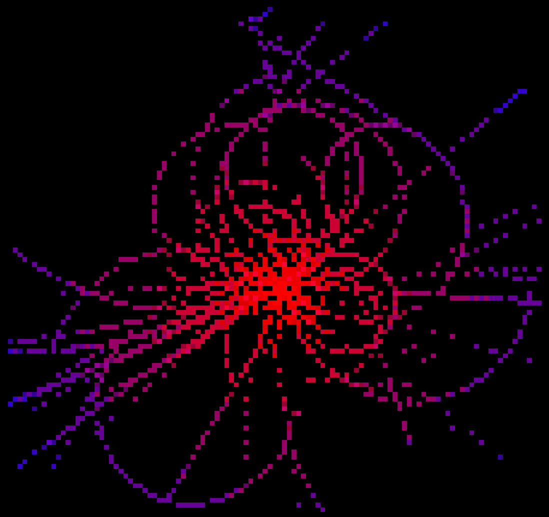
The hadronic yield from dynamical quark recombination



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A. Ayala, G. Paic, — ICN-UNAM

M. Martínez — Frankfurt

XIII Mexican School of Particles and Fields, San Carlos Sonora. 07/Oct/08.

Outline

■ Motivation

The strong interaction properties

New states of matter

■ Hadronization mechanism

Recombination, fragmentation

Dynamical hadron-quark transition

Variational Monte Carlo simulation

■ Applications

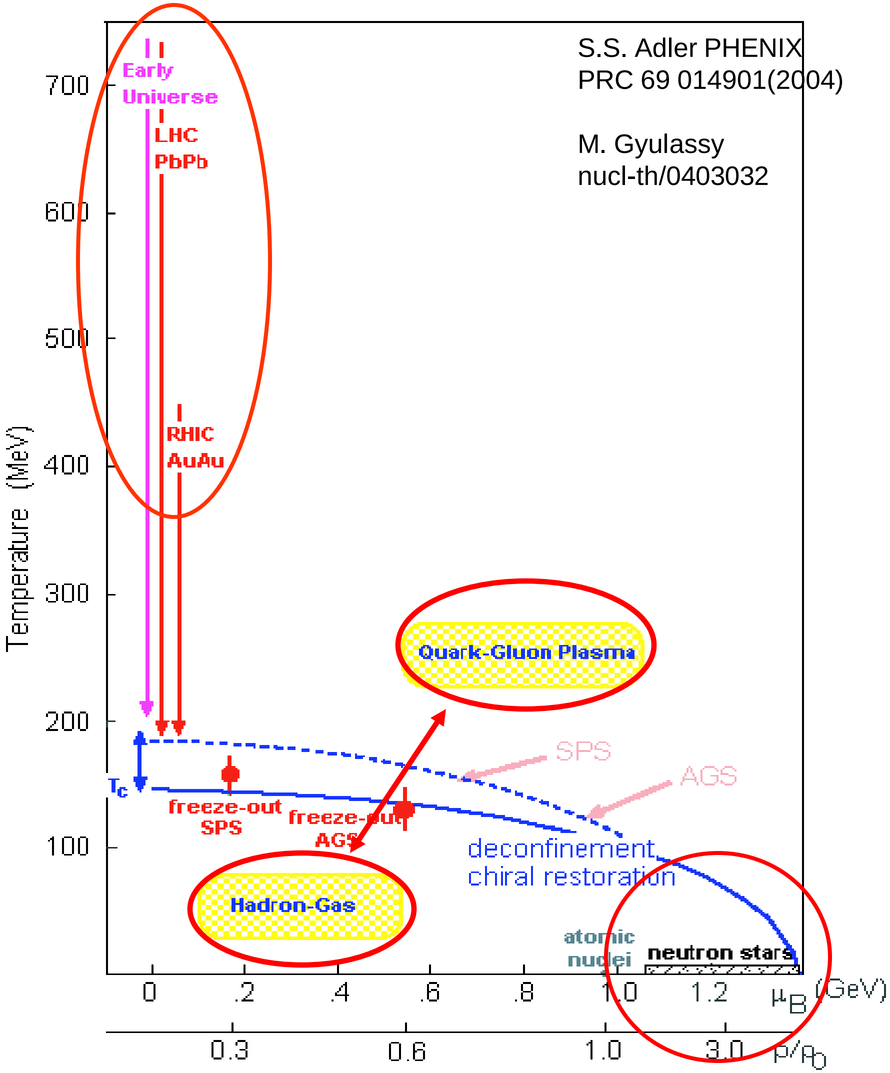
The transition to strange matter

Color screening of quark-antiquark states

Hadronization and the proton/pion ratio

Motivation

- High density and/or temperature
- u, d, s quarks
- New phases of matter
- Color screening of quark-antiquark states
- proton/pion ratio at RHIC



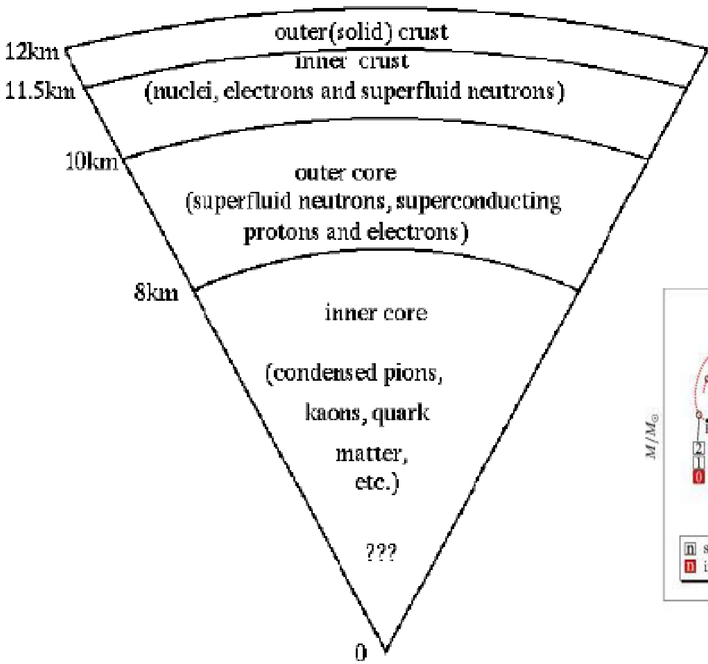
The search

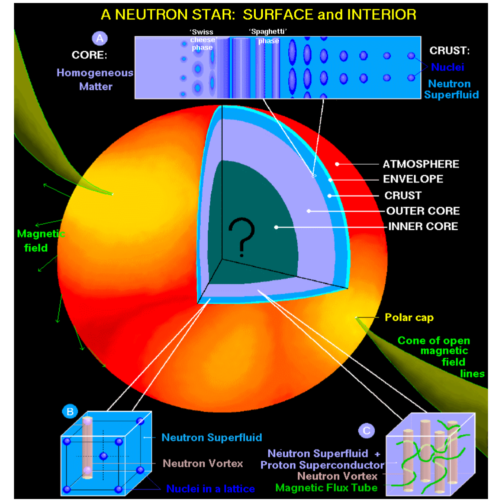
Neutron Stars

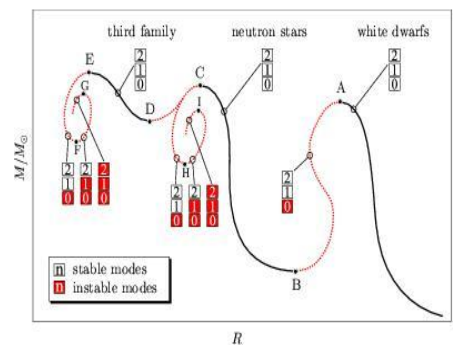
Relativistic Heavy Ion Collisions

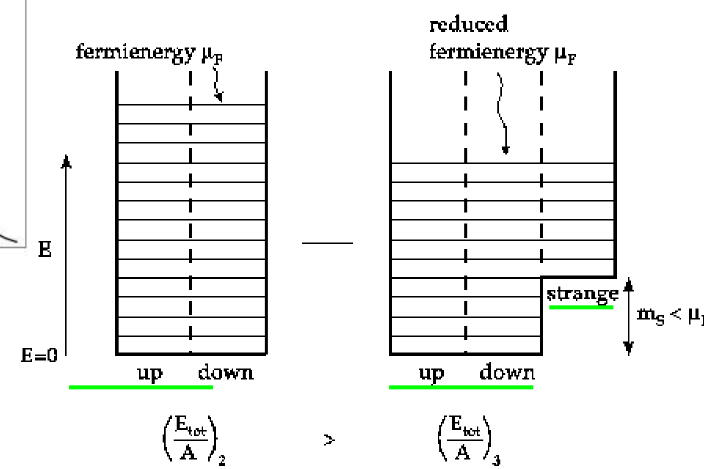
Matter at the core of stars *[Gerlach PR68, Glendenning AA00, Greiner NPA00]*

- Quark matter u, d
- Strange matter *[Witten PRD84]*, s
- *Pion Condensates*









Less stable More stable

They modify the properties of the star: Mass, radius, emission frequency,...

