Quark Coalescence
in bulk matter and at high-p_T
in heavy ion collisions

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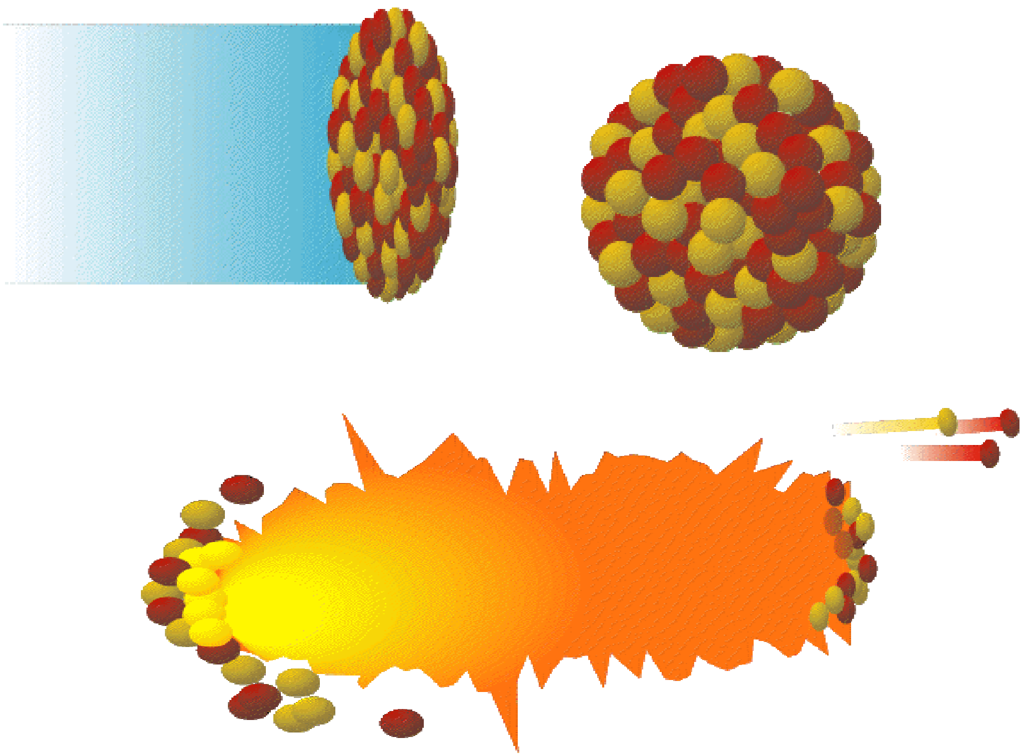
Relativistic heavy ion collisions ($\sqrt{s}$=20-200 AGeV)



What was produced in the center of the collision?

Hot QCD matter
(QGP, CQM, QAP,
CGC, ropes, ...)

↓

Hadronization
(microscopical mech.)

↓

Final state hadrons

?

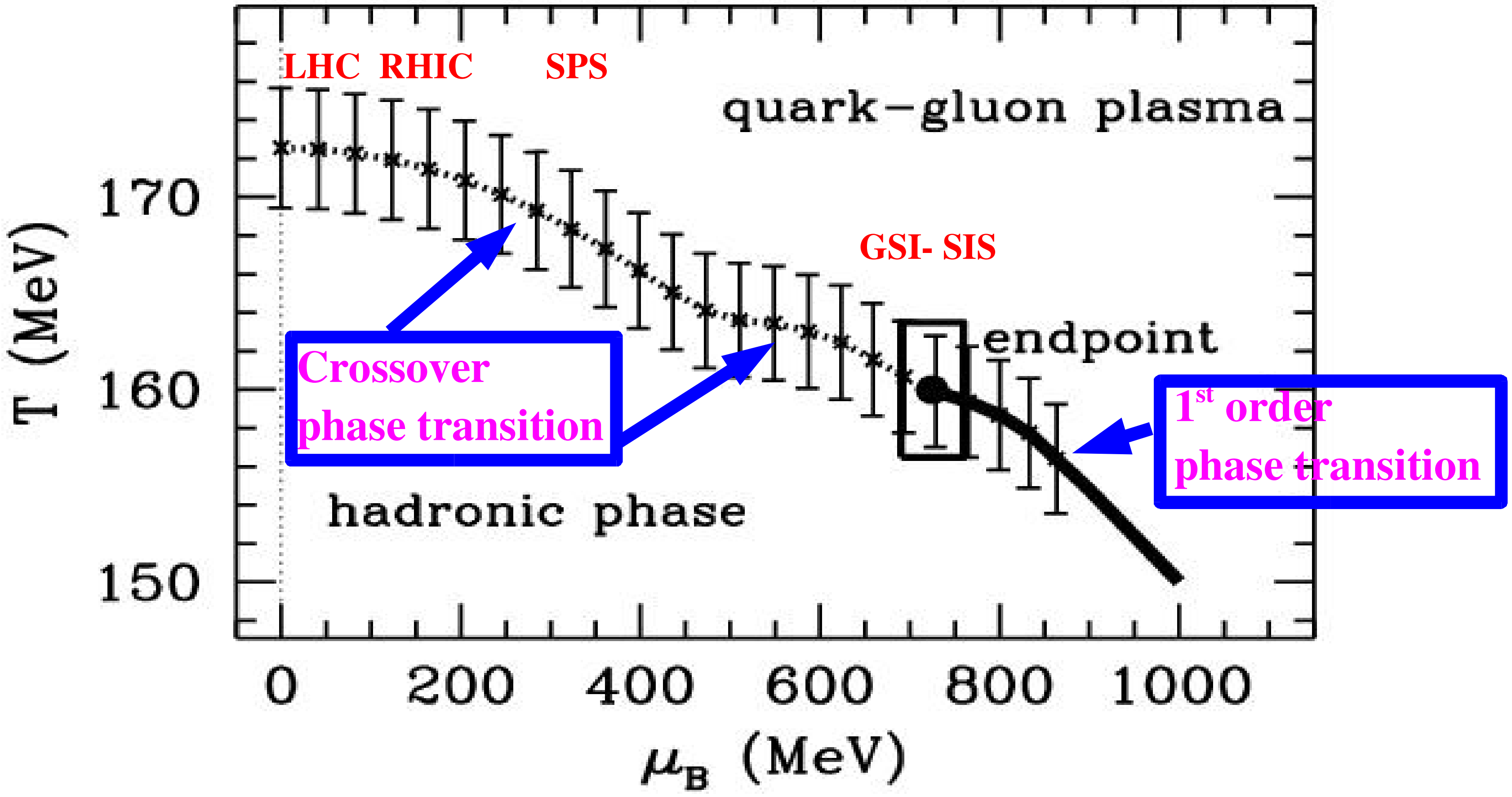
Early models: initial state ⇔ final state ⇨ QGP signatures

These days: initial state ➞➞➞➞➞ final state

microscopical mechanisms
(QCD, strong interaction, ...) ➔ **Testing QCD**

Quark matter formation in heavy ion collisions

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



Crossover phase transition at small and intermediate baryon densities:

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

⇒ **QUARK COALESCENCE**

COALESCENCE: deuteron production in heavy ion collisions

Statistical quantum mechanics: [Feynman '72] ⇒ Dover et al. PRC44(1991)1636.

projecting the deuteron density matrix onto the two-nucleon density matrix:

[e.g. R. Scheibl, U. Heinz, PRC59(1999)1585.]

$$\frac{dN_d}{d^3P_d} \sim \frac{1}{2!} \int d^3x_1 d^3x_2 \ \ d^3x_1' d^3x_2' \ \ \phi_d^*(x_1,x_2)\phi_d(x_1',x_2') \ \left\langle \psi^+(x_2',t_f)\psi^+(x_1',t_f)\psi(x_1,t_f)\psi(x_2,t_f)\right\rangle$$

Deuteron wave-function: $\phi_d(x_1,x_2) = (2\pi)^{-3/2} \exp[i P_d (x_1+x_2)/2] \ \ \varphi_d(x_1-x_2)$

Internal wave-function: $\varphi_d(r) = (\pi d^2)^{-3/4} \exp(-r^2/2d^2)$ ⇤ **inner structure !!**

Wigner transformation: $D(r,q) = \int d^3\xi \exp[-iq\xi] \varphi_d(r+\xi/2) \varphi_d^*(r-\xi/2)$

$\Rightarrow 8\exp(-r^2/d^2 - q^2 \cdot d^2)$

Two-nucleon density matrix ↣ one-particle density matrix:

(at freeze-out the nucleons are uncorrelated)

$$\left\langle \psi^+(x_2',t_f)\psi^+(x_1',t_f)\psi(x_1,t_f)\psi(x_2,t_f)\right\rangle = \left\langle \psi^+(x_2',t_f)\psi(x_2,t_f)\right\rangle \left\langle \psi^+(x_1',t_f)\psi(x_1,t_f)\right\rangle$$

One-body Wigner function from the one-particle density matrix:

$$\left\langle \psi^+(x',t_f)\psi(x,t_f)\right\rangle = \int \frac{d^3p}{(2\pi)^3} f^W(p;t_f,(x+x')/2) \exp[ip(x-x')]$$

The deuteron spectrum:

$$\frac{dN_d}{d^3P_d} = \frac{3}{(2\pi)^6} \int d^3r_d d^3q \, d^3r \, D(r,q) \, f_p^W(q_+, r_+) \, f_n^W(q_-, r_-)$$

Energy conservation: scattering on a third body before coalescence

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. Biro et al, PLB347,1995,6]:

$$\sigma_{12}(k) = \frac{m_3^2}{4\pi^2}\sqrt{\frac{2m_1m_2}{(m_1+m_2)^2}} \;\; |M_{12}|^{12} = 16\, m_3^2 \sqrt{\pi}\, \alpha_{eff}^2 \rho^3 \frac{a}{(1+(ka)^2)^2}$$

➡ a: Bohr radius

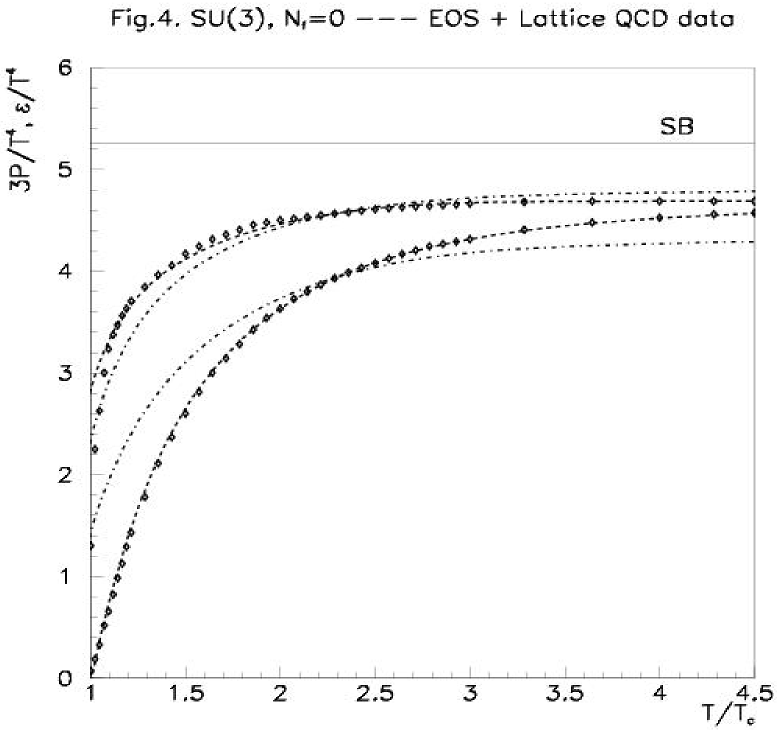
--- quark coalescence rate:

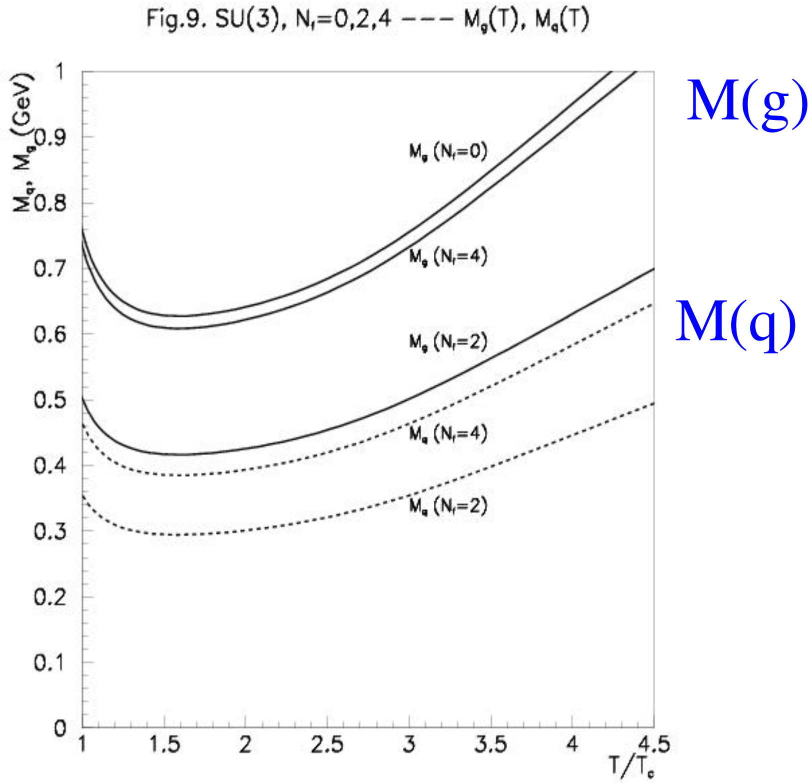
$$\langle \sigma_{12} v_{12} \rangle = \frac{\int d^3P_1 d^3P_2\, f_1(P_1)\, f_2(P_2) \;\; \sigma_{12} v_{12}}{\int d^3P_1 d^3P_2\, f_1(P_1)\, f_2(P_2)}$$

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

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]

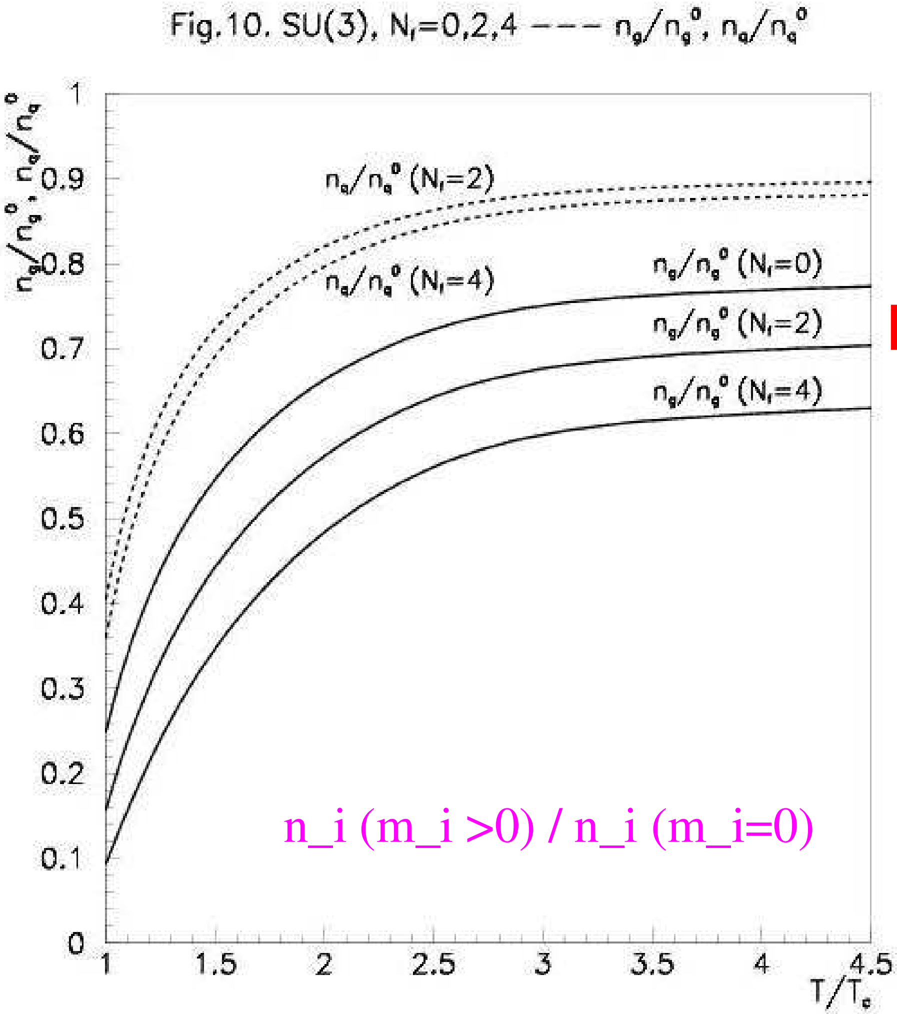
➔ Quark and antiquark dominated matter (QAP)

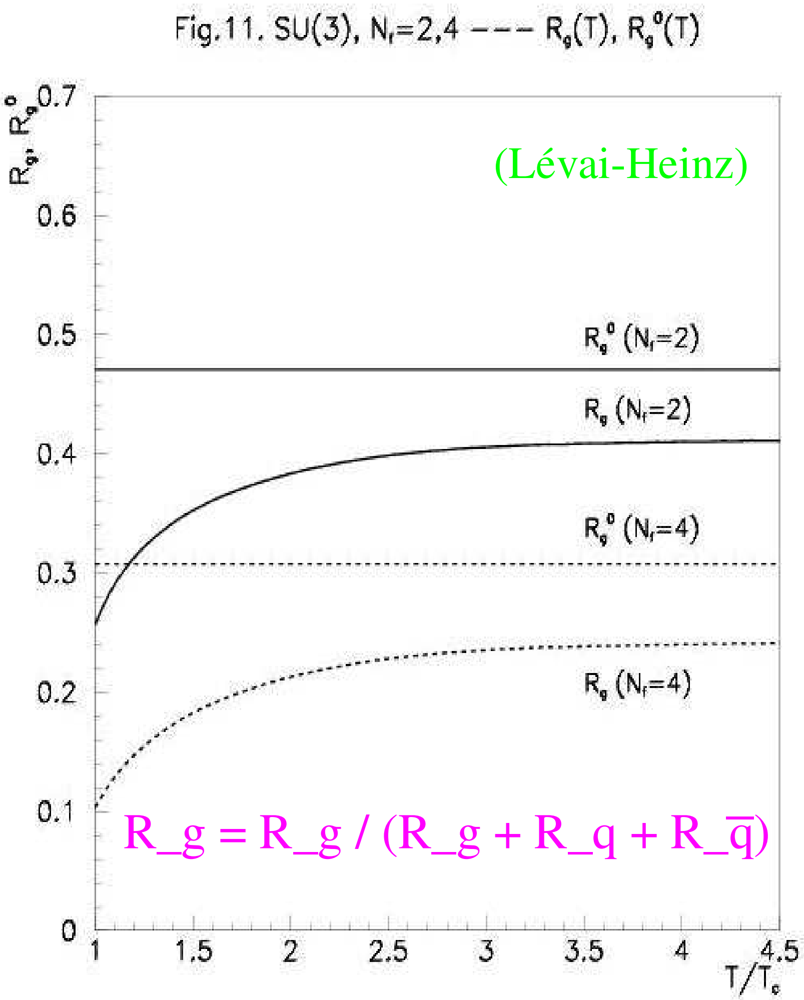
HADRONIZATION ⇔ QUARK COALESCENCE (ALCOR '95)

('Cross-over' phase transition) [T. Biró, P.L., J. Zimányi]

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 matter formation in heavy ion collisions

ALCOR model for quark matter hadronization [Biró T.,L.P., Zimányi J. 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

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

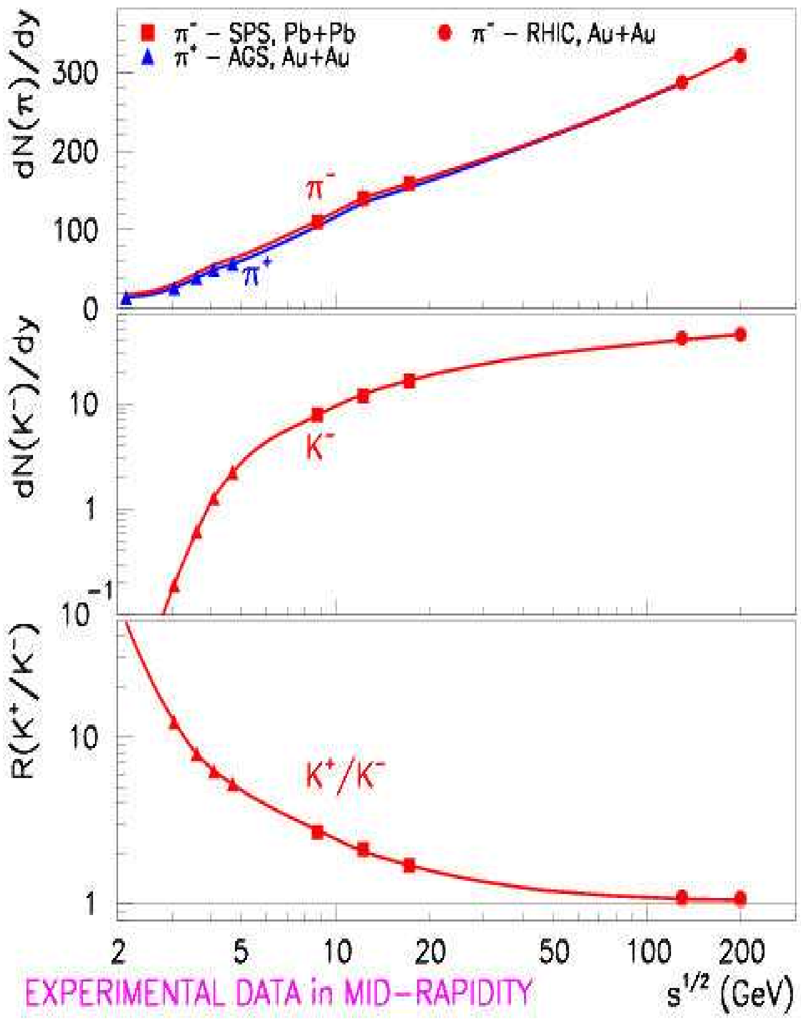
Heavy hadron resonances are produced -> decay

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

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

Quark matter formation between $\sqrt{s}$ = 5 - 200 A GeV

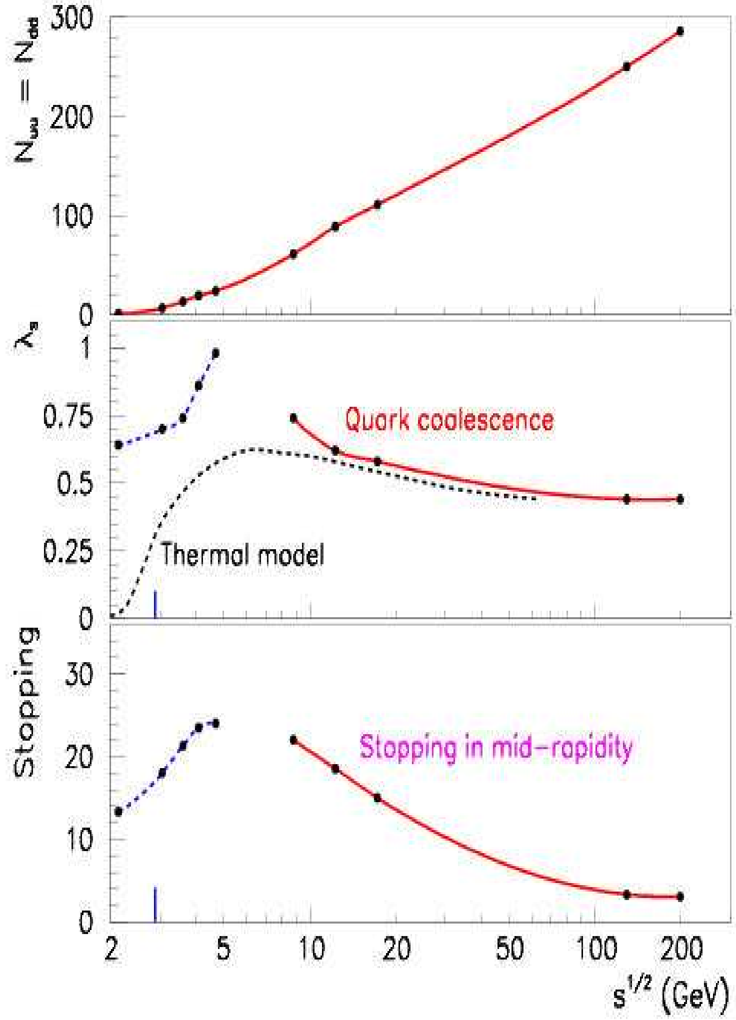
ALCOR model for quark matter hadronization [Zimányi J., Biró T.,L.P.]



