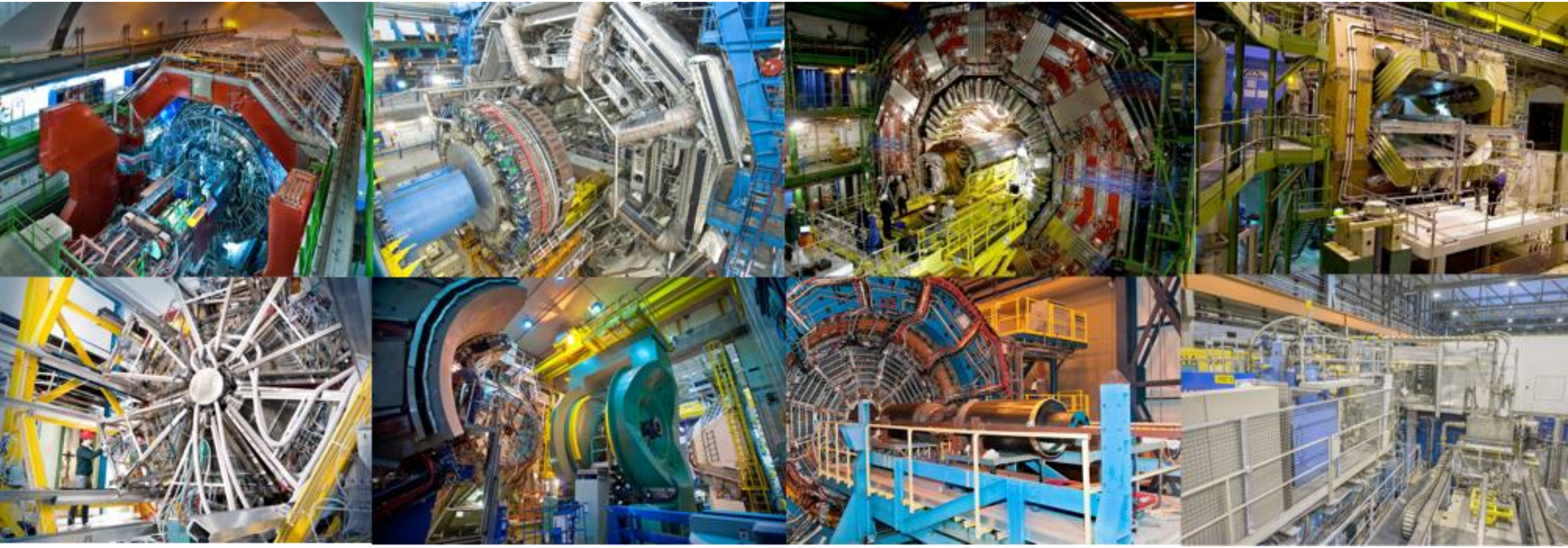
The physics of heavy-ion collisions



Alexander Kalweit, *CERN*

Overview

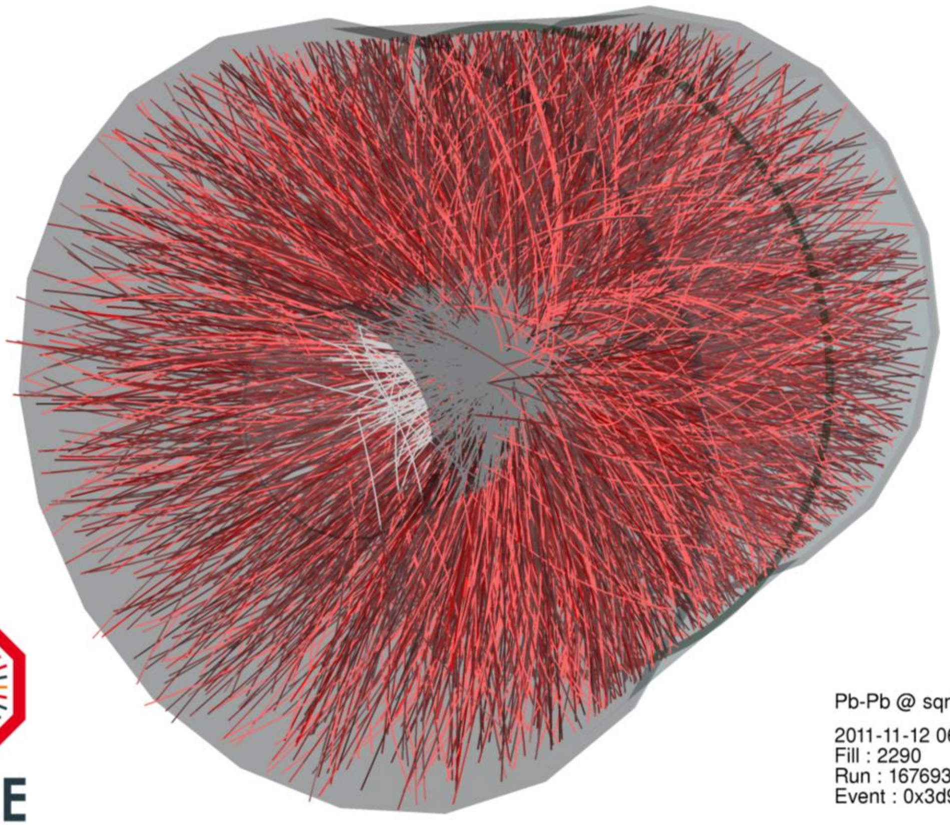
- Three lectures (one hour each):
  - Friday, 10:30h-11:30h (Prevessin)
  - Saturday, 11:30h-12:30h (Meyrin)
  - Monday, 10:30h-11:30h (Prevessin)

- Specialized discussion sessions with **heavy-ion experts** in the afternoons on Friday and Monday.

- Feel free to contact me for any questions regarding the lecture:
  Alexander.Philipp.Kalweit@cern.ch

- Many slides, figures, and input taken from:

  Jan Fiete Grosse-Oetringhaus, Constantin Loizides, Federico Antinori, Roman Lietava



ALICE
A JOURNEY OF DISCOVERY

Outline and discussion leaders

- Introduction
- The QCD phase transition
- QGP thermodynamics and soft probes (Francesca)
  - Particle chemistry
  - QCD critical point and onset of de-confinement
  - (anti-)(hyper-)nuclei
  - Radial and elliptic flow
  - Small systems
- Hard scatterings (Leticia, Marta)
  - Nuclear modification factor
  - Jets
- Heavy flavor in heavy-ions
  - Open charm and beauty
  - Quarkonia
- Di-leptons

→ Heavy-ion physics is a huge field with many observables and experiments: impossible to cover all topics! I will present a personally biased selection of topics.

Francesca Bellini

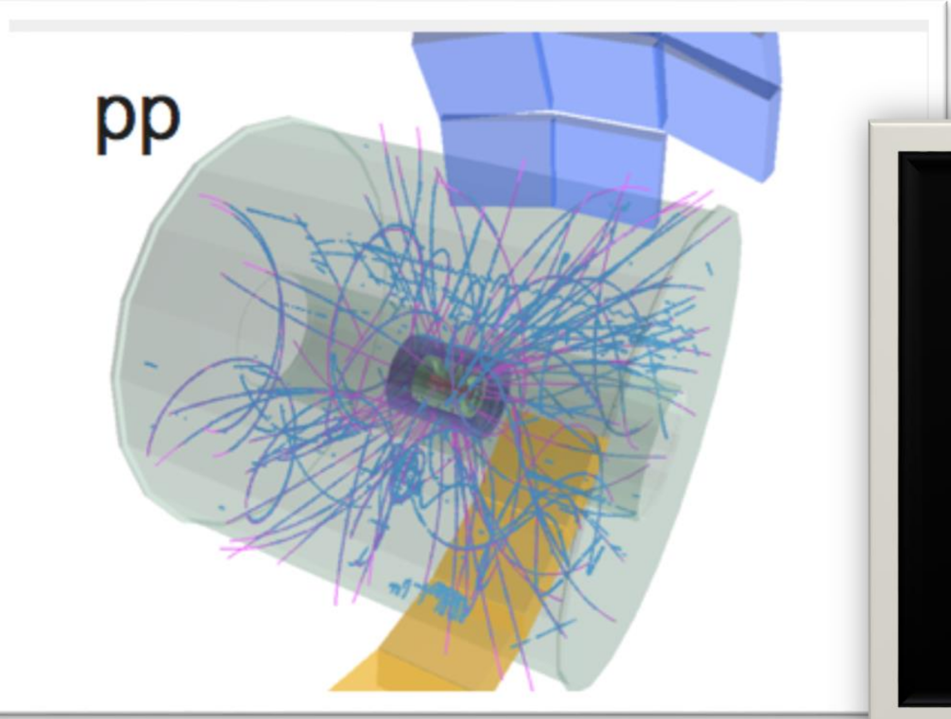
Leticia Cunqueiro

Marta Verweij

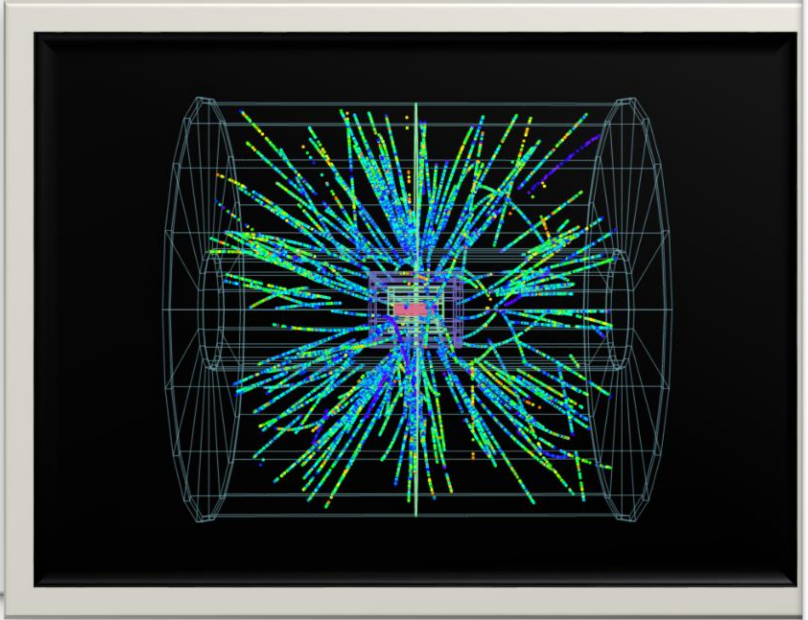
Introduction

pp / p-Pb / Pb-Pb collisions

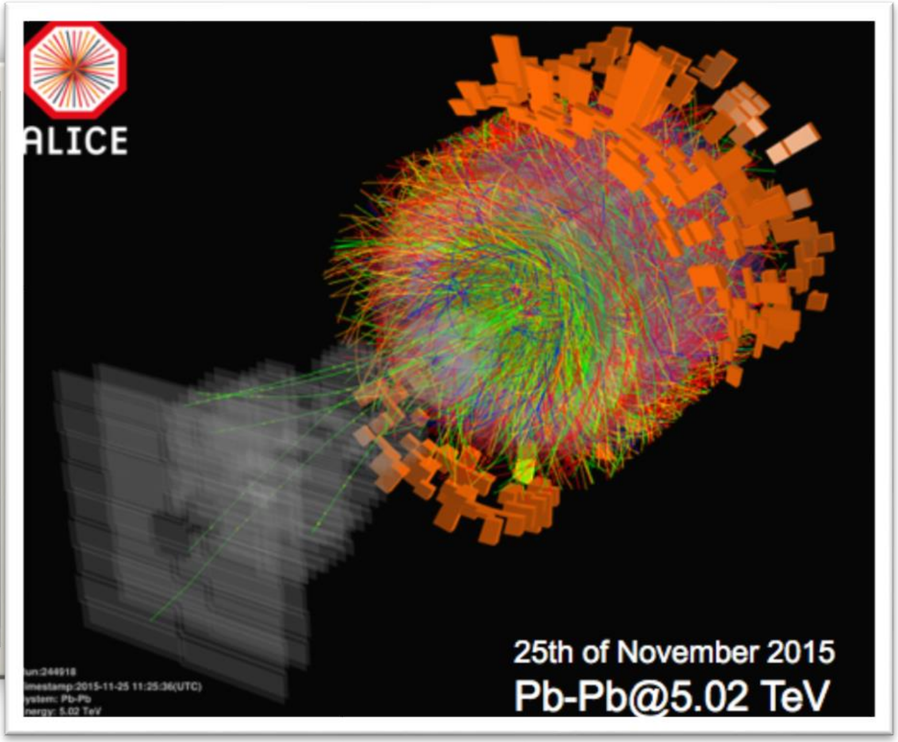
- The LHC can not only collide protons on protons, but also heavier ions.
- Approximately one month of running time is dedicated to heavy-ions each year.



p-Pb



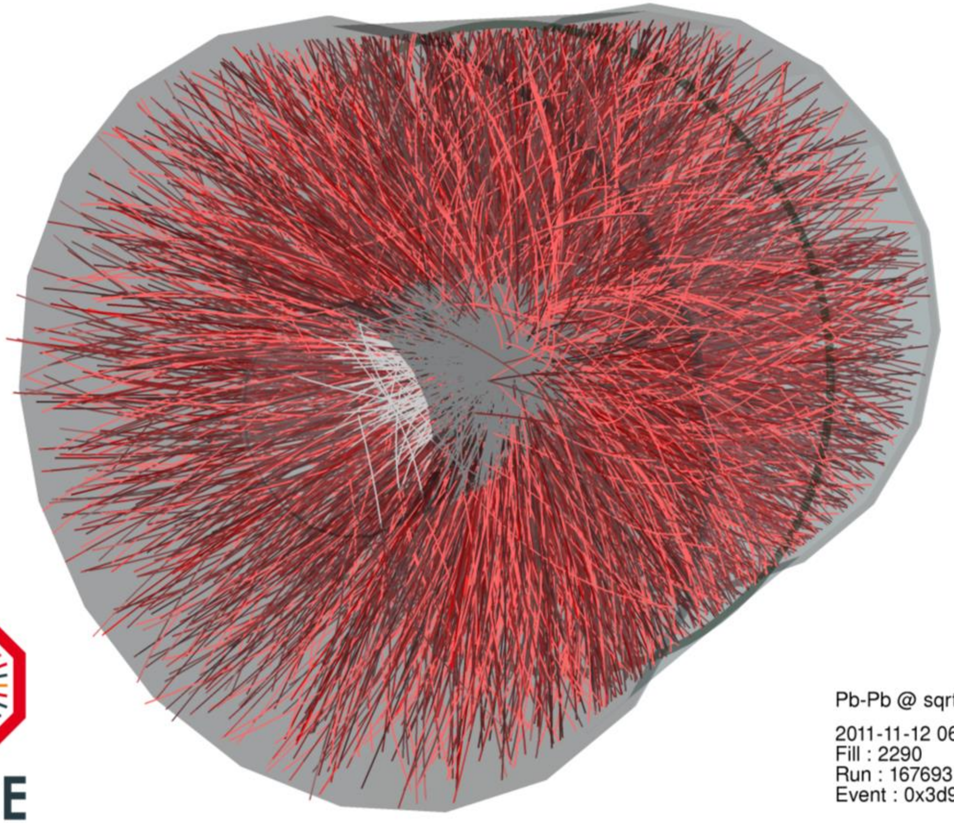
Pb-Pb



Heavy-ions at the LHC

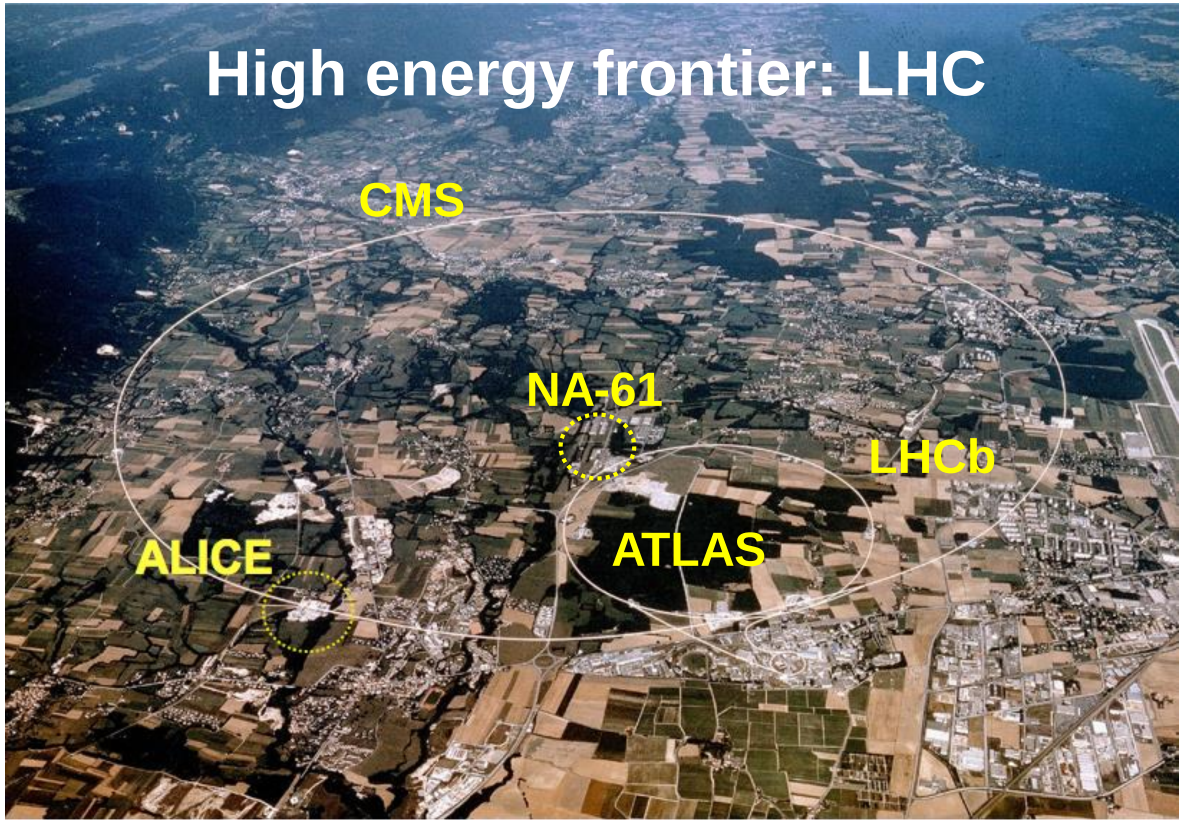
- Energy per nucleon in a $^{208}_{82}$Pb-Pb collision at the LHC (Run 1):
  - pp collision energy $\sqrt{s}$ = 7 TeV
  - beam energy in pp E_{beam} = 3.5 TeV
  - Beam energy per nucleon in a Pb-Pb nucleus: $E_{beam,PbPb}$ = 82/208* 3.5 = 1.38 TeV
  - Collision energy per nucleon in Pb-Pb: $\sqrt{s_{NN}}$ = 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

→What can we learn from these massive interactions?



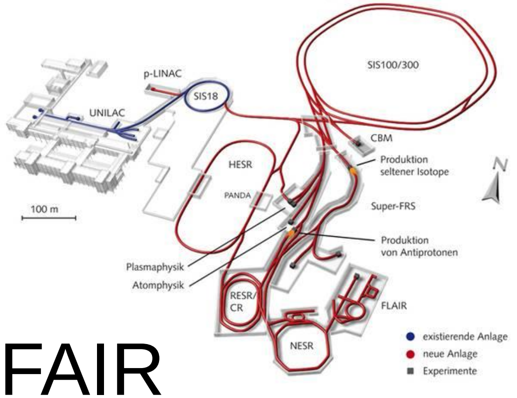
ALICE
A JOURNEY OF DISCOVERY

Heavy-ion experiments

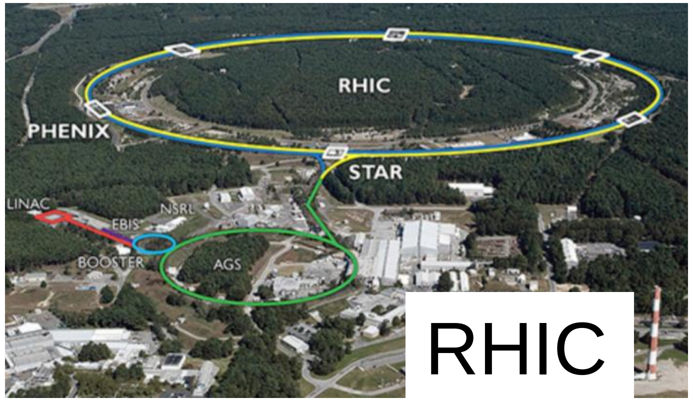


→ By now **all major LHC experiments have a heavy-ion program**: LHCb took Pb-Pb data for the first time in November 2015.

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



FAIR



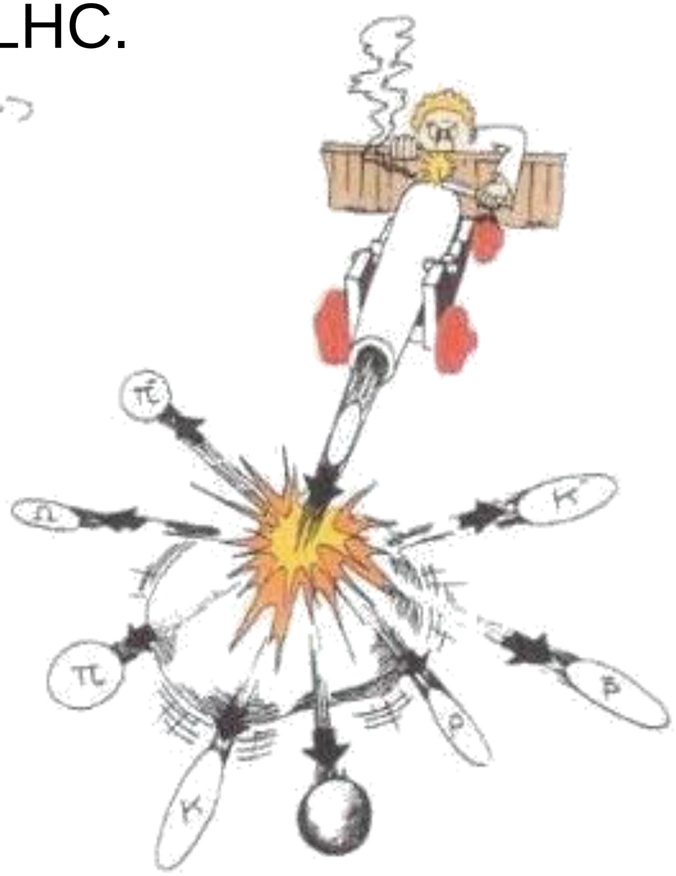
RHIC

Increasing the beam energy over the last decades…

..from early fixed target experiments at GSI/Bevalac and SPS to collider experiments at RHIC and LHC.

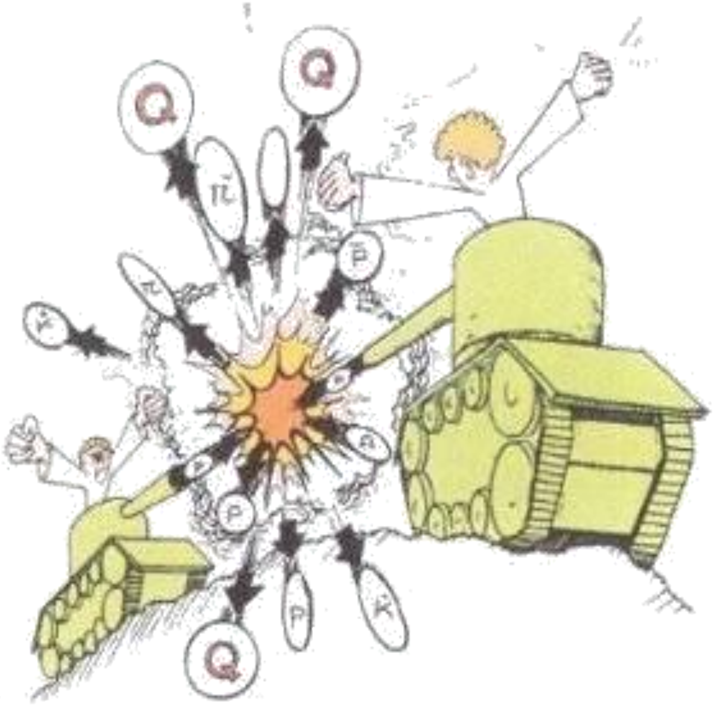
SIS

GSI Darmstadt, $\sqrt{s_{NN}}$~2.4 GeV



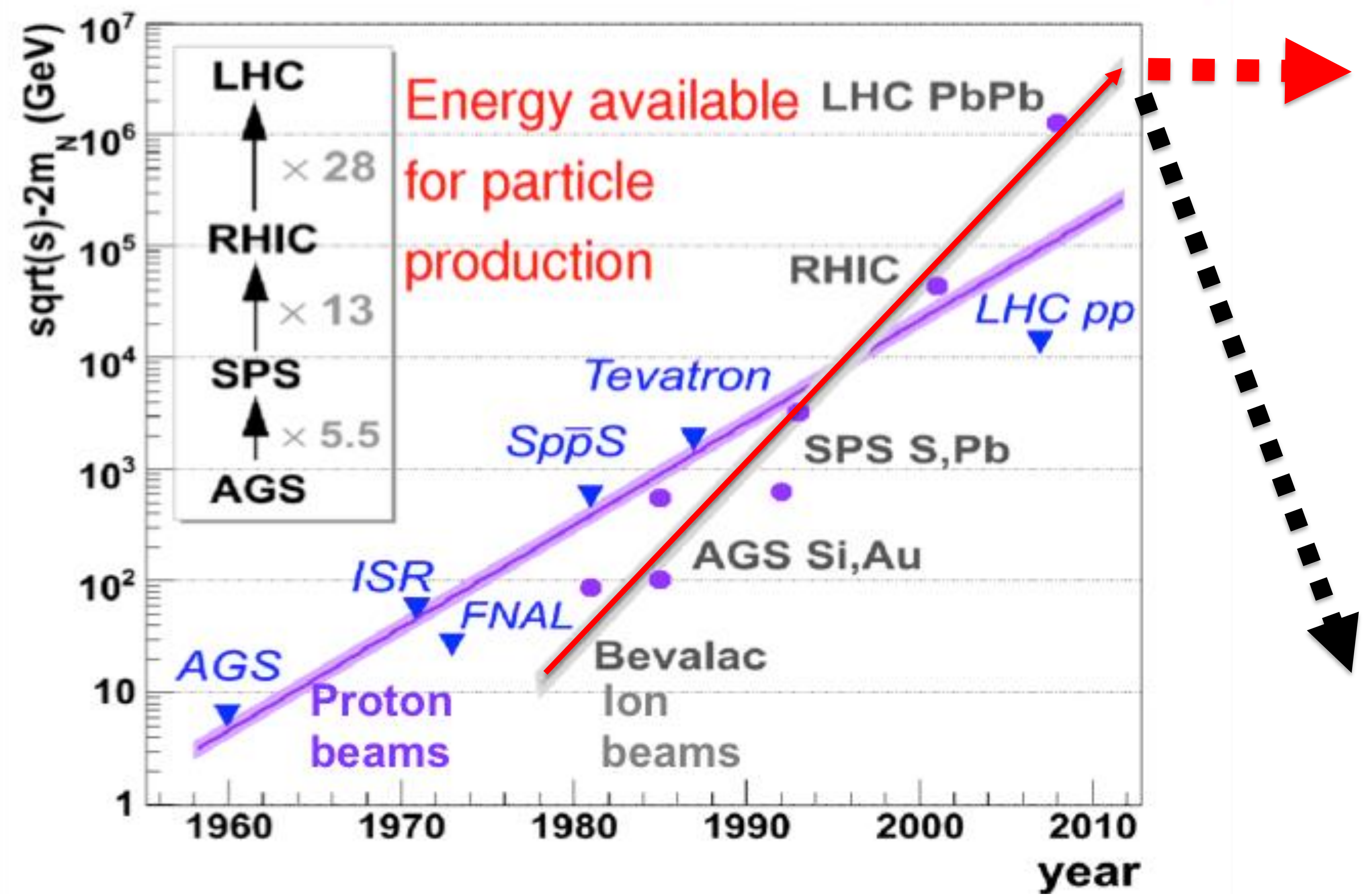
SPS

CERN, $\sqrt{s_{NN}}$~6-20 GeV

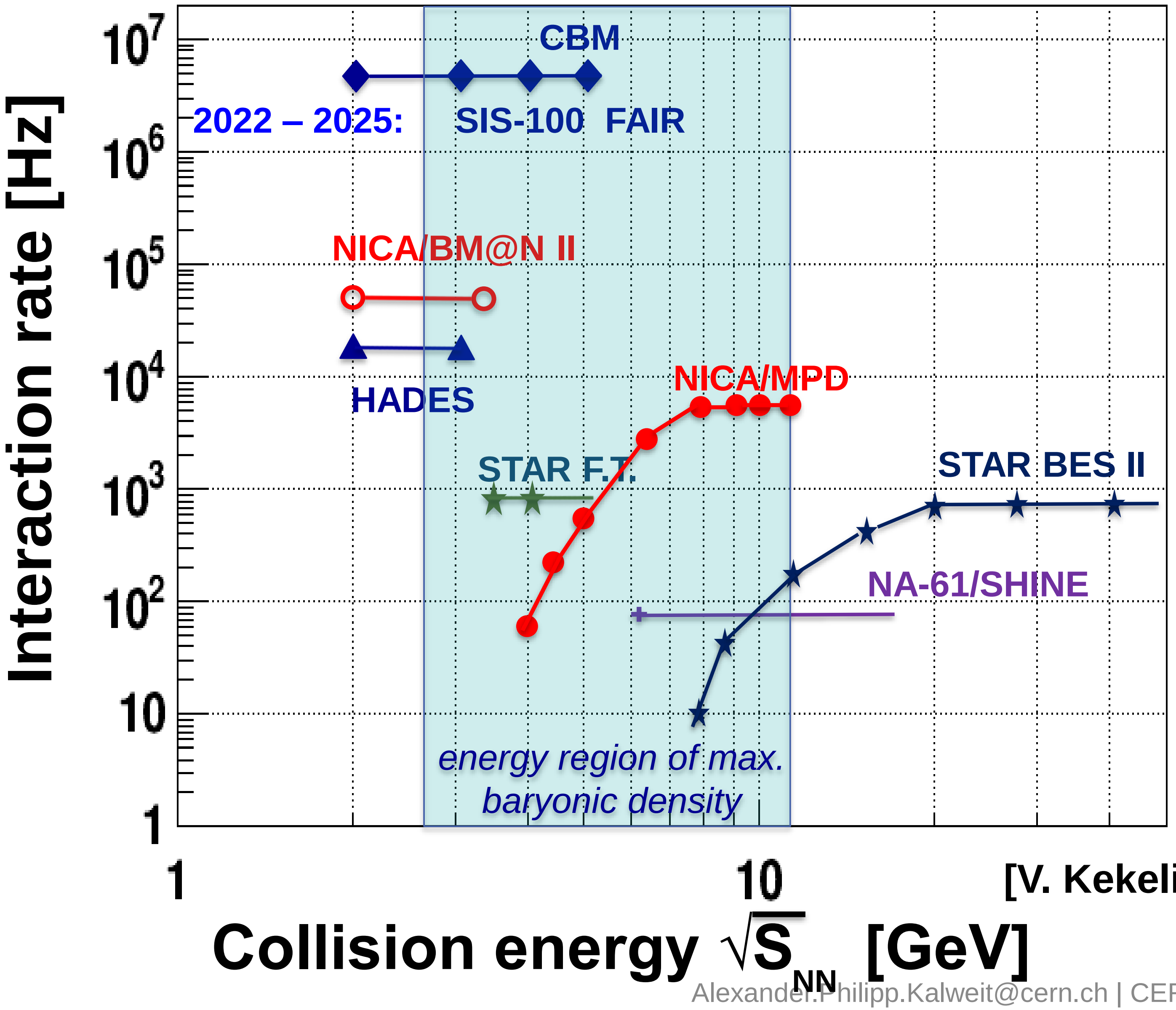


RHIC/LHC

Brookhaven → RHIC $\sqrt{s_{NN}}$~8-200 GeV (BES)
CERN → LHC $\sqrt{s_{NN}}$ = 5.02 TeV


sqrt(s)-2m_N (GeV)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
LHC
× 28
RHIC
× 13
SPS
× 5.5
AGS
Energy available for particle production
LHC PbPb
RHIC
LHC pp
Tevatron
SppS
SPS S,Pb
AGS Si,Au
ISR
FNAL
AGS
Bevalac
Proton beams
Ion beams
1960
1970
1980
1990
2000
2010
year

Energy ranges covered by different non-LHC accelerators



[V. Kekelidze, SQM2017 talk]

→ Collider experiments allow for very high $\sqrt{s_{NN}}$ and fixed target experiments allow for very high interaction rates at lower $\sqrt{s_{NN}}$.

