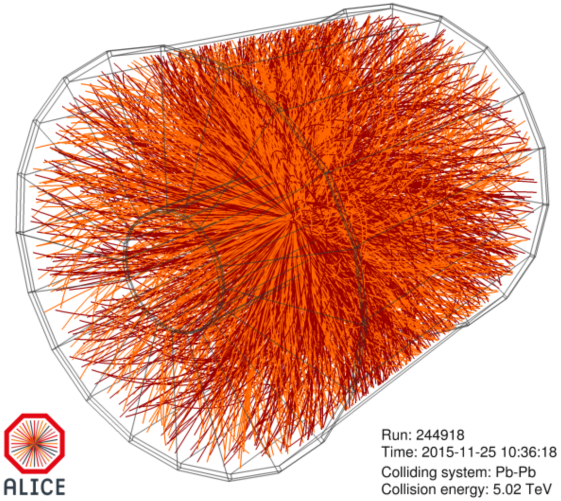
Physics at the LHC

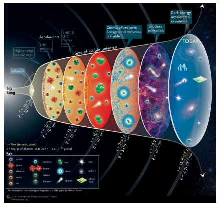
Hot QCD matter produced in ultra-relativistic heavy-ion collisions

Lecture 2
January 8, 2020

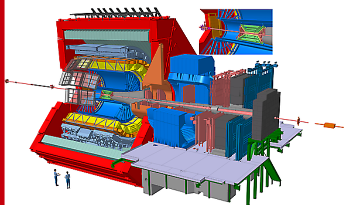


Silvia Masciocchi
GSI Darmstadt and Heidelberg University

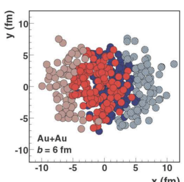
In the first lecture (Dec 18)



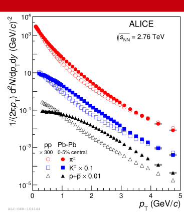
Heavy-ion collisions: Little Bangs



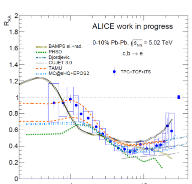
Experimental program at the LHC, ALICE



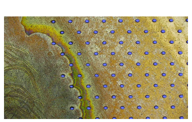
Global characteristics



Bulk particle production

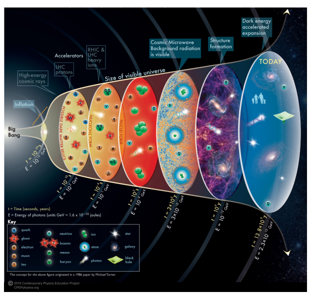


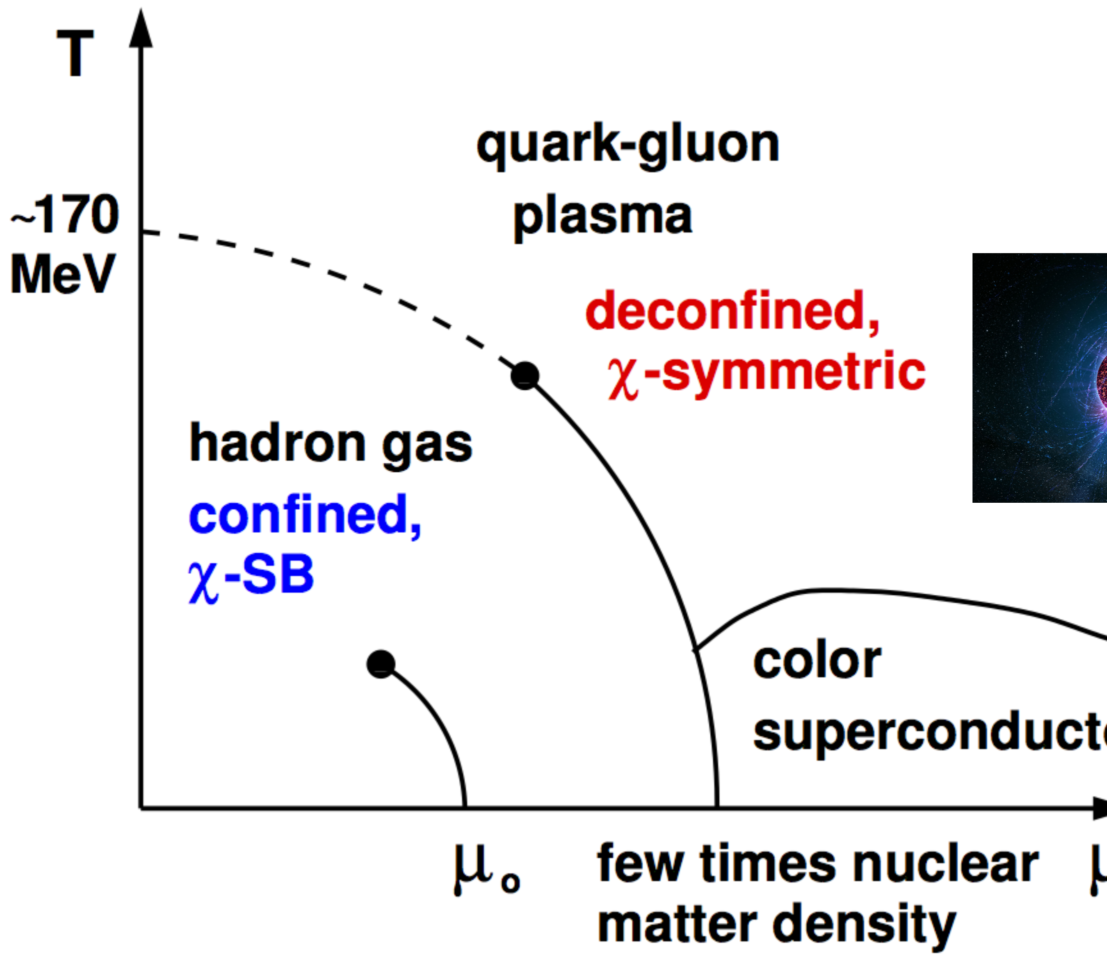
Quark-gluon plasma tomography with hard probes

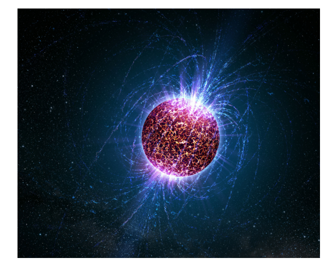


Research plans for near and further future

Early universe (few μs after the Big Bang)







Neutron stars

Baryo-chemical potential

Summary:

- Features of particle production in hadron interactions (pp on) inspire a thermodynamic treatment of QCD matter

- QCD phase diagram: μ_B and T

- With basic thermodynamic arguments, a phase transition from a hadron gas to a quark-gluon plasma is proposed

$$T_c \simeq 144\,\mathrm{MeV} \qquad \epsilon_{QGP} \simeq 850\,\mathrm{MeV/fm^3}$$

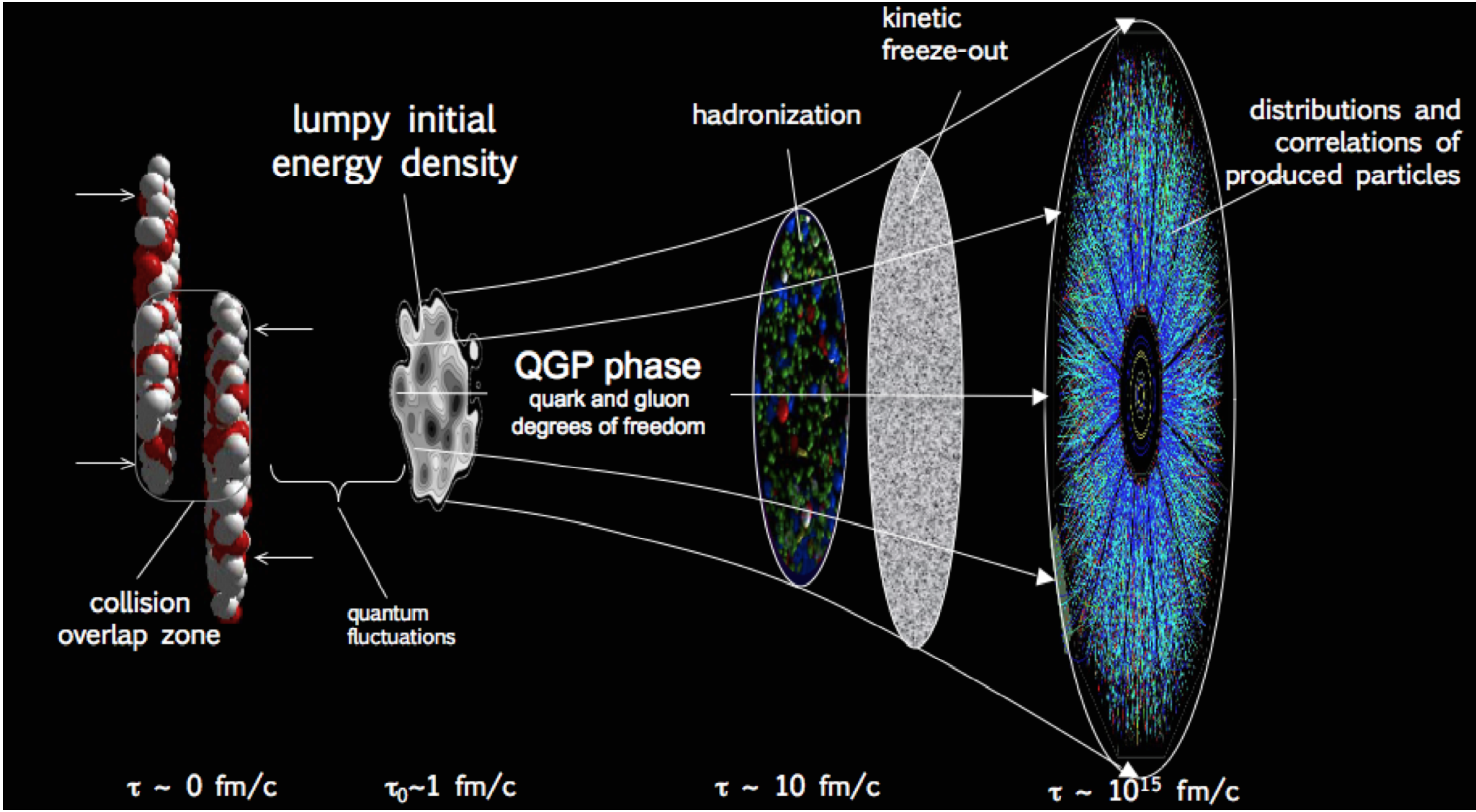
- Rigorous computations with Lattice QCD at $\mu_B = 0$:

$$T_C(\mu_B=\mu_Q=\mu_S=0) = (156.5 \pm 1.5)\ \mathrm{MeV}$$

$$\varepsilon_C \approx 0.42\ \mathrm{GeV/fm^3} \qquad (\sim 2.5 \times \varepsilon_{nuclear})$$

(lattice at $\mu_B > 3T_c$ difficult. Progress in the last years!)

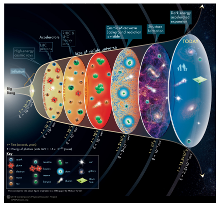
Heavy-ion collision evolution



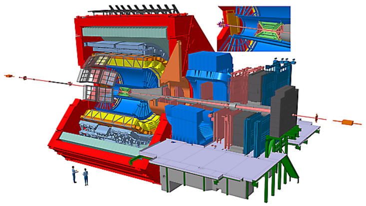
Time ~ 10^{-22} s

Volume ~ 50,000 fm^3 < 10^{-40} m^3

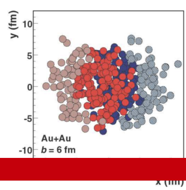
Outline



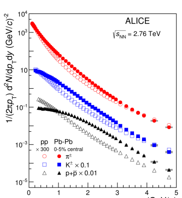
Heavy-ion collisions: Little Bangs



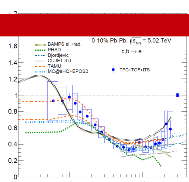
Experimental program at the LHC, ALICE



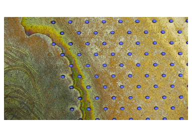
Global characteristics



Bulk particle production



Quark-gluon plasma tomography with hard probes

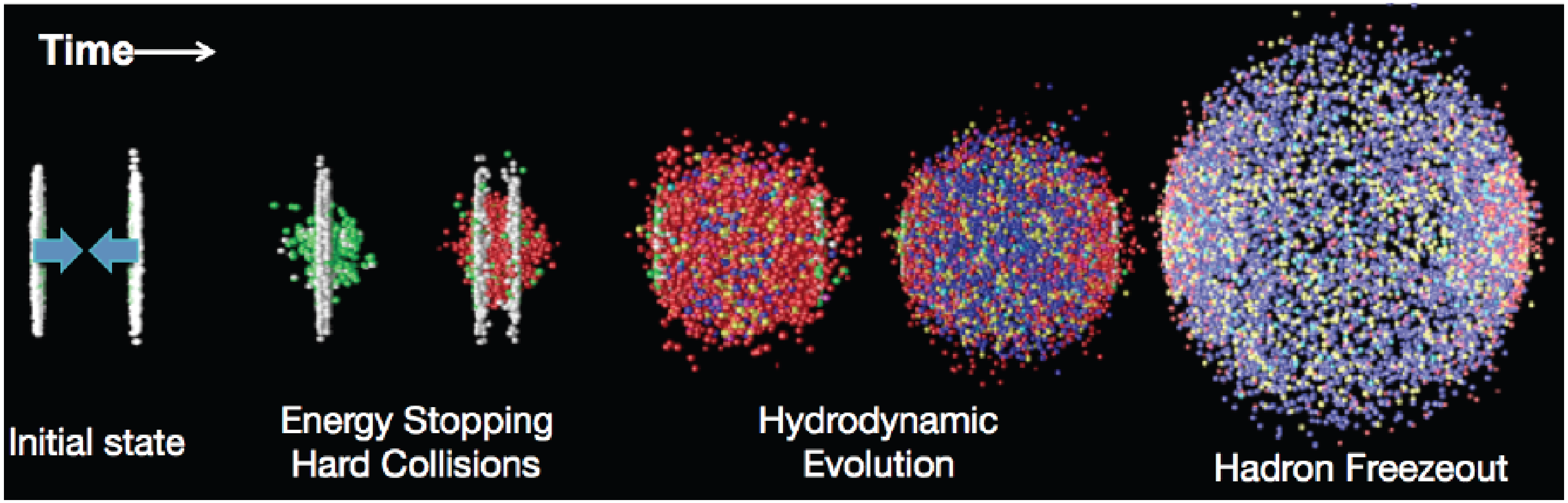


Research plans for near and further future

Outline

- Historical view: experimental opportunities, first theoretical ideas
- Thermodynamics of strongly interacting matter and phase diagram
- QCD matter under extreme conditions in nature and in the lab
- Global characteristics: centrality, energy density, multiplicities
- Bulk (soft) particle production
  - Thermal model, particle yields and chemical freeze-out
  - Small systems
  - (hyper-)(anti-)nuclei
  - Hydrodynamics, flow and correlations
  - Particle spectra, Blast-Wave fits and kinetic freeze-out
- Hard probes
  - Jets, heavy quarks, heavy quarkonia
- Future

Reminder: Ultra-relativistic heavy-ion collisions

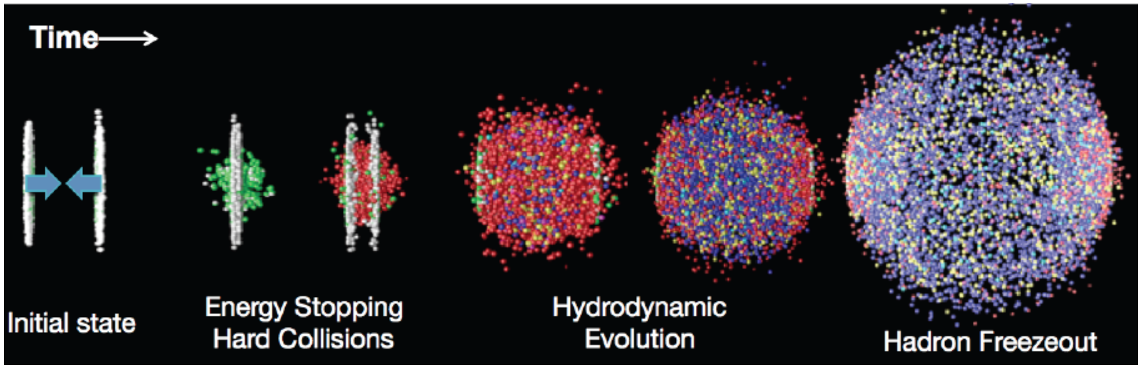


1. Initial conditions, pre-equilibrium, hard scattering processes
2. Thermalization: equilibrium is established ($t_{eq} \leq 1$ fm/c)
3. Expansion and cooling ($t_{QGP} < 10 – 15$ fm/c)
4. Hadronization (quarks and gluons form hadrons)
5. Chemical freeze-out: inelastic collisions cease, yields are defined
6. Kinetic freeze-out: elastic collisions cease, spectra are frozen ($t_{had} \sim 3\text{-}5$ fm/c)

$\approx 10^{-22}$ s

Measurements can only be performed at stages 5 and 6
From those, we want to deduce information on phases 2, 3, 4

Particle yields



1. Initial conditions, pre-equilibrium, hard scattering processes
2. Thermalization: equilibrium is established ($t_{eq} \leq 1$ fm/c)
3. Expansion and cooling ($t_{QGP} < 10 – 15$ fm/c)
4. Hadronization (quarks and gluons form hadrons)

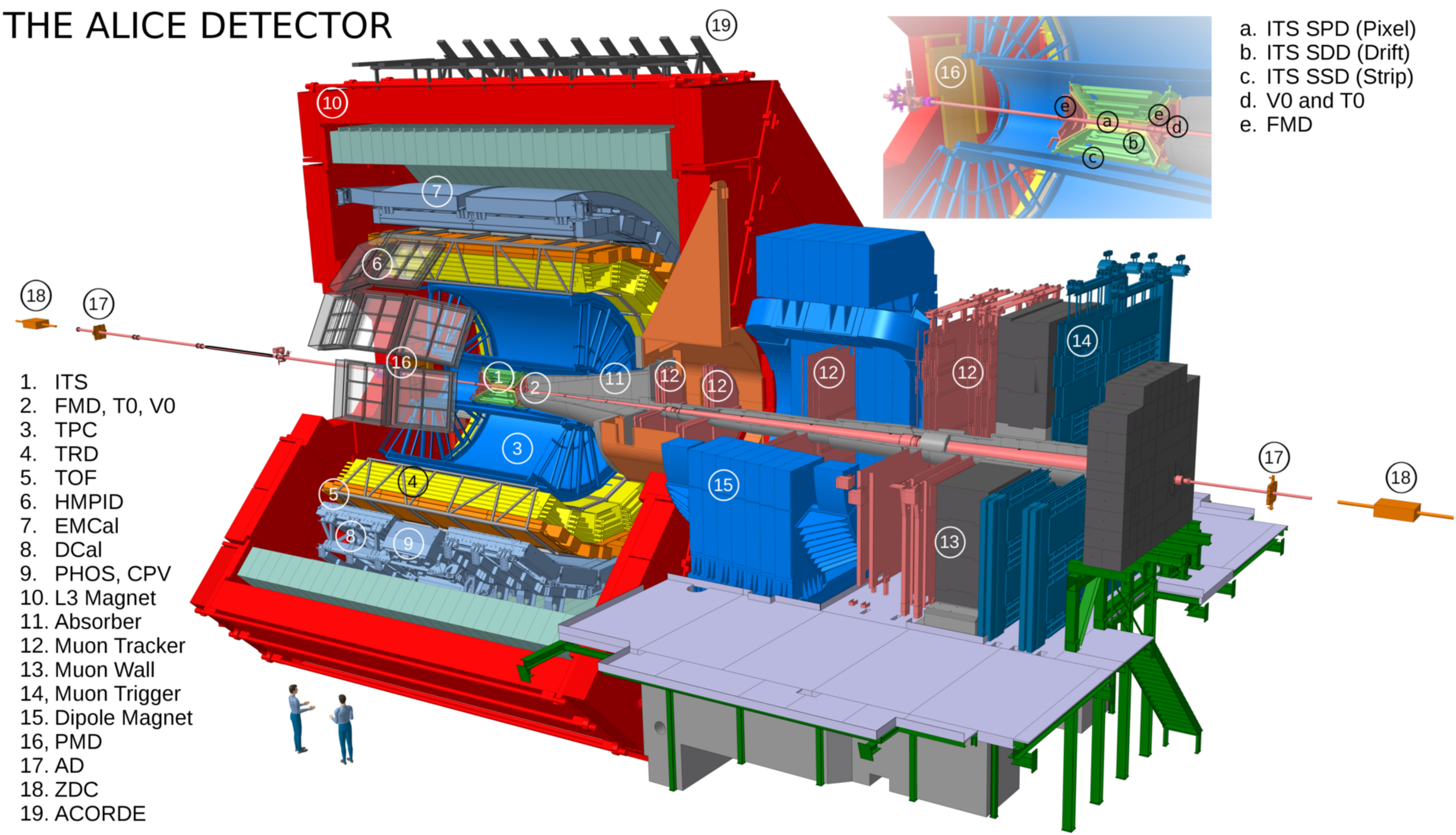
5. Chemical freeze-out:
    inelastic collisions cease
    yields and the distribution over species are defined
    - close to the phase boundary?
    - hadron abundances in equilibrium?
    - connection to hadronization?

