4. Nuclear Matter and Deconfined Quarks and Gluons

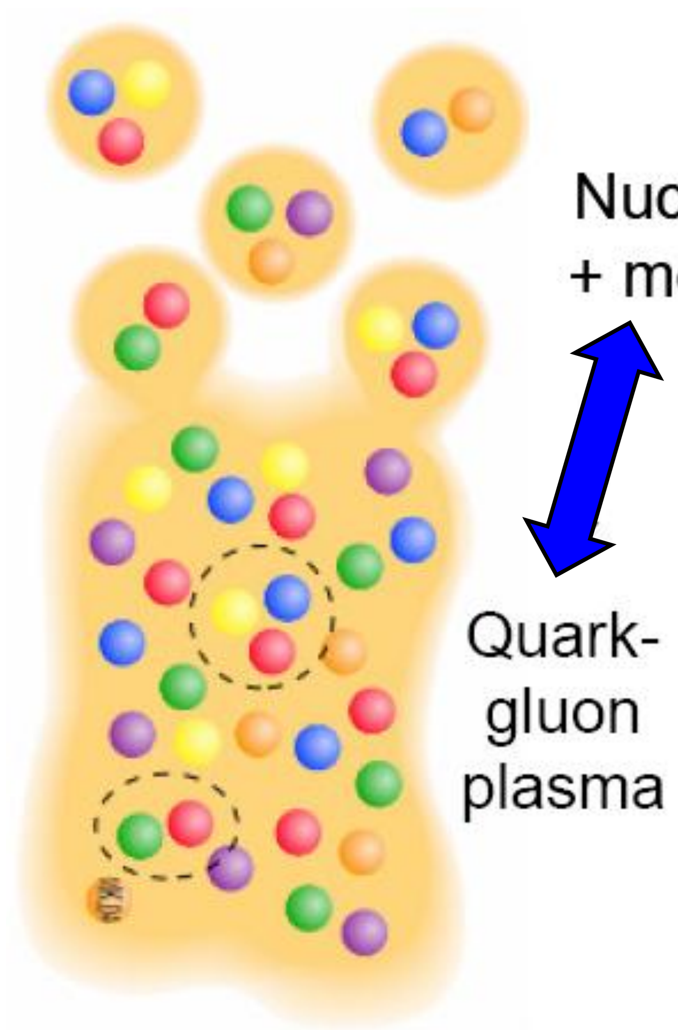
The Standard Model of particle physics predicts a cosmological, QCD–related smooth transition between an early high-temperature phase dominated by quarks and gluons (~12 ps after Big Bang) and a low-temperature phase dominated by hadrons.

The very large energy densities at the high temperatures of the early universe have essentially disappeared through expansion and cooling. Nevertheless, a fraction of this energy is carried today by quarks and gluons, which are confined into protons and neutrons.

According to the mass-energy equivalence $E = mc^2$, we experience this energy as mass. More than 99% of the mass of ordinary matter comes from protons and neutrons, and in turn about 95% of their mass comes from this confined energy.

Dürr et al., Science, 322 , 1224-1227 (2008).

Melting Nuclear Matter: Quark Gluon Plasma



http://www-linux.gsi.de/~andronic/intro_rhic/

- Can we produce the QGP phase in the lab?
- What are the properties?
- Phase transition?

According to today’s understanding such a phase existed 10 ps after the big-bang and lasted for about 10 μs.

Quark Gluon Plasma – A new state of matter

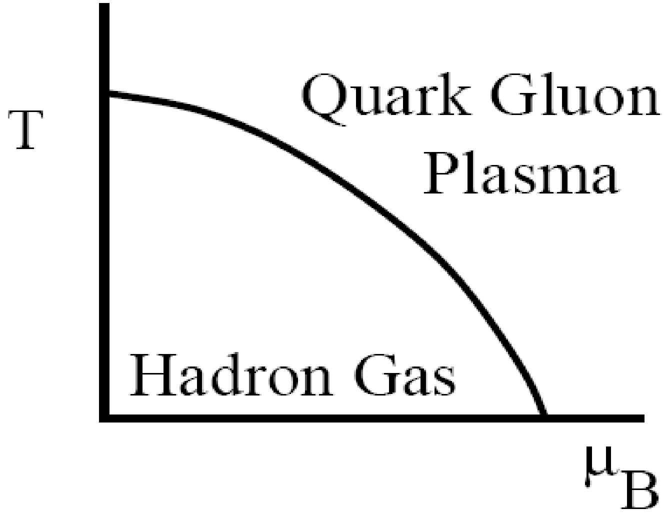
Shortly after the property of **asymptotic freedom** has been discovered the transformation of nuclear matter into a deconfined phase has been discussed.

If temperature and/or nuclear densities are high enough strongly interacting quarks become free:

Quark Gluon Plasma:

- Ignoring interactions between quarks and gluons: **ideal gas**
- Significant interaction between quarks and gluons: **liquid** (hydrodynamic system)

Phase diagram in ~1980



μ_B = baryon chemical potential; measure of net baryon density

T_c = critical temperature [150 - 200 MeV @ $\mu_B = 0$]

ρ_c = critical density [0.5 - 2 baryons/fm^3]

Remark: 100 MeV $\leftrightarrow$ 1.16 $\times$ 10^{12} K

Thermo-dynamical phase transition:

Gibbs free energy: $$G(p,T) = U + pV - TS$$

$$dG = Vdp - SdT + \underbrace{\sum_j \mu_j dn_j}$$

Change of #particle of jth chemical component. μ is the chemical potential of this component:

$$\mu_j \equiv \left(\frac{\partial G}{\partial n_j} \right)_{T,p,n_{i \neq j}}$$

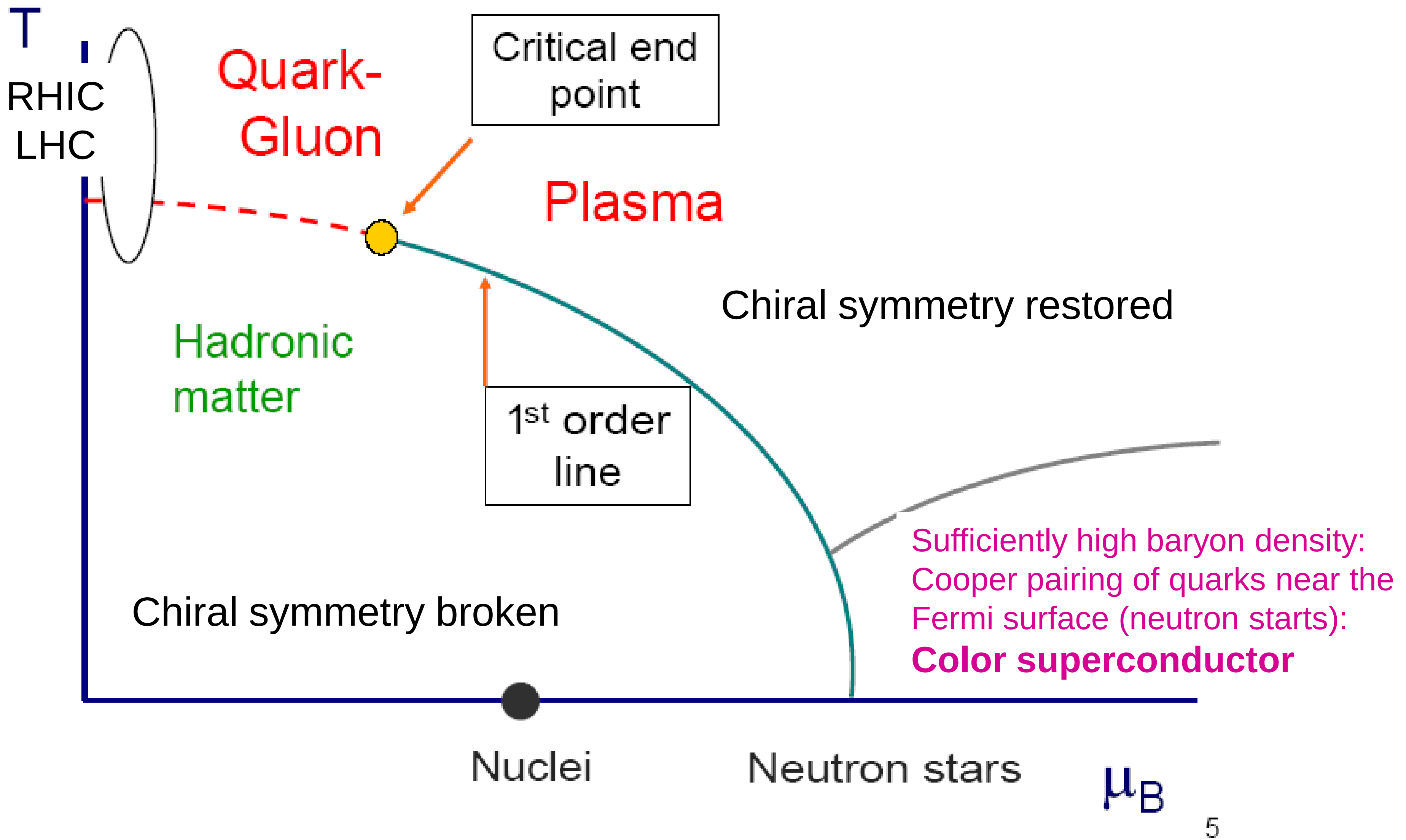
Phase boundary (equilibrium):