LHC Run 2

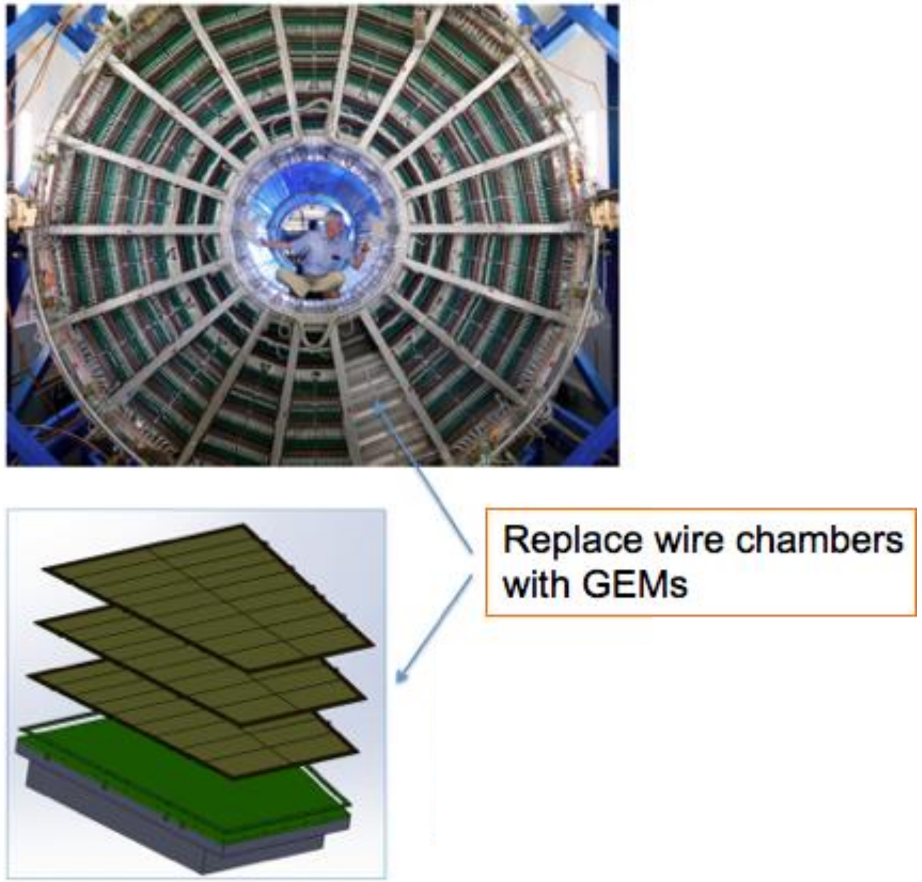
- LHC Run 2 data taking and analysis is now in full swing.
- Significant increase in integrated luminosity (approx. 4 times in Pb-Pb) allow more **precise investigation of rare probes**.
- Various collision systems at different center-of-mass energies are ideally suited for **systematic studies of particle production**.

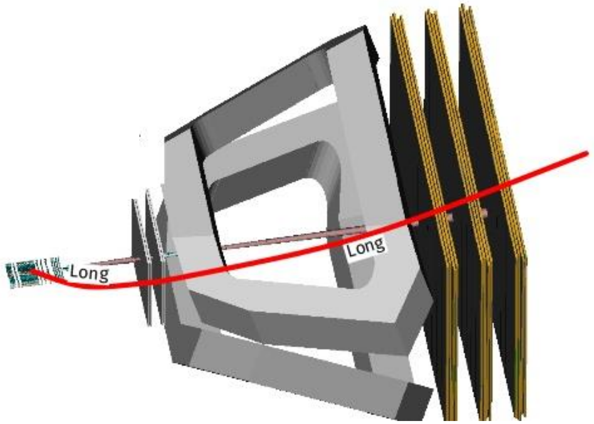
Run 1(2009-2013)	Run 2 (2015-now)
Pb-Pb 2.76 TeV	**Pb-Pb** 5.02 TeV
p-Pb 5.02 TeV	**p-Pb** 5.02 TeV, 8.16 TeV
pp 0.9, 2.76, 7, 8 TeV	**pp** 5.02, 13 TeV

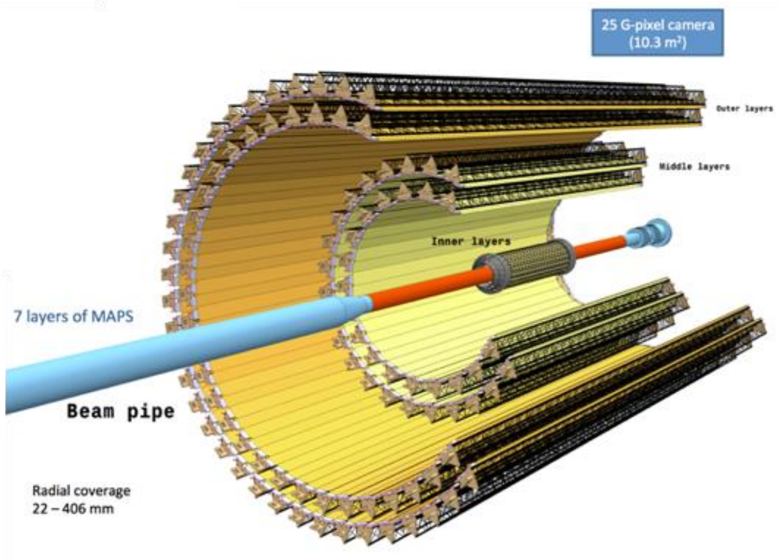
LHC Run 3 and 4

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

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







The QCD phase transition

The standard model

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

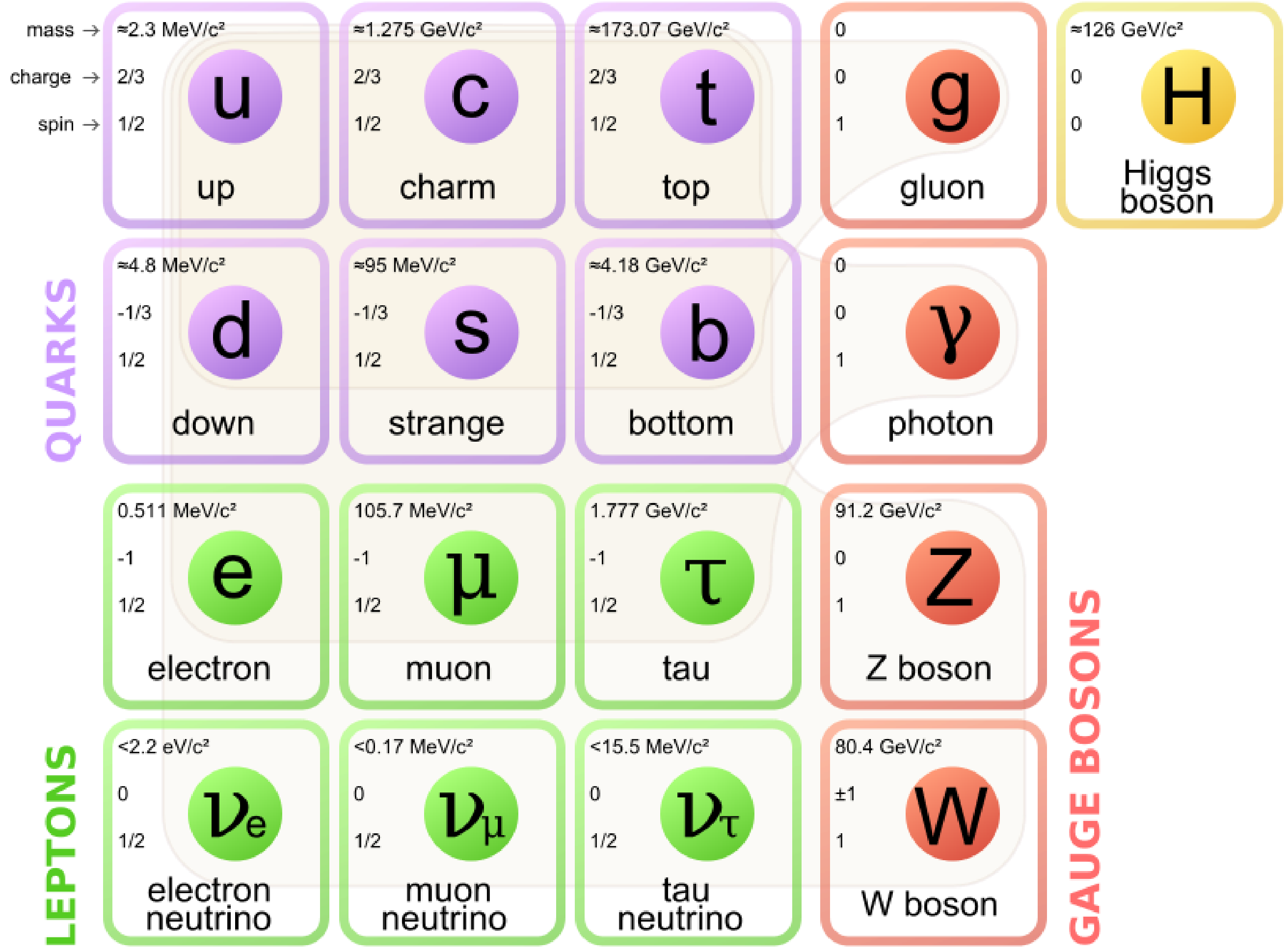
1. Elektromagnetic: γ
2. Weak interaction: W&Z
3. **Strong interaction: Gluons**
4. Gravitation: Graviton?

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 tensor

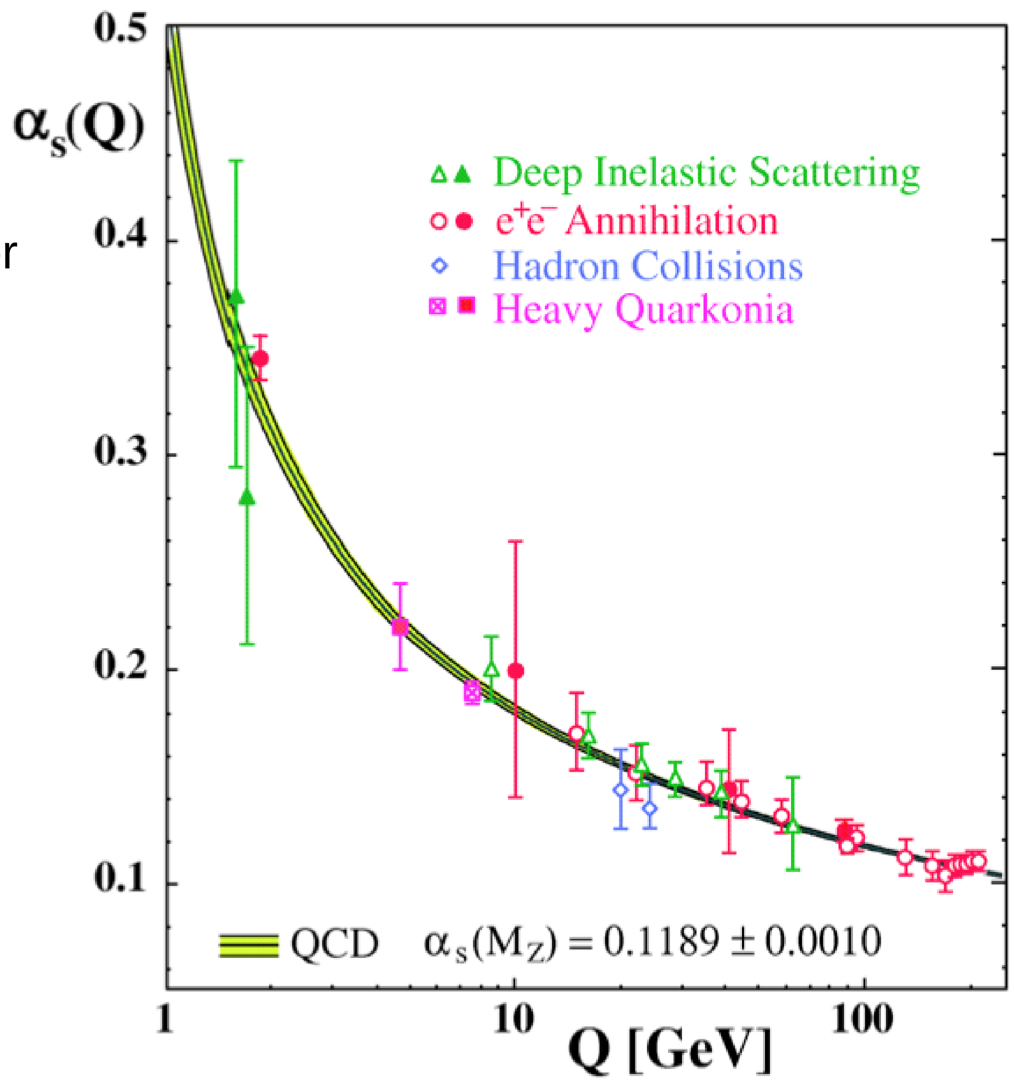
Properties of QCD relevant for heavy-ions:

(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.

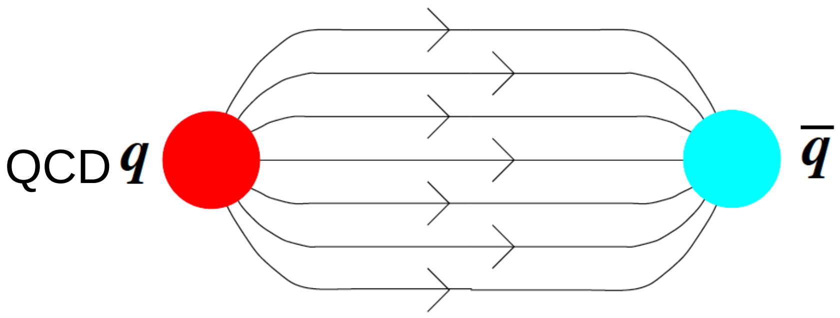
→ See also QCD lecture by Bryan Webber.

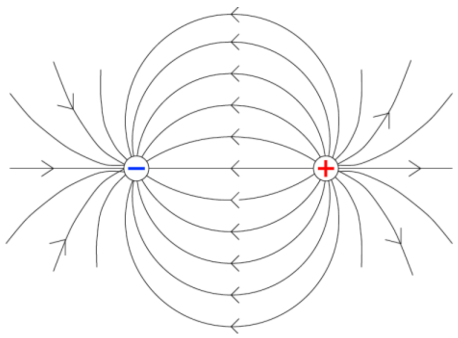


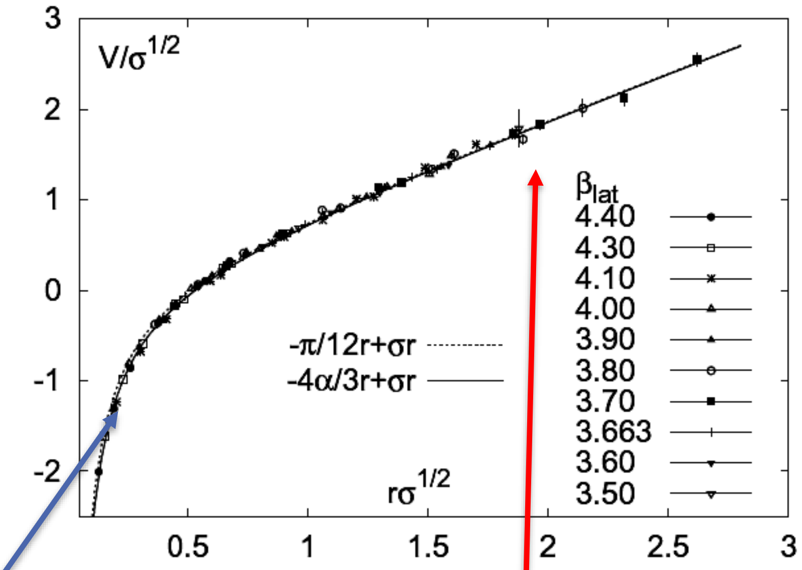
[Prog.Part.Nucl.Phys. 58 (2007) 351-386]

(De-)confinement (1)

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

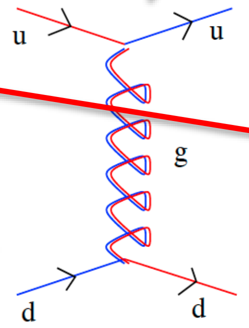


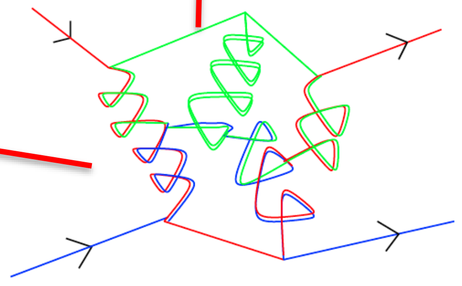




- Potential grows linearly with distance
  → ***Cornell potential***:

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

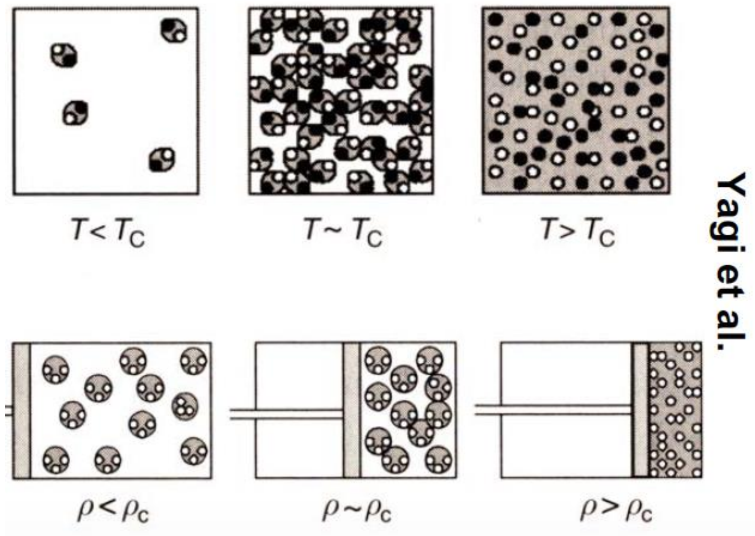


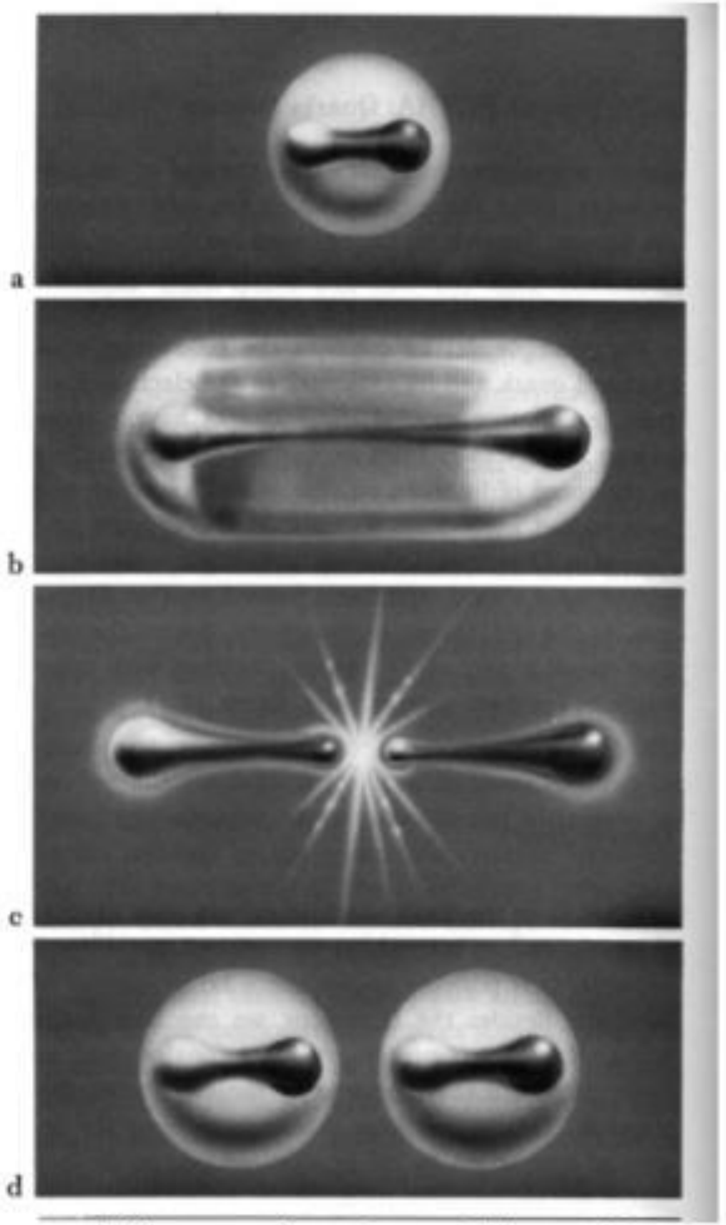


- "String tension" is huge:
  K ~ 880 MeV/fm

(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).





[illustration from Fritzsch]

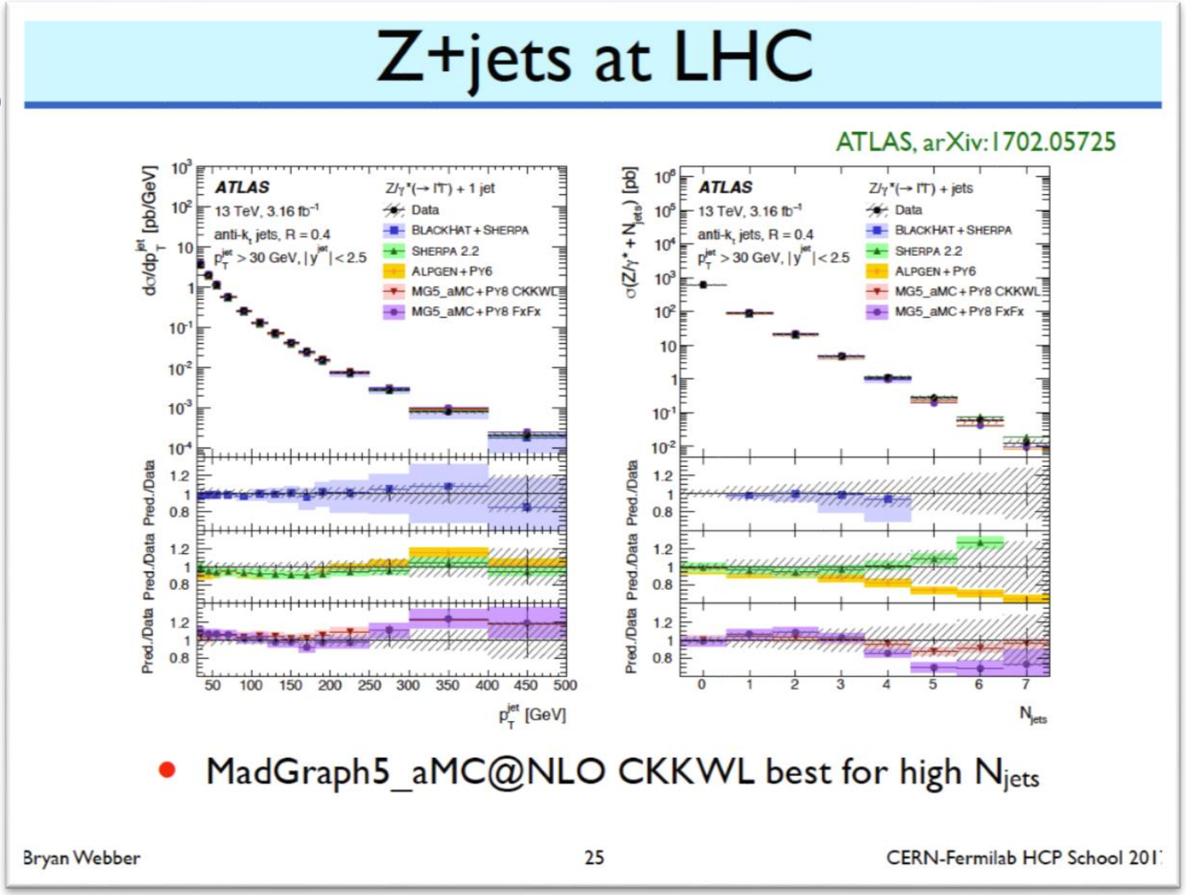
Ab-initio QCD calculations

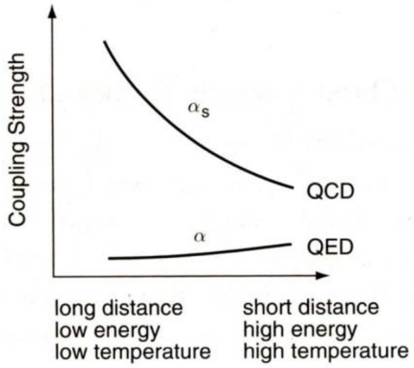
- *Ab-initio*: a calculation without modeling (and model parameters), but directly derived from the basic theory and only based on fundamental parameters.

