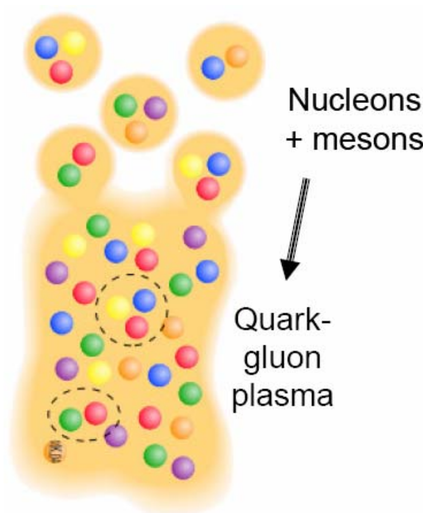


Melting Nuclear Matter:

Quark Gluon Plasma

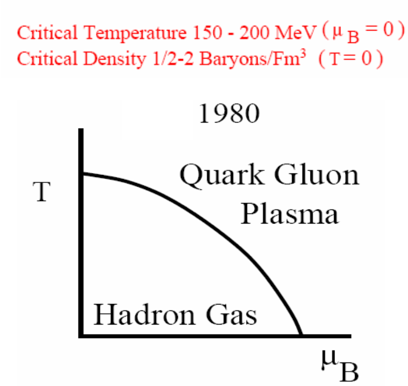
Quark Gluon Plasma – A new state of matter

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)

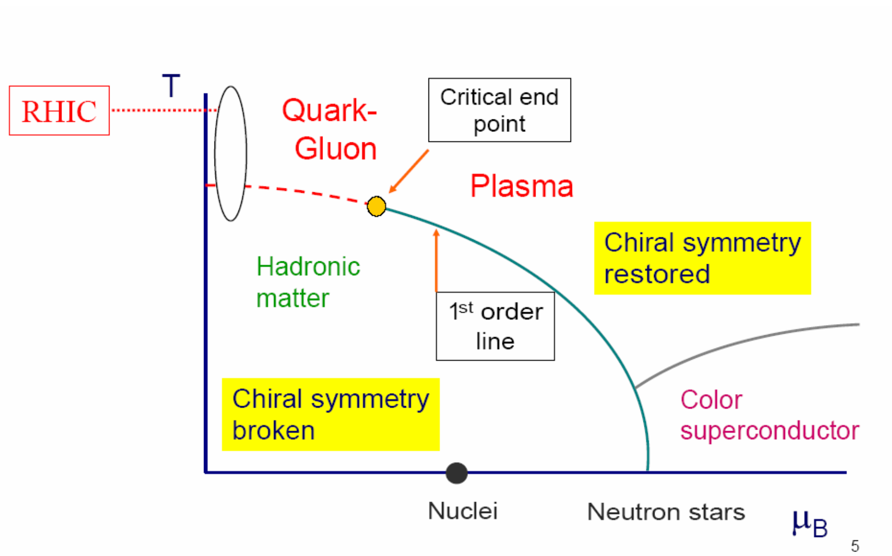


μ_B = baryon chemical potential

measure of the net baryon density

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

Phase diagram as of today



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)

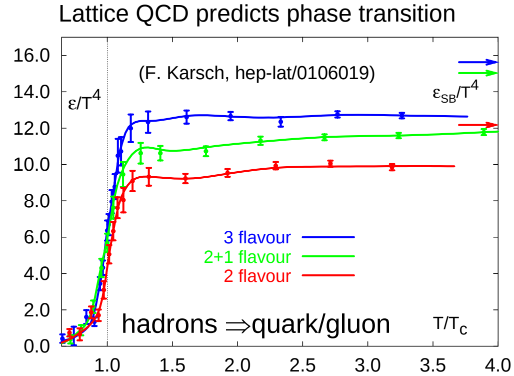
$$\epsilon \sim \frac{\pi^2}{30} N T^4$$

Degrees of freedom

QGP: $N \sim 2 \times 8 + 4 \times 3 \times N_F$

Hadronic gas phase (only pions): N = 3

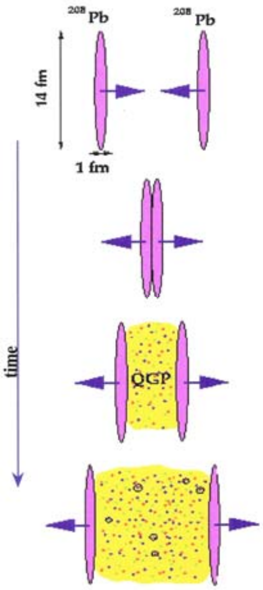
Lattice QCD predicts phase transition



Critical temperature: T_C = 173 MeV
(zero net-baryon density)
Critical density: $\rho_c \sim 0.7$ GeV fm^{-3}

nuclear density: $\rho = 0.15$ GeV fm^{-3}
Inside nucleon: $\rho = 0.5$ GeV fm^{-3}

Heavy Ion Collision



Ideal way to get conditions of extremely high T and ρ.

