Lecture 22

decoding the QCD phase structure with relativistic nuclear collisions

- introduction – the LHC era and relativistic nuclear collisions
- the ALICE experiment and TPC detector
- the hadron resonance gas and (u,d,s) hadron production
- experimental determination of the QCD phase boundary
- loosely bound objects
- summary and outlook

phenomenology results obtained in collaboration with
Anton Andronic, Krzysztof Redlich, and Johanna Stachel
arXiv:1710.09425,
Nature 561 (2018) 321

most of the new data are from the ALICE collaboration
at the CERN LHC

newest results including pion-nucleon phase shifts
from arXiv:1808.03102
Phys.Lett. B 792 (2019) 304-309

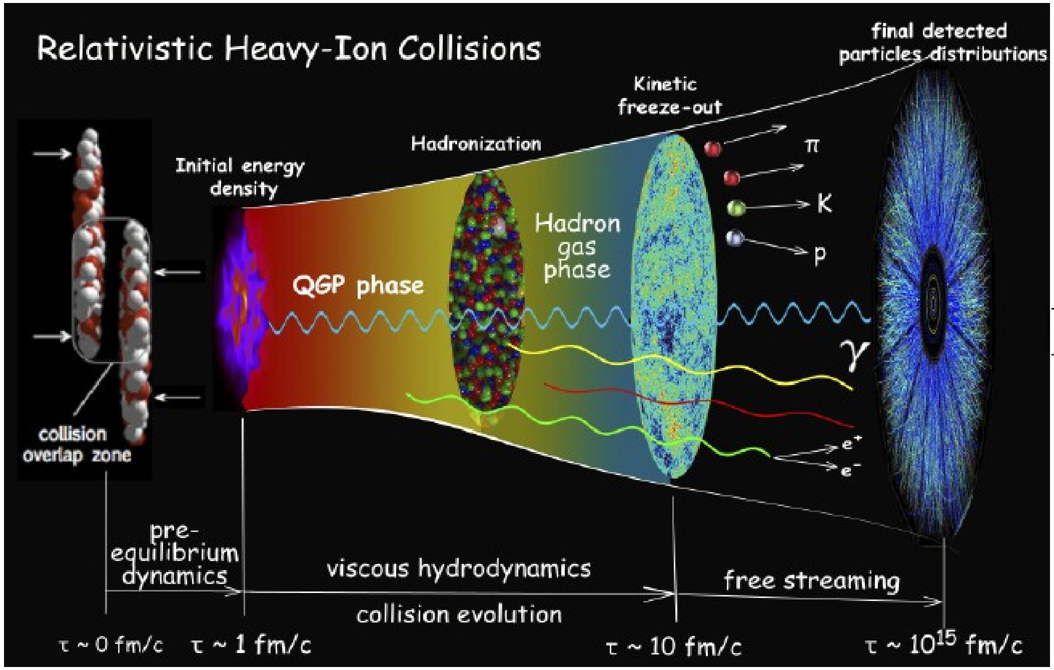

MESON conferences 1991-2018

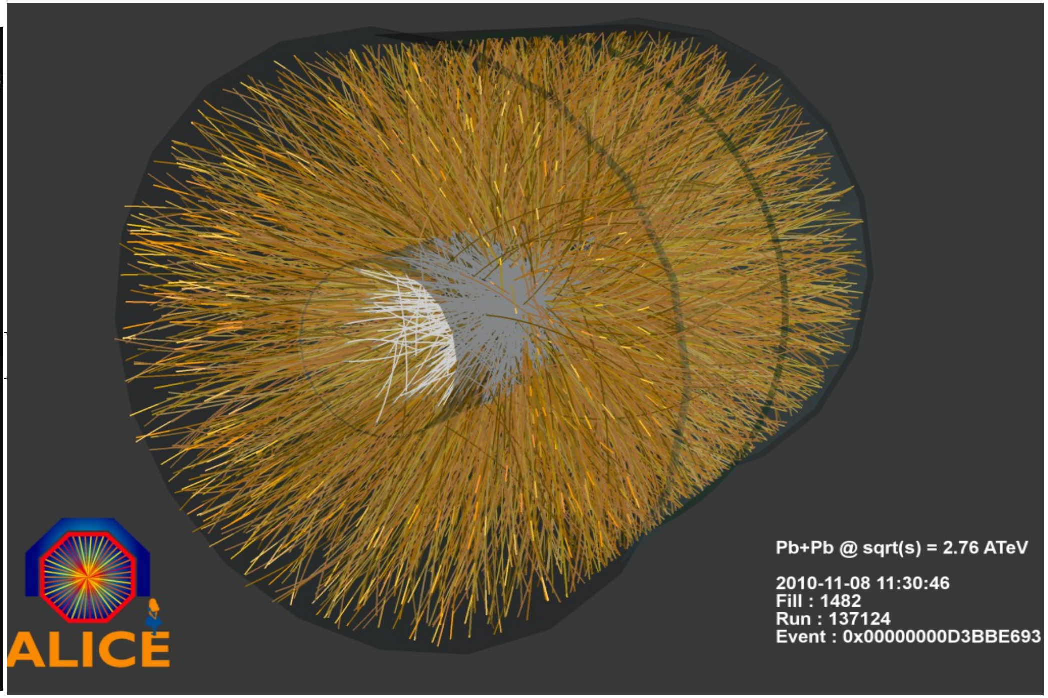
time line and matter in the early universe

times and temperatures from section on big bang cosmology in PDG report

- inflation up to 10^{-32} s
- 10^{-32} to 10^{-12} s: cosmic matter consists of **massless** particles and fields quarks, leptons, neutrinos, photons, Z, $W^{\pm}$, H ??? lots of speculations
- 10^{-12} s: electroweak phase transition, T $\approx$ 100 GeV
- 10^{-12} – 10^{-5} s quark-gluon plasma phase
  particles acquire mass through Higgs mechanism, QGP consists of: $\bar{q}qg\bar{l}l\gamma ZW^{\pm}H$, all in equilibrium + ν_e, ν_μ, ν_τ
- 10^{-5} s QCD phase transition, T = 155 MeV
- 10^{-5} s to 1 s annihilation phase, T(1 s) $\approx$ 1 MeV
  cosmic matter converts into protons, neutrons, leptons, neutrinos, photons
- t > 1 s: leptons annihilate and reheat universe, neutrinos decouple, light element production commences

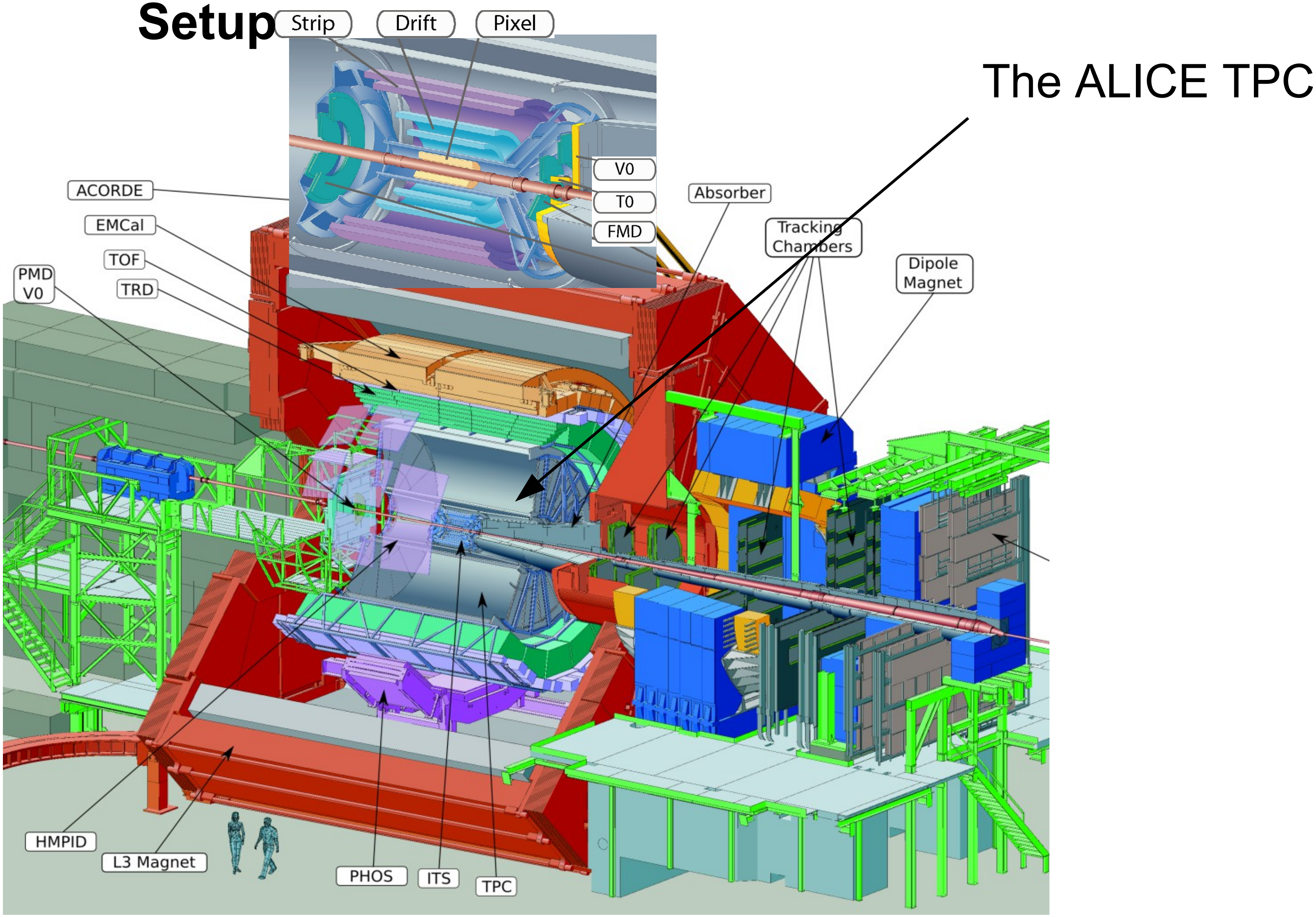
the Quark-Gluon Plasma formed in nuclear collisions at very high energy