- In QCD, there are two *ab-initio* approaches relevant for heavy-ion physics:
  - Perturbation theory: **pQCD**
  - Lattice QCD: **LQCD**

- Perturbation theory is only applicable for small values of α_S:
  → only possible for large momentum transfers as in jets.

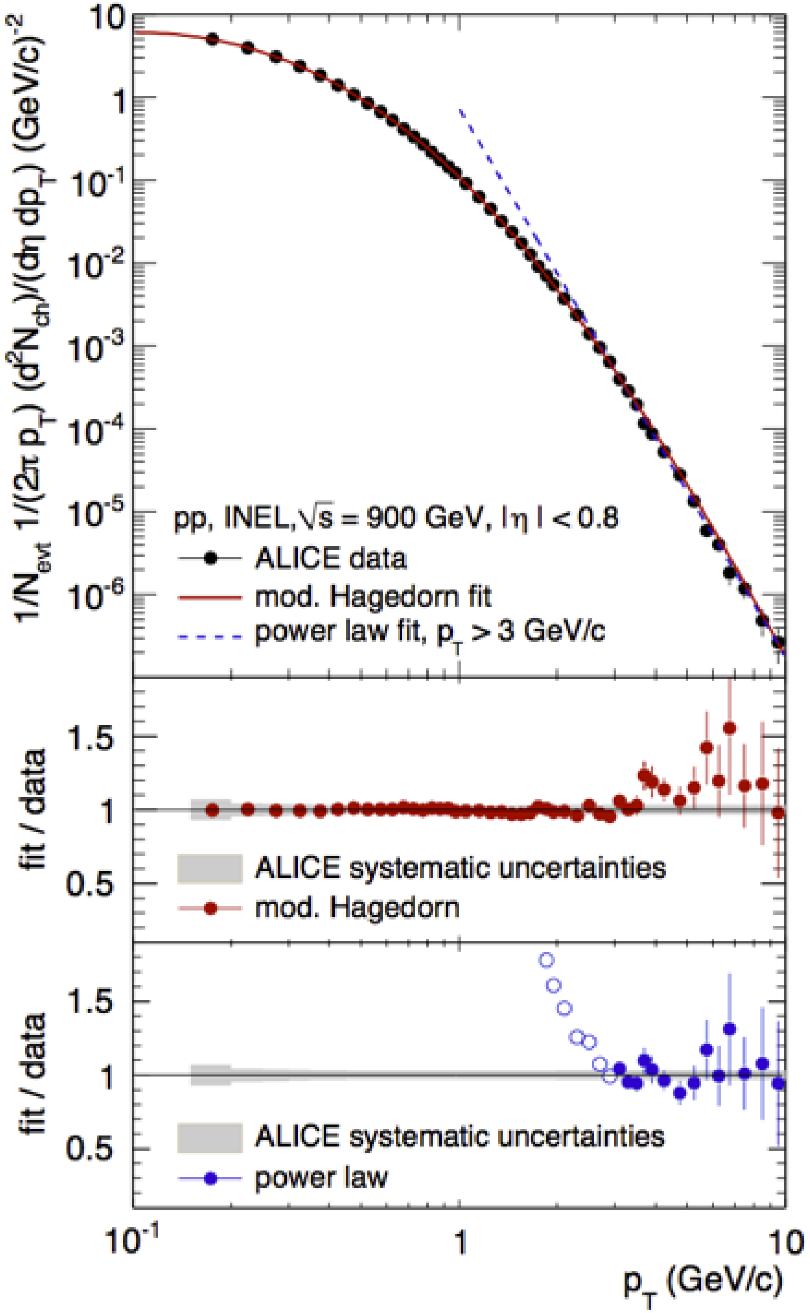
- **(De-)confinement** cannot be described by pQCD, but with LQCD!





Soft and hard probes

- Phenomenologically, we can distinguish:
  - A *thermal* (*soft QCD*) part of the transverse momentum spectrum which **contains most of the yield** and shows roughly an exponential shape (thermal-statistical particle chemistry and flow).
  - A *hard part* (power-law shape, **pQCD**) which is studied in jet physics (energy loss mechanisms etc., R_{AA} in heavy-ion physics)

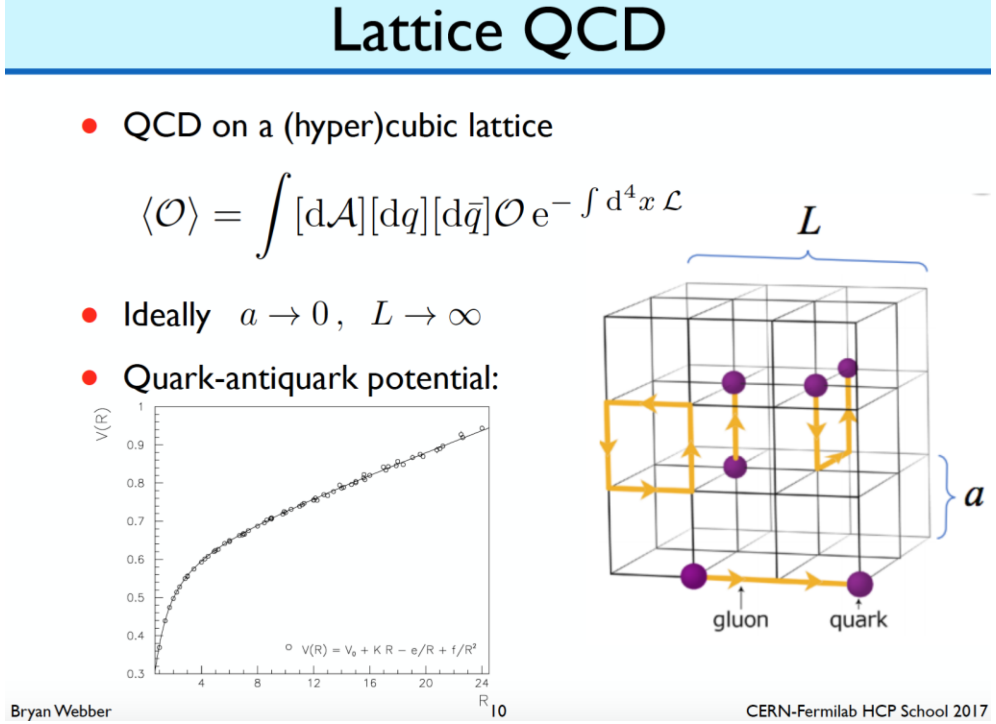


→ Even at LHC energies ~98% of all particles are produced at p_T < 2 GeV/*c*.
→ ~80% are pions, ~13% are kaons, ~4% are protons.
→ The ***bulk*** of the produced particles is not accessible with pQCD methods.

Lattice QCD (LQCD)

- Solve QCD **numerically** by discretizing Lagrangian on a space-time grid.
- Static theory, no dynamical calculations possible as computations are done in imaginary time ($\tau \rightarrow \iota\tau$).
- Only directly applicable (extrapolation methods exist) to systems with no net-baryon content:
  number of baryons = number of anti-baryons
  (early universe, midrapidity LHC
  → $\mu_B \approx 0$ MeV)

- Computationally very demanding
  → dedicated supercomputers.

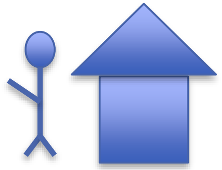


JUGENE in Jülich
(294,912 cores, ~ 1 PetaFLOPSS

QGP as the asymptotic state of QCD

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

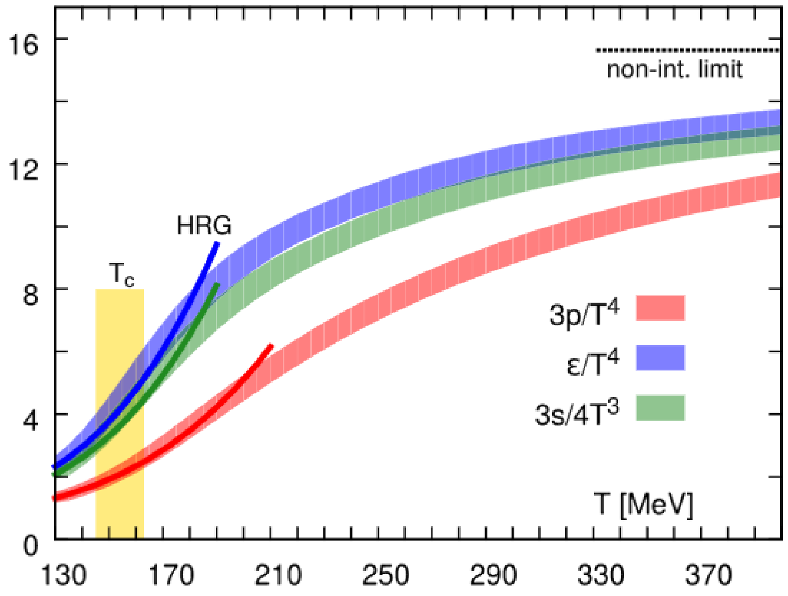
Critical temperature
$T_c \approx$ 156 MeV

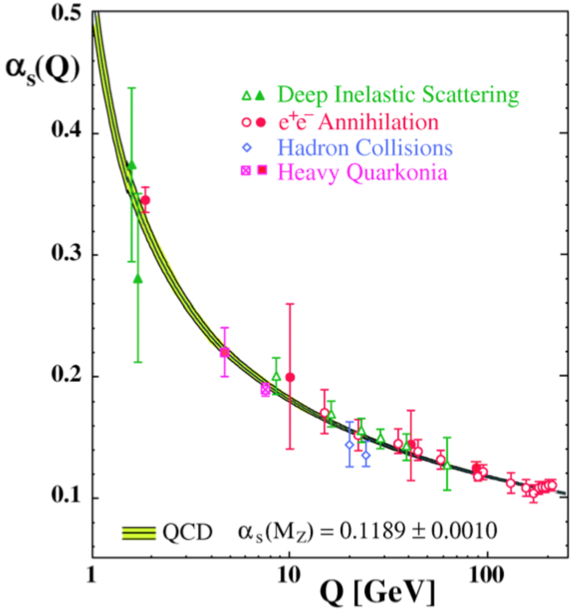
$T \rightarrow \infty$

Temperature T

→ Are such extreme temperatures reached in the experiment?
Yes..
→ Is it for all quark flavors the same?
Not clear yet..
→ …

[PRD 90 094503 (2014)]





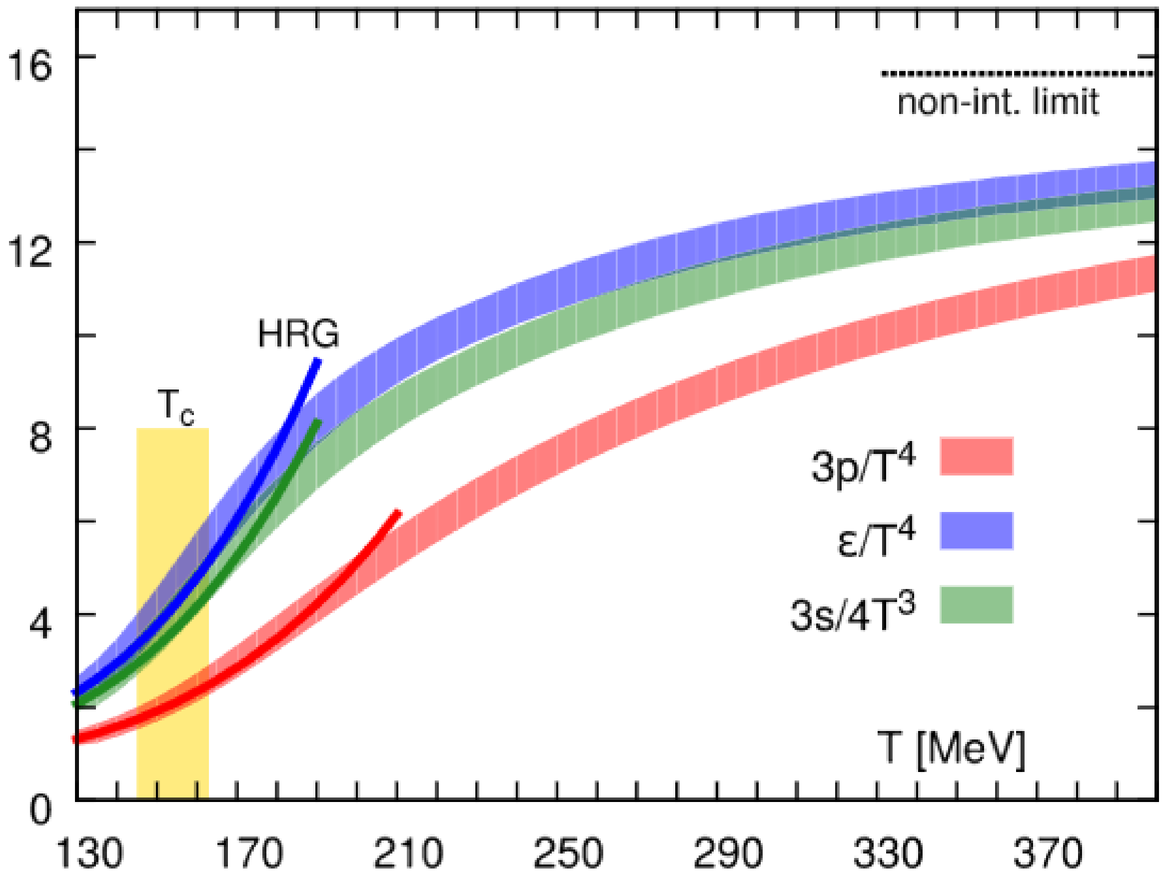
Phase transition in Lattice QCD

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

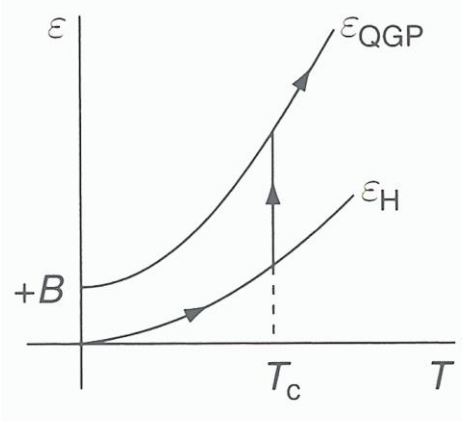
[PRD 90 094503 (2014)]

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

Energy density *ε*
Pressure *p*
Entropy density *s*



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



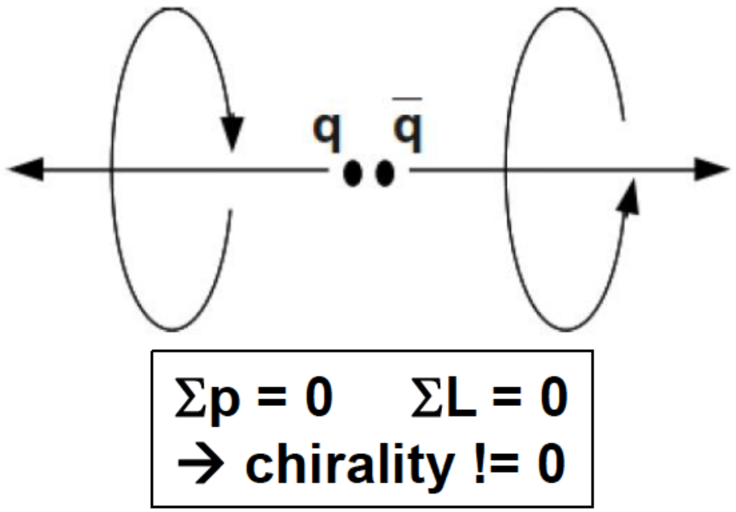
For comparison:

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

Chiral symmetry

- QCD Lagrangian is symmetric under $SU(2)_L \times SU(2)_R$
  → In the dynamics of QCD, the interaction between right handed (spin parallel to momentum vector) and left handed (spin anti-parallel to momentum vector) quarks vanishes *in the case of massless quarks*.

- Light quarks have a finite small bare (current) mass
  → explicit breaking of chiral symmetry.



- Creation of coherent q-qbar pairs in QCD vacuum (as in cooper pairs in superconductivity).
  - Has a non-zero chiral charge
  - Not symmetric under $SU(2)_L \times SU(2)_R$
    → *spontaneous symmetry breaking in the QCD ground state* (pseudo-goldstone boson: pions)

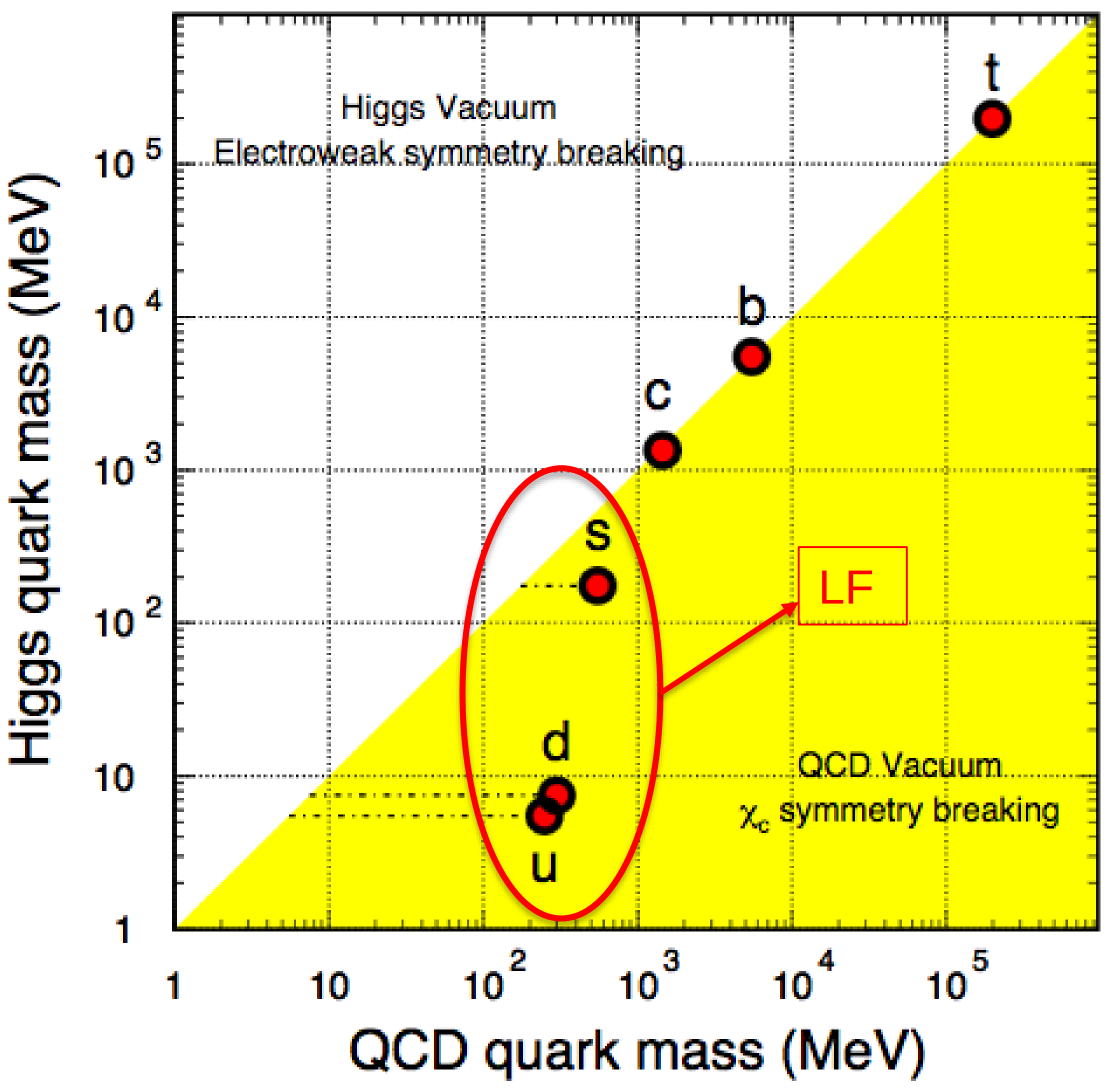
- Quarks acquire ~350MeV additional (constituent) mass
  - Only relevant for the *light* u,d,s quarks.

Spontaneous breaking of chiral symmetry

- Consequences:
  - Isospin symmetry: constituent quark masses $m_u \approx m_d$ → isospin symmetry
  - Isospin symmetry is not based on a fundamental relation, but due to the fact that the acquired masses are much larger than the bare masses
  - *m*(nucleon) >> *m*(bare u+u+d) 938 MeV >> ~10 MeV

- In the QGP, chiral symmetry is expected to be restored!

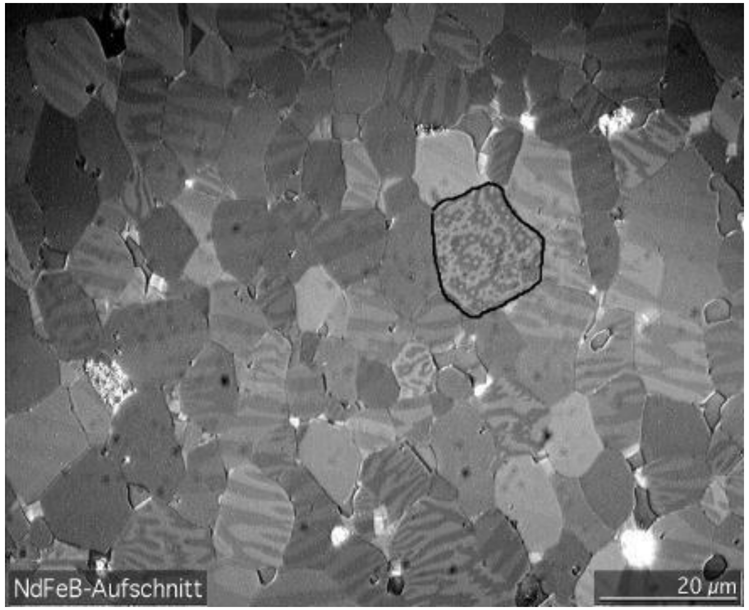
arXiv:nucl-ex/0610043

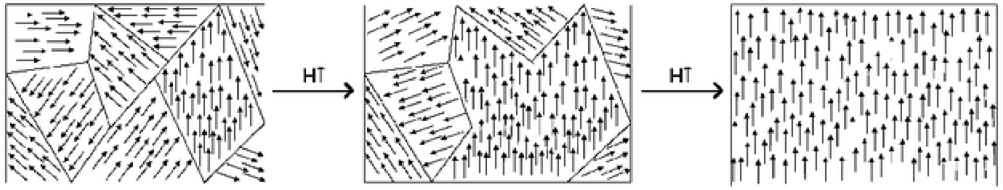


Spontaneous and explicit symmetry breaking

→ Best explained in an analogy to ferromagnetism:

QCD	Ferromagnetism
• chiral symmetry	• symmetry of $\hat{H}$ under rotations of spin axis
• quark-antiquark-condensate $<\overline{\psi}\psi>$	• magnetisation $M = <\uparrow>$
• *explicit symmetry breaking* by current mass m_{curr}	• *explicit symmetry breaking* by external magnetic field h
• *spontaneous symmetry breaking* by constituent mass m_{cons} for $T < T_C$	• *spontaneous symmetry breaking* by quantum mechanical exchange forces for $T < T_C$ (Curie temperature)





Magnetic domains

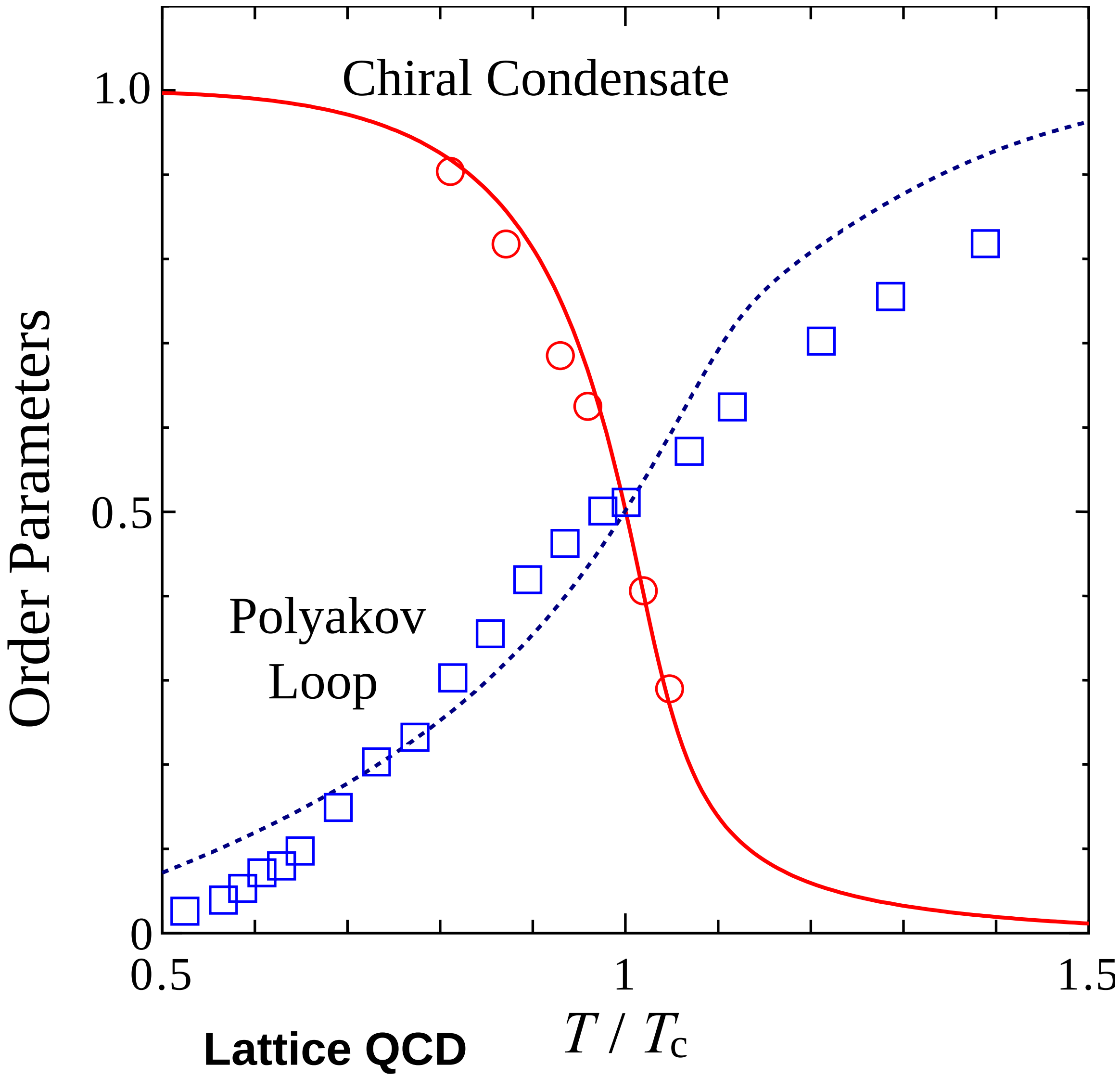
Chiral and de-confinement transition

- **Both phase transitions take place at the same temperature** in Lattice QCD (**de-confined ↔ confined** and **chiral symmetry restored ↔ chiral symmetry broken**).

- The fact that both phase transitions occur at the same temperature is not linked from first principles QCD!

  → Experimental verification: di-leptons and net-charge fluctuations (see later).

