Parton matter
in the early stage of
ultrarelativistic heavy ion collisions

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Project: "Quarks, Hadrons and High Energy Collisions"

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Project: "Quarks, Hadrons and High Energy Collisions"

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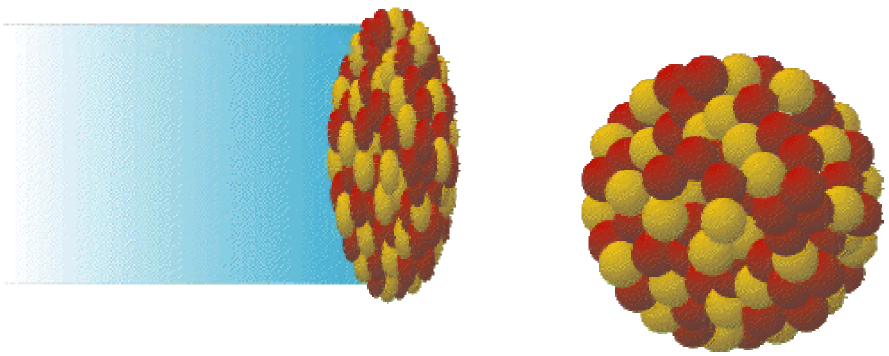
Relativistic heavy ion collisions: 1980-2000



BEVALAC E(lab) = 1 GeV/A

↓

CERN SPS E(lab) = 158 GeV/A

Q: How strong is the stopping ??

A: Strong stopping !!!

Lots of particle in midrapidity !

↓

Hidrodynamical description
(thermodynamical equil.)

↓

EOS for nuclear matter
(EOS for neutron stars)

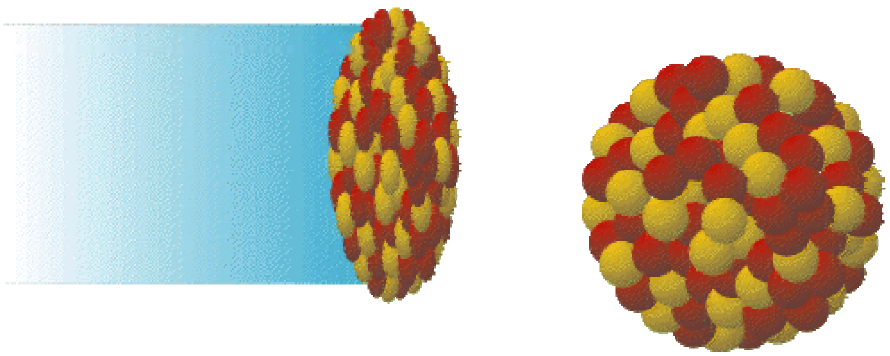
⇨ **Strongly interacting nuclear matter + fireball formation**

Only one problem: p + p ⇔ Au + Au

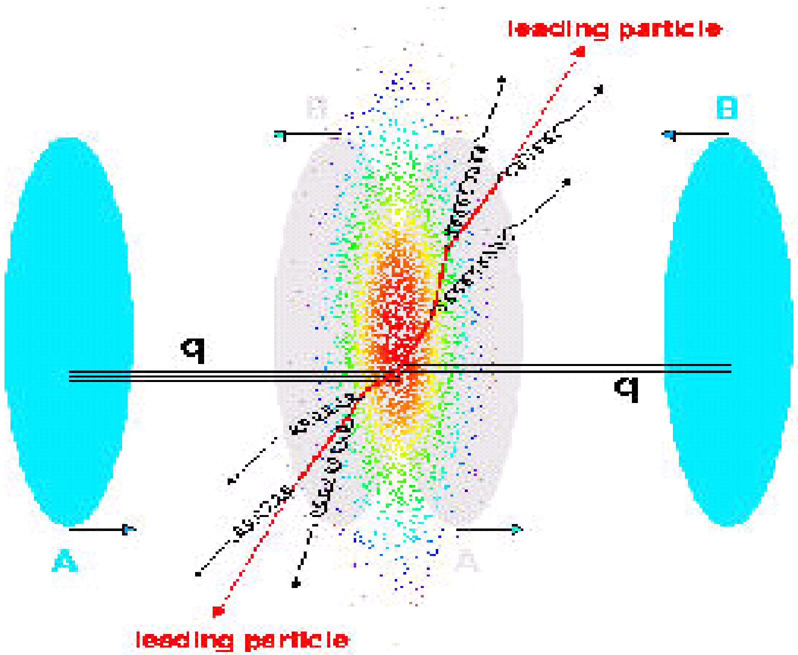
A1: string ↔ string-melting

A2: val quark ↔ quark matter ➔ **Soft physics**

<u>Relativistic heavy ion collisions</u> ($\sqrt{s}$=20-200 AGeV)



Collision of two extended objects consist of protons and neutrons.



Release of
subnuclear
degrees of freedom

↓

Quarks and gluons
with high energies ← **Jets**

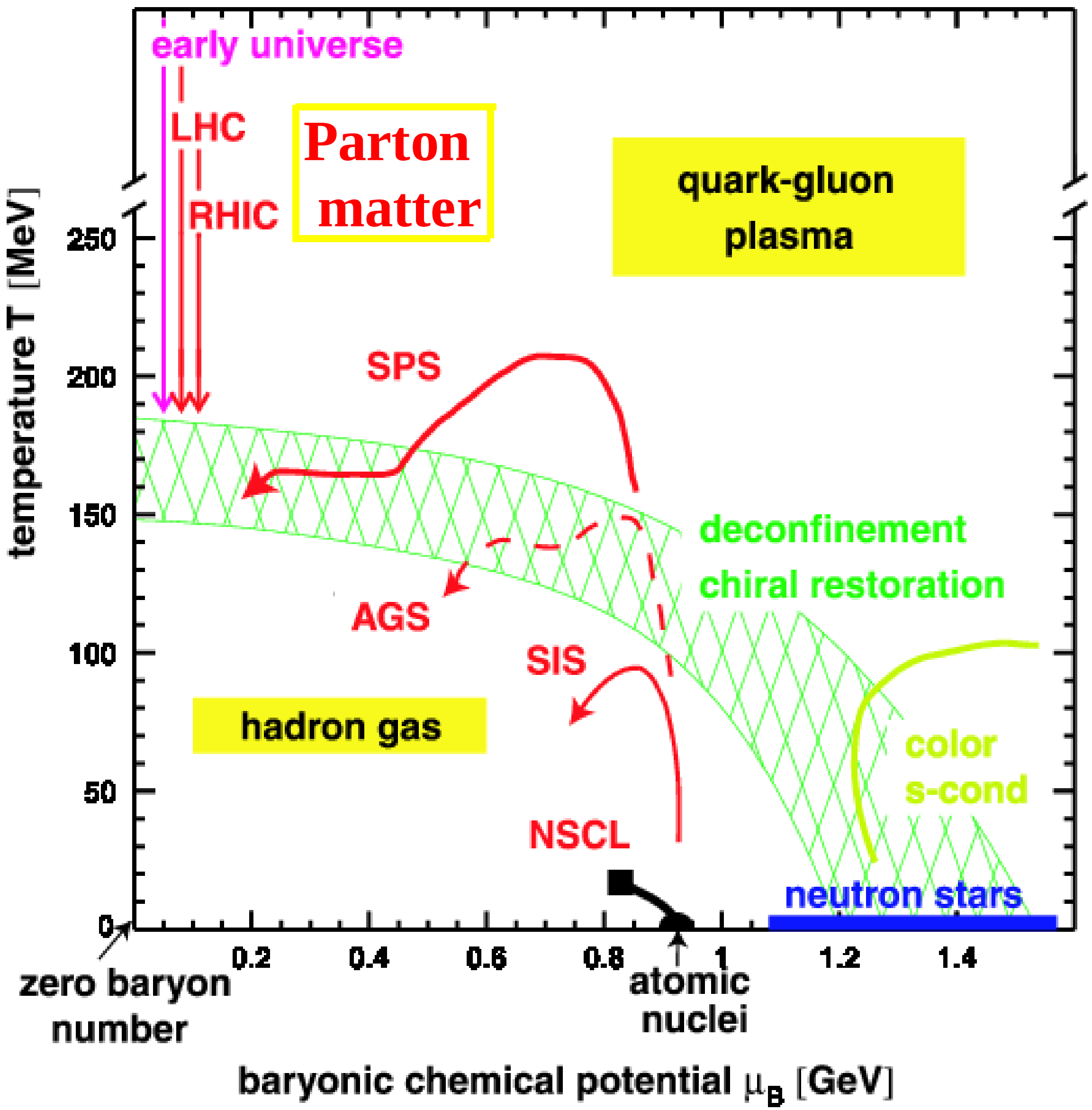
↓

Production
Propagation
Hadronization
in dense matter

Testing the produced hot dense matter ➔ **Testing QCD**

Finding QGP !

EOS for strongly interacting nuclear/hadronic/quark matter:



Bulk matter :

Hydrodynamical models
Thermal description (T,μ)

Freeze-out criteria for expanding and diluting fireballs

Particle production in
$0 \leqslant p_T \leqslant 3$ GeV

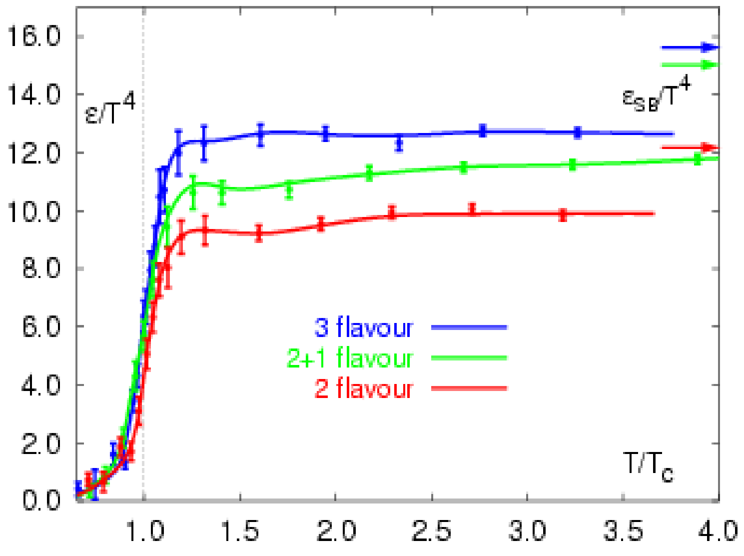
Exponential hadron spectra verify thermal description

