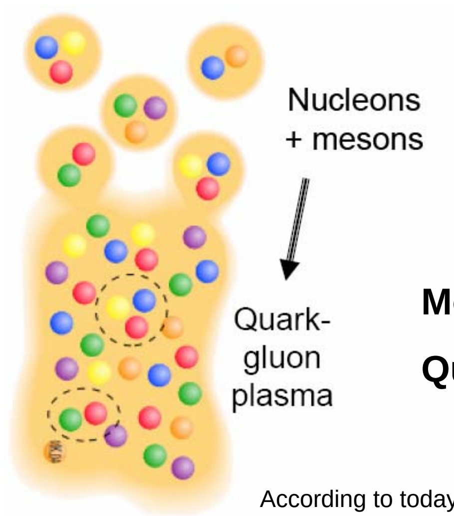


Melting Nuclear Matter:

Quark Gluon Plasma

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:

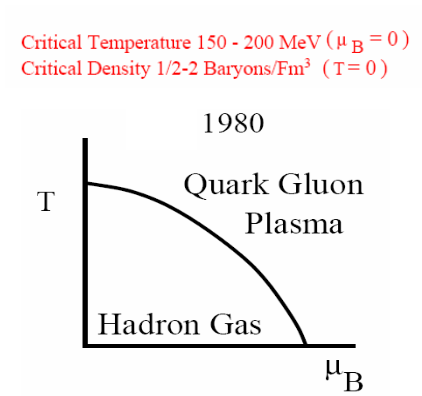
If temperature and/or nuclear densities are high enough strongly interacting quarks become free:

Quark Gluon Plasma:

- Ignoring interactions between quarks and gluons: **ideal gas**

Or

- Significant interaction between quarks and gluons: **liquid** (hydrodynamic system)

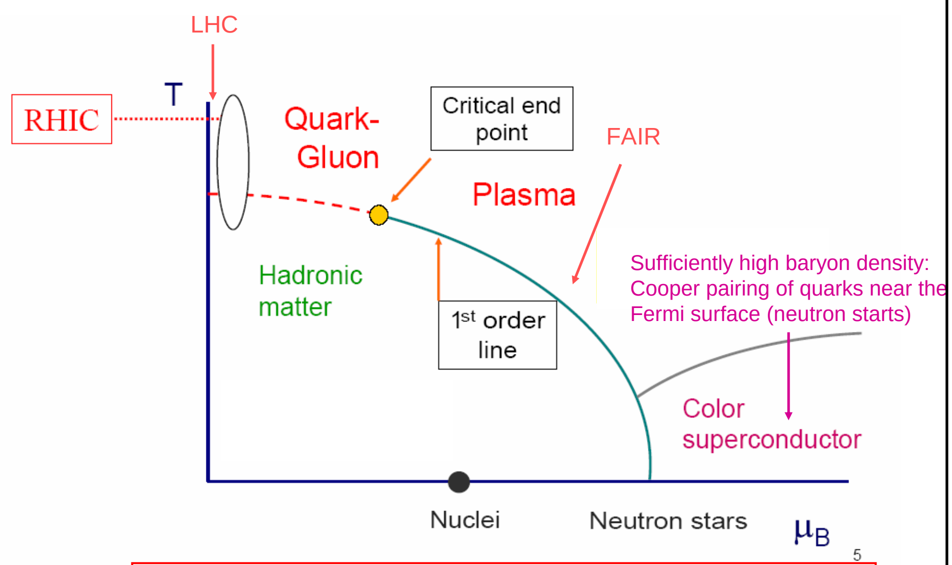


μ_B = baryon chemical potential

measure of the net baryon density

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

Phase diagram as of today



Reminder: Chemical Potential
= Change of energy when adding additional baryon $\mu_i = \left(\frac{\partial U}{\partial N_i}\right)_{S,V,N_{j\neq i}}$
= net baryon density

Phase Transition & Critical Temperature

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)

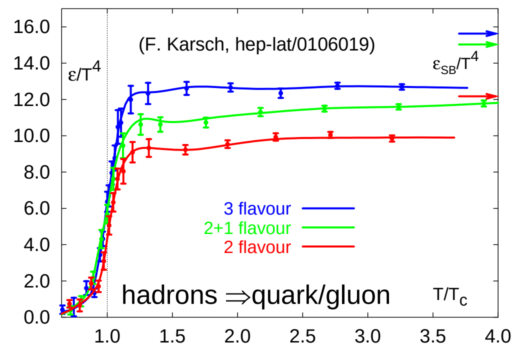
$$\epsilon \sim \frac{\pi^2}{30} N T^4$$

