Introduction to Heavy-Ion Physics: experimental perspective

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***Research interest**: LHC Physics utilizing the ALICE detector*

science & innovation
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Science and Innovation
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NRF National Research Foundation

Disclaimer

- Field of ultra-relativistic Heavy Ion Physics is very rich:
  - 6+ large active experiments, with more than 30-year history
  - Active and broad Theory community
- This talk will focus on the **introductory concepts** and **examples** from an **experimental** heavy-ion physics **perspective**
- It is inspired by a few heavy-ion lectures and/or presentations by various people over the years. They are all acknowledged here.

Basic:

- A particle is considered **ultra-relativistic** if its speed is approximately close to the speed of light *c*. → its energy is almost completely due to its momentum, i.e. approximated by ***E* = *pc***

- The ultra-relativistic limit $pc \gg mc^2$ is assumed or a **relativistic (Lorentz) factor**

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}},$$

υ = relative velocity [m/s], *c* = speed of light, 3×10^8 [m/s], → larger than unity ($\gamma \gg 1$),

→it expresses how much the measurements of time, length, and other physical properties change for an object while that object is moving

Example: at the Relativistic Heavy ion Collider (RHIC at BNL) and Large Hadron Collider (LHC at CERN), the relativistic factors γ ~ 100 and 2500, respectively. This translates to beam rapidity (y - a measure for relativistic velocity) = 5.3 and 8.5

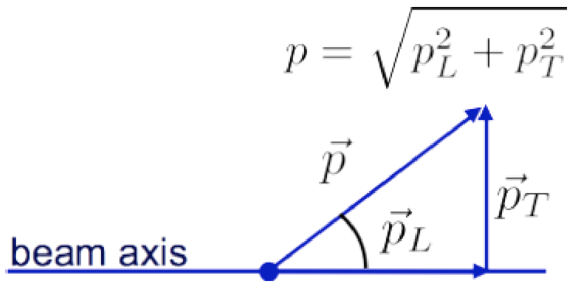
Basic Kinematics

- Transverse momentum

$$p_T = p\sin\theta$$

transverse mass:

$$m_T = \sqrt{p_T^2 + m^2}$$



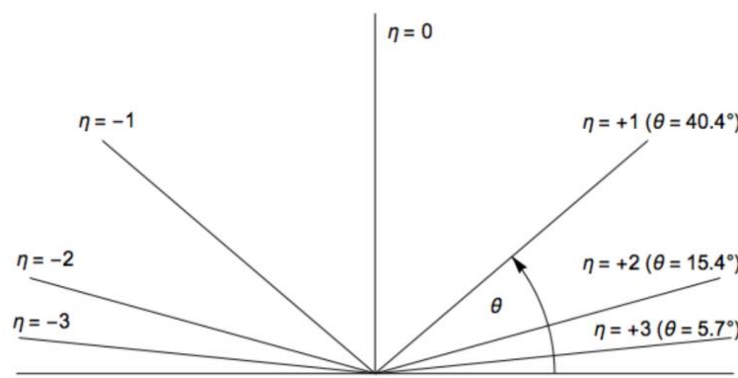
- Rapidity y (additive under Lorentz transformation)

$$y = \text{arctanh}\,\beta_L = \frac{1}{2}\ln\frac{1+\beta_L}{1-\beta_L} = \frac{1}{2}\ln\frac{E+p_L}{E-p_L}$$

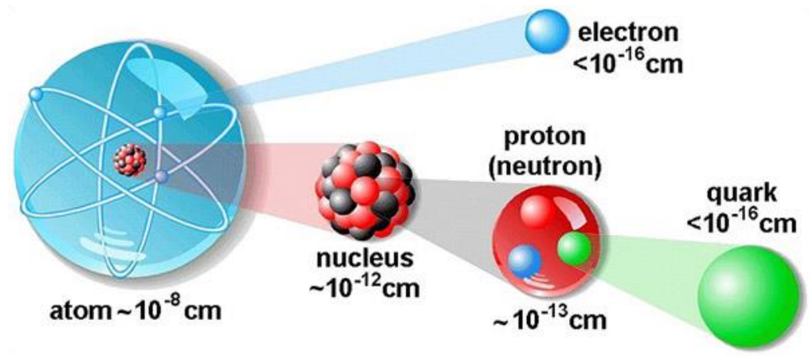
- Pseudorapidity η

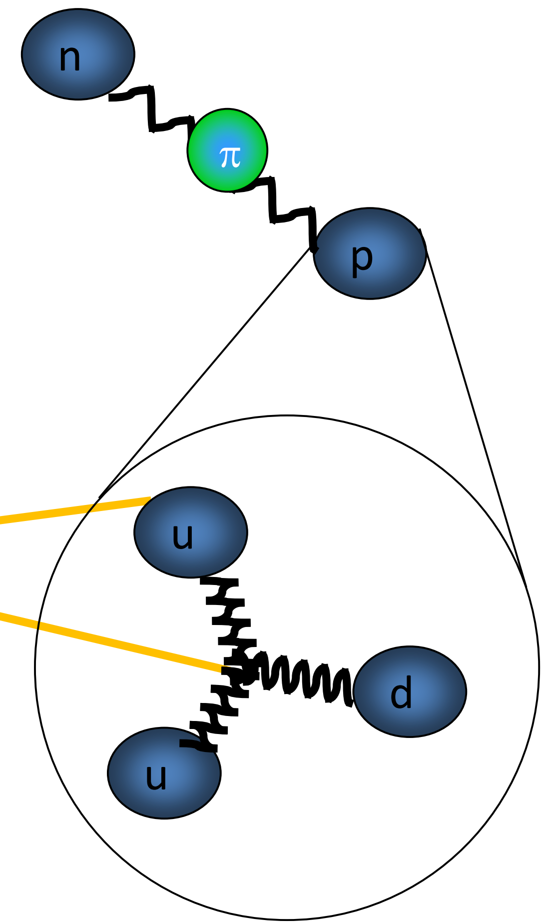
$$y \overset{p \gg m}{\approx} \frac{1}{2}\ln\frac{1+\cos\vartheta}{1-\cos\vartheta} = -\ln\left[\tan\frac{\vartheta}{2}\right] =: \eta$$

Pseudorapidity



Basics: Strong force





- ❑ **Nuclei** are held together by exchanging **mesons**
- ❑ **Nucleons** composed of **quarks** are held together by exchanging **gluons**

→ manifestations of the **strong force**, but nucleons and quarks are very different…

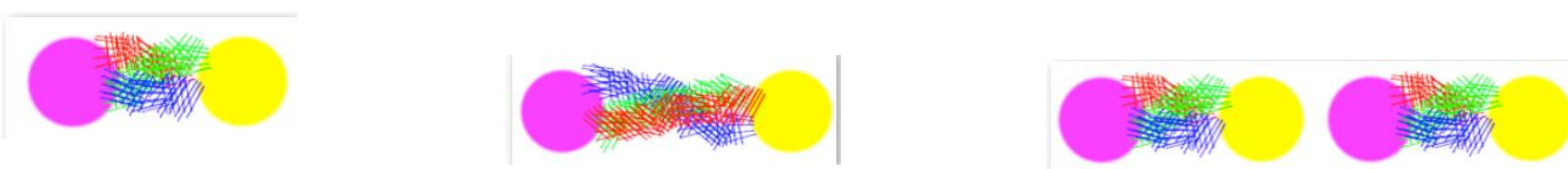
- ❑ **Hadrons** are composed of **partons**: **quarks** and **gluons**:
- ➢ **Meson** – hadron containing 2 quarks (1 light and 1 anti), e.g. pion ($u\bar{d}$), kaon ($u\bar{s}$), …
- ➢ **Baryon** – hadron containing 3 quarks, e.g. proton (*uud*), neutron (*udd*)….

Basics: Strong interaction, QCD and Confinement

- **Strong interaction**: keeps together quarks inside protons and neutrons and protons and neutrons inside atomic nuclei …
- ….and is **carried by** the **colour charge**
- Governed by the theory of **Quantum ChromoDynamics (QCD)**
- Important feature of QCD: **confinement → no “free” quarks**

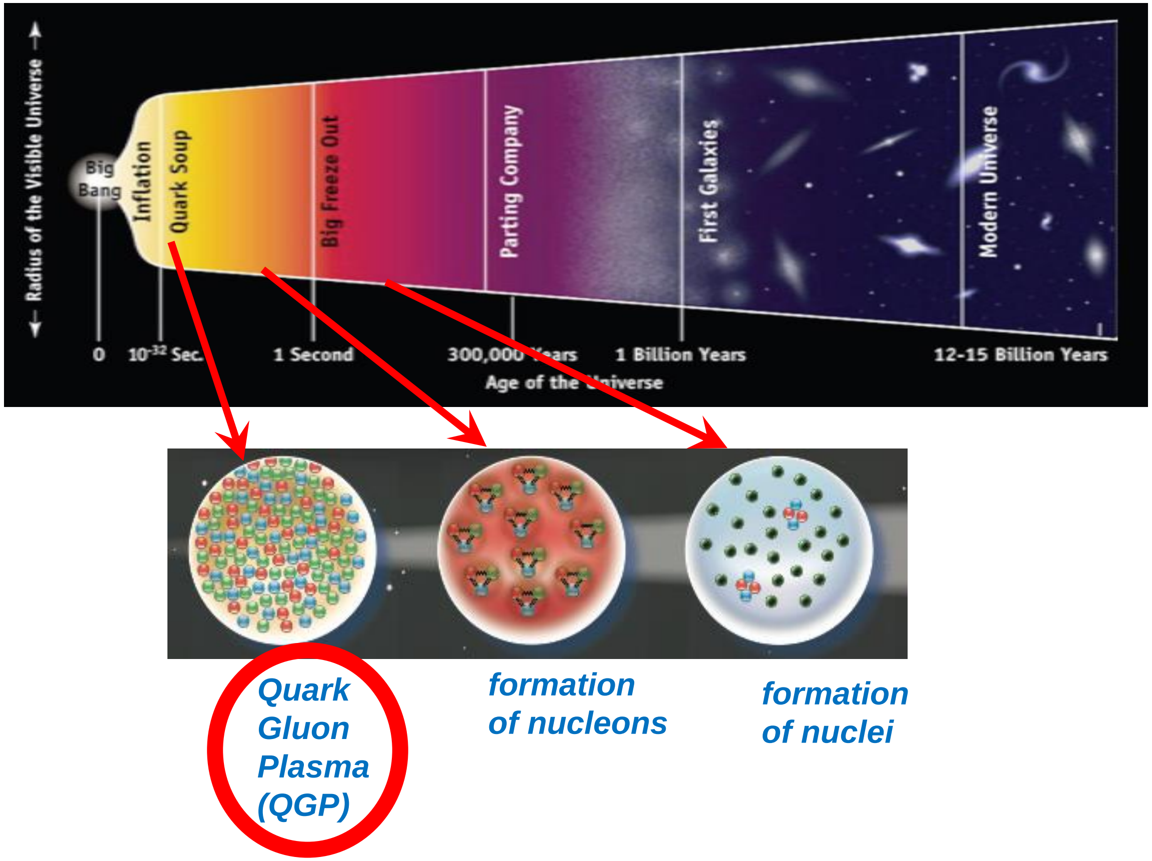
- To understand the strong interaction and the phenomenon of confinement → create and study a system of deconfined quarks and gluons→ **quark-gluon plasma**

Cartoon of quark-antiquark being “pulled” apart and their colour connection



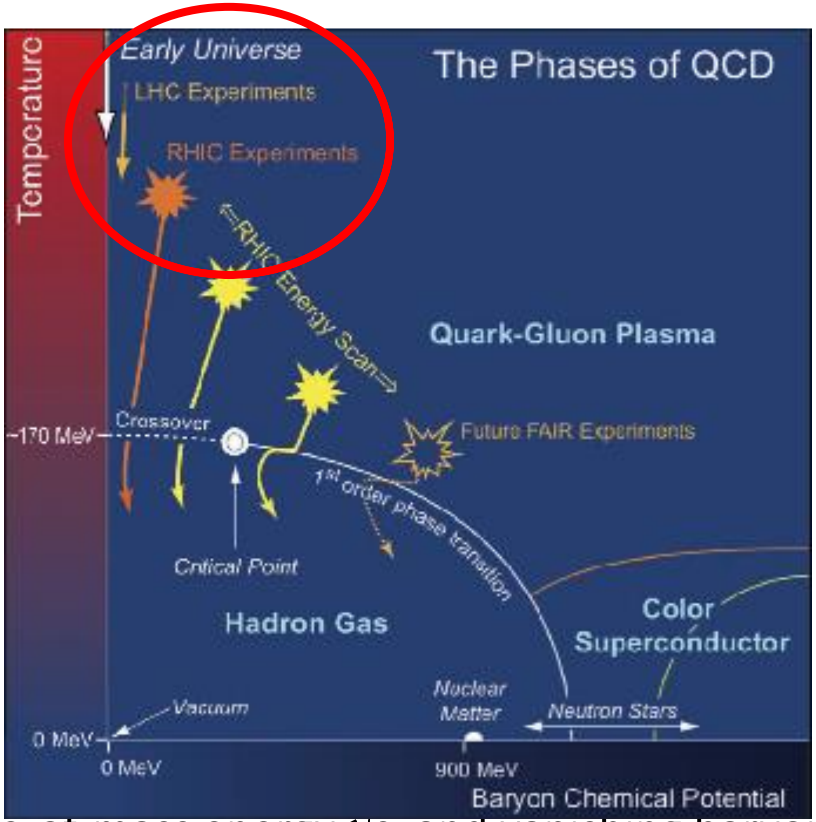
What is the quark-gluon plasma (QGP)?

- ❑ The first “matter” in the primordial Universe
- ❑ The phase transition from quarks to hadrons occurred in the cooling Universe, 10 μs after the Big Bang



How do we study the QGP?

- The phase transitions of hadrons to QGP are well established in lattice QCD
  - Temperature, $T \approx 170$ MeV (~ 2.10^{12}K) , 1 MeV = 11604525006.1598 Kelvin
  - Energy density $\varepsilon_c \approx 1$ GeV/fm^3, 1 femtometre (fm) = 10^{-15} m
- Deconfinement → colour confinement removed
- Chiral symmetry restoration plays: a role in the generation of hadron masses; accounts for 99% of the mass of nuclear matter

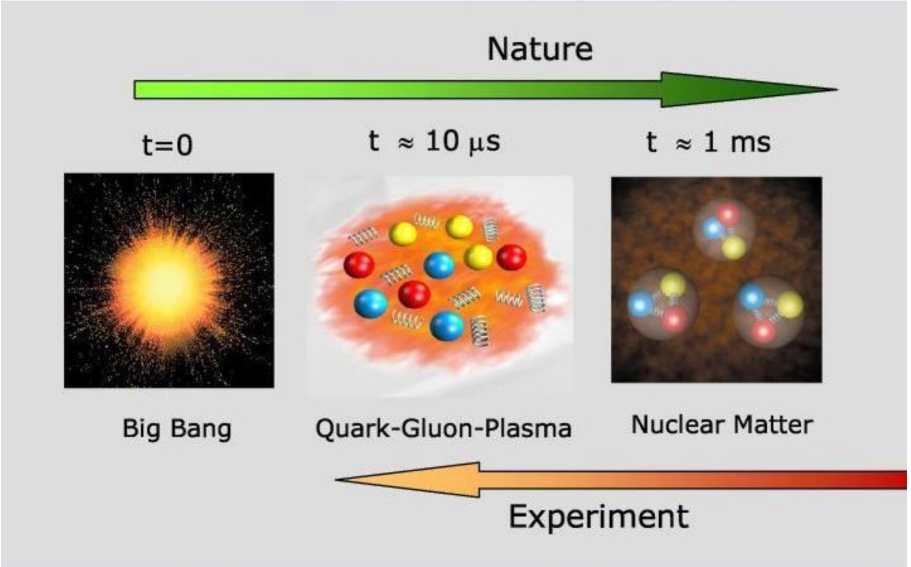


PoS CPOD2013 (2013) 001
arXiv:1308.3328

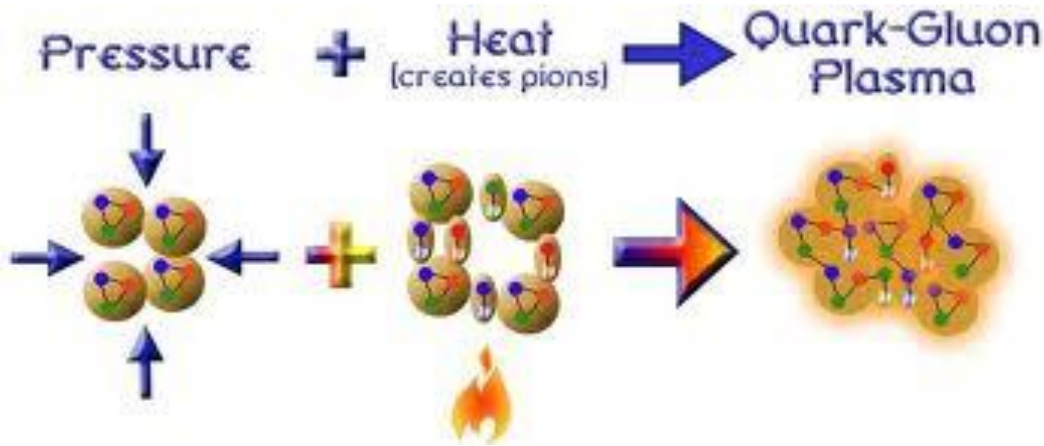
LHC: extremely high centre-of-mass energy √s, and vanishing baryon chemical potential ~0

→ An ideal environment for the QGP factory!!

