Production of light (anti-)(hyper-)nuclei in heavy-ion collisions

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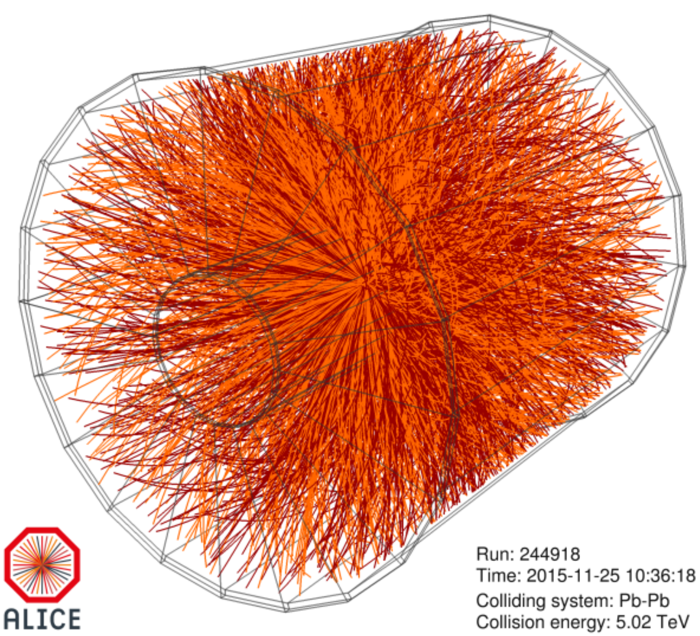
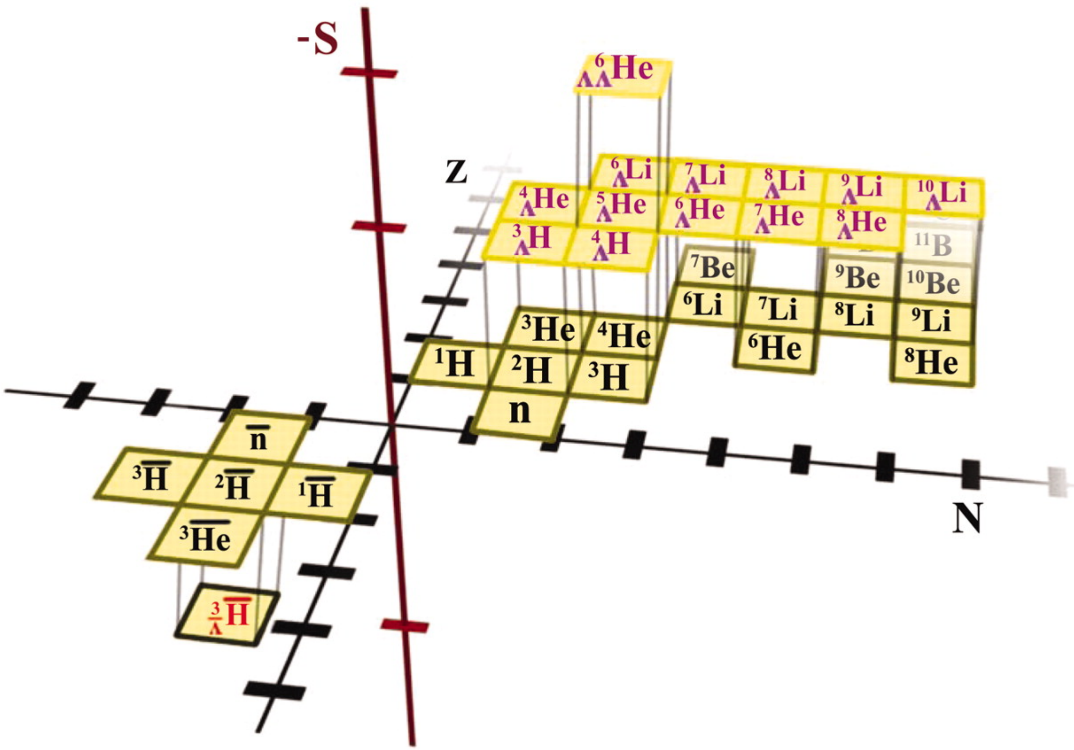


LEAP2018, Paris, March 15, 2018

Outline

- Ultra-relativistic heavy-ion collisions
- Particle production
  STAR and ALICE experiments
- Light nuclei measurements: motivation
- d, t, ^{3}He, ^{4}He measurements
- [Hypertriton $^{3}_{\Lambda}$H]
- [Exotica]
- Outlook



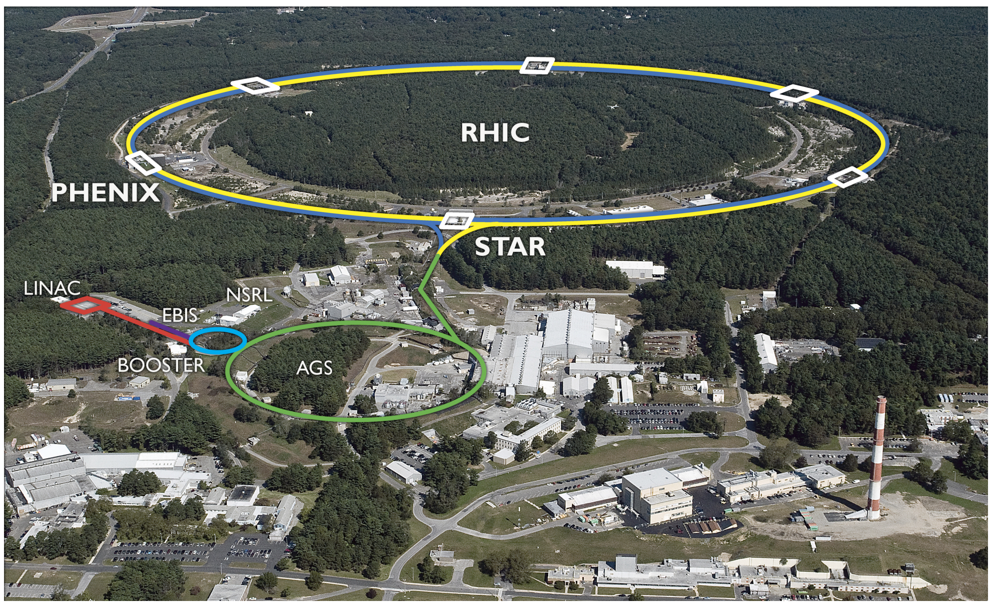
Heavy-ion collisions

Accelerate and collide large (fully stripped) ions:

Relativistic Heavy Ion Collider

RHIC

Brookhaven National Laboratory



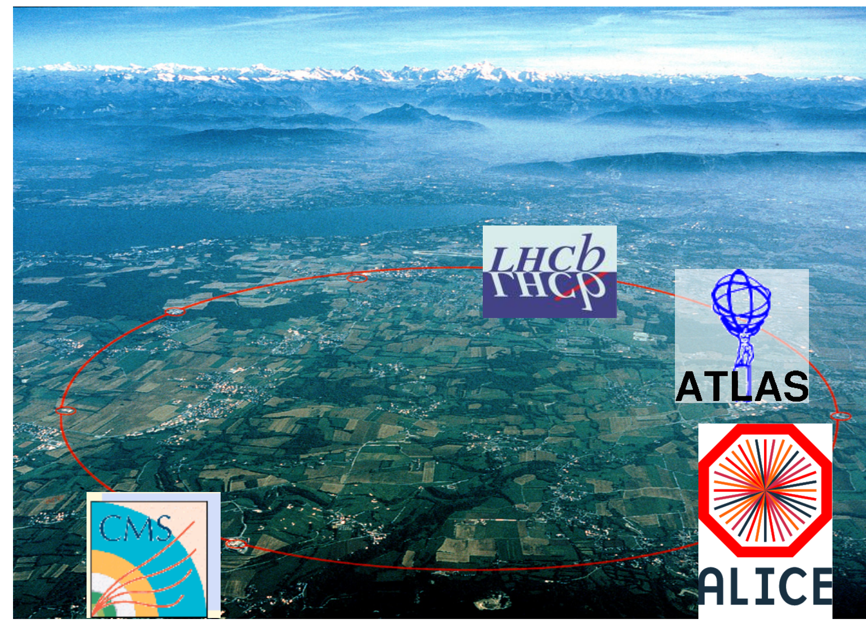
Au ions, p, d, ^{3}He

Au-Au: $\sqrt{s_{NN}}$ = 7 − 200 GeV

Large Hadron Collider

LHC

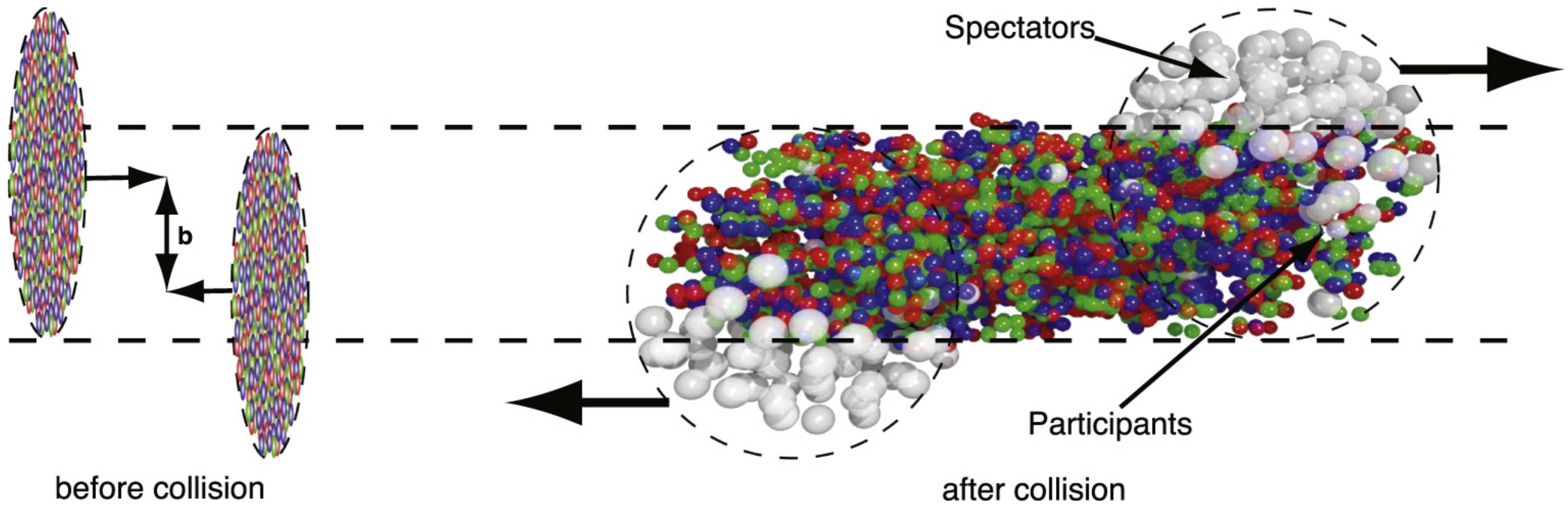
CERN, Geneva



Pb ions, p, Xe

Pb-Pb: $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

Heavy-ion collisions

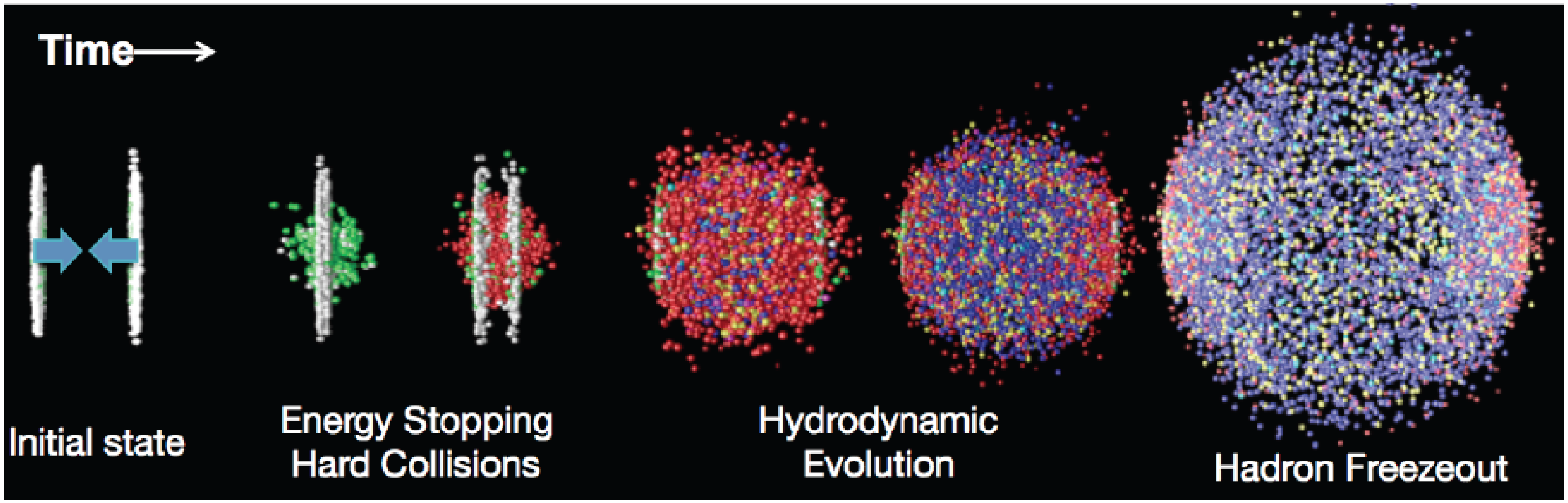


Create a small volume of matter at extremely high energy density:

- Volume ~ few 1000 fm^3
- Energy density ~ several GeV/fm^3
- Temperature of the system: few 10^{12} K ↔ Sun core: 15 x 10^6 K
  ~ 160 MeV

→ QCD matter under extreme conditions !!
→ deconfinement: transition to a Quark-Gluon Plasma

Heavy-ion collision evolution



Non-equilibrium evolution at early times:
- Gluon dominated, fast thermalization

Local thermal and chemical equilibrium: QGP
- Evolution ↔ relativistic fluid dynamics
- Expansion, dilution, cooling

Chemical freeze-out:
- Below a critical temperature, hadrons are formed
- Inelastic collisions cease → particle yields

Kinetic freeze-out:
- Elastic collisions cease → spectra

Therm. time ~ O(0.1 fm/c)
T_0 ~ O(500 MeV)

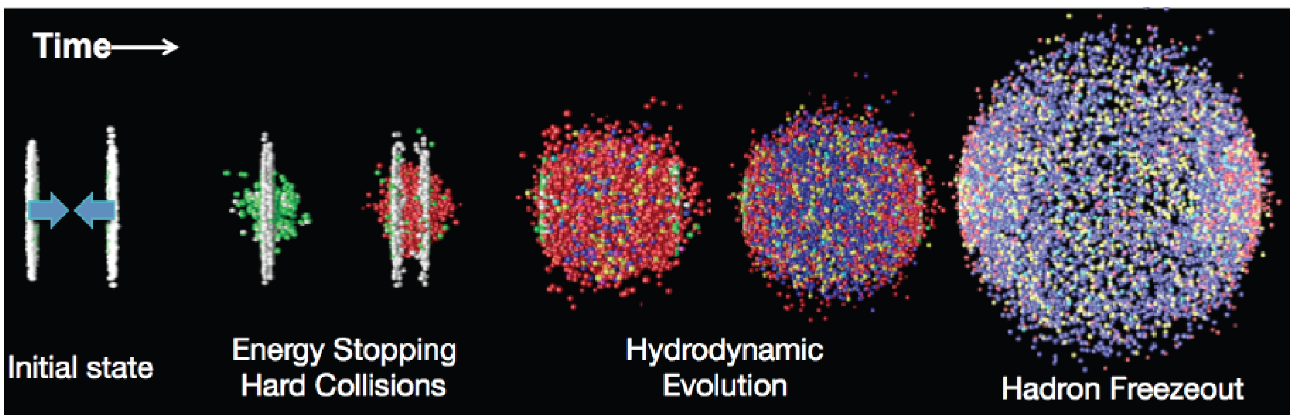
Homog. Volume ~ 5000 fm^3
Decoupling time ~ 10 fm/c
10^{-23}-10^{-22} s

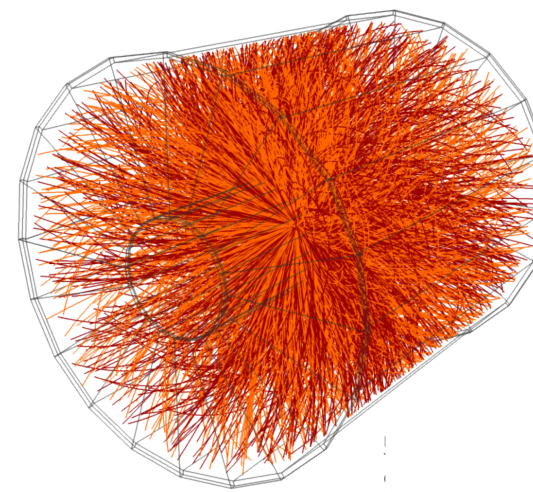
Particle production in heavy-ion collisions

One Pb-Pb collision at the LHC
Total energy in c.m.s. : 1.04 PeV !

~ 10^{-22} s

~ 5000 $fm^3 < 10^{-41}$ m^3





Thermalization
equilibrium is established
(t < 1 fm/*c*)

Expansion and cooling:
(t < 10-15 fm/*c*)

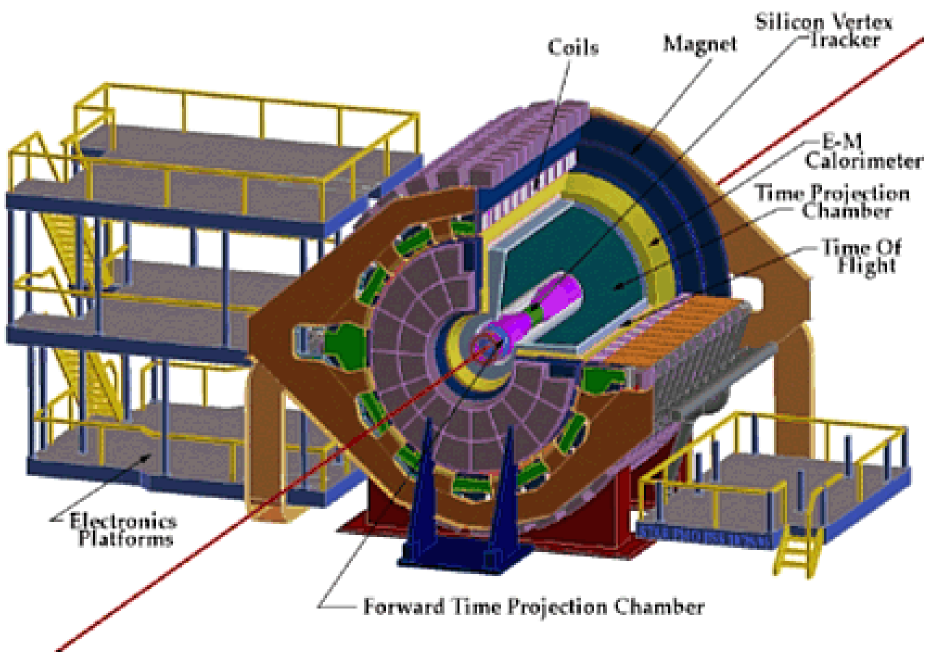
Chemical freeze-out
(particle yields)
Kinetic freeze-out
(particle spectra)

