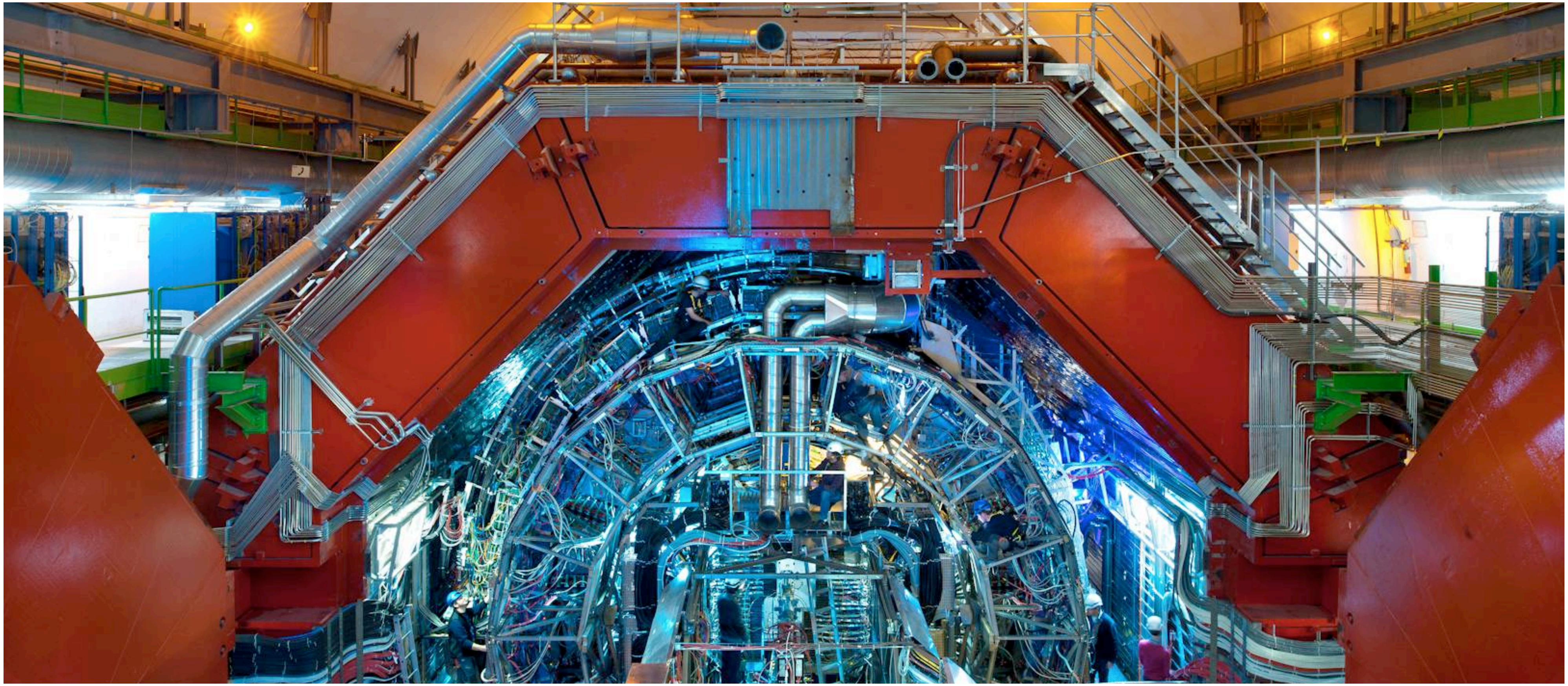
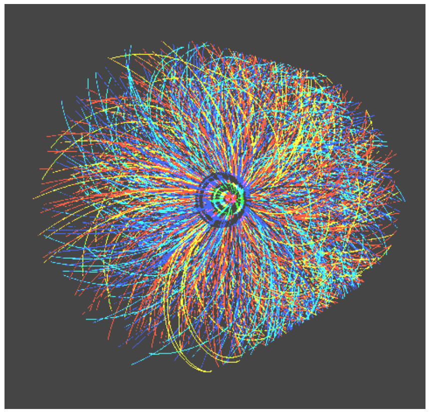


Produzione di (anti-)nuclei, barioni e risonanze adroniche in collisioni pp, p-Pb e Pb-Pb con l'esperimento ALICE

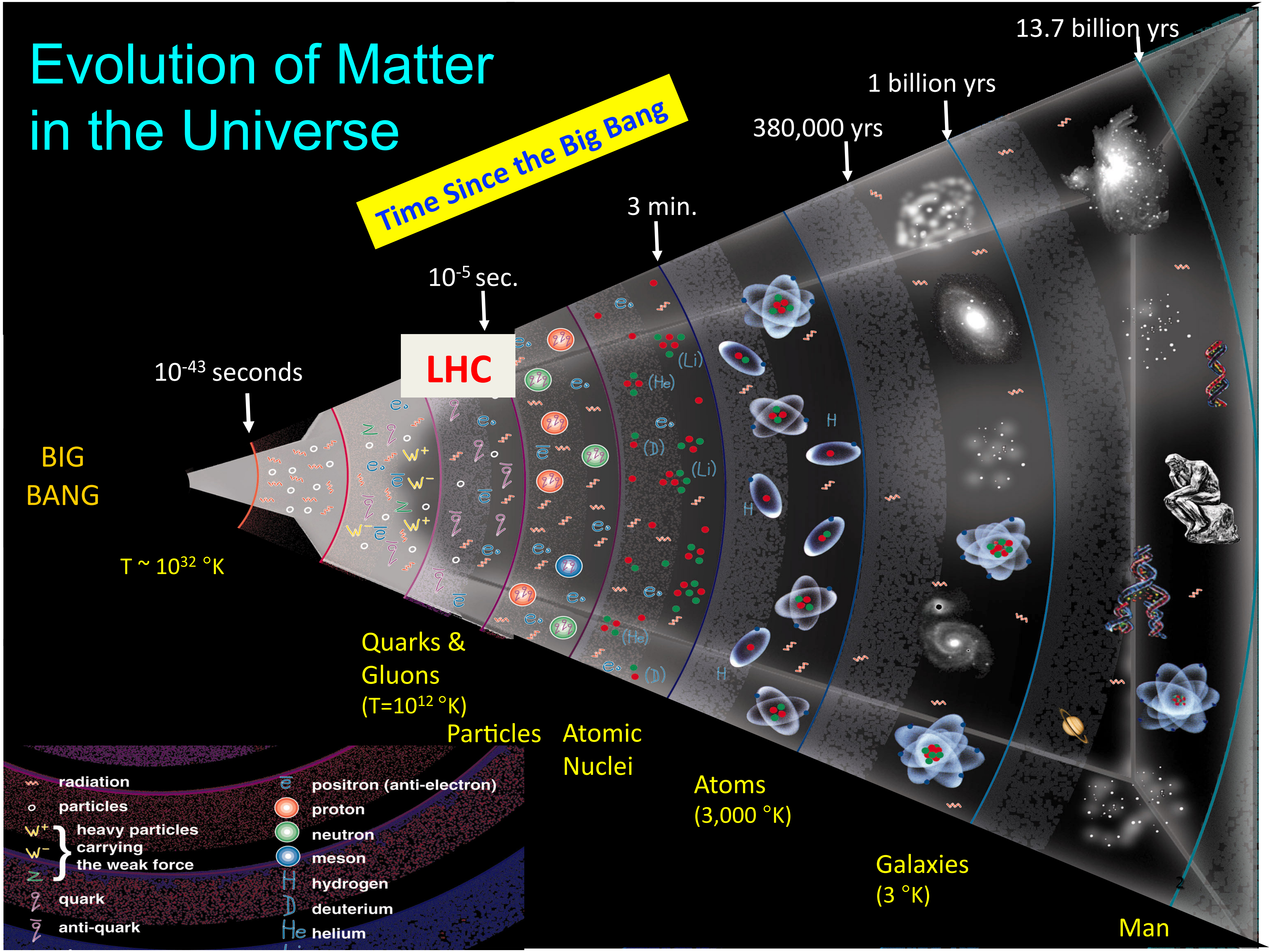


ALICE

Stefania Bufalino
Università e INFN, Torino
per la Collaborazione ALICE

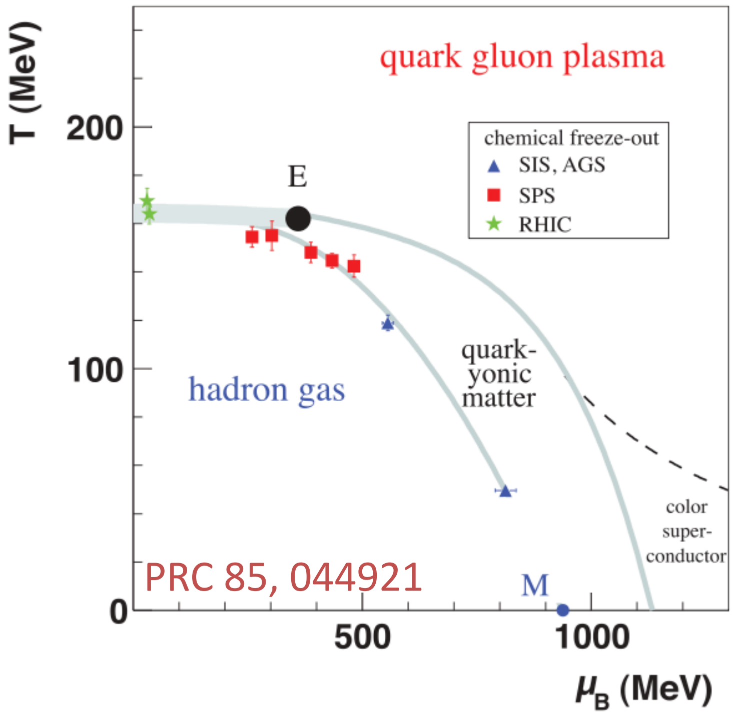
Congresso Nazionale
della Società Italiana di Fisica
Roma- 21-25 Settembre 2015

Evolution of Matter in the Universe



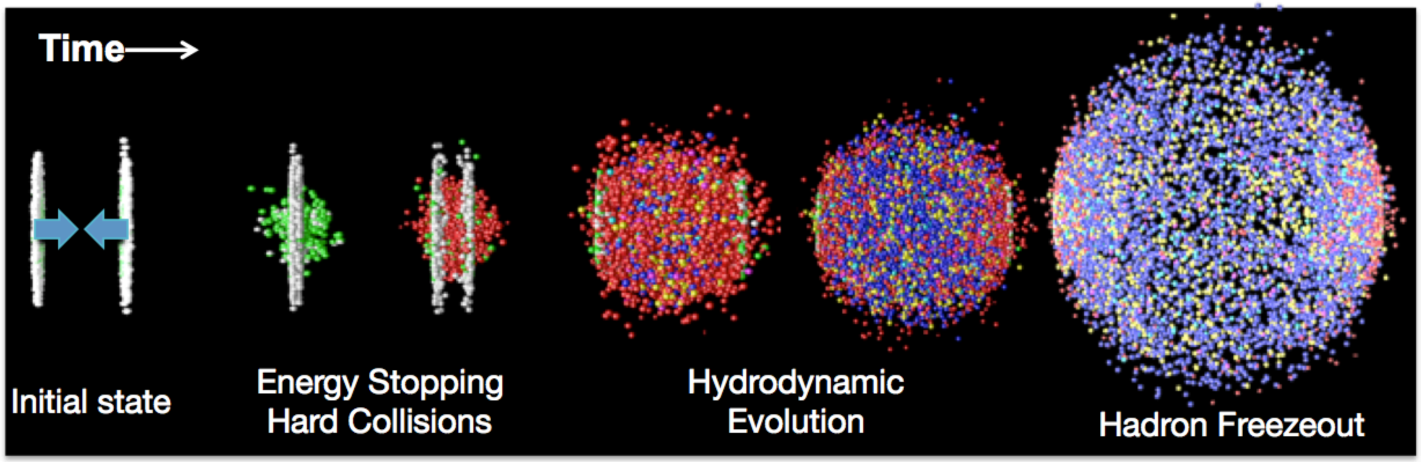
Congresso Nazionale
della Società Italiana di Fisica
Roma- 21-25 Settembre 2015