Paul Sorensen and Chun Shen

the ALICE experiment: Schematic Setup



the ALICE Time Projection Chamber TPC:

total investment costs: 15 MEuro

total manpower: >200 man/women years

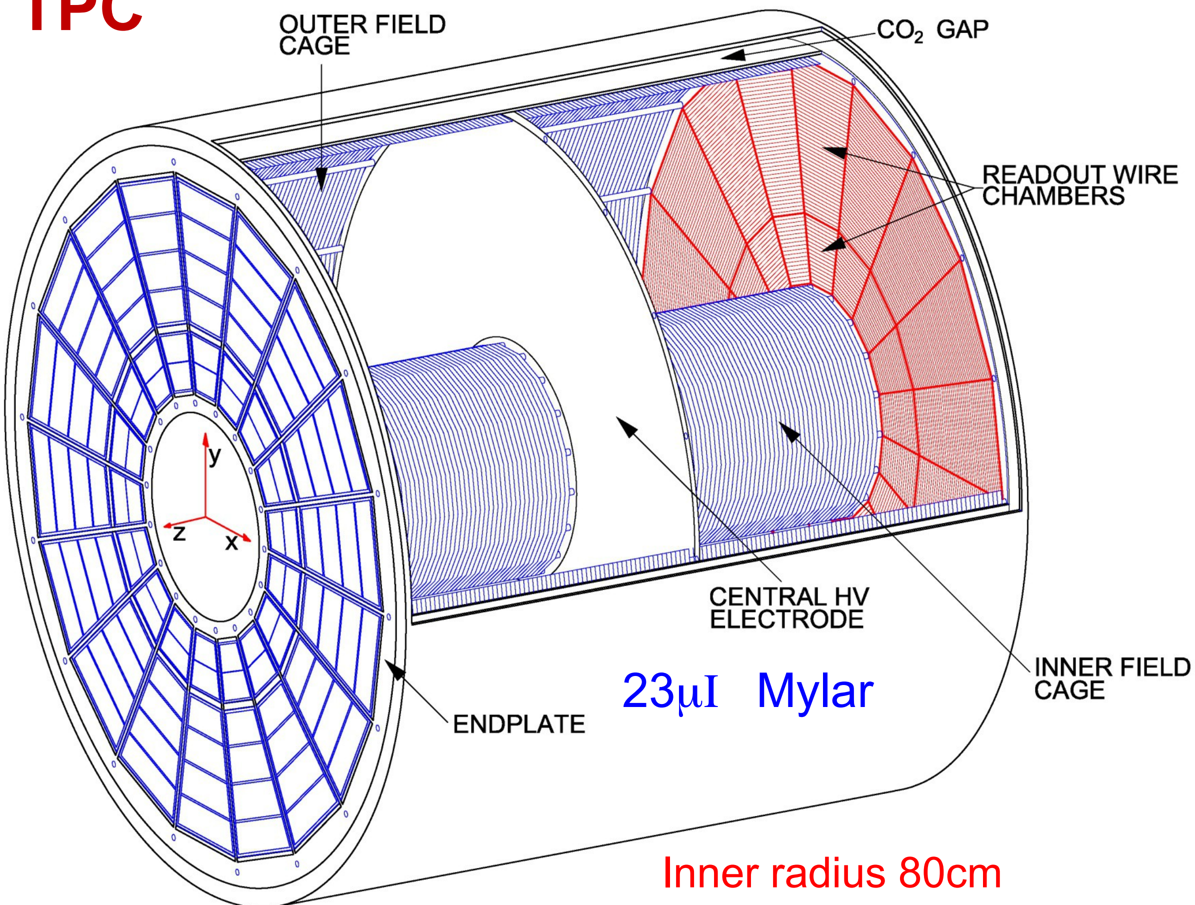
Bergen, Bratislava, CERN, Copenhagen, Darmstadt, Heidelberg, Frankfurt, GSI, Krakow, Lund

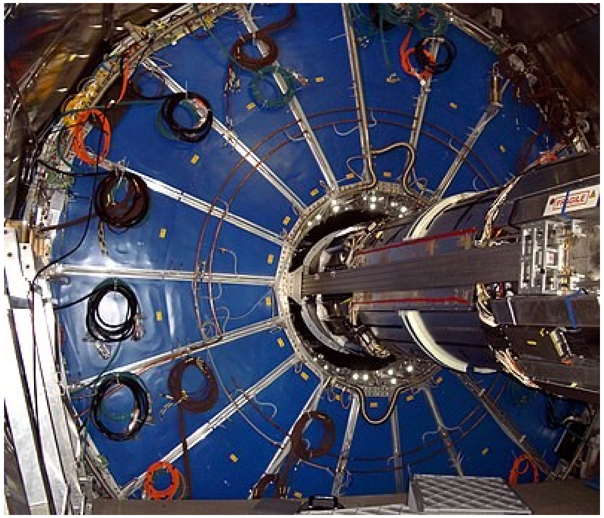
funding agencies from 8 countries

cooperation of about 50 scientists, no line management

project took 10 years to design, build and commission

ALICE TPC



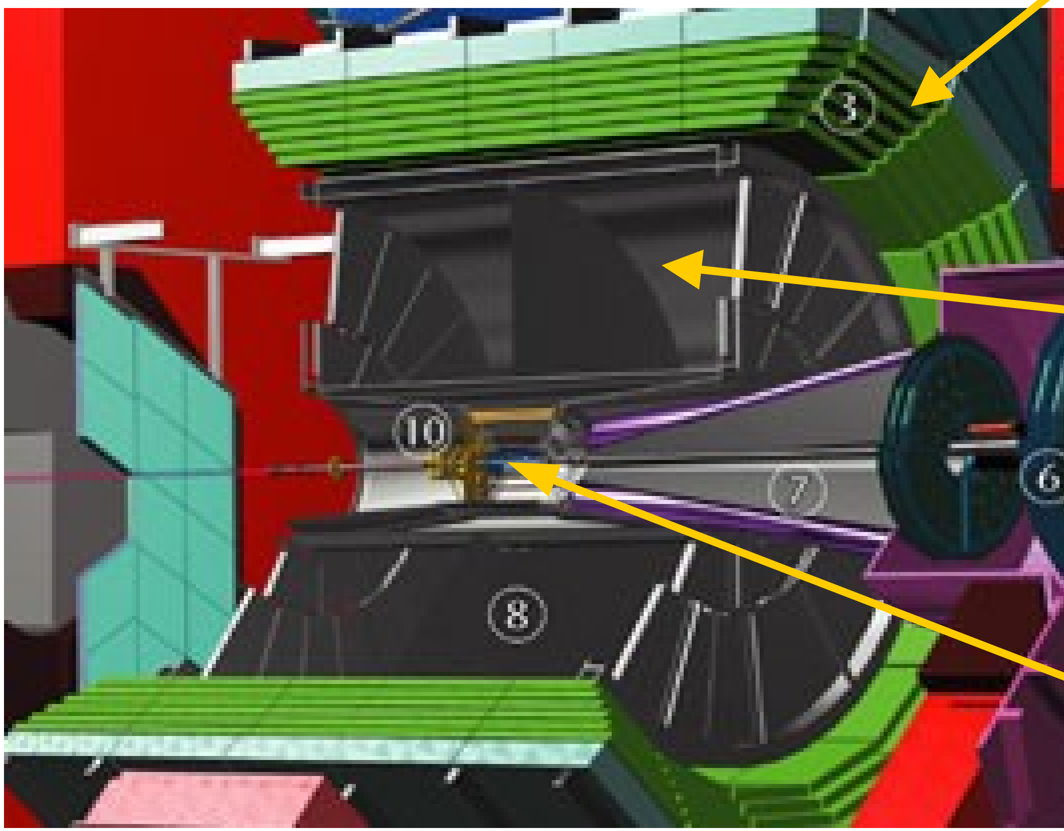


Nucl.Instrum.Meth.A 622 (2010) 316-367

arXiv:1001.1950 [physics.ins-det]

Inner radius 80cm
Outer radius 250cm
Length 2x250cm

The TPC in ALICE



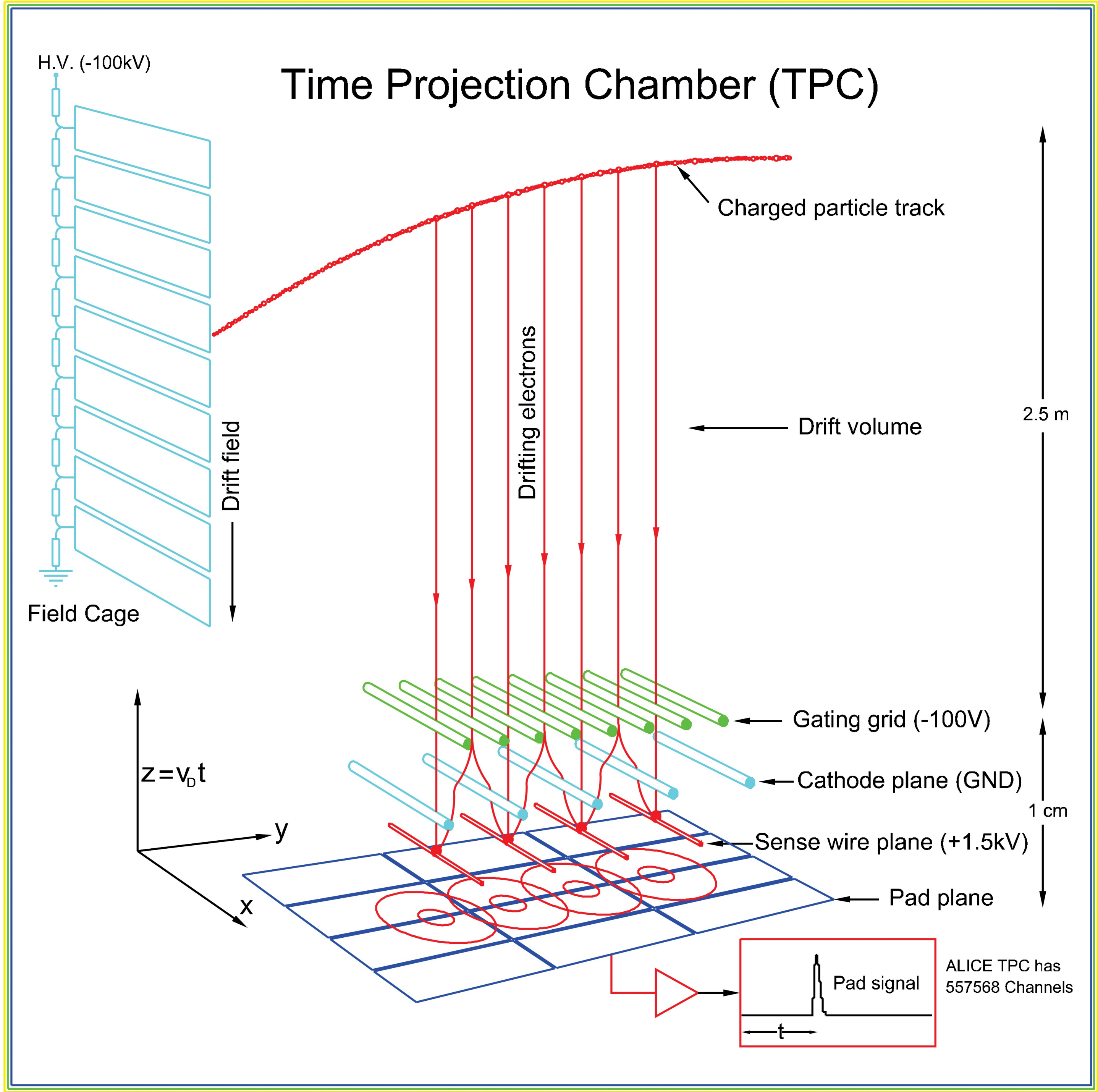
TRD
large area Transition Radiation Detector for electron identification

TPC
Time Projection Chamber large volume, high resolution and high rate tracking device