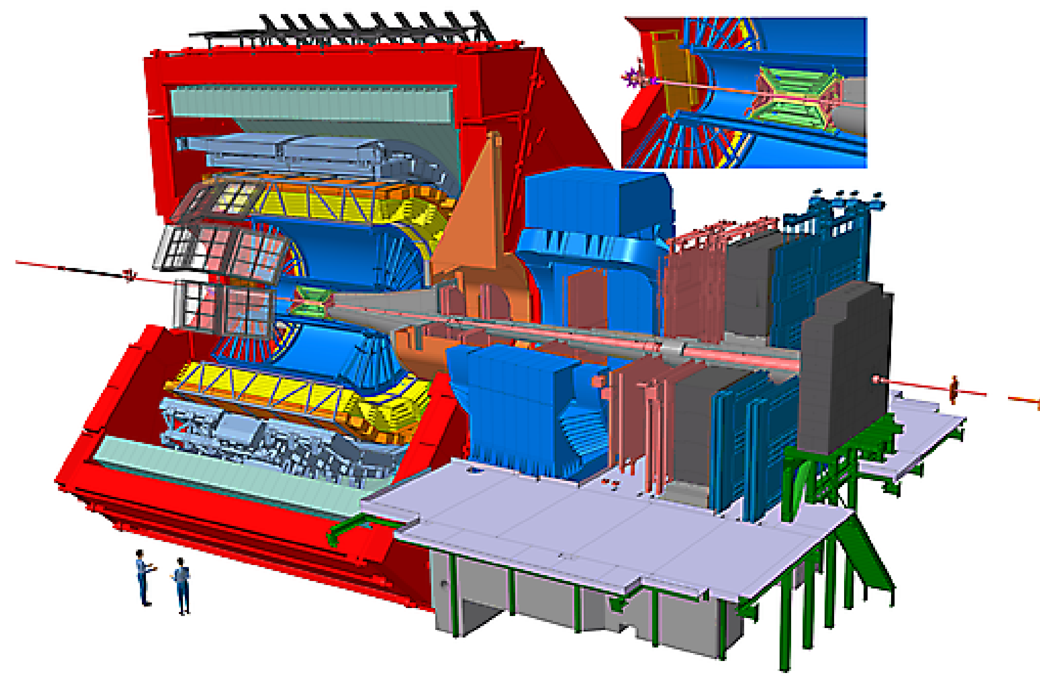
Thousands of particles

Heavy-ion experiments

STAR at RHIC

ALICE at the LHC

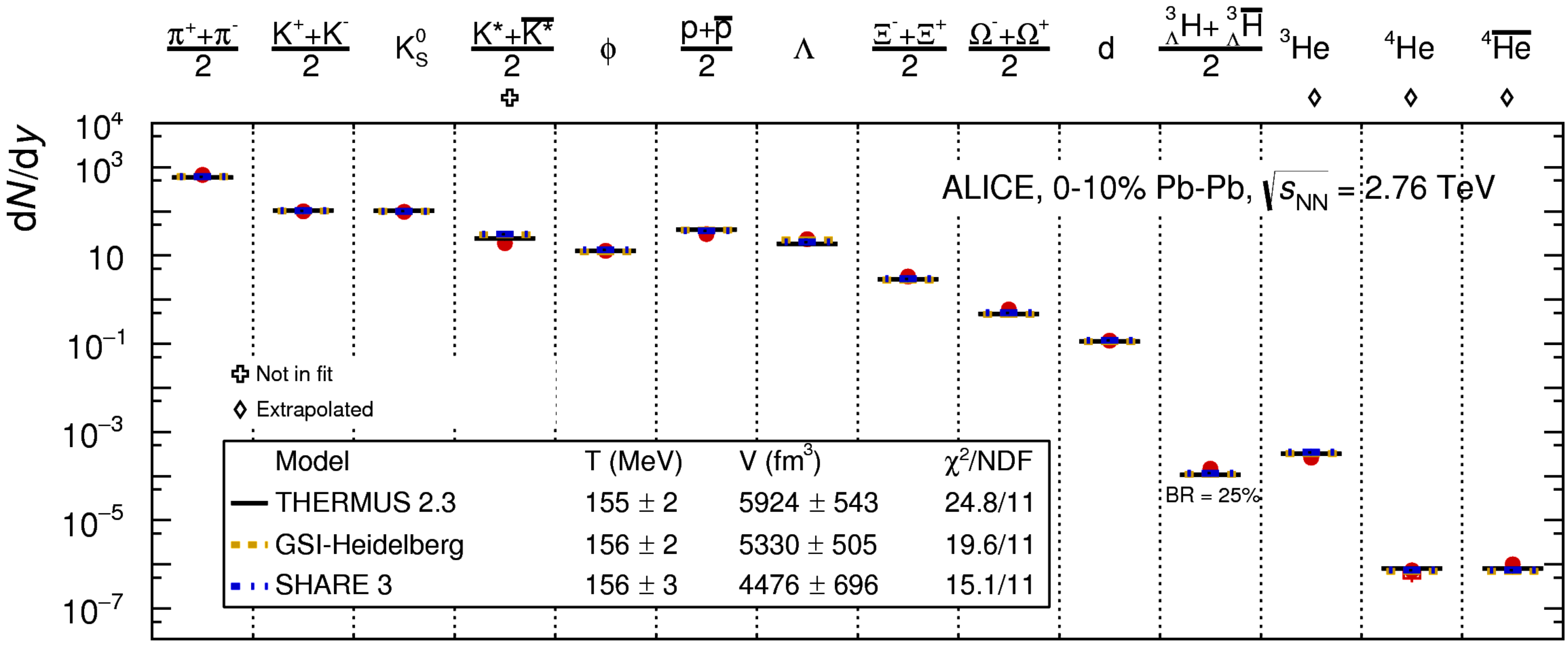




Identified particle yields

- Large data statistics
- Excellent detectors for particle identification

π K K^0_S K* Φ p Λ Ξ Ω d $^3_\Lambda H$ ^3He ^4He $^4\overline{He}$



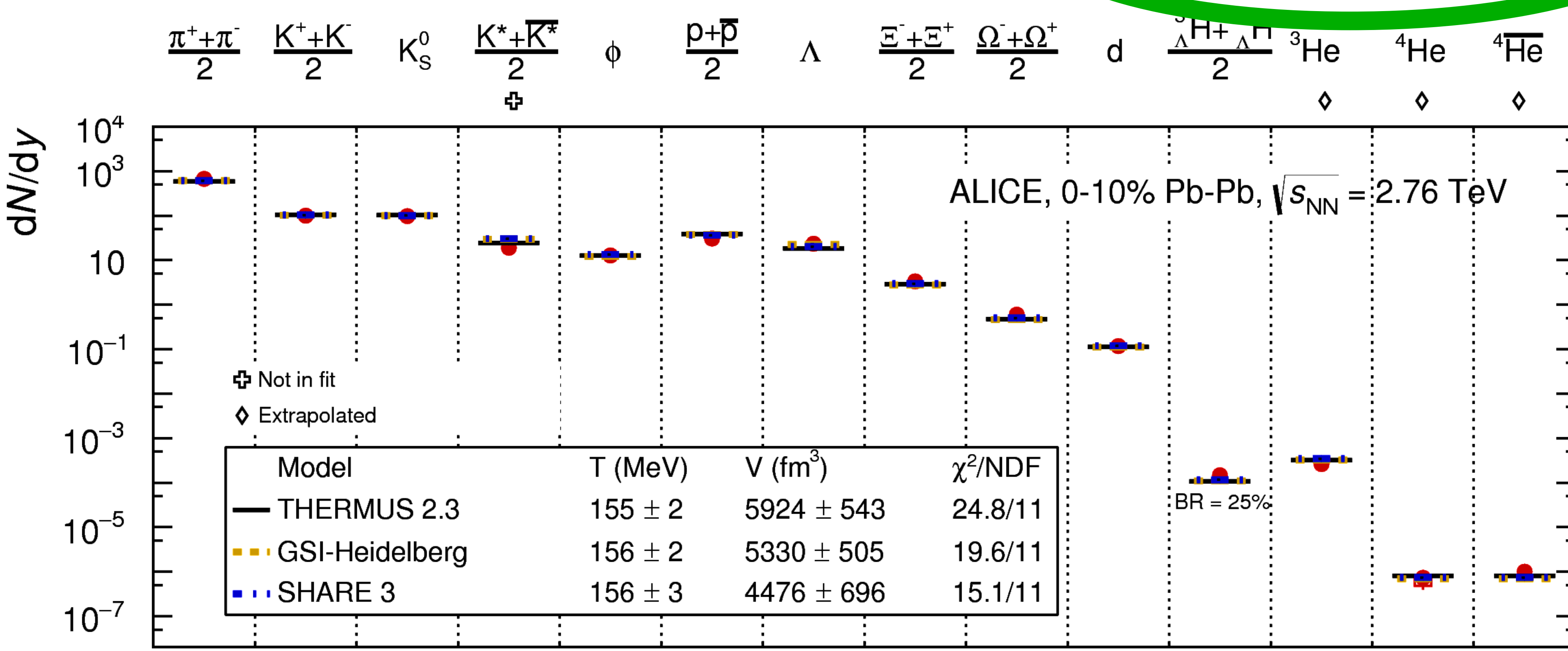
Nucl.Phys. A971 (2018) 1-20

Identified particle yields

- Large data statistics
- Excellent detectors for particle identification

Light nuclei

π K K^0_S K* Φ p Λ Ξ Ω d ${}^3_\Lambda H$ ${}^3He$ ${}^4He$ ${}^4\overline{He}$



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Light nuclei measurements: motivation

Light nuclei and anti-nuclei:

Proton, deuteron, triton, ^{3}He, ^{4}He

Hyper-triton $^{3}_{\Lambda}He$

+ anti-particles

- Study their production mechanism
  - ➔ Test model predictions, e.g. coalescence or thermal model
  - ➔ Dependence on collision system (AA, pp, pA)
- Search for rarely produced anti- and hyper-matter
- Measure their properties (example: $^{3}_{\Lambda}He$ lifetime)
- Explore QCD inspired model predictions for (unusual) multi-baryon states

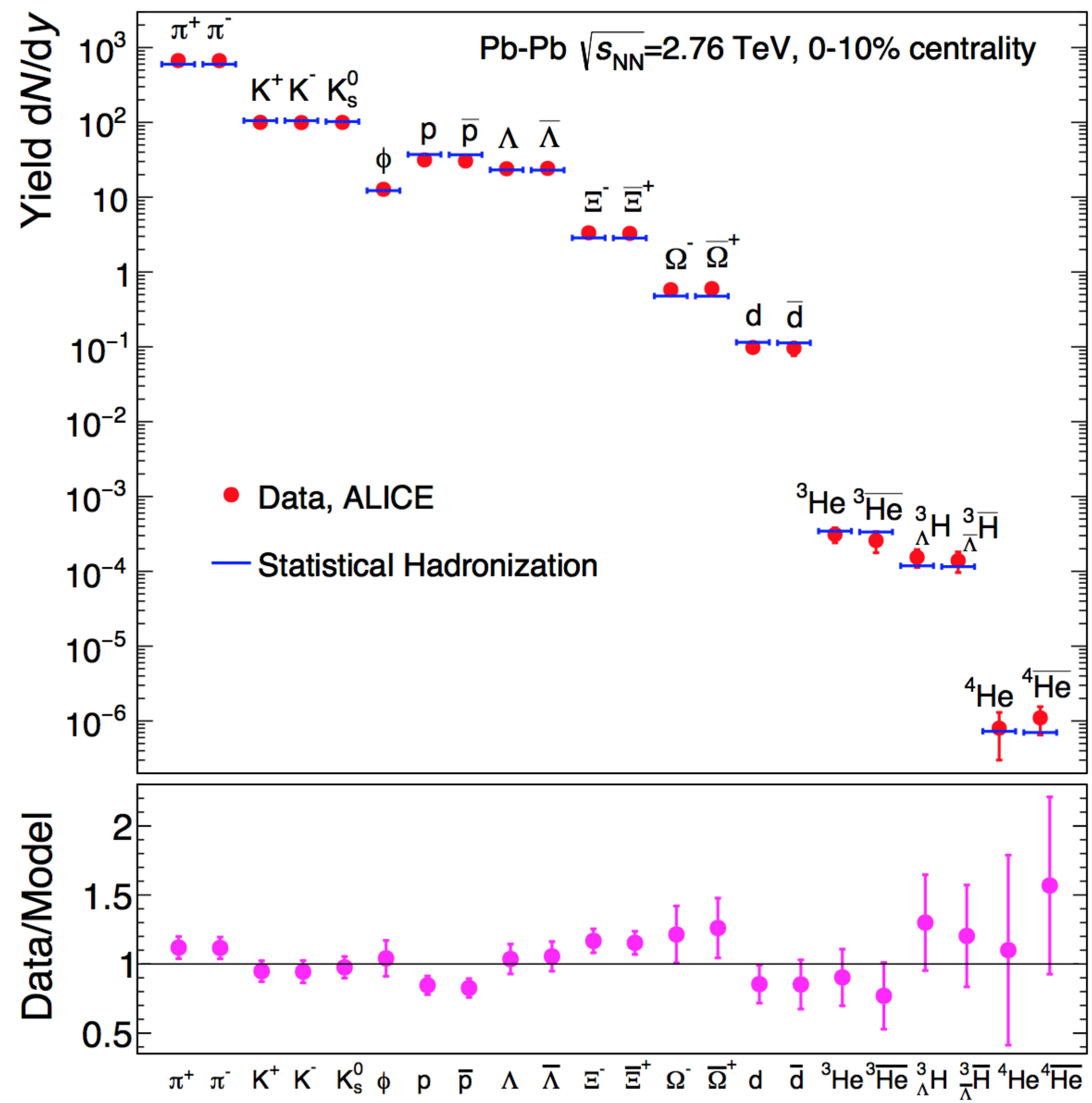
Production: statistical thermal model

Andronic, Braun-Munzinger-Stachel, Stöcker
PLB 697, 203 (2011)

Thermodynamic approach to particle production in heavy-ion collisions

Thermal production of particles at chemical freeze-out, T_{chem} → determines particle yields

No information on microscopic processes



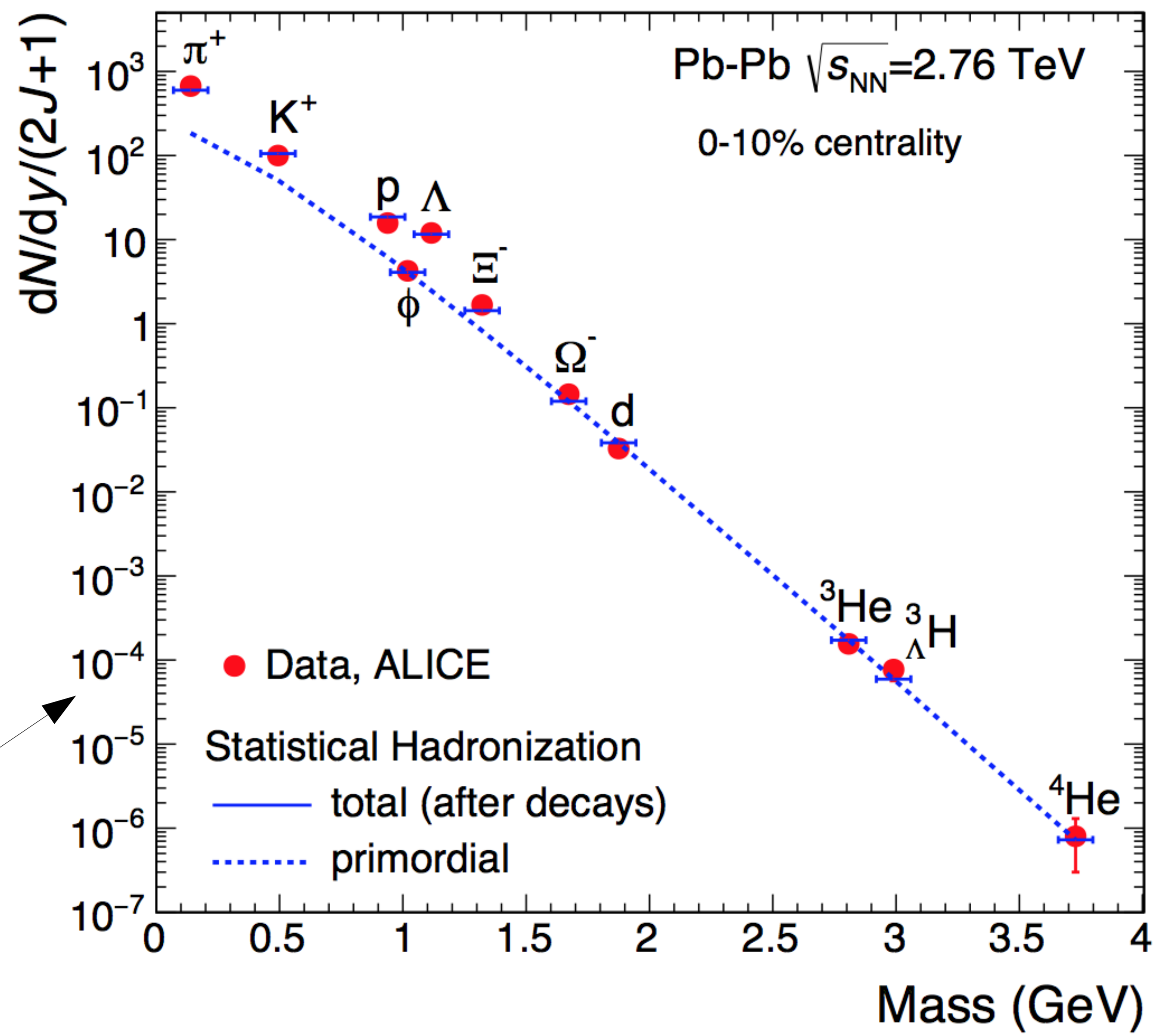
Andronic, Braun-Munzinger, Redlich, Stachel arXiv: 1710.09425

Production: statistical thermal model

Exponential dependence of the yield $\propto e^{(-M\, Tchem)}$

(Hyper-)nuclei very sensitive to T_{chem} because of their large mass M

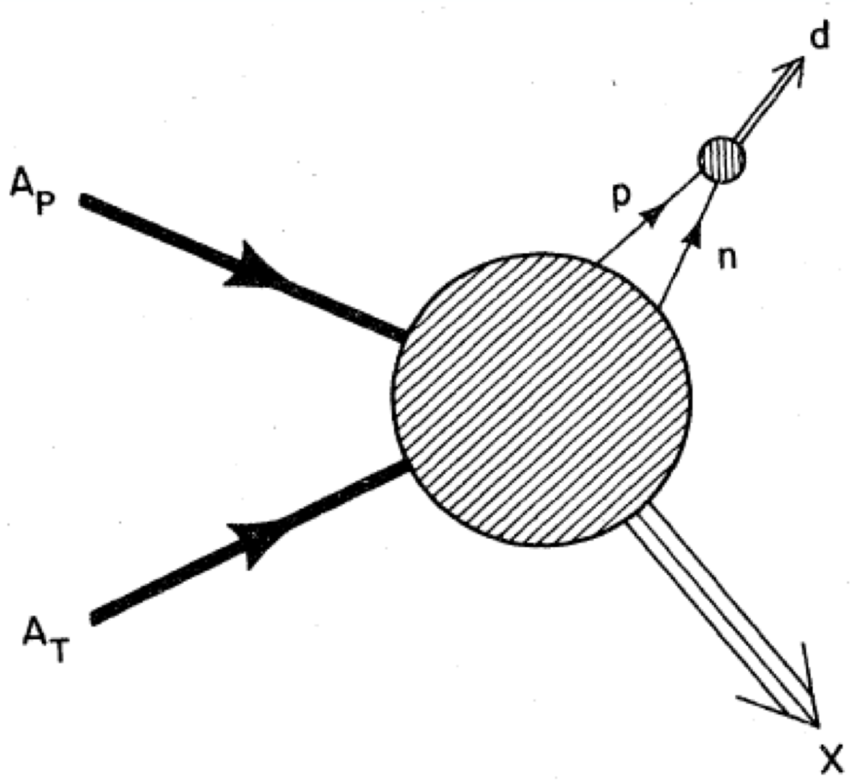
Measured hadron abundances devided by the spin degeneracy factor (2J+1)



Andronic, Braun-Munzinger, Redlich, Stachel arXiv: 1710.09425

Production: coalescence

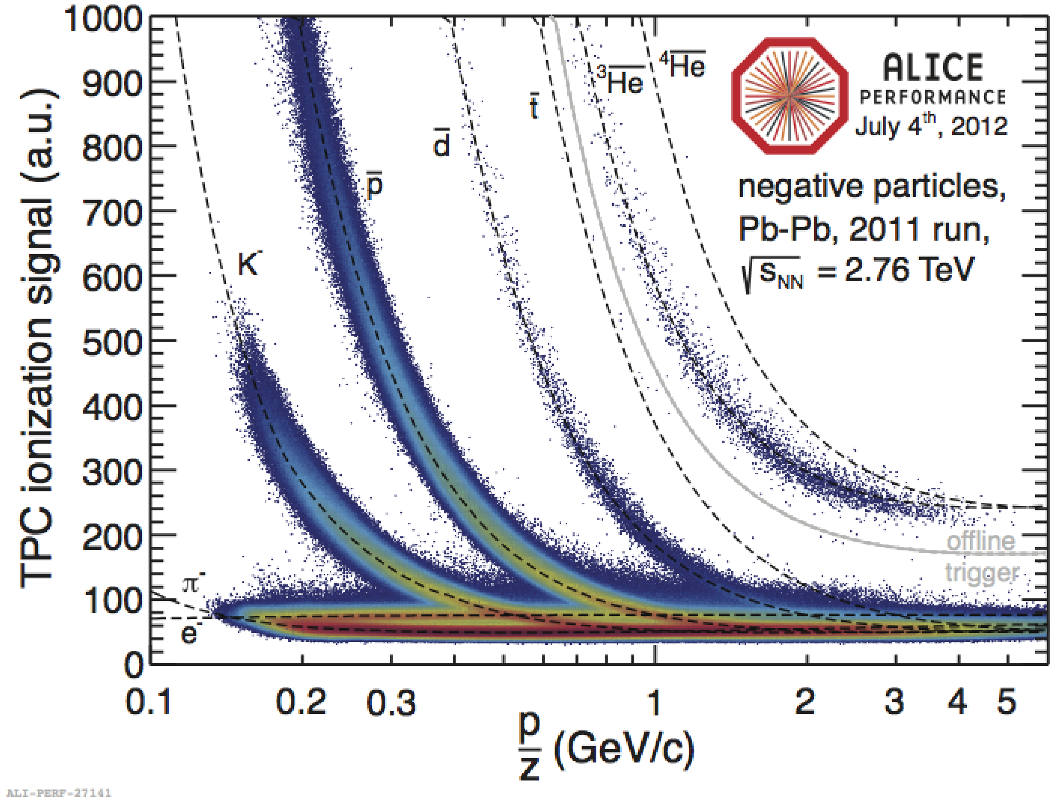
J. I. Kapusta, PRC21, 1301 (1980)