Creating the QGP in experiments

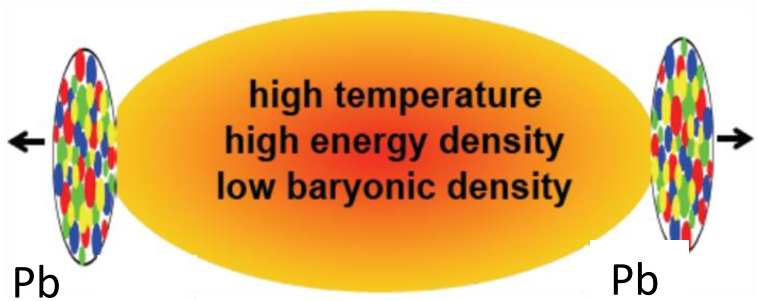


- "Ionize" nucleons with heat and "compress" them with density



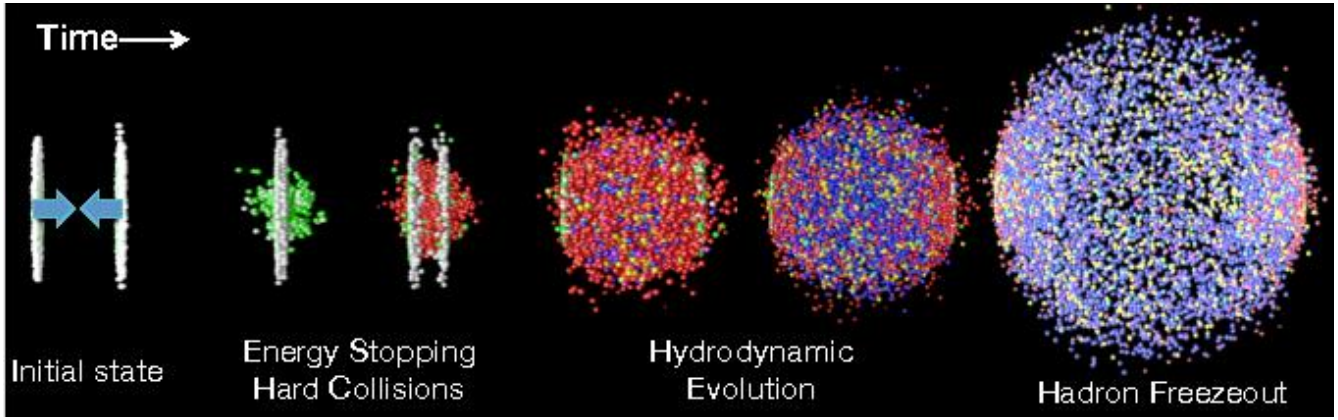
QGP - little "big bang" in the lab

- Collide **heavy nuclei e.g.** lead-lead (Pb-Pb) particle beams at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV (*1 TeV = 10^{12} eV*)



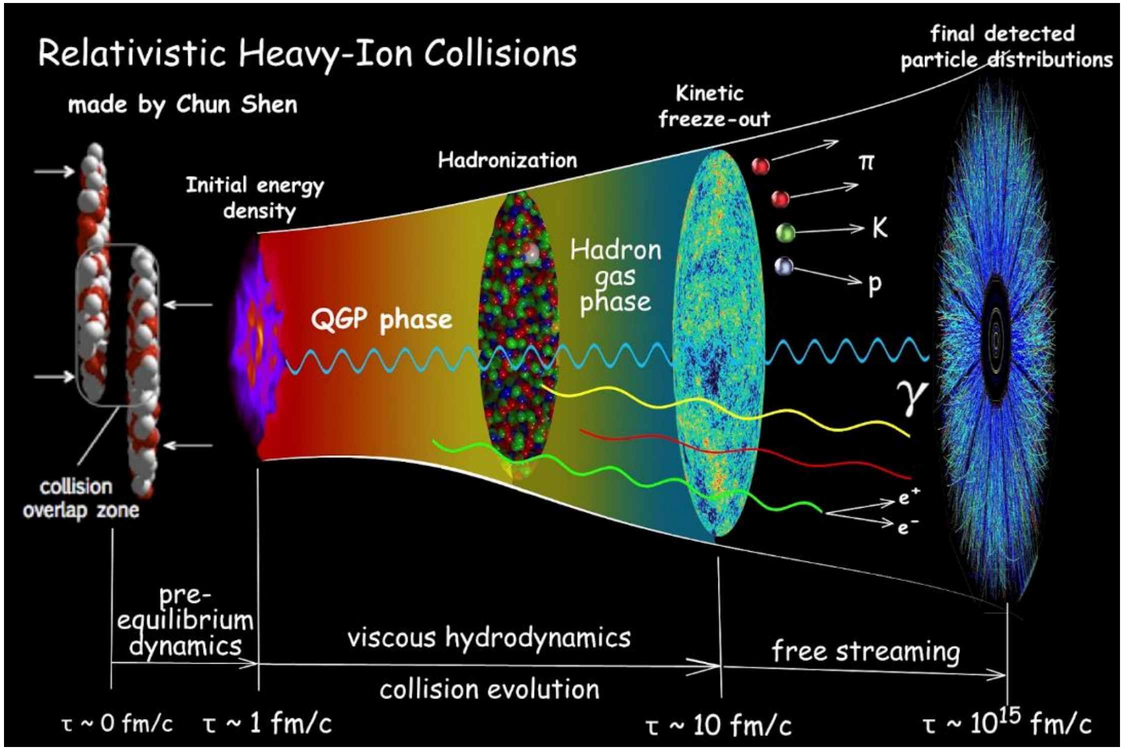
Pb: A = 208, Z = 82, N = 126
proton = 2 up + 1 down quarks
neutron = 2 down + 1 up quarks

- Follow the evolution of the collision
  - QGP fireball expands, cools down and then freezes out into a collection of final-state hadrons



QGP - little "big bang" in the lab

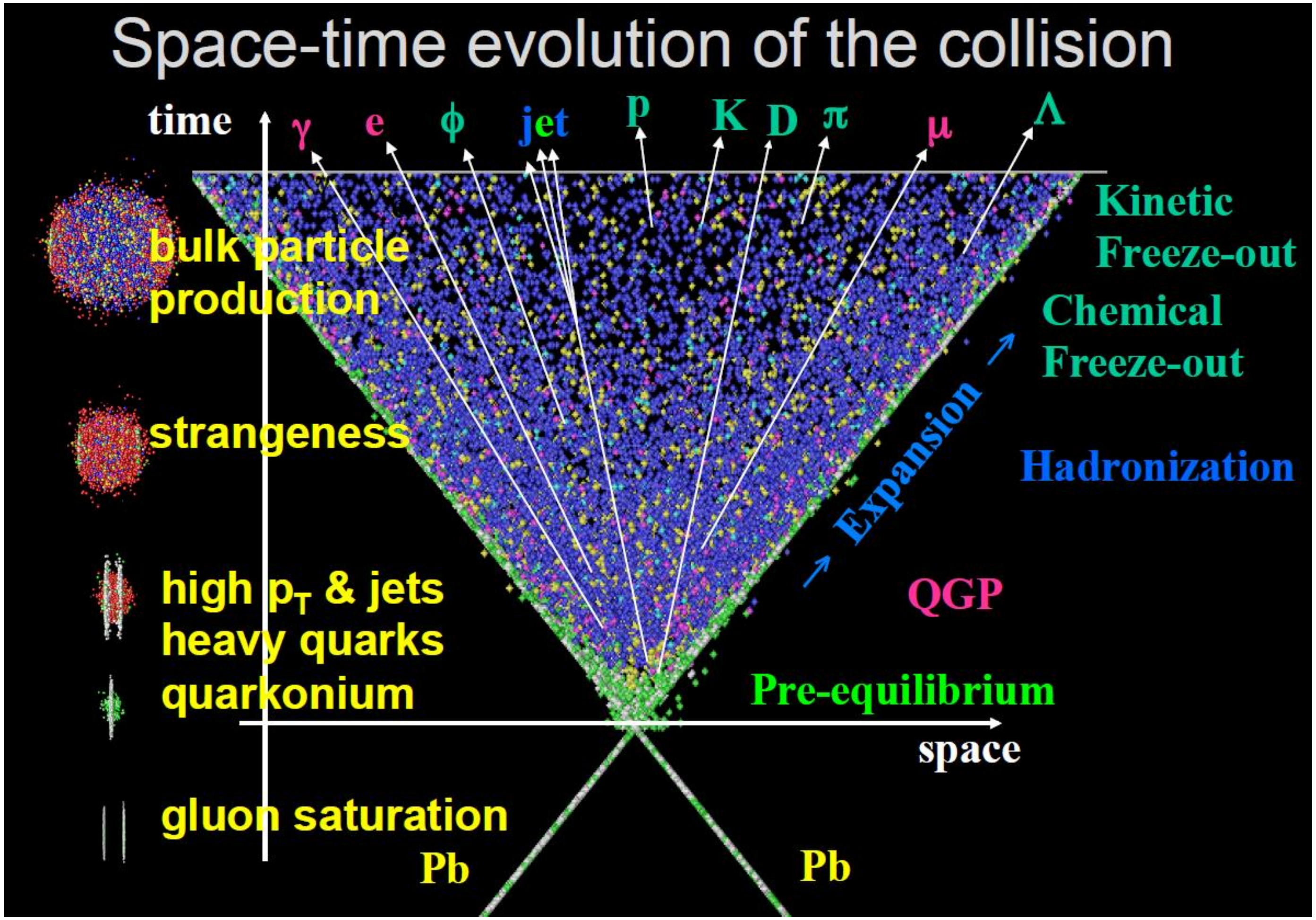
- Initial collision: $t \leq t_{coll}$, thermalization: equilibrium is reached: $t \sim 1$ *fm*/c, hadronization: expansion & cooling: $t \sim 10 - 15$ *fm*/c
- Chemical freeze-out: inelastic reaction cease; chemical composition of the system (particle yields & fluctuations) fixed
- Kinetic freeze-out: elastic reactions cease: spectra & correlations are frozen (free streaming hadrons), $t \sim 3–5$*fm*/c
- Hadrons reach the detectors



- Look at the stream of final-state particles which reach the detectors to study the evolution of a heavy–ion collision → study the formation and properties of the QGP

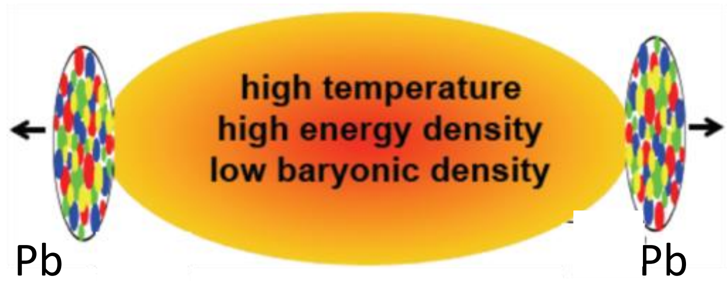
QGP measurements in heavy-ion collisions

- QGP cannot be measured directly → perform various measurements which, when combined, can provide reliable proof of the formation of the QGP → **signatures/observables of the QGP**



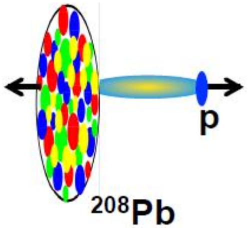
The paradigm

- **CORE business: AA collisions → create and characterize the QGP**

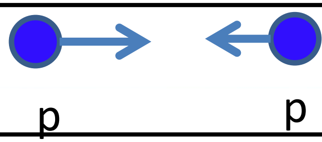


- **Role of the small systems**

- **Proton-nucleus (p-A) collisions: Control experiment**
  - Disentangle initial and final state effects
  - → Investigate cold nuclear matter effects (CNM)



- **Proton-proton (pp) collisions:** Baseline (reference)
  - Test pQCD theories



- **Surprising findings from small collisions (pp, p-Pb) → Similar features as in Pb-Pb?**

Ultra-relativistic heavy-Ion Experiments

- ❑ **AGS : 1986 – 2000 (fixed target)**
  - ➢ **Si** and **Au** beams; **up to 14.6 A GeV**
  - ➢ only hadronic variables

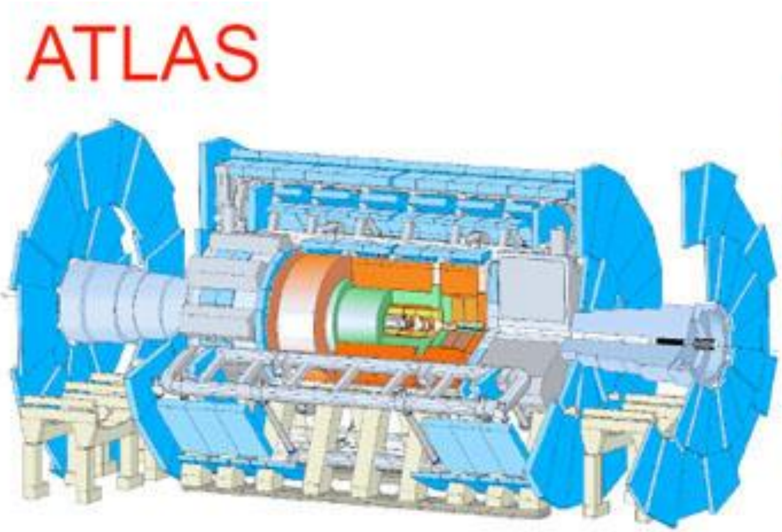
- ❑ **RHIC: 2000**
  - ➢ **Au beams** ; **up to √s = 200 GeV**
  - ➢ 4 experiments
- ❑ **RHIC-BES: 2011-2021**

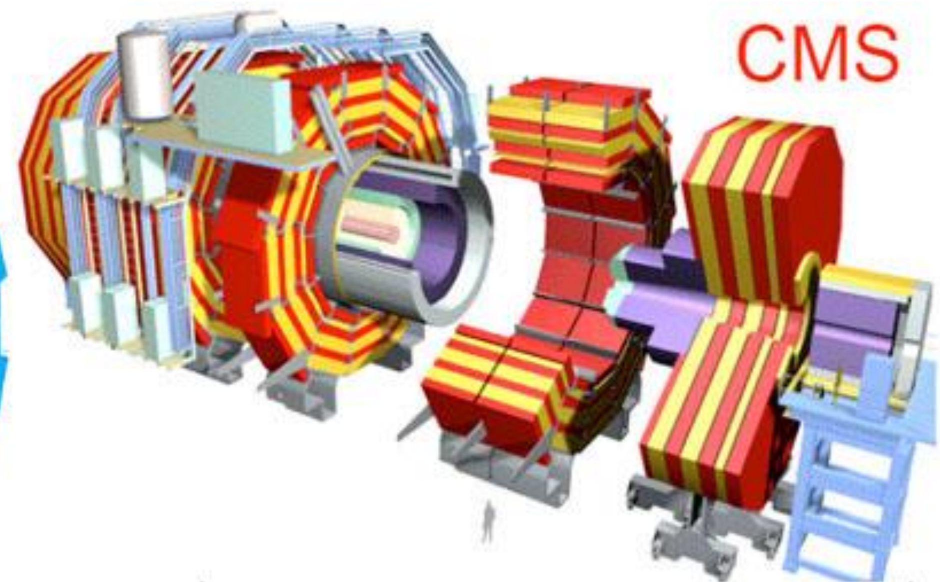
- ❑ **SPS: 1986 – (fixed target)**
  - ➢ **O**, **S** and **Pb** beams; **up to 200 A GeV**
  - ➢ hadrons, photons and dileptons