ITS

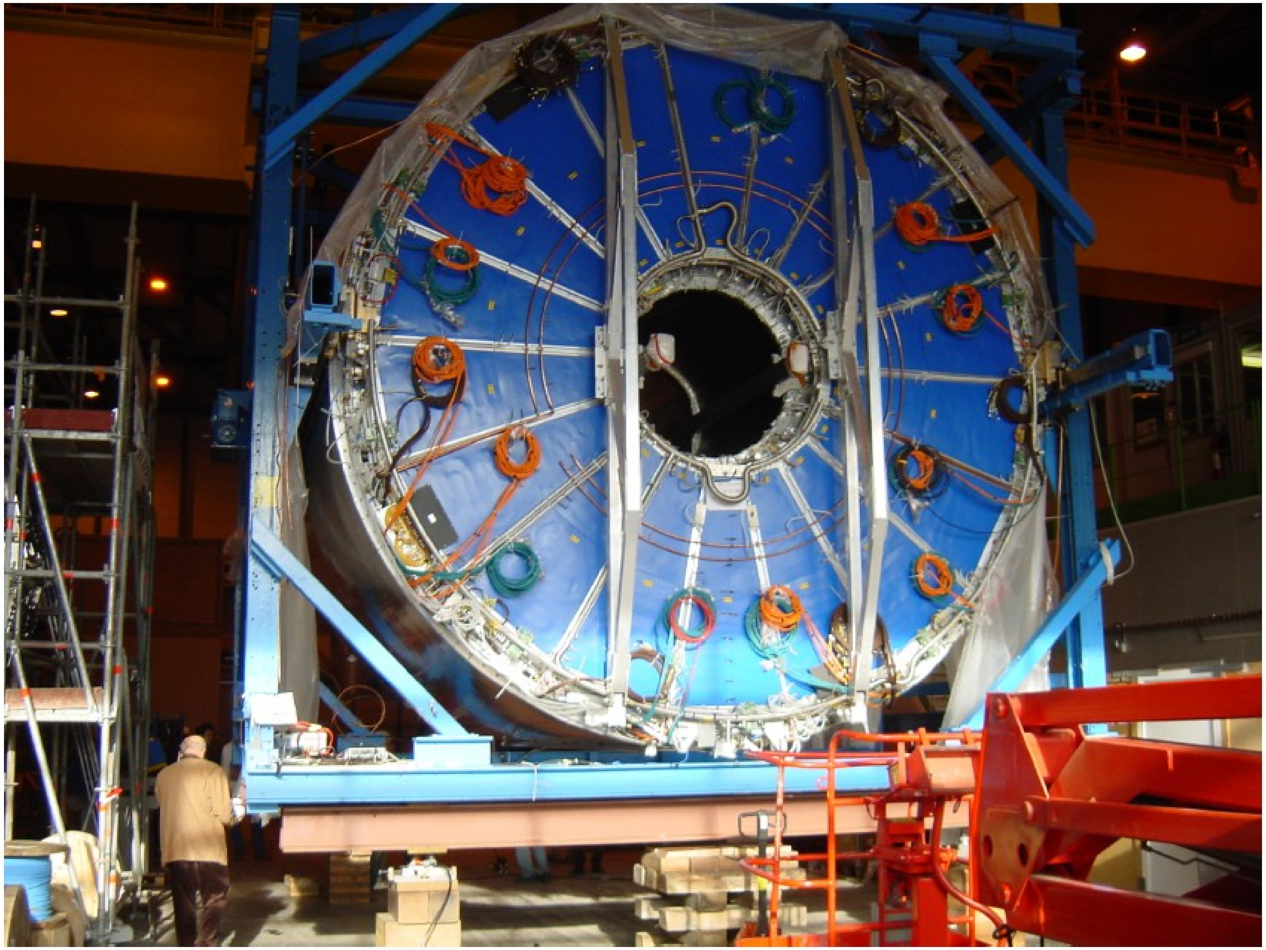
A vertex detector built from 6 layers of Si sensors

Principle of TPC operation

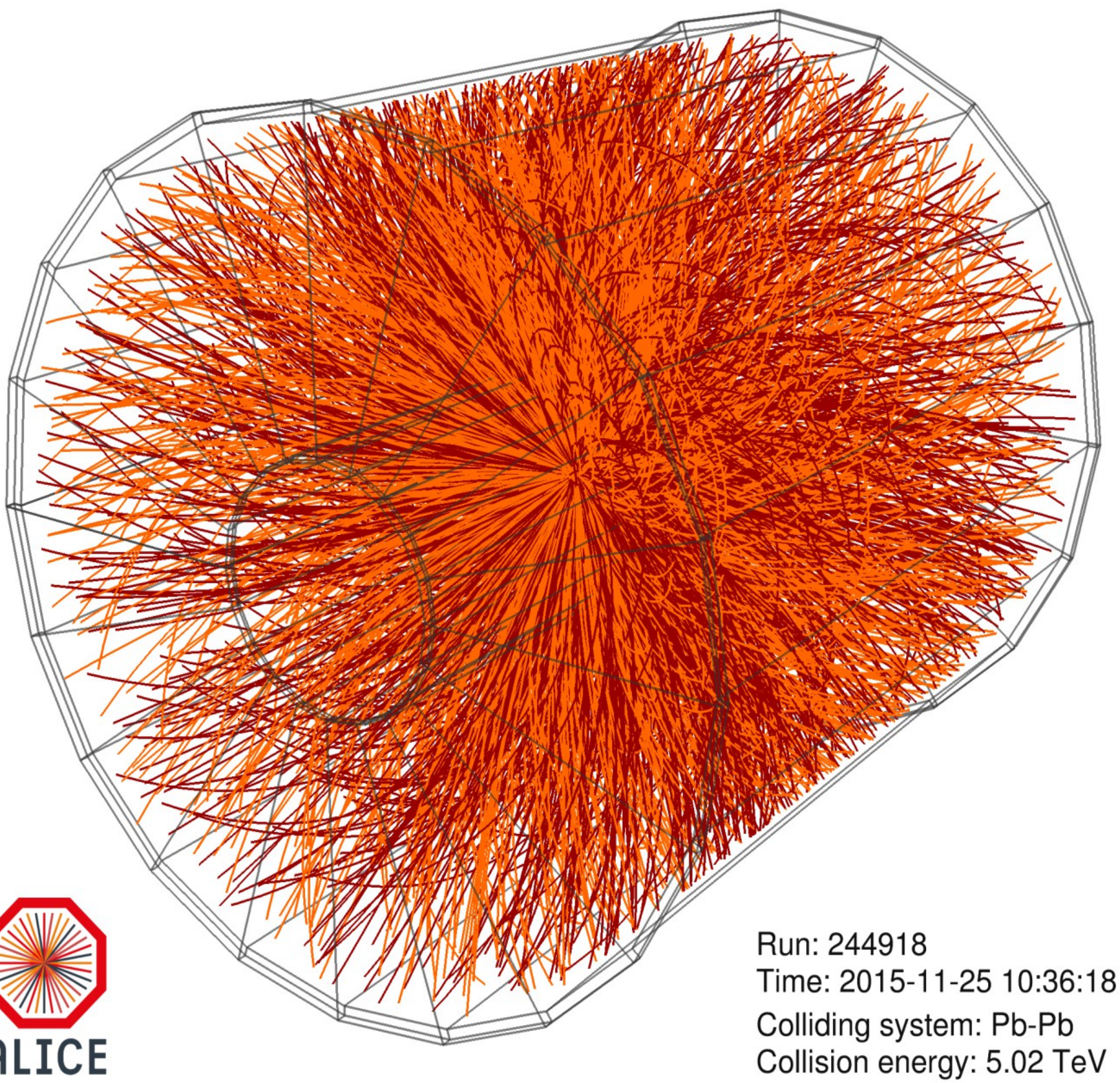



inside the TPC field cage, 2004

Ready to move into the experiment



PbPb collisions at LHC at $\sqrt{s}$ = 5.02 A TeV



Nov. 2015: PbPb 5 TeV/u

Snapshot taken with the ALICE TPC

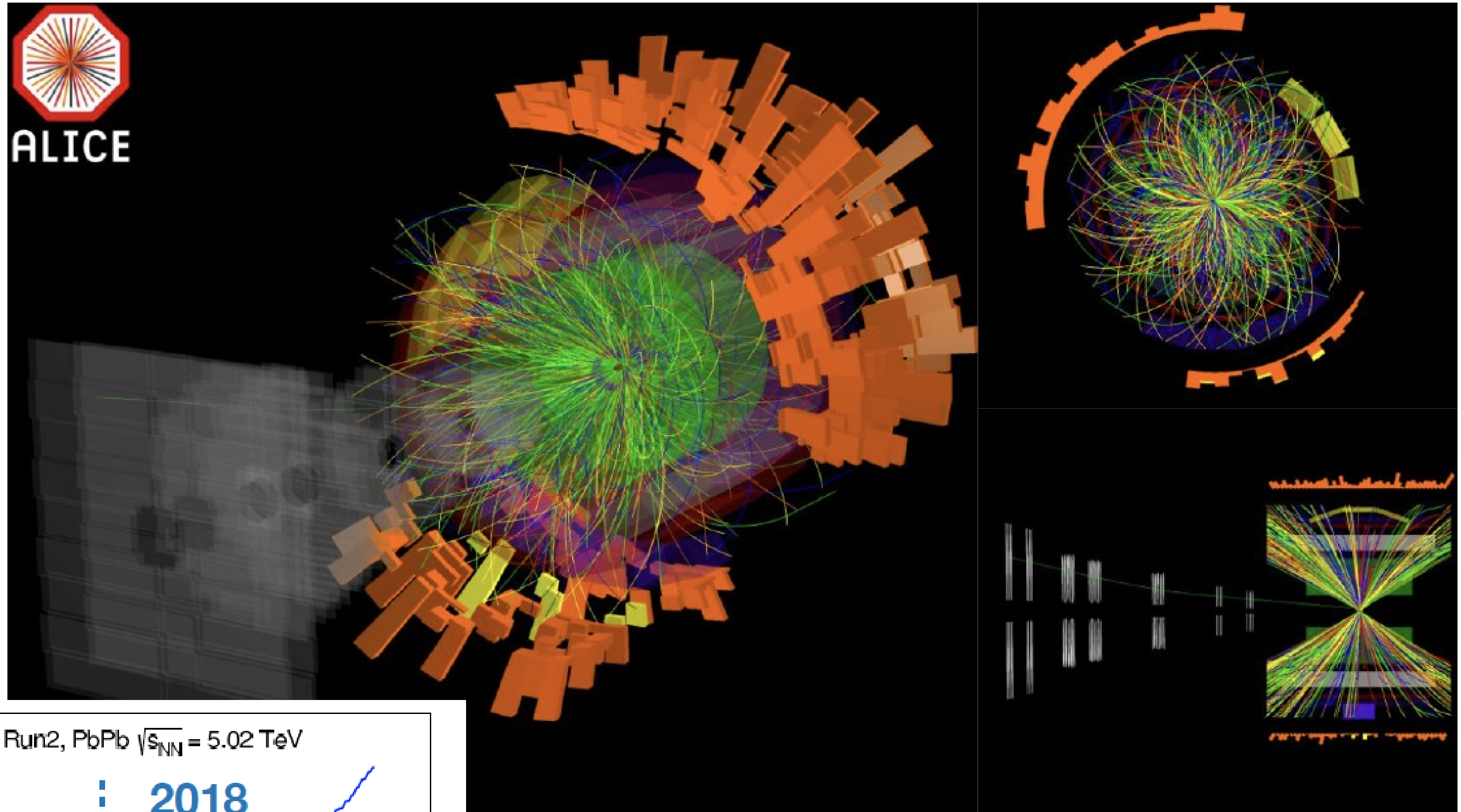
central Pb-Pb collisions
more than 32000
particles produced per collision