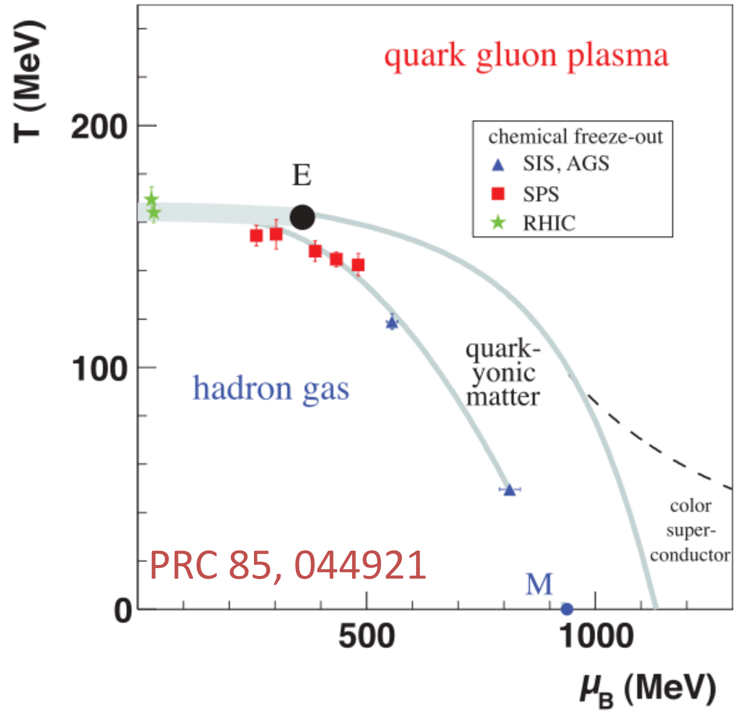
Heavy ion collisions evolution



ALICE

Heavy ion collisions evolution





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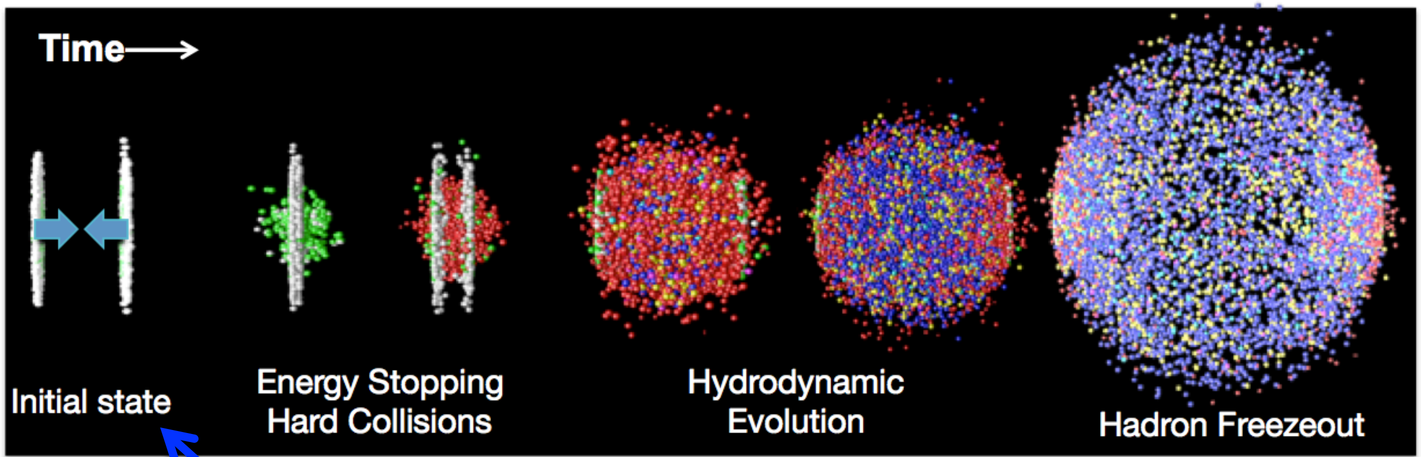
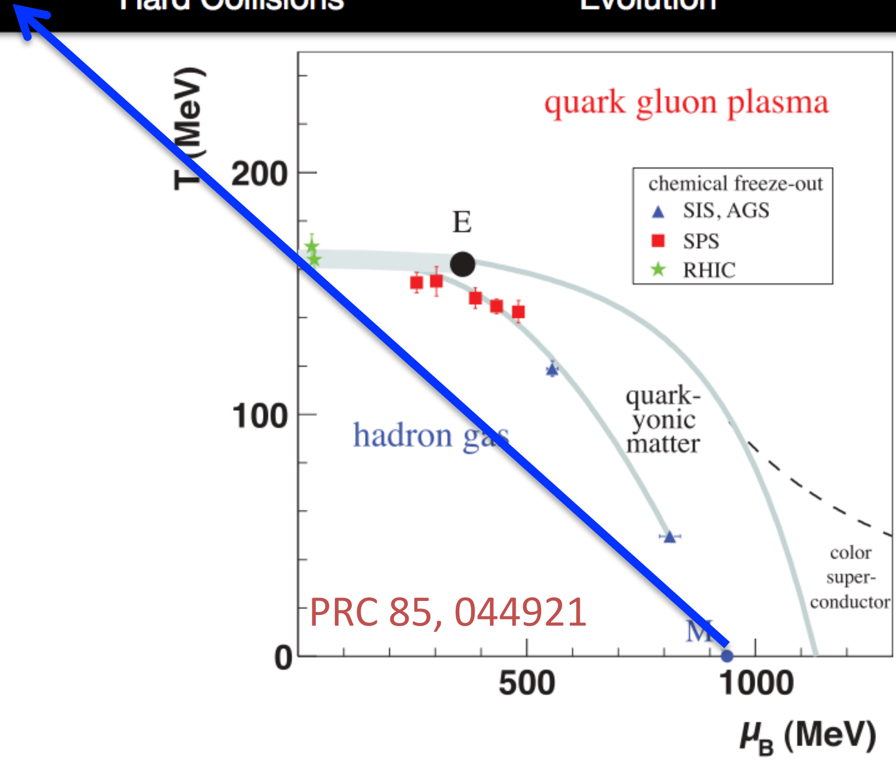
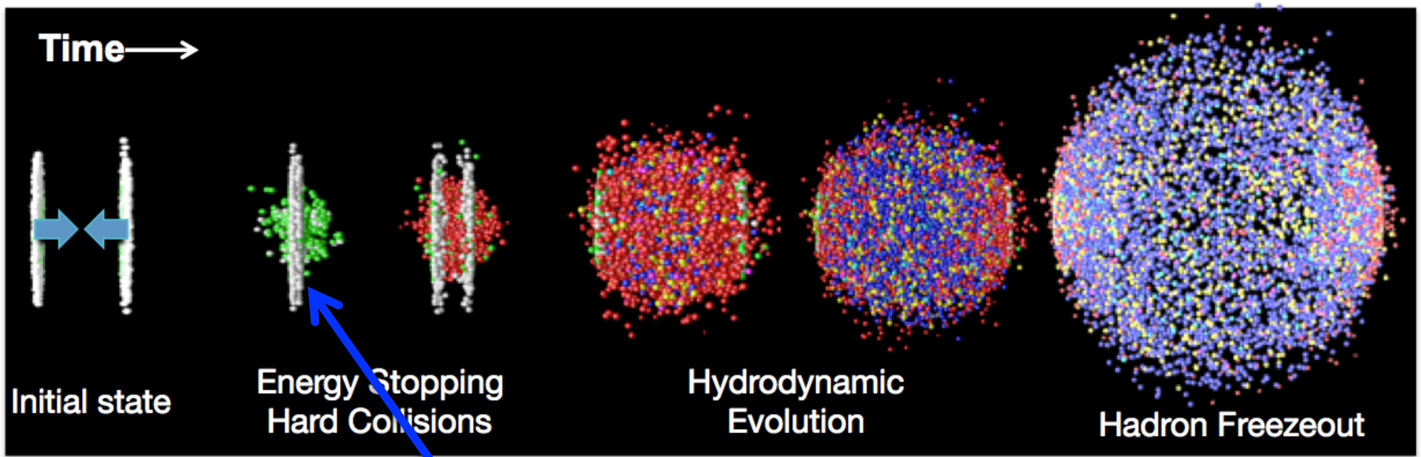
Heavy ion collisions evolution

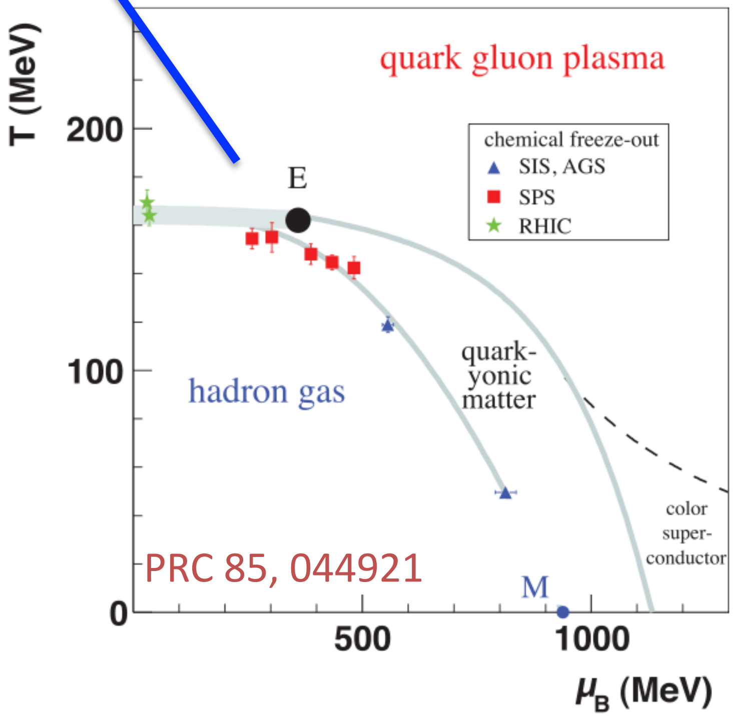




Heavy ion collisions evolution



Hard scattering



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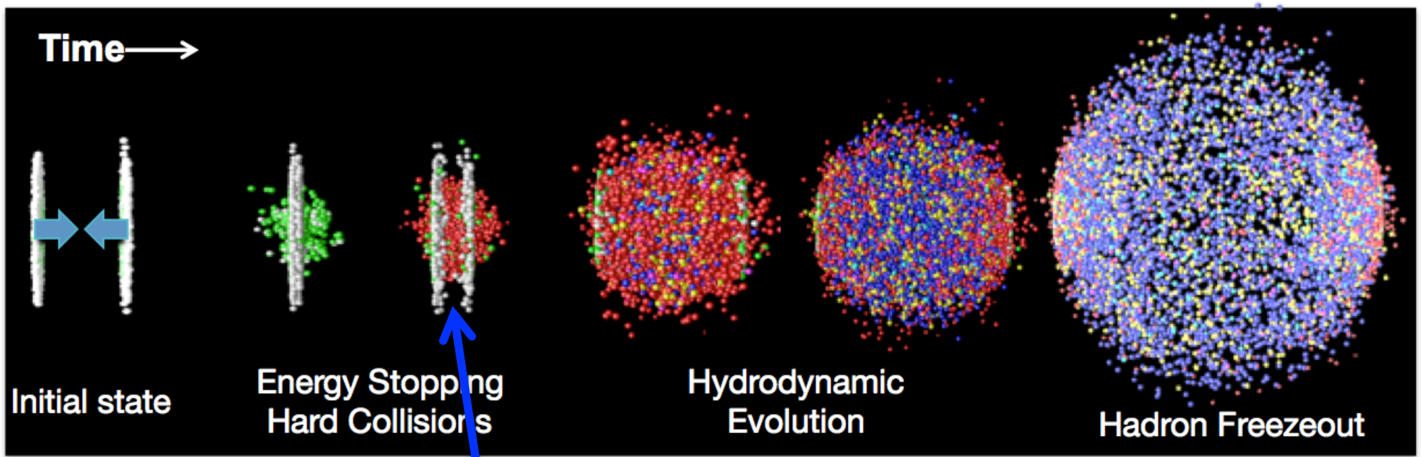
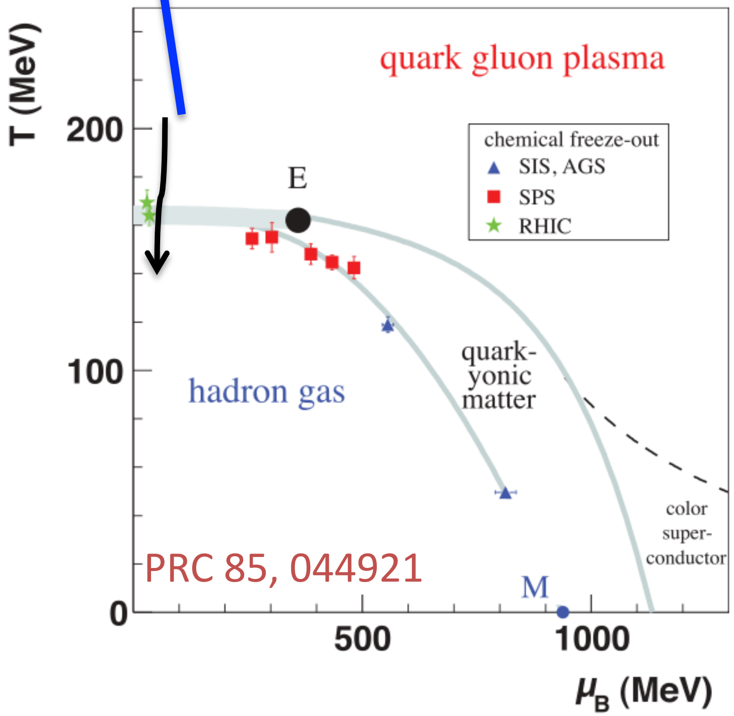
Heavy ion collisions evolution

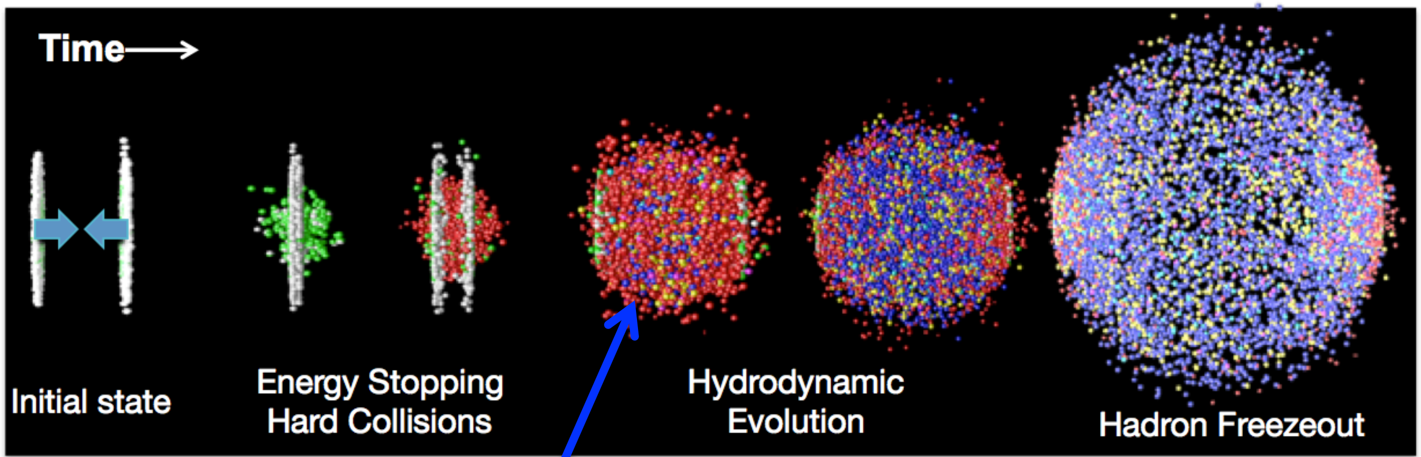


Hard scattering

thermalization



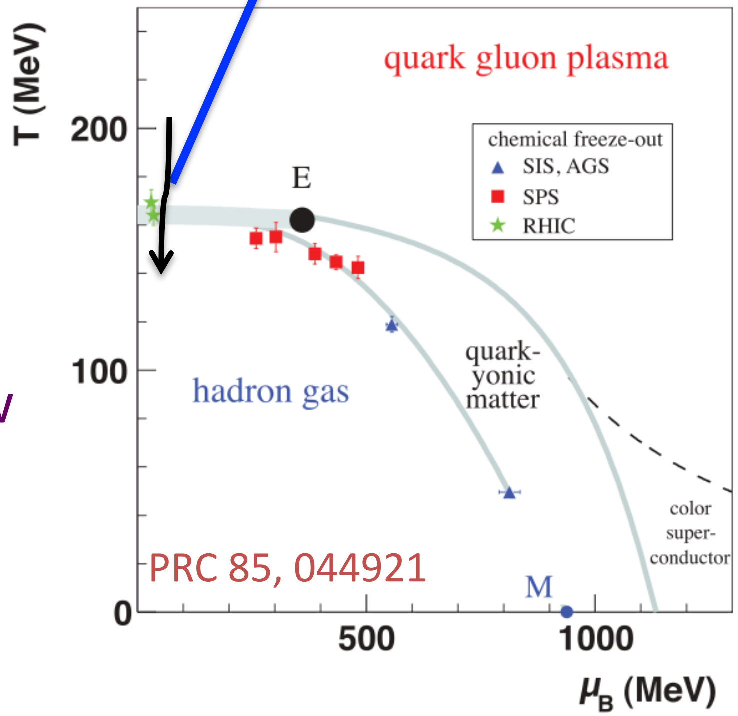
Heavy ion collisions evolution



Hard scattering

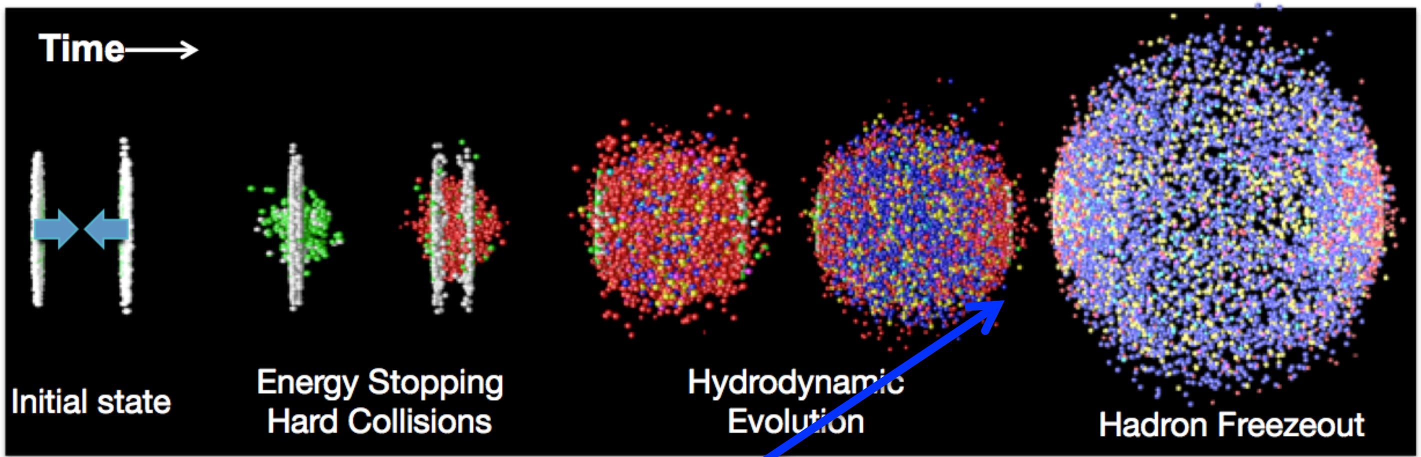
thermalization

Hydrodynamic flow
(radial and elliptic)