6. Kinetic freeze-out: elastic collisions cease, spectra are frozen

YIELDS

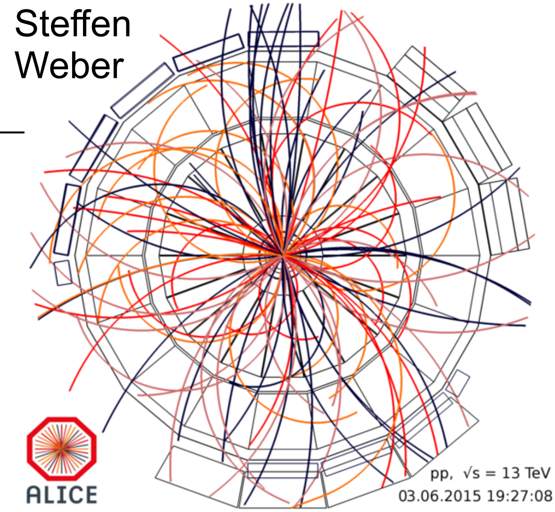
SPECTRA

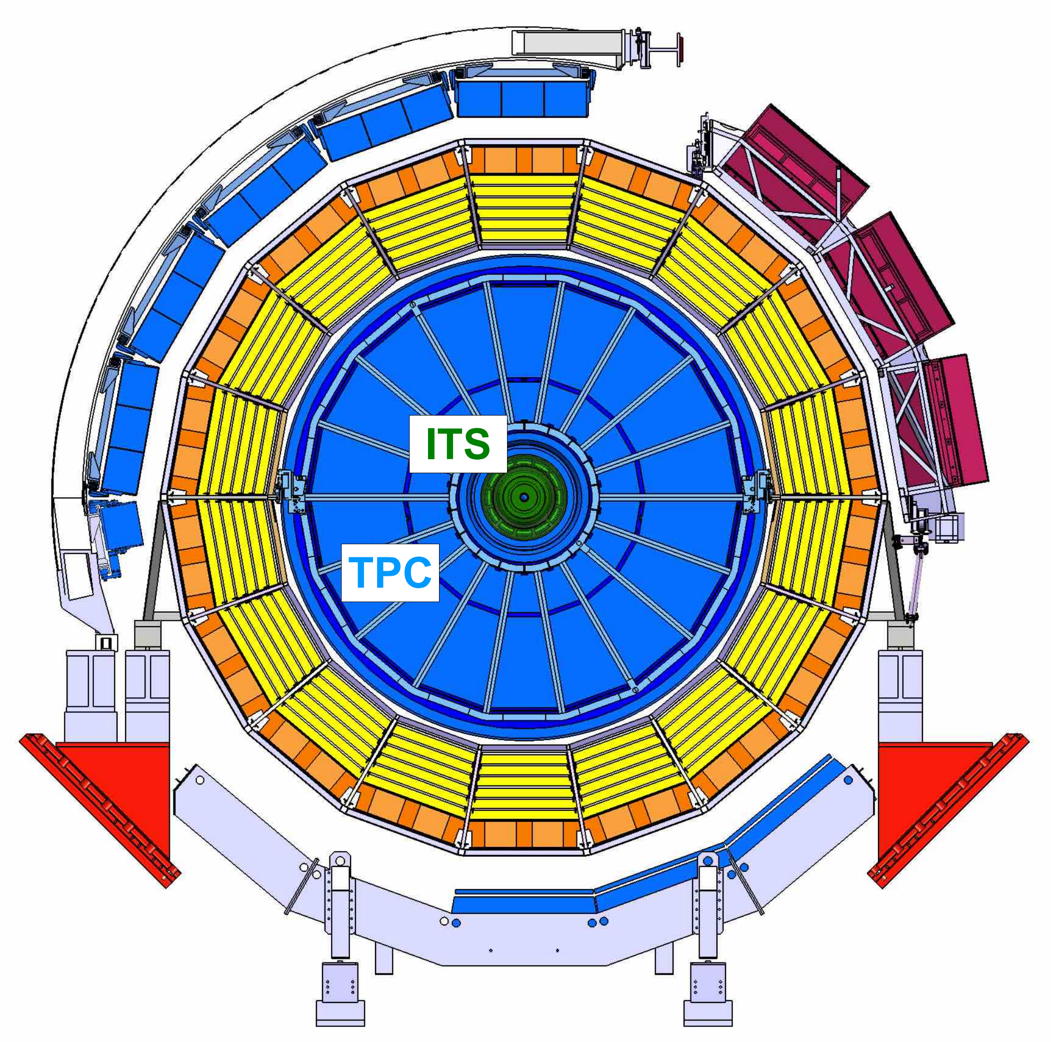
A Large Ion Collider Experiment



Track and vertex reconstruction

Steffen Weber



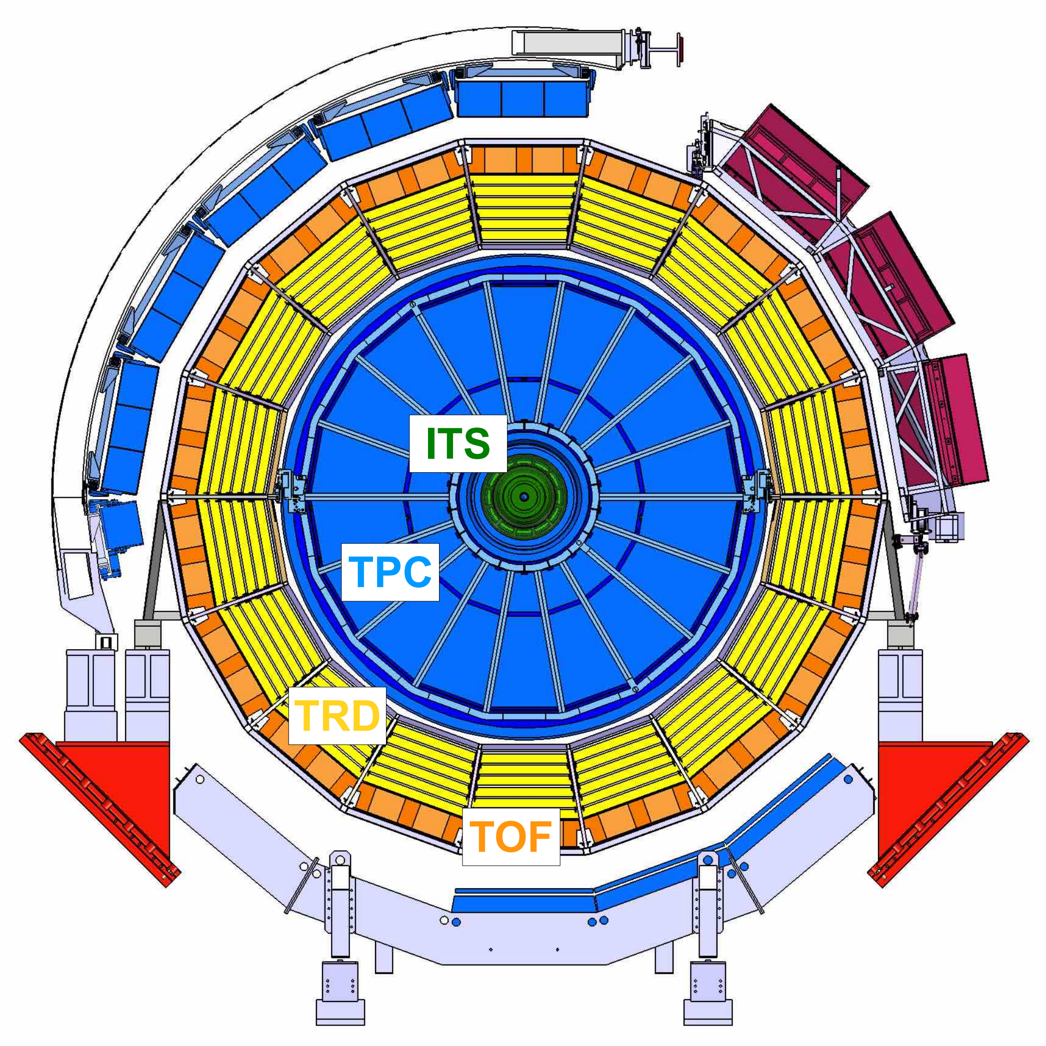


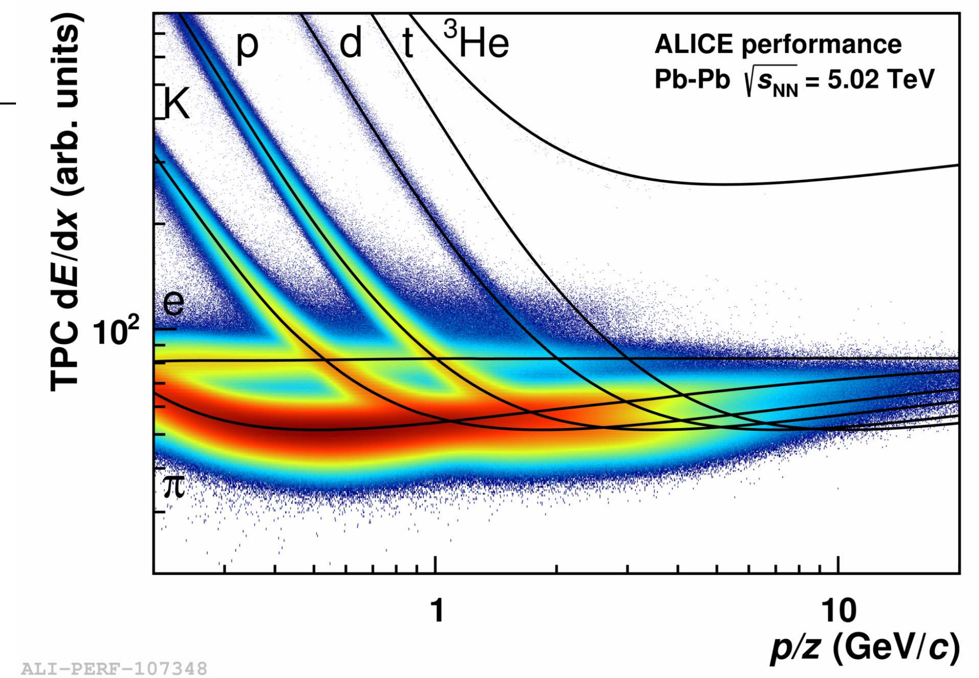
- L3 solenoid: B = 0.5 T → good acceptance for low momentum
- **Inner Tracking System ITS** in Run 1-2 with silicon pixel, drift and strip detectors
- **Time Projection Chamber TPC** 90 m^3 gas sensitive volume, in Run 1-2 with multi-wire proportional chambers

Spatial resolution (at vertex) ≈ 10 – 20 μm

Momentum resolution (perpendicular to beam) ≈ 1 %

Particle identification

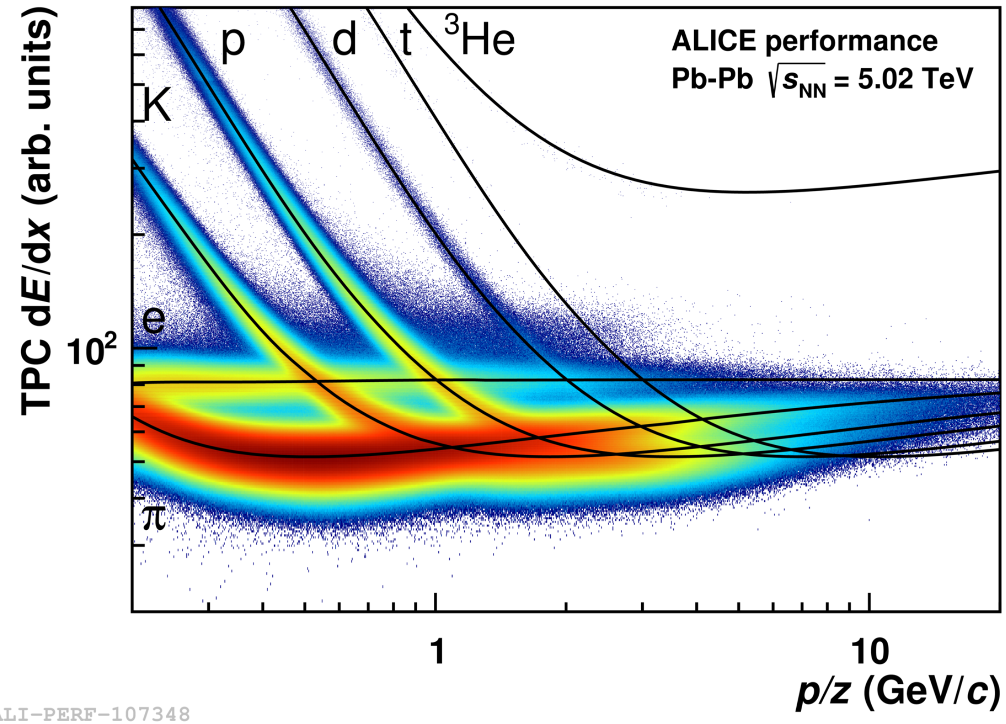




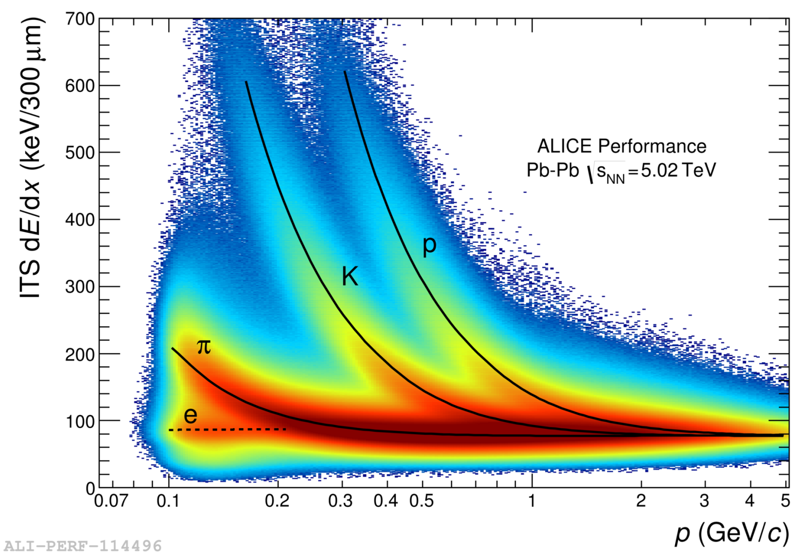
- **Time Projection Chamber TPC**
  specific energy loss dE/dx in gas
- **Inner Tracking System ITS**
  specific energy loss dE/dx in silicon
- **Transition Radiation Detector TRD**
  electron/hadron separation, trigger
- **Time-of Flight detector TOF**
  complementing the TPC at higher p
- **Calorimetry: EMCal, PHOS, DCAL**
- **Muon spectrometer**

