Heavy-ion collision experiment (Lecture1)

Daicui Zhou

Central China Normal University

1. Why do we study relativistic heavy-ion collisions?
2. Experimental basis
3. Particle Yields and Statistical Model
4. Jet quenching and energy loss
5. Quarkonia
6. Highlights from small systems
7. Summary and outlook

1. Why do we study relativistic heavy-ion collisions?

Strong-Interaction Physics

- Strong interaction
  – binds quarks into hadrons
  – binds protons and neutrons into nuclei
- QCD is a very successful theory…

  e.g. for jet production at high p_T and heavy-flavour production

  … with some open puzzles

Confinement

Impossible to find an isolated quark or gluon

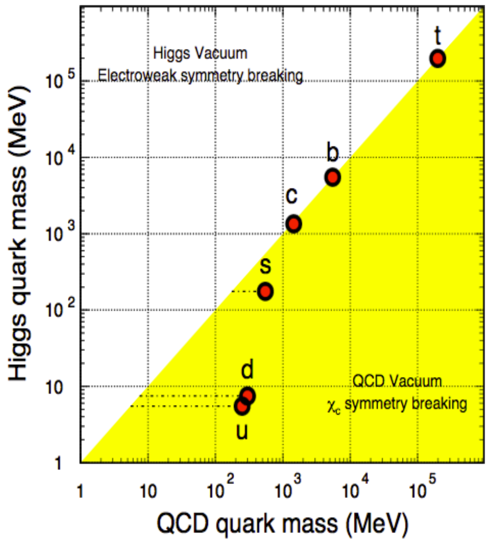
Why?

Hadron Masses

Proton consists of 2u+1d quark

m_{uud}~10 MeV， m_p = 938 MeV

Where is the extra mass generated?



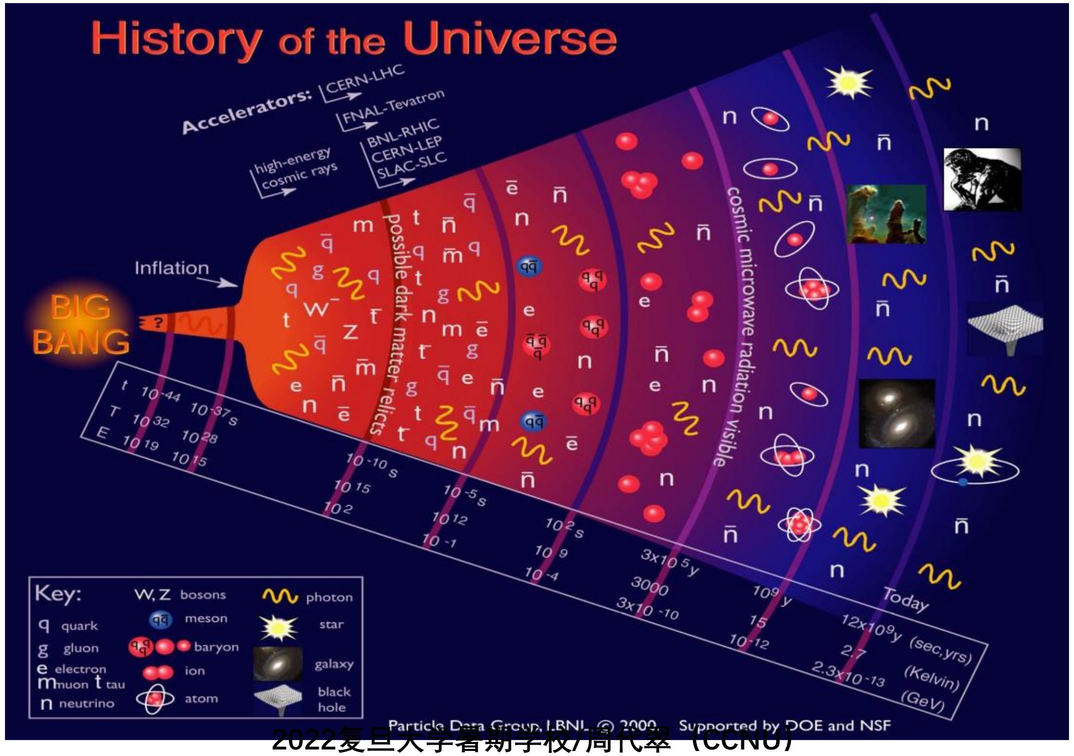
Fundamental Questions

- How do “free” quarks and gluons behave?
- How do quarks and gluons behave when chiral symmetry is restored?
- What generates the constituent masses?
- How does matter behave at very large densities and temperatures?

- In the early universe a phase with free quarks and gluons and restored chiral symmetry has existed
  - *Quark-gluon plasma* (QGP)
  - Recreate in the laboratory with heavy-ion collisions

What is the heavy-ion physics?

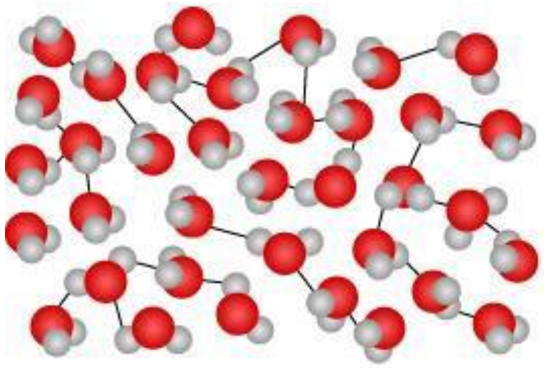
- **A way to study QCD**
  … without confinement
  … with quarks at their bare masses
- **A way to study matter**
  … at temperatures 10^5 times larger than in the sun core
  … at energy densities like 10 μs after the Big Bang
  …



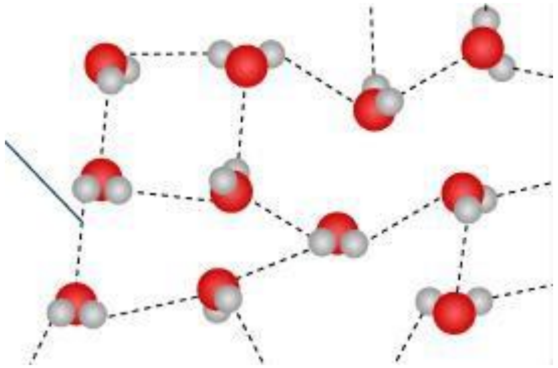
Phases of QED matter

Vapor

Water

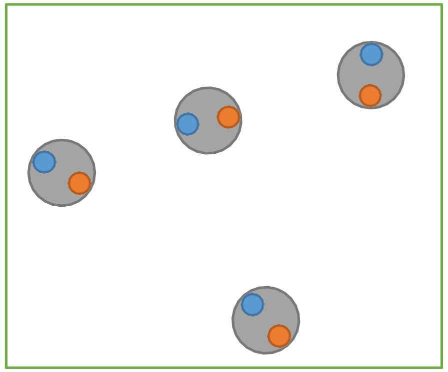


Ice

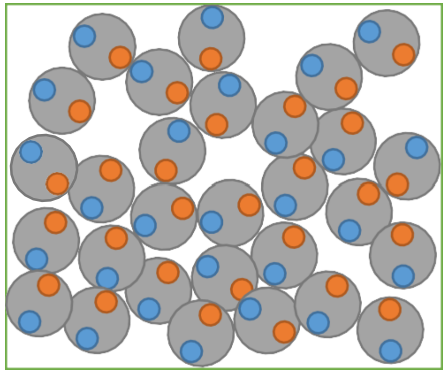


Ultra-dense QCD matter

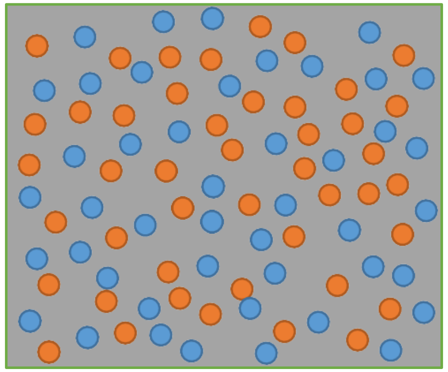
Increase the Temperature (T)



$T<T_C$



$T\sim T_C$



$T>T_C$

Ultra-dense QCD matter

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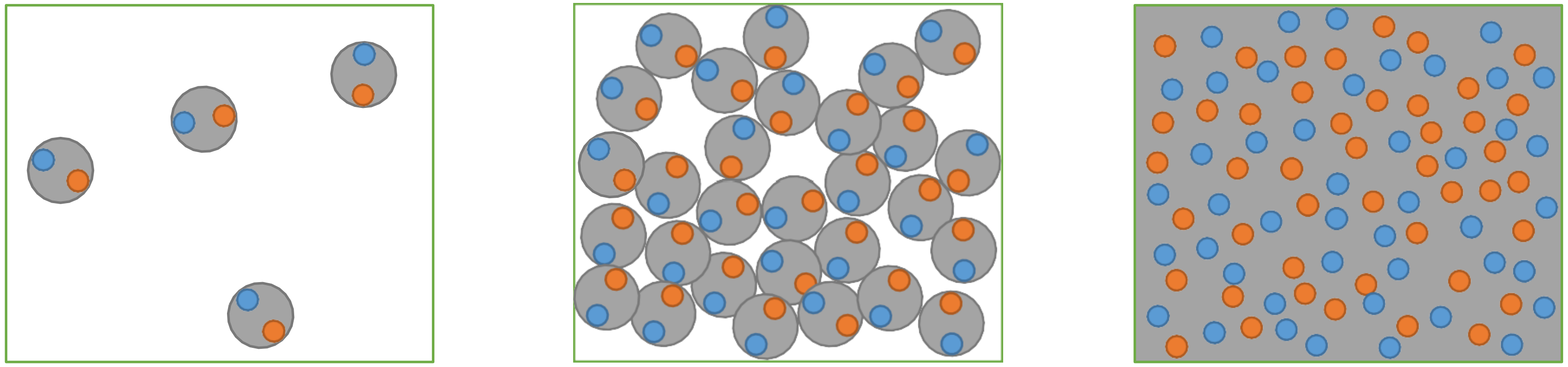
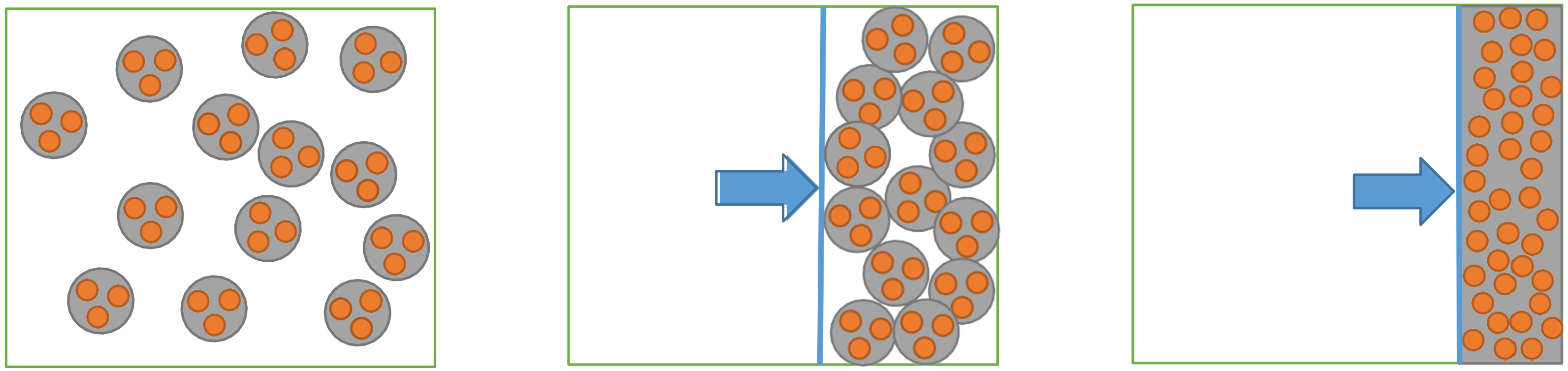


$T<T_C$ $T\sim T_C$ $T>T_C$

Increase the Density (ρ)