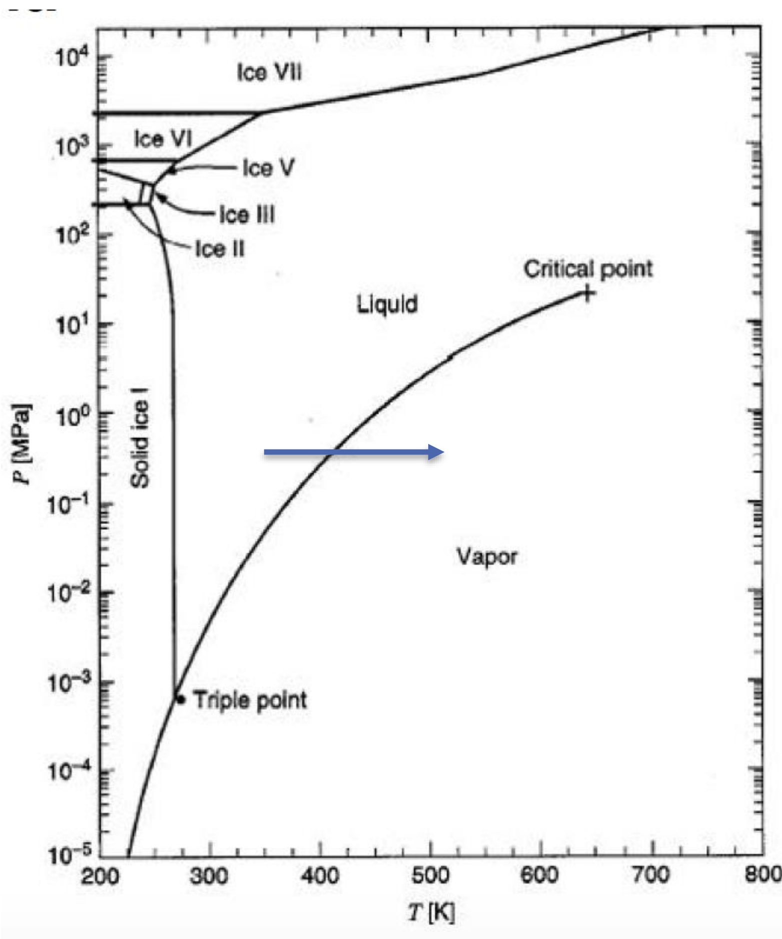
[PLB 723 (2013) 360]



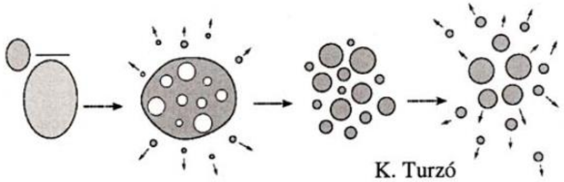
Lattice QCD

Summary: phase transitions from 0 to 10^{13} K

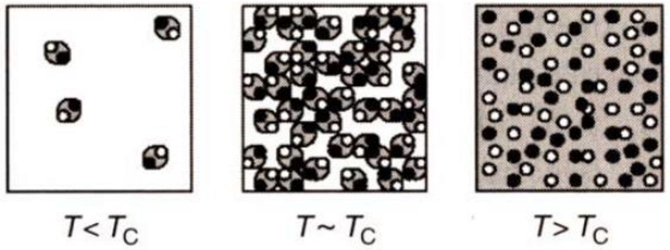
- Even in our everyday life we realise that matter comes in various forms:
  Solid → liquid → gas → plasma (*de-localisation*)
  ~0 K → ~ 273 K → ~ 373 K → ~2000K



- In our life as heavy-ion physicist, we continue further:
  - First, around T=10 MeV ($1.1 \cdot 10^{11}$K), the nucleons are not bound to nuclei anymore (low energy heavy-ion experiments at a few 100 MeV be



  - Then, at around T=156MeV ($1.8 \cdot 10^{12}$K) the (de-)confinement and chiral symmetry phase transition.

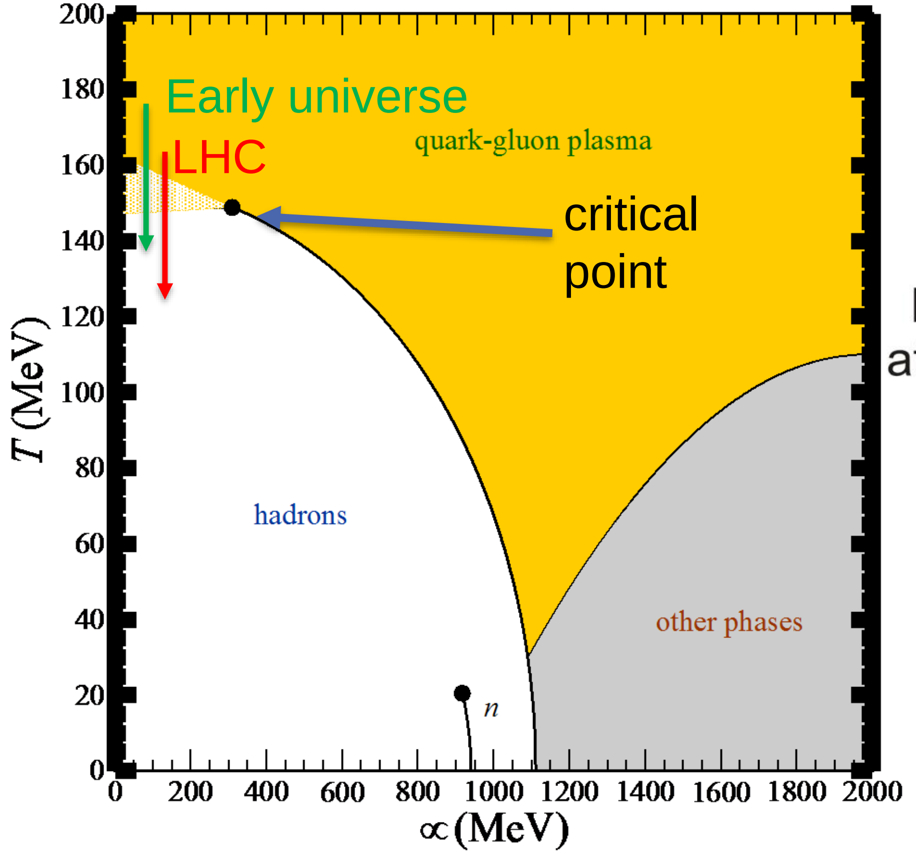


Phase transition: A phase transition is of n^{th} order if discontinuities in variations transverse to the coexistence curve occur for the first time in the n^{th} derivatives of the chemical potential (Ehrenfest defintion).

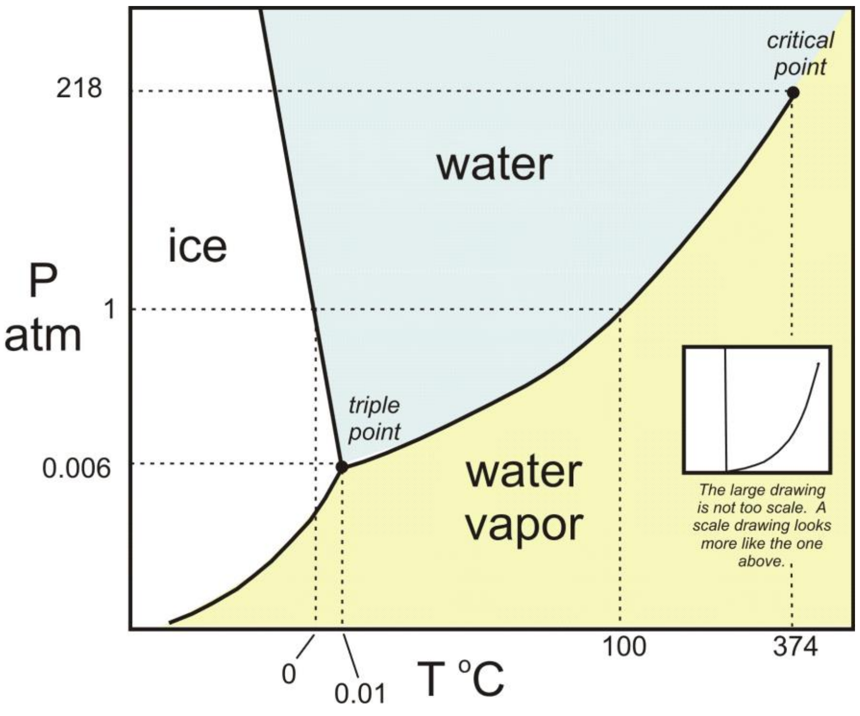
The phase diagram of QCD (1)

- The thermodynamics of QCD can be summarized in the following (schematic) phase diagram.
- Control parameters: temperature T and baryo-chemical potential μ_B.
- At LHC-energies ($\sqrt{s}$ = 5.02 TeV): $\mu_B \approx 0$ MeV << T_{ch}
- At SIS18: ($\sqrt{s}$ = 2.4 GeV): $\mu_B \approx 883$ MeV >> T_{ch}

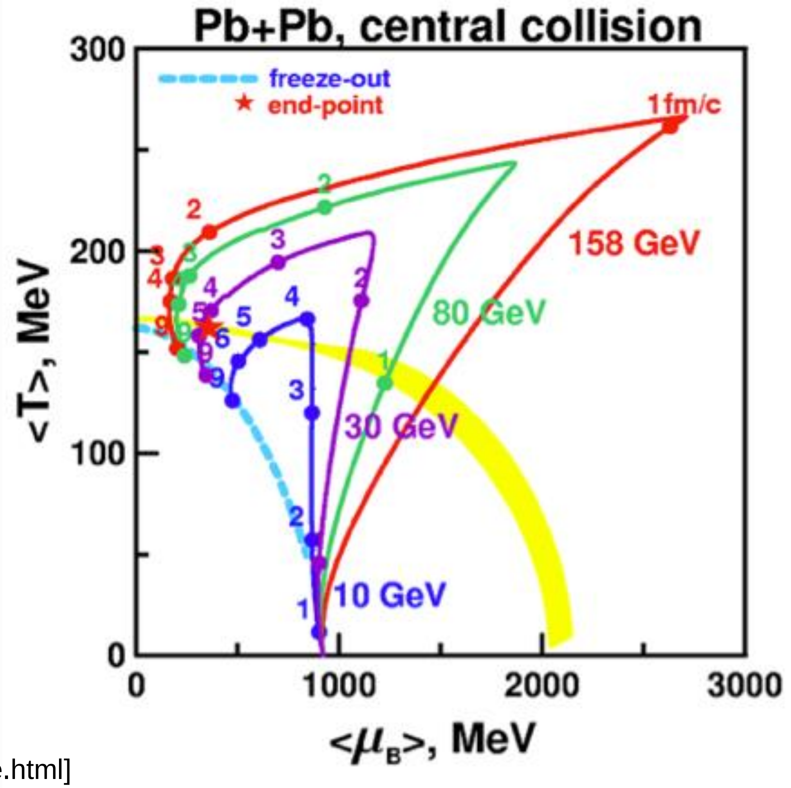
→ Different regions of the phase diagram are probed with different $\sqrt{s_{NN}}$.
=> beam energy scan (BES) at RHIC.



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



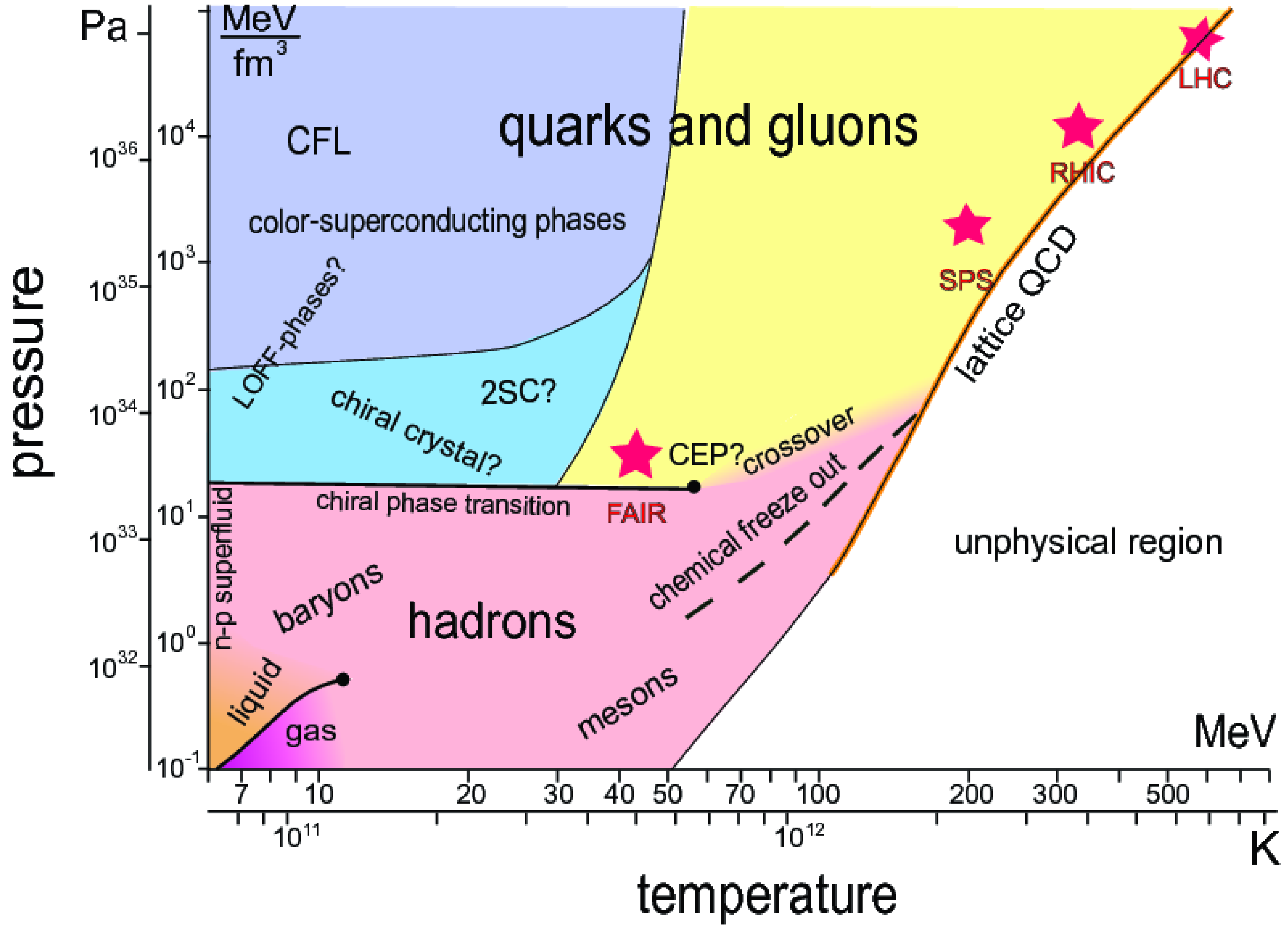
[http://serc.carleton.edu/research_education/equilibria/phaserule.html]



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

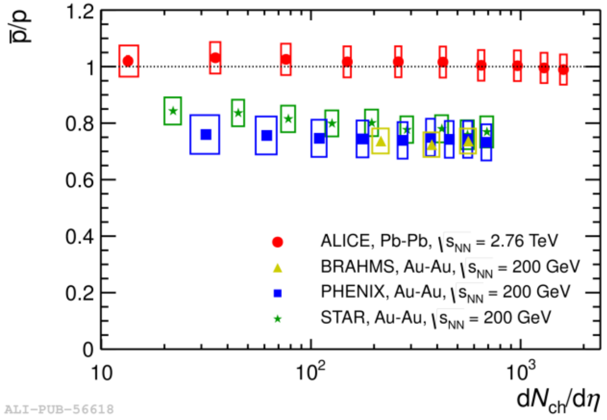
- In contrast to the (chemical freeze-out) temperature *T*, the baryochemical potential is a less intuitive quantity…
- It quantifies the net-baryon content of the system (baryon number transport to midrapidity).

fundamental thermodynamic relation

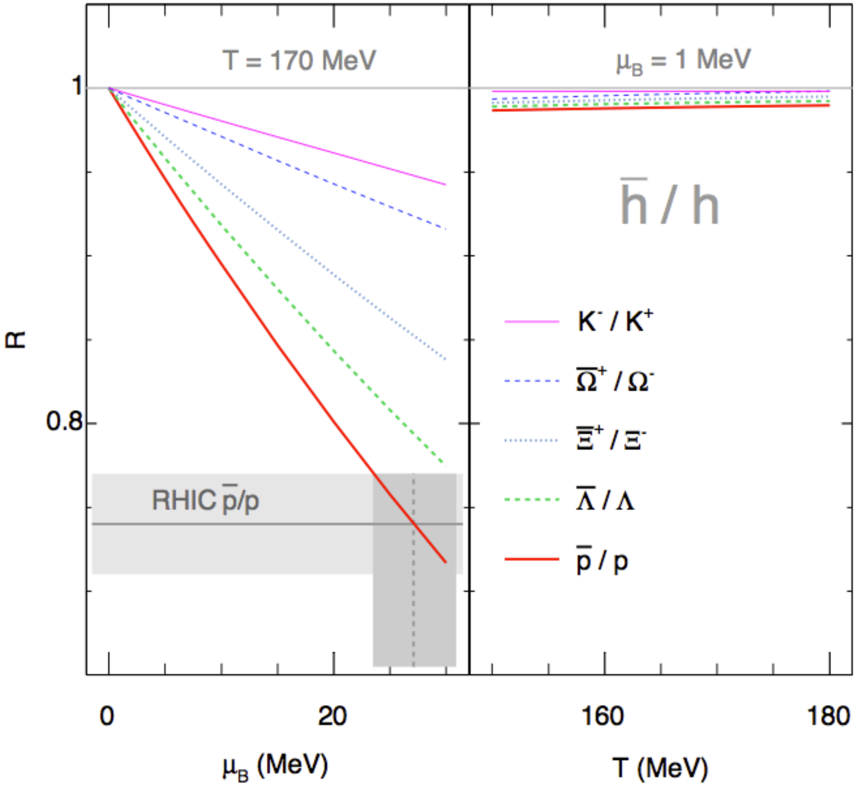
$$\mathrm{d}U = T\,\mathrm{d}S - p\,\mathrm{d}V + \Sigma \mu_i\,\mathrm{d}n_i \quad .$$

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

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



arXiv:1303.0737



(I. Kraus)

However, (anti-)nuclei are more sensitive:

$$\frac{n_{\bar{\mathrm{p}}}}{n_{\mathrm{p}}} = e^{-(2\mu_B)/T} \qquad \frac{n_{\bar{\mathrm{d}}}}{n_{\mathrm{d}}} = e^{-(4\mu_B)/T}$$

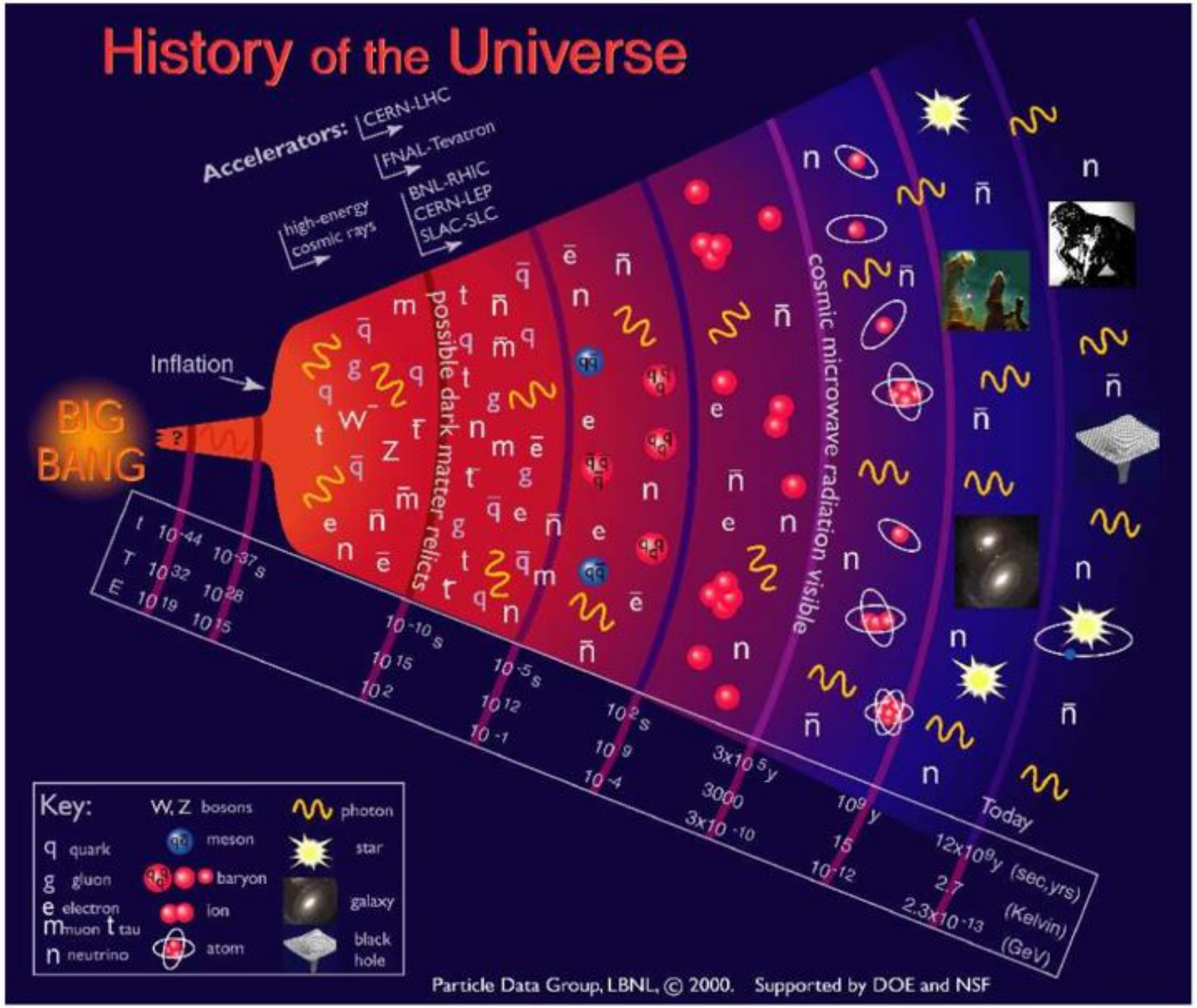
$$\frac{n_{^3\overline{\mathrm{He}}}}{n_{^3\mathrm{He}}} = e^{-(6\mu_B)/T}$$

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.

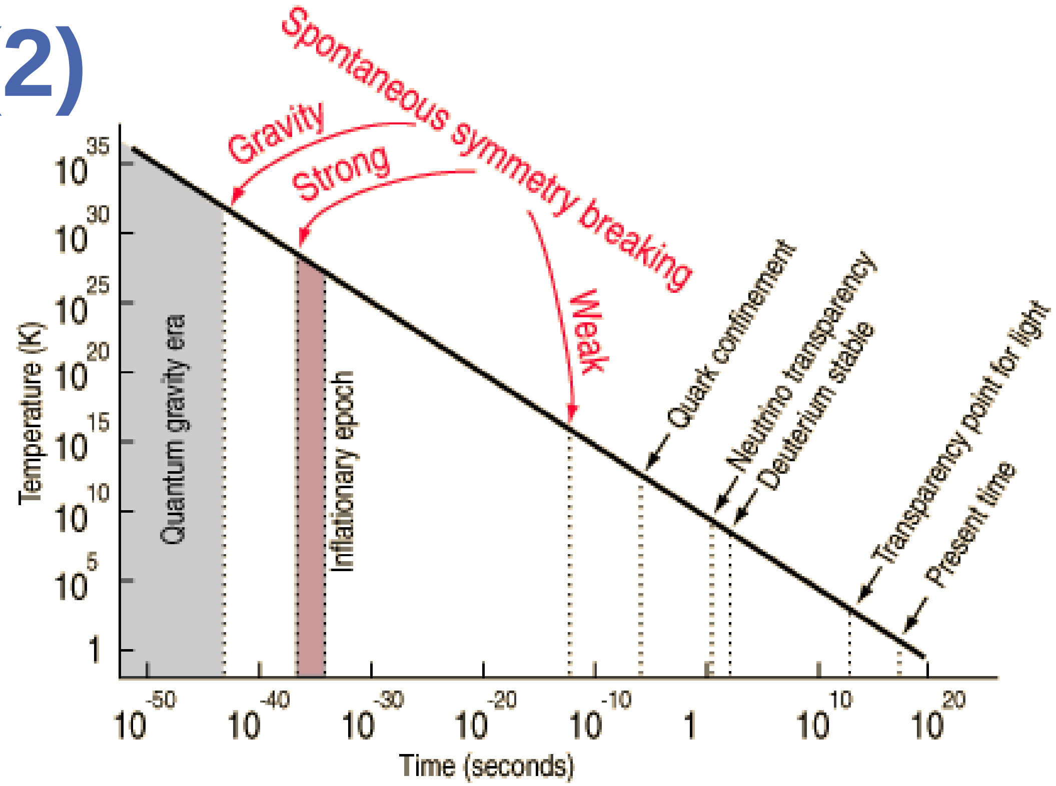
- In addition, there are similarities between the big bang (universe QGP) and the little bang (heavy-ions) concerning the **decoupling**.

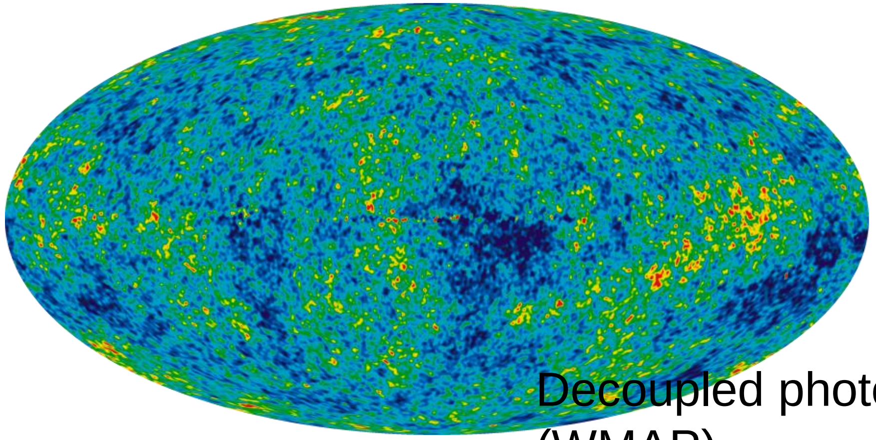


QGP and the early universe (2)

- 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



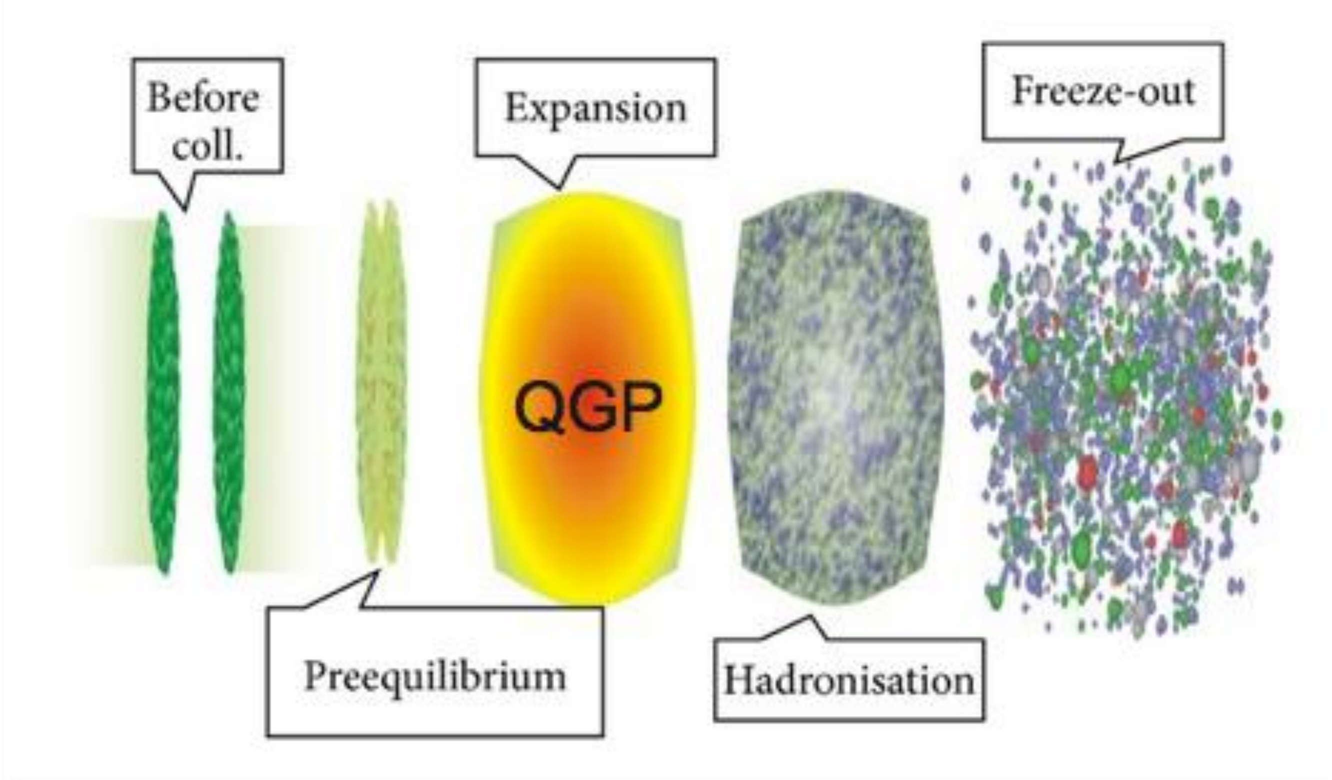


Decoupled photons (WMAP)

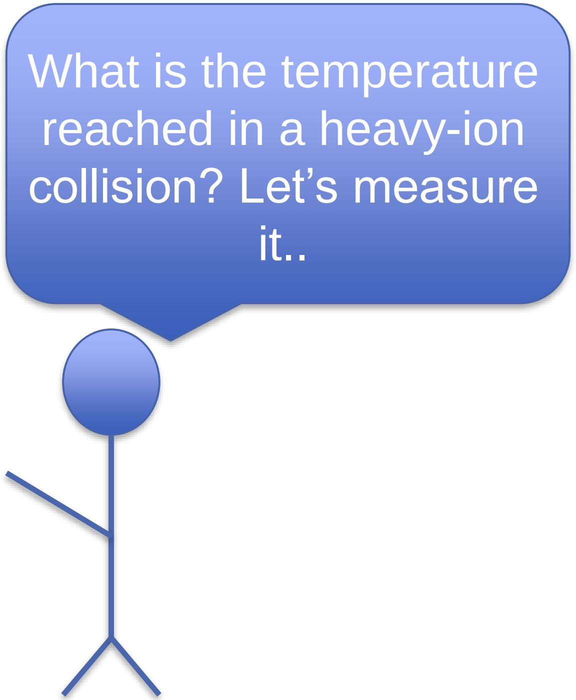
Can we reach such temperatures in the experiment?