ALICE: particle identification

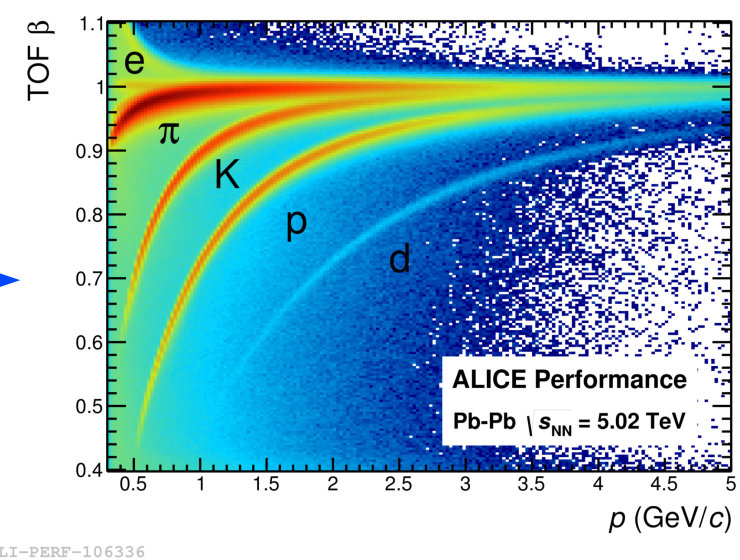
Time Projection Chamber



Inner Tracking System



Time Of Flight



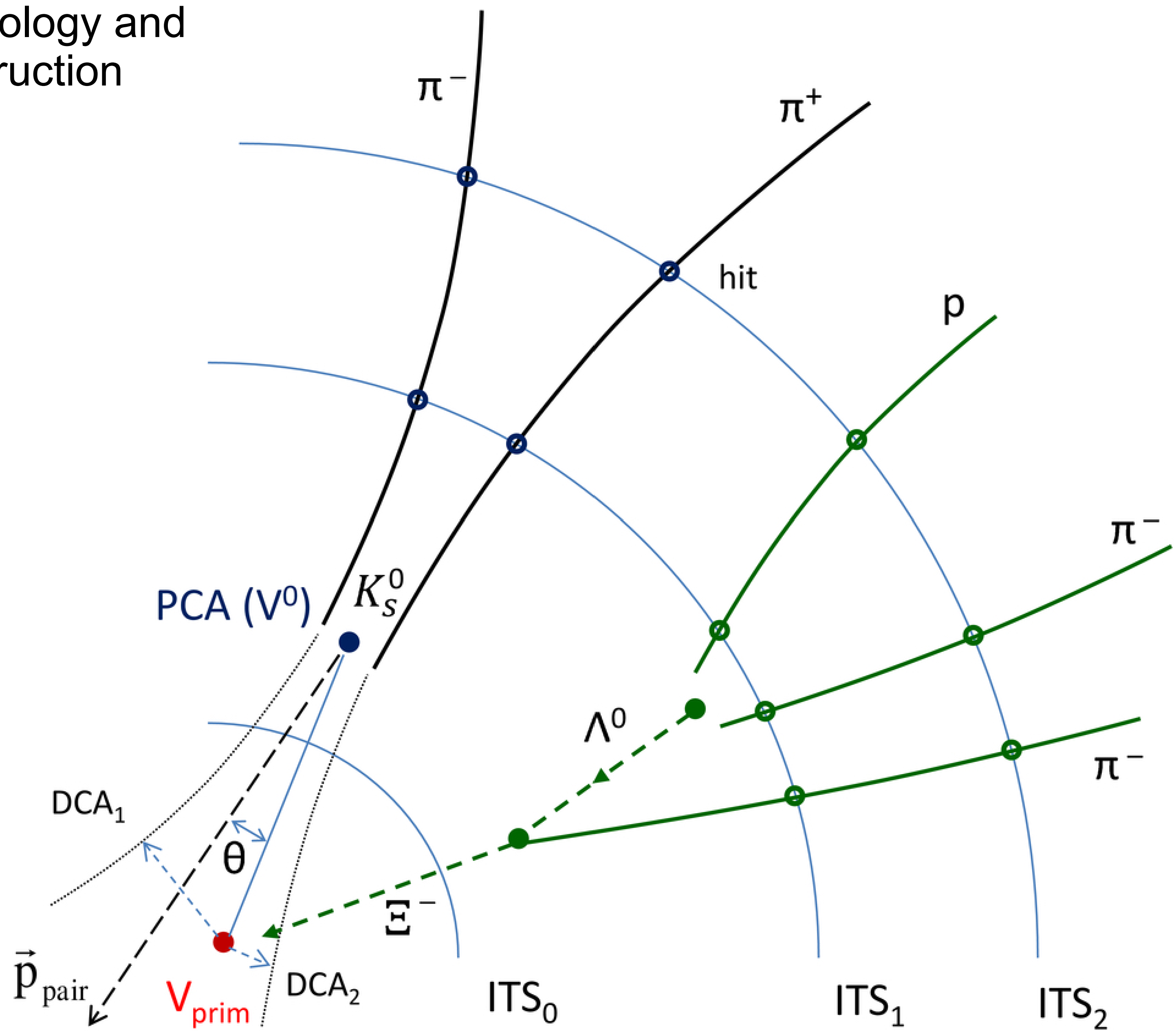
Particle decays

Selection on decay topology and invariant mass reconstruction

$K_S^0 \rightarrow \pi^+ \pi^-$

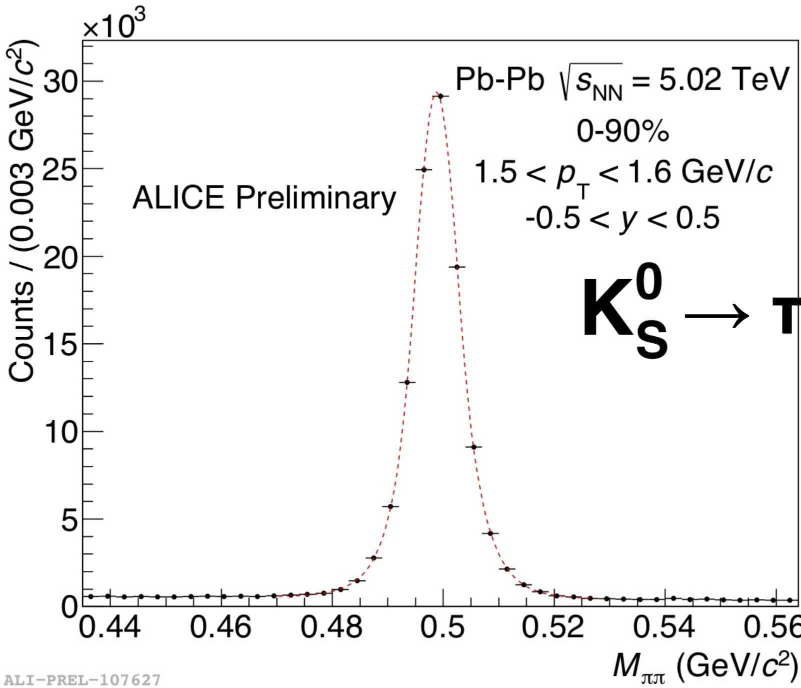
$\Lambda_0 \rightarrow p\, \pi^-$

$\Xi^- \rightarrow \Lambda_0\, \pi^-$

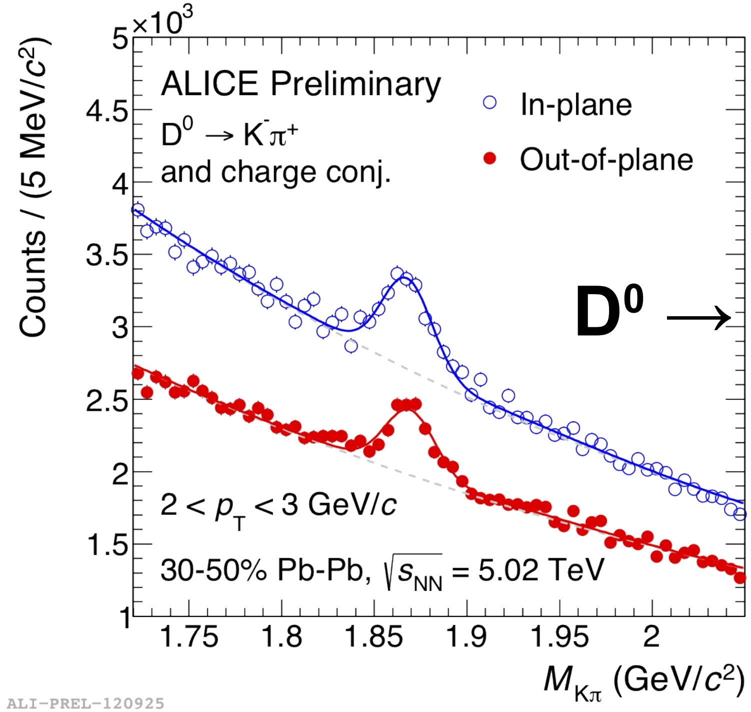


Int. J. Mod. Phys. A 29 (2014) 1430044

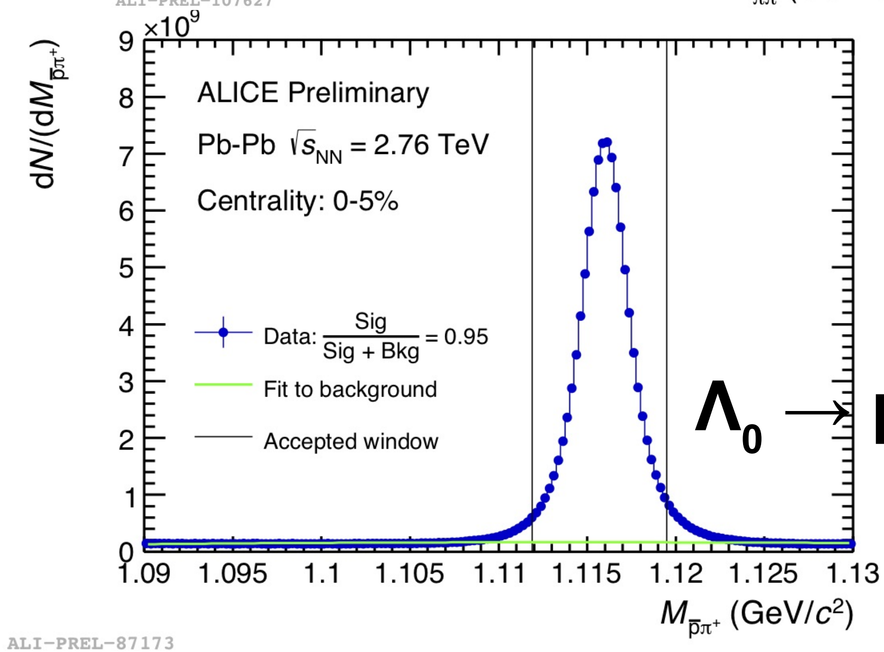
Invariant mass distributions (ALICE)



