Heavy-ion collision experiment (Lecture 1)

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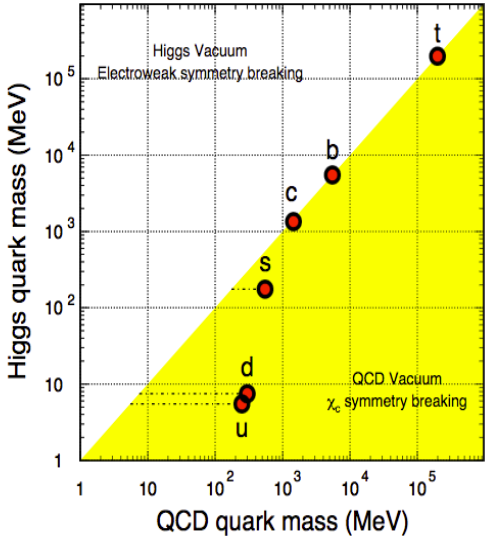
1. Introduction to relativistic heavy-ion collisions
2. Particle yields and statistical model
3. Hard probes of QGP: jets
4. Hard probes of QGP: heavy flavors
5. Quarkonia
6. Highlights from small systems
7. Summary and outlook

1. Introduction to 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	Hadron Masses
Impossible to find an isolated quark or gluon Why?	Proton consists of 2u+1d quark m_{uud}~10 MeV , m_p = 938 MeV Where is the extra mass generated?

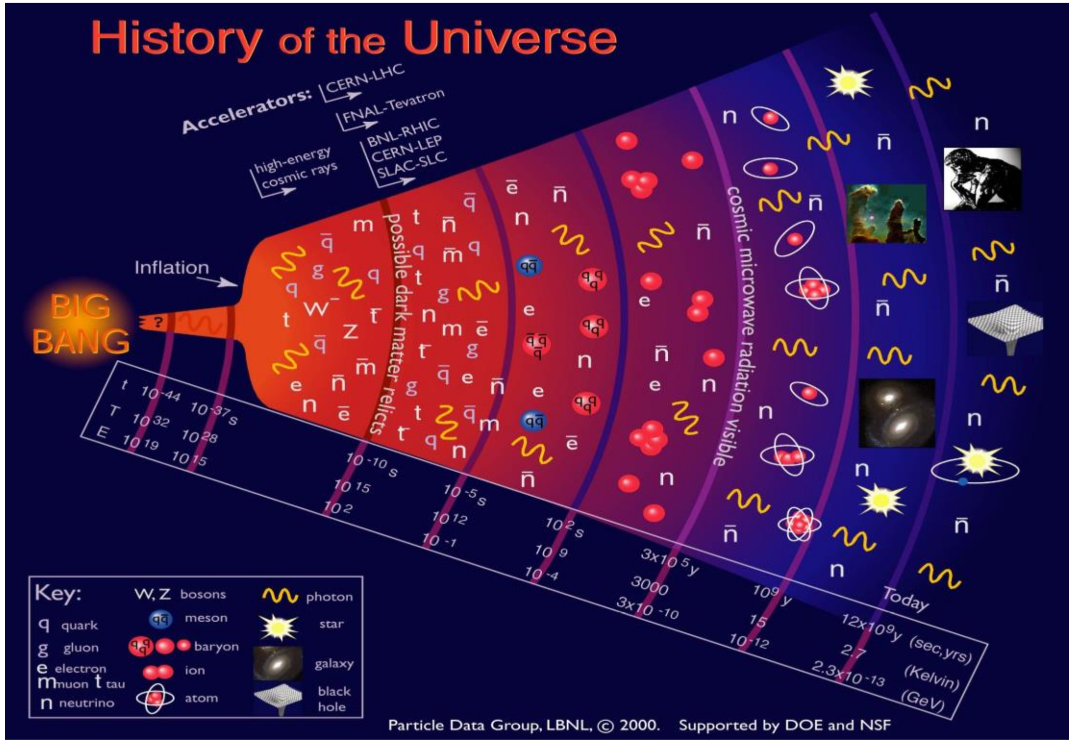


Fundamental Questions

- 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 high temperature and large density?
- 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 purpose of heavy-ion collision?

- **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
  …

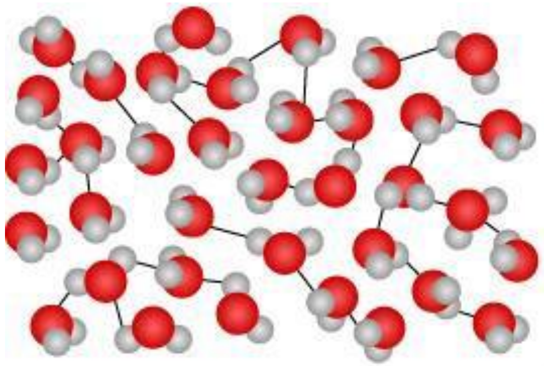


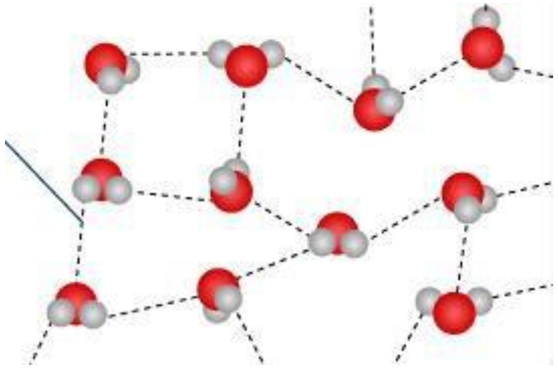
Phases of QED matter

Vapor

Water

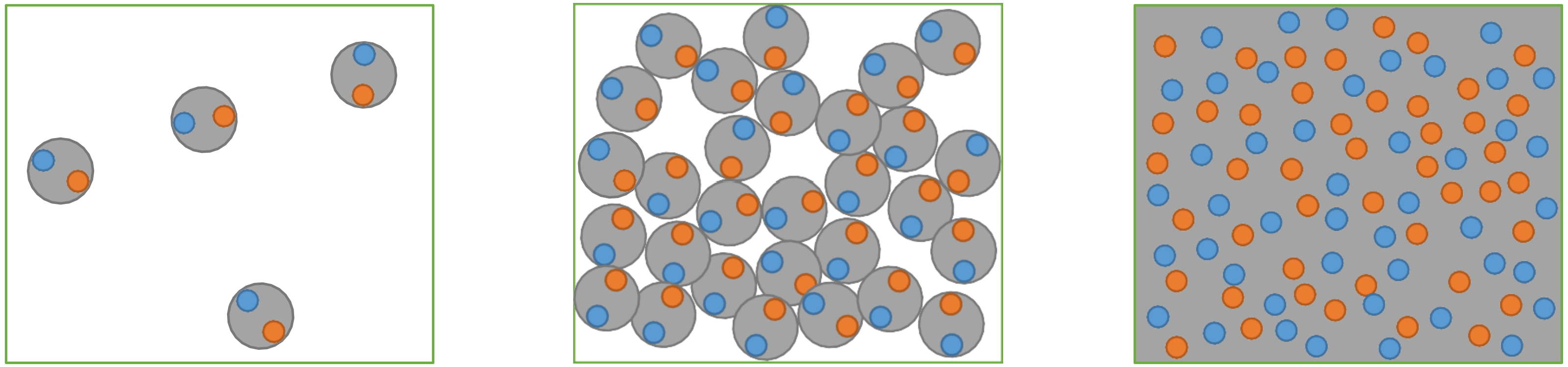
Ice





Ultra-dense QCD matter

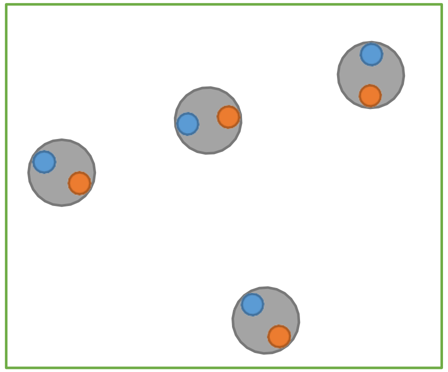
Increase the Temperature (T)



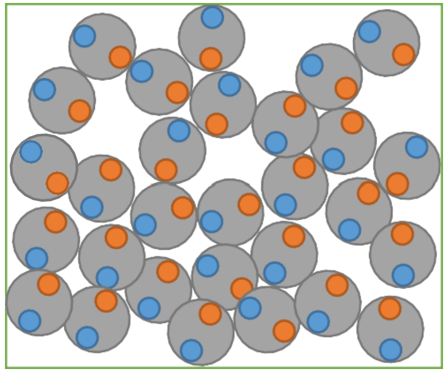
$T<T_C$ $T\sim T_C$ $T>T_C$

Ultra-dense QCD matter

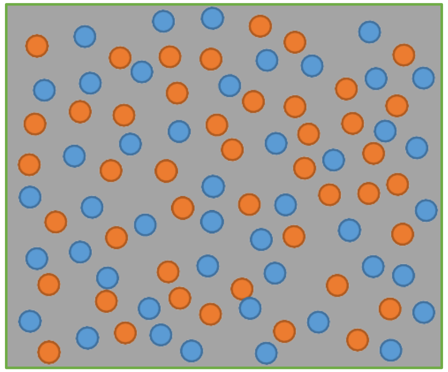
Increase the Temperature (T)



$T<T_C$

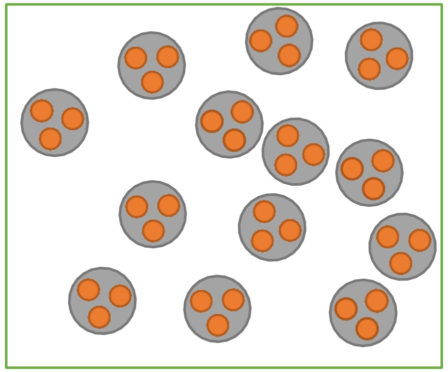


$T\sim T_C$

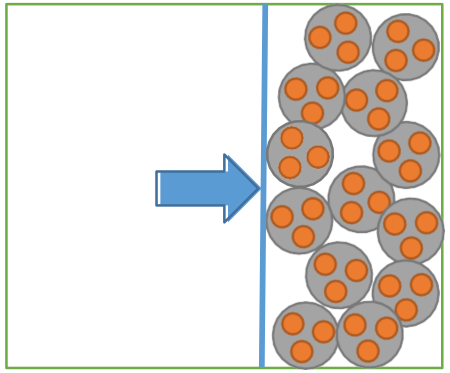


$T>T_C$

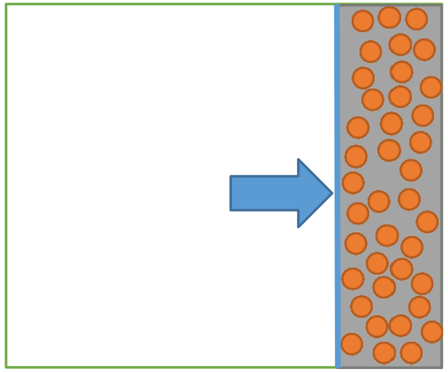
Increase the Density (ρ)



$\rho<\rho_C$



$\rho\sim\rho_C$



$\rho>\rho_C$

Fundamental properties of QCD

- **Confining property of QCD**

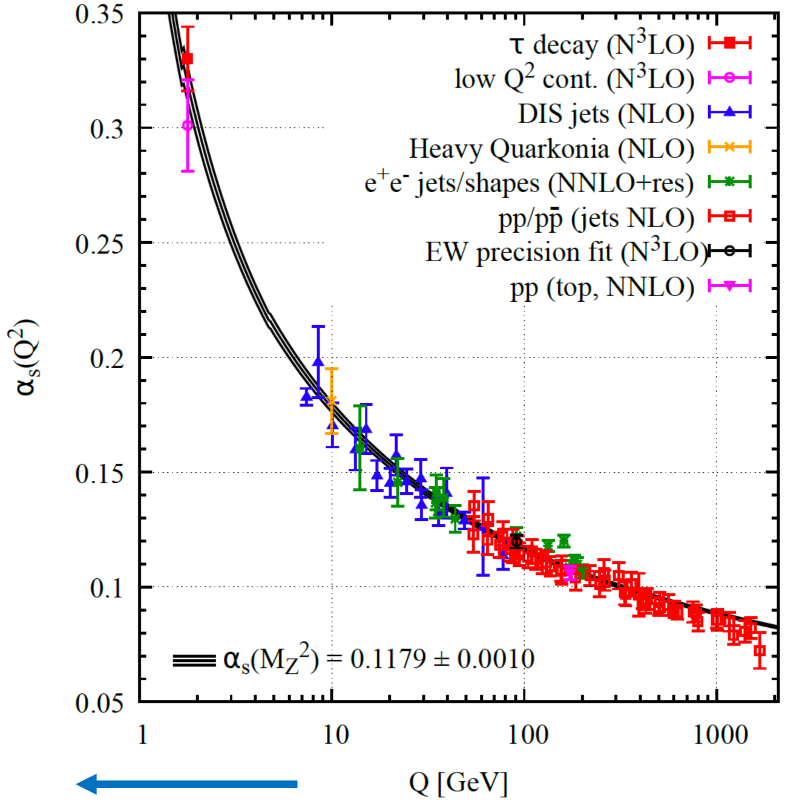
  Quarks and gluons exist in nature as confined in colorless hadrons: ordinary matter at room temperature