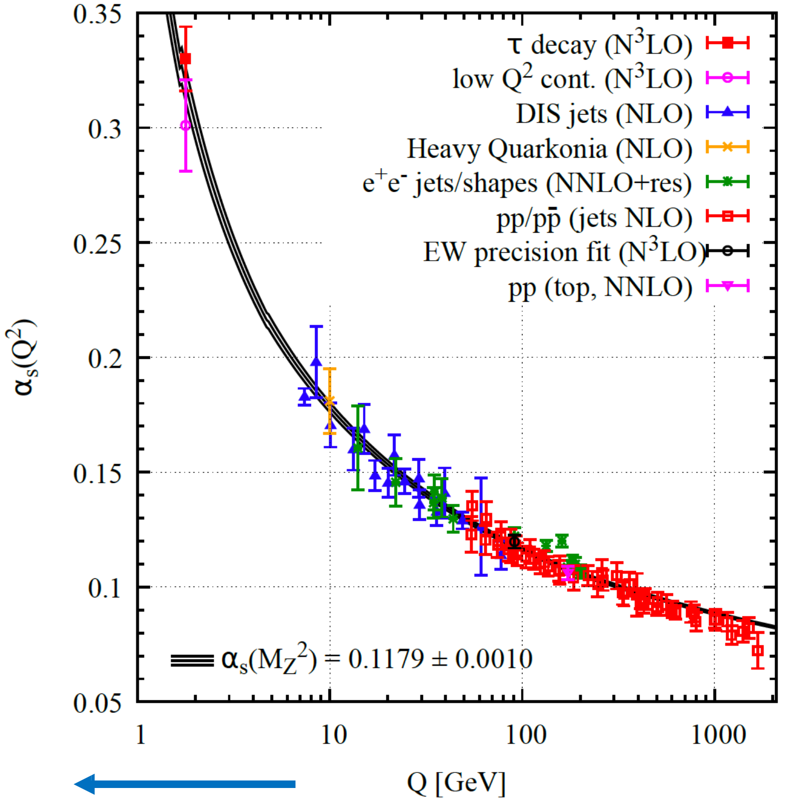
$\rho<\rho_C$ $\rho\sim\rho_C$ $\rho>\rho_C$

Fundamental properties of QCD

Quarks and gluons exist in nature as confined in colorless hadrons: ordinary matter at room temperature
→ confining property of QCD

The strong coupling, i.e. the effective strength of the interaction, becomes weaker for processes involving larger quadrimomentum exchange
→ asymptotic freedom

Chiral symmetry is explicitly broken by non-zero quark masses: (light) quarks acquire mass dynamically
→ the mass of hadrons is a consequence of the strong interaction acting among their constituents



Understanding confinement

Properties of the QCD vacuum:

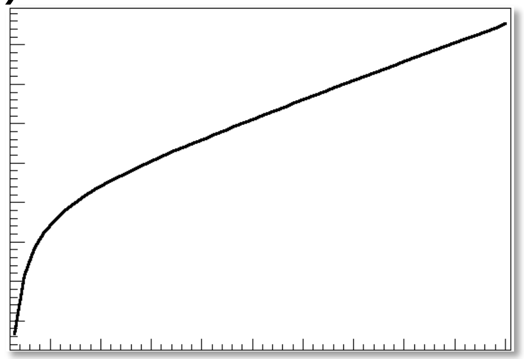
- Gluon-gluon self-interaction (non-abelian)
- QCD field lines compressed in flux tube (or “string”)

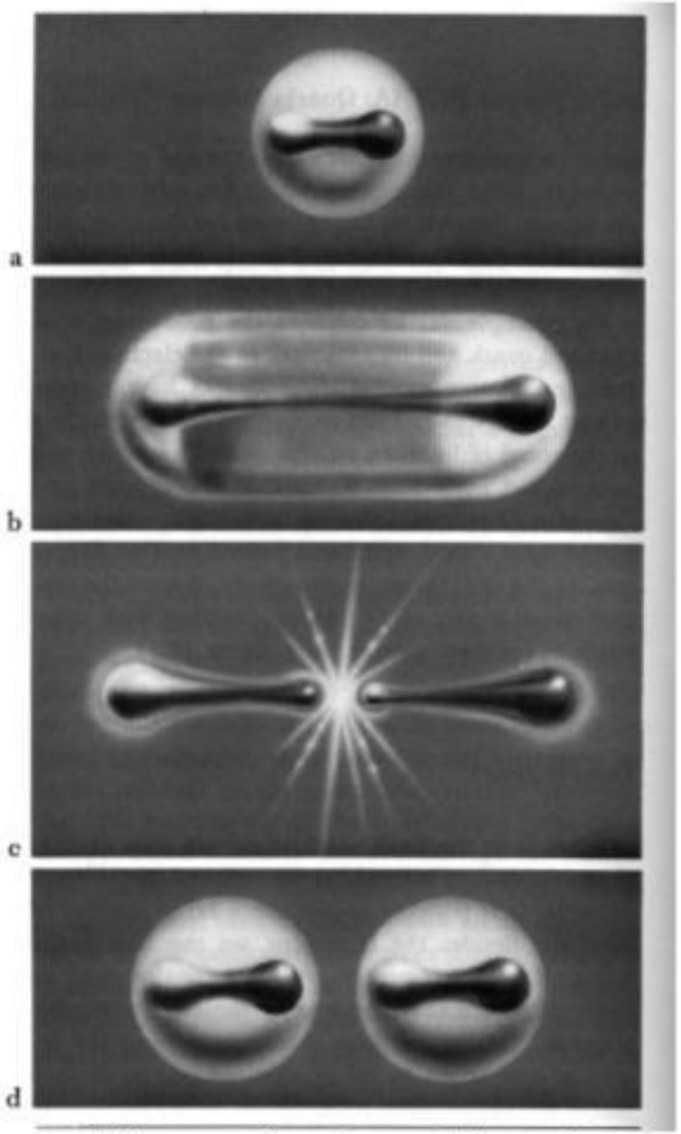
The q-qbar potential is of the form (Cornell potential):

$$V(r) = -\frac{a}{r} + \sigma r$$

qqg part
“Coulomb”-like

gg part



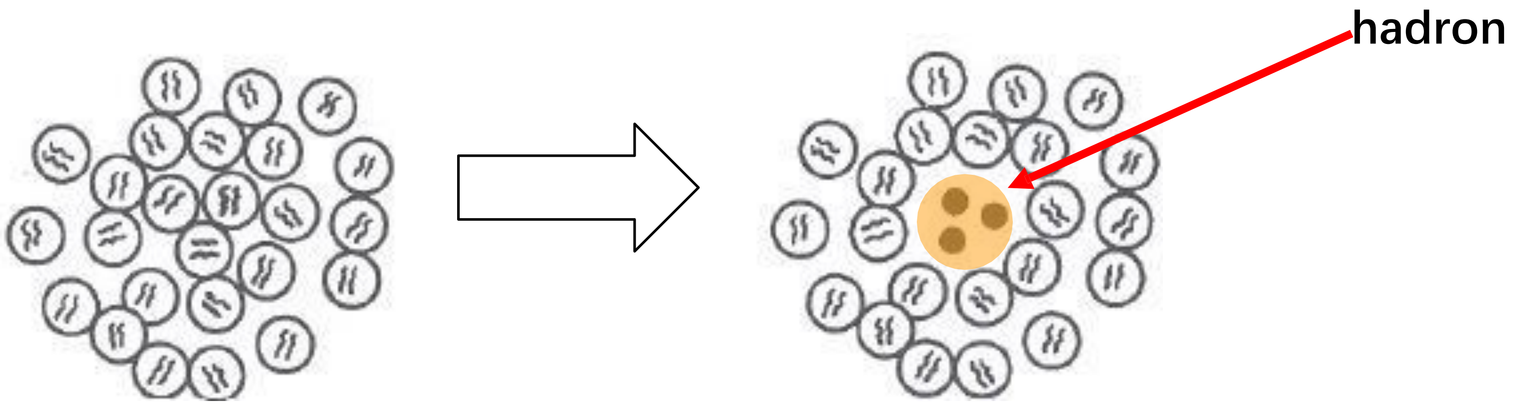


[illustration from Fritzsch]

- The potential grows with distance.
- If pulled apart, the energy in the string increases
- A new q-qbar pair is created once the energy is above production threshold.
- No free quark can be obtained by breaking a flux tube → confinement

Phenomenology of Confinement

- QCD vacuum can be seen as liquid of gluon-gluon pairs
- Why does this create confinement?
- ***MIT bag model*** : hadrons are confined in bubbles of
- perturbative (= empty) vacuum
  - – Surrounded by QCD vacuum exerting pressure



The MIT Bag Model

Inside the bag, quarks have very small masses and the interaction is weak

Outside the bag, quarks are not allowed to propagate, no colored partons, but quark and gluon condensates?

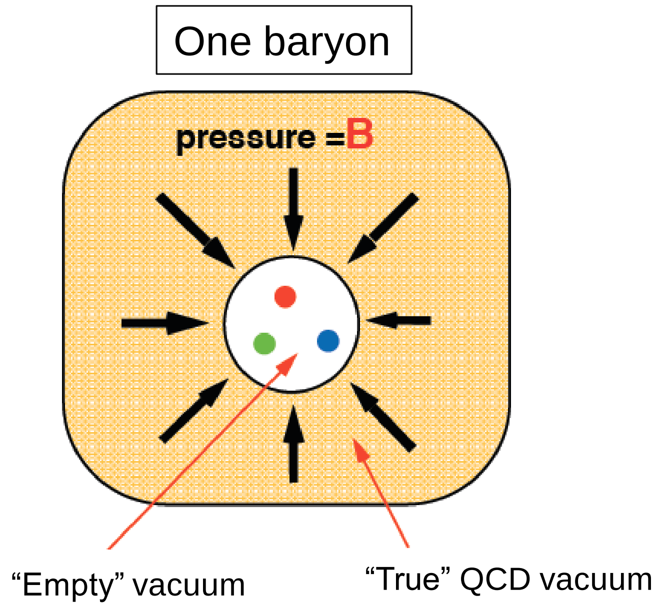
The equilibrium between the kinetic pressure of the quarks inside the hadron vs the pressure of the surrounding QCD vacuum ("bag pressure", B) defines the radius R of the hadron.

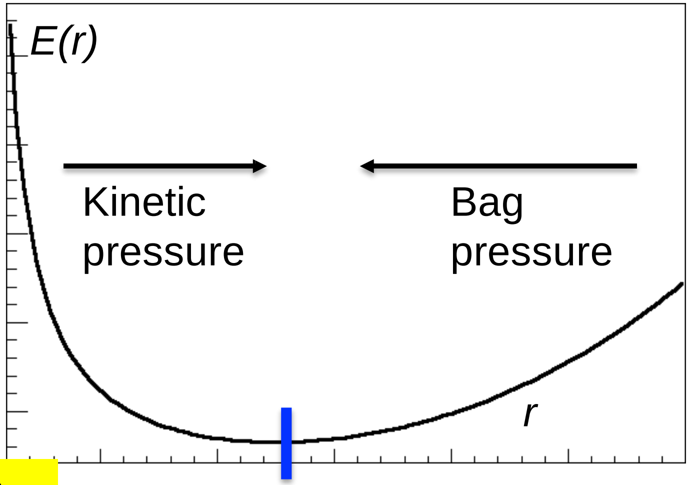
If the hadron can be modeled as N massless Dirac fermions in a spherical cavity,

$$E = \frac{2.04N}{R} + \frac{4\pi}{3} R^3 B$$

By asking $\partial E/\partial R = 0$ and $R(p) \sim 0.8$ fm

→ $B_{MIT} \sim (200\ \text{MeV})^4$





PRD9, 3471 (1974)

If kinetic pressure exceeds bag pressure? → deconfinement

Deconfinement

For a gas of massless, relativistic partons, the pressure can be calculated from the Stefan-Boltzmann law

$$P = \left(n_g + \frac{7}{8} n_f\right) \frac{\pi^2 T^4}{90}$$

where the degrees of freedom of the system are

n_g = 8 gluons x 2 spin = 16

n_f = 2 quark flavors x 2 spin x 3 colors + anti-q = 24

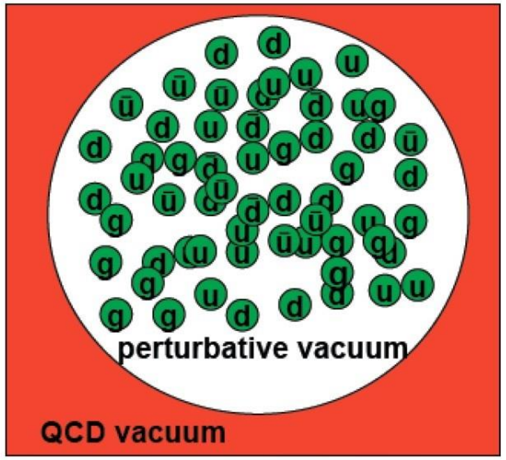
The systems gets **deconfined** if the kinetic pressure exceeds the bag pressure