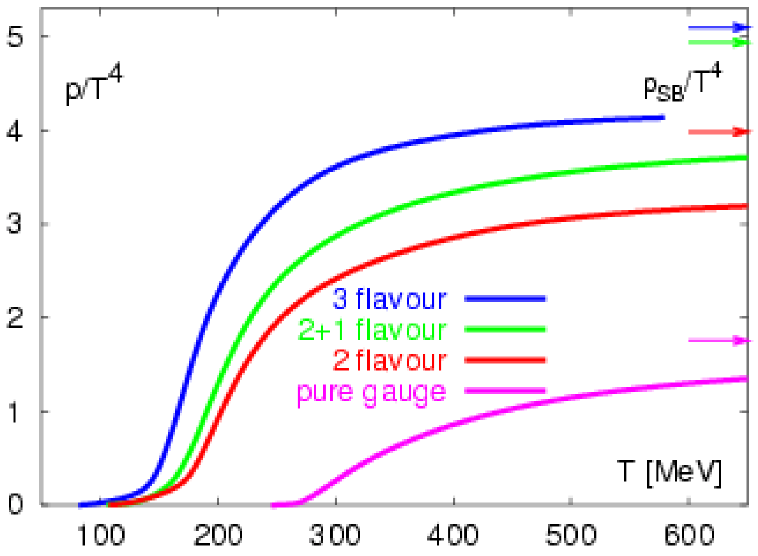
EOS for strongly interacting matter from lattice-QCD

zero baryon density (1990-2000)

finite baryon densities (2000 -)

➔ $\varepsilon(T, \mu)$, $P(T, \mu)$





More realistic EOS for deconfined matter

Non-ideal EOS ↣ quasi-particle picture of strongly interacting QM

Bogoliubov Lab. of Theoretical Physics

➢➢➢➢ Detailed microscopical picture of deconfinement is needed

0. Introduction --- parton matter, quark matter, EOS

1. How to test:

--- parton matter in the early stages ?

- ➣ **jet-tomography (induced jet energy loss, opacity)**

  (density evolution is integrated in time)

--- quark matter around phase transition?

- ➣ **hadronization models (quark coalescence)**

  (density at phase transition)

2. Can we calculate the early stages directly ?

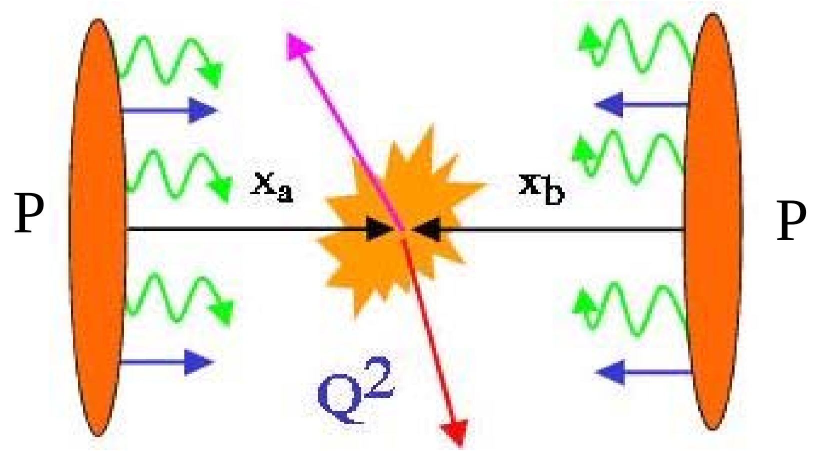
- ➣ **hard parton production from perturbative QCD;**
- ➣ **soft hadron production from non-perturbative QCD;**

  --- lattice QCD

  --- kinetic theory (pair production)

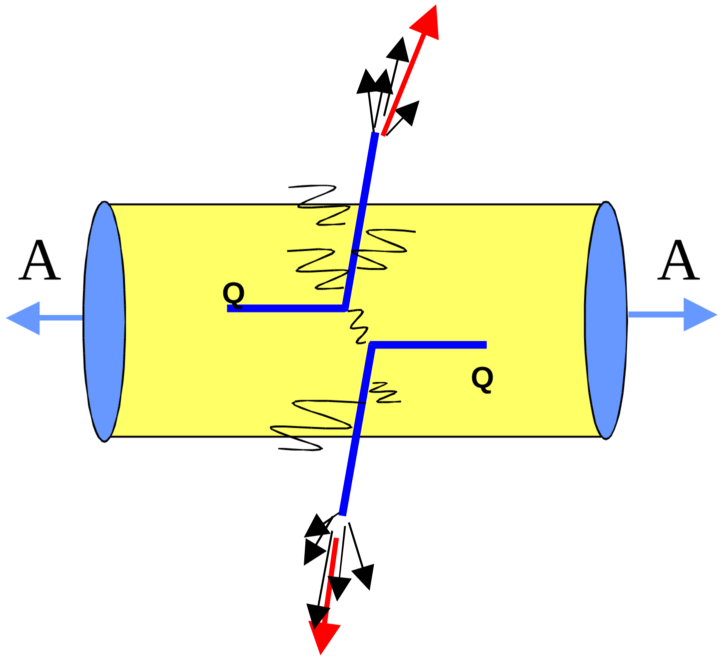
3. Summary

Jets in pp and in AA collisions:



Jet production in pp collision (in vacuum):

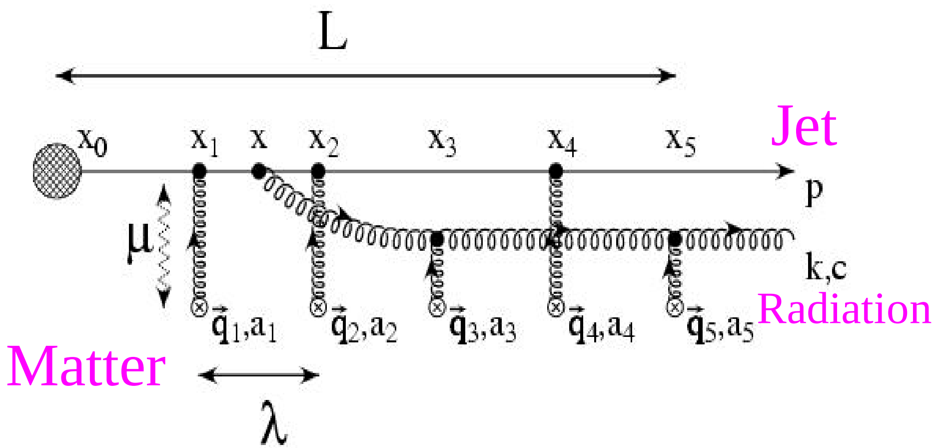
↣ pQCD description



Jet production and propagation in AA collision (inside hot dense matter)

↣ induced gluon radiation in a modified pQCD description

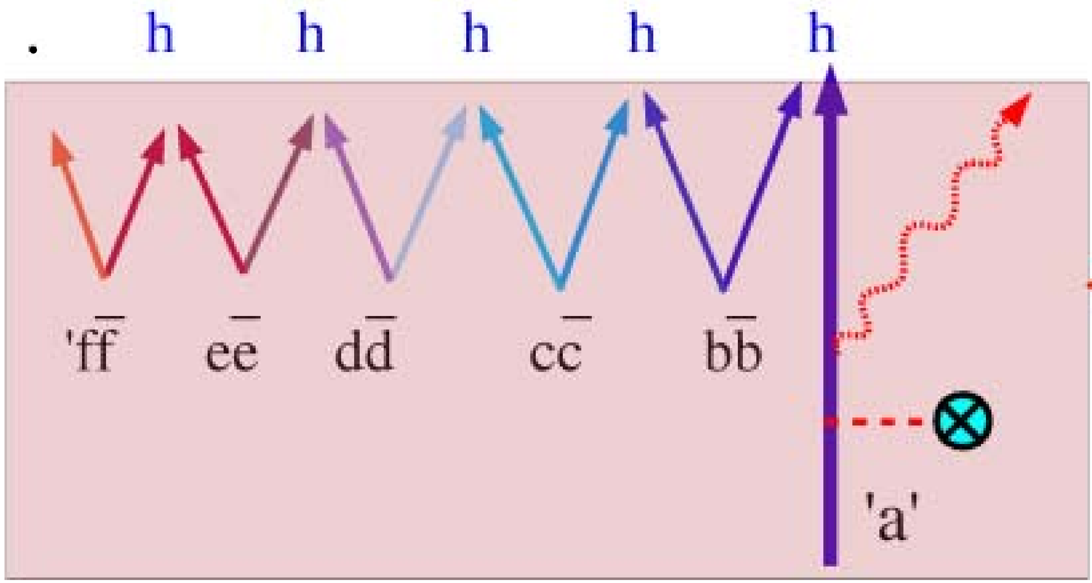
JET-TOMOGRAPHY



'Hard' physics: independent jet-fragmentation (FF) in matter

Fragmentation function: $D_c^h(z)\,dz$ ←

the probaility to produce a hadron h with momentum z p from a jet c with momentum p



← matter
$(L/\lambda,\ \mu(T),\ \ldots)$

1. Induced gluon radiation ➢➢➢➢➢ jet energy loss

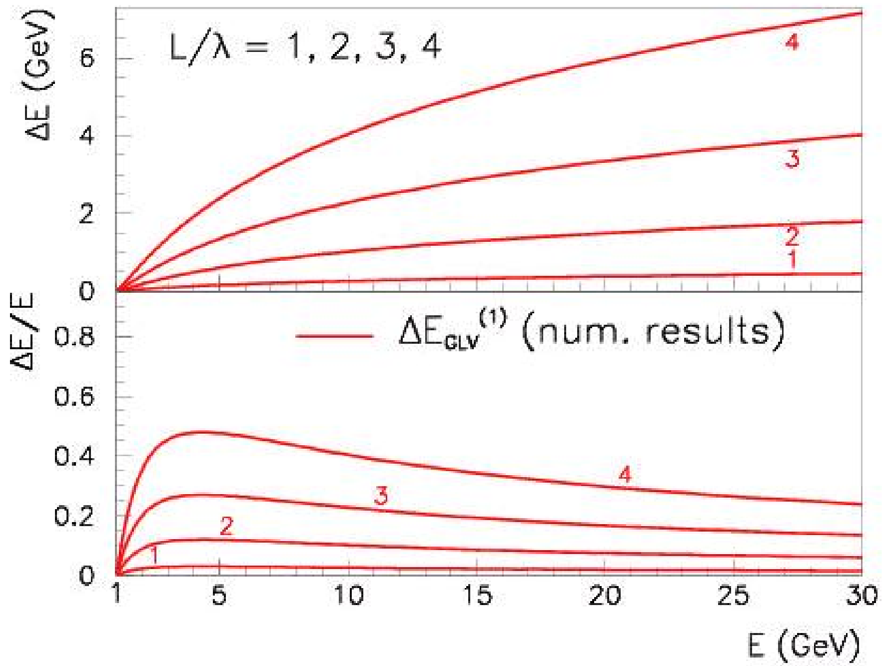
Jet-quenching: $E \Rightarrow E - \Delta E(E, L/\lambda, \mu, \ \ldots)$

$$D_c^h(z)\,dz \rightarrow D_c^h(z^o)\frac{z^o}{z}\,dz^o \quad where \quad z^o = 1 - \Delta E/E$$