- **Asymptotic freedom**

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

- **Mass of hadrons** is a consequence of the strong interaction acting among their constituents

  Chiral symmetry is explicitly broken by non-zero quark masses: (light) quarks acquire mass dynamically



Understanding confinement

Properties of the QCD vacuum:

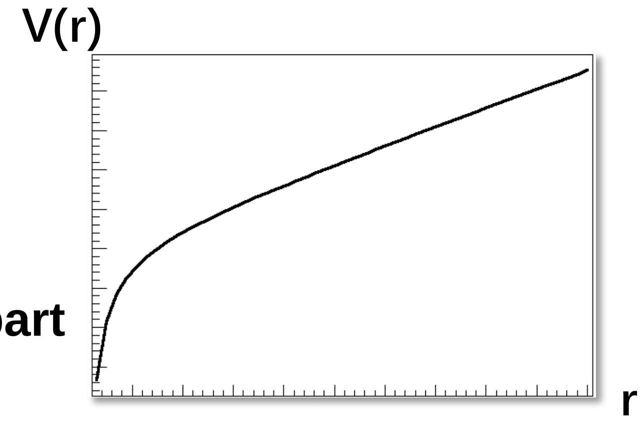
- Gluon-gluon self-interaction (non-abelian)
- QCD field lines compressed in flux tube (or “string”)

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

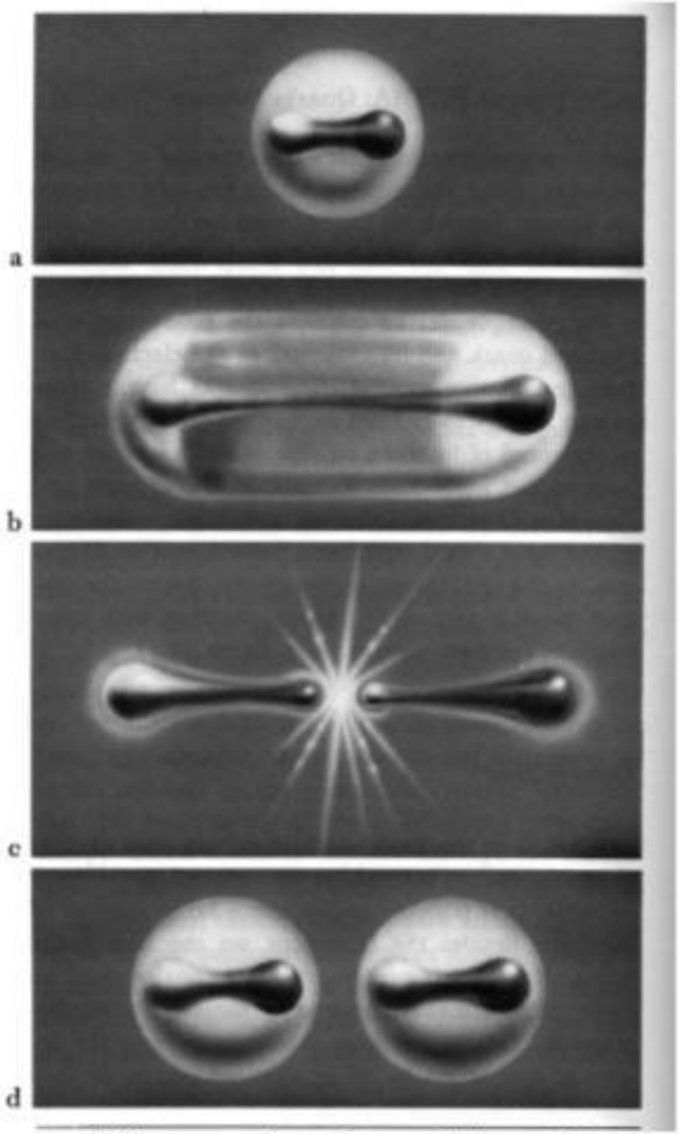
$$\boxed{V(r) = -\frac{a}{r} + \sigma r}$$

qqg part
“Coulomb”-like

gg part



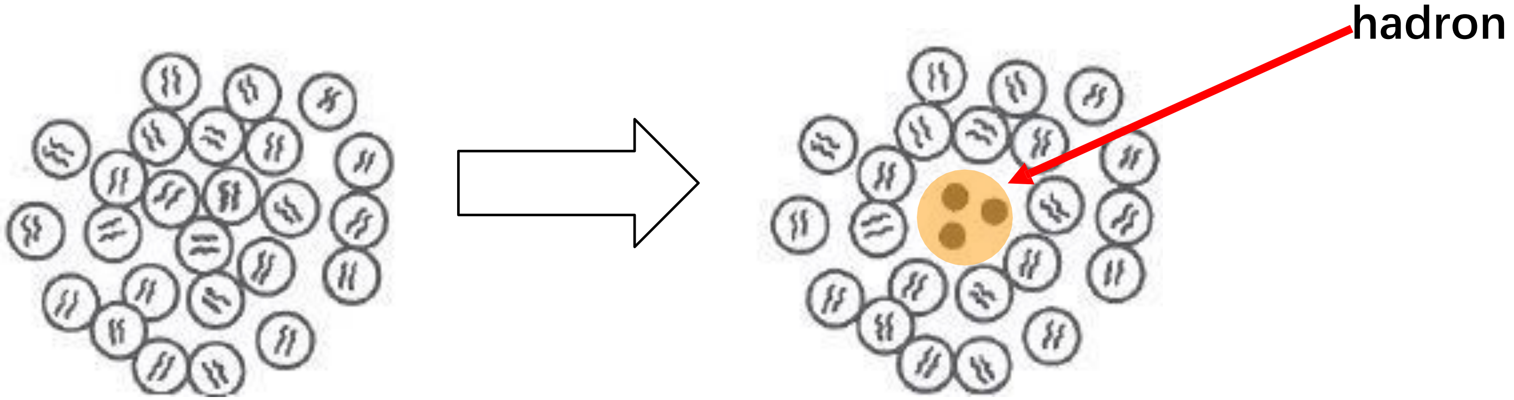
- The potential grows with distance.
- If pulled apart, the energy in the string increases
- A new q-qbar pair is created once the energy is above production threshold.
- No free quark can be obtained by breaking a flux tube → confinement



[illustration from Fritzsch]

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 QCD 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.

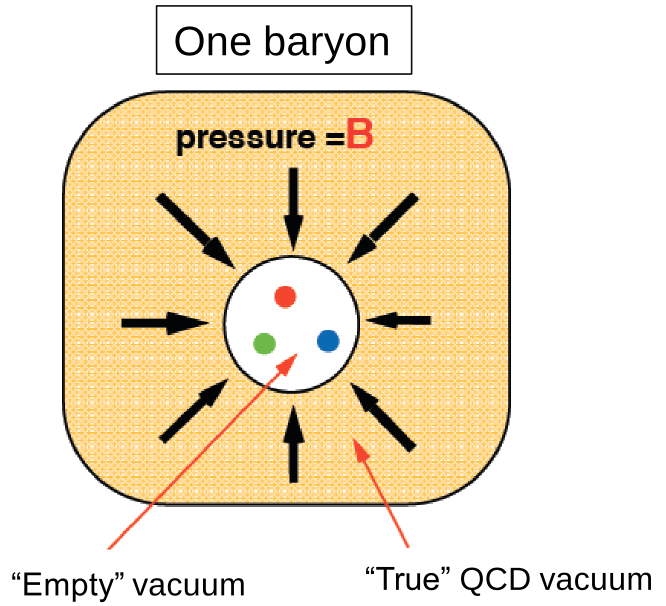
If the hadron can be modeled as *N* massless Dirac fermions in a spherical cavity,

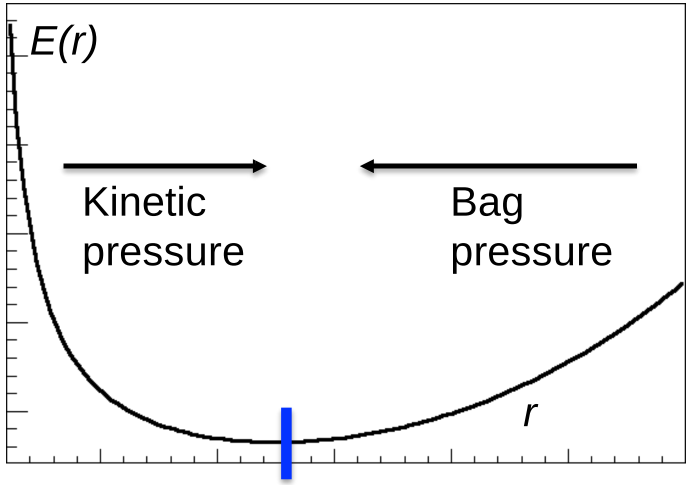
$$E = \frac{2.04N}{R} + \frac{4\pi}{3} R^3 B$$

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

→ $B_{MIT} \sim (200\ \mathrm{MeV})^4$

If kinetic pressure exceeds bag pressure? → deconfinement





PRD9, 3471 (1974)

Deconfinement

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

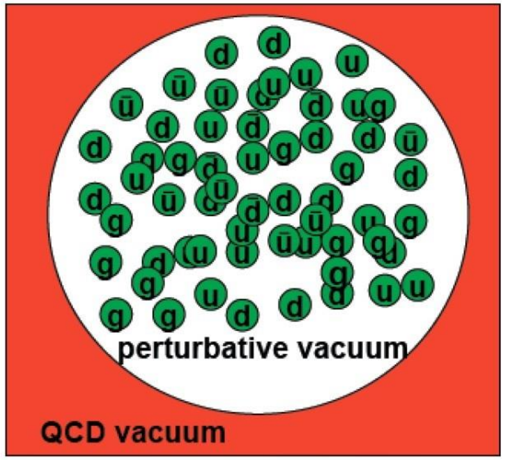
$$P = \left(n_g + \frac{7}{8} n_f \right) \frac{\pi^2 T^4}{90}$$

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

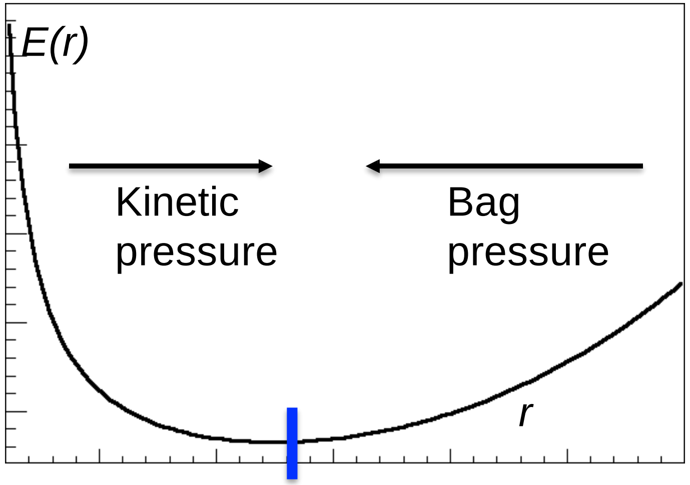
A gas of relativistic partons



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)**

QCD phase diagram

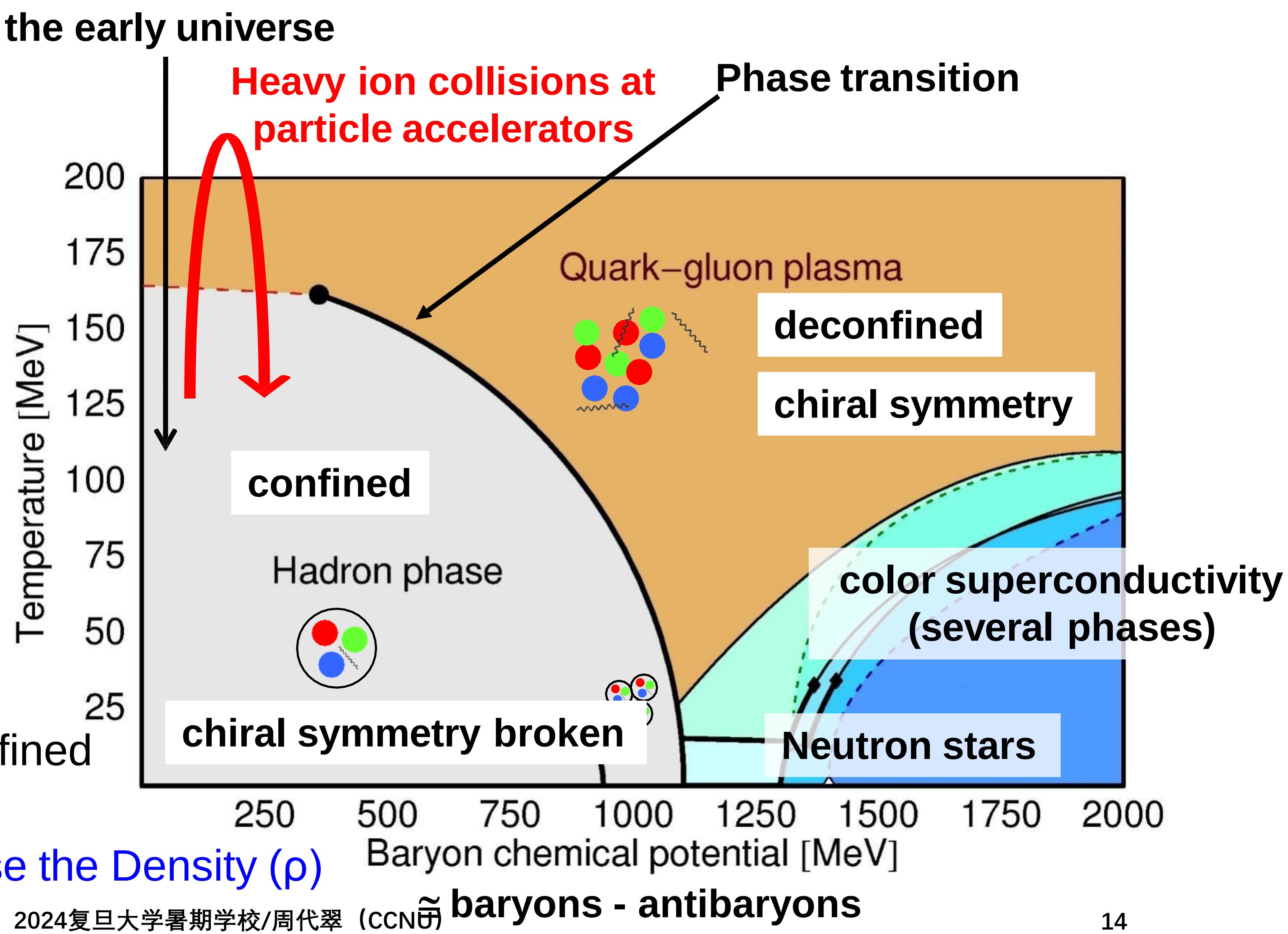
The phases of QCD matter can be summarized in a phase diagram as a function of two parameters:

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!

