NN}}$ (TeV)	$L_{integrated}$ (deliv)
pp	2009-2010	0.9	~ 0.2 nb^{-1}
pp	2011	2.76	~ 100 nb^{-1}
pp	2010-2011	7	~ 1.5 pb^{-1}
pp	2012	8	~ 2.5 pb^{-1}
p-Pb	2013	5.02	~ 15 nb^{-1}
Pb-Pb	2010-2011	2.76	~ 0.08 nb^{-1}

σ_{pp}(2.76 TeV) ~ 65 mb
σ_{Pb-Pb}(2.76 TeV) ~ 7660 mb
(Glauber model*)

ALICE

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
run: 137171, 2010-11-09 00:12:13

* Glauber model describes nucleus-nucleus collisions as an overlap of nucleon-nucleon collisions assuming a distribution of nucleons within nucleus volume accordingly to a Woods-Saxon profile. It allows to compute nucleus-nucleus cross section, N_{part}, N_{coll} for a given impact parameter, ...

Data taking in Run-2 at the LHC

System	Year	$\sqrt{s_{NN}}$ (TeV)	$L_{integrated}$ (deliv)
pp	2015-2017	13	~ 25 pb^{-1}
pp	2015, 2017	5.02	~ 1.3 pb^{-1}
p-Pb	2016	5.02	~ 3 nb^{-1}
p-Pb	2016	8.16	~ 25 nb^{-1}
Pb-p	2016	8.16	~ 20 nb^{-1}
Pb-Pb	2015	5.02	~ 0.25 nb^{-1}
(Xe-Xe)	2017	5.44	~ 0.3 μb^{-1}
Pb-Pb	2018 (exp)	5.02	~ 1 nb^{-1}

Pb (Z=82, A=208)
Xe (Z=54, A=129)
σ_{Pb-Pb}(5.5 TeV) ~ 7750 mb
(Glauber model)

Goals for Run 2:
- pp@13 TeV → reach 40 pb^{-1}
- Pb-Pb → 1 nb^{-1}
- high statistics pp@5 TeV sample (2017) "improve the reference"
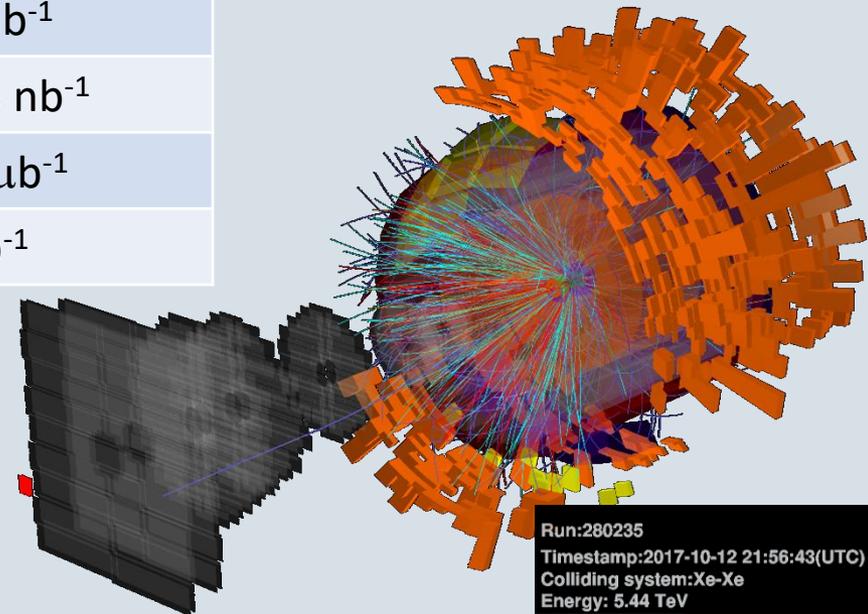
Run:280235
Timestamp:2017-10-12 21:56:43(UTC)
Colliding system:Xe-Xe
Energy: 5.44 TeV

Golden observables for ALICE

Pb-Pb (Xe-Xe) collisions

- Strangeness in the medium
- Collective phenomena/flow
- Electroweak probes (no strong interaction with medium)
- Jet and medium interaction (light quarks and gluons)
- Heavy flavors (heavy quarks in the medium)
- Light nuclei factory

SOFT PROBES

HARD PROBES

pp collisions

- Reference without medium effects
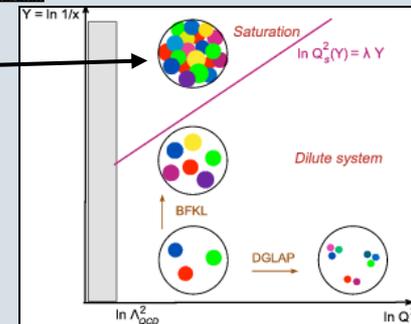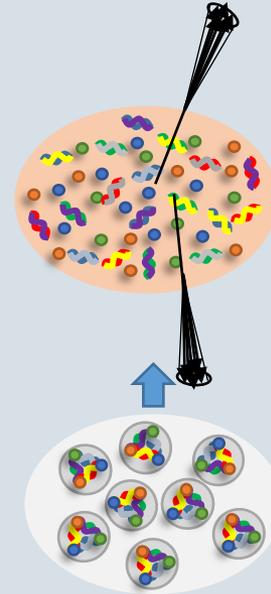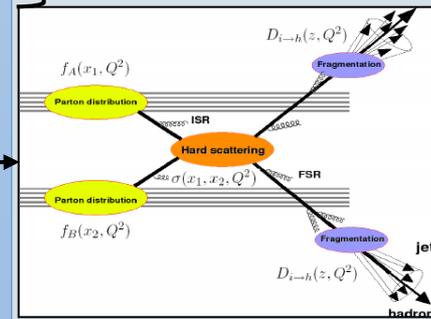- Collectivity in high multiplicity events?

p-Pb collisions

- Reference for cold matter effects
- Collectivity?