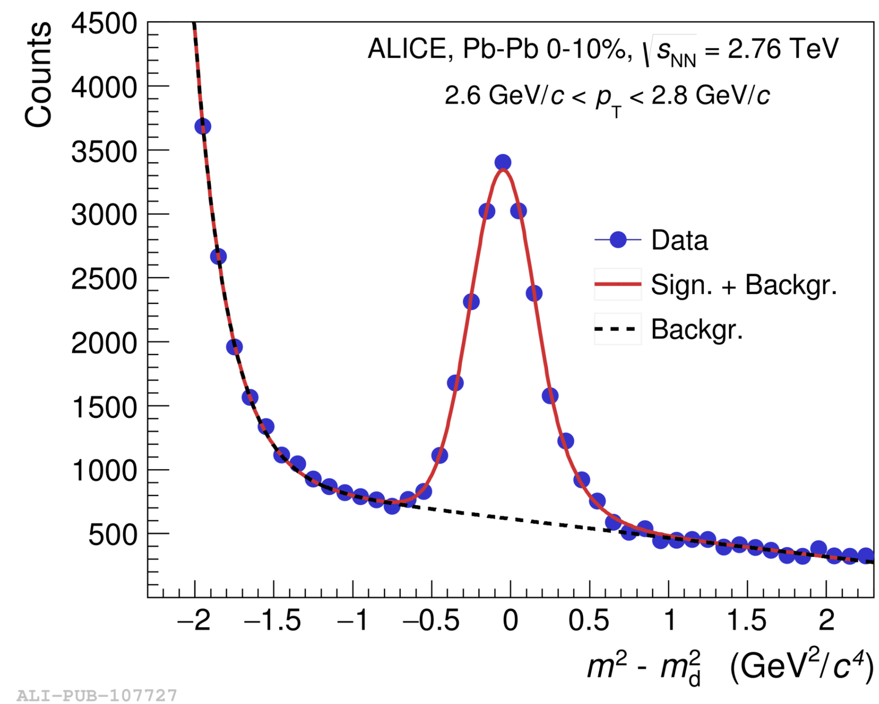
- Nuclei are formed by protons and neutrons which are nearby in space and have similar velocities (after kinetic freeze-out)
- Produced nuclei can break apart, and be eventually formed by final state coalescence
- Original idea rather simplistic. More elaborate ideas being worked on

Detection of light (anti-)nuclei

Time Projection Chamber (TPC)



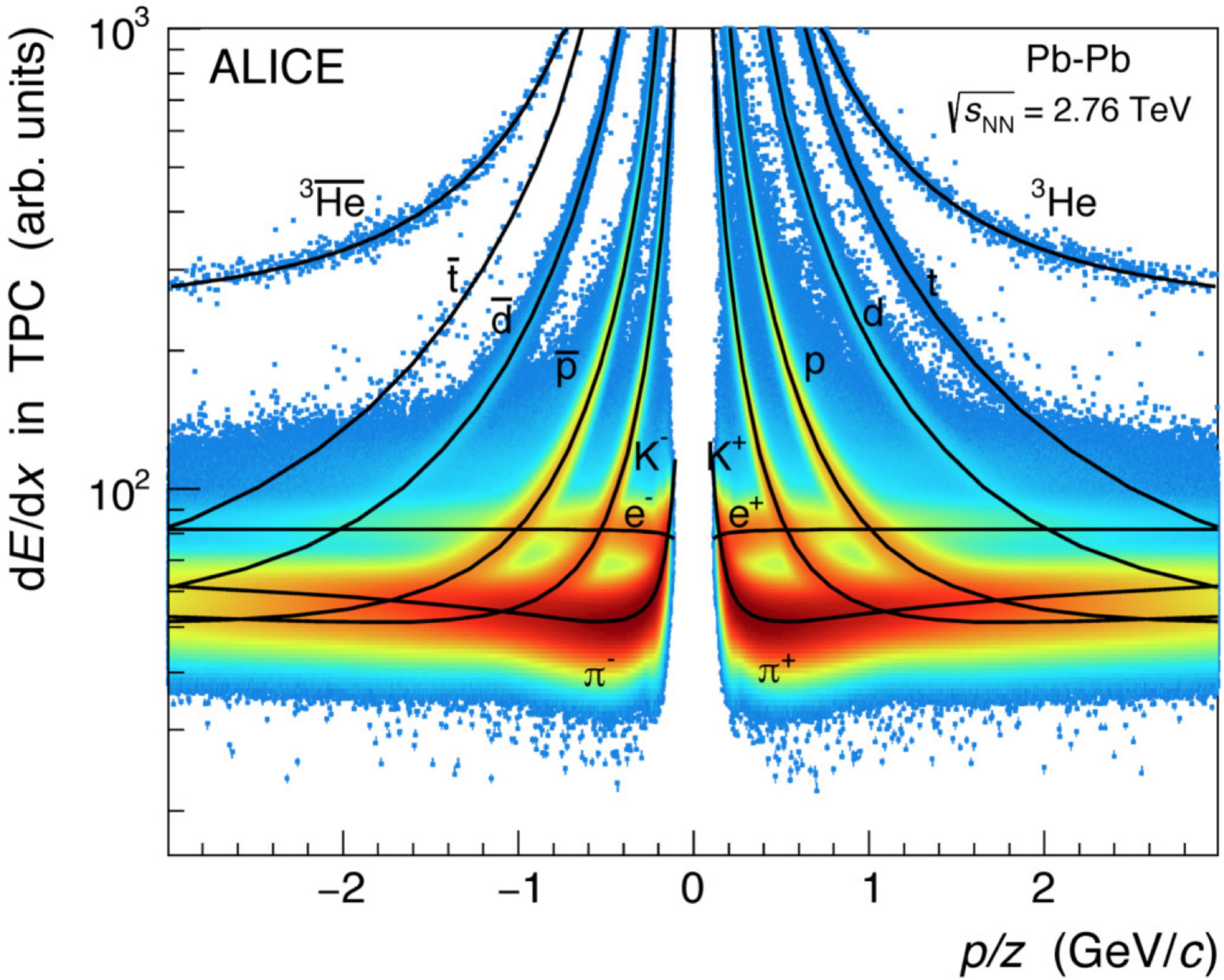
Time-Of-Flight detector (TOF)



Low momenta: identification via specific energy loss dE/dx by particles in the gas of the TPC

High momenta: velocity measurement with TOF is used to calculate the m^2 distribution

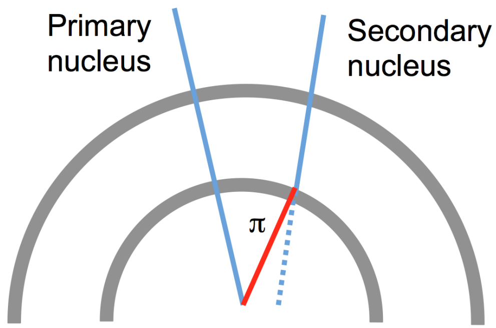
Time Projection Chamber: dE/dx

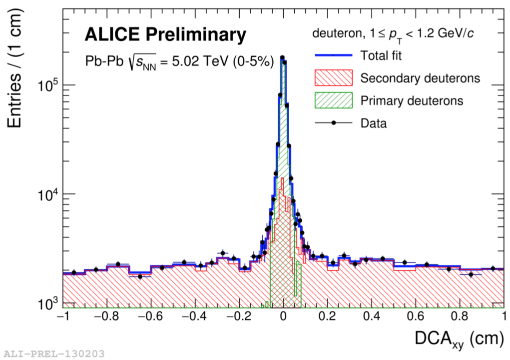


Phys.Rev. C93 (2016) 024917

Reconstruction issues

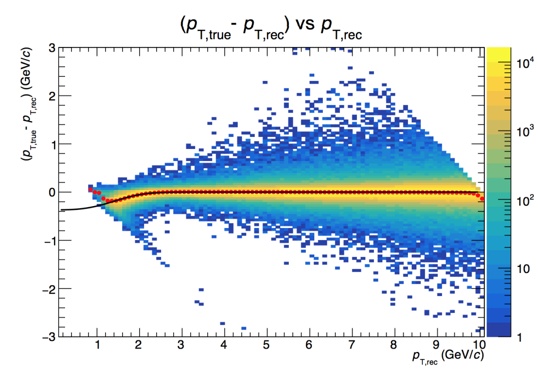
- **Absorption** of anti-matter in detector material
- **Secondary nuclei** emitted by spallation from the detector material
  - Impact parameter





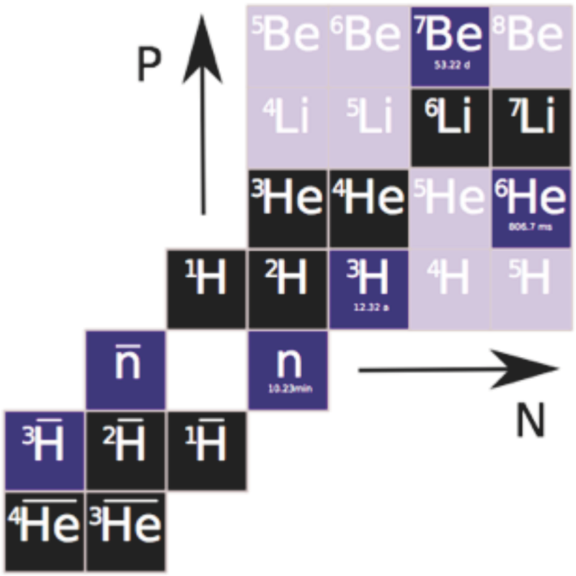
- Considerable **energy loss** of the heavy particles in the detector, and lack of correction for it

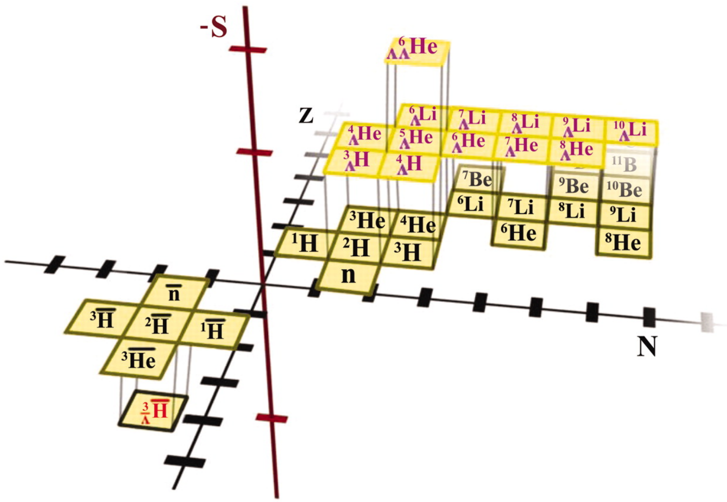
  Energy loss corresponds to slowing down of the particle along the trajectory
- Z=2 not properly considered in the energy loss



Results

- Deuteron, tritium, ^{3}He
  - Spectra
  - Nuclei and anti-nuclei production yields
  - Mass difference between nuclei and anti-nuclei
- ^{4}He: α and $\bar{\alpha}$ particles
  - Mass dependence of yields
- Coalescence parameters
- [Hyper-triton, its lifetime]
- [Exotica]



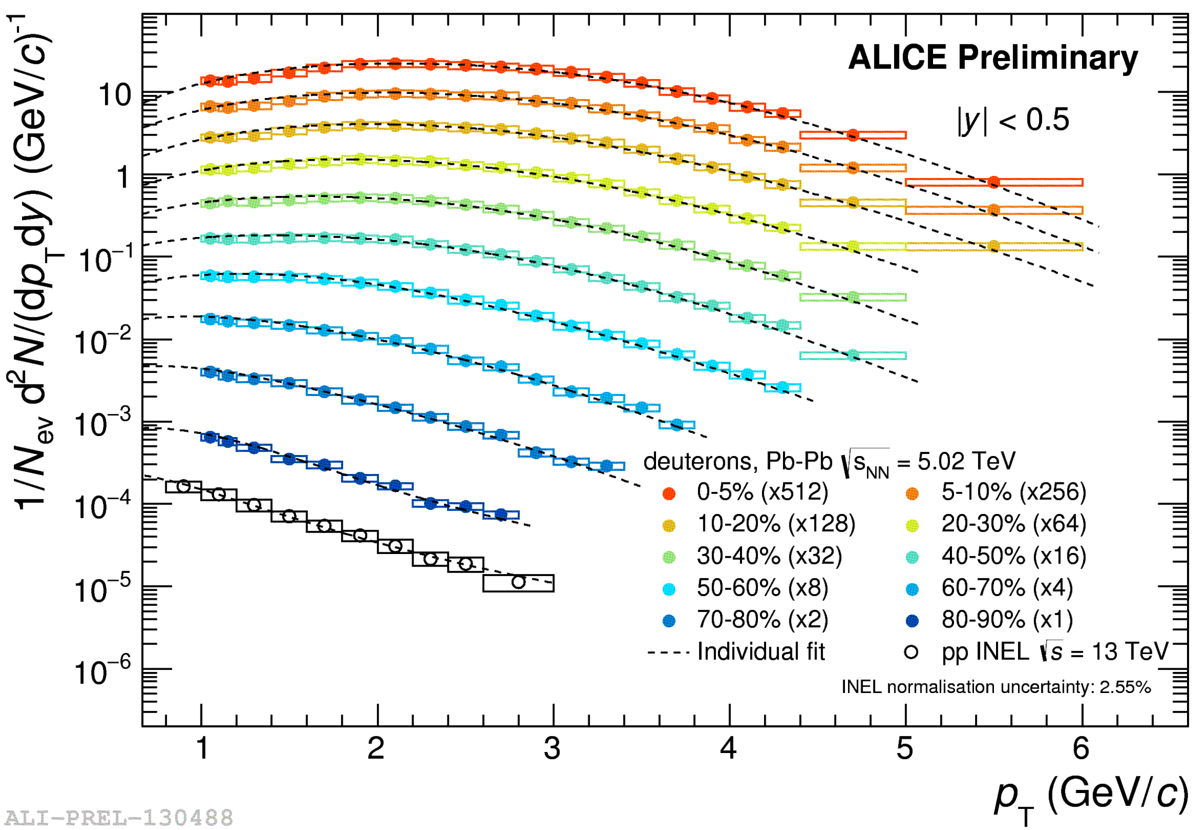


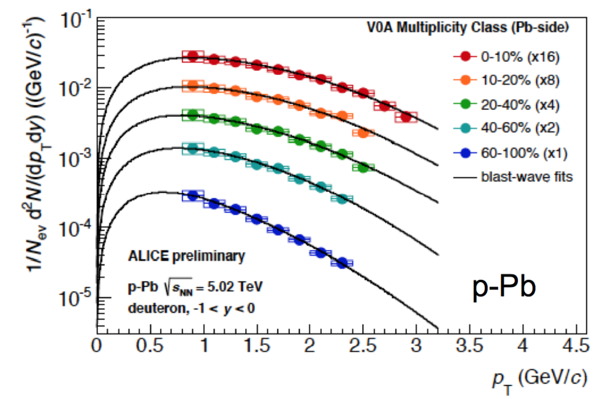
Deuteron and anti-deuteron spectra

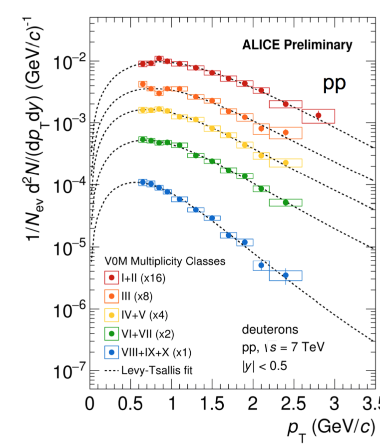
Transverse momentum spectra:

“harder” with increasing centrality of the collision (Pb-Pb, p-Pb)

→ signature of radial flow, due to the collective expansion of the system



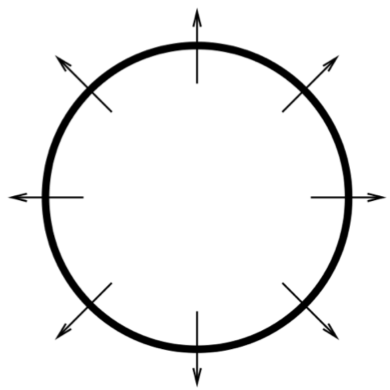




ALICE-PUBLIC-2017-006

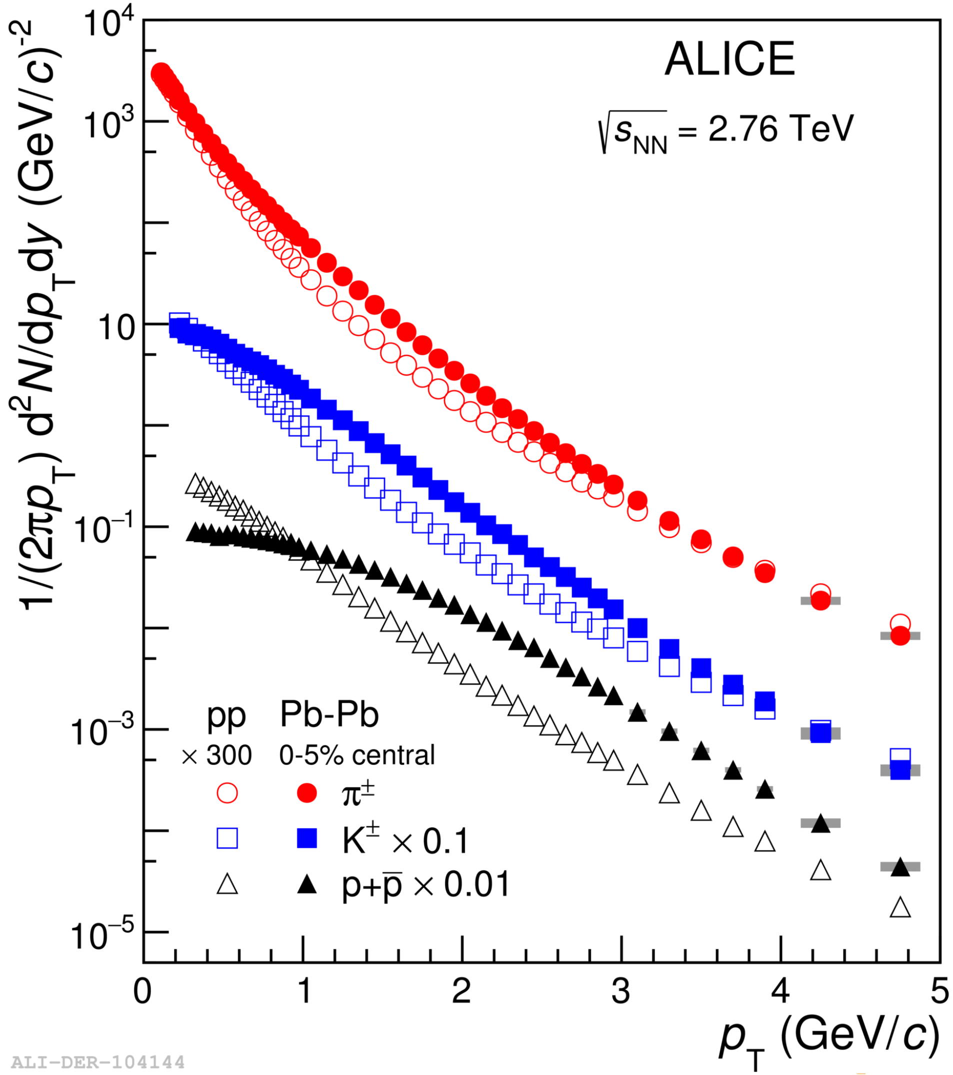
Phys.Rev. C97 (2018) no.2, 024615

Radial expansion



Internal pressure gradient → fluid velocity in radial direction
Depends on bulk viscosity ζ(T)