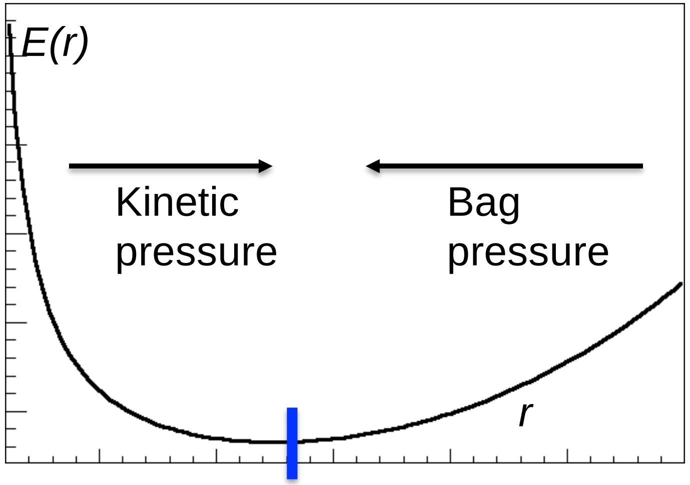
P > B → T^4 > (200 MeV)^4 * 90 / (16+7/3) / π^2

→ T_c > 141 MeV (critical temperature)

Above T_c, the system undergoes a phase transition to a state of matter where quark and gluons are (quasi) free, the **Quark-Gluon Plasma (QGP)**

A gas of relativistic partons





The QCD phase diagram

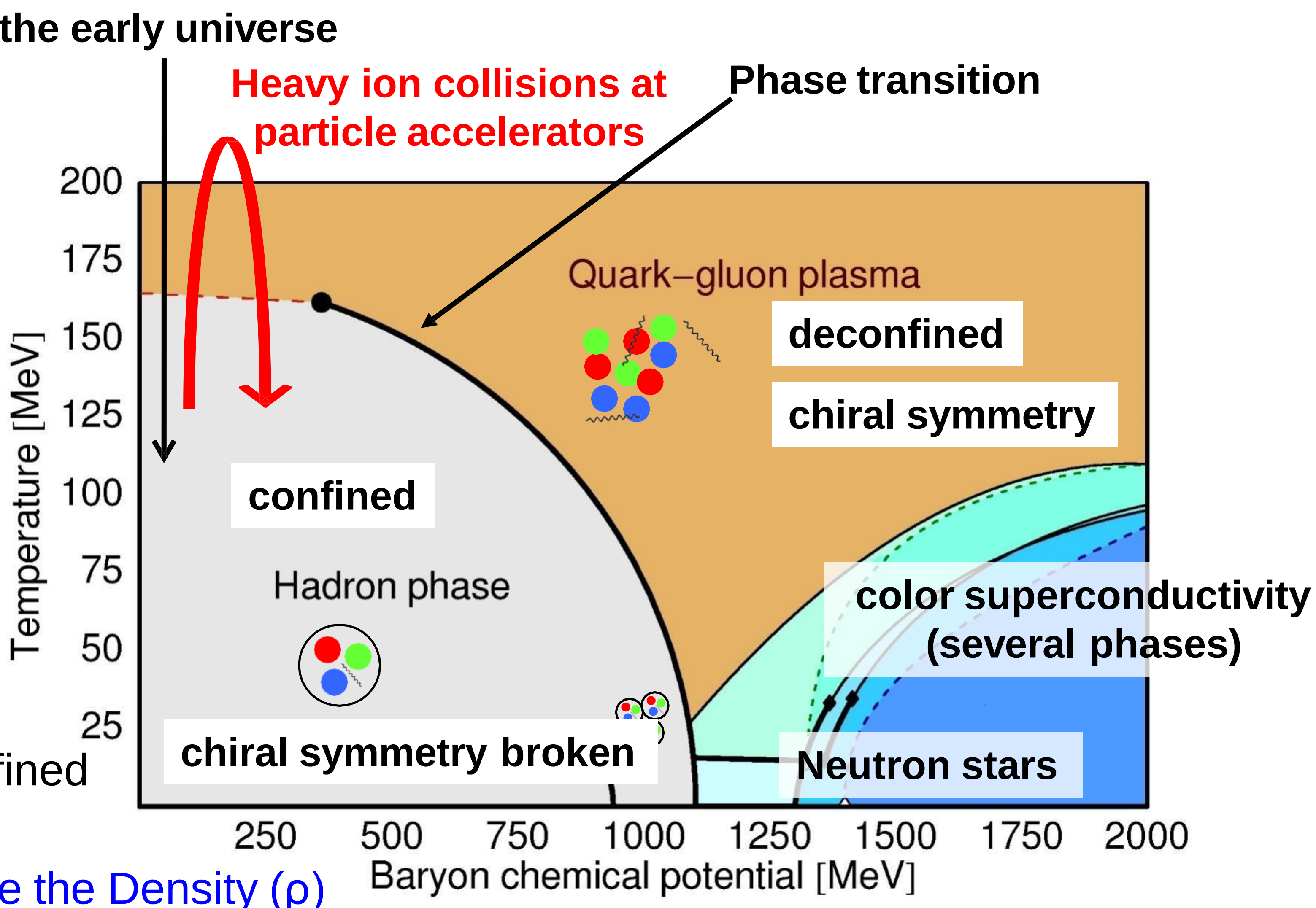
The phases of QCD matter can be summarized in a phase diagram as a function of two parameters:

temperature T and baryochemical potential μ_B

$$\mu_B = \frac{\partial E}{\partial n_B}, \quad n_B = n(B) - n(\overline{B})$$

$\mu_B = 0 \rightarrow$ antimatter / matter = 1
as at the LHC and in the Early Universe!

The quark-gluon plasma is the deconfined phase of strongly-interacting matter.

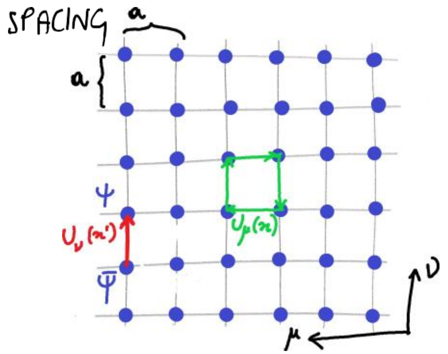


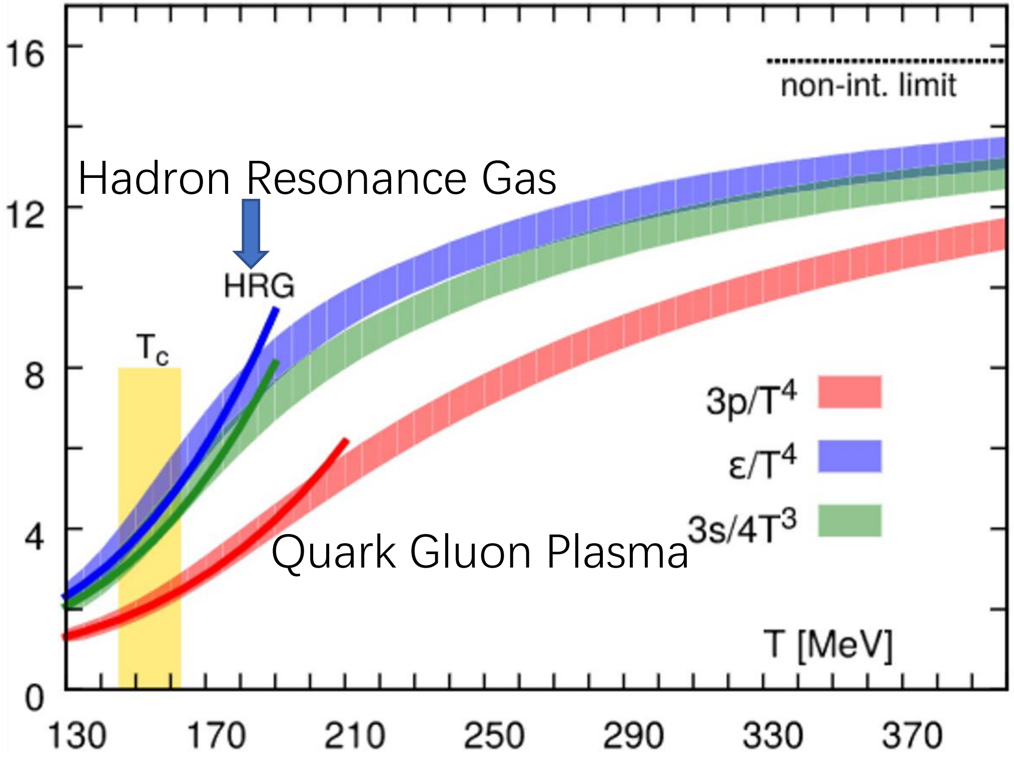
Increase the Density (ρ)

≅ baryons - antibaryons

Lattice QCD

- Lattice QCD (lQCD) is a well-established non-perturbative method to solve QCD starting from first principles, i.e. the QCD Lagrangian.
- discretization on a space-time lattice
  - → ultraviolet (i.e. large-momentum scale) divergencies can be avoided





[A Bazavov et al. PRD 90 094503 (2014)]

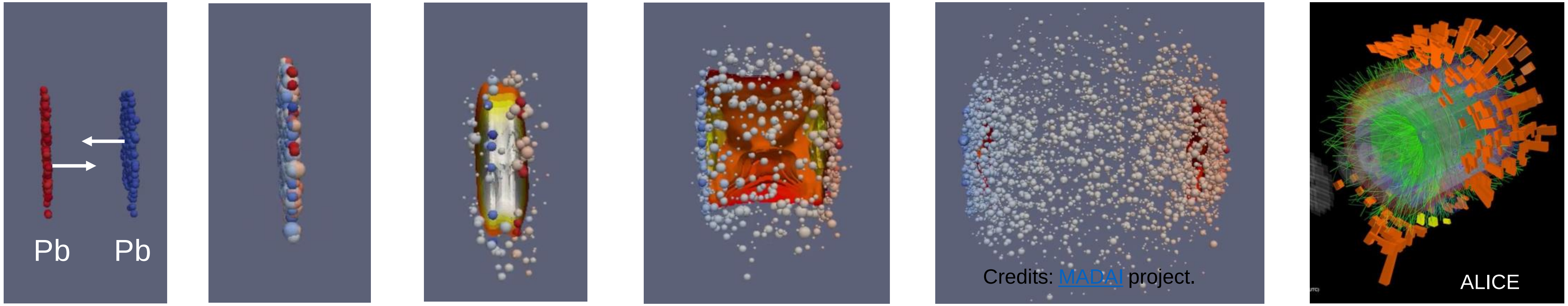
- around critical temperature (T_C): rapid change of
  - energy density ε
  - entropy density s
  - pressure density p
- due to activation of partonic degrees of freedom
- at zero baryon density → smooth crossover
- $T_C = (156.5 \pm 1.5)$ MeV [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
- $\varepsilon \sim O(\text{GeV/fm}^3)$

Lattice QCD predicts a **continuous cross-over** between hadron gas and quark gluon plasma

2. Experimental basis

Evolution of the heavy-ion collisions(figure 1)

Initial state | Hard scatterings | QGP formation | Hydrodynamic expansion | Hadronization and freeze-out | Detection