L. Cifarelli, R. Nania, FN, E. Scapparone, A. Zichichi,
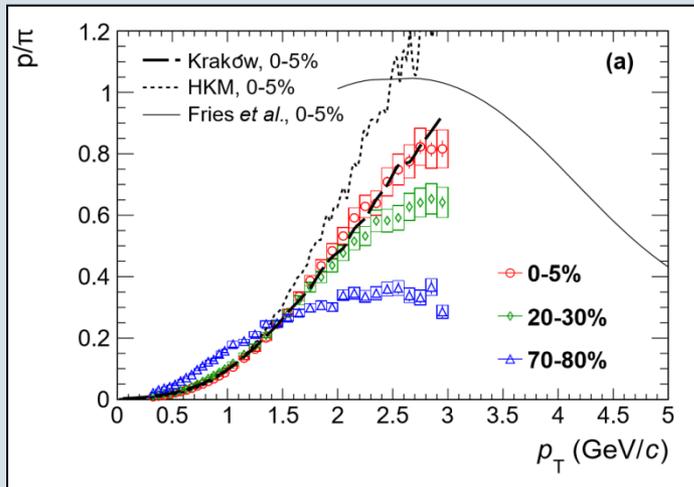NUOVO CIMENTO Vol. 39 (2016) N. 10
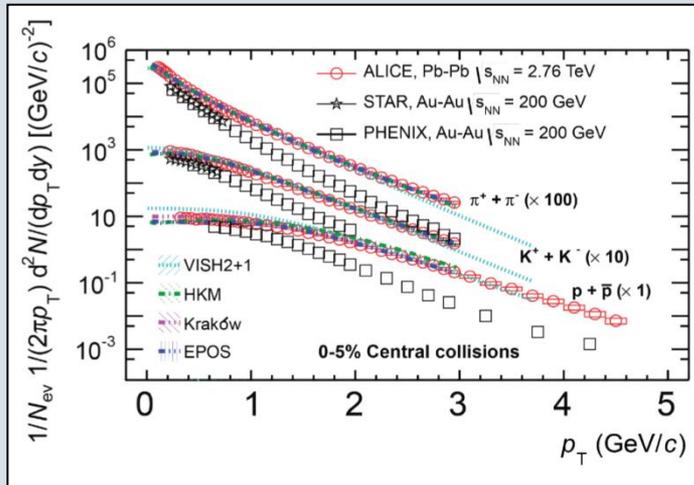
3Back

Medium is expanding → radial flow

Phys. Rev. C 88 044910 (2013)

Hardening of the p_T spectra observed at LHC wrt RHIC consistent with a higher radial flow developing in the medium expansion.

Mass ordering reproduced by hydro models, larger mass -> larger shift of the p_T distribution Blast-Wave fit (hydro approximation) used to extract radial flow parameters.
CAVEAT: QCD effects such as color reconnection can mimic radial flow!
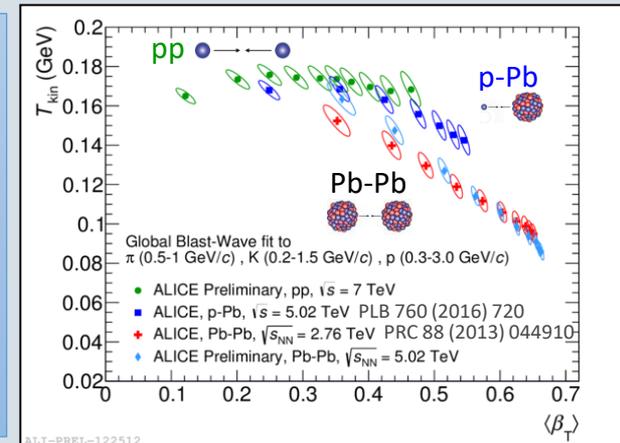
$$\frac{dN}{p_T dp_T} = N_{species} \int_0^R m_T r dr \int_0^{2\pi} d\phi_b I_0(\alpha_t) K_1(\beta_t) \boxed{(1+2s_2\cos(2\phi_b))}$$

$$\alpha_t(\phi_b) = (p_T/T_f)\sinh(\rho(\phi_b))$$

$$\beta_t(\phi_b) = (m_T/T_f)\cosh(\rho(\phi_b))$$

Added to model elliptic flow

$$\text{with } \rho(\phi_b) = \rho_0(r/R)^\gamma \boxed{\times (1+2\rho_2\cos(2\phi_b))}$$

$$\text{parameters}: T_f, \rho_0, \rho_2, s_2, \gamma, N_\pi, N_K, N_p$$