Formation time $\tau_0 = 1$ fm/c = $3{,}3 \cdot 10^{-24}$s

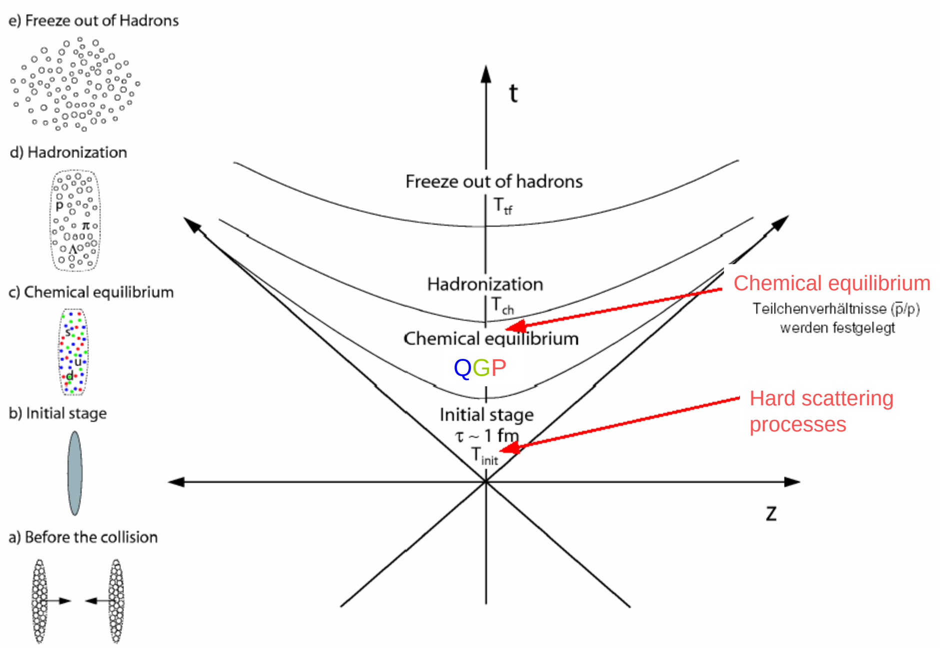
Temperature $O(10^{12}K)$

Lifetime 10 fm/c = $3{,}3 \cdot 10^{-23}$s

QGP in thermal / chem. equilibrium (!!):

start hadronization

Time development of Heavy Ion Collisions

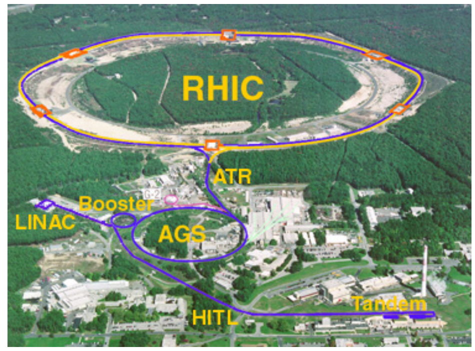


Heavy Ion Colliders

Brookhaven National Lab:

Relativistic Heavy Ion Collider (**RHIC**)

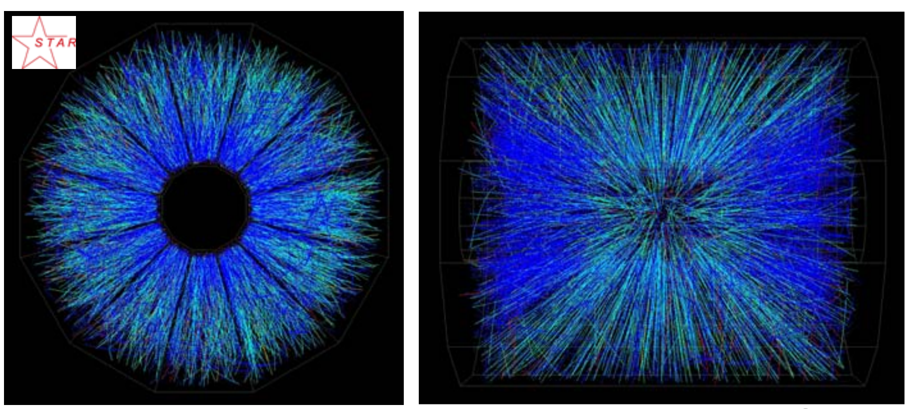
Experiments: **STAR, PHENIX, PHOBOS, BRAHMS**