Time

Temperature

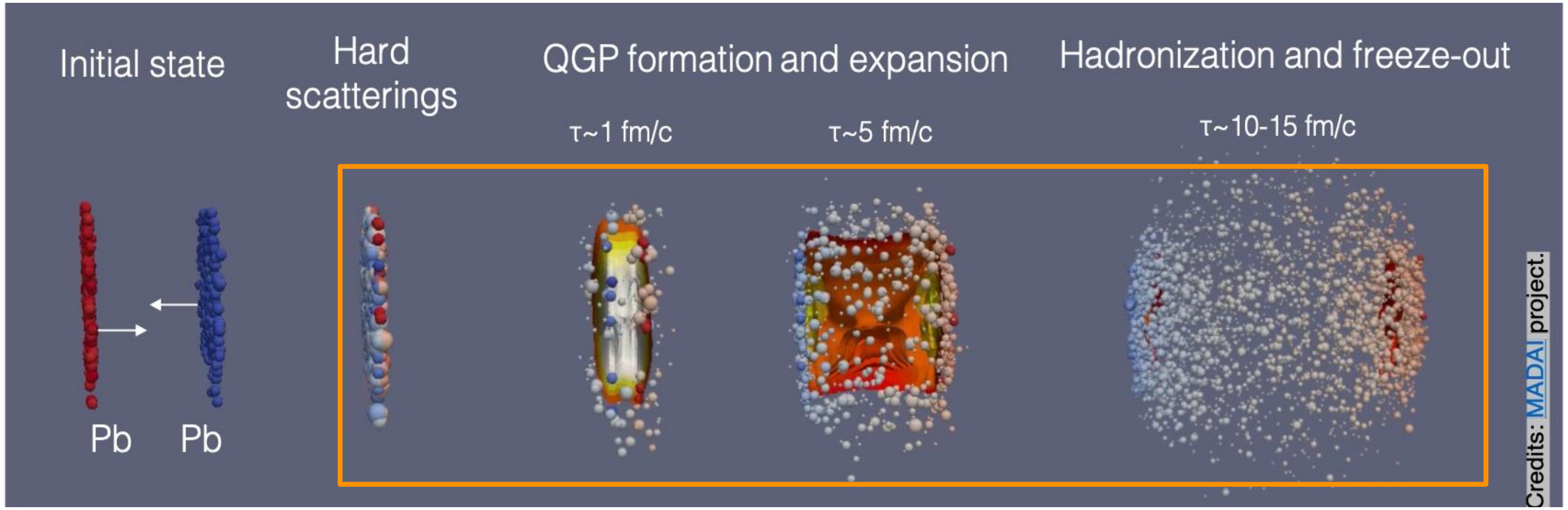
$T_{c,\,lQCD} \sim$ 155-159 MeV [1-4]

No direct observation of the QGP is possible

→ rely on emerging particles as "probes"

[1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
[2] A. Bazavov et al., Phys. Lett. B 795 (2019)
[3] Borsaniy et al. PRL 125 (2020) 5, 052001
[4] A. Andronic et al., Nature 561 (2018) 7723, 321-330

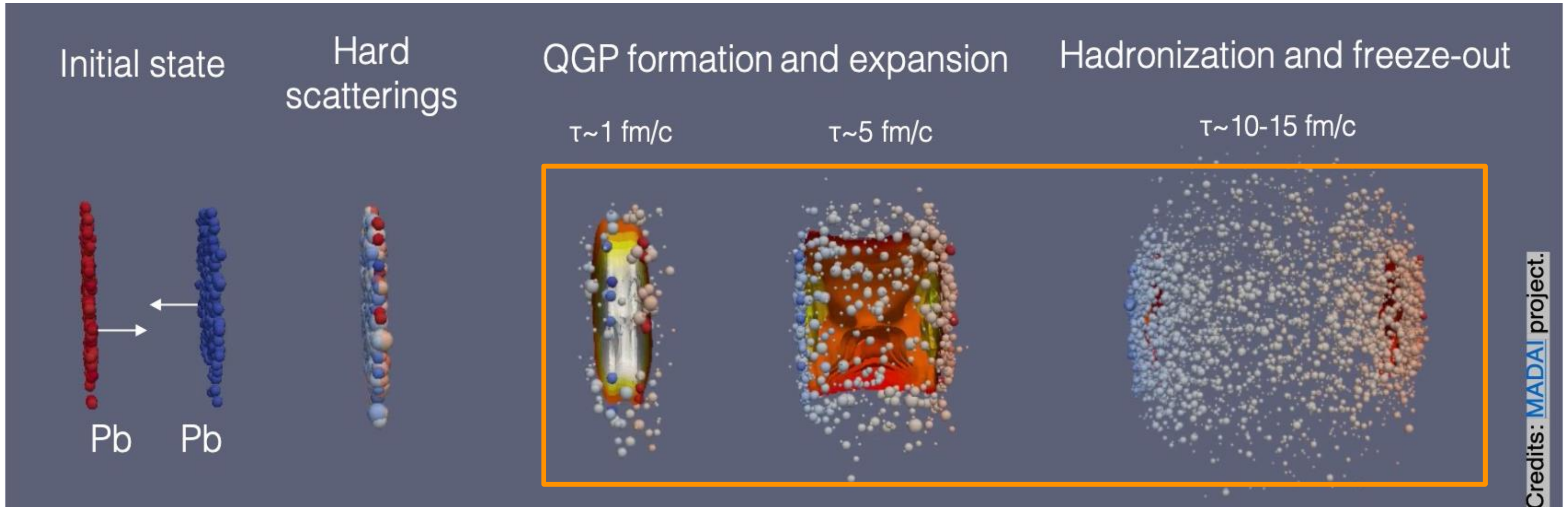
How to probe the QGP: hard probes



1 fm/c = 3x10^{-24} s, 1 MeV ~ 10^{10} K

Charm and beauty quarks (→ open HF, quarkonia), high-p_T partons (→ jets)
produced in the early stages in hard processes,
traverse the QGP interacting with its constituents
→ **rare, calibrated probes, perturbative QCD**
→ **in-medium interaction (energy loss) and transport properties**
→ **in-medium modification of the strong force and of fragmentation**

How to probe the QGP: soft probes



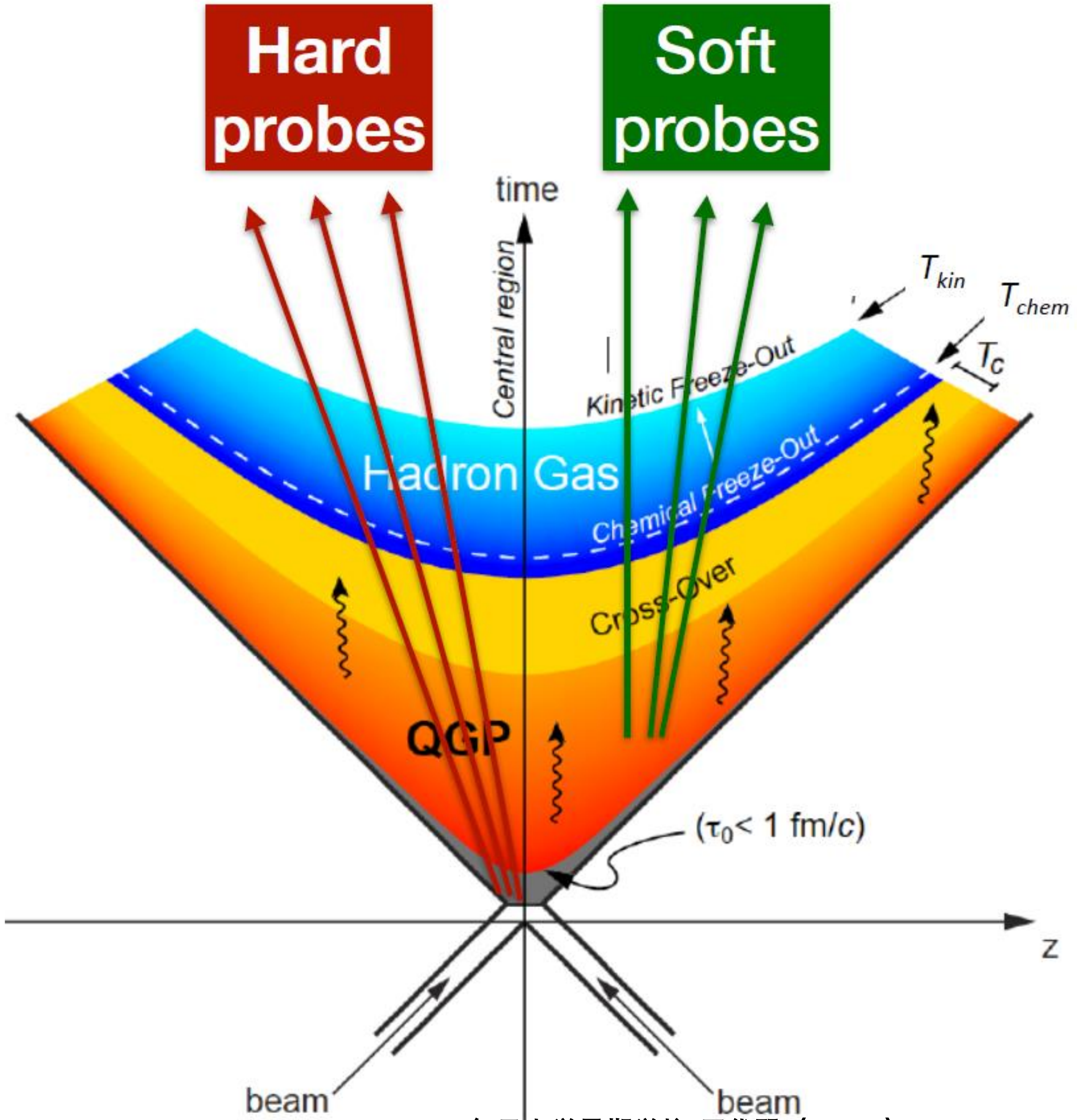
1 fm/c = 3x10^{-24} s, 1 MeV ~ 10^{10} K

Low-p_T particles, light flavour hadrons (u,d,s, + exotic states) produced from hadronization of the strongly-interacting, thermalized QGP constitute the bulk of the system

→ **non-perturbative QCD regime**

→ **thermodynamical and transport properties**

Evolution of the heavy-ion collisions(figure 2)



Hadron and ion colliders

With symmetric proton beams with energy E, the centre-of-mass energy is $\sqrt{s} = 2E$.

With heavy-nuclei, only protons can be accelerated, but neutrons are there too:

$$p_A = Z/A\, p_{proton}$$

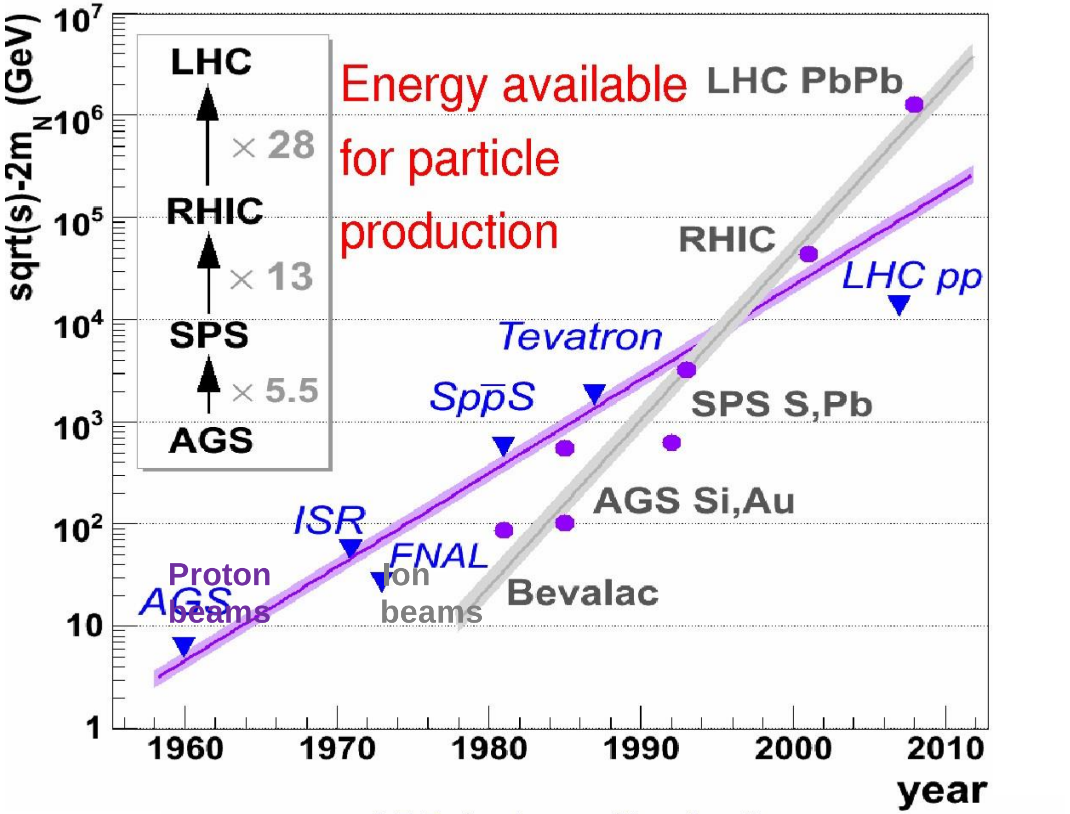
<u>At the LHC</u>, the rigidity of accelerated particles is fixed by the magnet field configuration (B_{max} = 8.3 T).