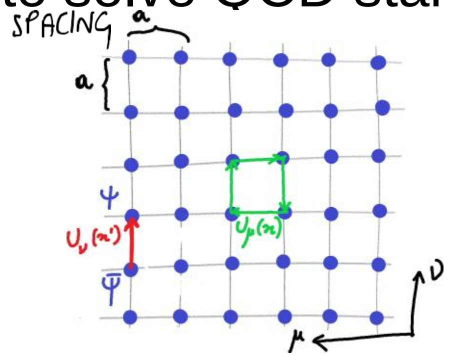
The quark-gluon plasma is the deconfined phase of strongly-interacting matter.

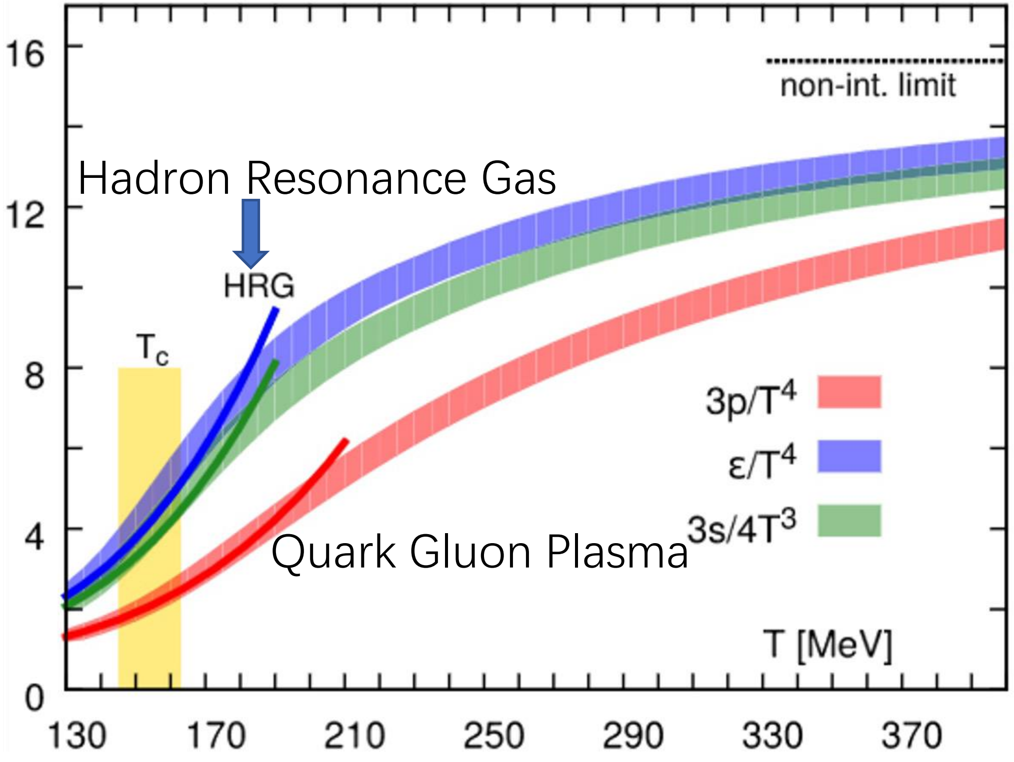


Increase the Density (ρ)

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)]

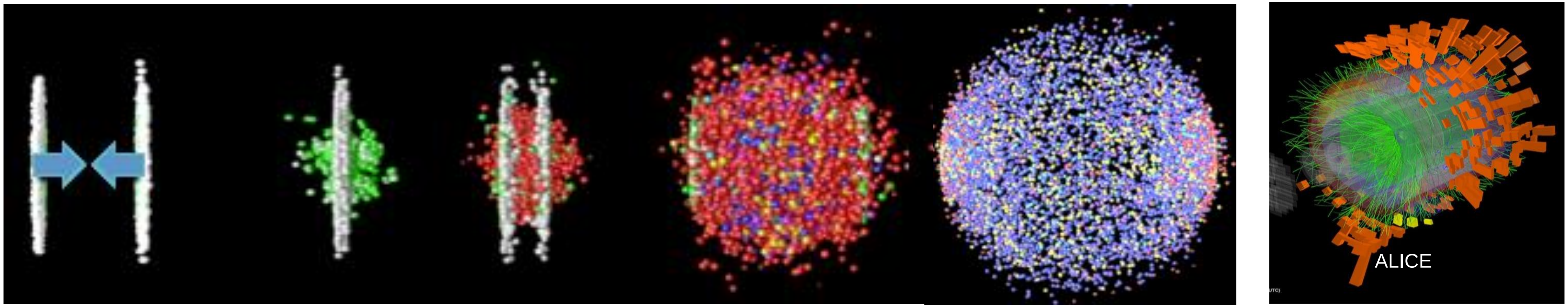
- around critical temperature (T_C): rapid change of
  - energy density ε
  - entropy density s
  - pressure density p
- due to activation of partonic degrees of freedom
- at zero baryon density → smooth crossover
- $T_C = (156.5 \pm 1.5)$ MeV [A Bazavov et al. Phys.Lett.B 795 (2019) 15]
- $\varepsilon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

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

相对论重离子碰撞的演化图像

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

τ=0 | τ=0.2-1 fm | τ=5 fm | τ=10–15 fm



$1\ \mathrm{fm}/c = 3\times10^{-24}\ \mathrm{s}$, $1\ \mathrm{MeV} \sim 10^{10}\ \mathrm{K}$

Time

Temperature

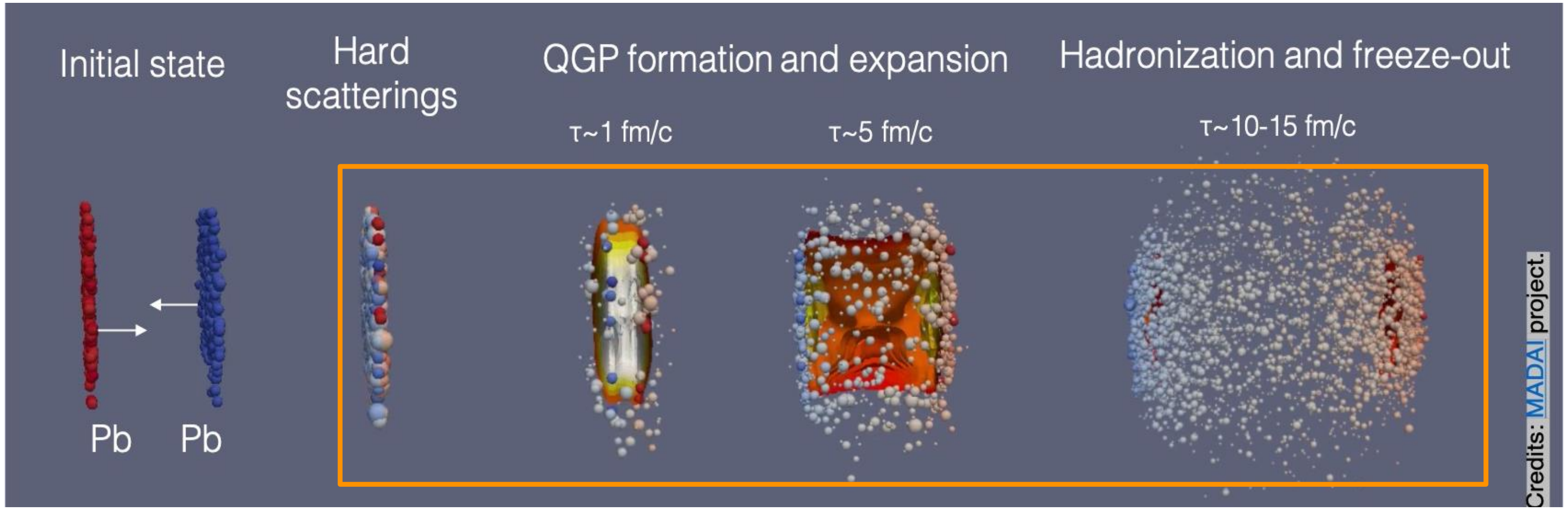
$T_{c,\ \mathrm{lQCD}} \sim 156\text{-}159\ \mathrm{MeV}$ [1-4]

- QGP 温度高达到了～4万亿摄氏度，比太阳中心温度（2000万度）高～20万倍，是一种理想流体,具有最小的约化粘滞系数（$2.5/4\pi > \eta/s > 1/4\pi$）

[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

- No direct observation of the QGP is possible → rely on emerging particles as “probes”

How to probe the QGP: hard probes



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

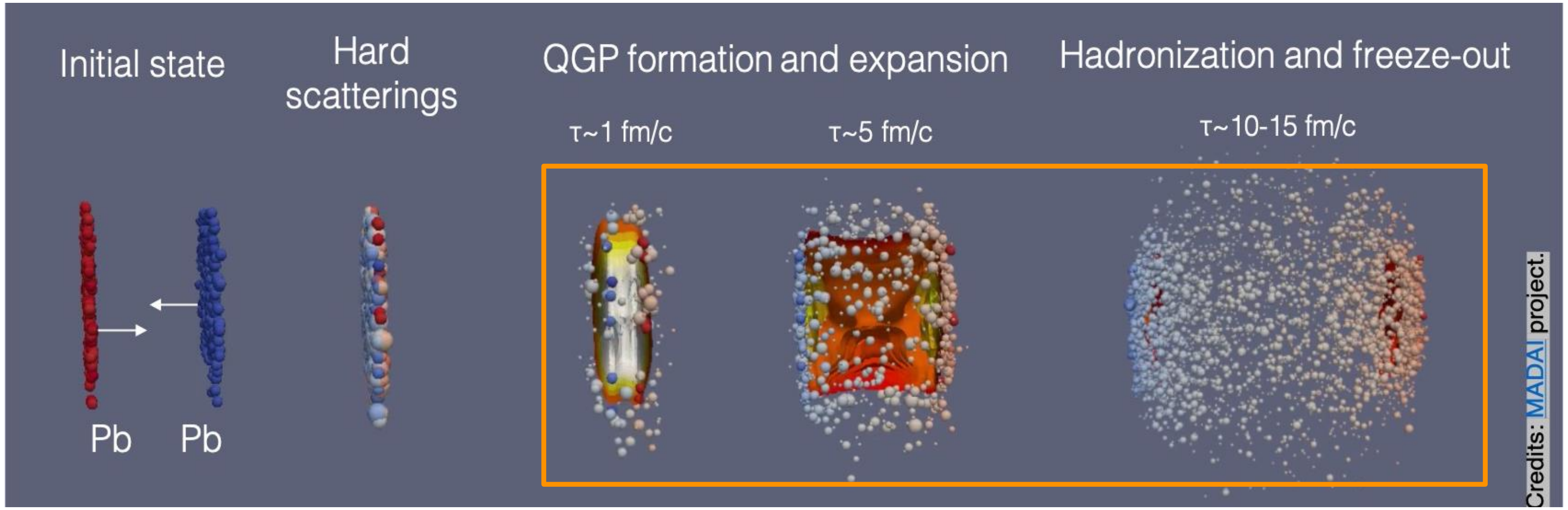
Charm and beauty quarks (→ open HF, quarkonia), high-p_T partons (→ jets)
produced in the early stages in hard processes,
traverse the QGP interacting with its constituents