Candidates:…

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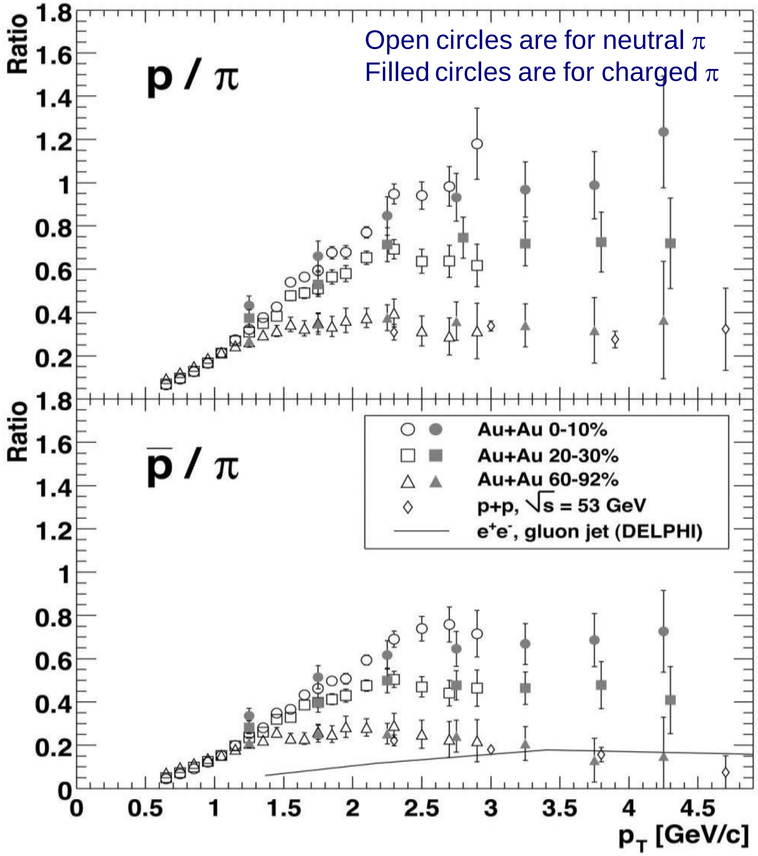
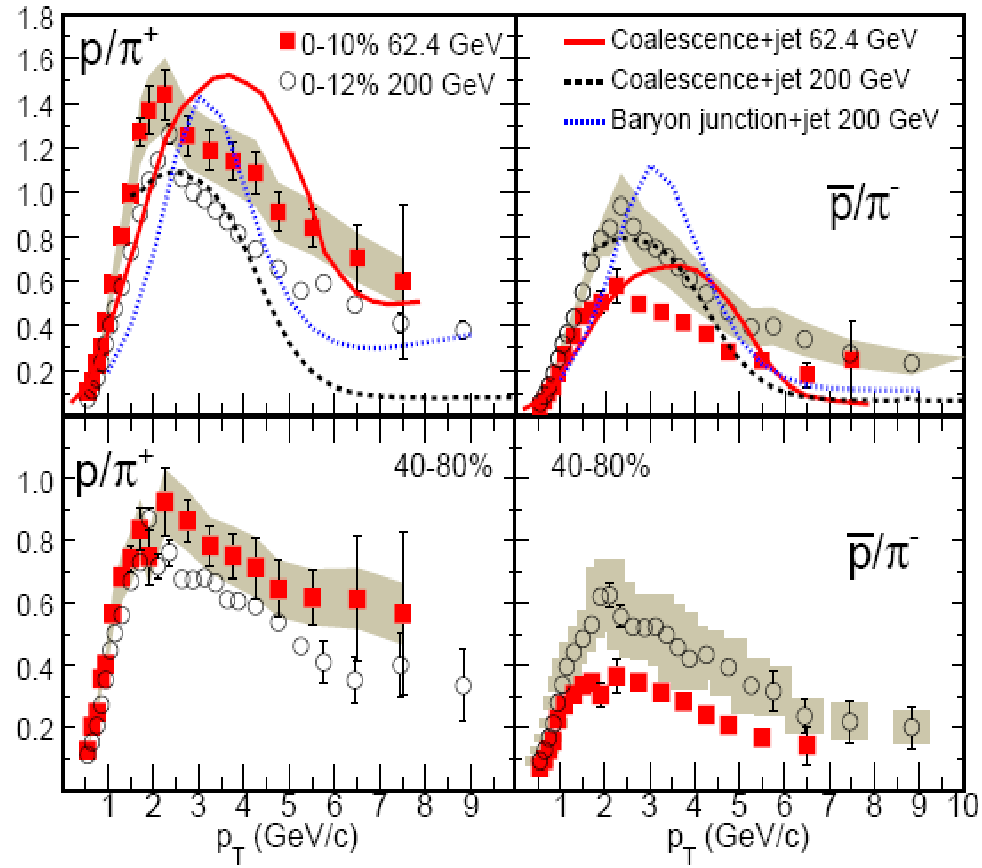
Proton to pion ratios from RHIC

PHENIX
Phys. Rev. C **69** 034909 (2004)



STAR
Phys.Lett.B655 104(2007)



For transverse momentum $p_t > 2$ GeV in Au+Au Collisions there is a large amount of baryons compared to mesons.

$$p_t=(\vec{p}^{\,2}-p_{||}^2)^{1/2}$$

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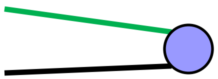
HADRONIZATION MECHANISM

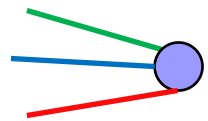
We can obtain information about the observed spectrum considering two mechanism: fragmentation and recombination of quarks.

In the **recombination** picture, 3 quarks or quark/antiquark pairs in a densely populated phase space can form a baryon or a meson, respectively.

$$q\bar{q} \rightarrow M$$



$$qqq \rightarrow B$$

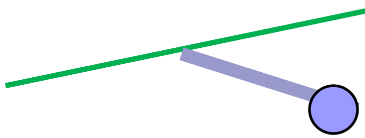


$$E\frac{dN_h}{d^3P} \propto \int_{\Sigma_f} d\sigma \frac{P\cdot u(r)}{(2\pi)^3} f(r,p,\tau)$$

In the **fragmentation** picture, the single parton spectrum is convoluted with a probability

$D_{i\rightarrow h}(z)$

of a parton *i* to hadronize into a hadron *h*, which carries a fraction z < 1 of the momentum of the parent parton.



$$E\frac{dN_h}{d^3P} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3}\int_0^1 \frac{dz}{z^2}\sum_\alpha w_\alpha(R,\tfrac{1}{z}P)D_{\alpha\to h}(z)$$

If hadrons were created by fragmenting partons, it would be easier to produce mesons than baryons!