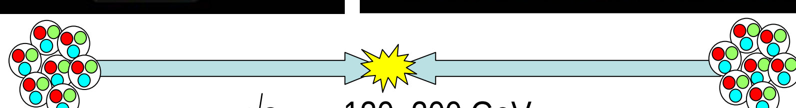


Facility	Location	System	Energy (CMS) $\sqrt{s_{NN}}$
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	CERN, Geneva	Pb+Pb	5.5 TeV

3 orders of magnitude by 2009

RHIC Collisions



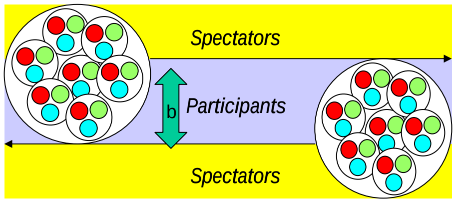


Gold $\sqrt{s_{NN}}$ = 130, 200 GeV Gold

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

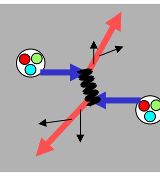
Several 1000 of particles

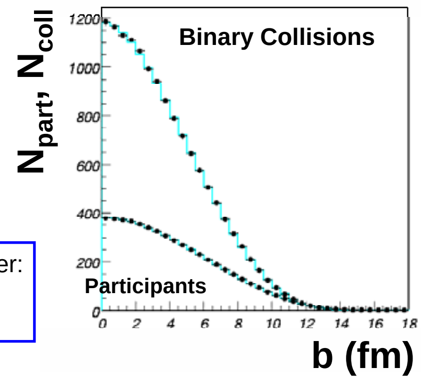
Geometry of AA Collisions



"Glauber" model of AA

Binary Collisions:
1. Jet Production
2. Heavy Flavor

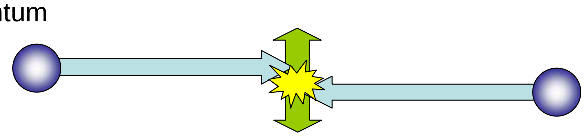




Cannot directly measure the impact parameter: Use total number of produced particles as measure for "centrality".

(Pseudo) Rapidity

- In hadronic collisions most particles have only small transverse momentum

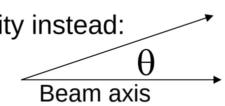


- Most observable particles carry only small fraction of (anti)proton longitudinal momentum ($x = p_z/p_{z,max}$)
- "Rapidity" variable "increases dynamic range" (x<.1)

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

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

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



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

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

Experimental probes for the QGP

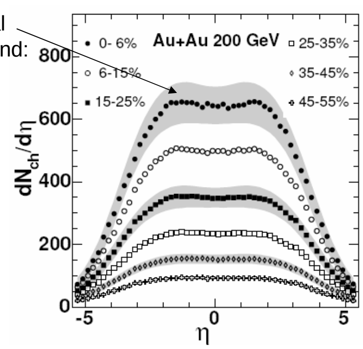
	Why	What
Global Observables	Is initial state dense enough?	• Particle Multiplicities • Energy Density
Collective Behavior	Is QGP a thermalized state?	• Hadron Yields • Elliptic Flow
Hard Probes	Formed early, probe medium	• Energy loss of jets • Charm production

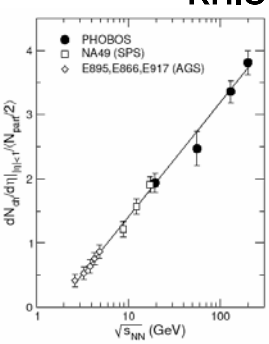
Charged particle density

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:

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

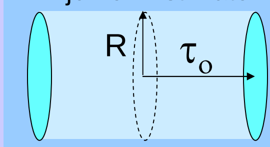
← 1.6

Bjorken estimate for energy density

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2 \text{ GeV (130 GeV)}$$

PHENIX

Bjorken Estimate



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

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

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

ε(200 GeV) = 4.6 x 1.14 = **5.2 GeV/fm³**

PHENIX PHOBOS

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: $V \sum_i n_i S_i = 0$

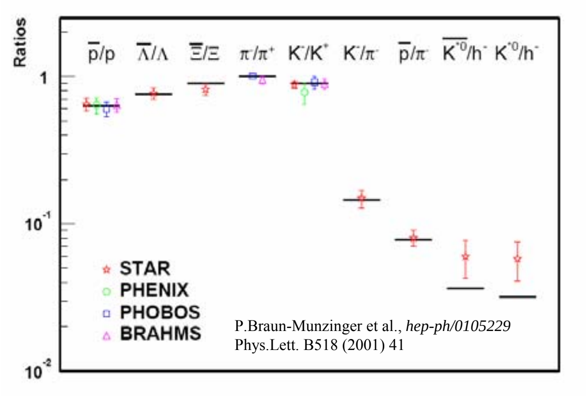
charge: $V \sum_i n_i I_{3_i} = \frac{Z - N}{2}$

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:



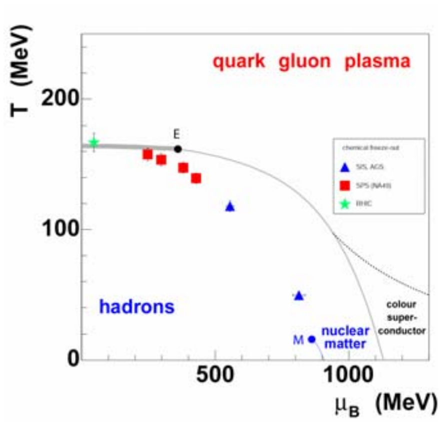
Fitting the data:

$$T_{Ch} = 174\,\text{MeV}$$
$$\mu_B = 46\,\text{MeV}$$

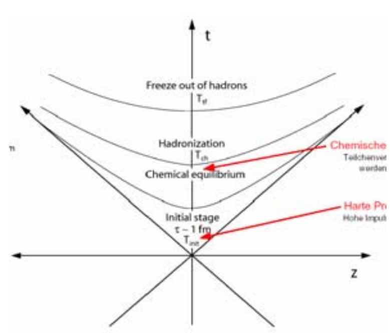
Agrees well with the theoretical calculation of T_c for phase transition

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

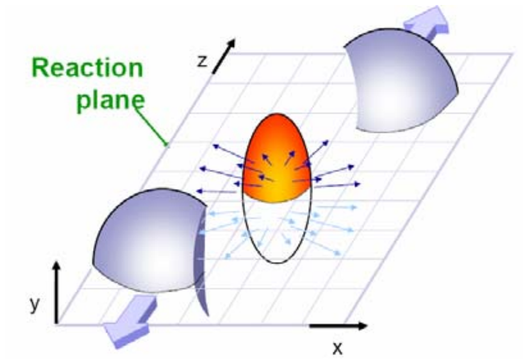
At RHIC phase transition at T_{ch} = 174 MeV, μ_B = 46 MeV:

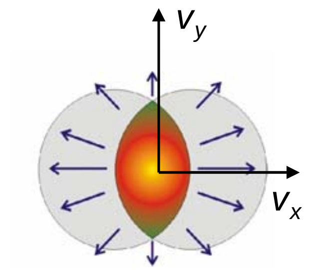


- RHIC data on the phase boundary
- Phase transition is likely to be a crossover and not a 1st order phase transition



Elliptical flow

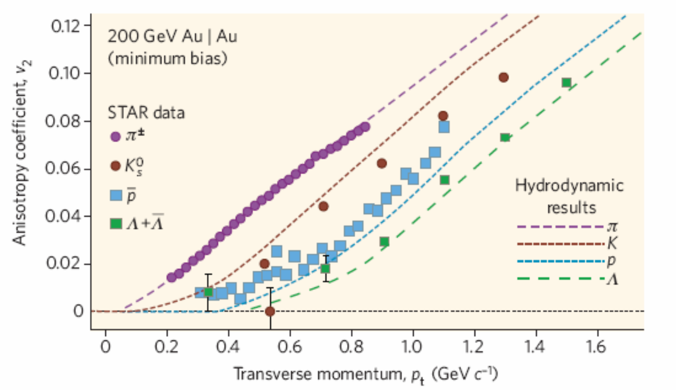




Elliptic flow (v_2):