N(q)

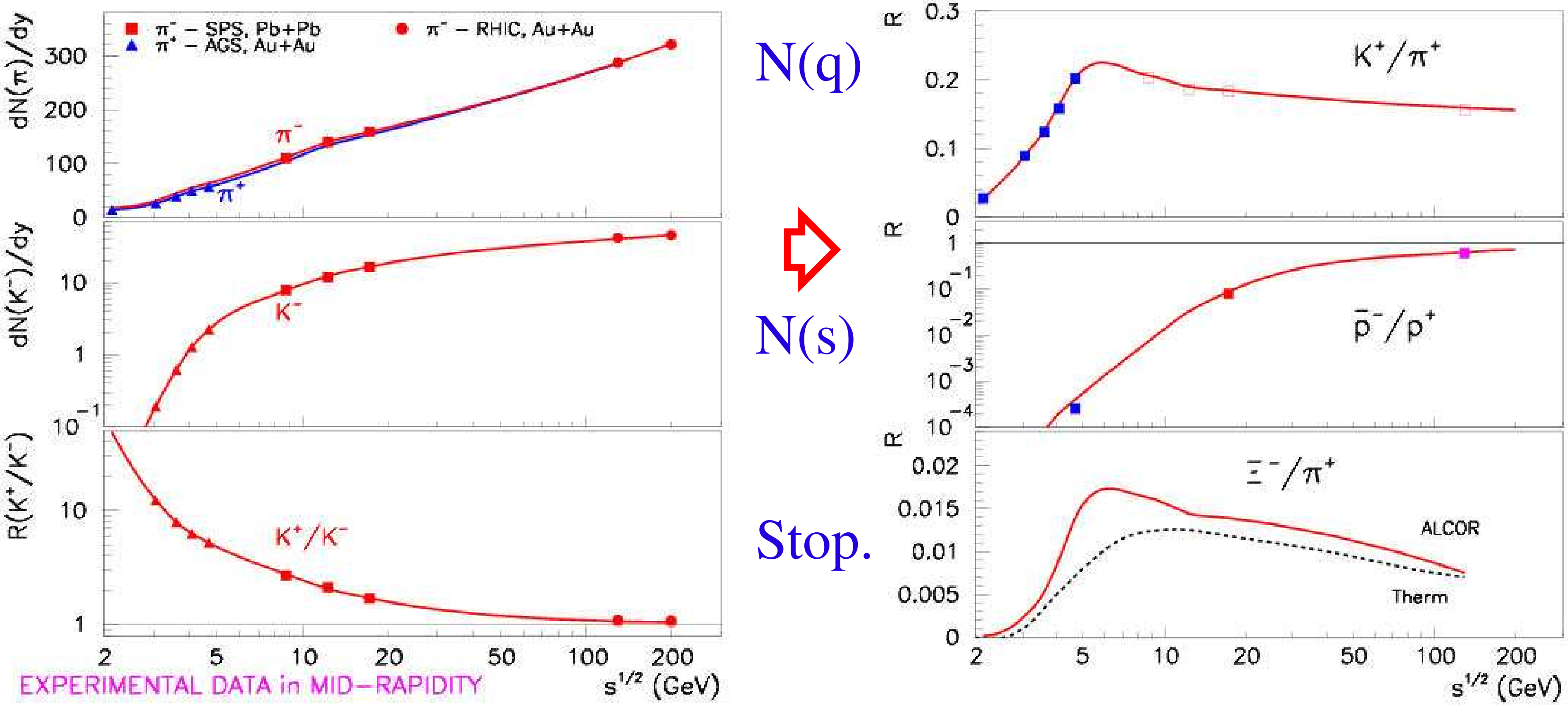
N(s)

Stop.



Quark matter formation between √s = 5 - 200 A GeV

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



Quark-coalescence reproduces most of the bulk properties
(particle numbers, ratios, their energy dependence)

What about gluons ? ⇔ QUARK ANTIQUARK PLASMA (QAP)

This description is valid for $p_T < 1.5$ GeV (99%)

It is valid at RHIC energy !

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

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

	ALCOR 130 AGeV fit	ALCOR 200 AGeV prediction
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

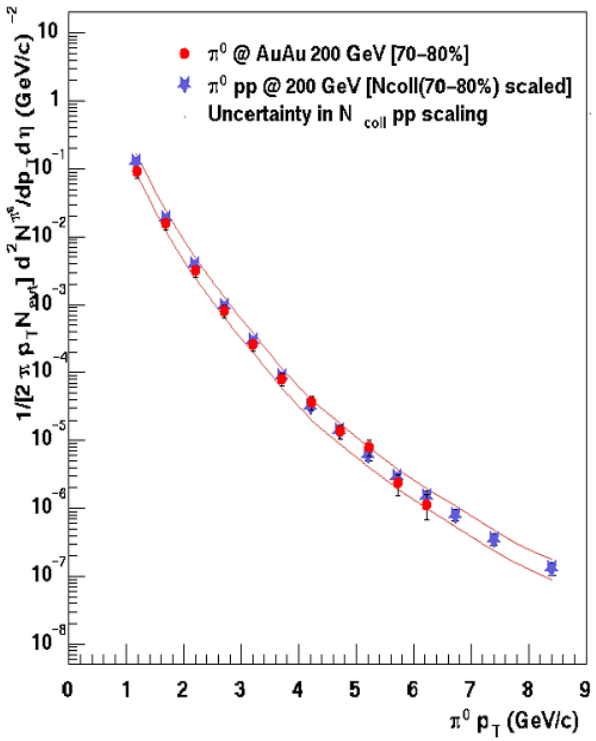
Au+Au dX/dy or R	STAR 130 AGeV	ALCOR	STAR 200 AGeV	ALCOR prediction
π^-	287 ± 20	287		322
K^-	41.9 ± 5.5	40.4		45.6
K^-/K^+	0.91 ± 0.11	0.93	0.92 ± 0.02	0.94
$\bar{\Xi}^+$	1.72 ± 0.1	1.76		2.23
$h^\pm$		690	780	780
K^+	46.2 ± 6.1	43.1		48.1
Ξ^-	2.05 ± 0.1	2.16		2.50
$(\Omega^- + \bar{\Omega}^+)$	0.55 ± 0.15	0.59		0.72
$\bar{p}^-/p^+$	0.64 ± 0.07	0.70	0.81 ± 0.05	0.76
$\bar{\Lambda}/\Lambda$	0.71 ± 0.04	0.75	0.81 ± 0.07	0.810
$\bar{\Xi}^+/\Xi^-$	0.83 ± 0.05	0.81	0.87 ± 0.06	0.86
$\bar{\Omega}^+/\Omega^-$	0.95 ± 0.15	0.88	1.01 ± 0.06	0.92
K^+/π^-	0.161 ± 0.024	0.15		0.150
K^-/π^-	0.146 ± 0.022	0.14		0.142
Λ/h^-	0.054 ± 0.001	0.047		0.050
$\bar{\Lambda}/h^-$	0.040 ± 0.001	0.037		0.042
Ξ^-/π^-	0.006 ± 0.001	0.007		0.008
K^{*0}	36.7 ± 5.5	28.5		31.7
Φ/K^{*0}	0.49 ± 0.13	0.37		0.37
Φ/K^-		0.26	0.13 ± 0.03	0.26
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)

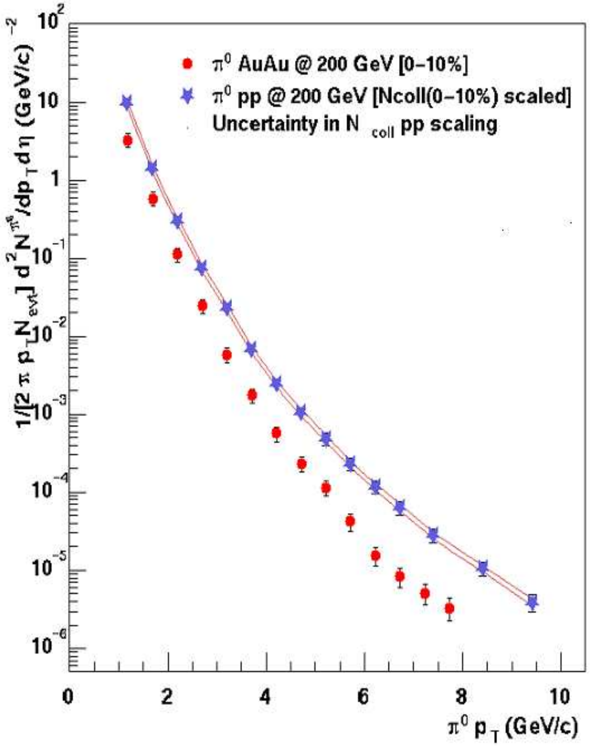
Exciting results from RHIC at $\sqrt{s}$ = 130 and 200 A GeV -- π^0

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



Peripheral coll. N(bin)=12.3±4

binary scaling is working



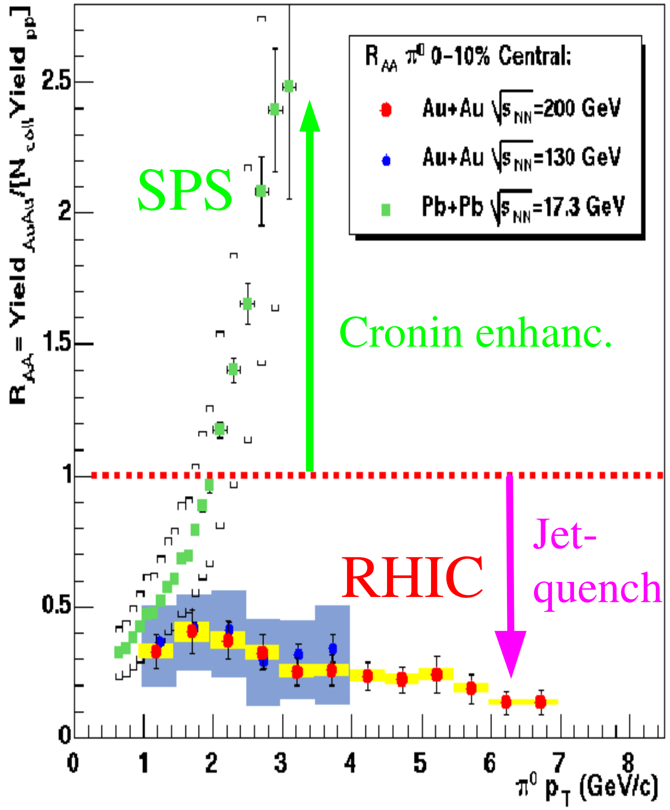
Central coll. N(bin)=975±94

binary scaling is violated

Nuclear modification factor:

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

PRL 88, 022301 (2002)



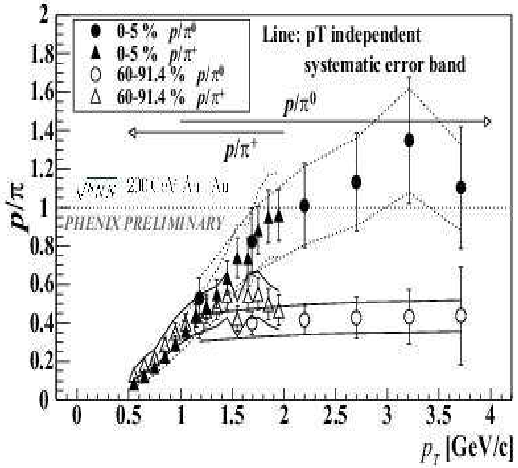
$$p_T > 6-8\,GeV: Hard\ physics - pQCD$$

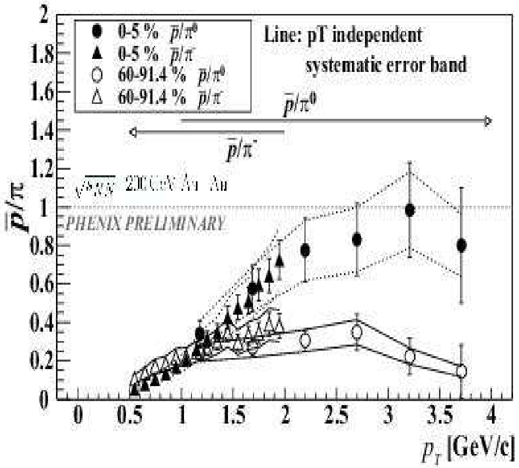
$$1.5\,GeV < p_T < 6\,GeV: Soft - hard\ overlap\,???$$

Exciting results from RHIC at √s = 130 and 200 A GeV -- $p/\pi^+, \bar{p}/\pi^-$

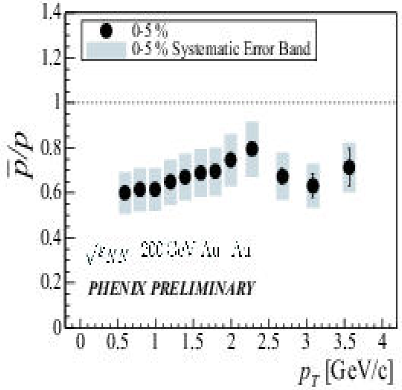
PHENIX Coll., T. Sakaguchi, nucl-ex/0209030, QM02 Conf.