→ 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



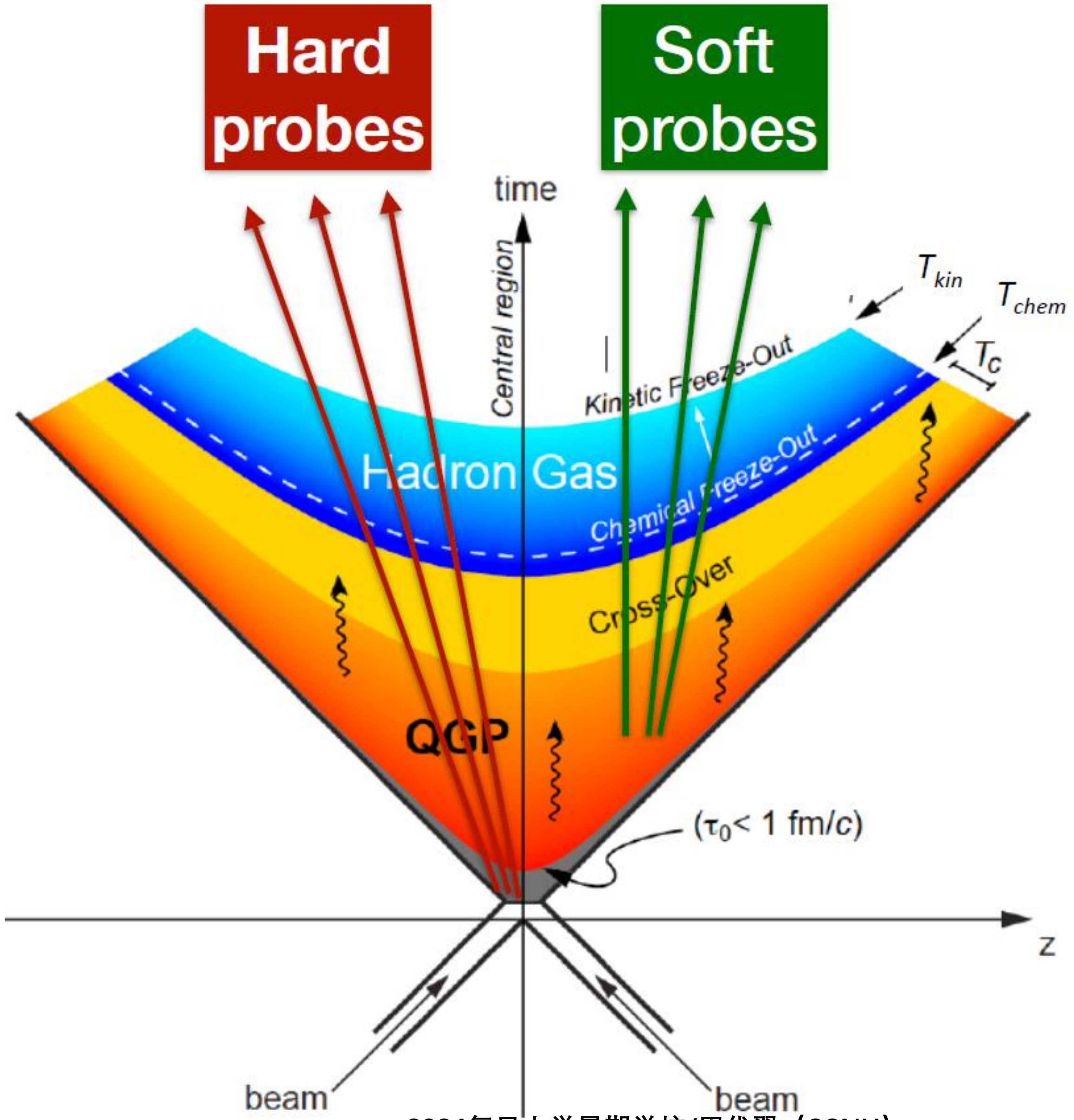
1 fm/c = 3x10^{-24} s, 1 MeV ~ 10^{10} K

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

→ **non-perturbative QCD regime**

→ **thermodynamical and transport properties**

Evolution of the heavy-ion collisions



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:

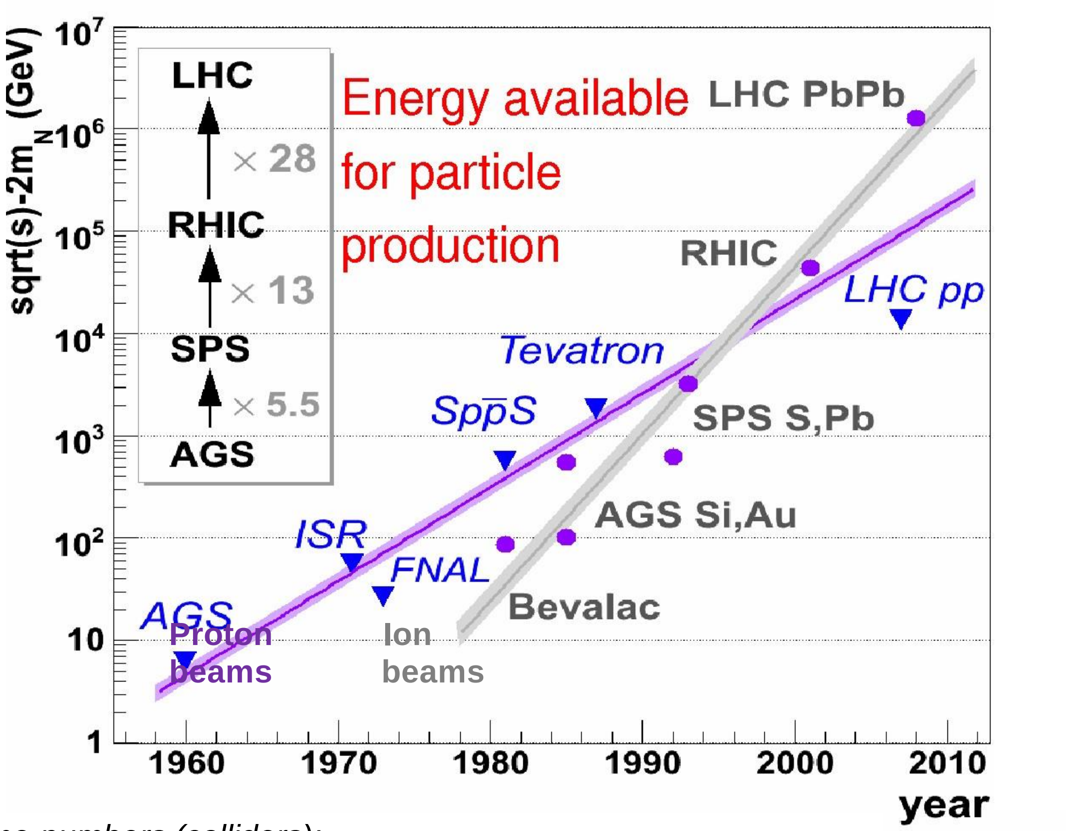
$$p_A = Z/A\, p_{proton}$$

<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

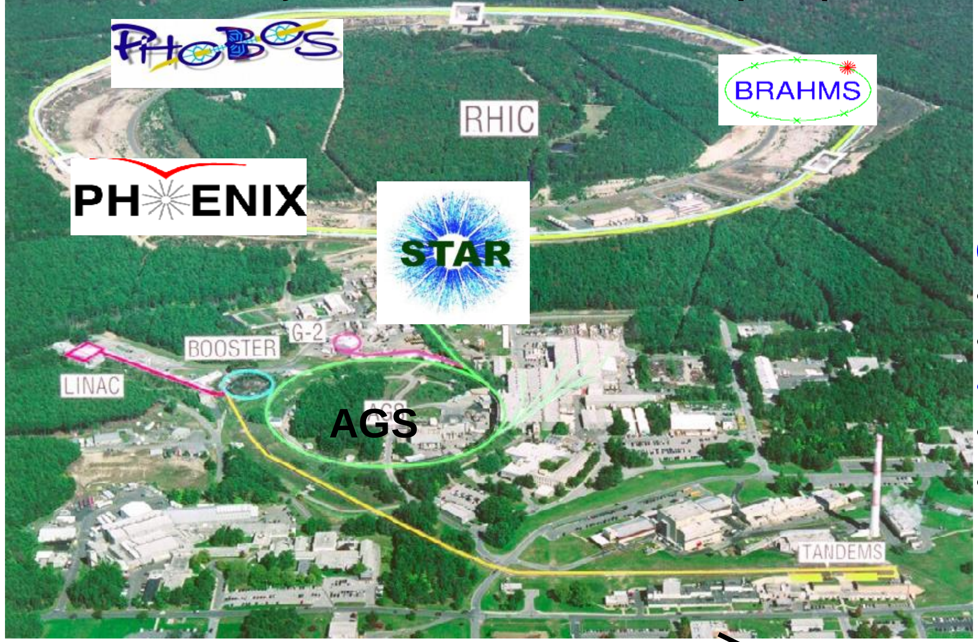
$\longrightarrow \sqrt{s}_{NN}$ = 5.02 TeV $\longrightarrow$ **$\sqrt{s}$ ~ 1.04 PeV**



<u>Some numbers (colliders):</u>
RHIC @ BNL (2000-) $\sqrt{s_{NN}}$ <200 GeV
[beam energy scan $\sqrt{s_{NN}}$ = 3, 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

世界上正在运行的高能重离子加速器

Relativistic **H**eavy **I**on **Col**lider, **B**rookhaven **(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 **P**roton **S**yncrotron and **L**arge **H**adron **C**ollider,
CERN (Switzerland/France)

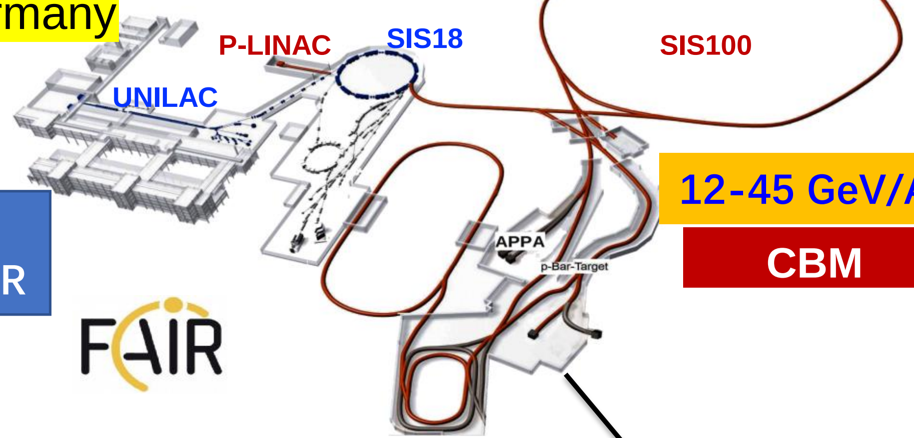
Brookhaven RHIC
- Operating since 2000
- Circumference 3.83 km, 2 rings
- Superconducting magnets
- $\sqrt{s_{NN}} = 3 - 200$ GeV in Au-Au
- Beam energy scan I: 2010-11
- Beam energy scan II: 2019-22
- Ongoing exp: **STAR，PHENIX**

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 $\sqrt{s_{NN}} = 2.76\text{-}5.5$ TeV
- Main ongoing: **ALICE, ATLAS, CMS, LHCb**

F. Bellini | SSL 2022 | Heavy Ions

世界上正在建造中的低能重离子加速器

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

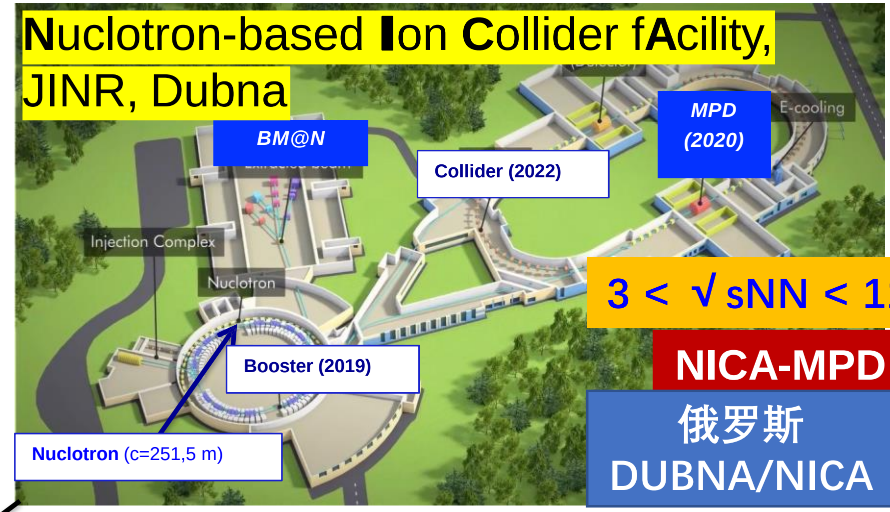


德国
GSI/FAIR

12-45 GeV/A

CBM

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

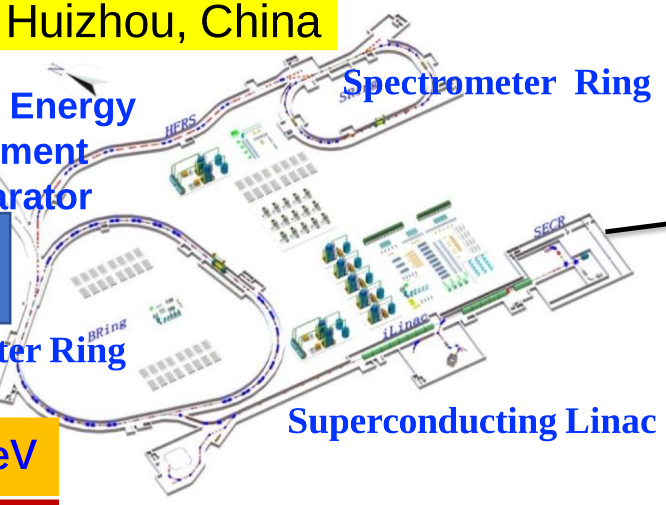


3 < √sNN < 11 GeV

NICA-MPD

俄罗斯
DUBNA/NICA

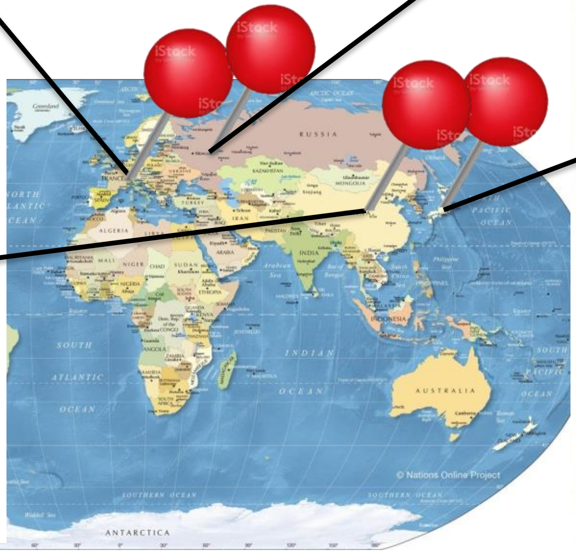
High-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Huizhou, China