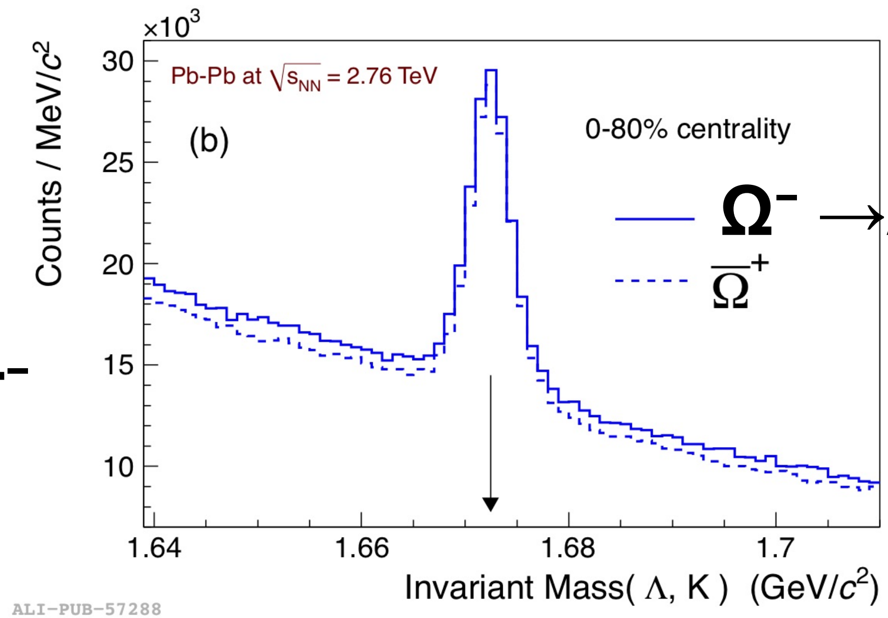
$K^0_S \rightarrow \pi^+ \pi^-$



$D^0 \rightarrow K^- \pi^+$



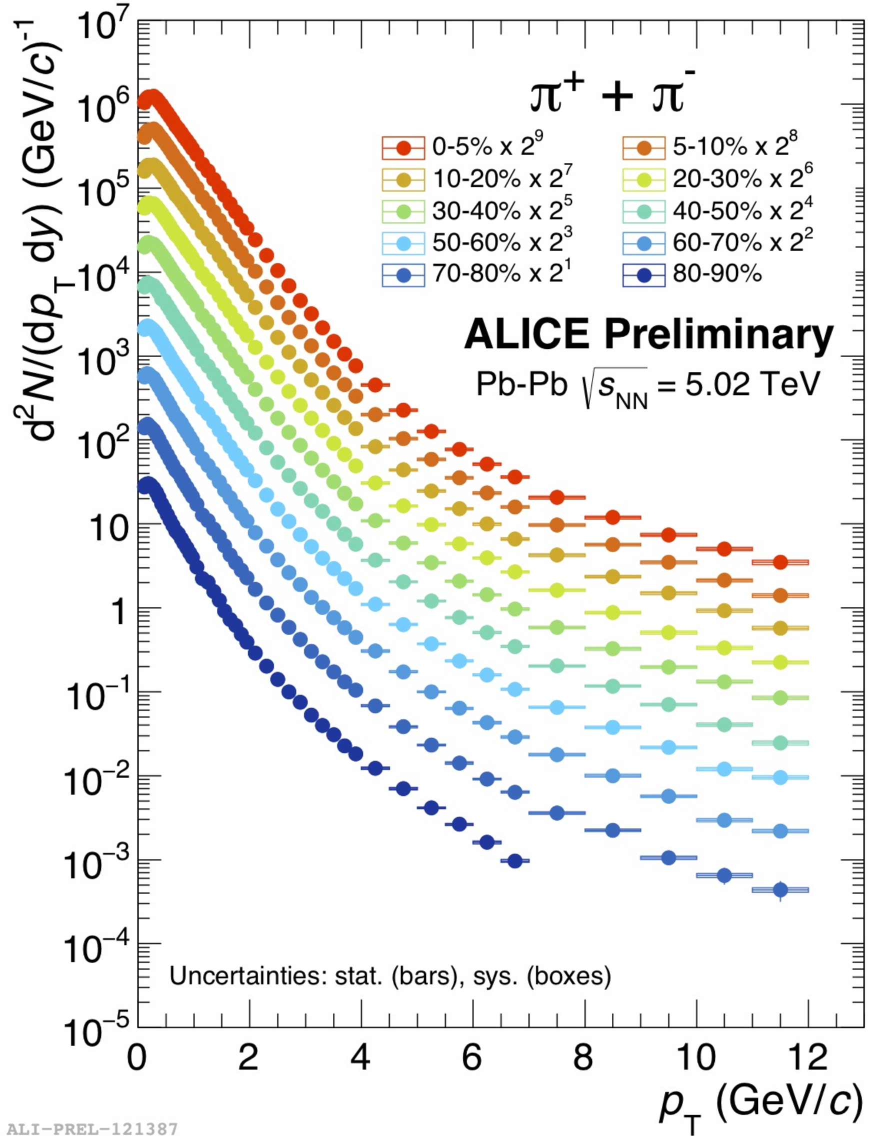
$\Lambda_0 \rightarrow p\, \pi^-$

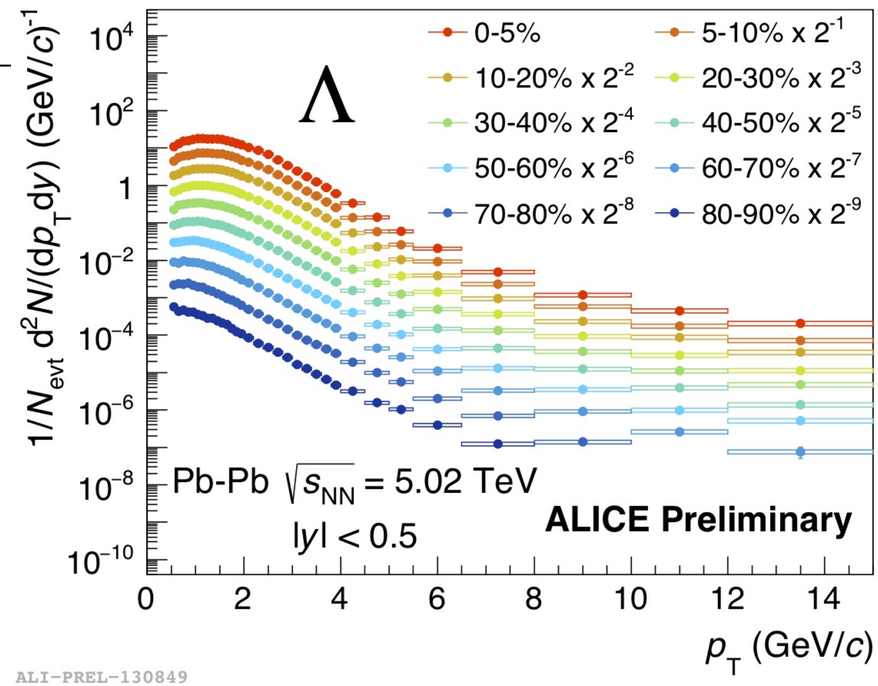


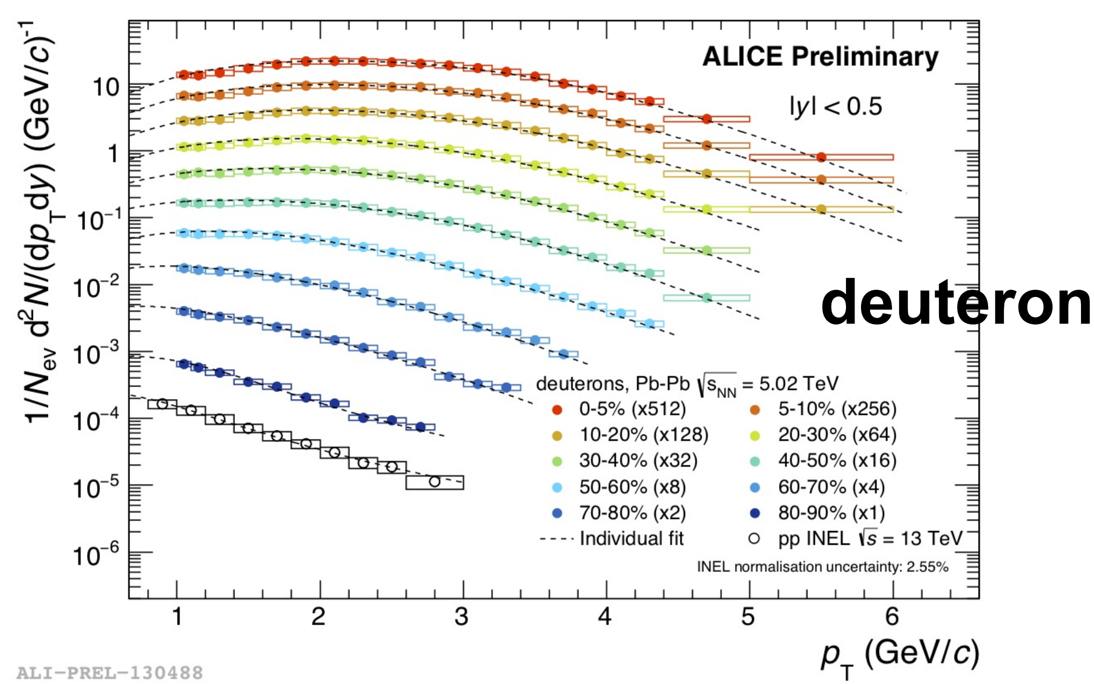
$\Omega^- \rightarrow \Lambda_0 K^-$

$\overline{\Omega}^+$

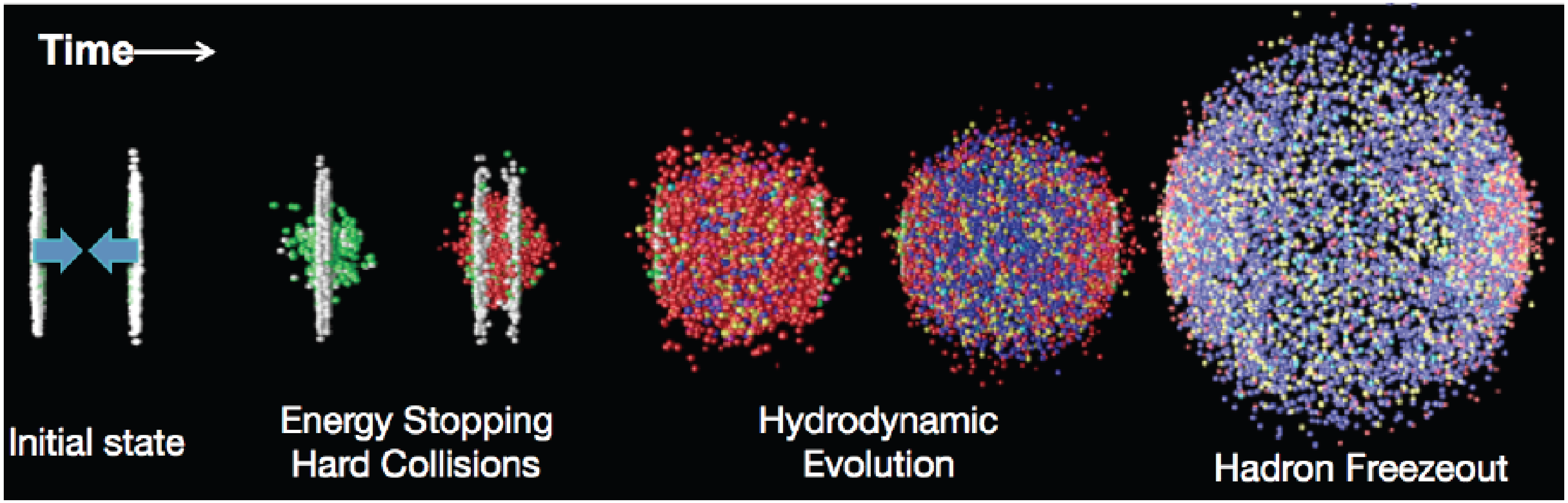
Identified particle spectra







Collision phases



Hydrodynamic evolution + freeze-out

Bulk particle production

Particles with momenta up to 2-3 GeV/c

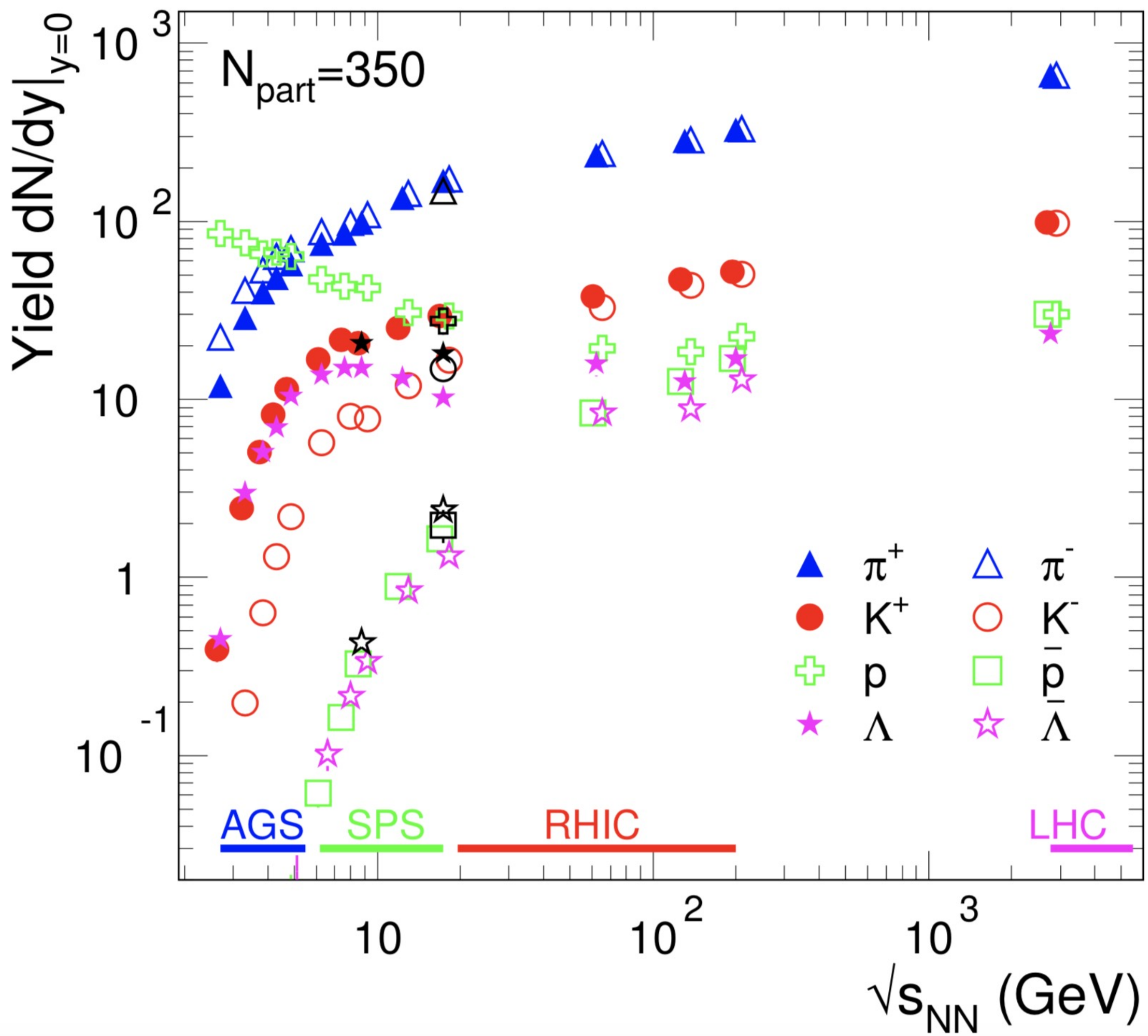
Particle yields

and the thermal model
(or statistical hadronisation model)

A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel

Nature, 561 (2018) 321

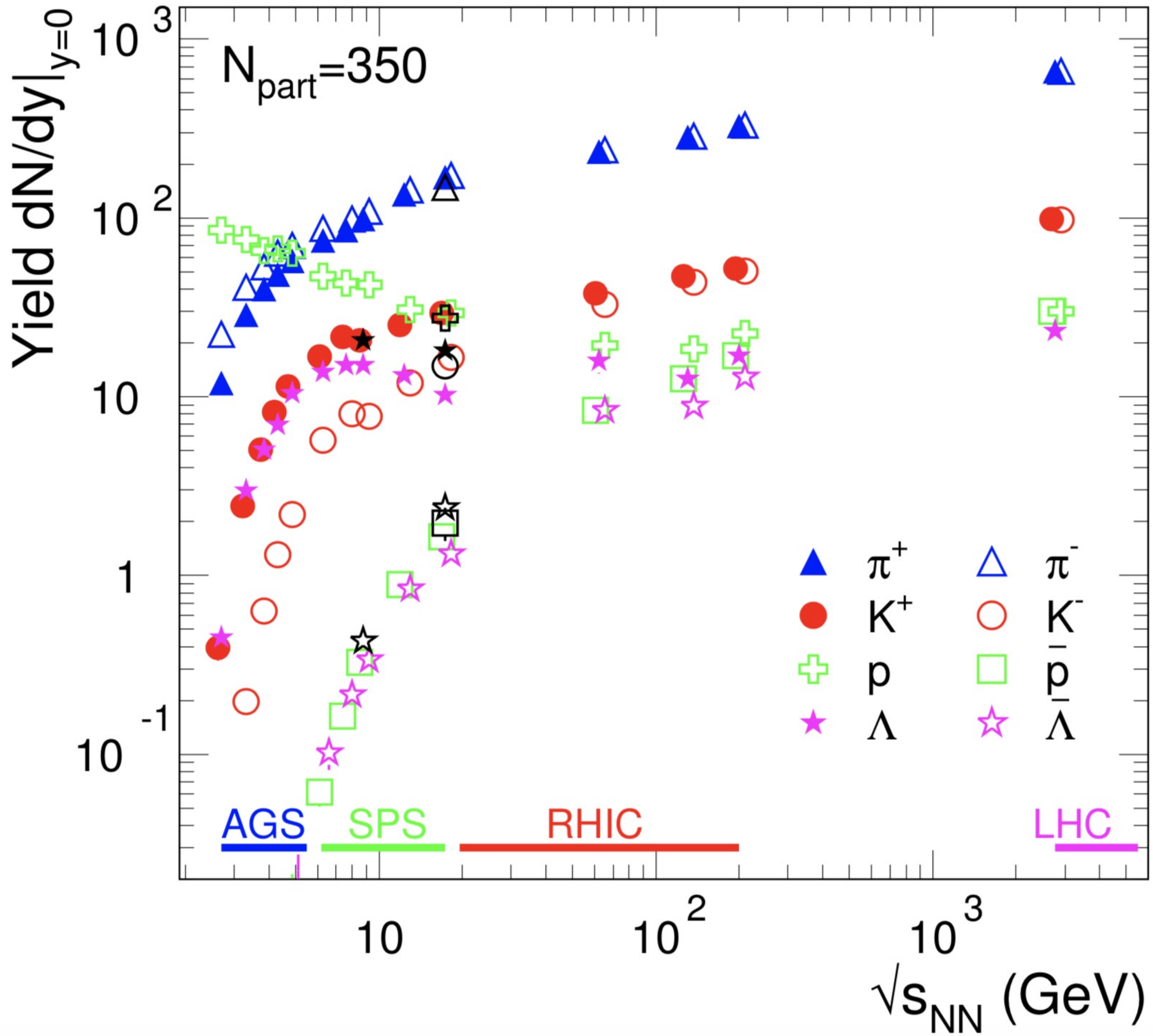
(p_T-integrated) hadron yields at mid-rapidity



A. Andronic, arXiv:1407.5003

- Central collisions
- $\pi^{\pm}$ ($u\bar{d}$, $\bar{u}d$), m=140 MeV
  $K^{\pm}$ ($u\bar{s}$, $\bar{u}s$), m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m= 1116 MeV
  not here: Ξ(dss), Ω(sss)
- At the highest energies: practically all newly created
- At lower energies:
  - Stopping power → baryons vs anti-b.
  - u, d quarks remnants from incoming nuclei

(p_T-integrated) hadron yields at mid-rapidity



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- $\pi^\pm$ ($u\bar{d}$, $\bar{u}d$), m=140 MeV
  $K^\pm$ ($u\bar{s}$, $\bar{u}s$), m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m= 1116 MeV
  not here: Ξ(dss), Ω(sss)
- Particle abundances clearly follow the mass hierarchy
- Natural to think of the thermal model

Core of the thermal model

Probability to find a particle on a given energy level j: $P_j = \dfrac{\exp\left(-E_j/k_B T\right)}{Z}$

Z: partition function
the sum over all
possible states

Boltzmann factor

Grand canonical partition function for species i computed as:

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln\left[1 \pm \exp\left(-(E_i - \mu_i)/T\right)\right]$$

$g_i = (2J_i+1)$ spin degeneracy factor

T temperature

$E_i = \sqrt{(p^2+m_i^2)}$ total energy; (+) for fermions, (-) for bosons

$\mu_i = \mu_B B_i + \mu_{I3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials (conservation on average of quantum numbers)

Initial conditions: I_3^{tot}, N_B^{tot}, $S^{tot}=0$, $C^{tot}=0$ (charm)

Thermal fits to hadron abundances

Based on the partition function Z, the individual hadron yields are:

$$n_i = \frac{N_i}{V} = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$$

- 555 particle species included in Z, up to light nuclei, charm, beauty
- Resonances are considered with their widths
- Canonical treatment applied whenever abundances are small

Fit: minimize

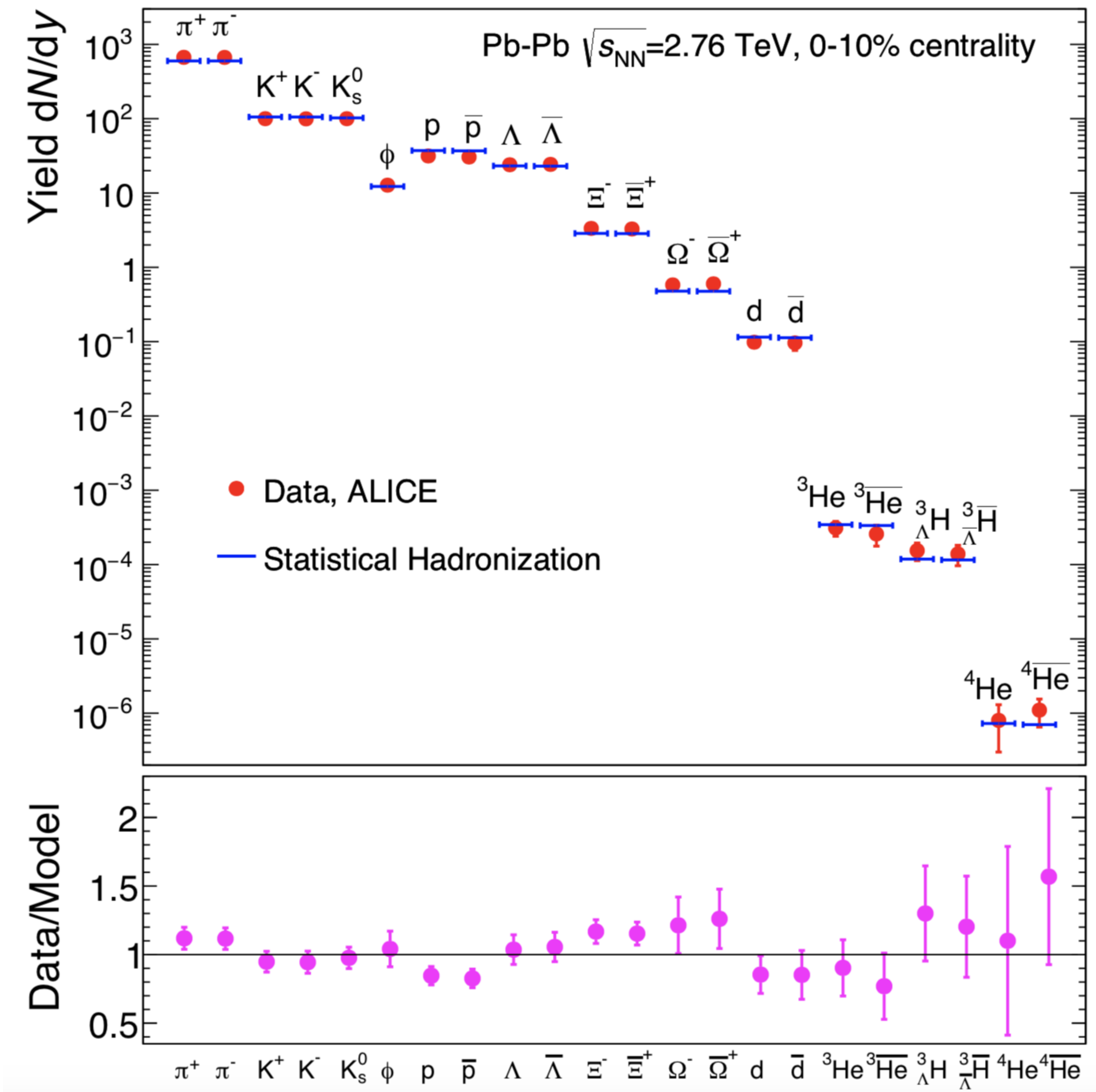
$$\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$$

N_i = measured hadron yield for particle i

σ_i = experimental uncertainty (statistical and systematic)

Free parameters: T, μ_B, V ... test of assumption on chemical equilibrium

Thermal fit: Pb-Pb, 2.76 TeV, 0-10%



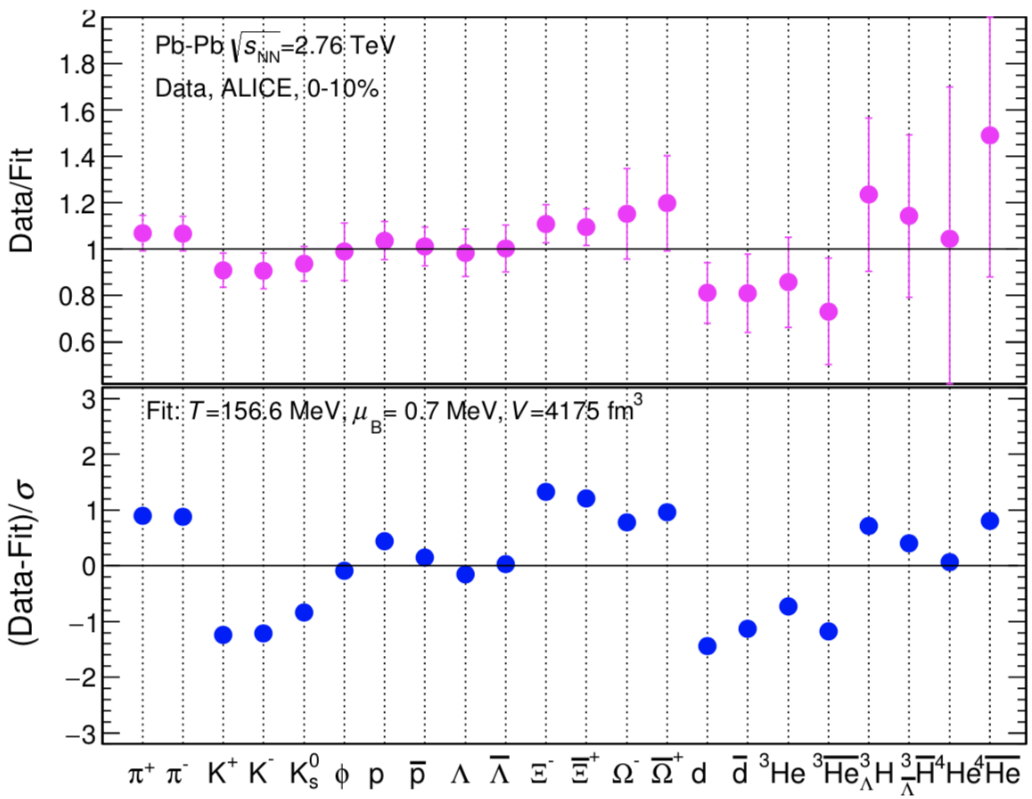
T_{CF} = 156.5 ± 1.5 MeV

μ_B = 0.7 ± 3.8 MeV

$V_{\Delta y=1}$ = 5280 ± 410 fm^3

χ^2/ndf = 29.3/19

LHC proton-puzzle clarified



arXiv:1808.03102

Non-strange baryon sector treated in S-matrix formalism (πN scattering phase shifts)
→ proton yield in model decreased by 17%