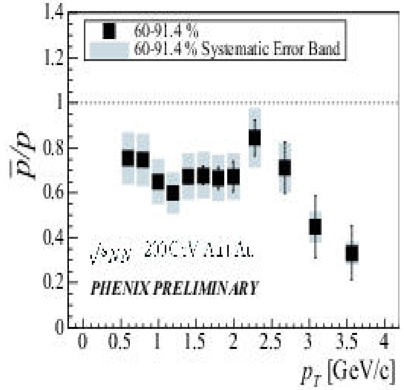
$$N(\bar{p}) > N(\pi^-) !!!$$

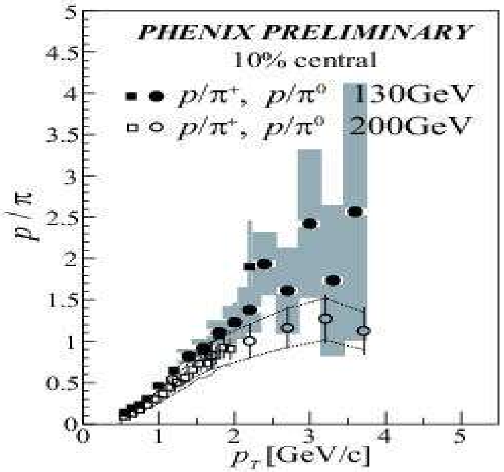


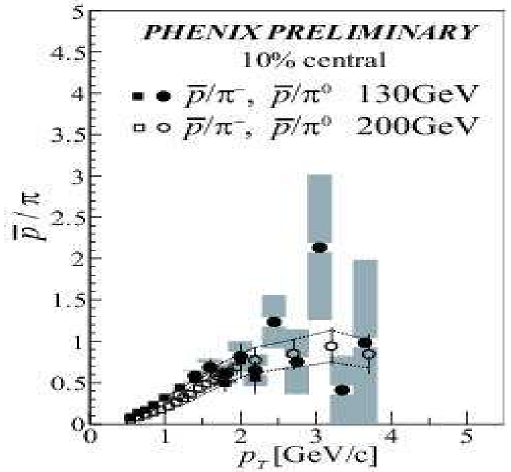


Anomalous antiproton (proton) production ??









What is the pQCD result?

What is the effect of jet-quenching ?

Where is the soft-hard limit ?

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

Perturbative QCD calculations in NLO:

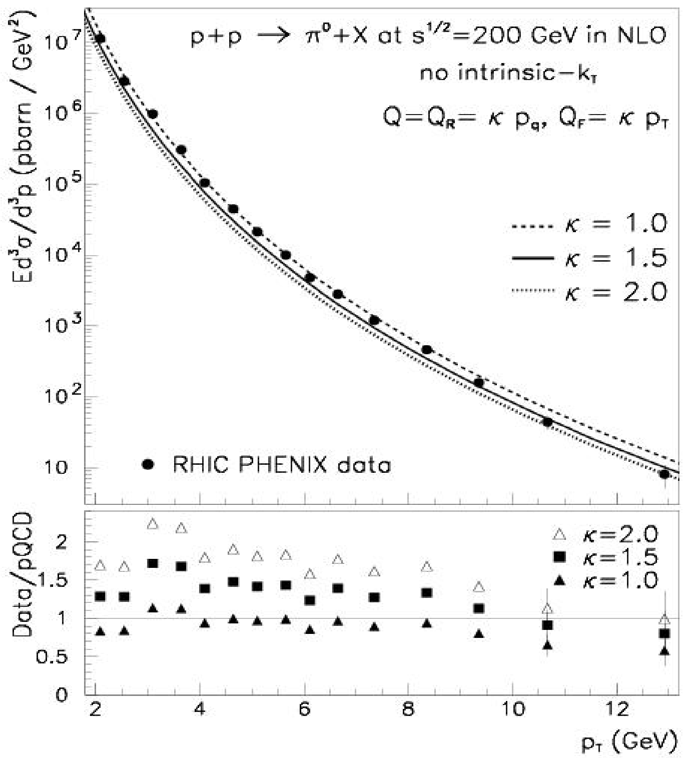
(M. Aversa et al. NPB327,105; P. Chiappetta et al. NPB412,3; P. Aurenche et al. NPB399,34; ...)

$$E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} = \int J\, dv\, dw\, dz_c \;\; f_{a/p} \;\; f_{b/p} \;\left[\frac{d\sigma^{BORN}}{dv} \delta(1-w) + \frac{\alpha_s}{\pi} K_{ab,c} \right] \;\; \frac{D_c^\pi(z_c)}{\pi z_c^2}$$

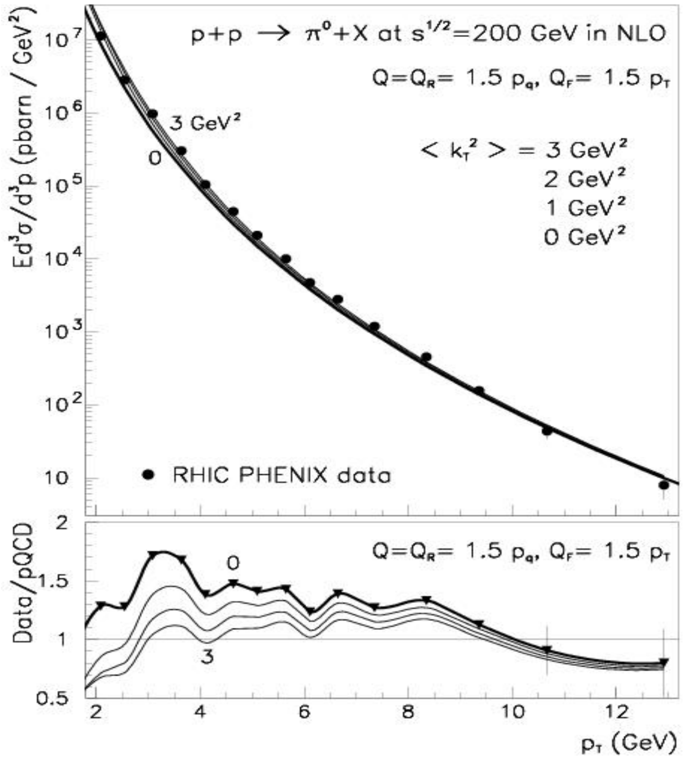
Data: PHENIX Coll., H. Torii, nucl-ex/0210005

in progress by G. Papp et al. (Budapest) (hep-ph/0212249)

Without intrinsic – k_T



with intrinsic – k_T

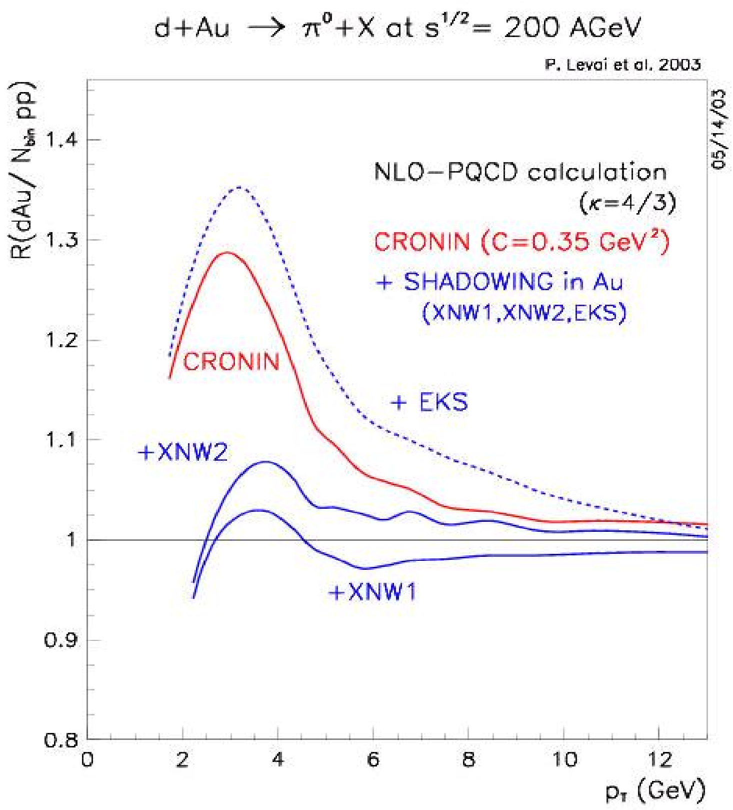


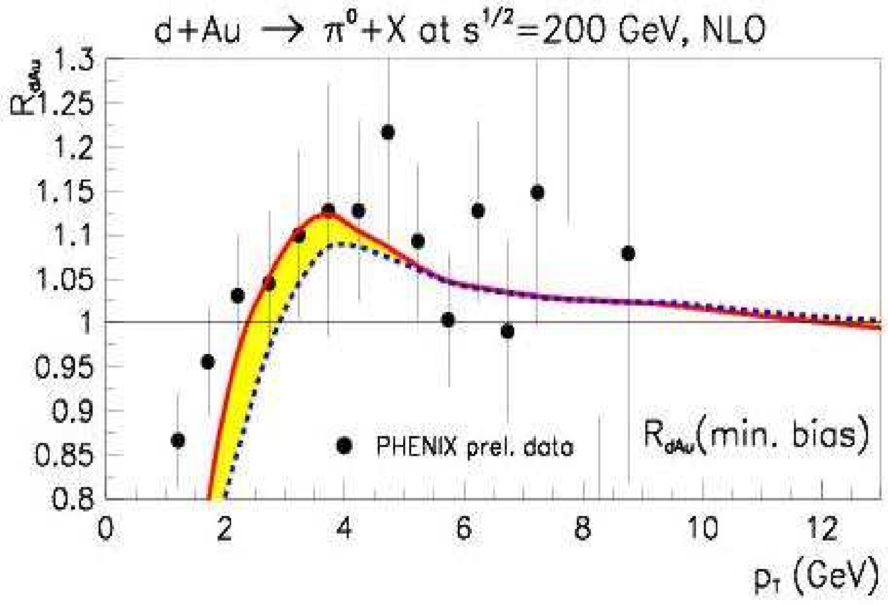
Hard physics: pion production in dAu collision at high- p_T

Perturbative QCD calculations in NLO for pp + CRONIN + SHADOWING:

in progress by P.L, G. Papp, G. Fai and G.G. Barnaföldi (Budapest)

Data: PHENIX Coll., nucl-ex/0306021

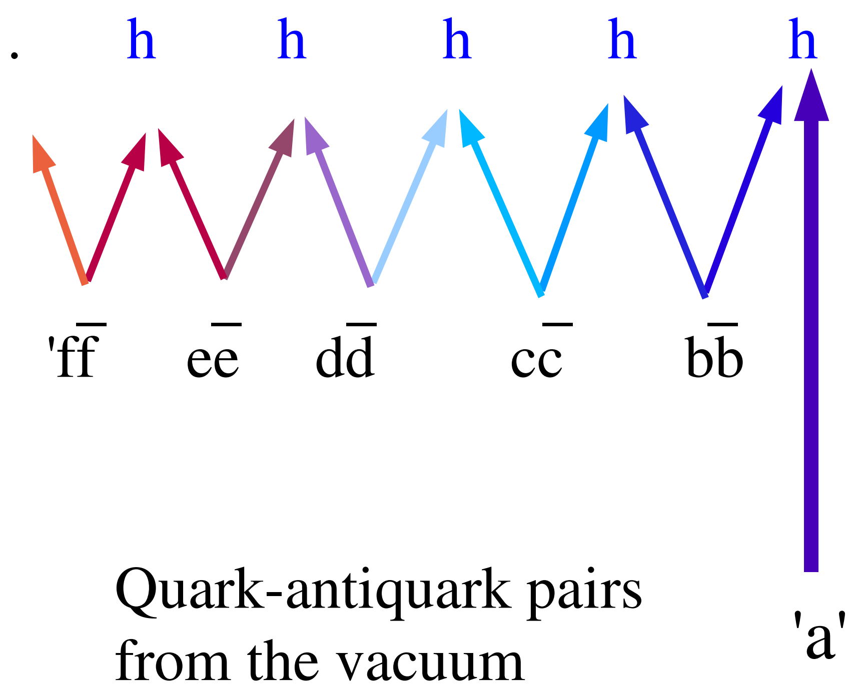




'Hard' physics: independent jet-fragmentation (FF)