'Jet-quenching' : induced jet energy loss --- in thin colored matter

M. Gyulassy, P. Levai, I. Vitev,
PRL85,5535(2000), NPB594,371(2001)

GLV: time-ordered pQCD (Feyman diagrams)
+ OPACITY expansion (N = 1,2,3, ...)
+ kinematical cuts

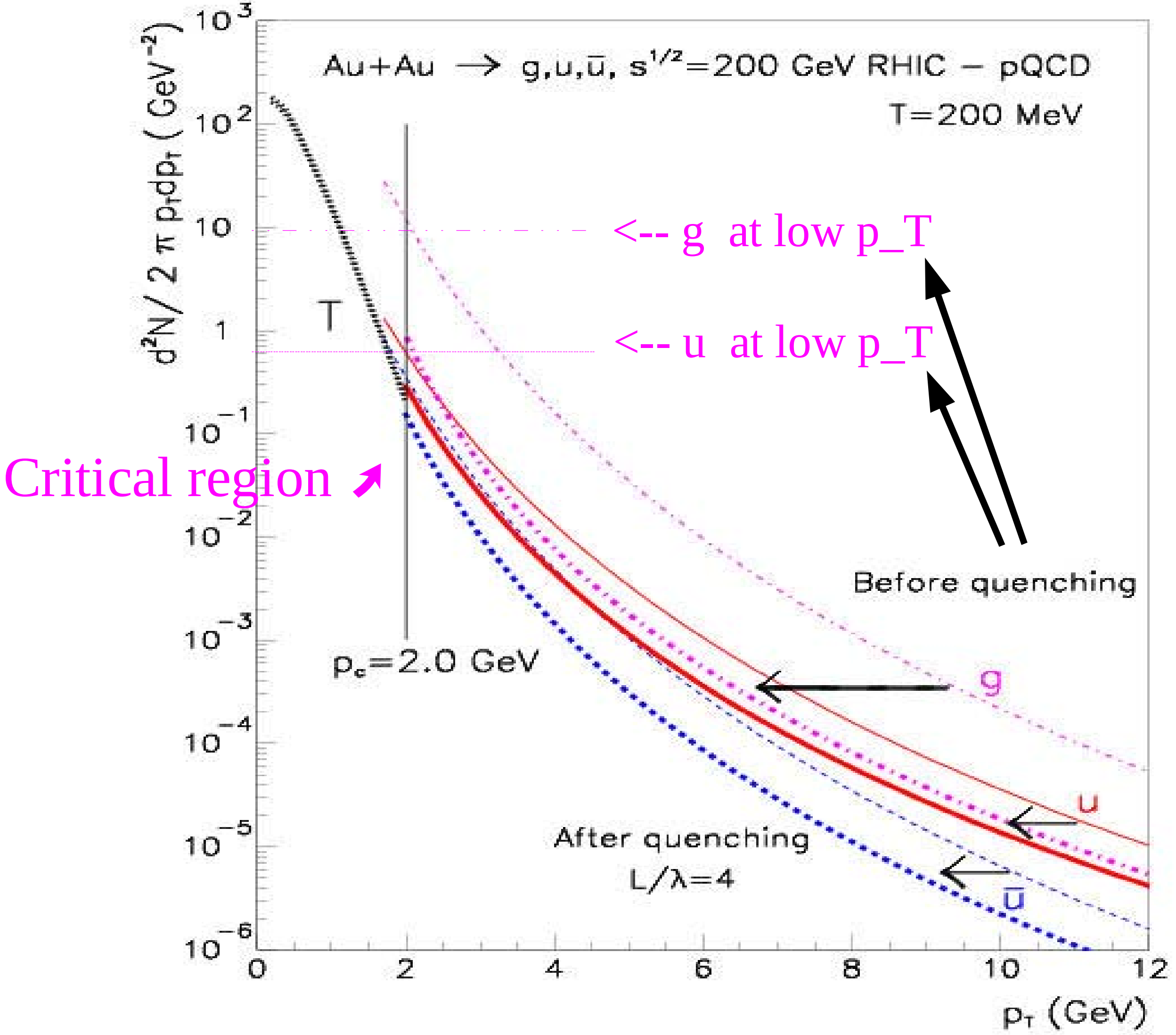


$$\Delta E_{GLV} \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}$$

E-dependent ΔE energy loss

E-independent ΔE/E
in the window
3 < E < 10-15 GeV

Initial parton distributions before and after quenching



Before quenching:

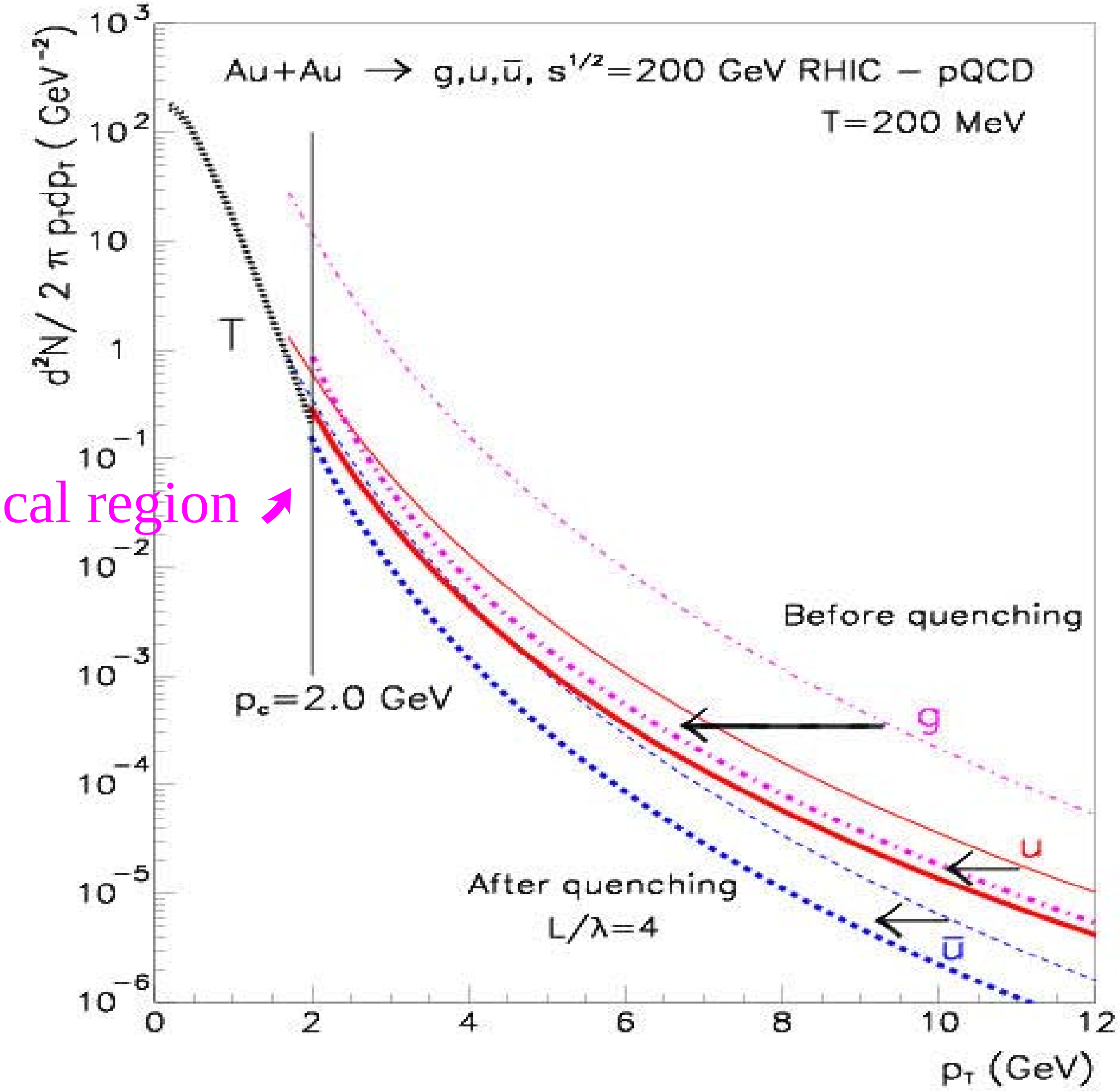
AuAu spectra
≡ binary scaled pp spectra

primary partons ➡
p_T > p_c : polinomial
p_T < p_c : suppressed or saturated

p_T > p_c :

80 % of dE_T/dy (y=0)

Initial parton distributions before and after quenching



Critical region ↗

Thermal --- Non-thermal distributions !!?!

After quenching:

radiated gluons ➡
thermal bath (T=200 MeV)
≡ **hot dense matter formation**

dE_T/dy (y=0) = 570 GeV
80 % is soft (p_T < p_c)
20 % is hard (p_T > p_c)

Modification in parton spectra is shifted to smaller hadronic p_T in case of independent jet fragmentation.