Static Recombination + Fragmentation in RHIC
Basic assumptions:

- At low p_t, the quark and antiquark spectra are thermal. These *recombine* into hadrons locally "instantaneously":

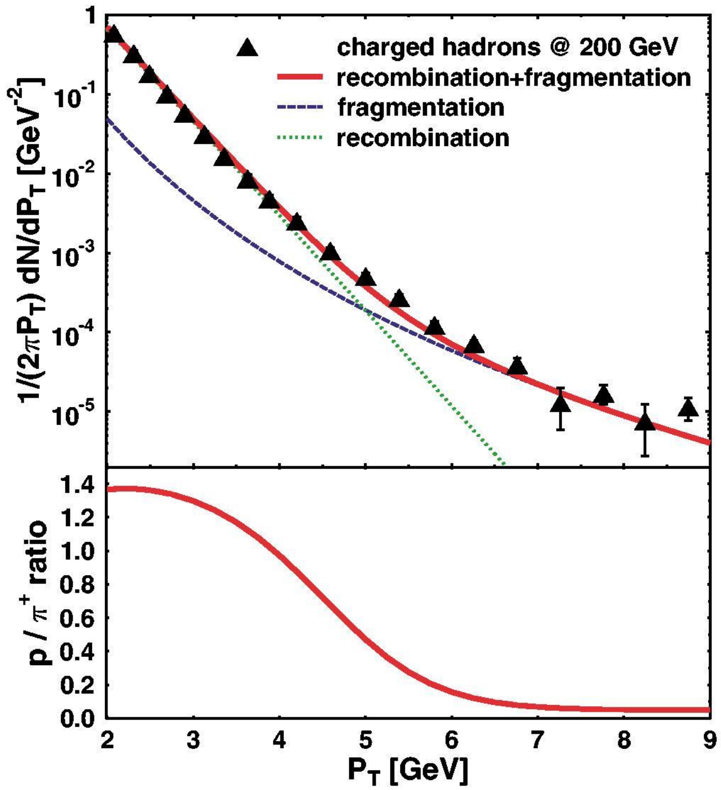
At intermediate p_t baryon to meson ratio depends only on degeneracy factors

$$\frac{dN_B^R}{dN_M^R} = \frac{C_B}{C_M} \sim 2,$$

- At high p_t, the parton spectrum is given by a pQCD power law, partons suffer jet energy loss and hadrons are formed via *fragmentation* of quarks and gluons

At low Pt, for an exponential quark spectrum, fragmentation is always suppressed with respect recombination.

At large Pt, when the spectrum is a power law, parton fragmentation wins over quark recombination.



R. F. Fries, B. Müller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003).

Modifications to the recombination model

Greco, Ko, and Levai: Add coalescence of parton minijets and thermal partons.

Hwa and Yang: Consider the effects from minijets and thermal soft partons in the thermal spectrum.

Recombination Model provides a quantitative scenario for hadron production. Difficulties:

- The hadronization process is instantaneous.
- There are not interactions among particles in the medium.

We propose to use the *String-flip model* to introduce the QCD-like dynamics of the interaction among particles.

The string-flip model

Horowitz, Moniz, Negele 80's

- Quarks as degrees of freedom
- Colors: red, blue, green
- Flavors: Up, Down

Property	**The model**
Confinement	Yes
Cluster separability	Yes
Gauge invariance, SU(3)	No
Exchange symmetry	Yes
Lorentz invariance and $q\bar{q}$ production	No
Low density limit (isolated hadrons)	Yes
High density limit (free Fermi gas of quarks)	Yes

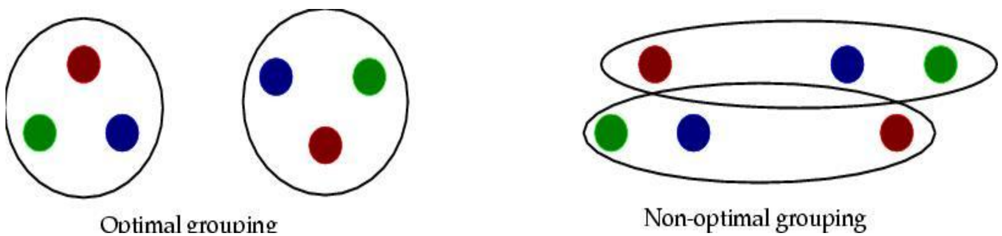
Selects the configuration with minimal energy of the system formed by bound quarks.

The quarks interact by a harmonic confining potential and form color singlet clusters.

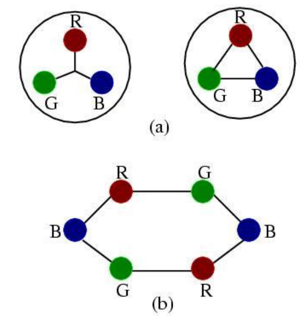
The inclusion of interactions between the quarks provides a dynamical picture of the system evolution from low to high energy density.

Many-body potential

- Gluon flux tubes producing a minimal configuration of the system.



- Color combinations to built singlets.



Increasing size clustering

Optimal two-colors pairing potential

Ex. red and blue quarks

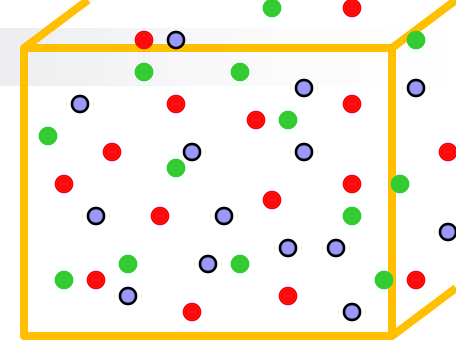
(Similar for color-anticolor)

$$
\begin{aligned}
V_{RB} &= \min_{P} \sum_{i=1}^{A} v(\mathbf{r}_{iR}, P(\mathbf{r}_{iB})) \\
&= \min_{P} \sum_{i=1}^{A} \frac{1}{2} k(\mathbf{r}_{iR} - \mathbf{r}_{jB})^2
\end{aligned}
$$

$$V_{baryon} = V_{RB} + V_{RG} + V_{GB}$$

$$V_{meson} = V_{RR} + V_{GG} + V_{BB}$$

Variational wave function



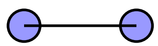
$$\Psi = e^{-\lambda V}\Phi_{FG}$$

Slater determinant

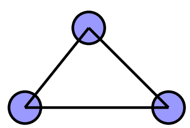
Variational parameter

Low density limit:

Definite predictions for baryons and mesons energy and variational parameter by solving the 2 and 3 body states bound by a harmonic potential



$$\frac{E_2}{2} - m = \sqrt{3} \qquad \lambda_3 = \frac{1}{\sqrt{3}}$$



$$\frac{E_3}{3} - m = \frac{3}{2\sqrt{2}} \qquad \lambda_2 = \frac{1}{\sqrt{2}}$$

High density limit: Gas of quarks

$$\lambda \longrightarrow 0 \qquad \Psi \approx \Phi_{FG}$$

Monte Carlo Simulation

$$\mathbf{E}(\lambda) = \mathbf{T_{FG}} + 2\lambda^2 < \mathbf{W} >_\lambda + < \mathbf{V} >_\lambda$$

$$\left(\frac{\partial E(\lambda)}{\partial \lambda}\right)_{\rho,\sigma} = 0$$

Kinetic E. of N-quarks gas. $W=\sum (x_n - y_n)^2/m$, Interaction induced term Potential energy