For the $^{208}Pb^{82+}$ ions used at the LHC:

$p_{Pb} = 82 / 208\, p_{proton}$

p_{proton} = 6.5 TeV (Run 2) $\longrightarrow p_{Pb}$ = 2.56 TeV

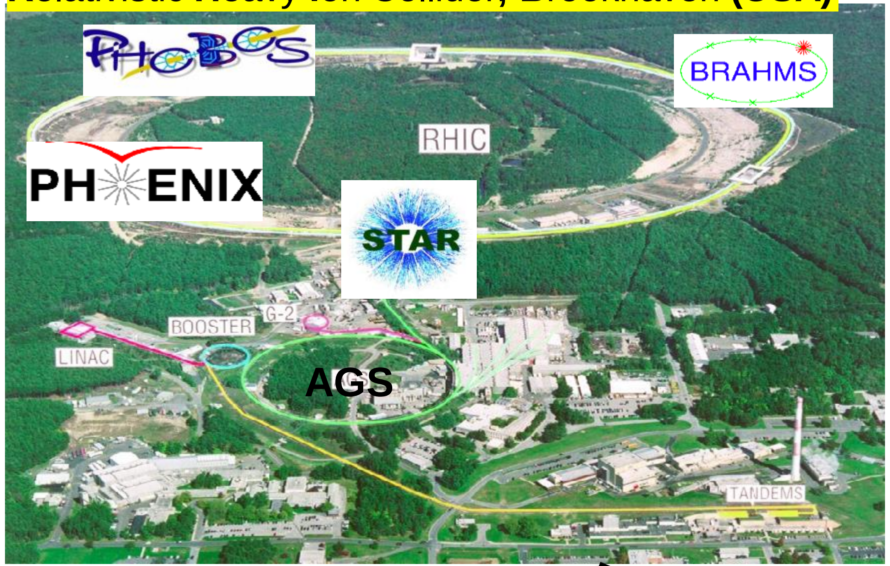
$\longrightarrow$ $\sqrt{s_{NN}}$ = 5.02 TeV $\longrightarrow$ **$\sqrt{s}$ ~ 1.04 PeV**



<u>Some numbers (colliders):</u>
RHIC @ BNL (2000-) $\sqrt{s_{NN}}$ <200 GeV
[beam energy scan $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, and 62.4 GeV]
LHC @ CERN (Run I, 2009-2013) $\sqrt{s_{NN}}$ = 2.76 TeV
LHC @ CERN (Run II, 2015-2018) $\sqrt{s_{NN}}$ = 5.02 TeV
HL-LHC @ CERN (Run III+IV, 2022-2030) $\sqrt{s_{NN}}$ = 5.5 TeV
NICA @ JINR (2021) 3 < $\sqrt{s_{NN}}$ < 11 GeV

Heavy-ion physics worldwide: present/high energy

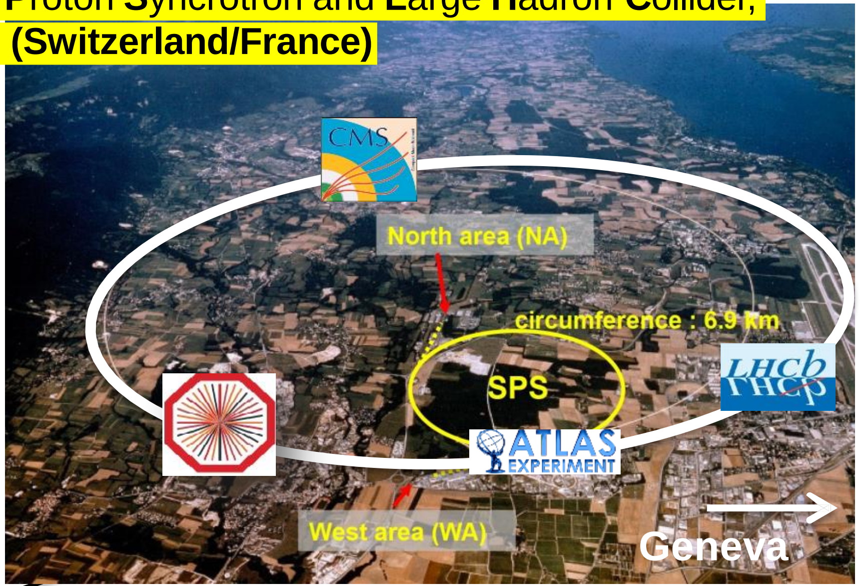
Relativistic Heavy Ion Collider, Brookhaven (USA)

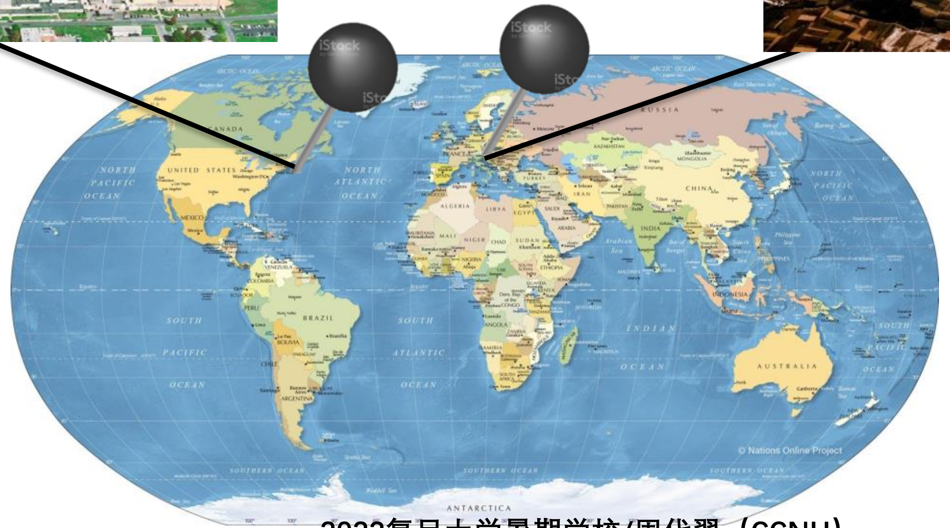


CERN SPS

- Operating since 1986
- Circumference 6.9 Km
- max p = 450 A/Z GeV
- $\sqrt{s_{NN}} < 20$ GeV
- Ongoing: NA61/Shine

Super Proton Syncrotron and Large Hadron Collider, CERN (Switzerland/France)





Brookhaven RHIC

- Operating since 2000
- Circumference 3.83 km, 2 rings
- Superconducting magnets
- $\sqrt{s_{NN}} = 3$ - 200 GeV in Au-Au
- Beam energy scan I: 2010-11
- Beam energy scan II: 2019-22
- Ongoing exp: STAR

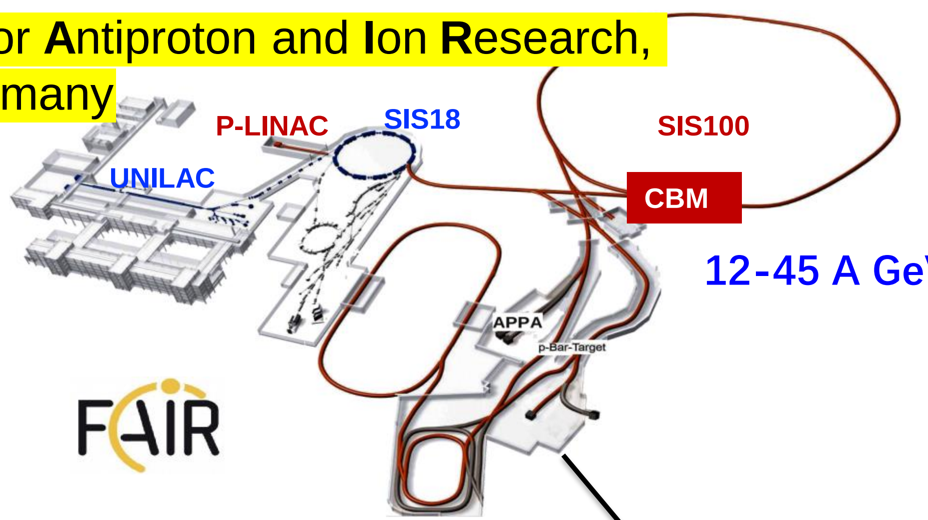
CERN LHC

- Operating since 2009
- Run III: started in 2022
- Circumference: 27 km
- B-field: 8 T, superconducting
- pp $\sqrt{s}$ = 0.9 – 13.6 TeV
- Pb-Pb $\sqrt{s_{NN}} = 2.76$-5.5 TeV
- Main ongoing: ALICE, ATLAS, CMS, LHCb

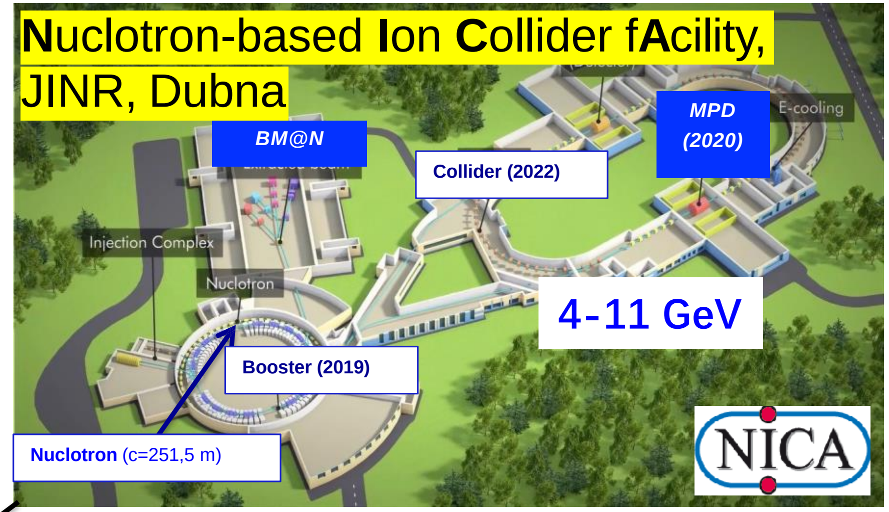
F. Bellini | SSL 2022 | Heavy Ions

Heavy-ion physics worldwide: future/low energy

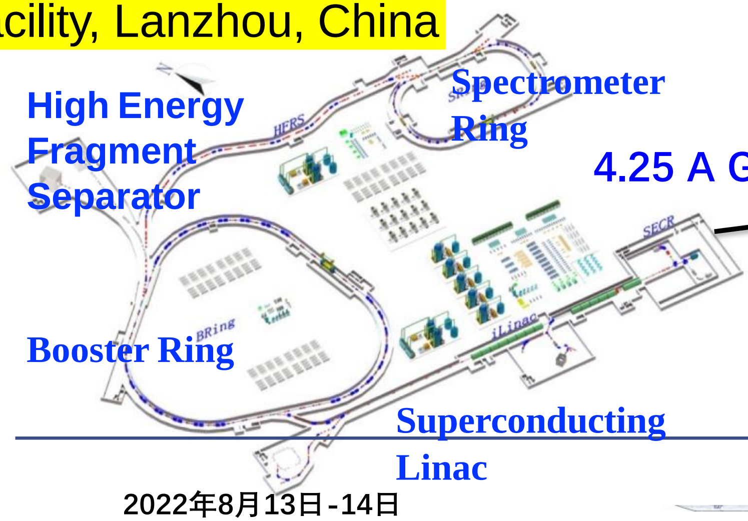
Facility for **A**ntiproton and **I**on **R**esearch, GSI, Germany