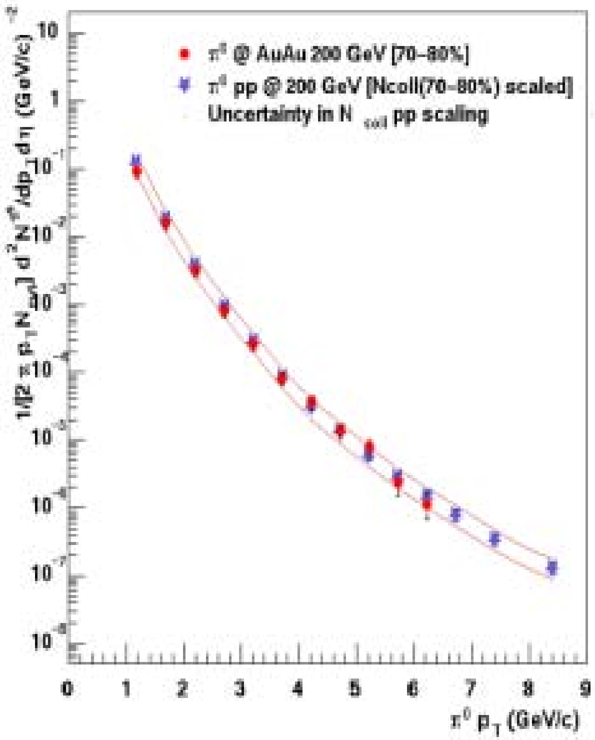
JET-QUENCHING

⇩ ⇩ ⇩ ⇩

SUPPRESSION in HADRON SPECTRA

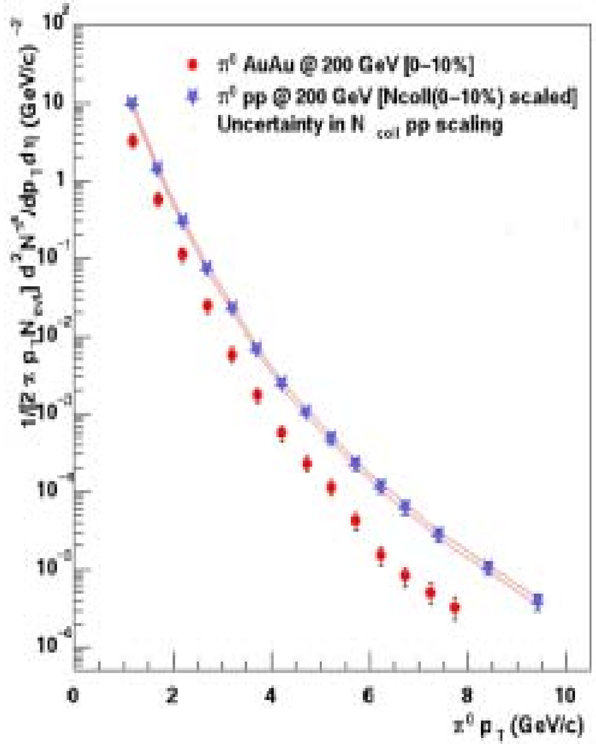
Exciting results from RHIC at √s = 130 and 200 A GeV -- π^0

PHENIX Coll., D. d'Enterria, hep-ex/0209051, QM02 Conf.



Peripheral coll. N(bin)=12.3±4

binary scaling is working



Central coll. N(bin)=975±94

binary scaling is violated

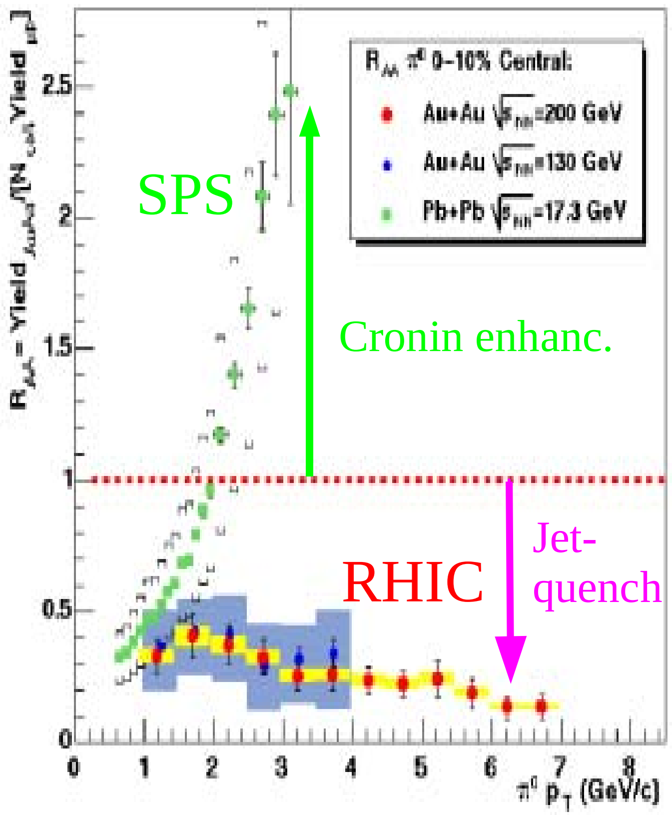
$$p_T > 6-8\,GeV : Hard\ physics - pQCD$$

$$1.5\,GeV < p_T < 6\,GeV : Soft - hard\ overlap$$

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle N_{bin}\rangle (dN/dp_T)_{pp}}$$

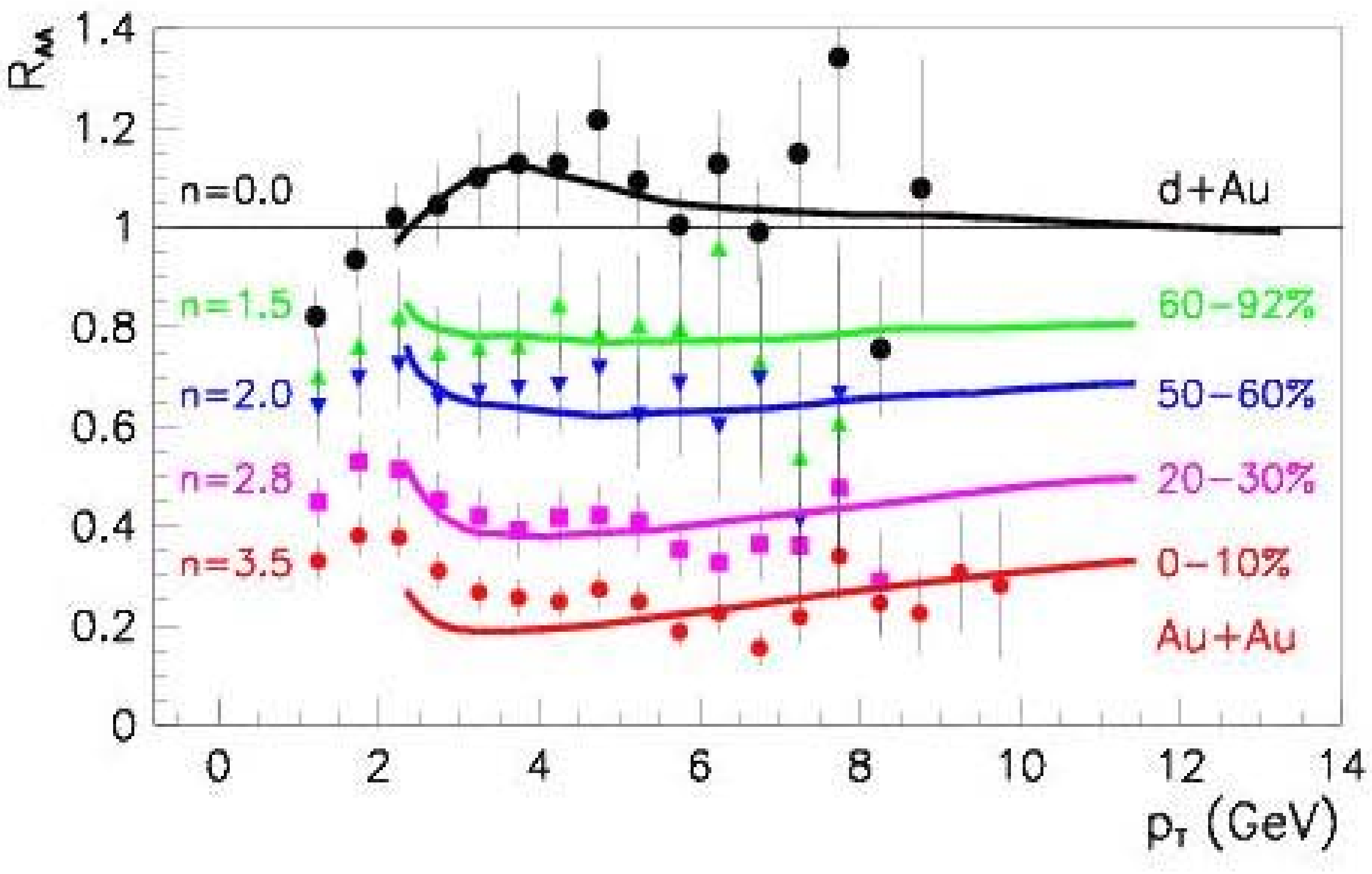
PRL 88, 022301 (2002)



Hard physics: pion production in AA collision at high- p_T

Perturbative QCD calculations in NLO for heavy ion collisions:
geometrical overlap + shadowing, multiscattring, jet-quenching, ...

$$E_\pi \frac{d\sigma^{AB}}{d^3p_\pi} = \int d^2b\, d^2r\;\; t_A(\vec{r})\, t_B(|\vec{b}-\vec{r}|)\;\; E_\pi \frac{d\sigma^{pp}}{d^3p_\pi} \otimes S(\ldots) \otimes M(\ldots) \otimes Q(\ldots)$$



