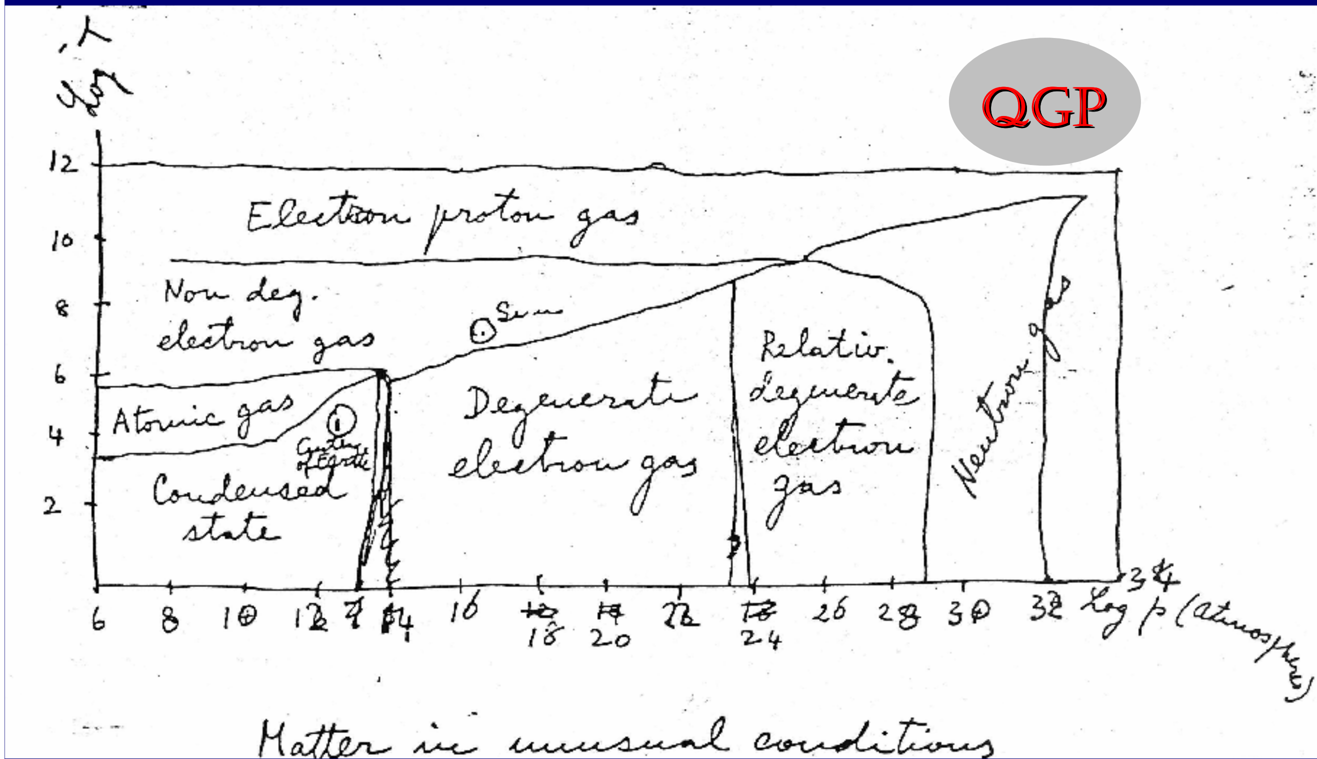
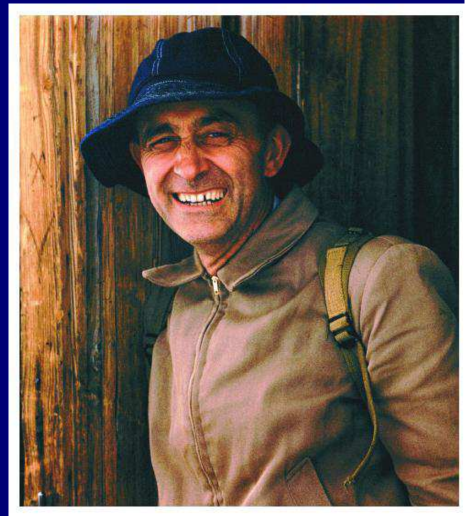
Introduction to the physics of the Quark-Gluon Plasma and the relativistic heavy-ion collisions

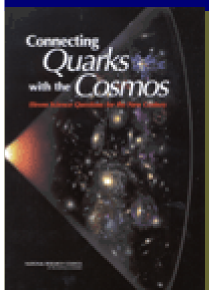
Villa Gualino-Torino, 7-3-2011

Matter under extreme conditions…

Fermi Notes on Thermodynamics







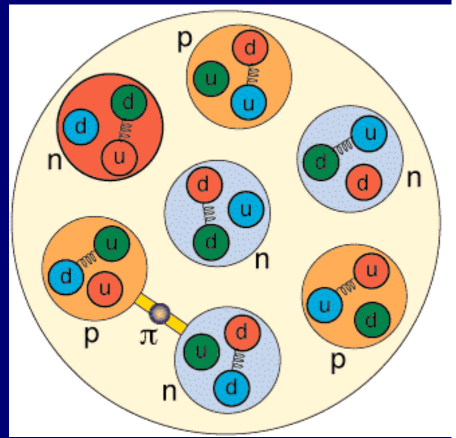
Eleven Science Questions for the New Century

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES…

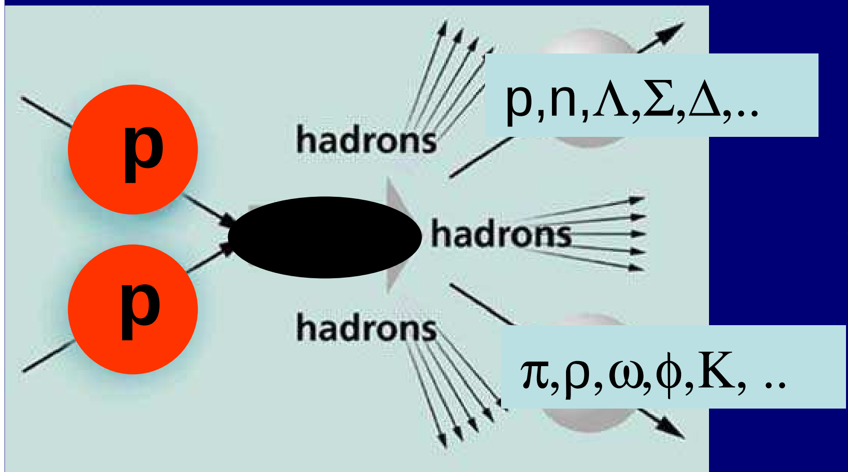
No. 7 - What Are the New States of Matter at Exceedingly High Density and Temperature? ***QGP is at $T > 10^{12} K$ and $\rho > 10^{40}$ cm^{-3}***

Let's start from 100 years ago …

1911 - Rutherford discovered the Nucleus
In '30 started the study of a new force:
Nuclear Force between nucleons



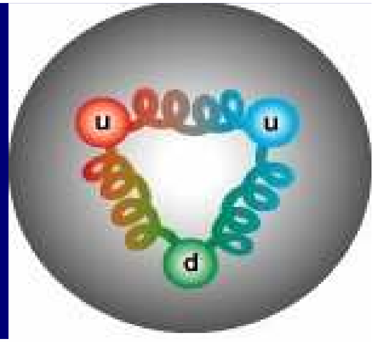
Bashing nucleons
with increasing energy …



It became clear that nucleons
and more generally **hadrons** are made of
quarks exchanging gluons

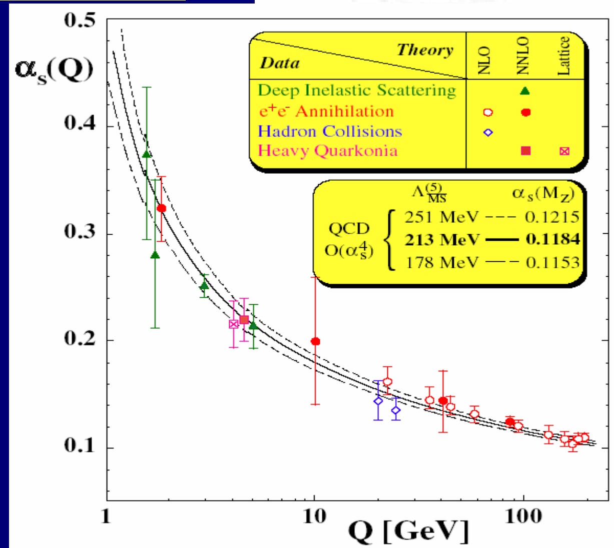
In 1974 the theory of the strong interaction was written down and called Quantum Chromodynamics

Quantum Chromodynamics



$$L_{QCD} = \sum_{i=1}^{n_f} \overline{\Psi}_i \gamma_\mu \left(i\partial^\mu - g A_a^\mu \frac{\lambda_a}{2} \right) \Psi_i - m_i \overline{\Psi}_i \Psi_i - \frac{1}{4} \sum_a F_a^{\mu\nu} F_a^{\mu\nu}$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu + i f_{abc} A_b^\mu A_c^\mu$$

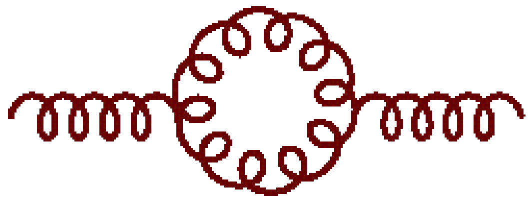


Similar to QED but 3 charges + gauge invariance imply that the gauge field (gluons) self-interact:

- **Asymptotic freedom**
- **Confinement**

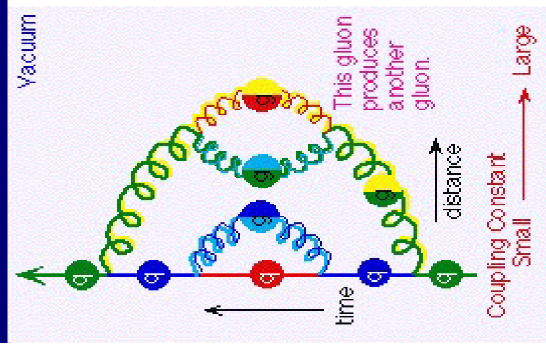
$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log\left(\frac{Q^2}{\Lambda^2}\right)}$$

$$\Lambda \sim 200 \text{ MeV} \simeq 1 \text{ fm}^{-1} \simeq (\text{hadron size})^{-1}$$



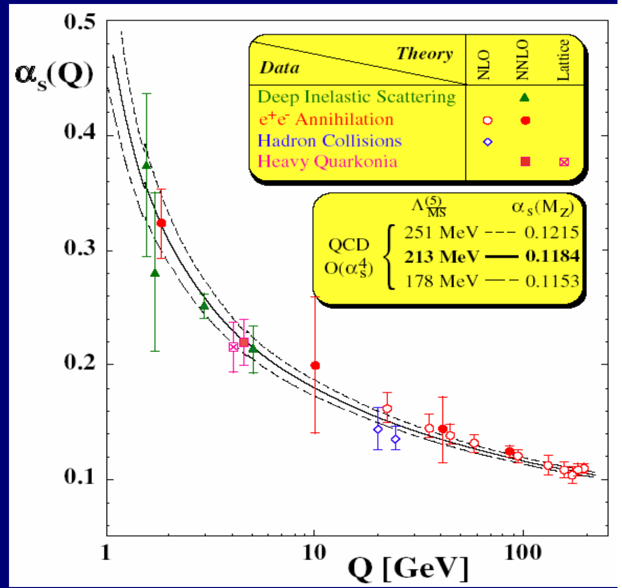
Two regimes:

- $Q \gg \Lambda_{QCD}$ one can use perturbative QCD **(pQCD)**
- $Q \sim \Lambda_{QCD}$, $Q > \Lambda_{QCD}$ non perturbative methods : *lattice QCD **(lQCD)*** and effective lagrangian approach