ALICE

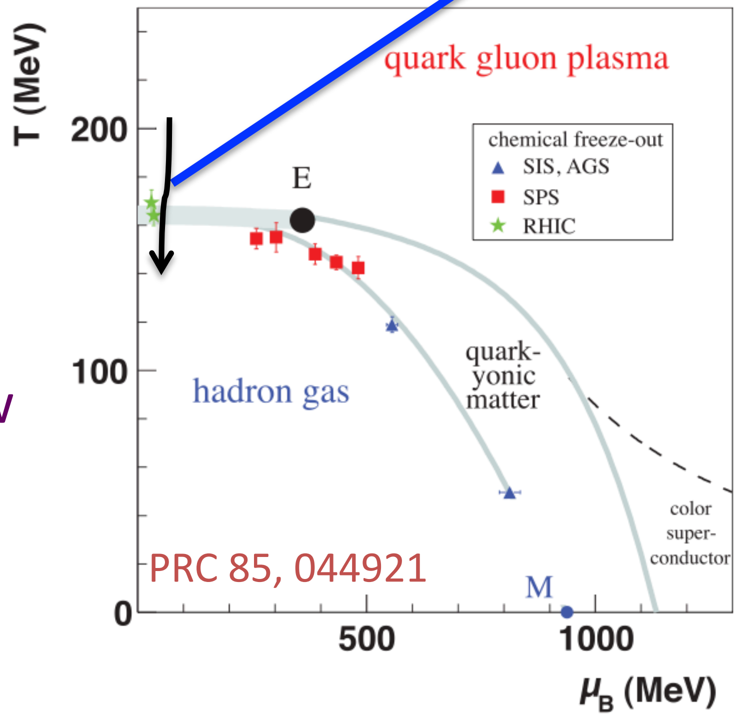
Heavy ion collisions evolution



Hard scattering

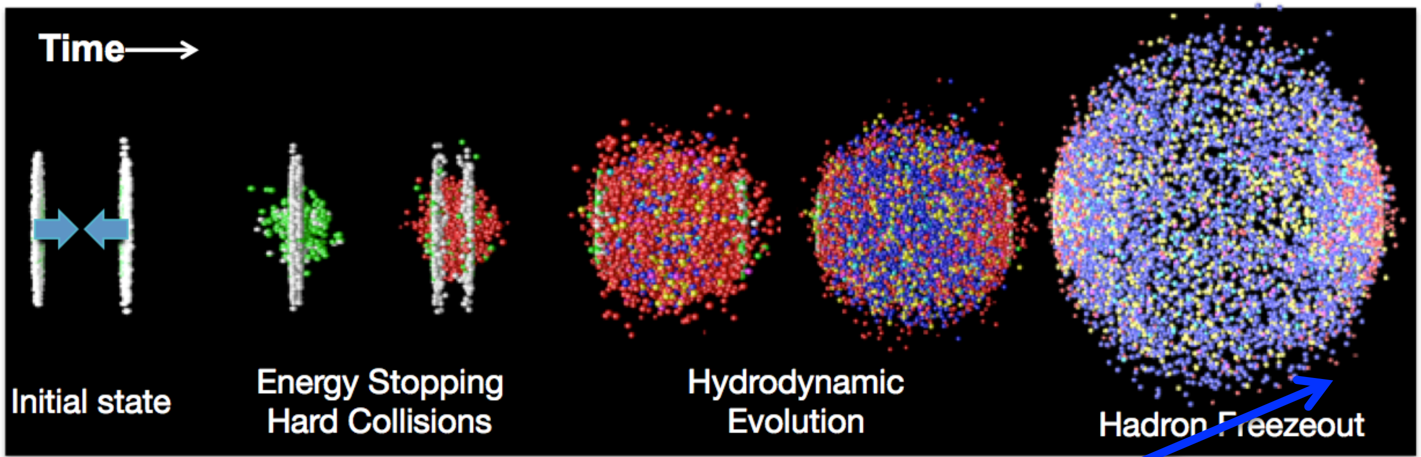
thermalization

Hydrodynamic flow
(radial and elliptic)



Chemical freezeout
(particle ratios)

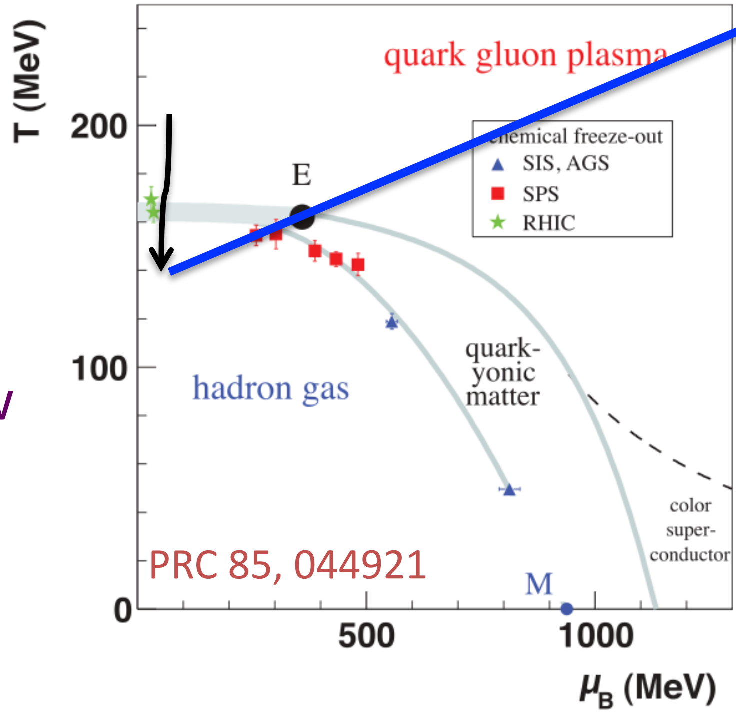
Heavy ion collisions evolution



Hard scattering

thermalization

Hydrodynamic flow
(radial and elliptic)



Chemical freezeout
(particle ratios)

Kinetic freezeout
(momentum distribution)

A selection of results from ALICE

- The ALICE (A Large Ion Collider Experiment) detector
  - Particle identification performance
- Anti-matter production
  - Results from pp, p-Pb and Pb-Pb collisions
  - comparison with thermal model and coalescence approach
- Collectivity
  - Particle spectra and radial flow
  - Baryon-to-meson ratio
- Resonances
  - Resonance suppression
  - Nuclear modification factors

The ALICE detector

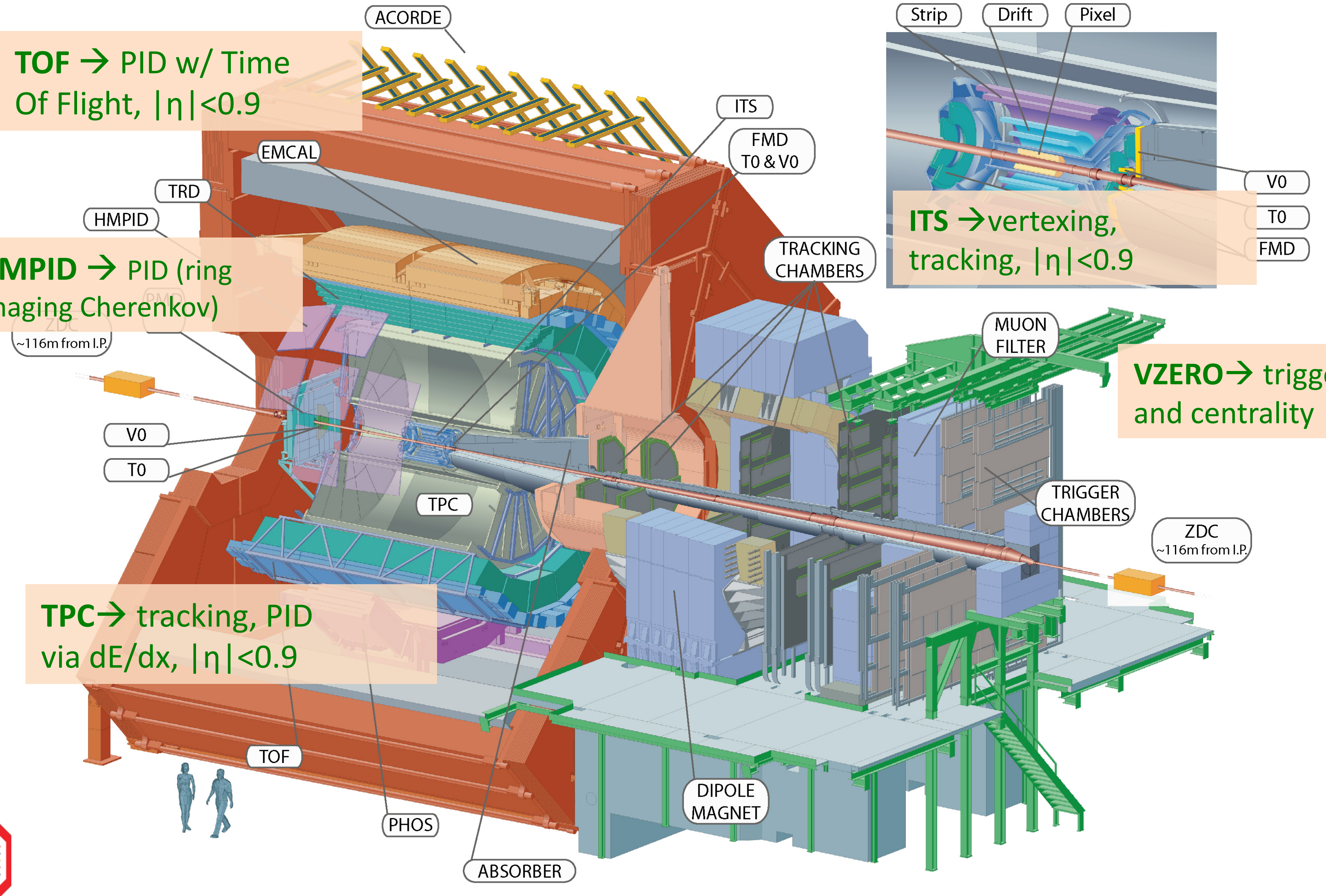
TOF → PID w/ Time Of Flight, |η|<0.9

HMPID → PID (ring imaging Cherenkov)

TPC→ tracking, PID via dE/dx, |η|<0.9

ITS →vertexing, tracking, |η|<0.9

VZERO→ trigger and centrality



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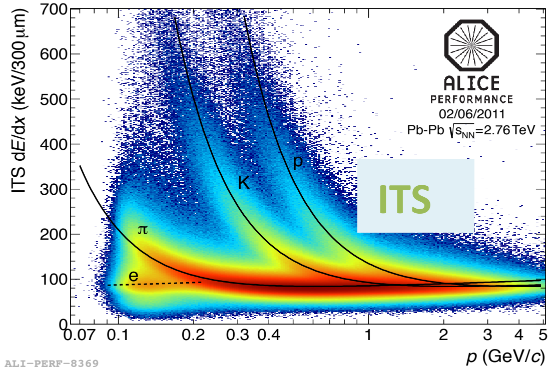
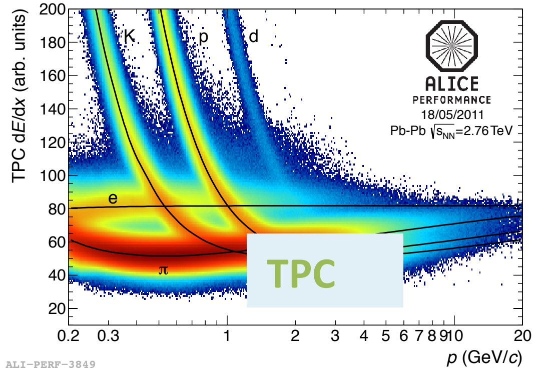
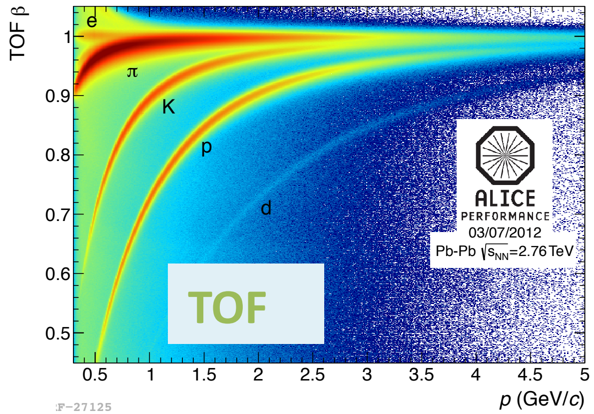
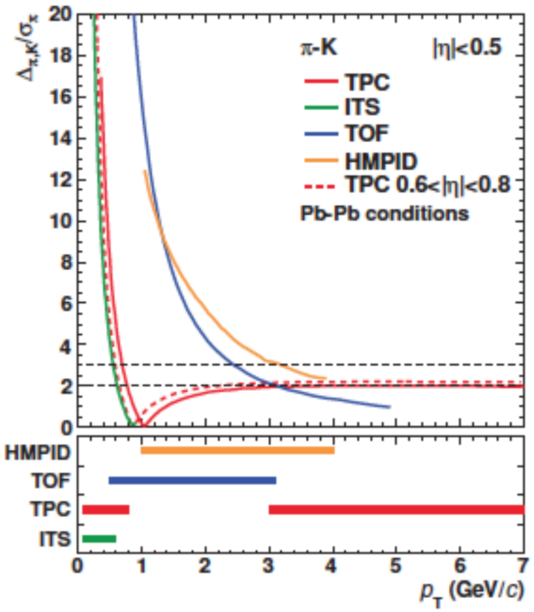
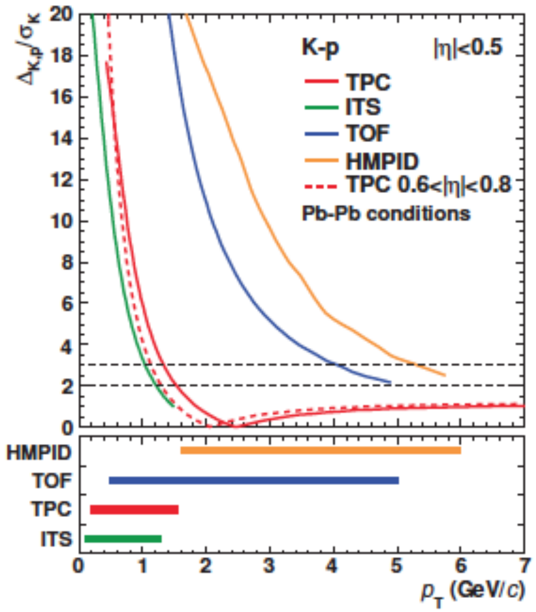
Particle identification

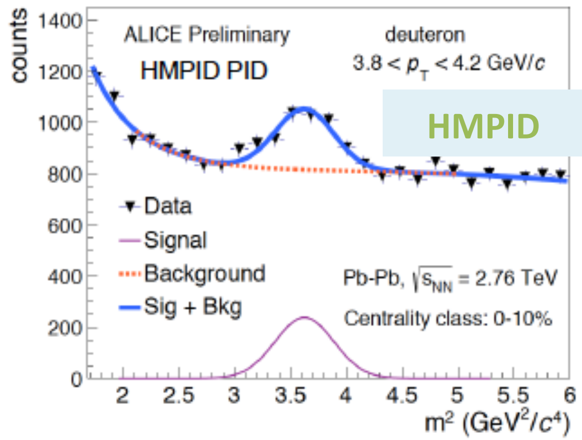












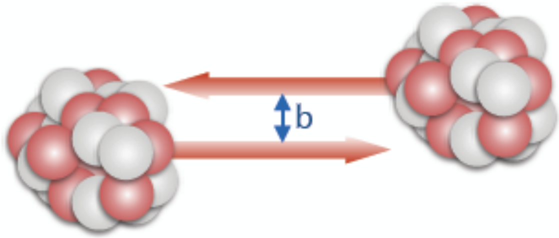
Excellent particle identification and separation power over a wide momentum range (~100 MeV/*c* – 20 GeV/*c* for π, K, p)

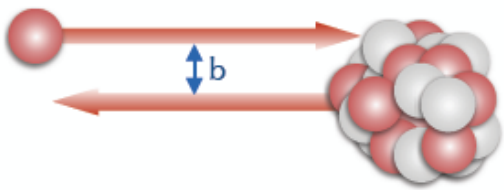
Int. J. Mod. Phys. A 29 (2014) 1430044

ALICE

Centrality of the collisions

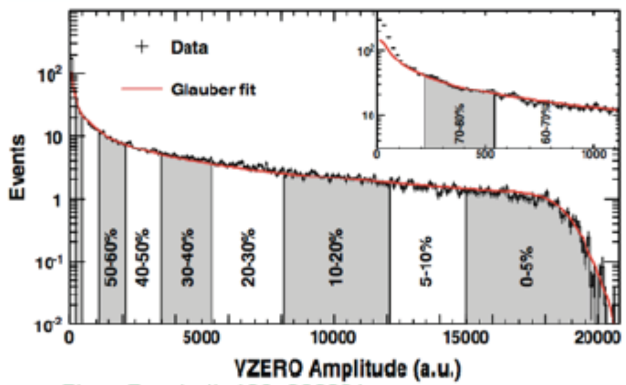
- Central collisions
  - ➢small impact parameter b
  - ➢high number of participant nucleons → high multiplicity
- Peripheral collisions
  - ➢large impact parameter b
  - ➢low number of participant nucleons → low multiplicity