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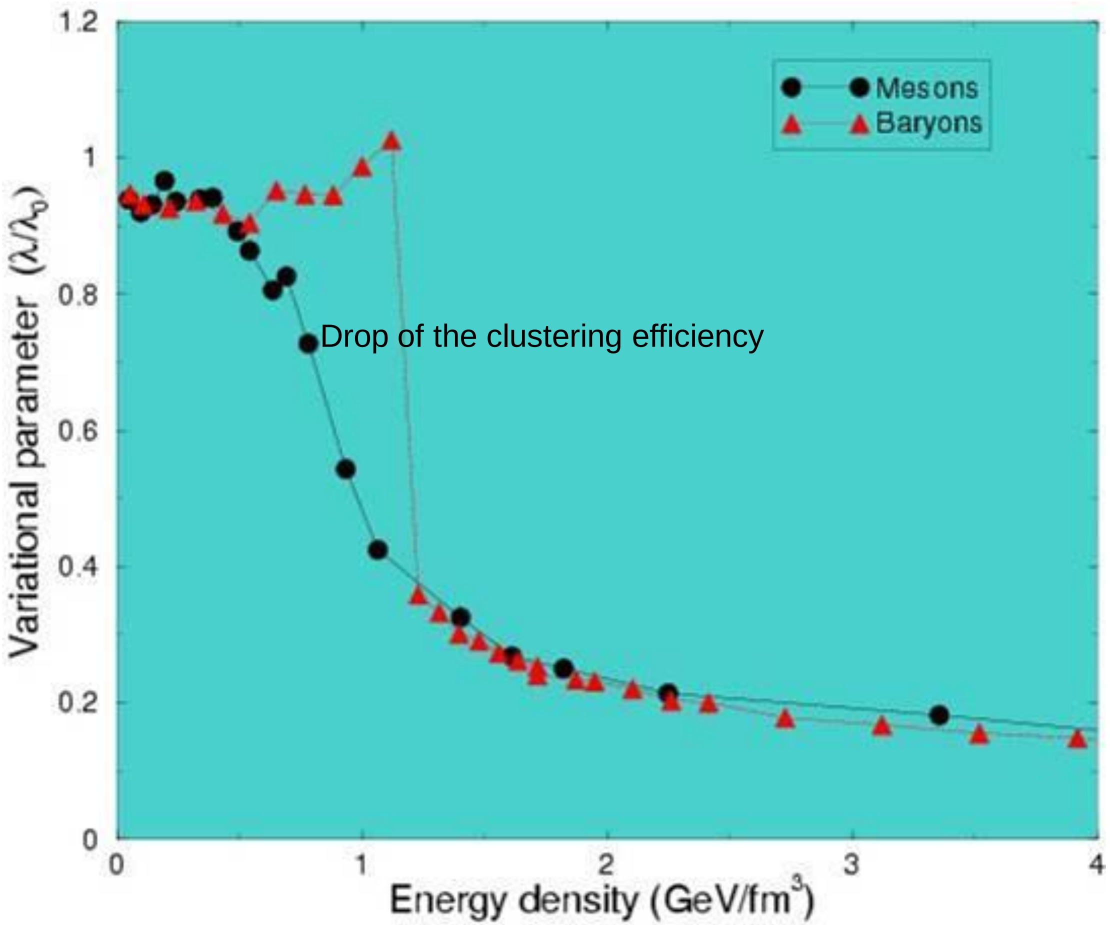
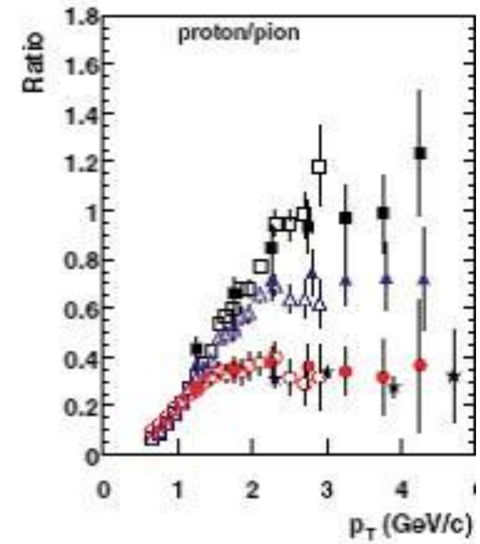
Variational Parameter evolution from the string-flip model





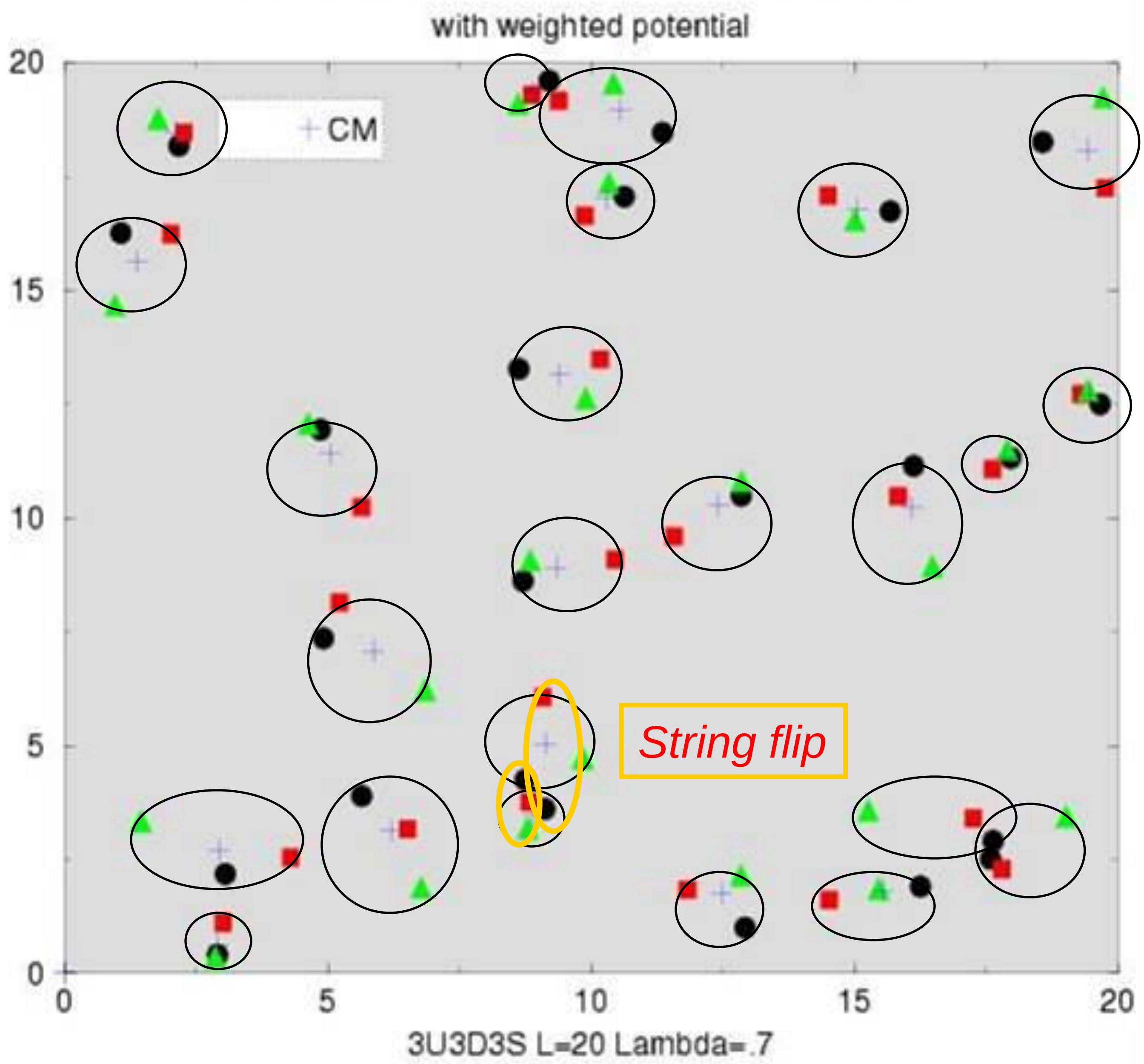
Proton/pion ratio
PHENIX Coll PRL 91 172301(03)

$$\Psi = e^{-\lambda V}\Phi_{FG}$$

$$V_{baryon} = V_{RB} + V_{RG} + V_{GB}$$

$$V_{meson} = V_{RR} + V_{GG} + V_{BB}$$

CLUSTERING AT LOW DENSITY



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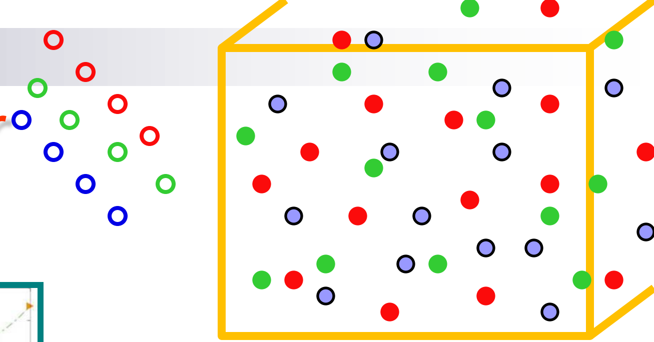
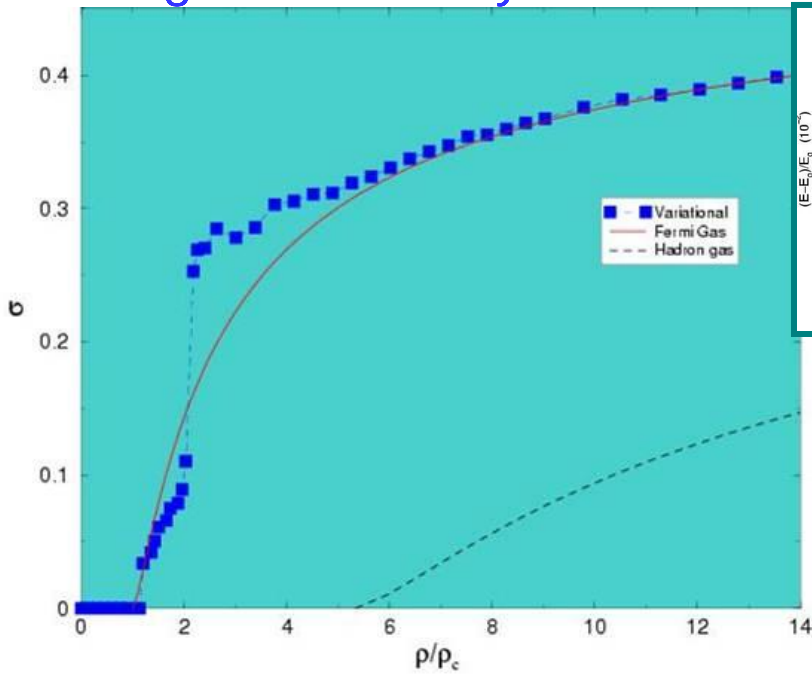
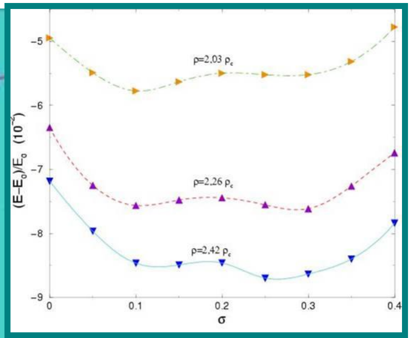
Transition to strange matter