- 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

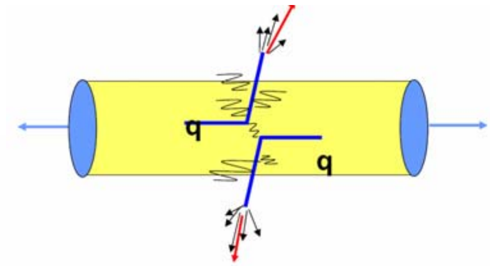
$$v_2 = \langle \cos 2\phi \rangle \quad \tan\phi = p_y / p_x$$

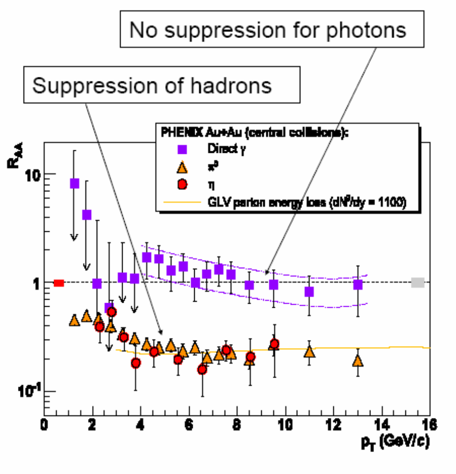


Higher transverse momenta are observed for particles emerging in the reaction plane whereas lower momenta are observed for particles perpendicular to the reaction plane (elliptical flow):

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.

Opaque Matter – jet quenching





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

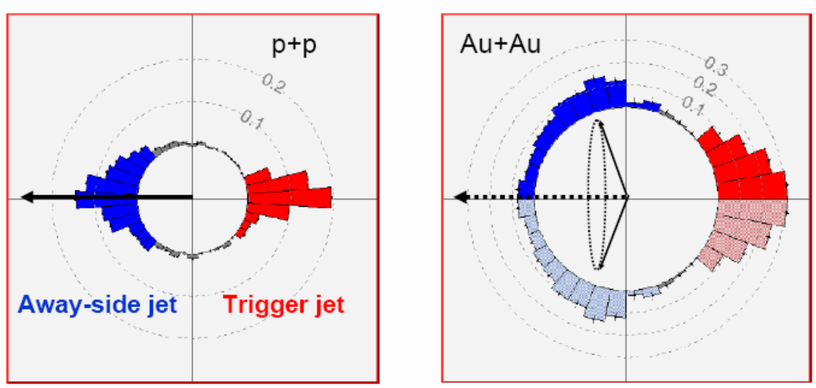
Area density of p+p coll's in A+A

Cross section in p+p coll's

Without nuclear effects:

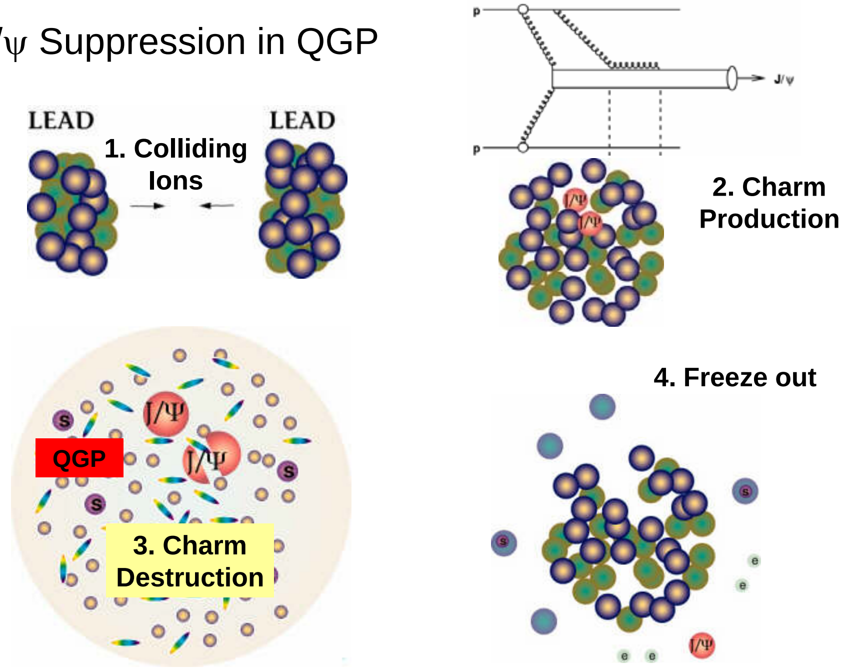
$R_{AA} = 1$.