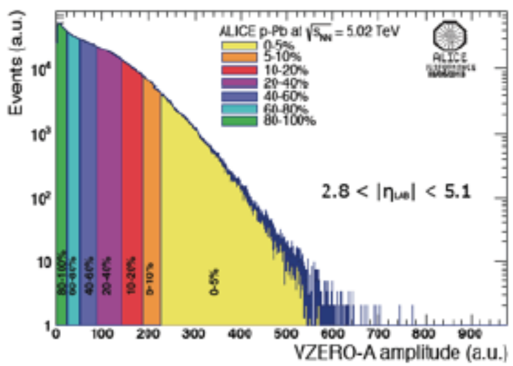


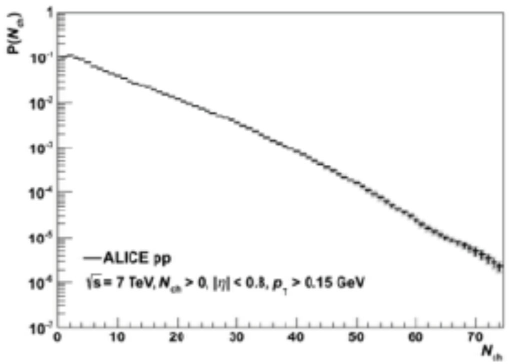
In pp centrality can't be defined

Midrapidity multiplicity can be used for differential studies



Phys. Rev. Lett. 106, 032301



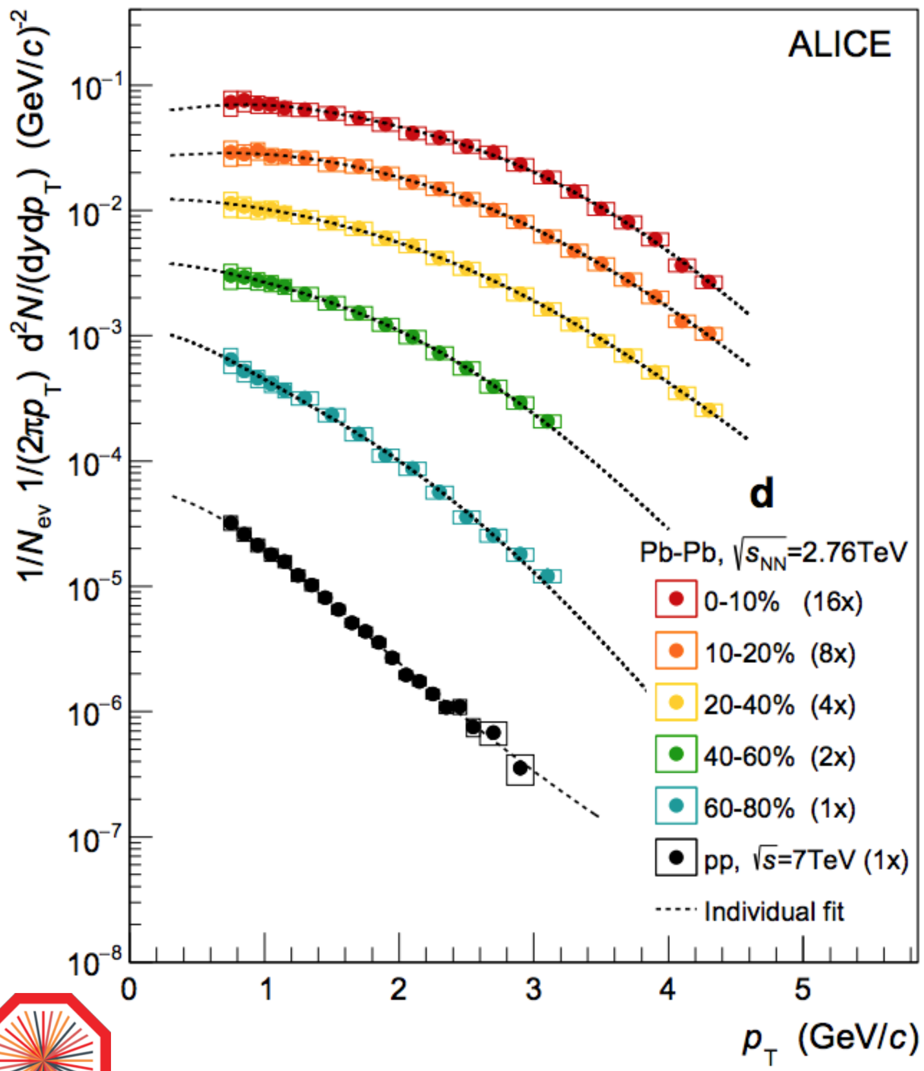


ALICE-PUBLIC-2013-001

The anti-matter production

Deuteron in pp and Pb-Pb collisions

ALICE Coll. arXiv:1506.08951 [nucl-ex]



pp

Invariant production spectrum is well fitted by the Levy-Tsallis function in pp

$$\frac{d^2N}{dp_T dy} = p_T \frac{dN}{dy} \frac{(n-1)(n-2)}{nC(nC + m_0(n-2))} \left(1 + \frac{m_T - m_0}{nC}\right)^{-1}$$

where m_0 is the reference mass of the deuteron and n,C are fit parameters.

C. Tsallis. J.Statist.Phys. 52 479-487(1988)

Pb-Pb

- The Blast-Wave (BW) function fits well the data.
- Characteristic hardening of the spectrum with increasing centrality.
- These fits are used for the extrapolation of the yield to the unmeasured region at low and high p_T.

Blast wave model: E. Schnedermann et al., Phys. Rev. C48, 2462 (1993)

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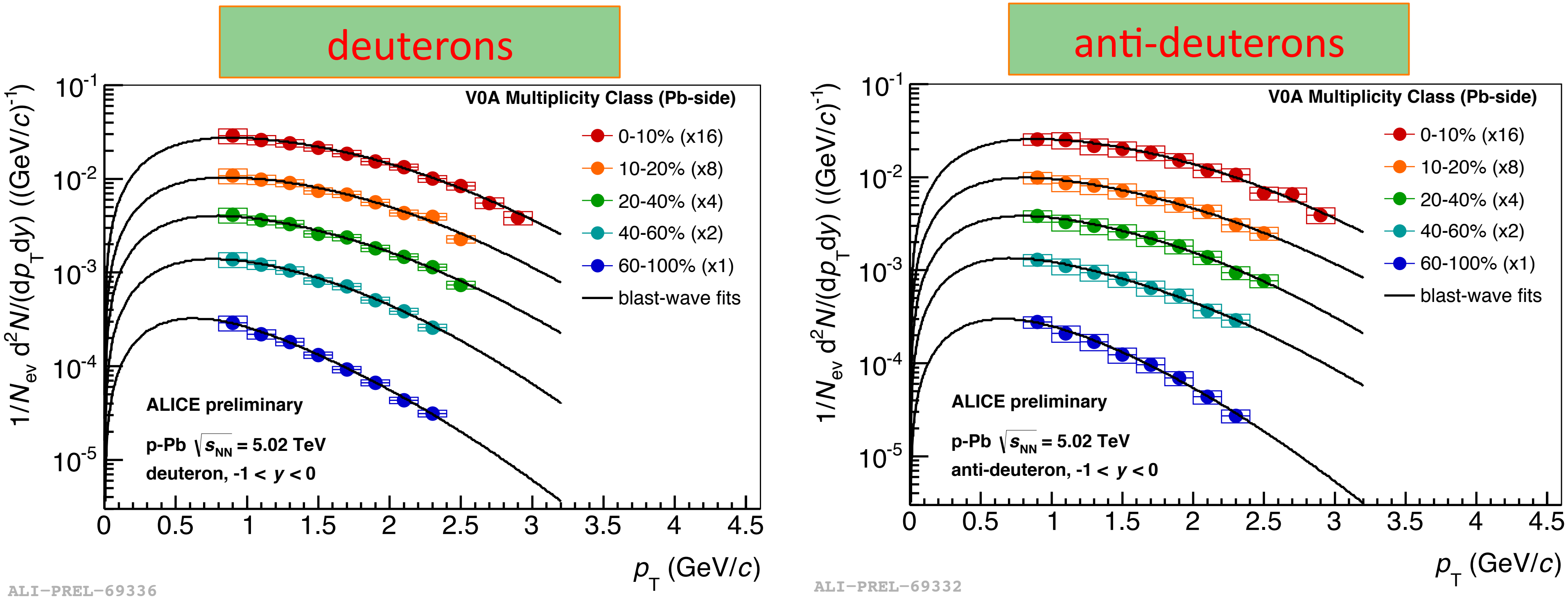
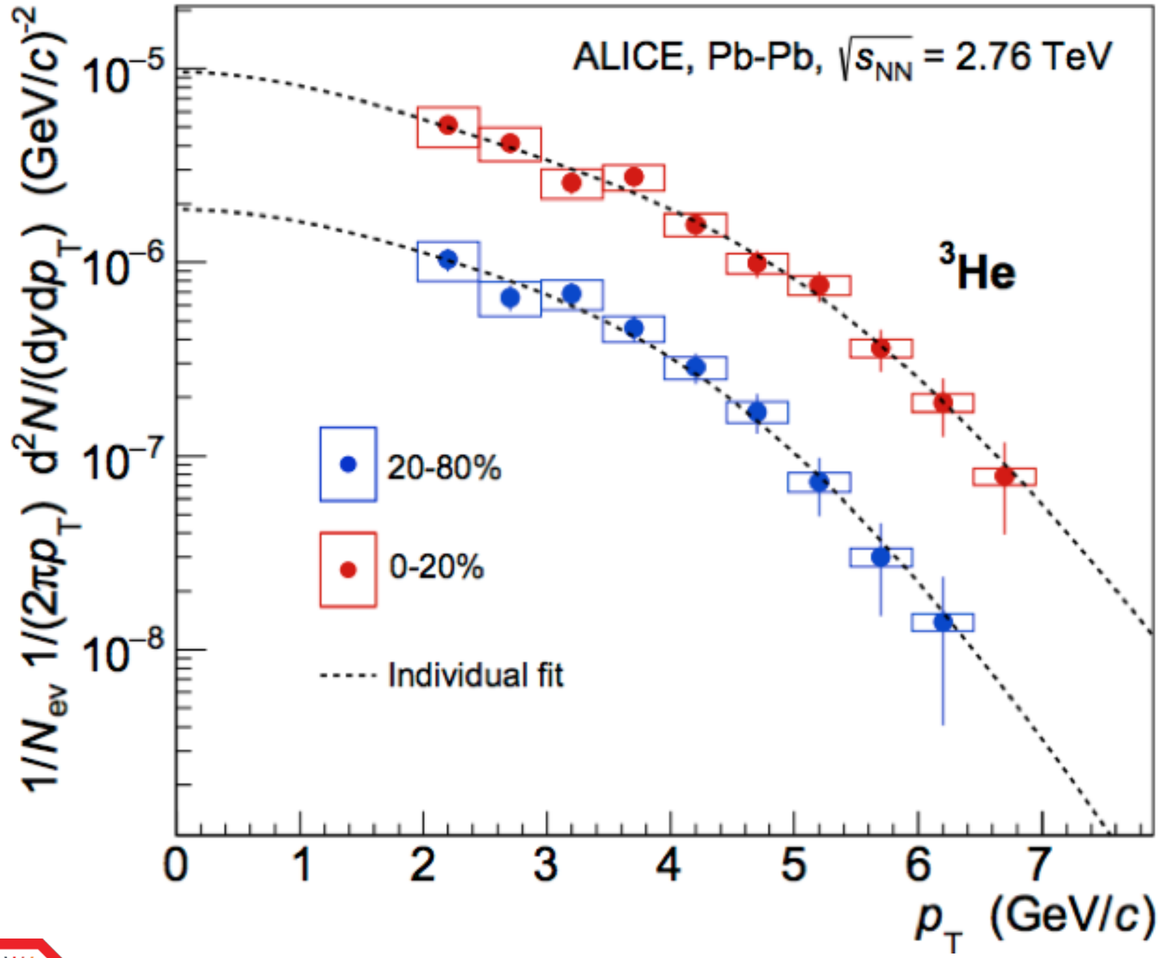
(Anti-)deuterons in p-Pb



Deuteron and anti-deuteron spectra become harder with increasing multiplicity also in p-Pb collisions

^{3}He production in Pb-Pb collisions



- Spectra fitted well with Blast-Wave functions in different centrality bins
- As for the deuteron spectra the ^{3}He spectra show radial flow

ALICE Coll. arXiv:1506.08951 [nucl-ex]

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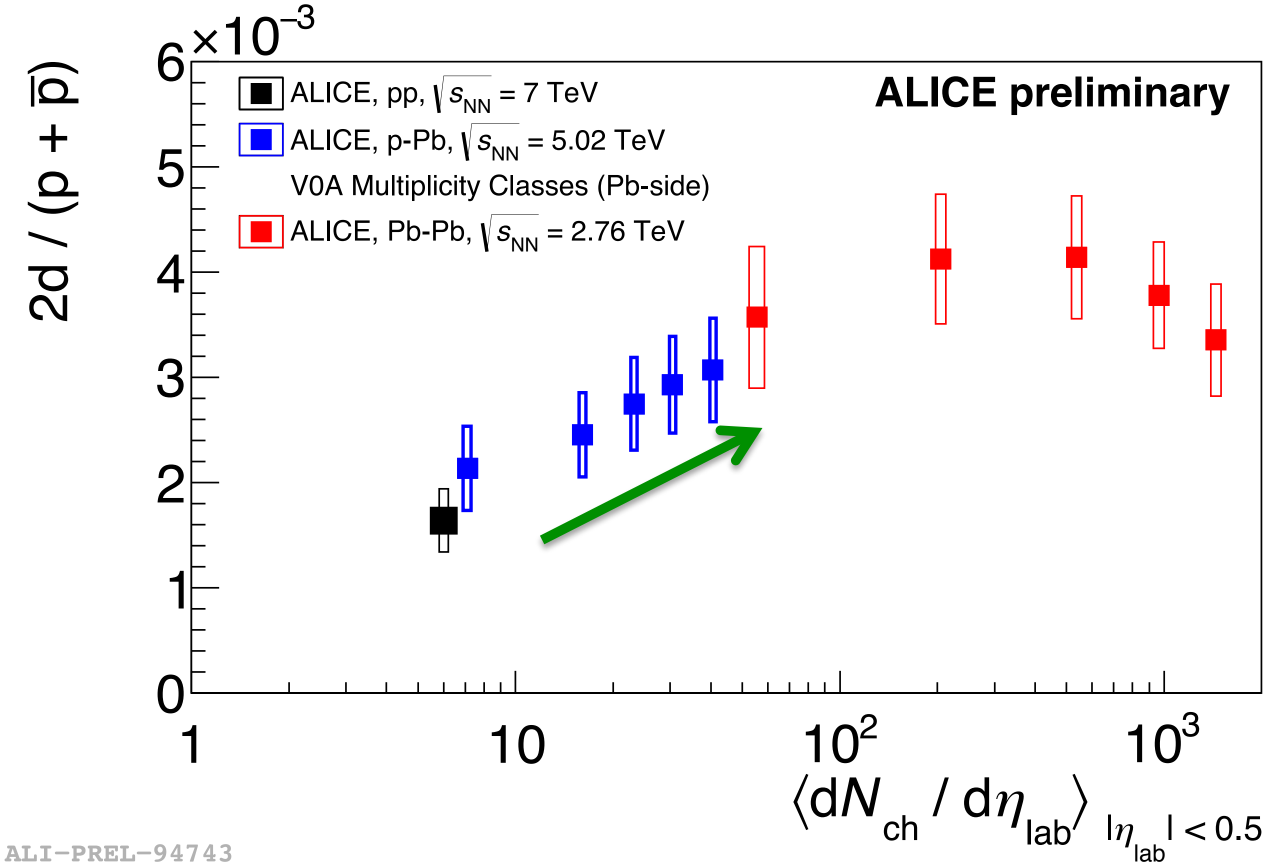
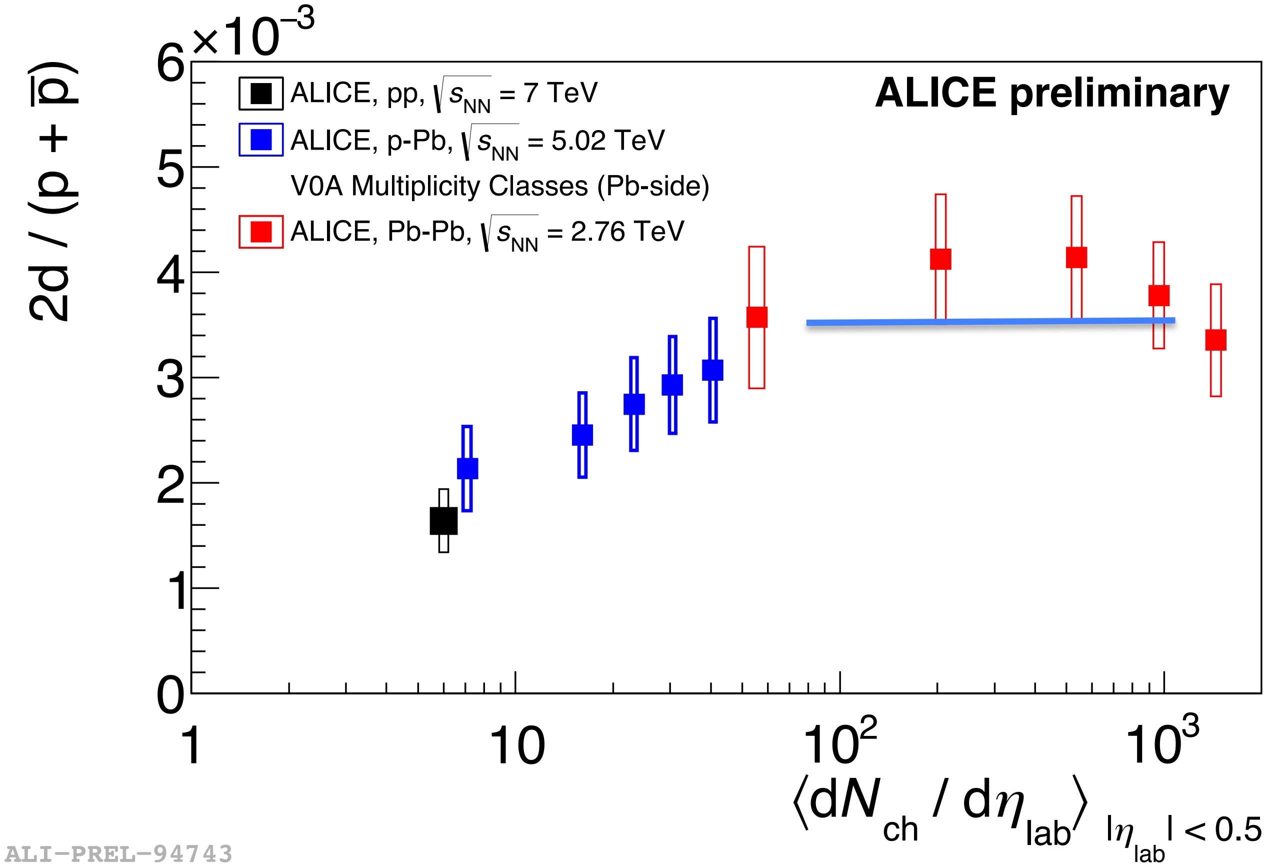
d/p ratio vs multiplicity