d+Au

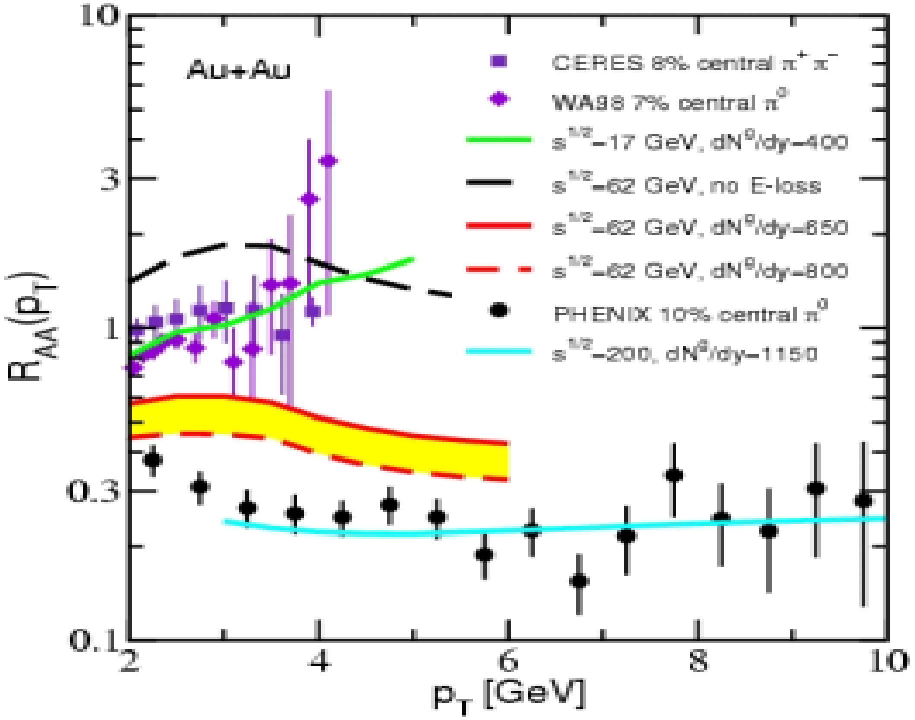
Au+Au

Hard physics: pion production in AA collision at high- p_T

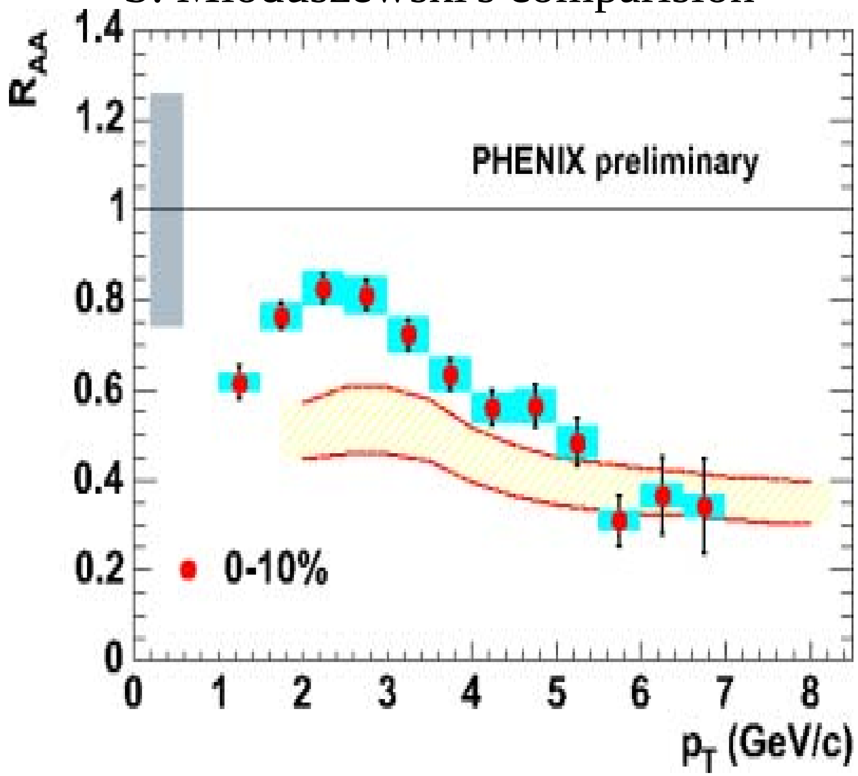
Au+Au collisions at 17, 62.4 , 200 A GeV

$$L/\lambda \;\rightarrow\; \int \tau\,\rho(\tau)\,d\tau$$ ***Opacity ↣ color charge density***

I. Vitev (nucl-th/0404052)



S. Mioduszewski's comparision



$\sqrt{s}$	=	**17**	**62**	**200 A GeV**
dN_g/dy	=	**400**	**700**	**1150**

''Testing deconfined matter around phase transition''

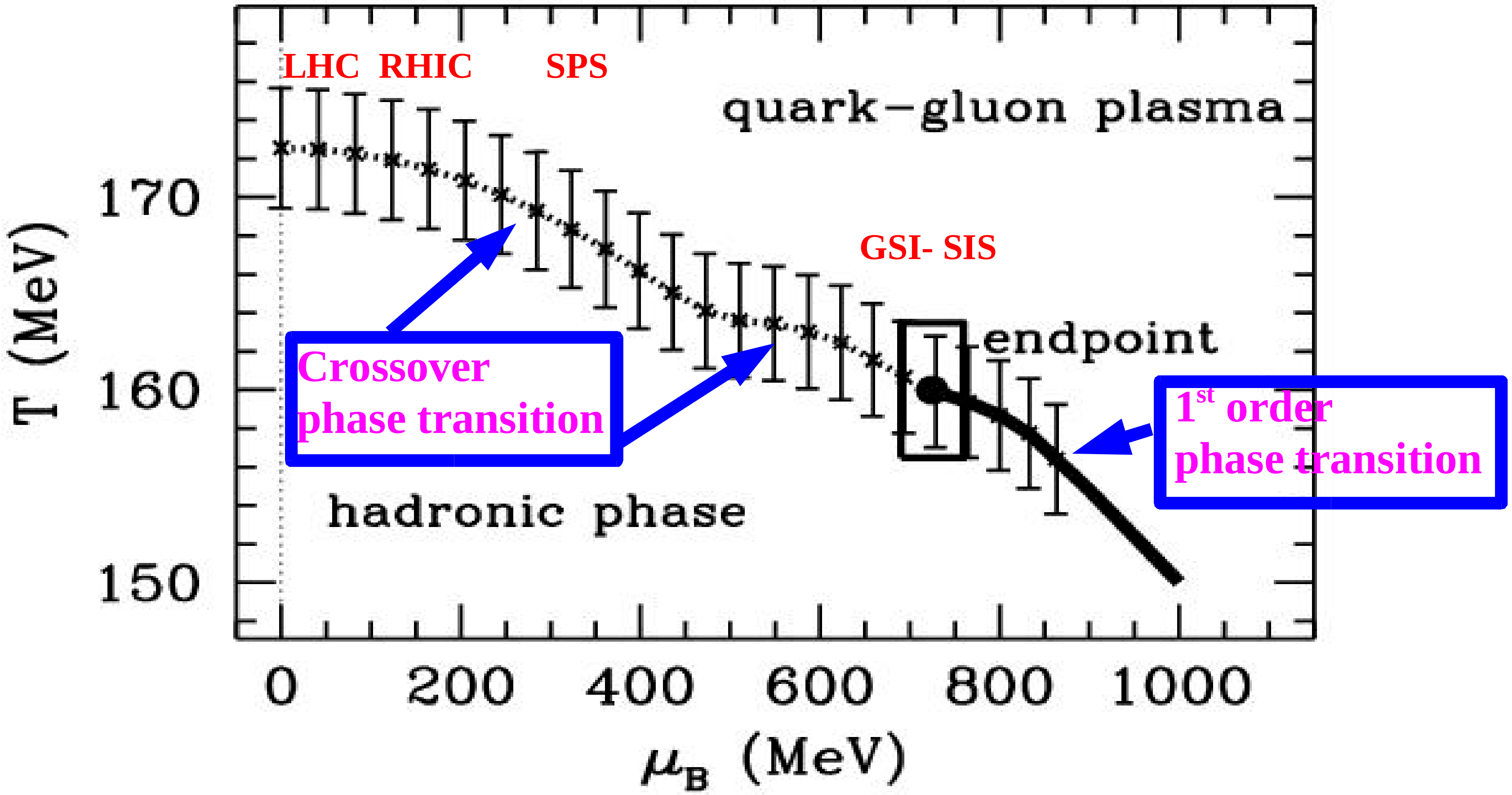
↕ ↕ ↕ ↕ ↕ ↕

Hadronization models and descriptions

(Phenomenological descriptions.)

Quark matter formation in heavy ion collisions

Lattice-QCD results at finite density, SU(3), Nf=2 $\mu>0$ (2002, Fodor et al.)



Crossover phase transition at small and intermediate baryon densities:

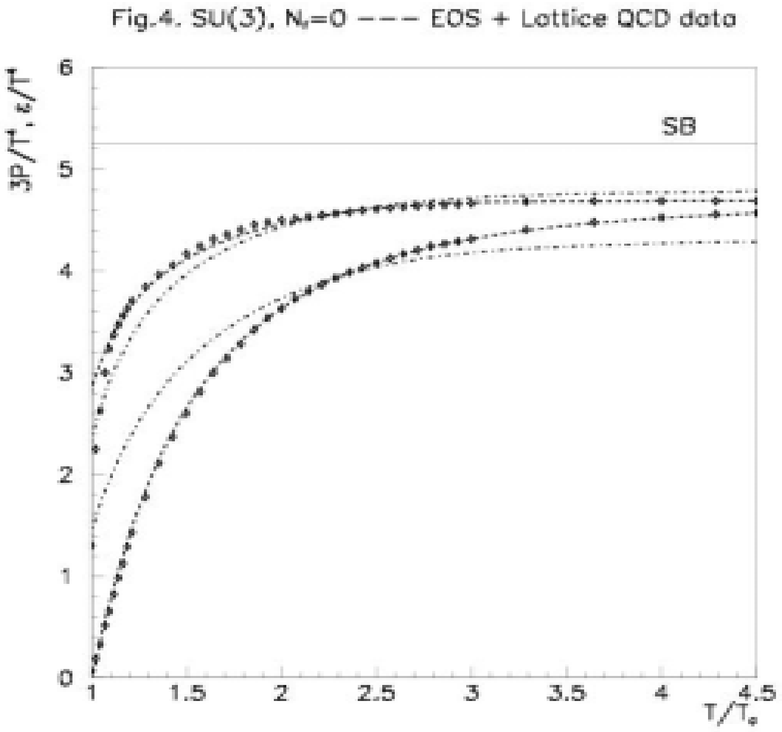
What is the microscopical mechanism of the hadronization ????