Where does the energy go to ?

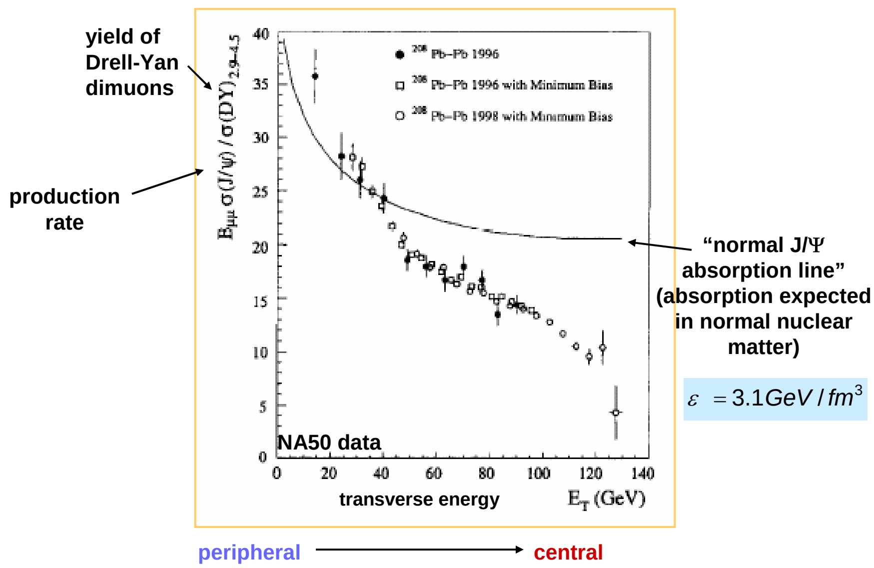


Lost energy of away-side jet is redistributed to angles away from 180° and low transverse momenta $p_T < 2$ GeV/c

J/ψ Suppression in QGP



J/ψ Suppression at SPS



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

CERN press release, February 10th, 2000

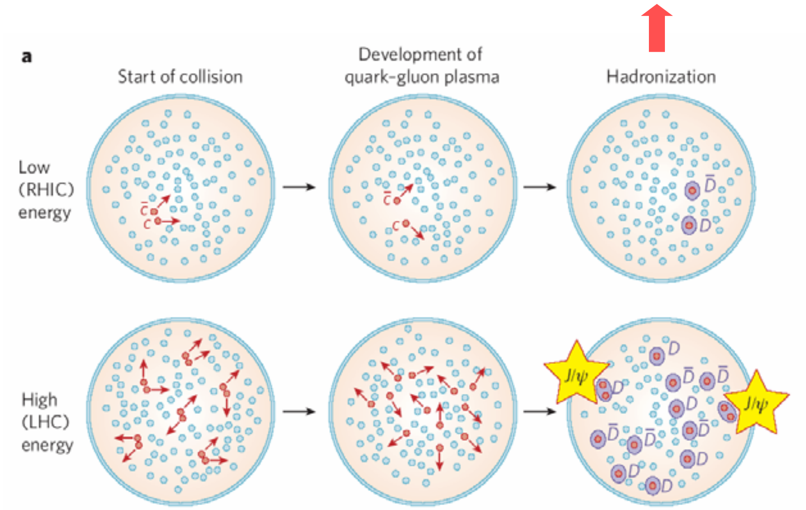
“... compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.”

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.