Quark-Gluon Plasma

Inside nuclei strong interaction manifest in an extremely non-perturbative regime ($\Lambda_{QCD} \sim 1\ fm^{-1}$) and *quarks are not the relevant degrees of freedom*



Several arguments already in the '70-'80 lead to think that at some temperature and/or density quarks *"can roam freely in a medium"-> QGP*

1) <u>ASYMPTOTIC FREEDOM</u>
   At large T there are interaction $q^2 \sim (3T)^2$ and the coupling is weak
2) <u>OVERLAP (percolation)</u>
   Hadrons Overlap does not allow to identify the hadrons itself: $T_0 \sim 150$ MeV
3) <u>BAG PRESSURE MODELING</u>
   Pressure of pion gas smaller than the quark gas one: $T_0 \sim 150$ MeV
4) <u>HAGERDON LIMITING TEMPERATURE</u>
   Hadron gas partition function has a singularity at $T_0 \sim 160$ MeV

Hagerdon's limiting temperature

From the Hadronic side increasing temperature leads to the production of higher mass hadronic states, but the density of states grows exponentially with the mass

Partition functon for a gas o particle with density of states *ρ(m)*

$$\rho(m) = Cm^{\alpha}e^{m/T_0} \qquad \alpha = -\tfrac{5}{2}, \ T_0 \simeq 160 \text{ MeV} \quad (\text{exp. fit})$$

$$\log \mathcal{Z}(T,V) = V\left(\frac{T}{2\pi}\right)^{3/2} C\int_{m_0}^{\infty} dm\, m^{\alpha+\frac{3}{2}} \exp\left\{m\left(\frac{1}{T_0}-\frac{1}{T}\right)\right\}$$

m>>T

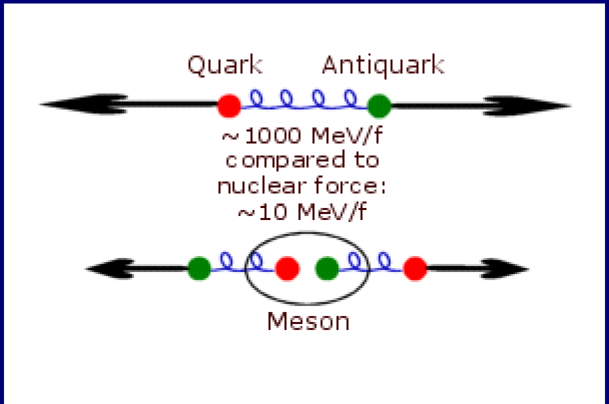
The integral is well defined for $T < T_0$, it diverges for $T \to T_0$:

hadronic matter can not exist for $T > T_0$

Hagerdon, Nuovo Cimento (1965): T_0 is a limiting temperature for hadronic systems

Cabibbo-Parisi, PLB59(1975): Divergency of the partition function has to be associated with a phase transition of hadronic matter to quark-gluon matter

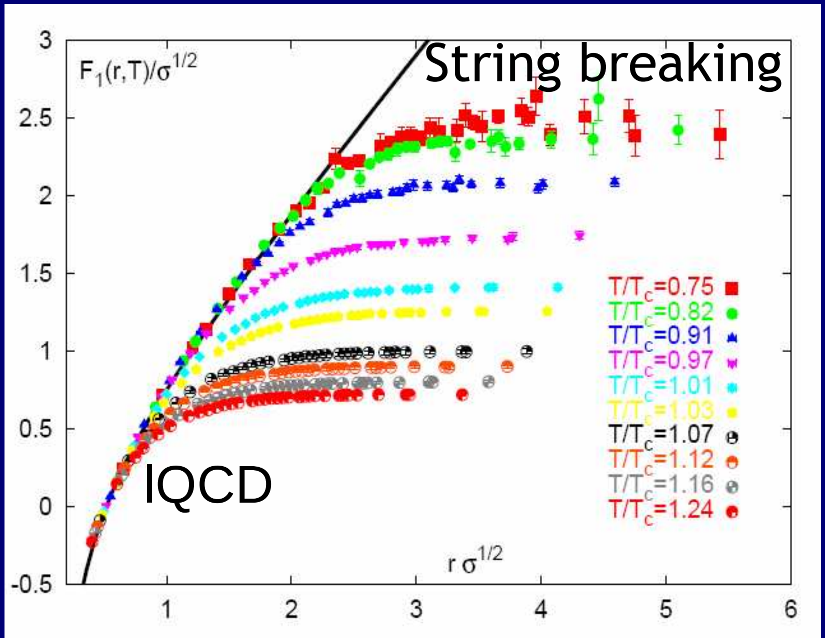
Quark-antiQuark free energy in lQCD



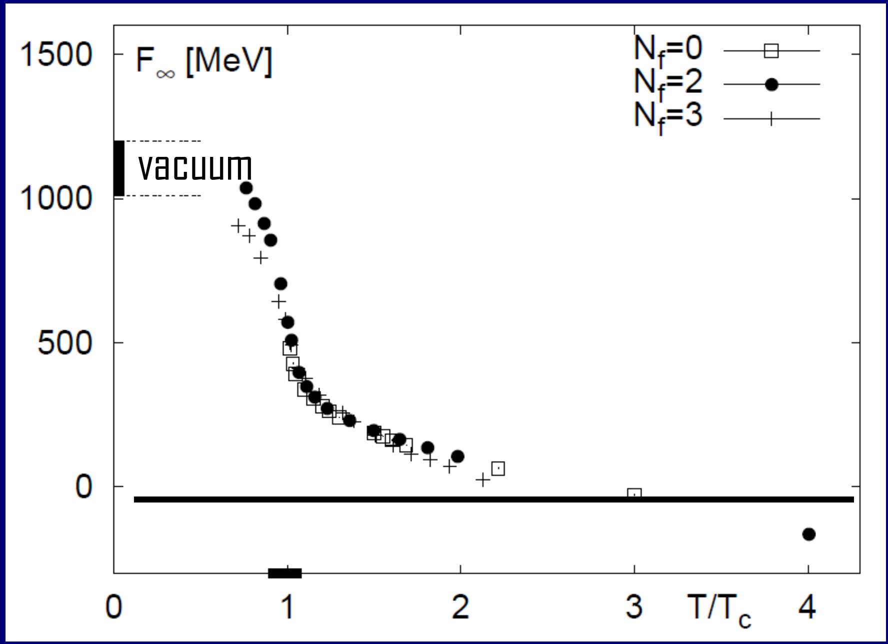
$$V_{Q\bar{Q}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$

We cannot observe quarks, but at large T we can envisage a weakly interacting gas of quarks and gluons

Charm Quarks



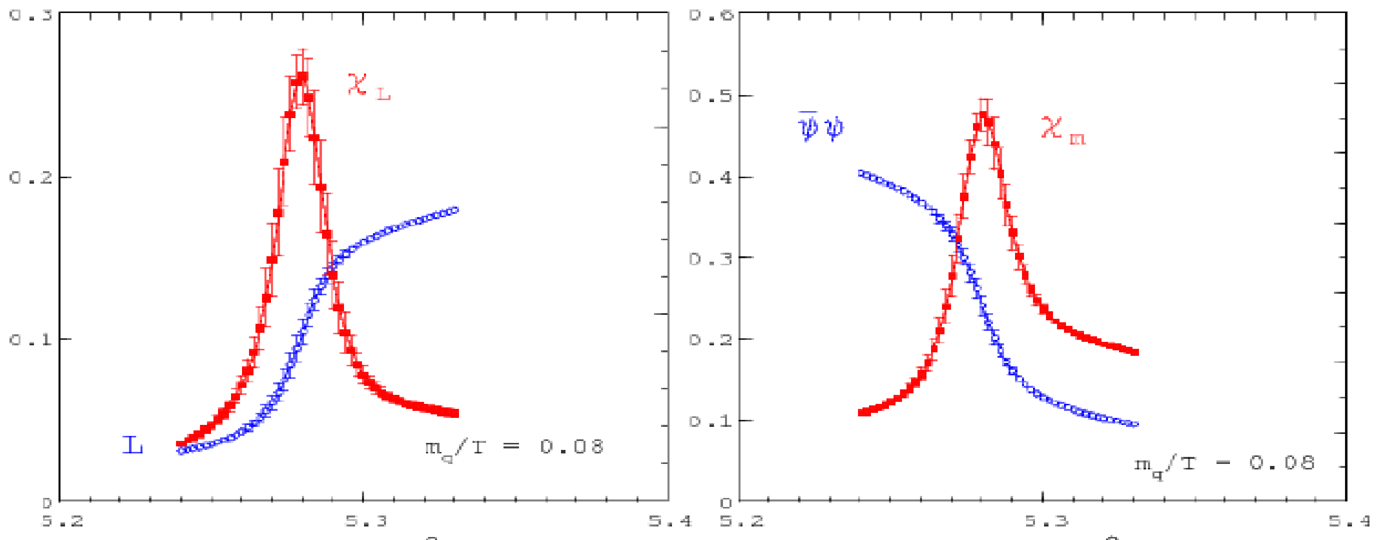
Asymptotic value



Kaczmarek et al., PPS 129,560(2004)

Order Parameters of the Phase Transition

Polyakov Loop | Chiral Condensate



lQCD   T~170 MeV   T~170 MeV

Fig. 2. Deconfinement and chiral symmetry restoration in 2-flavour QCD: Shown is $\langle L \rangle$ (left), which is the order parameter for deconfinement in the pure gauge limit $(m_q \to \infty)$ and $\langle \bar{\psi}\psi \rangle$ (right), which is the order parameter for chiral symmetry breaking in the chiral limit $(m_q \to 0)$. Also shown are the corresponding susceptibilities as a function of the coupling $\beta = 6/g^2$.

$$L \propto Tr\left(e^{ig\int_0^\beta A_0(\vec{x},t)d\tau}\right) = Tr\left(e^{-\beta H_{\mathrm{int}}}\right)$$

$$\langle q\bar{q} \rangle \approx (250\ MeV)^3 \ \to 0$$

What is the order of the phase transition? *[Ratti]*

The basic relations of reference

Ideally our reference is a gas of non-interacting massless quarks and gluons

$$n = \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{p/T} \pm 1} = \nu \frac{\zeta(3)}{\pi^2} T^3 \text{x d.o.f} \quad \nu = \begin{cases} 1 & \textit{bosons} \\ \frac{3}{4} & \textit{fermions} \end{cases}$$

where $\zeta(3) = 1.202$ (Riemann ζ function)

$$\epsilon = \int \frac{d^3p}{(2\pi)^3} \frac{p}{e^{p/T} \pm 1} = \nu' \frac{\pi^2}{30} T^4 \text{x d.o.f} \quad \nu' = \begin{cases} 1 & \textit{bosons} \\ \frac{7}{8} & \textit{fermions} \end{cases}$$

pressure: $\quad p = \frac{\epsilon}{3}$

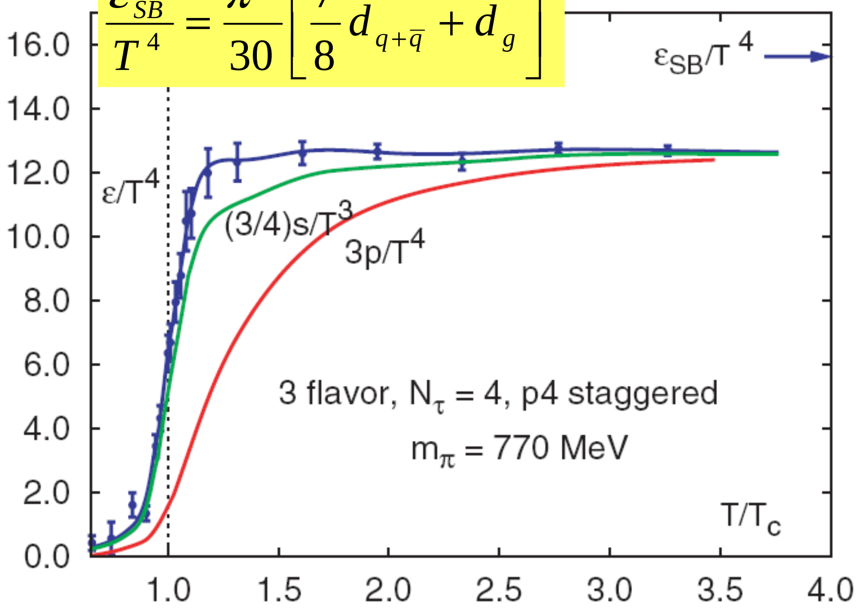
entropy density: $\quad Ts = \epsilon + P = \frac{4}{3}\epsilon \quad \Longrightarrow \quad s = \frac{4}{3}\frac{\epsilon}{T} = 2\nu' \frac{\pi^2}{45} T^4$