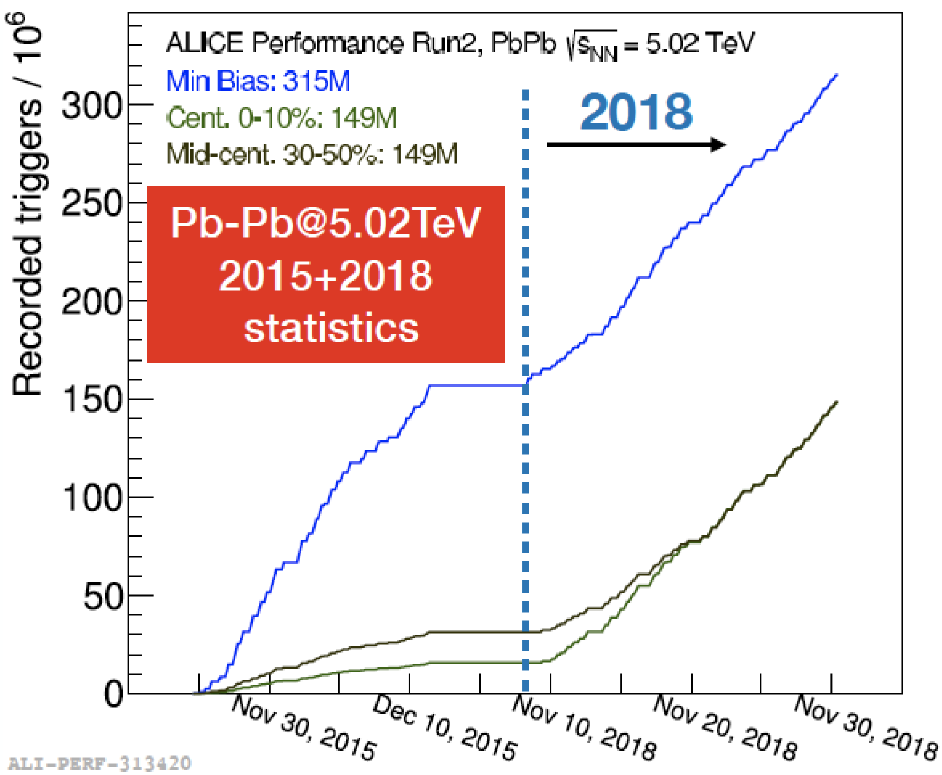
April 2022: ALICE upgraded

TPC with new GEM readout chambers,
new 6-layer Si pixel inner tracking system

and the fun has started with LHC Run3

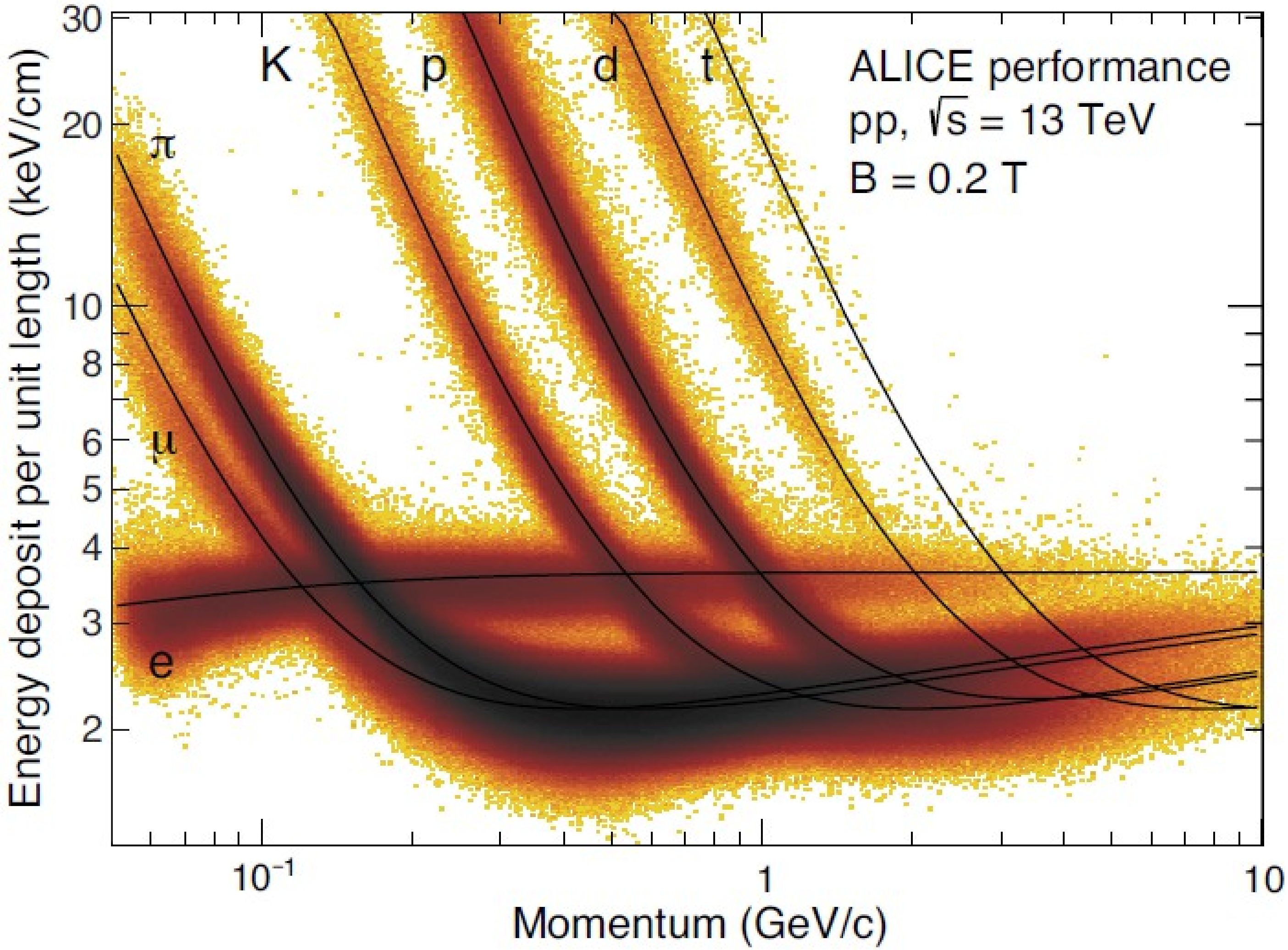
ALICE


ALICE


ALICE Performance Run2, PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
Min Bias: 315M
Cent. 0-10%: 149M
Mid-cent. 30-50%: 149M
2018
Pb-Pb@5.02TeV
2015+2018
statistics
Recorded triggers / 10^6
0
50
100
150
200
250
300
Nov 30, 2015
Dec 10, 2015
Nov 10, 2018
Nov 20, 2018
Nov 30, 2018
ALI-PERF-313420

particle identification with the ALICE TPC

from 50 MeV to 50 GeV



now PDG standard

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001, Fig. 34.15

hadron production and the QCD phase boundary

measure the momenta and identity of all produced particles at all energies and look for signs of equilibration, phase transitions, regularities, etc

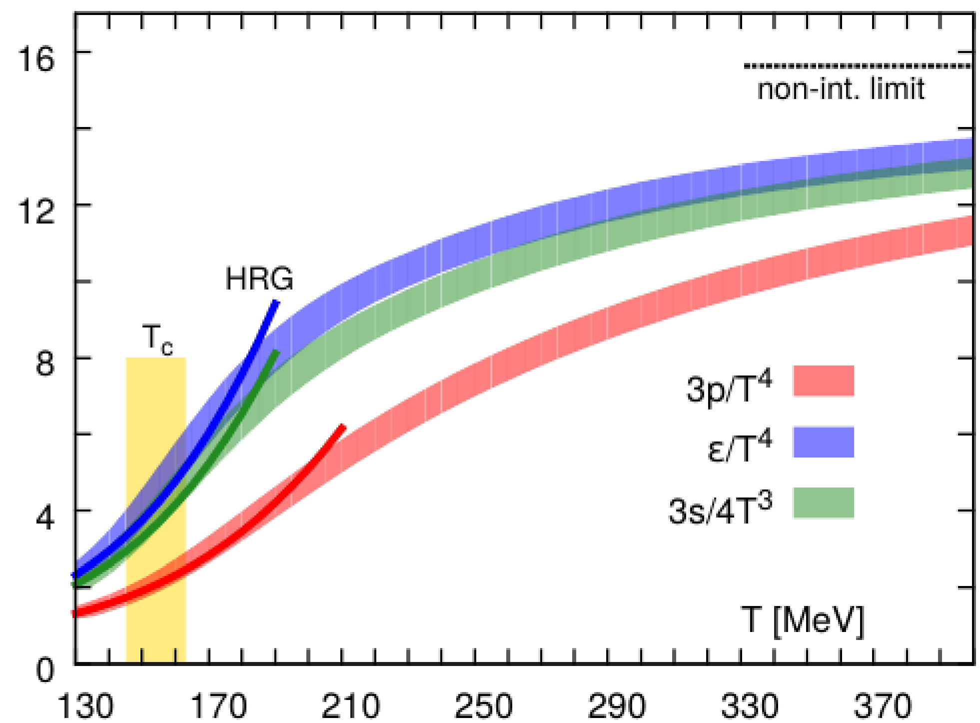
at the phase boundary, all quarks and gluons are converted ('hadronized') into hadrons which we measure in our detectors

duality between hadrons and quarks/gluons (I)

comparison of equation of state from LQCD
Phys.Rev. D90 (2014) 094503
HOTQCD coll.

with hadron resonance gas predictions (colored lines)

essentially the same results also from Wuppertal-Budapest coll.
Phys.Lett. B730 (2014) 99-104



pseudo-critical temperature

$T_c = 156.5 \pm 1.5$ MeV, very new and improved
arXiv:1807.05607

$\varepsilon_{crit} = 420 \pm 60$ MeV/fm^3

$\varepsilon_{nucl} = 450$ MeV/fm^3

duality between hadrons and quarks/gluons (II)

in the dilute limit T < 165 MeV:

$$\ln Z(T,V,\mu) \approx \sum_{i\in\ mesons} \ln \mathcal{Z}^{M}_{M_i}(T,V,\mu_Q,\mu_S) + \sum_{i\in\ baryons} \ln \mathcal{Z}^{B}_{M_i}(T,V,\mu_b,\mu_Q,\mu_S)$$

where the partition function of the hadron resonance model is expressed in mesonic and baryonic components. The chemical potential μ reflects then the baryonic, charge, and strangeness components $\mu = (\mu_b, \mu_Q, \mu_S)$.

thermal model of particle production and QCD

partition function Z(T,V) contains sum over the full hadronic mass spectrum and is fully calculable in QCD

for each particle i, the statistical operator is:

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

particle densities are then calculated according to:

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

from analysis of all available nuclear collision data we now know the energy dependence of the parameters T, mu_b, and V over an energy range from threshold to LHC energy and can confidently extrapolate to even higher energies

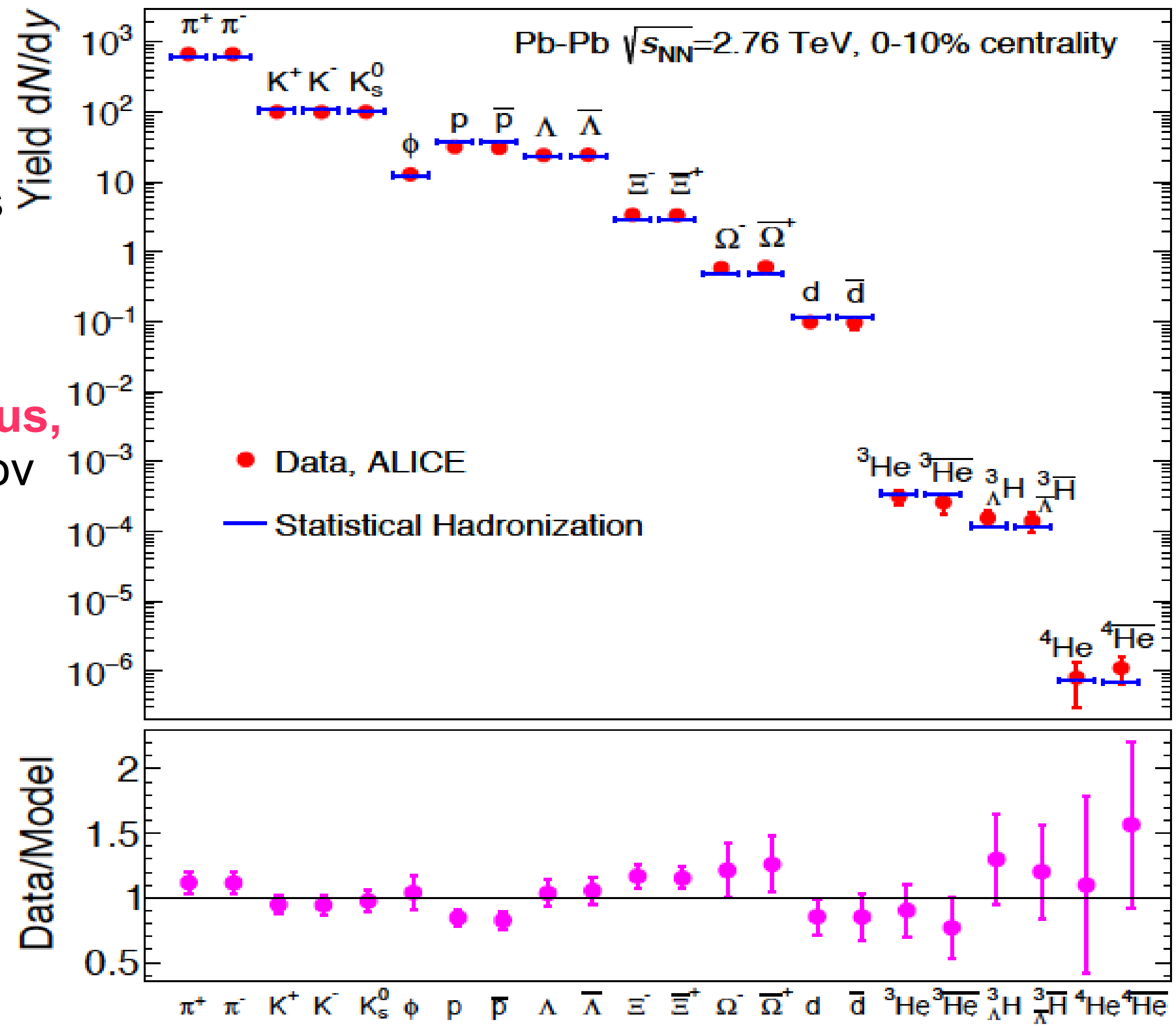
in practice, we use the full experimental hadronic mass spectrum from the PDG compilation (vacuum masses) to compute the 'primordial yield'

comparison with measured hadron yields needs evaluation of all strong decays

Oct. 2017 update: excellent description of ALICE@LHC data

fit includes loosely bound systems such as deuteron and hypertriton
hypertriton is bound-state of (Λ,p,n),
Λ separation energy about 130 keV
size about 10 fm, the **ultimate halo nucleus,**
produced at T=156 MeV. close to an Efimov state

proton discrepancy about 2.8 sigma



Andronic, pbm, Redlich, Stachel, arXiv:1710.09425, Nature 561 (2018) 321

J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, Confronting LHC data with the statistical hadronization model, J.Phys.Conf.Ser.**509** (2014) 012019, arXiv:1311.4662 [nucl-th].

the proton anomaly and the Dashen, Ma, Bernstein S-matrix approach

R. Dashen, S. K. Ma, and H. J. Bernstein, Phys. Rev. **187**, 345 (1969).

The S-matrix formalism [20–24] is a systematic framework for incorporating interactions into the description of the thermal properties of a dilute medium. In this scheme, two-body interactions are, via the scattering phase shifts, included in the leading term of the S-matrix expansion of the grand canonical potential. The resulting interacting density of states is then folded into an integral over thermodynamic distribution functions, which, in turn, yields the interaction contribution to a particular thermodynamic observable.

thermal yield of an (interacting) resonance with mass M, spin J, and isospin I

$$\langle R_{I,J}\rangle = d_J \int_{m_{th}}^{\infty} dM \int \frac{d^3p}{(2\pi)^3} \frac{1}{2\pi} B_{I,J}(M) \times \frac{1}{e^{(\sqrt{p^2+M^2}-\mu)/T}+1},$$

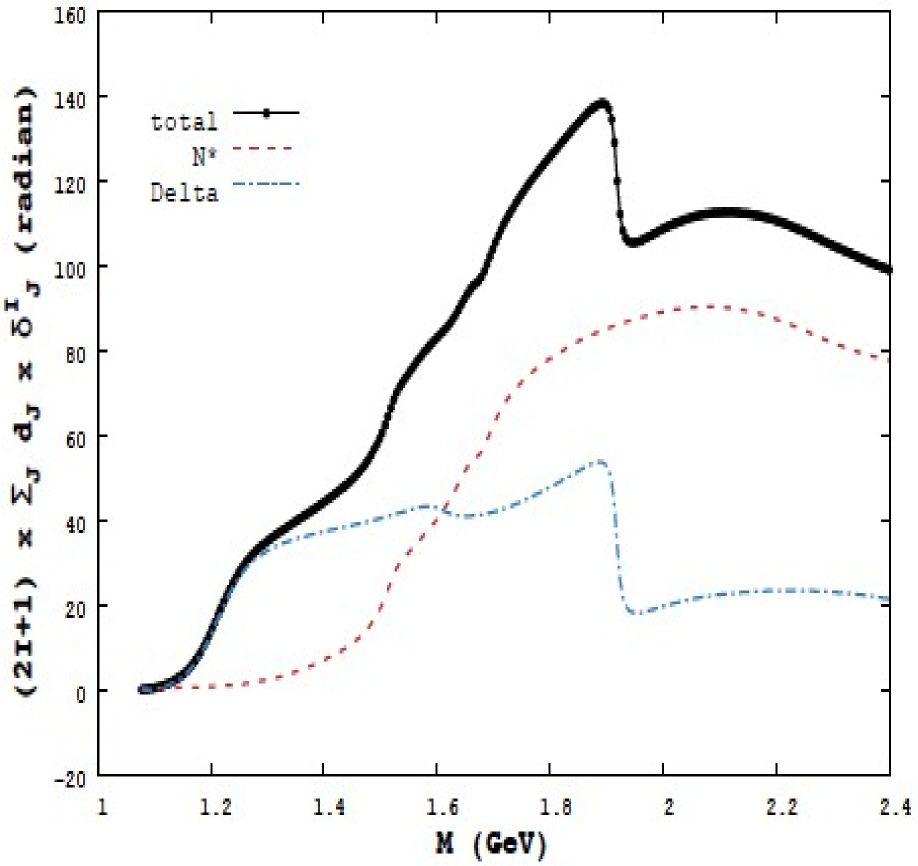
A. Andronic, pbm, B. Friman, P.M. Lo, K. Redlich, J. Stachel, arXiv:1808.03102, update Jan. 2019

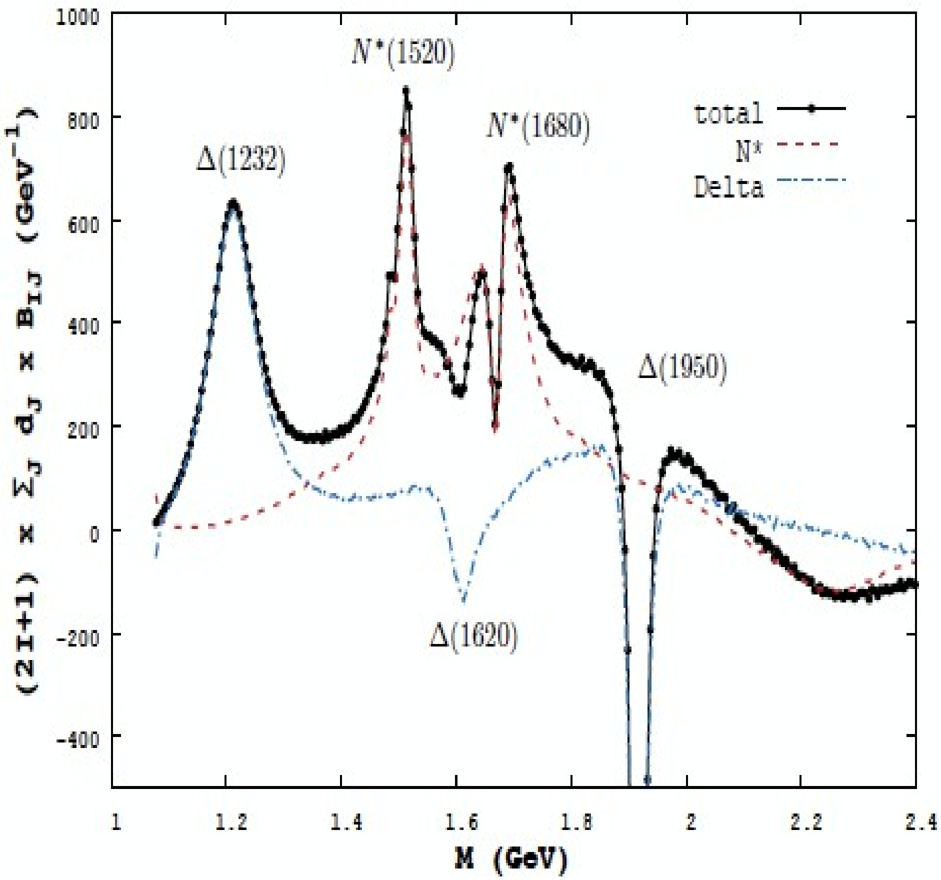
need to know derivatives of phase shifts with respect to invariant mass