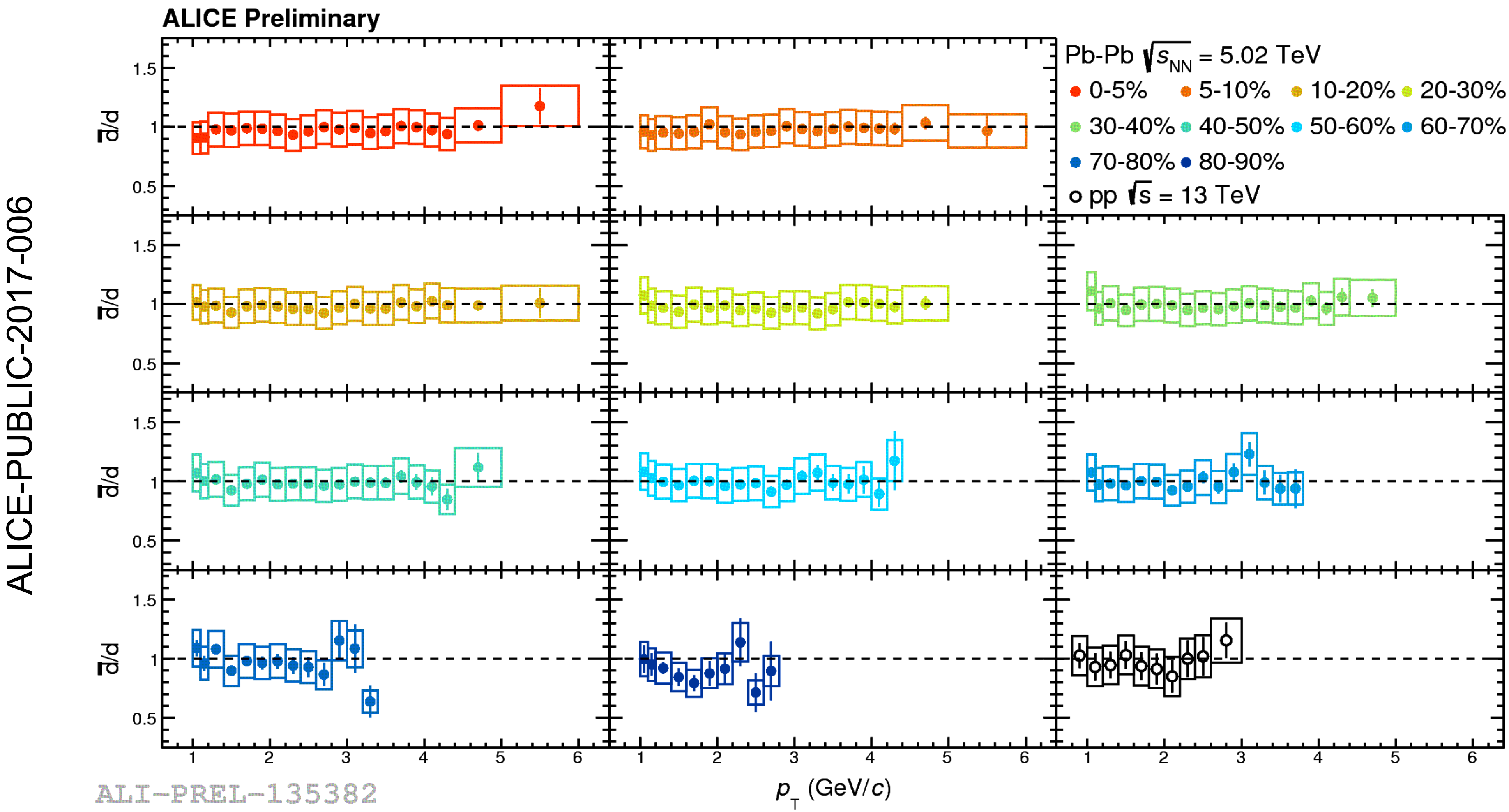
Demonstrated by particle spectra



Matter and anti-matter

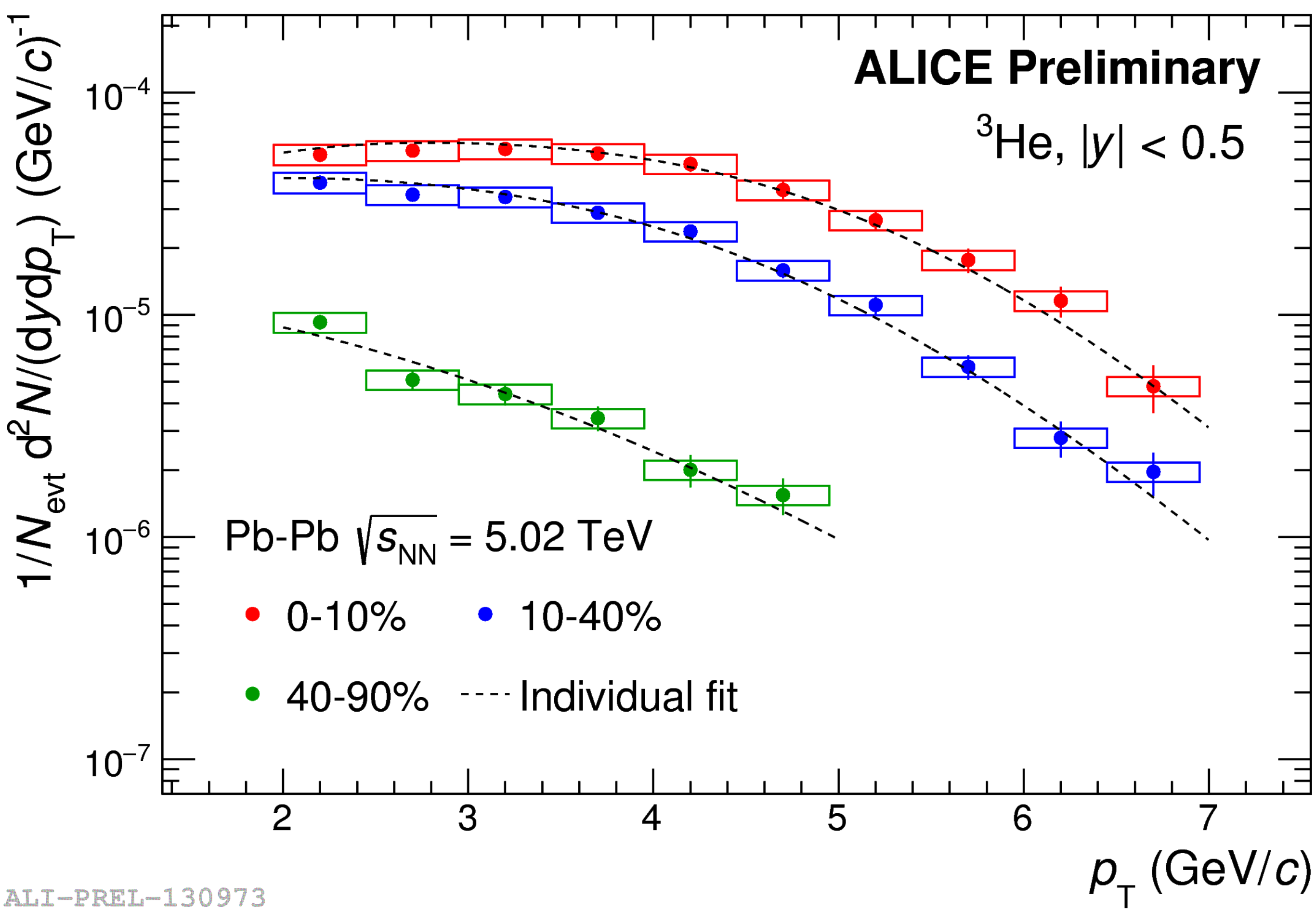
... are produced in IDENTICAL amounts at the LHC

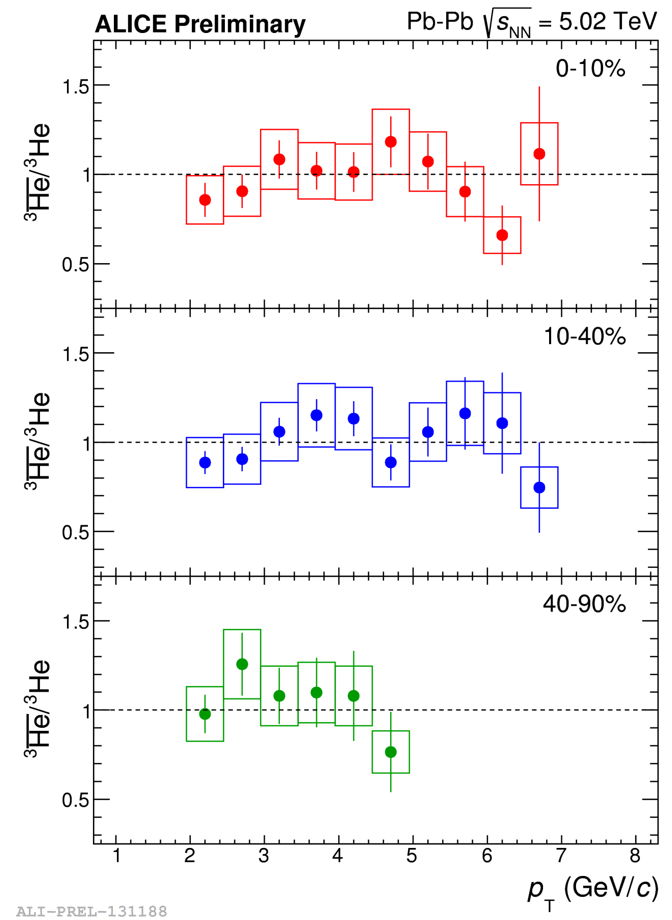
⟺ zero baryo-chemical potential μ_B ~ net baryon density at mid-rapidity



^{3}He and $^3\overline{\text{He}}$ spectra in Pb-Pb

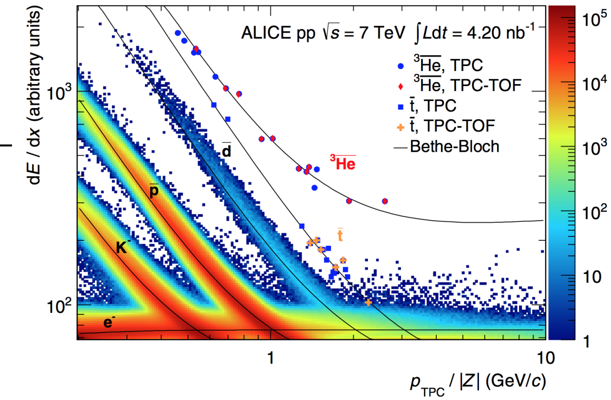
Spectra and matter / antimatter ratio for ^{3}He



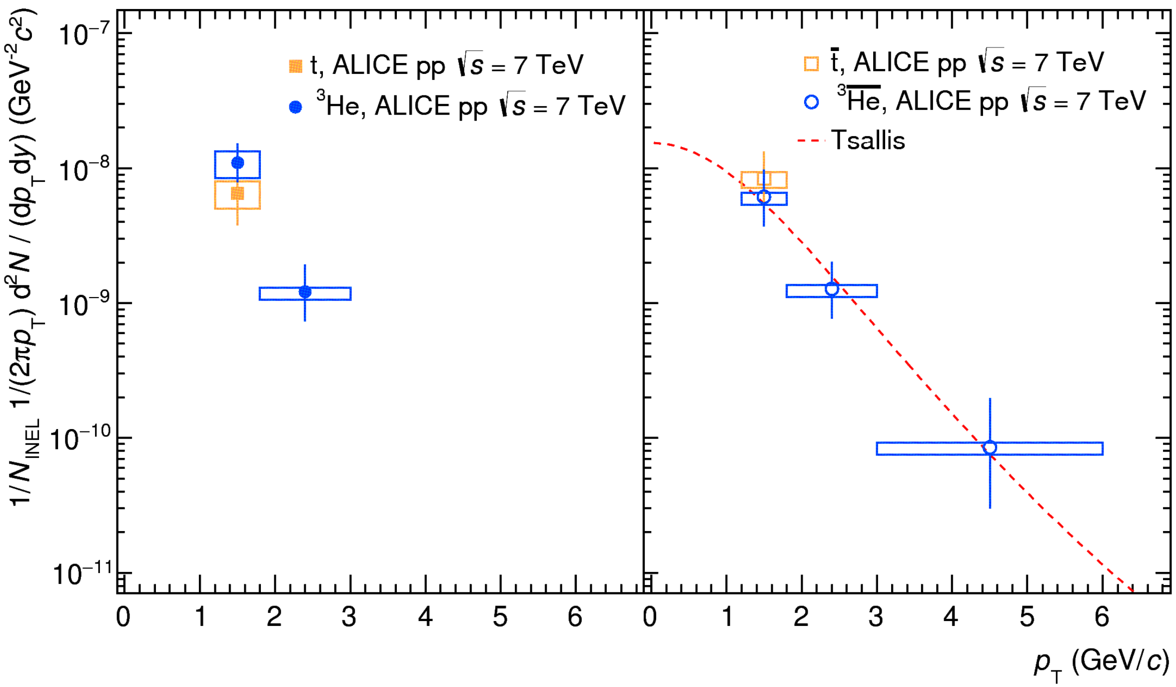


^{3}He and $^3\overline{\text{He}}$ spectra in pp

Very important: yields in proton-proton collisions



Phys.Rev. C97 (2018) no.2, 024615



Relevant for **dark matter searches**

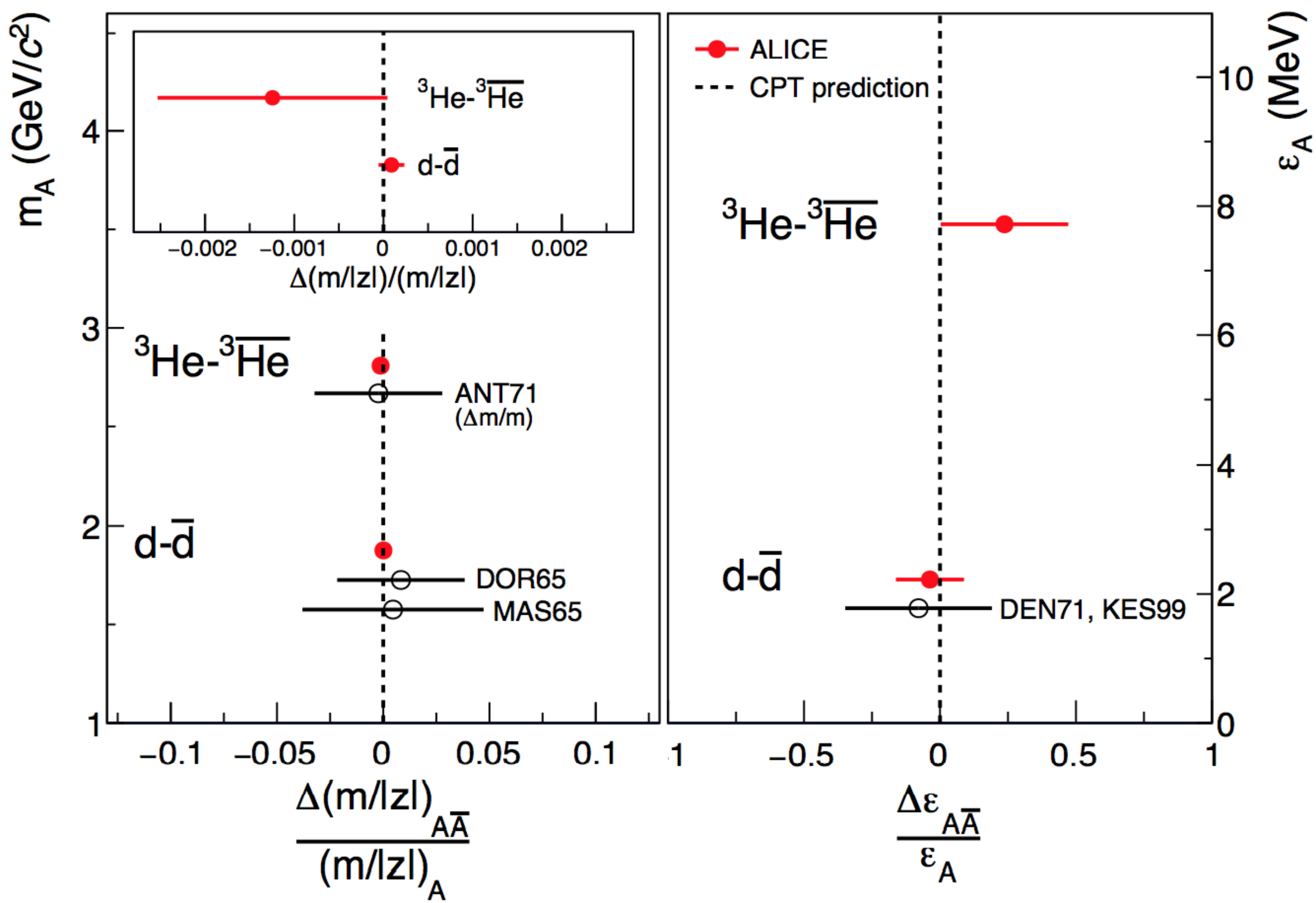
Dark matter annihilation in the galactic halo results in matter – antimatter production: → search for excess of antimatter!

$$\chi + \chi \rightarrow \gamma\gamma,\ e^+e^-,\ p\bar{p},\ d\bar{d},\ \mathrm{He}\overline{\mathrm{He}}, \ldots$$

Our data: crucial input to estimate backgrounds

Light nuclei: test of CTP violation

The measurement of the difference between the ratios of mass and charge of deuterons (d) and anti-deuterons ($\bar{d}$) and of ^{3}He and $^3\overline{\text{He}}$ confirms CPT invariance to an unprecedented precision for light nuclei