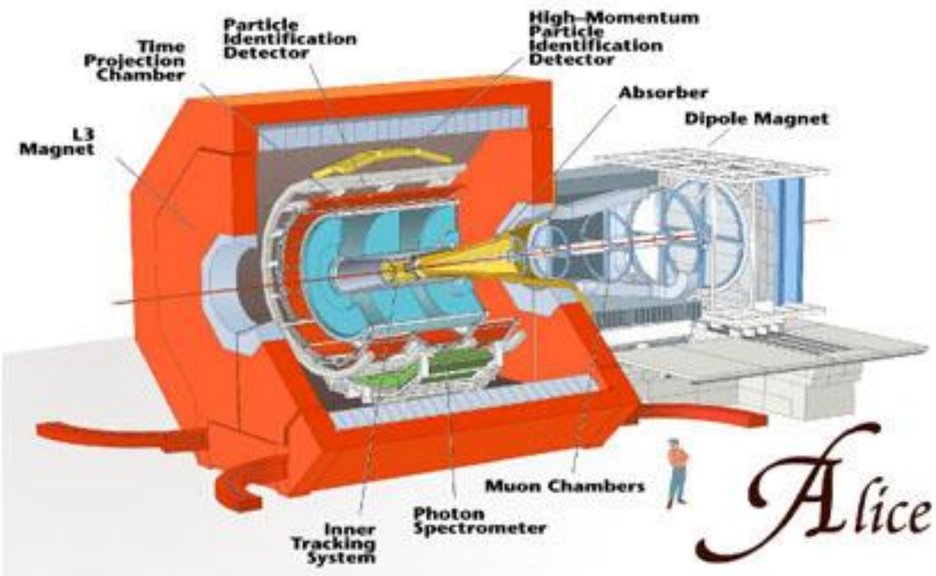
- ❑ **LHC: 2008 - ongoing**
  - ○ **Pb-Pb: up to $\sqrt{s_{NN}}$ = 2.76, 5.02, $\sqrt{s_{NN}}$ = Xe-Xe: 5.44 TeV**

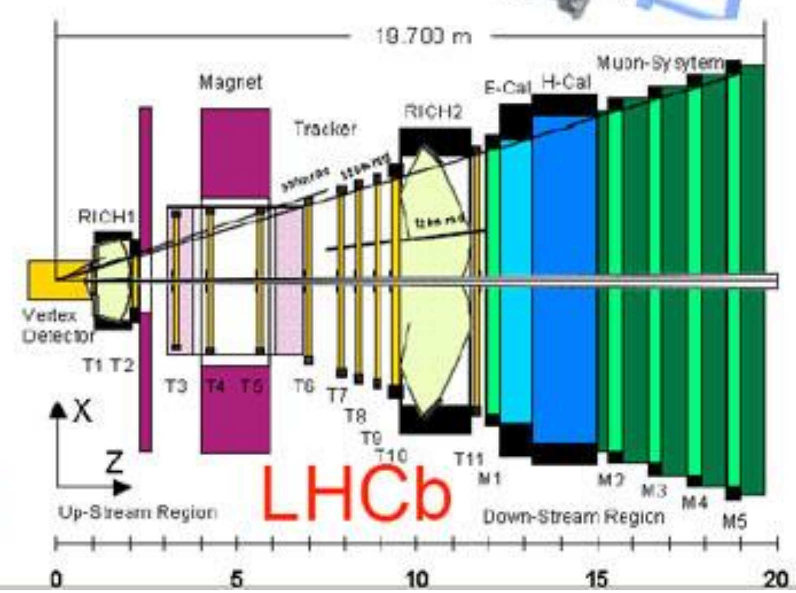
ALICE, CMS, ATLAS and LHCb

Ulta-relativistic heavy-ion experiments at the LHC

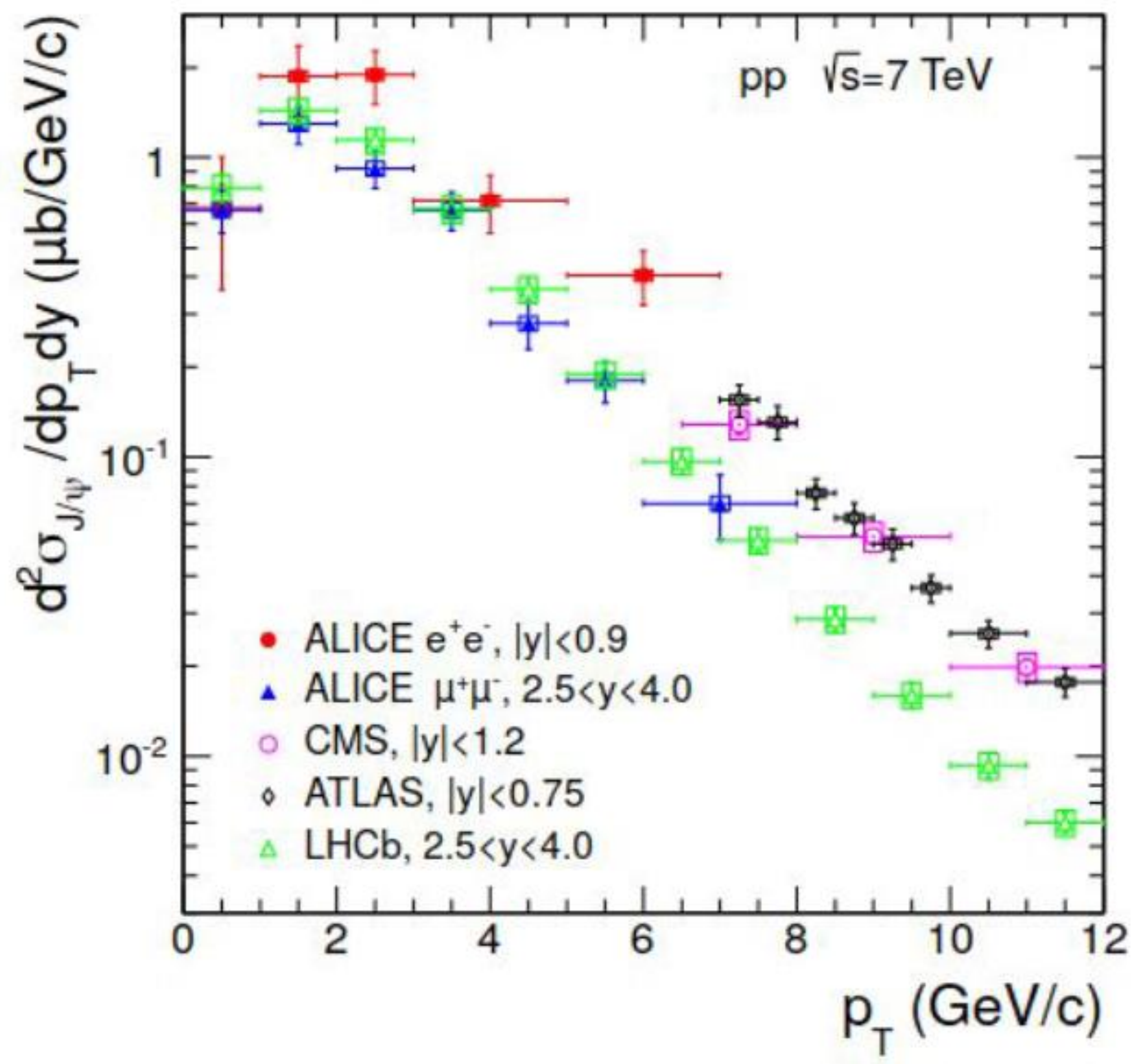




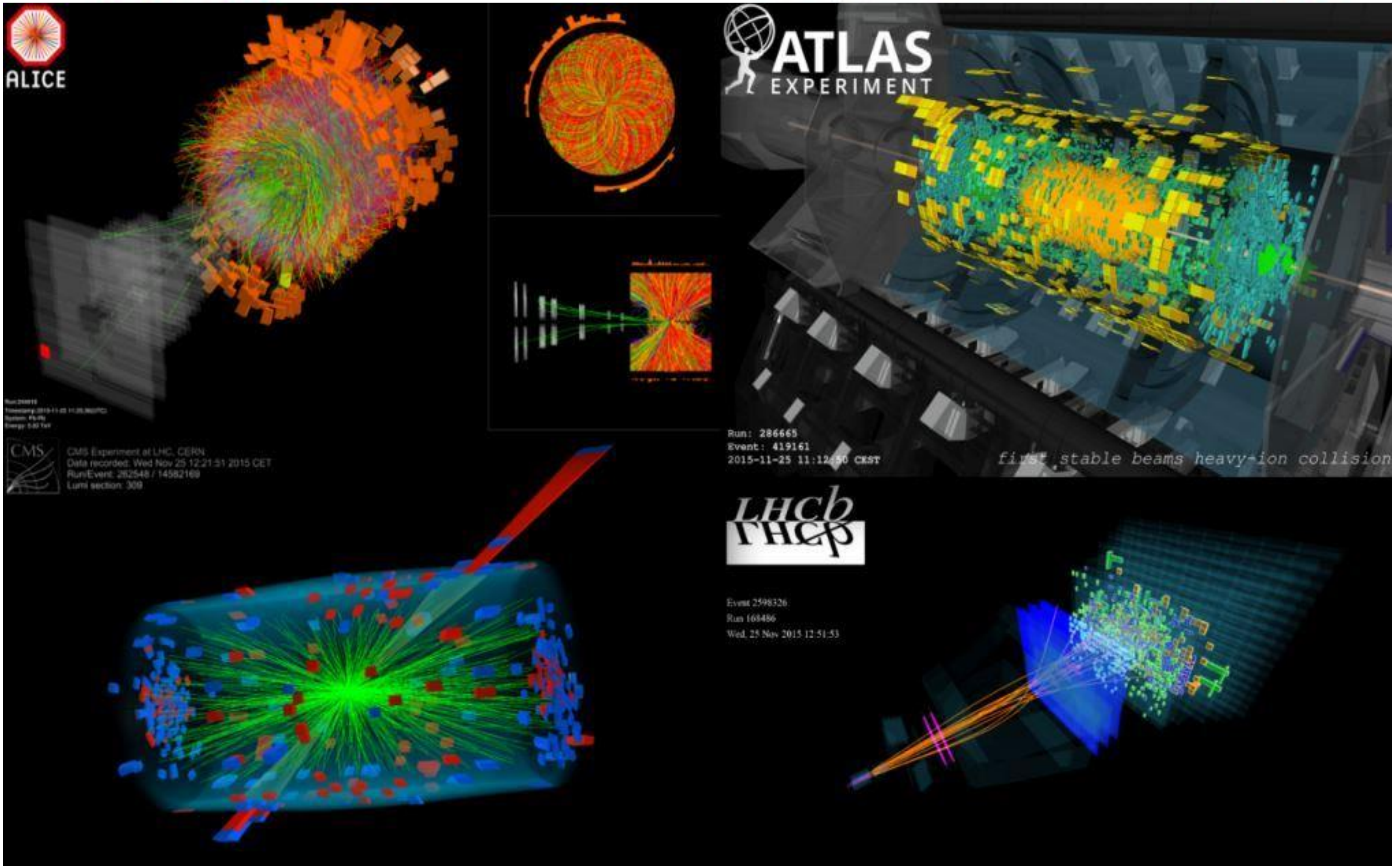




Complementary kinematic coverage at the LHC

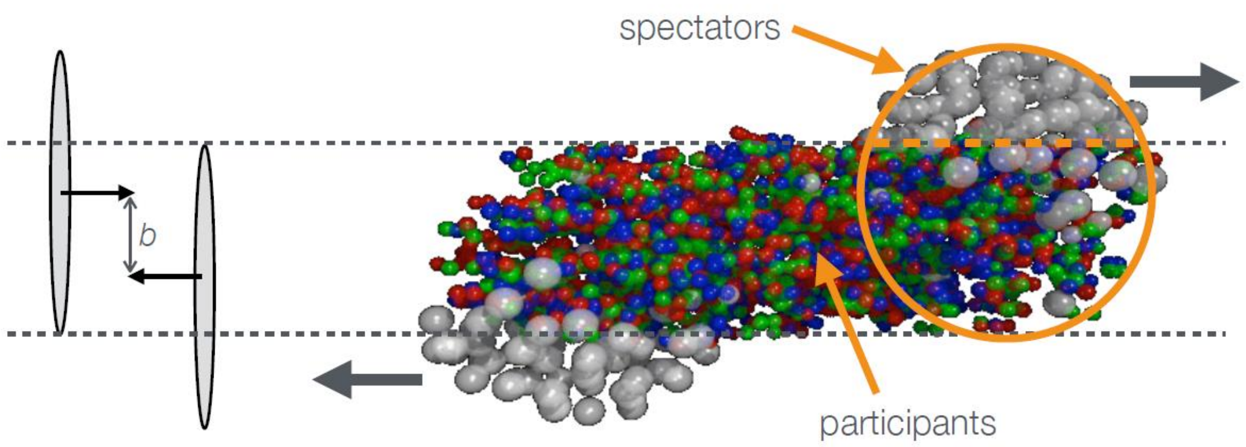


Example of an event from Pb-Pb collisions at the LHC in 2015



The geometry of a heavy-ion collision: Centrality

- System size dependent on collision **centrality** given by impact parameter, ***b*** → *the* distance between the centers of colliding nuclei in a plane perpendicular to the collision



Central collision, small *b:*

- high number of participants (N_{part})
- High multiplicity

Peripheral collision, large *b*;

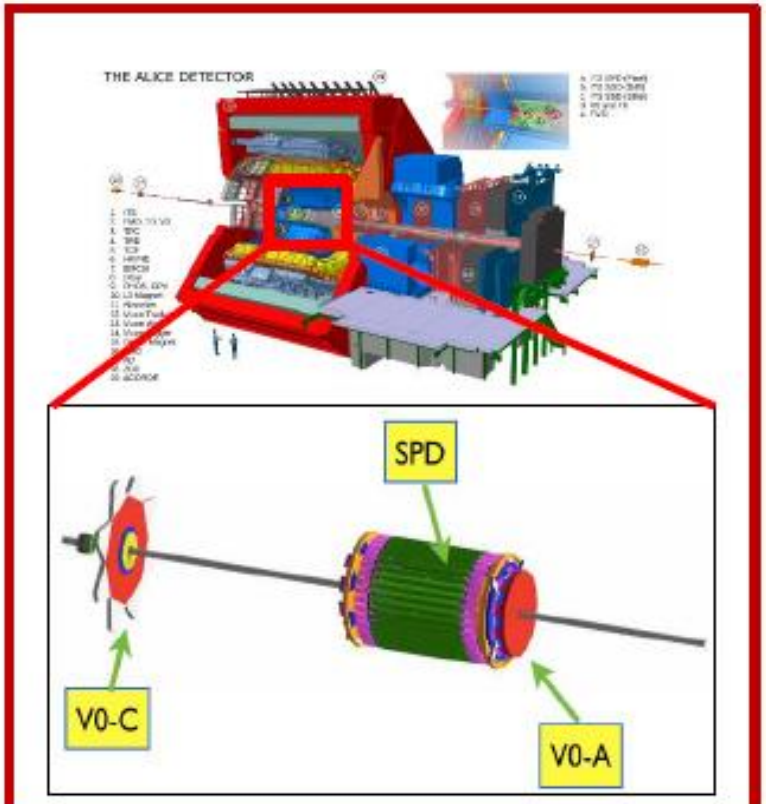
- Low number of participants (N_{part})
- Low multiplicity

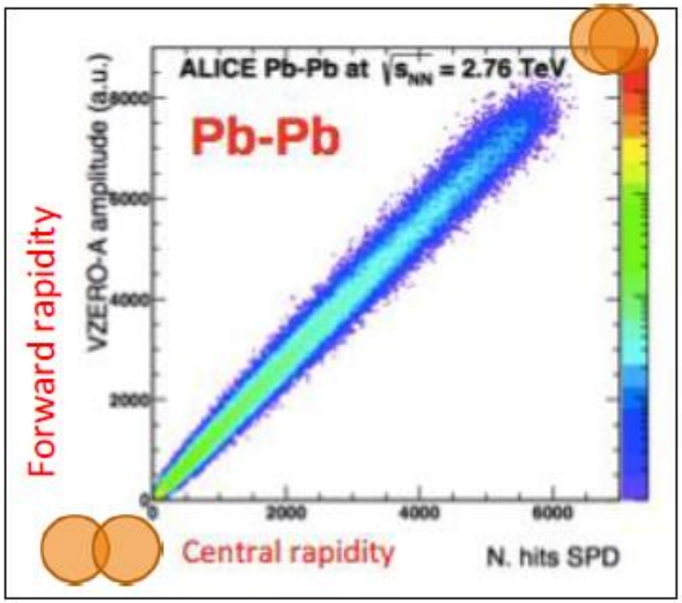
- N_{coll}: number of inelastic nucleon-nucleon collisions
- N_{part}: number of nucleons which underwent at least one inelastic nucleon-nucleon collisions