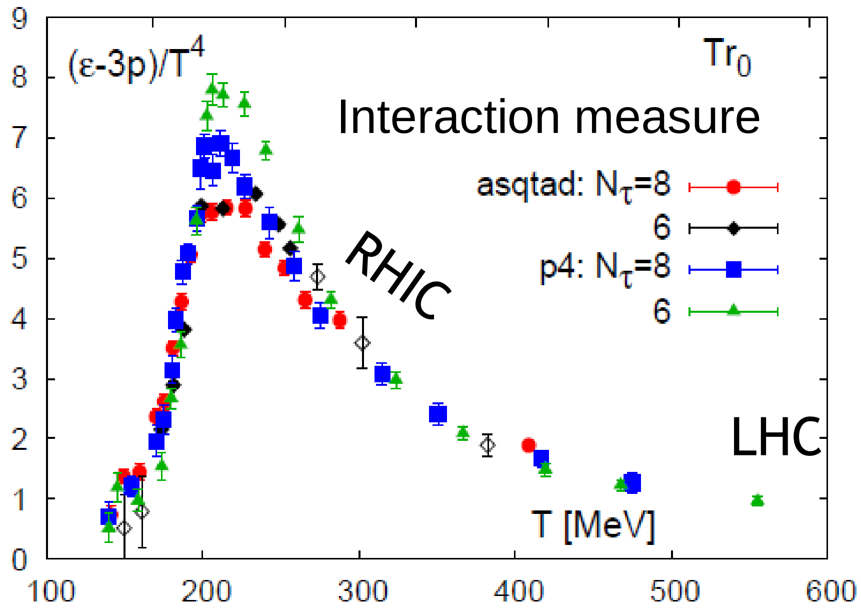
Multiplied by degrees of freedom

$d_{q+q}=2*2*3*N_f=24\text{-}30$, $d_g=8*2$

From lattice QCD

$$\frac{\varepsilon_{SB}}{T^4} = \frac{\pi^2}{30}\left[\frac{7}{8}d_{q+\bar{q}} + d_g\right]$$





Enhancement of the degrees of freedom towards the QGP

$$\varepsilon_c \approx 0.7\, GeV / fm^3$$
$$T_c \cong 175 \pm 15\, MeV$$

Stefan-Boltzmann limit not reached by 20 % for ε :

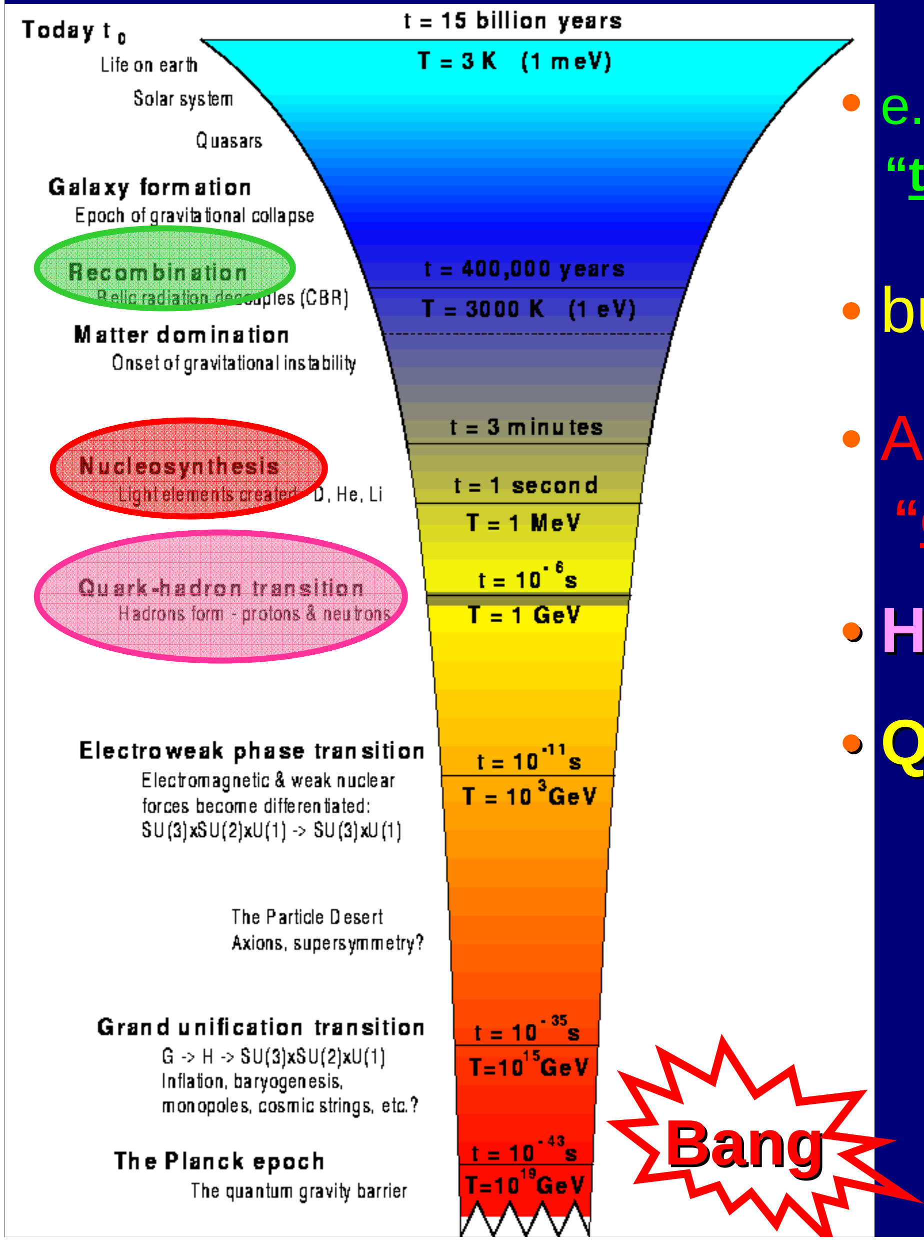
QGP as a weak interacting gas?!

In Ads/CFT this can be a very strong interacting system

[Cotrone]

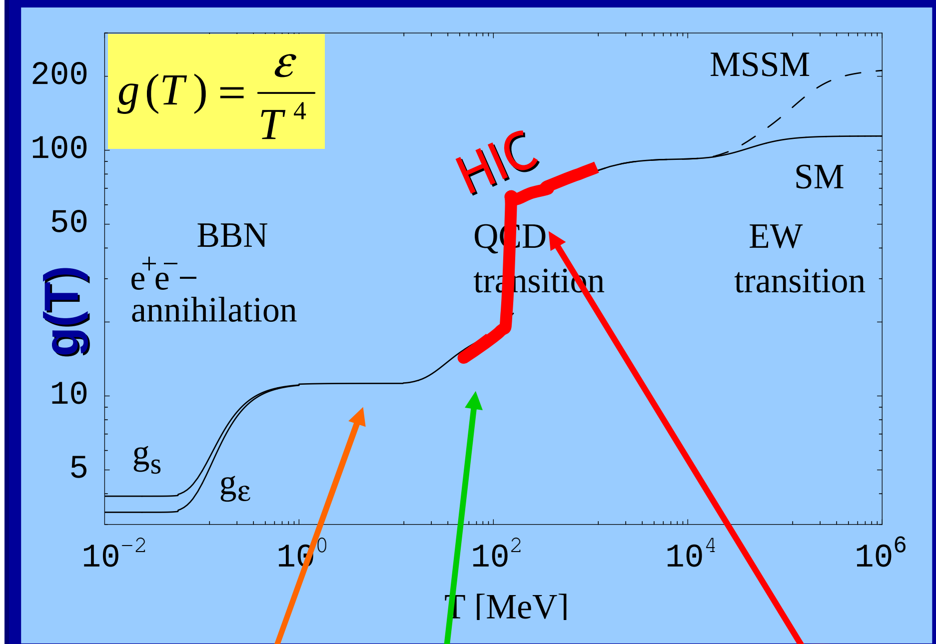
No interaction means also ε=3p (for a massless gas)

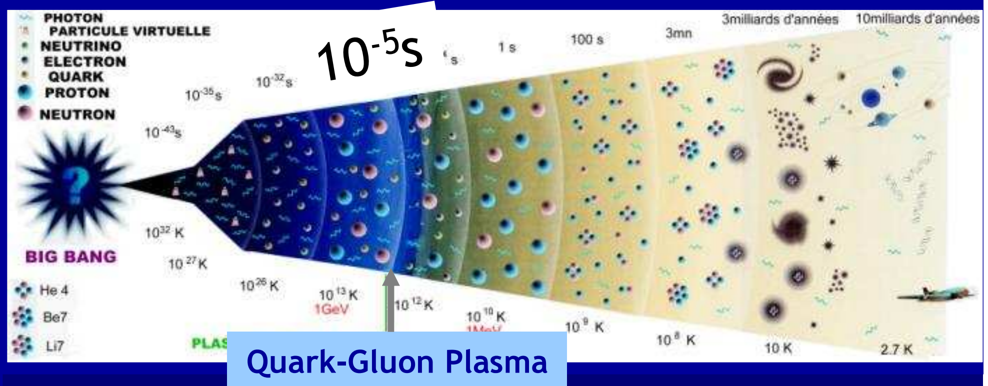
QGP in the Early Universe Evolution

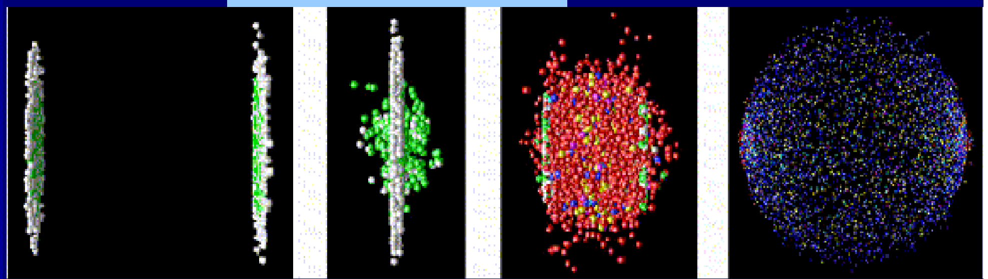


- e. m. decouple ($T \sim 1$ eV , $t \sim 3{\cdot}10^5$ ys)
  "**thermal freeze-out**"
- but matter *opaque* to e.m. radiation
- Atomic nuclei ($T \sim 100$ KeV, $t \sim 200$s)
  "**chemical freeze-out**"
- **Hadronization ($T \sim 0.2$ GeV, $t \sim 10^{-5}$s)**
- **Quark and gluons**

Degrees of freedom in the Universe



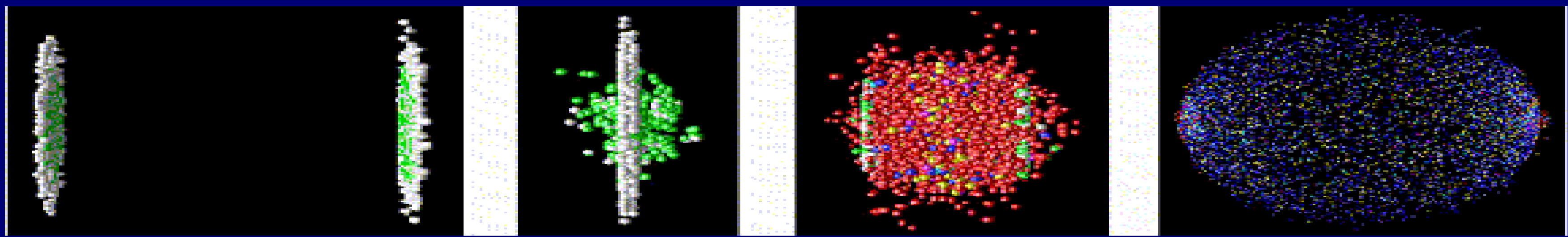




$$g(T) = 2_\gamma + 4_e + 4_\nu + 3_\mu + 3_\pi + \ldots + 16_g + 31.5_{uds} + 21_{cb} + \ldots$$

D.J.Schwartz, Ann. Phys. 2004

How to produce a matter with ε >>1 GeV/fm^3 lasting for τ > 1 fm/c in a volume much larger than an hadron?