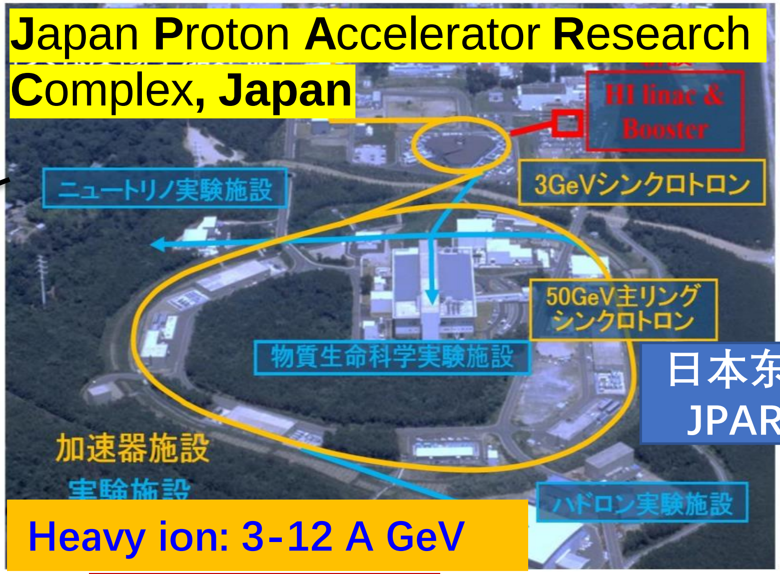
中国
惠州/HIAF

4.25 A GeV

CEE



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



日本东海
JPARC

Heavy ion: 3-12 A GeV

JARC/实验组

Heavy-ion physics at the LHC

2010-2012		2015-2018		2022-2025		2028-2030		2032-2034		2036-2042
Run I	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

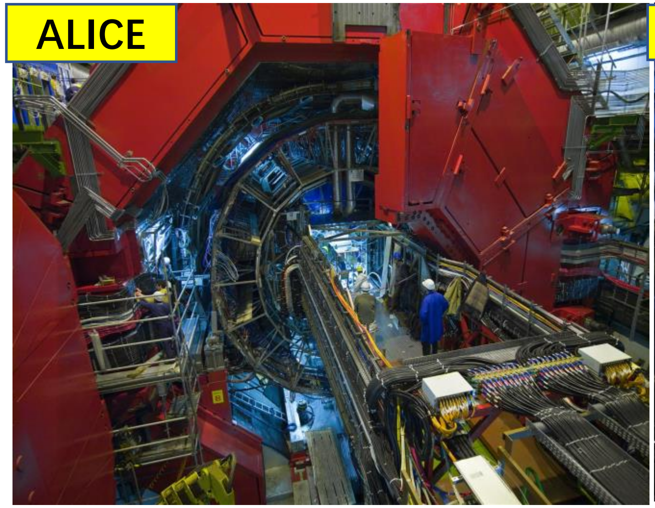
High luminosity LHC

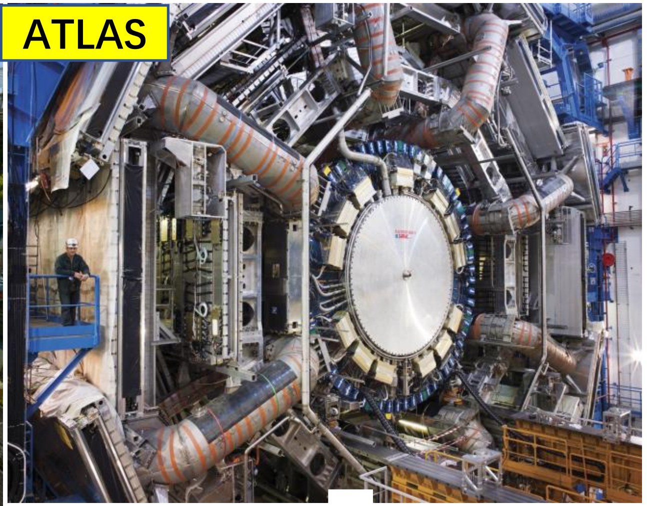
Major upgrades for
ALICE and LHCb

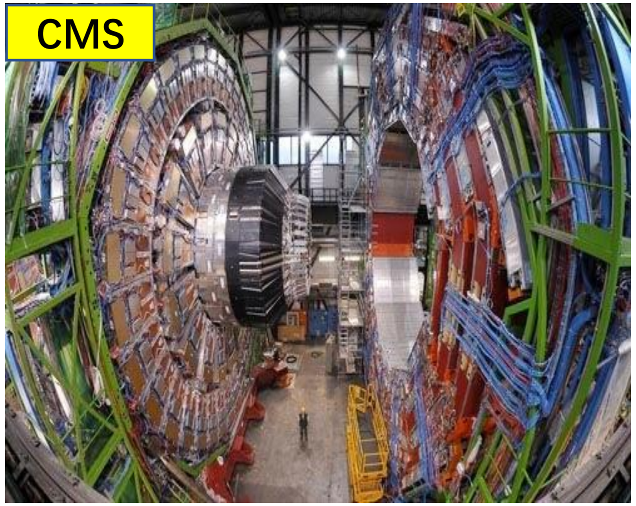
We are here

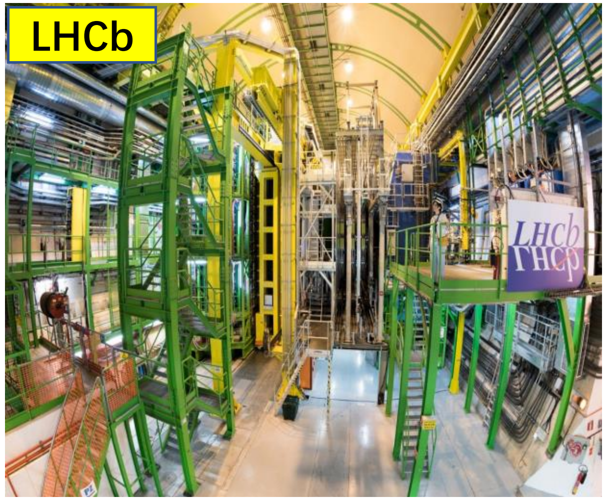
ATLAS and CMS phase II
ALICE ITS3 and FoCal

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







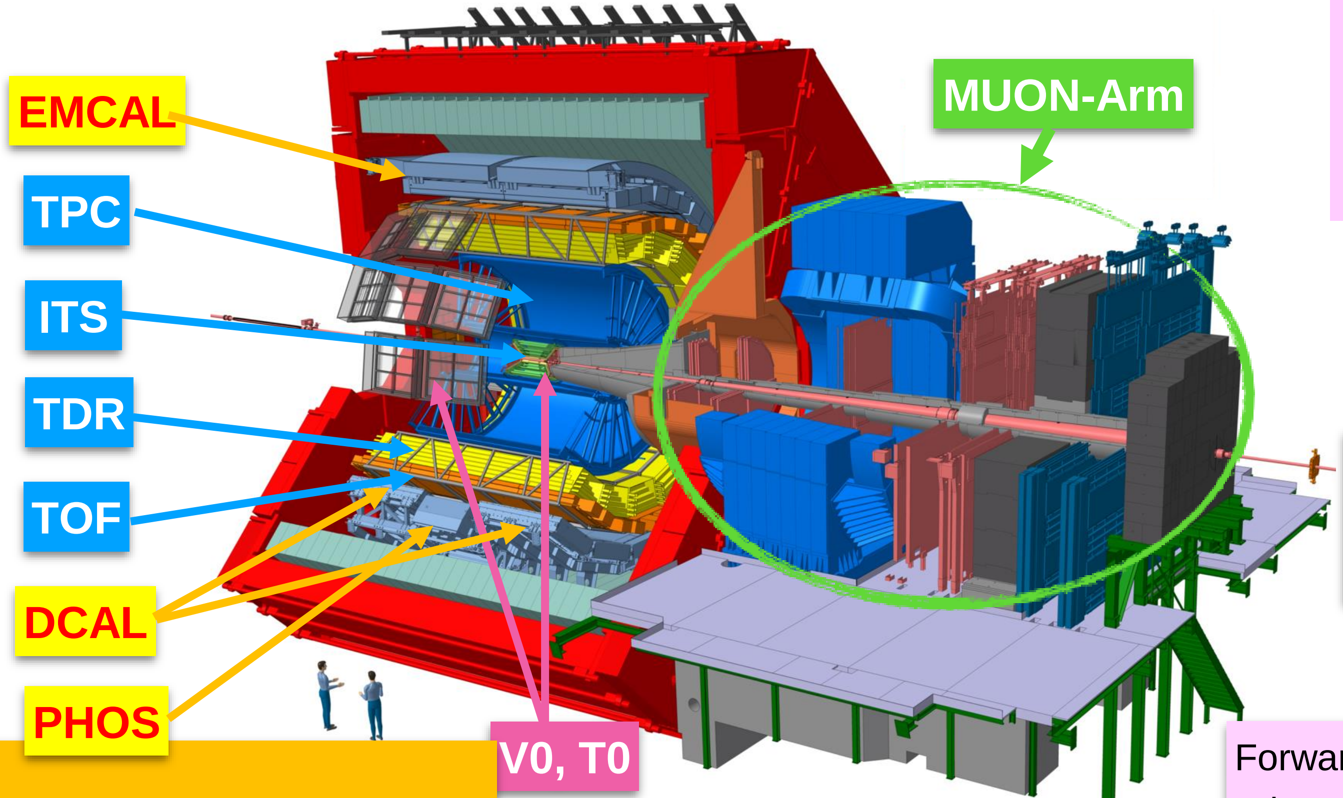


Dedicated heavy-ion detector: ALICE

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



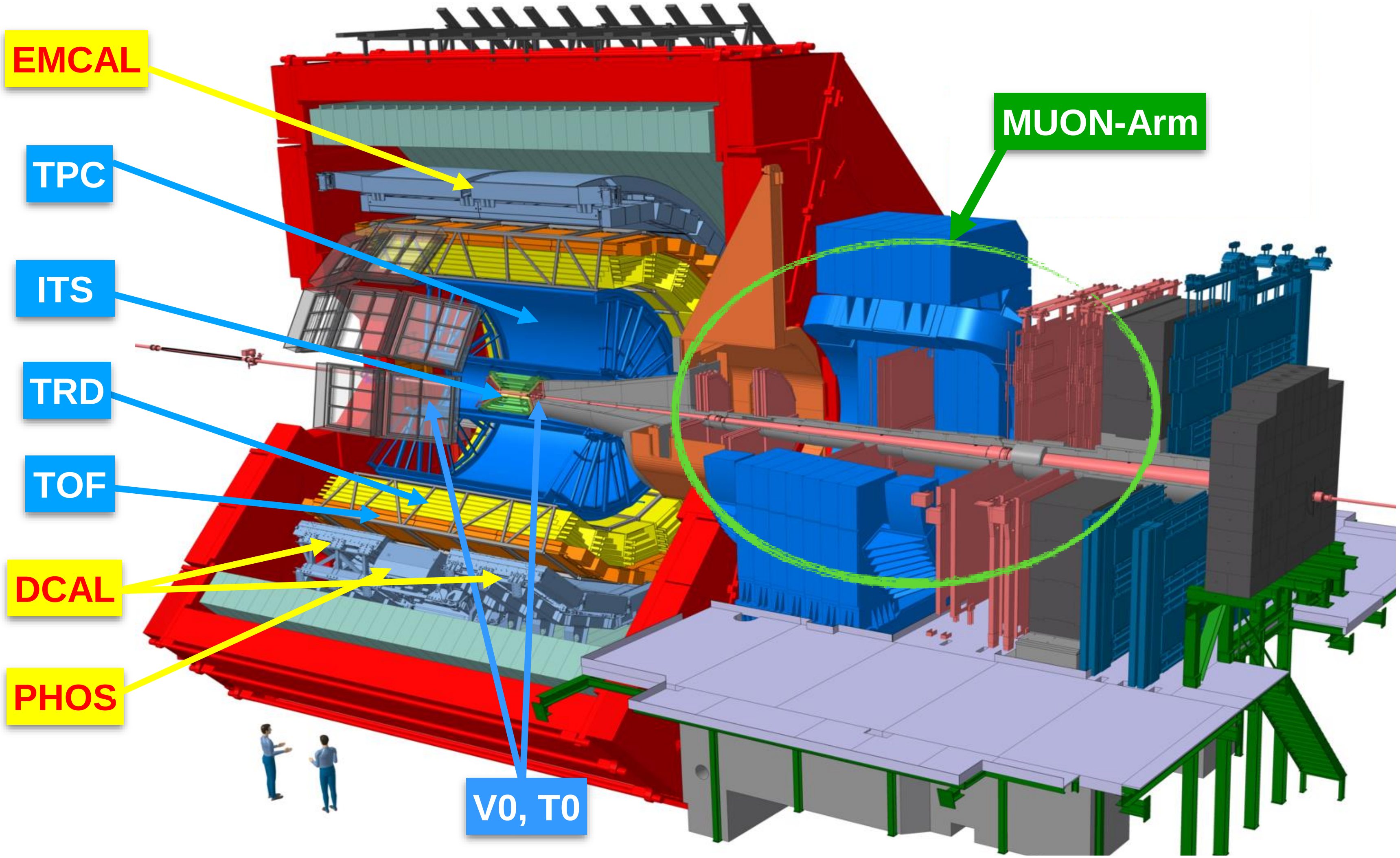
Muon-Arm ($-4<\eta<-2.5$):
Muon trigger, tracking, PID;
Heavy-floavor hadrons and W/Z^0