Degrees of freedom

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

Hadronic gas phase (only pions): N = 3

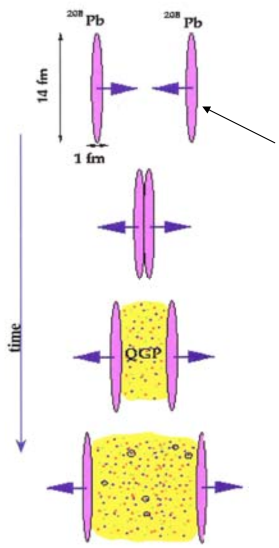
Lattice QCD predicts phase transition



Critical temperature: T_C = 173 MeV
(zero net-baryon density)
Critical density: ρ_c ~ 0.7 GeV fm^{-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)

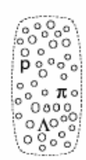
Lifetime 10 fm/c = 3,3*10^{-23}s

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

QGP in thermal / chem. equilibrium:

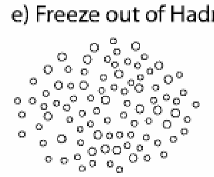
Particle ratios (e.g. p/p are defined)

d) Hadronization



$t = 10^{22} s$

e) Freeze out of Hadrons



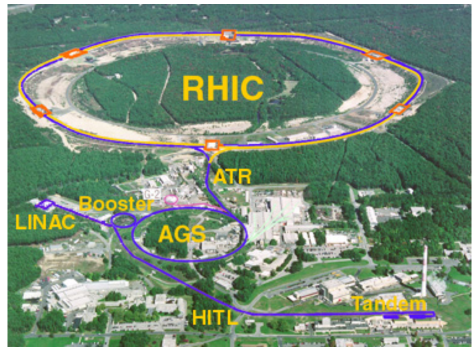
J. Pawlowski / U. Uwer

Heavy Ion Colliders

Brookhaven National Lab:

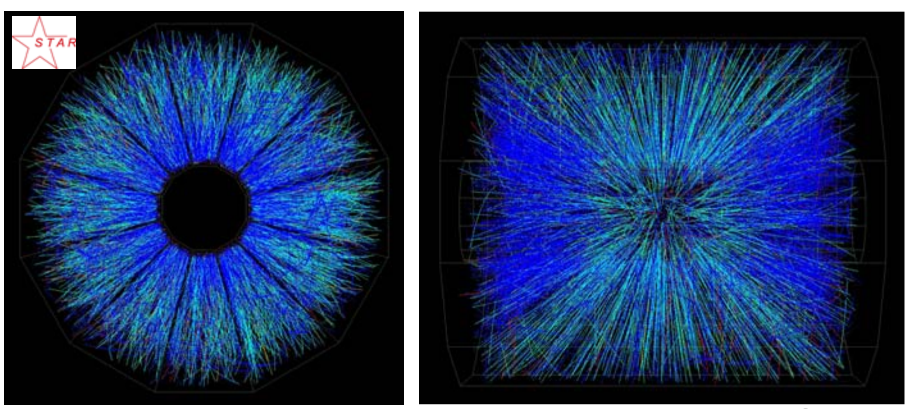
Relativistic Heavy Ion Collider (**RHIC**)

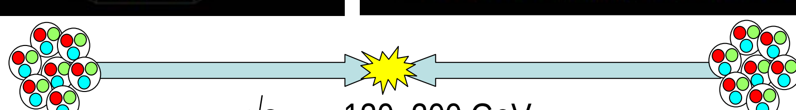
Experiments: **STAR, PHENIX, PHOBOS, BRAHMS**



Facility	Location	System	$\sqrt{s_{NN}}$ 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

RHIC Collisions



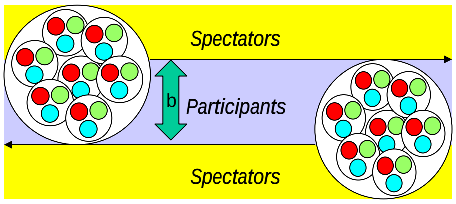


Gold $\sqrt{s_{NN}}$ = 130, 200 GeV Gold

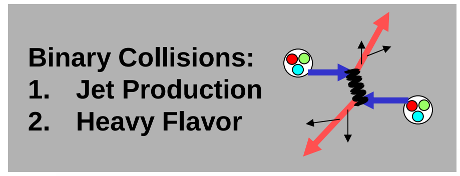
(center-of-mass energy per nucleon-nucleon collision)