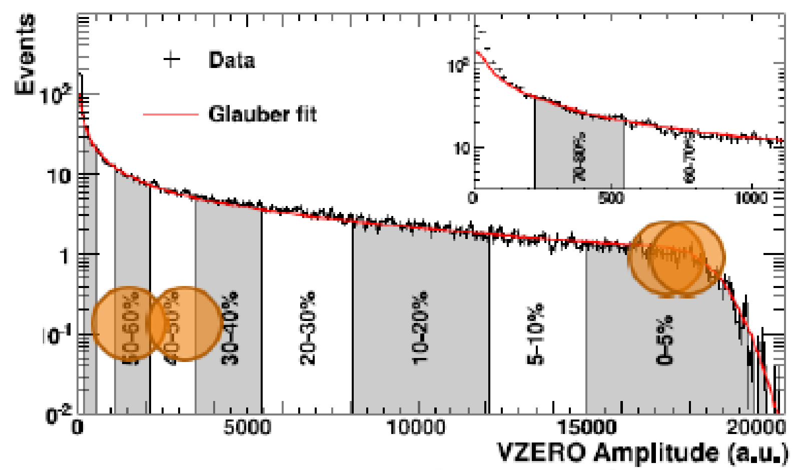
- Classify events in "centrality classes" → percentiles of total hadronic AA cross section
- Determine $\langle N_{part} \rangle$ and $\langle N_{coll} \rangle$ with a **model of the collision geometry** (Glauber model)

How do we measure centrality

- Use a multiplicity of produced particles in the acceptance of a given detector e.g. SPD
- **Or** "Zero Degree Calorimeters" to measure the energy of the spectator nucleons







- Produced by a simple model (red fit function):

  $N_{charged} = P \times [f\, N_{part} + (1-f)\, N_{coll}]$

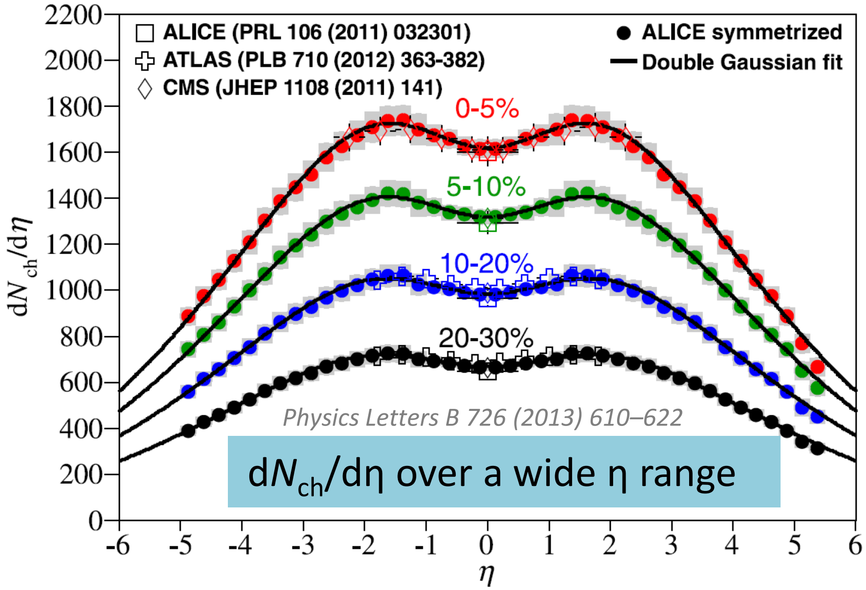
- N_{part} & N_{coll} distributions from Glauber Model
  Input: Wood-Saxon nuclear density profile
  Inelastic NN cross section

Some QGP Diagnostics

Observable	Why	What
Global Observables	Is initial state dense enough?	• Particle Multiplicities • Energy Density • Size of the fireball • QGP temperature
Collective Behaviour	Is QGP a thermalized state?	• Hadron Yields • Elliptic Flow, correlations
Hard Probes	Formed early, probe medium	• Energy loss of jets • Heavy-quark production

Global observable: Multiplicity dN_{ch}/dη of charged particles

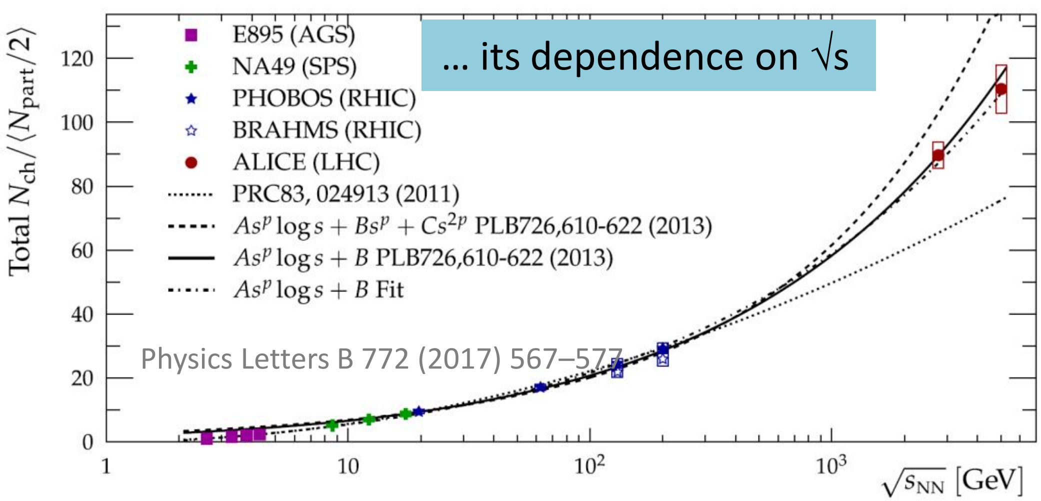
- ❑ *T*he average number of charged particles produced in a collision at a given √s
- ❑ Key observable to characterize the collision geometry and properties QGP



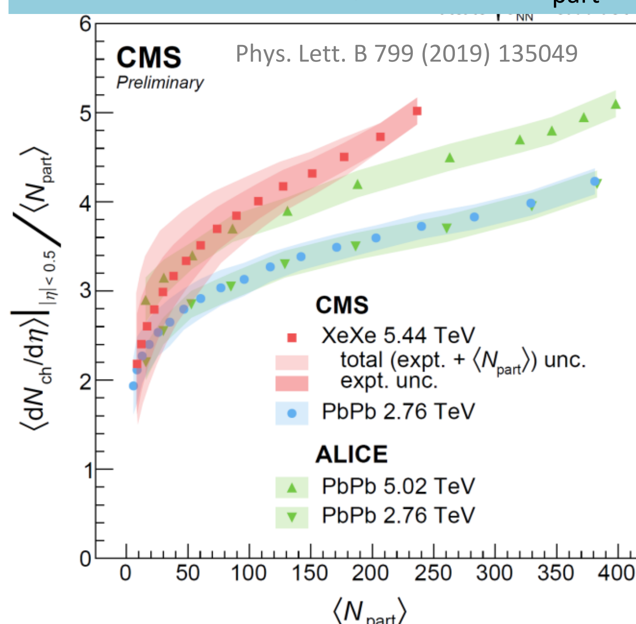
dN_{ch}/dη over a wide η range

- ❑ Central collision @ $\sqrt{s_{NN}}$ = 5.02 TeV ~ 19 000 charged particles → x4 RHIC
- ❑ Increase in central Pb-Pb is stronger than in small system: pp and p-Pb
  - ➢ understanding contributions to particle production from **hard** (**high-momentum transfer**) & **soft** (**low-momentum transfer**) processes

… its dependence on √s



… and on collision geometry N_{part}



Global observable: Energy density

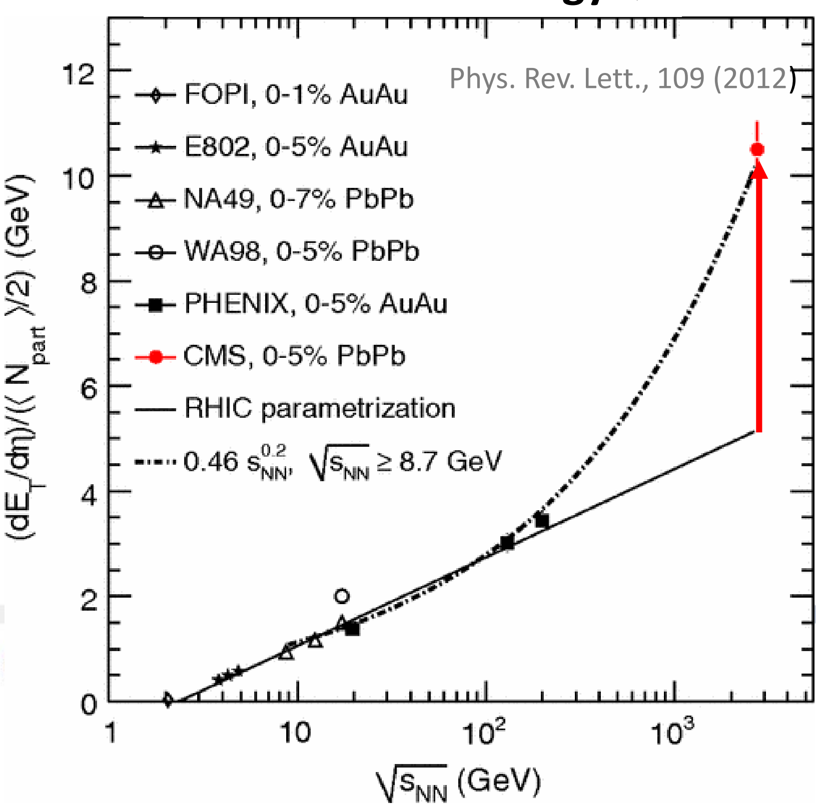
- ❑ Evaluated utilizing Bjorken's formula

S – ***transverse dimension of the nucleus***
τ_0 – ***formation time (~1 fm/c)*** *– the time it takes for energy initially stored in the field to materialize into particles*

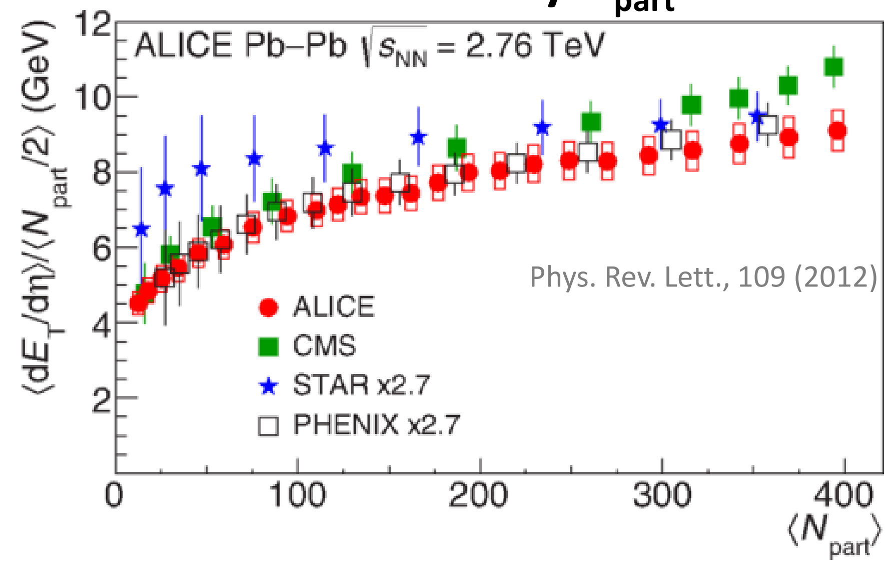
$$\varepsilon = \frac{E}{V} = \frac{1}{Sc\tau_0} \frac{dE_T}{dy}\bigg|_{y=0}$$

- ❑ Estimated from measured transverse energy

centre-of-mass energy √s



Centrality N_{part}



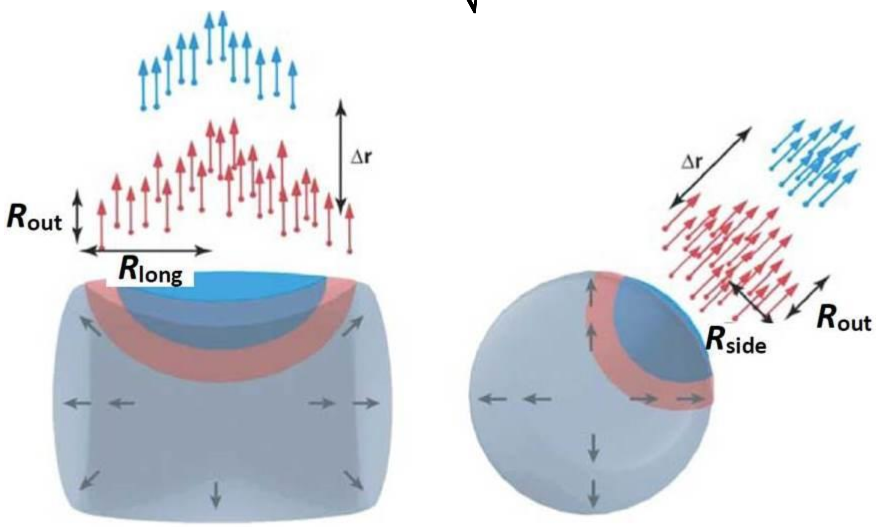
- ❑ LHC: transverse energy ~ x3-4 RHIC,
- ❑ Estimated energy density, ε >15 GeV/fm^3

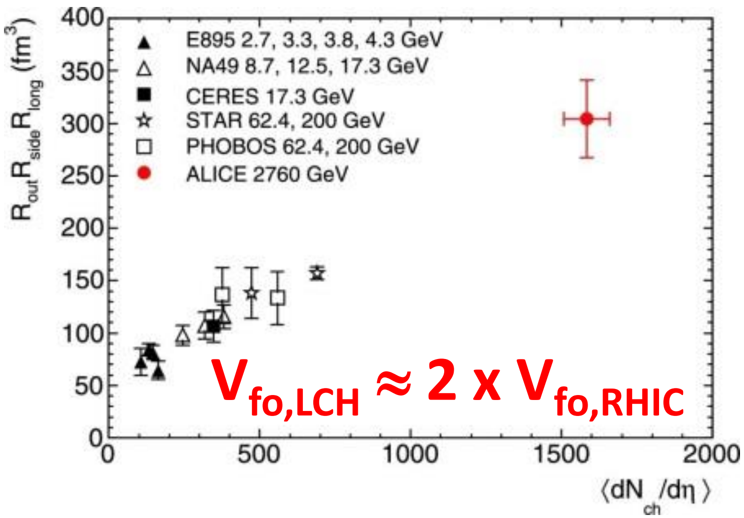
Global observable: Size of the QGP fireball

- QGP fireball expands, cools and then freezes out into a collection of final-state hadrons → Determine the **freeze-out volume** (***V**$_{fo}$*) and particles **emission time** (**τ_f**)

Freeze-out volume: V_{fo} ~ (2π)

Emission time: $\tau_f R_{long}\sqrt{m_T/T_f}$





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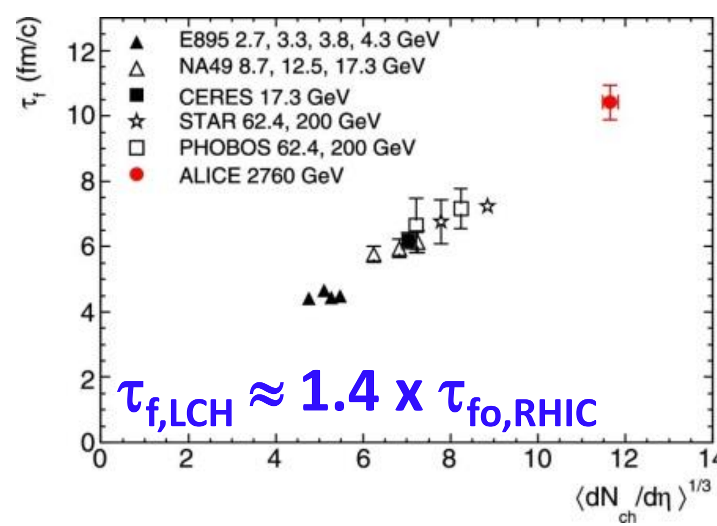