$$(dG)_{T,p} = \sum \mu_j dn_j = 0$$

2-phase system (1,2):

$$\mu_1(p,T) = \mu_2(p,T)$$

Phase diagram of QCD



μ = Change of energy when adding additional baryon
= net baryon density

Phase Transition & Critical Temperature & Order Parameter

Energy density of hadron gas

(ideal gas)

$$\epsilon = \int \frac{d^3p}{(2\pi)^3} \sum_i \frac{E_i}{e^{\beta E_i} \pm 1}$$

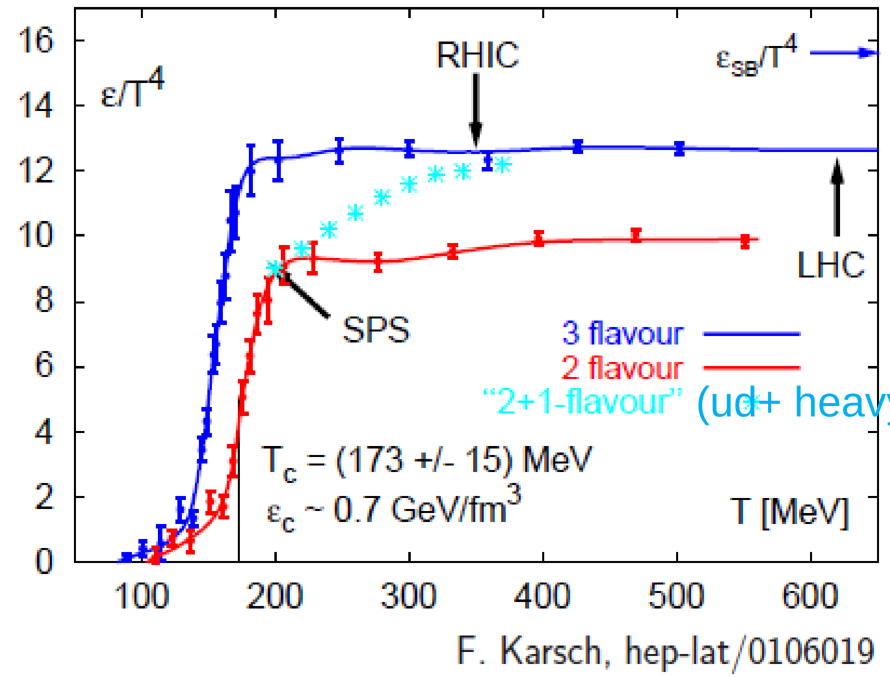
at large T
(ignoring masses)

$$\epsilon \sim \frac{\pi^2}{30} N T^4$$

Degrees of freedom

Lattice QCD predicts phase transition

hadrons ⇒quark/gluon



(ud + heavy s)

Critical temperature: T_C = 173 MeV

(zero net-baryon density)

Critical density: ρ_c ~ 0.7 GeV fm^{-3}

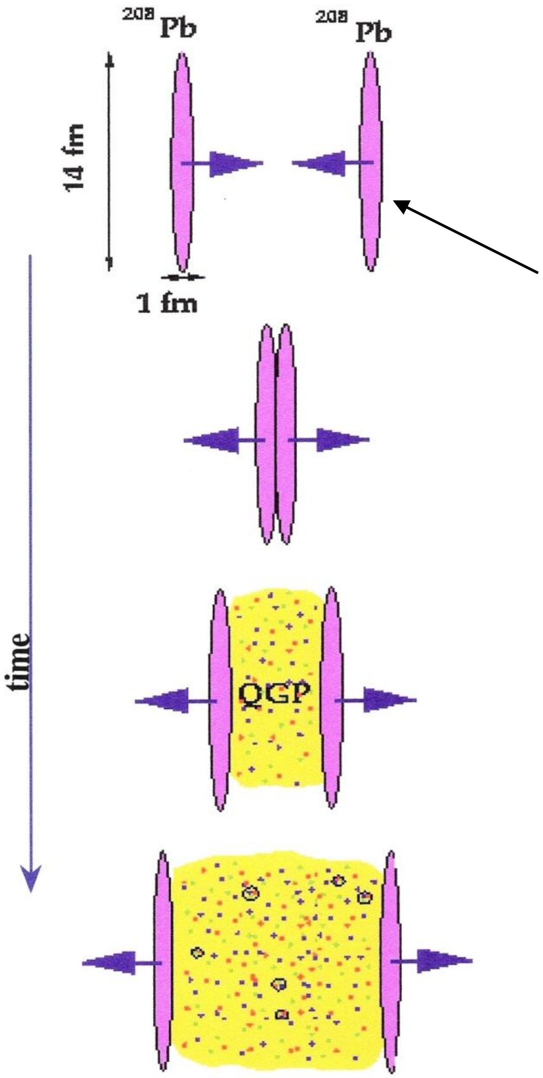
QGP: $$N = 2 \times 8 + \frac{7}{4}(2 \times 3 \times N_f)$$

Hadronic gas phase (only pions): N = 3

nuclear density: ρ = 0.15 GeV fm^{-3}

Inside nucleon: ρ = 0.5 GeV fm^{-3}

Time development of Heavy Ion Collision



= ideal way to get conditions of extremely high T and ρ.

Lorentz contratcion: 100 (RHIC), 2700 (LHC)

Formation time τ_0 = 1 fm/c = 3,3*10^{-24}s

Temperature O(10^{12}K)

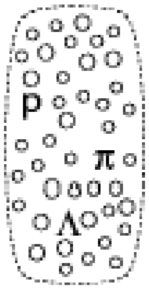
Lifetime 10 fm/c = 3,3*10^{-23}s

Critical temp. corresponds to energy densities of ~ 1 GeV/fm^3

QGP in thermal / chem. Equilibrium.

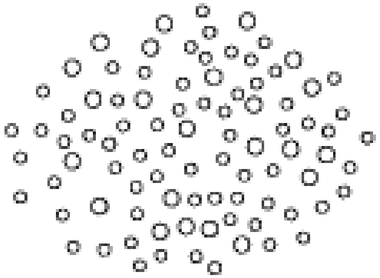
Cool down: hadronization

d) Hadronization



Critical temperature: T_c

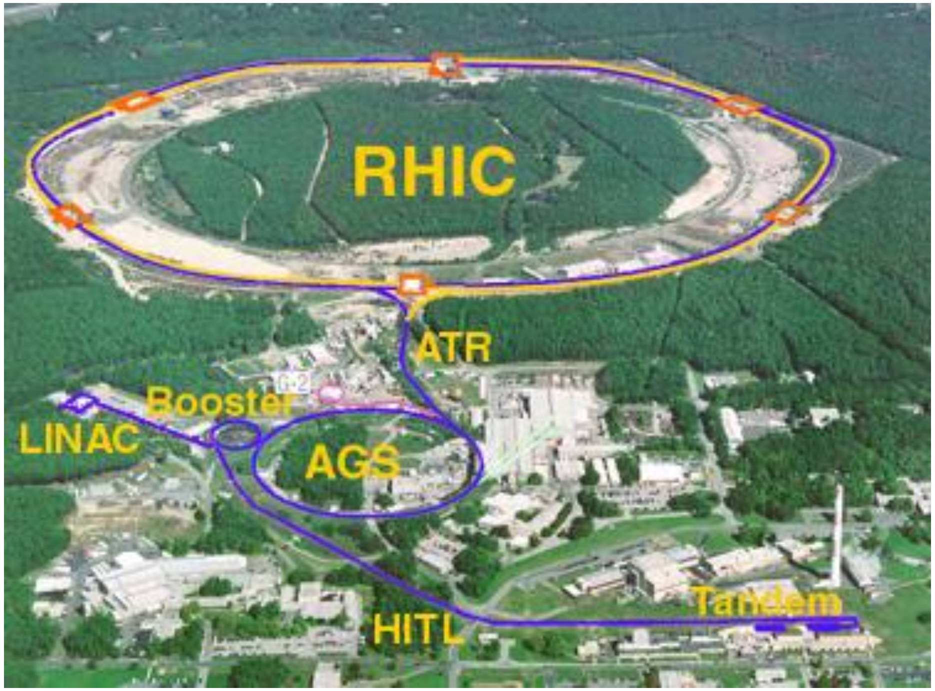
e) Freeze out of Hadrons



1. Chemical freeze-out: inelastic collisions cease. (Close to phase boundary?). Yields are frozen. Temperature: T_{ch}
2. Kinetic freeze-out: elastic collisions cease. Spectra are frozen (t+ = 3…5 fm/c).