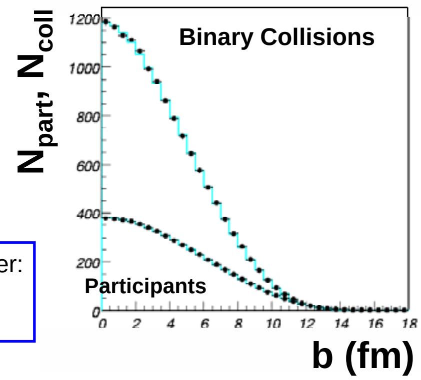
Several 1000 of particles

Geometry of AA collisions – Impact parameter



"Glauber" model of AA

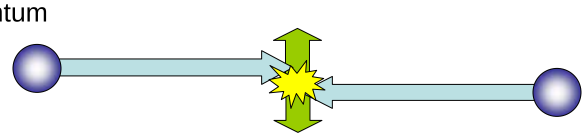




Cannot directly measure the impact parameter: Use total number of produced particles as measure for "centrality" (↔ "peripheral").

(Pseudo) Rapidity

- In hadronic collisions most particles have only small transverse momentum

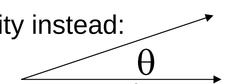


- Observable particles carry only small fraction of (anti)protons longitudinal momentum ($x = p_z/p_{z,max}$)
- "Rapidity" variable "increases dynamic range" ($x < 0.1$)

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

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

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



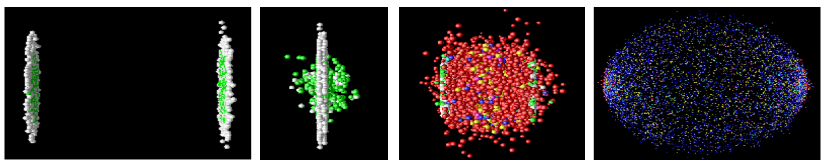
- Particle density $dN/d\eta$ related to dN/dy:

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

$\beta = v/c$
small deviations
for slow particles

Experimental probes for the 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

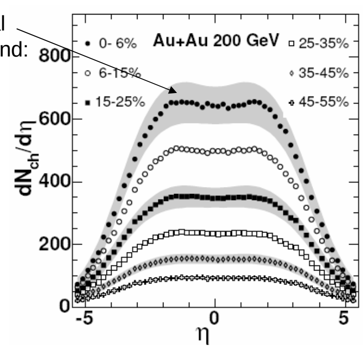


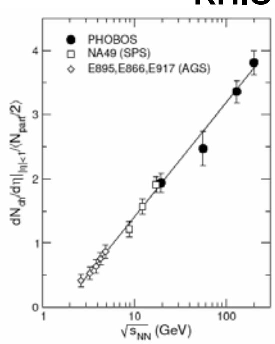
Charged particle density

RHIC

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

At mid rapidity particles have $<p_T> \sim 500$ MeV





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

From SPS to RHIC the particle density has increased by factor 2, one therefore would naively expect also an increase in energy density.

Transverse energy:

$$\left.\frac{dE_T}{d\eta}\right|_{|\eta|\le 1} = E_{part} \cdot \left.\frac{dN_{Ch}}{d\eta}\right|_{|\eta|\le 1} \cdot f_{neutral}$$

$f_{neutral}$ ← 1.6

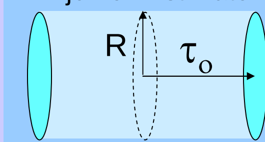
Bjorken estimate for energy density

at $\sqrt{s_{NN}}$ = 130 GeV

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2 \text{ GeV}$$

PHENIX

Bjorken Estimate



$$\varepsilon_{BJ} = \frac{dE_T / dy|_{y=0}}{\pi R^2 \tau_o} = 4.6\, GeV/fm^3$$

(if $R \sim 1.18A^{1/3}$ & $\tau_o \sim$ 1fm/c)

Experiments find for different $\sqrt{s_{NN}}$ approximately a *constant* amount of transverse energy(E_T) per particle, implying :