- Rise with multiplicity or particle density

The d/p ratio increases with the charged particle multiplicity: this is consistent with the coalescence picture

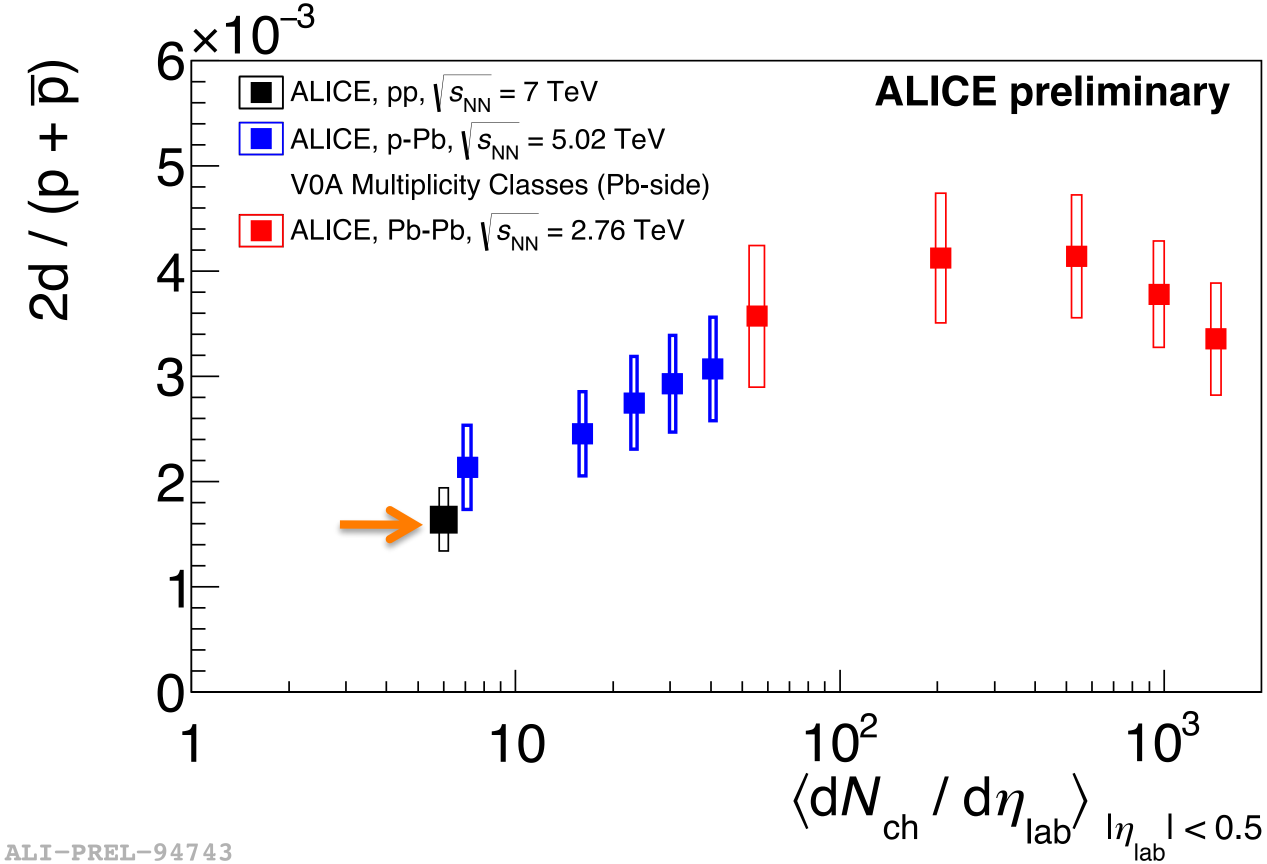
d/p ratio vs multiplicity



- Rise with multiplicity or particle density
- saturation in heavy-ion collisions within the errors

The d/p ratio increases with the charged particle multiplicity: this is consistent with the coalescence picture

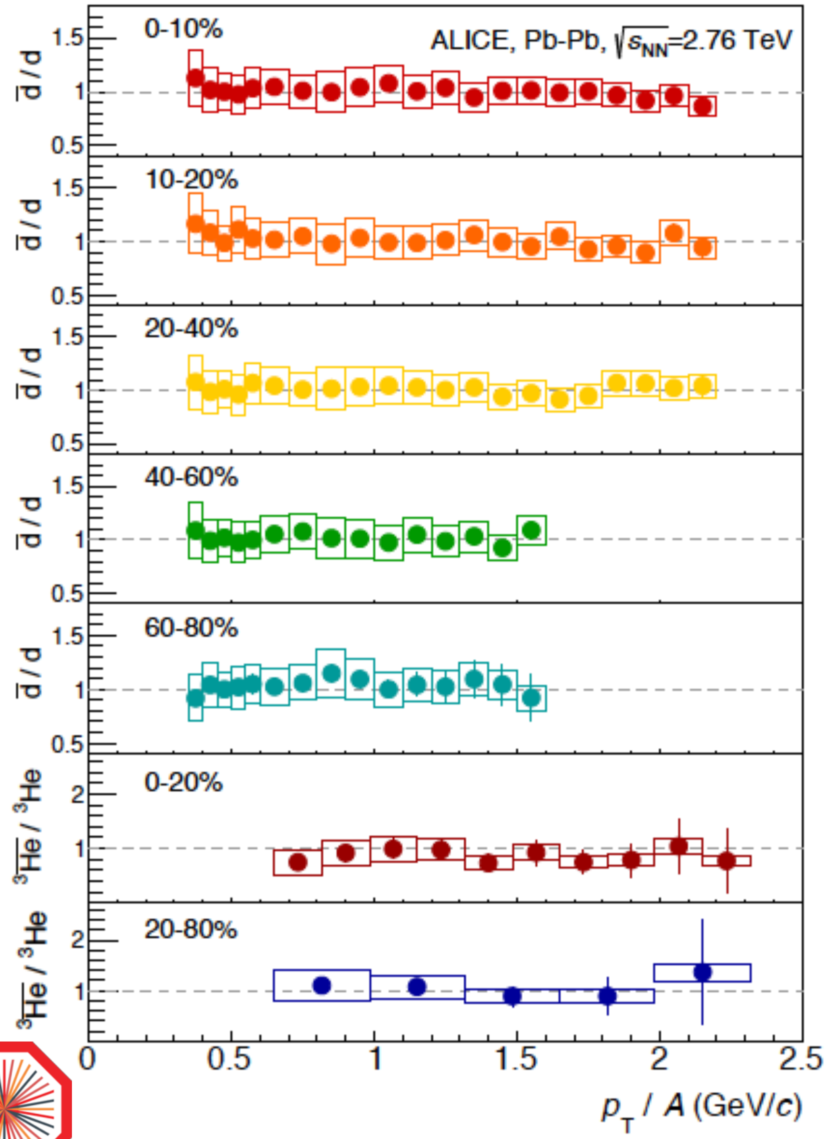
d/p ratio vs multiplicity



- Rise with multiplicity or particle density
- saturation in heavy-ion collisions within the errors
- ratio in pp collisions is a factor 2.5 lower than in Pb-Pb collisions

The d/p ratio increases with the charged particle multiplicity: this is consistent with the coalescence picture

(Anti-)nuclei/nuclei ratio



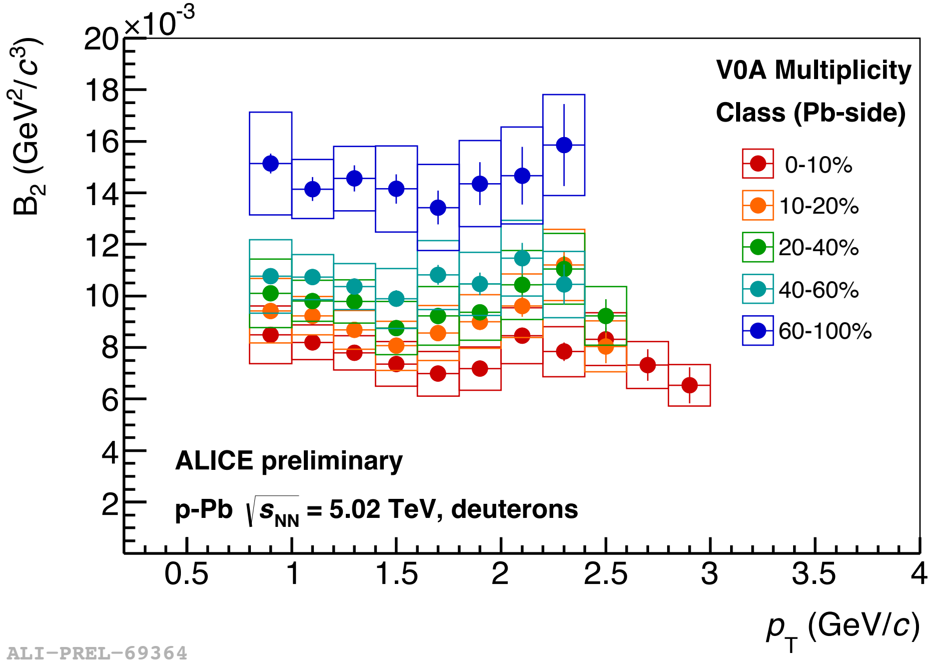
The ratio nuclei/anti-nuclei is compatible with unity

Systematic uncertainties dominated by the limited knowledge of the cross sections of anti-nuclei interacting with the material of the detector

→ spectra for nuclei and anti-nuclei are consistent within the current uncertainties

ALICE Coll. arXiv:1506.08951 [nucl-ex]

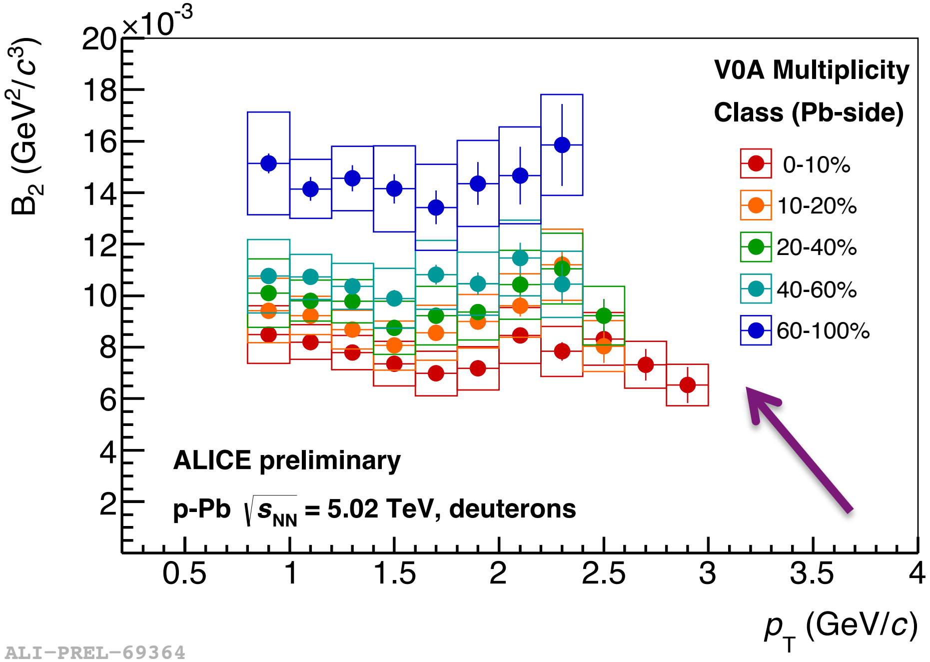
Deuterons B_2



The formation probability of deuterons can be quantified through the coalescence parameter B_2

$$B_2 = \frac{E_d \frac{d^3N_d}{dp_d^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^2}$$

Deuterons B_2



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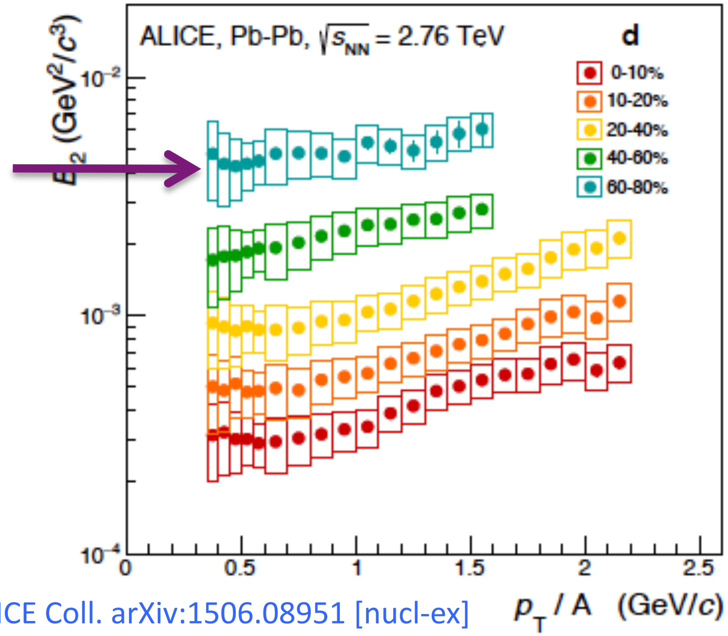
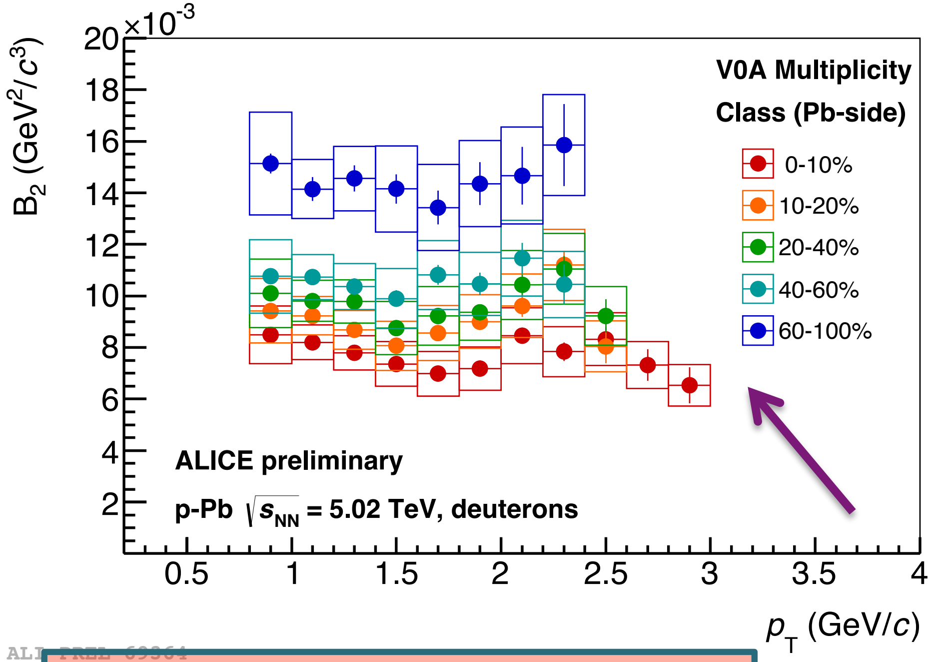
First order prediction of coalescence model:
B2 independent of p_T
➜ Observed in p-Pb and peripheral Pb-Pb