T_{CF} = 156.6 ± 1.7 MeV

μ_B = 0.7 ± 3.8 MeV

$V_{\Delta y=1}$ = 4175 ± 380 fm^3

χ^2/ndf = 16.7/19

Thermal fits at different collision energies: T_{CF}, μ_B

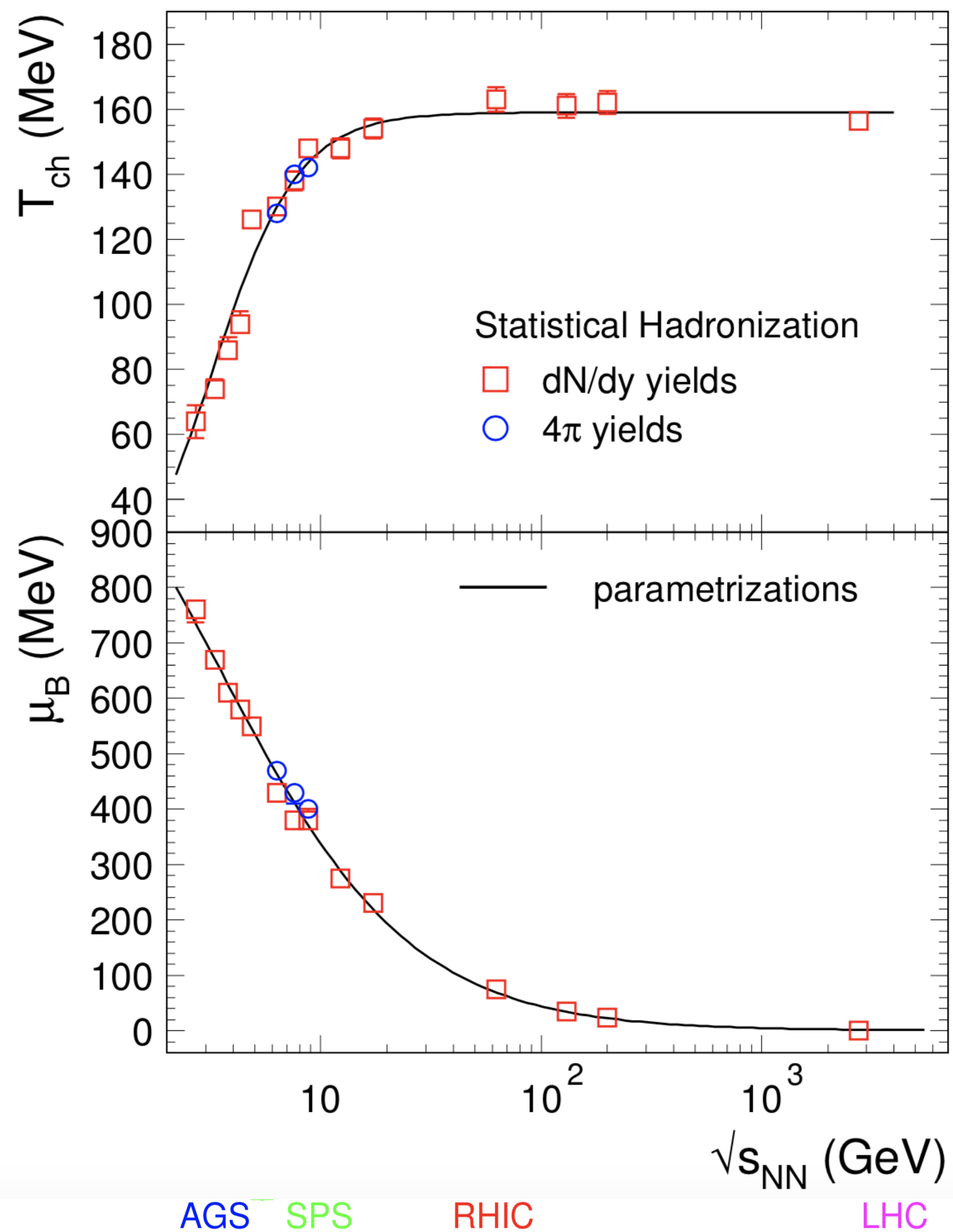
Central collisions

Thermal fits indicate a limiting temperature

$$T_{lim} = 158.4 \pm 1.4 \text{ MeV}$$

$$\mu_B \rightarrow 0 \text{ MeV}$$

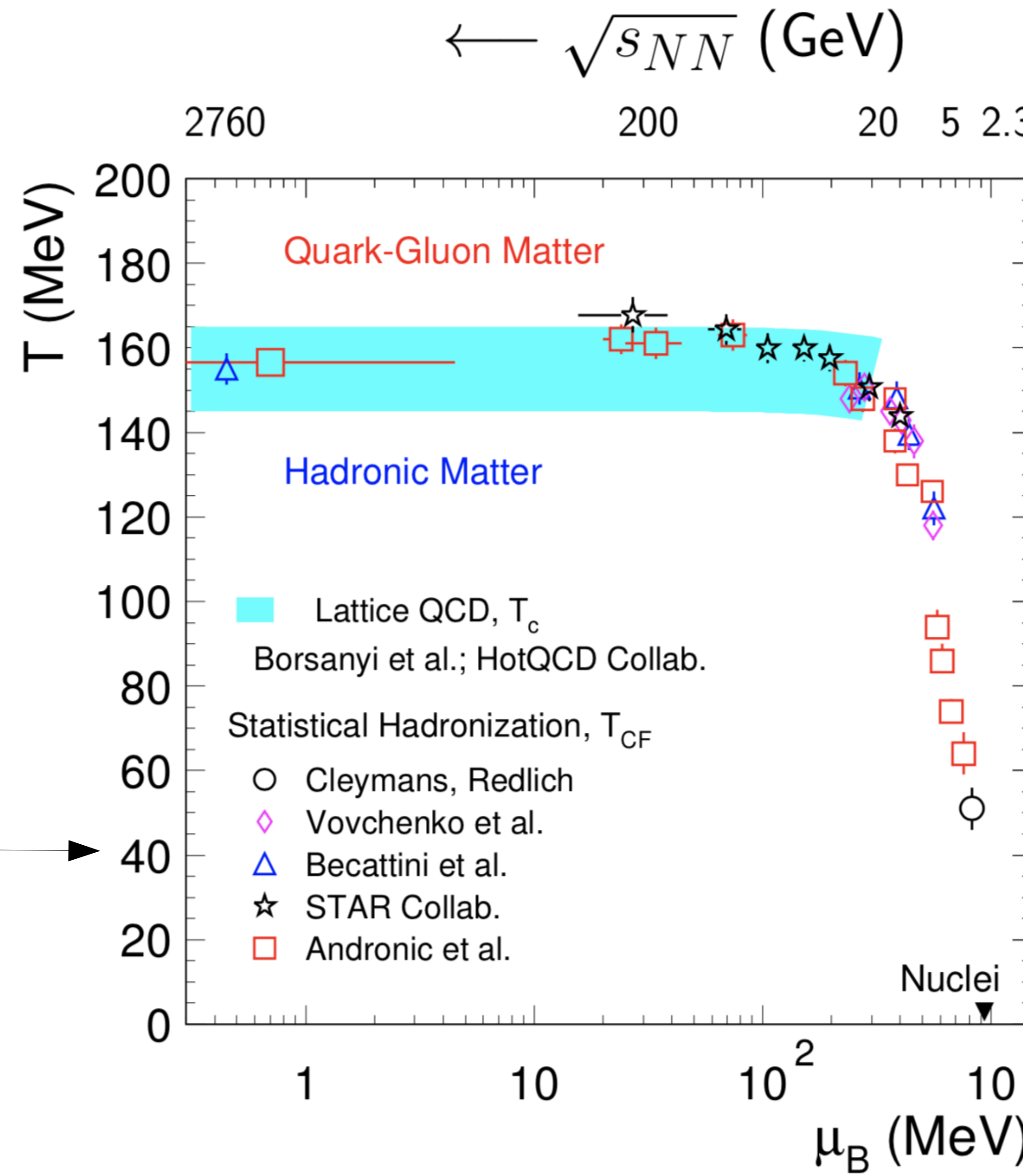
NPA 772 (2006) 167
PLB 673 (2009) 142



Back to the phase diagram of QCD

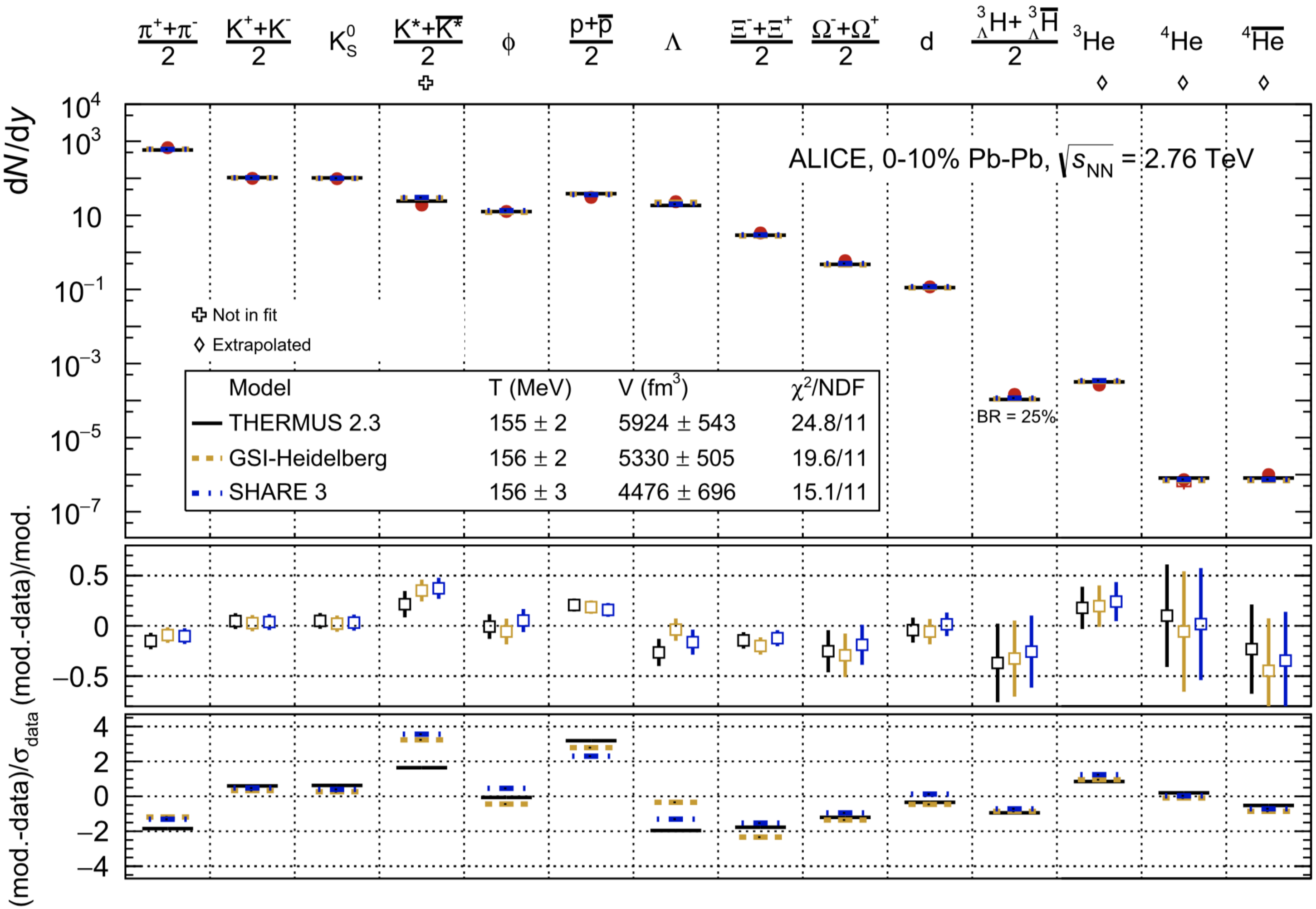
Agreement with the latest lattice QCD results !

Several realizations of the thermal model concept



More thermal models

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

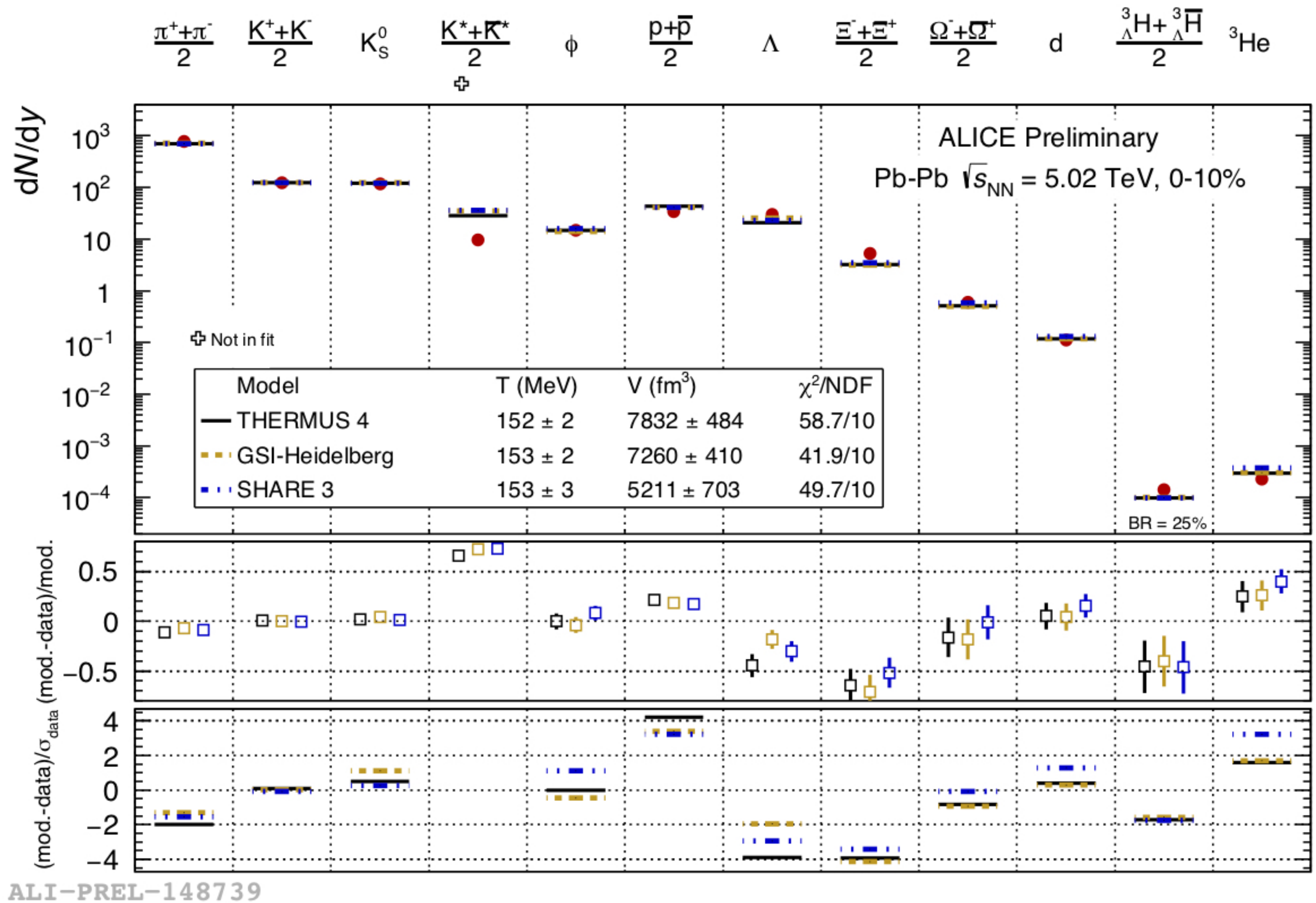


THERMUS: Wheaton et al, Comput.Phys.Commun, 180 84
GSI-Heidelberg: Andronic et al, Phys. Lett. B 673 142
SHARE: Petran et al, arXiv:1310.5108

QM2018

More thermal models

ALICE 0-10% Pb-Pb data $\sqrt{s_{NN}}$ = 5.02 TeV



Slightly lower temperature ≈ 153 MeV

Larger volume

Higher χ^2/ndf

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

QM2018

Thermal model and charm (at the LHC)

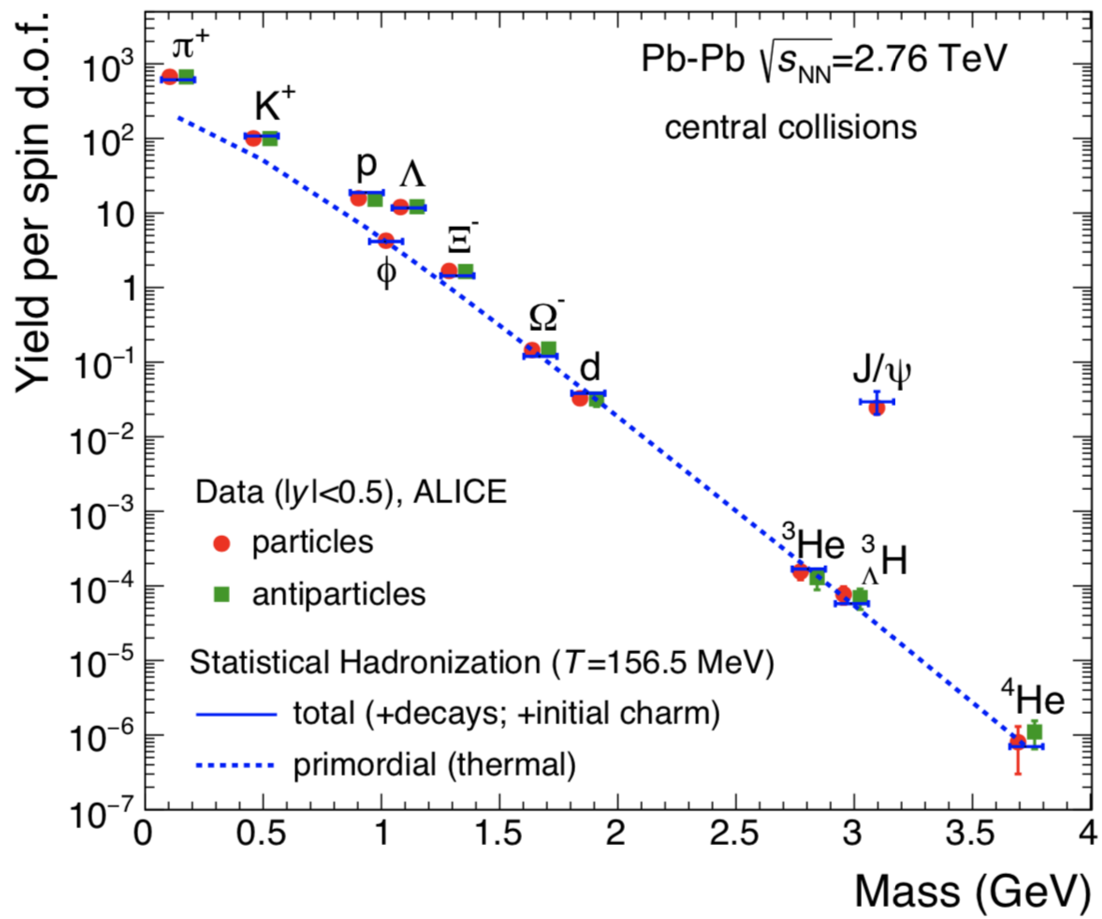
Also at the LHC, amount of charm produced thermally is very small (negligible).