Large compared to $\varepsilon_{crit} \sim 1$ GeV/fm³ at critical temperature

at $\sqrt{s_{NN}}$ = 200 GeV

ε = 4.6 x 1.14 = **5.2 GeV/fm³**

PHENIX PHOBOS

Scaling by nb. of particles

Hadron yields

In case of termal/chemical equilibrium the hadron yields are defined through a thermo-dynamical model:

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

baryon number : $V \sum_i n_i B_i = Z + N$

strangeness : $V \sum_i n_i S_i = 0$

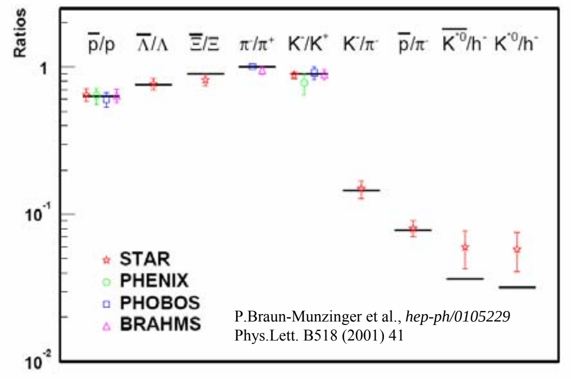
charge : $V \sum_i n_i I_{3_i} = \frac{Z - N}{2}$

Free parameter: μ_B, T_{ch}

Fixed through conservation laws: V, μ_S, μ_{I3}

Chemical Freeze Out

Use thermal model to describe particle / anti-particle ratio:



Fitting the data:

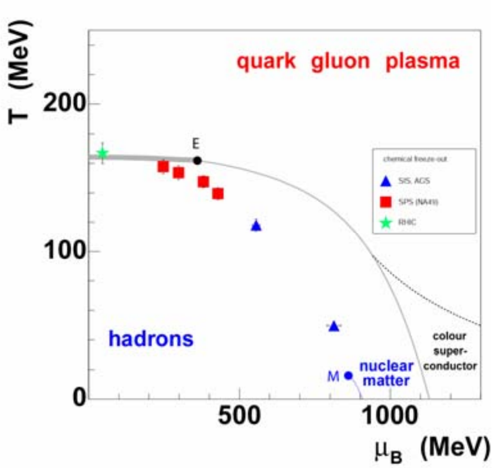
$T_{Ch} = 174\ \text{MeV}$

$\mu_B = 46\ \text{MeV}$

Agrees well with the theoretical calculation of T_c for phase transition

Hadron yields are in chemical equilibrium: early evolution of the colliding system determine the final values of many observables. Matter state in thermal equilibrium !

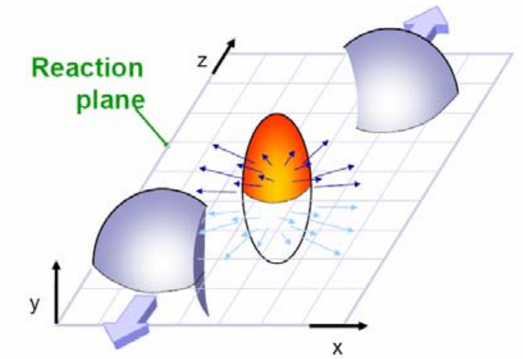
At RHIC phase transition at T_{ch} = 174 MeV, μ_B = 46 MeV:

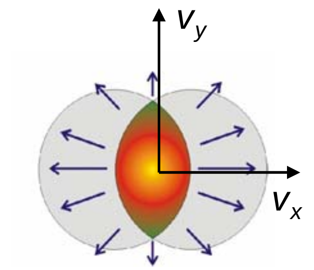


- RHIC data on the phase boundary
- Phase transition is likely to be a crossover and not a 1st order phase transition

Elliptical flow

Matter state in thermal equilibrium described by relativistic hydrodynamics ?

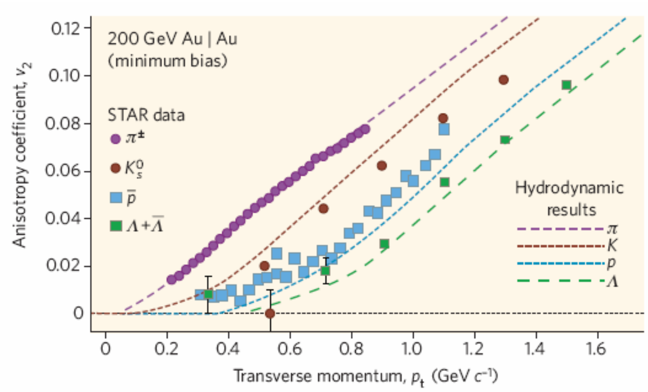




Elliptic flow (v_2):