ALICE Coll. arXiv:1506.08951 [nucl-ex]

ALICE

Deuterons B_2



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First order prediction of coalescence model:
B2 independent of p_T
➜ Observed in p-Pb and peripheral Pb-Pb

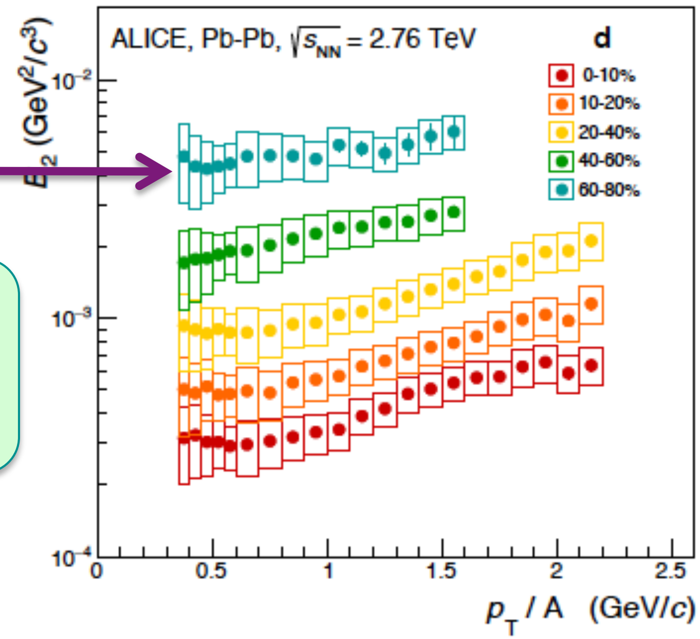
Second order prediction of coalescence model:

B2 scales like HBT radii

- decrease with centrality in Pb-Pb is explained as an increase in the source volume
- increasing with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume in HBT

$$B_2 = \frac{3\pi^{3/2}\langle C_d\rangle}{2m_T R_\perp^2(m_T)R_\parallel(m_T)}$$

R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)

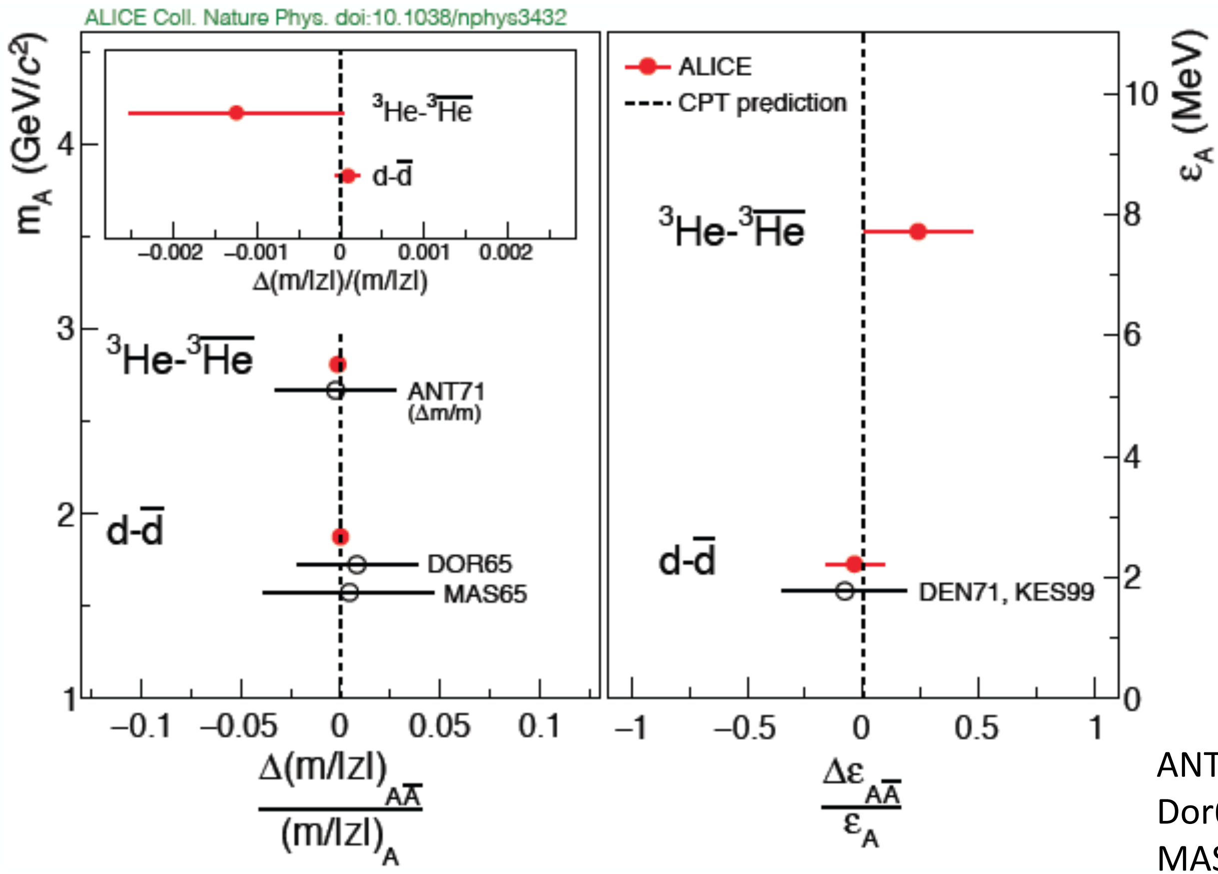


ALICE Coll. arXiv:1506.08951 [nucl-ex]

ALICE

Nuclei/anti-nuclei mass difference

Test of the CPT invariance looking at the mass difference between nuclei and anti-nuclei



This test shows that the **mass of nuclei and anti-nuclei are compatible within the** uncertainties.
The binding energies are compatible in nuclei and anti-nuclei as well.

ANT71: *Nucl. Phys. B31 (1971) 235*
Dor65: *Phys.Rev.Lett14 (1965) 1003*
MAS65: *Nuovo Cim.39 (1965) 10*
DEN71: *Nucl. Phys. B31 (1971) 253*
KES99: *Phys.Lett. A255 (1999) 221*

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Observation of the anti-α

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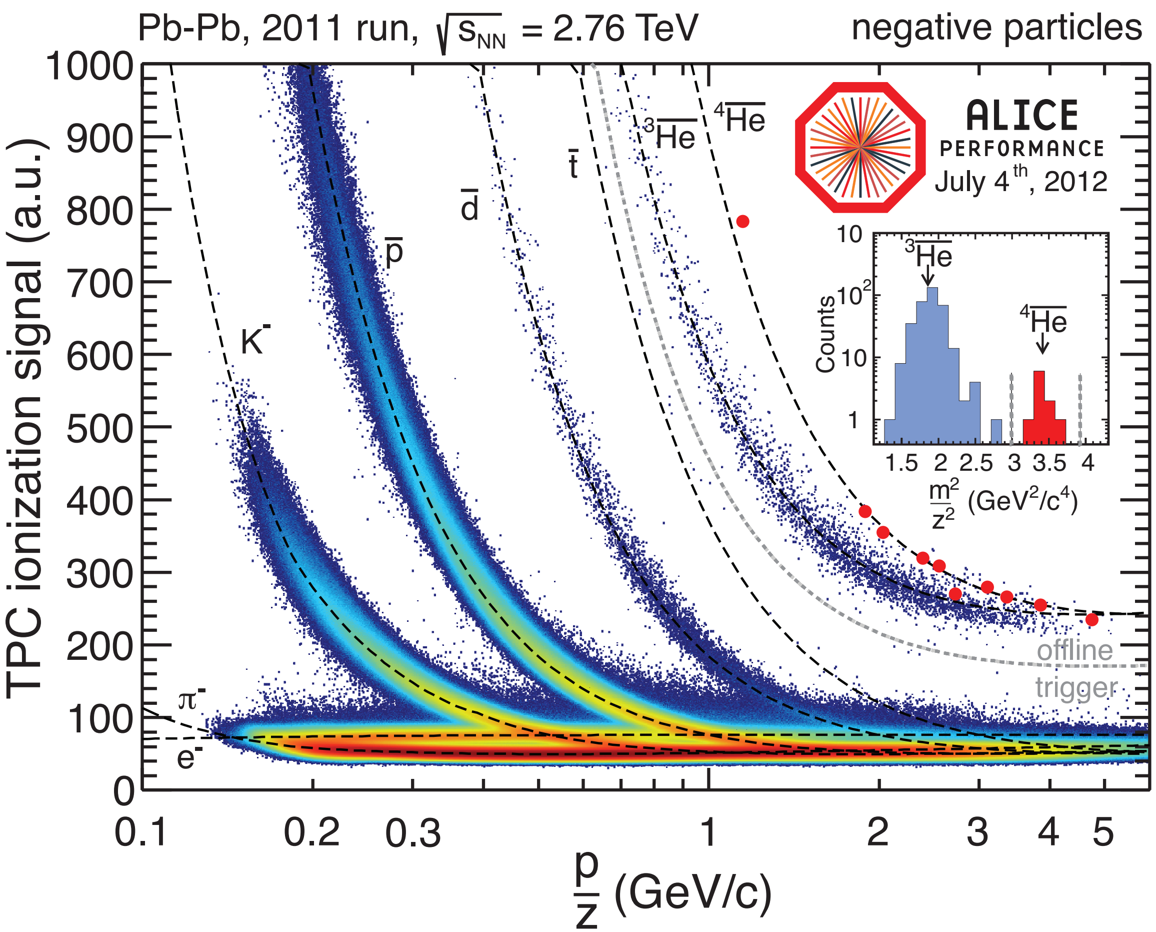


ALI-PERF-36713

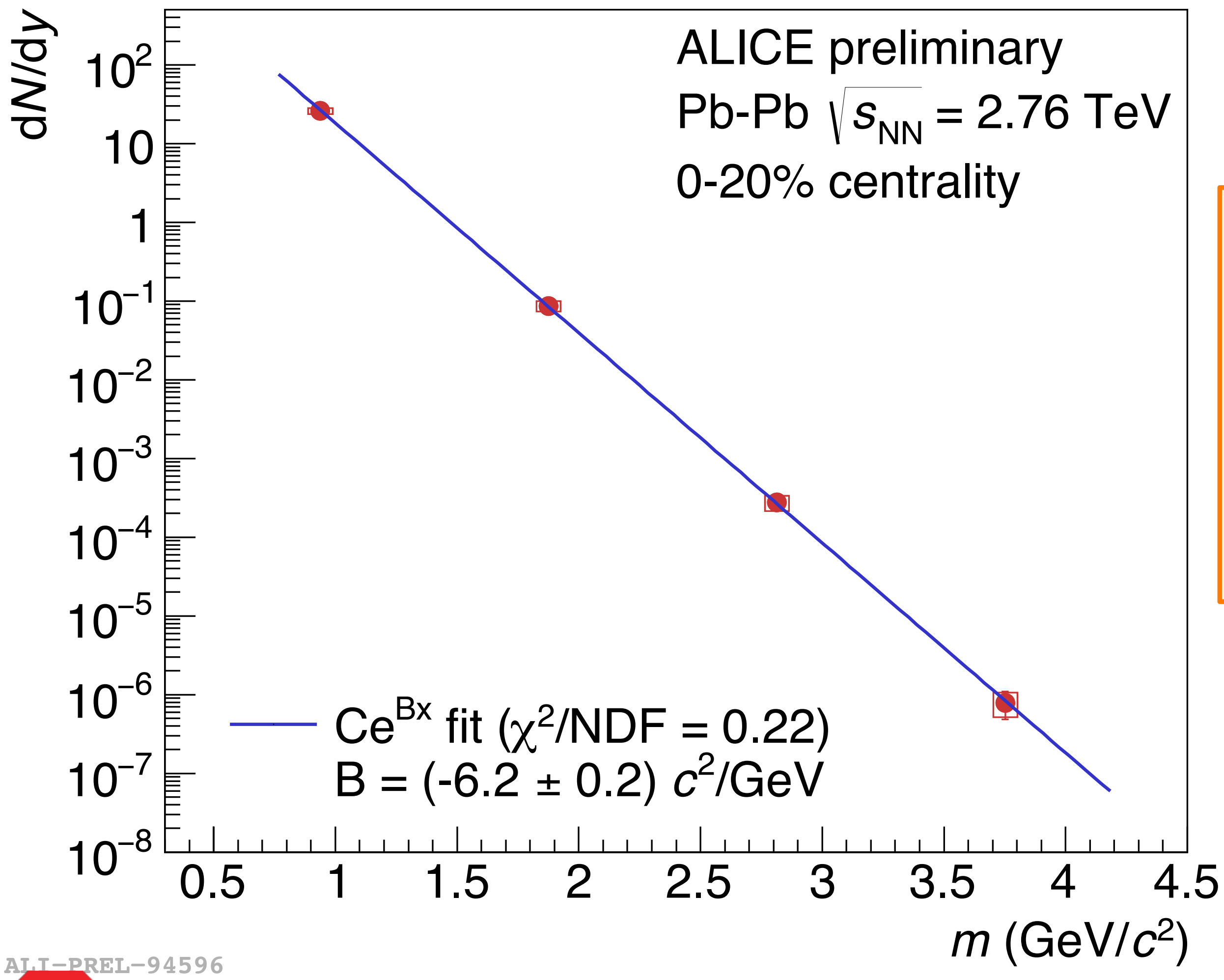
In the 2011 run data, 10 anti-α combining the PID from TPC and TOF were identified

- An offline trigger selects events with at least one ^{3}He or ^{4}He candidate.

- The statistics corresponds to about 23 million events of trigger mix (central, semicentral, min. bias)

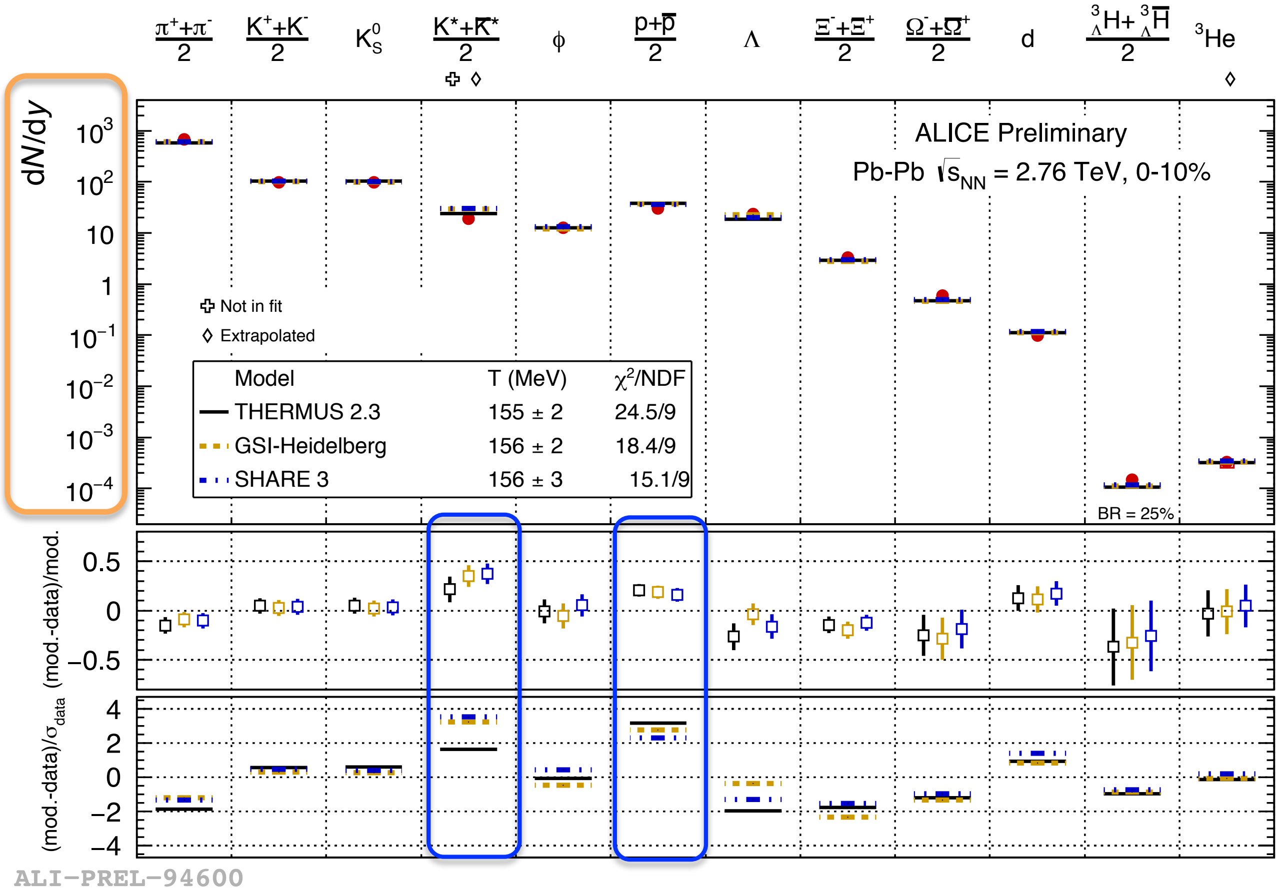
ALICE

Nuclei mass ordering in Pb-Pb



- ➢Theoretical models prediction verified with nuclei!
- ➢Each nucleon added gives a penalty factor of ~300 in the integrated yield