G. Toledo and J. Piekarewicz, PRC 65 045208(02)

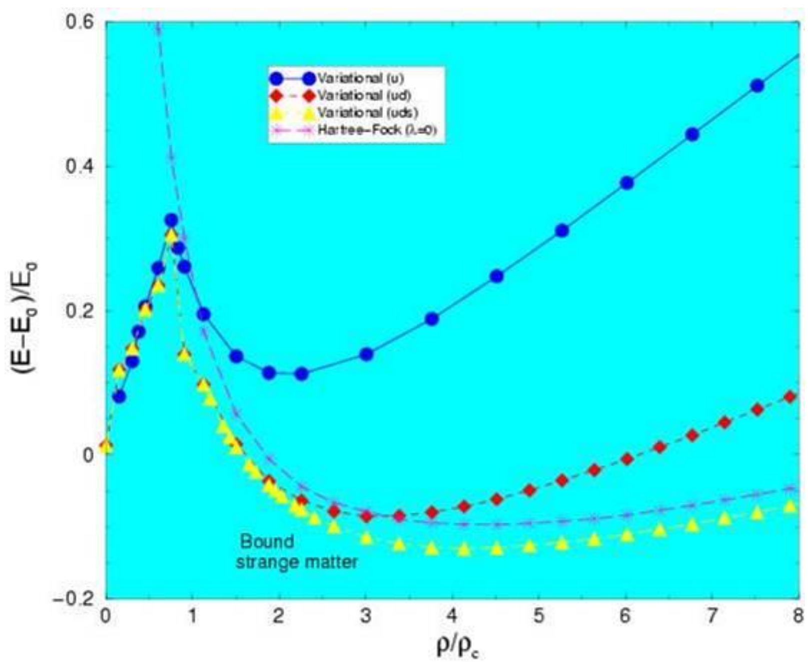
Strangeness-density relation





Compiting minima

Energy-density relation



$$N = N_u + N_d + N_s \qquad \sigma \equiv \frac{N_s}{N} \qquad \frac{\partial E}{\partial \sigma} = 0$$

- In the model, discontinuous,
- Interaction efects are important

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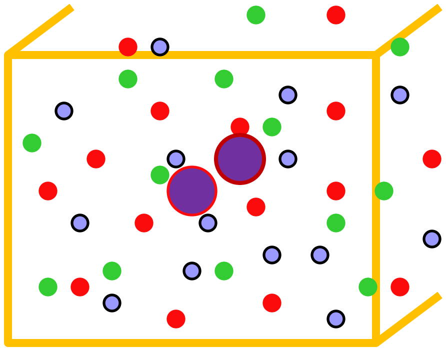
Color screening

G. Toledo & J. Piekarewicz PRC 70, 3526(04)

Matsui and H. Satz Suppresion PLB 178, 416(86)
J. Rafelski et al Enhancement by recombination PRC 63, 054905(01)

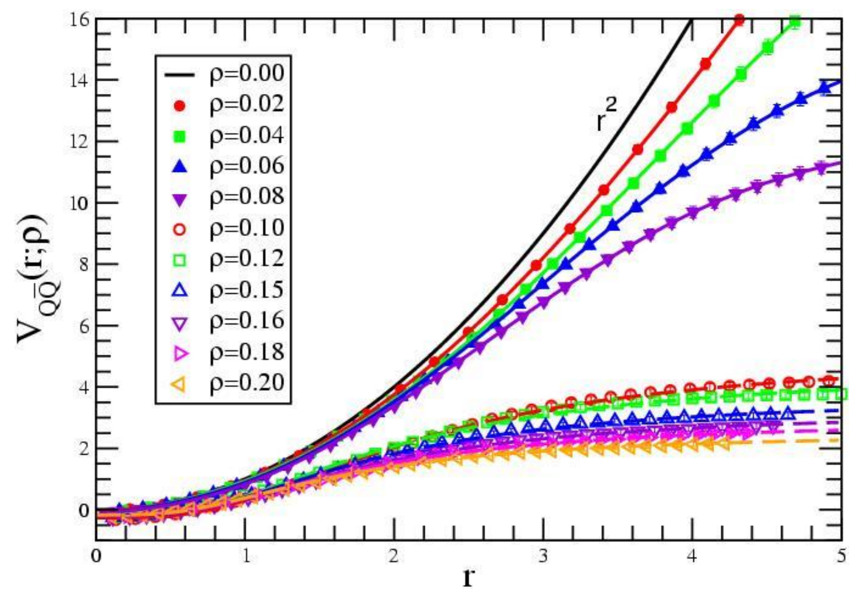


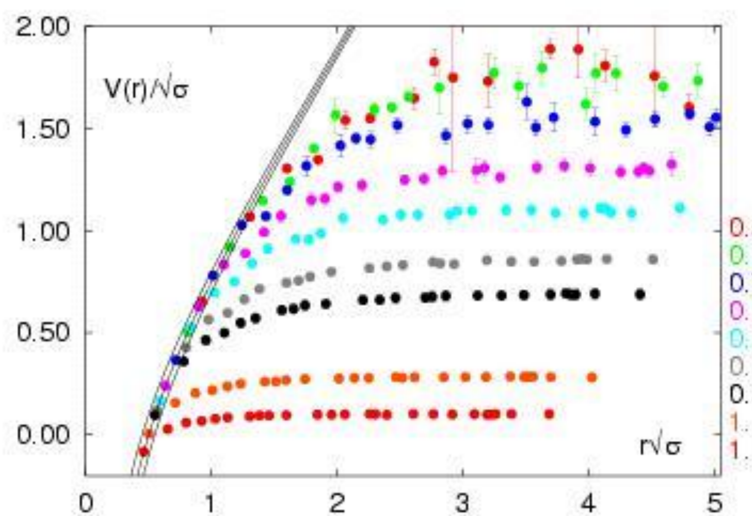
We can compute the potential of a heavy-quark pair by the change on the system potential energy due to their appearence at a relative distance r

$$V_{QQ}(r)=\langle V\rangle_{A+1}(r) - \langle V\rangle_{A}$$

- Heavy-quark pair (j/psi) in the medium at relative distance r
- Light quarks configuration fixed.
- Potential change due to the medium.

quark-antiquark potential at zero temperature and finite baryon density





Lattice QCD result at finite temperature and zero baryon density F. Karsch Nucl. Phys B (2001), hep-lat/0312037

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Solving the Schroedinger eqn. for the quark-antiquark potential

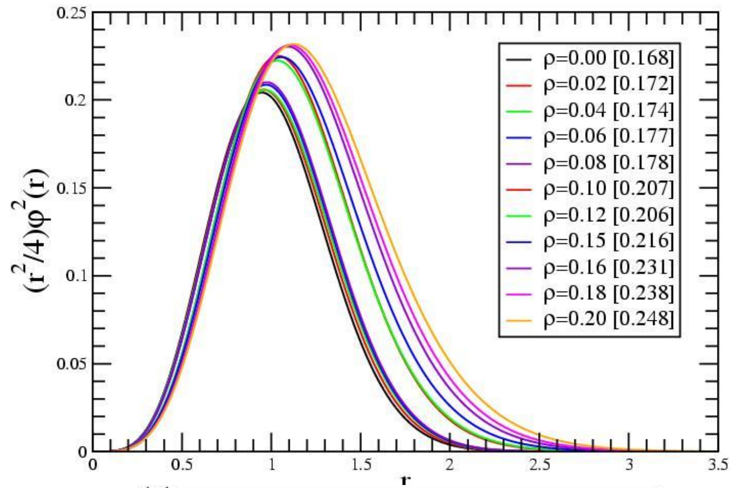
$\Phi_{j/\psi}(r) = \varphi(r)/r\,|\chi_c\chi_c>$