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

$$v_2 = \langle \cos 2\phi \rangle \quad \tan\phi = p_y / p_x$$



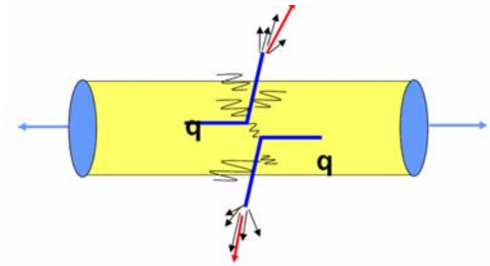
Higher transverse momenta are observed for particles emerging in the reaction plane whereas lower momenta are observed for particles perpendicular to the reaction plane (elliptical flow):

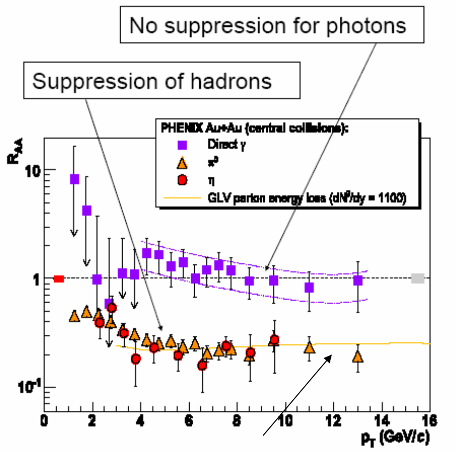
Bulk evolution described by relativistic hydrodynamics and an equation of state determined by weakly interacting quarks and gluons: confirms the idea that fireball reaches equilibrium quickly.

Matter state seems to behave like ideal liquid (no viscosity)

Opaque Matter – jet quenching

Energy loss in dens medium





Calculation assuming very dens gluon gas

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

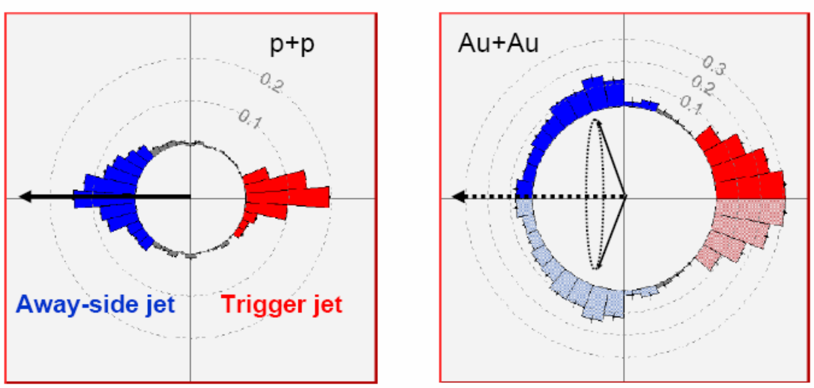
Area density of p+p coll's in A+A

Cross section in p+p coll's

Without nuclear effects:

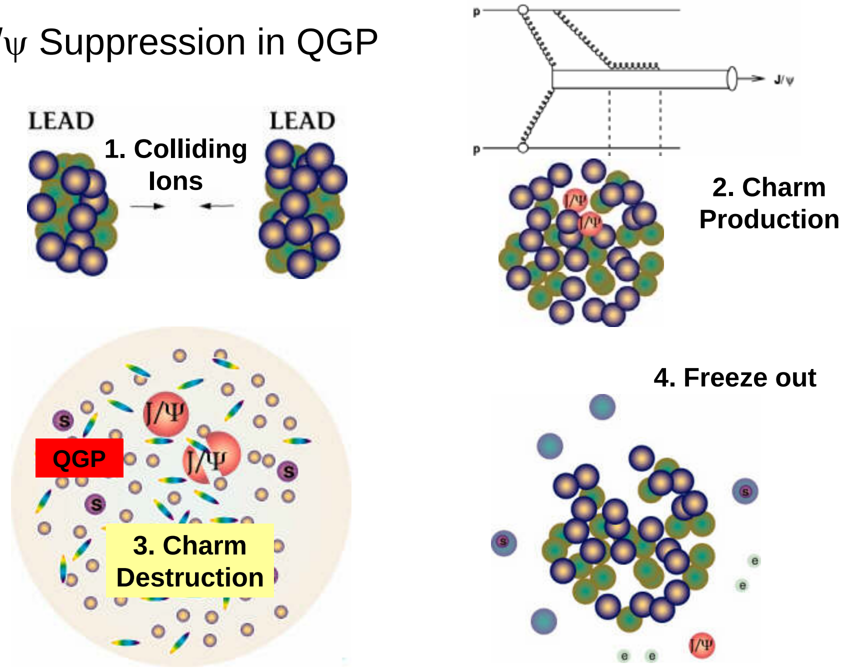
$R_{AA} = 1$.