Thermal model fit to ALICE data



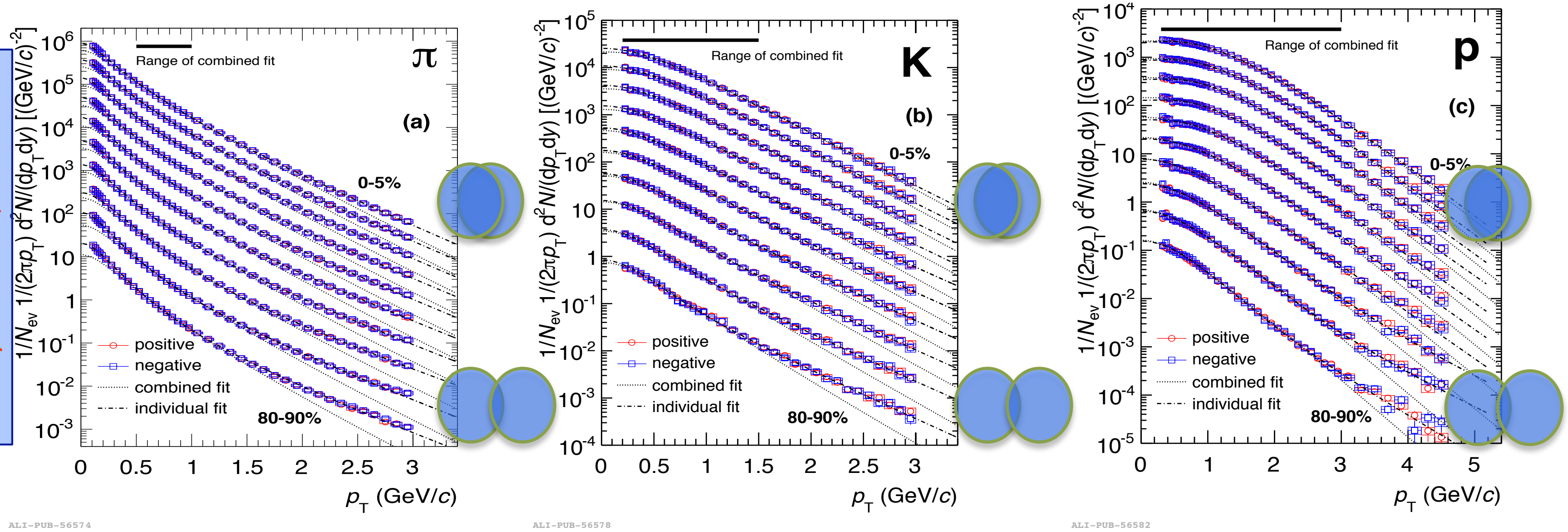
- Describes hadron production assuming **chemical equilibrium over seven order of magnitude**
- Measured absolute yields (d*N/dy*) in Pb-Pb collisions are well described by a thermal model with a temperature T=156 ± 2 MeV
- Deviations for
  - Protons: incomplete hadron spectrum, baryon annihilation in hadronic phase, ...?
  - K*0 resonance: re-scattering in the late hadronic phase?

THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

Collectivity

Invariant p_T distributions in Pb-Pb

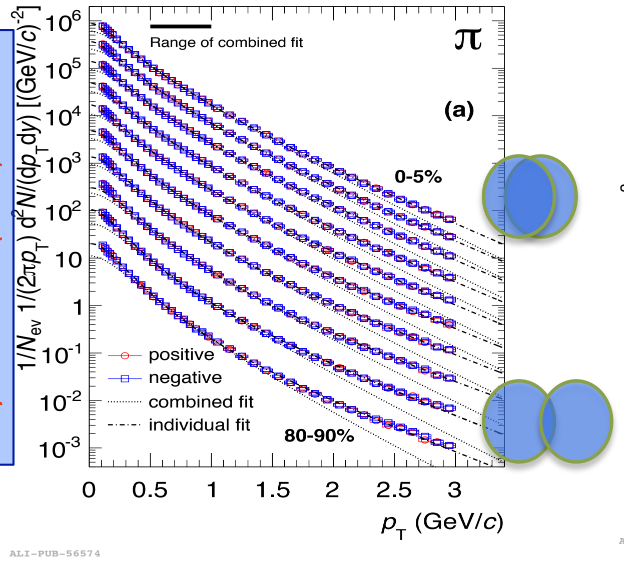
Phys. Rev. C88, 044910

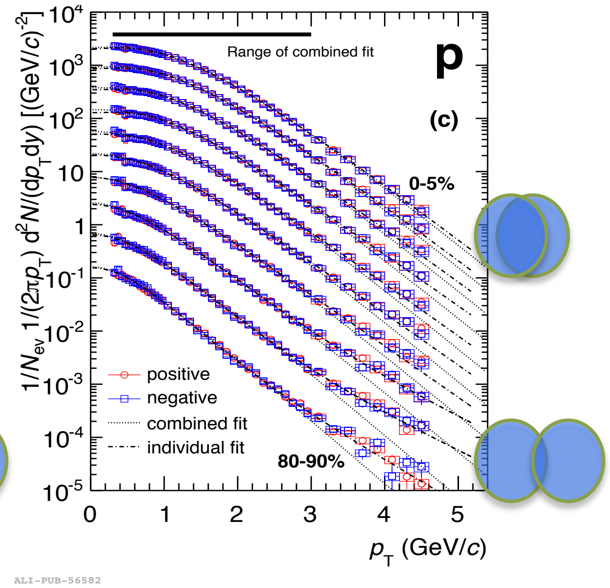


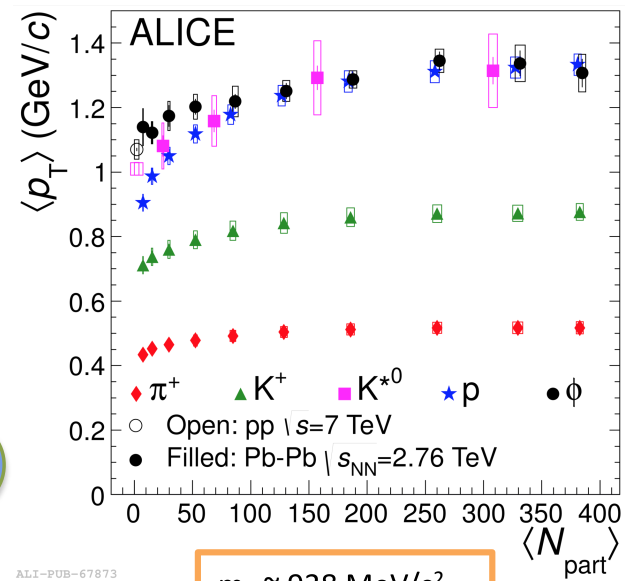
Hardening of the spectrum with increasing centrality.
Mass ordering *as* expected from hydrodynamics.

Invariant p_T distributions in Pb-Pb

Phys. Rev. C88 (2013) 044910







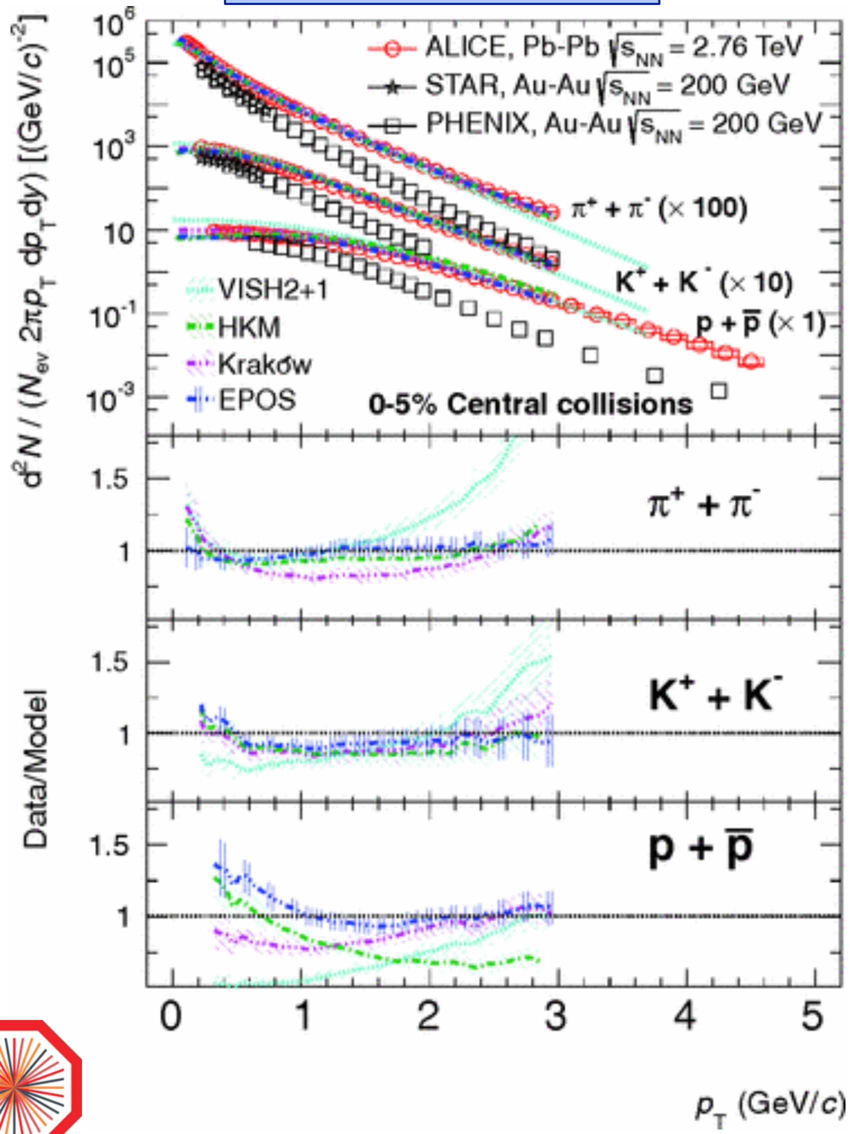
m_p ~ 938 MeV/c^2
m_Φ ~1018 MeV/c^2

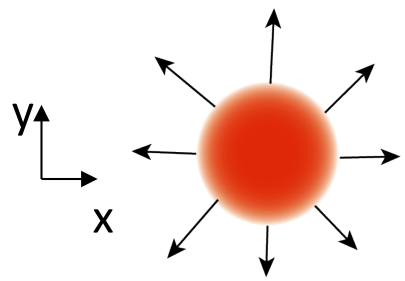
Hardening of the spectrum with increasing centrality.
***Mass ordering** as* expected from hydrodynamics.

- Particles with similar mass have similar mean p_T *in central Pb-Pb*
- Expected in presence of **collective hydrodynamic expansion**
  → Clear signature of **radial flow**

Blast-Wave fit

Phys. Rev. C88 (2013) 044910





In a thermalized system the radial expansion is driven by the pressure gradient from inside to outside. Resulting in boosted p_T spectra

✧ Hydro models describe spectra fairly well

Simultaneous **Blast-Wave model fit to** the π, K, p spectra in central Pb-Pb collisions:

- radial flow **$\langle\beta_T\rangle \approx 0.65$ ~10% larger** than at RHIC
- kinetic freeze-out temperature ***$T_{kin} \approx 95$ MeV***

ALICE

Blast-Wave fit

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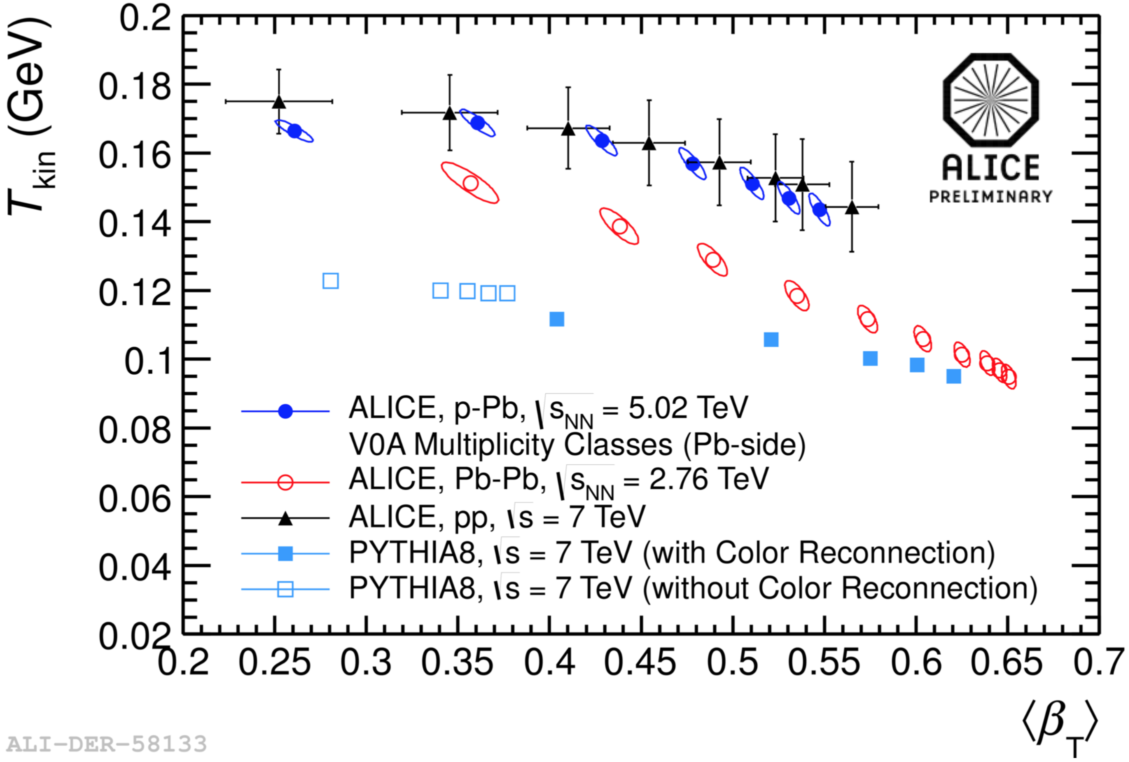
Roma- 21-25 Settembre 2015

ALICE, Phys. Lett. B 728 (2014) 25-38



In **Pb-Pb:**
-Clear evolution with centrality

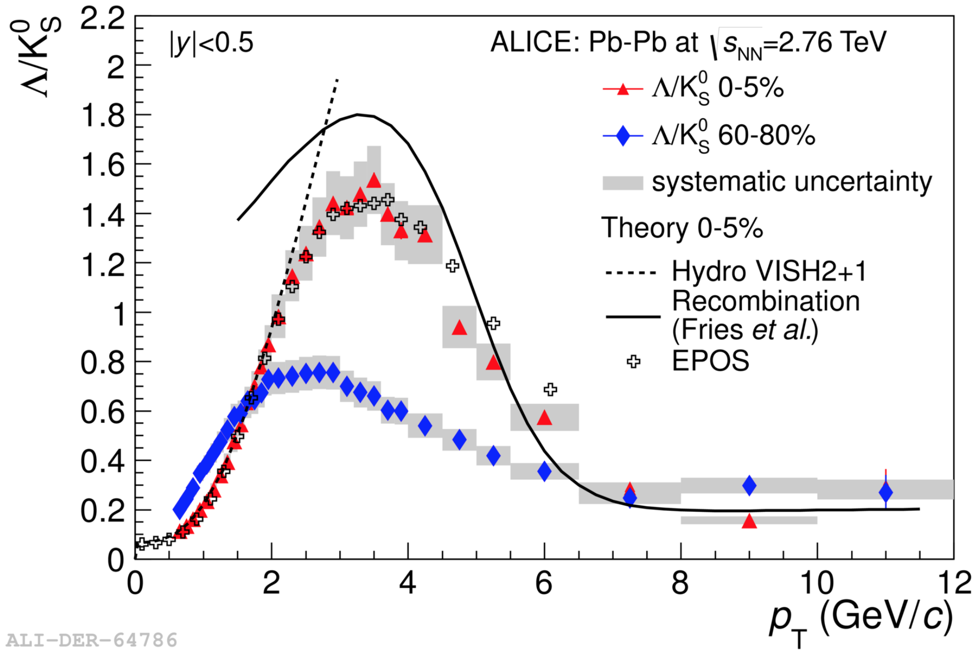
In **p-Pb:**
- qualitatively similar trend of the parameters
- Larger $<\beta_T>$ in p-Pb for similar particle multiplicity density