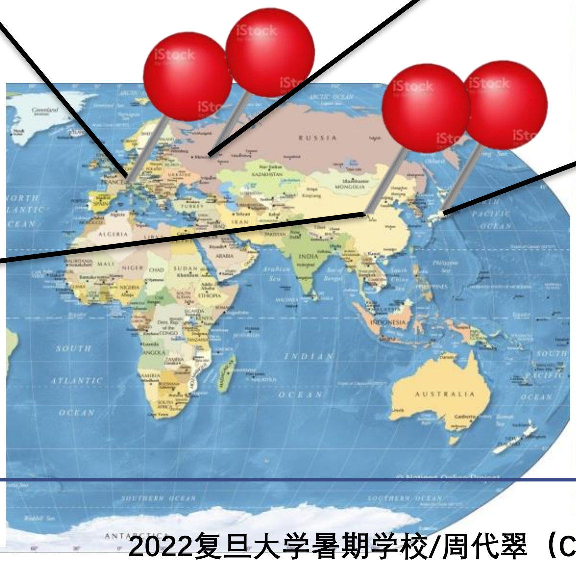


Nuclotron-based **I**on **C**ollider f**A**cility, JINR, Dubna

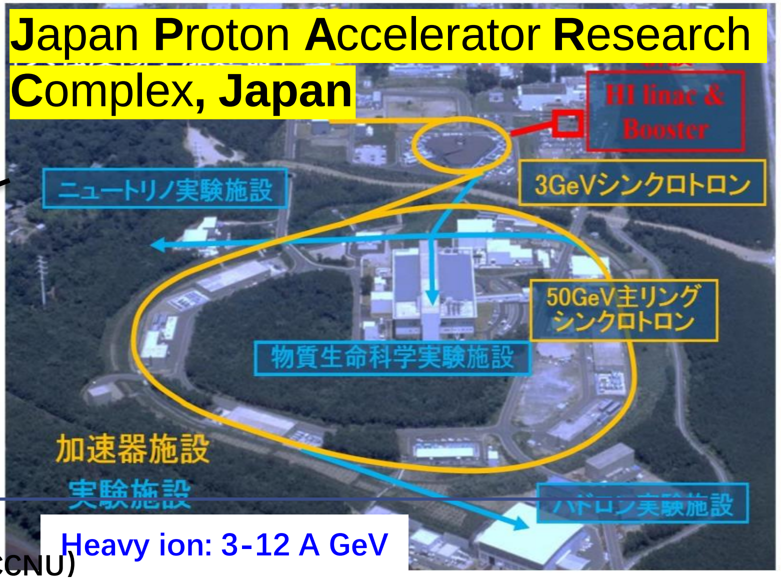


High-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Lanzhou, China





Japan **P**roton **A**ccelerator **R**esearch **C**omplex, **Japan**



Heavy-ion physics at the LHC

2010-2012		2015-2018		2022-2025		2028-2030		2032-2034		2036-2039
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

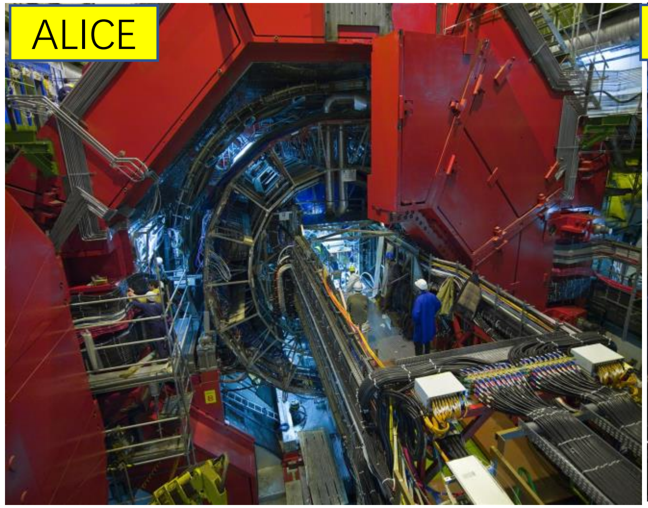
High luminosity LHC

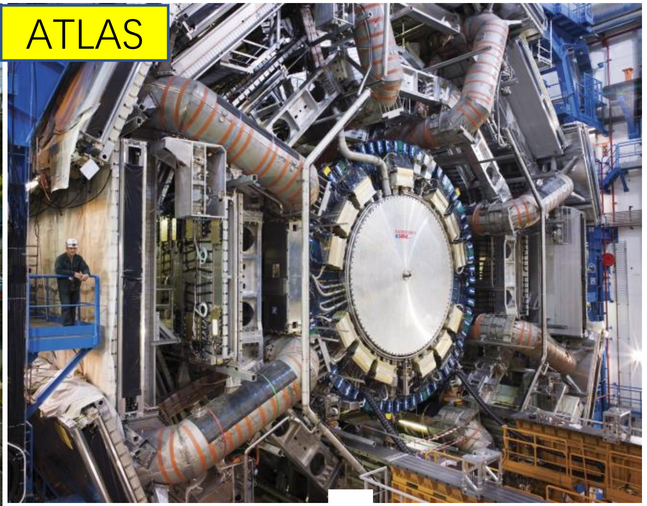
Major upgrades for **ALICE and LHCb**

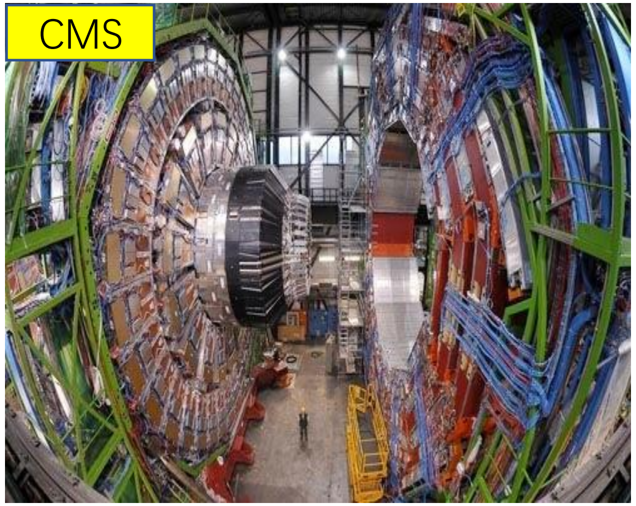
We are here

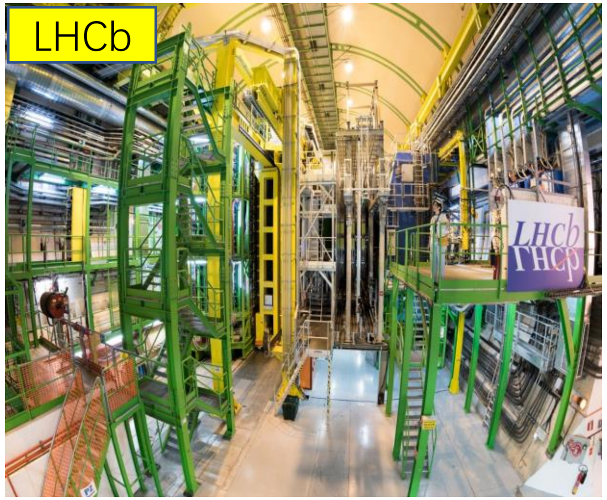
ATLAS and CMS phase II
ALICE ITS3 and FoCal

ALICE 3: a whole new dedicated HI detector!
LHCb upgrade II







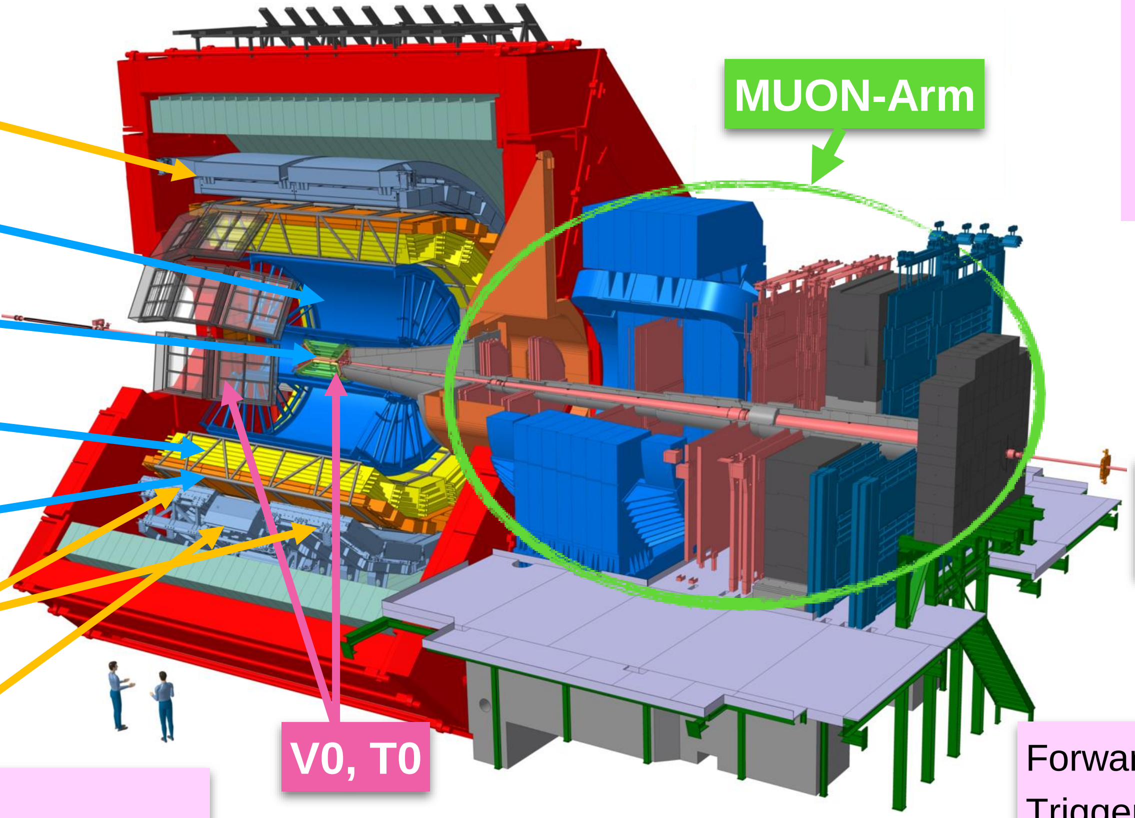


Dedicated heavy-ion detector: ALICE

Dedicated to measure
hadrons, electrons, muons and photons to cope with very high multiplicities

Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

Solenoid: magnetic field B = 0.5 T



Muon-Arm ($-4<\eta<-2.5$):
Muon trigger, tracking, PID

Forward rapidity detector (**V0, T0, ZDC, SPD):**
Trigger, centrality selection, event plane rec.