Charm ($c\bar{c}$) produced in very early hard parton scatterings.

Still, experimental data (LHC) indicate thermalization of charm

Here: add 10 $c\bar{c}$ pairs “on top” at mid-rapidity (|y|<0.5)

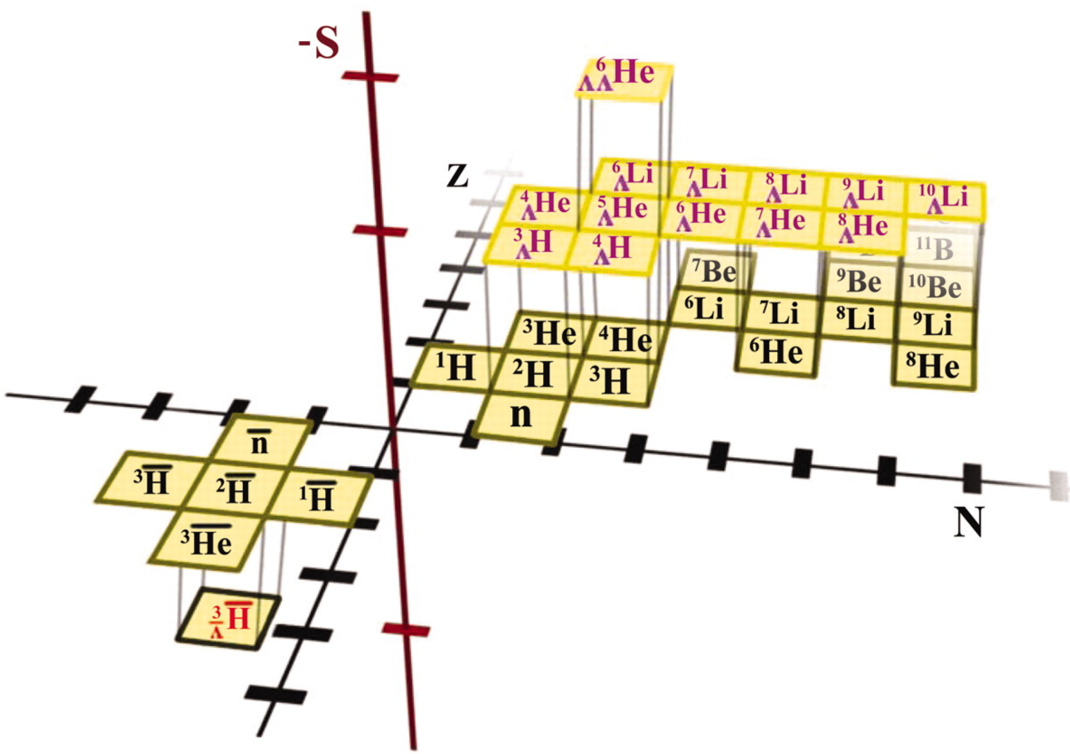
(30 times the thermal amount)



arXiv:1901.09200

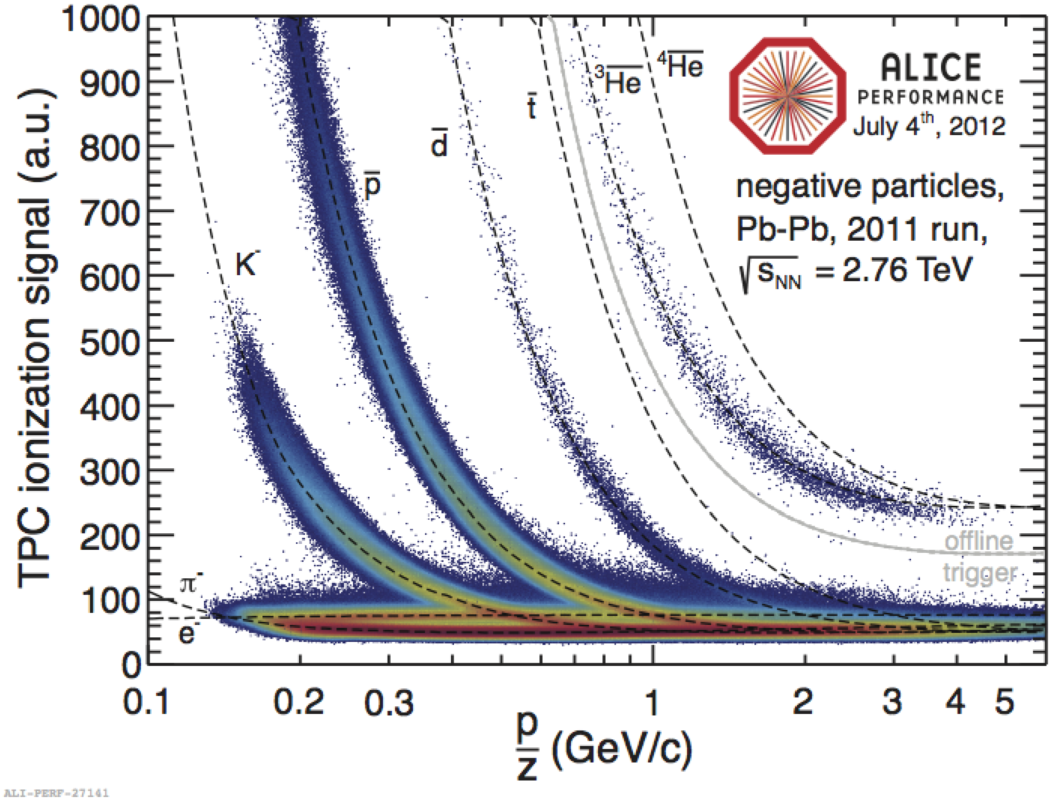
Production of light nuclei and anti-nuclei

and (anti-)hyper-nuclei



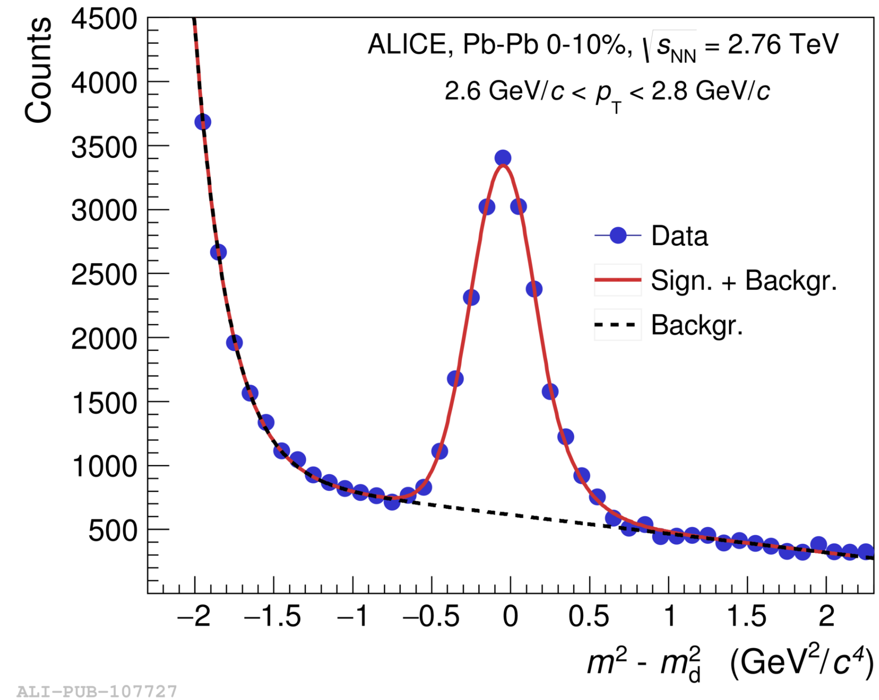
Detection of light (anti-)nuclei

Time Projection Chamber (TPC)



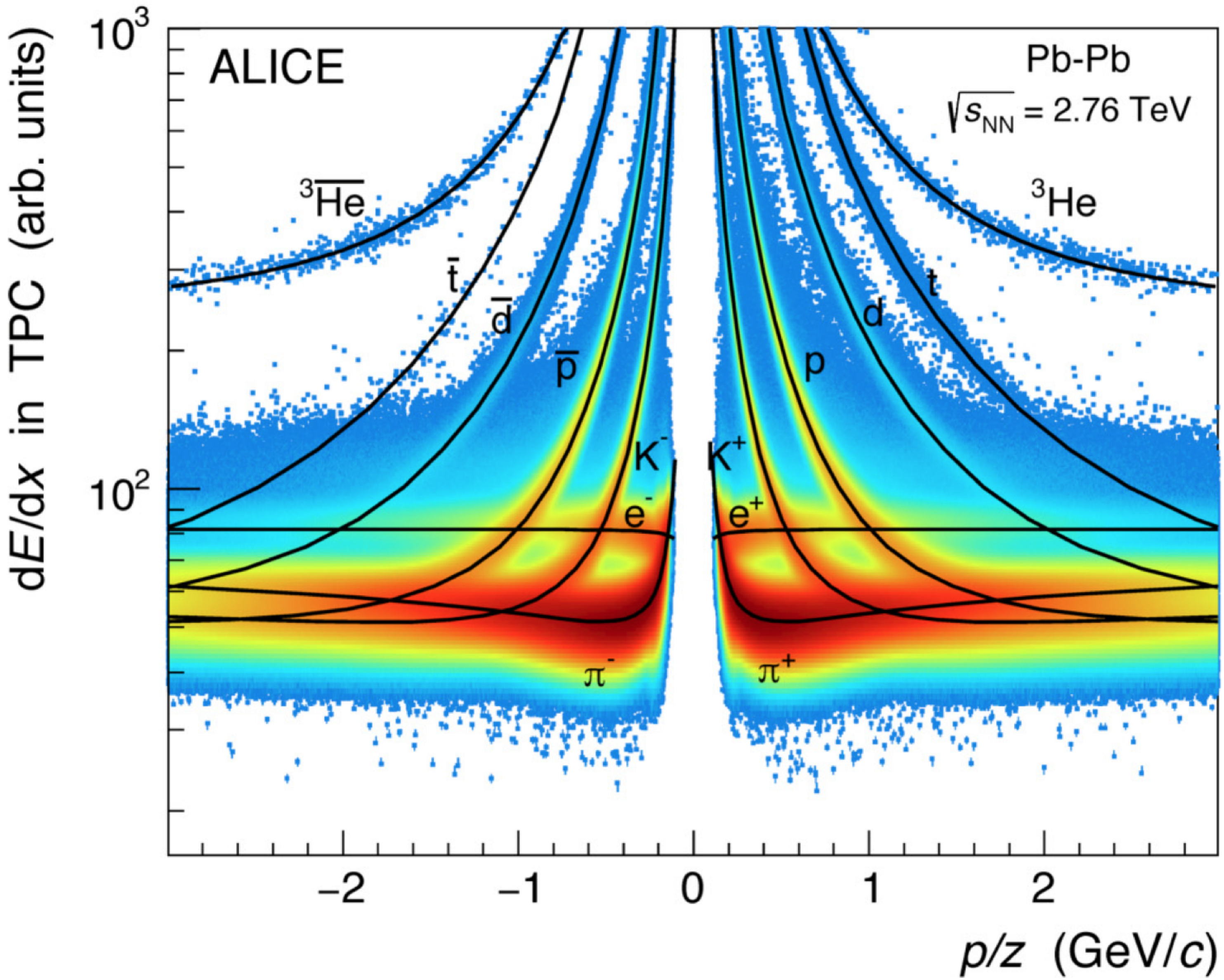
Low momenta: identification via specific energy loss dE/dx by particles in the gas of the TPC

Time-Of-Flight detector (TOF)



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

Time Projection Chamber: dE/dx



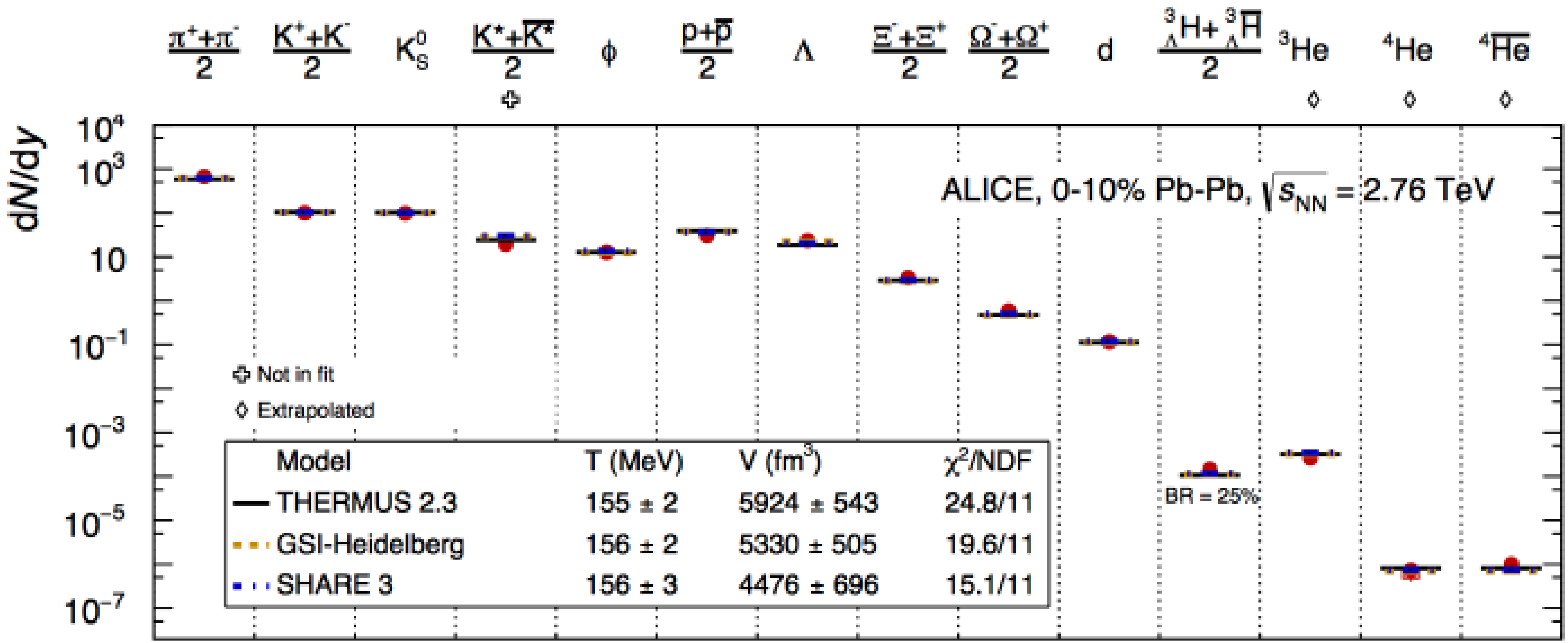
Phys.Rev. C93 (2016) 024917

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 ${}^3_\Lambda H$ ${}^3He$ ${}^4He$ $\overline{{}^4He}$



Nucl.Phys. A971 (2018) 1-20

Light nuclei measurements: motivation

Light nuclei and anti-nuclei:

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

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

+ anti-particles

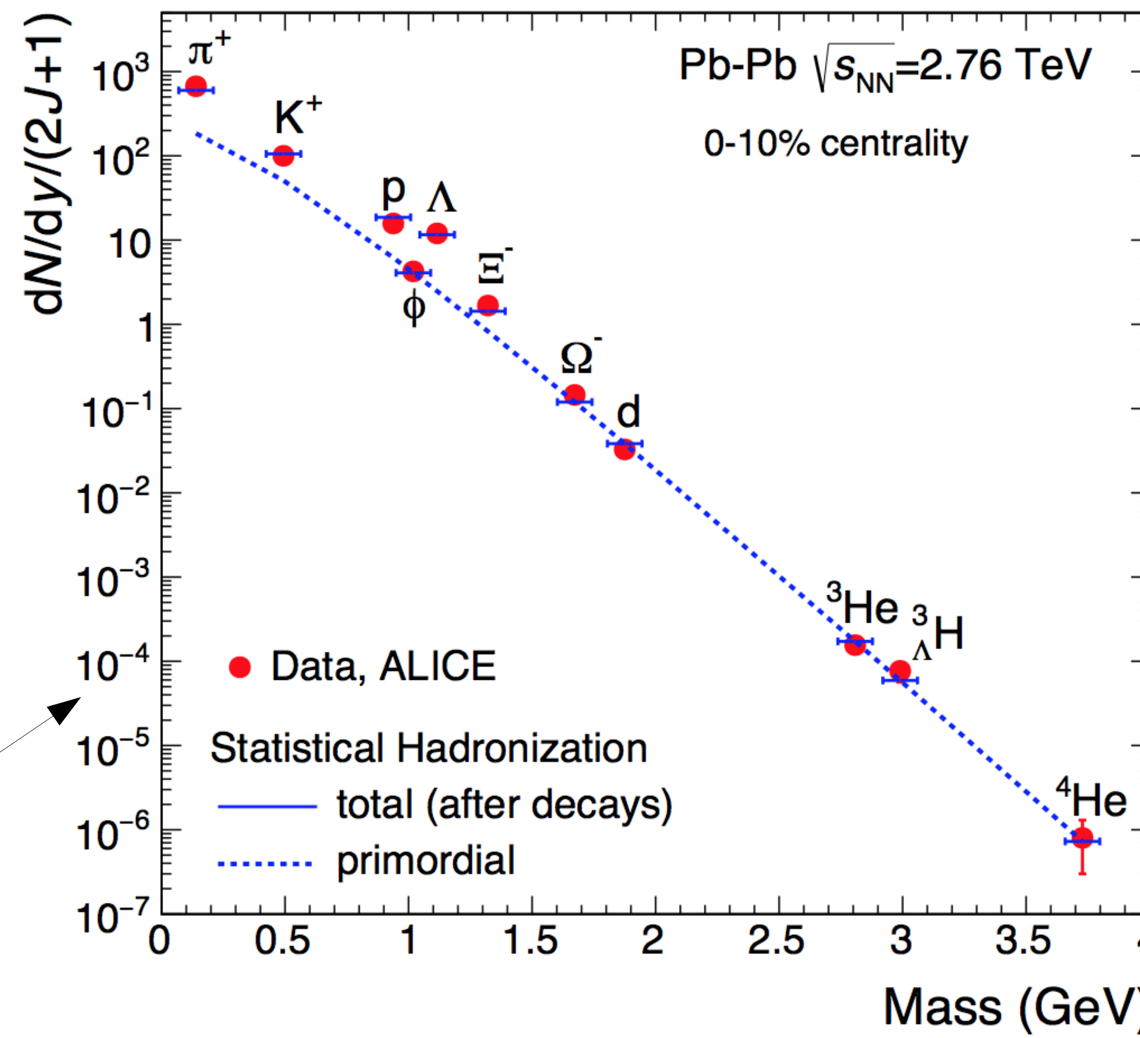
- Study their production mechanism
  - ➔ Test model predictions, e.g. coalescence or thermal model
  - ➔ Dependence on collision system (AA, pp, pA)
- Search for rarely produced anti- and hyper-matter
- Measure their properties (example: $^{3}_{\Lambda}He$ lifetime)
- Explore QCD inspired model predictions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