Where does the energy go to ?

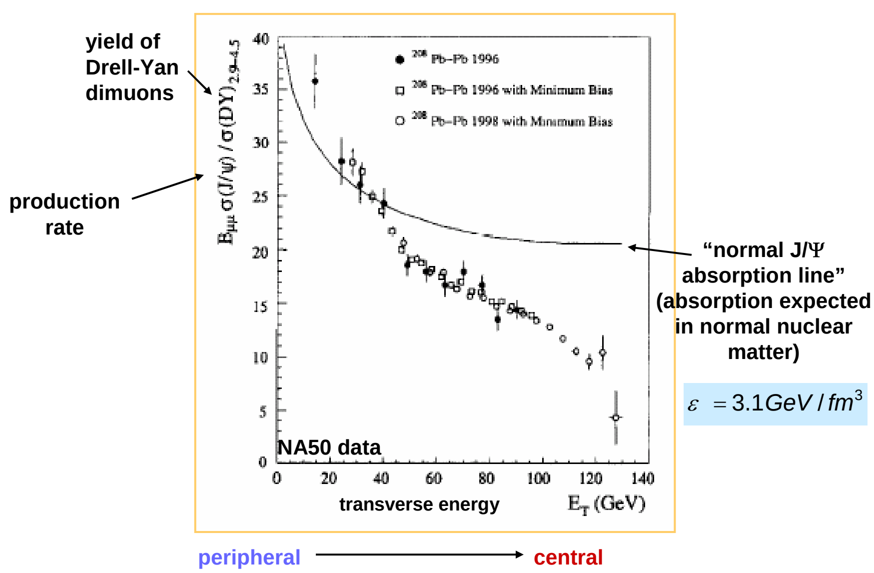


Lost energy of away-side jet is redistributed to angles away from 180° and low transverse momenta $p_T < 2$ GeV/c

J/ψ Suppression in QGP



J/ψ Suppression at SPS



C. Lourenco, Nucl. Phys. A 685(2001)384c

PRESS RELEASE

CERN press release, February 10th, 2000

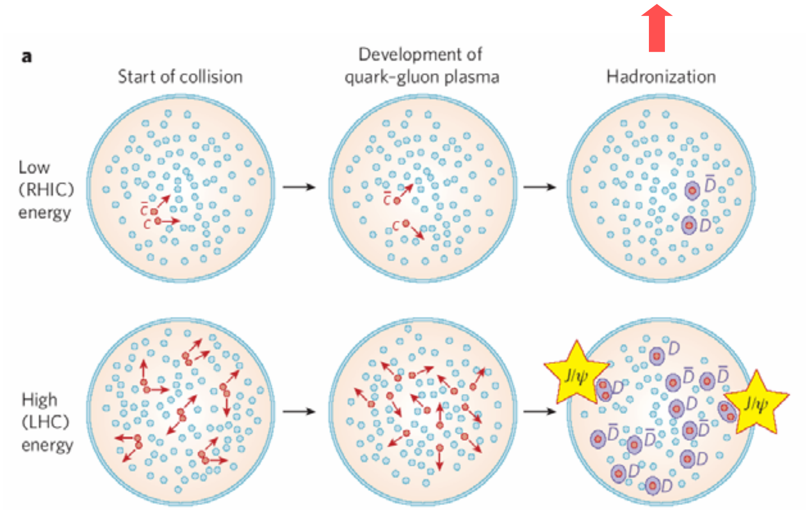
"... compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely."

Interpretation is not uncontroversial:

Beside the absorption of the charmonium in the nuclear medium its break-up by hadrons in the collision could lead to suppression also in absence of plasma formation.

J/ψ yields at RHIC / SPS and at LHC

suppression



Enhancement: clear finger print of QGP

Next step… LHC & ALICE