→ We would need initial temperatures of more than 200 MeV.

→ Let's look first at a schematic evolution of a heavy-ion collision:

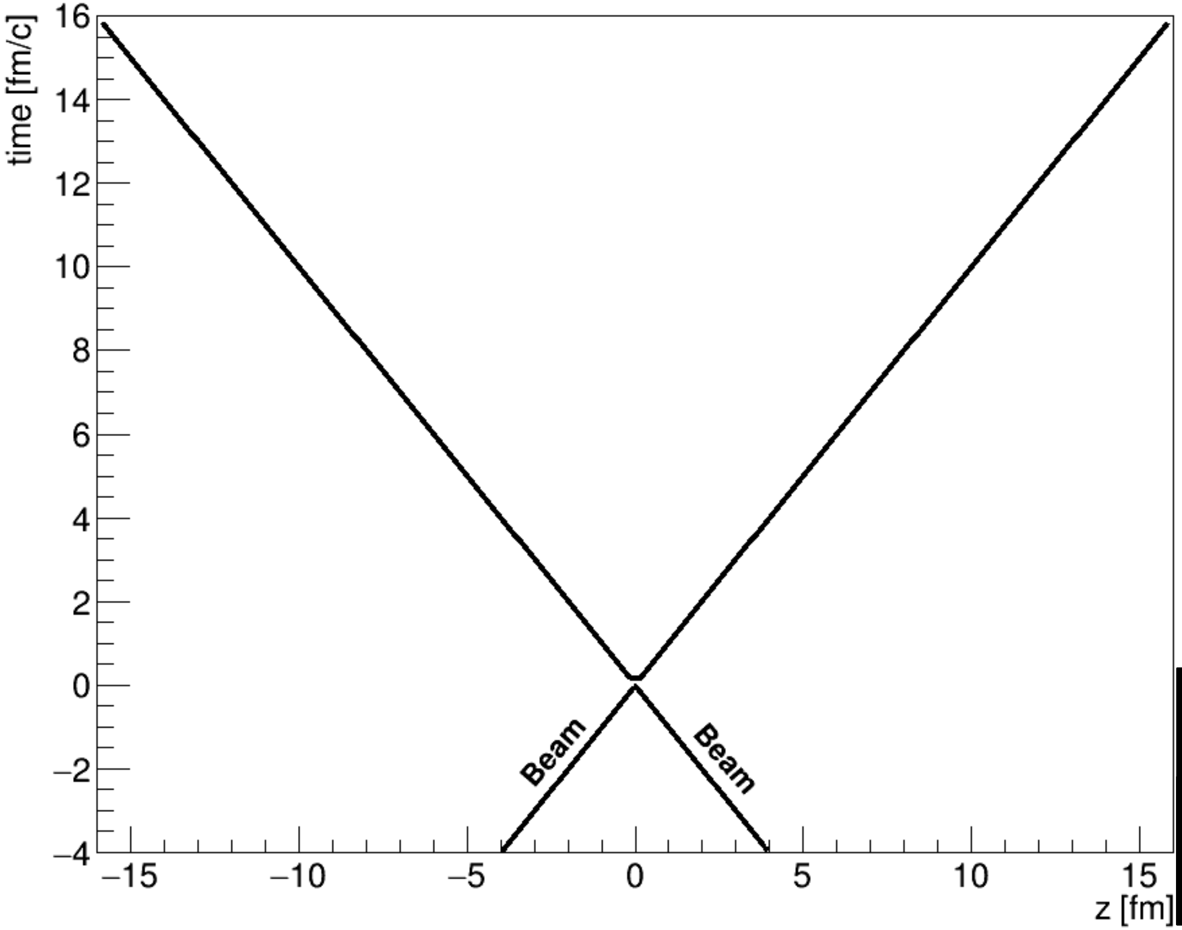


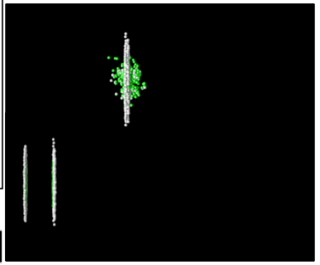
[arXiv:1207.702]



Heavy ion collision

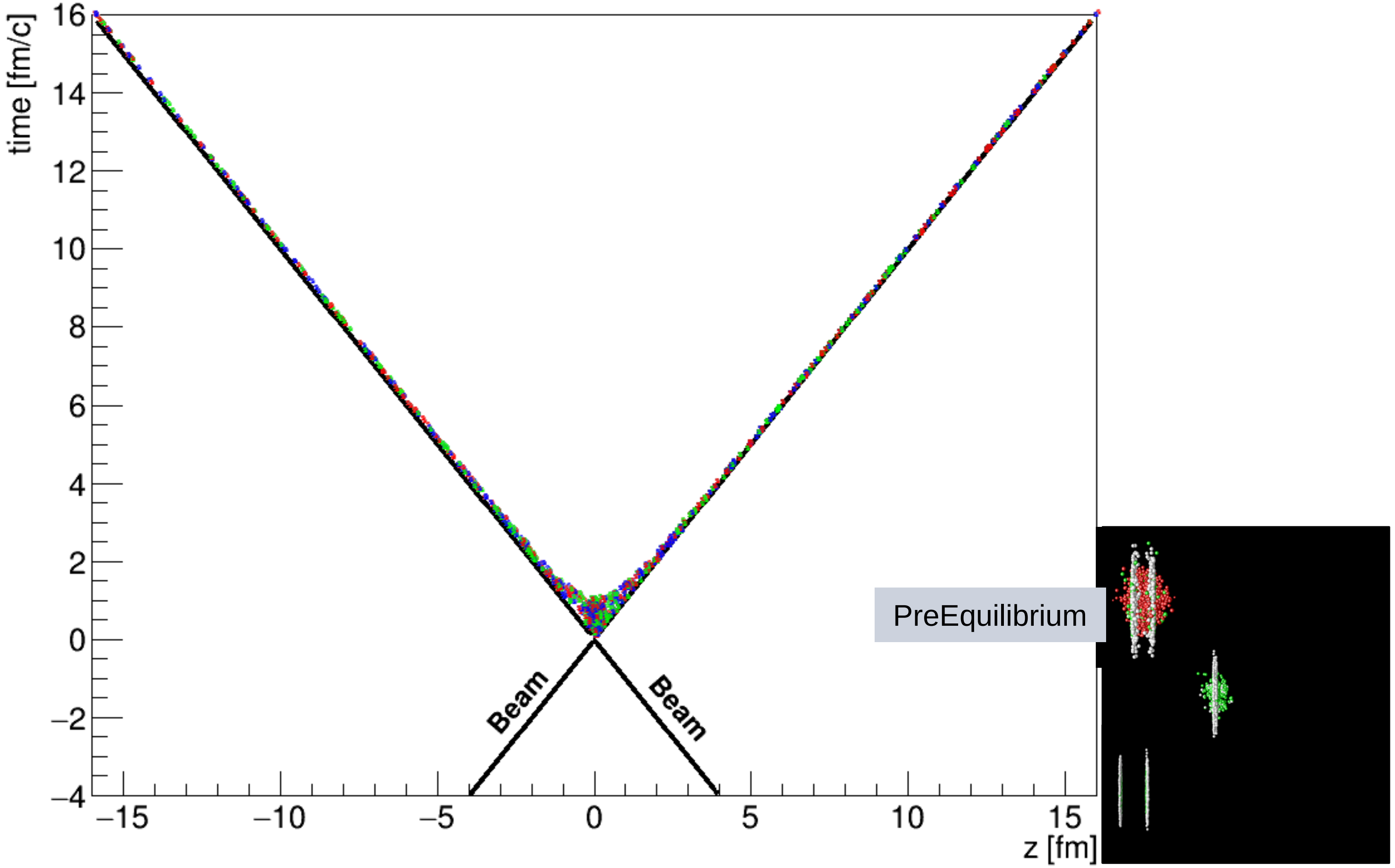
Colliding nuclei





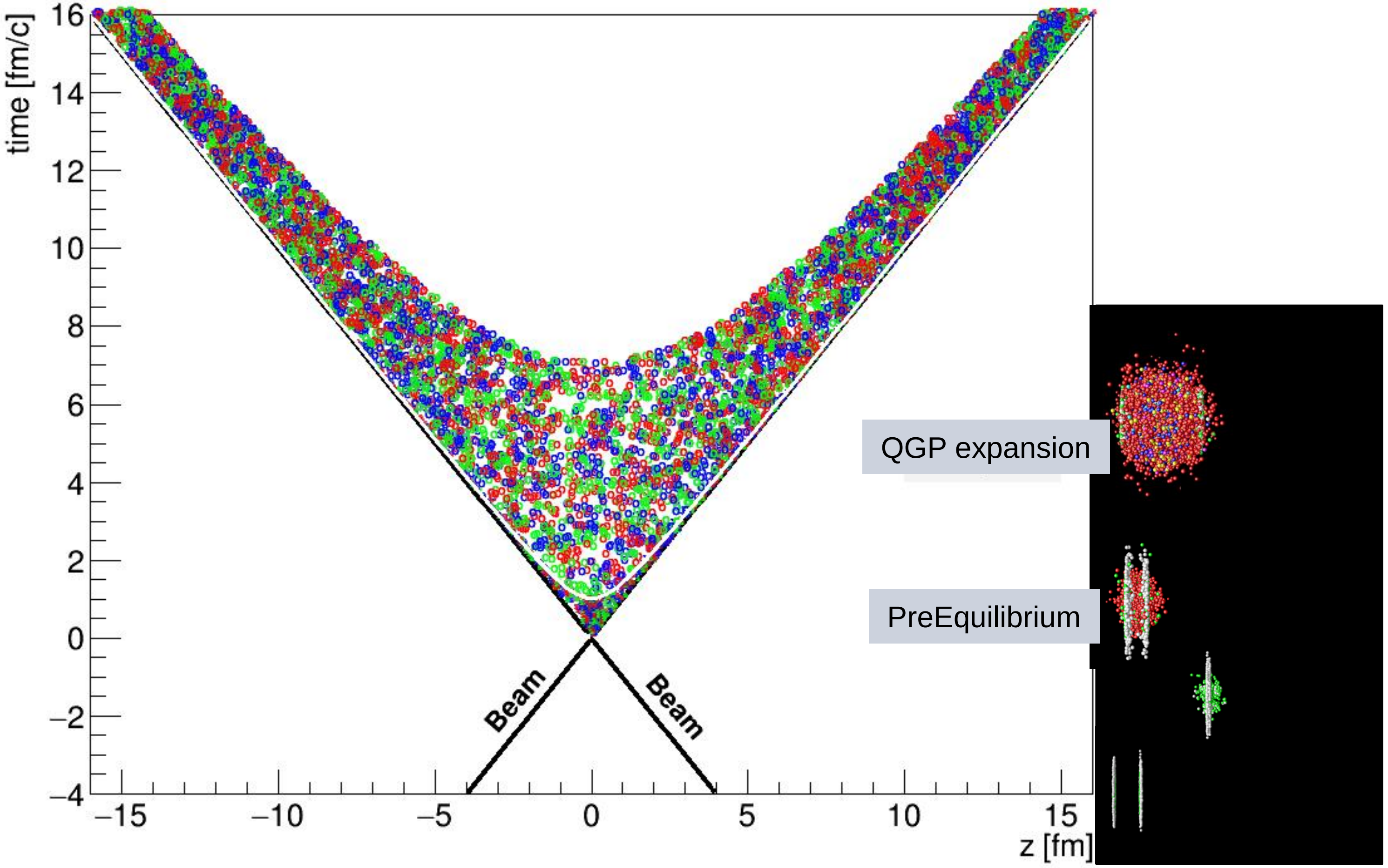
Heavy ion collision

Production of colour medium and equilibration



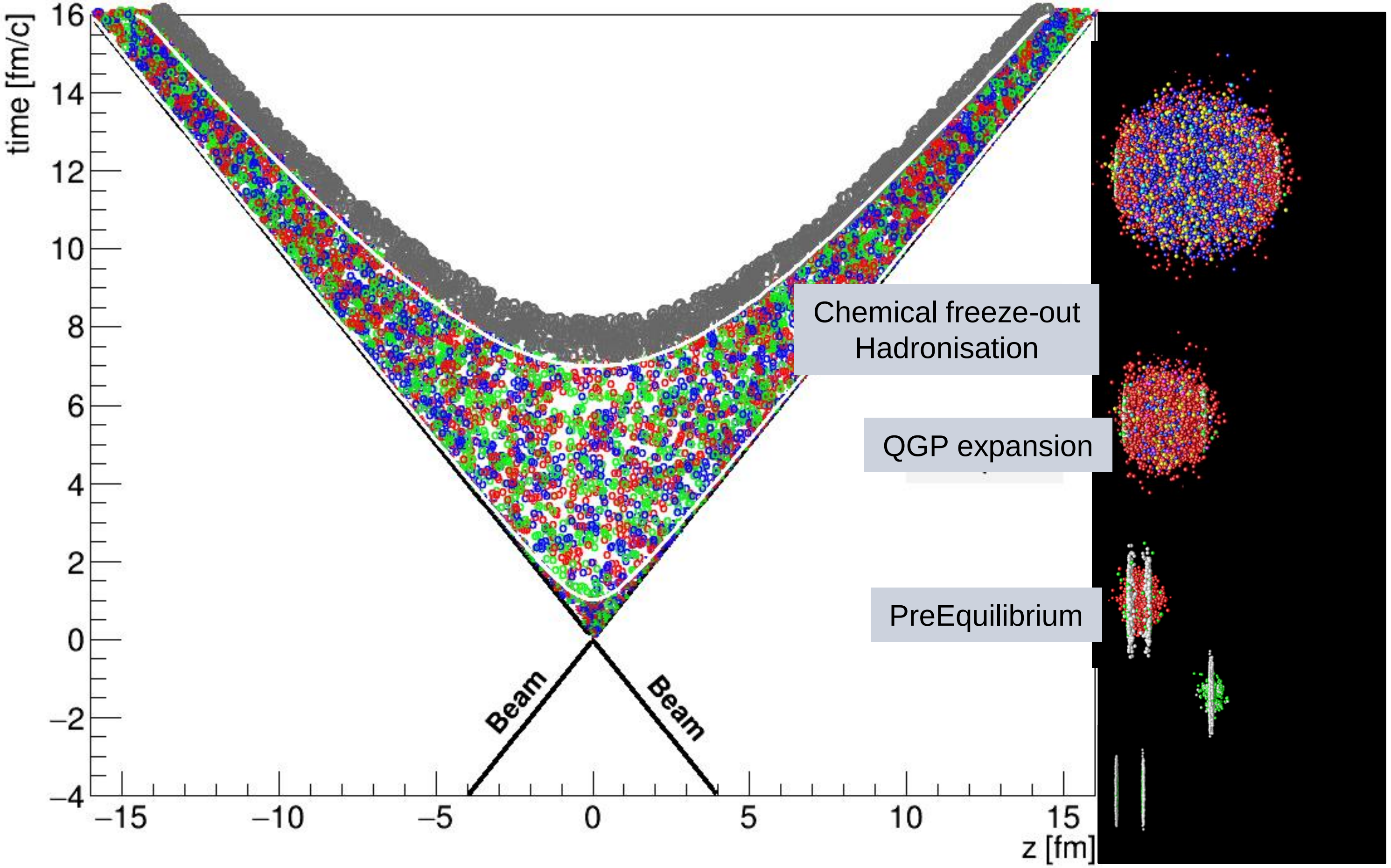
Heavy ion collision

QGP and expansion



Heavy ion collision

Hadronisation and Chemical freeze-out



Heavy ion collision

Particle detection
($t \approx 10^{15}$fm/c)

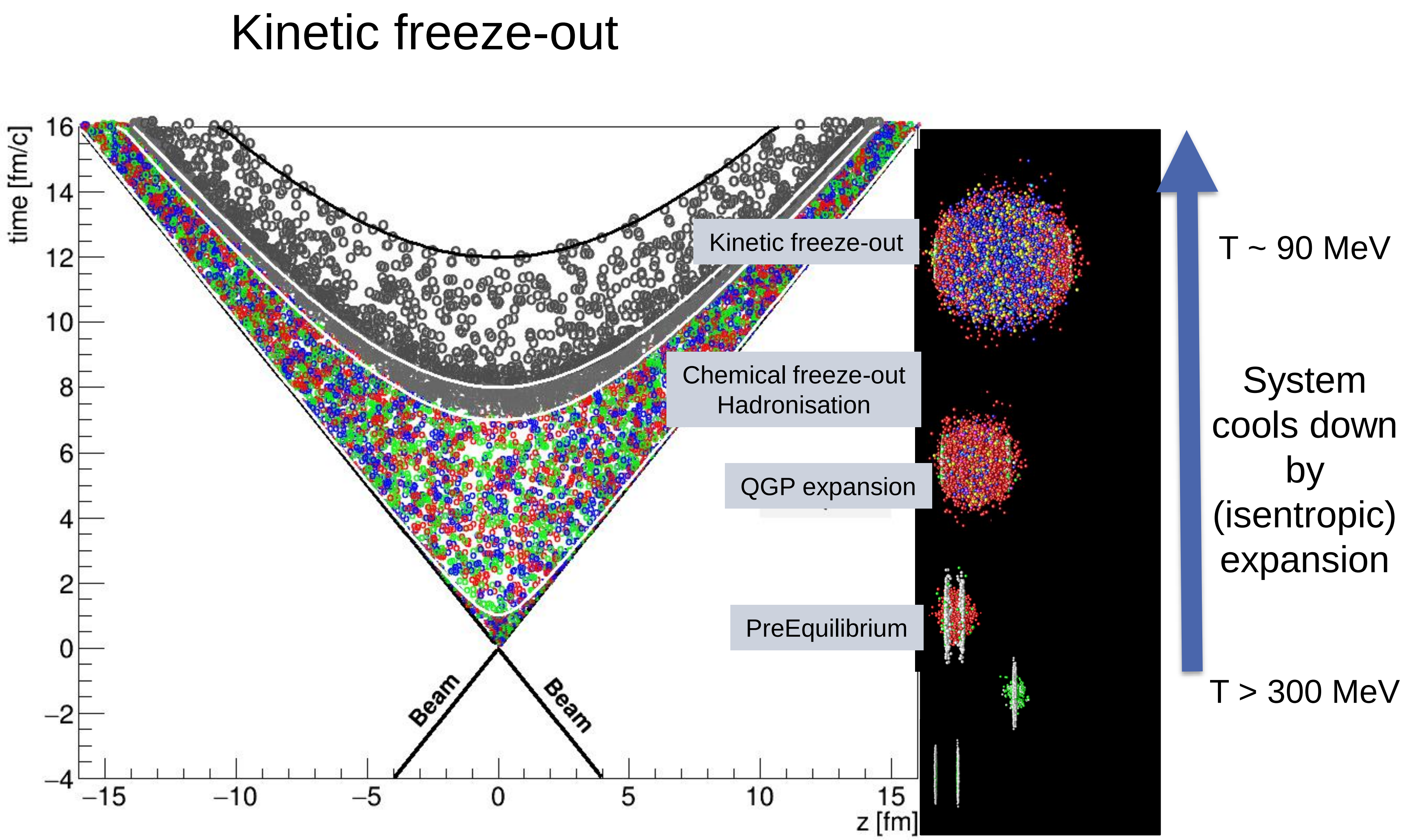
Kinetic freeze-out
(t=10fm/c)

Chemical freeze-out

Hydrodynamic
evolution (t~0.5fm/c)

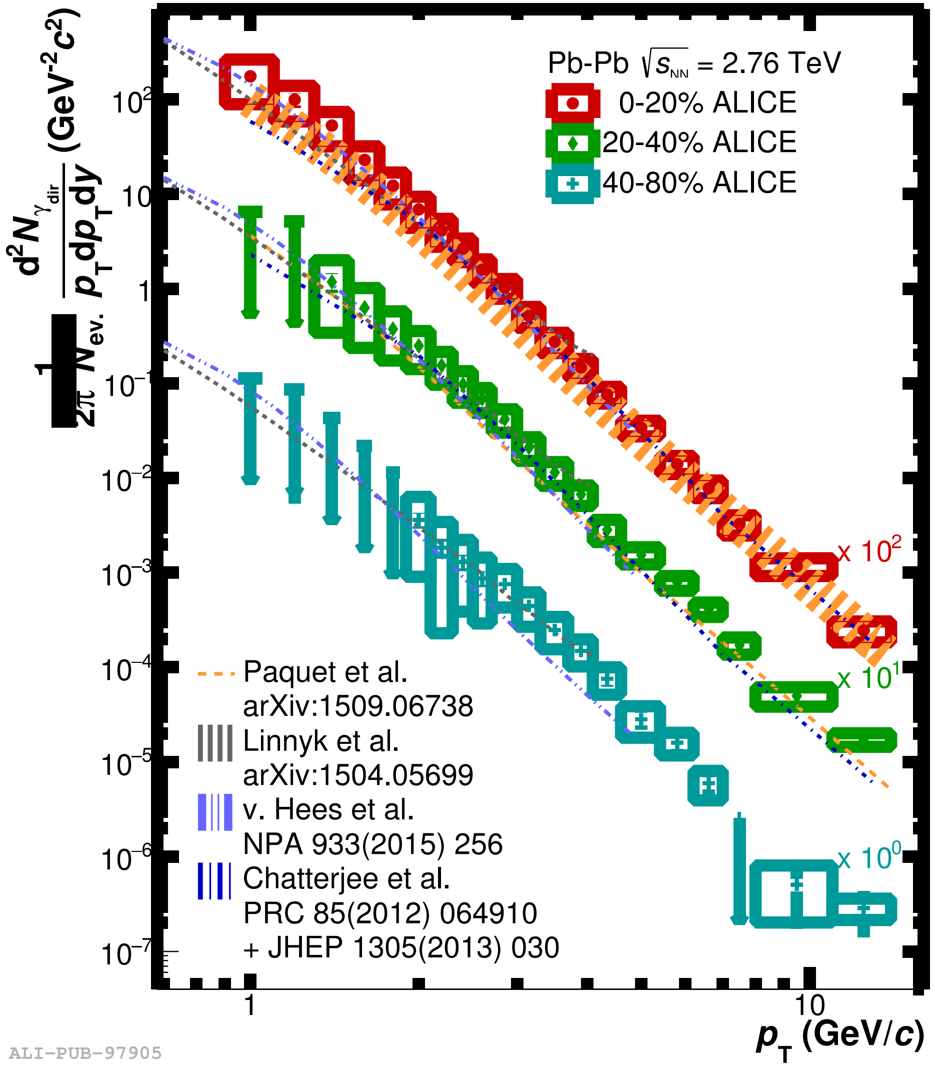
Pre-equilibrium

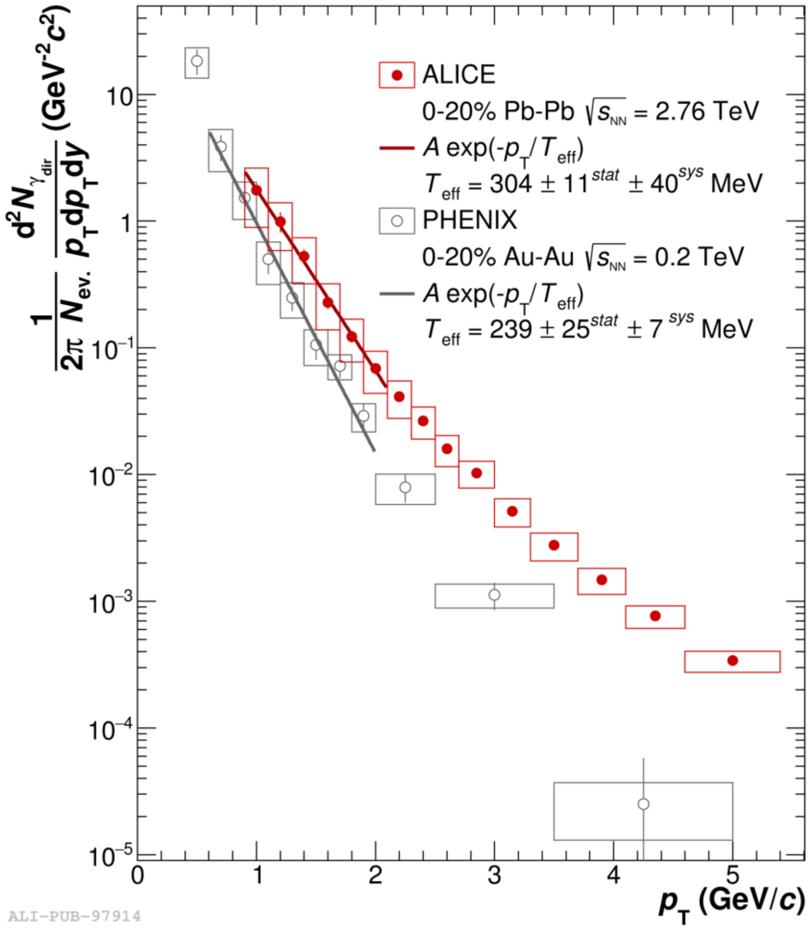
Collision (t=0fm/c)



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.