Nature Phys. 11 (2015) n10, 811

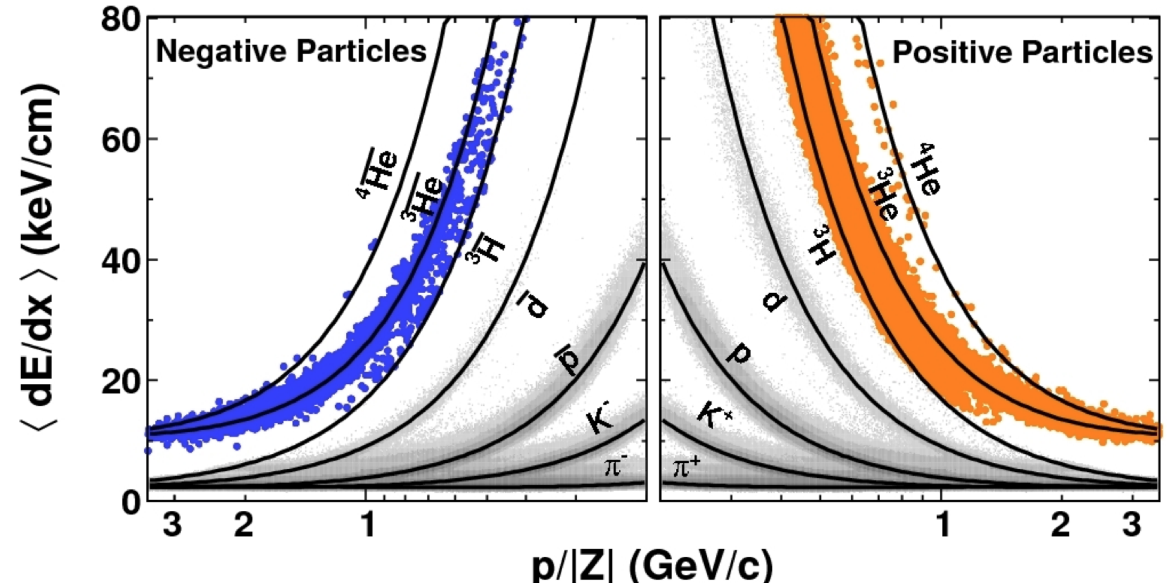
Anti-matter: $^{4}\overline{\text{He}}$

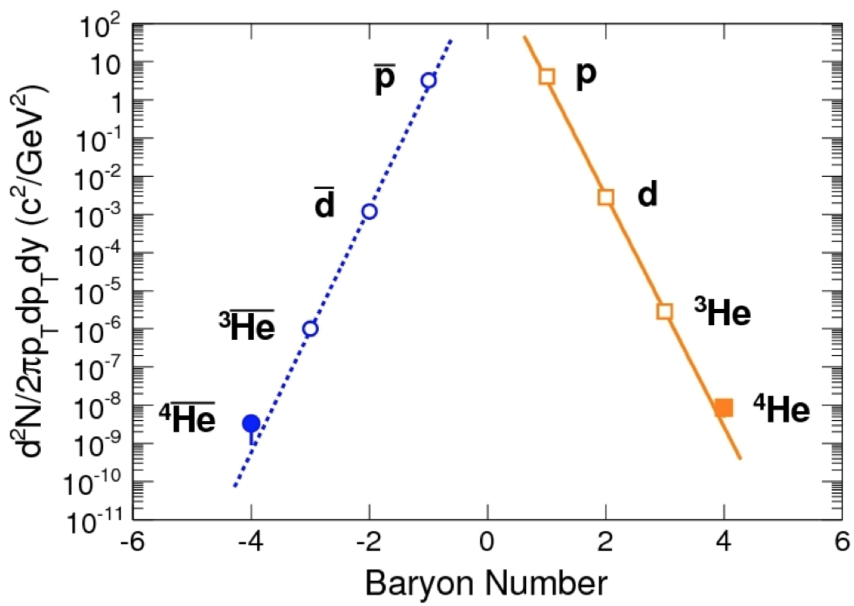
2010

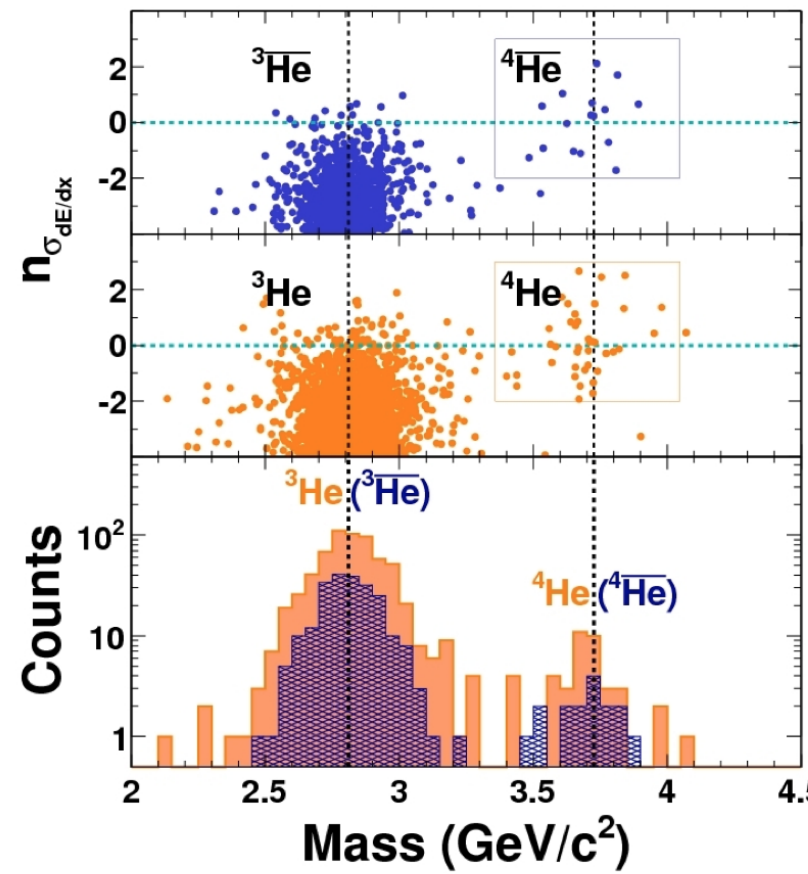
First observation by STAR

Nature 473 (2011) 353

~ 15 candidates







Measurement of ^{4}He and $^{4}\overline{\text{He}}$ in ALICE

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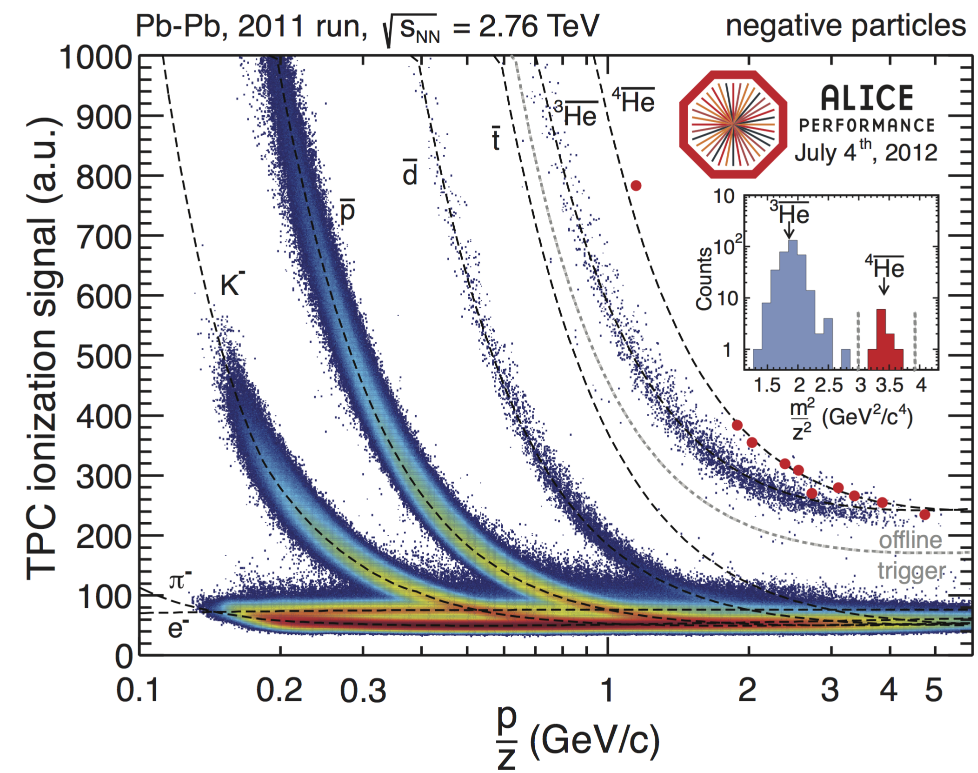
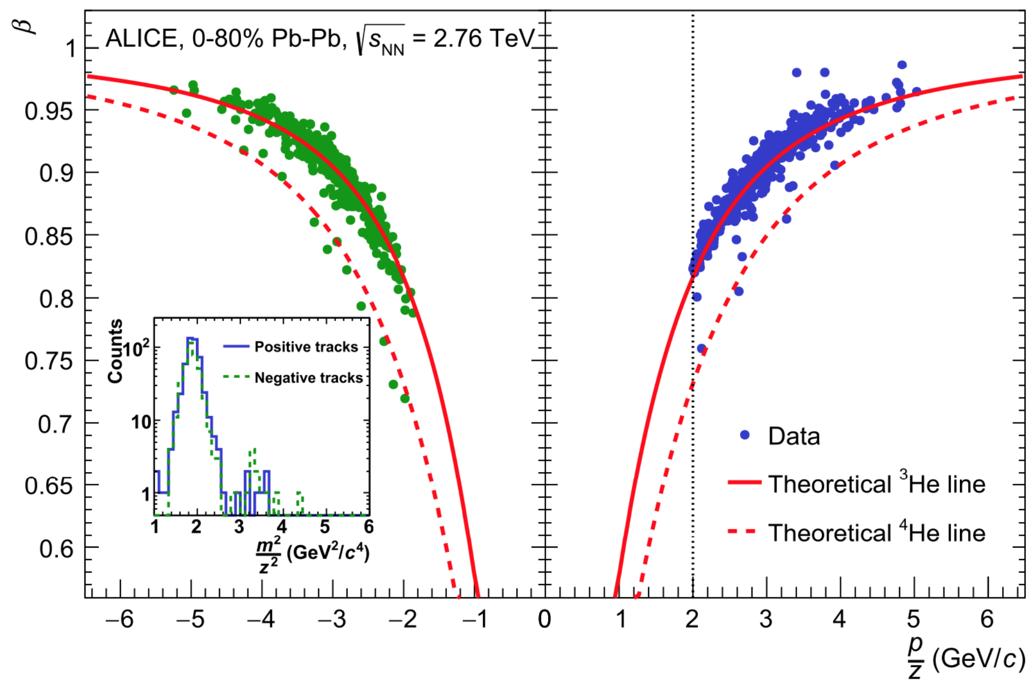
2011 data: 10 candidates

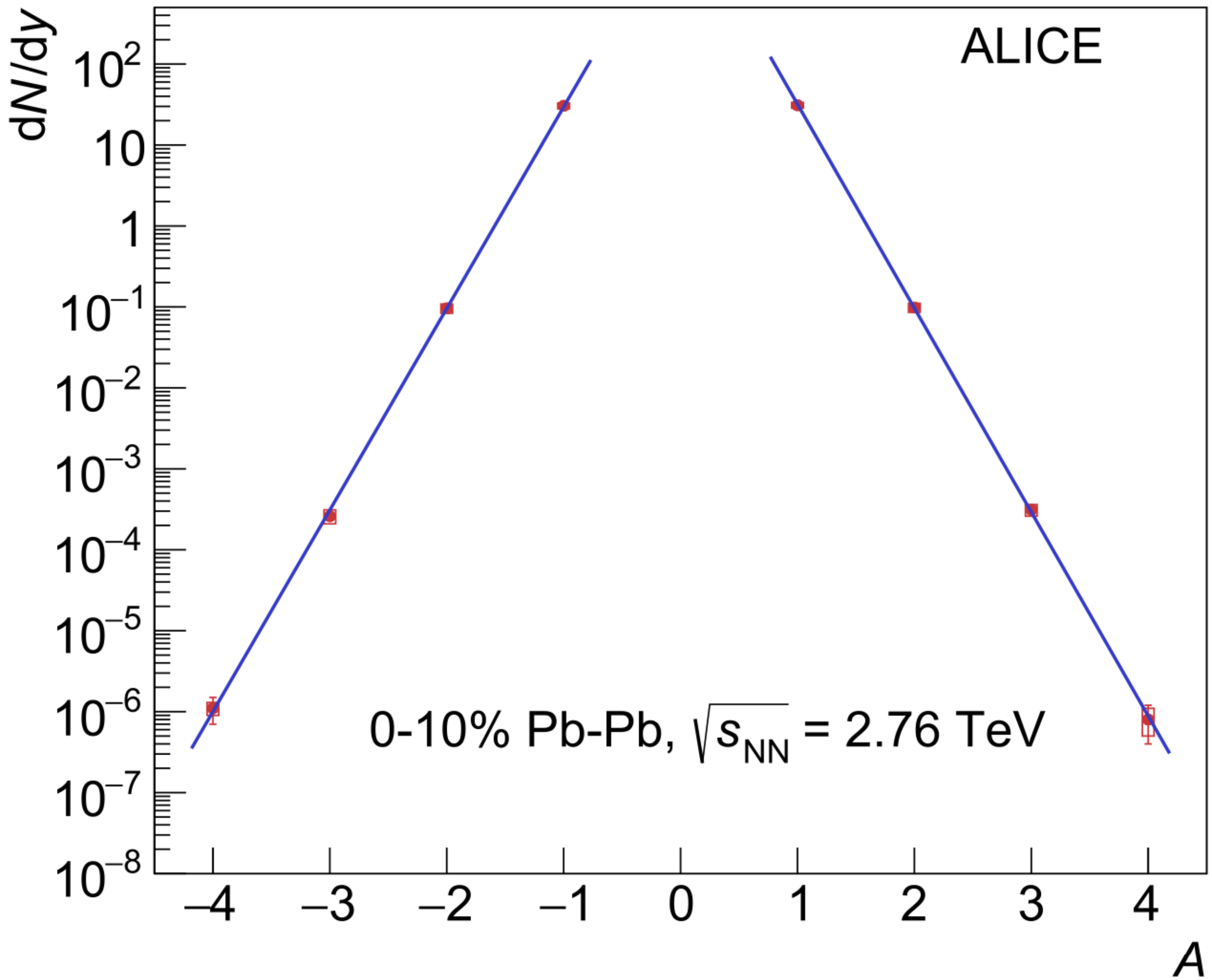


ALI-PERF-36713



Yield dependence on the mass

Nuclei production yields follow an exponential decrease with mass, as predicted by the thermal model



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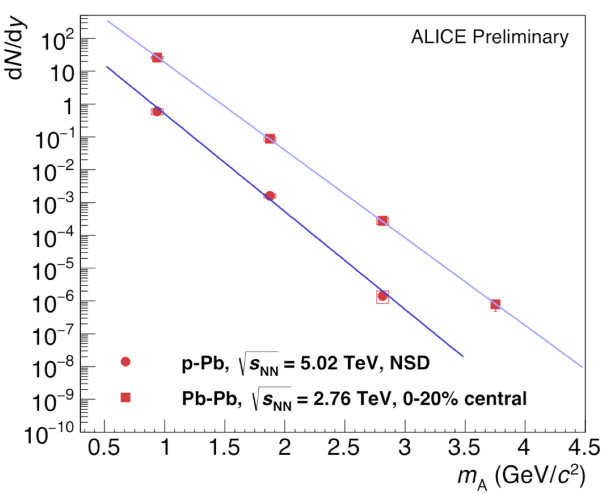
Pb-Pb: penalty factor for adding one baryon ~ 300

p-Pb: ~ 600



Coalescence parameter B_A

Baryons close in phase-space at freeze-out can form a (anti-)nucleus.

Phase-space: space and momentum. Since nuclei are generally larger than the source, phase-space is reduced to momentum space.

Relation between the spectra of single nucleons and of nuclei with A nucleons

$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_p \frac{dN_p}{d^3P_p} \right)^Z \left(E_n \frac{dN_n}{d^3P_n} \right)^N \qquad P_p = P_n = P_A / A$$

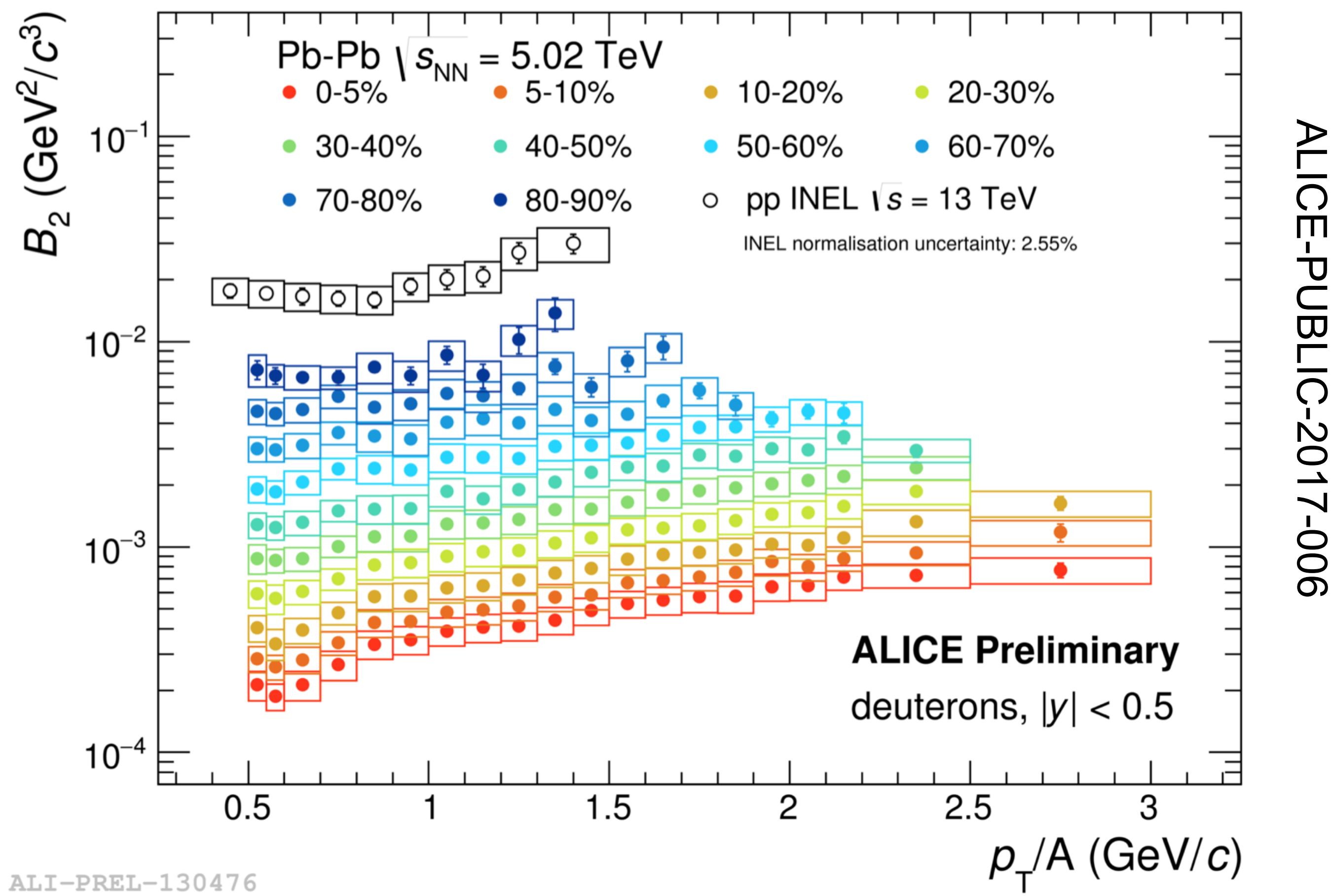
→ assume that protons and neutrons have the same mass and the same momentum spectrum:

$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_p \frac{dN_p}{d^3P_p} \right)^A \qquad \rightarrow \qquad B_A = \frac{E_A \frac{dN_A}{d^3P_A}}{\left(E_p \frac{dN_p}{d^3P_p} \right)^A}$$

The simplest coalescence model expects flat B_A wrt transverse momentum

Deuteron: coalescence parameter B_2

$$B_2 = \frac{E_2 \frac{d^3 N_2}{d P_2^3}}{\left(E_p \frac{d^3 N_p}{d P_p^3} \right)^2}$$



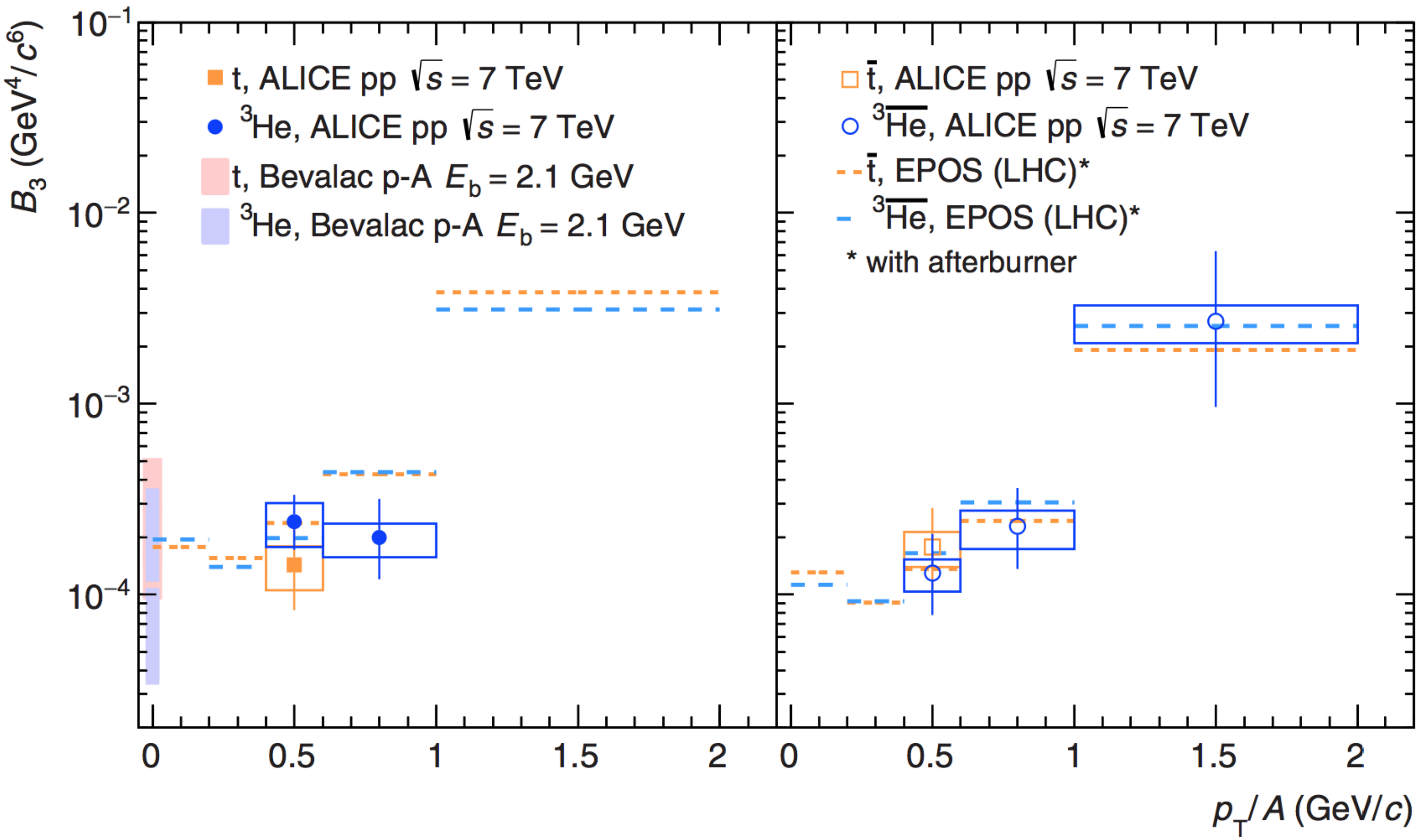
Not flat → problems for the simple coalescence model to describe the data

Work on “advanced coalescence” : dependence on source volume and dynamic

^{3}He: coalescence parameter B_3

$$B_3 = \frac{E_3 \frac{d^3 N_3}{d P_3^3}}{\left(E_p \frac{d^3 N_p}{d P_p^3}\right)^3}$$

Proton-proton collisions, √s = 7 TeV



Phys.Rev. C97, 024615 (2018)

Coalescence parameter B_3 in pp collisions used as input of theory calculations to obtain estimate of background in the AMS experiment

Impact on dark matter searches

Coalescence parameter B_3 in pp collisions used as input of theory calculations to obtain estimate of background in the AMS experiment

Before ALICE's pp measurement

B_3 extrapolated from larger colliding systems (pA, AA):

Nuclear yields and size of emission region by Hanbury Brown-Twiss (HBT) interferometry

No pp data available!