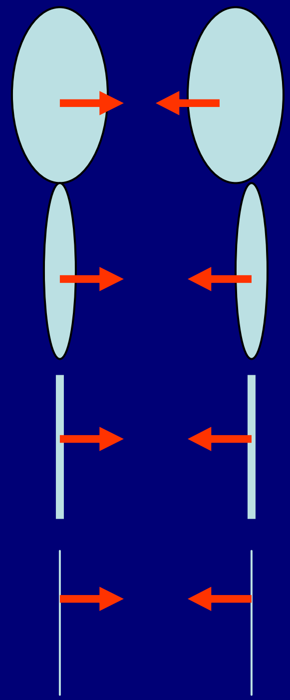


Let's bash again at higher energy…

High Energy Heavy Ion Collision Facilities

Accelerator	Lab.	E_{beam} [AGeV]	$\sqrt{s}$[AGeV]	Contraction
AGS ('80s)	BNL	10 (*)	4.5	2
SPS (94-…)	CERN	160(*)	17.3	9
RHIC (00-…)	BNL	100 +100	200	100
LHC (09-…)	CERN	2750+2750	5500	2750

$$s_{NN} = (p_A + p_B)^2 = E_{CMS}^2$$



$$\gamma_{CM} = \frac{E}{m} = \frac{\sqrt{s}}{m}$$

Fixed target $\boxed{\sqrt{s_{NN}} \cong \sqrt{2mE_{beam}}}$

Collider $\boxed{\sqrt{s_{NN}} \cong 2\,E_{beam}}$

Max energy density complete stopping

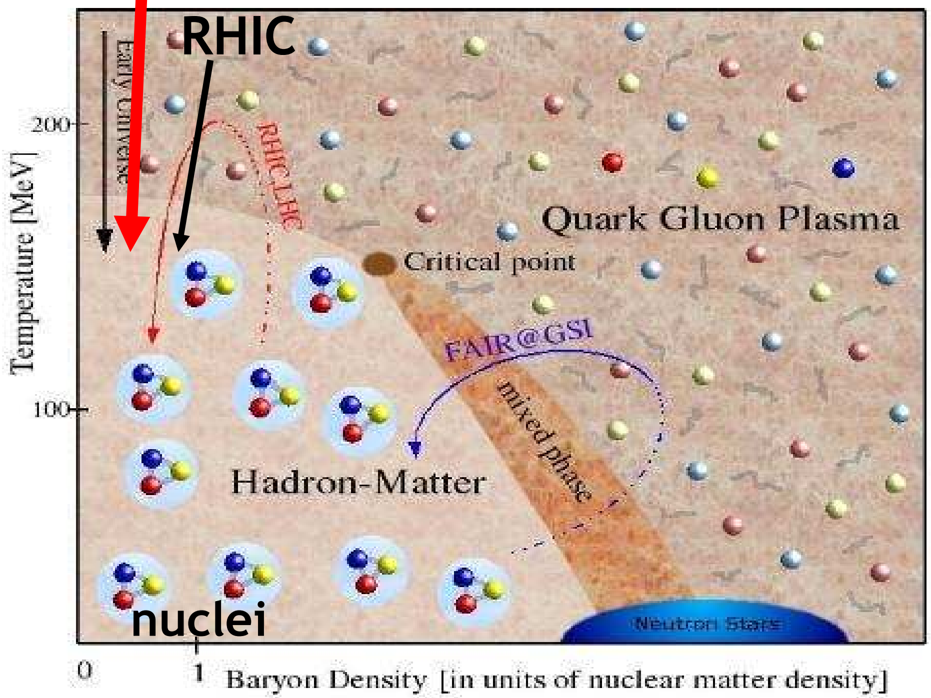
$$\varepsilon_{\max} = \frac{E_{CM}}{V_A} = \frac{3\gamma\sqrt{s}N_{part}}{4\pi R^3} = \frac{3sN_{part}}{4\pi m R^3}$$

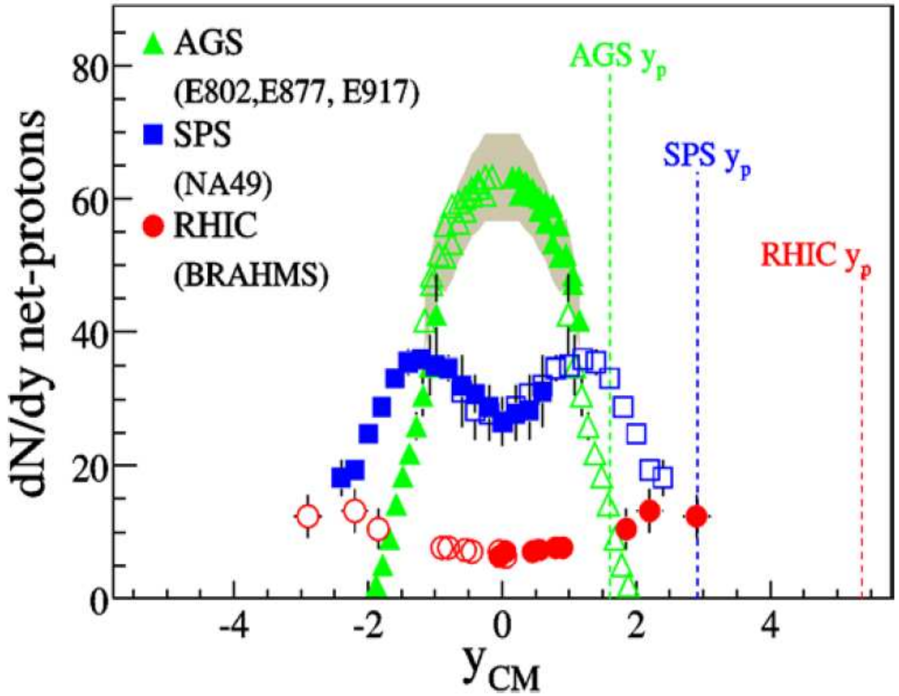
RHIC -> ε_{max}~ 10^2 GeV/fm^3

LHC -> emax~ 3 10^3 GeV/fm^3

Exploring the phase diagram

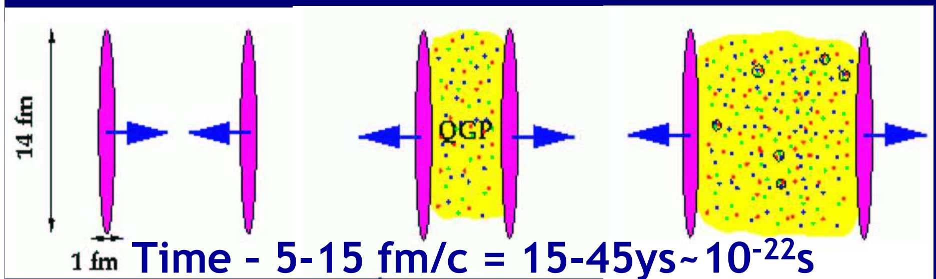
LHC





new medium created from the energy deposited μ_B=0 (quark=antiquarks)

Hotter-denser-longer increasing E_{beam}

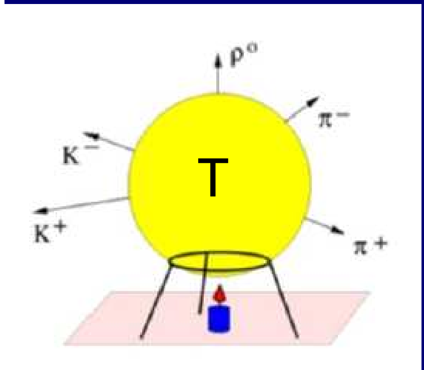


Increasing beam energy -> transparency

Energy distributed in a larger volume

How to make simple estimates?

Statistical Model analysis



Temperature

Chemical Potential

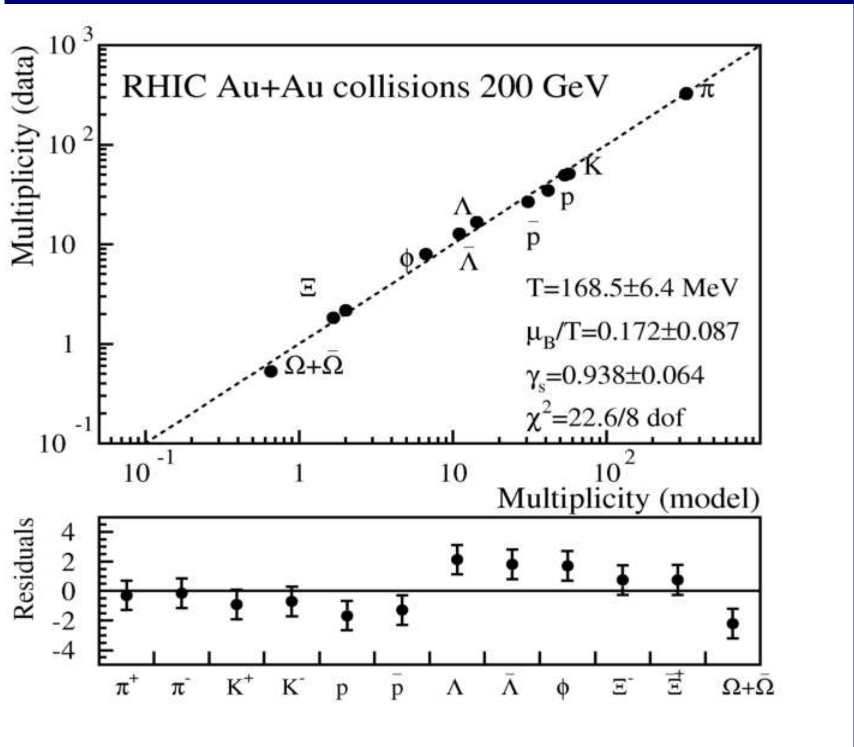
$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3p \left[e^{\sqrt{p^2+m_j^2}/T + \mu \cdot q_j/T} \pm 1 \right]^{-1}$$