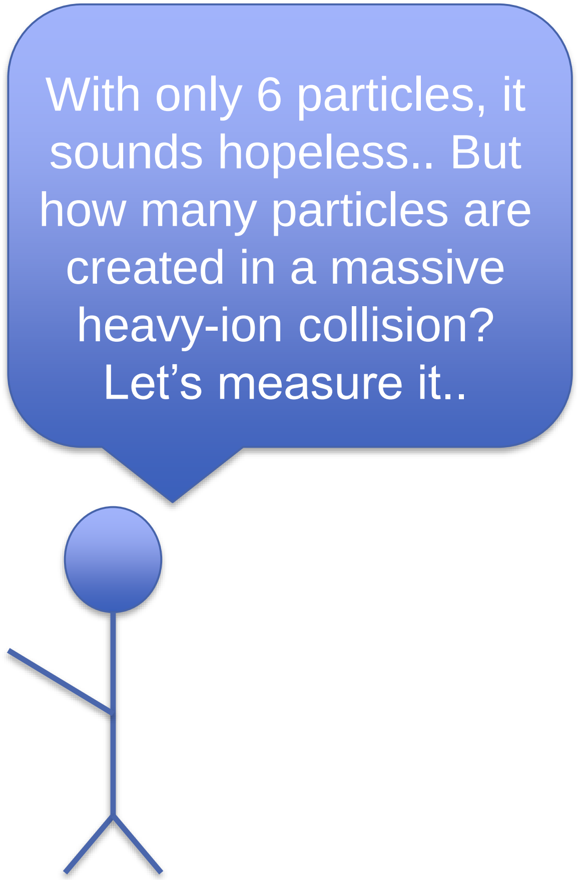
QGP thermodynamics and soft probes

Thermodynamics

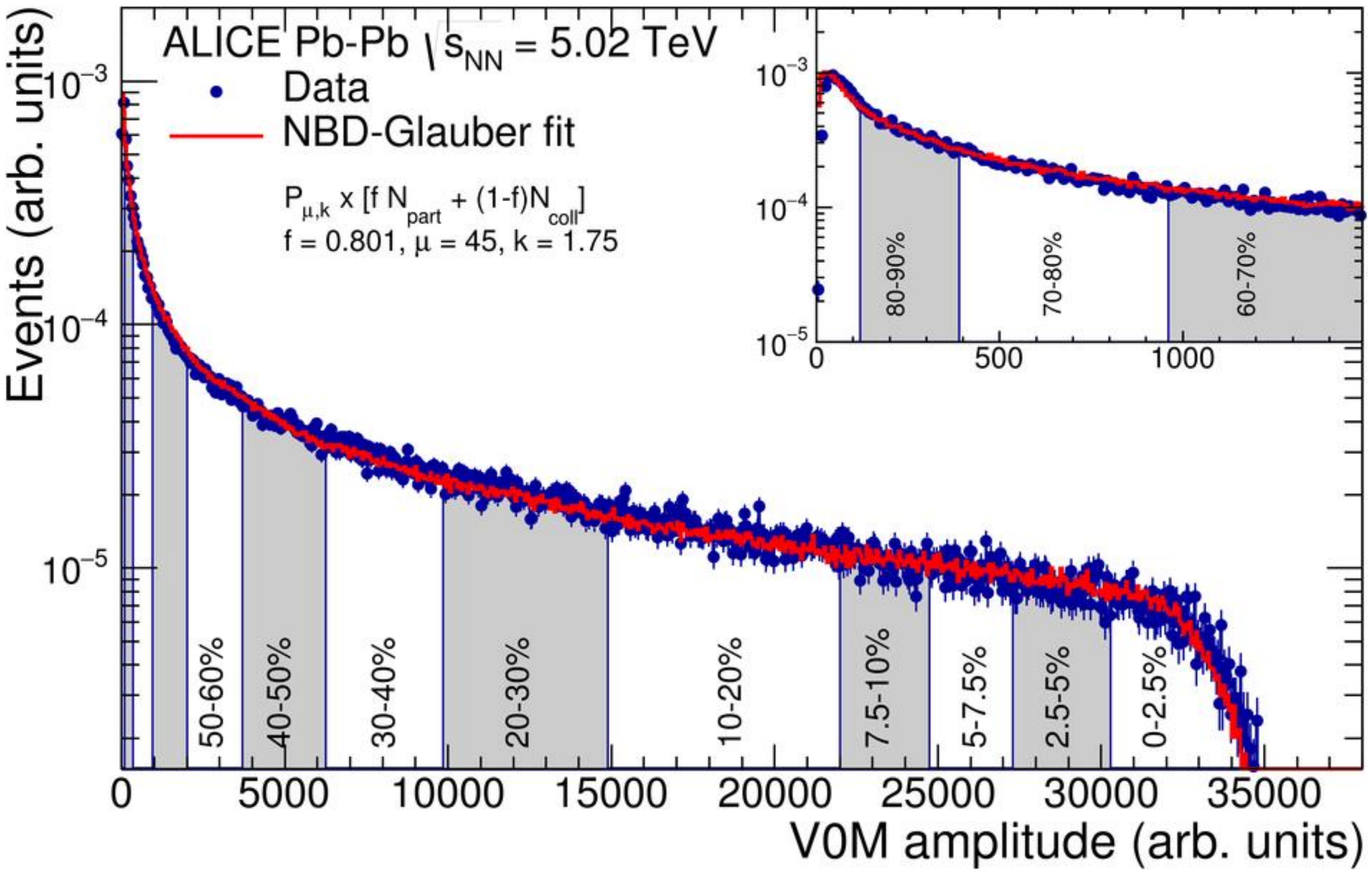
- It is important to distinguish between:
  - a system of *individual particles*
  - a ***medium*** in which individual degrees of freedom do not matter anymore and thermodynamic (hydrodynamic) concepts (many body theories) can be applied.

- Thermodynamic (hydrodynamic) are typically used for systems with 10^5-10^{23} particles in *local thermodynamic equilibrium*.
  - *Average (minimum bias)* pp collision at the LHC: $dN_{ch}/d\eta \approx 6$

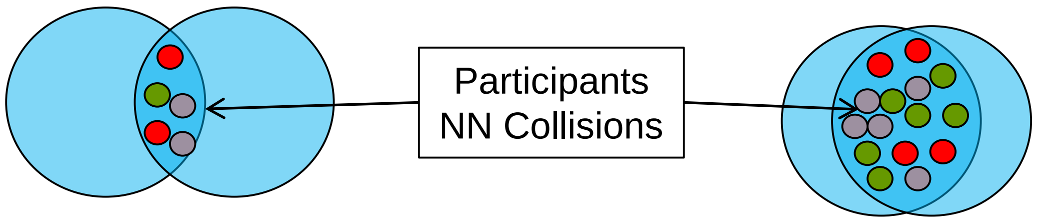
- Lifetime of the system must be long enough so that equilibrium can be established by several (simulations indicate 5-6) interactions between its constituents.



Geometry of heavy ion collisions



~ # charged particles



Centrality Variables:

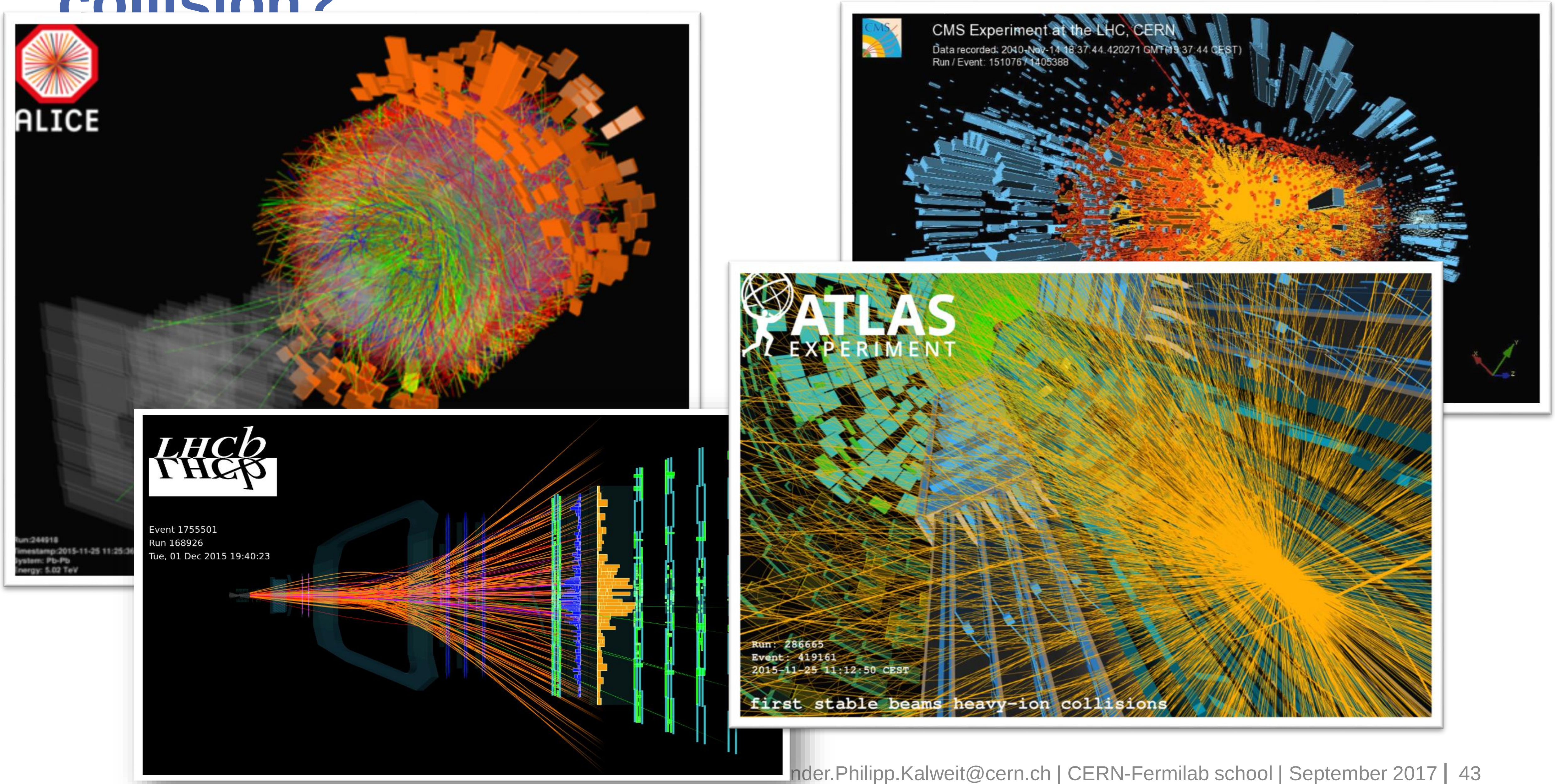
- N_{coll}: Number of nucleon-nucleon collisions
- N_{part}: Number of participating nucleons

- Percentile of hadronic cross-section:

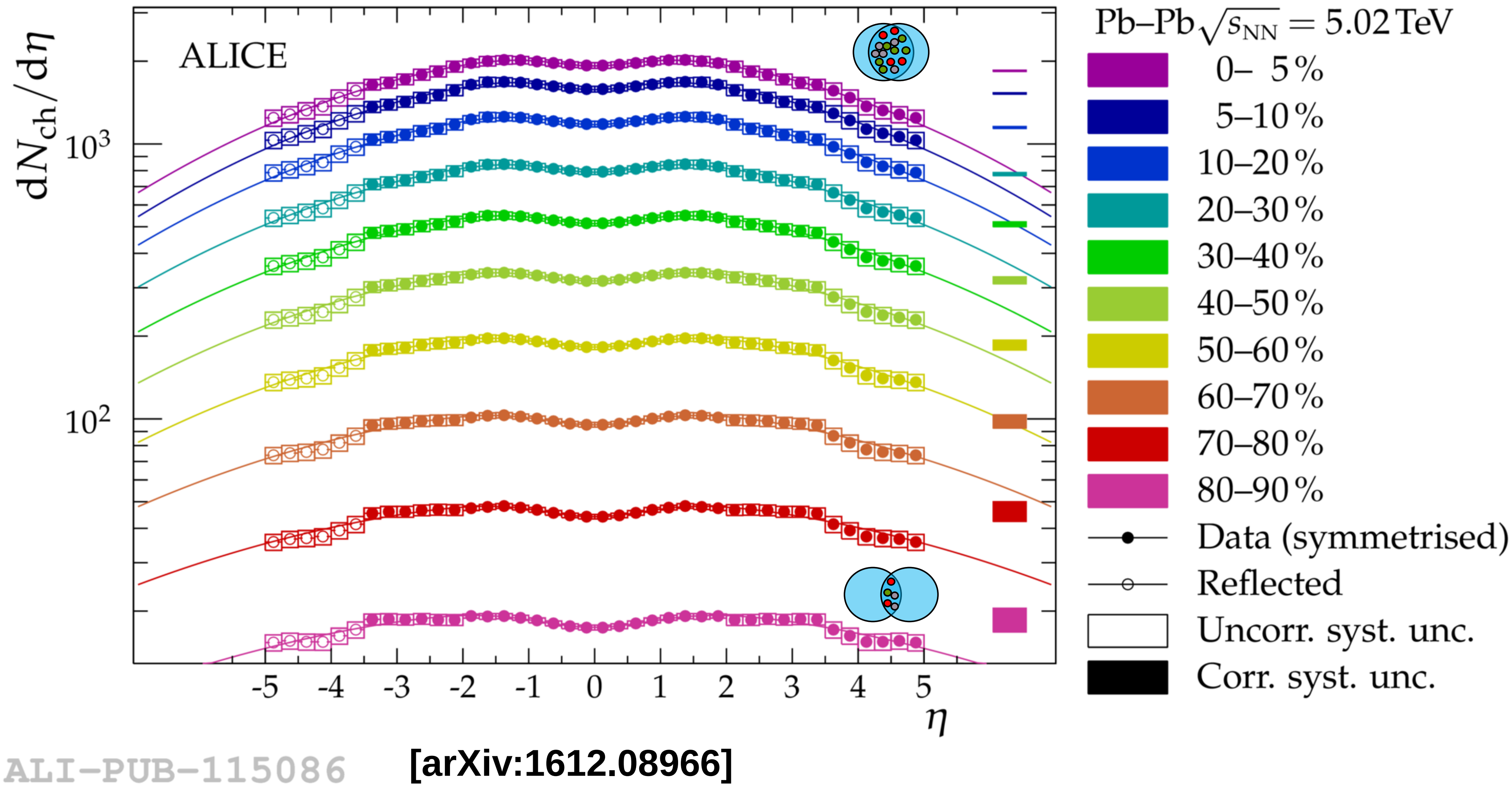
0-5% => central ("many particles")
80-90% => peripheral ("few particles")

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

How many particles are created in such a collision?



dN_{ch}/dη in 5.02 TeV Pb-Pb collisions at the LHC



[arXiv:1612.08966]

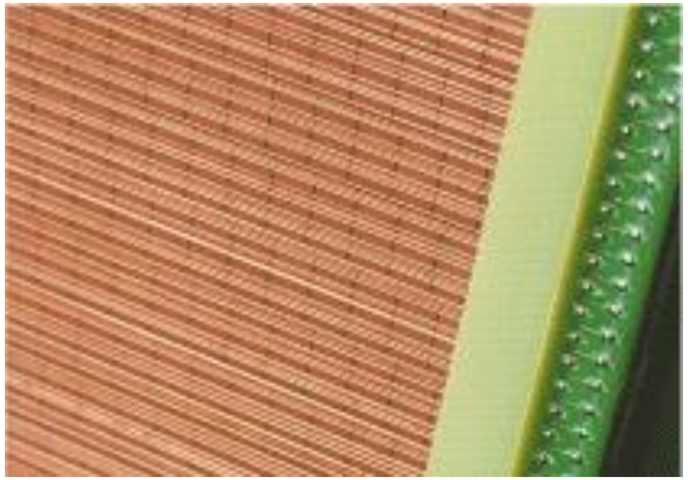
dN_{ch}/dη ≈ 1943 ± 54 at midrapidity.

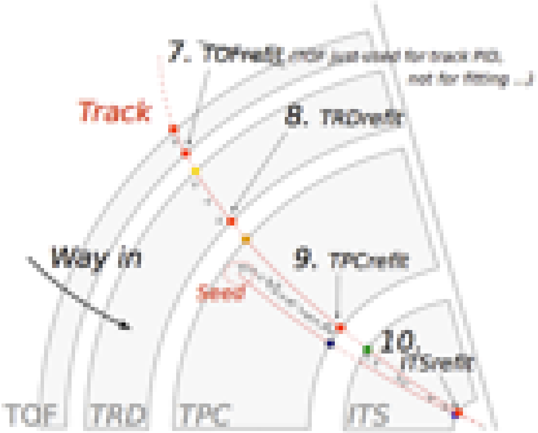
→ Even at LHC energies, 95% of all particles are produced with p_T < 2 GeV/c in pp and Pb-Pb collisions.

→ Bulk particle production and the study of collective phenomena are associated with ***"soft" physics*** in the non-perturbative regime of QCD.

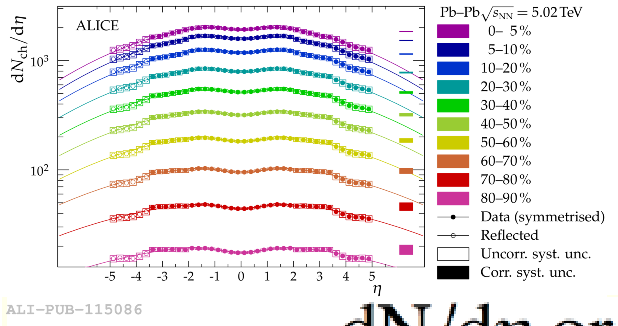
Instrumentation for heavy-ion experiments: granularity

- In order to cope with the high density of particles, heavy-ion detectors have to be very granular (e.g. large TPC with small read-out pads).
- Track seeding typically in outer detectors (where track density is lower) and then Kalman filter propagation to the primary vertex.

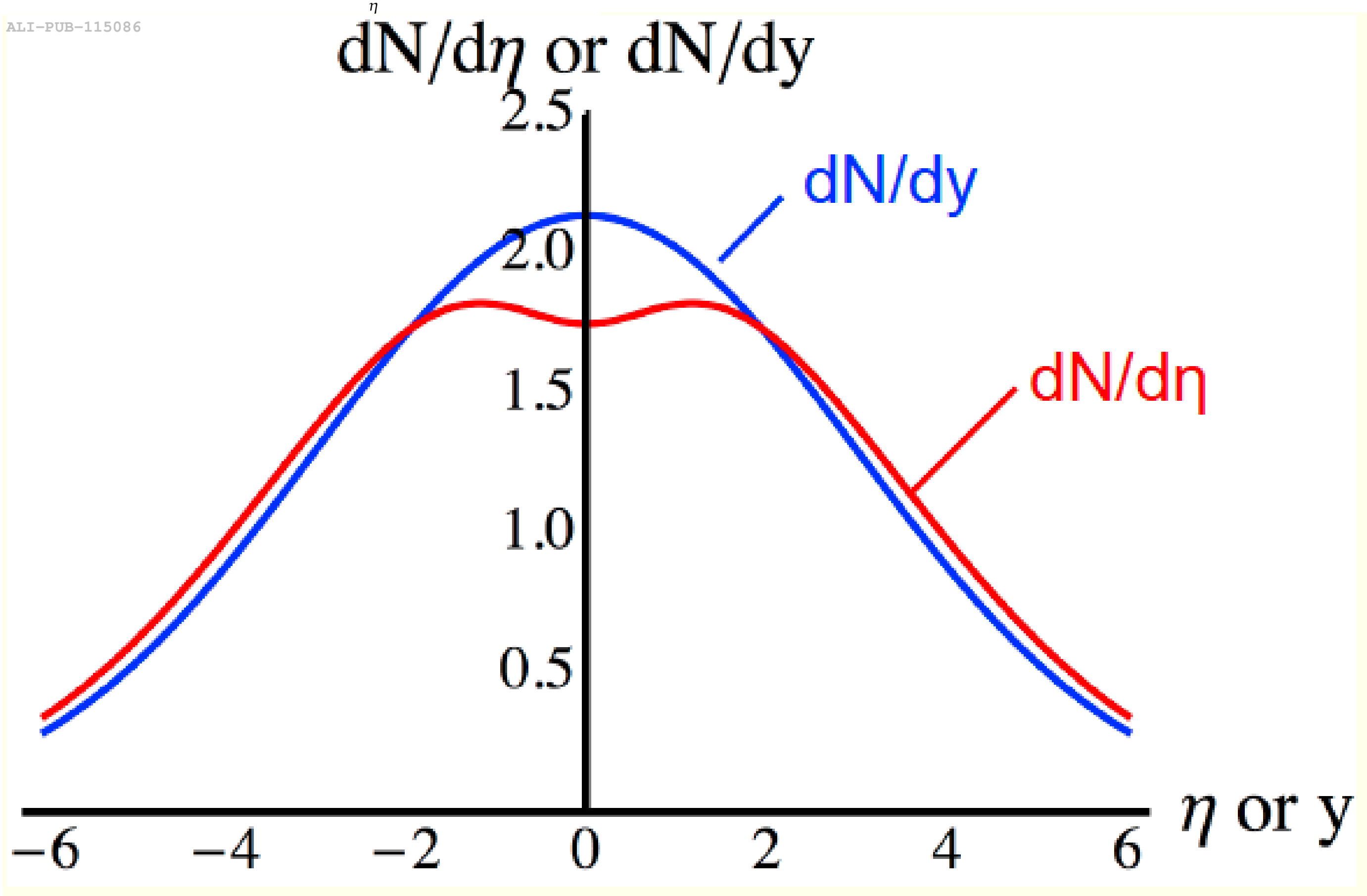




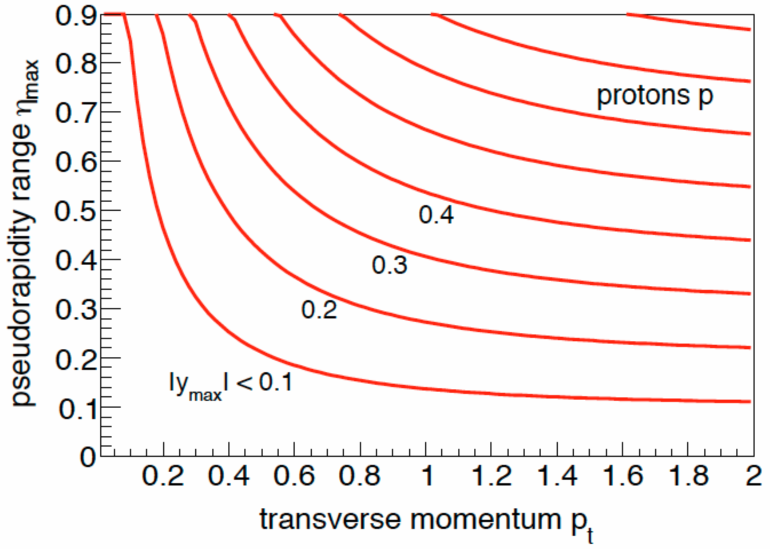
Short reminder: (Pseudo-)rapidity



$$\frac{dN}{d\eta} = \sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}} \frac{dN}{dy}$$



→ Always keep in mind: Rapidity and pseudo-rapidity are not the same, especially at low transverse momenta!

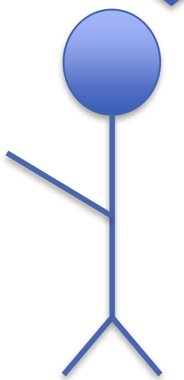


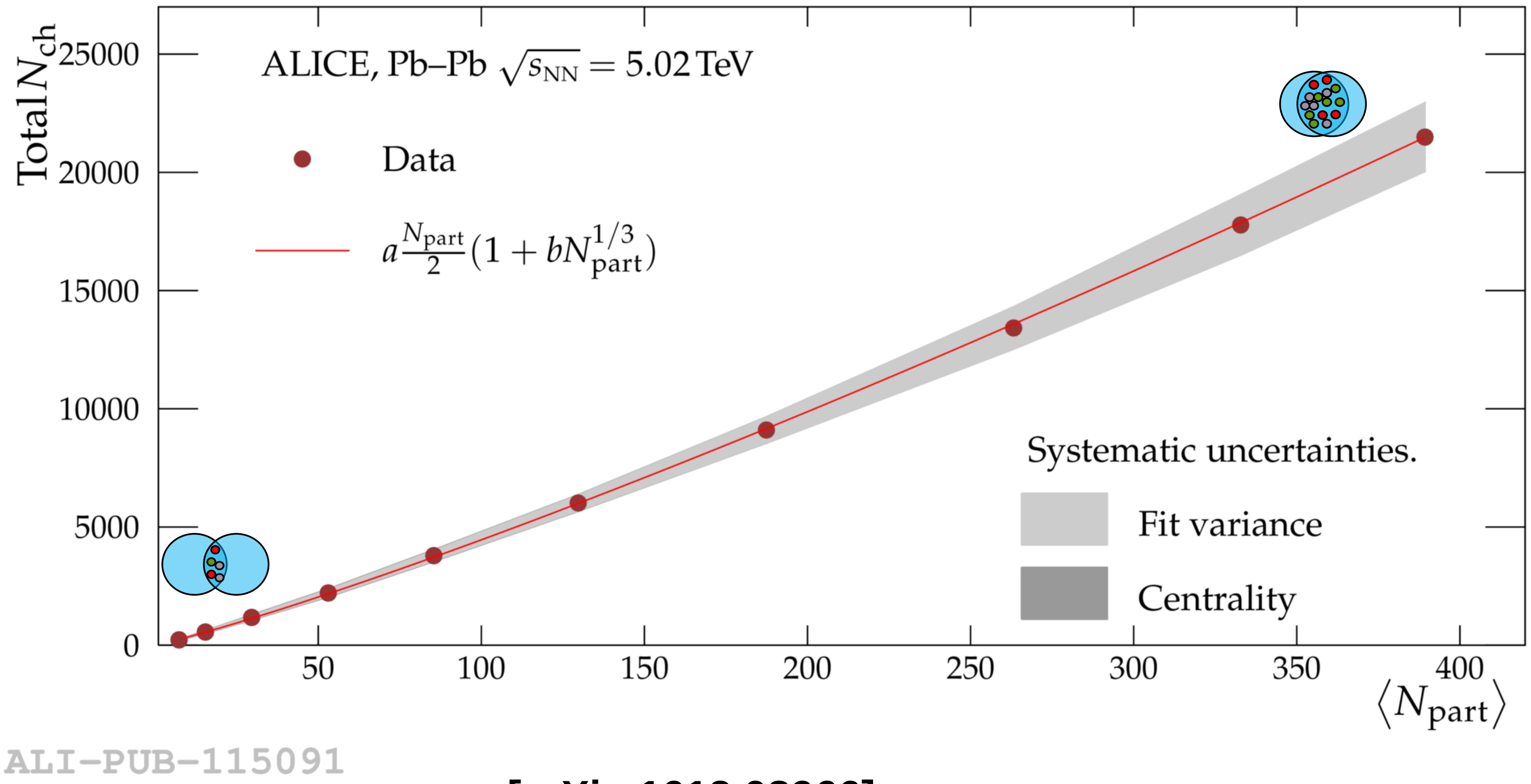
From: K. Reygers

Total number of charged hadrons in Pb-Pb collisions

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

So, we have enough particles, but are they in local thermodynamic equilibrium? How can we test that?





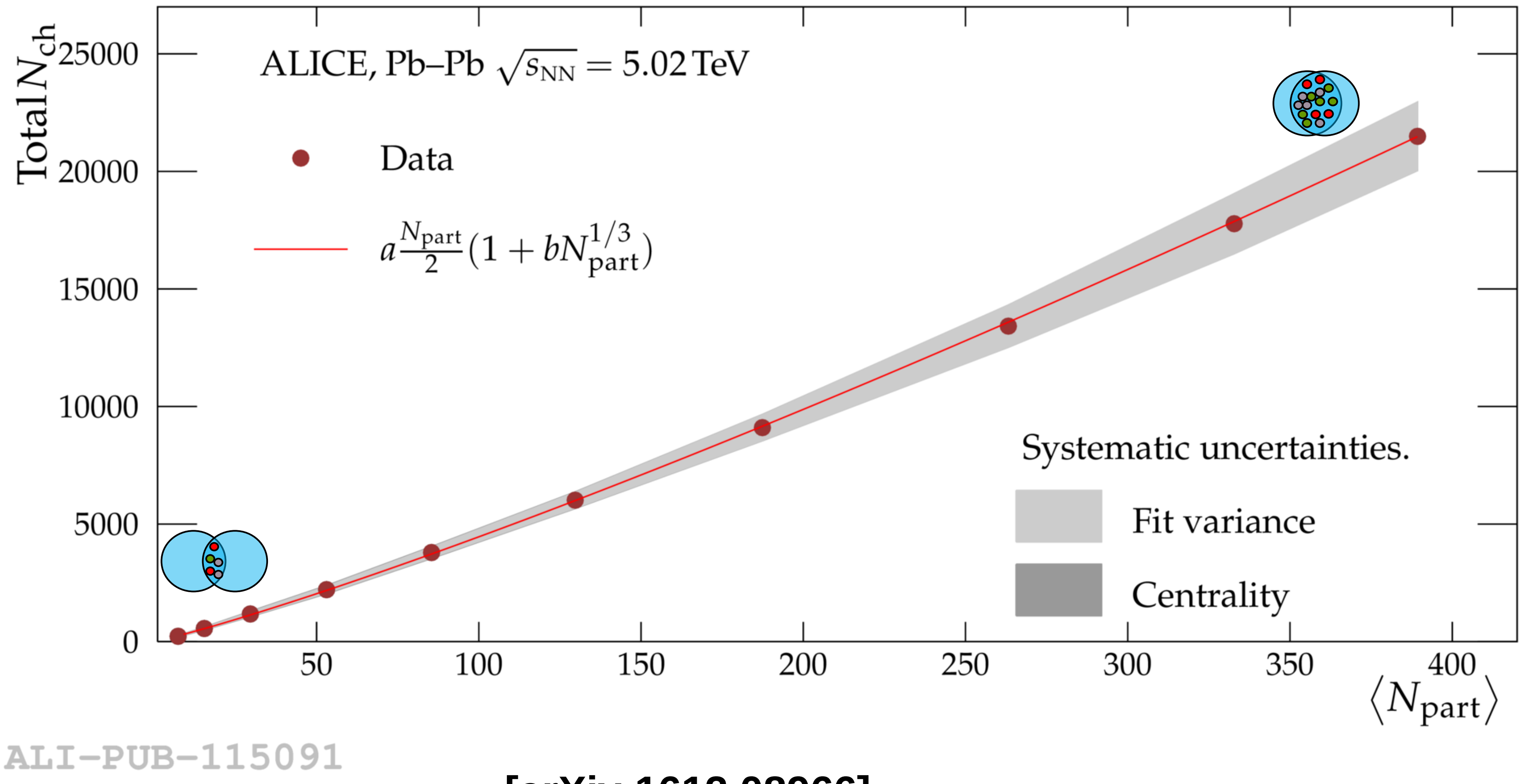
[arXiv:1612.08966]

Total number of charged hadrons in Pb-Pb collisions

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

Success of **hydro models** describing **spectral shapes and azimuthal anisotropies** supports idea of matter in local thermal equilibrium (*kinetic*).