LHC: $V_{fo,LCH} \approx 2 \times V_{fo,RHIC}$, $\tau_{f,LCH} \approx 1.4 \times \tau_{fo,RHIC}$

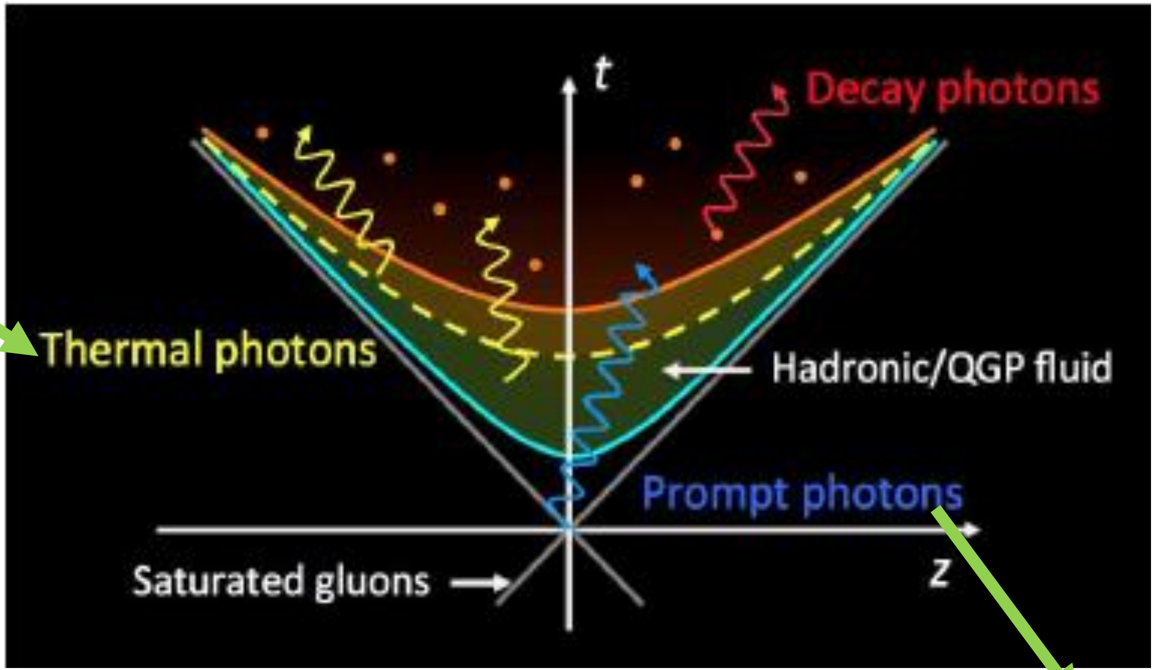
for comparison: R_{Pb} ~ 7 fm → V ~ 1500 fm^3

→ substantial expansion!

QGP temperature: photon (γ) spectrum

- Photons created during the entire space-time evolution after a collision, leave the medium unaffected due to the larger mean-free paths → they provide a direct way to examine the early hot phase of the collision

- Provide information on initial the temperature, collective flow & space–time evolution of the QGP



(Inclusive γ - γ from π^0 decays)

- provide information on parton distributions in nuclei

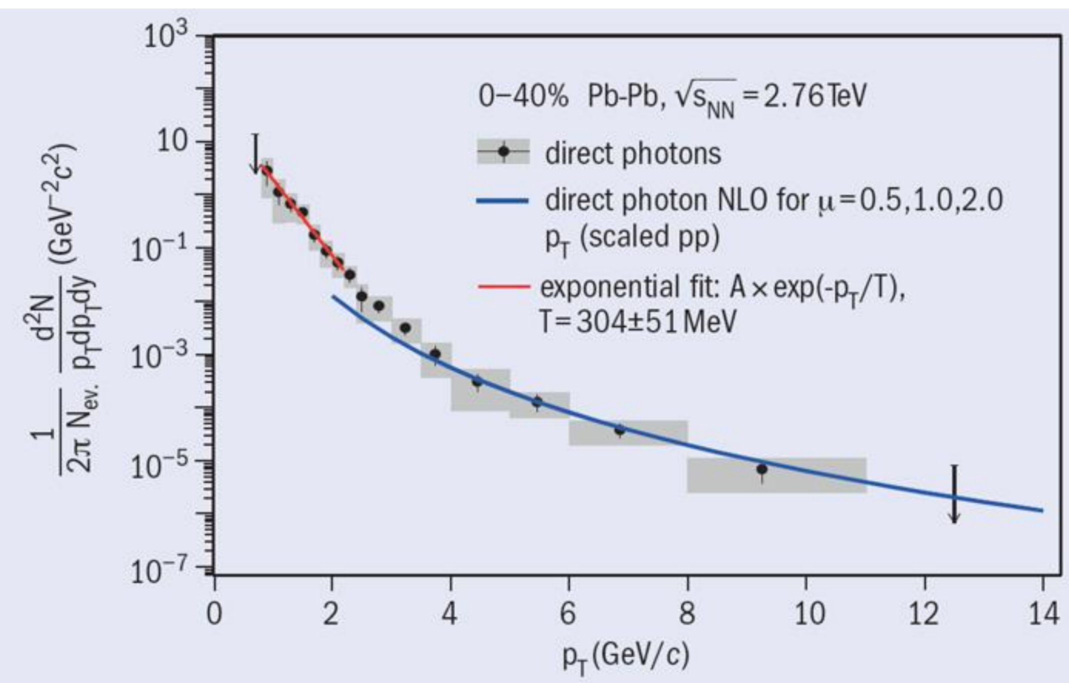
- Measurements: electron and positron tracks
  - Photon Conversion Method (PCM)
  - Electromagnetic calorimeter

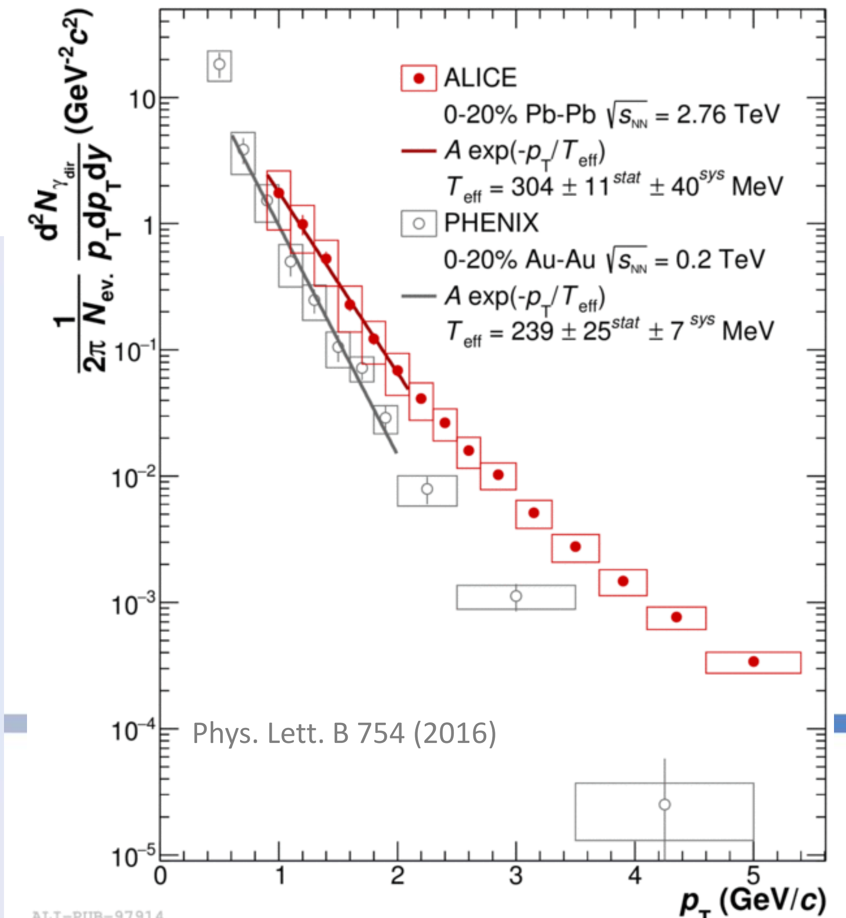
arXiv:1412.7781v1 [nucl-th] 25 Dec 2014

QGP temperature: photon (γ) spectrum

- Spectrum fit: inverse slope exponential function ∝ $\exp(-p_T/T_{eff})$ → inverse slope parameter reflects effective temperature $\boldsymbol{T_{eff}}$ averaged over different T during QGP space-time evolution
  - Direct prompt γ → power law spectrum - high p_T
  - Thermal Photons → exponential spectrum - low p_T

- LHC, $\mathbf{T_{eff}}$ = **304 ± 51 MeV**
  → ~ 2 T_c → ~ 1.4 T_{RHIC}

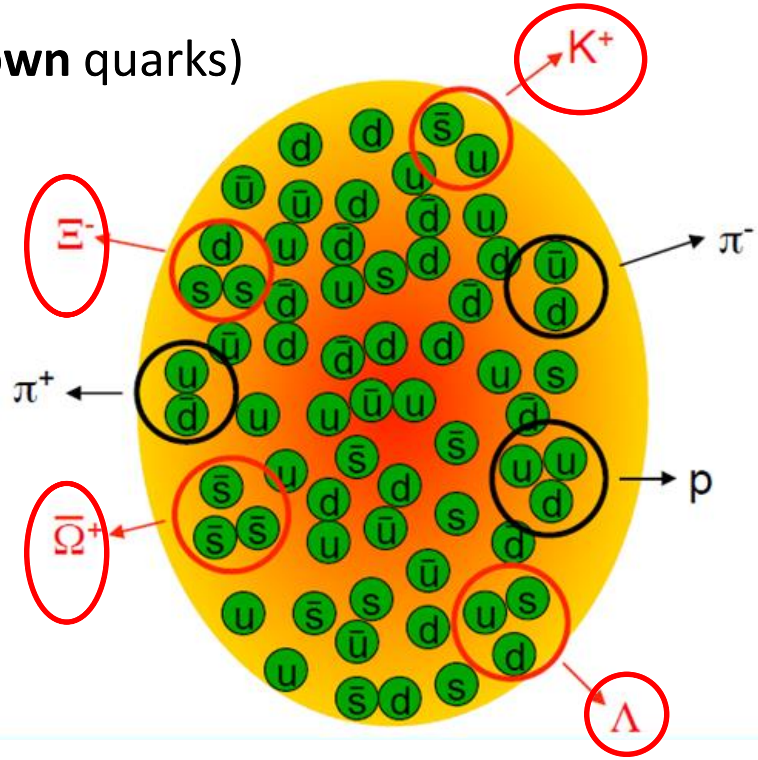




Part 2

Strangeness enhancement

- ❑ First signature of the QGP - observed in the 1980s at CERN SPS
- ❑ **Strange hadrons:** contain 1 or more strange quark (s)
- ❑ They are heavier than normal matter (**up** and **down** quarks)
- ❑ Harder to produced: “freshly” made from the kinetic energy of the colliding system
- ❑ Their **abundance** is sensitive to the conditions, structure & dynamics of the QGP
  → **large number (enhancement) → QGP formation**



- ❑ **Measurements:** Count strange particles produces in a colliosion:
  - ➢ Ratio = strange particles/non-strange particles
  - ➢ Ratio of strange particle yield in AA / strange particle yield pp
  - ➢ The higher ratio than predicted by theories that do not predict the QGP
    → **enhancement has been observed**

Strangeness enhancement at the LHC

- **Restoration of chiral symmetry** plays a role in the generation of hadron masses, accounts for 99% of the mass of nuclear matter

  - increase production of strange hadrons

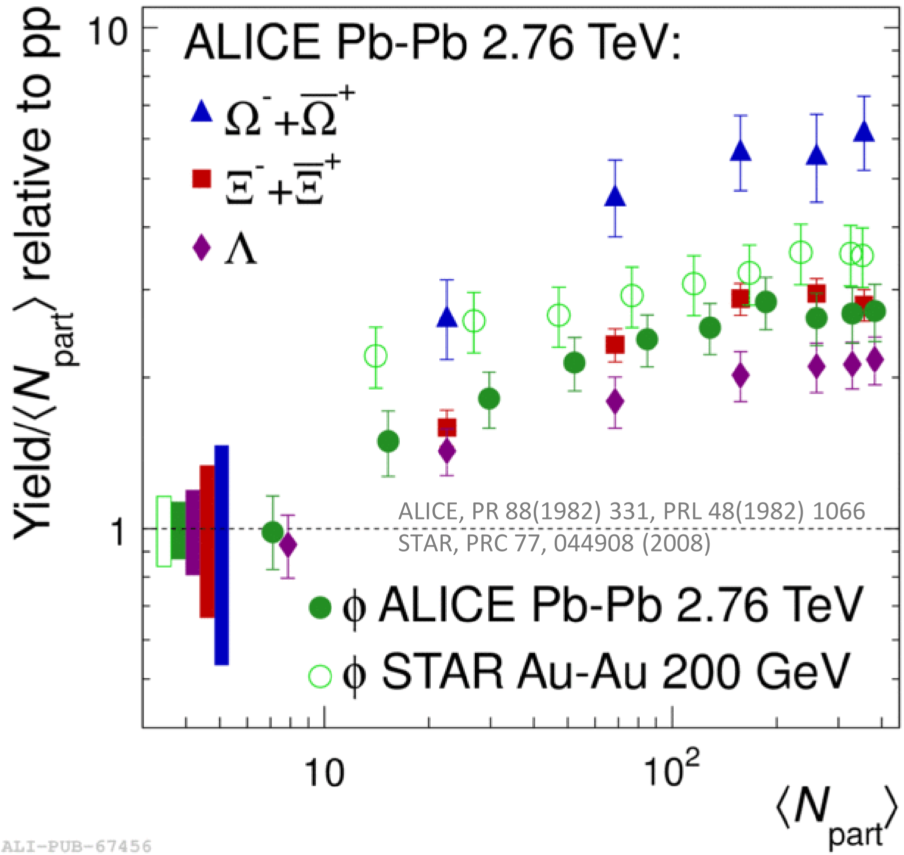
    Lambda (Λ) – has 1 strange (s) quark

    Xi (Ξ) – 2 strange (s) quarks

    Omega (Ω) – 3 strange (s) quarks

  - *strange* (s) quark masses expected to go back to the current value in QGP: m_s ~ 150 MeV ~ T_C