   Temperature: T_{fo}

Heavy Ion Colliders



Brookhaven National Lab:

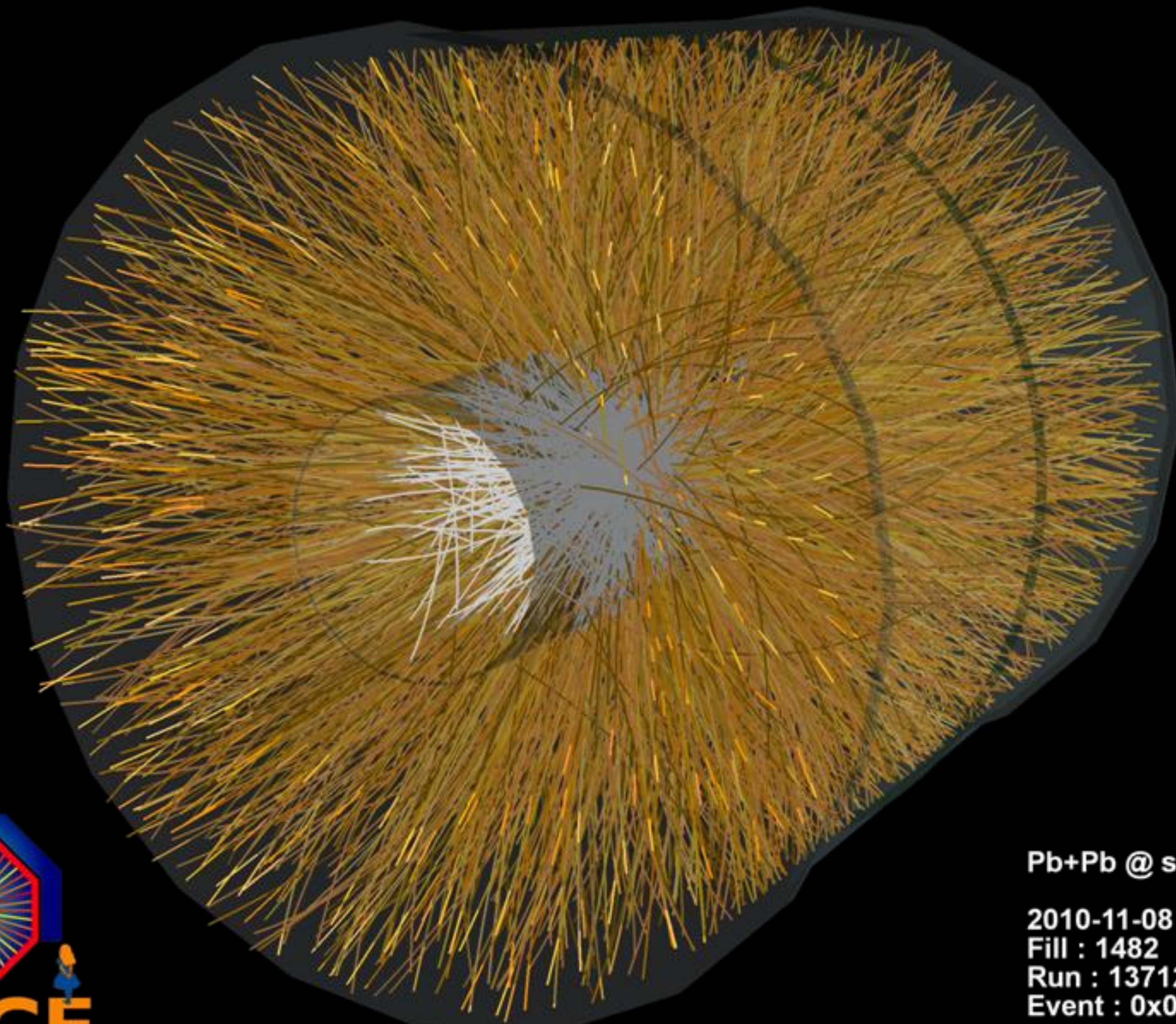
Relativistic Heavy Ion Collider (**RHIC**)

Experiments: **STAR, PHENIX, PHOBOS, BRAHMS**

$\sqrt{s_{NN}}$

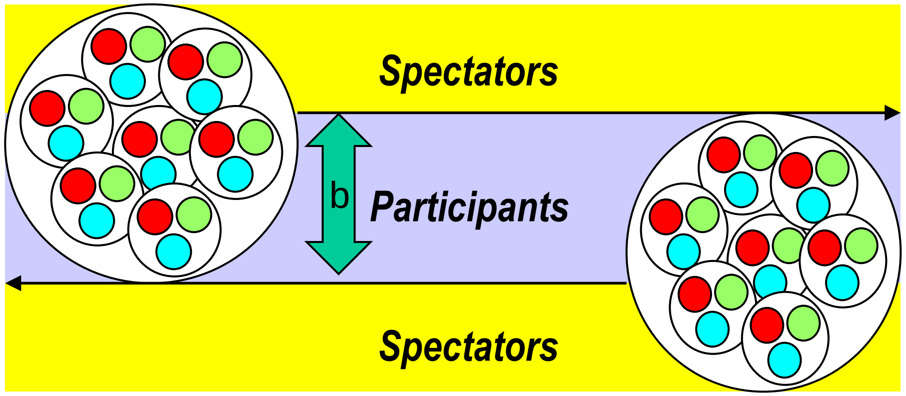
Facility	Location	System	Energy (CMS)
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	**CERN, Geneva**	**Pb+Pb**	**5.5 TeV**

First Pb+Pb collisions in ALICE



ALICE

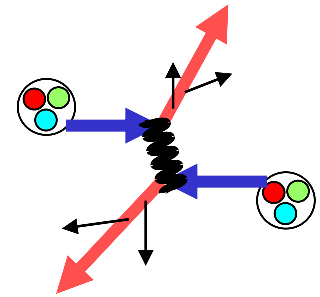
Geometry of AA collisions – Impact parameter

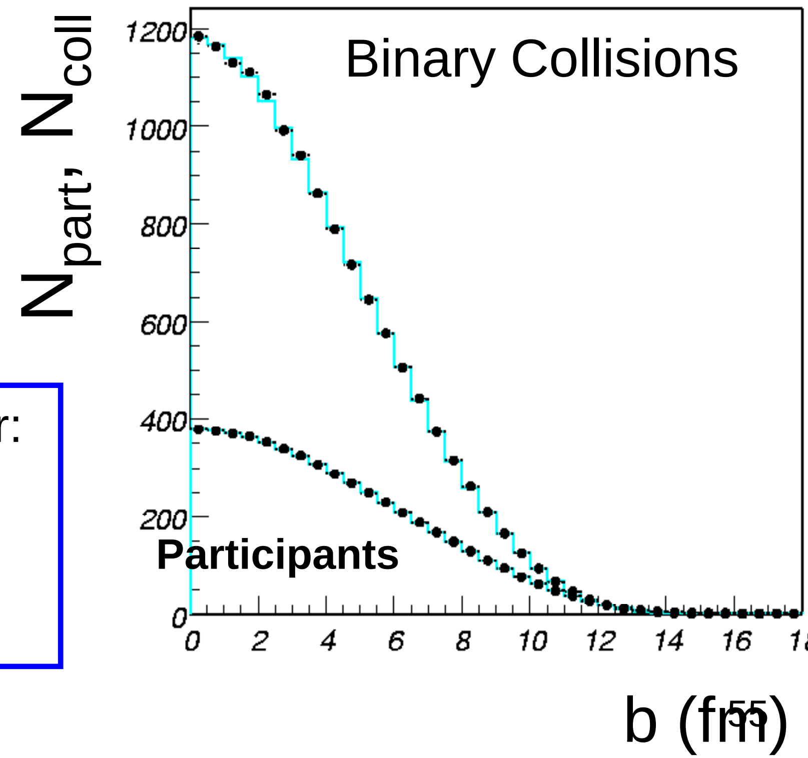


“Glauber” model of AA

Binary Collisions:

1. Jet Production
2. Heavy Flavor





Cannot directly measure the impact parameter:

Use total number of produced particles and detected “spectators” as a measure for the “centrality” of the heavy ion collision.