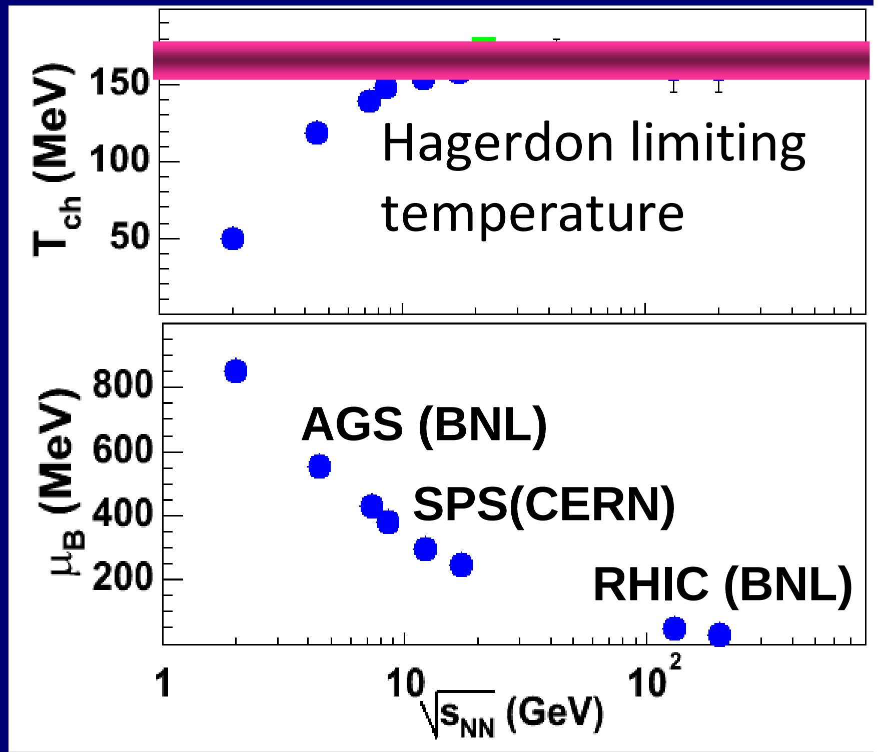
Yield

Mass

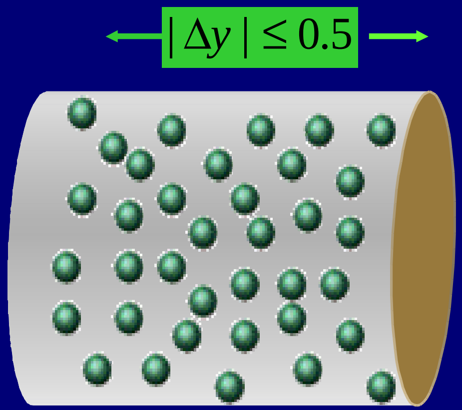
Quantum Numbers

F. Becattini





Energy Density and Temperature Estimate I



Particle streaming from origin

$$\frac{z}{t} = \mathrm{v}_z = \tanh y_z$$
$$\rightarrow dz = \tau \cosh y \, dy$$

Energy density a la Bjorken:

$$\varepsilon_0 = \frac{\Delta E}{\Delta V} = \frac{E \cdot \Delta N}{A_T \cdot \Delta z} = \frac{m_T}{\pi R^2 \tau_0} \frac{\Delta N}{\Delta y} = \frac{1}{\pi R^2 \tau_0} \frac{dE_T}{dy}$$

theory estimate

$\tau_{RHIC} \sim 0.6\text{-}1 \; fm/c$

experiments

$dE_T/dy \sim 720$ GeV

We can estimate the initial ε_0

$$\varepsilon_{RHIC} \sim 5-8 \; GeV/fm^3$$

Is this correct?

Energy Density and Temperature Estimate II

Entropy Conservation

$$S = sV = \text{cost} \Rightarrow s_0\tau_0 = s\tau \Rightarrow T_0^3\tau_0 = T\tau$$

1D expansion

$$\tau = \tau_0\left(\frac{T_0}{T}\right)^3$$

$$\varepsilon = \varepsilon_0\left(\frac{\tau_0}{\tau}\right)^{4/3}$$

But this means that the previous estimate cannot be correct because it supposes that $\varepsilon \sim \tau^{-1}$, but to conserve entropy $\varepsilon \sim \tau^{-4/3}$

$$\varepsilon = \frac{1}{\pi R^2\tau_0}\frac{dE_T}{dy}\left(\frac{\tau_f}{\tau_0}\right)^{1/3} = \varepsilon_{Bjorken} \cdot 2 \approx 10 - 15\ GeV \cdot fm^{-3}$$

$$T_0 = \left(\frac{30}{\pi^2}\frac{\varepsilon_0}{g}\right)^{1/4} \Rightarrow \left(\frac{8\times 12}{10}\right)^{1/4} fm^{-1} = 1.7\ fm^{-1} = 335 MeV$$

<u>Estimate of QGP lifetime</u> (τ_0~0.6 fm/c at RHIC)

$$\tau_{QGP} = \tau_0\left(\frac{T_0}{T_c}\right)^3$$

RHIC - $T=2T_c \rightarrow \tau_{QGP}=0.6*2^3 = 5$ fm/c

LHC - $T=3.5\ T_c \rightarrow \tau_{QGP}=0.4*3.5^3 = 15$ fm/c

So with uRHIC

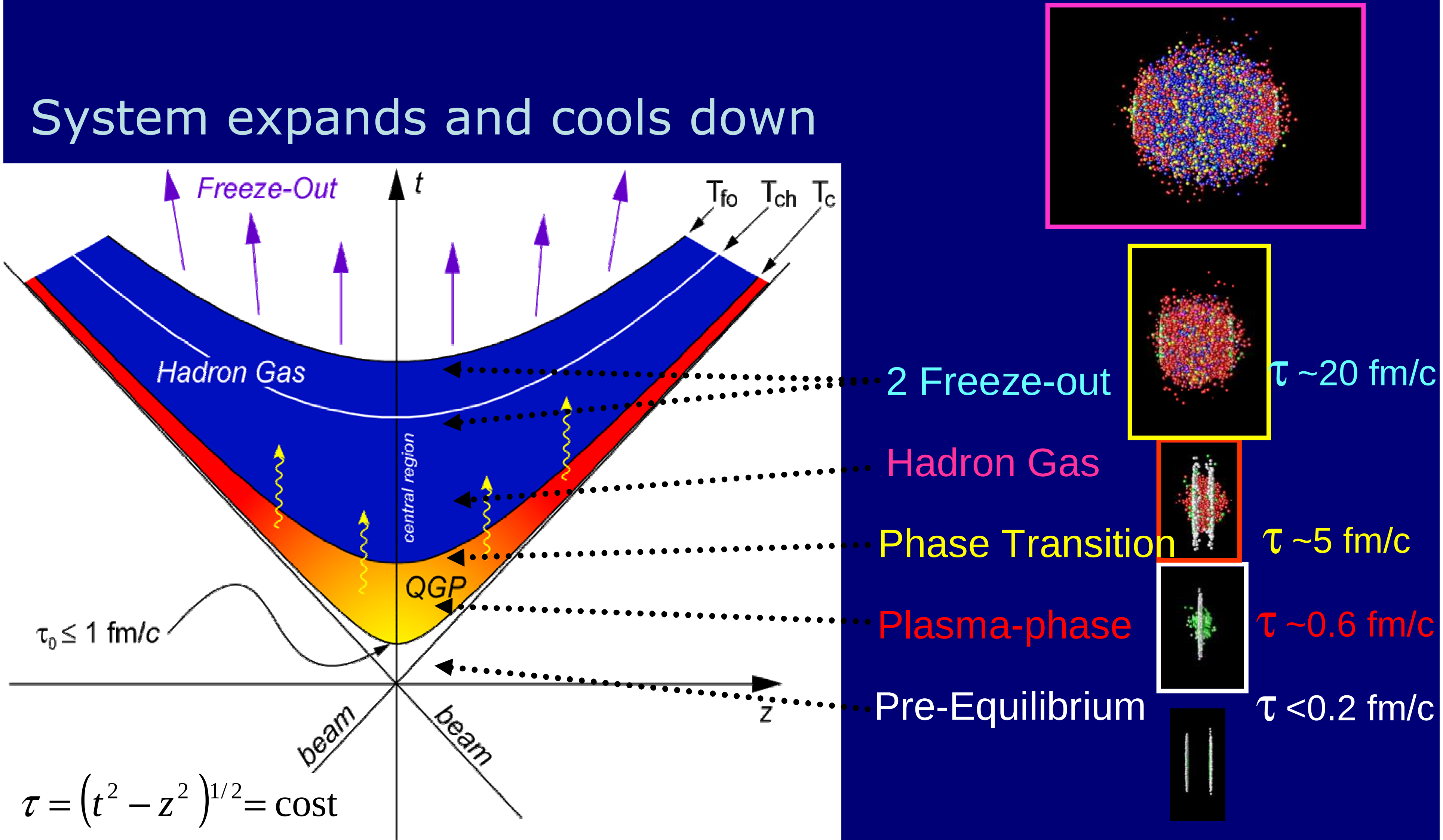
$\varepsilon_0 >> \varepsilon_c$

$\tau_{QGP} > 1$ fm/c

V> 10^3 fm^3

Different stages of the Little Bang

System expands and cools down



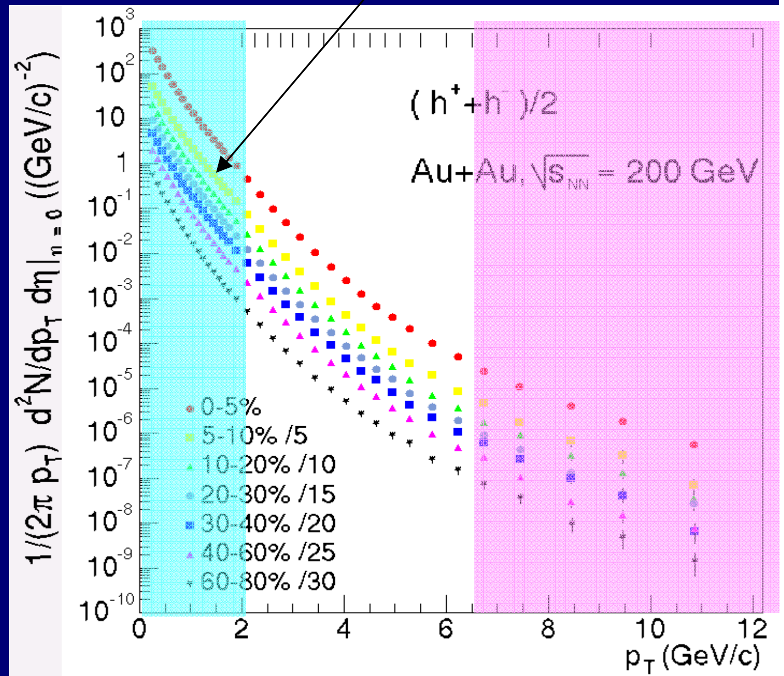
Soft and Hard probes

SOFT ($p_T \sim \Lambda_{QCD}$, T)

DRIVEN BY *NON PERTURBATIVE QCD*

Hadron yields, collective modes of the bulk, strangeness enhancement, fluctuations, thermal radiation, dilepton enhancement

95% of particles



HARD ($p_T \gg \Lambda_{QCD}$)

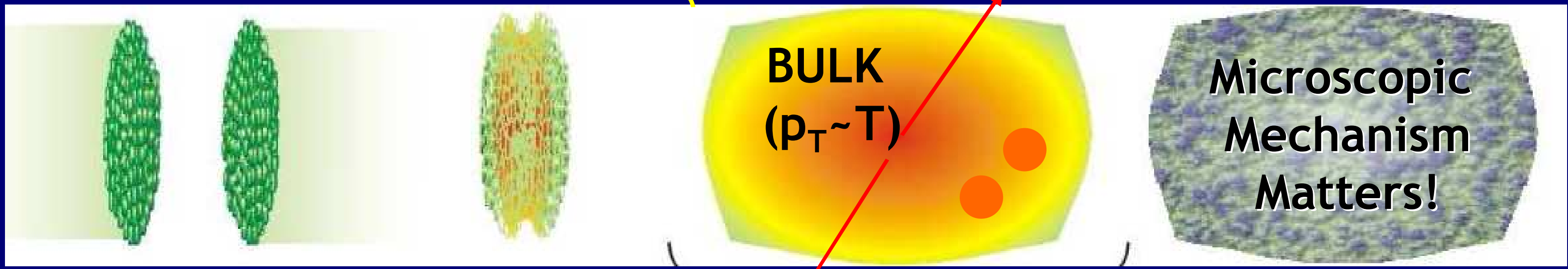
EARLY PRODUCTION, PQCD APPLICABLE, COMPARABLE WITH PP, PA

jet quenching, heavy quarks, quarkonia, hard photons

The Several Probes

[Romatschke], [Snellings],[Beraudo]