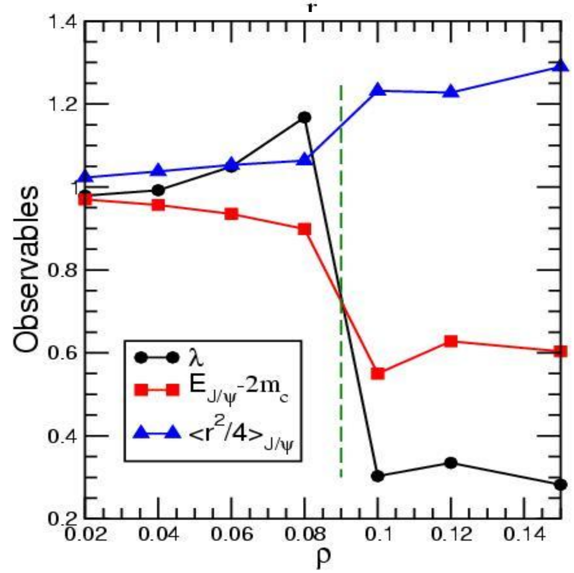
In the isolated case

$E_{j/\psi} = 2m_c + 3(4k/m_c)^{1/2}/2$

$r^2_{j/\psi} = 3/8(km_c)^{1/2}$

Ground state density weighted by $r^2/4$ for a set of medium densities





We compute the **bound state energy** (red line) and the **mean squared radius** (blue line).

Strongly linked to the phase transition (black line)

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Observations

- Hadronic matter modeled in terms of quarks
- Dynamical interpolation between hadronic and quark matter
- Strange quarks abundance is sensitive to the approach
- Transition influenced by the interaction
- Screening of heavy quarks and wf correlate with the transition

Proton to pion ratio from dynamical recombination in RHIC

PRC 77 044901(08), A. Ayala, M. Martínez, G. Paic, G. Toledo

Recombination Model provides a quantitative scenario for hadron production in thermal medium. Difficulties:

• The hadronization process is instantaneous.

• There are not interactions among particles in the medium.

We propose an alternative model in which:

- the dynamical evolution of the system with collision energy density is considered
- hadronization is not instantaneous and that accounts for properties of hadrons during freezeout

Dynamical recombination with finite hadronization time

In the hydrodynamic description of the relativistic heavy ion collisions, we can relate the thermodynamical variables of the system to the proper time.
The particle spectrum can be set with a degeneracy factor given in the recombination model:

$$E\frac{dN_h}{d^3P} = \int_{\tau_0}^{\tau_F} d\tau P(\tau) \int_{\Sigma_f} d\sigma \frac{P \cdot u(r)}{(2\pi)^3} f(r,p,\tau)$$

- Incorporate probability of forming a given hadron with proper time from an initial evolution

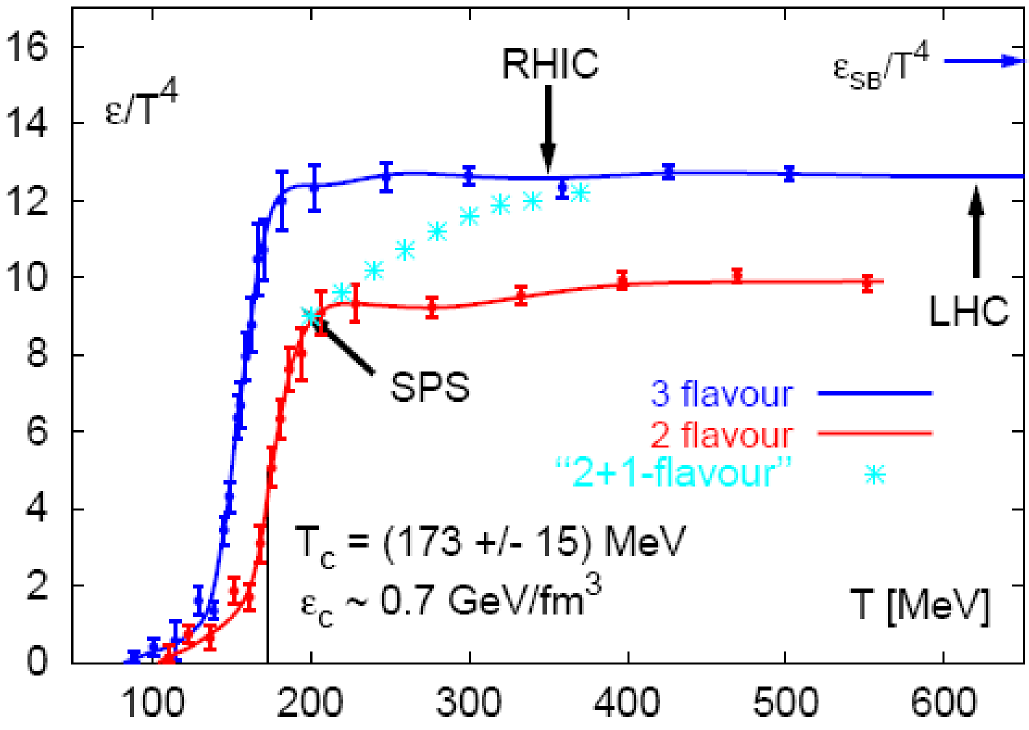
$$F(x,P) = e^{-P\cdot v(x)/T}\mathcal{P}(\epsilon)$$

- **To obtain the profile of P(τ) ≈ P(ε), we relay on the Monte Carlo Simulation using the *String Flip Model.***

The function P(τ) gives the information about the evolution of the system with proper time and accounts for a hadronization process which is not instantaneous but that occurs over a proper time interval.

Time – Energy density Relationship via the temperature

Finite interval in temperature for phase transition from Lattice QCD.



F. Karsch et al. PLB478,447(00)
Lect. Notes in Phys. 583, 209(02)

Can be parameterized by

$$\epsilon/T^4 = a\left[1+\tanh\left(\frac{T-T_c}{bT_c}\right)\right]$$

$$T = T_0\left(\frac{\tau_0}{\tau}\right)^{v_s^2}$$

a=4.82 and b=0.132

critical temperature T_c = 175 MeV,
speed of sound v_s =1/3,
consider different initial times
keep final temperature close to
T=100-120 MeV.