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, photon, high pT pi0 and electrons

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

ALICE 大型探测装置



ALICE 国际合作组

- 40个国家
- 169个研究机构
- 2000名合作者

中国组（七个单位）

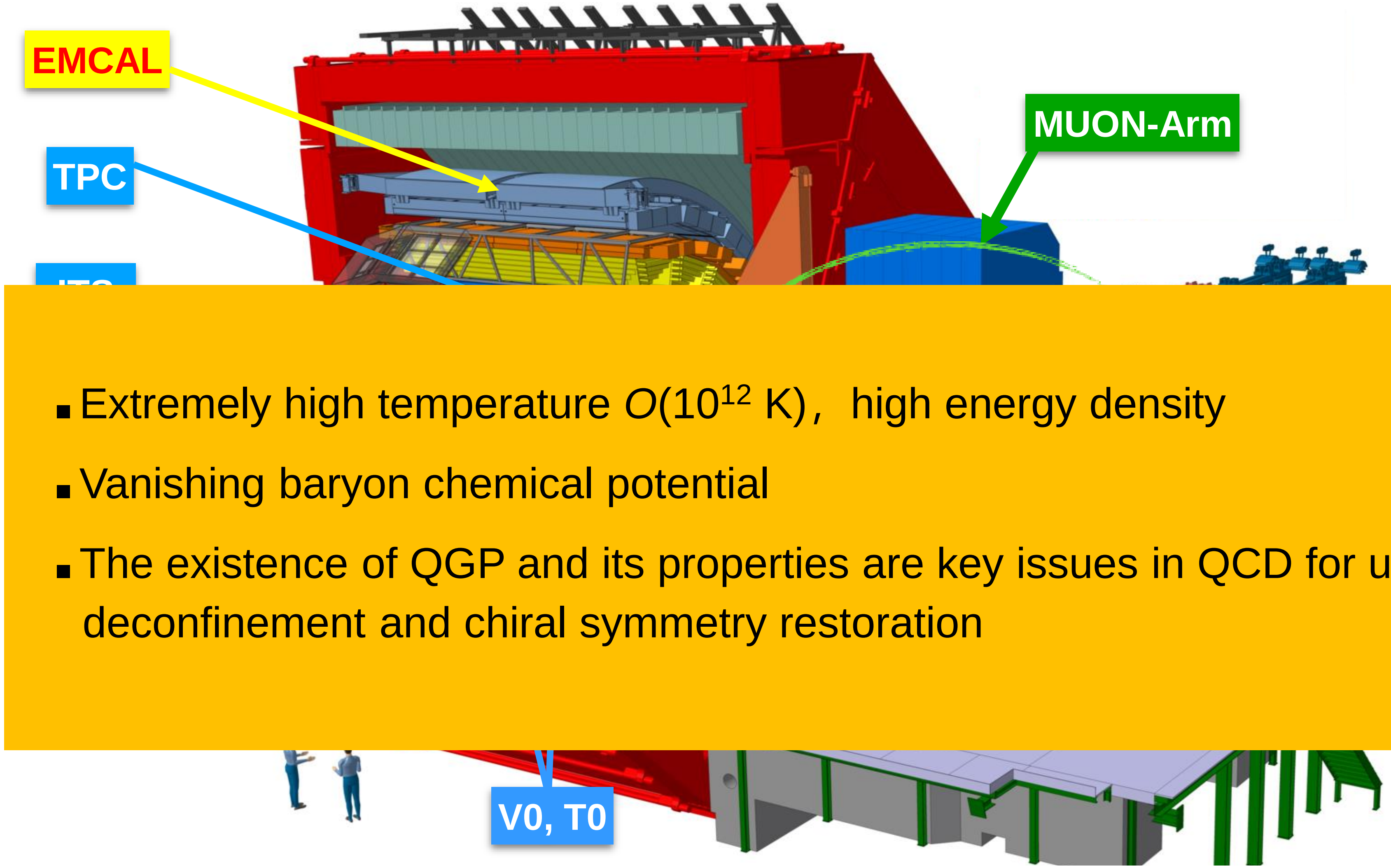
华中师范大学
中国原子能科学研究院
复旦大学
中国科学技术大学
中国地质大学
华中科技大学
湖北工业大学

ALICE 探测器:

长: 26 米
高: 16 米
重: 10,000 吨

中国组的贡献： 光子谱仪(PHOS)，取样电磁量能器（DCAL/EMCAL）,基于硅像素的内层径迹探测器（ITS2），前向缪子径迹探测器（MFT），正在研制中的前向强子量能器（FOCAL）和 内层探测器升级（ITS3）

LHC-ALICE 大型探测装置



- Extremely high temperature $O(10^{12}$ K), high energy density
- Vanishing baryon chemical potential
- The existence of QGP and its properties are key issues in QCD for understanding deconfinement and chiral symmetry restoration

中国组（七个单位）

院

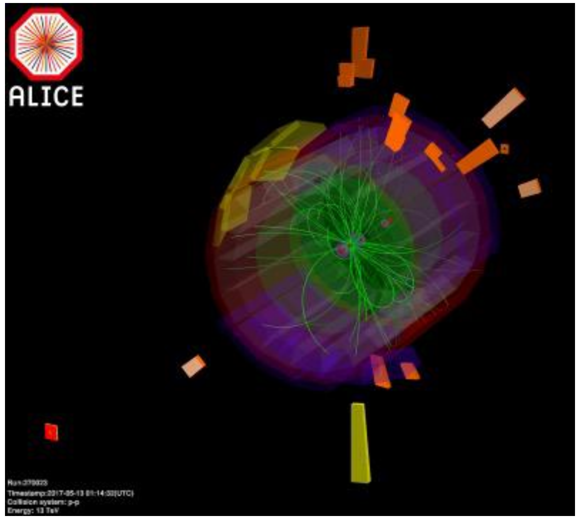
高: 16 米
重: 10,000 吨

中国组的贡献： **光子谱仪(PHOS)，取样电磁量能器（DCAL/EMCAL）,基于硅像素的内层径迹探测器（ITS2），前向缪子径迹探测器（MFT），正在研制中的前向强子量能器（FOCAL）** 和 内层探测器升级（ITS3）

LHC上运行的粒子束流

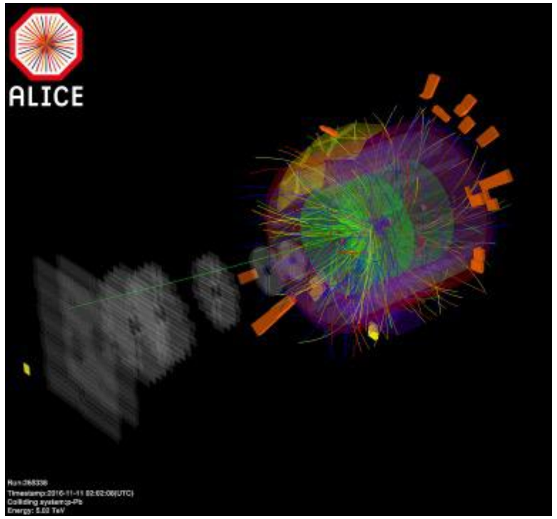
Comprehensive study of Pb-Pb, p-Pb, pp as well as the collision of lighter ions: Xe (done), O (planned for 2024)

pp



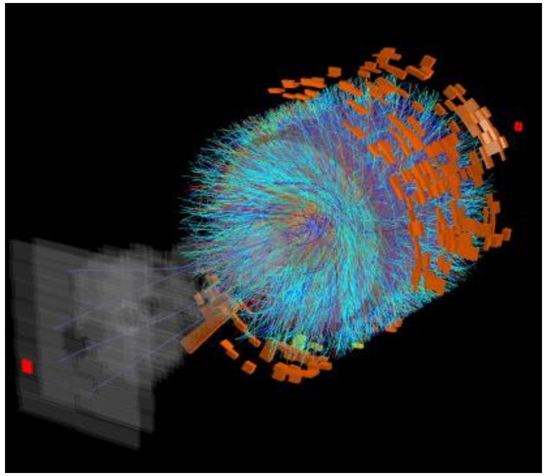
$^{(*)}\sqrt{s_{\mathrm{NN}}} = 0.9, 2.76, 5.02, 7, 8, 13\ TeV$

p-Pb



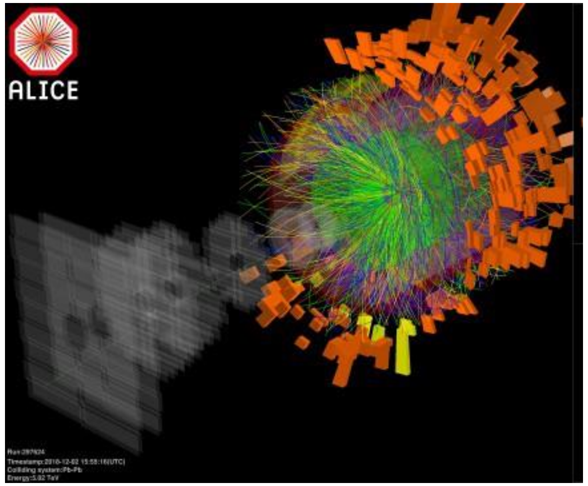
$^{(*)}\sqrt{s_{\mathrm{NN}}} = 5.02, 8.16\ TeV$

Xe-Xe



$^{(*)}\sqrt{s_{\mathrm{NN}}} = 5.44\ TeV$

Pb-Pb

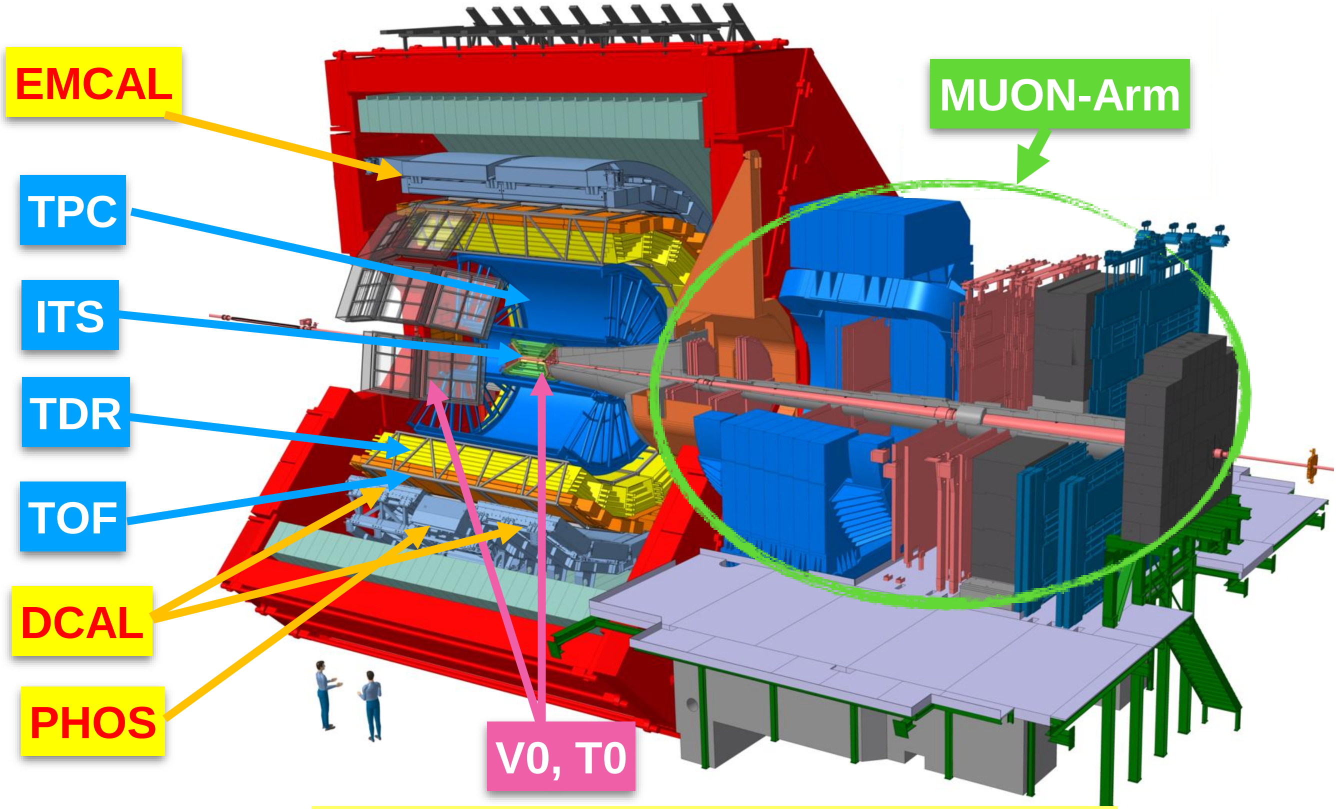


$^{(*)}\sqrt{s_{\mathrm{NN}}} = 2.76, 5.02\ TeV$

(*) collisions energy in Run 1 and 2

ALICE shopping list

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



Chinese team on physics:

- Photons and jets
- Heavy-flavors and quarkouniums
- Collectivity
- Exotic particle properties and CME
- Cold nuclear effects

Soft physics

- Event multiplicity and particle production
- Correlations and fluctuations

Hard probes

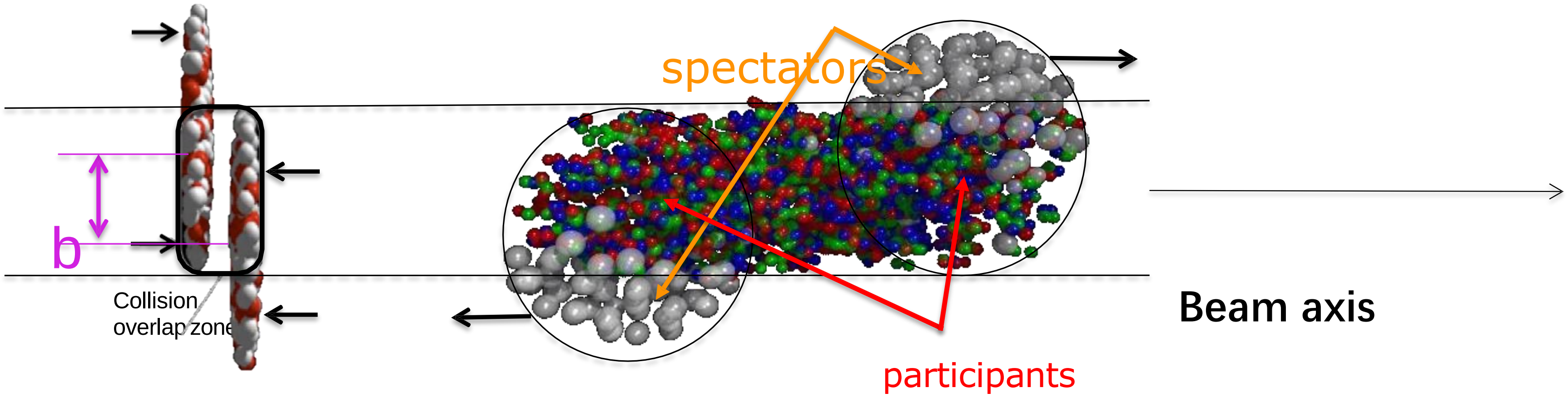
- Heavy quarks, jets and high-p_T photons
- Ultra-peripheral collisions

New physics: magnetic field effects, exotic particles, light nuclei, antimatter…

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**)

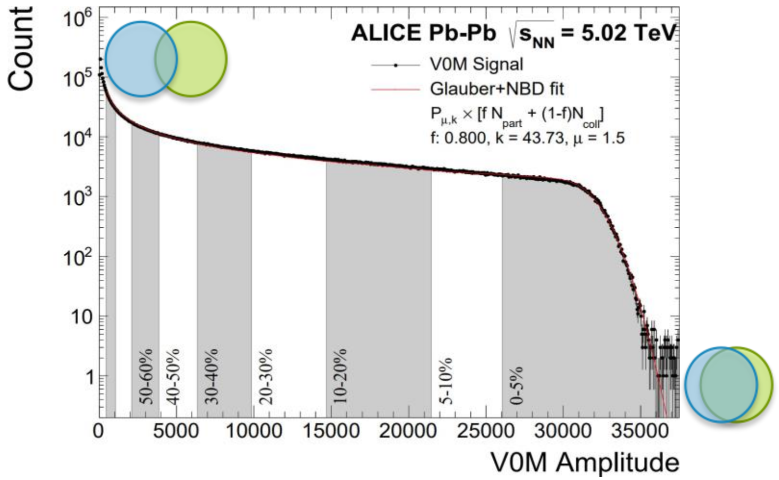


Other variables related to centrality:

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

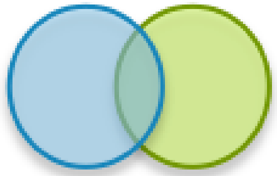
Geometry of heavy-ion collisions

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

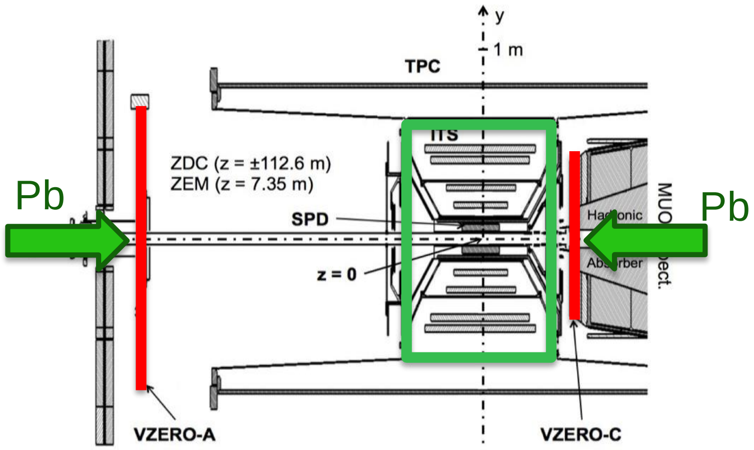


ALICE, PRL 106 (2011) 032301, PRC 91 (2015) 064905

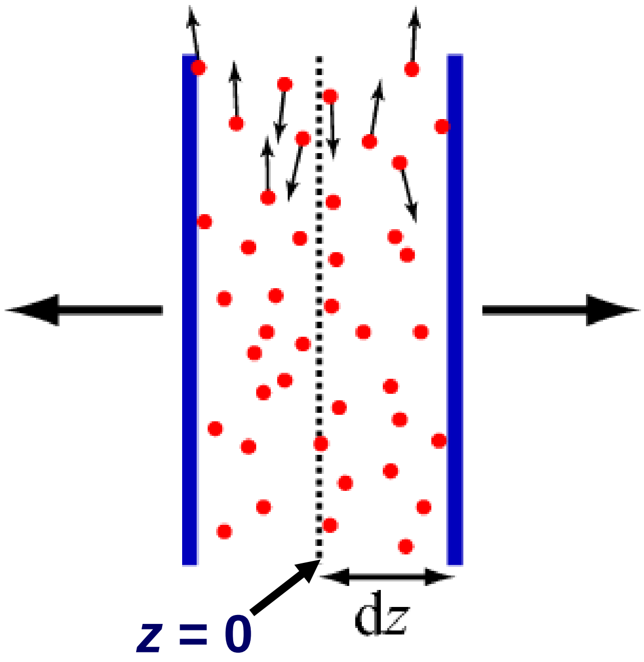
More **peripheral** collision
→ larger impact parameter
→ smaller overlap region
→ less participants
→ fewer particles produced



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

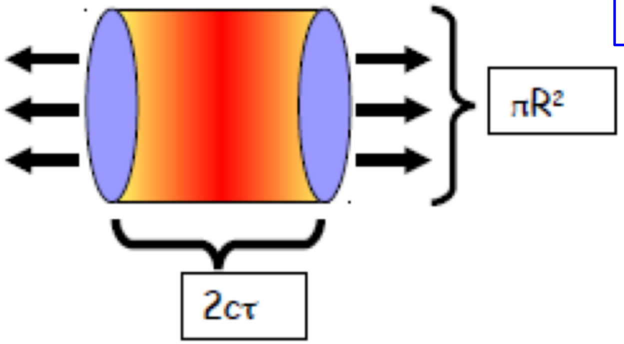


$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \longleftrightarrow \boxed{dN/d\eta}$$

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/fm³

Bjorken estimate:

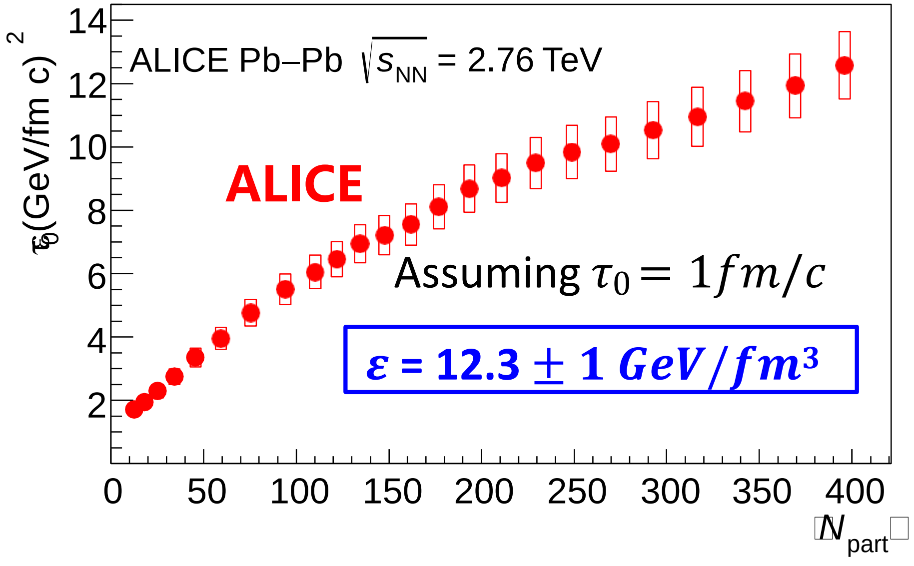


According to LQCD, the QGP is formed when:

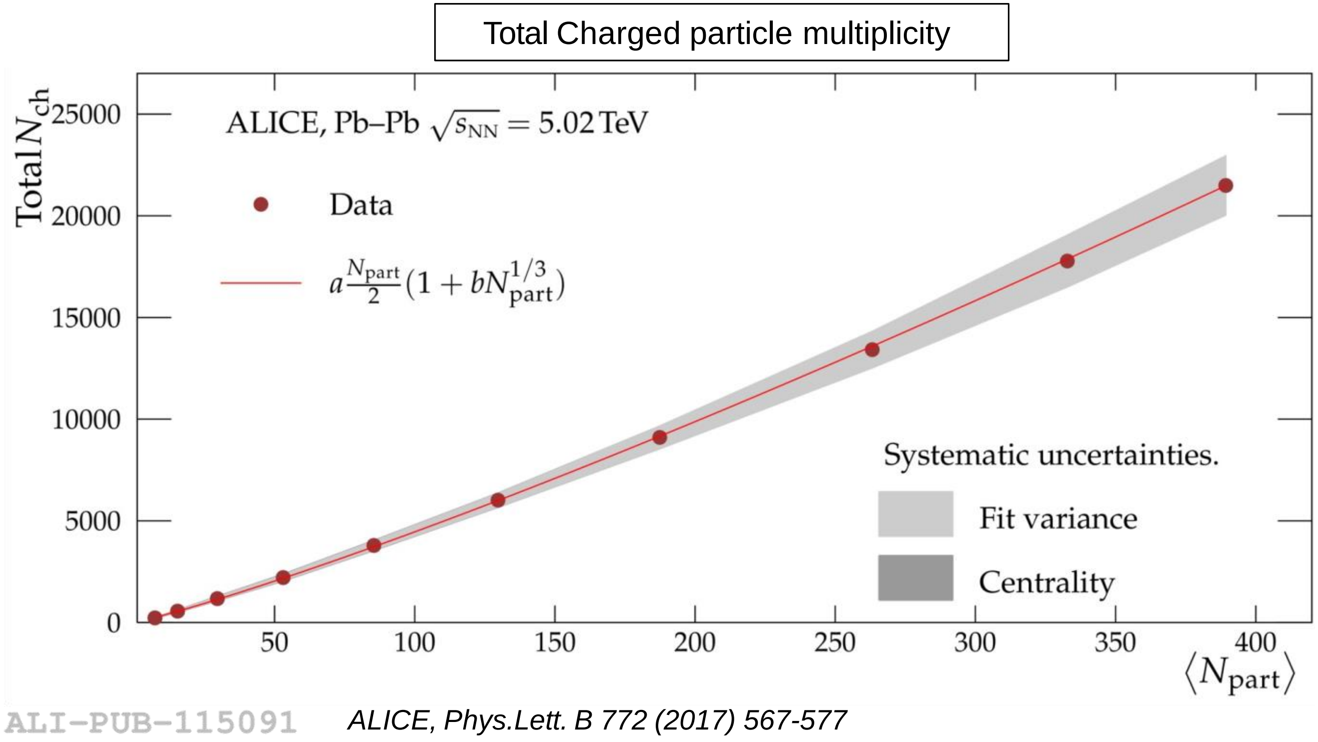
$\varepsilon_c = (0.42 \pm 0.06) \quad GeV/fm^3$

$T_c = (156.5 \pm 1.5) \quad MeV$

Phys. Rev. D **27**, 140



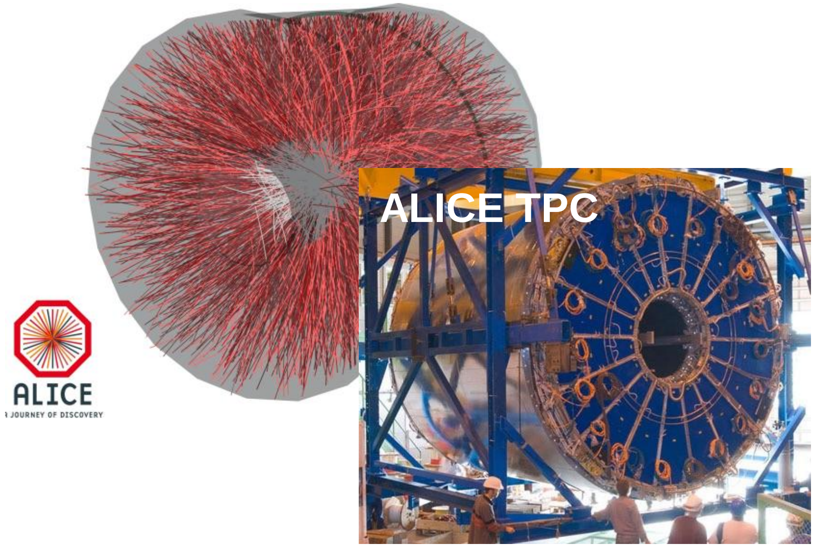
How many particles are created in a collision?