Central Barrel ($|\eta|<0.9$)

- **ITS, TPC**: vertexing + 2π tracking and PID down to very low pT~0.1 GeV/c
- **EMCal/Dcal, PHOS:** high-p_T electron trigger, PID

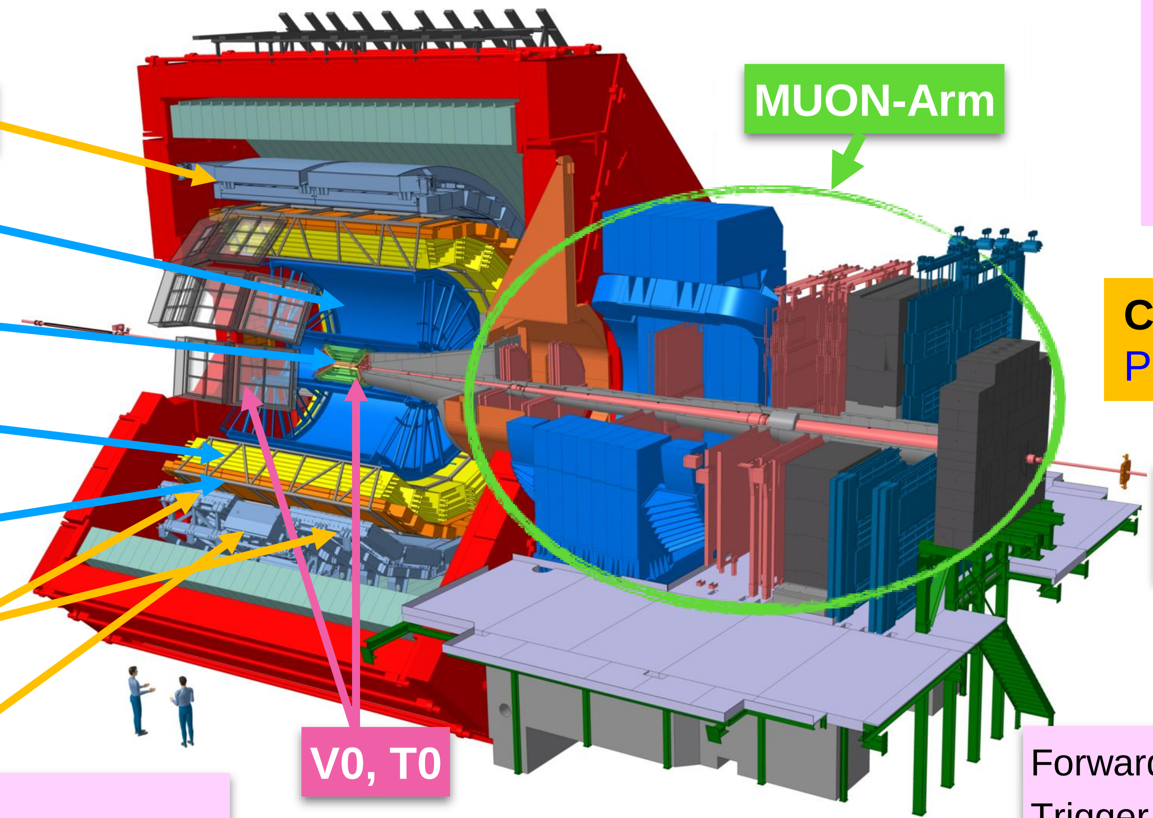
TOF, TRD, HMPID, etc.:
Particle identification detectors

Dedicated heavy-ion detector: ALICE

Countries: 40
Institutes: 176
Members: 2002

Detector:
Length: **26** meters
Height: **16** meters
Weight: **10,000** tons

Solenoid: magnetic field B = 0.5 T



Dedicated to measure hadrons, electrons, muons and photons to cope with very high multiplicities

Collisions systems (so far) :
Pb-Pb, pp, p-Pb, Pb-p, Xe-Xe

Muon-Arm ($-4<\eta<-2.5$):
Muon trigger, tracking, PID

Forward rapidity detectors (**V0, T0, ZDC, SPD**):
Trigger, centrality selection, event plane rec.

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- **ITS, TPC**: vertexing + 2π tracking and PID down to very low pT~0.1 GeV/c
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TOF, TRD, HMPID, etc.:
Particle identification detectors

Chinese participation:
CCNU, CIAE, CGU, Fudan, HUST, HTU, USTC

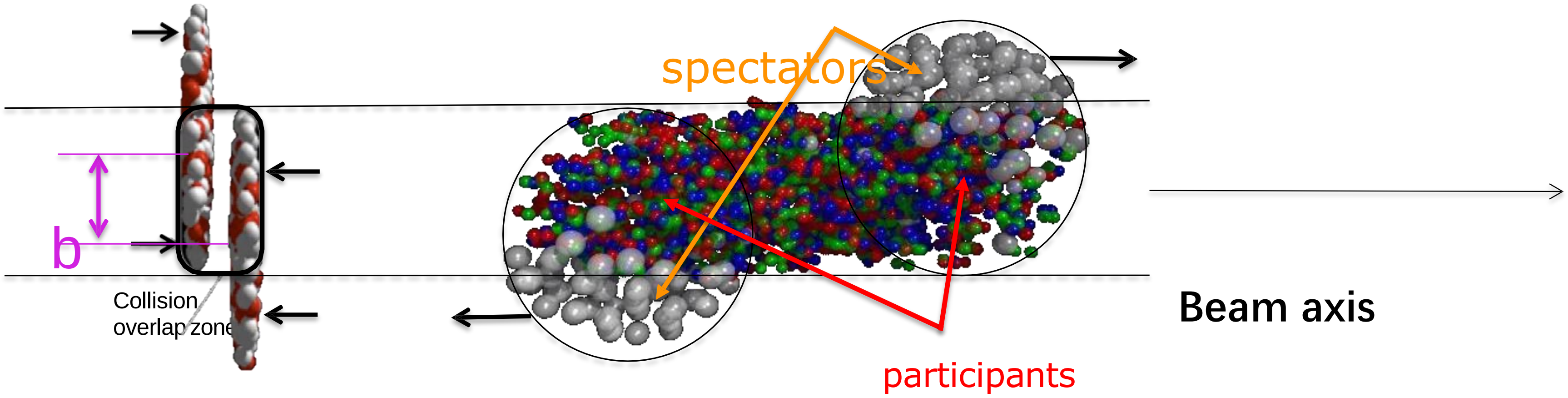
Hardware contribution from China:
- PHOS: FEE;
- DCAL/EMCAL: one supermodule
- ITS2: 520 modules, MAPS design
- MFT: five readout discs

Physics on:
- Photons and jets
- Heavy-flavors and quarkoniums
- Collectivity
- Exotic particle properties
- Cold nuclear effects

Geometry of heavy-ion collisions

We can control the geometry of the collision only by selecting in **centrality**.

Centrality = fraction of the total hadronic cross section of a nucleus-nucleus collision, typically expressed in percentile, and related to the impact parameter (**b**)



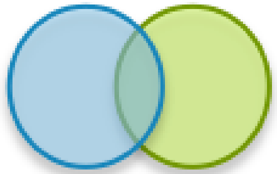
Other variables related to centrality:

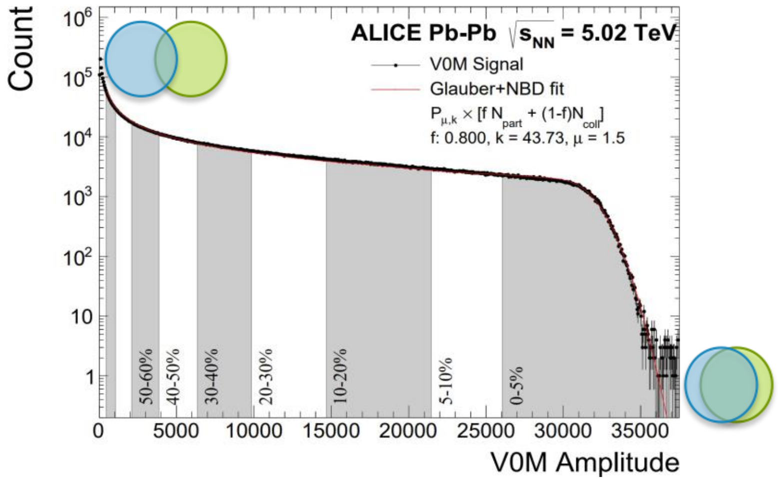
- **N_{coll}**, number of binary nucleon-nucleon collisions
- **N_{part}**, number of participating nucleons

Geometry of heavy-ion collisions

More **central**, ie. “head-on” collisions
→ smaller impact parameter
→ larger overlap region
→ more participants
→ more particles produced

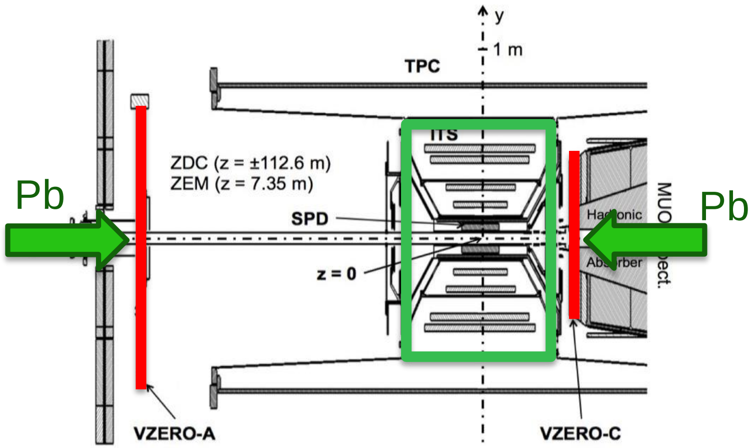
More **peripheral** collision
→ larger impact parameter
→ smaller overlap region
→ less participants
→ fewer particles produced



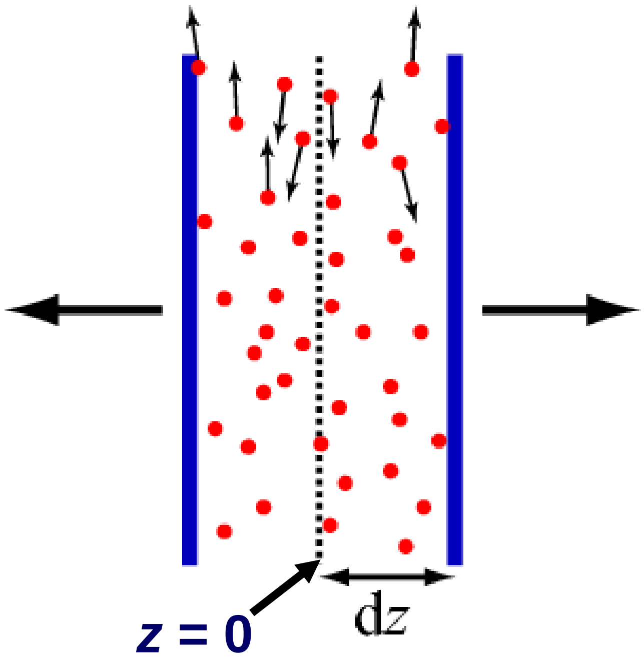


ALICE, PRL 106 (2011) 032301, PRC 91 (2015) 064905

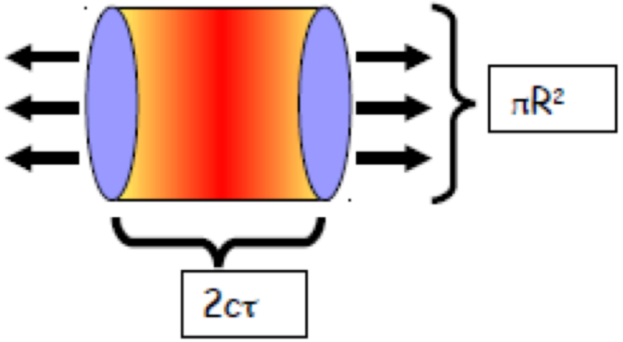
Centrality is determined by **counting the number of particles (multiplicity)** or **measuring the energy deposition** in a region of phase space *independent* from the measurement, to avoid biases/autocorrelations in the results.



Bjorken's Estimate of the Energy Density



Bjorken estimate:



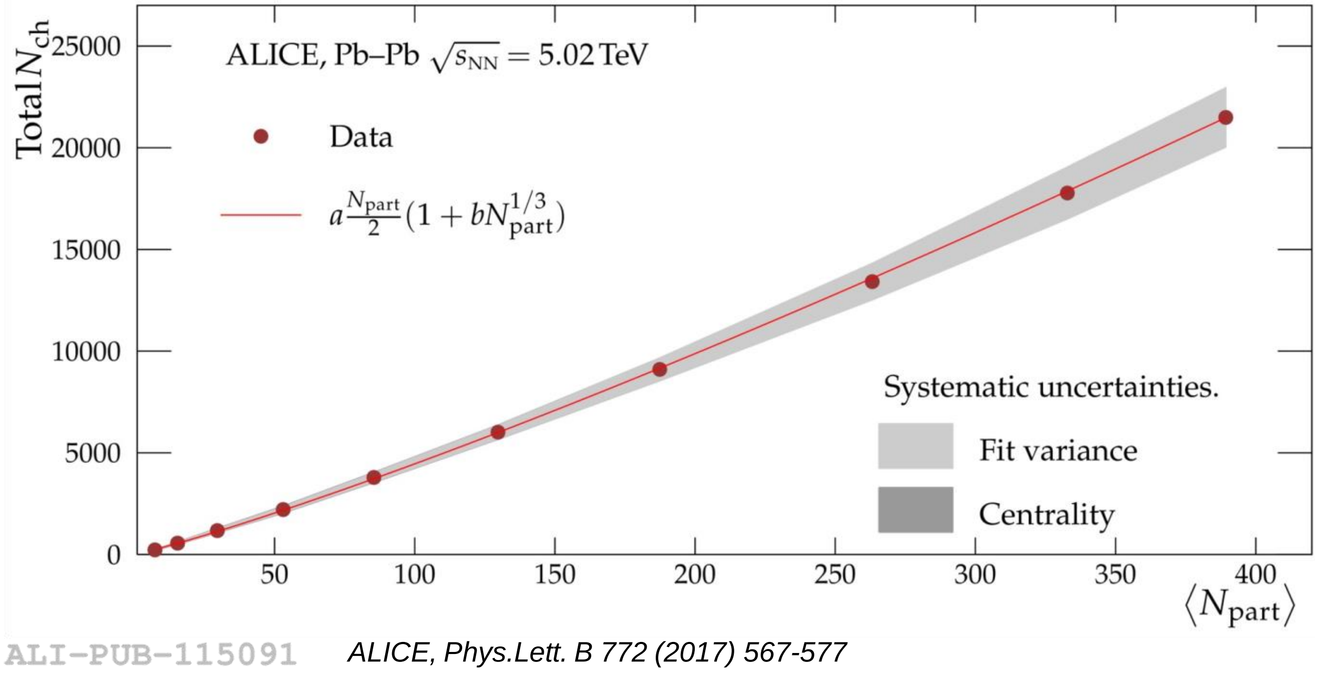
$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y} \longleftrightarrow \mathrm{d}N/\mathrm{d}\eta$$

Related to thermalization time τ_0 (1 fm/*c*)

- Central Pb–Pb collisions at 5.02 TeV d*N*/dη ~ 2000
  - ➡ Energy density ε ~18 GeV/fm^3
  - ➡ Above deconfinement transition (~1 GeV/fm^3)

How many particles are created in a collision?