Initial Conditions Quark-Gluon Plasma Hadronization



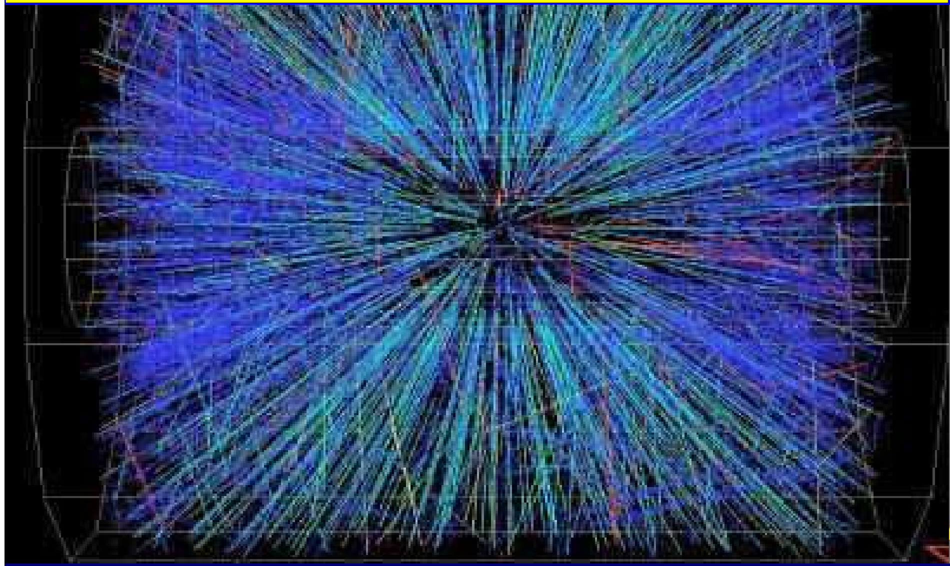
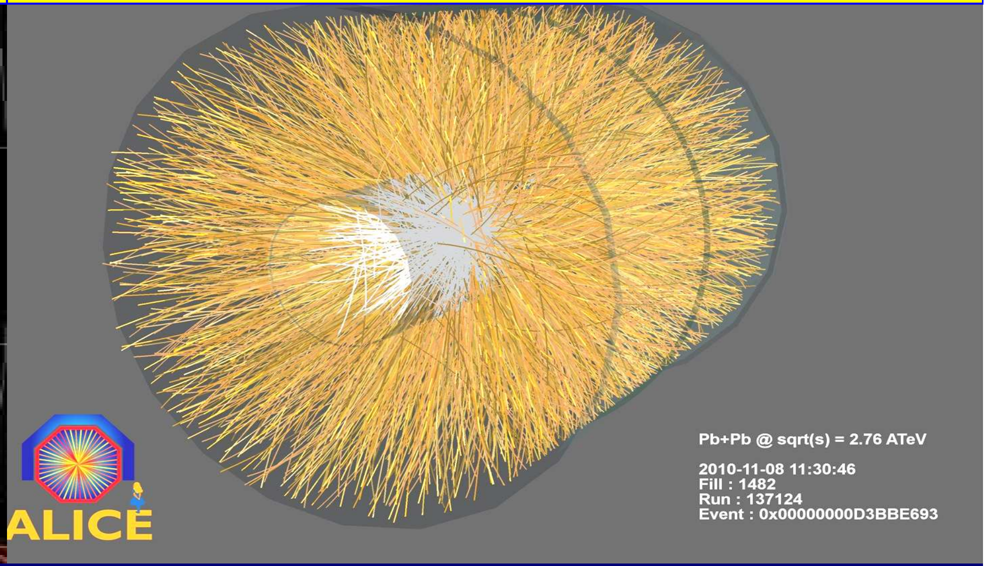
CGC (x<<1)
Gluon saturation
[Albacete]

MINIJETS
(p_T>>T,Λ_{QCD})
[Bruna]

Heavy Quarks
(m_q>>T,Λ_{QCD})
[Arnaldi]

[Becattini]
[Blume]

- **Initial Condition** – "exotic" non equilibrium CGC
- **Bulk** – Hydrodynamics *BUT* finite viscosities (η,ζ)
- **Minijets** – perturbative QCD *BUT* strong Jet-Bulk "talk"
- **Heavy Quarks** – Brownian motion (?) *BUT* strongly dragged by the Bulk
- **Quarkonia** – Are suppressed (only resonances?) or regenerated
- **Hadronization** – Microscopic mechanism can modify QGP observables

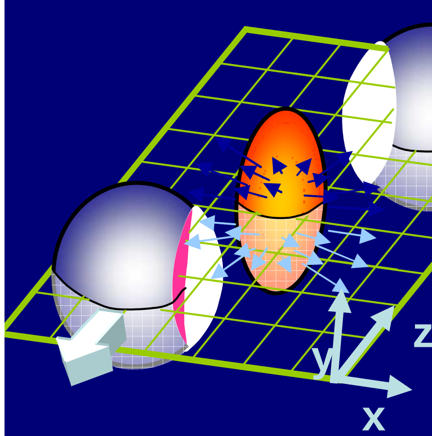
RHIC	LHC
	

- Dominance of QGP phase (τ_{QGP}> 10 fm/c)
  - Vanishing hadronic contamination?
- A n
  - L
- Ver
  - In
- Existence of a primordial non-equilibrium phase
  - Color Glass Condensate (CGC) as high-energy limit of QCD?

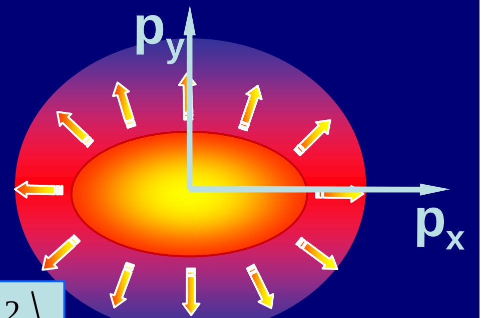
Hopefully with several other surprises…

Enjoy the School!

Collective Expansion of the Bulk



v_2/ε measures efficiency
in converting the eccentricity
from *Coordinate* to *Momentum space*



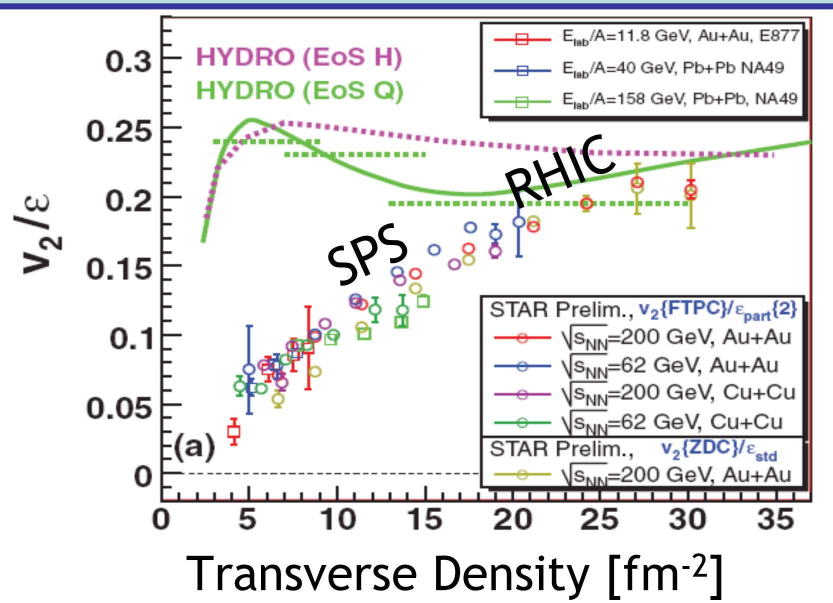
$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

η/s viscosity

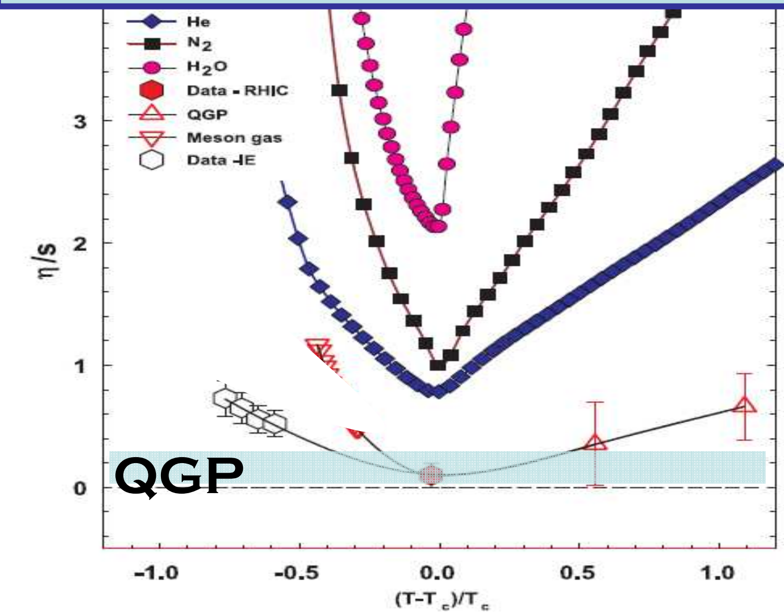
$c_s^2 = dP/d\varepsilon$ – EoS

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

For the first time close
to ideal Hydrodynamics

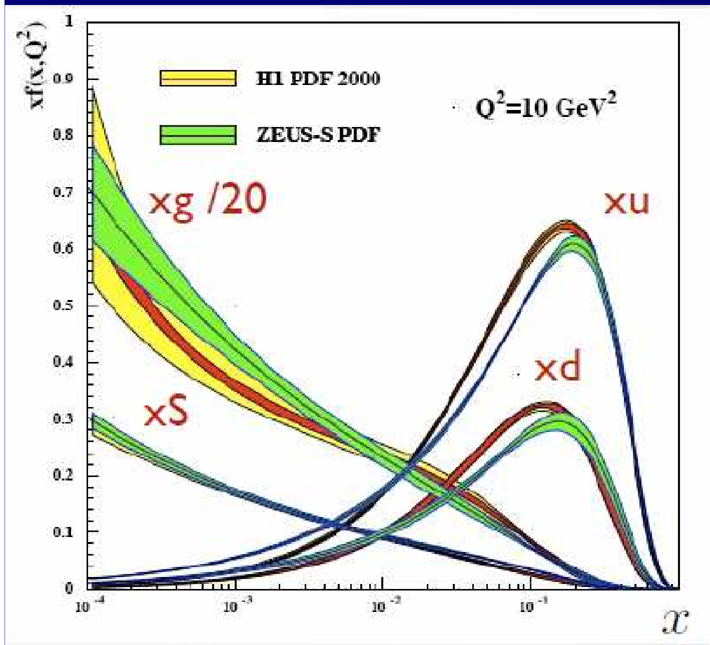


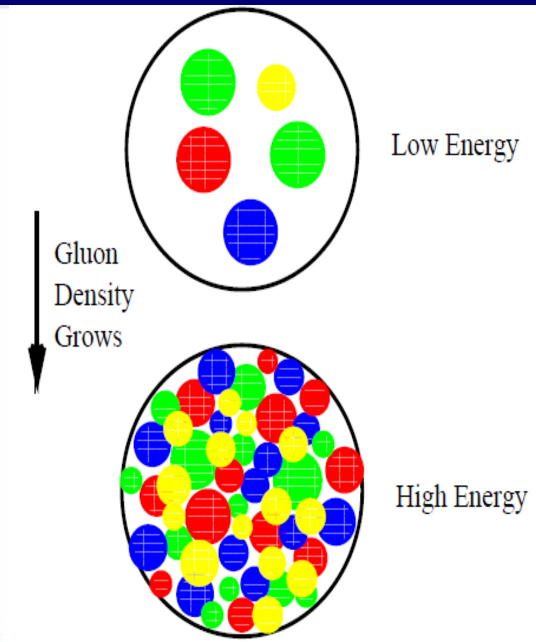
The fluid with lowest ever
observed η/s

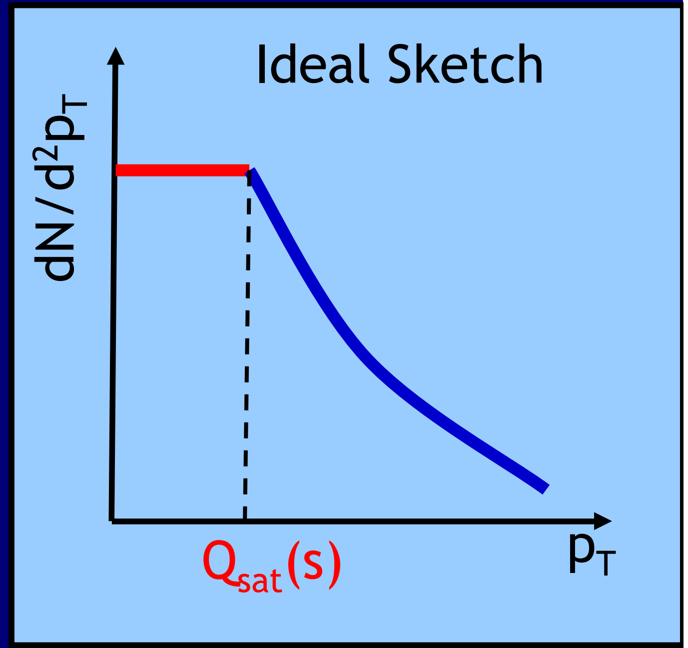


Color Glass Condensate initial conditions?