  - copious production of $s\bar{s}$ pairs by gluon-gluon (gg) fusion



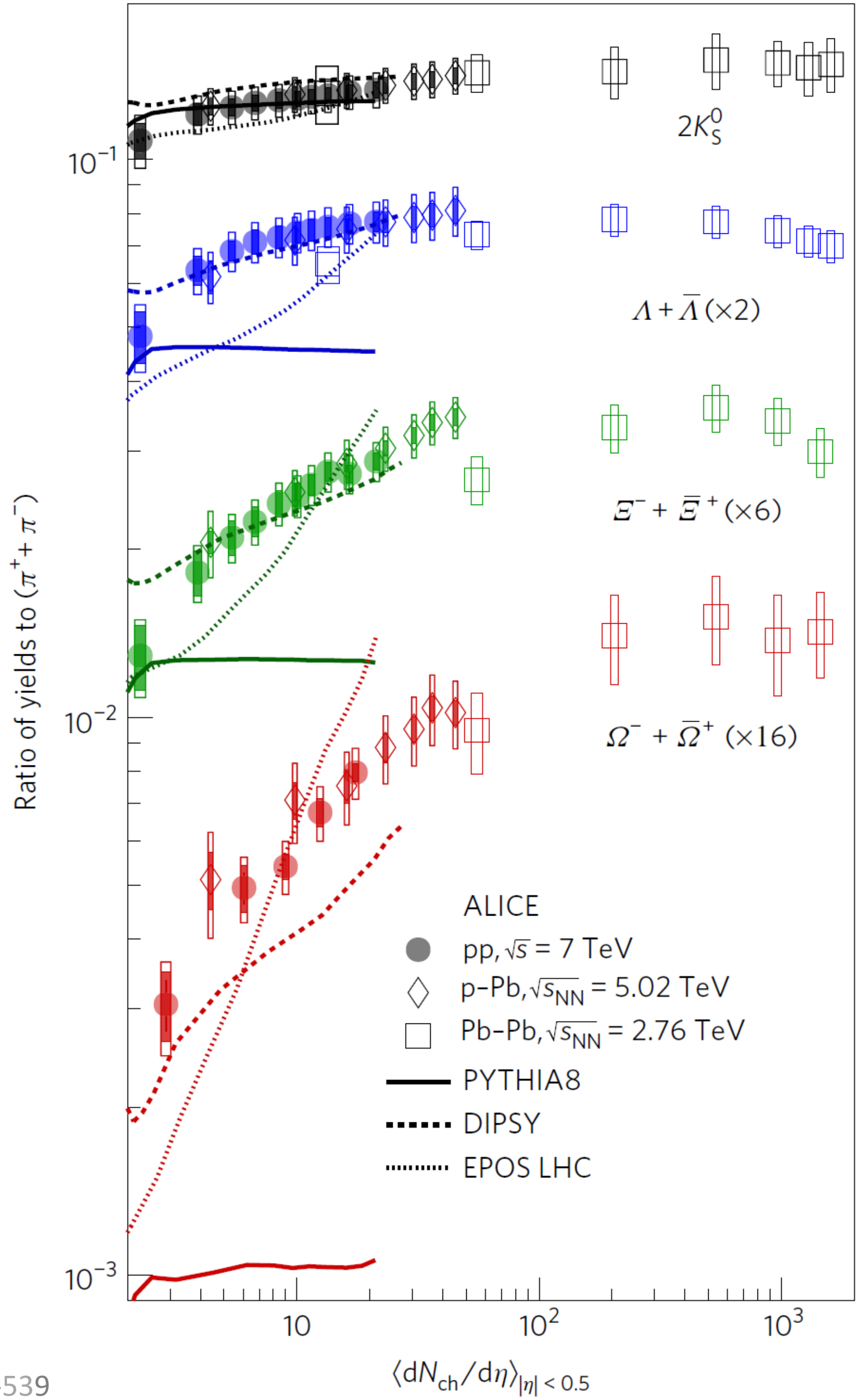
- **Deconfinement:** stronger effect for multi-strange baryons

  → **Strangeness enhancement increases with strangeness content**

Strangeness enhancement

How does it compare in small collisions: **p-Pb** & **pp** where the QGP is not expected**?**

- ❑ Smooth evolution of particle yield ratios with the multiplicity
- ❑ Enhanced production of multi-strange hadrons in high-multiplicity pp!
- ❑ **Strangeness enhancement is** considered a **defining feature of QGP**
  → **collective expansion of the system**
- ➢ But not produced by traditional "**soft**" QCD models (e.g. PYTHIA)
- ➢ reasonably reproduced by models including hydro (e.g. DIPSY) JHEP01 (2017) 140



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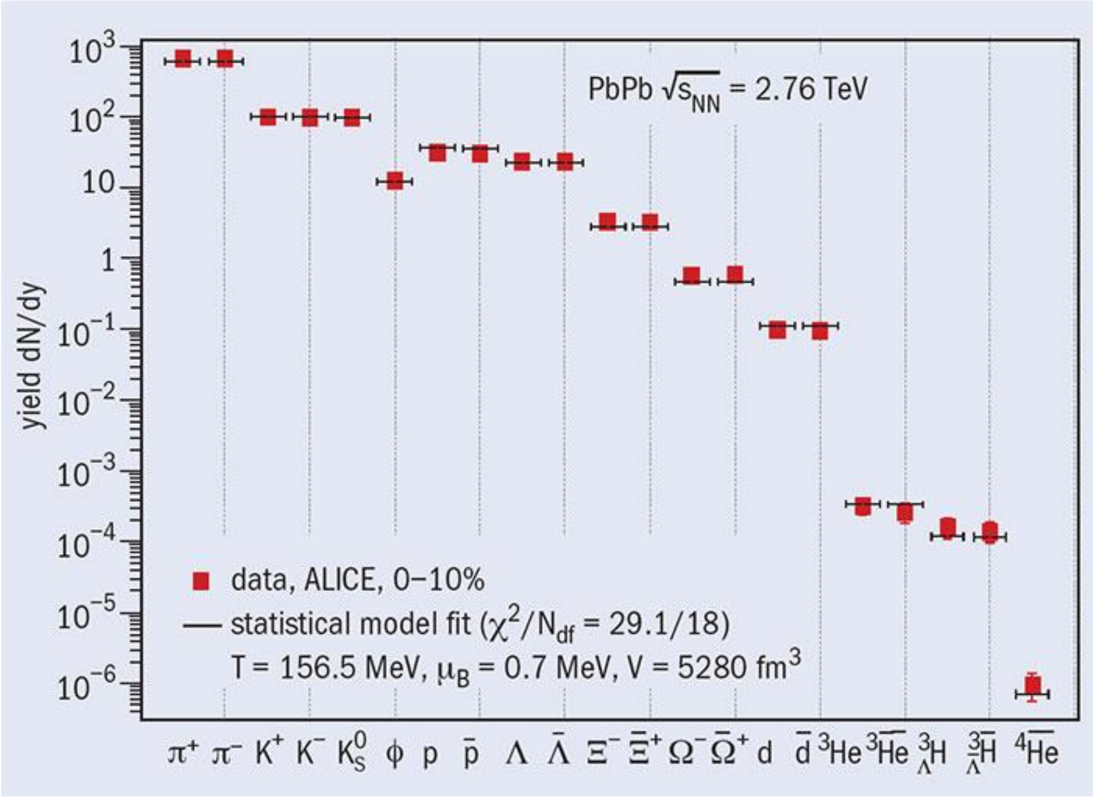
Collective Behaviour	Is QGP a thermalized state?	• Hadron Yields • Elliptic Flow
Hard Probes	Formed early, probe medium	• Energy loss of jets • Charm production

Collective behaviour: Hadron yields & chemical freeze out

Chemical freeze-out: inelastic reaction cease; the chemical composition of the system (particle yields & fluctuations) is fixed

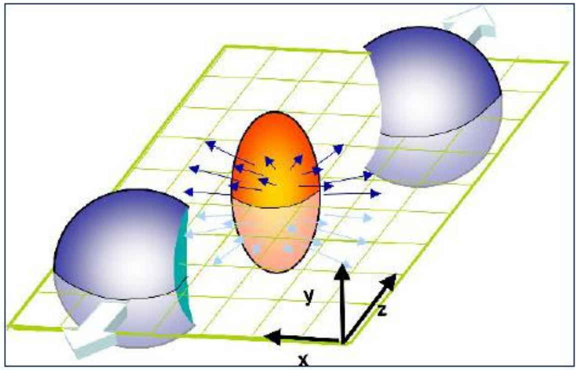
- **How does the partonic system hadronized**? → Final state particle production
  - Mass ordering of observed **non-strange and strange mesons**
  - Mass ordering of observed **baryons to light nuclei**
  - **Particles/antiparticles** get closer with increasing energy

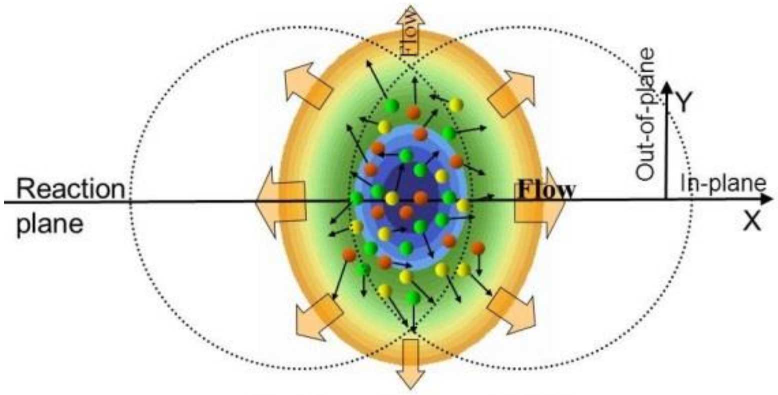


Nuclear Physics A971, (2018) 1-20

- **Can the yields be observed in a single model**?
  - Statistical hadronization: Ratio ^{4}He/anti^{4}He consistent with unity
  - Supported by thermal models

Collective behaviour: Does the QGP have flow (υ_2)?





Driven by overlap geometry

- Non-central collisions are azimuthally asymmetric
- Transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena
- **Elliptic flow**: initial spatial anisotropy + hydro = final momentum anisotropy
- Quantified by the second Fourier coefficient, υ_2

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2 v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)\right]$$

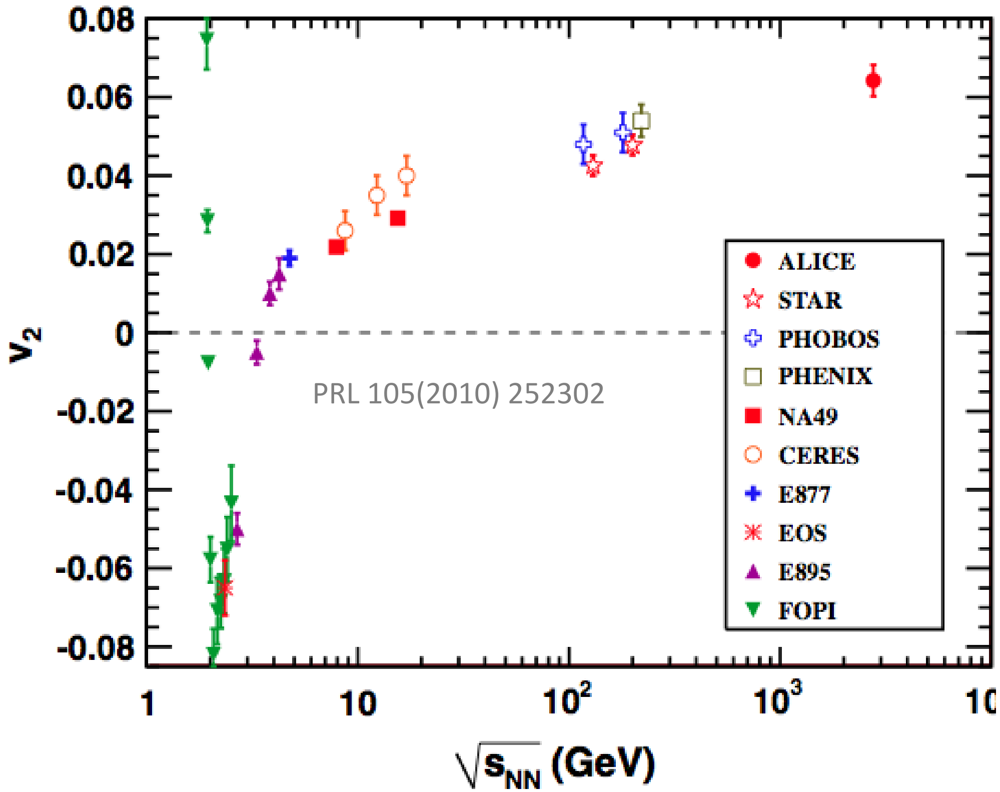
$$v_2 = < cos2(\varphi_{part} - \Psi_{EP}) >$$

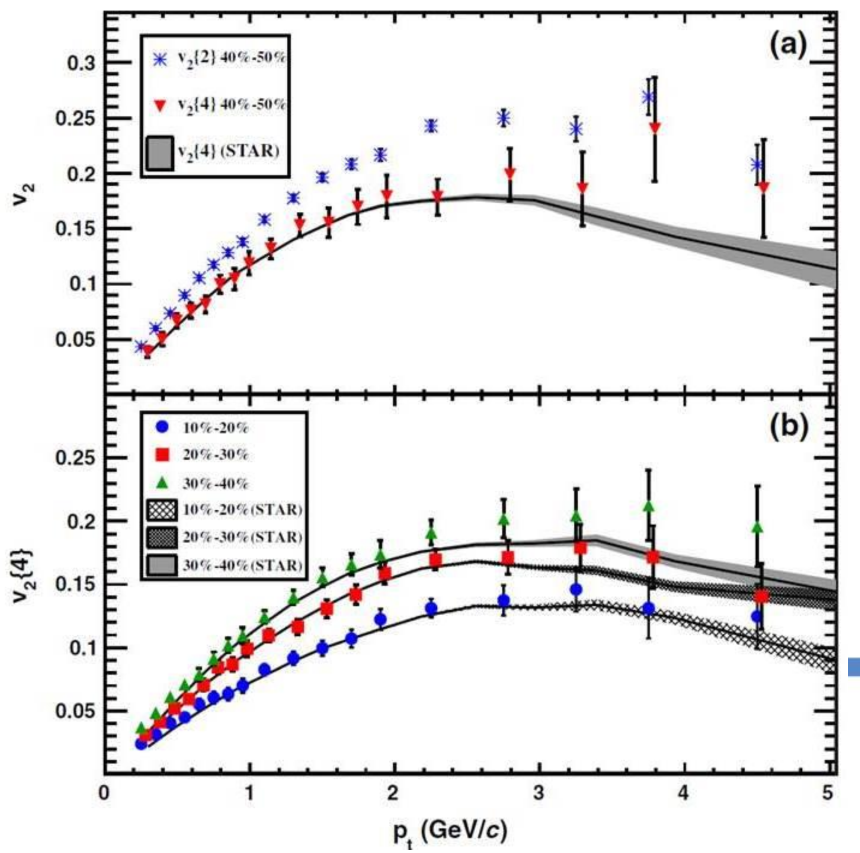
- Related to pressure gradients & shear viscosity to entropy ratio (η/s)
- **Flow (υ_2) provides information about the transport properties of the QGP**
  - Flow at high p_T → path-length dependence of energy loss
  - Flow at low p_T → sensitive to thermalization/collective motion

Collective behaviour: Does the QGP have flow (υ_2)?

- **υ_2 of identified particles**: as expected, υ_2 large at hydro limit ➔ flow patterns consistent with ideal hydrodynamics
- **υ_2 of identified particles** very similar at LHC and RHIC

→ the system still behaves very close → similar hydrodynamic behavior to the ideal liquid





Some QGP Diagnostics

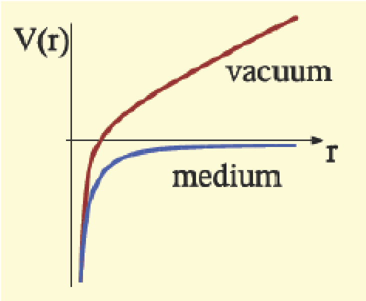
Observable	Why	What
Global Observables	Is initial state dense enough?	• Particle Multiplicities • Energy Density
Collective Behaviour	Is QGP a thermalized state?	• Hadron Yields • Elliptic Flow, correlations
Hard Probes	Formed early, probe medium	• Quarkonium suppression in the QGP

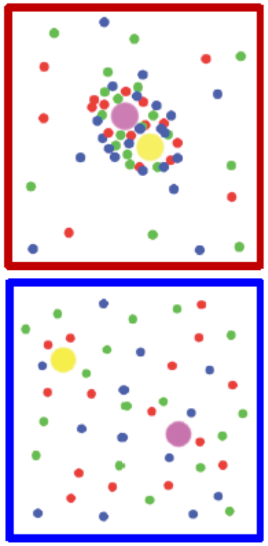
Quarkonium suppression in the QGP?