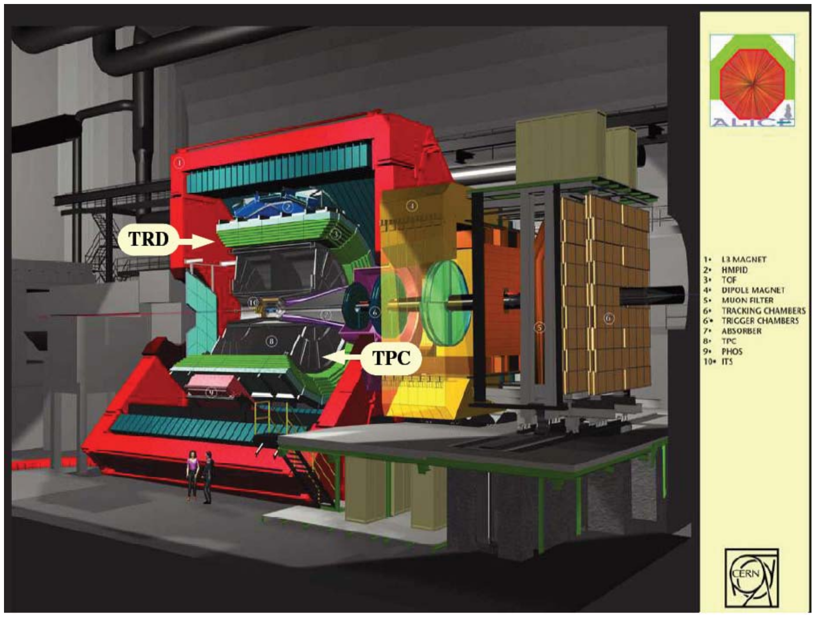
J/ψ yields at RHIC / SPS and at LHC

suppression

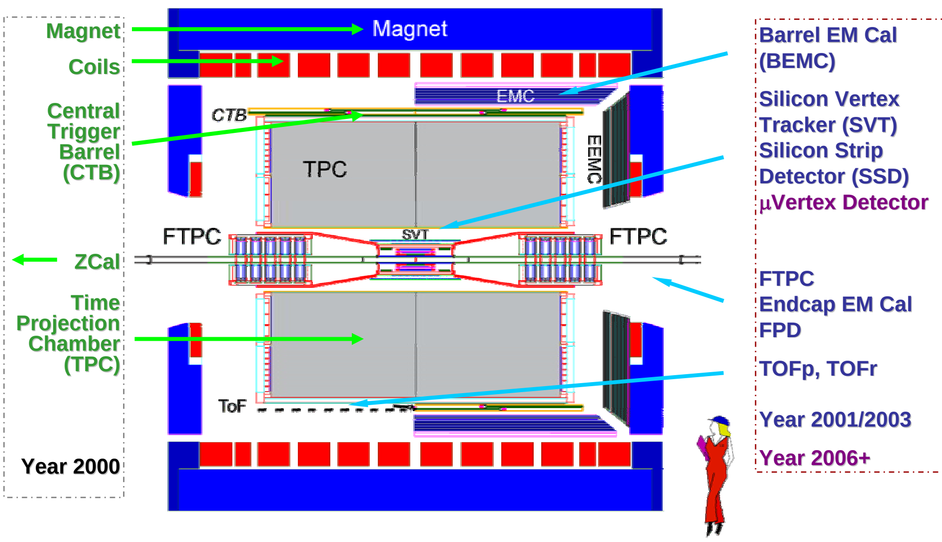


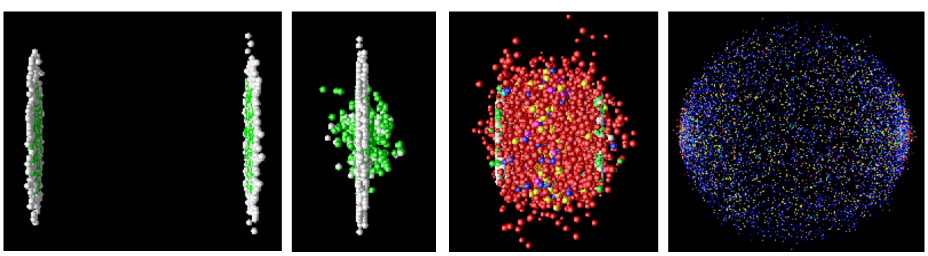
Enhancement: clear finger print of QGP

Next step… LHC & ALICE



Example: Solenoid Tracker At RHIC = STAR





Lorentz-contracted nuclei ($\Delta z \sim R/\gamma$) | Hard Collisions | Parton Dynamics | Hadron Dynamics

b) Liberation of quarks and gluons due to the high energy deposited in the overlap region of the two nuclei.
c) Equilibration of quarks and gluons
d) Crossing of the phase boundary and hadronization (T_{Ch})
Inelastically interacting hadron gas
e) Thermal Freeze-out

Hadron yields

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

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

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}