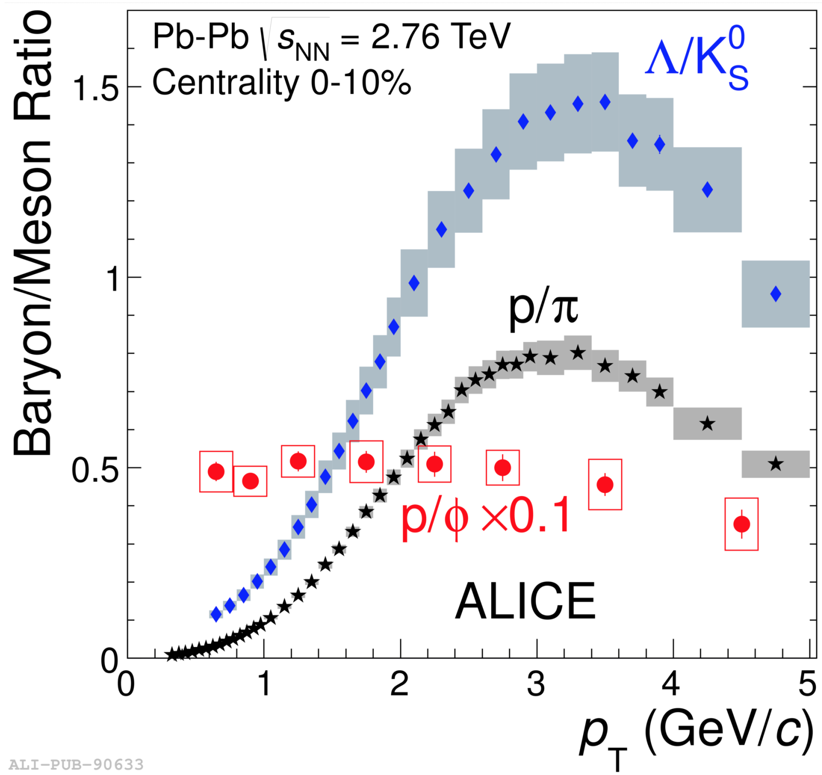
In **pp:**
- Measurements versus multiplicity follow

Qualitatively PYTHIA-CR shows a similar trend as the data
→ other final state mechanisms can mimic the effects of radial flow!

Baryon-to-meson ratio

ALICE, Phys. Lett. B 728 (2014) 25-38
ALICE, Phys. Rev. C 91 (2015) 024609





Ratio enhancement at intermediate p_T
- **Hydro** describes only the rise < 2 GeV/c
- **Recombination** overestimates the effect
- **EPOS** gives good description of the data (with **flow**)

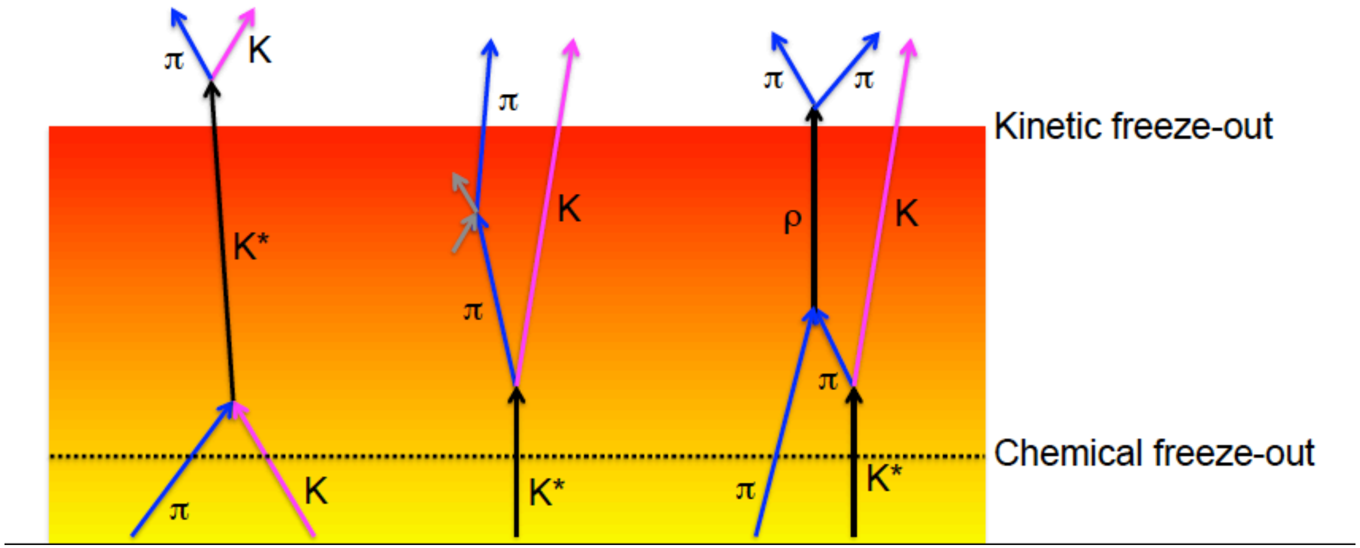
Flat p/φ ratio
→ Mass dependence of the spectral shapes (**hydro**)

Resonances

Hadronic phase

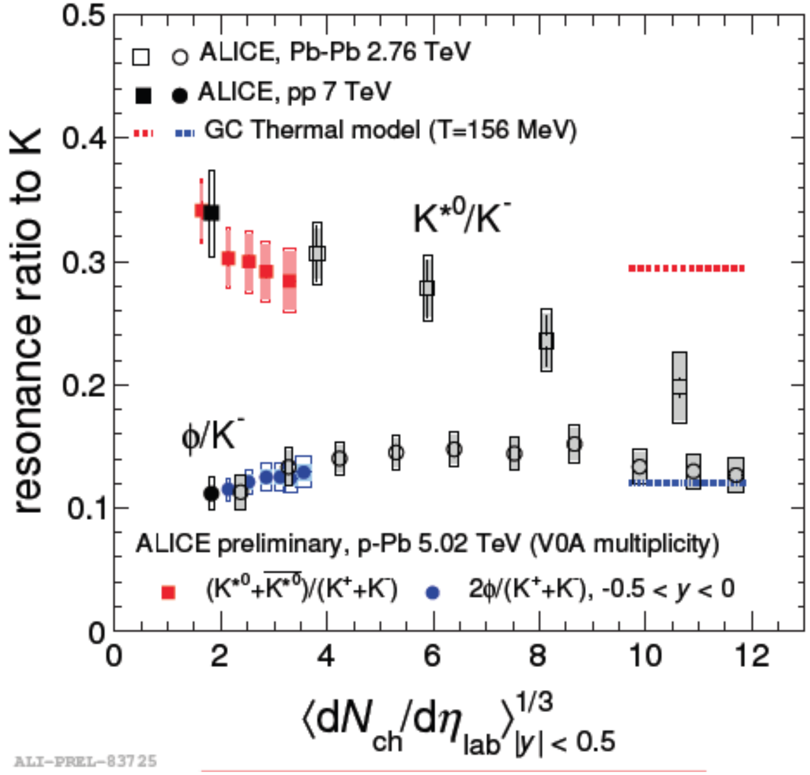
- Reconstructible resonance yields may be changed by hadronic processes after chemical freeze-out:

- Regeneration: pseudo-elastic scattering of decay products (e.g. $\pi k \rightarrow K^{*} \rightarrow \pi k$)
- Re-scattering:
  - Resonance decay products undergo elastic scattering
  - Or pseudo-elastic scattering through a difference resonance
  - Resonance not reconstructed through invariant mass



Ratios of Yields

- K^{*0}/K
  - Central Pb–Pb: significantly suppressed w.r.t. peripheral, pp, p–Pb, or thermal model
  - Consistent with the hypothesis that re-scattering is dominant over regeneration
- ϕ/K
  - No strong dependence on centrality or collision system
  - ϕ lifetime ~10 xlonger than K^{*0}, re-scattering effects not significant
  - Ratio for central Pb–Pb consistent with thermal model
- Ratios in p–Pb consistent with trend from pp to peripheral Pb–Pb



pp: ALICE, *Eur. Phys. J. C 72 2183 (2012)*
Pb–Pb: ALICE, *Phys. Rev. C 91 024609 (2015)*
Thermal Model: J. Stachel *et al., SQM 2013*

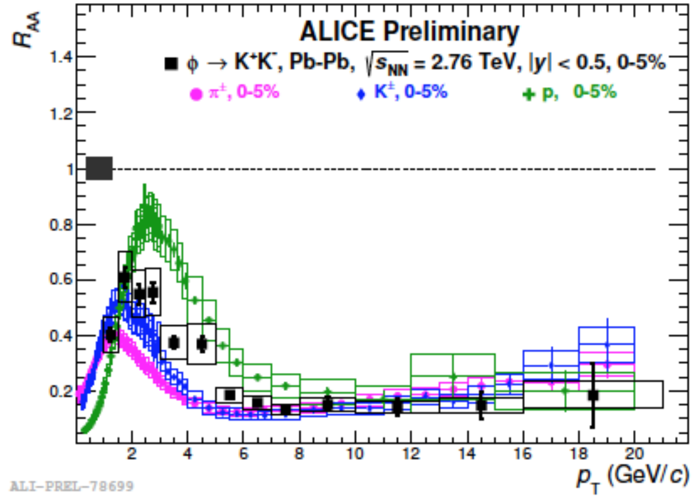
Nuclear Modification Factors

In Pb–Pb:

– Shape differences between p and ϕ due to differences in reference (pp) spectra

– Strong suppression of all hadrons at high p_T

$$R_{AA}(p_T) = \frac{\text{Yield(A–A)}}{\text{Yield(pp)} \times \langle N_{coll} \rangle}$$

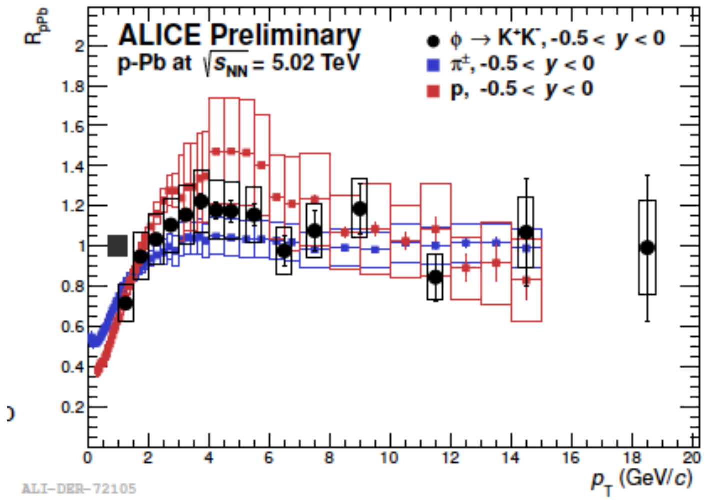


In p–Pb:

– No suppression of ϕ w.r.t. pp for p_T > 1.5 GeV/c

– Intermediate p_T: *Cronin peak for* p, smaller peak for ϕ

– Possible mass dependence or baryon/meson differences in R_{pPb}



Summary

Anti-matter measurements:

- Both coalescence and thermal model are successful in the description of particular aspects of the measurements:
  - ➢Integrated yields well described by the thermal model
  - ➢Particle ratios and coalescence parameter trends in agreement with the coalescence model predictions

Signatures of collectivity

- Hydrodynamic models successfully describe the evolution in Pb-Pb
- Suggestions for collective behaviour in small systems → more investigation

Resonance Suppression:

– Central Pb–Pb: K^{*0} suppressed (re-scattering) ϕ not suppressed (longer lifetime)
  - From K^{*0}/K^{-} ratio: lower limit on lifetime of hadronic phase: 2 fm/*c*

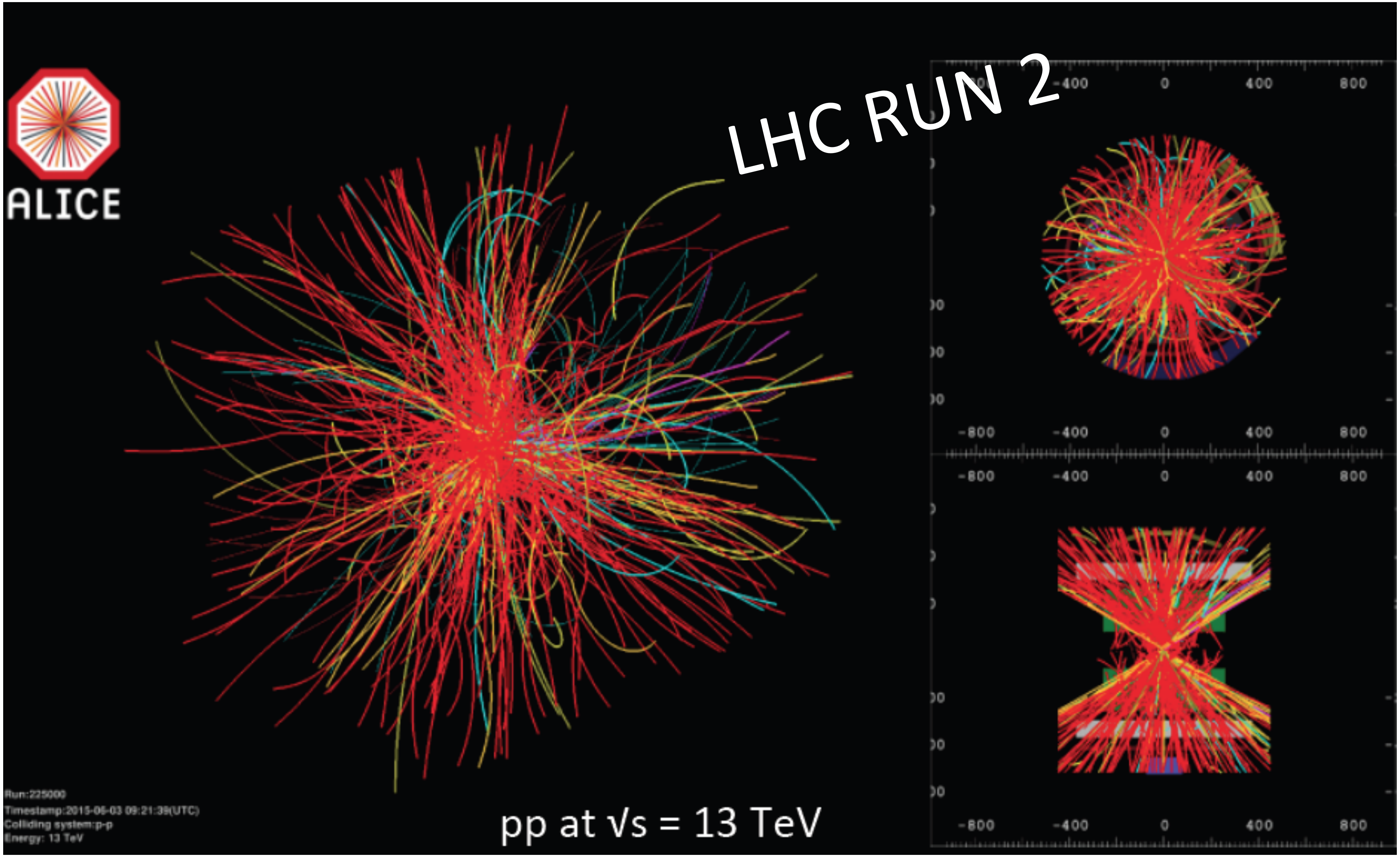
– p–Pb: K^{*0}/K and ϕ/K ratios follow trend from pp to peripheral Pb–Pb

Nuclear Modification Factors:

– High-p_T suppression observed in central Pb–Pb (RAA) but not in p–Pb
– High-p_T behavior of resonances similar to stable hadrons

ALICE

What's next?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Colliding system:p-p
Energy: 13 TeV
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