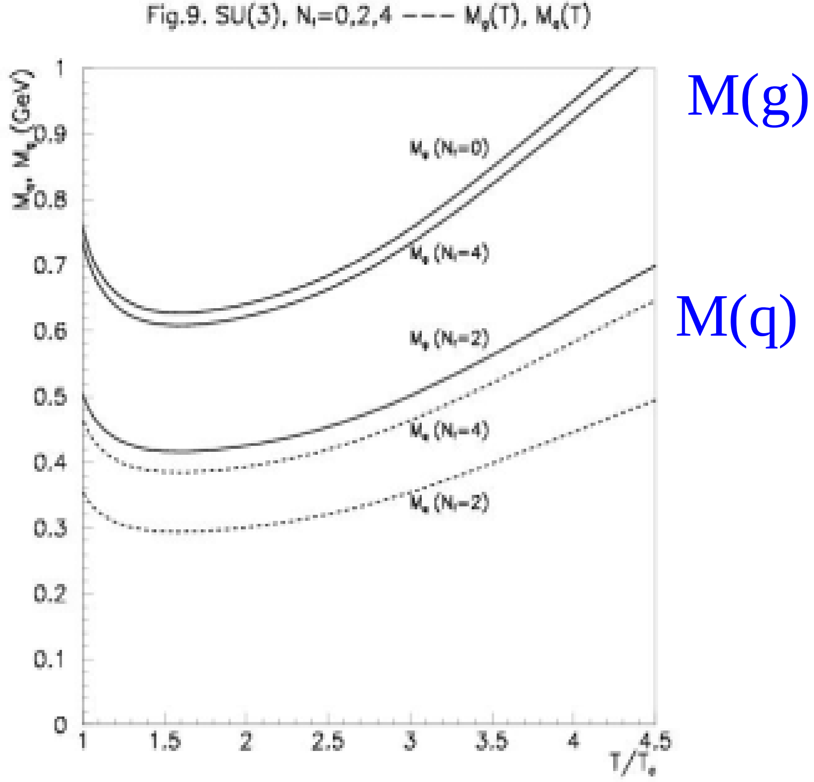
⇒ **QUARK COALESCENCE as one possibility**

WE WANT TO FIND SOME "DECONFINED" PHASE !!

Quark matter formation in heavy ion collisions

Lattice-QCD results around T_c, SU(3), Nf=0,2,4 μ=0 (1990 - ...)





Understanding in a quasiparticle picture: M(Q) ≃300 MeV, M(G)≃ 500-800 MeV

[L.P, Heinz U., 1996, PRC51,3326]

➔ Quark and antiquark dominated matter (QAP)

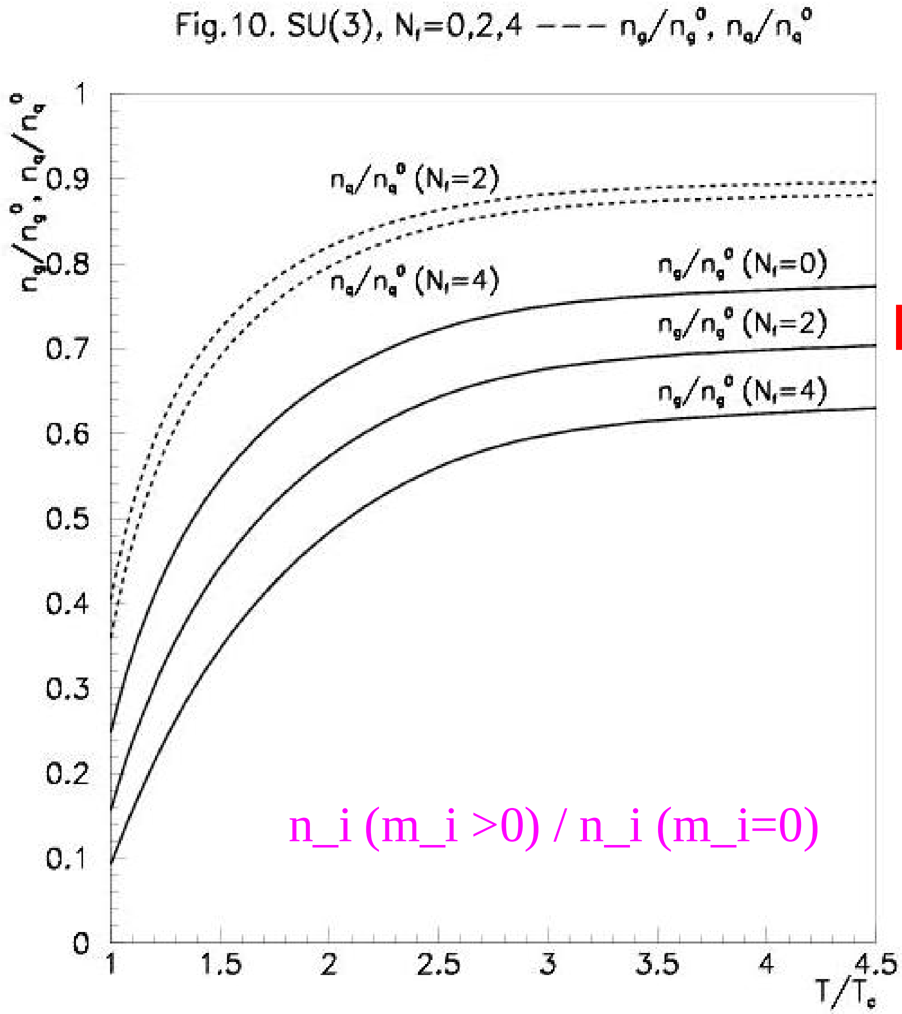
HADRONIZATION ⇔ QUARK COALESCENCE (ALCOR '95)

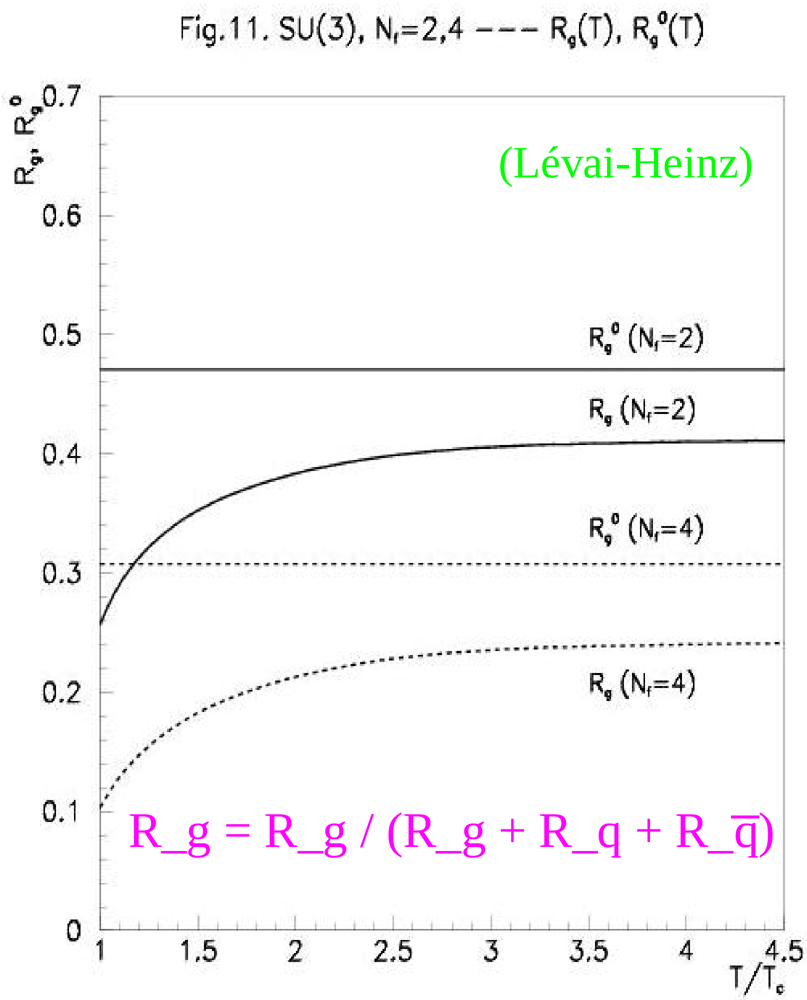
('Cross-over' phase transition) (T.S. Biro, P.L., J. Zimányi)

Interior of quark stars (G.G. Barnafoldi, B. Lukacs, P.L., 2003)

Quark matter formation in heavy ion collisions

Lattice-QCD results around T_c, SU(3), Nf=0,2,4 μ=0





➔ GLUON numbers are strongly suppressed at T_c and they will decay

QUARK-ANTIQUARK PLASMA

QUARK COALESCENCE: meson production in bulk quark matter

Meson production: binding of a quark and an antiquark, $q + \bar{q} \Rightarrow M$

(constituent quark model, non-relativistic approx.)

--- (anti)quarks are inside a deconfined phase [QGP, QAP, CQM]

$\Rightarrow$ asymptotic wave functions do not exist inside deconf. phase !!!!

--- the interaction between quark and antiquark drives the meson production

$\Rightarrow$ non-relativistic $V(q\bar{q})$ potential (lattice-QCD results around T_c !)

--- direct calculation of coalescence matrix elements

$$M_{12} = \int d^3x_1 d^3x_2 \;\; \phi_M(|x_1 - x_2|) \;\; e^{-iPX} \;\; V_{12}(|x_1 - x_2|) \;\; \varphi_q(x_1)\varphi_{\bar{q}}(x_2)$$

$\Rightarrow$ $V_{12}(r)$ is an effective coalescence potential: $V_{12} = -\alpha_{eff} \frac{\langle \lambda_1 \lambda_2 \rangle}{r}$

$\Rightarrow$ many coalescence channels exist (π, ρ, K, K*, ϕ, ...)

--- introducing 1+2 $\rightarrow$ 3 coalescence cross section [e.g. ALCOR, PLB347,1995,6]:

$$\sigma_{12}(k) = \frac{m_3^2}{4\pi^2} \sqrt{\frac{2m_1 m_2}{(m_1+m_2)^2}} \;\; |M_{12}|^{12} = 16\, m_3^2 \sqrt{\pi}\, \alpha_{eff}^2 \rho^3 \frac{a}{(1+(ka)^2)^2}$$

➡ a: Bohr radius

--- quark coalescence rate:

$$\langle \sigma_{12} v_{12} \rangle = \frac{\int d^3P_1 d^3P_2 f_1(P_1) f_2(P_2) \;\; \sigma_{12} v_{12}}{\int d^3P_1 d^3P_2 f_1(P_1) f_2(P_2)}$$

Can we use such a non-relativistic approximation ??? ➣ Quark mass !?!