Centrality measurement

Two variables:

- zero degree calorimeter
- charged track multiplicity

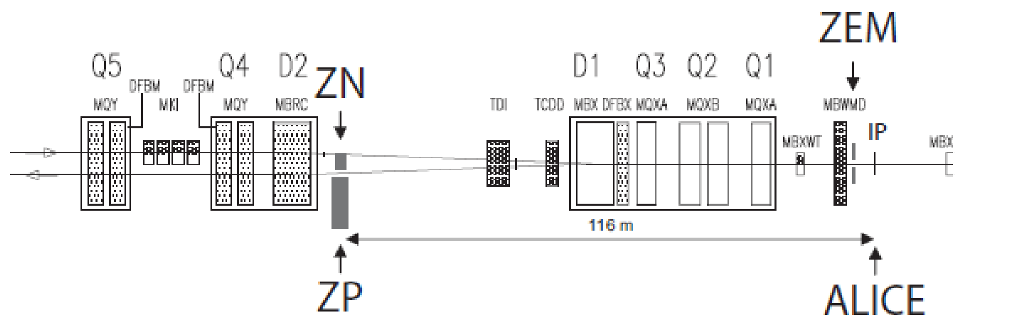
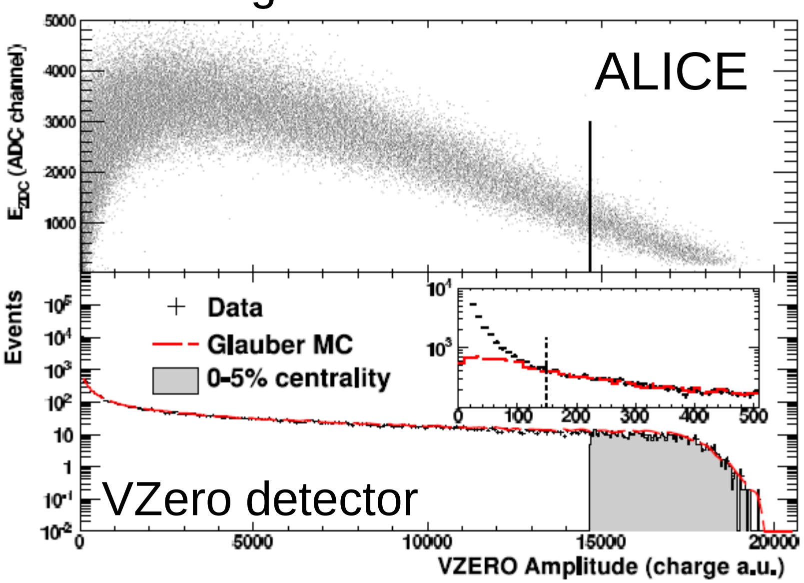
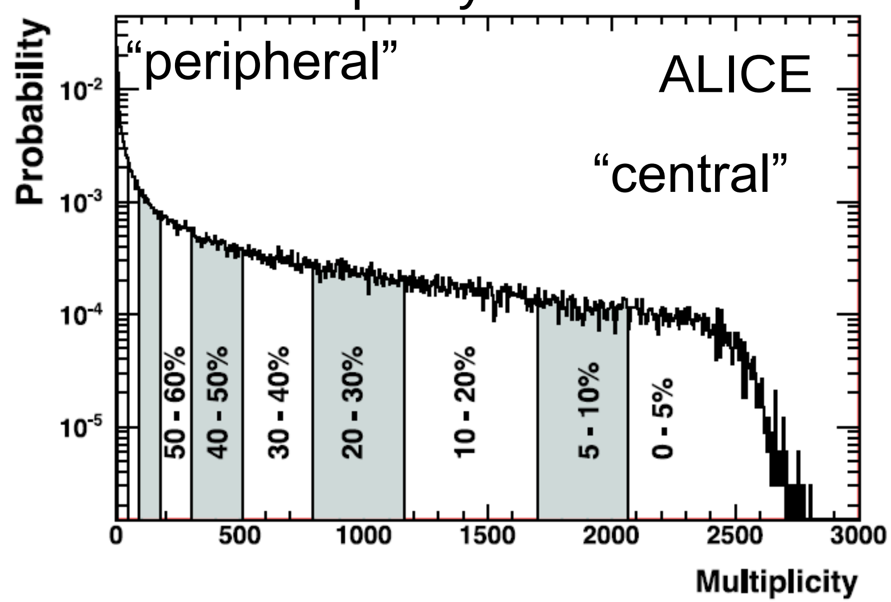


Figure 5.1: Schematic top view of the side of the ALICE beam line opposite to the muon arm. The locations of the neutron (ZN), proton (ZP) and forward electromagnetic (ZEM) calorimeters are shown. The position of the beam line dipoles (Dx) and quadrupoles (Qx) are also indicated.

Zero degree calorimeter

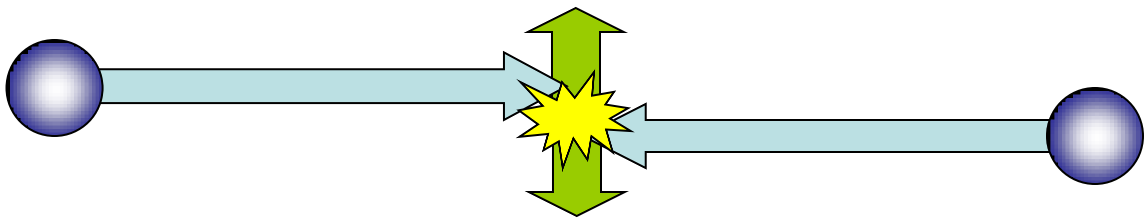


TPC multiplicity



(Pseudo) Rapidity

- In hadronic collisions most particles have only small transverse momentum

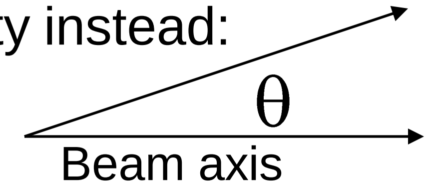


- Observable particles carry only small fraction of (anti)protons longitudinal momentum ($x = p_z/p_{z,max}$)
- "Rapidity" variable "increases dynamic range" ($x < 0.1$)

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \sim \ln(x)$$

- Rapidity not easy to measure. Use pseudo-rapidity instead:

$$\eta = -\ln\tan\theta/2$$



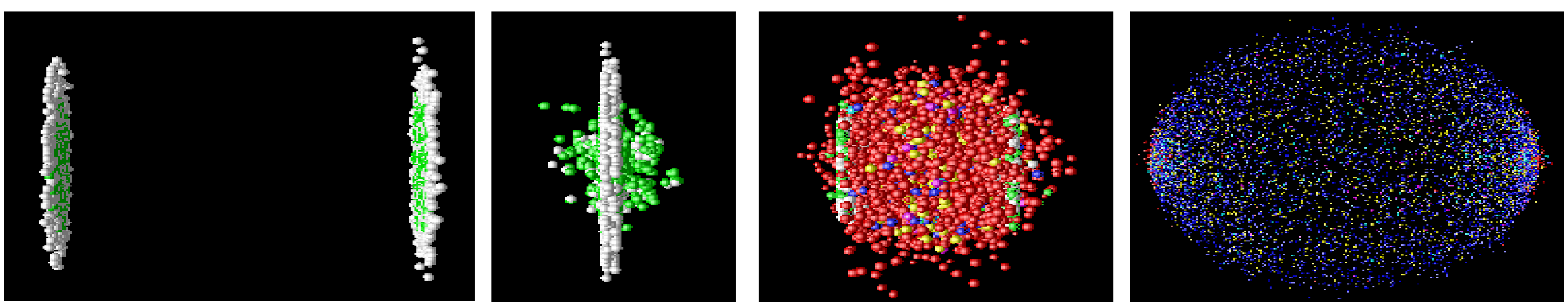
- Particle density dN/dη related to dN/dy:

$$\frac{dN}{d\eta d\mathbf{p}_T} = \beta\frac{dN}{dyd\mathbf{p}_T}$$

β=v/c
small deviations
for slow particles

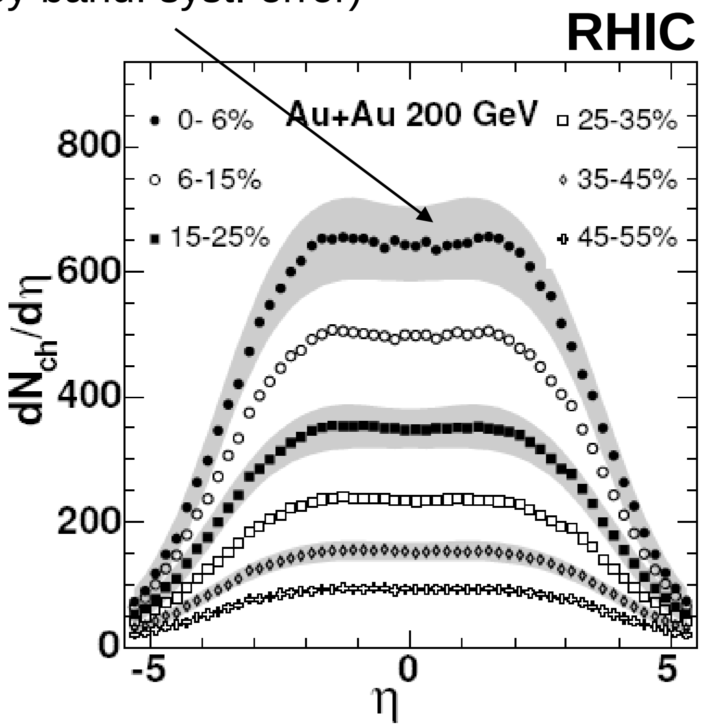
Experimental probes for QGP

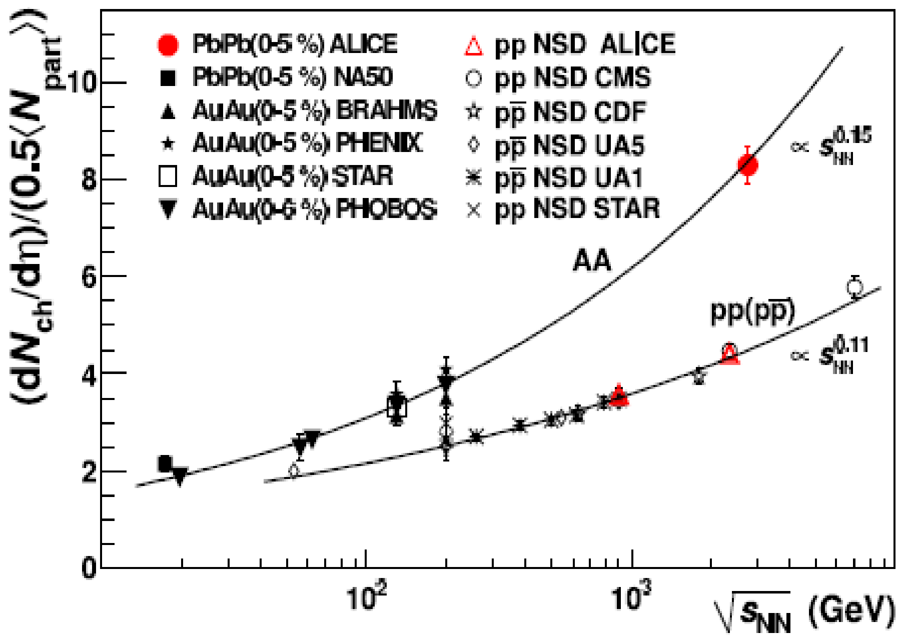
	Why	What
Global Observables	Is initial state dense enough?	• Particle Multiplicities • Energy Density
Collective Behavior	Is QGP a thermalized state?	• Hadron Yields • Elliptic Flow
Hard Probes	Formed early, probe medium	• Energy loss of jets • Charm production



Charged particle density

6% most central collisions
(grey band: syst. error)





At mid rapidity particles have $\langle p_T \rangle \sim 500$ MeV

Particle density at mid rapidity is a measure of energy density:

Energy density - Bjorken Estimate

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = E_{\text{part}} \times \left.\frac{dN_{\text{ch}}}{d\eta}\right|_{\eta=0} \times f_{\text{neutral}}$$

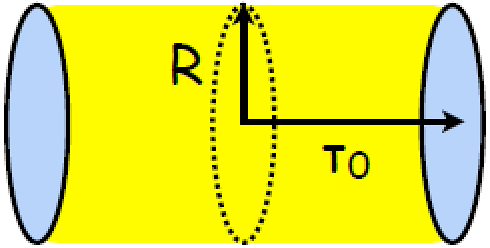
$$= 0.5\ \text{GeV} \times 600 \times 1.6 \approx 500\ \text{GeV}$$

$\langle p_t \rangle$ @ $\eta=0$ — $dN/d\eta$ — $f_{neutral}$

Energy density:

$$\epsilon_{\text{Bj}} = \frac{dE_T/d\eta}{\pi R^2 \tau_0} \approx 5\ \text{GeV/fm}^3$$

[$\sqrt{s}$ = 200 GeV]



$R \approx 1.18\ A^{1/3}$ fm

$A \approx 200$

$\tau_0 \approx 1$ fm/c

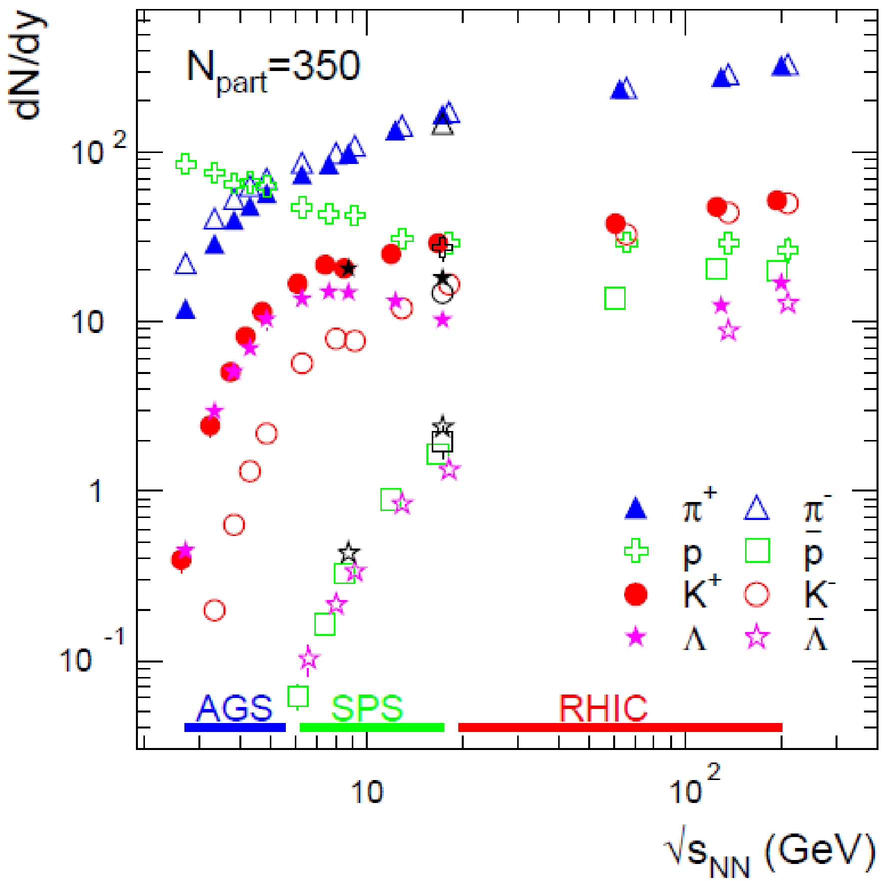
Compare to:

Nuclear Density: ρ = 0.15 GeV/fm^3

Inside Nucleon: ρ = 0.5 GeV/fm^3

ε_{crit}~1 GeV/fm^3 at critical temperature

Hadron yields at mid-rapidity



- Large amount of newly created particles.
- Large variety of species
- Mass hierarchy in production: u,d quarks are remnants from incoming nuclei

Analysis of hadron yields provides a “snapshot” of AA collision at chemical freeze-out (the earliest in the collision timeline we can look with hadronic observables).

Thermal model for yields

Grand canonical partition function for specie i:

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln\left[1 \pm \exp\left(-(E_i - \mu_i)/T\right)\right]$$

+ = fermions,
- = bosons

$g_i = (2J_i + 1)$ Spin degeneracy factor

$E_i = \sqrt{p^2 + m_i^2}$ total energy

$\mu_i = \mu_B B_i + \mu_{I_3} I_{3,i} + \mu_S S_i + \mu_C C_i$ chemical potential

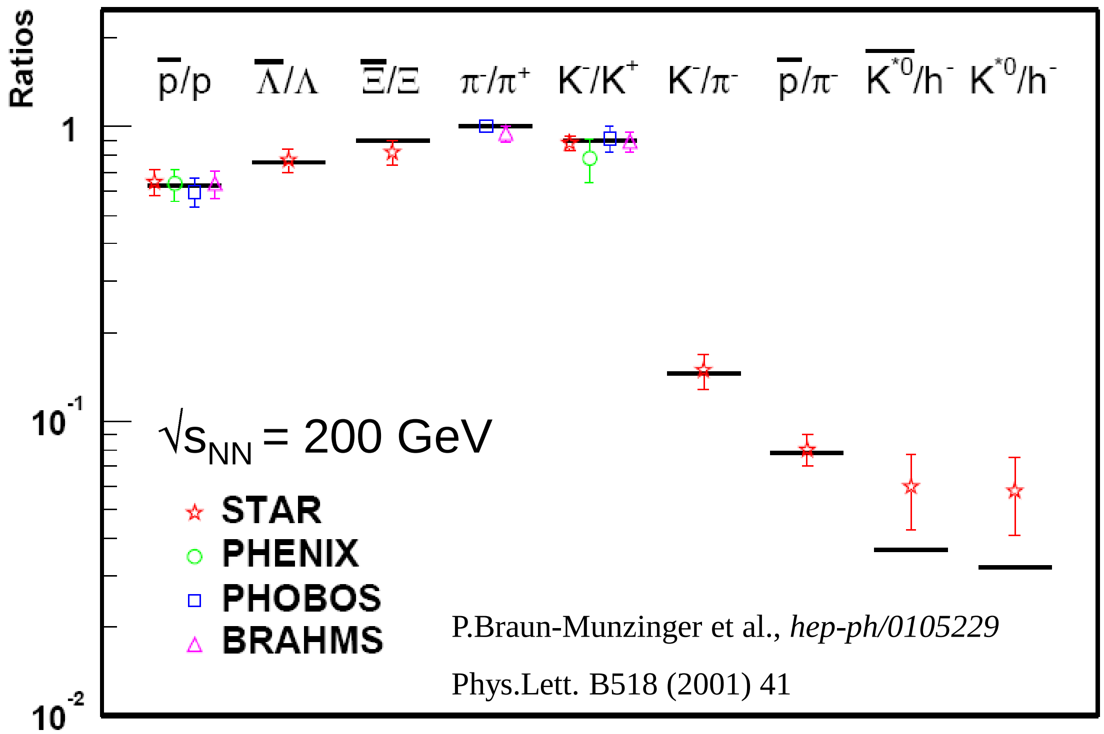
μ ensures (on average) conservation of quantum numbers:

Baryon number $N_B = V \cdot \sum n_i B_i$

Isospin $I_{3,tot} = V \cdot \sum n_i I_{3,i}$

Strangeness, charm $0 = V \cdot \sum n_i S_i = V \cdot \sum n_i C_i$

$$n_i(\mu_B,T) = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp\left(\frac{E_i - \mu_B B_i - \mu_S S_i - \mu_{I_3} I_{3i}}{T}\right) \pm 1}$$



Fit of particle multiplicites with T_{Ch} and μ_B as free parameter:

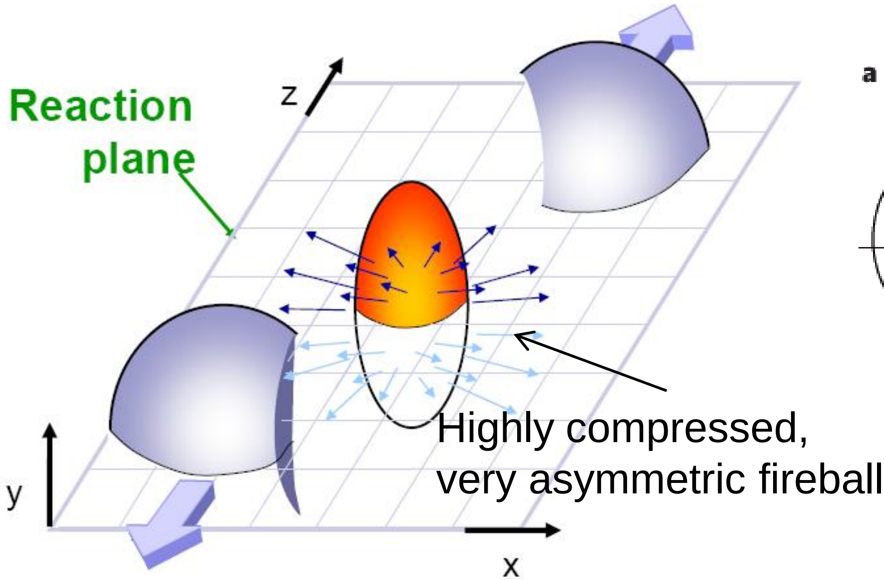
T_{Ch} = 174 MeV

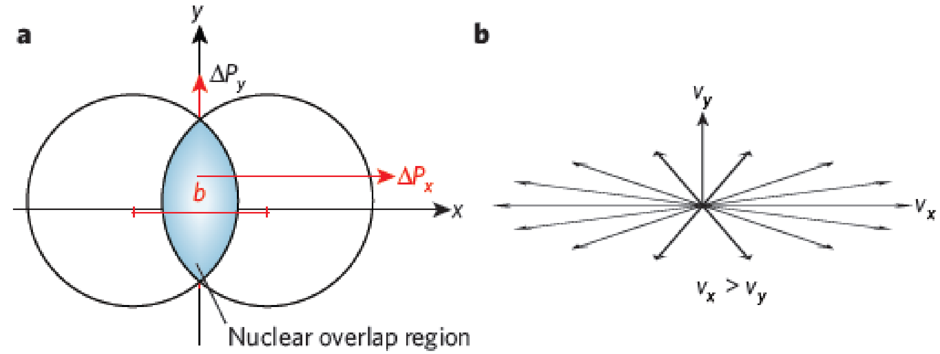
μ_B = 46 MeV

T_{Ch} agrees well with the theoretical calculation of T_c for phase transition

Hadron yields are well described by thermal model.

Elliptical flow - properties of QGP





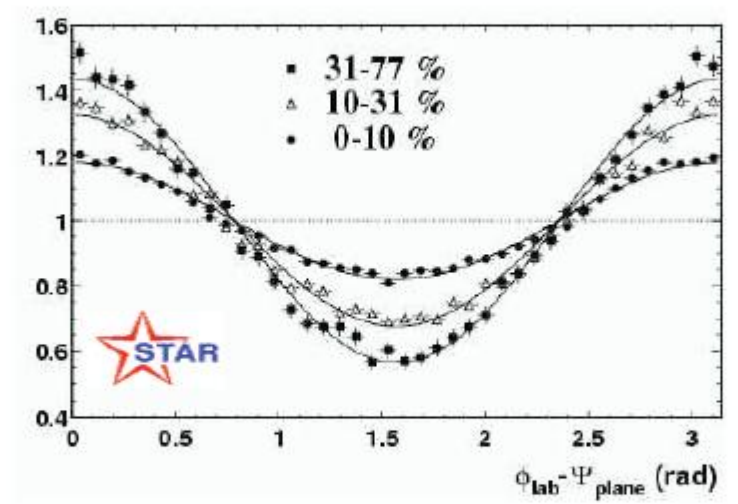
$$\tan\phi = \frac{\Delta p_y}{\Delta p_y}$$

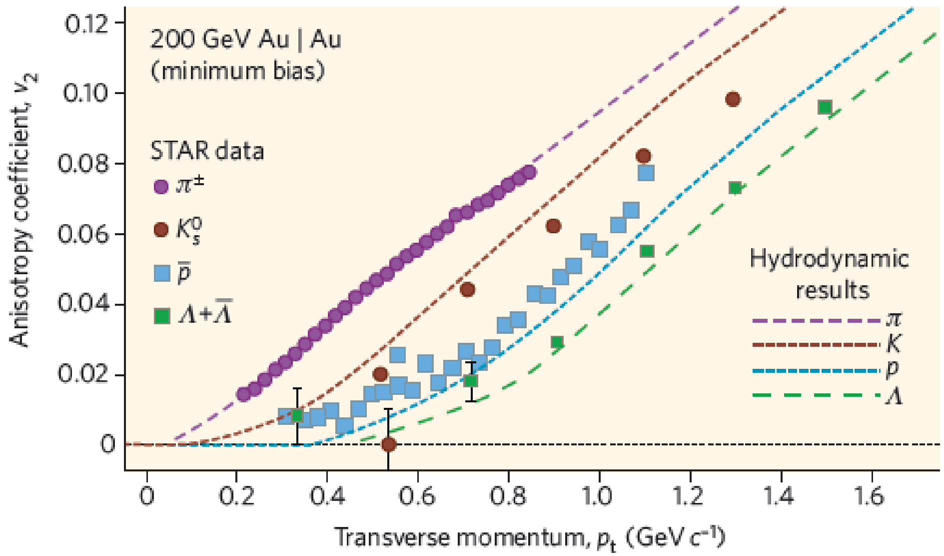
Anisotropy and elliptical flow:

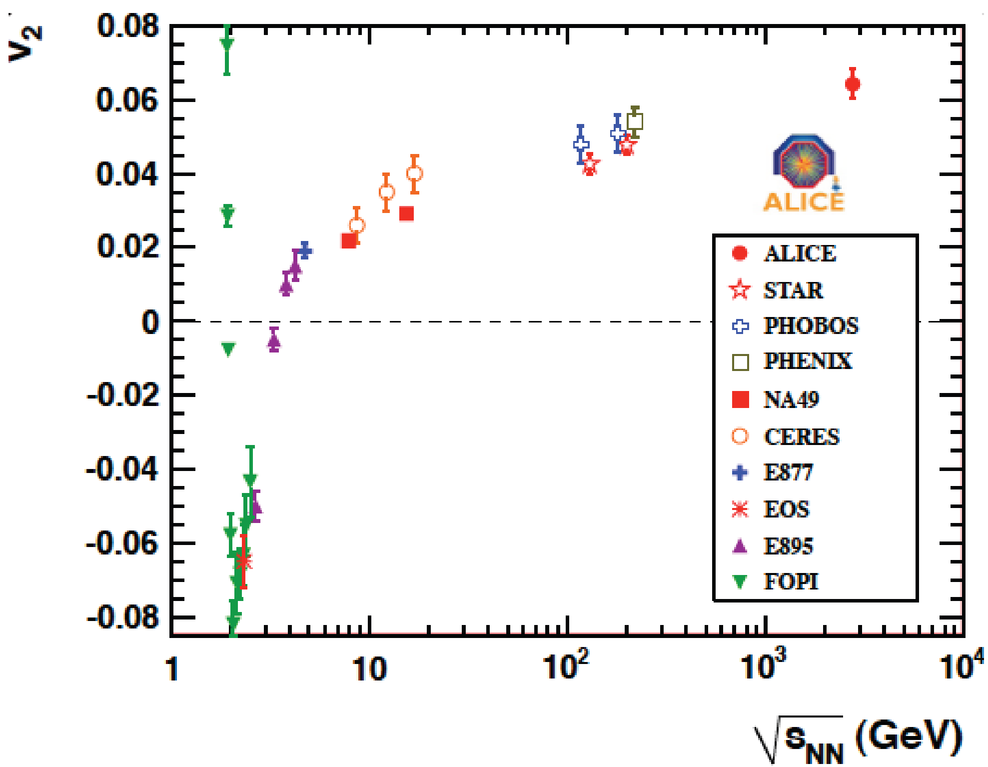
- Gradients of almond-shape surface will lead to preferential expansion in the reactions plane.
- Anisotropy of emission is quantified by 2nd Fourier coefficient of angular distribution: v_2