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

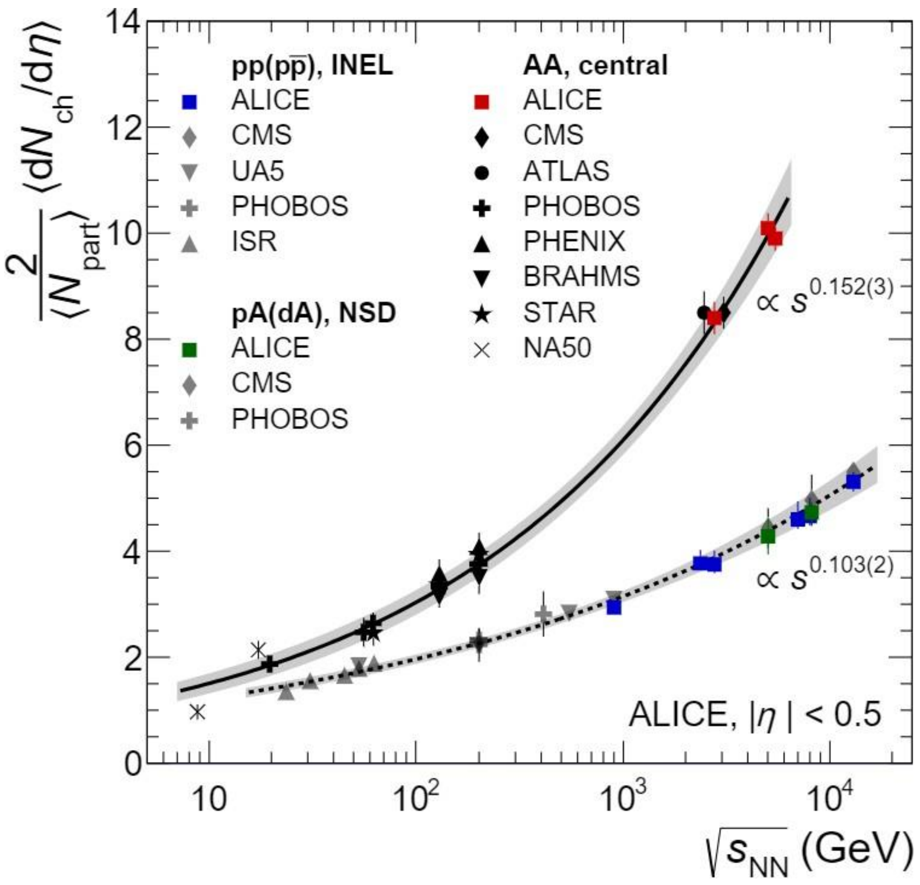
In a central Pb-Pb collision at the LHC, more than 20000 charged tracks must be reconstructed.

→ **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 $\sqrt{s_{NN}}$

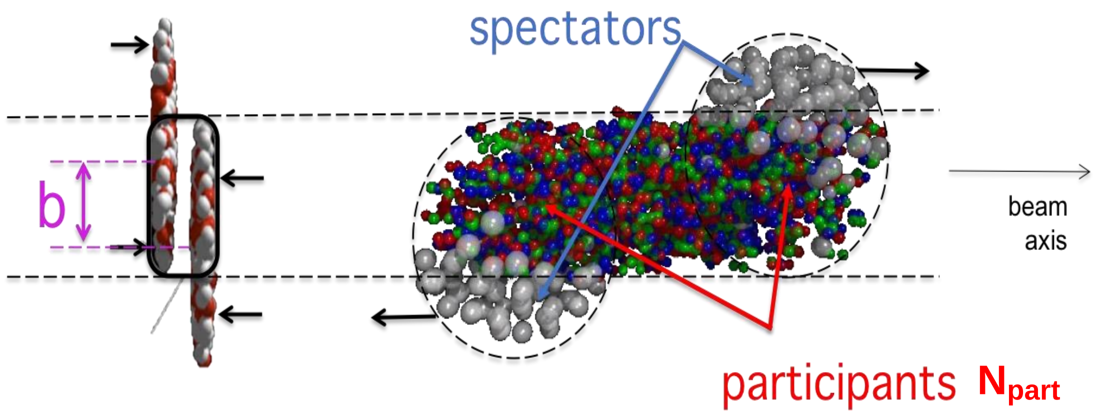


ALICE *Phys. Rev. Lett.* **116** (2016) 222302

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

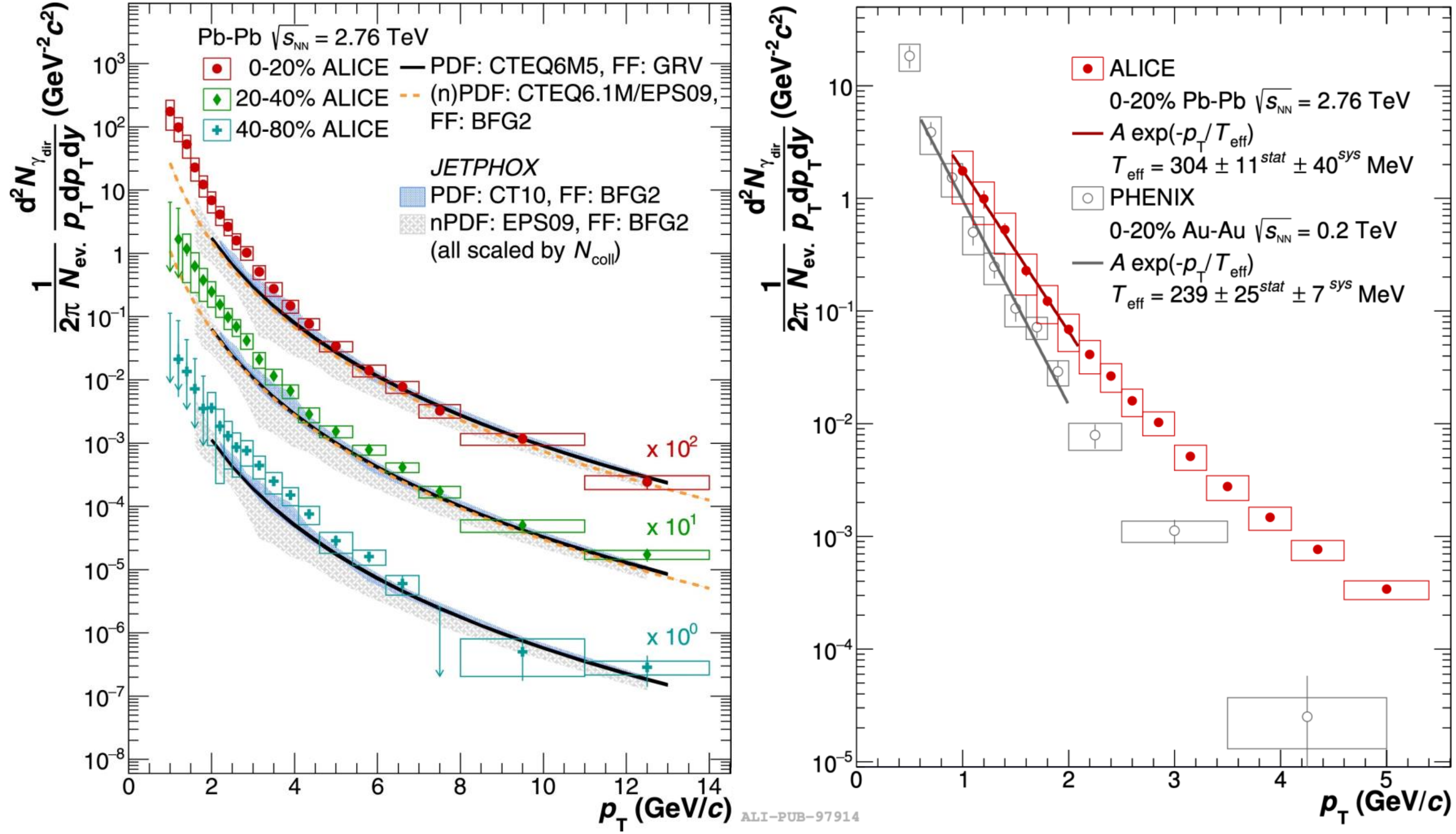
Particle production per participant in AA collisions follows a steeper power law than in pp, pA and increased by **2-3x** from RHIC to the LHC

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



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

- 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

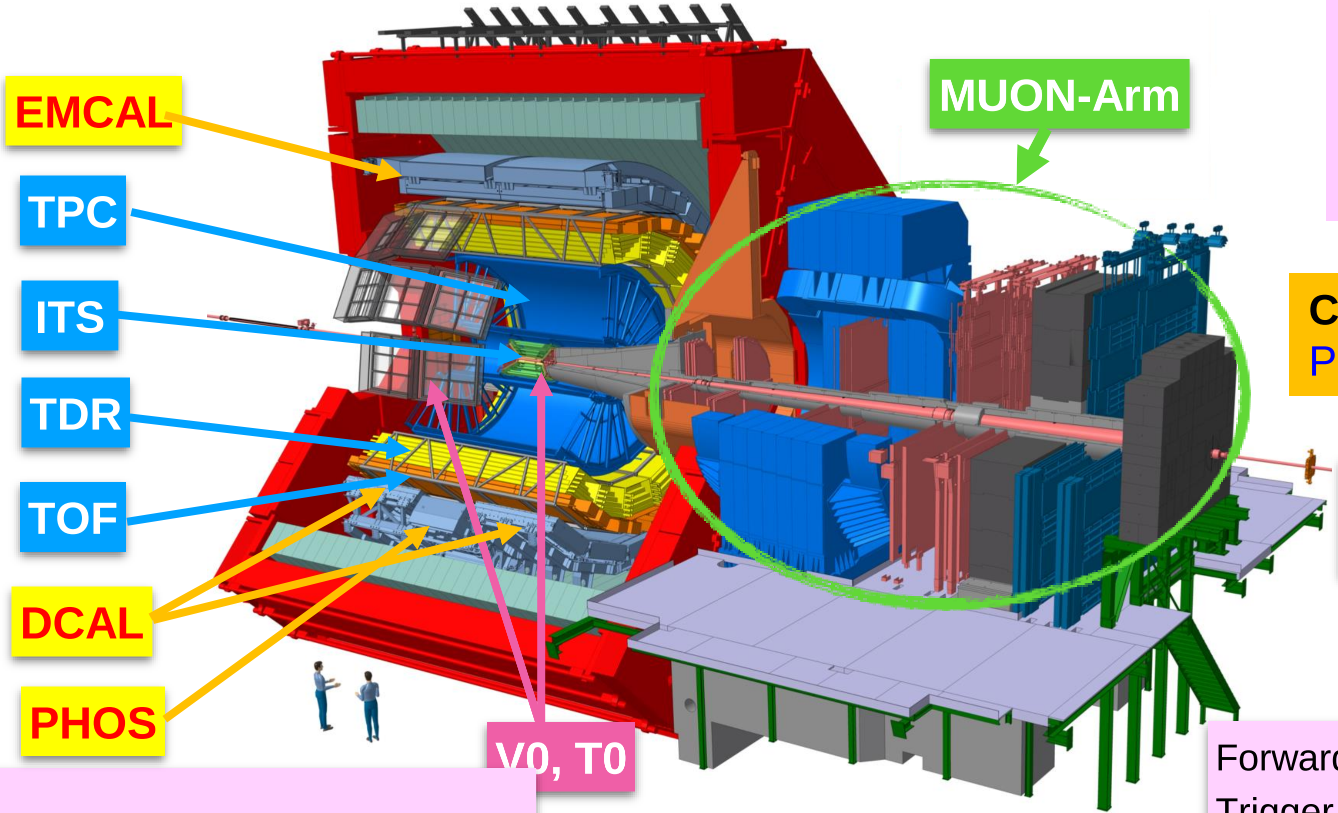
backup

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

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 $\pi0$, and electron trigger, PID

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

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

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 quarkouniums
- Collectivity
- Exotic particle properties
- Cold nuclear effects