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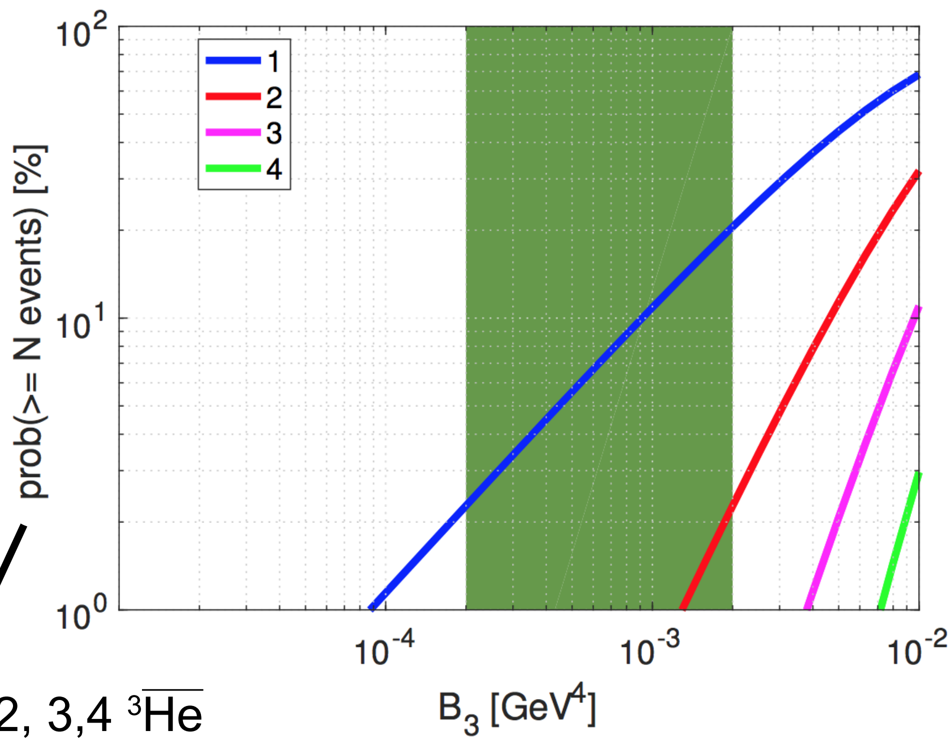
Phys.Rev. C96, 103021 (2017)

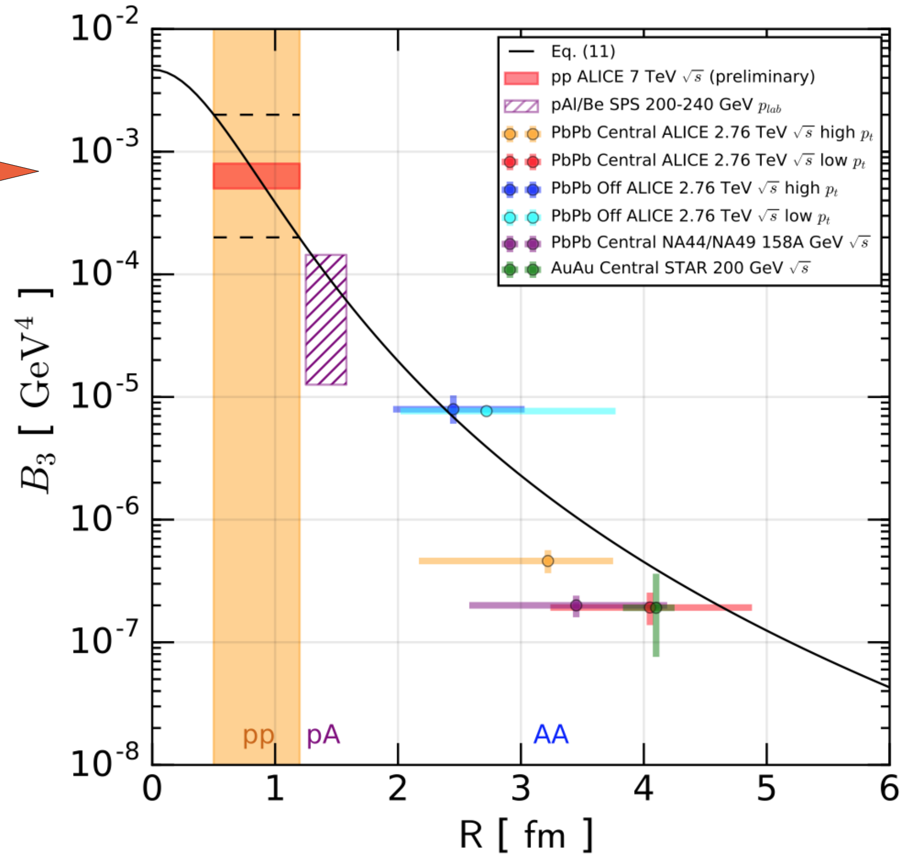


Probability to find ⩾ 1, 2, 3,4 $^3\overline{He}$ events in a 5-ys analysis of AMS02

Impact on dark matter searches

Coalescence parameter B_3 in pp collisions used as input of theory calculations to obtain estimate of background in the AMS experiment

2017: ALICE's pp measurement



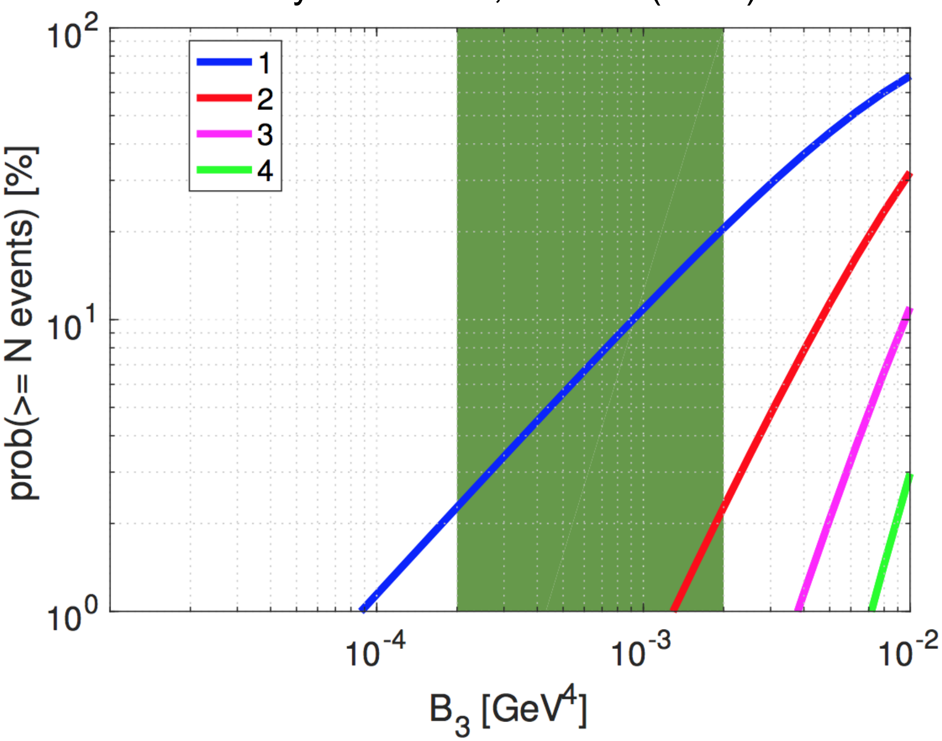
K. Blum et al.

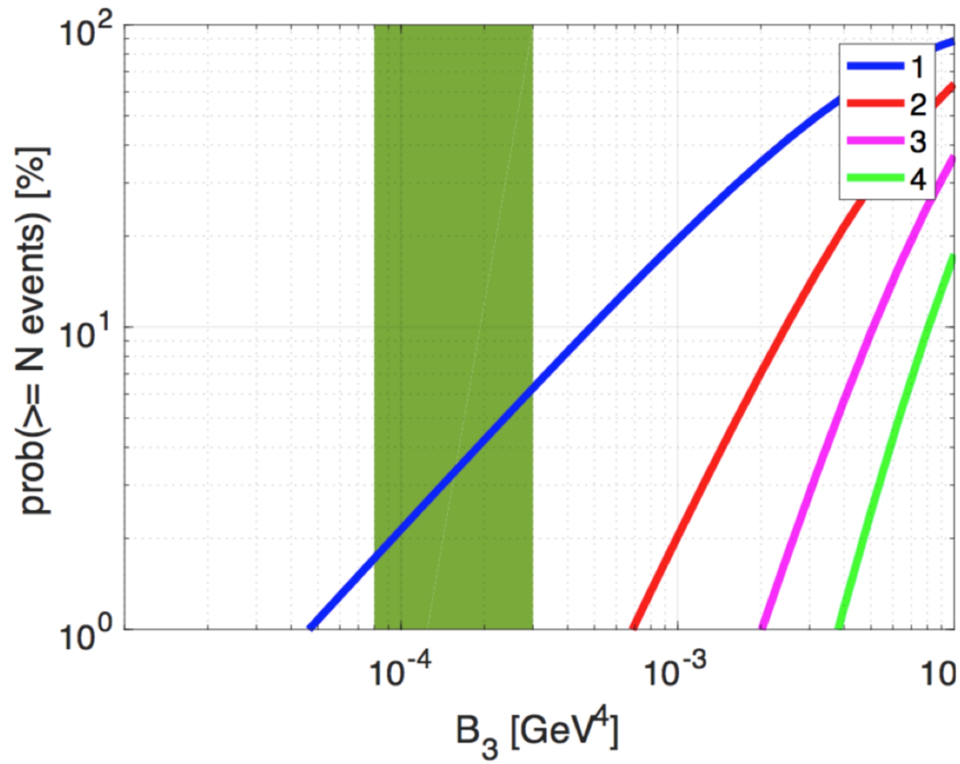
Impact on dark matter searches

Coalescence parameter B_3 in pp collisions used as input of theory calculations to obtain estimate of background in the AMS experiment

Before ALICE's pp measurement → With ALICE's pp measurement

Phys.Rev. C96, 103021 (2017)





K. Blum et al.

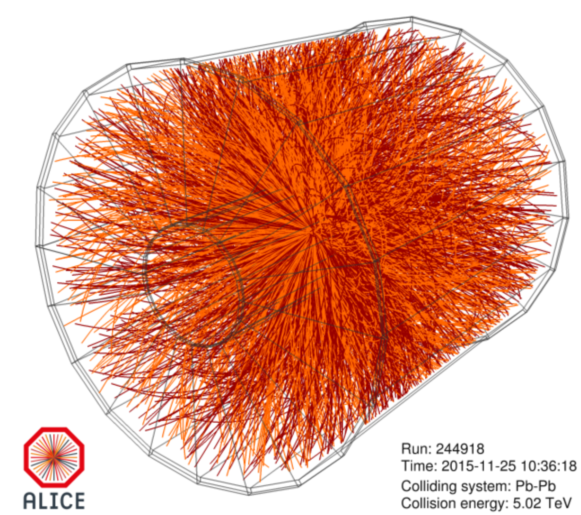
Summary and outlook

- Ultra-relativistic heavy-ion collisions:
  factory of matter, antimatter and hypermatter

- **Nuclei production mechanism**: models under investigation
  New data allow more measurements, more observables

- Open question: large and loosely bound objects created in an environment with temperature ≫ 10 times the binding energy?
  $T_{chem} \approx 154$ MeV, $E_{binding} \approx 2.2$(d) / 8.5(t) / 7.7(^{3}He) MeV, $E_\Lambda \approx 130$ keV
  Snowballs in hell (Peter Braun-Munzinger)

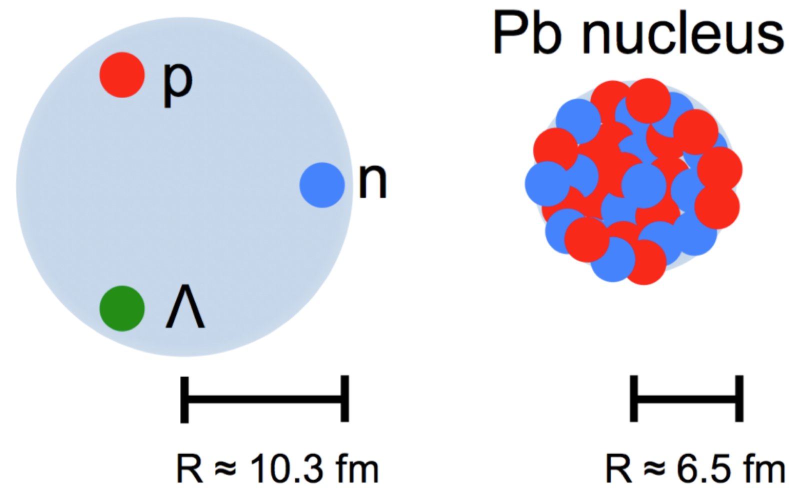
- Excellent prospects:
  - ALICE detector upgrades
  - LHC Pb-Pb "high luminosity" starts in 2021
  - Plenty of high precision data!



SPARES

(Anti-)Hypertriton $^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\Lambda}\overline{\mathrm{H}}$

- Lightest hyper-nucleus
  - m = 2.99116 ± 0.00005 GeV/c^2
  - lifetime ~ 215 ps



- Loosely bound state: $B_\Lambda \approx 130$ keV

  Large and fragile object

- Reconstructed via decay topology:
  - 2-prong: $^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$
  - 3-prong: $^{3}\mathrm{H} \rightarrow d + p + \pi^{-}$

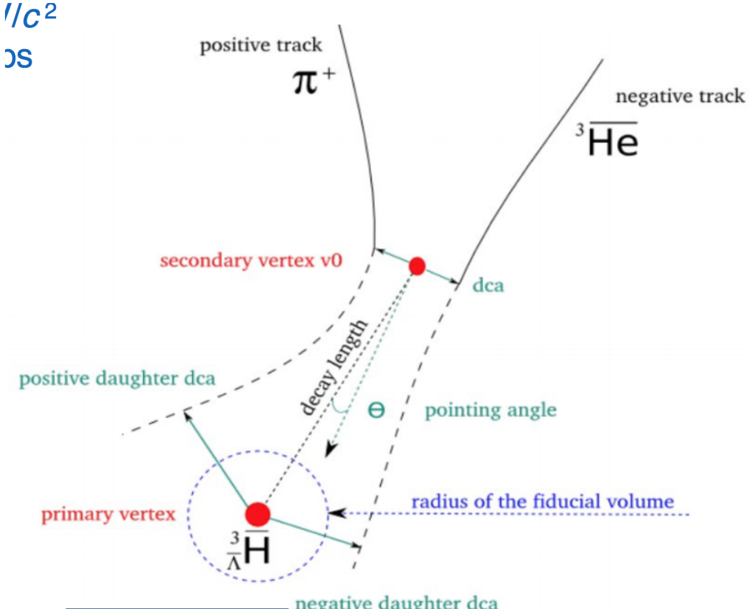
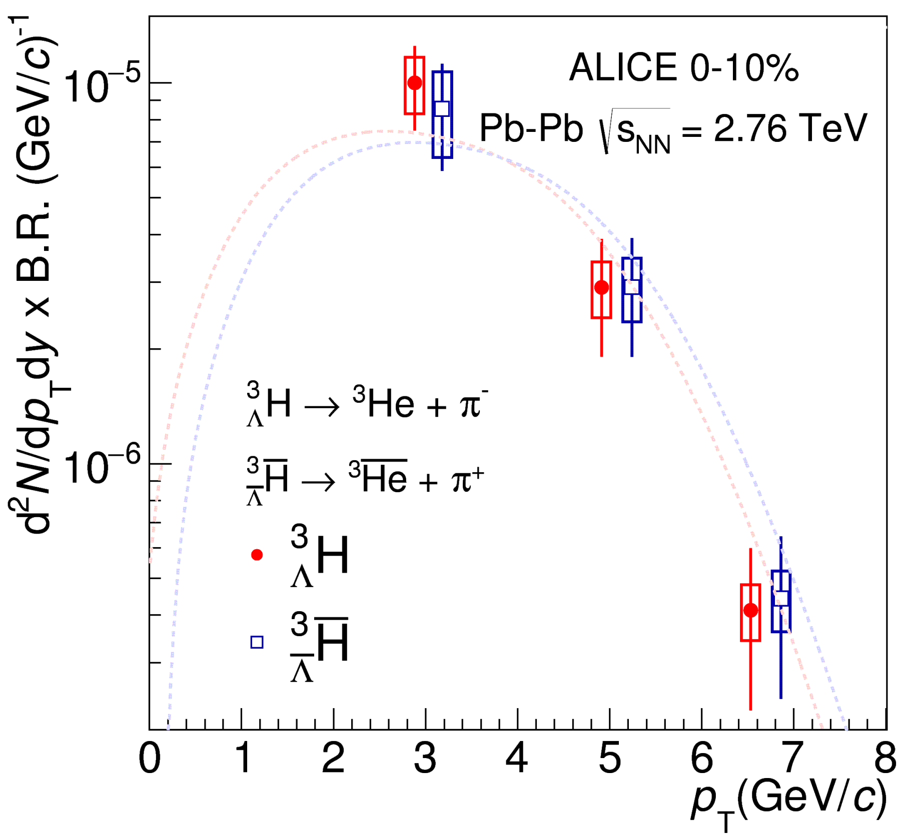


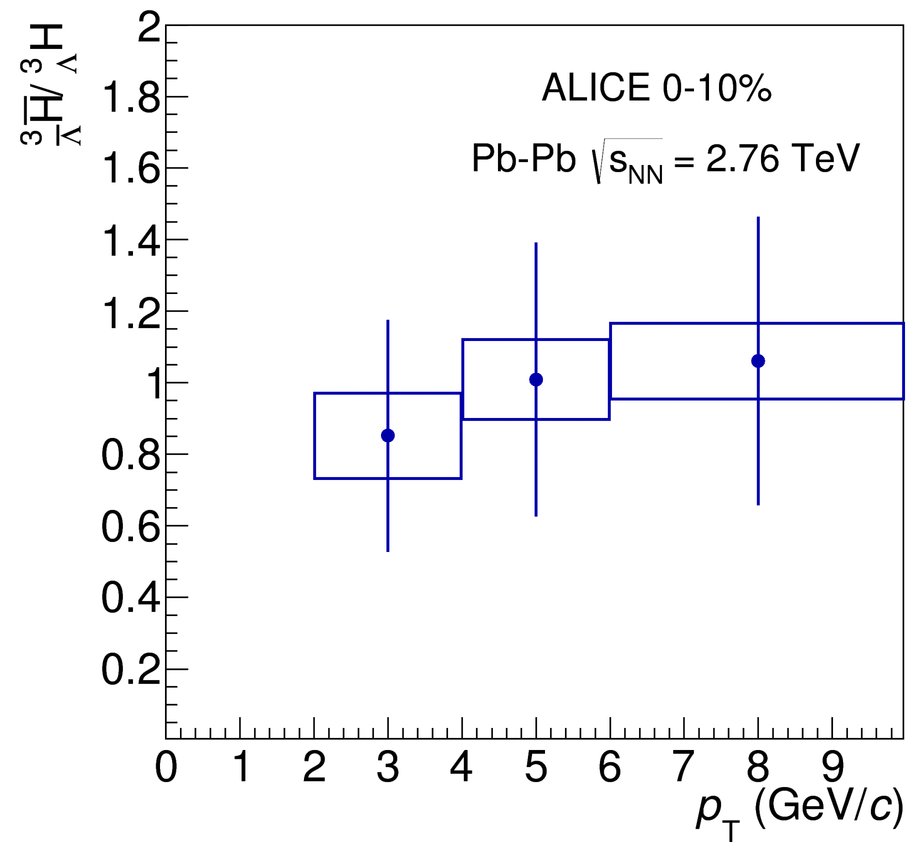
Image not in scale

(Anti-)Hypertriton: spectra

PLB 754 (2016) 360-372

2011 Pb-Pb data, $\sqrt{s_{NN}}$ = 2.76 TeV

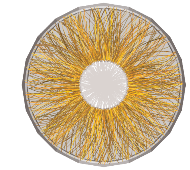




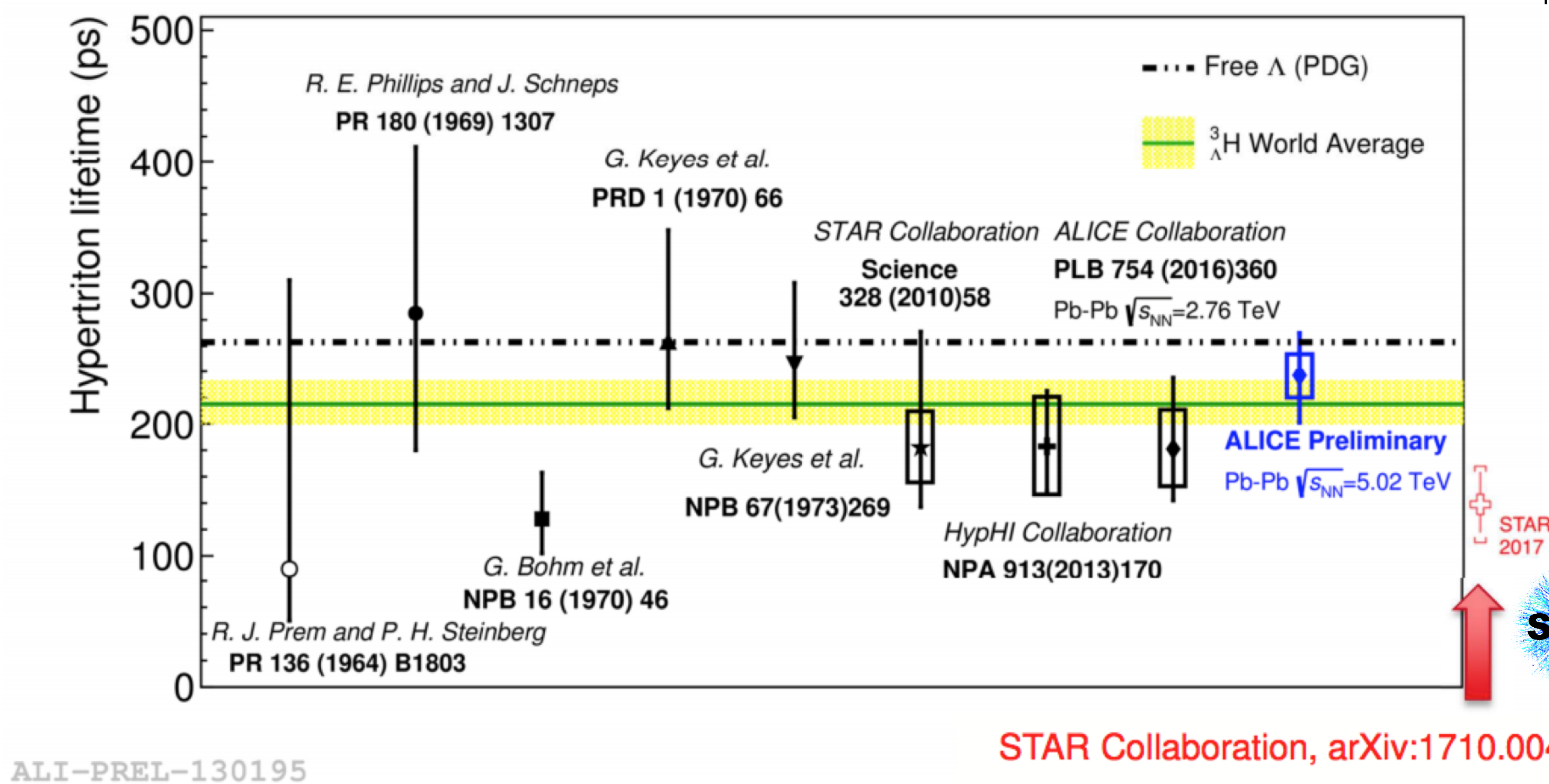
Blast-wave fit used to extract the p_T-integrated yield

Ratio consistent with unity

(Anti-)Hypertriton: lifetime



2011 Pb-Pb data
$\sqrt{s_{NN}}$ = 5.02 TeV



STAR Collaboration, arXiv:1710.00436v1 [nucl-ex]

$$\tau = \left(142^{+24}_{-21}(stat.) \pm 31(syst.)\right) ps$$

Puzzle: lifetime shorter than the one of the free Λ?