$$N/N_0 = 1 + 2v_2 \cos(2\phi)$$

- Supports idea of collective expanding medium in thermal equilibrium







Elliptical flow measured at RHIC agrees well with hydrodynamic models assuming an ideal liquid (i.e. no viscosity): Expanding medium behaves like an ideal liquid.

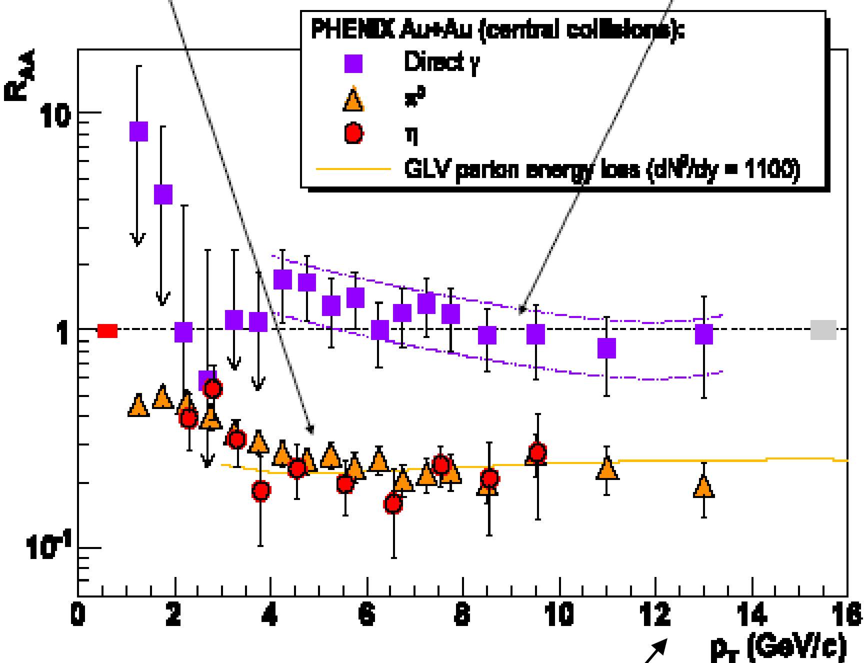
Bulk evolution described by relativistic hydrodynamics and an equation of state determined by weakly interacting quarks and gluons: confirms the idea that fireball reaches equilibrium quickly.

Effect of QGP on hard (early) particles

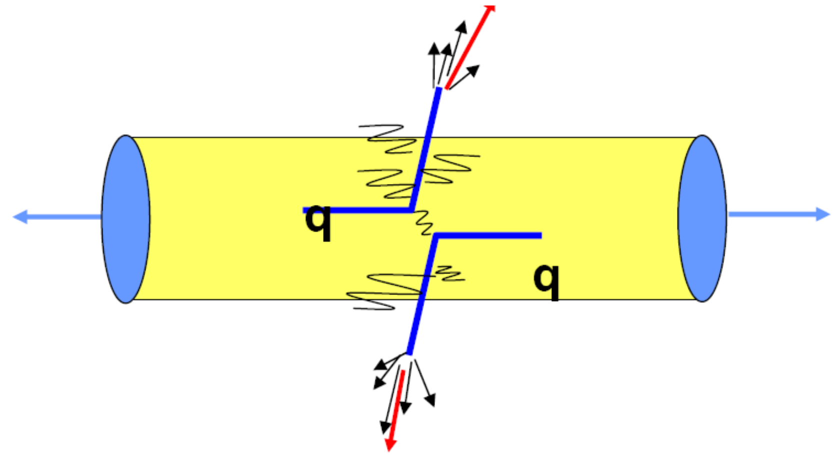
Energy loss in dens medium

No suppression for photons

Suppression of hadrons



Calculation assuming very dens gluon gas



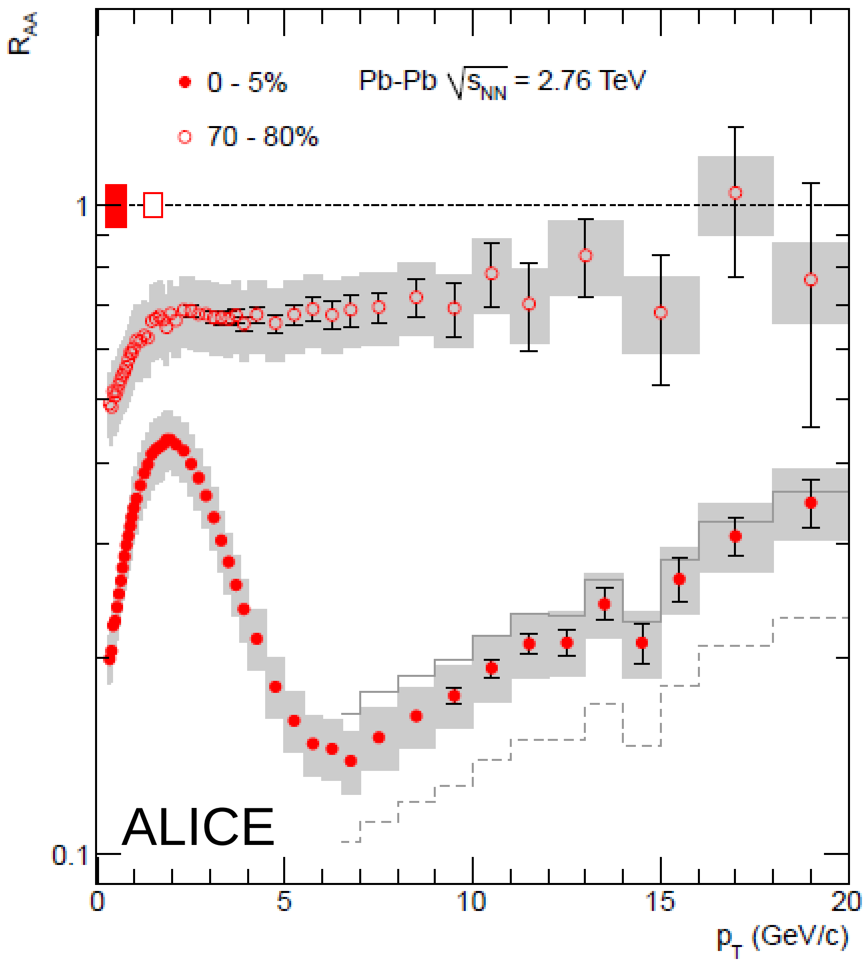
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T dy}{T_{AA}\left(d^2\sigma_{NN}/dp_T dy\right)}$$

Area density of p+p coll's in A+A

Cross section in p+p coll's

Without nuclear effects:

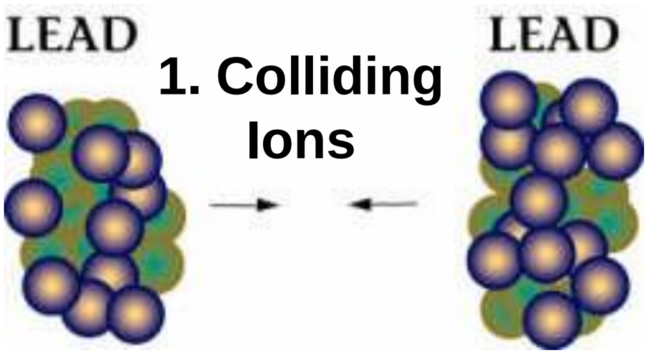
$R_{AA} = 1.$

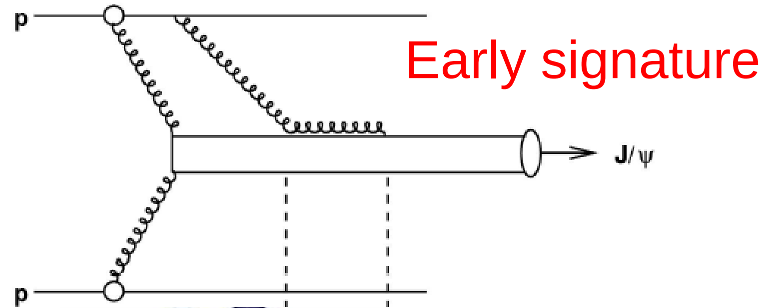


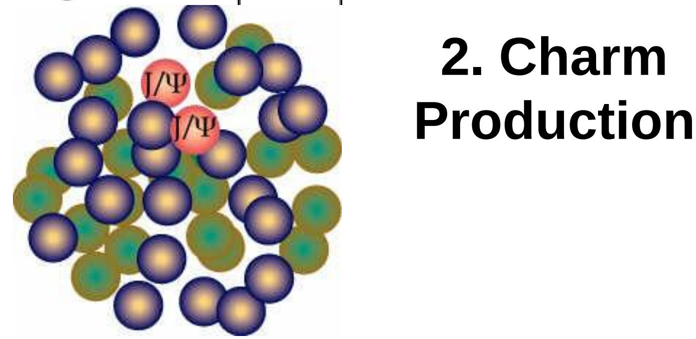
Clear effect of a opaque nuclear medium confirmed at LHC.

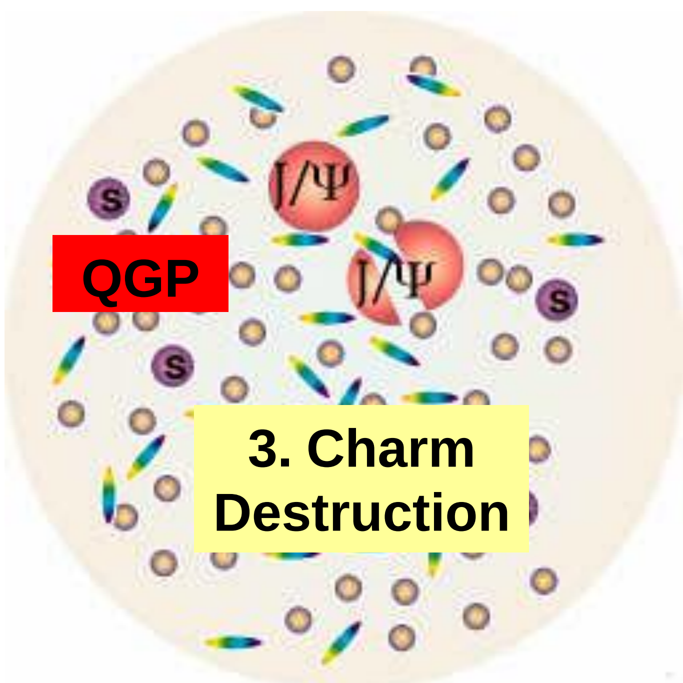
Figure 3: R_{AA} in central (0–5%) and peripheral (70–80%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Error bars indicate the statistical uncertainties. The boxes contain the systematic errors in the data and the p_T dependent systematic errors on the pp reference, added in quadrature. The histograms indicate, for central collisions only, the result for R_{AA} at $p_T > 6.5$ GeV/c using alternative pp references obtained by the use of the p$\bar{\text{p}}$ measurement at $\sqrt{s_{NN}} = 1.96$ TeV [26] in the interpolation procedure (solid) and by applying NLO scaling to the pp data at 0.9 TeV (dashed) (see text). The vertical bars around $R_{AA} = 1$ show the p_T independent uncertainty on $\langle N_{\text{coll}} \rangle$.

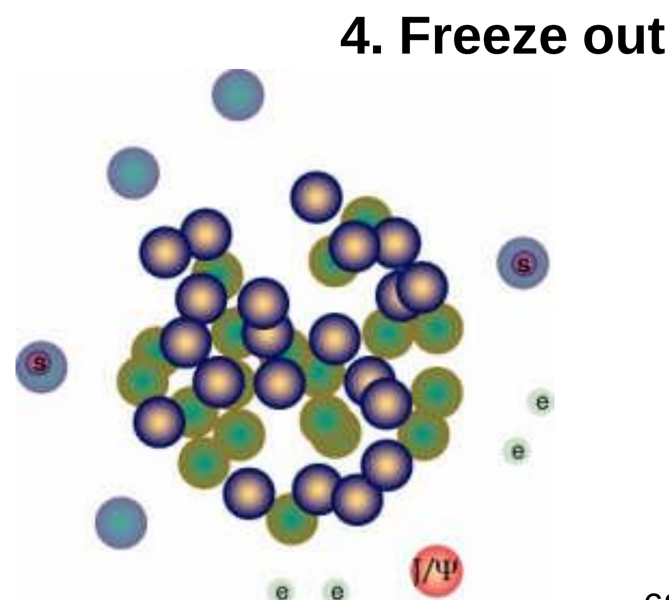
J/ψ Suppression in QGP





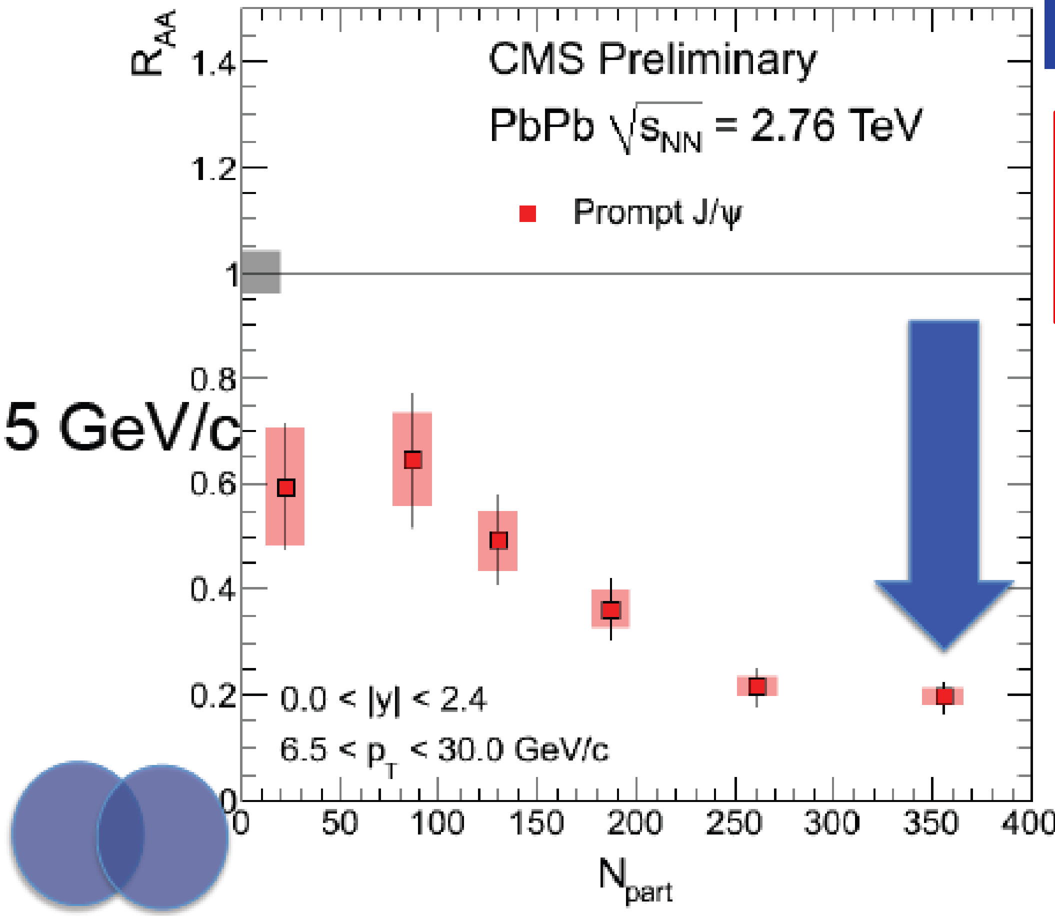






Prompt J/ψ R_{AA}

PbPb
$\sqrt{s_{NN}}$=2.76 TeV



CMS
$p_T^{J/\psi}$ > 6.5 GeV/c

Confirms the large suppression seen at RHIC.

Factor 5 suppression

Central 0-10% R_{AA}= 0.20 ± 0.03 ± 0.01

Peripheral 50-100% R_{AA}= 0.59 ± 0.12 ± 0.10

QGP

- Clear evidence of a new phase of matter in thermal quilibirium in the early stage of the Heavy Ion collision.
- Predictions of clear experimental signatures not easy:

  QCD + Thermodynamics + relativistic Hydrodynamics needed to describe the observables. Modeling involved.
- Exciting time: Huge set of measurements expected in the next year will unreveal the properties of this phase of matter.