Parton distr. funct







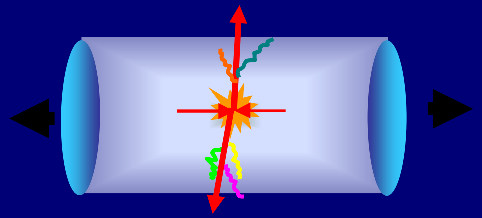
At small x (p_T) dense gluon matter
Gluons of small x (p_T) -> larger size >1/Q_s overlap
and the gluon dostribution stops growing

At RHIC Q^2 ~ 2 GeV^2
At LHC Q^2 ~ ?

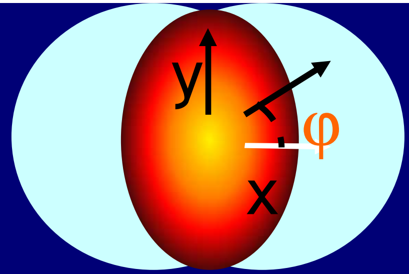
$$x = \frac{p_T}{\sqrt{s}} e^y$$

$$Q^2_{sat}(s) \propto \alpha_s(Q^2) \frac{xg(x,Q^2)}{\pi R^2} \propto A^{1/3}$$

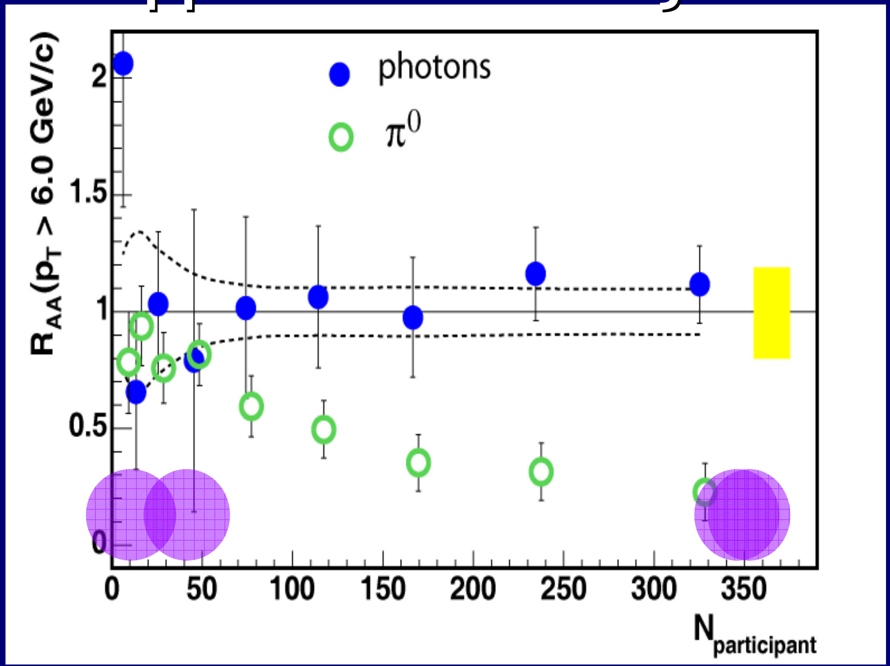
What is the impact
of a different intial condition?



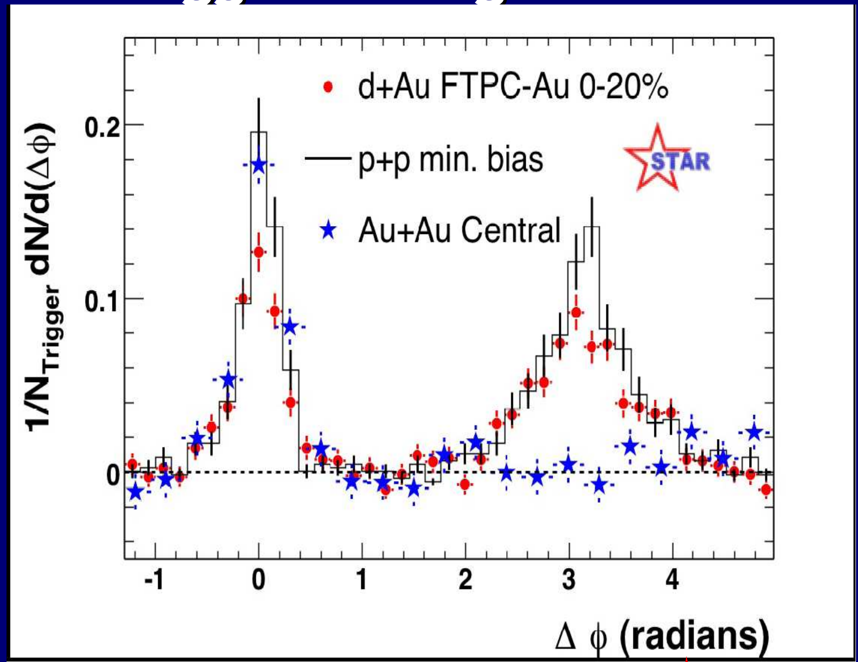
Jet Quenching



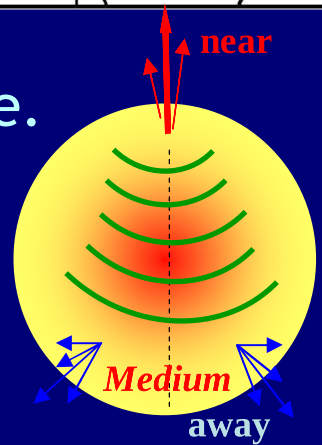
Suppression of minijets



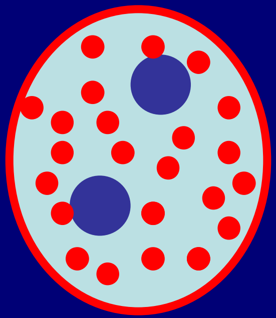
Jet triggered angular correl.



Suppression should increase with density and temperature.
Allows a further measure of energy density.
It is due to gluon radiation?
Jet energy loss produce mach cones?



Heavy Quarks dragged by the medium?



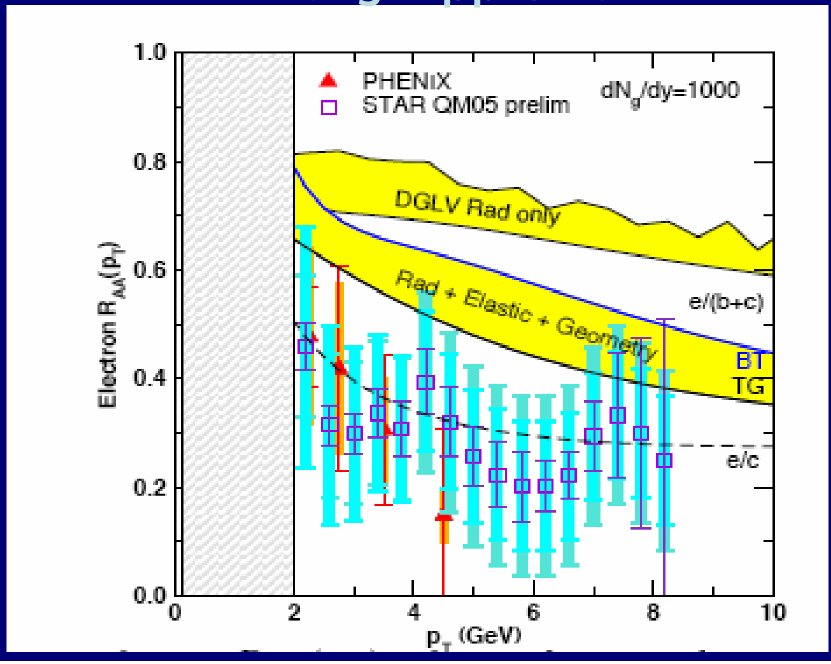
- $m_{c,b} >> \Lambda_{QCD}$ produced by pQCD processes (out of equil.)
- $\tau_0 << \tau_{QGP}$ they go through all the QGP lifetime
- $m_{c,b} >> T_0$ *no thermal production*

A better test of pQCD scattering and energy loss:

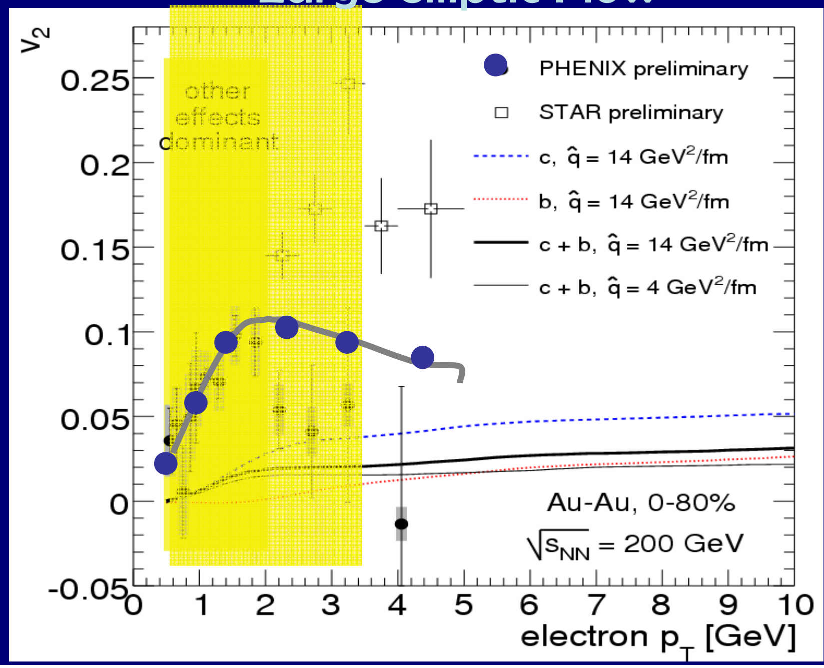
- $m_Q >> m_q$ small drag from the bulk

Indirect measurement from semileptonic decay (D->Keν) came as a surprise:

Strong suppression

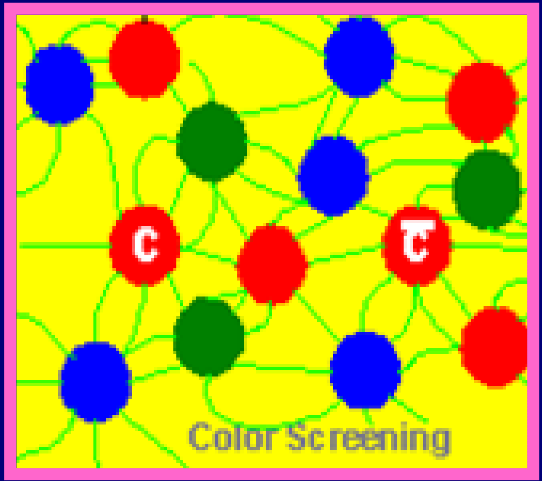


Large elliptic Flow



Quarkonia Suppression?