$m(q) \simeq 330$ MeV, $T \simeq 175$ MeV ➣ **OK**

Quark matter formation in heavy ion collisions

ALCOR model for quark matter hadronization [Zimányi J., Biró T.,L.P. PLB347,6, 1995]

Massive quarks and antiquarks are the basic d.o.f. $u, \bar{u}, d, \bar{d}, s, \bar{s}$

Quarks from nucleus are melted (stopping)
Newly produced light quark-antiquark pairs
Newly produced strange quark-antiquark pairs

$$\frac{dN(u)}{dy} = P * N_u^{(total\,u)} + \frac{dN(\langle u\bar{u}\rangle)}{dy}$$

$$\frac{dN(s)}{dy} = \frac{dN(\langle s\bar{s}\rangle)}{dy}$$

Attractive potential between (anti-)quarks

$$V_{eff}(r) = -\alpha_{eff}\frac{\langle\lambda_i\lambda_j\rangle}{r}$$

Heavy hadron resonances are produced -> decay

RESULT: analysis and understanding of the particle numbers and their ratios + energy dependence

Input parameters: $\underline{P}; \underline{\langle u\bar{u}\rangle} = \langle d\bar{d}\rangle; \langle s\bar{s}\rangle = \underline{f_s} * (\langle u\bar{u}\rangle + \langle d\bar{d}\rangle); \underline{\alpha_{eff}}$

Quark matter formation at RHIC at $\sqrt{s}$ = 130 & 200 A GeV

ALCOR model for quark matter hadronization **2004 April**

	ALCOR 130 AGeV	ALCOR 200 AGeV
New pairs, $dN_{u\bar{u}}/dy$	250	286
Strangeness, f_s	0.22	0.22
Stopping, in %	3.3	3.0
Interaction, α_{eff}	0.55	0.55

Au+Au **dX/dy** or **R**	STAR 130 AGeV	ALCOR	STAR 200 AGeV	ALCOR
π^-	287 ± 20	287	327 ± 32	322
K^-	41.9 ± 5.5	40.4	49.5 ± 7.4	45.6
K^-/K^+	0.91 ± 0.11	0.93	0.92 ± 0.02	0.94
Ξ^+	1.72 ± 0.1	1.76	1.81 ± 0.08	2.23
$h^\pm$		690	780	780
K^+	46.2 ± 6.1	43.1	51.3 ± 7.7	48.1
Ξ^-	2.05 ± 0.1	2.16	2.16 ± 0.09	2.59
$\langle \Omega^- + \overline{\Omega}^+ \rangle$	0.55 ± 0.15	0.59	0.59 ± 0.14	0.72
$\overline{p}^-/p^+$	0.64 ± 0.07	0.70	0.77 ± 0.05	0.76
$\overline{\Lambda}/\Lambda$	0.71 ± 0.04	0.75	0.81 ± 0.07	0.810
$\overline{\Xi}^+/\Xi^-$	0.83 ± 0.05	0.81	0.84 ± 0.06	0.86
$\overline{\Omega}^+/\Omega^-$	0.95 ± 0.15	0.88	0.95 ± 0.15	0.92
K^+/π^+	0.161 ± 0.024	0.15	0.16 ± 0.02	0.150
K^-/π^-	0.146 ± 0.022	0.14	0.15 ± 0.02	0.142
Λ/h^-	0.054 ± 0.001	0.047		0.050
$\overline{\Lambda}/h^-$	0.040 ± 0.001	0.037		0.042
Ξ^-/π^-	0.006 ± 0.001	0.007	0.007 ± 0.001	0.008
K^{*0}	36.7 ± 5.5	28.5		31.7
Φ/K^{*0}	0.49 ± 0.13	0.37	0.55 ± 0.15	0.37
Δ^{++}/p^+		0.39	0.24 ± 0.04	0.39
ρ^0/π^0		0.22	0.20 ± 0.04	0.22

Quark-coalescence:

reproduces most of the
bulk properties at RHIC energies
(particle numbers, ratios,
their energy dependence)

Quark matter formation at SPS at E(beam) = 158 & 80 A GeV

ALCOR model for quark matter hadronization **2004 April**

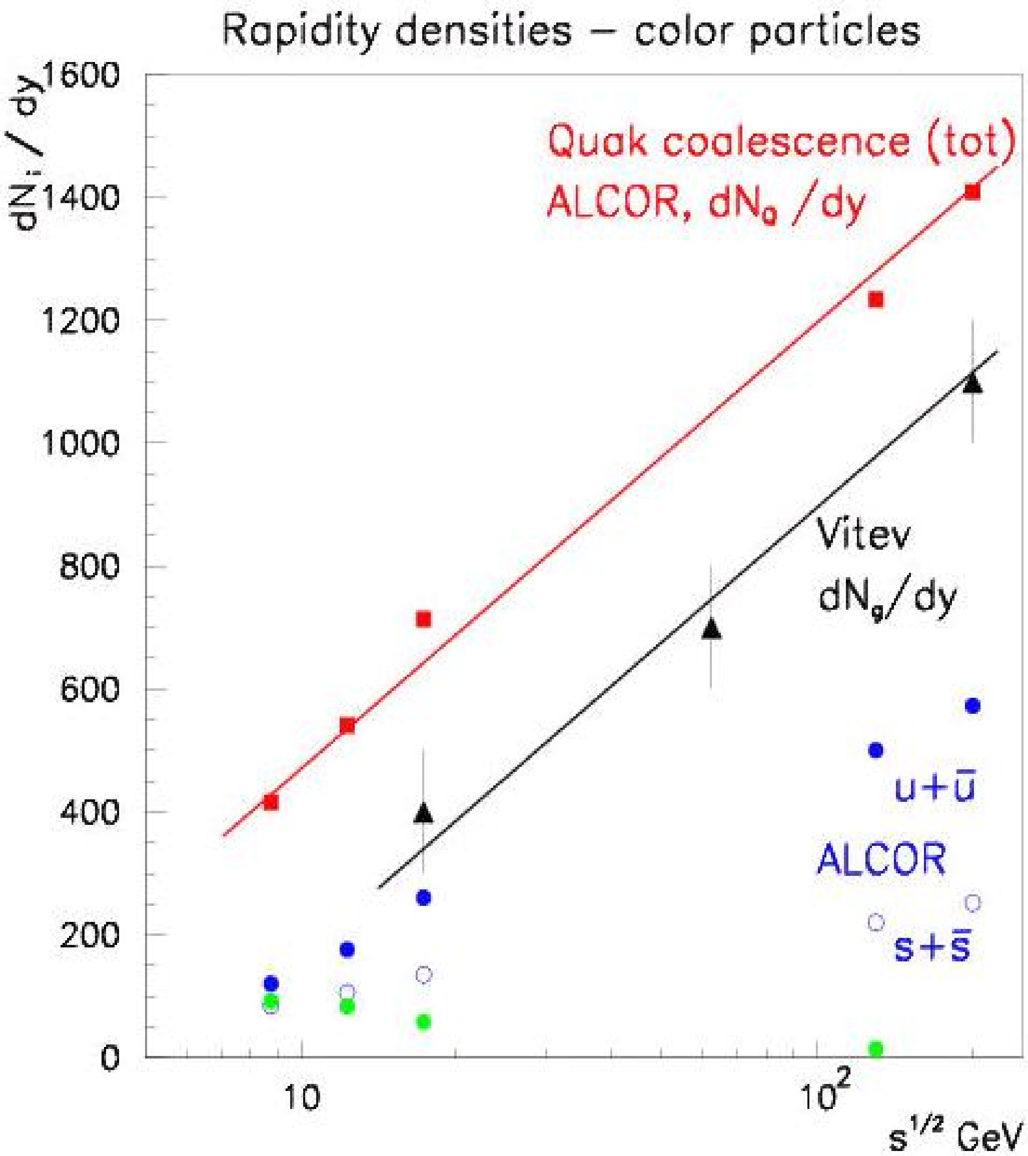
	ALCOR 158 GeV fit	ALCOR 80 GeV
New pairs, $dN_{u\bar{u}}/dy$	123	88
Strangeness, f_s	0.26	0.30
Stopping, in %	14.	20.
Interaction, α_{eff}	0.7	0.9

Pb+Pb dX/dy or R	NA49 158 AGeV	ALCOR	NA49 80 AGeV	ALCOR
π^-	175.4 ± 9	175	140.4 ± 7	140
K^-	16.8 ± 0.8	18.1	11.7 ± 0.6	11.2
K^-/K^+	0.56 ± 0.05	0.62	0.47 ± 0.05	0.46
$\bar{\Xi}^+$	0.33 ± 0.04	0.36		0.31
K^+	29.6 ± 1.5	29.1	24.6 ± 1.2	24.2
Ξ^-	1.49 ± 0.08	1.84		1.81
$\bar{p}^-/p^+$	0.07 ± 0.01	0.070	0.033 ± 0.004	0.031
$\bar{\Lambda}/\Lambda$	0.148 ± 0.015	0.138	0.079 ± 0.01	0.096
$\bar{\Xi}^+/\Xi^-$	0.22 ± 0.03	0.19	0.13 ± 0.02	0.17
$\bar{\Omega}^+/\Omega^-$	0.46 ± 0.1	0.34		0.41
Ξ^-/π^-	0.009 ± 0.001	0.0105		0.013
$\bar{\Xi}^+/\pi^+$	0.0022 ± 0.0006	0.0021		0.0023
Ω^-/π^-	0.0015 ± 0.0002	0.0022		0.0022
$\bar{\Omega}^+/\pi^+$	0.00065 ± 0.00007	0.00078		0.00097

Quark-coalescence:

reproduces most of the
bulk properties at SPS energies
(particle numbers, ratios,
their energy dependence)

Color partcle densities --- quarks or gluons ???