→ decisive measurements with 2018 Pb-Pb data !

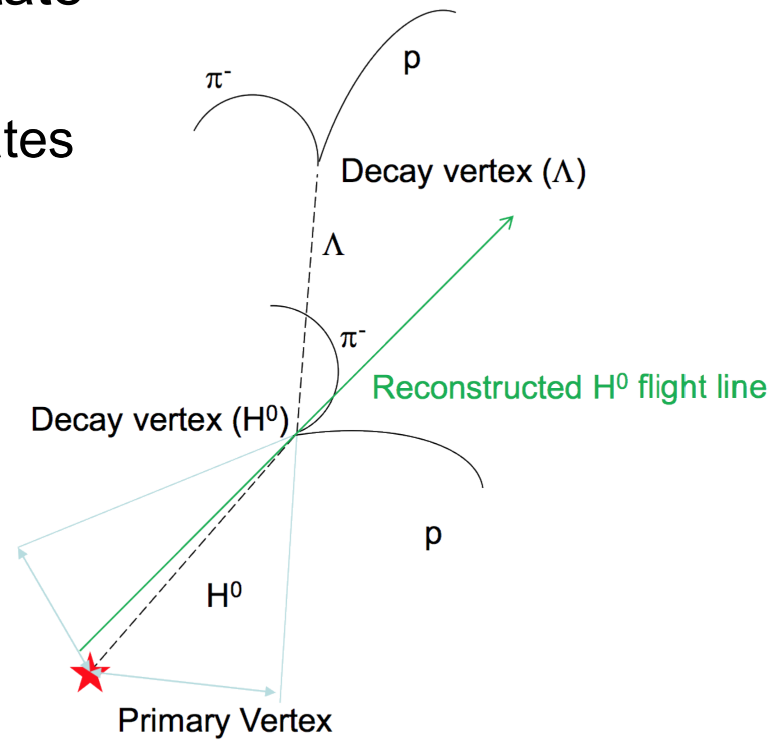
Search for exotica

H-dibaryon: hypothetical udsuds bound state

- First predicted by Jaffe PRL 38, 195617 (1977)
- Several predictions of bound and resonant states
- Recent lattice models predict weakly bound states

  Inoue et al. PRL 106, 162001 (2011)

  Beane et al. PRL 106, 102002 (2011)
- Renewed interest!

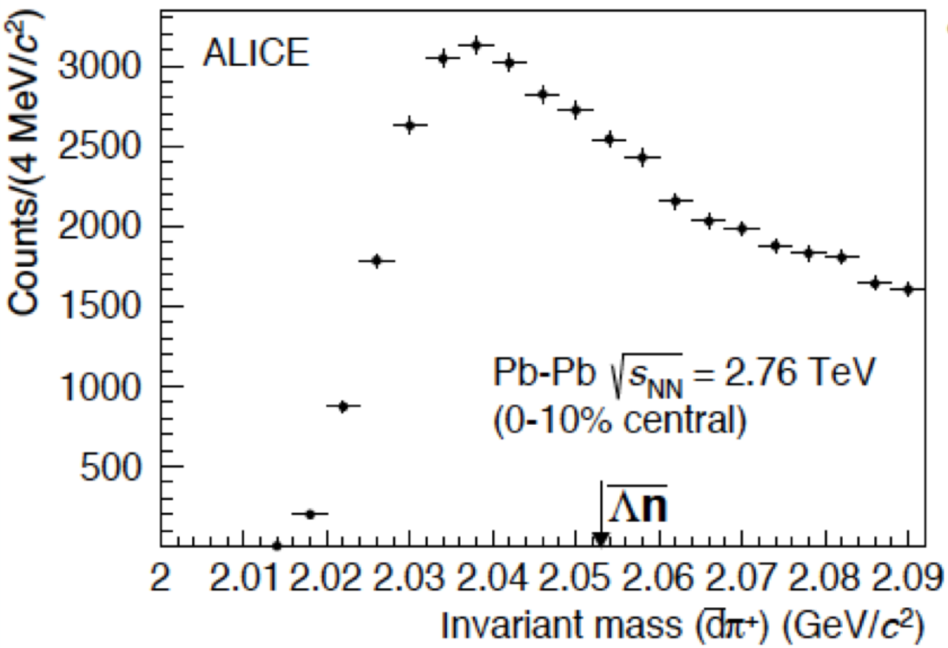


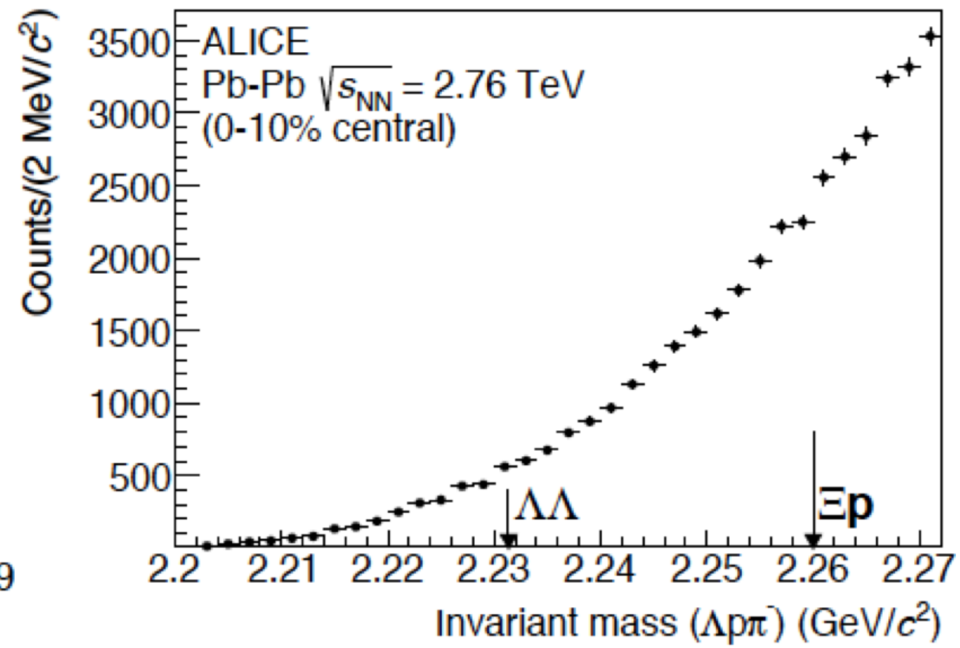
Λn possible bound state?

HypHI Collaboration observed signals in $(d + \pi^-)$ and $(t + \pi^-)$ mass distributions PRC 88, 041001 (2013)

Search for bound states with ALICE

Invariant mass analysis of the two hypothetical states: Λn and ΛΛ

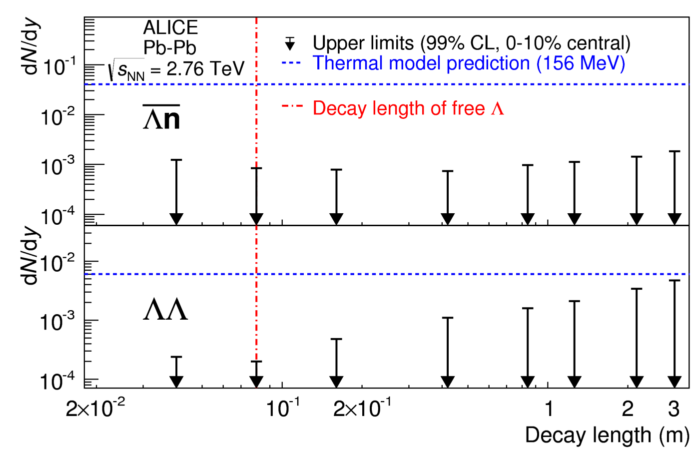




No visible signal

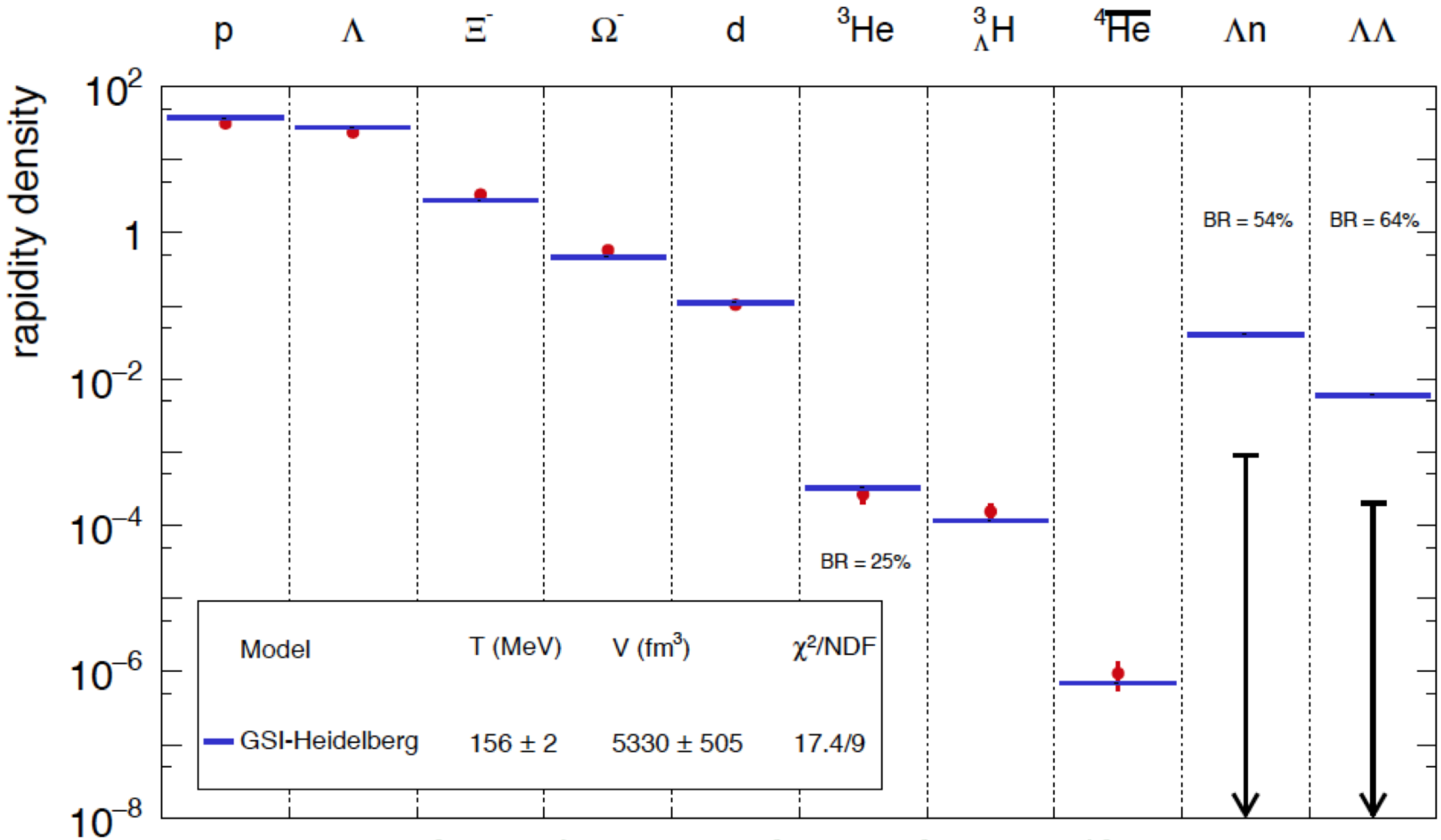
→ **Upper limits**

(for different lifetimes assumed for the bound state)



PLB 752, 267 (2016)

Exotica: comparison with thermal yields

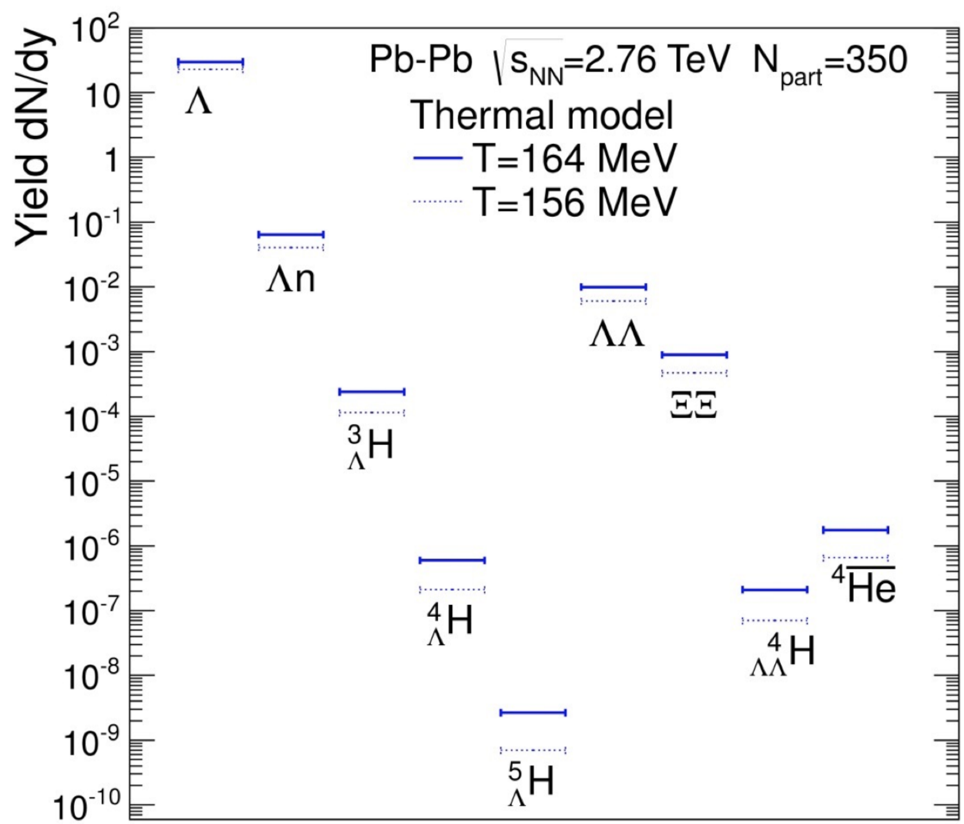


Simplified plot, CERN Courier (September 2015)

- Good fit quality for d, ^{3}He, $^{3}_{\Lambda}$H, $^{4}\overline{\mathrm{He}}$
- ΛΛ and Λn upper limits are factors > 25 below the expectations from the thermal model

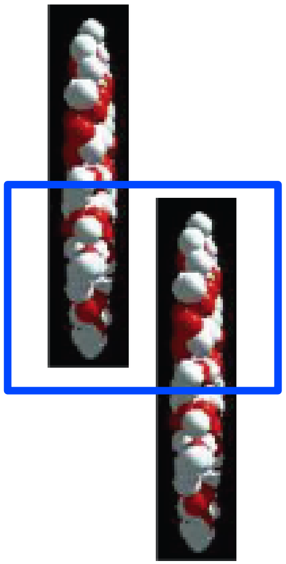
Search for more exotica

Several models propose the existence of so-far undetected multi-baryon states

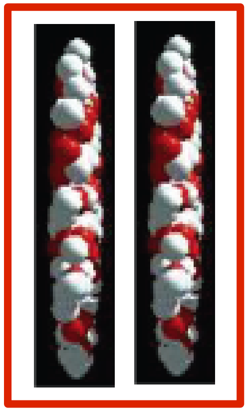


A. Andronic, private communication

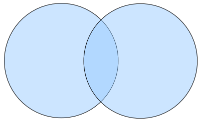
Geometry of a Pb-Pb collision



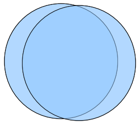
Central collisions
→ high number of **participants**
→ high multiplicity
→ higher energy density



Peripheral collisions
→ low number of **participants**
→ low multiplicity
→ lower energy density



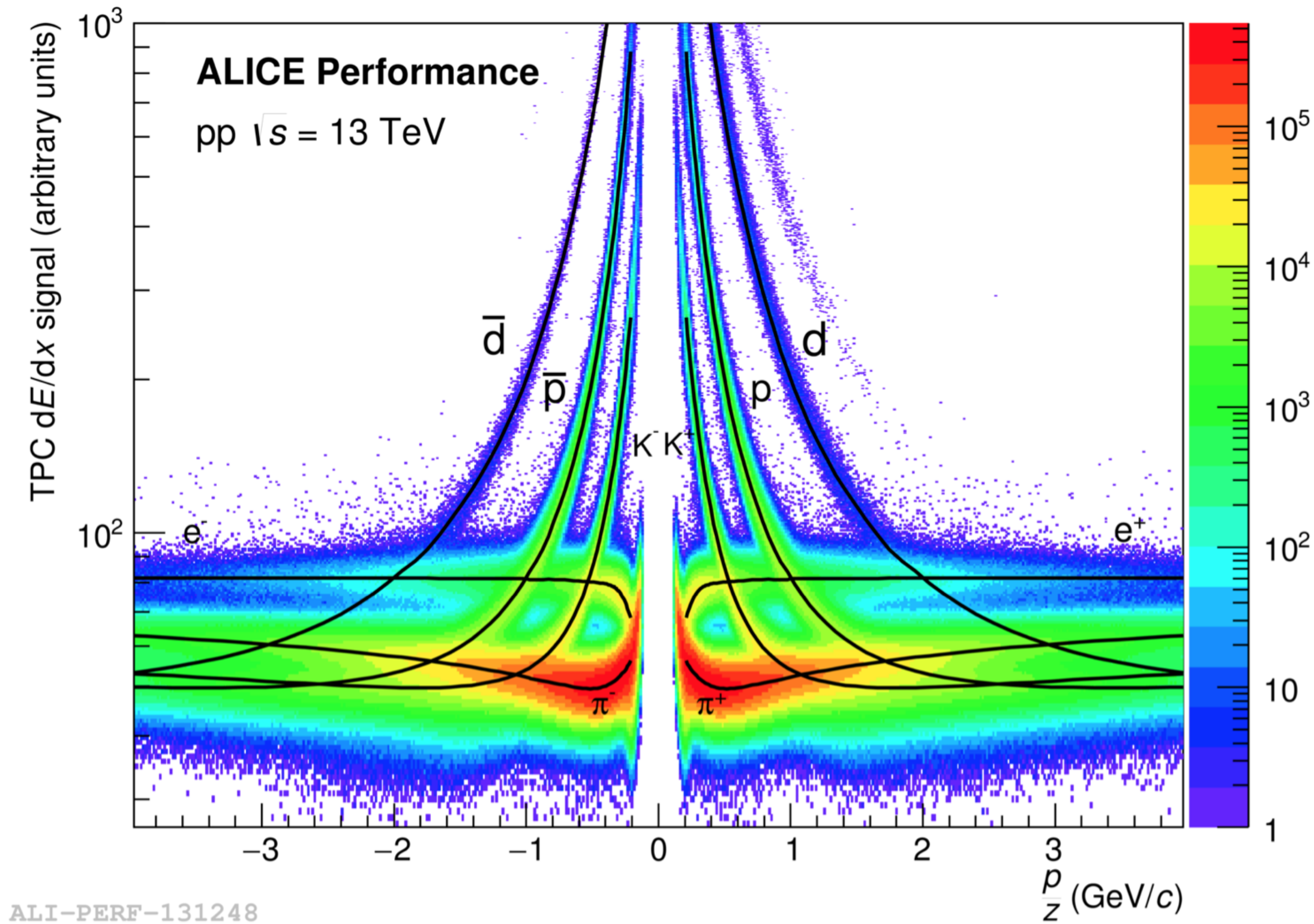
peripheral



central

Centrality:
percentile of total hadronic cross section

Time Projection Chamber: dE/dx



ALICE-PUBLIC-2017-006

Matter – antimatter at lower energies

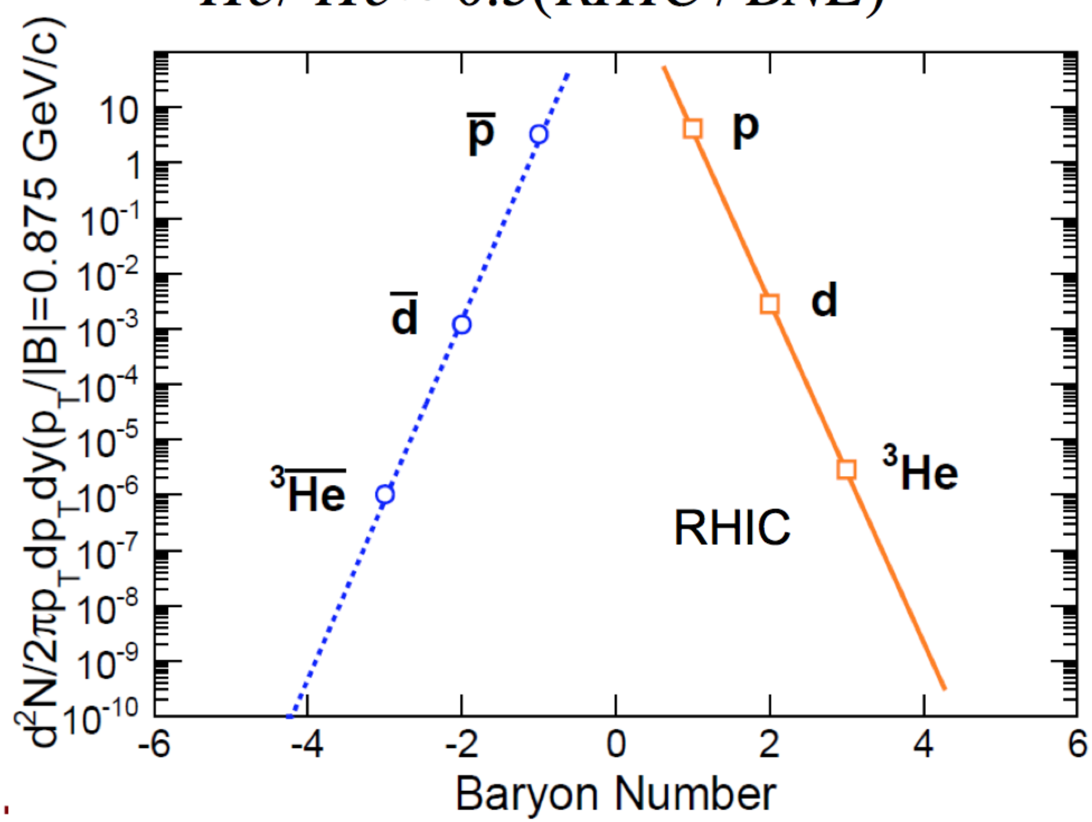
Matter and antimatter are not created equal

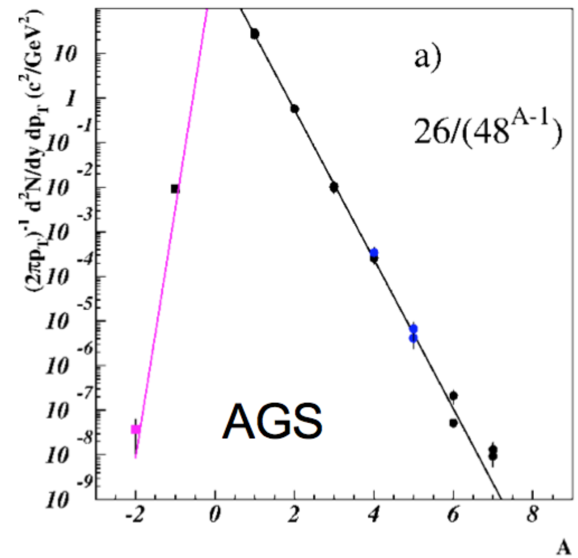
But we are getting there !