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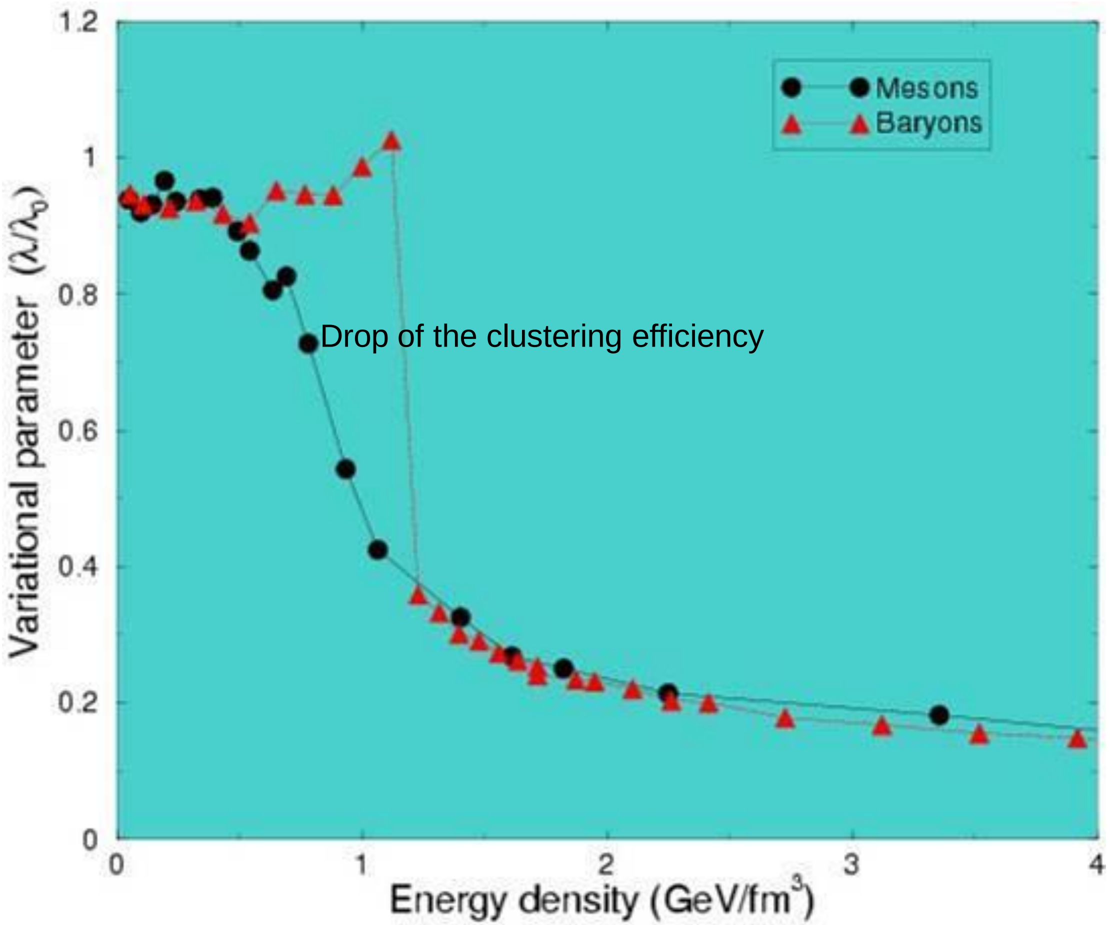
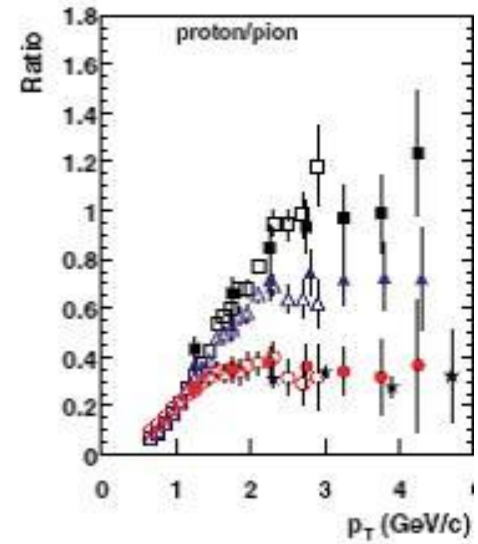
Variational Parameter evolution from the string-flip model





Proton/pion ratio
PHENIX Coll PRL 91 172301(03)

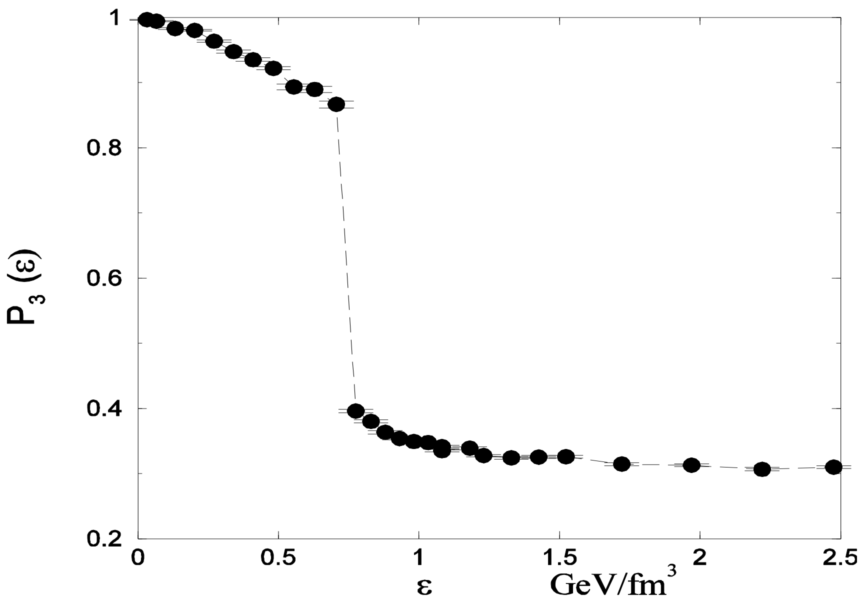
$$\Psi = e^{-\lambda V}\Phi_{FG}$$

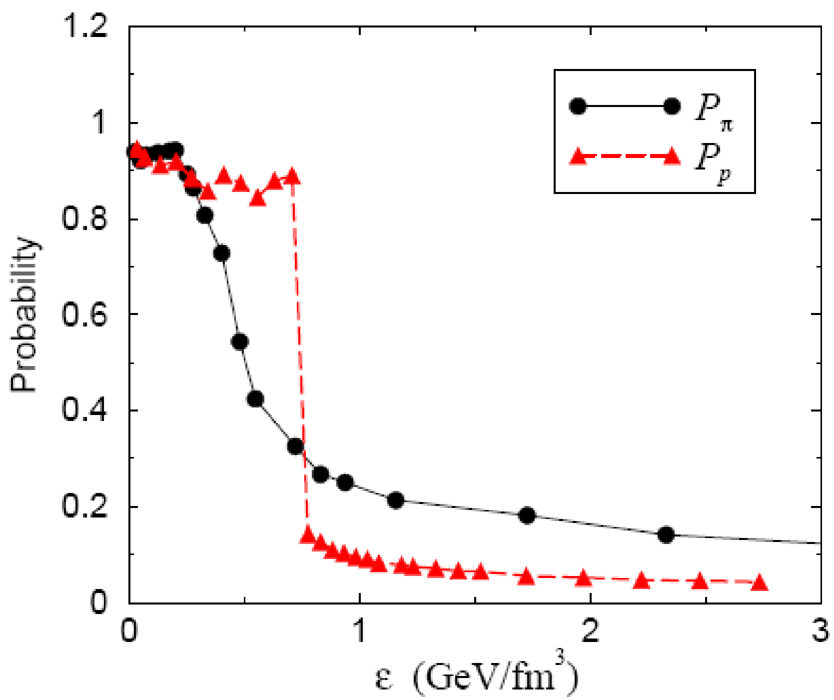
$V_{baryon} = V_{RB} + V_{RG} + V_{GB}$

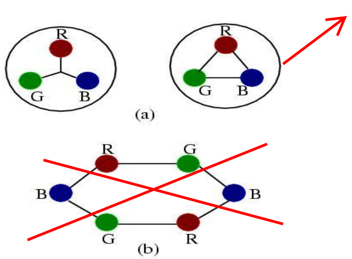
$V_{meson} = V_{RR} + V_{GG} + V_{BB}$

Percentage of clusters of 3 quarks as a function of energy density

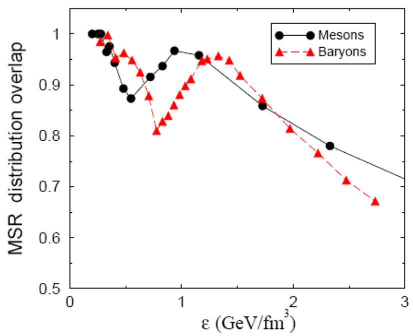
Probability $P(\varepsilon)=\lambda \times P_3$