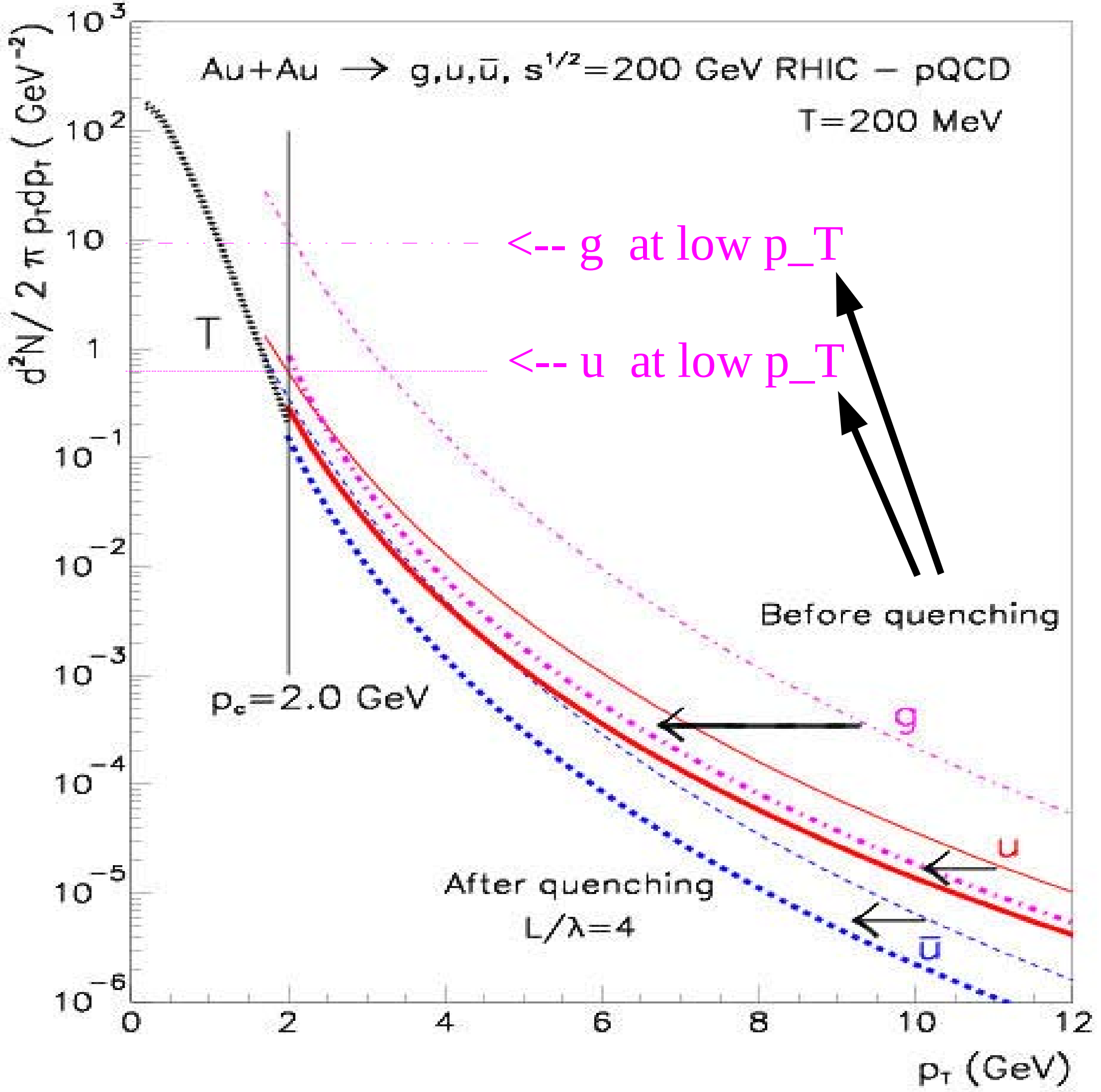
S^1/2 (GeV)	Quark-coalesc dNq/dy	Jet-quench dNg/dy	L/λ
17.3	710±100	400±100	1.5± .5
62.4	1000±100	700±100	....
200.0	1400±100	1100±100	3.5± .5
	ALCOR	I. Vitev	P. Levai

Quench: earlier stage

Quark coalescence: later stage

Entropy is OK

Initial parton distributions from perturbative QCD



Before quenching:

AuAu spectra
≡ binary scaled pp spectra

soft parton spectra:
only estimate based on
energy conservation

Non-perturbative QCD ➡

soft parton spectra:
calculation directly

Duality:
gluon field ↔ gluon particles

Kinetic theory:
pair production from
strong fields

Initial gluon distribution from non-perturbative (lattice-) QCD

A. Krasnitz, Y. Nara, R. Venugopalan, PRL87 (2001) 192302.

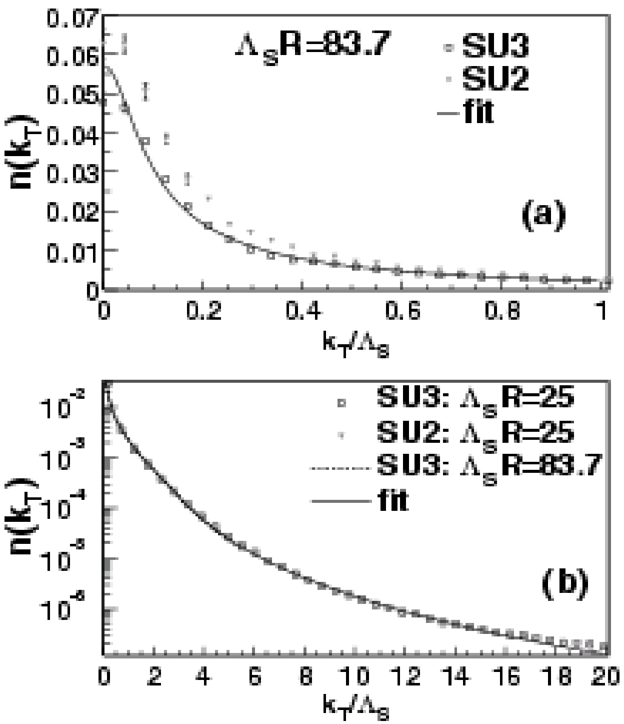


FIG. 2. Transverse momentum distribution of gluons, normalized to the color degrees of freedom, $n(k_T) = \tilde{f}_n/(N_c^2 - 1)$ [see Eq. (3)] as a function of $\Lambda_s R$ for SU(3) (squares) and SU(2) (triangles). (a) For soft momenta; (b) for all momenta. The solid lines correspond to the fit in Eq. (4).

The SU(3) gluon momentum distribution can be fitted by the following function:

$$\frac{1}{\pi R^2}\frac{dN}{d\eta d^2k_T} = \frac{1}{g^2}\tilde{f}_n(k_T/\Lambda_s), \qquad (3)$$

where $\tilde{f}_n(k_T/\Lambda_s)$ is

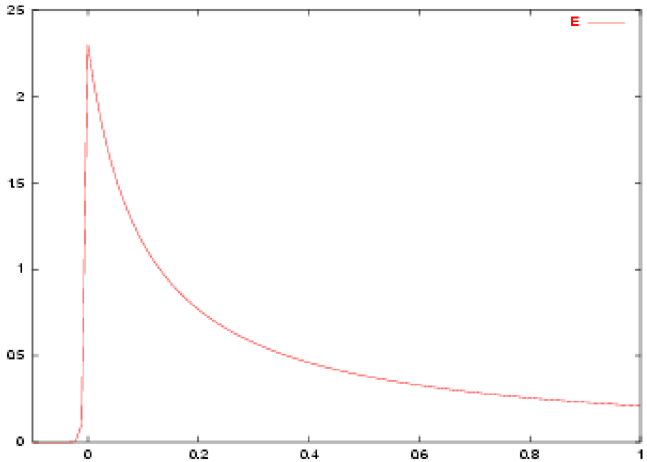
$$\tilde{f}_n = \begin{cases} a_1[\exp(\sqrt{k_T^2 + m^2}/T_{\rm eff}) - 1]^{-1} & (k_T/\Lambda_s \leq 3) \\ a_2\Lambda_s^4 \log(4\pi k_T/\Lambda_s)k_T^{-4} & (k_T/\Lambda_s > 3) \end{cases} \qquad (4)$$

with $a_1 = 0.0295$, $m = 0.067\Lambda_s$, $T_{\rm eff} = 0.93\Lambda_s$, and $a_2 = 0.0343$. At low momenta, the functional form is approximately that of a Bose-Einstein distribution in two dimensions even though the underlying dynamics is that of classical fields. The functional form at high momentum is motivated by the lowest order perturbative calculations

Non-thermal distributions (Tsallis-distribution) --- T.S. Biro, A. Parvan
V. Toneev

Initial parton distributions from kinetic theory in strong field

V.V. Skokov, P. Levai, in preparation

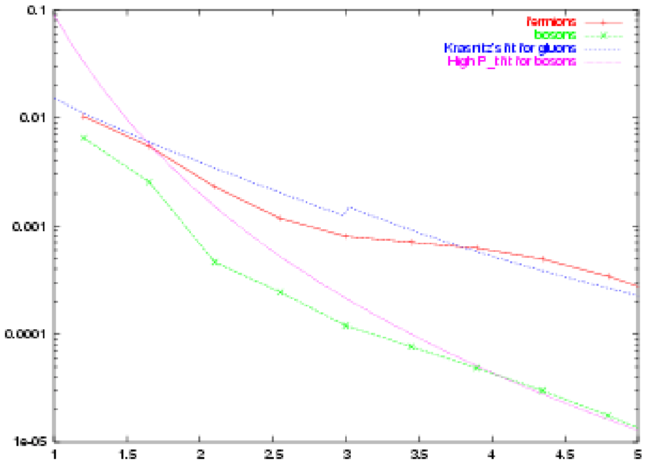


(Chromo-) Electric field impulse
(overlapping heavy ions)

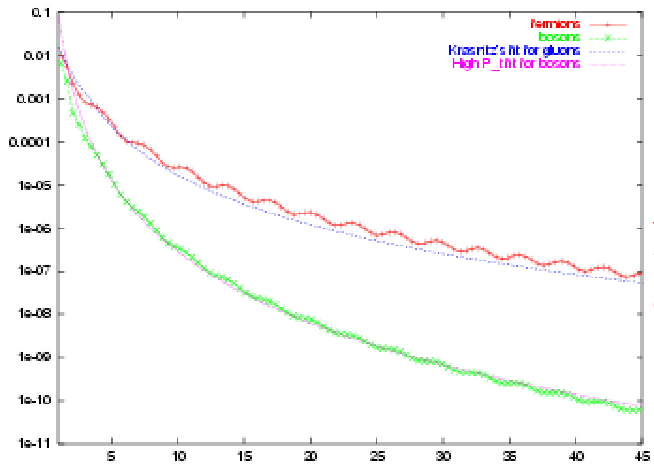
Boson production by Klein-Gordon eq. + $A^{\mu}(t)$

Fermion production by Dirac eq. + $A^{\mu}(t)$

Num.
Simulations
➣→



Low-p_T spectra



High-p_T spectra

Fermion+
antiferm.

Boson

Fermion dominance, 90 % of ε in fermion-antifermion pairs !!

SUMMARY:

Ultrarelativistic heavy ion collisions:

phase structure of strongly interacting matter;
EOS;
hadronization;

Early stage: parton matter with high energy densities (QCD)
Later stage: quark-antiquark dominated deconfined matter

How has the parton matter been produced?
How has the QGP - QAP transformation happened?

Application of non-perturbative QCD and effective QCD methods.

EXPERIMENTAL DATA from RHIC and LHC!
Strong demand for theoretical investigations !!!