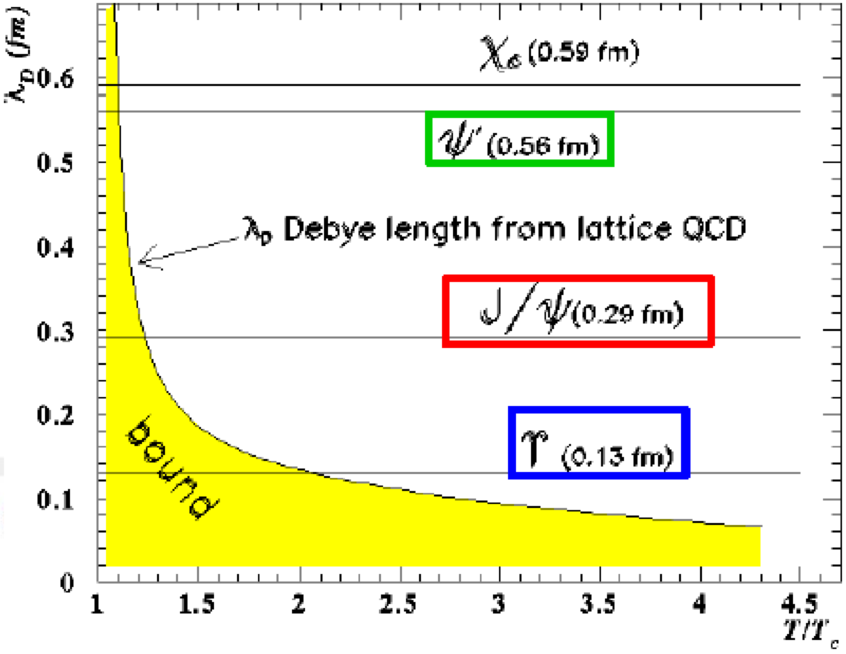
Matsui & Satz, PLB 168 (1986) 415)

❑ Signature first proposed by Matsui and Satz
Pre-resonant $q\bar{q}$ states "melt" in the QGP - in the plasma phase, the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening)

❑ Chamornium ($c\bar{c}$) and bottomium ($b\bar{b}$) states with r > λ_D will not bind, **their production will be suppressed**



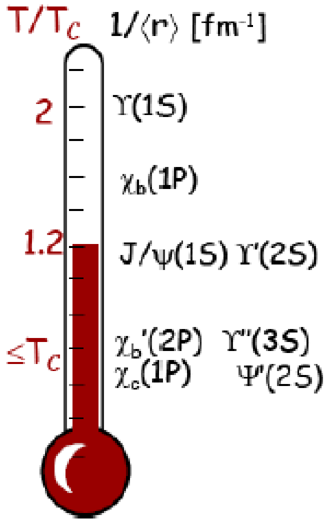


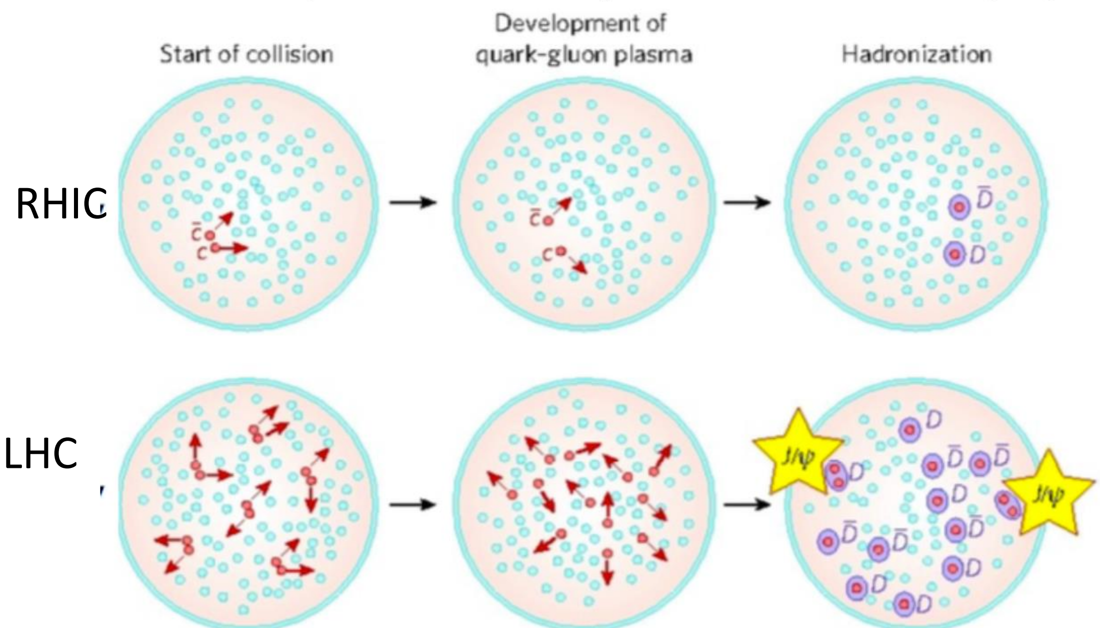


❑ λ_D, and therefore which quarkonium states will be suppressed **depends on the temperature**

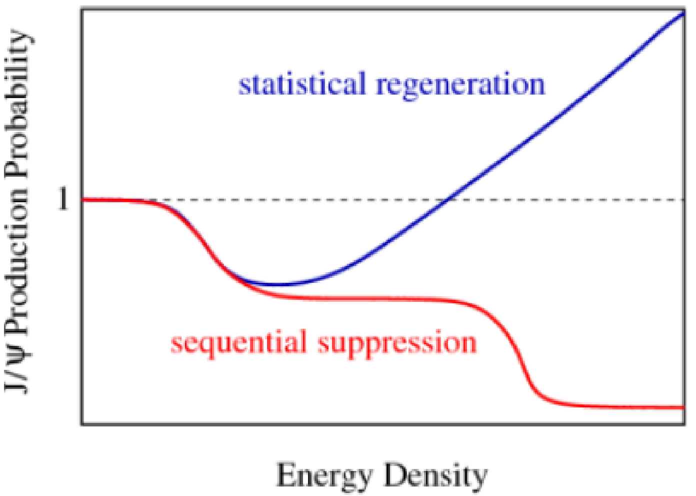
Quarkonium states as QCD thermometer?

- Different states melt at different temperatures (**sequential suppression)**
- Non-correlated quarks can recombine (**kinetic/statistical regeneration)**





Pictures: A. Moczy, H. Satz



P. Braun-Muzinger, J Stachel, PLB (2000) 490
R. Thews, et al, PRC (2001) 054905

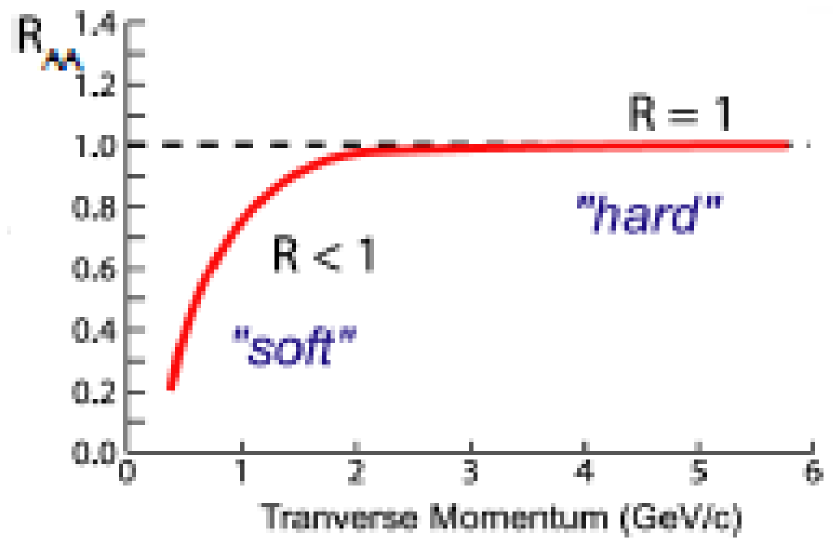
How do we measure suppression?

- Take the ratio of particle production yields in AA to pp collisions, normalized to the number of binary nucleon collisions in **AA → Nuclear modification factor**

$$R_{AA} = \frac{AA}{\text{rescaled } pp} = \frac{d^2N_{AA}/dp_T\,dy}{\langle N_{binary}\rangle\, d^2N_{pp}/dp_T\,dy}$$

- ***R_{AA} = 1*** no nuclear/medium effects→ production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions **(binary scaling)**

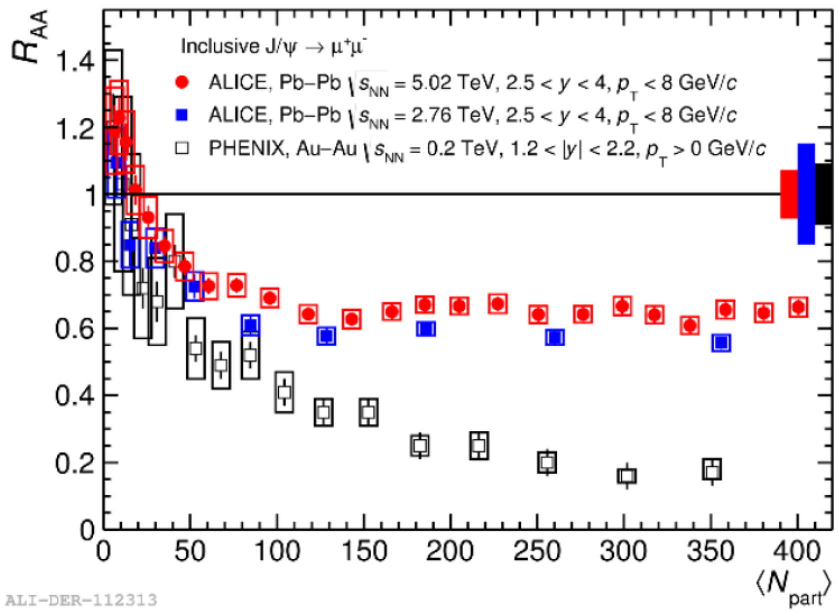
- ***$R_{AA} \neq 1$*** effects from the medium, e.g. parton energy loss in the medium **→ suppression of particle production**

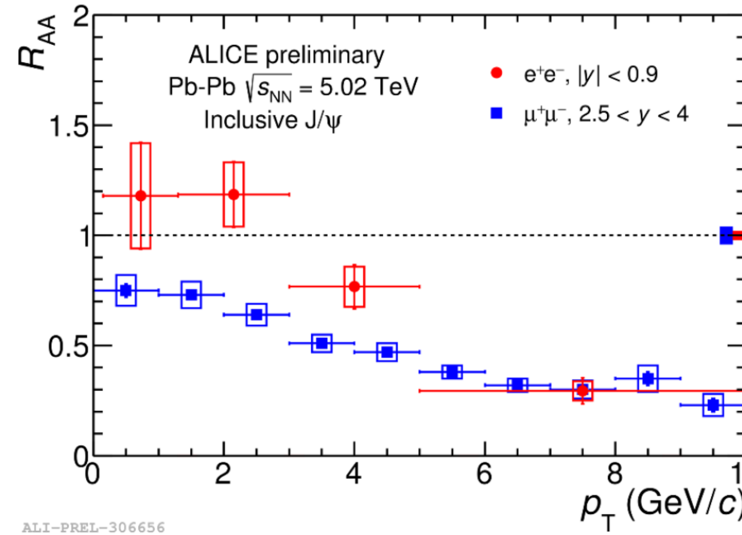


J/ψ suppression and regeneration

- Results at 5.02 TeV with improved pp reference

PLB 766 (2017) 212

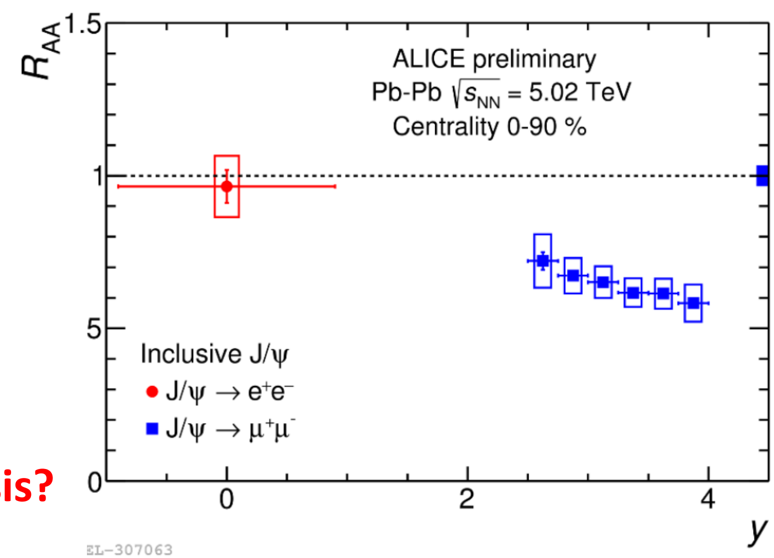




- Large suppression of J/ψ at RHIC than LHC
- Less suppression at mid-rapidity wrt forward rapidity
- A clear sign of charm-quark recombination

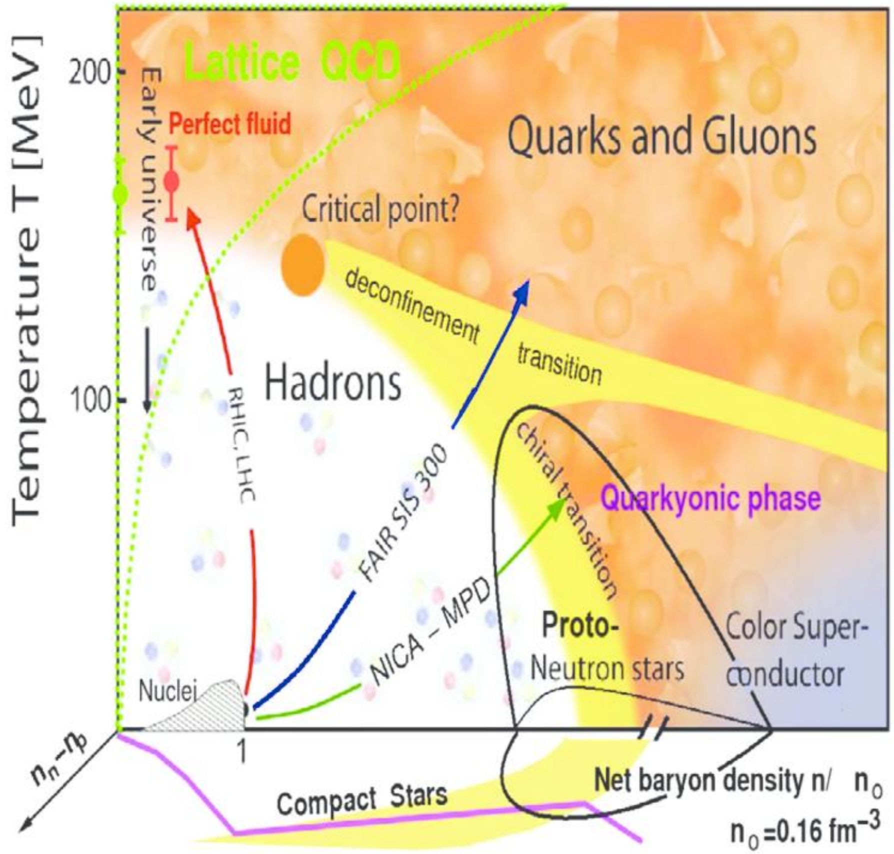
→ regenerated J/ψ's concentrated at low p_T

→ Do measurements support the regeneration hypothesis?