Production: statistical thermal model

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

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

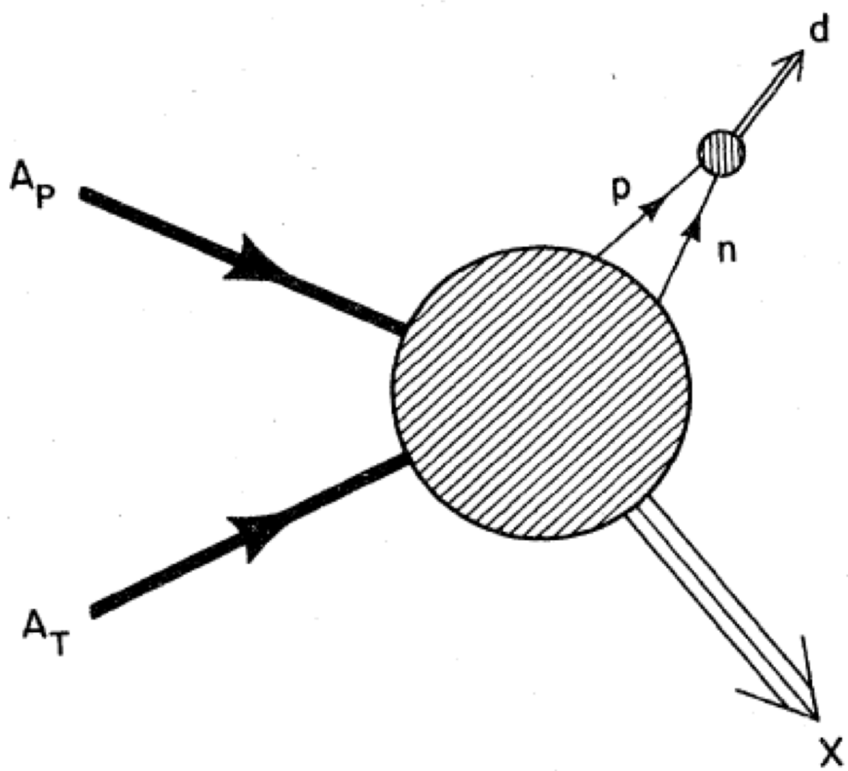
Measured hadron abundances devided by the spin degeneracy factor (2J+1)



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

Production: coalescence

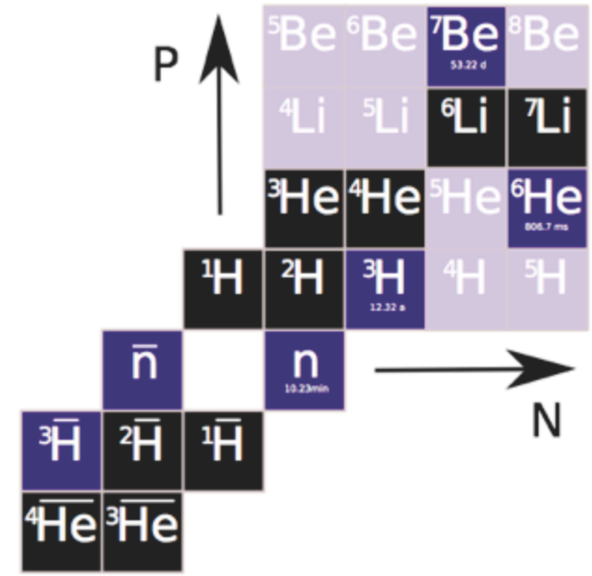
J. I. Kapusta, PRC21, 1301 (1980)

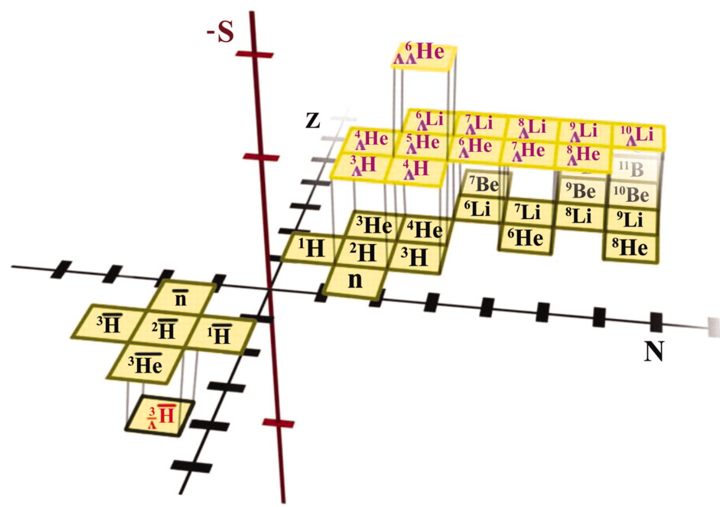


- Nuclei are formed by protons and neutrons which are nearby in space and have similar velocities (after kinetic freeze-out)
- Produced nuclei can break apart, and be eventually formed by final state coalescence
- Original idea rather simplistic. More elaborate ideas being worked on

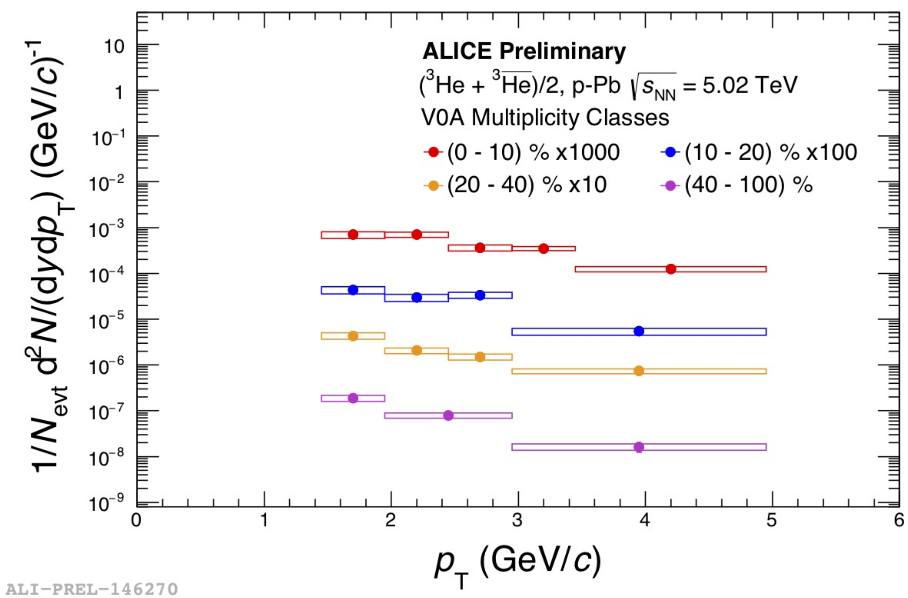
Experimental measurements

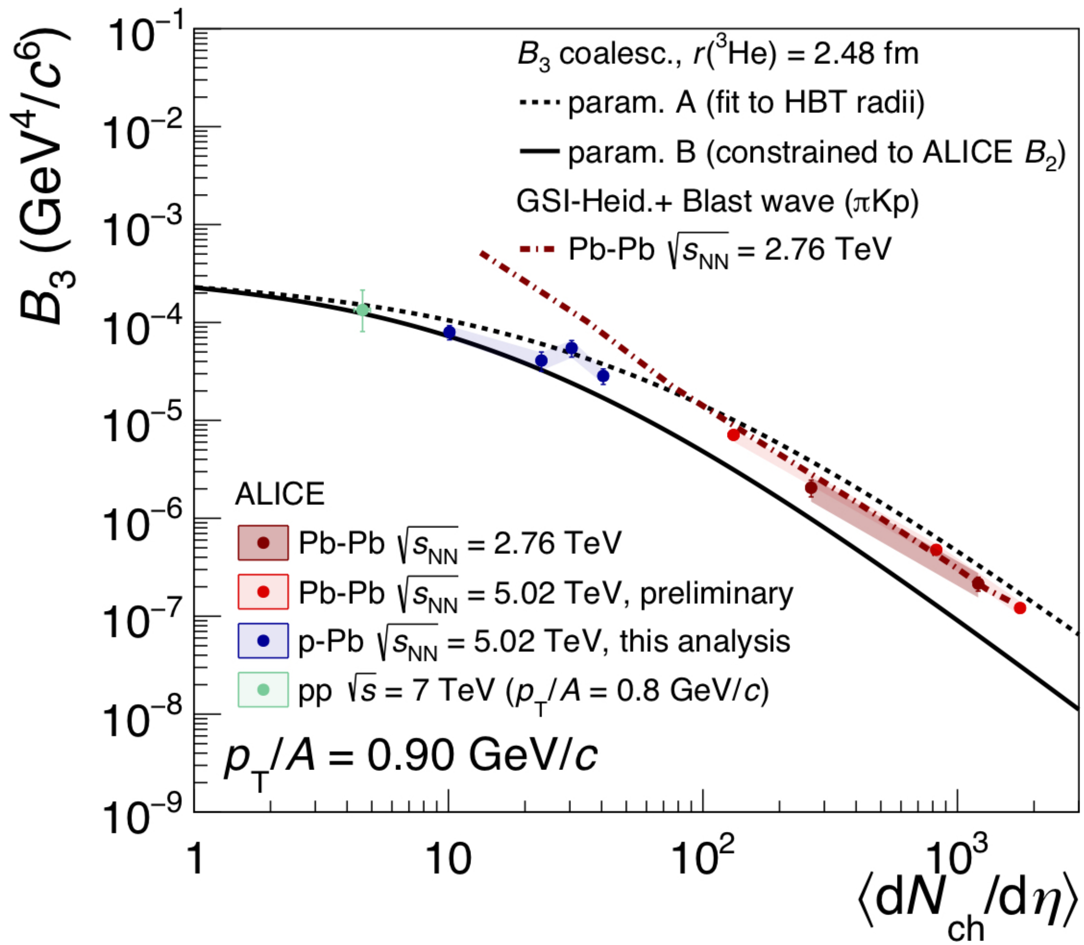
- Deuteron, tritium, ^{3}He
  - Spectra
  - Nuclei and anti-nuclei production yields
  - Mass difference between nuclei and anti-nuclei
- ^{4}He: α and $\bar{\alpha}$ particles
  - Mass dependence of yields
- Coalescence parameters
- Hyper-triton, its lifetime
- Exotica





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

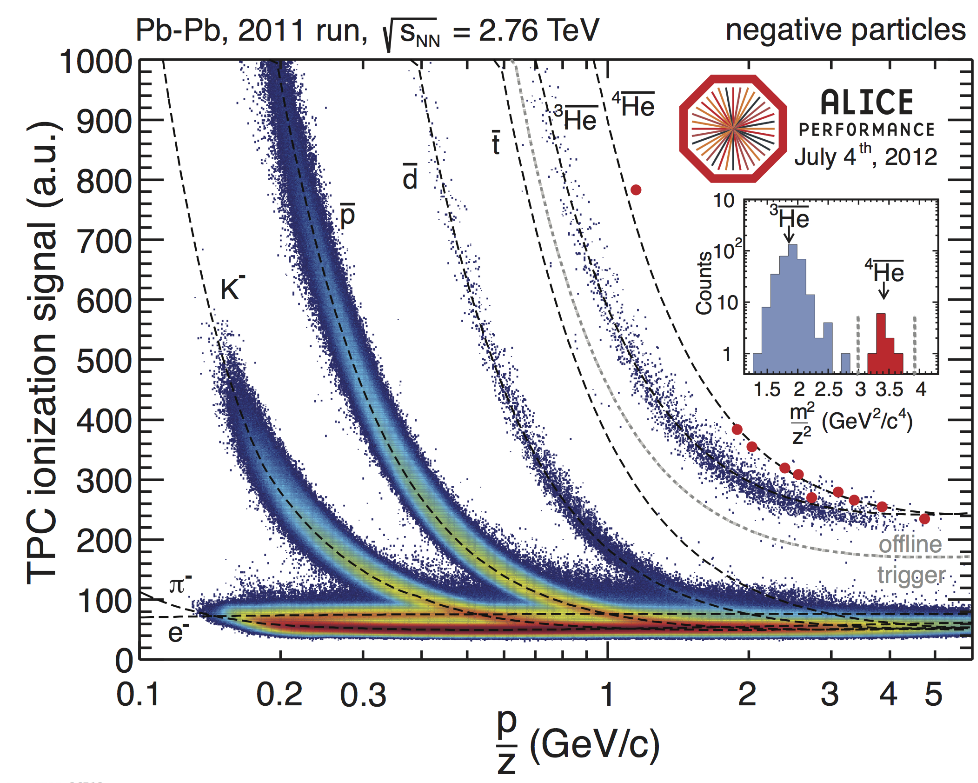


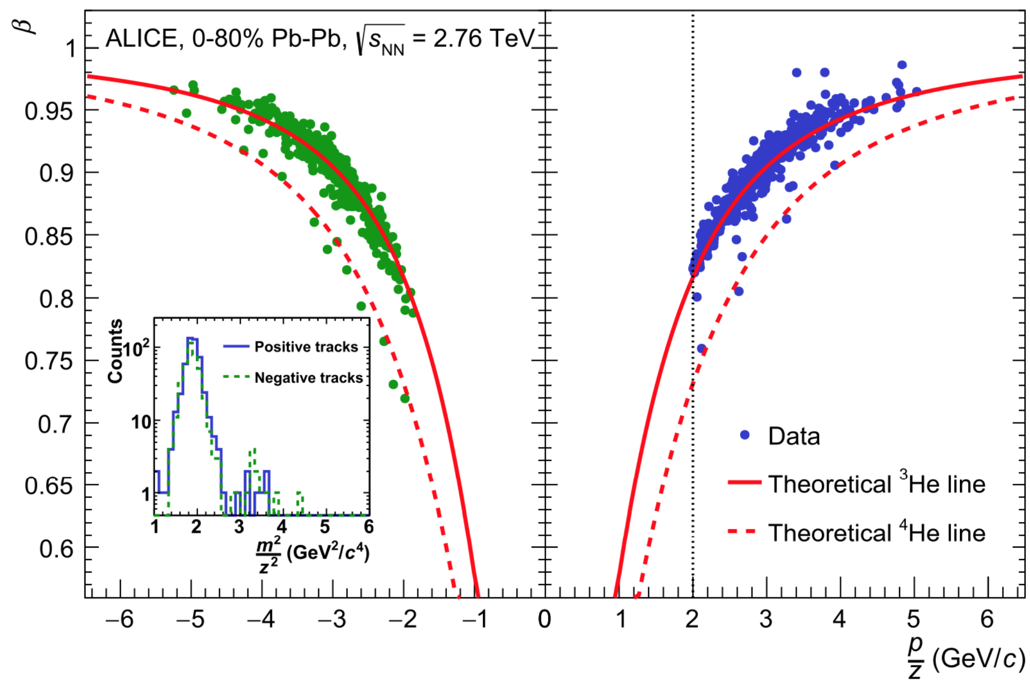


Measurement of ^{4}He and $^4\overline{\text{He}}$ in ALICE

Nucl.Phys. A971 (2018) 1-20

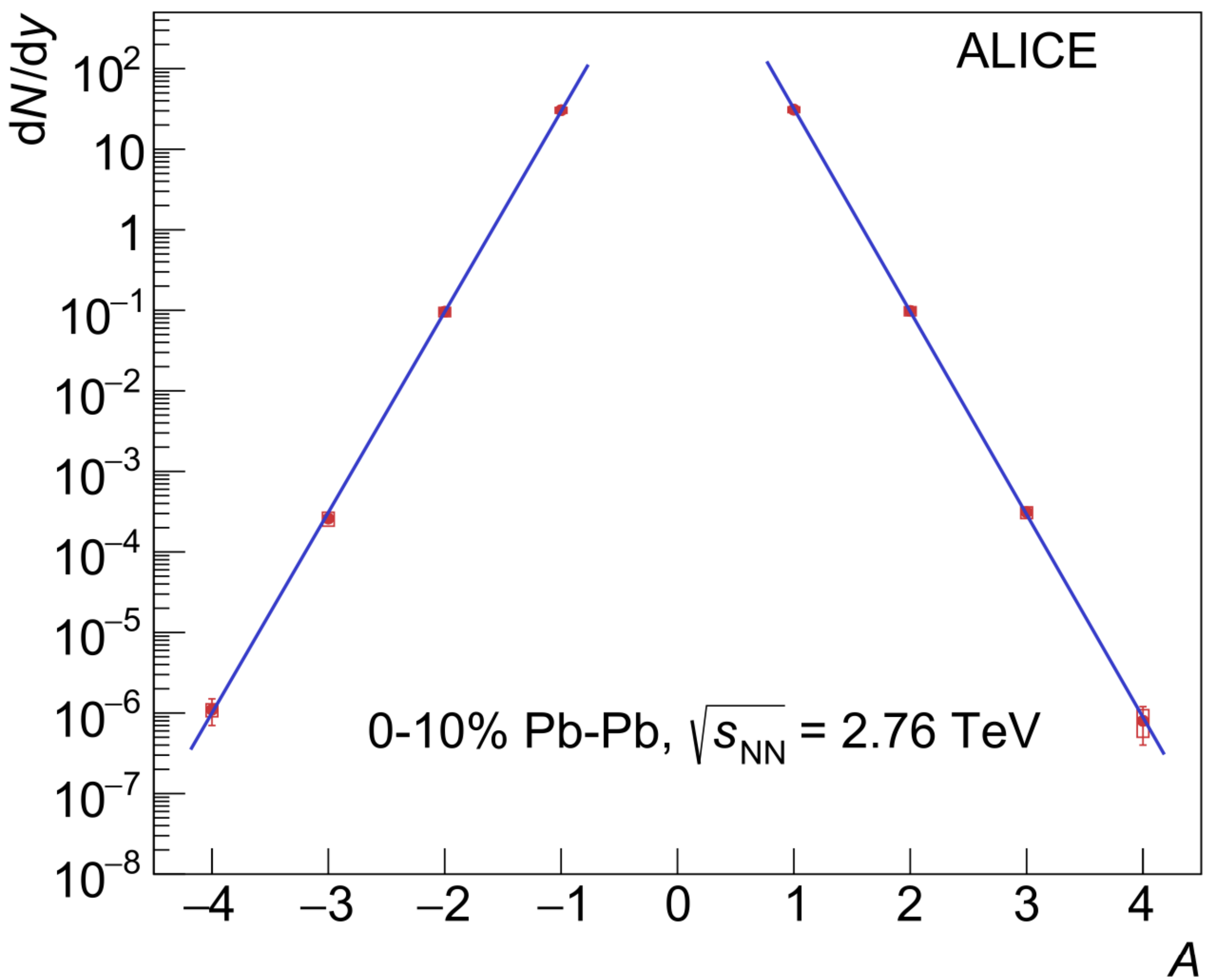
2011 data: 10 candidates





Yield dependence on the mass

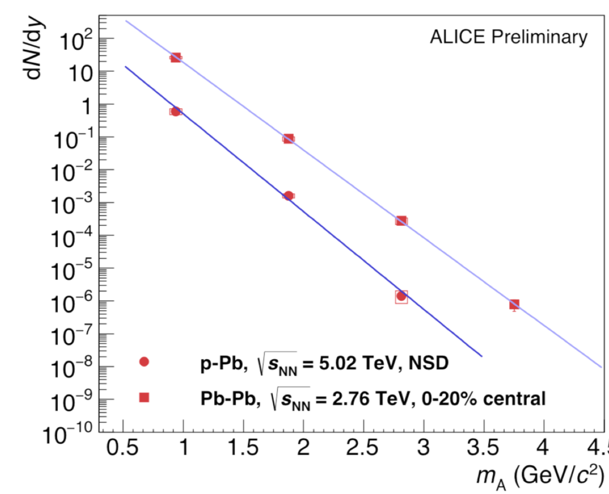
Nuclei production yields follow an exponential decrease with mass, as predicted by the thermal model