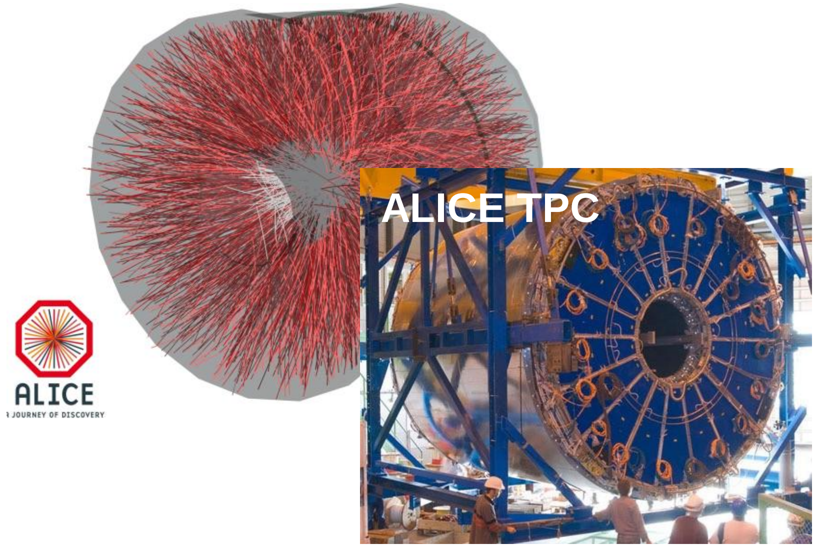
Total Charged particle multiplicity



ALICE, Phys.Lett. B 772 (2017) 567-577

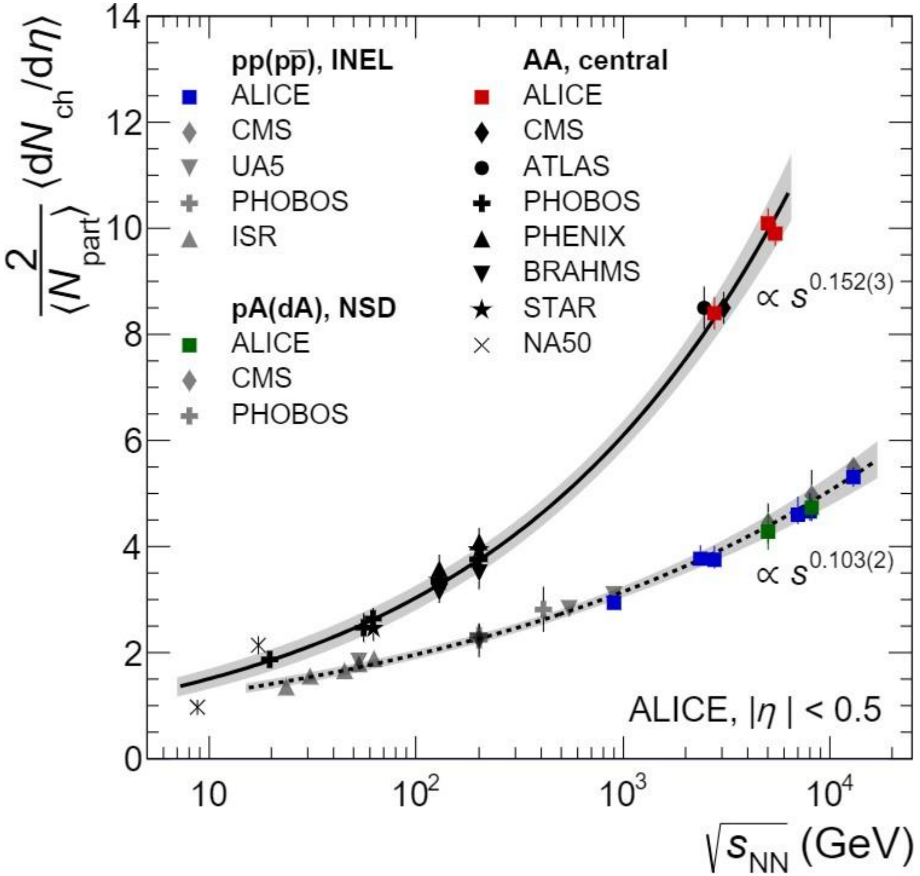
In a central Pb-Pb collision at the LHC, more than 20000 charged tracks must be reconstructed.

→ **High granularity tracking systems, primary importance of tracking, vertexing calibration**



Charged particle density in central AA collisions

Average charged particle multiplicity density normalized to the average N_{part} vs $\sqrt{s_{NN}}$

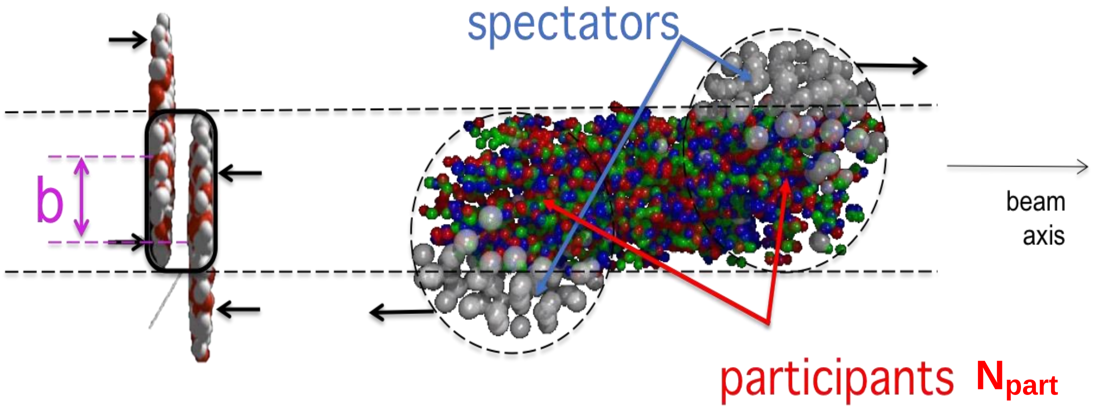


ALICE *Phys. Rev. Lett.* 116 (2016) 222302

ALICE Eur. *Phys. J. C* (2019) 79:307

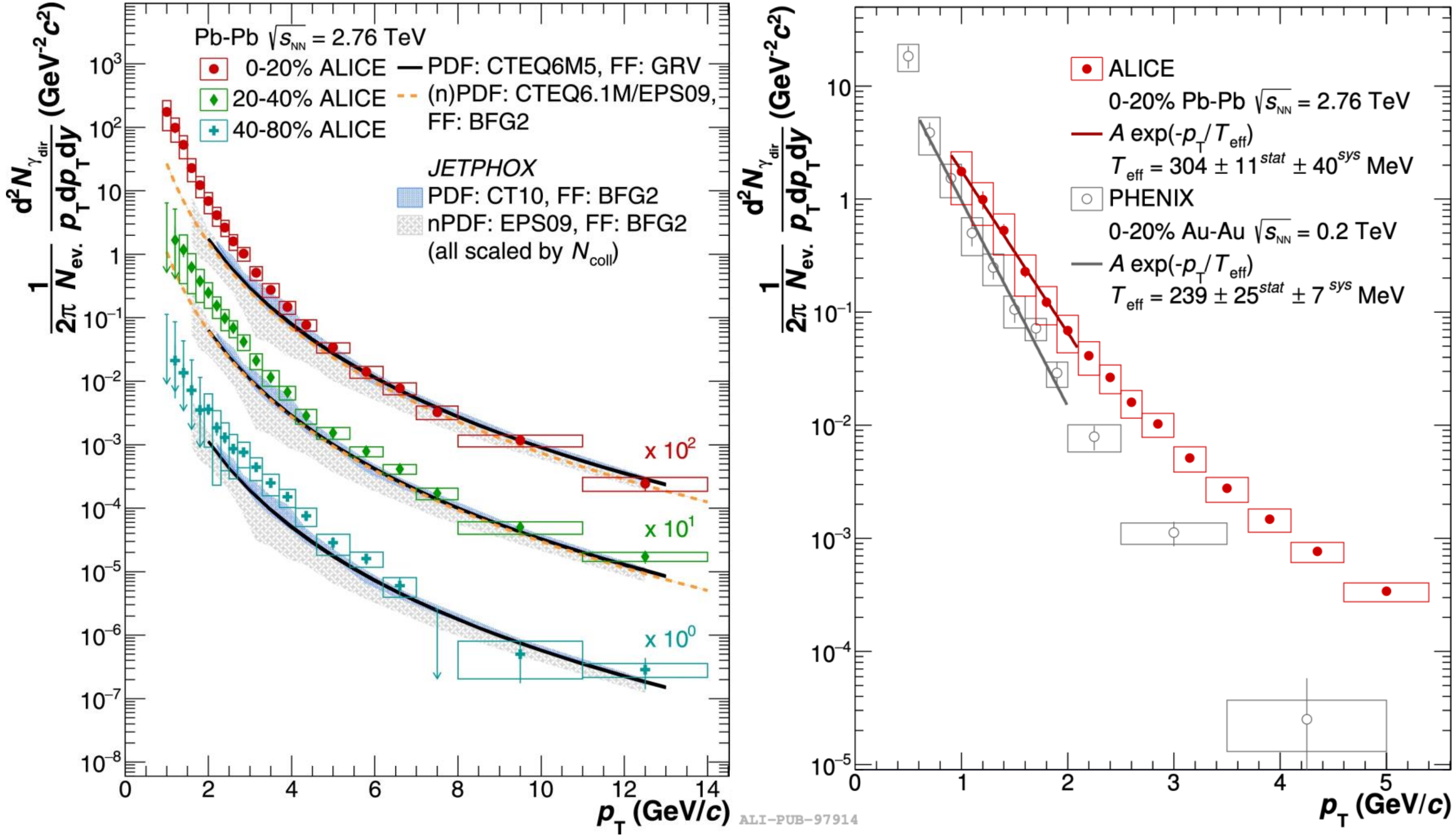
Particle production per participant in AA collisions follows a steeper power law than in pp, pA and increased by **2-3x** from RHIC to the LHC

AA collisions are more efficient in transferring energy from beam- to mid- rapidity than pp



- ALICE: Pb–Pb at 5.02 TeV — highest energy so far
  - ➡ For 0–5% most central collisions, confirms trend from lower energies

Temperature of the QGP



- Low-p_T: 2.6σ excess w. r. t. models in 0–20% central — thermal contribution
- T_{eff} = 297 ± 12(stat.) ± 41 (syst.) MeV in central collisions — above T_c ~ 170 MeV
- 30% higher than at RHIC (Au–Au at $\sqrt{s_{NN}}$=200 GeV)

ALICE *Phys. Lett.* **B754** (2016) 235