Future of heavy-ion experiments

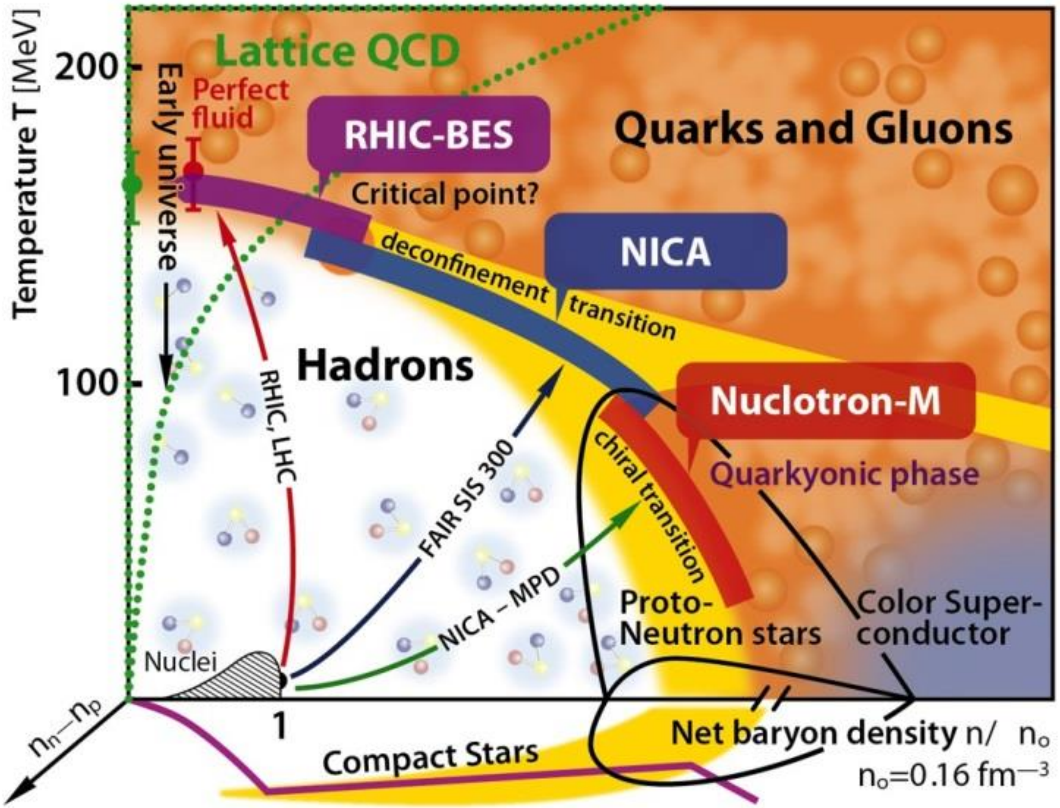
- ❑ **Extremely high √s &** at vanishing baryonic density $\mu_B \sim$ **0** → equal amount of matter and antimatter
- ➢ **LHC,** **HL-HLC** @ CERN (Geneva, Switzerland)
- ○ ALICE Phase IIb upgrade, LHCb + fixed target, etc
- ➢ **RHIC, RHIC-BES** @ BNL (USA) final wrap of BES-II in 2021/2022
- ○ Towards the EIC
- ❑ **High net-baryon densities:** similar to those in the **core of a neutron star**. EoS & other properties, inform on the nature of the medium including QGP → **CBM @ FAIR-Germany,**
- ❑ **Maximum baryonic density:** determine the existence & location of the transition region. Establish the character of the associated phase transformation → **NICA @ JINR** (Dubna, Russia)



THANK YOU

EXTRA slides

Heavy ion experiments



- **RHIC:** earlier (62.4, 130 and 200 GeV) & later (54.5 GeV) collected data sets of Au+Au collisions
- **RHIC-BES:** Phase I (BES I) completed in 2011, Au+Au data, energy range from 39 GeV to 7.7 GeV.
- 2015 BES program extended to energies < sqrt(sNN) = 7.7 GeV by the implementation of the fixed-target mode of data taking (FXT) in the STAR experiment, in addition to the standard collider configuration
- 2021 early wrap of final phase of BES-II
- Next construct a brand-new nuclear physics research facility—the Electron-Ion Collider (EIC). https://www.bnl.gov/newsroom/news.php?a=219079

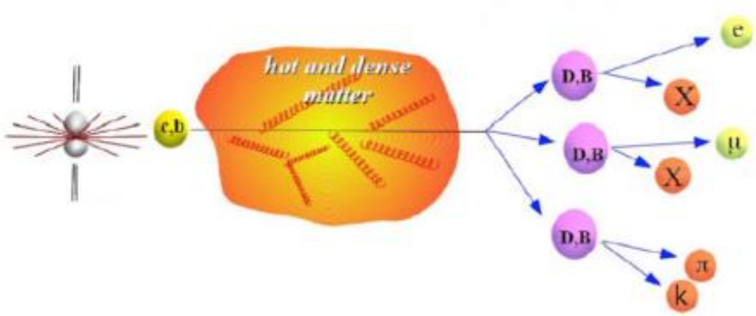
Nuclotron-based Ion Collider fAcility (NICA):

- Nuclotron ion beams extracted to a fixed target and colliding beams of ions, ions-protons, polarized protons, and deuterons
- Projected maximum kinetic energy of the accelerated ions is 4.5 GeV, and 12.6 GeV for protons
- **2013**: tender for scientific equipment supply was completed
- **2019**: most equipments delivered and mounted -> First tests began in late 2019
- Construction expected to be completed in **2022**

Heavy quarks: two "historical" pillars

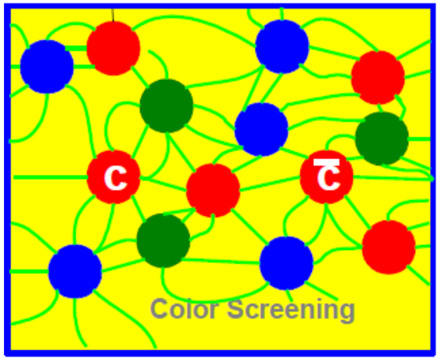
Open heavy flavour: Charm hadrons (D^0, $D^{\pm}$, ...), bottom hadrons (B^0, $B^{\pm}$,...)

- ❑ Mass dependence of radiative parton energy loss ("dead cone" effect) Dokshitzer and Kharzeev, Phys. Lett. B519(2001) 199[arXiv:hep-ph/0106202]



Bound states (Quarkonia): $c\bar{c}$ **mesons (J/ψ, ψ'..)** & $b\bar{b}$ **mesons (ϒ, ...)**

- ❑ QQbar states "melt" (dissociate) in QGP (Debye screening) Matsui & Satz, PLB 168 (1986) 415)



→ Probe of QCD interaction dynamics in extended systems

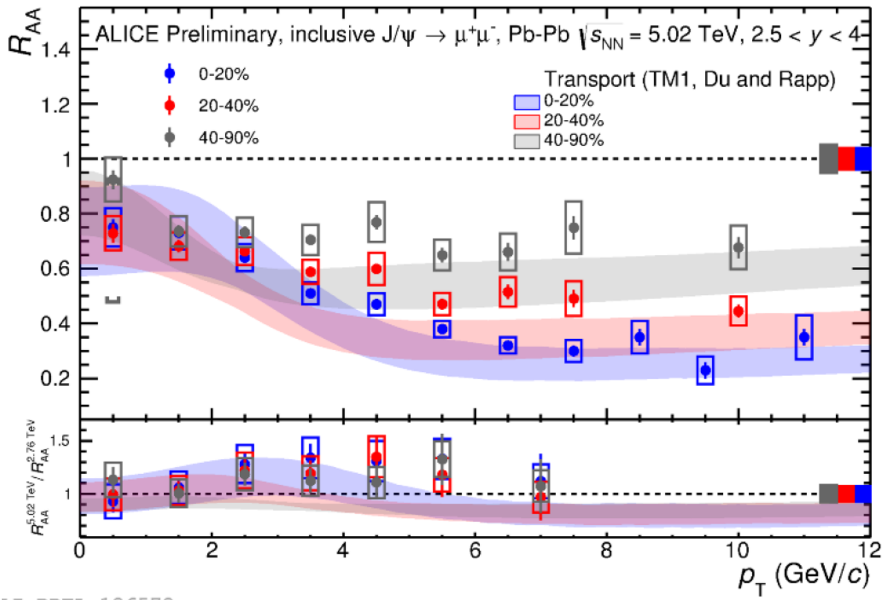
→ Probes of de-confinement and QGP temperature

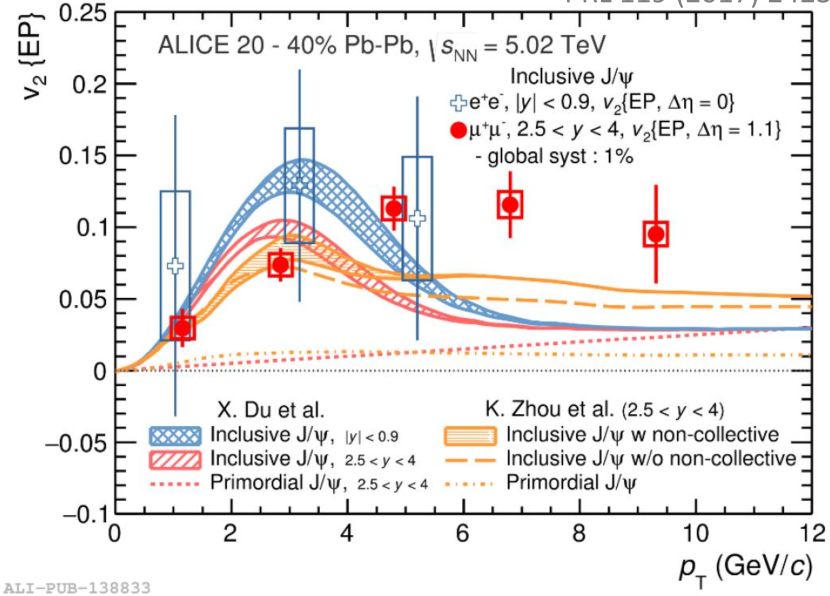
- ❑ Probe medium transport properties via collective expansion of the medium
- ❑ Evolved and extended significantly over the years

J/ψ regeneration

- The regeneration component is expected to contribute mainly at low p_T
- R_{AA} increase at $2 < p_T < 6$ GeV/c from $\sqrt{s_{NN}}$ = 2.76 to 5.02 TeV
- Transport models fairly reproduce the trend as a function of p_T and centrality

PRL 119 (2017) 242301





- Elliptic flow, v2, is non-zero in semicentral collisions→ regenerated J/ψ inherit charm-quark flow in the QGP
- Described by models including a strong regeneration component from recombination of thermalized quarks in the QGP

Caveat: precise description of the data is a challenge for models especially at high p_T

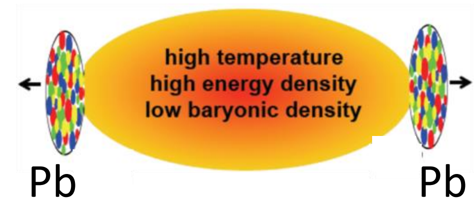
science & technology
Department: Science and Technology
REPUBLIC OF SOUTH AFRICA

National Research Foundation

The paradigm

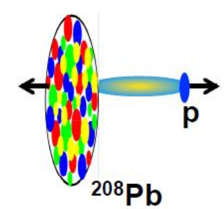
❑ CORE business: AA collisions → create and characterize the QGP

- Global properties ⇔ the QGP fireball
- Strangeness enhancement ⇔ historic signature
- Anisotropy, correlations ⇔ collective expansion
- Bulk particle production ⇔ hadronization
- High-p_T and jets ⇔ opacity of the QGP
- Heavy-flavour production ⇔ transport properties
- Quarkonium production ⇔ de-confinement in the QGP

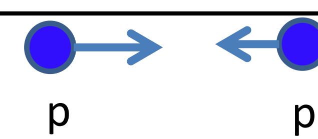


❑ Role of the small systems:

- **Proton-nucleus (p-A) collisions: Control experiment**
  - disentangle initial and final state effects
  - → Investigate cold nuclear matter effects (CNM)



- **Proton-proton (pp) collisions:**
  - ✓ Baseline (reference)
  - ✓ Test pQCD theories

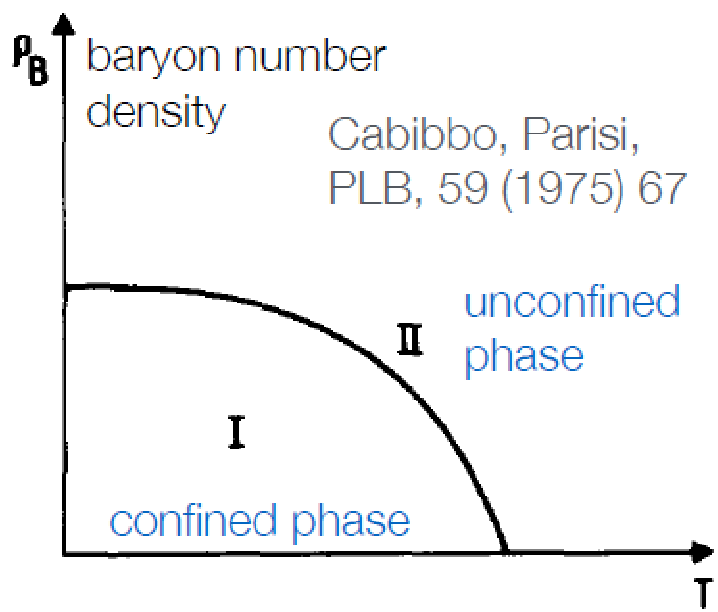


Historical idea of the quark-gluon plasma (QGP)

- **1973 birth of QCD**: All ideas in place
  - Yang-Mills theory, SU(3) color symmetry, asymptotic freedom; confinement in color-neutral objects
- **1975 – idea of quark deconfiment at high temperatures and/or density**:
  - Collins, Perry, PRL 34 (1975) 1353: Idea based on weak coupling (asymptotic freedom)

"Our basic picture then is that matter at densities higher than nuclear matter consist of a quark soap."

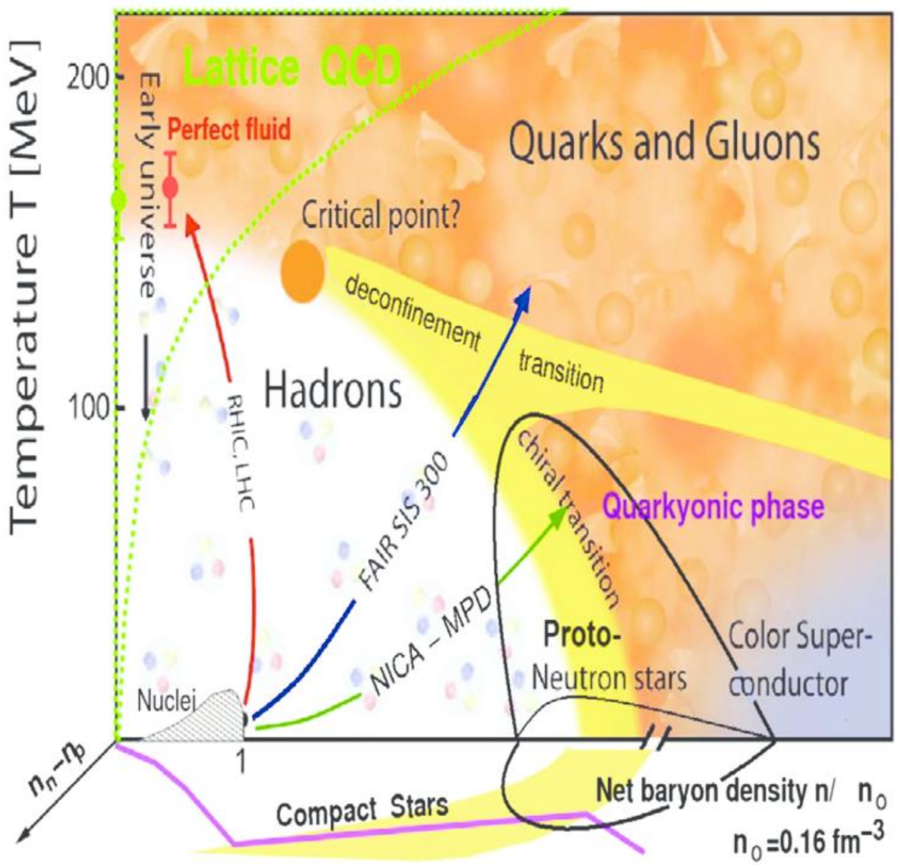
- Cabbibo, Parisi, PLB, 59 (1975) 67:
  - exponential hadron spectrum not necessarily connected with a limiting temperature
  - Rather: **Different phase in which quarks are confined**



- It was soon realized that a **new state** could be created and studied in **heavy-ion collisions**

Phase diagram of strongly interacting (QCD) matter

- At high energy density ε and/or high temperature, matter transition from hadron to **quark-gluon plasma (QGP)** – a medium of **“free” quarks** and **gluons**
  - Deconfinement → colour confinement removed
  - Chiral symmetry restoration → role in the generation of hadron masses, accounts for 99% of mass of nuclear matter



- Critical energy density (energy /volume)

ε_c ~1 GeV/fm^3 ~ 10 $\varepsilon_{nucleus}$

1 femtometre (fm) = 10^{-15} m

1 MeV = 11604525006.1598 Kelvin

Modelling Hadronic Matter, April 2016
Journal of Physics Conference Series 706(3):032001, DOI:10.1088/1742-6596/706/3/032001

A-A collisions at the CERN LHC

- ❑ **LHC RUN 1 (2010-2013)**
  - $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
  - Confirm RHIC findings
  - Study properties of QGP
- ❑ **LHC Run 2 (2015 -2018)**
  - $\sqrt{s_{NN}}$ = 5.02 TeV, 2018 statistics x9 for central collisions
  - Precise characterization of QGP properties
- ❑ **Surprising findings from small collisions (pp, p-Pb)**

→ Similar features as in Pb-Pb?

Luminosity, $L = \frac{1}{\sigma}\frac{dN}{dt}$ - Number of events detected (N) in a certain time (t) to interaction cross section (σ)