Nucl.Phys. A971 (2018) 1-20

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

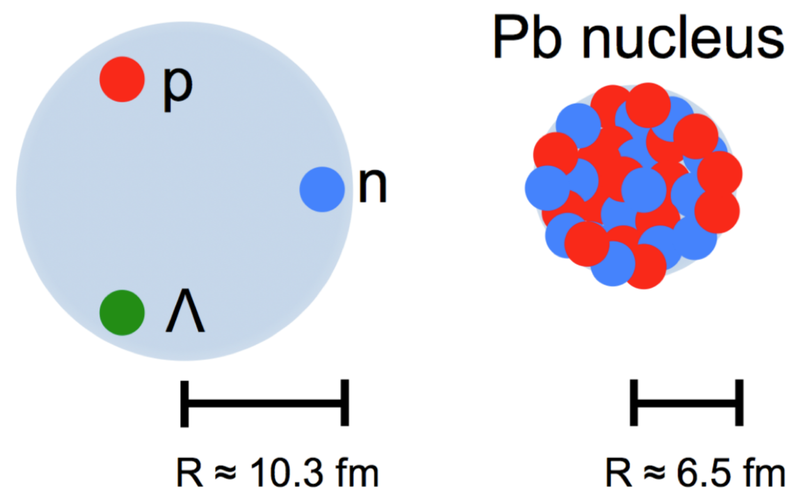
p-Pb: ~ 600



pp: ~ 1000

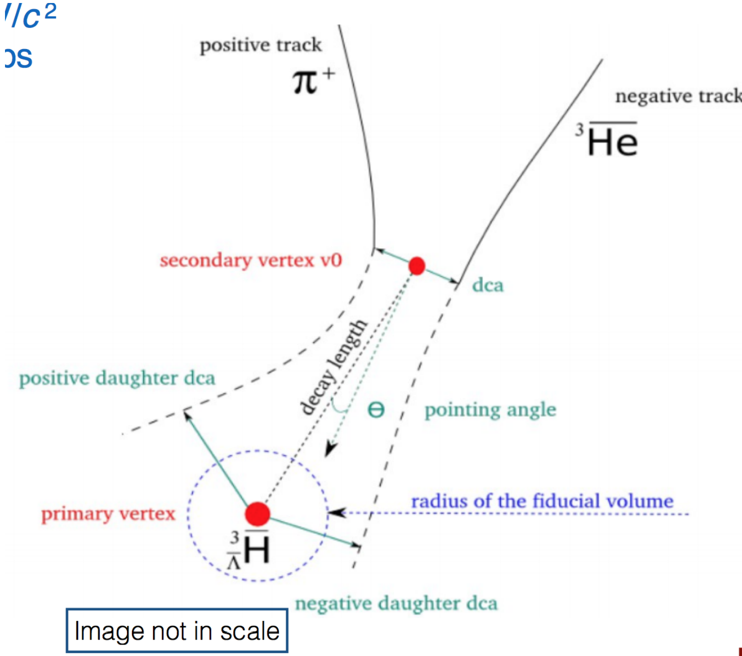
(Anti-)Hypertriton $^{3}_{\Lambda}H$ and $^{3}_{\Lambda}\overline{H}$

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



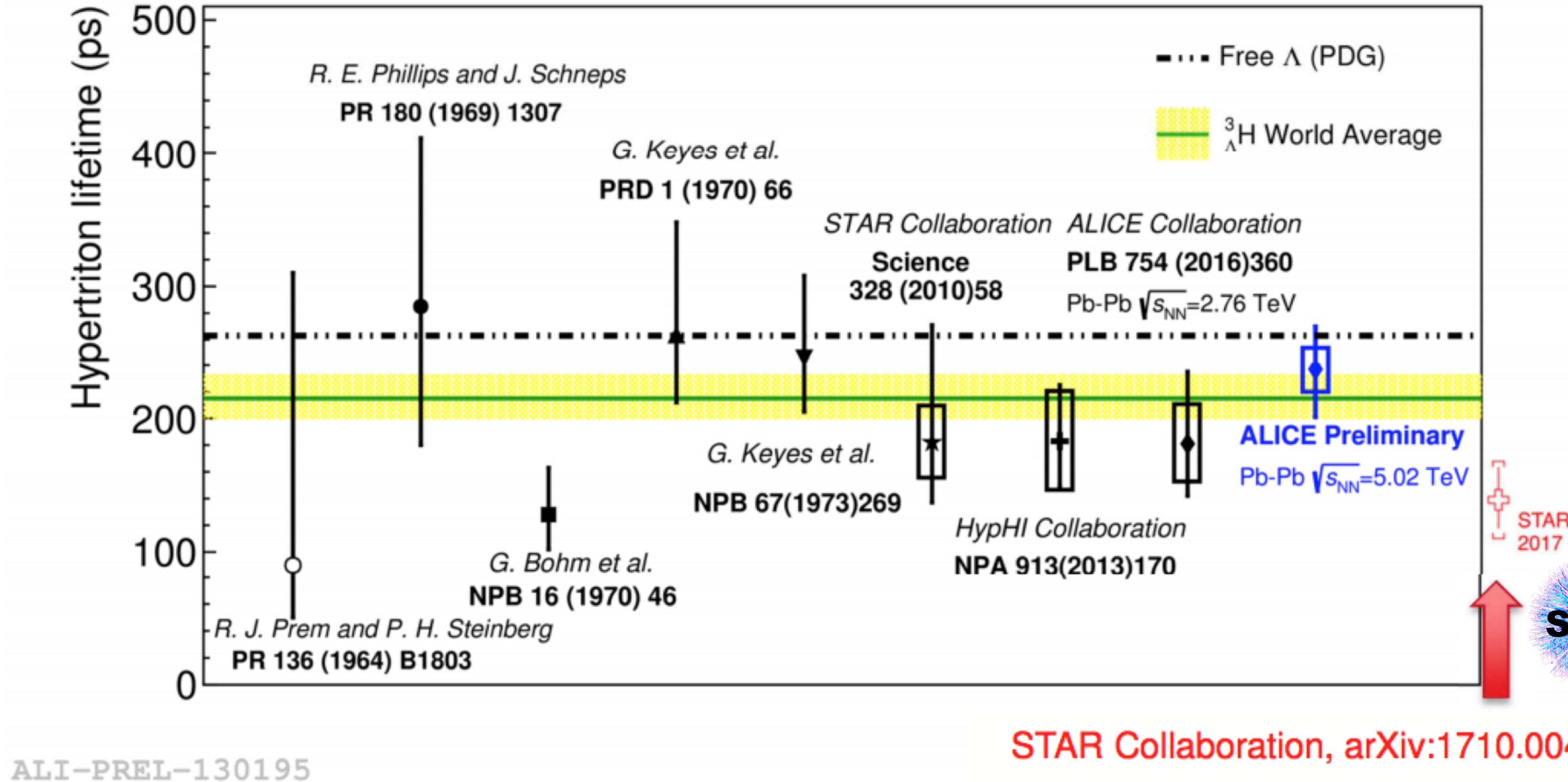
- Loosely bound state: $B_\Lambda \approx 130$ keV
  Large and fragile object

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



(Anti-)Hypertriton: lifetime

2015 Pb-Pb data
$\sqrt{s_{NN}}$ = 5.02 TeV



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

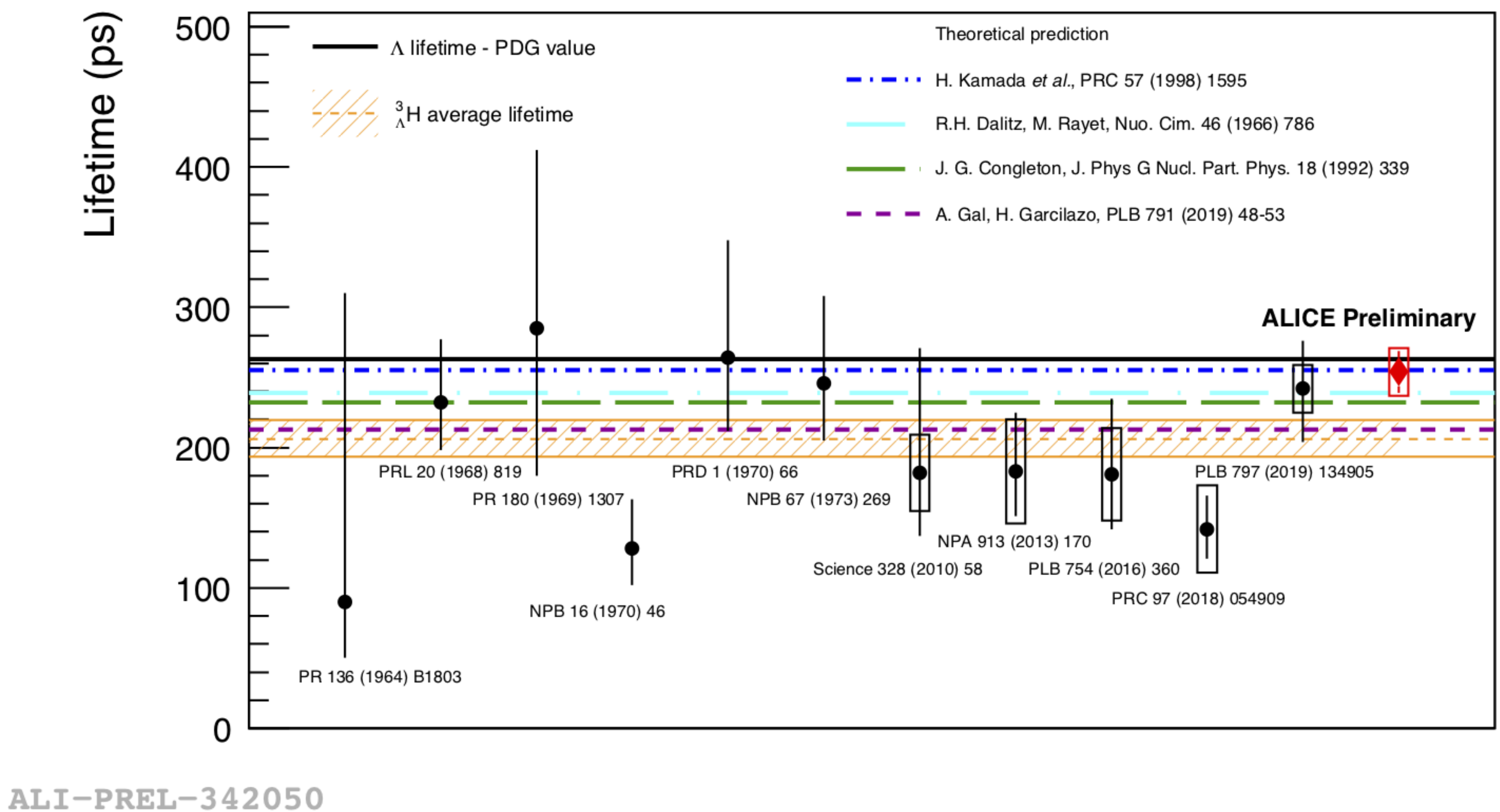
$$\tau = \left(142^{+24}_{-21}(stat.) \pm 31(syst.)\right) ps$$

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

→ decisive measurements with 2018 Pb-Pb data !

(Anti-)Hypertriton: lifetime

2018 Pb-Pb data
$\sqrt{s_{NN}}$ = 5.02 TeV

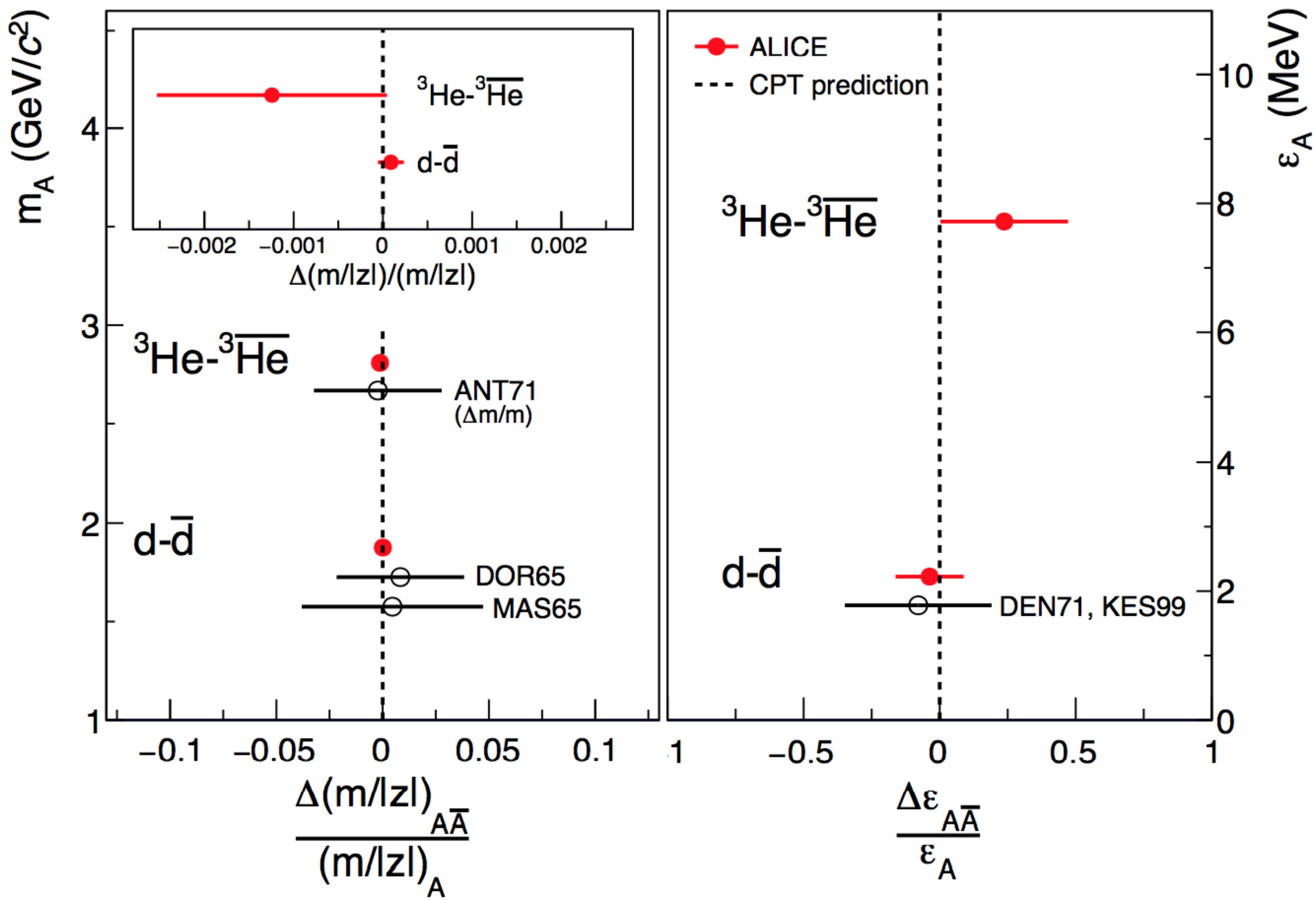


2018 data results: no puzzle

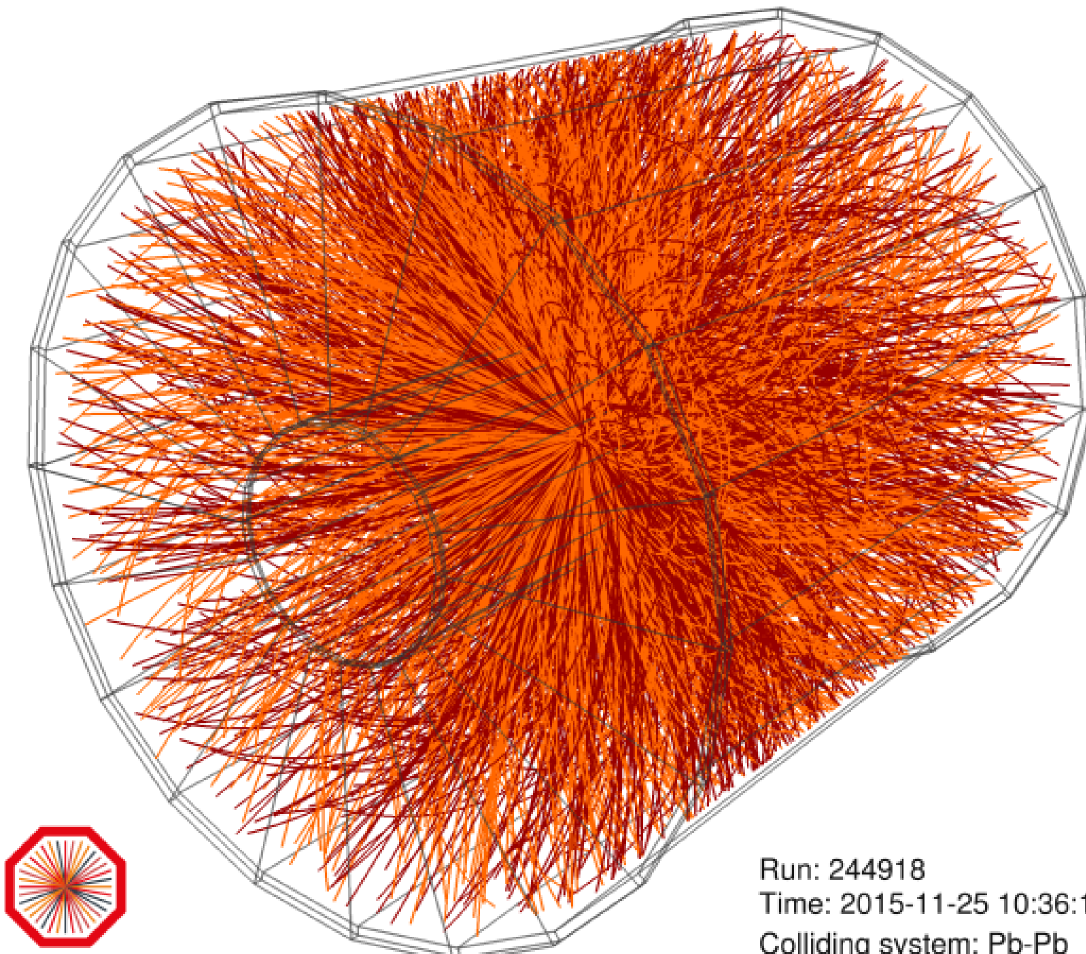
Light nuclei: test of CTP violation

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



Bulk particle production



ALICE

Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV