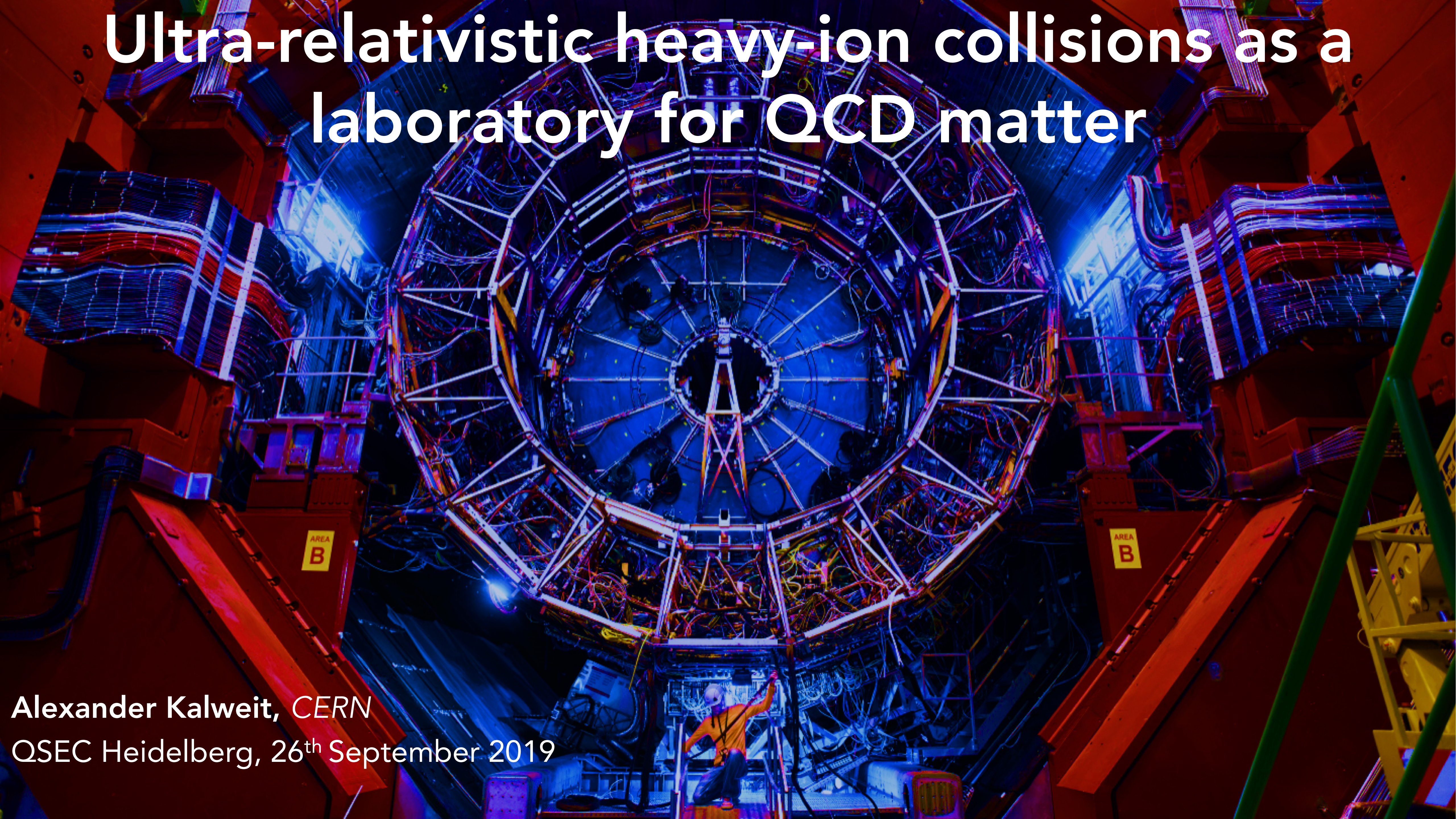
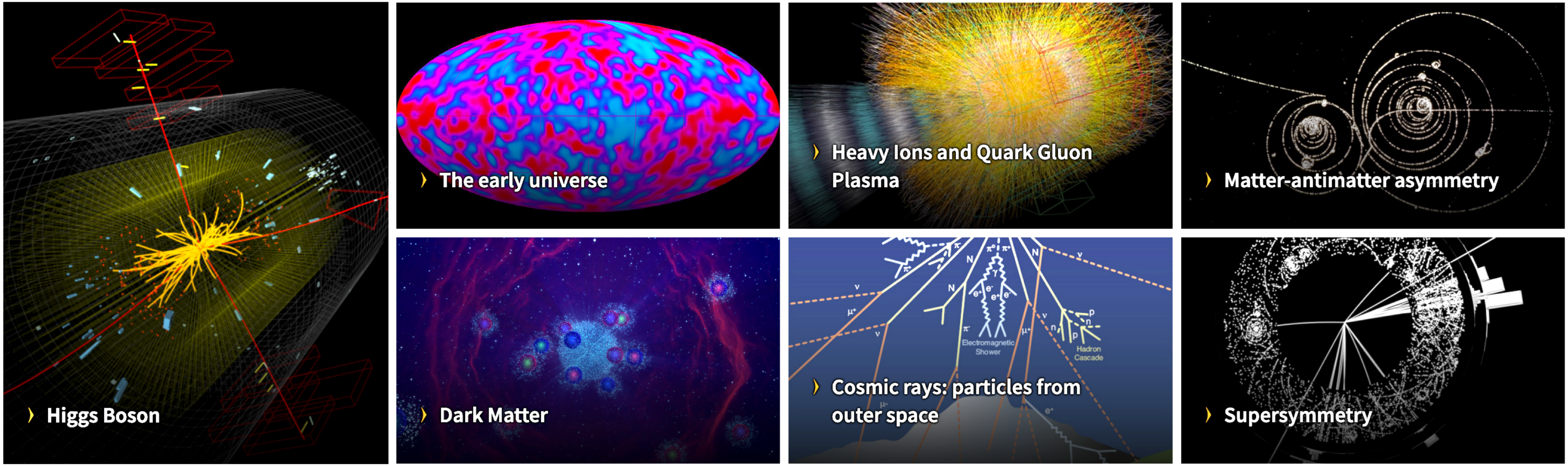


Ultra-relativistic heavy-ion collisions as a laboratory for QCD matter

Alexander Kalweit, *CERN*

QSEC Heidelberg, 26th September 2019

The physics program of CERN

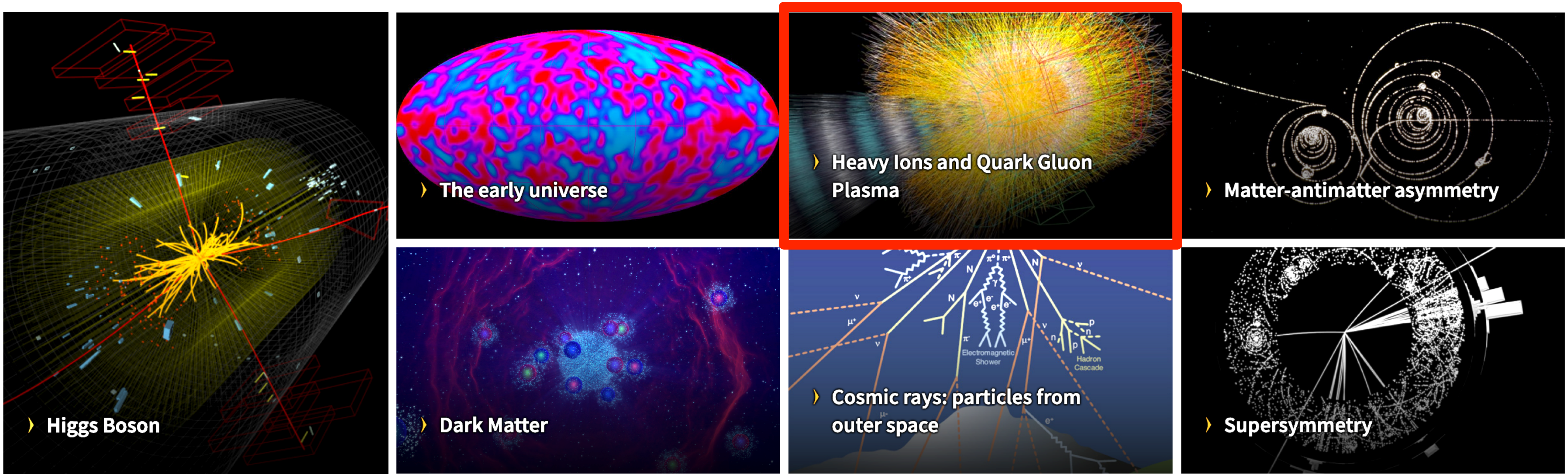


→ CERN's main focus are the core topics of particle physics: the study of the fundamental constituents of matter

→ But the physics program at the laboratory is much broader, ranging from nuclear to high-energy physics, from studies of antimatter to the possible effects of cosmic rays on clouds

[https://home.cern/science/physics]

The physics program of CERN



→ CERN's main focus are the core topics of particle physics: the study of the fundamental constituents of matter

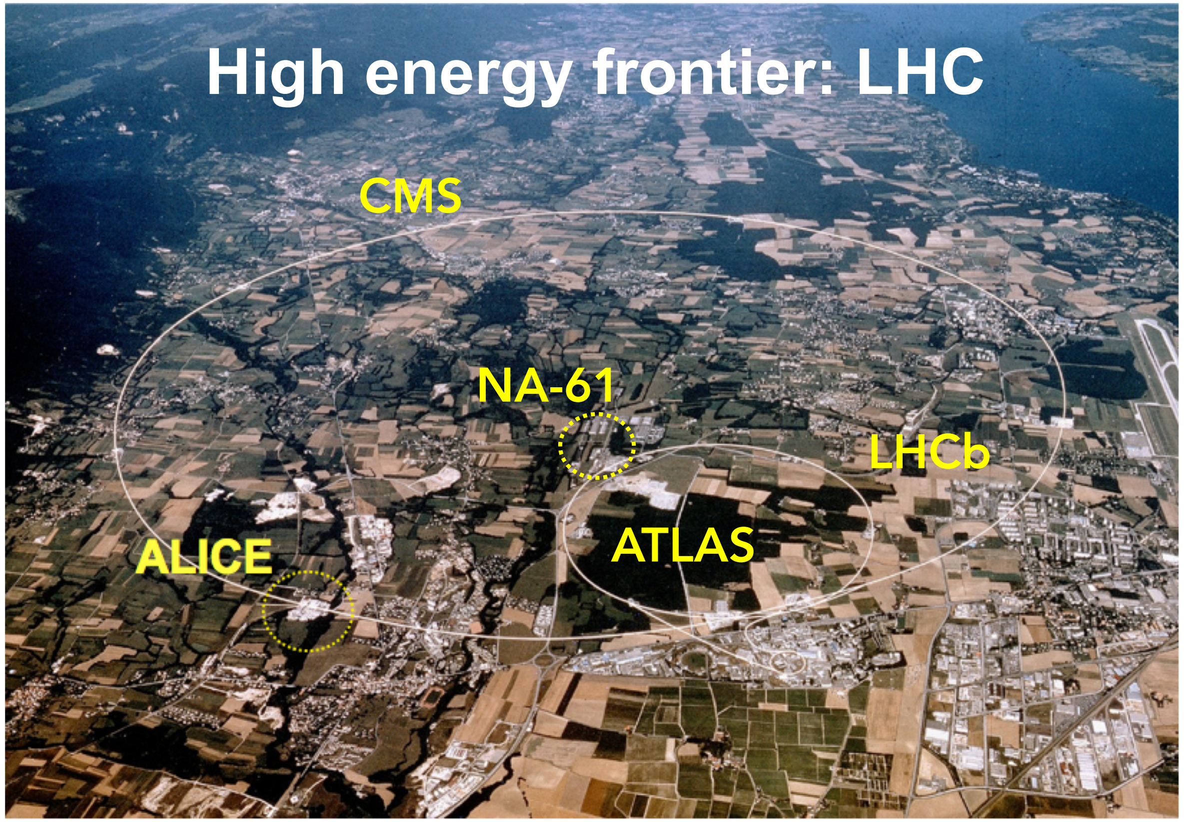
→ But the physics program at the laboratory is much broader, ranging from nuclear to high-energy physics, from studies of antimatter to the possible effects of cosmic rays on clouds

Large Hadron Collider (LHC)

#CERNOpenDays: a big success and a big thank you!

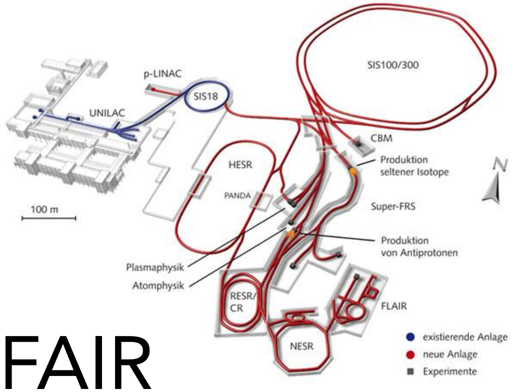
- 75000 visitors in two days at CERN.
- 20000 visitors underground.
- 4500 visitors in the ALICE cavern.
- Many thanks to the numerous volunteers from Heidelberg!

Heavy-ion experiments

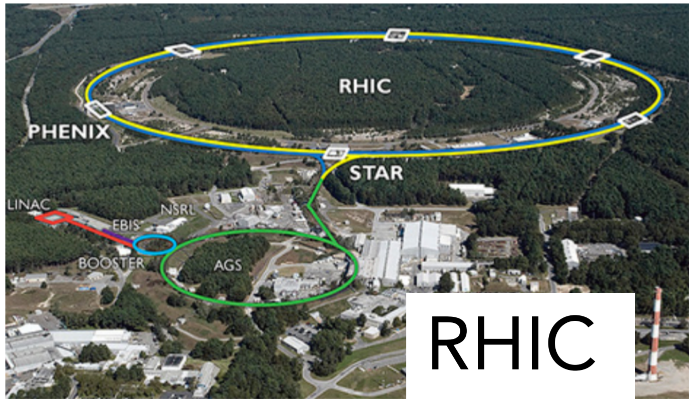


→ By now **all major LHC experiments have a heavy-ion program**: LHCb took Pb-Pb data for the first time in November 2015.

Low energy frontier: RHIC (BES), SPS
→ future facilities: FAIR (GSI), NICA



FAIR

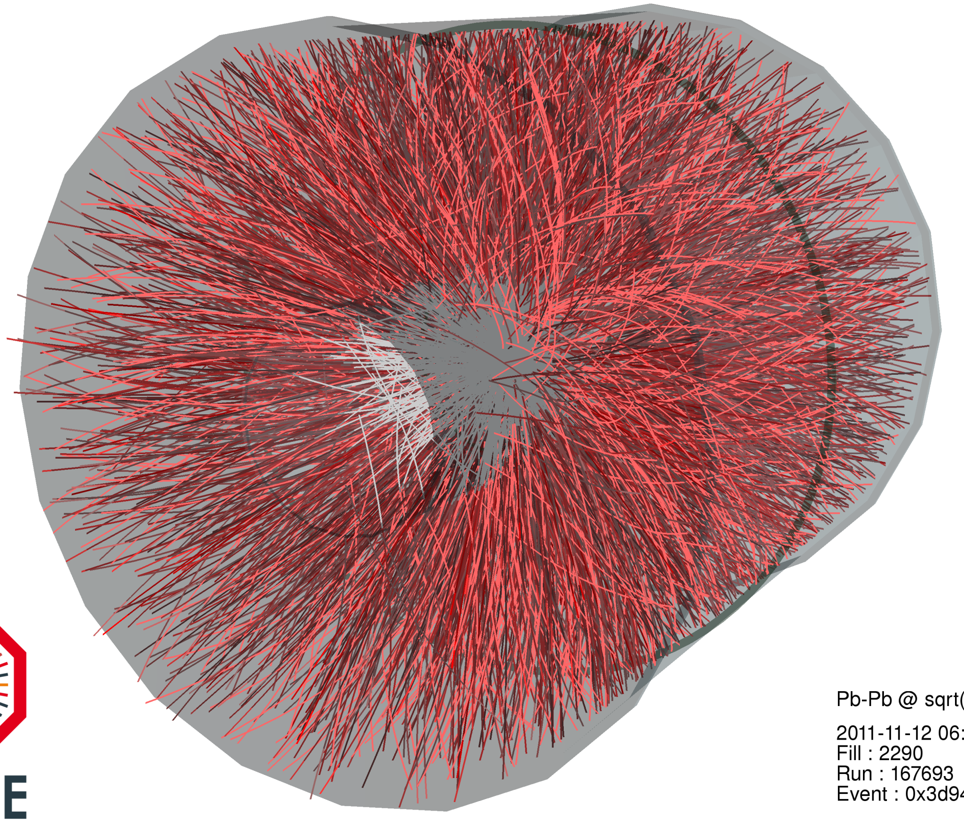


RHIC

Heavy-ions at the LHC

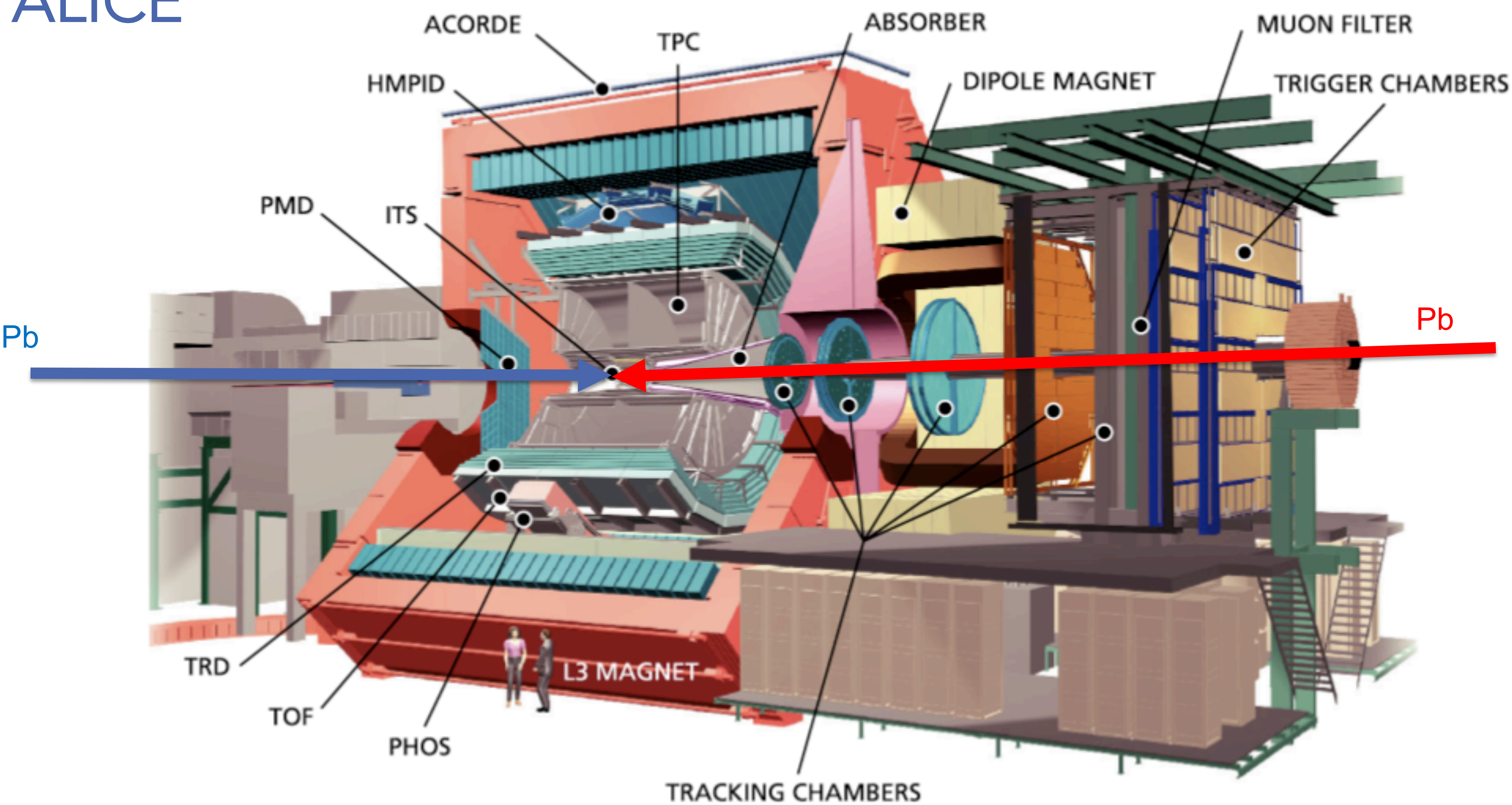
- Energy per nucleon in a $^{208}_{82}$Pb-Pb collision at the LHC (Run 1):
  - pp collision energy $\sqrt{s}$ = 7 TeV
  - beam energy in pp E_{beam} = 3.5 TeV
  - Beam energy per nucleon in a Pb-Pb nucleus: $E_{beam,PbPb}$ = 82/208* 3.5 = 1.38 TeV
  - Collision energy per nucleon in Pb-Pb: $\sqrt{s_{NN}}$ = 2.76 TeV
  - Total collision energy in Pb-Pb: **$\sqrt{s}$ = 574 TeV**
  - Run 2: $\sqrt{s_{NN}}$ = 5.02 TeV and thus **$\sqrt{s}$ = 1.04 PeV**
- Ultra-relativistic: $E_{beam} >> m_p$

→This very large kinetic energy of the beam is converted into the production of many new particles at each collision (e.g. $m_\pi \approx$ 139.57 MeV).



ALICE
A JOURNEY OF DISCOVERY

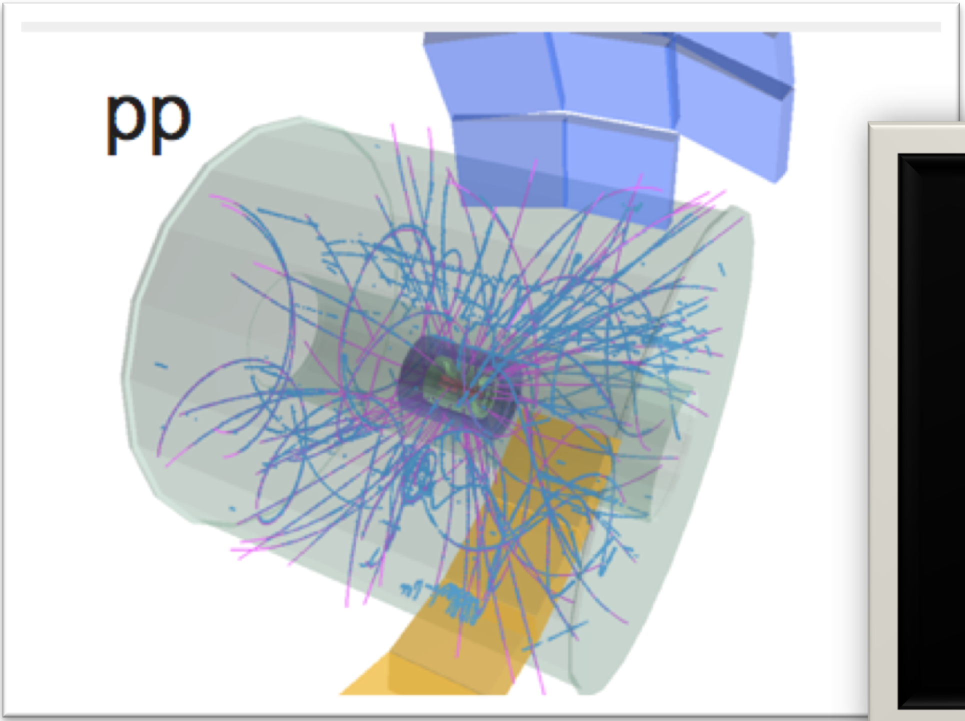
ALICE



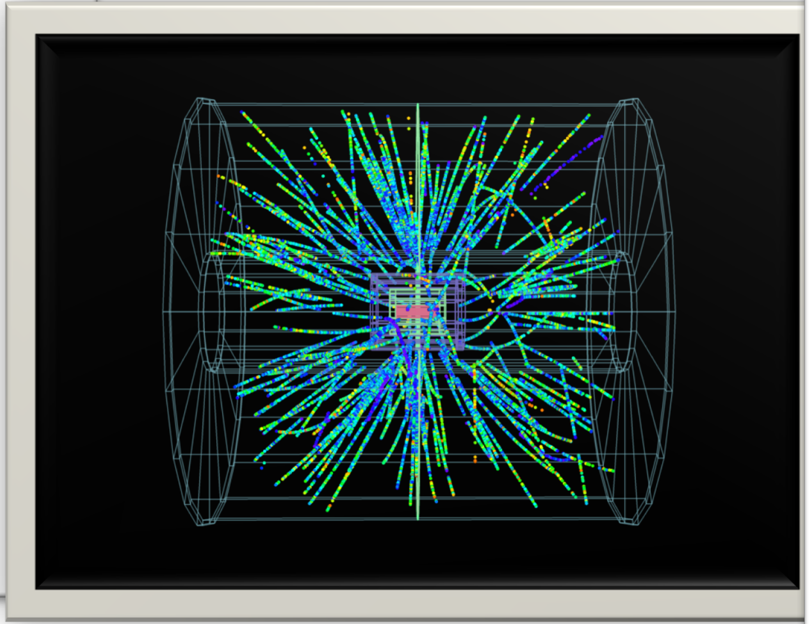
ALICE: **A** **L**arge **I**on **C**ollider **E**xperiment

pp / p-Pb / Pb-Pb collisions

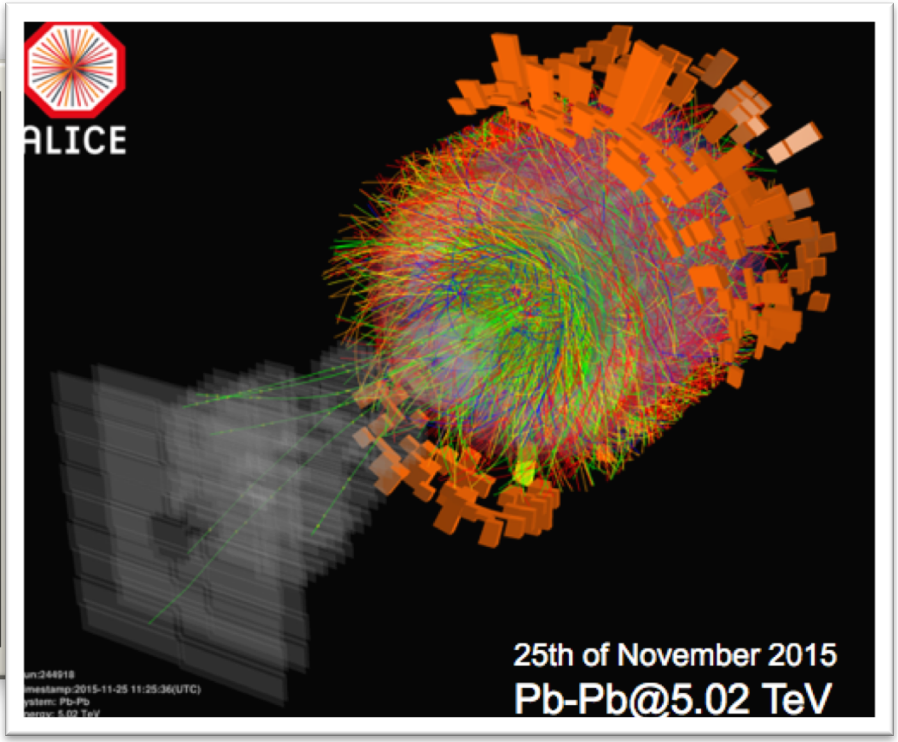
- The LHC can not only collide protons on protons, but also heavier ions.
- Approximately one month of running time is dedicated to heavy-ions each year.



p-Pb

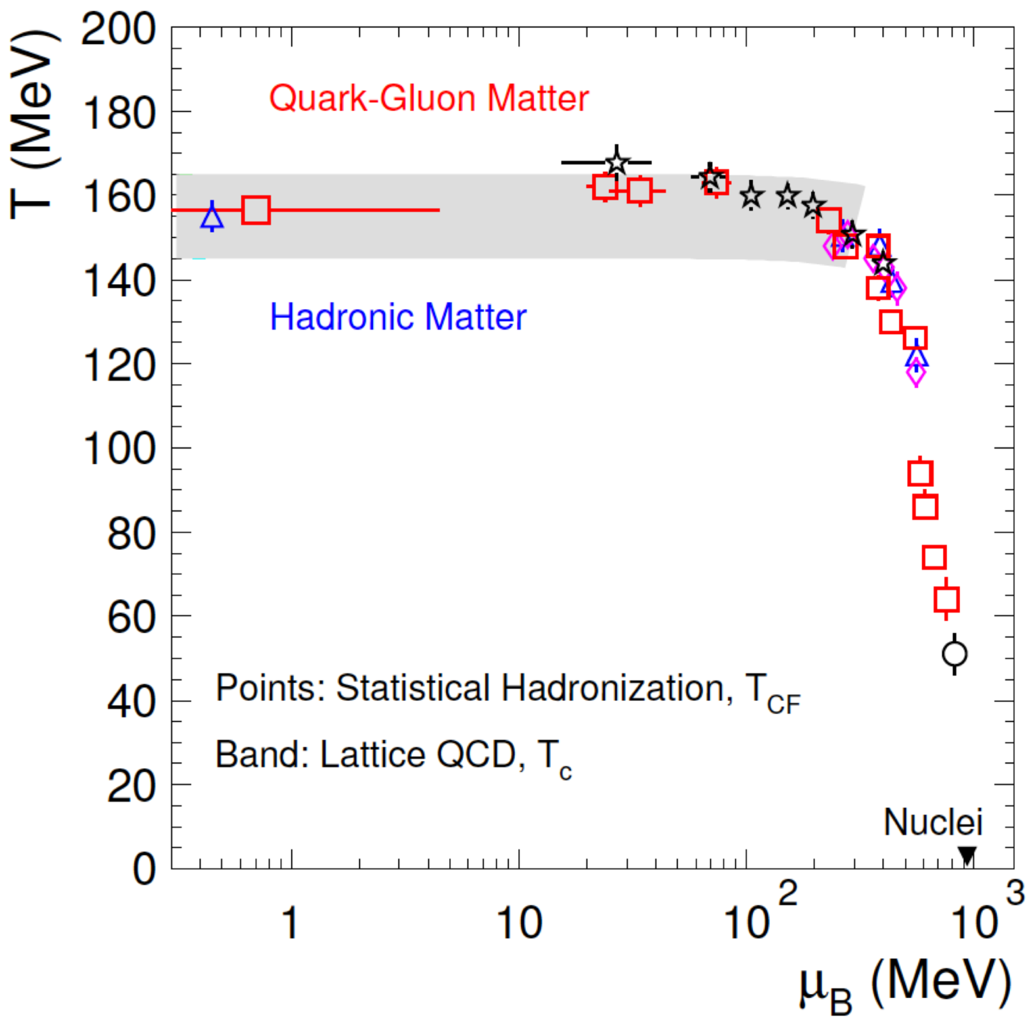


Pb-Pb



Outline

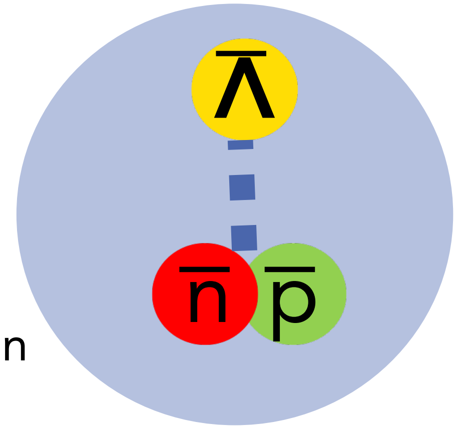
[A. Andronic et al. Nature 561 (2018) no.7723, 321-330]



My talk consists of two major parts:

1. Short general introduction to ultra-relativistic heavy-ion physics and the QCD phase diagram

2. A textbook example for a quantum system under extreme conditions: the **anti-hyper-triton** production in heavy-ion collisions



anti-hyper-triton

Short general introduction to heavy-ion physics

The standard model

The standard model describes the **fundamental** building blocks of matter (Quarks and Leptons) and their Interactions:

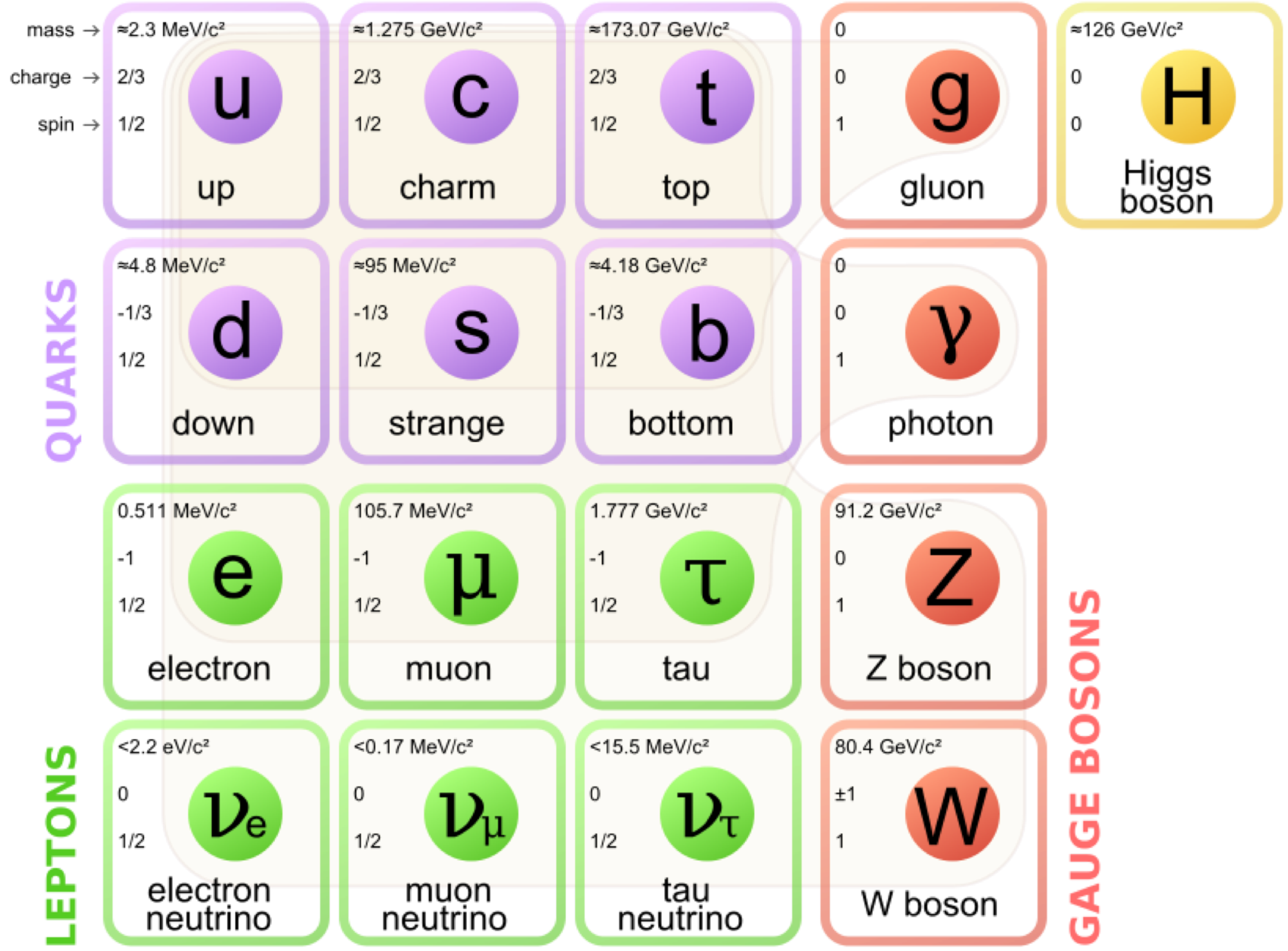
1. Elektromagnetic: γ
2. Weak interaction: W&Z
3. **Strong interaction: Gluons**
4. Gravitation: Graviton?

Dramatic confirmation of the standard model in the last years at the LHC: discovery and further investigation of the Higgs-Boson.

However, no signs of physics beyond the standard model were found so far (SUSY, dark matter..).

→ In heavy-ion physics, we investigate physics within the standard model and not beyond it.

→ Discovery potential in **many body phenomena of the strong interaction** (as in QED and solid state physics: magnetism, electric conductivity, viscosity,..)!



[https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg]

Heavy-ions and Quantum Chromodynamics

Heavy-ion physics is the physics of *high energy density Quantum Chromodynamics (QCD)*:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(i\gamma^{\mu} D_{\mu} - m)q - \frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu}_{a}$$

Quark-field

Quark-mass

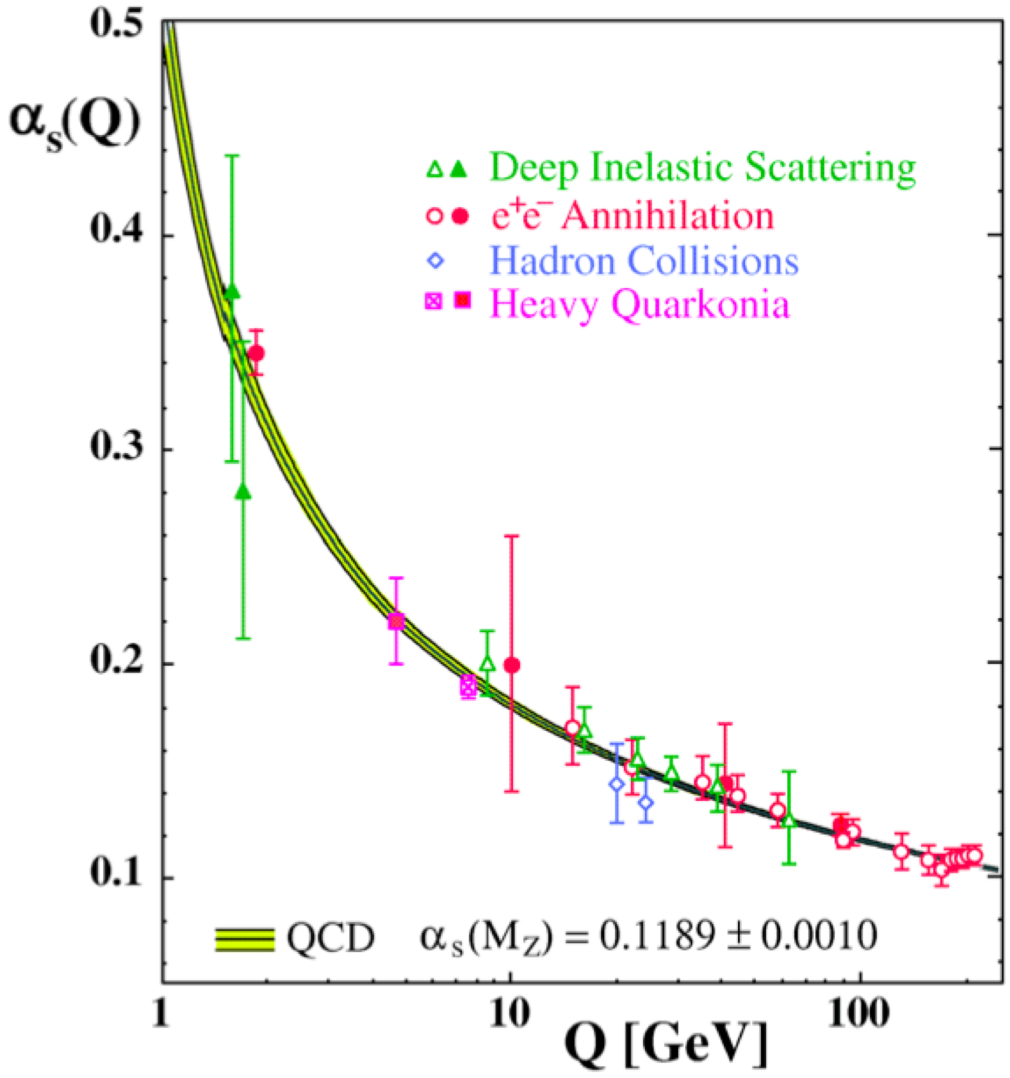
Gluon field strength

Properties of QCD relevant for heavy-ions:

(a.) *Confinement*: Quarks and gluons are bound in color neutral mesons ($q\bar{q}$) or baryons (qqq).

(b.) *Asymptotic freedom*: Interaction strength decreases with increasing momentum transfer ($\alpha_S \rightarrow 0$ for $Q^2 \rightarrow \infty$).

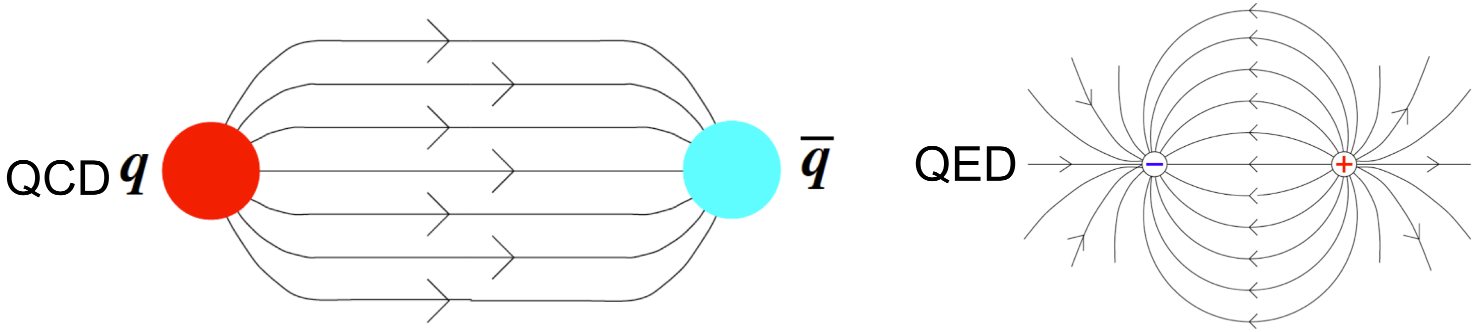
(c.) *Chiral symmetry*: Interaction between left- and right handed quarks disappears for massless quarks.

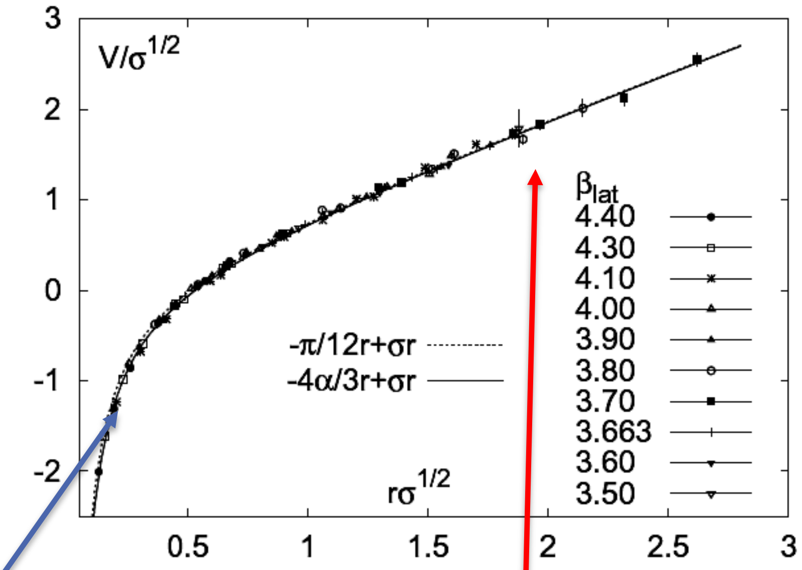


[Prog.Part.Nucl.Phys. 58 (2007) 351-386]

(De-)confinement (1)

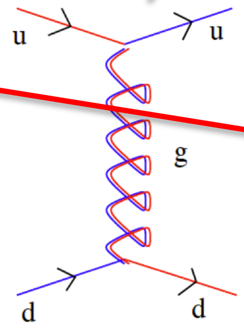
- QCD vacuum:
  - Gluon-gluon self-interaction (non abelian) → in contrast to QED
  - QCD field lines are compressed in a flux tube

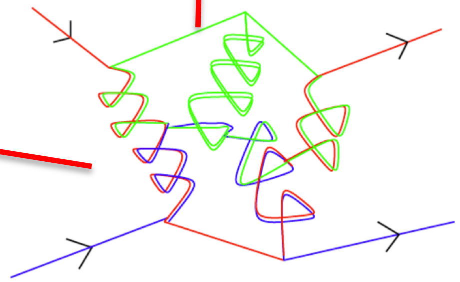




- Potential grows linearly with distance
  → ***Cornell potential:***

$$V(r) = -\frac{A(r)}{r} + Kr$$

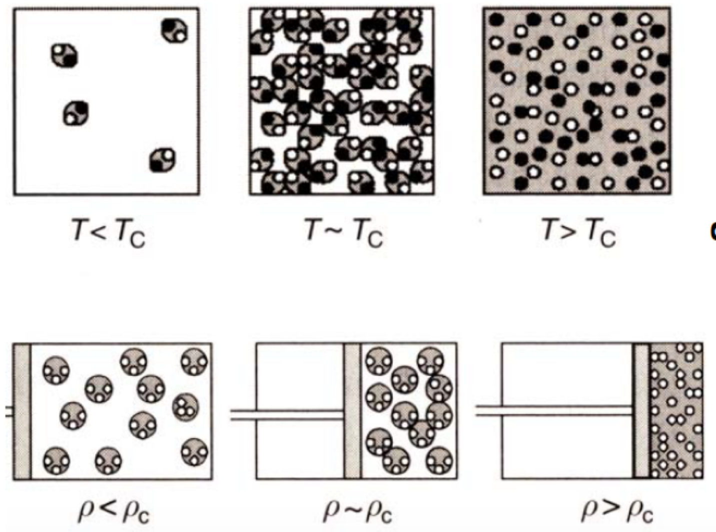




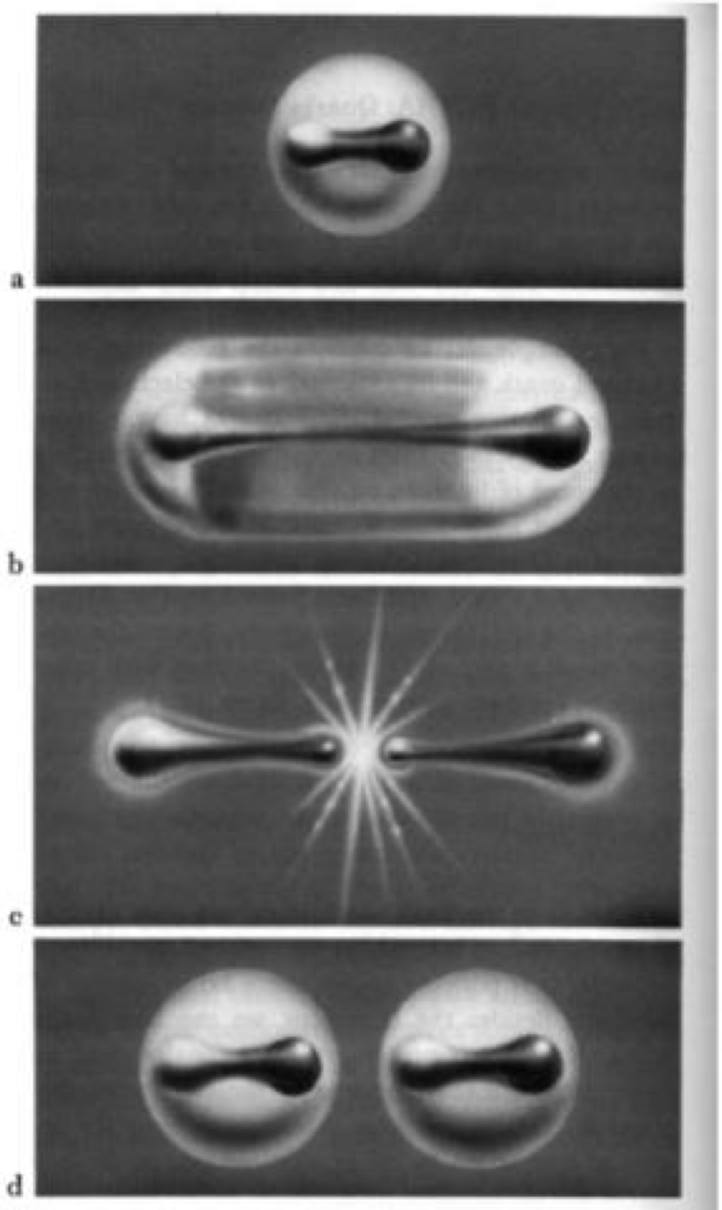
- "String tension" is huge:
  K ~ 880 MeV/fm

(De-)confinement (2)

- Pulled apart, the energy in the string increases.
- New q-qbar is created once the energy is above the production threshold as it is energetically more favorable than increasing the distance further.
- No free quark can be obtained → confinement.
- Percolation picture: at high densities / temperatures, quarks and gluons behave quasi-free and *color conductivity* can be achieved: Quark-Gluon-Plasma (QGP).

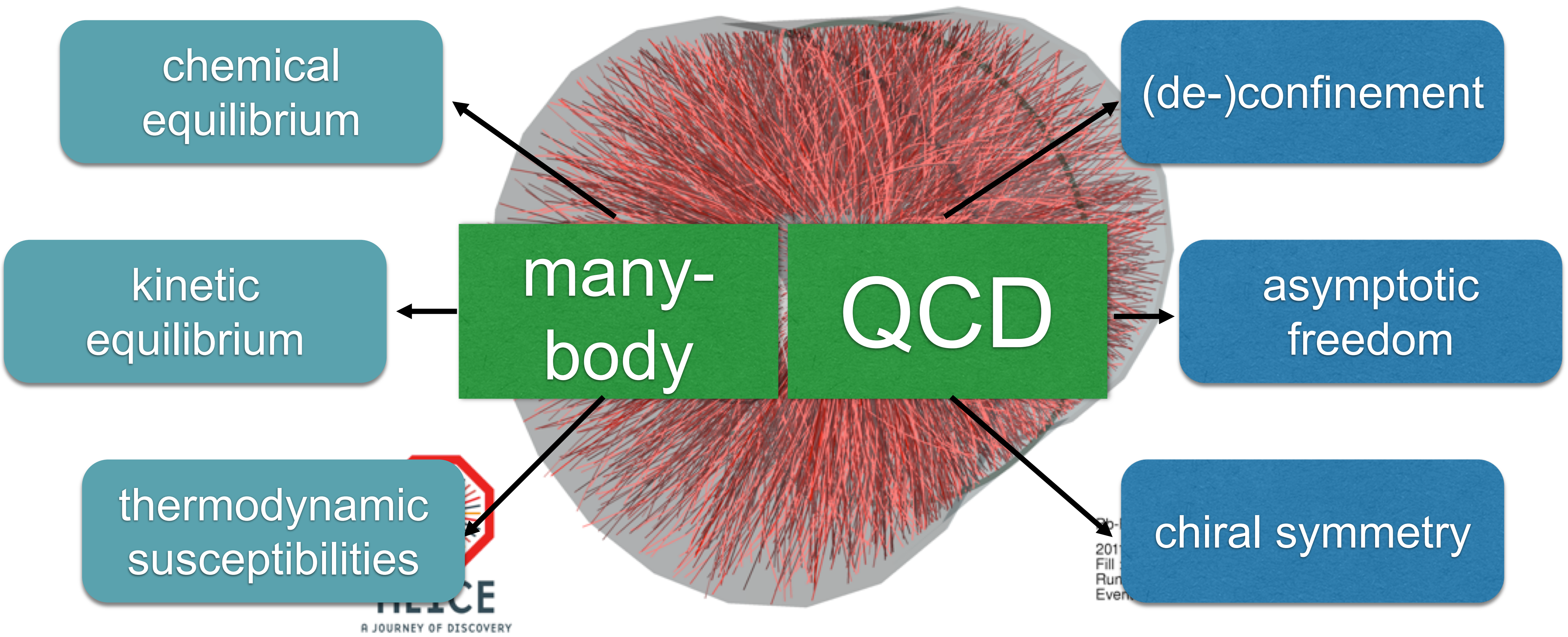


Yagi et al.



[illustration from Fritzsch]

Heavy-ion physics and QCD

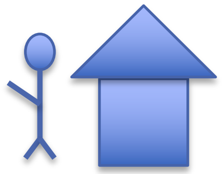


central (0-5%) Pb-Pb collisions (LHC): $dN_{ch}/d\eta \approx 1600$

QGP as the asymptotic state of QCD (1)

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

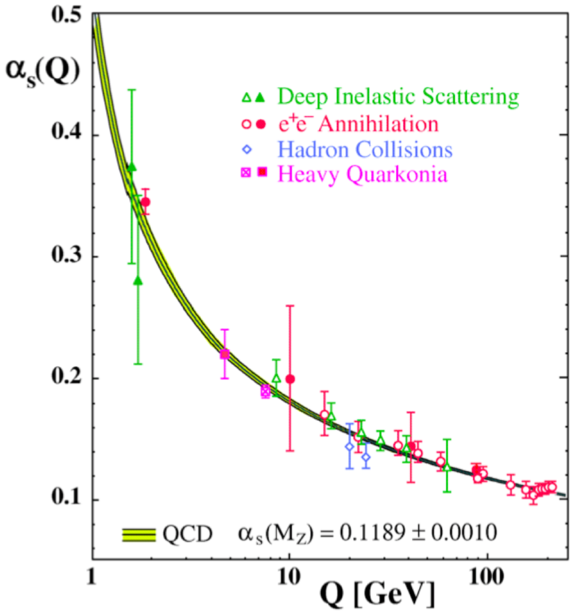
bound quarks & gluons



Asymptotic freedom: *free quarks & gluons*

$T \longrightarrow \infty$

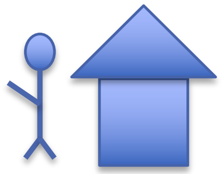
Temperature T



QGP as the asymptotic state of QCD (2)

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

bound quarks & gluons



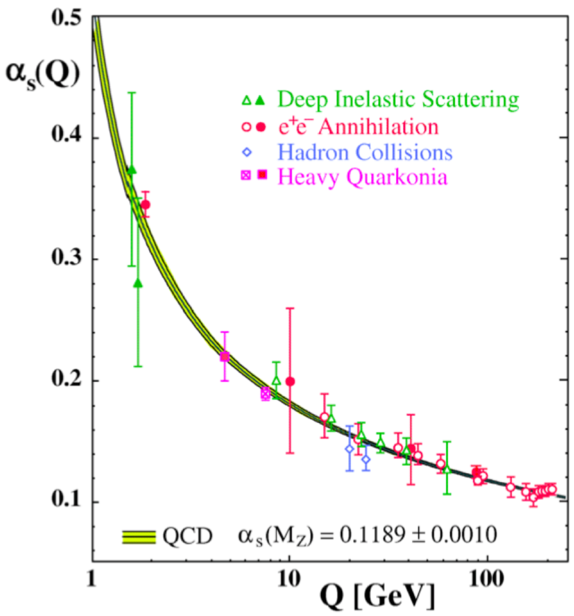
Where is the phase transition?
→ Lattice QCD

Asymptotic freedom: *free quarks & gluons*

$T_0 \approx 1/40$ eV

$T \longrightarrow \infty$

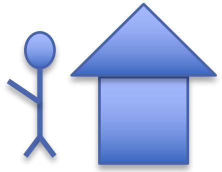
Temperature T



QGP as the asymptotic state of QCD (3)

Quark-Gluon-Plasma (QGP): at extreme temperatures and densities quarks and gluons behave quasi-free and are not localized to individual hadrons anymore.

bound quarks & gluons



Where is the phase transition?
→ Lattice QCD

Asymptotic freedom: *free quarks & gluons*

Temperature T

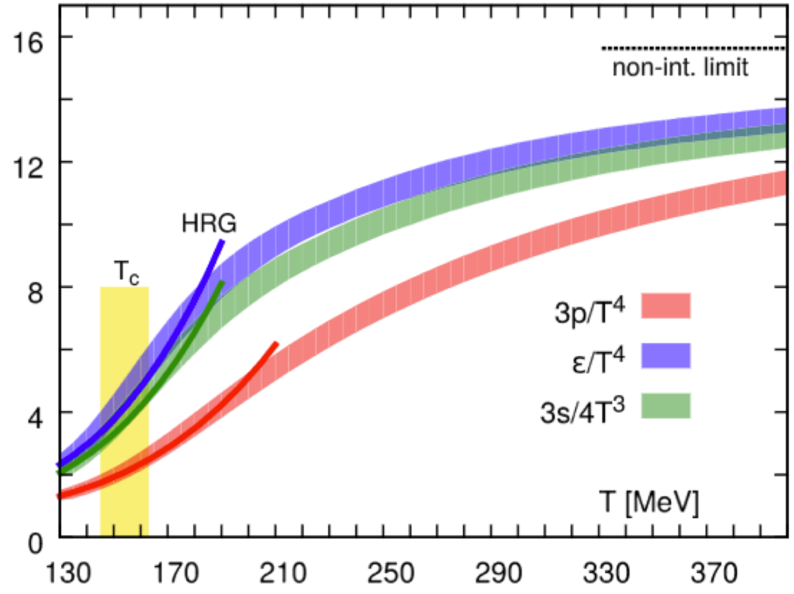
$T_0 \approx 1/40$ eV

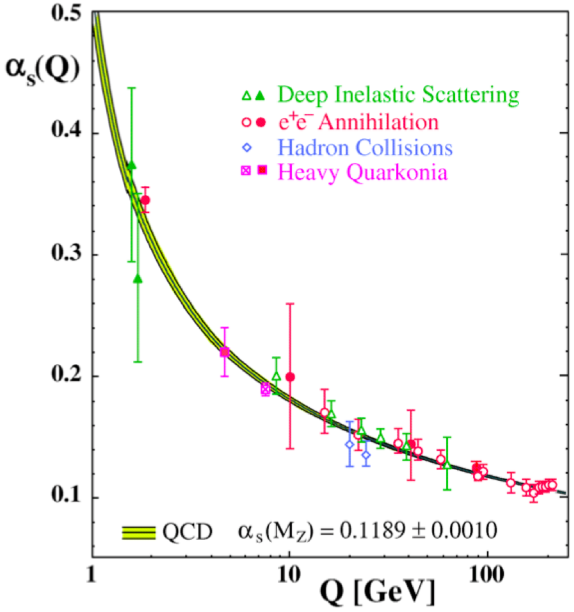
Critical temperature
$T_c \approx 156$ MeV

$T \rightarrow \infty$

→ Are such extreme temperatures reached in the experiment?
Yes..

[PRD 90 094503 (2014)]



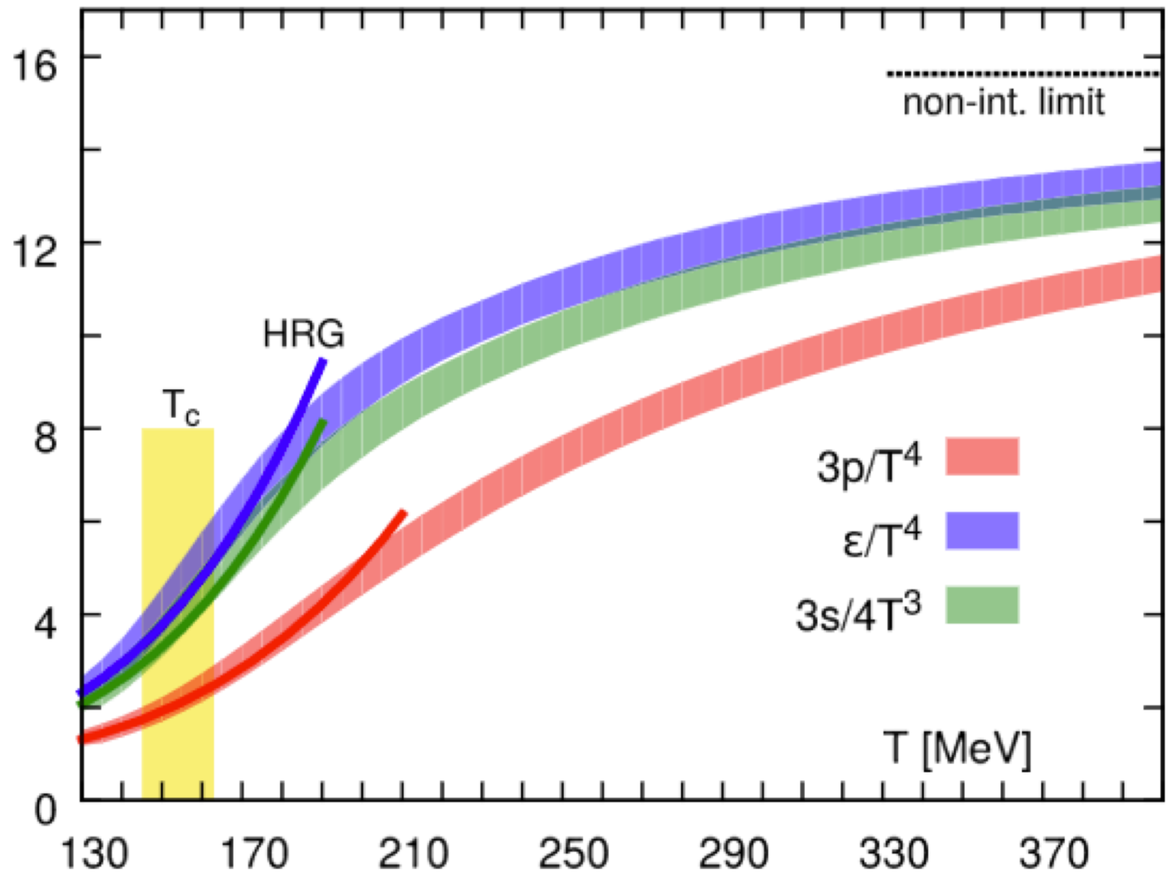


Phase transition in Lattice QCD

Critical temperature
$T_c \approx 156$ +/- 9 MeV

[PRD 90 094503 (2014)]

Energy density ε
Pressure p
Entropy density s

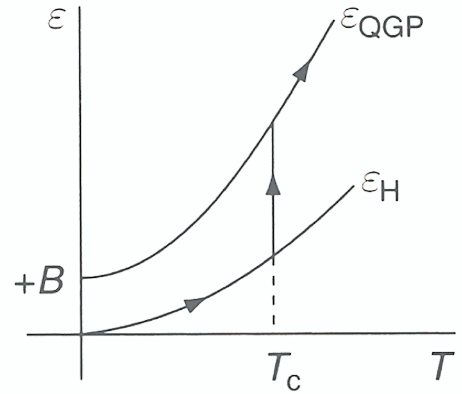


For comparison:

T=156 MeV ≙ $1.8 \cdot 10^{12}$ K
Sun core: $1.5 \cdot 10^7$ K
Sun surface: 5778 K

Steep rise in thermodynamic quantities due to change in number of degrees of freedom → phase transition from **hadronic to partonic** degrees of freedom.

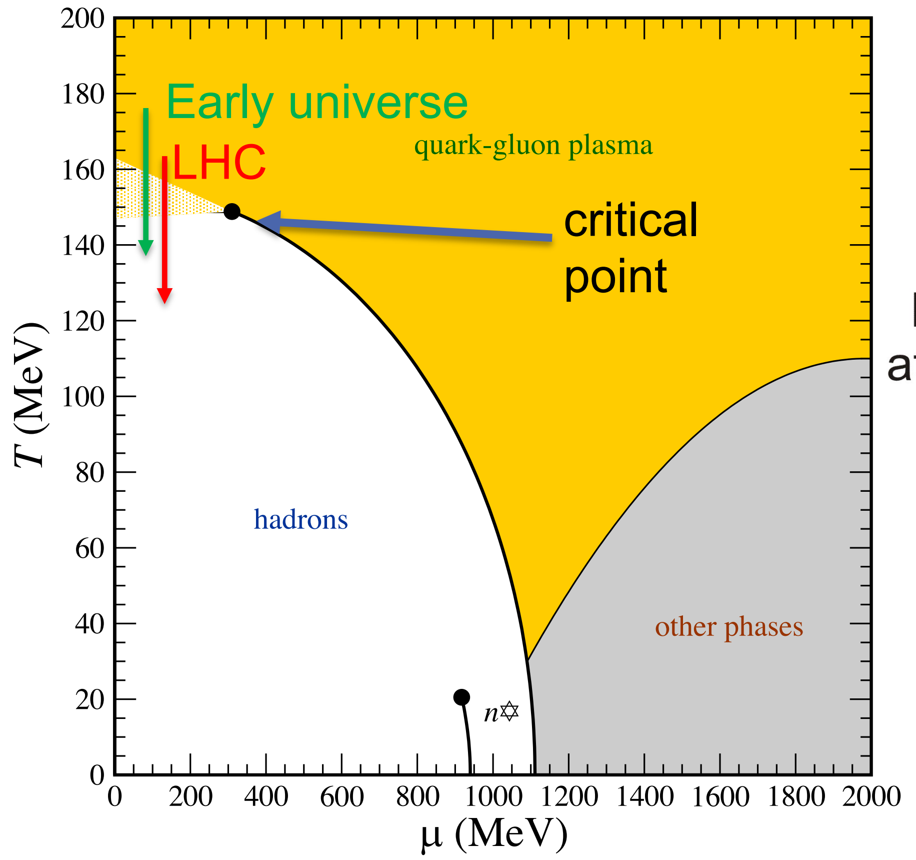
Smooth *crossover* for a system with net-baryon content equal 0. For a *first order phase transition*, the behavior would be not continuous.



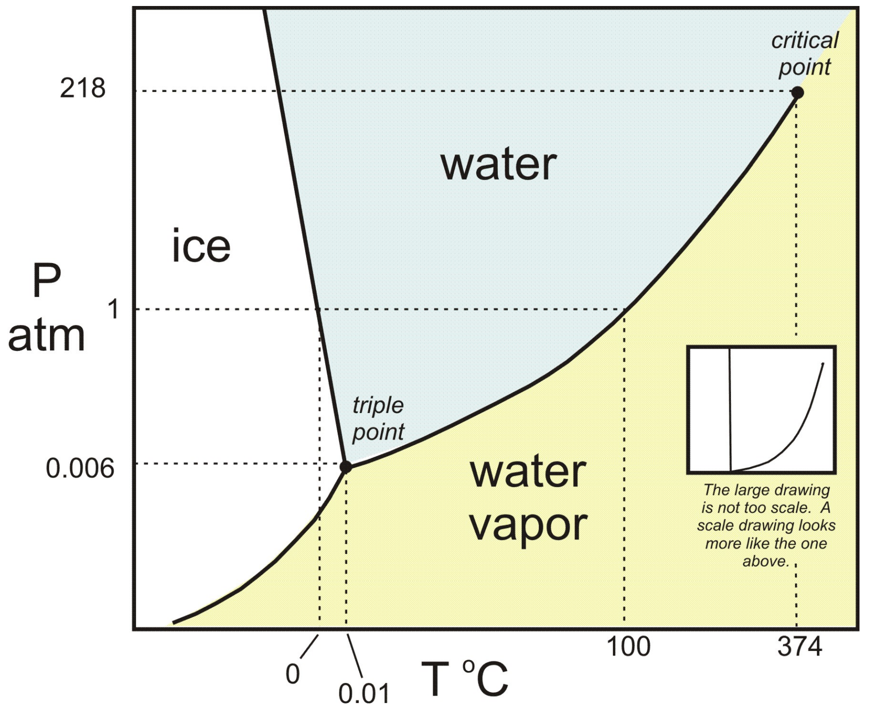
The phase diagram of QCD (1)

- The thermodynamics of QCD can be summarized in the following (schematic) phase diagram.
- Control parameters: temperature *T* and baryo-chemical potential μ_B.

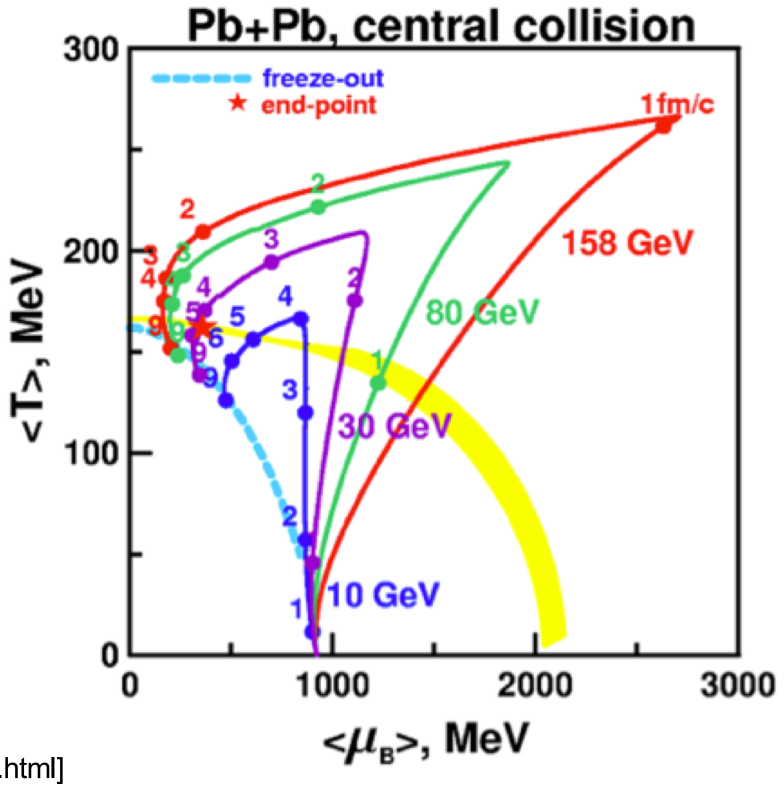
→ Different regions of the phase diagram are probed with different $\sqrt{s_{NN}}$.



[Ann. Rev. Nucl. Part. Sci. 62 (2012) 265]



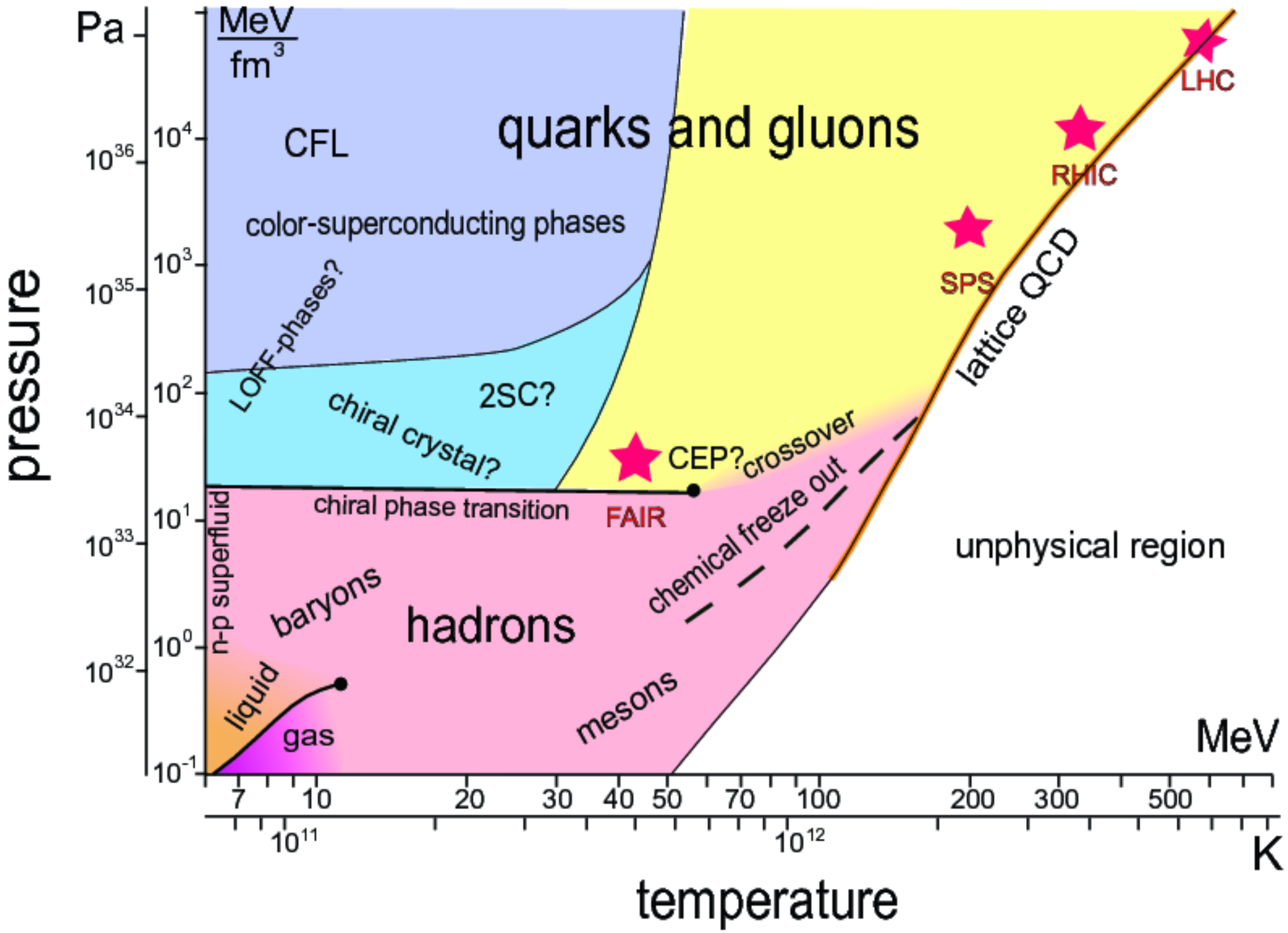
[http://serc.carleton.edu/research_education/equilibria/phaserule.html]



Y.B. Ivanov et al., Phys. Rev. C 73 (2006) 30.

The phase diagram of QCD (2)

→ Alternative representation which is not used in practice, but to emphasize more the similarity to the phase diagram of water.



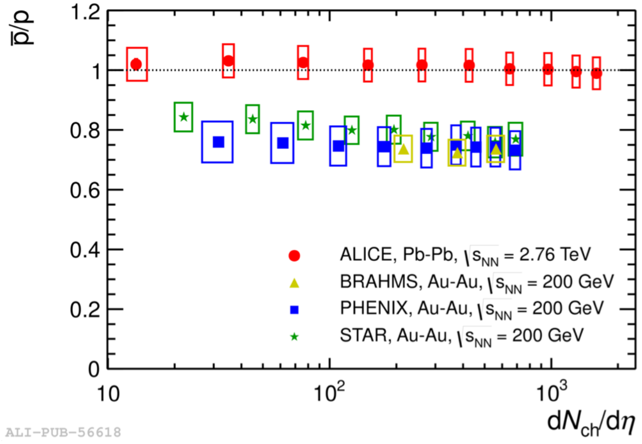
The baryochemical potential μ_B

- In contrast to the (chemical freeze-out) temperature T, the baryochemical potential is a less intuitive quantity…
- It quantifies the net-baryon content of the system (baryon number transport to midrapidity).

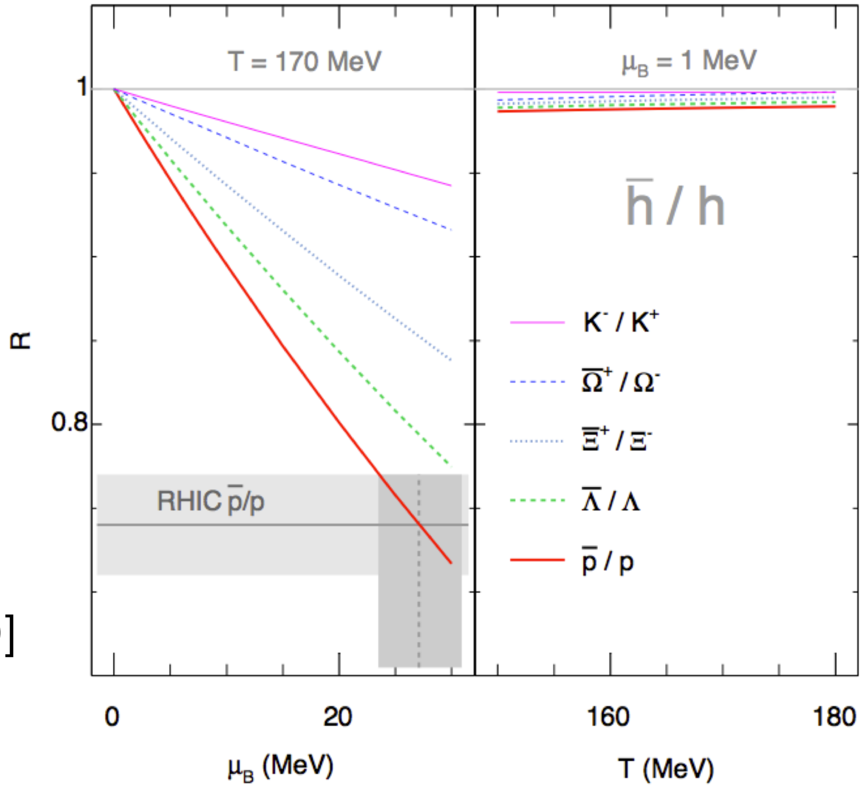
fundamental thermodynamic relation

$$\mathrm{d}U = T\,\mathrm{d}S - p\,\mathrm{d}V + \Sigma\mu_i\,\mathrm{d}n_i \quad .$$

$$\Rightarrow \mu_i := \left(\frac{\partial U(S,V,n_j)}{\partial n_i}\right)_{S,V,n_{j\neq i}}$$



[Phys. Rev. C88 (2013) 044910]



(I. Kraus)

$$\mu_B \approx 0 \quad => \quad \bar{p}/p \approx 1$$

However, (anti-)nuclei are more sensitive:

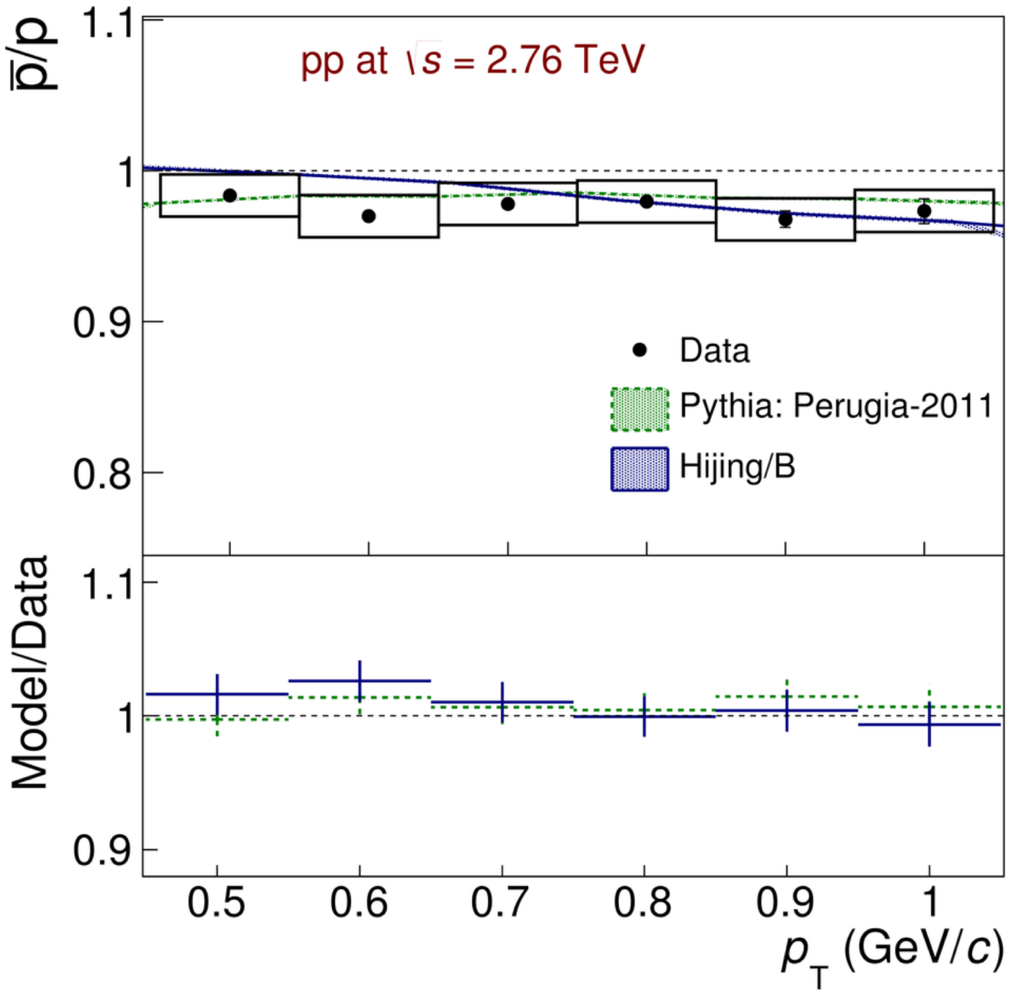
$$\frac{n_{\bar{p}}}{n_p} = e^{-(2\mu_B)/T}$$

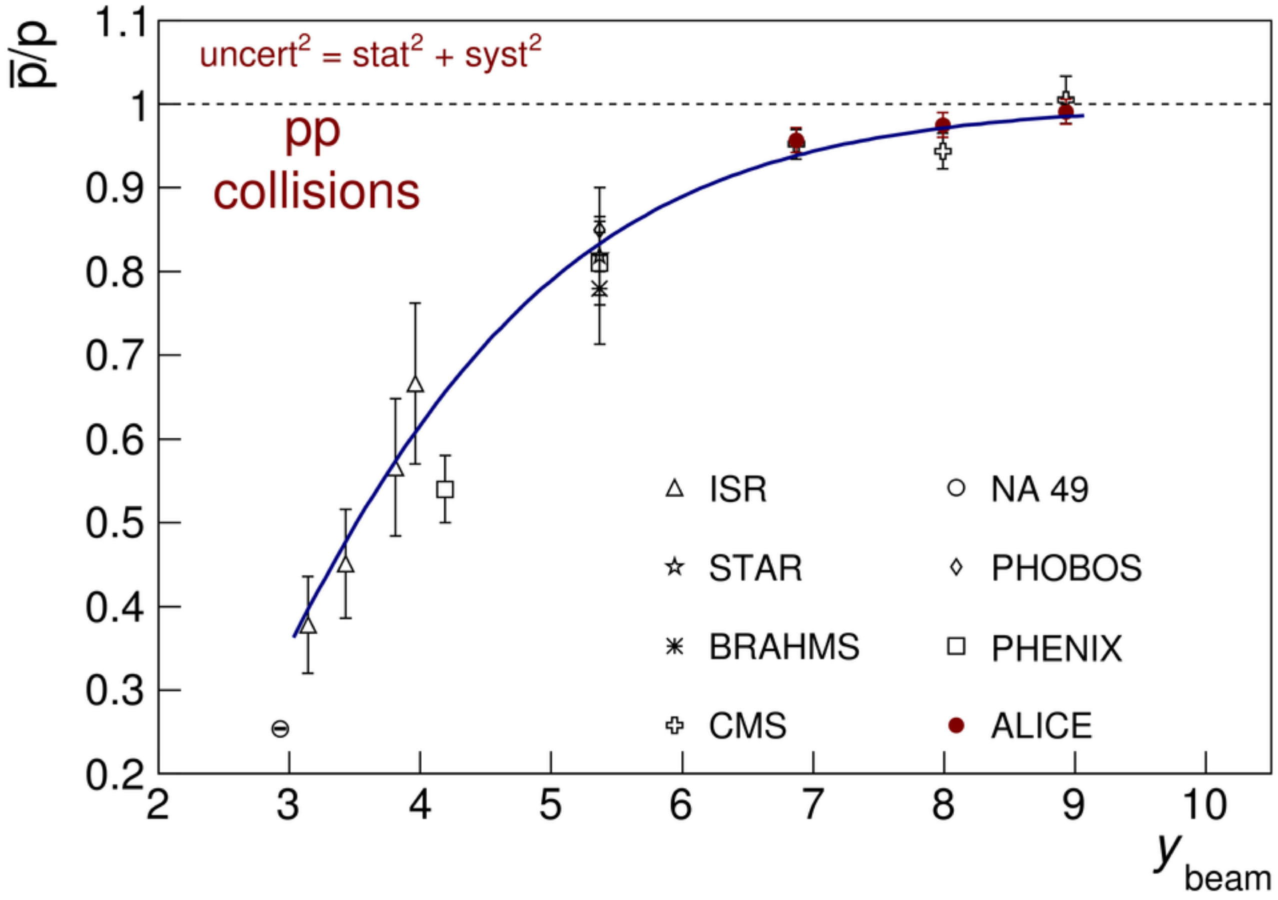
$$\frac{n_{\bar{d}}}{n_d} = e^{-(4\mu_B)/T}$$

$$\frac{n_{^3\overline{\mathrm{He}}}}{n_{^3\mathrm{He}}} = e^{-(6\mu_B)/T}$$

[Eur. Phys. J. C 73 (2013) 2496]

Particle to anti-particle ratios (1)

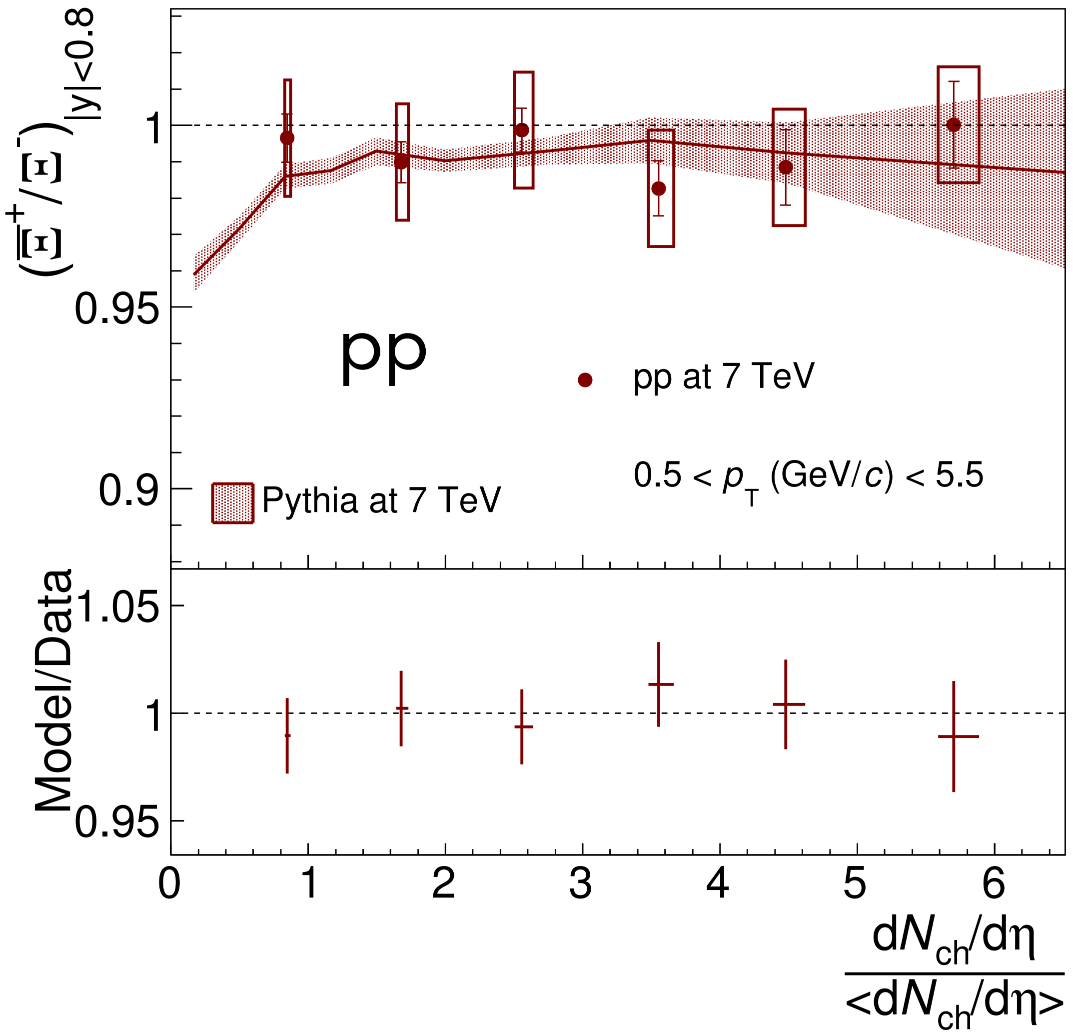


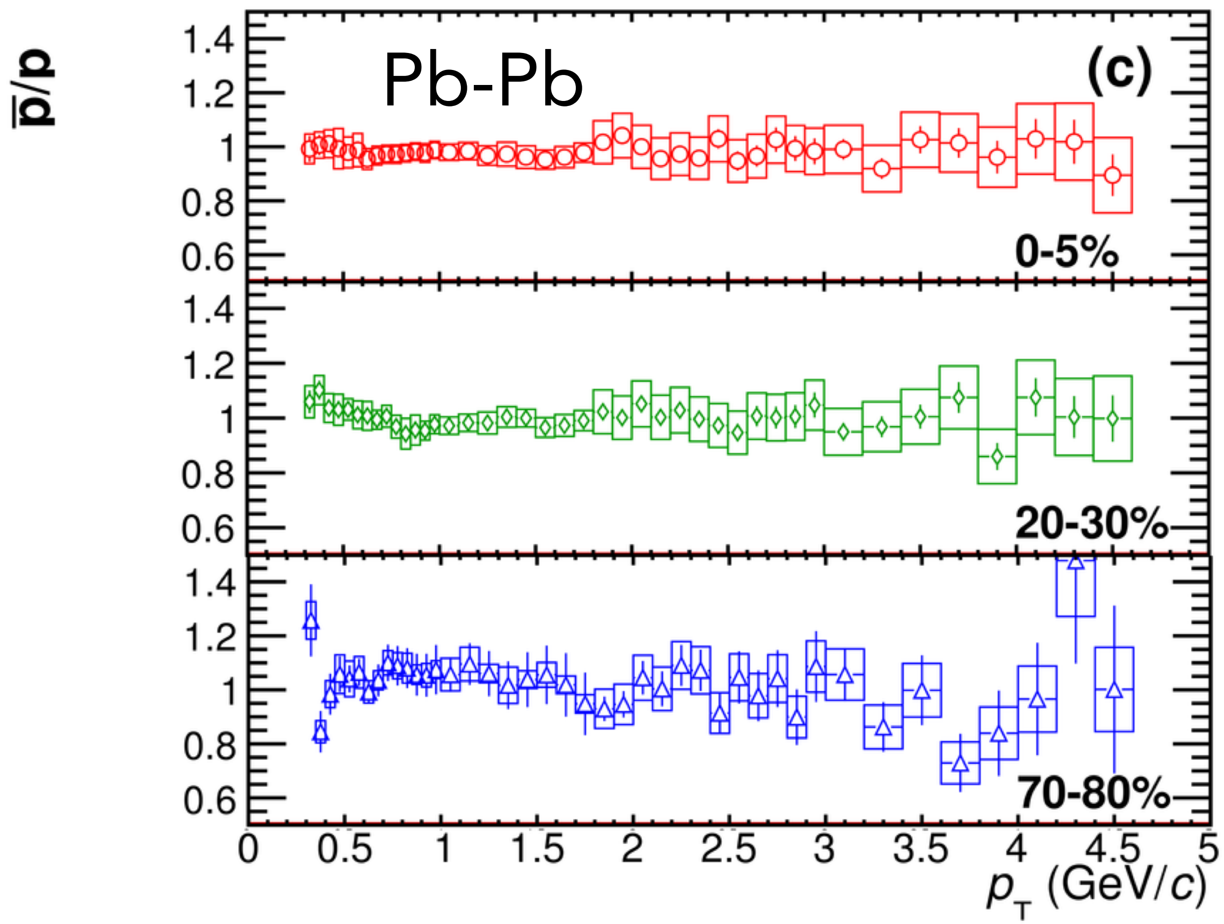


Particle to anti-particle ratios (2)

[Eur. Phys. J. C 73 (2013) 2496]

[Phys. Rev. C 88 (2013) 044910]





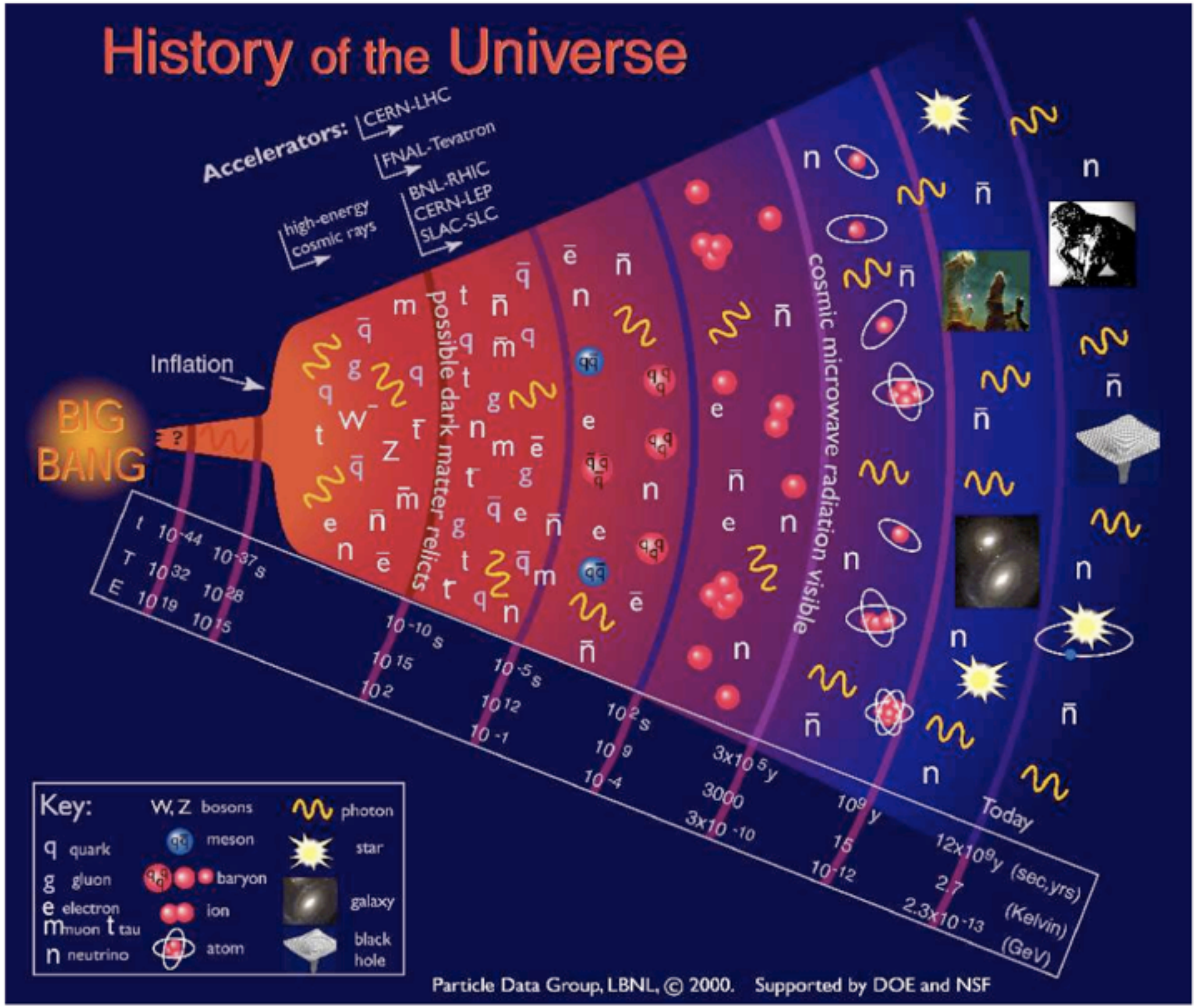
→ At LHC energies, anti-particle to particle ratios are consistent with unity do not change as a function of multiplicity/centrality going from pp to p-Pb and AA collisions.

QGP and the early universe (1)

- Big bang in the early universe and little bang in the laboratory.

- The Universe went through a QGP phase about 10ps after its creation and froze out into hadrons after about 10μs which later formed nuclei.

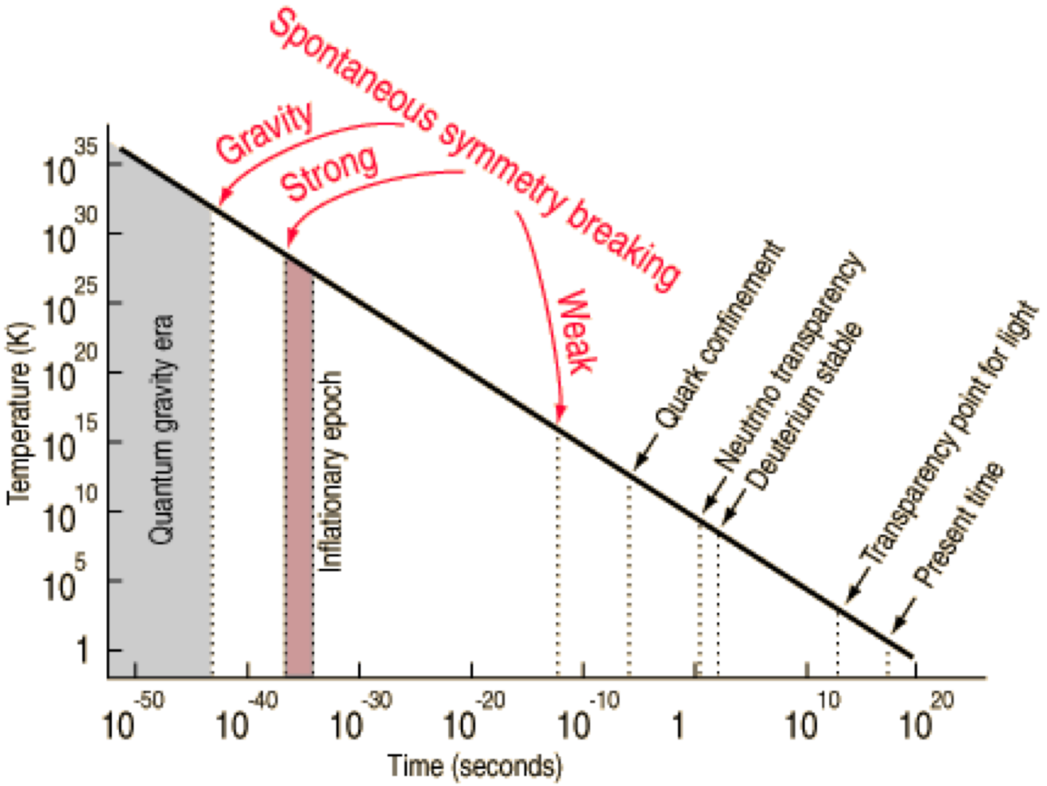
- In addition, there are similarities between the big bang (universe QGP) and the little bang (heavy-ions) concerning the **decoupling**.

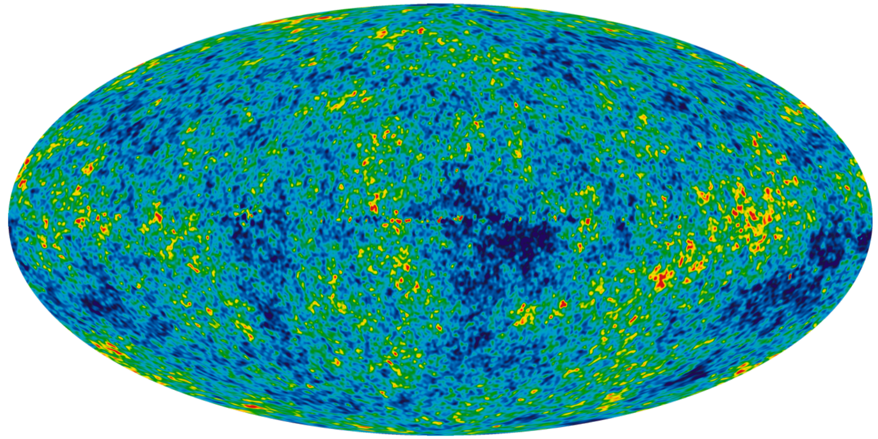


QGP and the early universe (2)

- Decoupling: different type of particles fall out of thermal equilibrium with each other and *freeze out* when the mean free path for interaction is comparable to the size of the expanding system.

- Examples of this analogy:
  - Early Universe: neutrinos decouple early as their interaction is weak.
  - Heavy-ions:
    - chemical freeze-out (inelastic interactions changing particle type) happens before kinetic freeze-out (elastic interactions changing only momenta)
    - Kinetic freeze-out of strange particles might happen before the kinetic freeze-out of non-strange particles

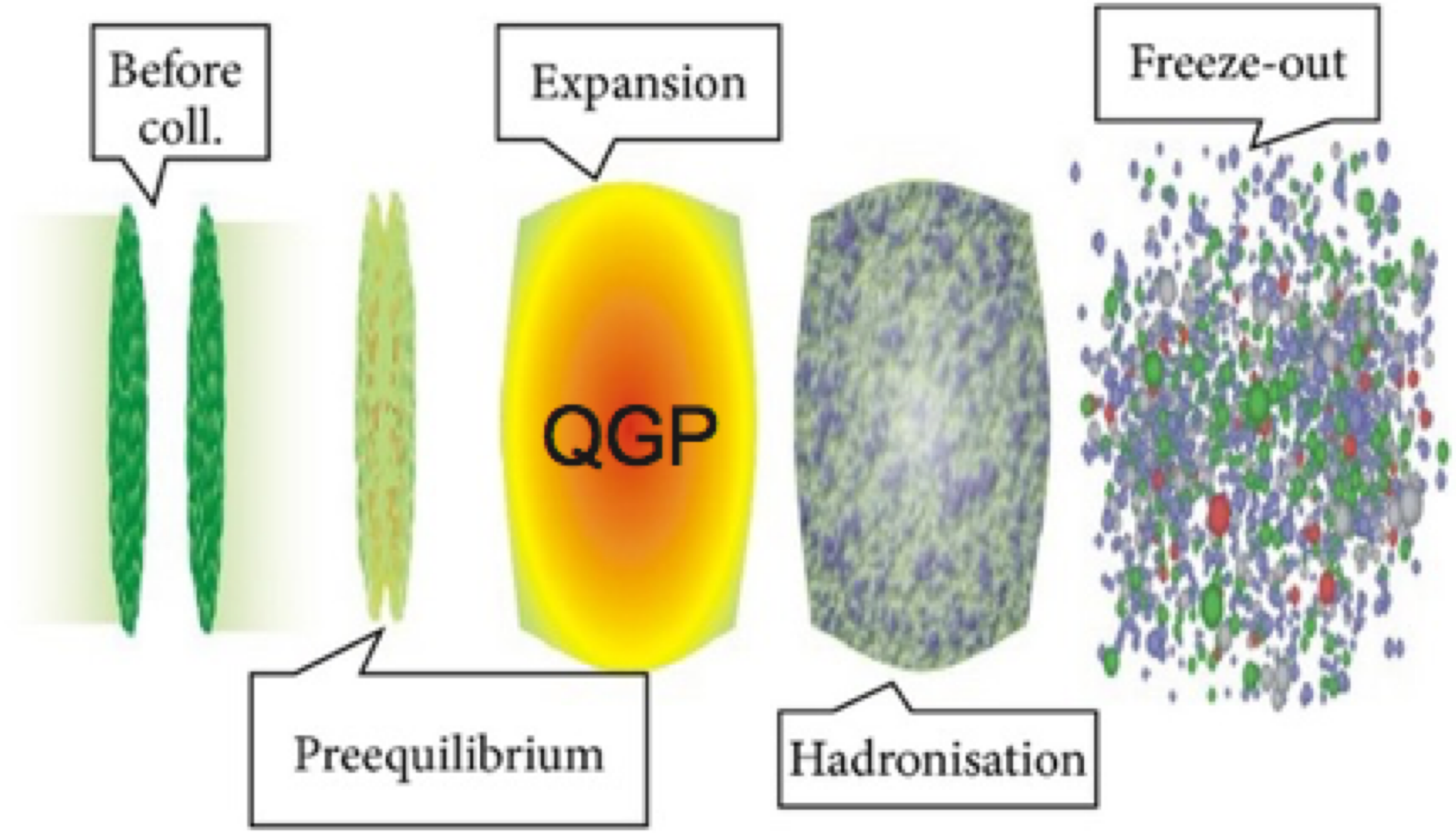




Decoupled photons (WMAP)

Can we reach such temperatures in the experiment?

→ We would need initial temperatures of more than 200 MeV.
→ Let's look first at a schematic evolution of a heavy-ion collision:

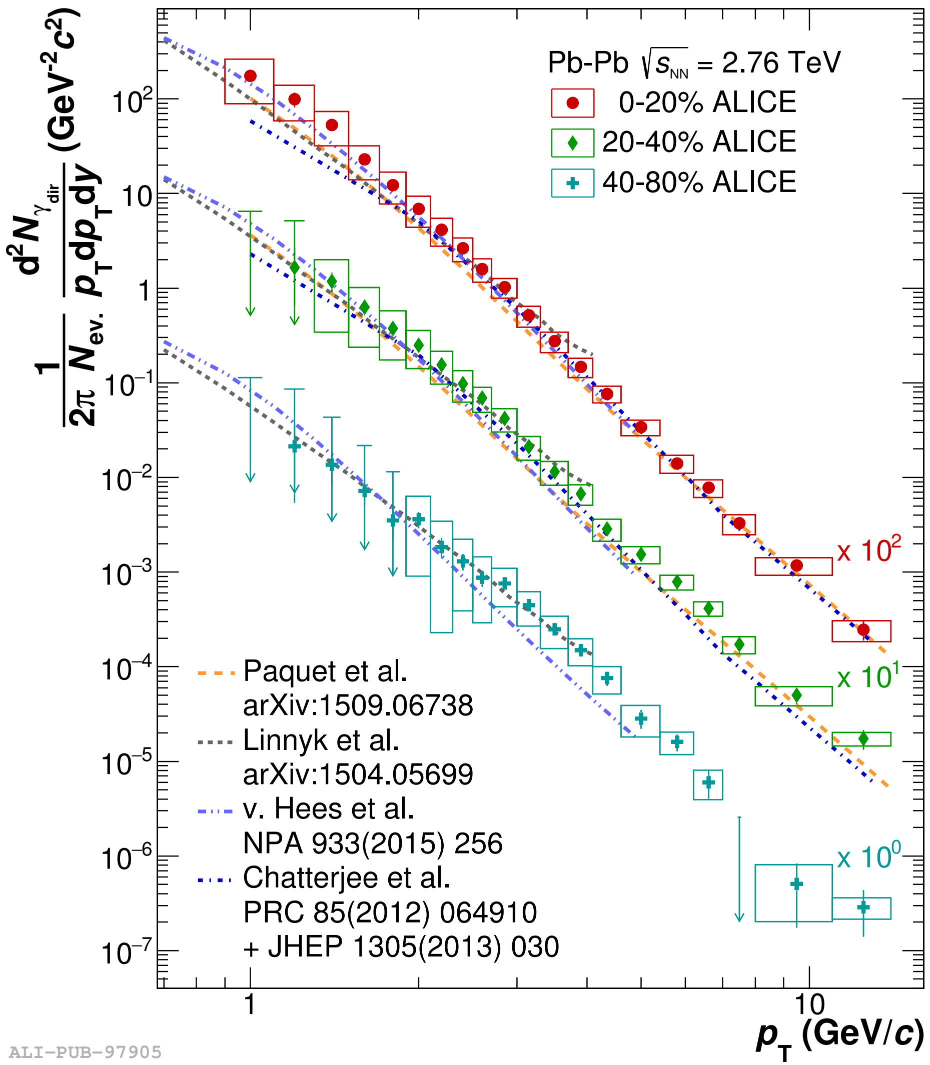


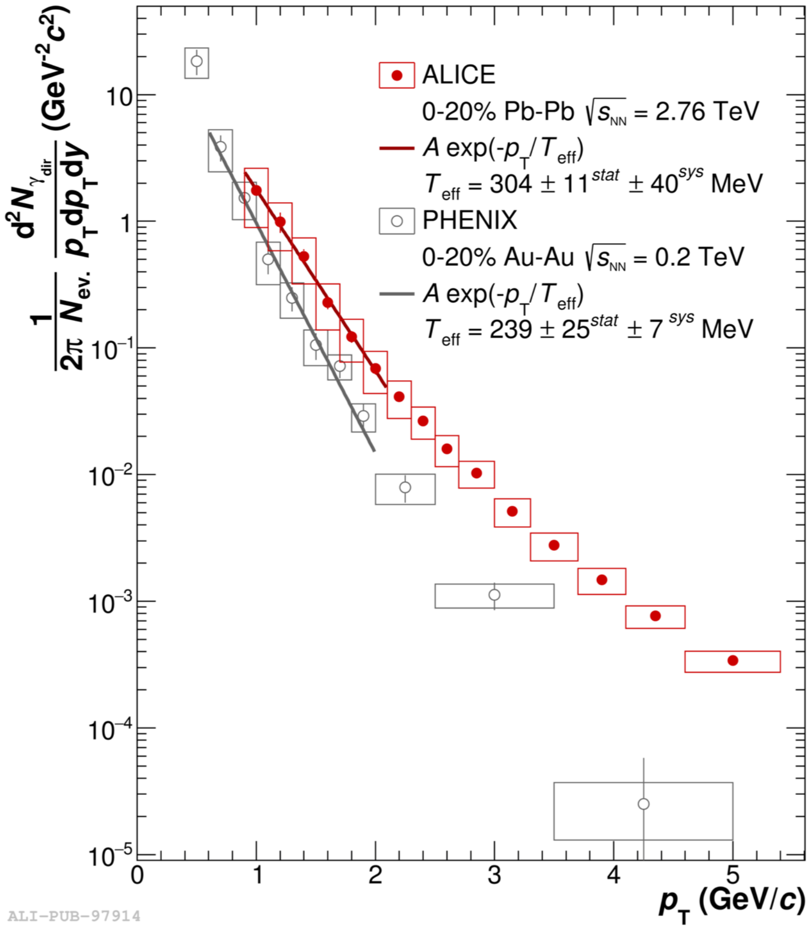
What is the temperature reached in a heavy-ion collision? Let's measure it..

[arXiv:1207.7028]

Direct photons – black body radiation from the QGP

The challenging measurement of direct (subtract decay such as $\pi^0 \rightarrow \gamma\gamma$) photons gives access to the initial temperature of the system created in heavy-ion collisions. However, model comparisons are needed as direct photons are also emitted at later stages of the collision.



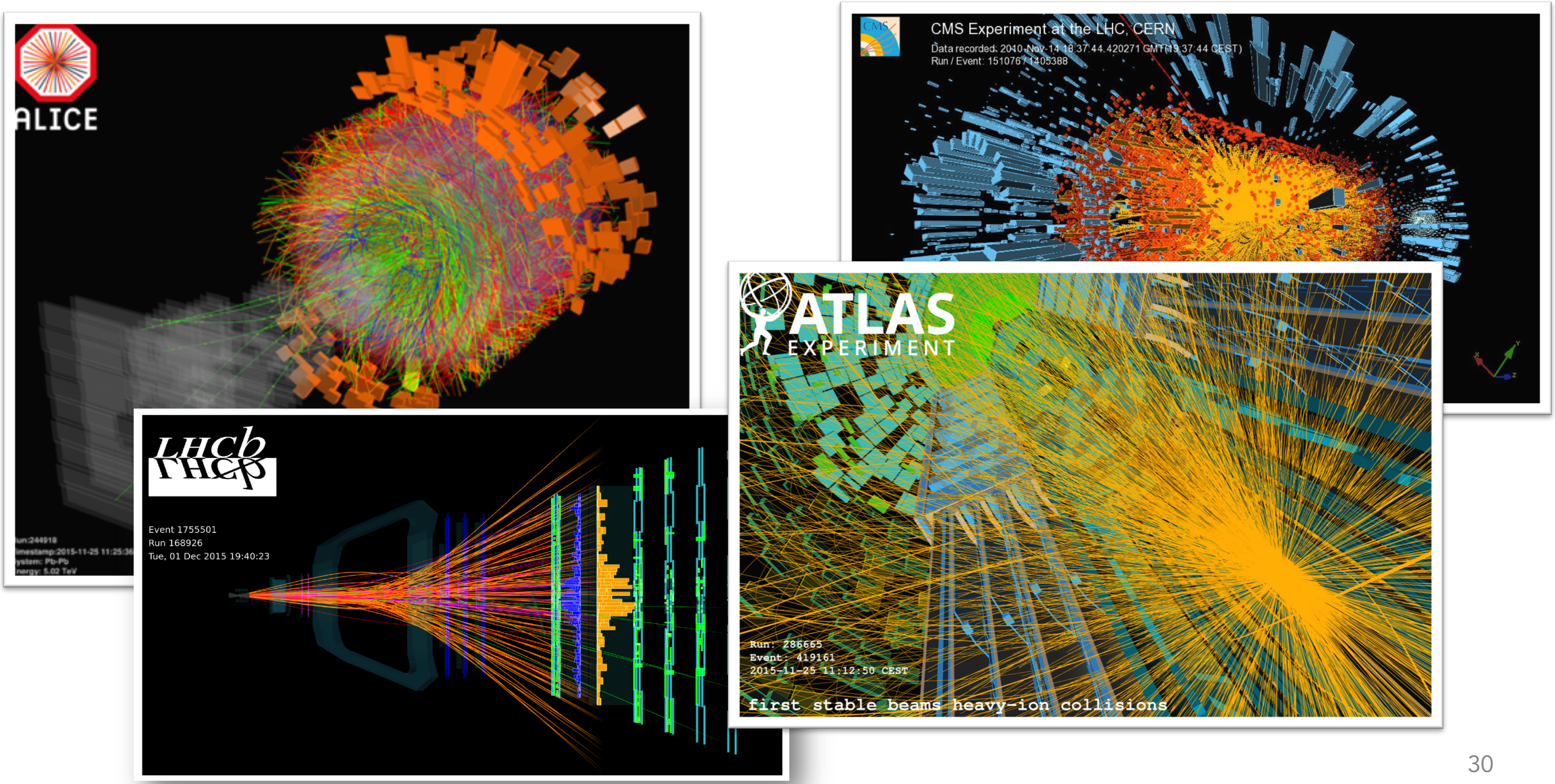


[Phys. Lett. B 754 (2016) 235-248]

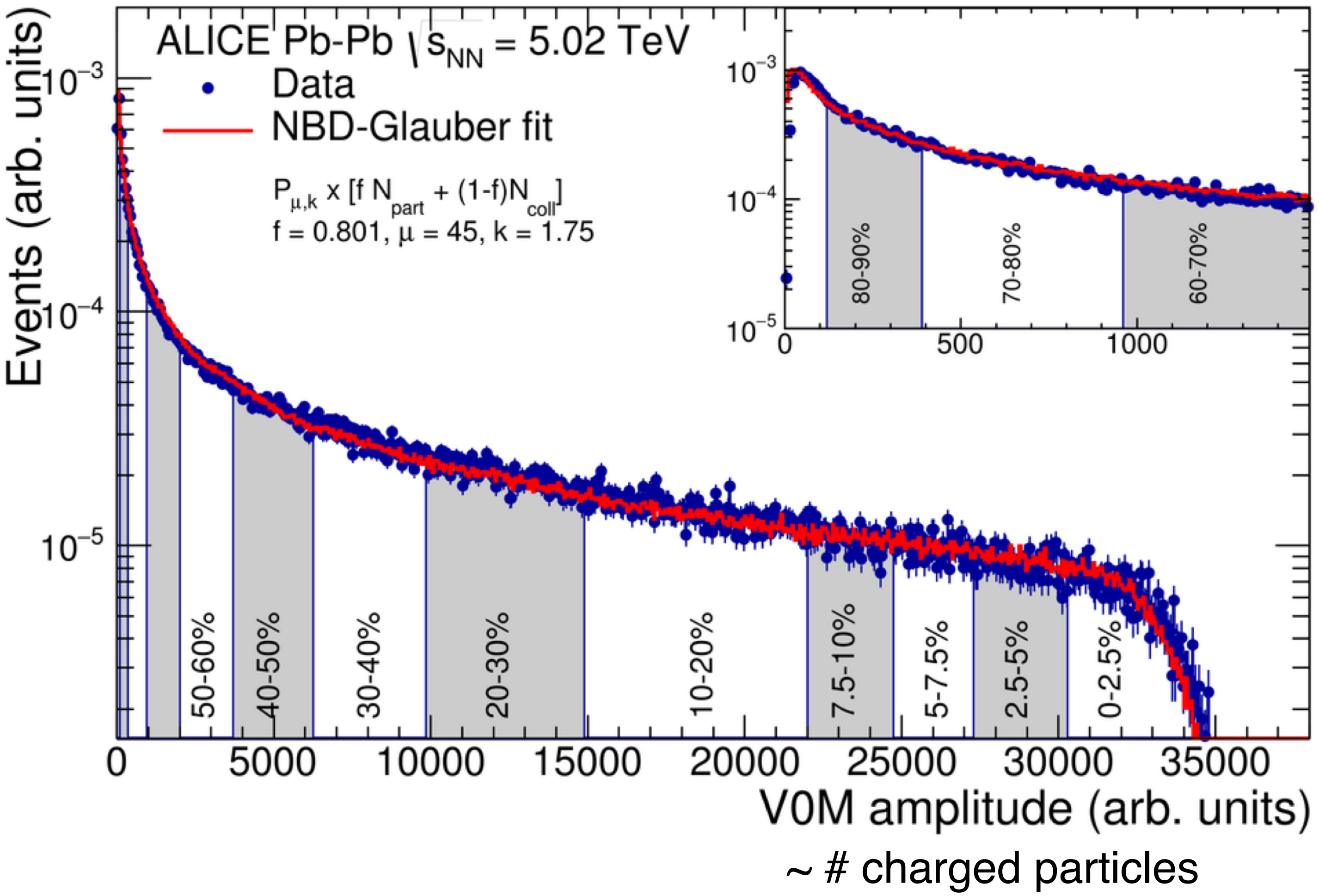
T_{eff} = 304 ± 11 ± 40 MeV

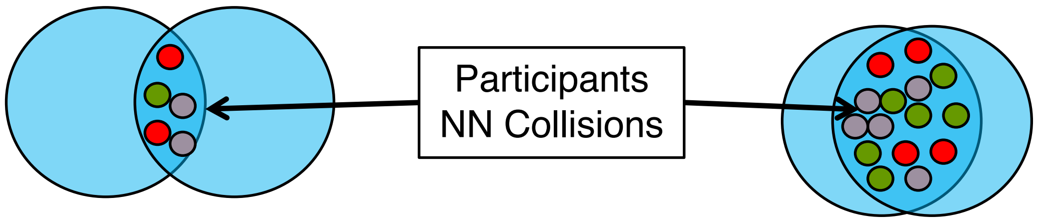
→ Effective temperature of approx. 300 MeV is observed as a result of a high initial temperature and the blue-shift due to the radial expansion of the system.

How many particles are created in such a collision?



Geometry of heavy ion collisions





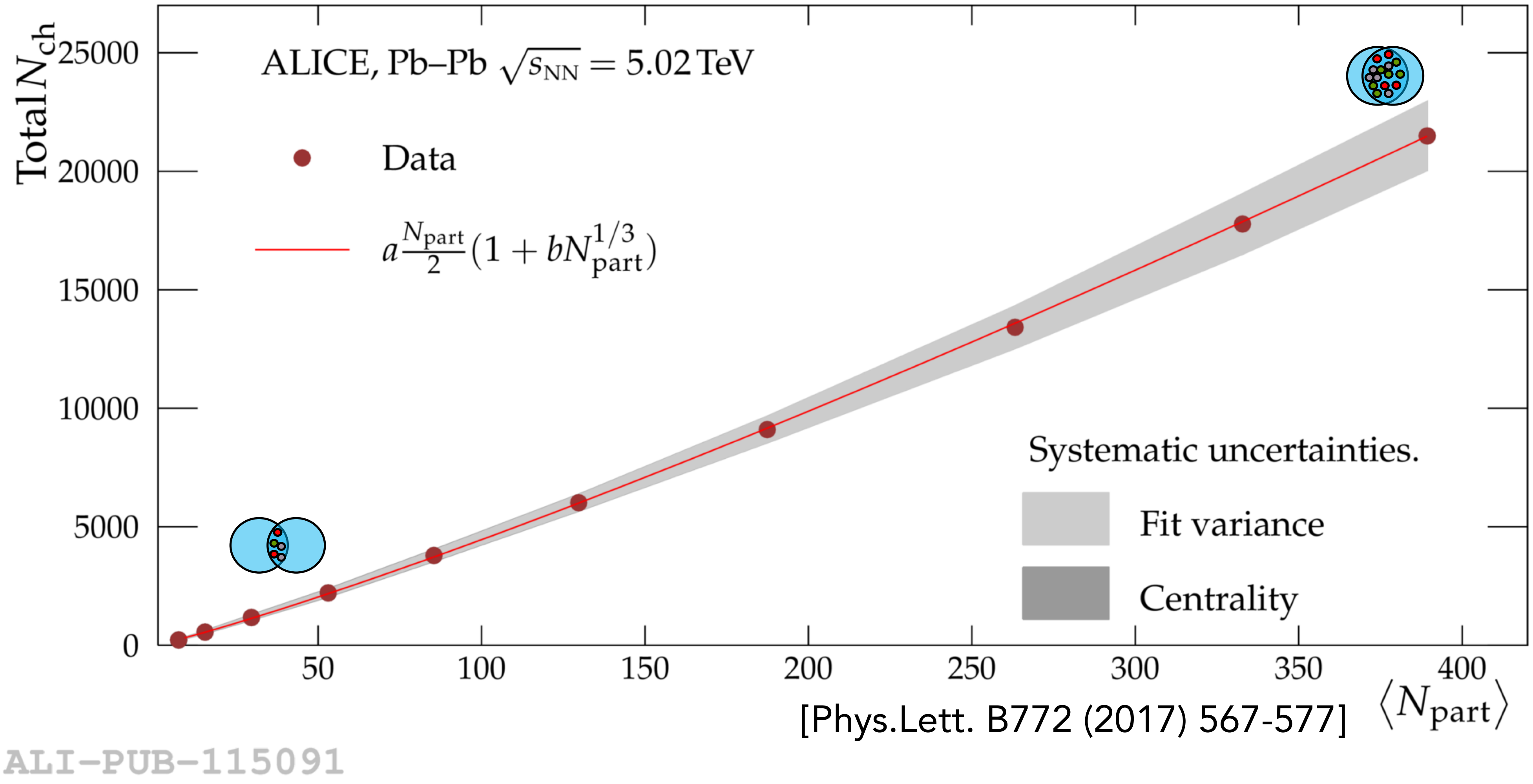
Centrality Variables:

•N_{coll}: Number of nucleon-nucleon collisions
•N_{part}: Number of participating nucleons

• Percentile of hadronic cross-section:
0-5% => central ("many particles")
80-90% => peripheral ("few particles")

→ We can determine (a posteriori) the geometry of heavy ion collisions. More details on the ***Glauber model*** when discuss hard probes..

Total number of charged hadrons in Pb-Pb collisions



[Phys.Lett. B772 (2017) 567-577]

→ Collisions of heavy-ions at high energy accelerators allow the creation of several tens of thousands of hadrons (1 << N << 1mol) **in apparent local thermodynamic equilibrium** in the laboratory.

A very short introduction to statistical thermodynamics

- A small example: barometric formula (density of the atmosphere at a fixed temperature as a function of the altitude *h*).

- Probability to find a particle on a given energy level *j*:

$$P_j = \frac{\exp\left(-\frac{E_j}{k_B T}\right)}{Z}$$

Boltzmann factor

Partition function *Z*
(*Zustandssumme = "sum over states"*)

- Energy on a given level is simply the potential energy: $E_{pot} = mgh$. This implies for the density n (pressure p):

$$\frac{p(h_1)}{p(h_0)} = \frac{n(h_1)}{n(h_0)} = \frac{N \cdot P(h_1)}{N \cdot P(h_0)} = \exp\left(-\frac{\Delta E_{pot}}{k_B T}\right) = \exp\left(-\frac{mg}{RT}\Delta h\right)$$

Statistical-thermal model for heavy-ion collisions

- Starting point: grand-canonical partition function for an *relativistic ideal quantum gas of hadrons* of particle type i (i = pion, proton,… → full PDG!):

$$\ln Z_{GK_i} = \pm g_i \frac{V}{2\pi^2\hbar^3} \int_0^\infty dp\, p^2 \ln\left(1 \pm e^{-\beta(\epsilon(p)-\mu_i)}\right)$$

(-) for bosons, (+) for fermions (quantum gas)

$\beta = \frac{1}{kT}$

$E_i = \sqrt{p^2 + m_i^2}$ *dispersion relation (relativistic)*

spin degeneracy (g_i)

$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3_i} + \mu_C C_i$

chemical potential representing each conserved quantity

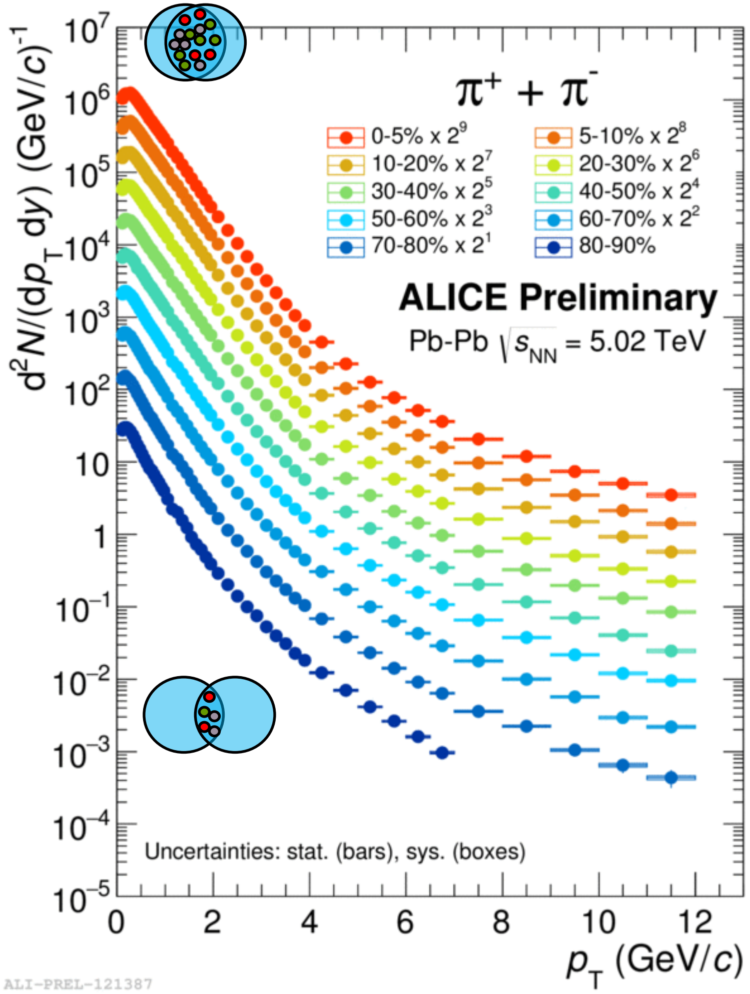
Only two free parameters are needed: **(T,μ_B)**. Volume cancels if particle ratios n_i/n_j are calculated. If yields are fitted, it acts as the third free parameter.

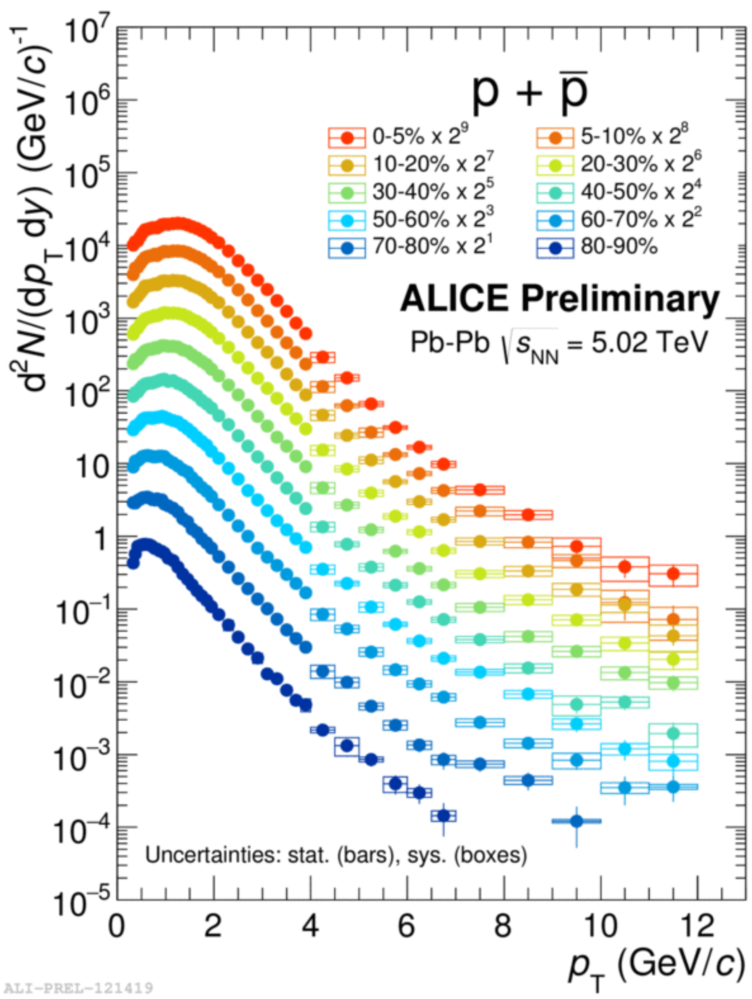
- Once the partition function is known, we can calculate all other thermodynamic quantities:

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} \quad P = \frac{\partial(T\ln Z)}{\partial V} \quad s = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial T}$$

Partition function shown here is only valid in the resonance gas limit (HRG), i.e. relevant interactions are mediated via resonances, and thus the non-interacting hadron resonance gas can be used as a good approximation for an interacting hadron gas.

p_T-spectra of identified particles



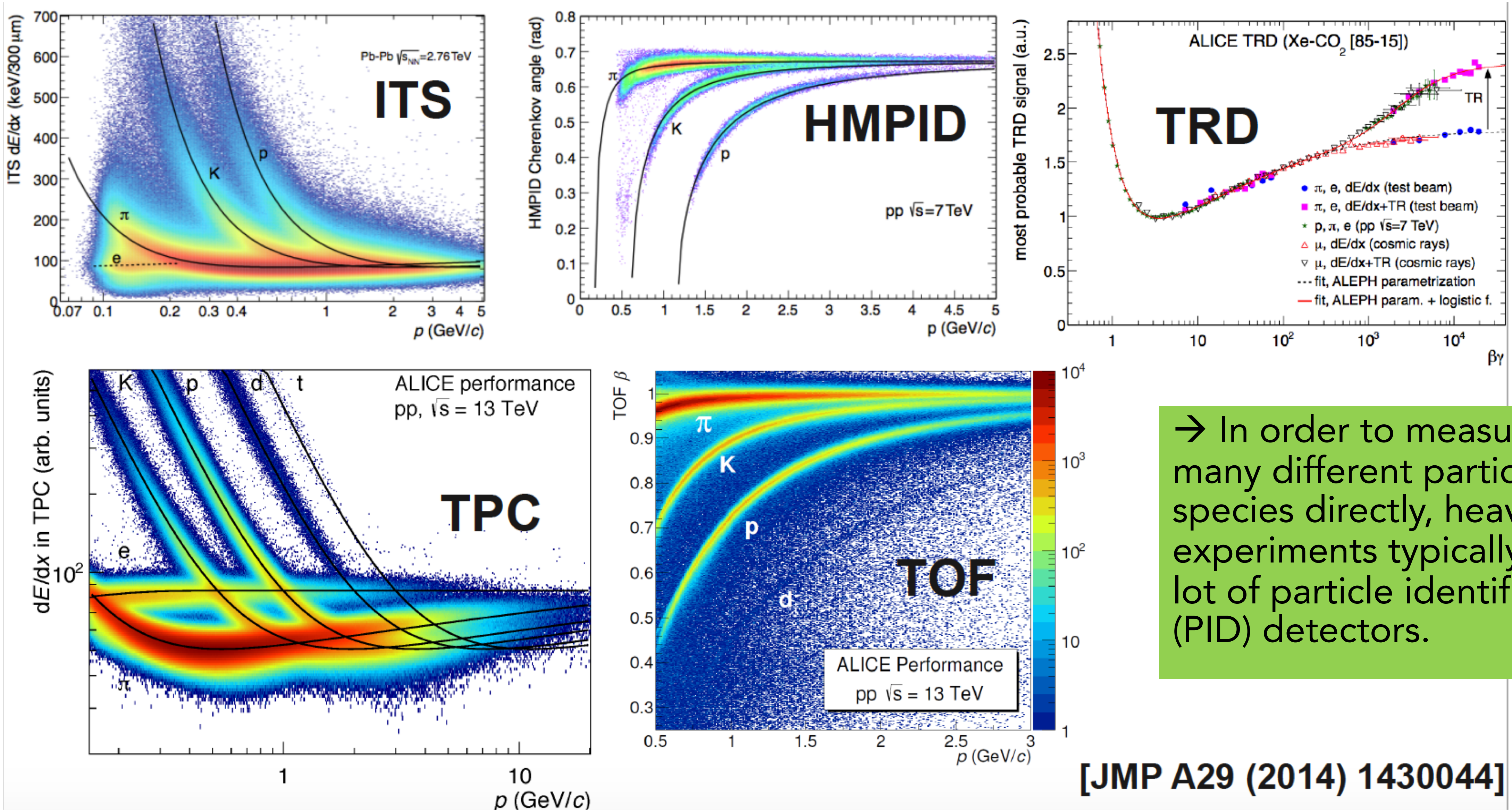


momentum in transverse direction to beam axis

1. Identify particle in the detector (pion, kaon, proton, Lambda, Xi, Omega, anti-deuteron…)
2. Fill p_T-spectrum
3. Interpolate unmeasured region at low p_T (at high p_T negligible)
4. Integrate:

$$\frac{dN}{dy} = \int \frac{d^3N}{dp_T dy d\varphi} \, d\varphi dp_T$$

Instrumentation for heavy-ion experiments: PID



→ In order to measure as many different particle species directly, heavy-ion experiments typically have a lot of particle identification (PID) detectors.

[JMP A29 (2014) 1430044]

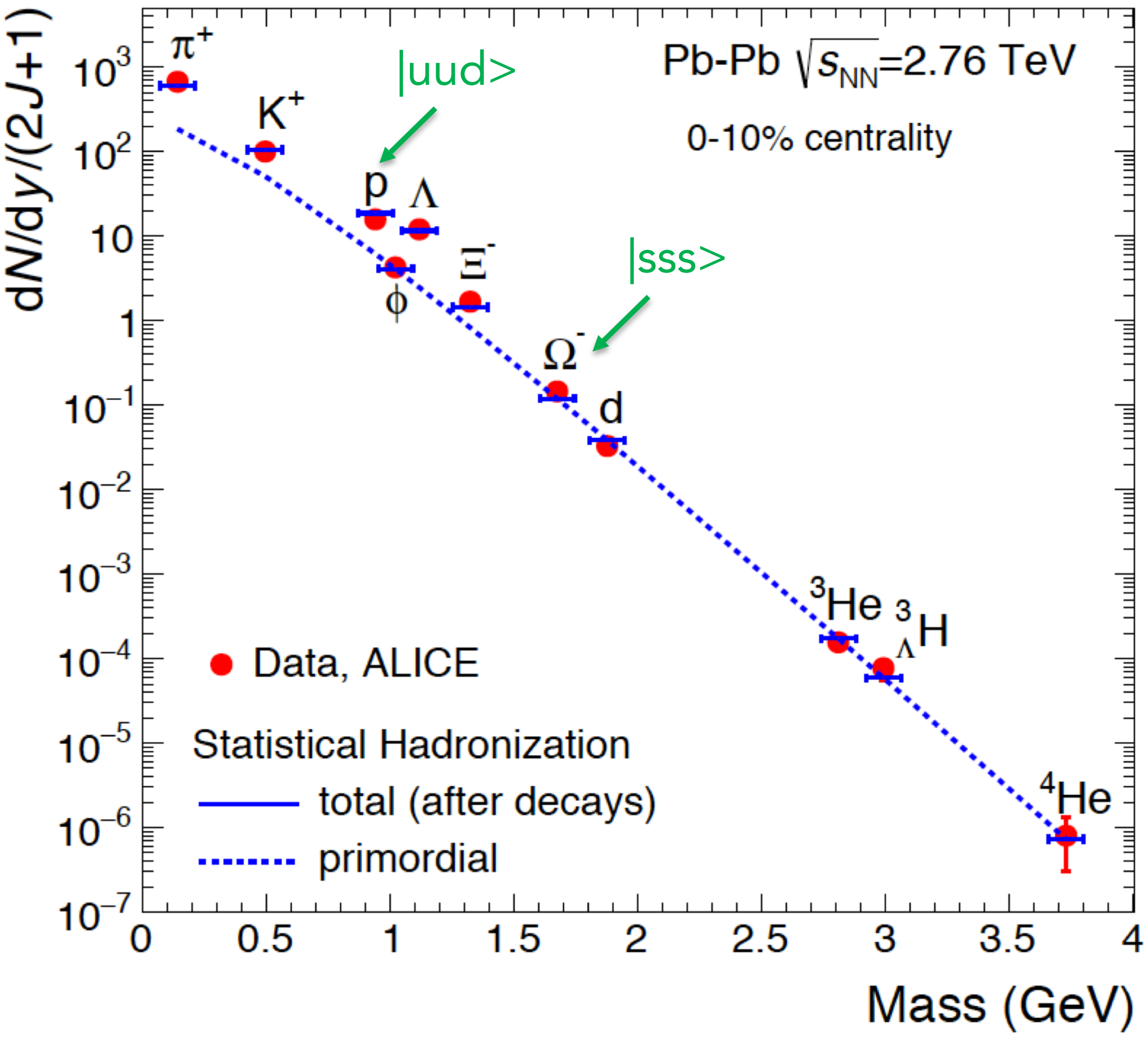
Chemical equilibrium at the LHC

Production yields of light flavour hadrons from a chemically equilibrated fireball can be calculated by statistical-thermal models (roughly $dN/dy \sim \exp\{-m/T_{ch}\}$, in detail derived from partition function)

→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 7 orders of magnitude with a **common** chemical freeze-out temperature of $T_{ch} \approx 156$ **MeV**.

→ This includes **strange hadrons** which are rarer than u,d quarks. Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).

→ Light (anti-)nuclei are also well described despite their low binding energy ($E_b << T_{ch}$).



[A. Andronic et al Nature 561 (2018) no.7723, 321-330]

Chemical equilibrium vs collision energy (1)

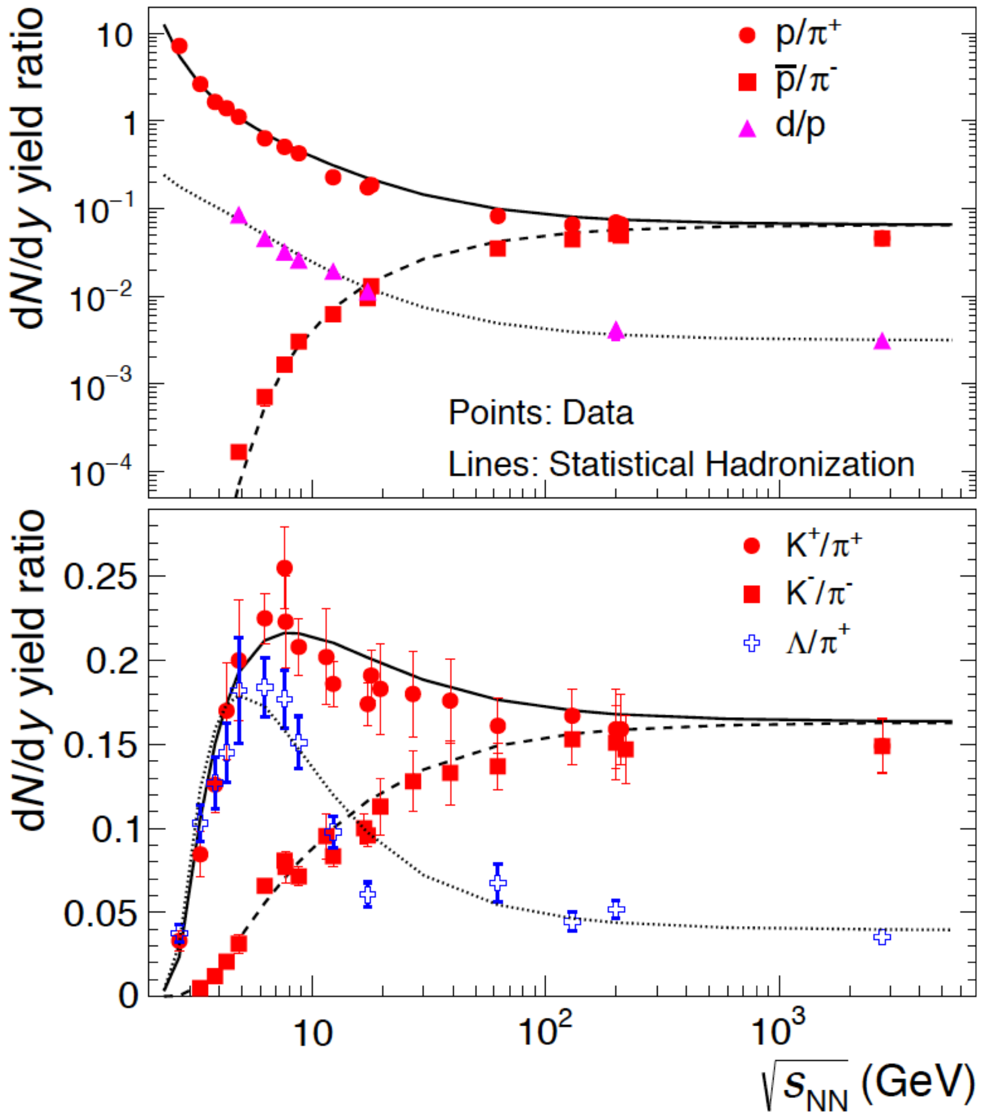
- Hadron yields from SIS up to RHIC and LHC can be described in a hadro-chemical model applying thermal fits.

- Effective parameterization of (T, μ_B) as a function of collision energy:

$$T[\mathrm{MeV}] = T_{lim}\left(1 - \frac{1}{0.7 + (\exp(\sqrt{s_{NN}}(\mathrm{GeV})) - 2.9)/1.5}\right)$$

$$\mu_b[\mathrm{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\mathrm{GeV})},$$

- Particle ratios can be calculated (or predicted) at any collision energy….



[A. Andronic et al Nature 561 (2018) no.7723, 321-330]

Chemical equilibrium vs collision energy (2)

[A. Andronic *et al.*, Nature 561 (2018) no.7723, 321-330]

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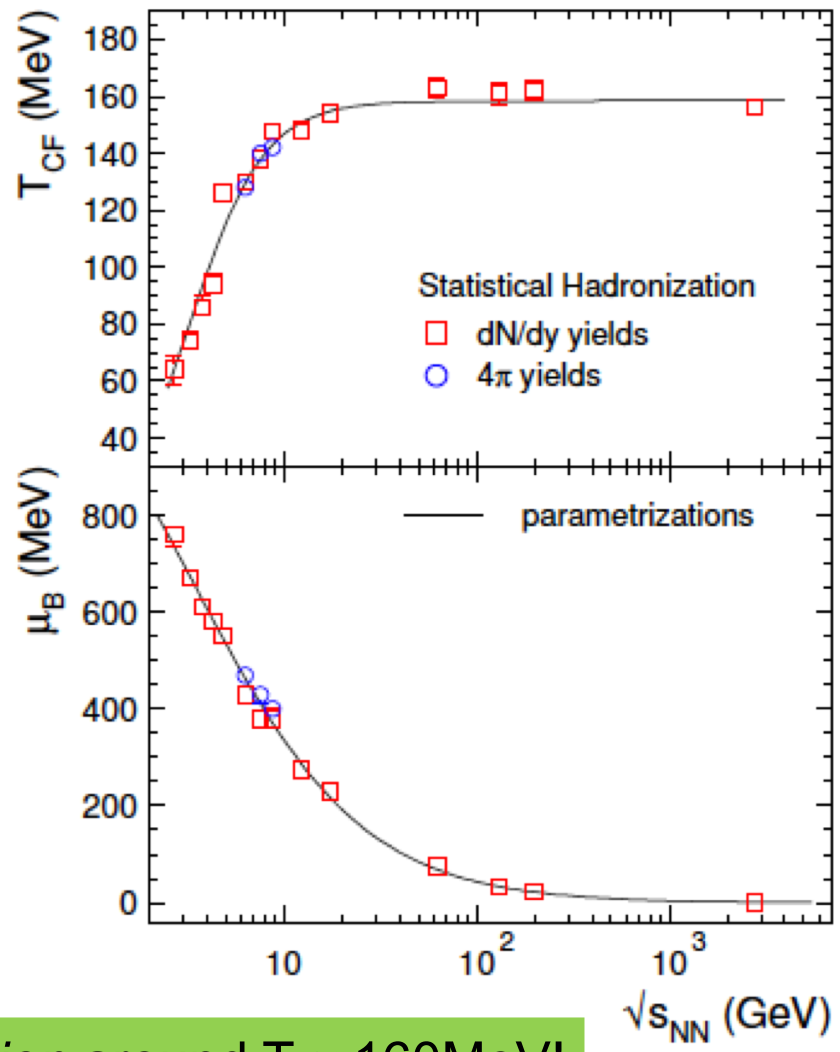

→ One observes a *limiting temperature of hadron production* around T ≈ 160MeV!

Chemical equilibrium vs collision energy (3)

- Hadron yields from SIS up to RHIC and LHC can be described in a hadro-chemical model applying thermal fits.
- Effective parameterization of (T, μ_B) as a function of collision energy:

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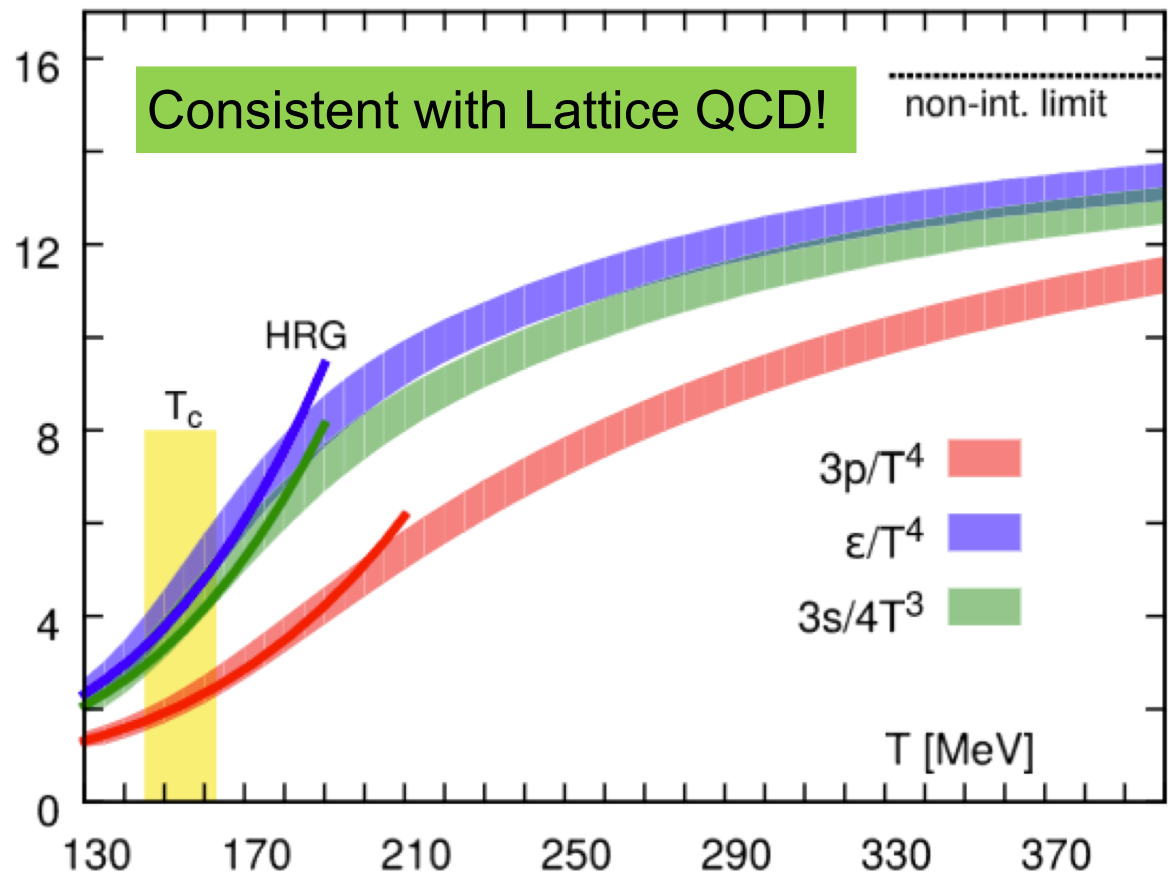
$$\mu_b[\mathrm{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\mathrm{GeV})},$$

- Particle ratios can be calculated (or predicted) at any collision energy….

[PRD 90 094503 (2014)]



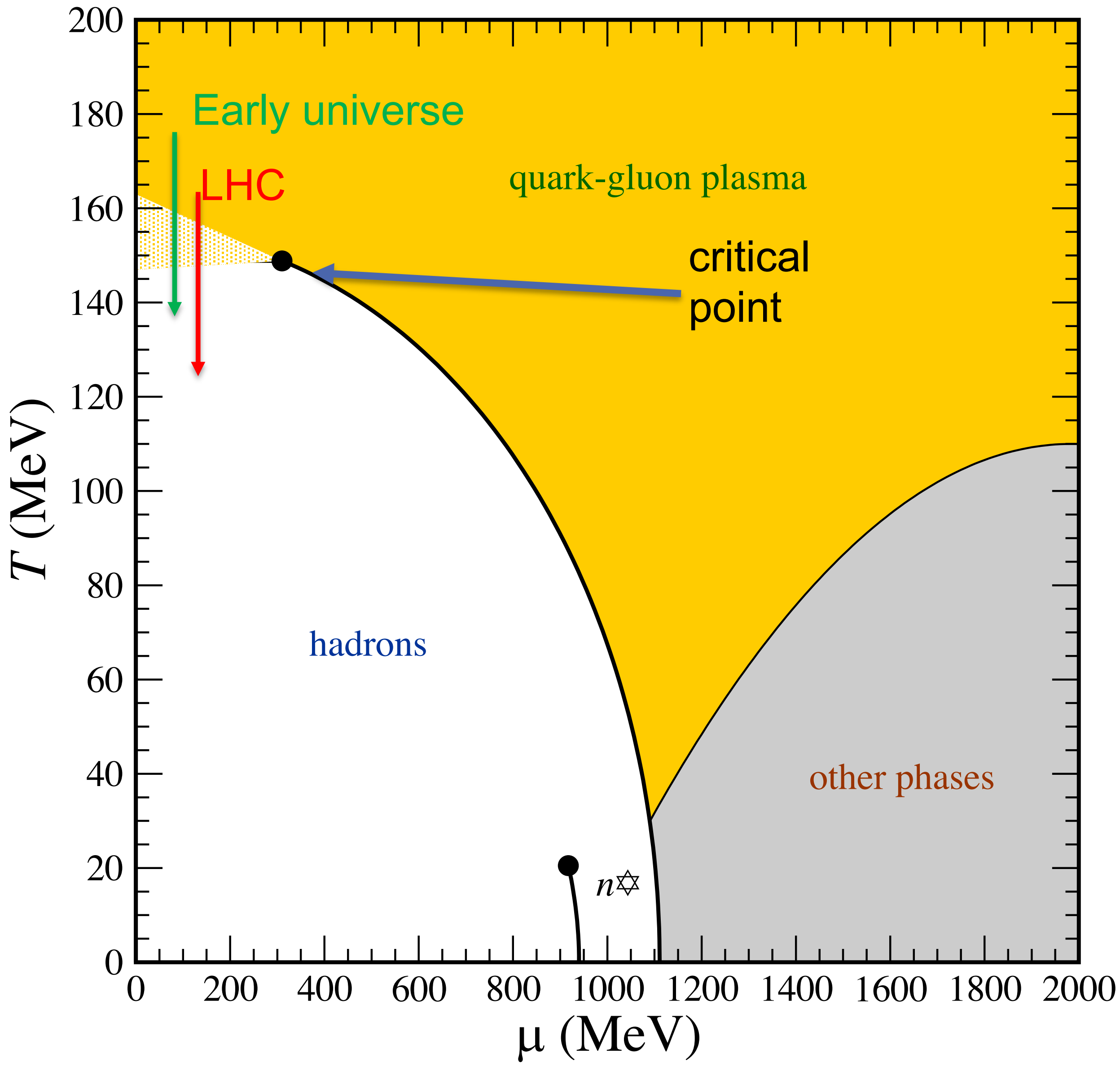
→ One observes a *limiting temperature of hadron production* around T ≈ 160MeV!

Chemical freeze-out line

- By colliding nuclei with different center of mass energies, different regions of the phase diagram are explored.

- Thermal model fits to the experimental data define the chemical freeze-out line in the QCD phase diagram.

- The previously schematic phase diagram becomes one which is actually measured!



[Ann. Rev. Nucl. Part. Sci. 62 (2012) 265]

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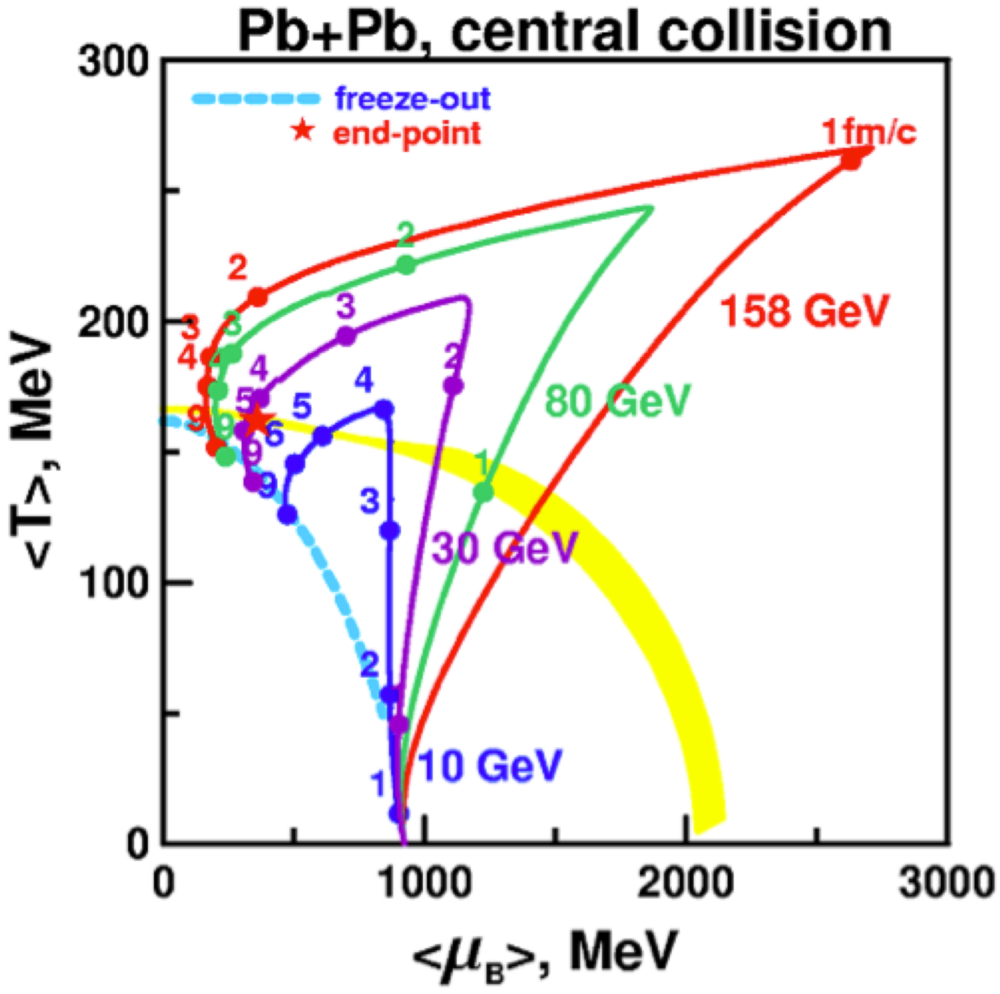

[Y.B. Ivanov et al., Phys. Rev. C 73 (2006) 30]

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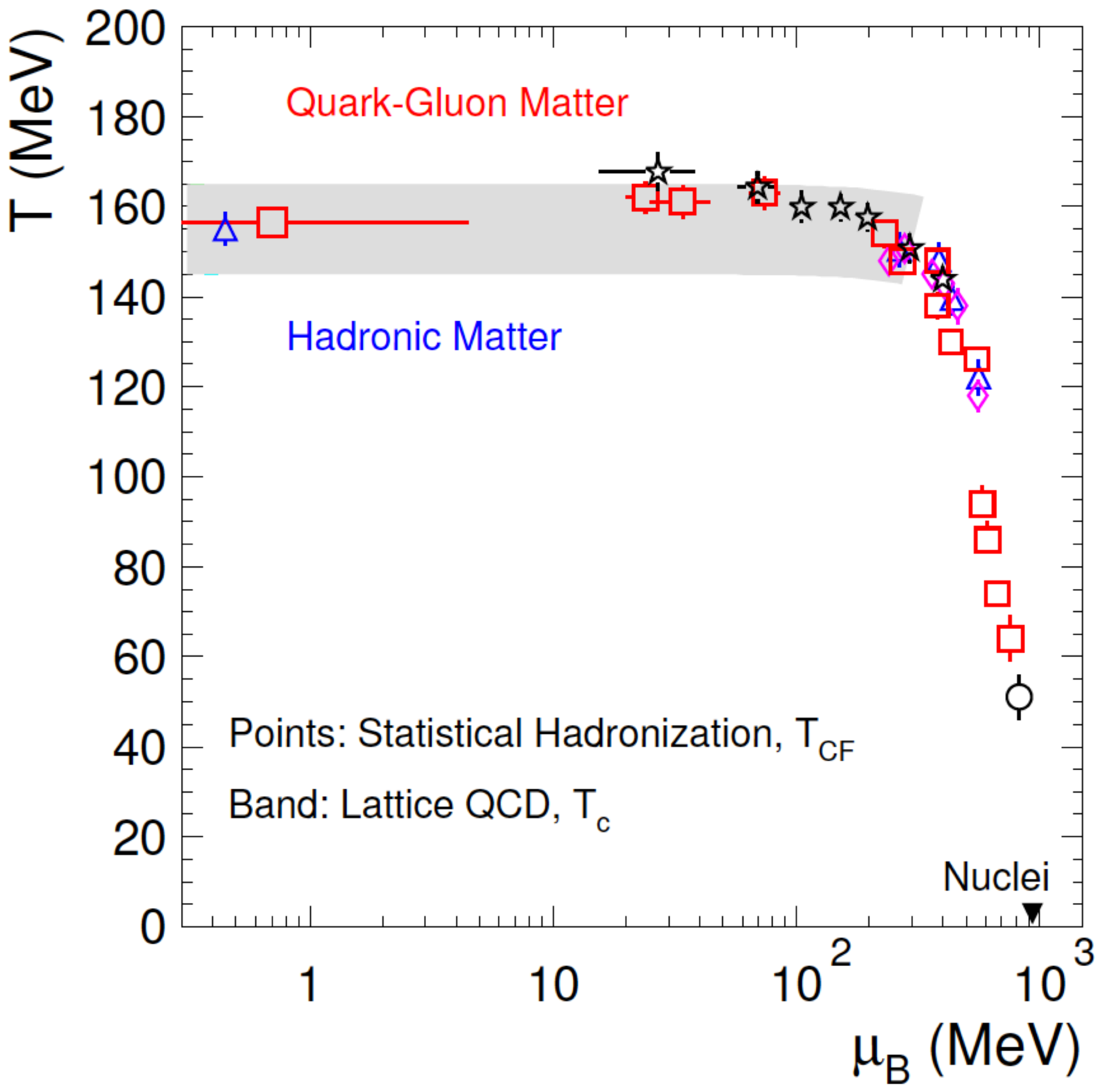


[A. Andronic et al Nature 561 (2018) no.7723, 321-330]

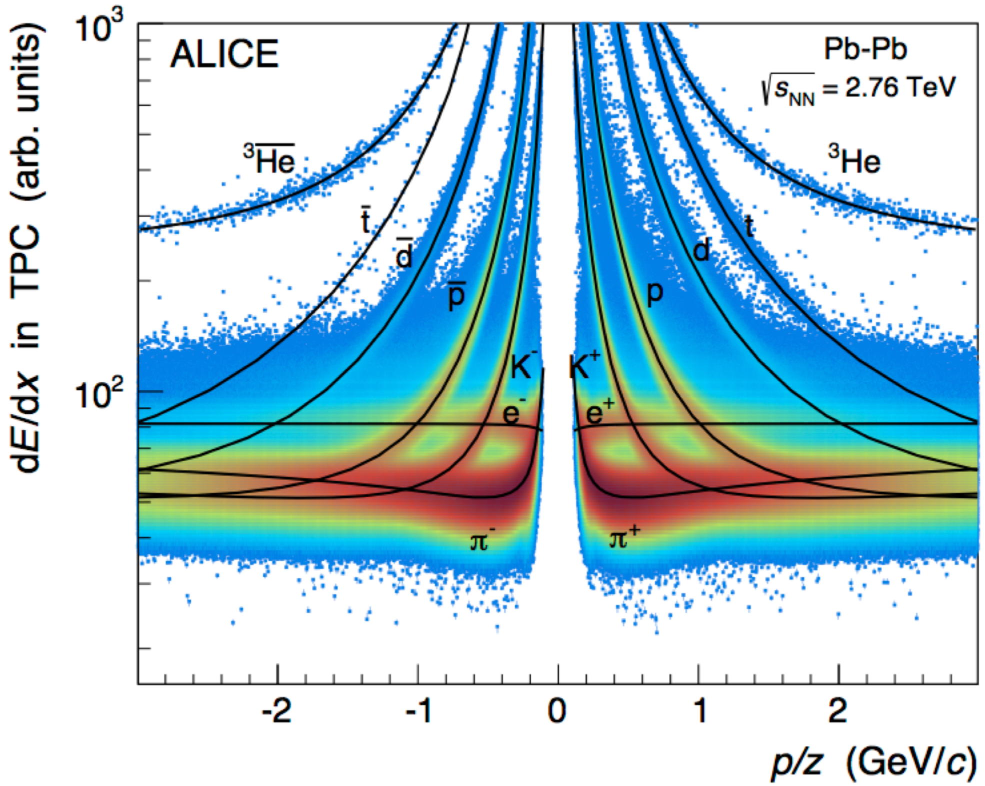
The anti-hyper-triton $\overline{{}^{3}_{\Lambda}H}$

Measurements of (anti-)(hyper-)nuclei

Collisions at the LHC produce a large amount of (anti-)(hyper-)nuclei.

- Matter and anti-matter are produced in equal abundance at LHC energies.
- Open puzzle: production yields are in agreement with thermal model prediction even though light (anti-)nuclei should be dissolved in such a hot medium.

[ALICE-PUBLIC-2017-006]



[PRC 93 (2016) 024917]

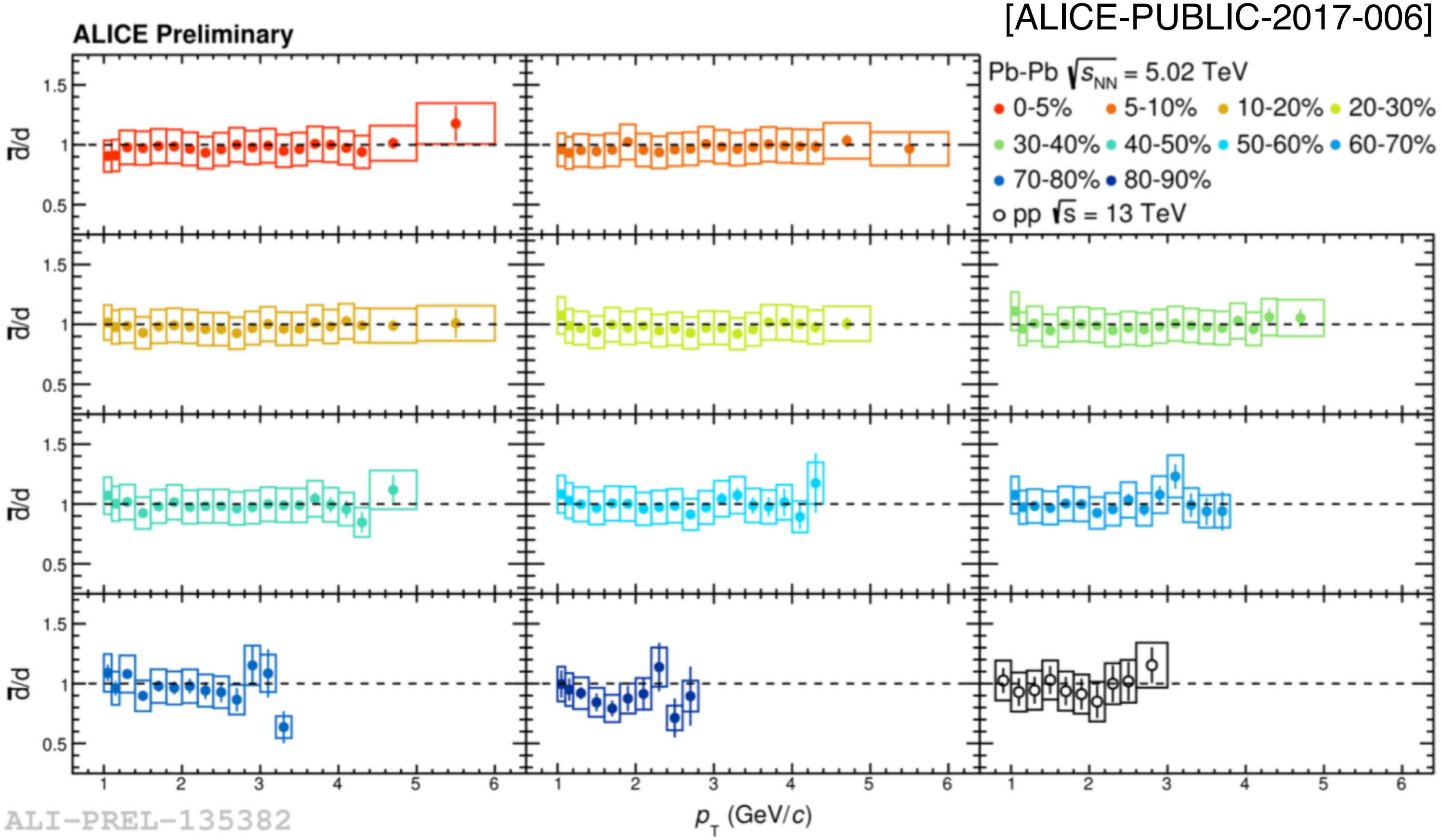
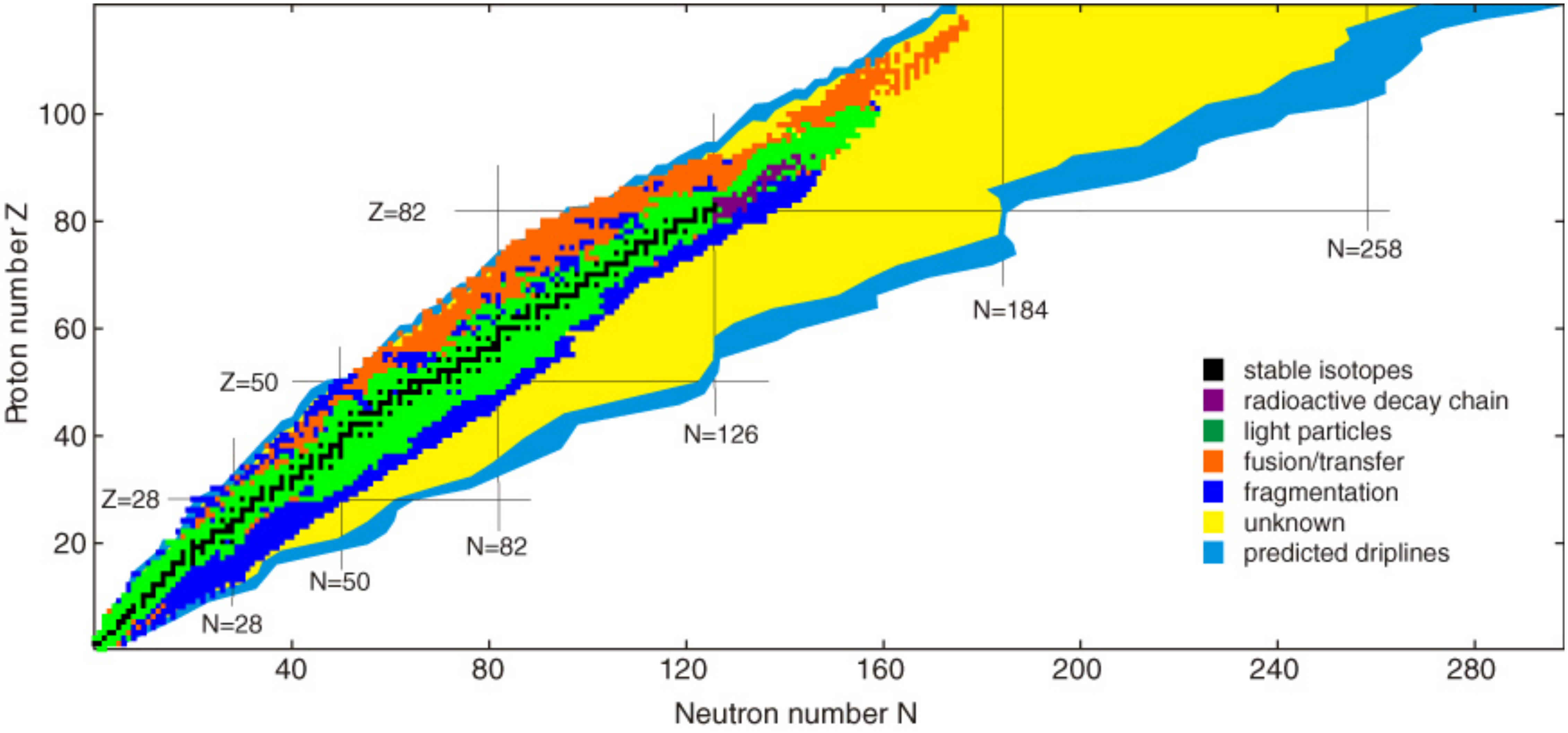


Table of nuclides

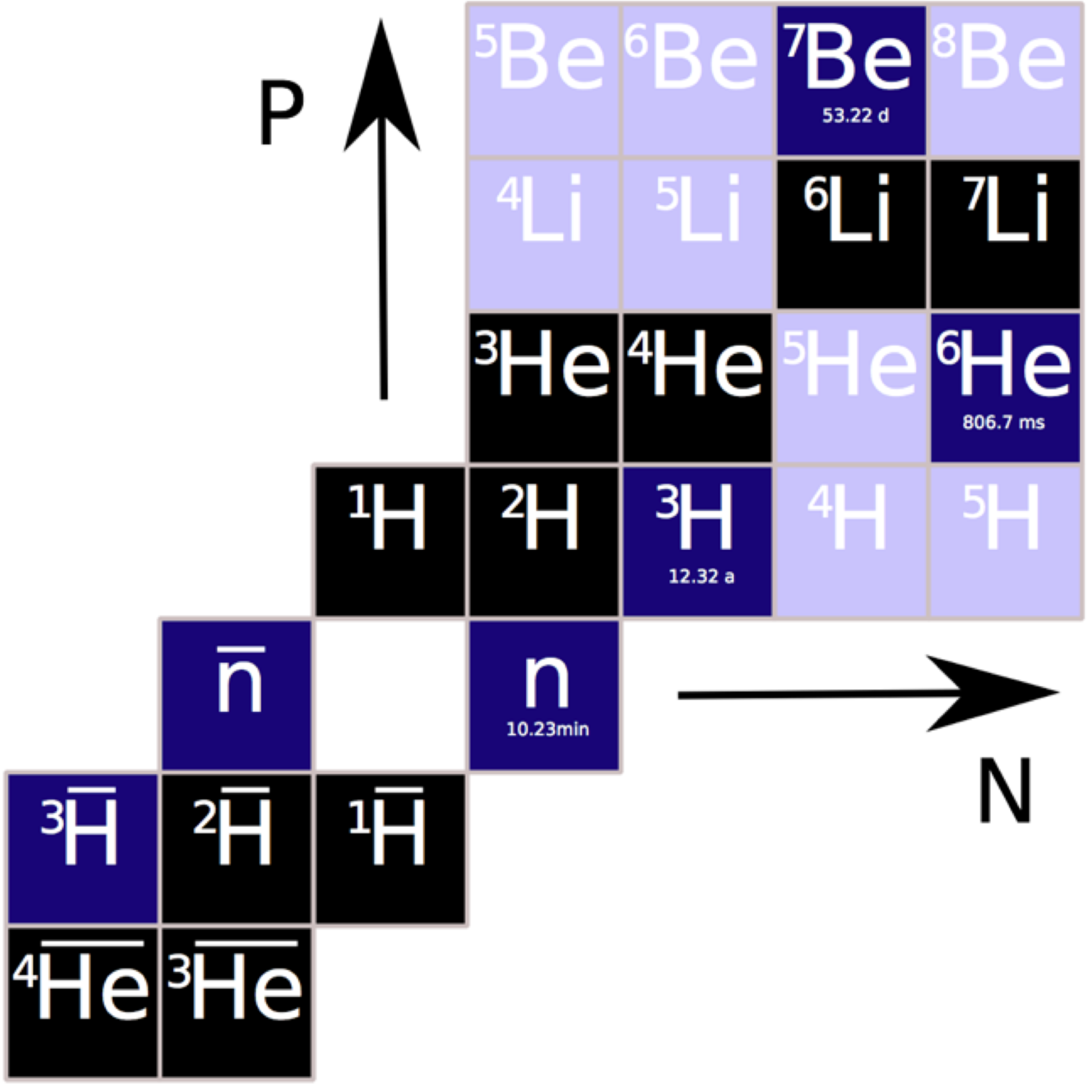


Light (anti-)nuclei

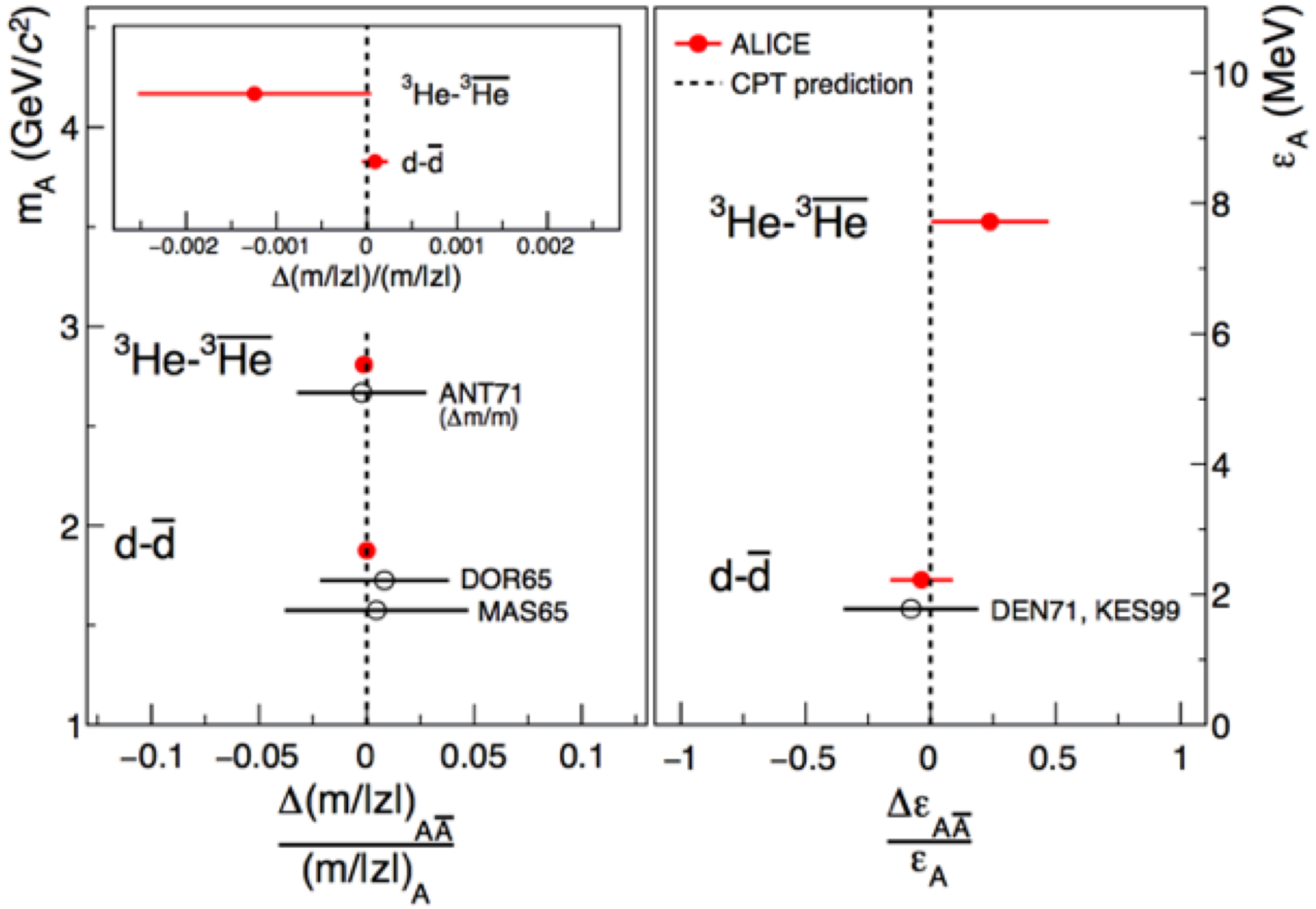
- Even in Pb-Pb collisions at LHC energies, light anti-nuclei are rarely produced.

- (Anti-)nuclei up to the (anti-)alpha are in reach (1st observation of the anti-alpha by the STAR experiment at RHIC in 2011).

→ A very good and very stable particle identification is needed to separate these rare particles from the background.



Side remark: testing CPT with anti-nuclei



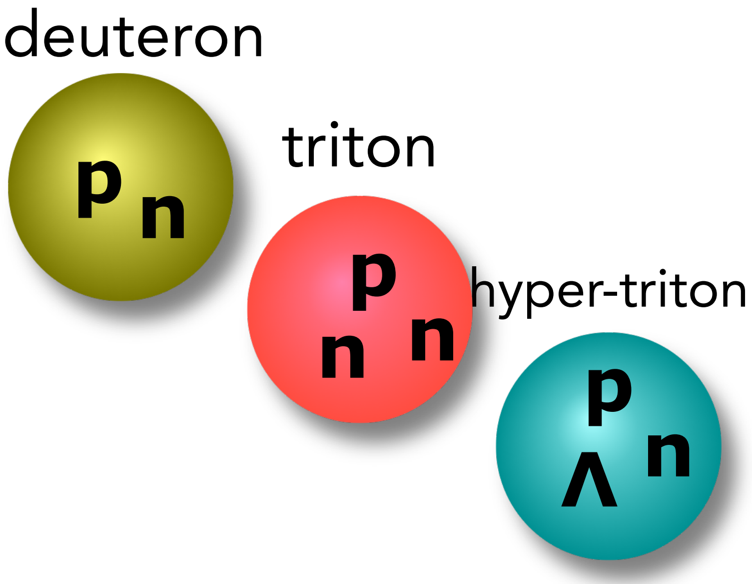
[Nature Physics 11 (2015) 811-814]

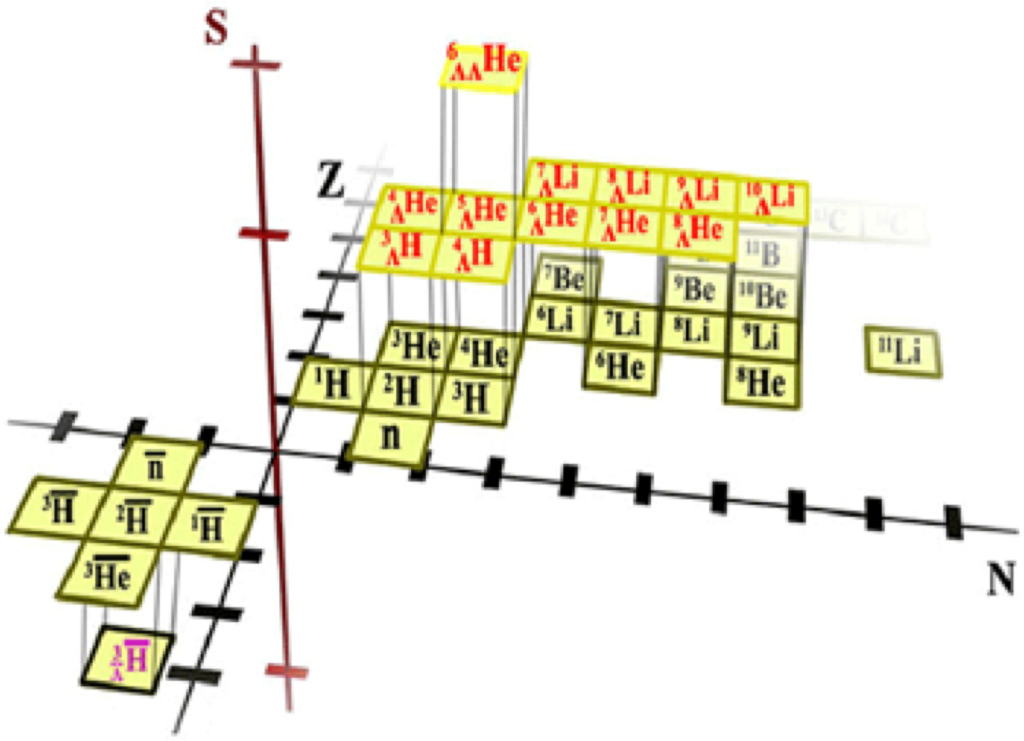
The ALICE collaboration performed a test of the CPT invariance looking at the mass difference between nuclei and anti-nuclei.

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

Hyper-nuclei

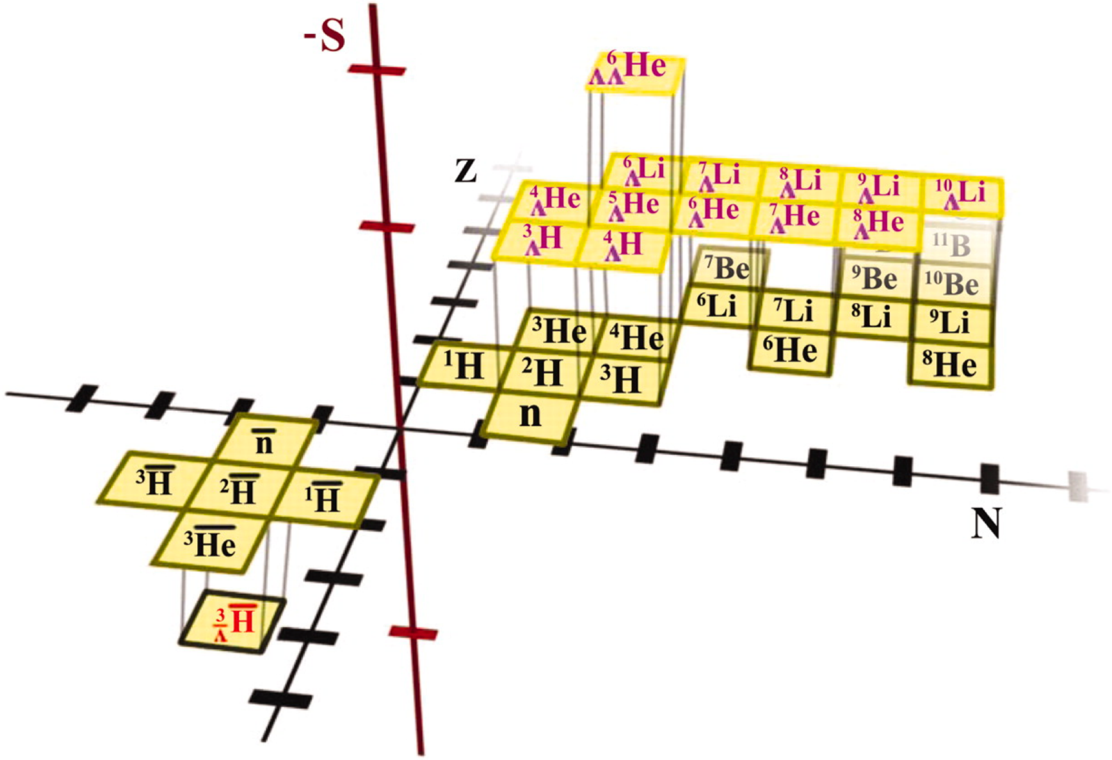
- By 'replacing' one nucleon by one hyperon, the table of nuclides can be extended in a third dimension.
- Hyper-nuclei have a long tradition in nuclear physics: discovery in the 1950s by M. Danysz and J. Pniewski in a nuclear emulsion exposed to cosmic rays.

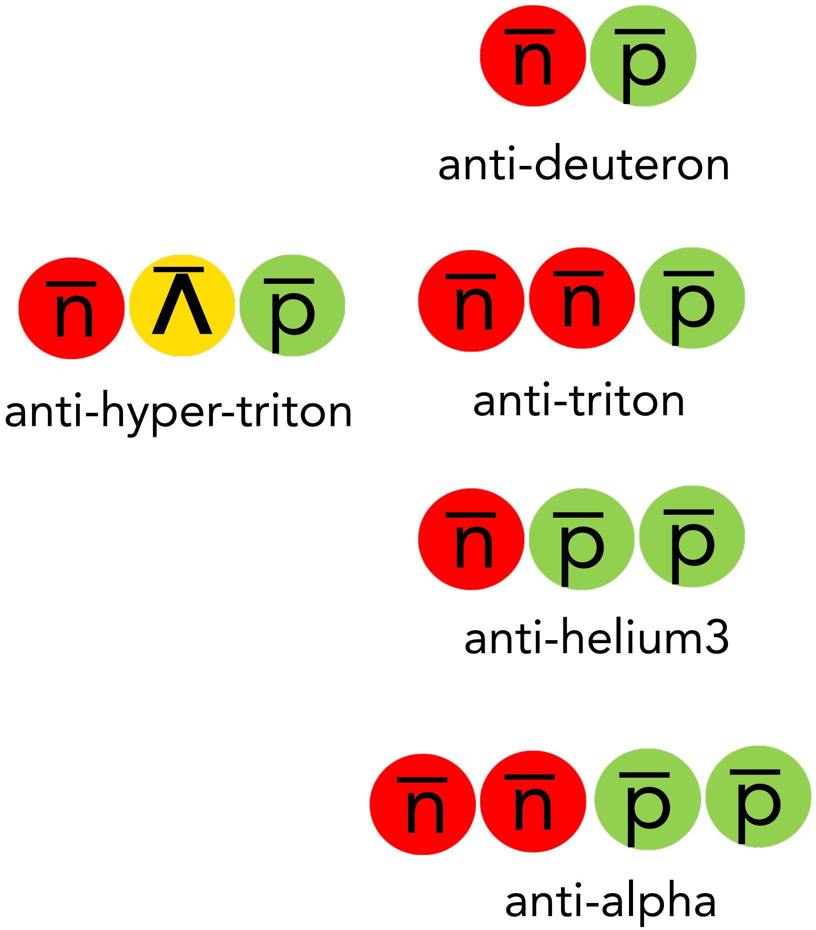




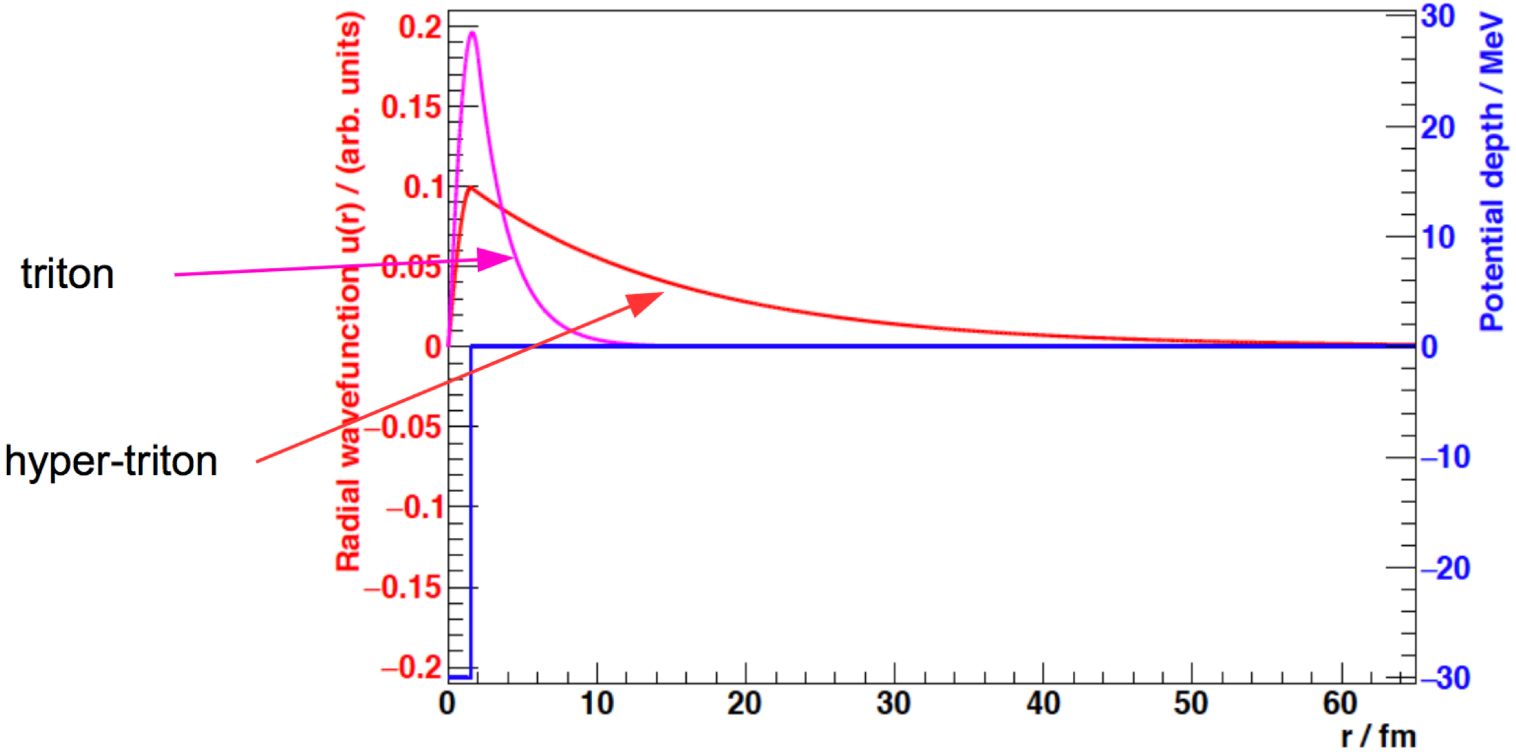
The STAR Collaboration, **Science 328, 58 (2010)**

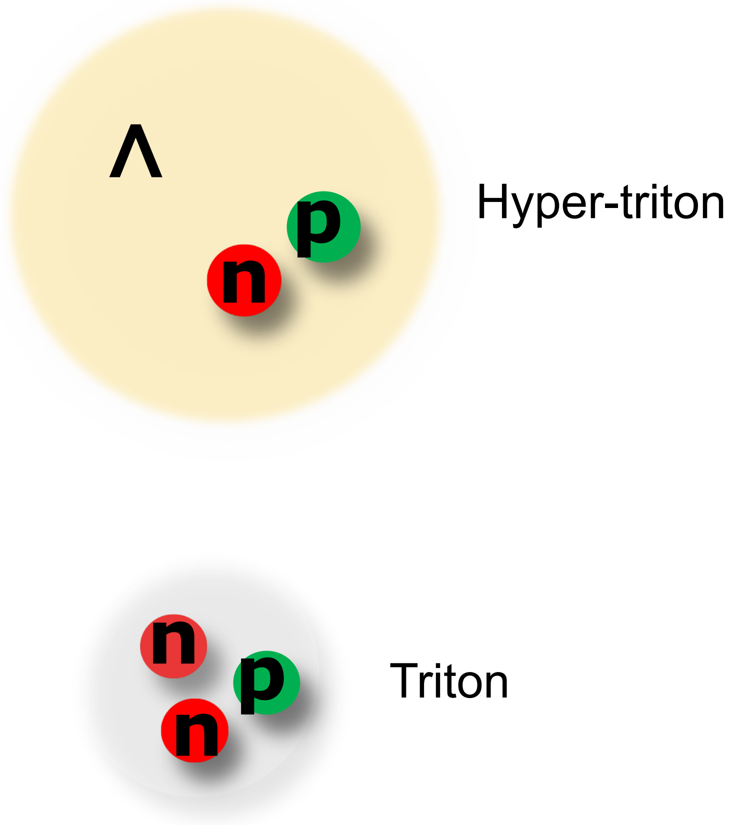
Light anti-(hyper-)nuclei





The anti-hyper-triton (2)





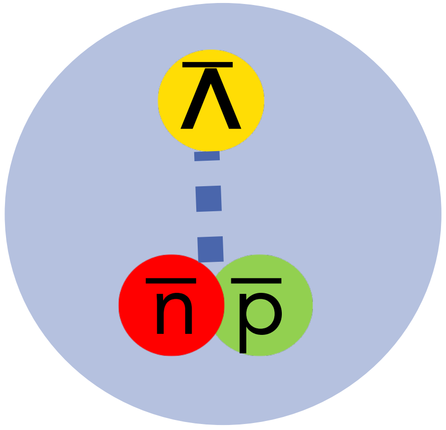
B. Dönigus, August 2017, link to EMMI workshop discussion [link]

[P. Braun-Munzinger, B. Dönigus, Nucl. Phys. A 987 (2019) 144]

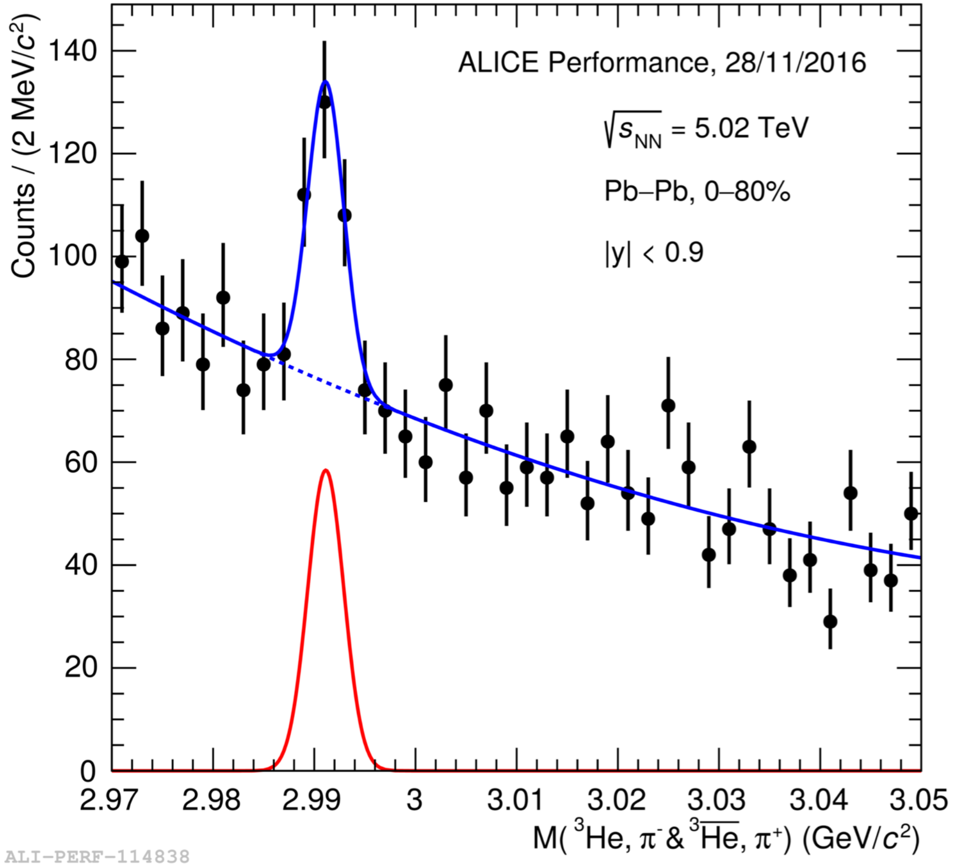
The anti-hyper-triton (1)

The anti-hyper-triton is a textbook example for **a quantum system under extreme conditions**.

- Small Lambda separation energy with respect to the medium in which it is created ("snowball in hell", Stachel, Braun-Munzinger, G. Brown).
- Laboratory to test hyperon-nucleon potentials ("mini neutron star").
- Wide wave function: strong quantum properties could influence its production.
- Efimov-like state (see [H.W. Hammer, Phys. Rev. C 100, 034002] for details).



anti-hyper-triton

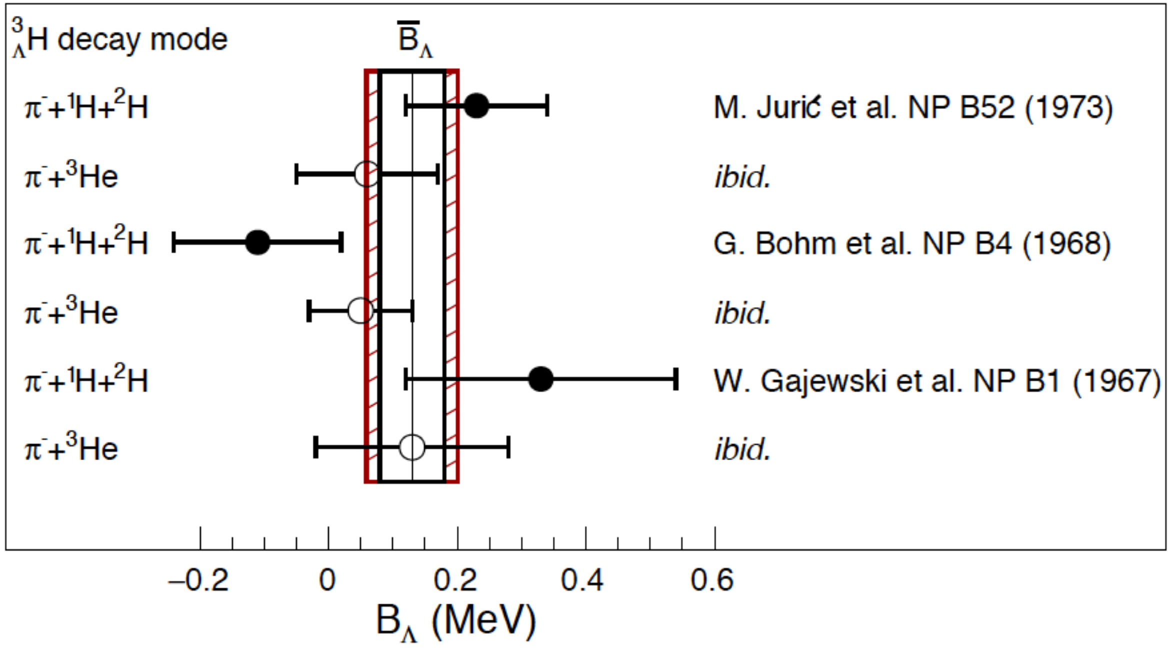


Known (un-)knowns about the anti-hyper-triton (1)

- Wide wave-function is related to the small Lambda separation energy

  → questioned by a recent measurement of the STAR collaboration

  → Homework for the experimental community to settle this question!



[PoS Hadron2017 (2018) 207]

Known (un-)knowns about the anti-hyper-triton (2)

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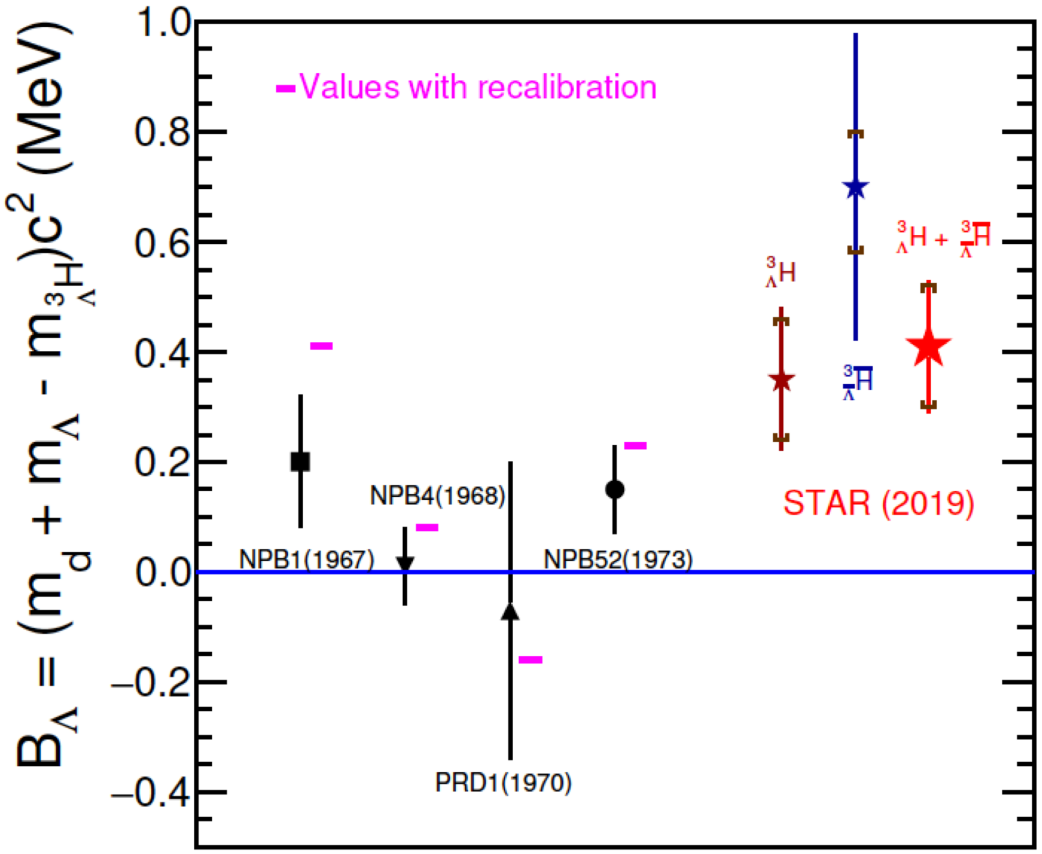
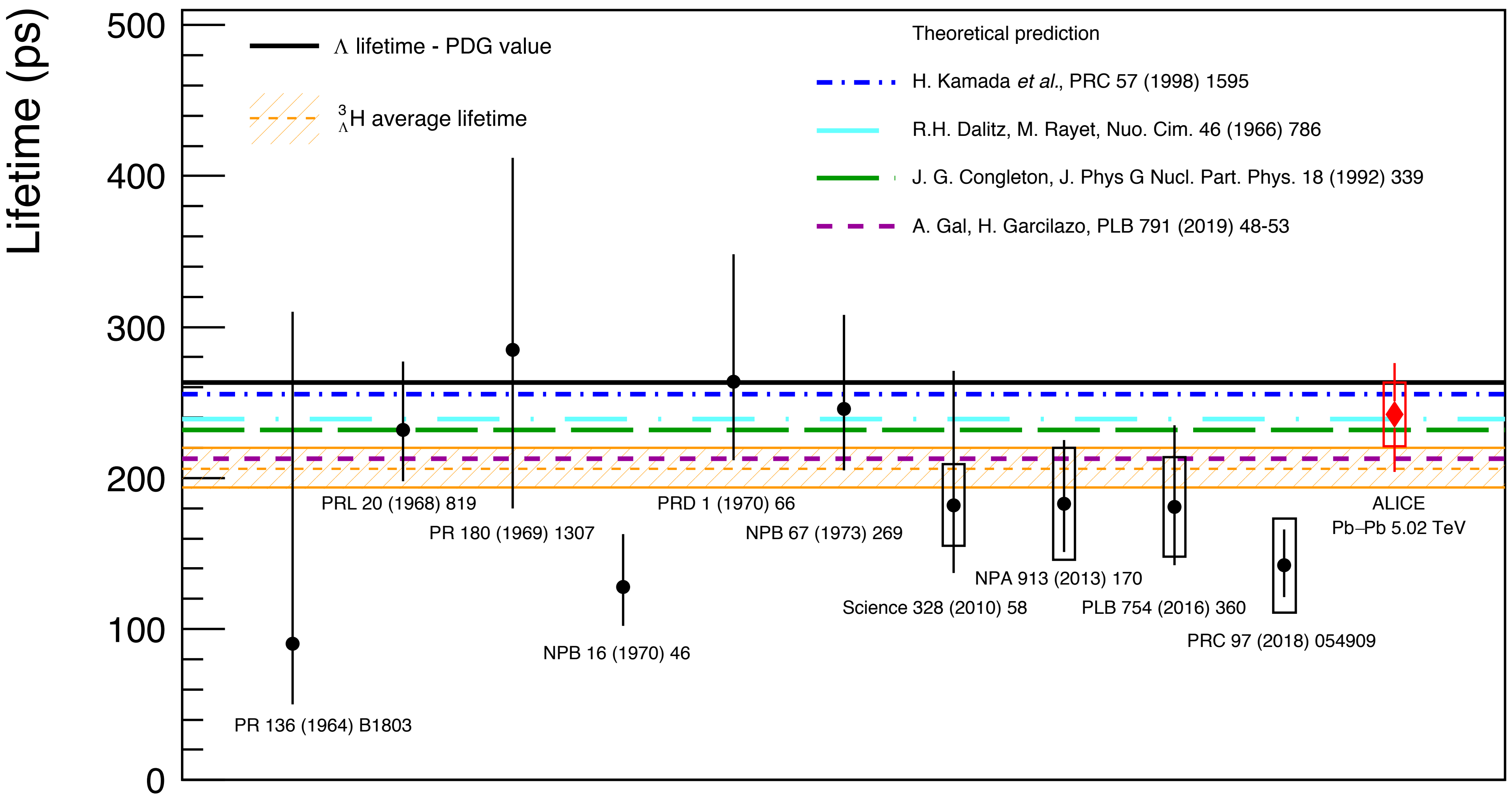


[STAR, arXiv:1904.10520]

(anti-)hyper-triton lifetime

[ALICE, 1907.06906]



→ Latest ALICE measurement in line with the expectation of a weakly bound Lambda. Measurements with even further increased statistical precision are on their way.

Is the production depending on the wave-function?

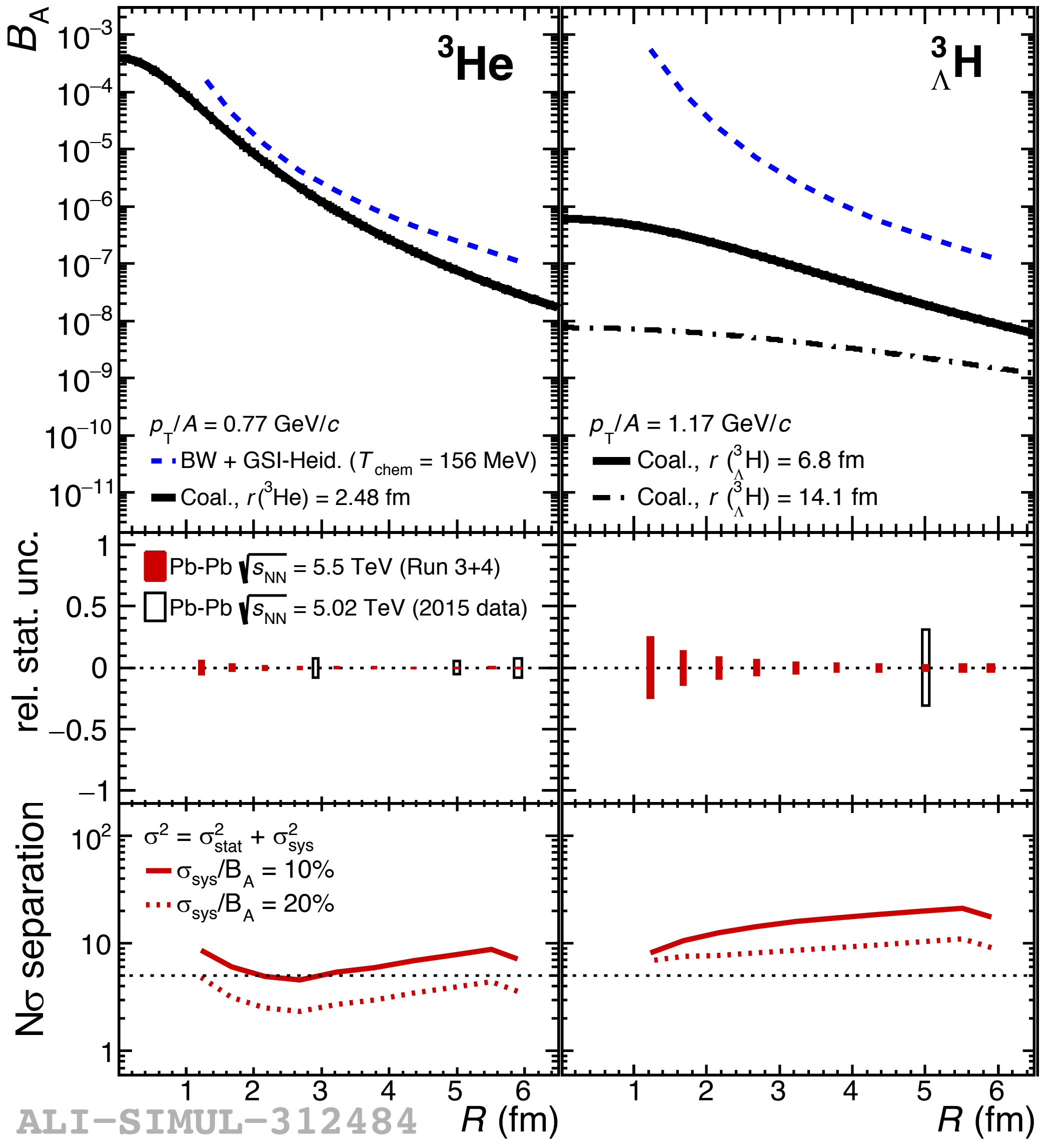
In a coalescence-like picture, there is a dependence as the production probability corresponds to the overlap of the Wigner-function of the hyper-triton with the emitting source.

→ Systematic measurements of anti-(hyper-)nuclei yields at the LHC will settle the "snowball in hell" question:

→ Thermal production of multi-quark bags?
[Nature 561 (2018) no.7723, 321-330]

→ Final-state coalescence?
[Phys.Rev. C59 (1999) 1585-1602]

→ Constant (re-)generation and destruction with a "memory effect"
[Phys.Rev. C99 (2019) no.4, 044907]

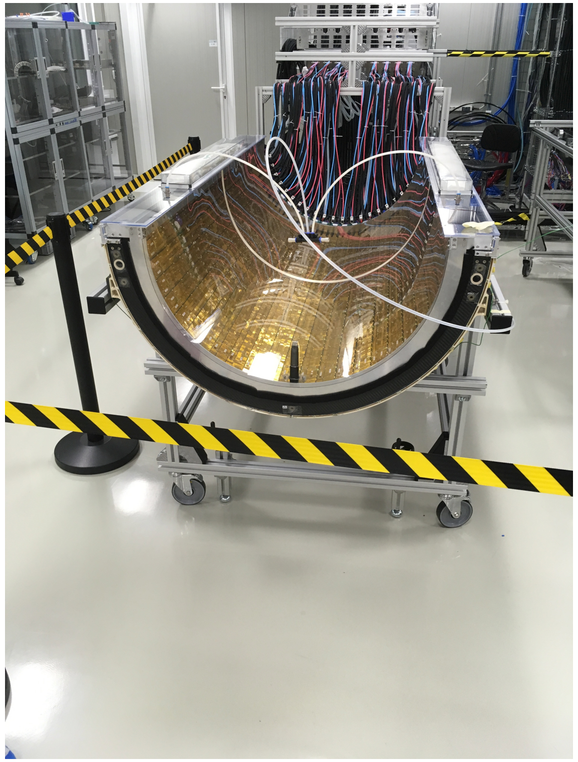


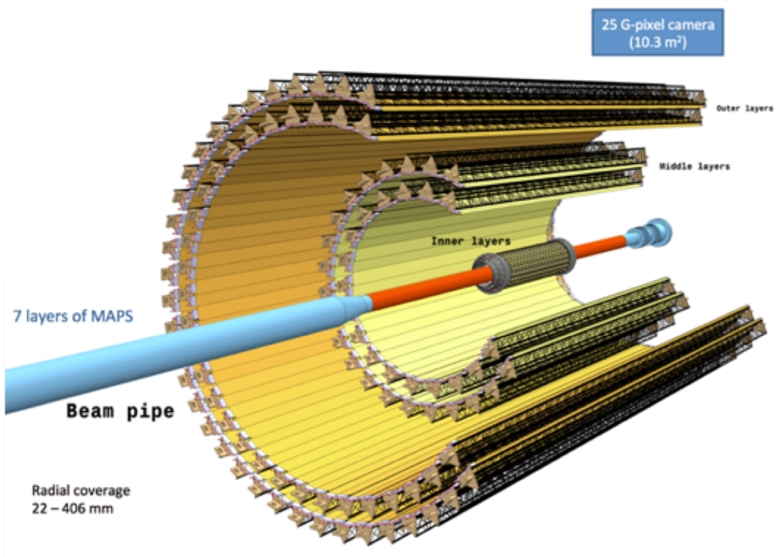
[CERN Yellow Report, arXiv:1812.06772]

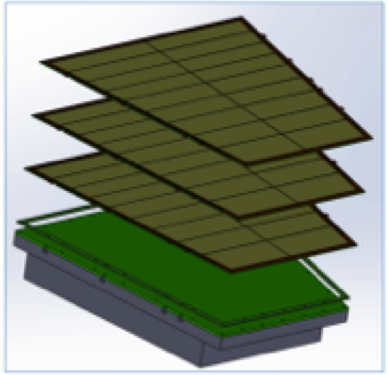
Currently ongoing upgrades

Major detector upgrades in long shutdown 2 (2019-2020) are opening a new era for heavy-ion physics:

- New pixel Inner Tracker System (ITS) for ALICE
- GEM readout for ALICE TPC => continuous readout
- 50 kHz Pb-Pb interaction rate





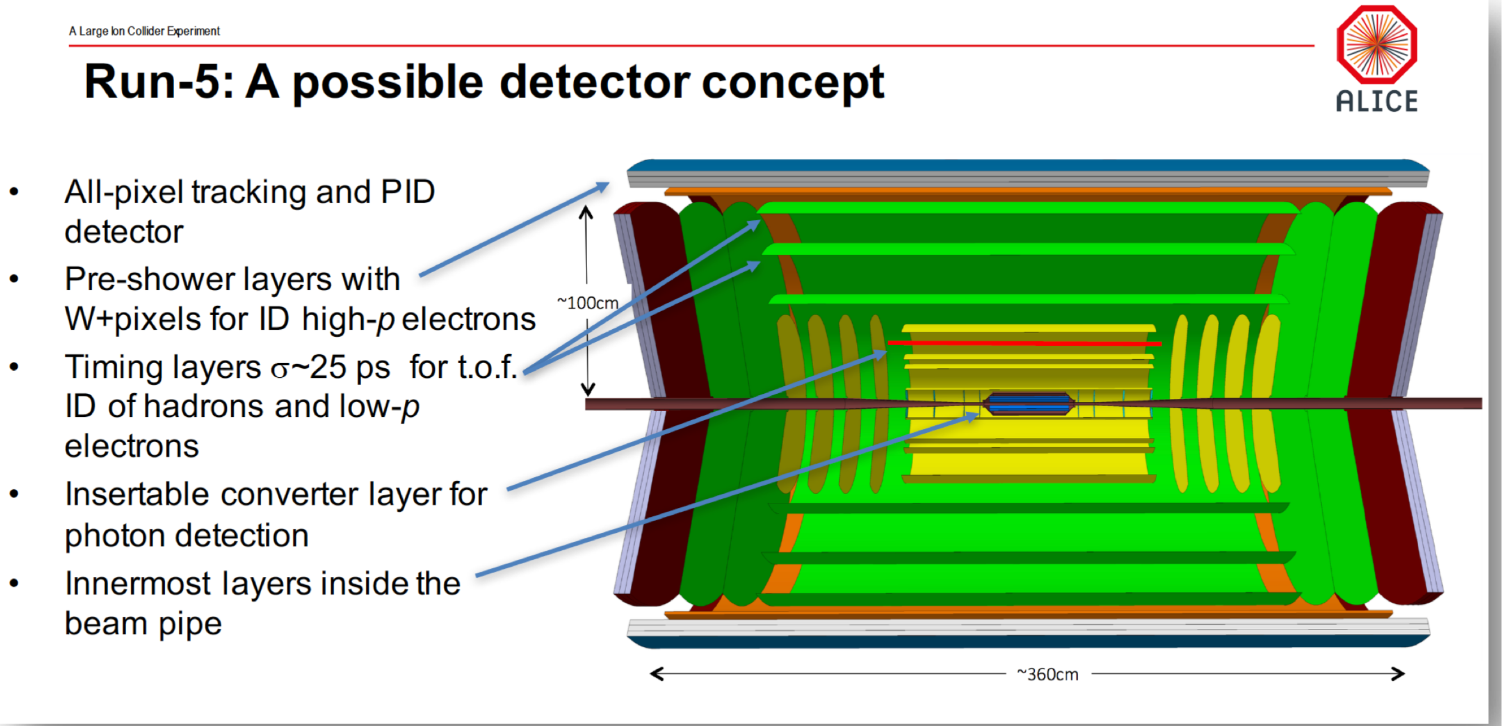


Replace wire chambers with GEMs

Plans for ALICE-II: thin, precise, fast

- ITS 3 (2024 → ultra-light and granular tracker) as testing ground for a completely new detector

- ALICE-II: gain up to two orders of magnitude in statistics by exploiting higher luminosity with lighter ions:
  - Very high rate (10 MHz Ar-Ar)
  - Low material budget
  - Hadron and electron ID (for X)
  - Extended rapidity acceptance ($|\eta|<4$)
  - Ideal tool to study (besides many other topics): anti-hyper-nuclei Ω_{cc}, Ω_{ccc}, B_c, XYZ states



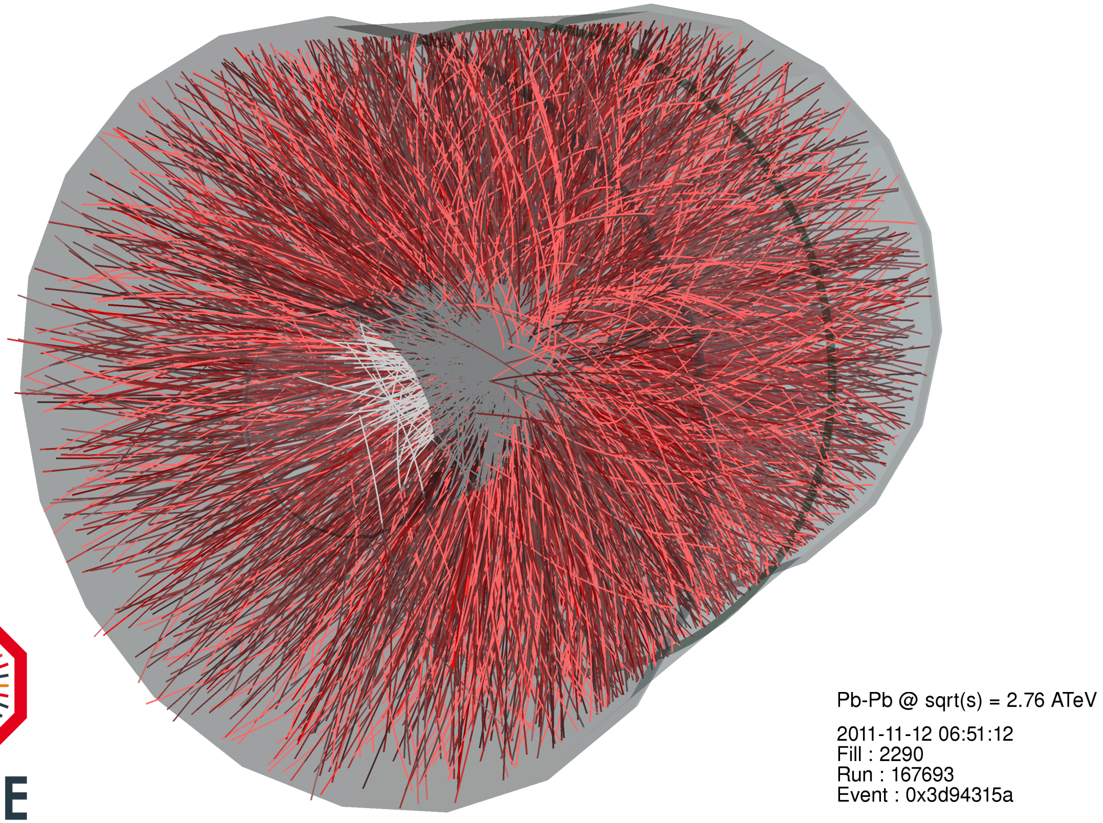
A. Dainese / L. Musa, Heavy-ion town meeting 2018

Summary

- Ultra-relativistic heavy-ion collisions provide the unique opportunity to study a hot and dense QCD medium.

- Despite their very violent nature, they allow for the production and the study of the even most fragile and exotic QCD objects in the laboratory.

ALICE
A JOURNEY OF DISCOVERY



Additional slides