$$B_{I,J}(M) = 2\,\frac{d\delta_J^I}{dM}.$$

pion nucleon phase shifts and thermal weights for N* and Δ resonances

GWU/SAID phase shift analysis, 15 partial waves for each isospin channel

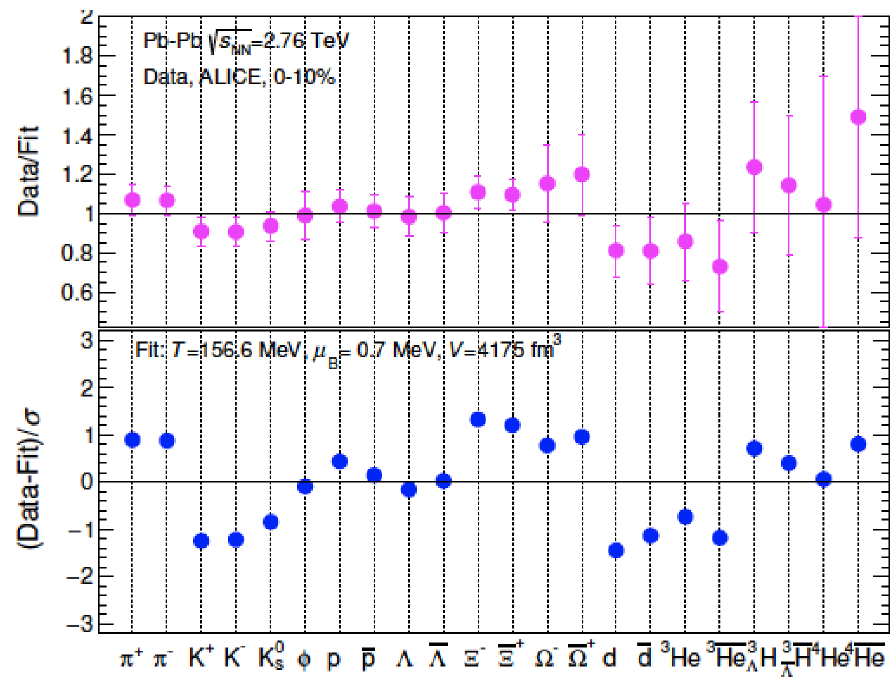




Jan. 2019 update: excellent description of ALICE@LHC data

proton discrepancy of 2.8 sigma is now explained in arXiv:1808.03102
explicit phase shift description of baryon resonance region
(Andronic, pbm, Friman, Lo, Redlich, Stachel)

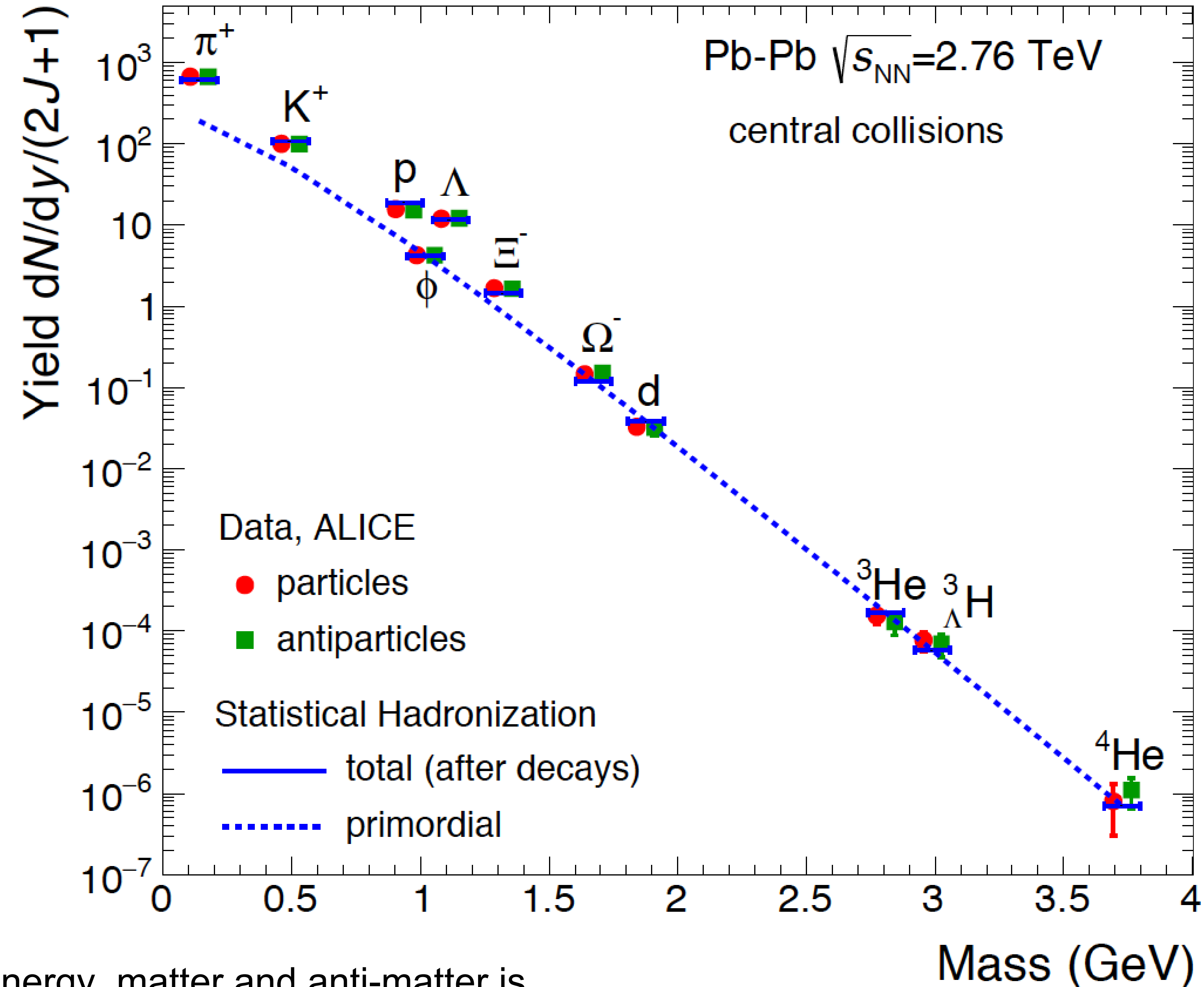
Contributions of three- and higher resonances and inelastic channels are taken into account with normalization with normalization to LQCD susceptibilities



$$\chi^2 = 19.7 \, \text{per} \;\; 19 \;\; \text{dof}$$

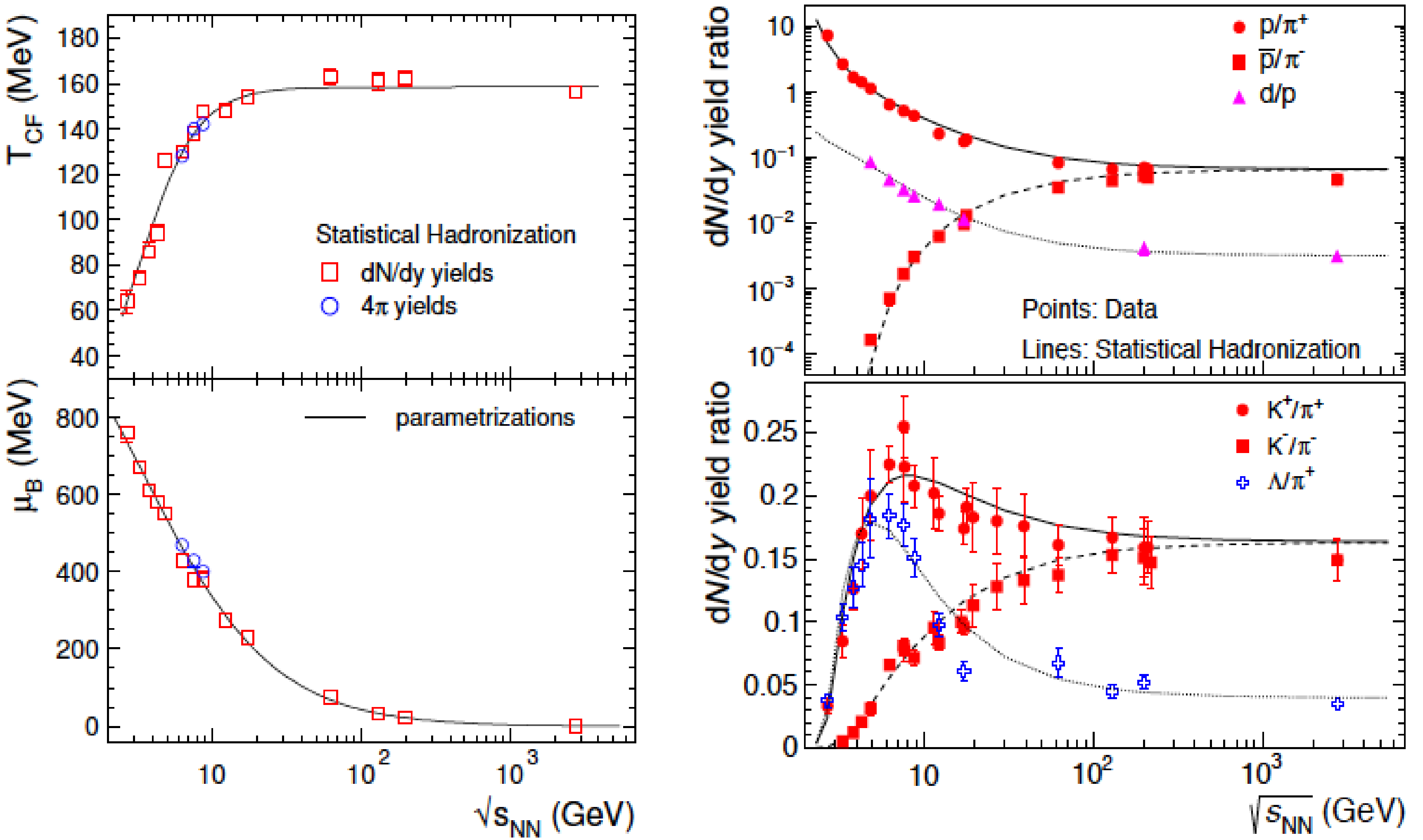
very good fit!