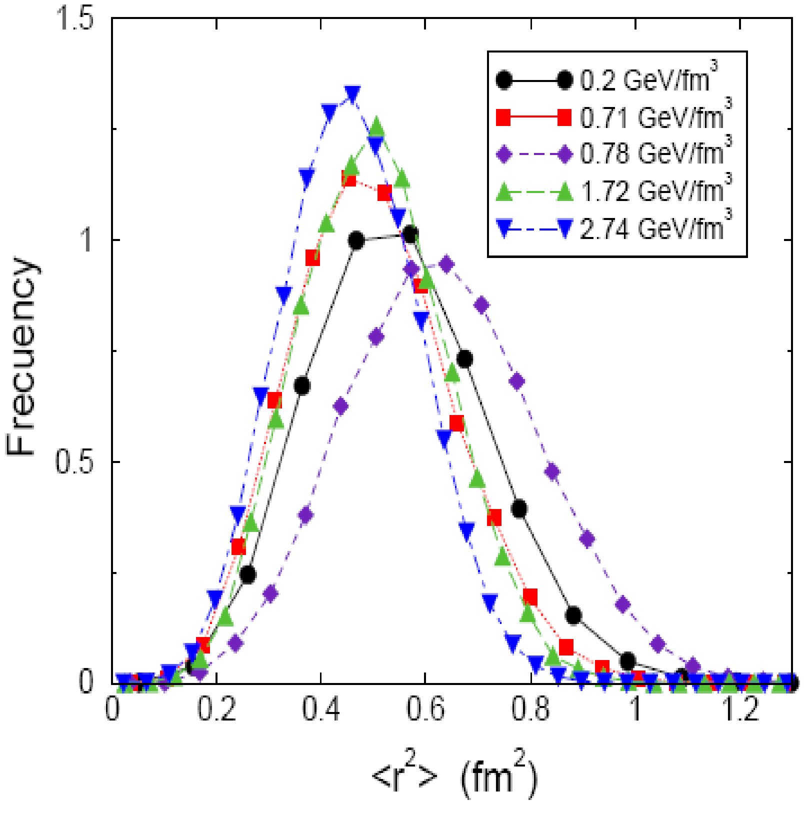




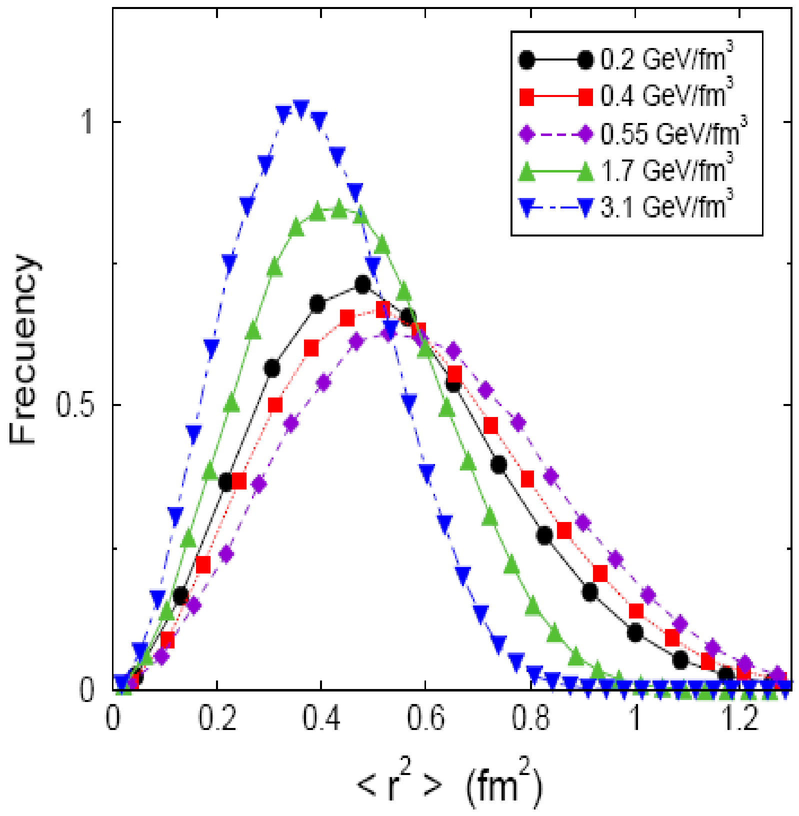
Hadron spatial distribution



Baryon



Meson



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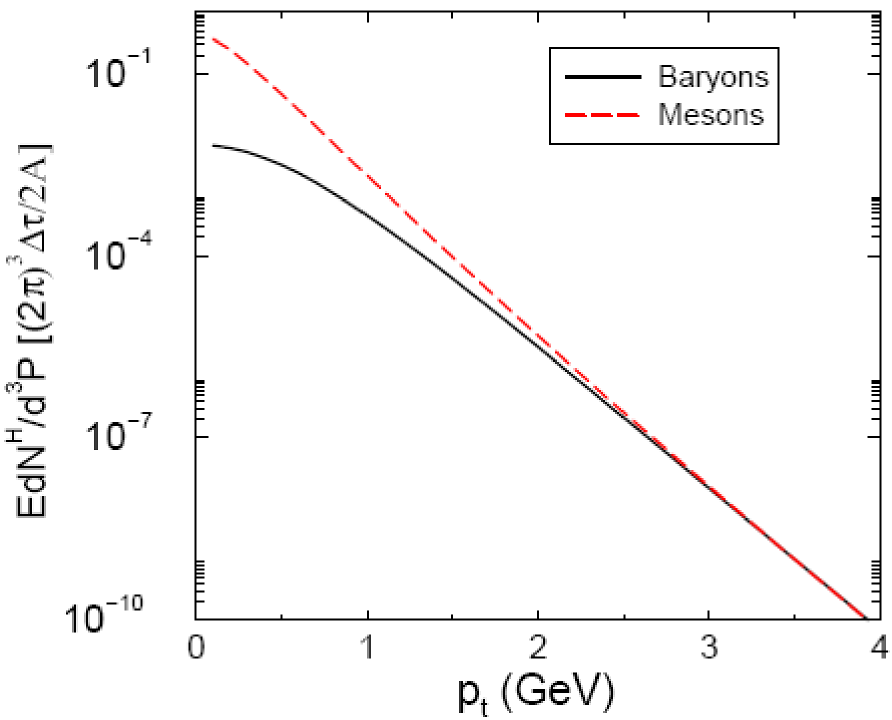
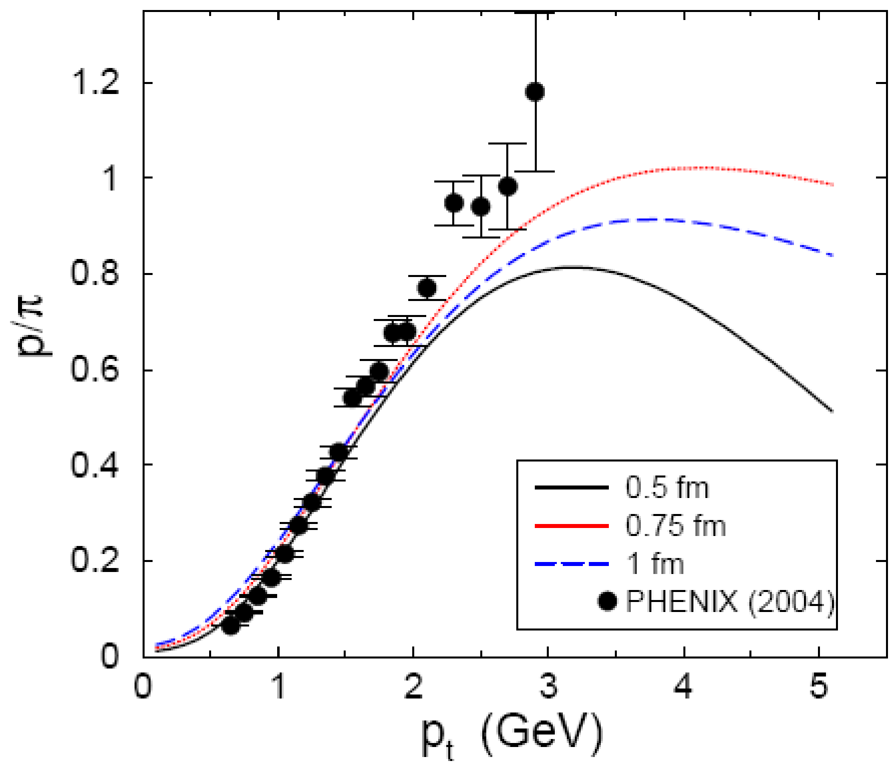
Final answer in terms of hadron properties

$$E\frac{dN_h}{d^3P} = \int_{\tau_0}^{\tau_F} d\tau P(\tau) \int_{\Sigma_f} d\sigma \frac{P \cdot u(r)}{(2\pi)^3} f(r,p,\tau)$$

Momentum distributions

p/π ratio prediction





Several initial evolution times

and same final freeze-out τ_f =3.5fm

Summary

- Hadronic matter modeled in terms of quarks
- Dynamical interpolation between hadronic and quark matter
- We computed the hadron production as a function of the energy density
- Transition influenced by the interaction
- Radius, baryon fraction, correlation function, correlate with the transition.
- Substantial differences are found between the meson and baryon hadronization, which may explain the observation of the proton/pion ratios.

Thanks !!