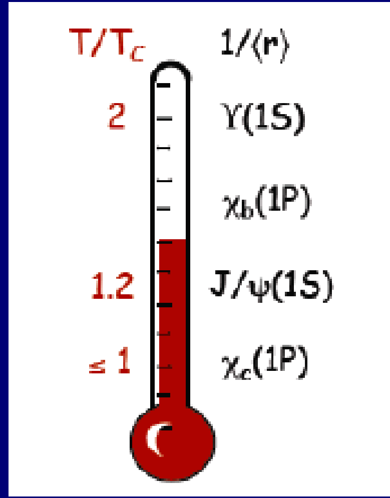
$Q\bar{Q}$ Quarkonium dissoved by charge screening: Thermometer



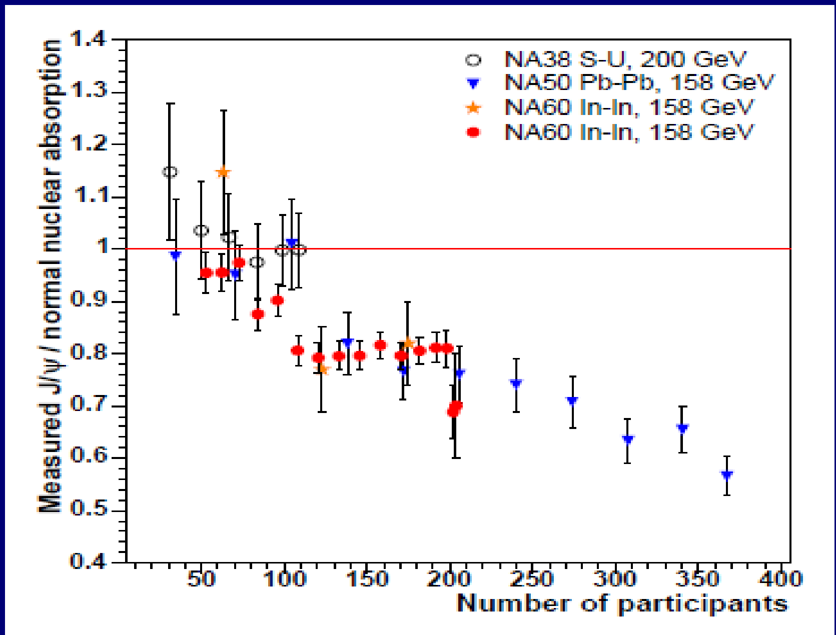
$$V \approx \quad -\alpha_{eff} \frac{e^{-m_D r}}{r}$$

$$r_{Q\bar{Q}} \approx \frac{1}{m_D} \approx \frac{1}{gT}$$

χ_c, J/Ψ, χ_b, Υ, ...



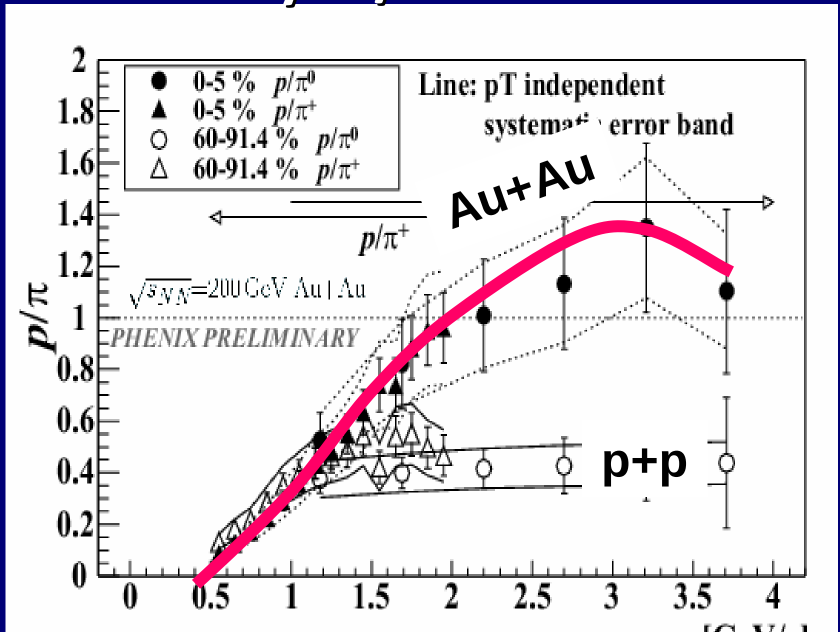
More binding smaller radius
higher temperature



Suppression at SPS!
More suppression at RHIC
because of high the higher temperature?!
and even more at LHC?

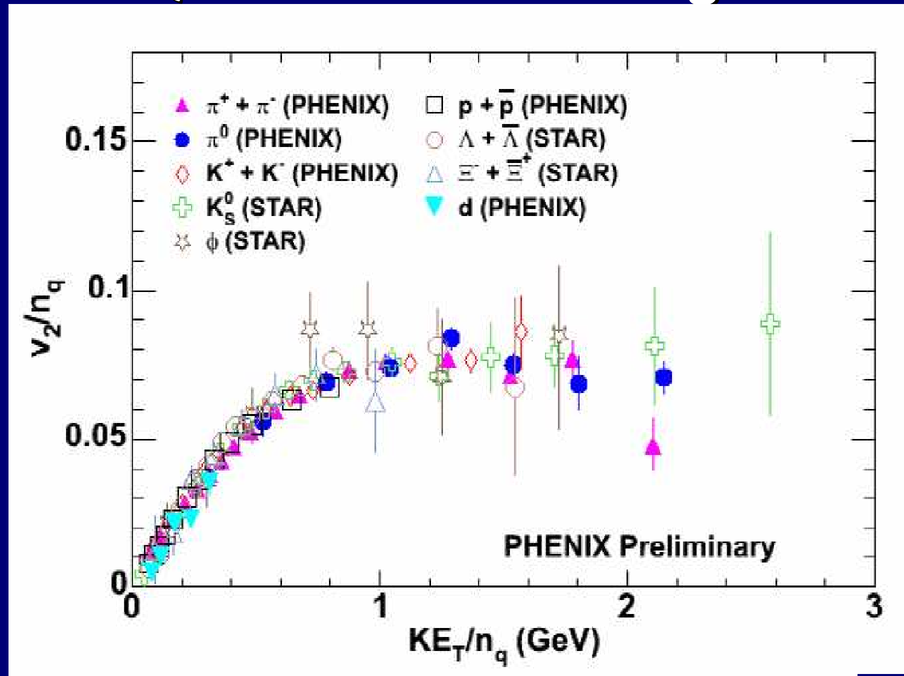
Hadronization Modified

Baryon/Mesons



PHENIX, PRL89(2003)

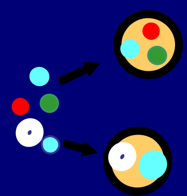
Quark number scaling



Use medium and not vacuum

-> Quark coalescence

More easy to produce baryons!



$$\frac{dN_M}{d^3P} = \sum_{a,b} f_a(r_a, p_a) \otimes f_b(r_b, p_b) \otimes \Phi_M(r_{ab}, q_{ab})$$

$$v_{2,M}(p_T/2) \quad v_{2,B}(p_T/3) \quad \boxed{\frac{1}{n} V_2\left(\frac{p_T}{n}\right)}$$

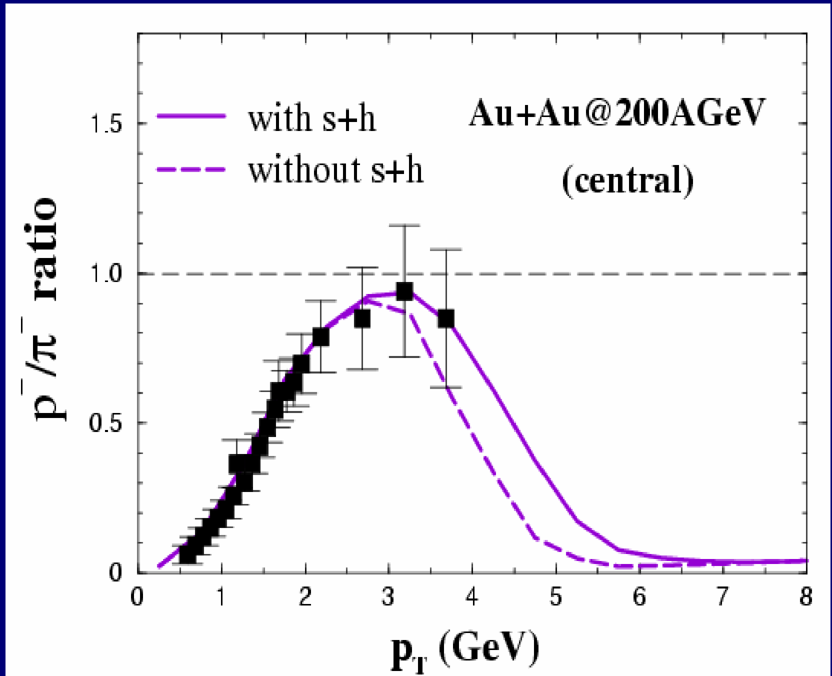
Hadronization is modified

Dynamical quarks are visible

Fries-Greco-Sorensen - Ann. Rev. Part. Sci. 58, 177 (2008)

Hadronization Modified

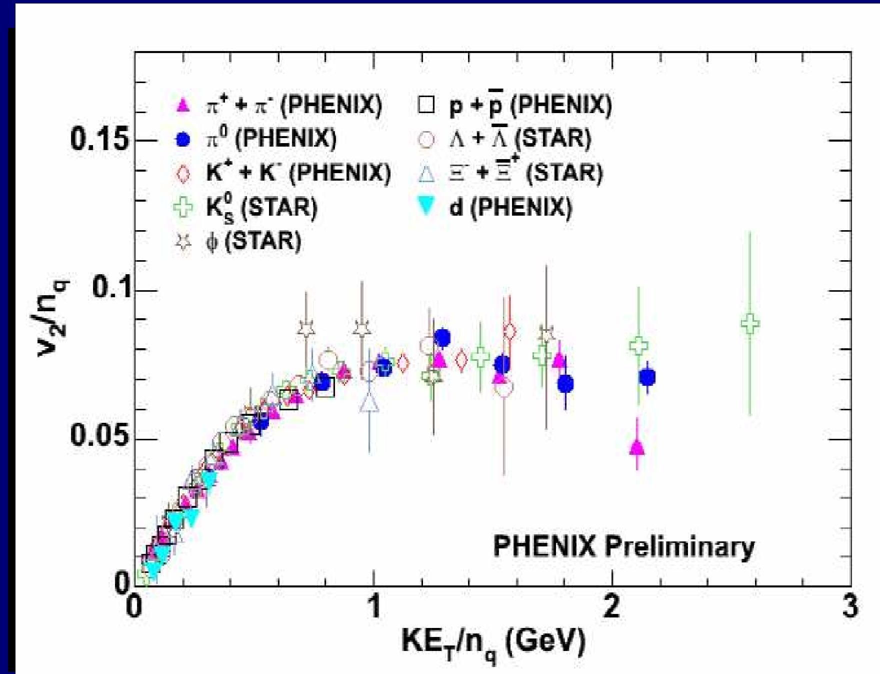
Baryon/Mesons



$$\frac{dN_q}{p_T dp_T d\varphi} = \frac{dN_q}{p_T dp_T}\left[1 + 2v_2 \cos(2\varphi)\right]$$

$$\frac{dN_H}{d^2 p_T}(p_T) \propto \left[\frac{dN_q}{d^2 p_T}(p_T/n)\right]^n$$

Quark number scaling



Coalescence scaling v_2

$$v_{2,M}(p_T) \approx 2v_{2,q}(p_T/2)$$
$$v_{2,B}(p_T) \approx 3v_{2,q}(p_T/3)$$

Dynamical quarks are visible
Collective flows