at LHC energy, production of (u,d,s) hadrons is governed by mass and quantum numbers only
quark content does not matter



at LHC energy, matter and anti-matter is produced with equal yields

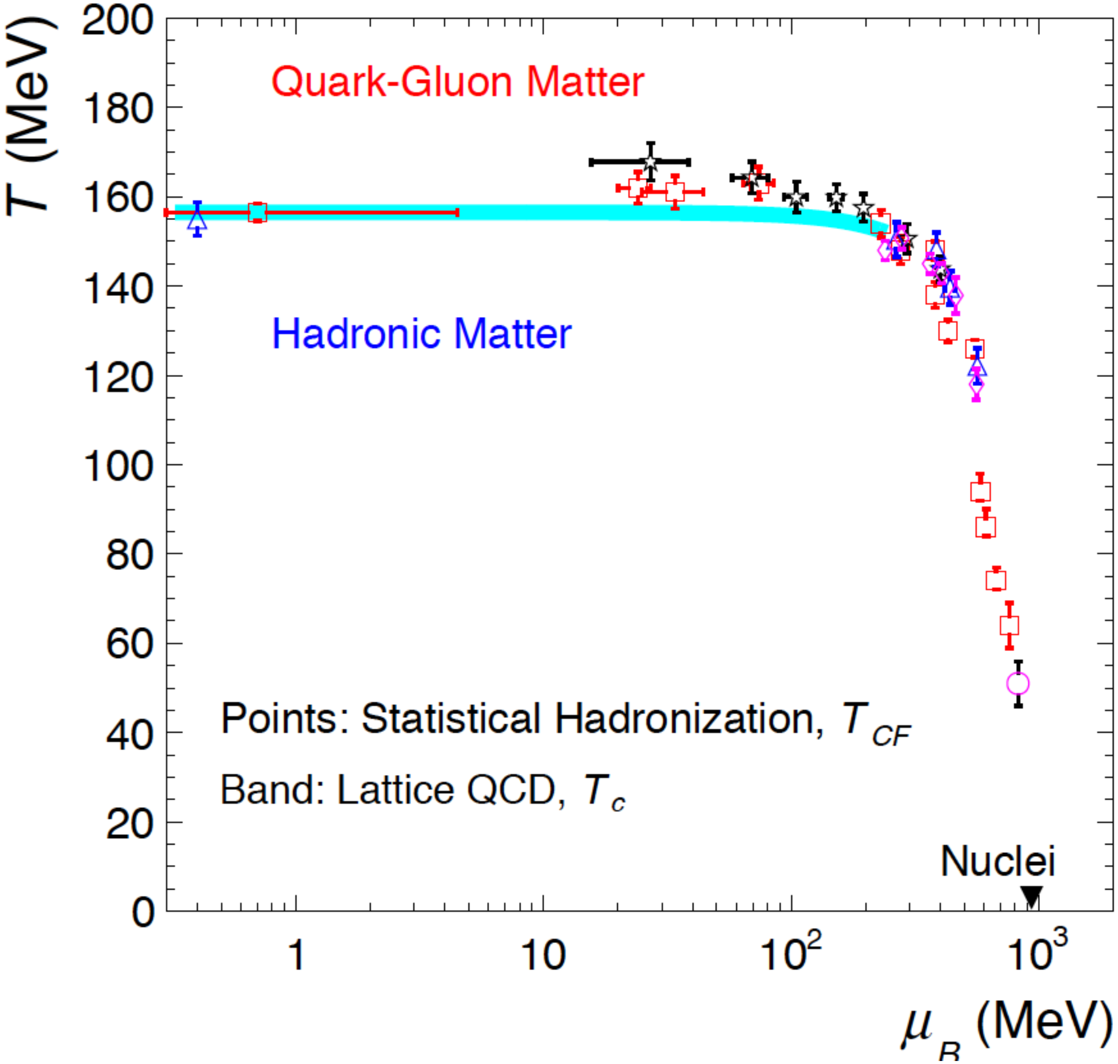
energy dependence of hadron production described quantitatively



together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy

excellent description also of K+/pi+ ratio including the 'horn'

the QGP phase diagram, LQCD, and hadron production data

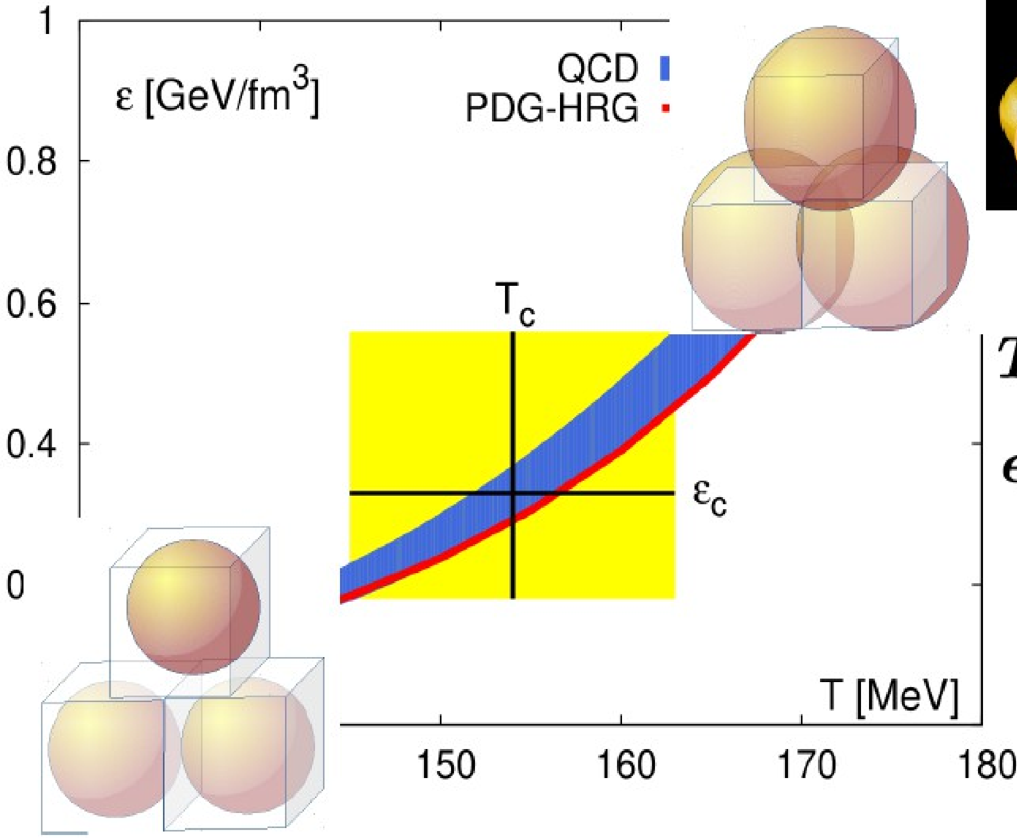


quantitative agreement of chemical freeze-out parameters with LQCD predictions for baryo-chemical potential < 300 MeV

cross over transition at μ_B = 0 MeV

Crossover transition parameters

PDG: Particle Data Group hadron spectrum



dense packing of spheres (DPS)

$$\epsilon^{\mathbf{DPS}} = 0.74\epsilon^{\mathbf{nucleon}}$$
$$\simeq 0.33\ \mathbf{GeV/fm^3}$$
$$(R_p \simeq 0.8\mathbf{fm})$$

overlapping hadrons = QGP ??

$$T_{pc} = (156.5 \pm 1.5)\ \mathbf{MeV}$$
$$\epsilon_{pc} = (0.42 \pm 0.06)\mathbf{GeV/fm^3}$$

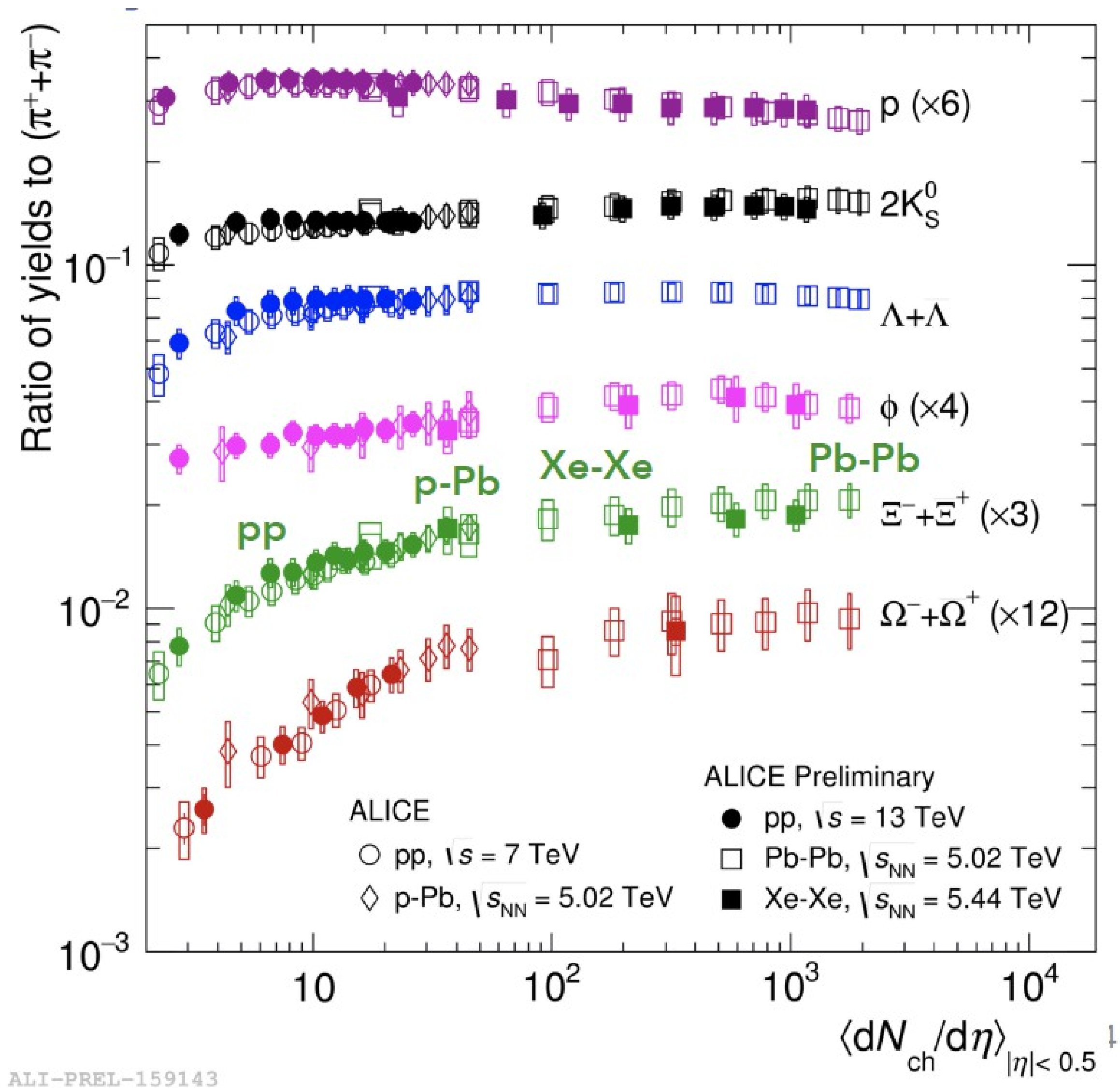
compare with:

$$\epsilon^{\mathbf{nucl.\ mat.}} \simeq 150\ \mathbf{MeV/fm^3}$$
$$\epsilon^{\mathbf{nucleon}} \simeq 450\ \mathbf{MeV/fm^3}$$