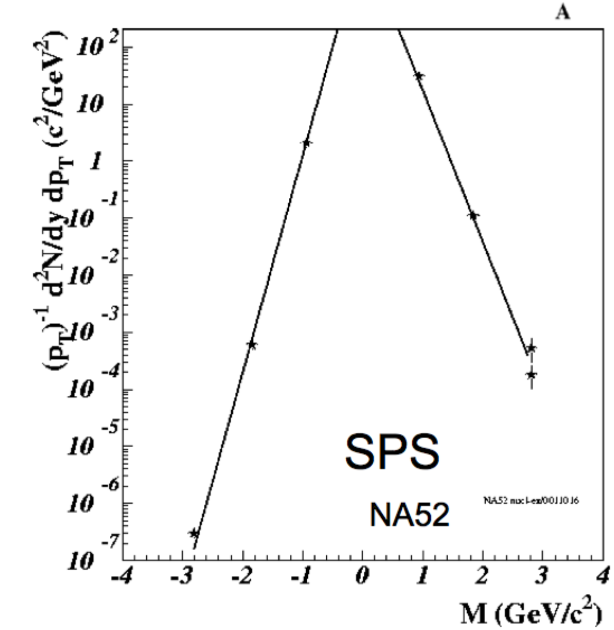
$^3\overline{He}/^3He \approx 10^{-11}$ (AGS,Cosmic)

$^3\overline{He}/^3He \approx 10^{-3}(SPS/CERN)$

$^3\overline{He}/^3He \approx 0.5(RHIC/BNL)$



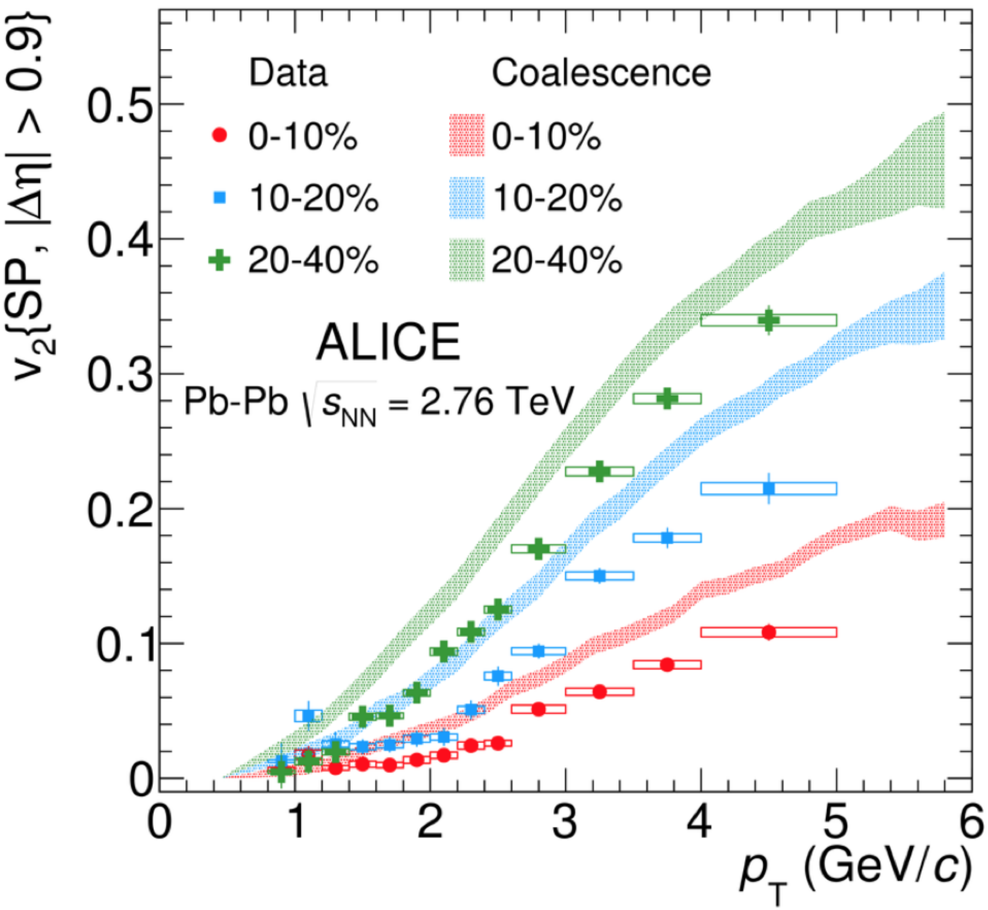




Zhangbu Xu

Deuteron flow and coalescence

Eur. Phys. J. C77 (2017) 658



Elliptic flow of deuterons from proton v_2 using simple coalescence:

$$v_{2,d}(p_T) = \frac{2v_{2,p}(p_T/2)}{1 + 2v_{2,p}^2(p_T/2)}$$

D. Molnar, S.A. Voloshin, Phys. Rev. Lett. 91, 092301 (2003)

- ➢ Unsatisfactory description

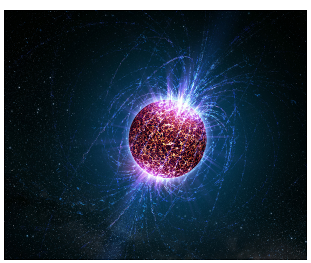
Heavy-ion physics

Explore strongly-interacting matter at extreme conditions

Extreme temperatures

≈ 160 MeV ≈ 2 x 10^{12} K (Sun core: 15 x 10^{6} K)

and/or



Extreme densities

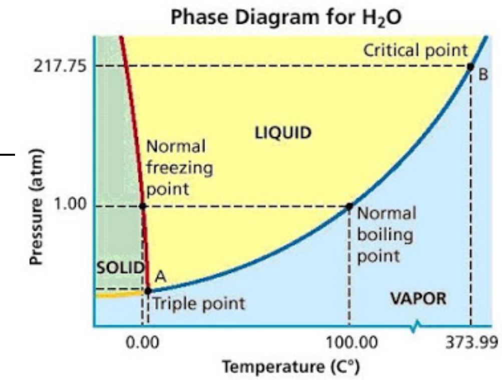
≈ few GeV/fm^3 (few times ground-state nuclear matter. ε_{proton} ≈ 0.44 GeV/fm^3)

to study fundamental properties of QCD:

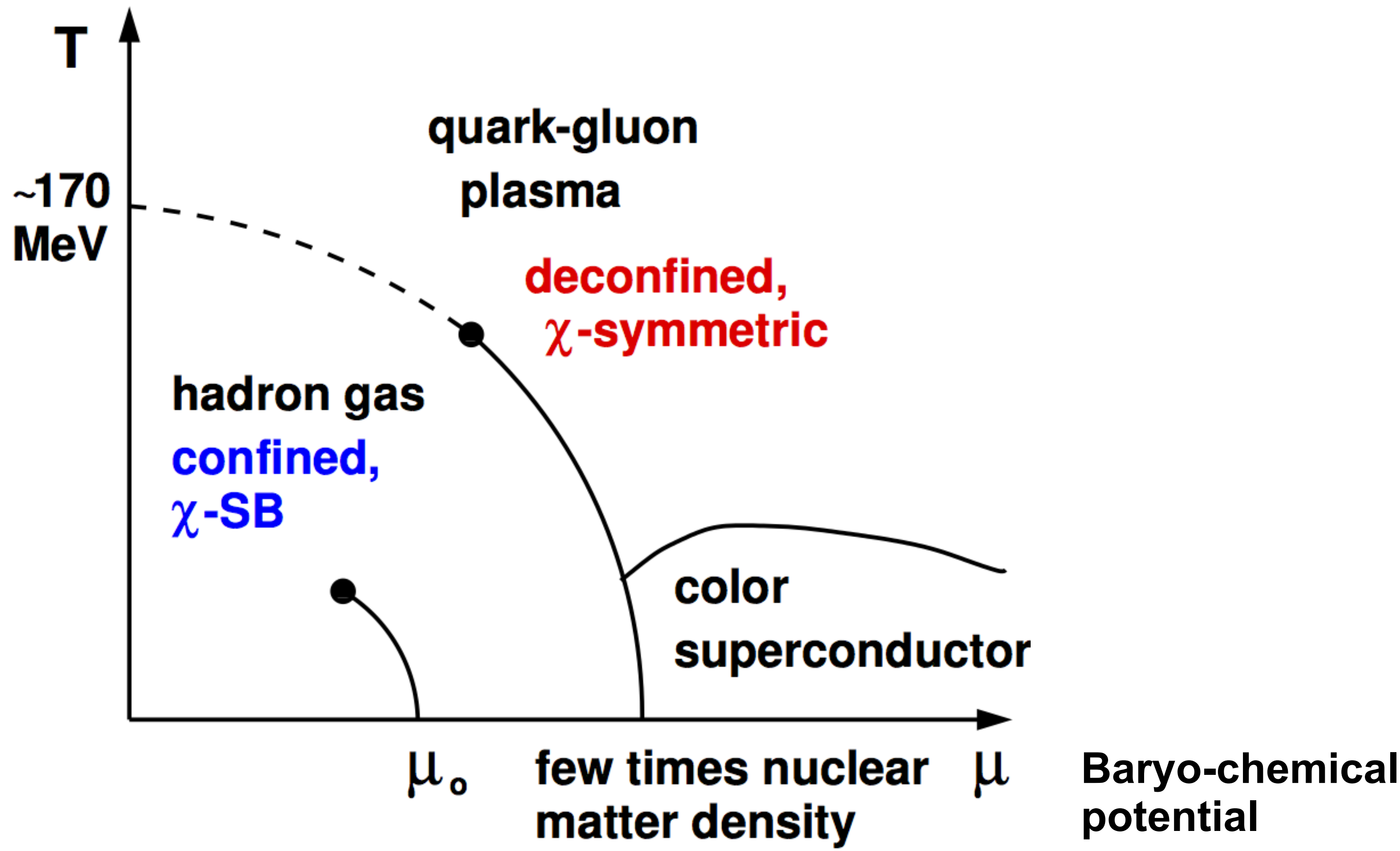
compressibility of nuclear matter, confinement, QCD-matter phases, hadronization, transport coefficients, etc.

The QCD phase diagram

H_20

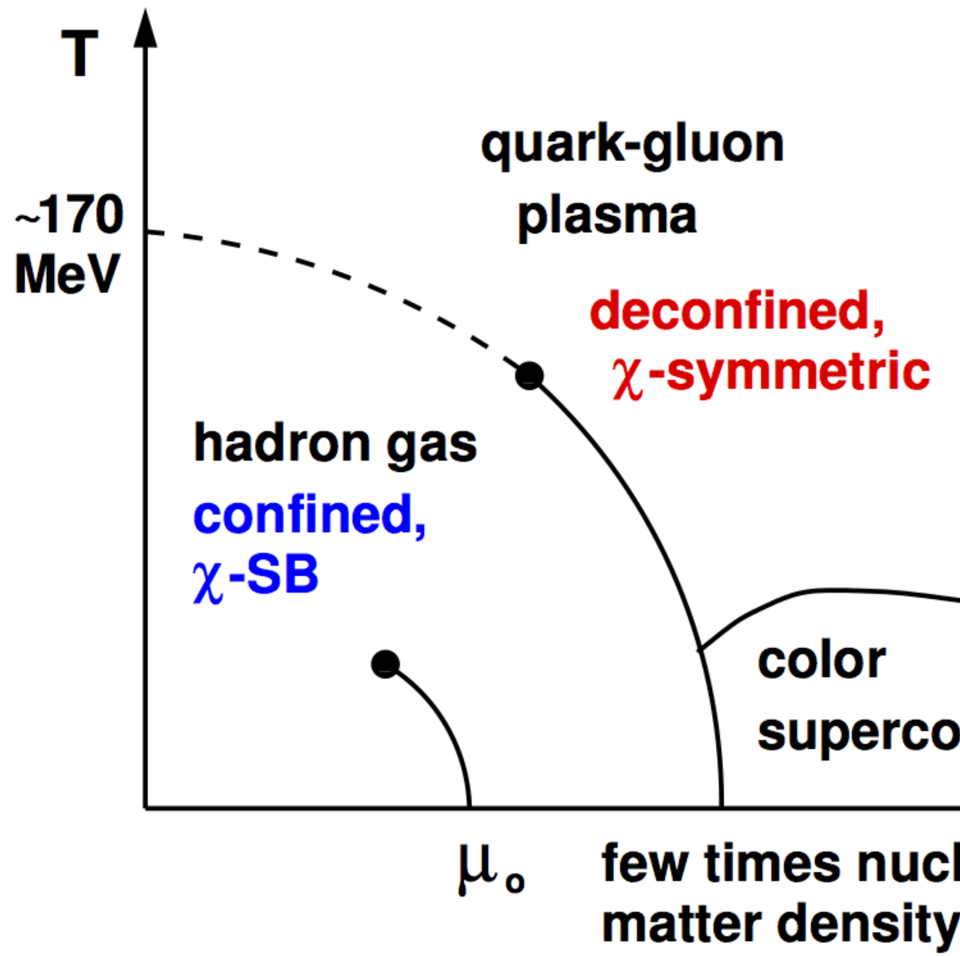


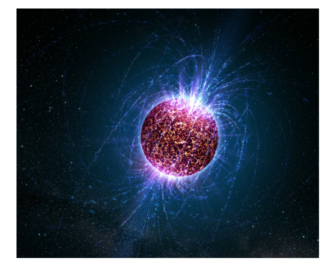
Phases of matter



The QCD phase diagram

Early universe (few μs after the Big Bang)





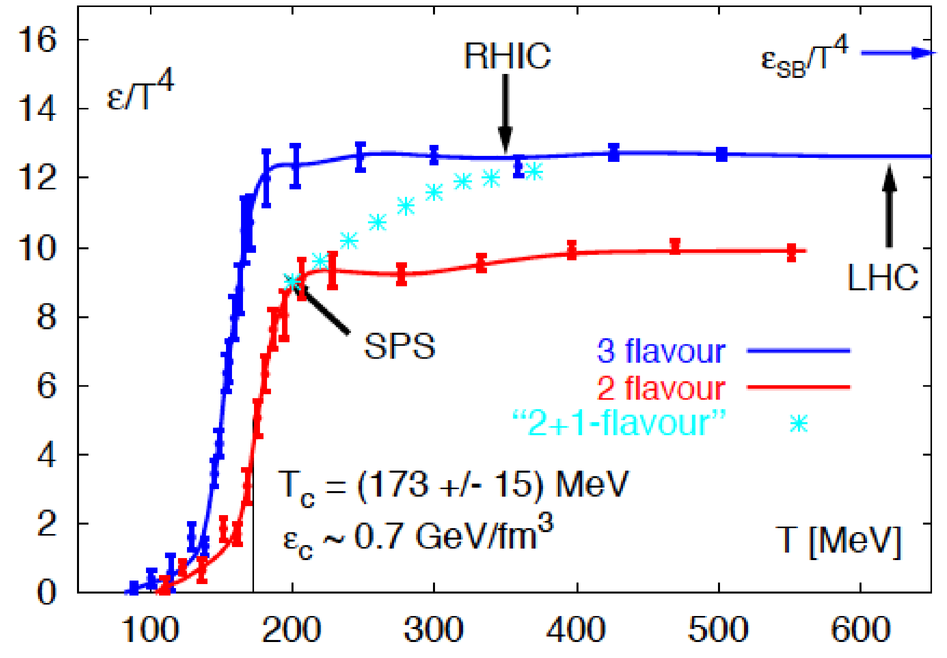
Neutron stars

Baryo-chemical potential

Phase transition: first ideas

- **1965 Hagedorn**: limiting temperature for hadronic systems ~ 140 MeV
- **1975 Cabibbo and Parisi, Collins and Perry**: asymptotic freedom → deconfined phase of matter at high densities or temperatures
- **1981 on, QCD on space-time lattice**: critical transition temperature from hadronic phase to the deconfined, plasma phase

Energy density



F. Karsch, 2001
hep-lat/0106019

PLB101(1981)89

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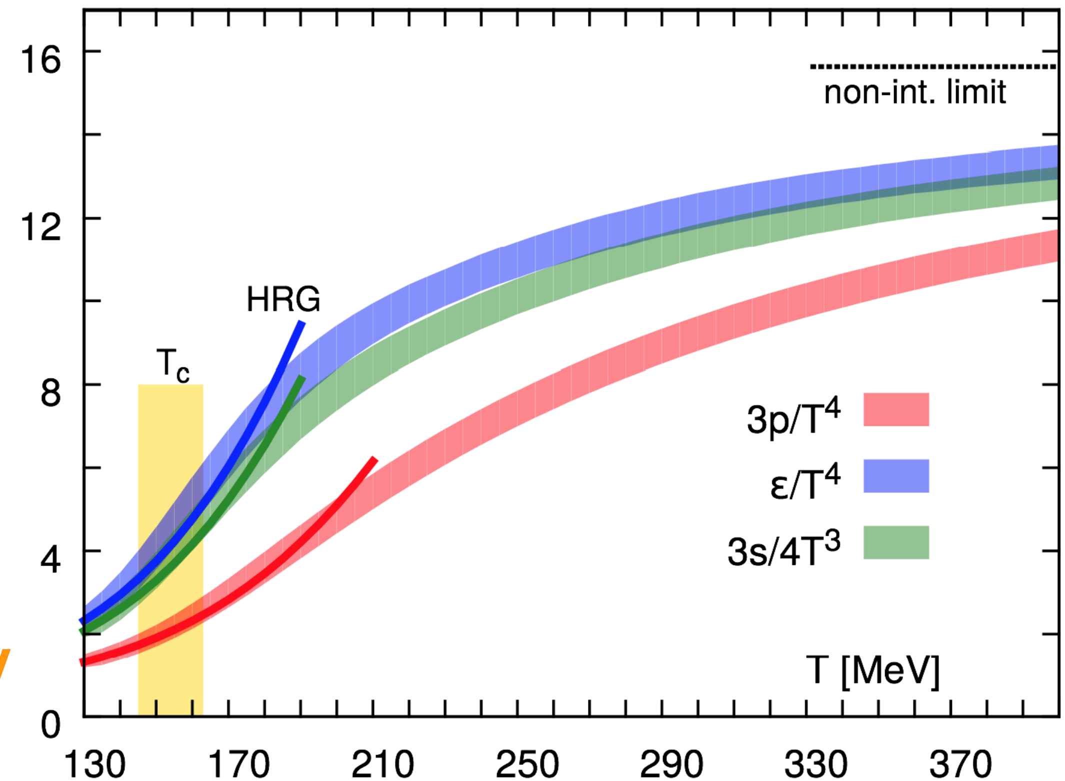
Energy density

T_c = 145 – 164 MeV



A. Bazavov at al.
arXiv:1701.04325

F. Karsch, 2001
hep-lat/0106019

PLB101(1981)89

The QCD phase diagram

LHC

TeV energies

High temperature and low net baryon density