Success of **thermal models** describing **yields of hadrons composed of up, down, and strange quarks** supports idea of matter in local thermal equilibrium (*chemical*).



[arXiv:1612.08966]

Equilibrium models such as hydro typically need 5-6 interactions to work. Where does this picture break down? Does it work in pp and pPb? → **What is the smallest possible QGP droplet?**

A short introduction to statistical thermodynamics (1)

- The **maximum entropy principle** leads to the thermal most likely distribution of particle species.

- Entropy: the number of possible micro-states Ω being compatible with a macro-state for a given set of macroscopic variables (*E*, *V*, *N*):

$$S = k_B \cdot \ln\Omega$$

- Compatibility to a given macroscopic state can be realized *exactly* or *only in the statistical mean*.

L. Boltzmann

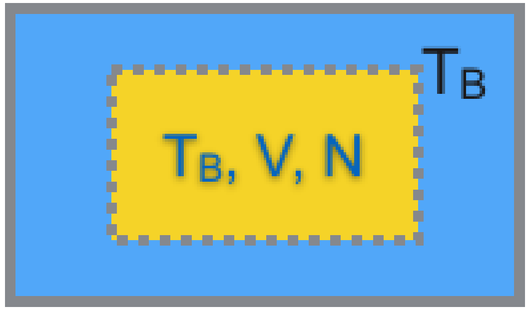
A short introduction to statistical thermodynamics (2)

- We therefore distinguish three different *statistical ensembles*:

  (i) micro-canonical: *E*, *V*, *N* fix

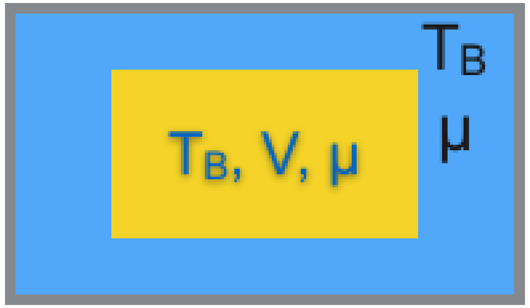
Statistical model for e^+e^- collisions.

  (ii) canonical: *T*, *V*, *N* fix
  ➔ given volume element is coupled to a heat bath



Strangeness conservation in peripheral HI collisions.

  (iii) grand-canonical: *T*, *V*, *μ* fix
  ➔ given volume element can also exchange particles with its surrounding (heat bath and particle reservoir)



Central relativistic heavy-ion collisions.

A short introduction to statistical thermodynamics (3)

- 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):

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

QGP thermodynamics and soft probes

Particle chemistry

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!):

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

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

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

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

spin degeneracy

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

chemical potential representing each conserved quantity

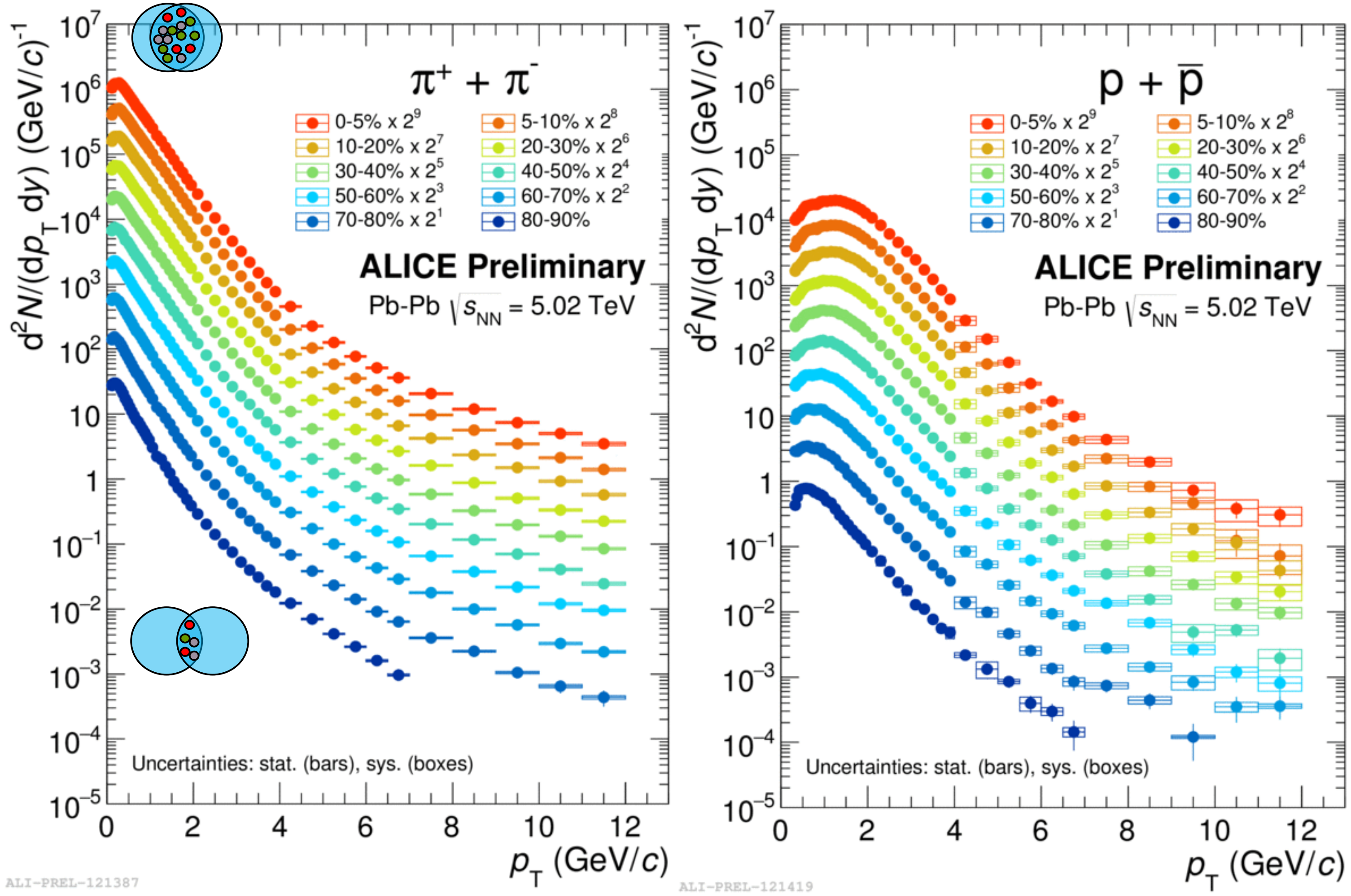
Only two free parameters are needed: (T, μ_B). Volume cancels if particle ratios n_i / n_j are calculated. If yields are fitted, it acts as the third free parameter.

- 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.

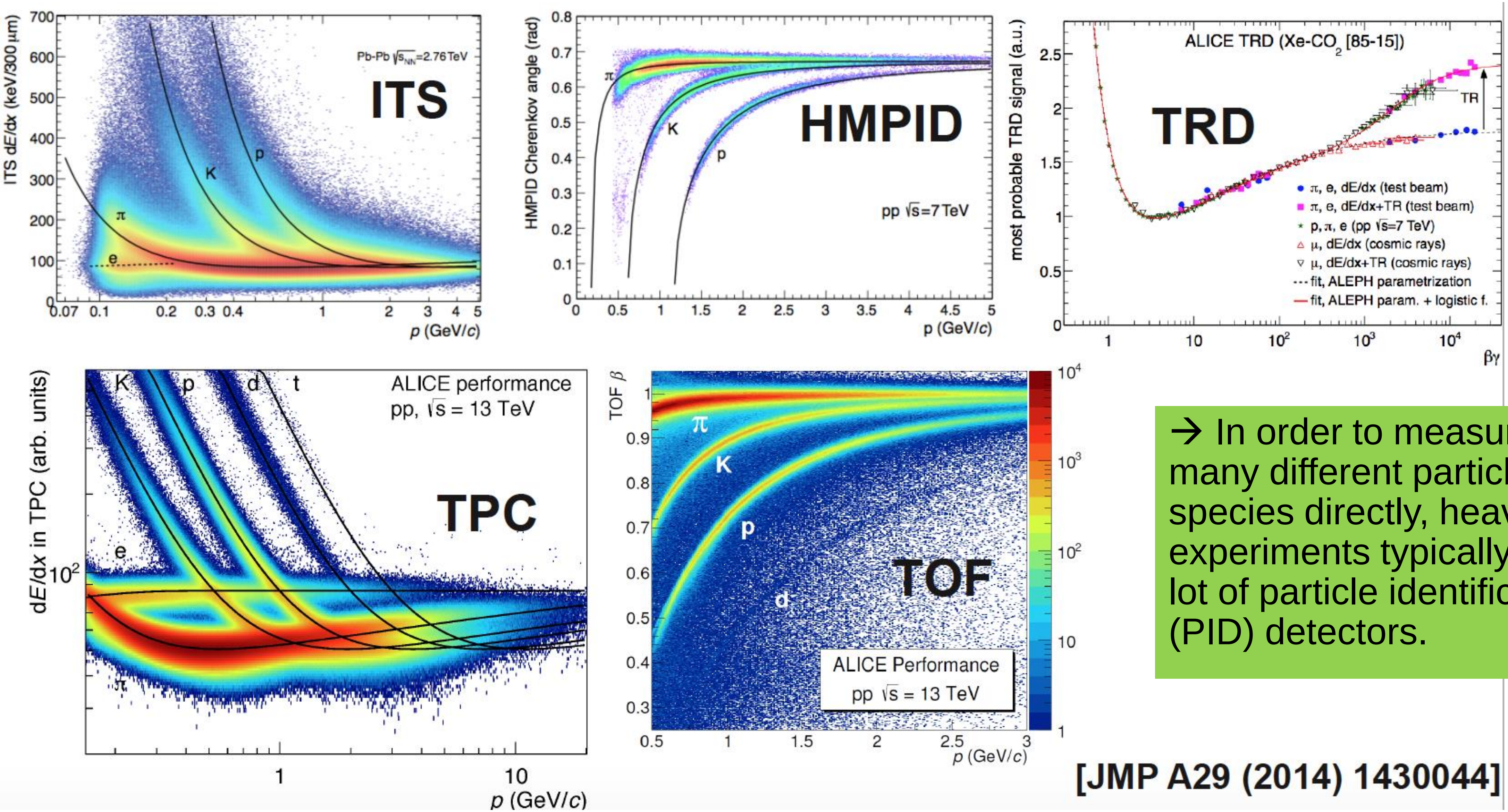
p_T-spectra of identified particles



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]

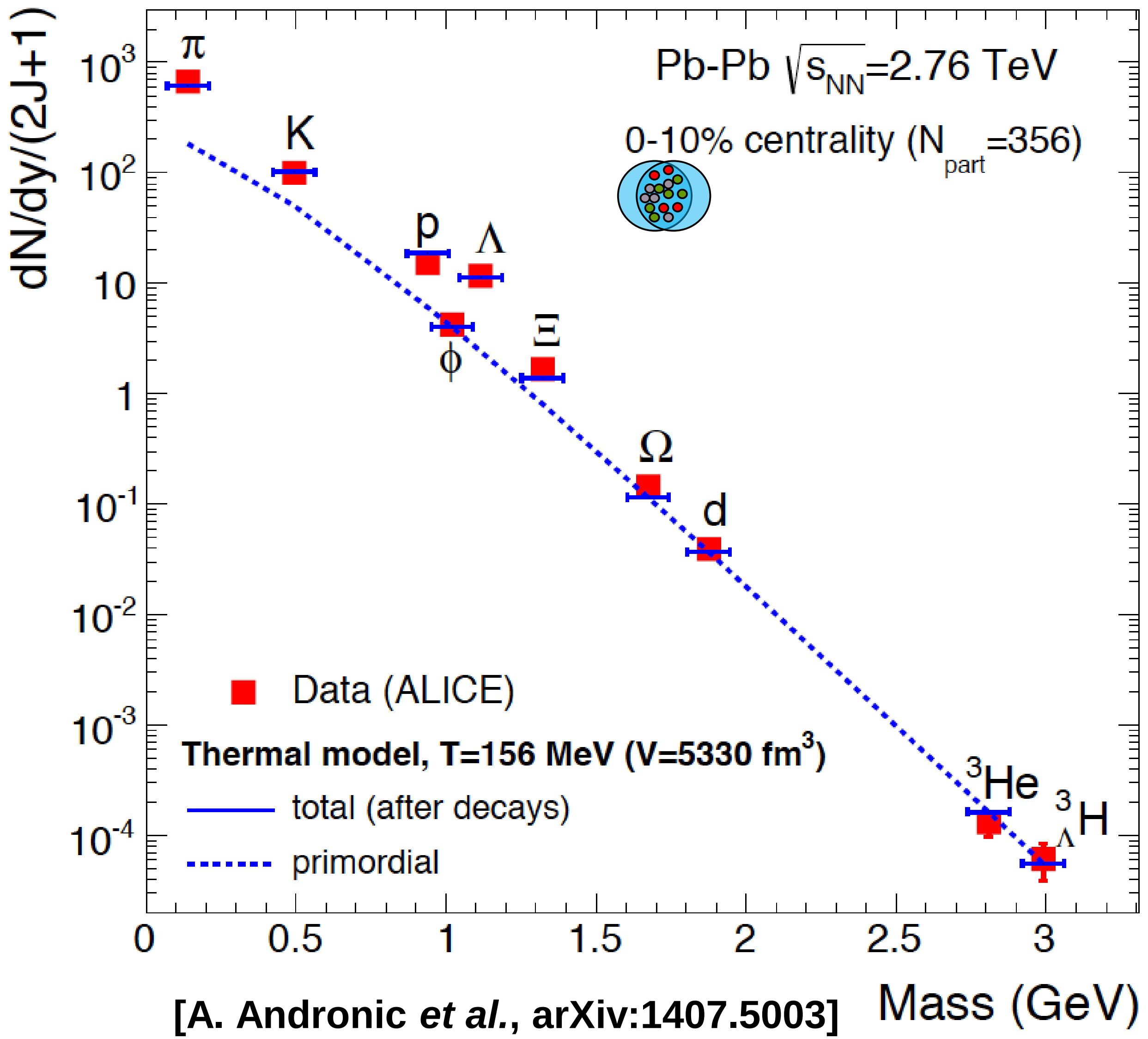
Chemical equilibrium at the LHC (1)

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**.

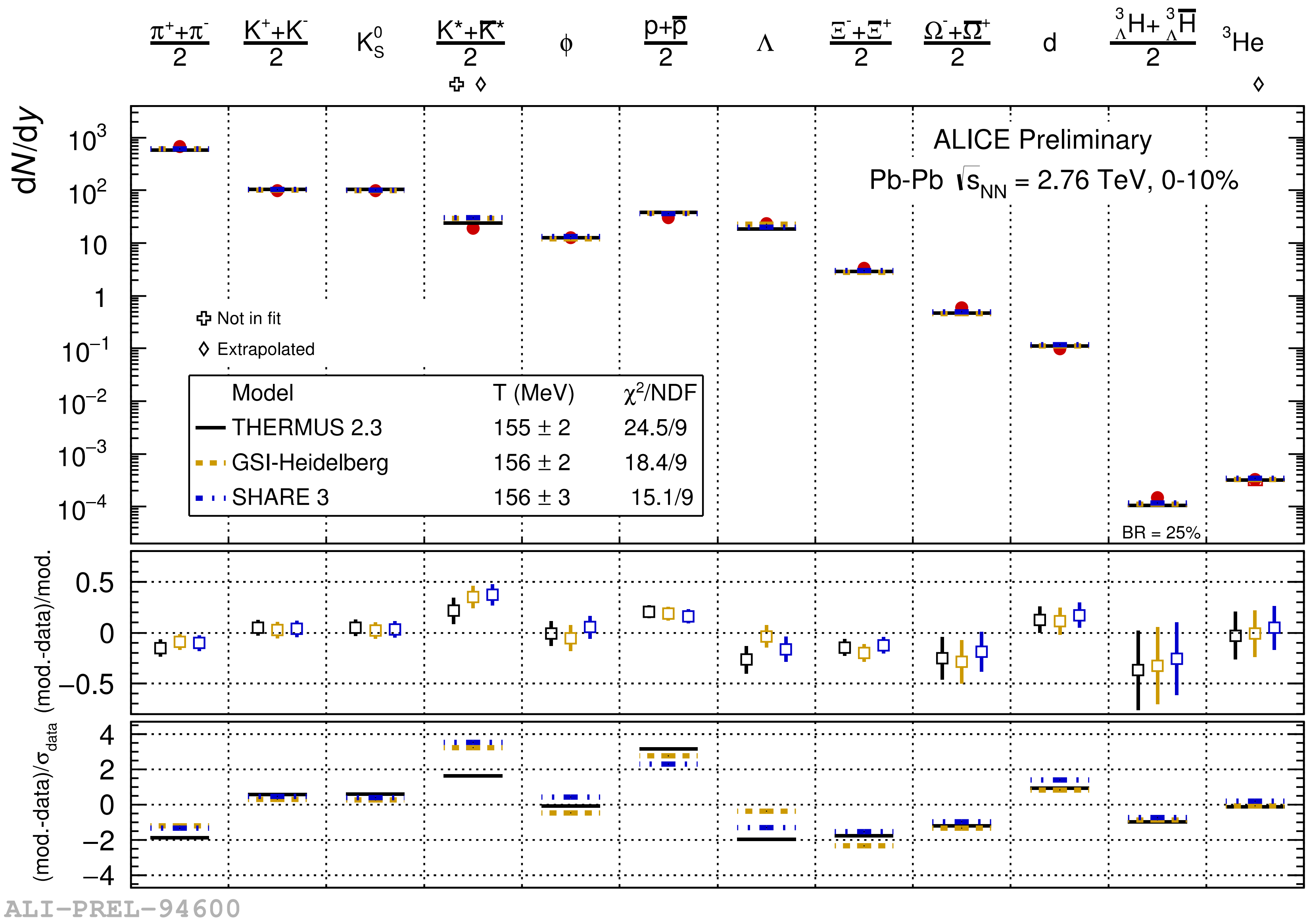
→ This includes **strange hadrons** which are rarer than u,d quarks. Approx. every fourth to fifth quark (every tenth) is a strange quark in Pb-Pb collisions (in pp collisions).

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



[A. Andronic *et al.*, arXiv:1407.5003]

Chemical equilibrium at the LHC (2



Particle yields of light flavor hadrons are described over 7 orders of magnitude within 20% (except K*0) with a common chemical freeze-out temperature of Tch ≈ 156 MeV (prediction from RHIC extrapolation was ≈ 164 MeV).

Hadrons are produced in apparent chemical equilibrium in Pb-Pb collisions at LHC energies.

Largest deviations observed for protons (incomplete hadron spectrum, baryon annihilation in hadronic phase,..?) and for K*0.

Three different versions of thermal model implementations give similar results.

[Wheaton et al, Comput.Phys.Commun, 18084]
[Petran et al, arXiv:1310.5108]
[Andronic et al, PLB 673 142]

Chemical equilibrium vs collision energy

[A. Andronic et al., NPA 834 (2010) 237]

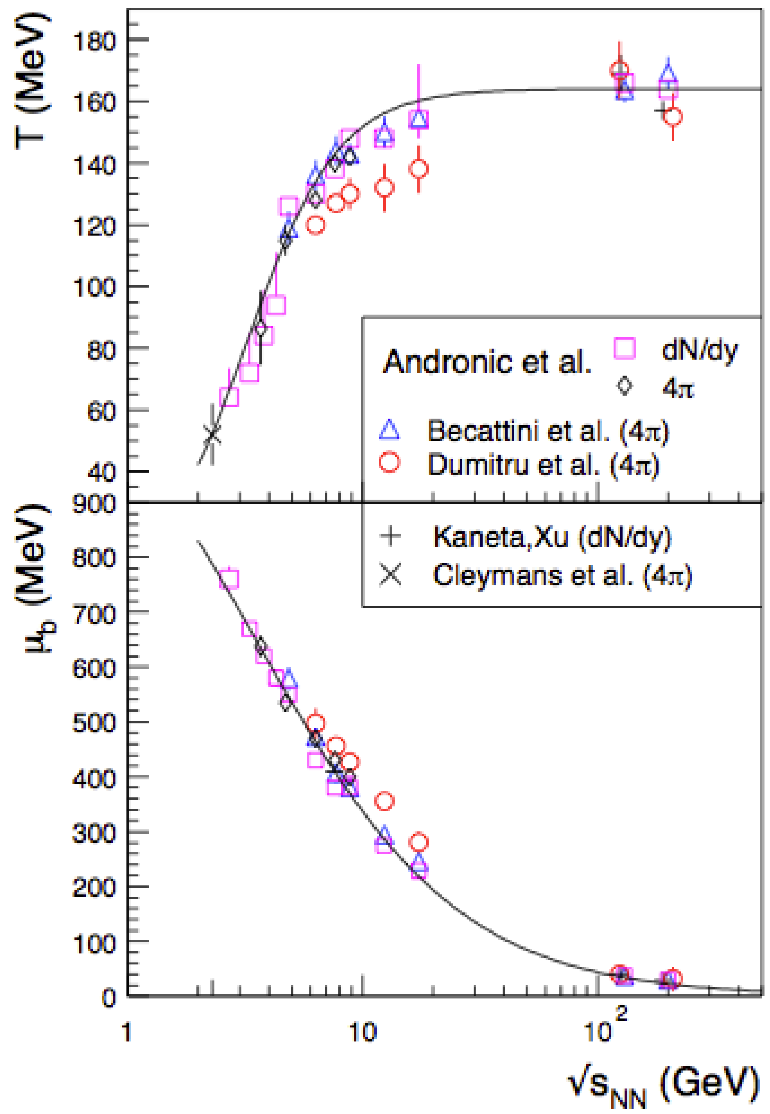
- Hadron yields from SIS up to RHIC and LHC can be described in a hadro-chemical model applying thermal fits.

- 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….



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

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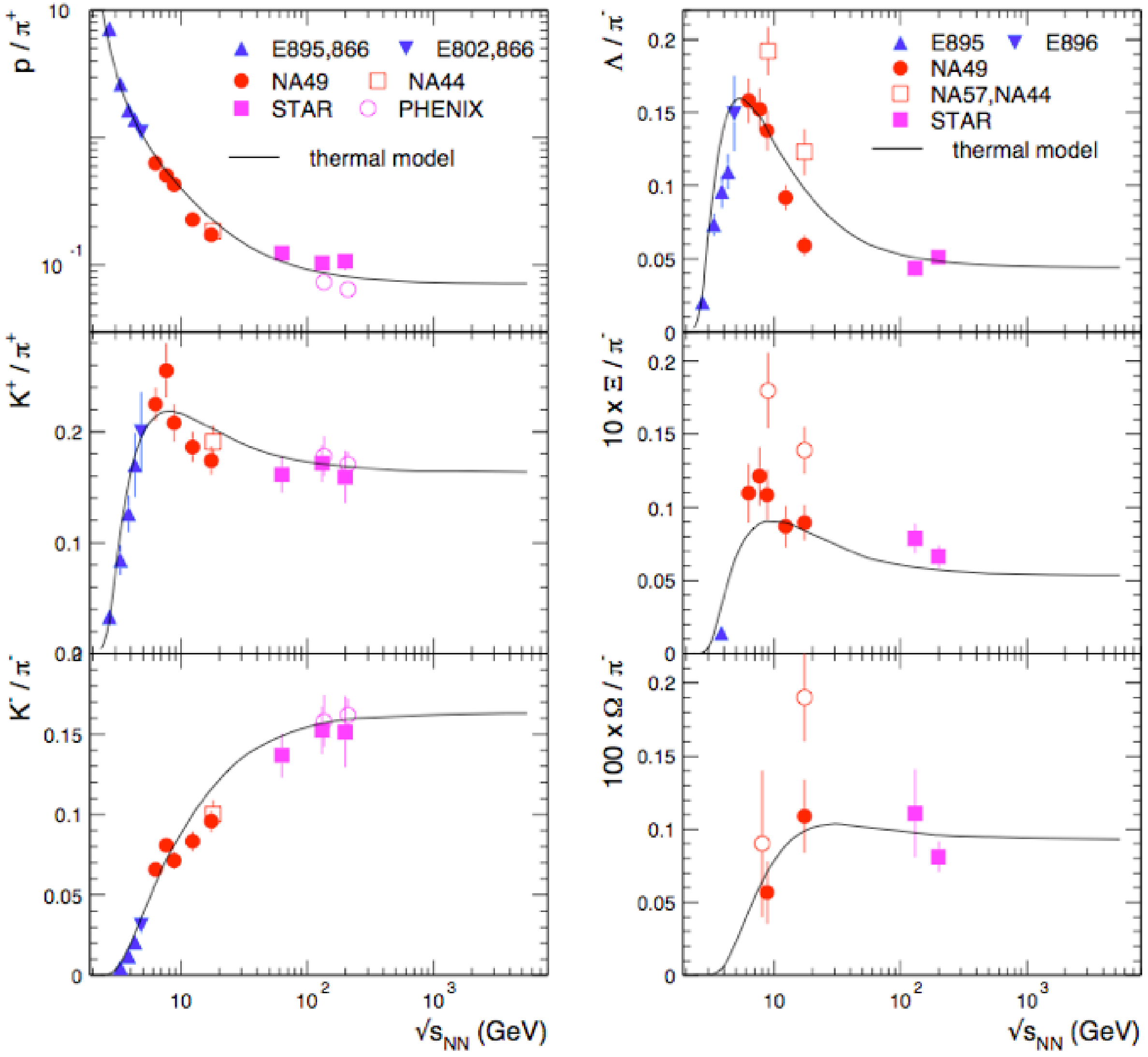
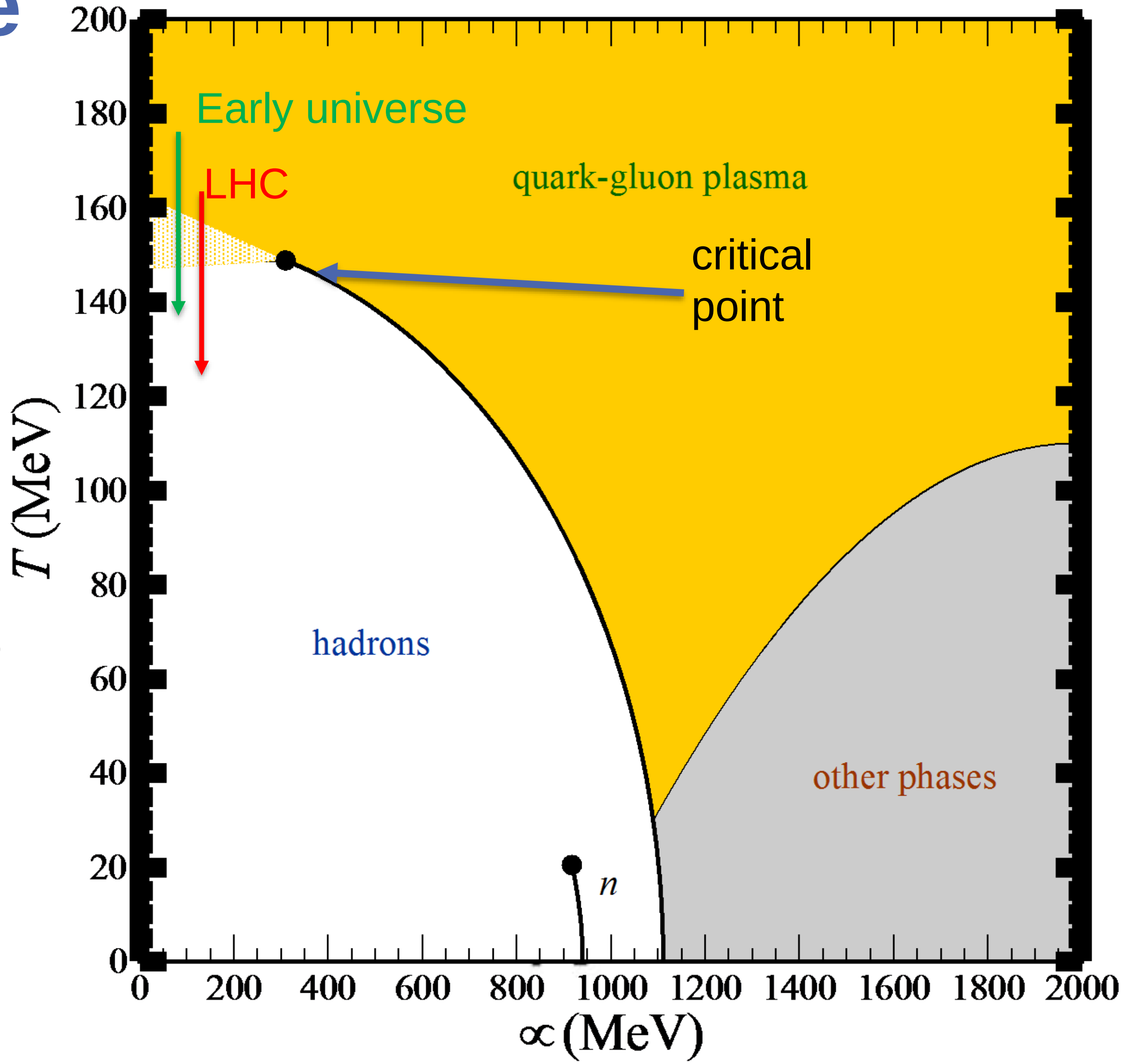


Chemical freeze-out line

- 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.