A. Bazavov et al. (hotQCD) ,
Phys. Rev. D90 (2014) 094503

slide courtesy Frithjof Karsch

from pp to Pb-Pb collisions: smooth evolution with system size ALICE coll., Nature Phys. 13 (2017) 535-539 1606.07424 [nucl-ex]



universal hadronization can be described with few parameters in addition to T and mu_B

transition from canonical to grand-canonical thermodynamics

The Hypertriton

mass = 2990 MeV, binding energy = 2.3 MeV

Lambda sep. energy = 0.13 MeV

molecular structure: (p+n) + Lambda

2-body threshold: (p+p+n) + pi- = ^{3}He + pi-

rms radius = $(4\ \mathrm{B.E.}\ M_{red})^{-1/2}$ = 10.3 fm =
rms separation between d and Lambda

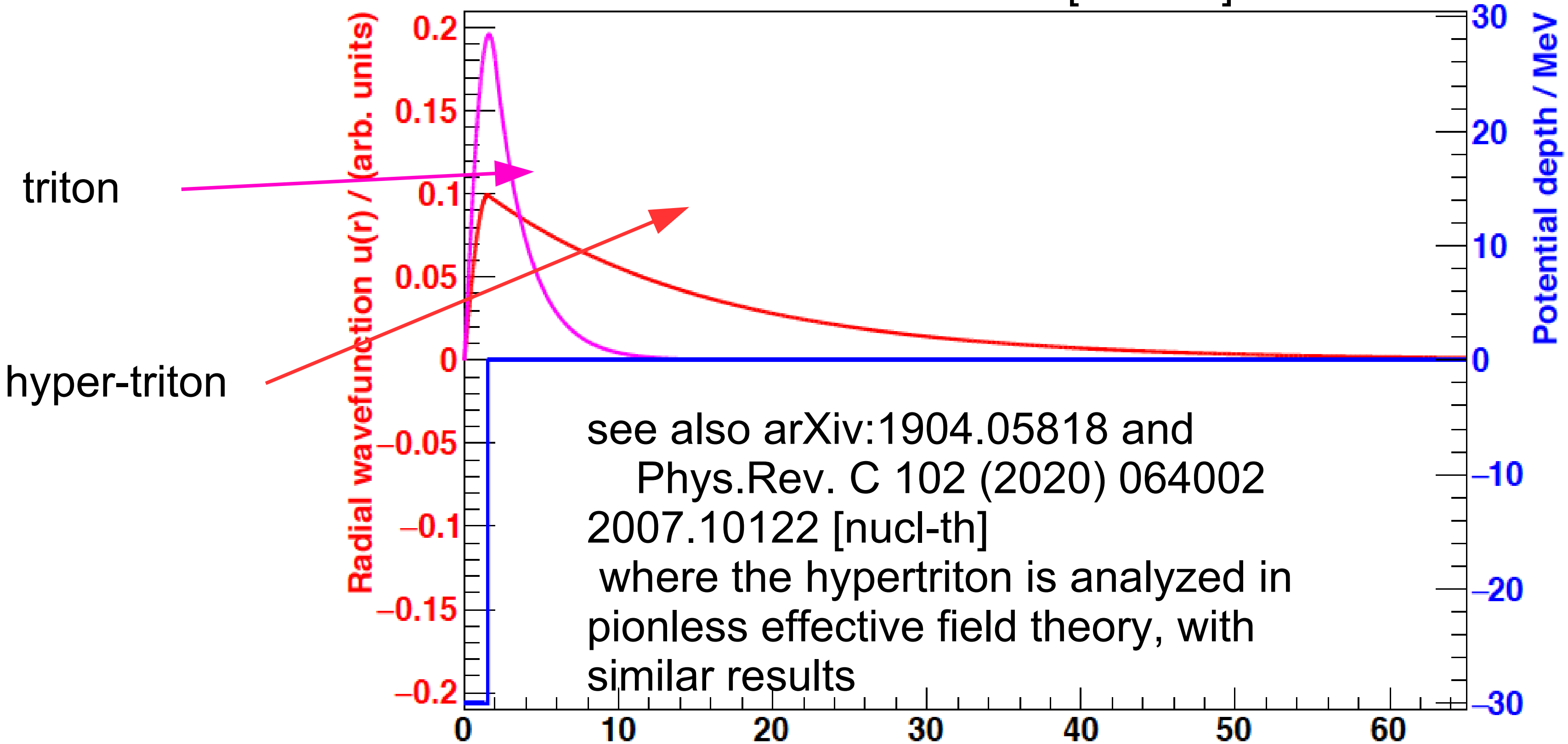
in that sense: hypertriton = (p n Lambda) =
(d Lambda) is the ultimate halo state

yet production yield is fixed at 156 MeV temperature
(about 1000 x Lambda separation energy.)

wave function of the hyper-triton – schematic picture

figure by Benjamin Doenigus, August 2017

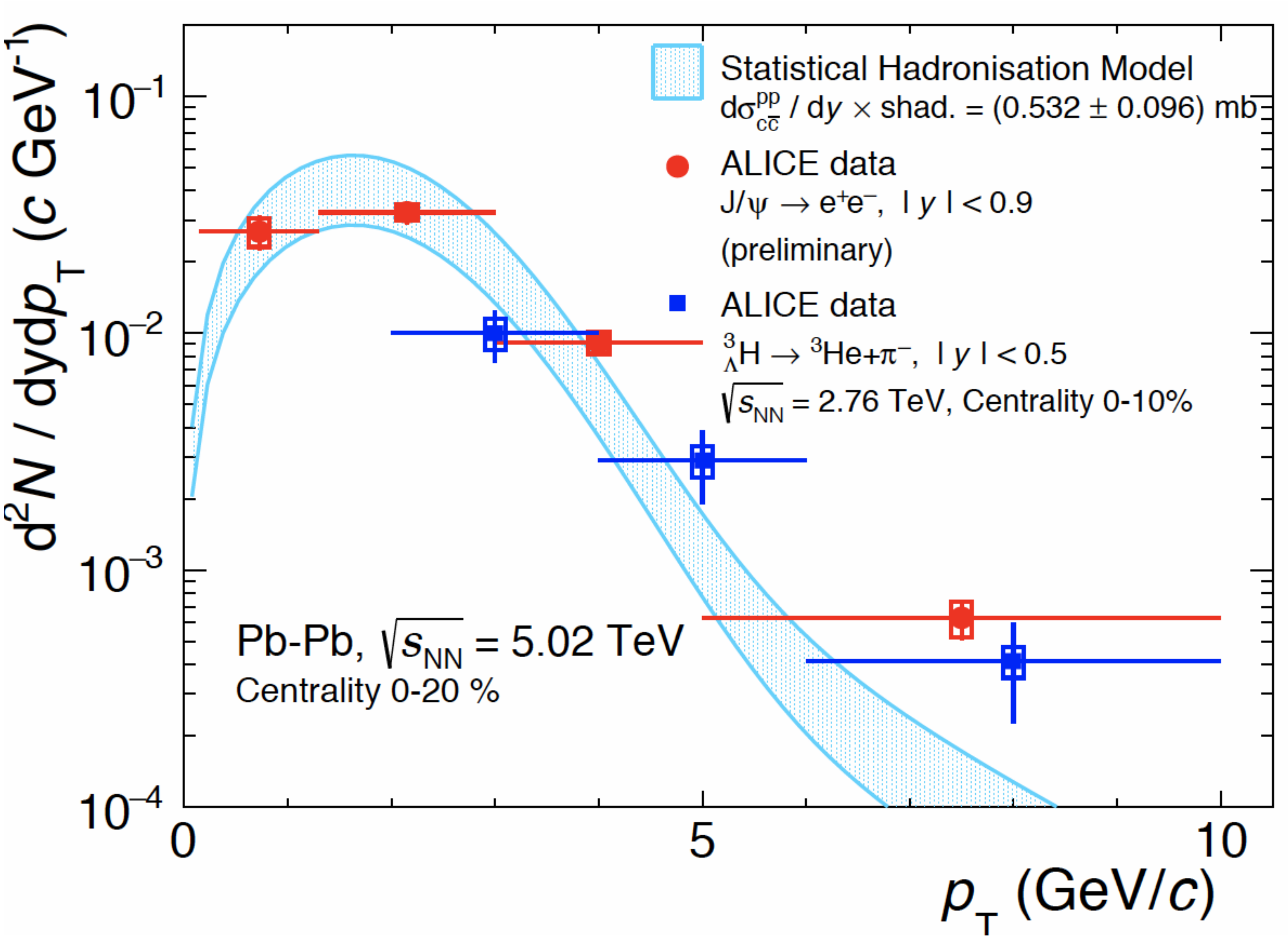
see also: Nucl. Phys. A 987 (2019) 144-201
arXiv:1809.04681 [nucl-ex]



see also arXiv:1904.05818 and
Phys.Rev. C 102 (2020) 064002
2007.10122 [nucl-th]
where the hypertriton is analyzed in pionless effective field theory, with similar results

Wavefunction (red) of the hypertriton assuming a s-wave interaction for the bound state of a Λ and a deuteron. The root mean square value of the radius of this function is $\sqrt{\langle r^2 \rangle} = 10.6$ fm. In blue the corresponding square well potential is shown. In addition, the magenta curve shows a "triton" like object using a similar calculation as the hypertriton, namely a deuteron and an added nucleon, resulting in a much narrower object as the hypertriton.

J/psi and hyper-triton described with the same flow parameters in the statistical hadronization model



binding energies:
J/psi 600 MeV
hypertriton 2.2 MeV
Lambda S.E. 0.2 MeV

from review: hypernuclei and other loosely bound objects produced in nuclear collisions at the LHC, pbm and Benjamin Doenigus, to appear in Nucl. Phys. A, arXiv:1809.04681

doorway state hypothesis:
all nuclei and hyper-nuclei, penta-quark and X,Y,Z states are formed as virtual, compact multi-quark states at the phase boundary. Then slow time evolution into hadronic representation. Excitation energy about 20 MeV, time evolution about 10 fm/c

Andronic, pbm, Redlich, Stachel, arXiv :1710.09425

how can this be tested?

precision measurement of spectra and flow pattern for light nuclei and hyper-nuclei, penta-quark and X,Y,Z states from pp via pPb to Pb-Pb

a major new opportunity for ALICE Run3/4
and beyond LS4 for X,Y,Z and penta-quark states

also new opportunities for
GSI/FAIR and JINR/NICA
experiments

summary

- statistical hadronization model is an effective tool to understand the phenomenology of hadron production in relativistic nuclear collisions from SIS to LHC energy with predictive power for future facilities
- deeply rooted in duality 'hadrons – quarks' near QCD phase boundary
- present precision is mostly limited by incomplete knowledge of hadron mass spectrum and related branching ratios for decays
- measurements from ALICE at the 5% accuracy level show deviations for protons, now quantitatively understood by using experimental pion-nucleon phase shifts
- yields of light nuclei and hyper-nuclei successfully predicted
  → maybe produced as quark bags?
- coalescence approach not microscopic enough for loosely bound states

key results:
experimental location of QCD phase boundary for μ_b < 300 MeV:
T_c = 156 ± 3 MeV
new insight into hadronization