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

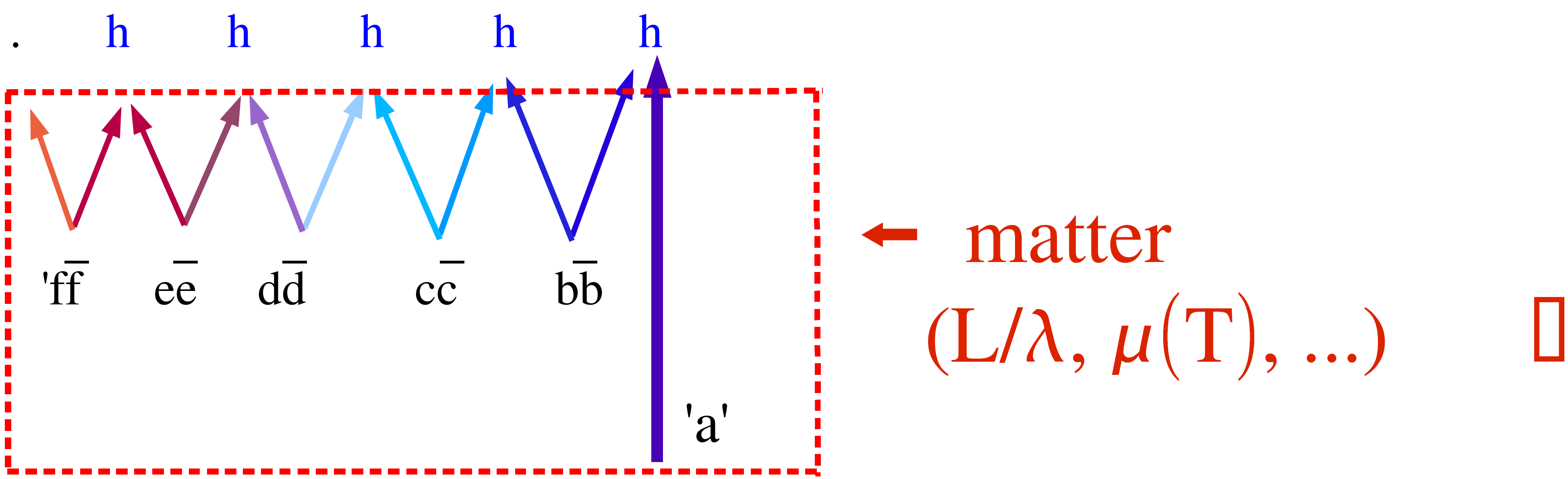


FF – parameterization of the pair creation : $D_c^h(z) = A z^{\alpha}(1-z)^{\beta}$
(selfsimilar system, PDF)

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

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

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



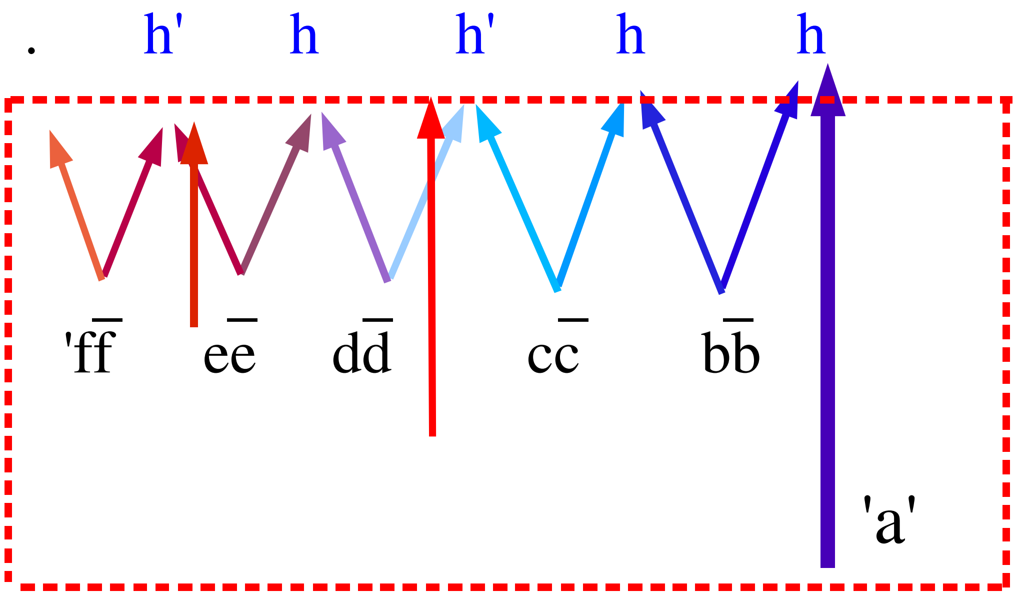
1. Induced gluon radiation ➢➢➢➢➢ jet energy loss

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

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

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: $E \Rightarrow E - \Delta E(E, L/\lambda, \mu, \ldots)$ at high p_T

2. Dense parton matter ➢➢➢➢➢ comoving partons are favoured
   jet fragmentation is screened

   Parton coalescence becomes dominant at intermediate p_T

   How to describe it microscopically ??

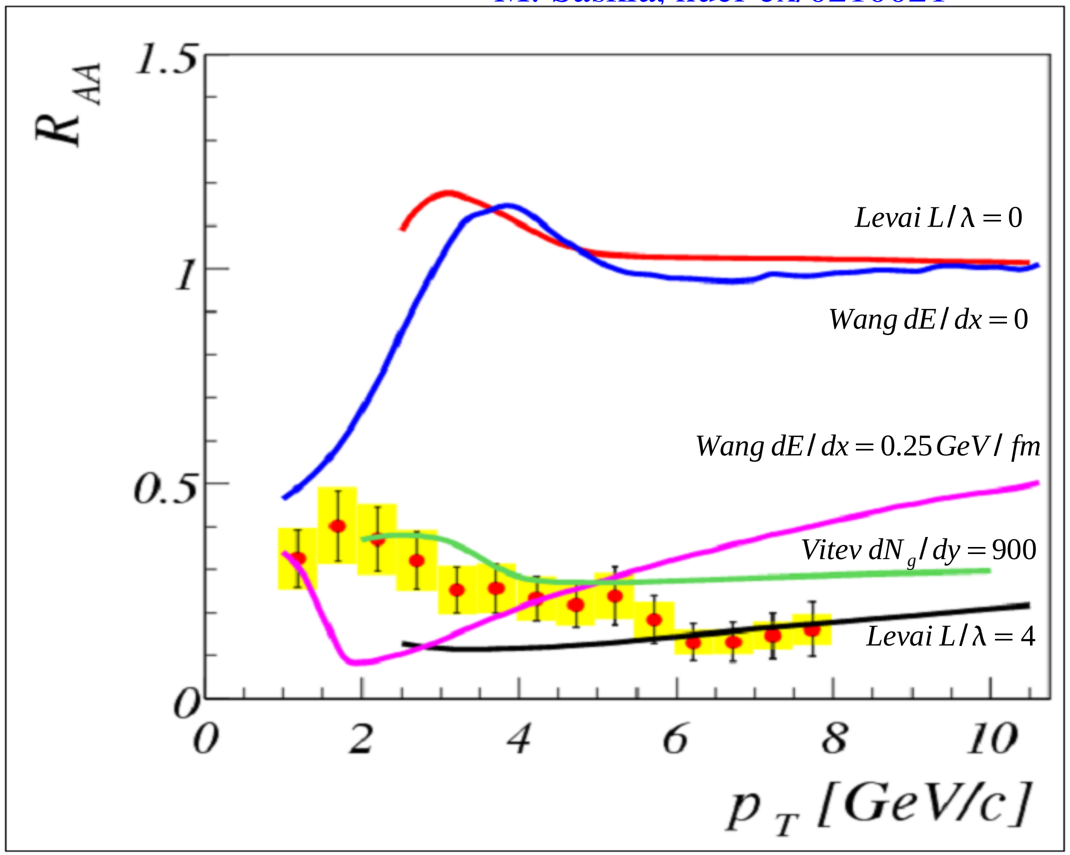
Hard physics: pion production in AA collision at high- p_T

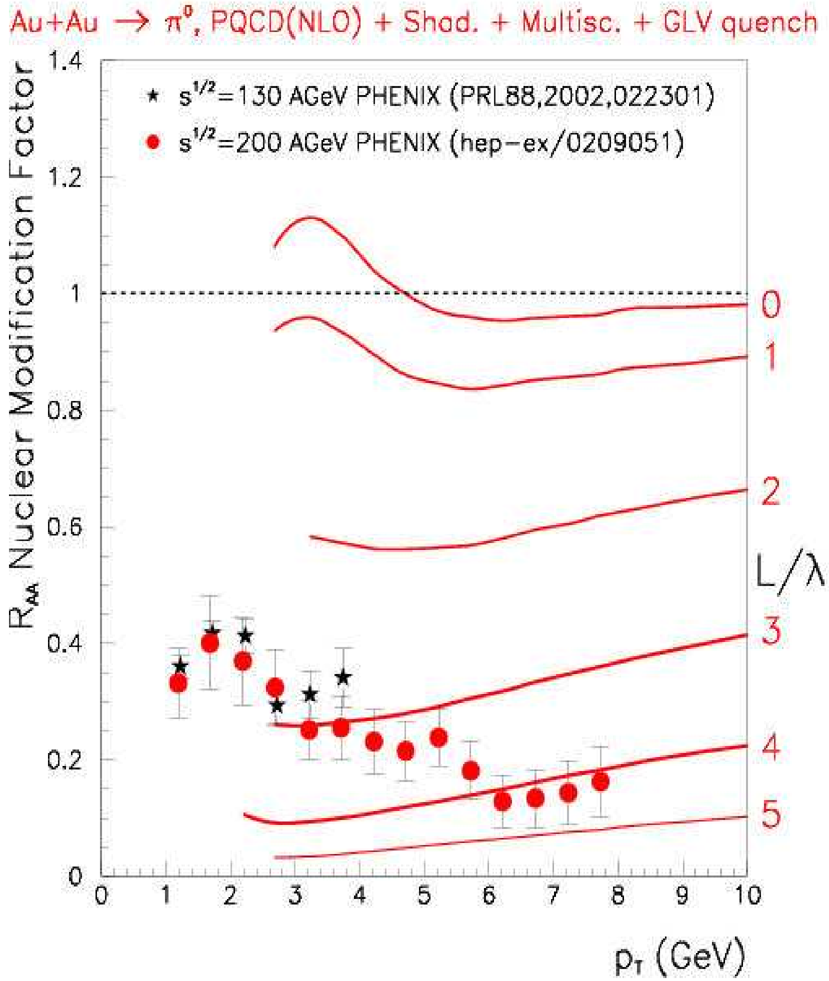
Perturbative QCD calculations in NLO for heavy ion collisions:

geometrical overlap + shadowing, multiscattring, jet-quenching, ...