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

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.
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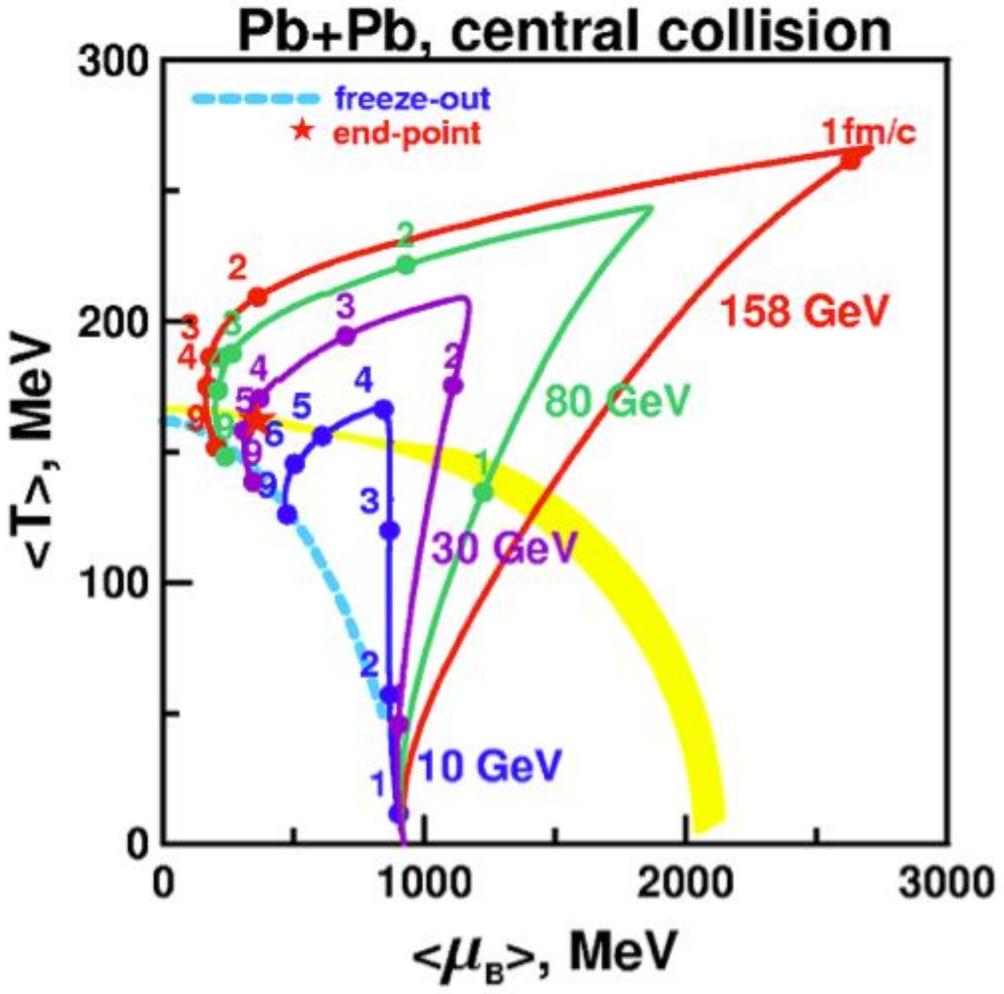

Y.B. Ivanov et al., Phys. Rev. C 73 (2006) 30.

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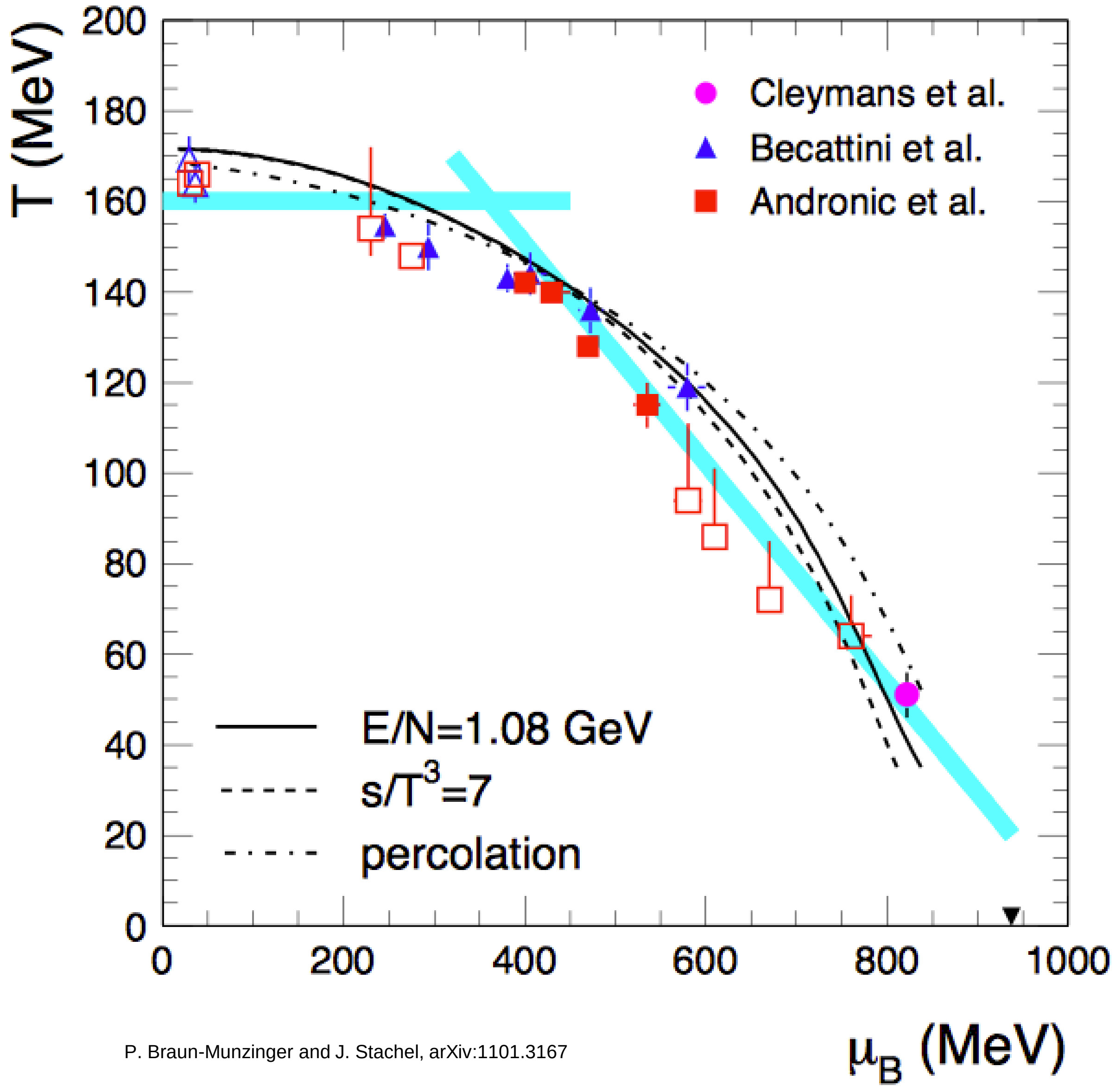
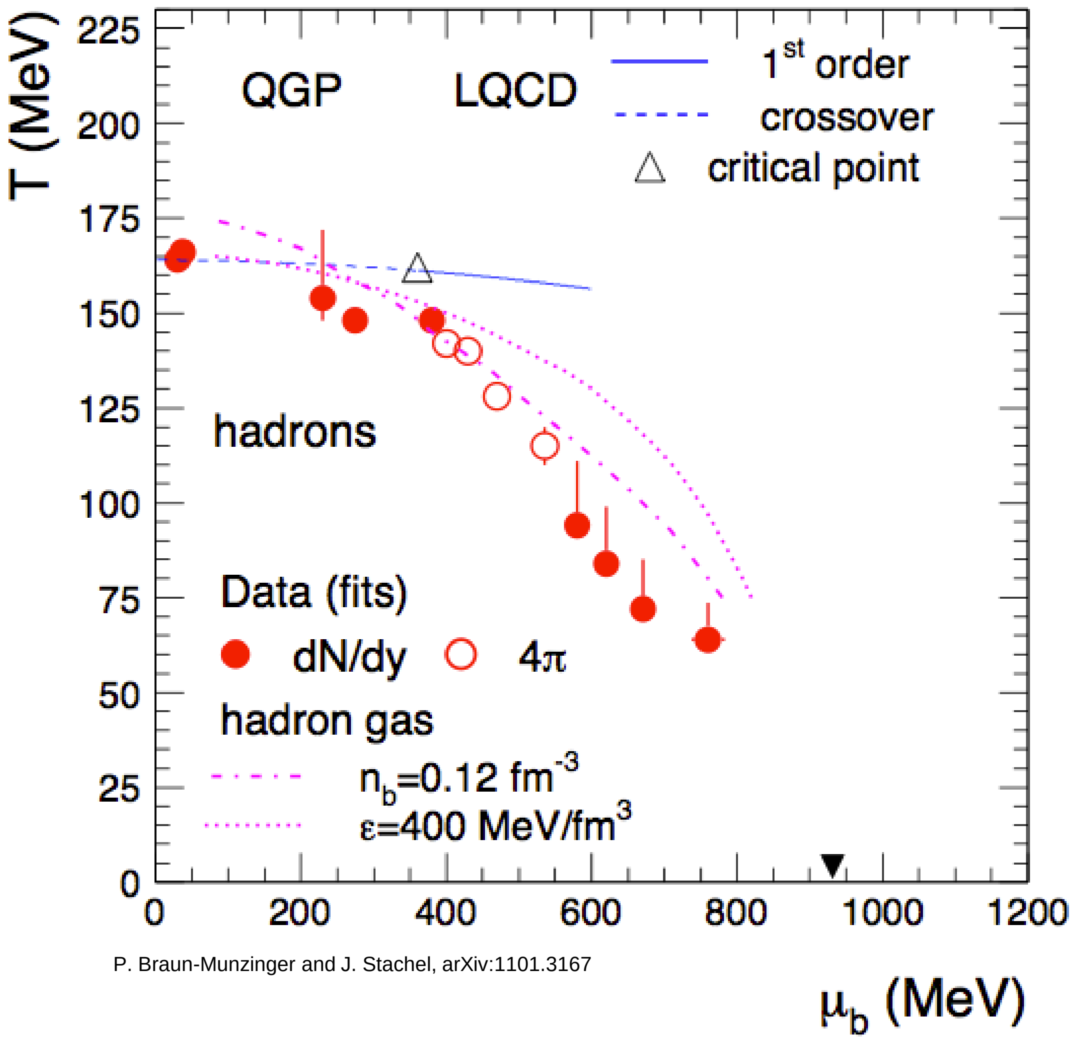


P. Braun-Munzinger and J. Stachel, arXiv:1101.3167

Chemical freeze-out as a proof of QGP existence?



P. Braun-Munzinger and J. Stachel, arXiv:1101.3167

A priori, a thermal model description is not related to the QGP itself. It describes a *hadron gas and not a parton gas*.

However, the *chemical freeze-out line* determined by thermal fits coincides with the phase boundary calculated by lattice QCD above top SPS energies!

However, a detailed study of collision rates and timescales of fireball expansion imply that equilibrium cannot be reached in the hadronic phase…

Do multi-particle collisions near TC equilibrate the system? A rapid change in density near the **phase transition** can explain this [1].

Alternatively, the system is 'born into equilibrium' by the filling of phase space during hadronization [2].

[1] Braun-Munzinger, P., Stachel, J. & Wetterich, C., Phys. Lett. B. 596, 61–69 (2004).

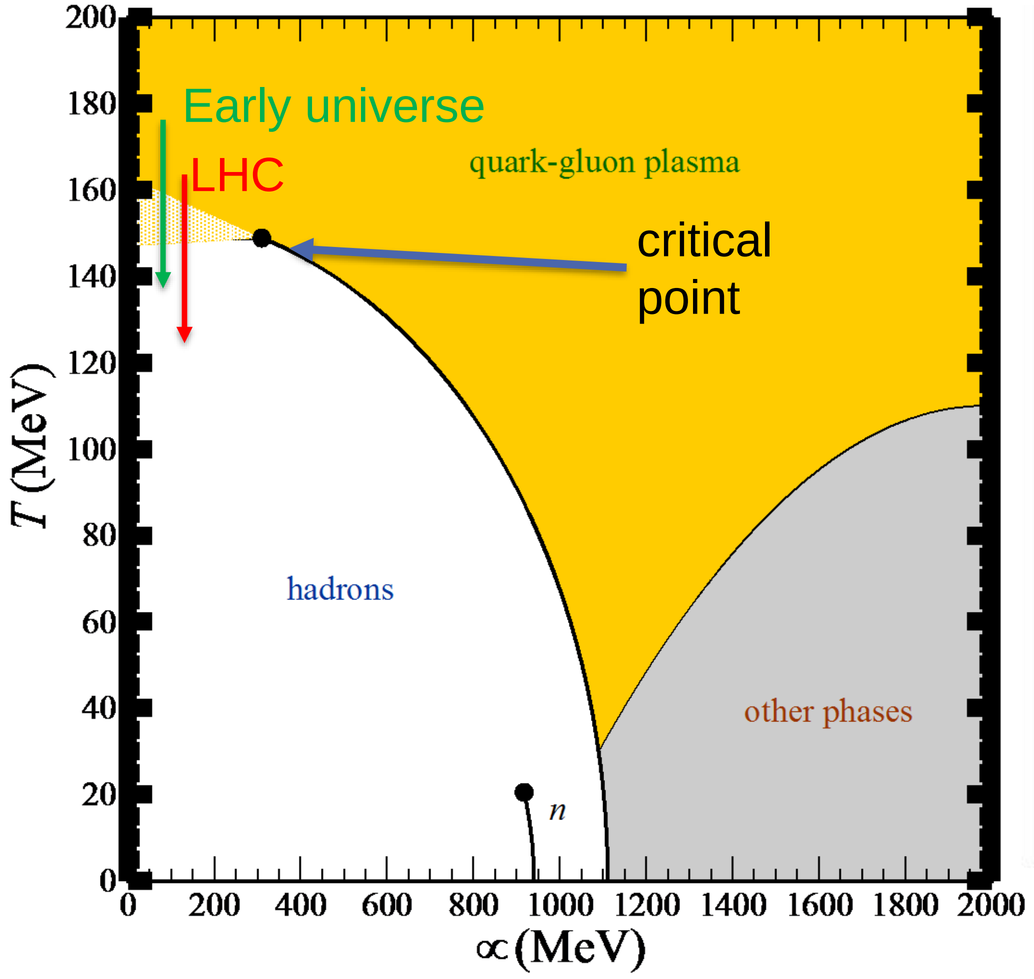
[2] Stock, R. Phys. Lett. B 456, 277–282 (1999).

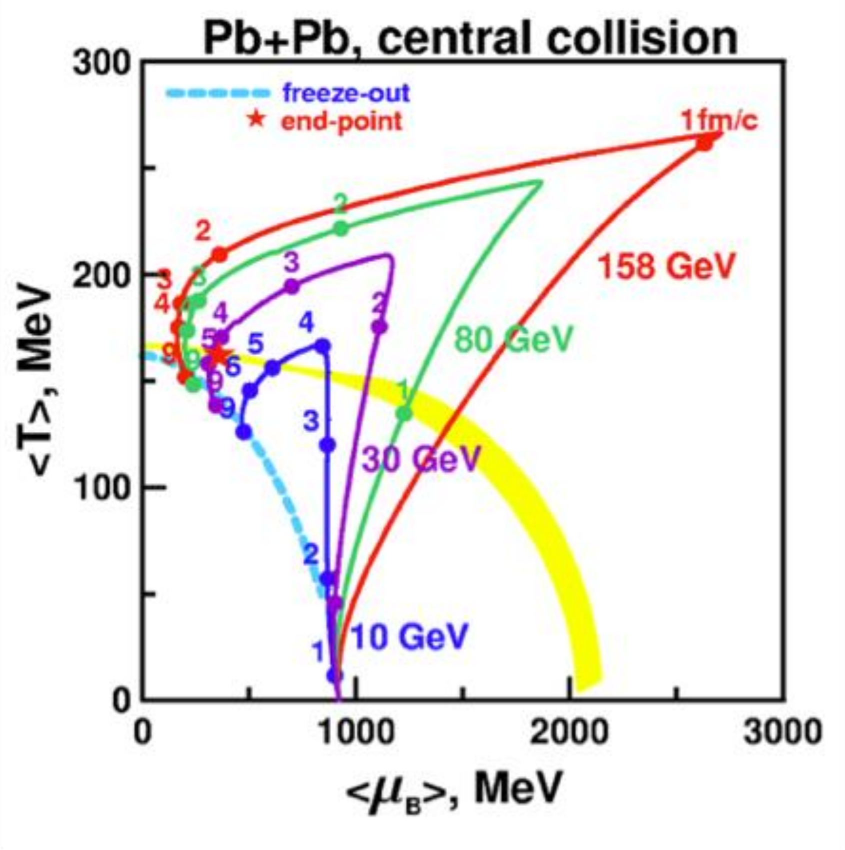
QGP thermodynamics and soft probes

Search for QCD critical point and onset of de-confinement

The QCD critical point

- By a variation of beam energies, one might hit the critical point in the QCD phase diagram => ***critical chiral dynamics***.





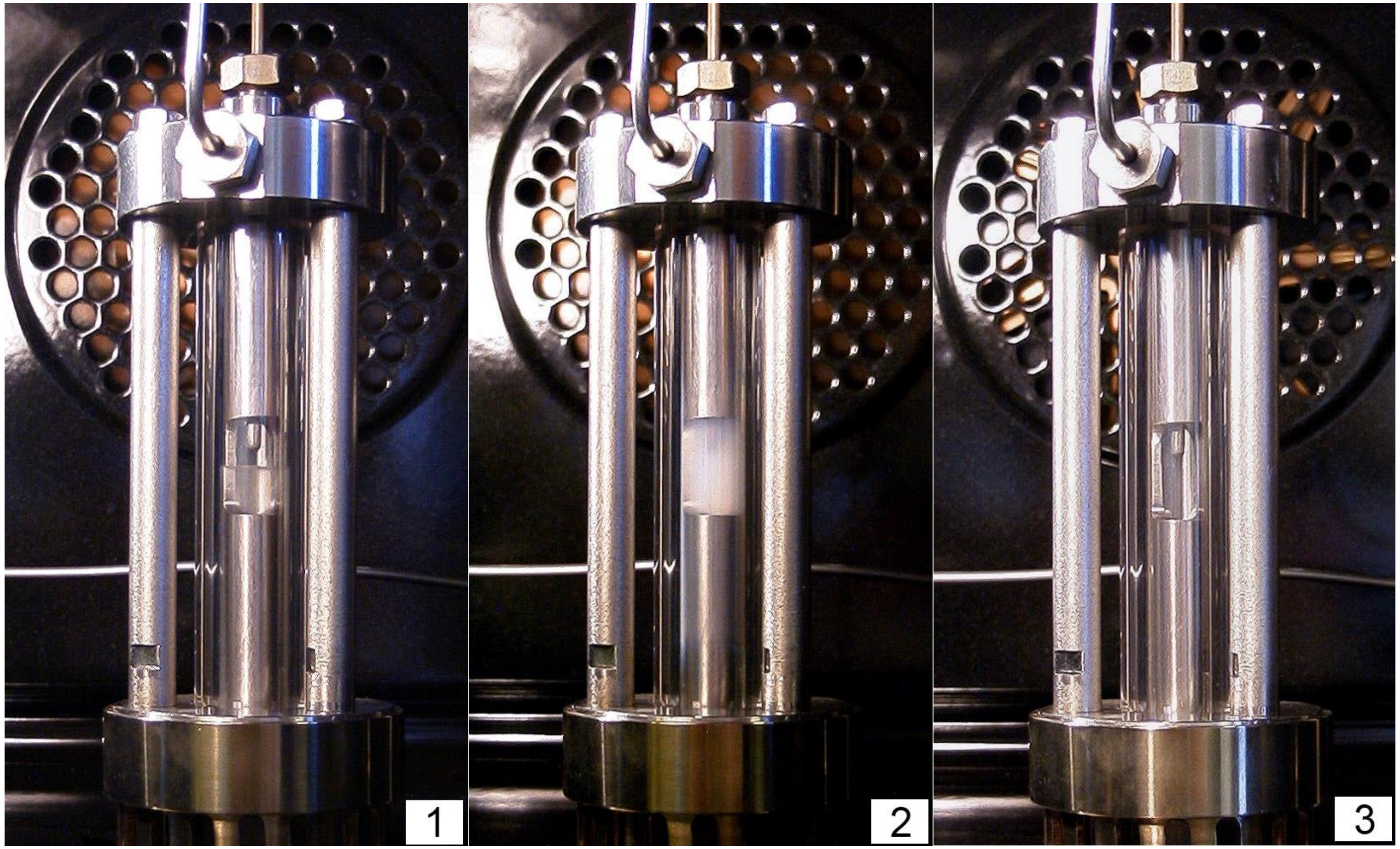
Y.B. Ivanov et al., Phys. Rev. C 73 (2006) 30.

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

=> Beam energy scan (BES) at RHIC.

Critical fluctuations – in ordinary matter

- Phase transitions are often connected to critical phenomena.
- Example: Opalescence of Ethene at the critical point (divergence of correlation lengths).

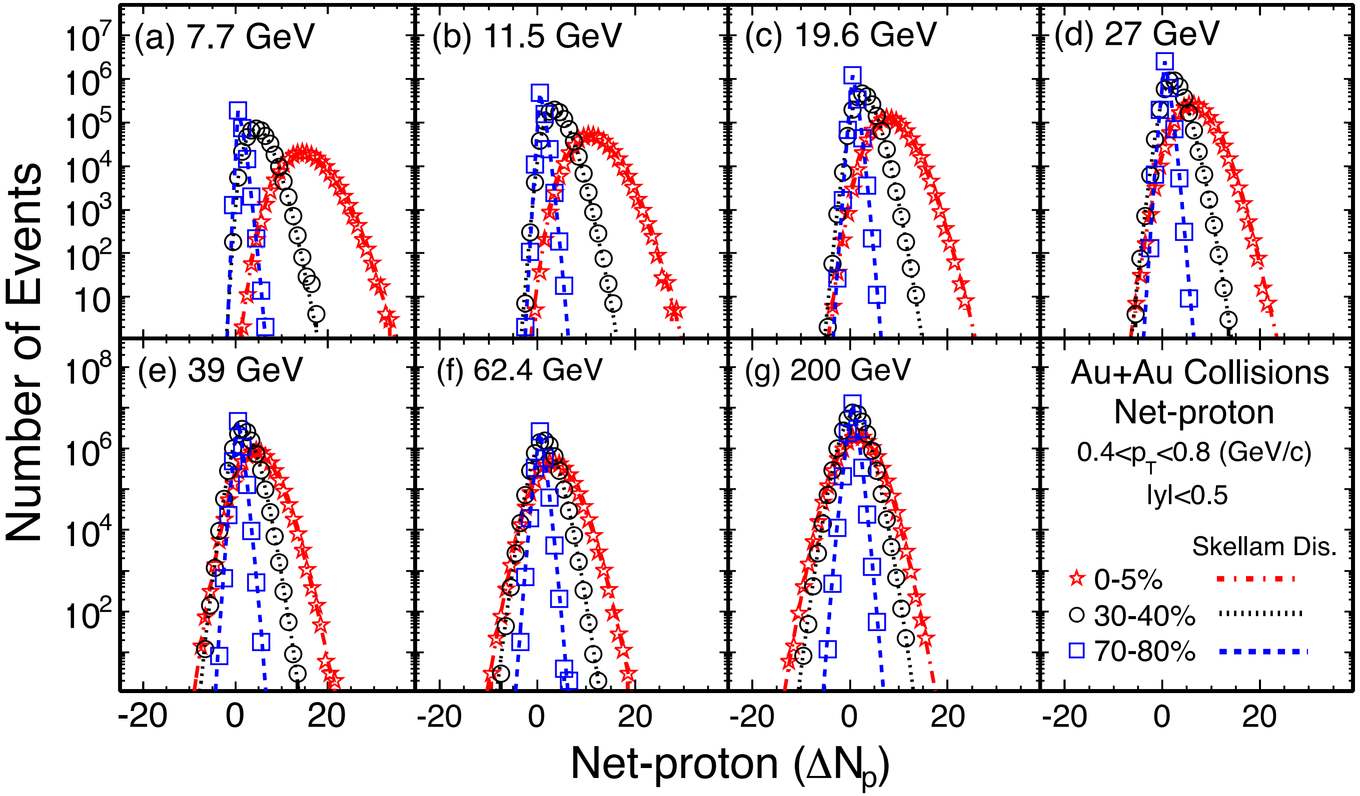


[S. Horstmann, Ph.D. Thesis University Oldenburg]

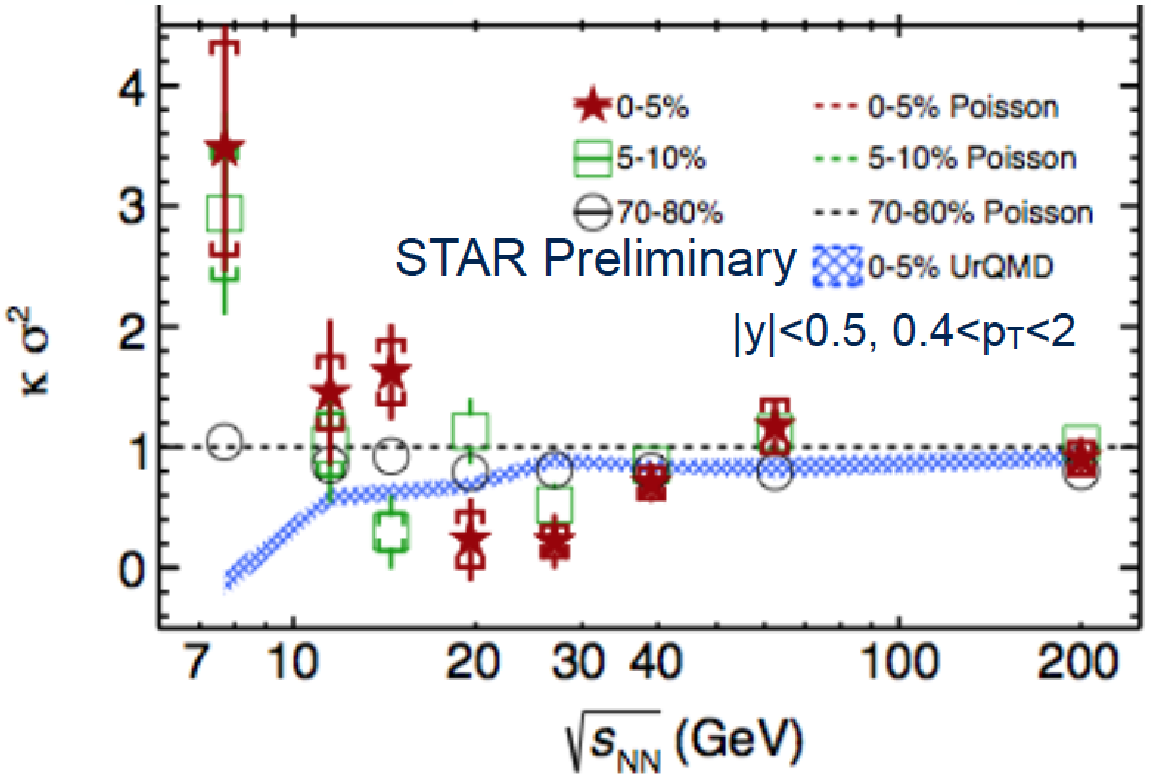
Critical fluctuations – in quark matter

- In the QCD case, **event-by-event fluctuations** in the conserved charges of QCD (Baryon number *B*, Strangeness *S*, electric charge *Q*).
- Key observable: baryon number fluctuations quantified as the higher moments χ_B of the net-proton (N_p-$N_{anti\text{-}p}$) distribution => fixed at chemical freeze-out

→ Hint for deviation from Poisson baseline in kurtosis around $\sqrt{s_{NN}} \approx 20$ GeV?



[PRL 112 (2014) 032302]



END OF LECTURE 1..