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

Data: PHENIX Coll., D. d'Enterria, hep-ex/0209051
M. Saskia, nucl-ex/0210021



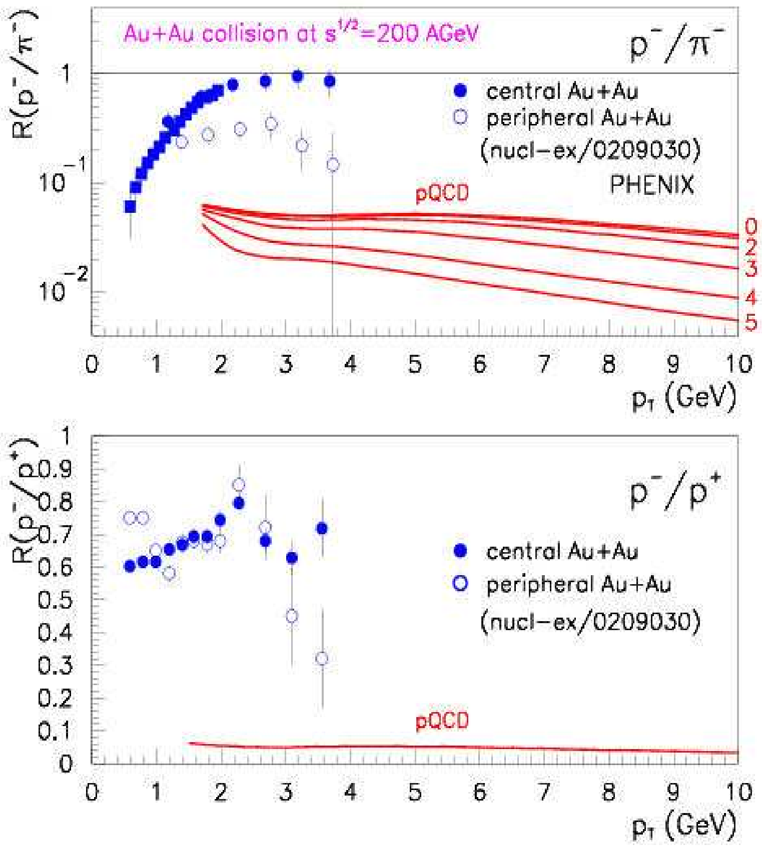


Hard physics: proton and antiproton production in AA collision

Perturbative QCD calculations in NLO for heavy ion collisions:

geometrical overlap + shadowing, multiscattring, jet-quenching, ...

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



Data: PHENIX Coll., T. Sakaguchi, nucl-ex/0209030

$$p_T \ < \ 4\,GeV$$

PQCD underpredicts data by a factor of 10 !!

- **-- even for peripheral collisions**
- **-- quenching makes it worst for central coll.**
- **-- may agree for p_T > 6 GeV or higher**
  (see previous slide for pions)

Problem has already appeared in pp collision:

X. Zhang, G. Fai, P. Levai, PRL89,272301(2002)

New production mechanism at intermediate p_T!?

1.5 GeV < p_T < 6 GeV

How to enhance baryon (antibaryon) production relative to meson's?

Basic question in HIJING and RQMD and other transport codes.

Answers:

a, String melting → Color ropes (diquark-antidiquark production is enhanced)

but at RHIC we expect deconfined state in the central rapidity

b, Junction physics: junction-antijunction pair decays into B-antiB pair

useful mechanism for baryon stopping into mid-rapidity

D. Kharzeev, M. Gyulassy, I. Vitev, ...

→ **c, Coalescence from constituent quarks and antiquarks:**

$N(B) = C * N(Q) * N(Q) * N(Q)$

$N(M) = C' * N(Q) * N(\bar{Q})$ **It works well (ALCOR, MICOR,...)**

J. Zimanyi, T.S. Biro, P. Csizmadia, P. Levai, ...

A. Bialas, J. Pisut, R. C. Hwa, C.B. Yang, ...

d, PQCD with relatively enhanced intrinsic k_T

too much phenomenology

X. Zhang, G. Fai, P. Levai, ...

e, PQCD with modified fragmentation function (D_h/c)

.....

Parton coalescence for hard pion and proton (anti-p) production

Basic assumptions:

A, Deconfined matter was formed, partons are good degrees of freedom;

B, Momenta are large enough to neglect hadron masses;

1.5 GeV < p_T < 6-8 GeV (semi-hard p_T region)

C, Momentum correlation (space correlation) drives hadronization;

momentum correlation (Δ) ↔ hadron size (R)

PROGRAMME:

1, Initial parton distributions in central Au+Au collisions

- **p+p → g, u, ~~u~~, ... [PDF, d/dt]**
- **Au+Au → g, u, ~~u~~, ... [shadowing, multiscatterings, ...]**
- **parton distribution at low p_T**

2, Many - body processes for partons during collisions

- **parton energy loss in Au+Au at high p_T**
- **thermalization at low p_T**

3, Parton coalescence into hadrons:

- **coalescence equation for partons (linear coalescence)**
- **meson and baryon production (e.g. q+q+q → B)**
- **dependence on the Δ(M) and Δ(B)**
- **measurable signatures for coalescence (ratios, p_T dependence)**
- **overlap with low-p_T region (non-linear coalescence)**

Parton coalescence: meson production

V. Greco, C.M. Ko, P. Levai, (nucl-th/0301093)

Basic coalescence equation: $1 + 2 \to M$

$$\frac{dN_M}{d^3P_M} = g_M \int d^3r_a d^3r_b \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3} f_1^W(\vec{p}_1,\vec{r}_a)\; f_2^W(\vec{p}_2,\vec{r}_b) \cdot \delta^3(\vec{P}_M - \vec{p}_1 - \vec{p}_2)\; \mathcal{F}_M^W(\vec{r}_a - \vec{r}_b, \vec{p}_1 - \vec{p}_2)$$

f_i^W: the Wigner function of parton i $(\to dN_i/d^3p)$

$\mathcal{F}_M^W$: the Wigner function of the produced meson M $(\to$ box-like$)$

$$\mathcal{F}_M(\vec{r}_a - \vec{r}_b, \vec{p}_1 - \vec{p}_2) = \frac{1}{\Delta_p^3\,\Gamma_r^3}\frac{9\pi}{2}\Theta(\Delta_p - |\vec{p}_1 - \vec{p}_2|)\cdot\Theta(\Gamma_r - |\vec{r}_a - \vec{r}_b|)\,,$$

Δ_p: a sharp cutoff in the relative momenta

Γ_r: a correlation length in space (the size of the meson)

Longitudinally invariant coalescence rate:

$$\frac{dN_M}{d^2P_M} = \frac{g_M}{V}\frac{6\pi^2}{\Delta_p^3}\int d^2p_1\, d^2p_2\, \frac{dN_1}{d^2p_1}\frac{dN_2}{d^2p_2}\,\delta^2(\vec{P}_{M,\perp} - \vec{p}_{1,\perp} - \vec{p}_{2,\perp})\,\Theta(\Delta_p - |\vec{p}_1 - \vec{p}_2|)\,.$$

Transverse explosion: comoving partons are able to coalesce, $\Phi_1 = \Phi_2$

$$\frac{dN_M}{2\pi P_{M,\perp} dP_{M,\perp}} = \frac{g_M}{V}\frac{6\pi^2}{\Delta_M^3}\int p_{1,\perp}dp_{1,\perp}\, p_{2,\perp}dp_{2,\perp}\,\frac{dN_1}{2\pi p_{1,\perp}dp_{1,\perp}}\,\frac{dN_2}{2\pi p_{2,\perp}dp_{2,\perp}} \cdot \frac{1}{P_{M,\perp}^2}\,\delta\left(1 - \frac{p_{1,\perp} + p_{2,\perp}}{P_{d,\perp}}\right)\,\Theta(\Delta_M - |p_{1,\perp} - p_{2,\perp}|)$$

R.C. Hwa, C.B. Yang, (nucl-th/0211010)

R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, (nucl-th/0301087)

Parton coalescence: baryon production

G. K. L. (nucl-th/0301093)

Basic coalescence equation: $1+2+3 \longrightarrow B$

$$\frac{dN_B}{d^3P_B} = g_B \int d^3r_1\, d^3r_2\, d^3r_3 \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}\frac{d^3p_3}{(2\pi)^3}\; f_1^W(\vec{p}_1,\vec{r}_1)\; f_2^W(\vec{p}_2,\vec{r}_2)\; f_3^W(\vec{p}_3,\vec{r}_3)$$
$$\cdot\, \delta^3(\vec{P}_B - \vec{p}_1 - \vec{p}_2 - \vec{p}_3)\; \mathcal{F}_B^W(\vec{\rho},\vec{\lambda};\vec{q}_\rho,\vec{q}_\lambda)$$

f_i^W: the Wigner function of parton i $\quad(\to dN_i/d^3p)$

$\mathcal{F}_B^W$: the Wigner function of the produced baryon B $\quad(\to$ box-like$)$

$$\mathcal{F}_B(\vec{\rho},\vec{\lambda};\vec{q}_\rho,\vec{q}_\lambda) = \frac{1}{\Delta_\rho^3\,\Gamma_\rho^3}\frac{9\pi}{2}\,\Theta(\Delta_\rho - |\vec{q}_\rho|)\cdot\Theta(\Gamma_\rho - |\vec{\rho}|)\,\cdot$$
$$\cdot\,\frac{1}{\Delta_\lambda^3\,\Gamma_\lambda^3}\frac{9\pi}{2}\,\Theta(\Delta_\lambda - |\vec{q}_\lambda|)\cdot\Theta(\Gamma_\lambda - |\vec{\lambda}|)\,.$$

$\Delta_\rho, \Delta_\lambda$: sharp cutoffs in the relative momenta

$\Gamma_\rho, \Gamma_\lambda$: correlation lengths in space ($\sim$ the size of the meson)

Longitudinally invariant coalescence rate:

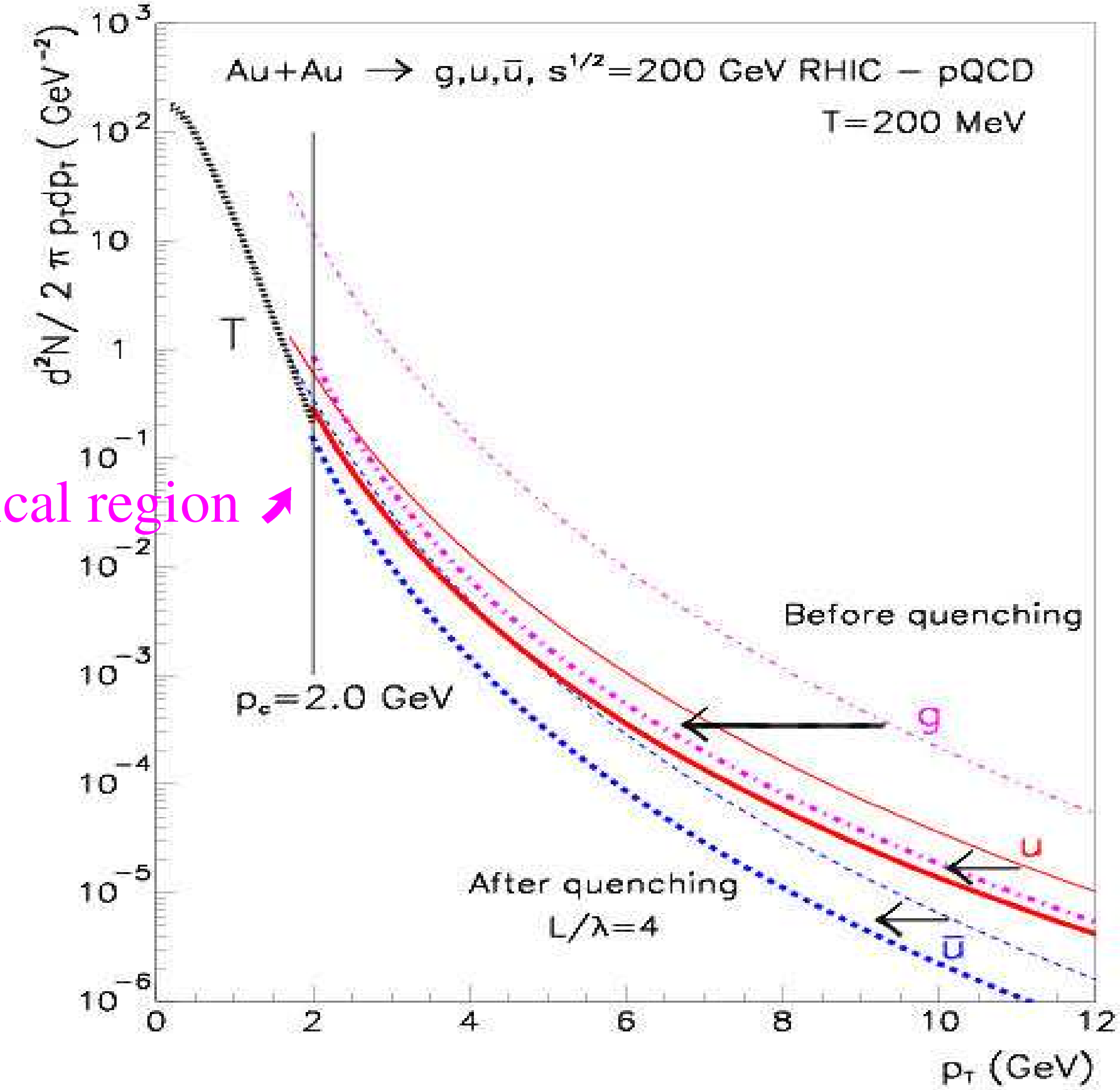
$$\frac{dN_B}{d^2P_B} = \frac{g_B}{V^2}\frac{36\pi^4}{\Delta_\rho^3\,\Delta_\lambda^3}\int d^2p_1\, d^2p_2\, d^2p_3 \frac{dN_1}{d^2p_1}\frac{dN_2}{d^2p_2}\frac{dN_3}{d^2p_3}$$
$$\cdot\,\delta^2(\vec{P}_{B,\perp} - \vec{p}_{1,\perp} - \vec{p}_{2,\perp} - \vec{p}_{3,\perp})\,\cdot\,\Theta(\Delta_\rho - |\vec{q}_{\rho,\perp}|)\cdot\Theta(\Delta_\lambda - |\vec{q}_{\lambda,\perp}|)\,.$$

Transverse explosion: comoving partons are able to coalesce. $\Phi_1 = \Phi_2 = \Phi_3 = \Phi_B$

$$\frac{dN_B}{2\pi P_{B,\perp}dP_{B,\perp}} = \frac{g_B}{V^2}\frac{36\pi^4}{\Delta_B^6}\int p_{1,\perp}dp_{1,\perp}\; p_{2,\perp}dp_{2,\perp}\; p_{3,\perp}dp_{3,\perp} \prod_{i=1,2,3}\frac{dN_i}{2\pi p_{i,\perp}dp_{i,\perp}}$$
$$\cdot\,\frac{1}{P_{B,\perp}^2}\,\delta\left(1 - \frac{p_{1,\perp}+p_{2,\perp}+p_{3,\perp}}{P_{B,\perp}}\right)\prod_{i=1,2,3}\Theta_i(\Delta_B - |p_{i,\perp} - p_{i+1,\perp}|)$$

Parton coalescence: initial parton distributions

G. K. L. (nucl-th/0301093)



Critical region ↗

After quenching:

radiated gluons ➡
thermal bath (T=200 MeV)

dE_T/dy (y=0) = 570 GeV

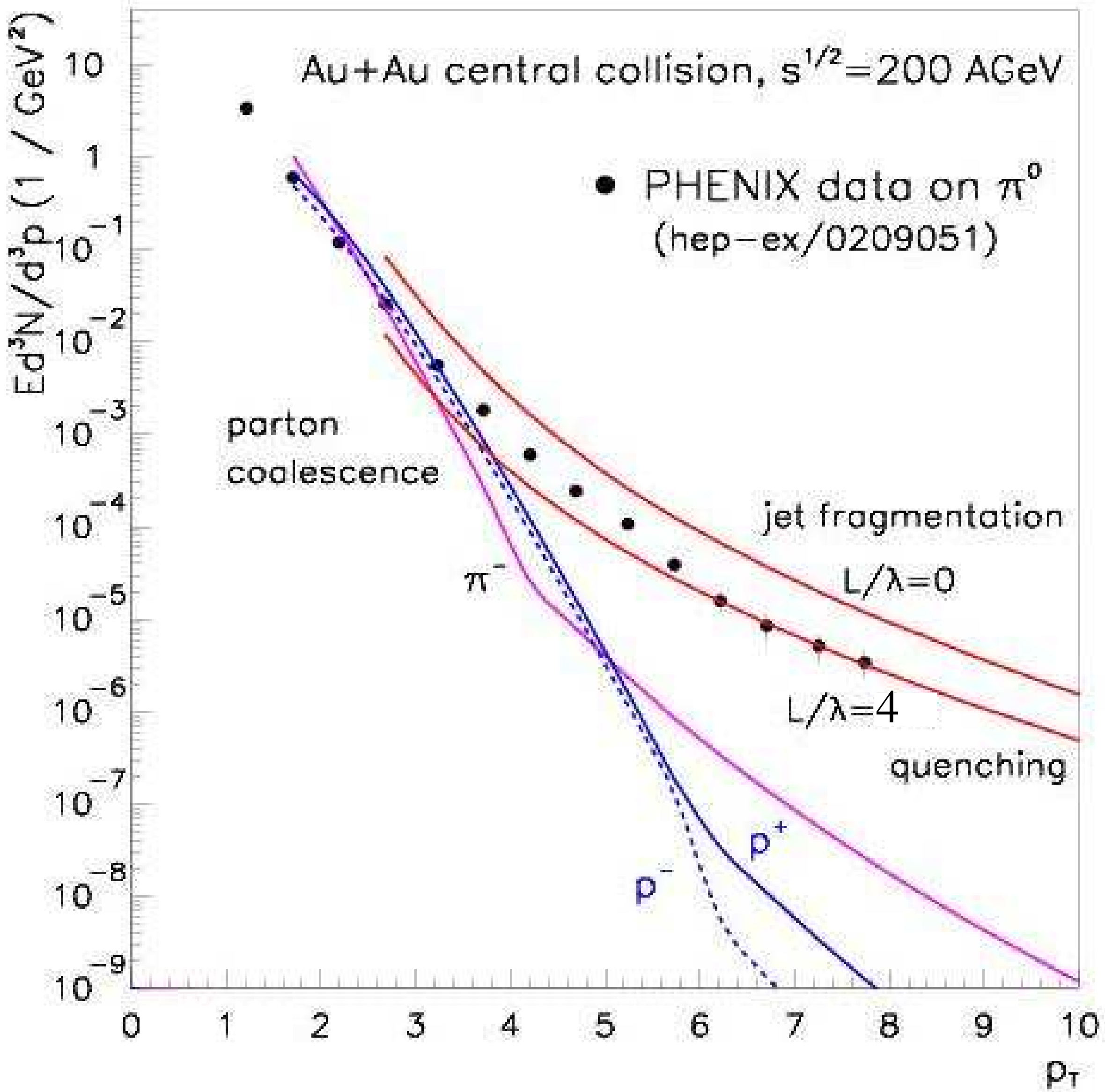
Modification in parton spectra
is shifted to higher hadron p_T:

$$p_T(parton) \Leftrightarrow \frac{p_T(M)}{2}$$

$$p_T(parton) \Leftrightarrow \frac{p_T(B)}{3}$$

Parton coalescence: final pion, proton and antiproton distributions

G. K. L. (nucl-th/0301093)



Intermediate p_T region:

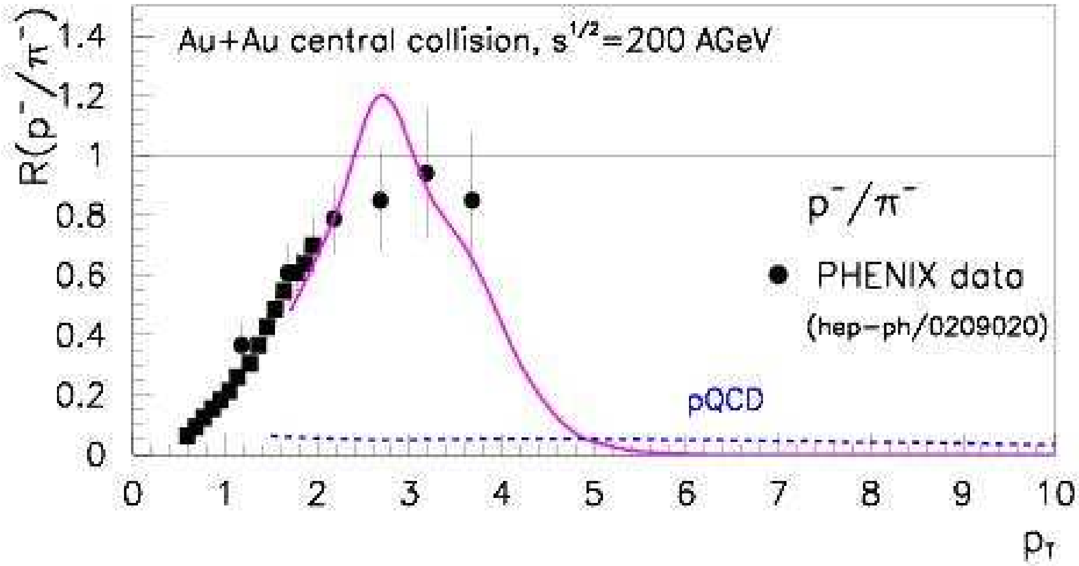
parton coalescence
is more effective, than
jet fragmentation,
especially for baryons

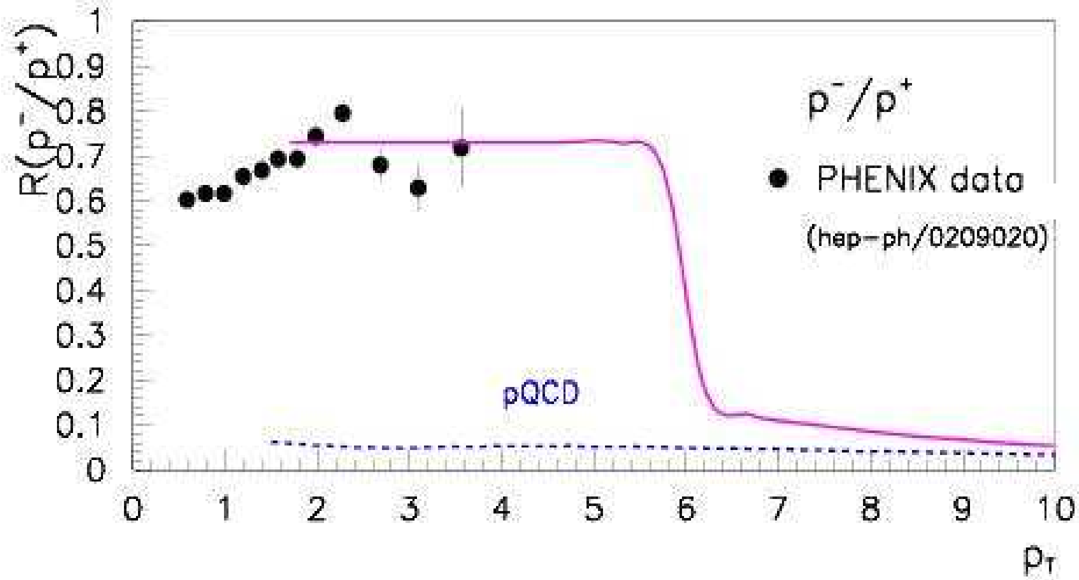
➡ it can explain
antiproton/pion
anomaly

+ suppression pattern
in pion spectra
at p_T= 1-5 GeV

Parton colescence: antiproton/pion and antiproton/proton ratio

G. K. L. (nucl-th/0301093)





Intermediate (coalescence) region:

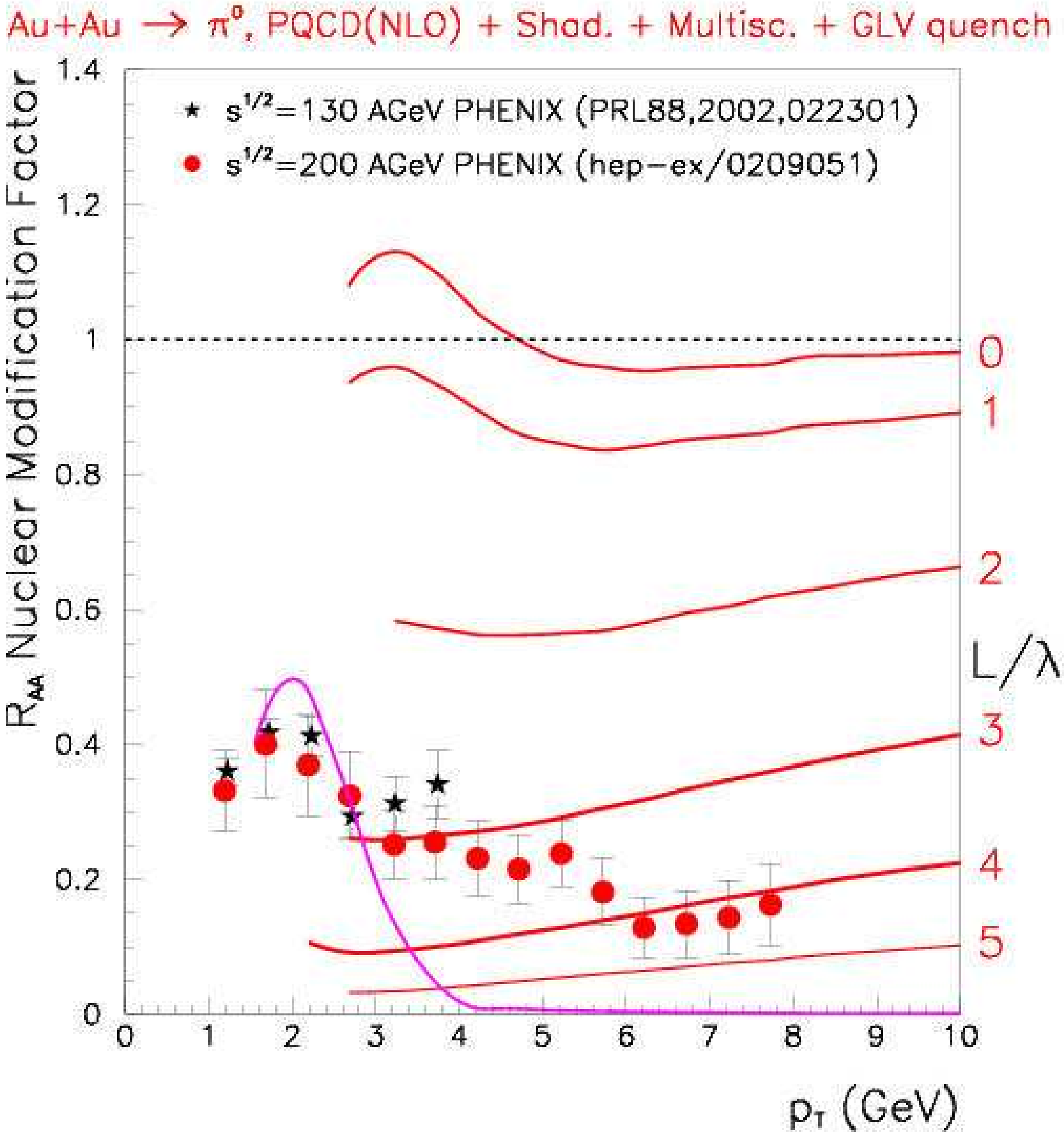
Location of the drop in
the antiproton/pion ratio:

- ☞ end of the intermediate region
- ☞ information about the partonic thermal bath (T, flow)
- ☞ shape analysis (details)

The edge of the drop in
the antiproton/proton ratio:

- ☞ p_c partonic cut-off
- ☞ Δ_p momentum window in the coalescence process

Parton colescence: R_AA nuclear modification factor



Intermediate (coalescence) region:

Location of the drop in
the R_AA factor:
(similarly to the ratios)

- ☞ end of the intermediate region
- ☞ information about the partonic thermal bath (T, flow)
- ☞ shape analysis (details)
- ☞ Δ_p momentum window in the coalescence process (crucial parameter)

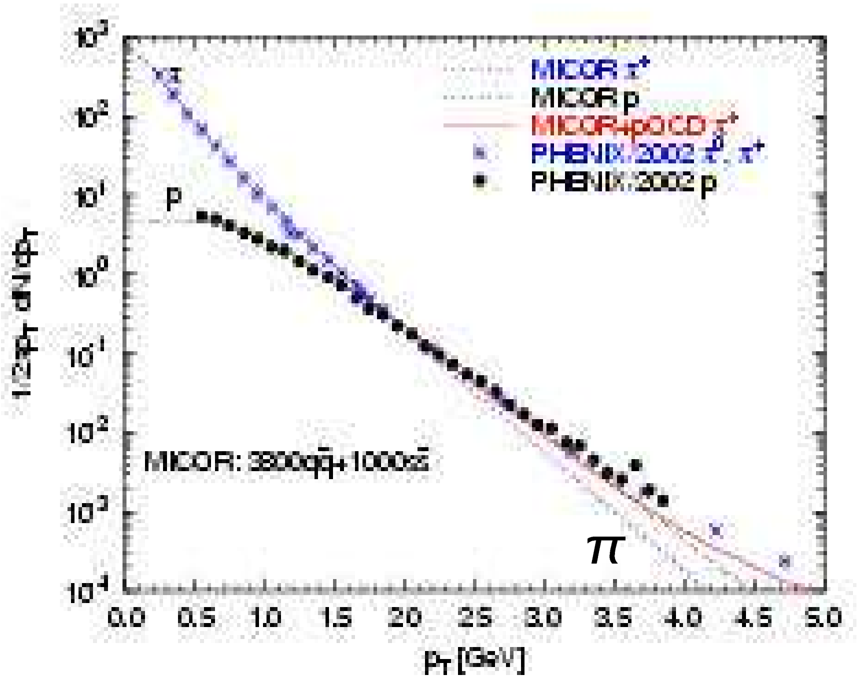
Question:
directly produced pions ?
Or directly produced resonances will decay into pions ?
Answer: MICOR model
P. Csizmadia, P. L.

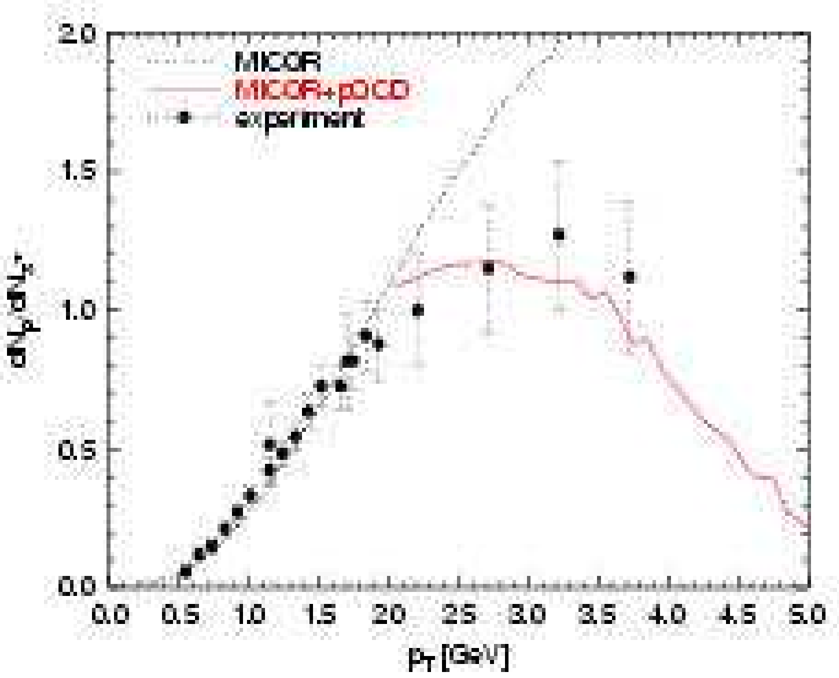
Quark coalescence at high p_T: MICOR + pQCD model

e.g. . proton/pion ratio P. Csizmadia, P.L. '03

MICOR model : quark-coalescence **(0 < p_T < 4-5 GeV)**

+ pert. QCD : + independent jet-fragment. **(2 < p_T < 10-20 GeV)**





MICOR: pion yield is decreasing faster than proton yield with increasing p_T

pQCD: FF pion yield is comparable with coal. yield, FF proton yield is negligible

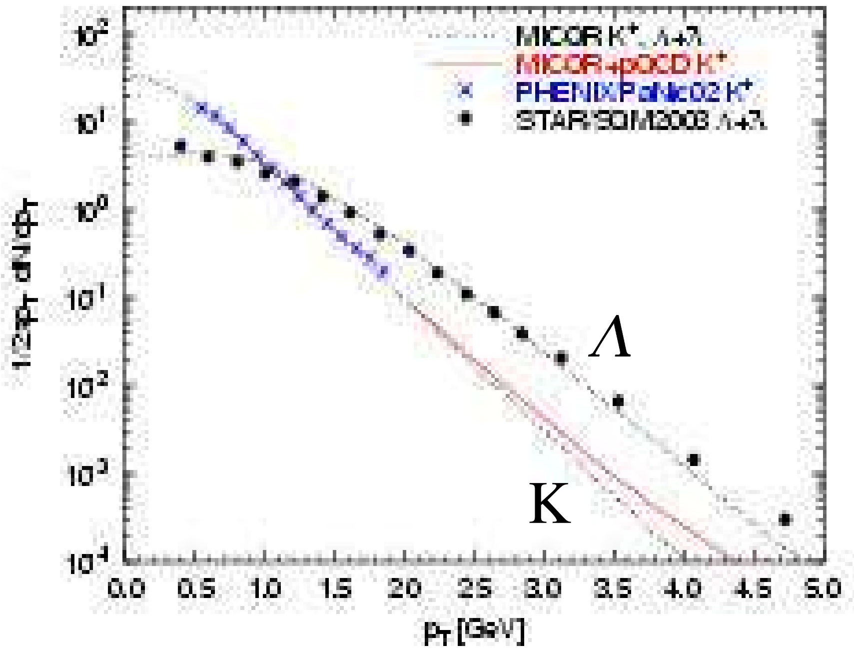
superposition: special structure in proton/pion ratio

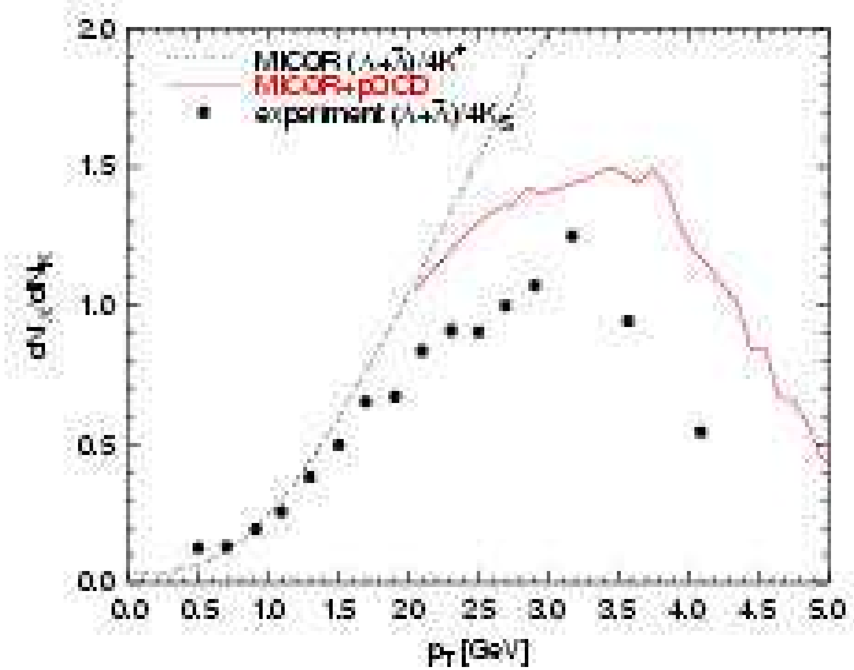
Quark coalescence at high p_T: MICOR + pQCD

Lambda/kaon arány P. Csizmadia, P.L. '03

MICOR model : quark-coalescence **(0 < p_T < 4-5 GeV)**

+ pert. QCD : + indep. Jet-fragmentation **(2 < p_T < 10-20 GeV)**





MICOR: kaon yield is decreasing faster then Λ-s with increasing p_T

pQCD: kaon yield comparable with coalescence rate, Λ yield is negligible

superposition: **Λ/K ratio display similar structure than proton/pion**

SUMMARY:

1. Three different region in particle production:
   - I. Soft region ($p_T < 1$ GeV)
     - Thermodynamics, hydrodynamics, ...
     - ALCOR-type quark coalescence (mass, T and V(r) are important)
   - II. Intermediate region ($1 < p_T <$ 5-6 GeV)
     - Parton coalescence driven by quantum mechanics is important (Gribov)
     - Jet partons participate in recombination with neighbour comovers
   - III. Hard region ($p_T >$ 5-6 GeV)
     - Perturbative QCD can be applied (PDF, FF, jet-quenching, ...)
     - Independent fragmentation is dominant

2. This picture is supported by
   - a, Pion suppression pattern
   - b, Antiproton/pion enhancement
   - c, Antiproton/proton ratio and its p_T dependence (have to be measured)
   - d, Elliptic flow phenomena

3. Further studies are needed (resonances, details in coalescence process,...)

4. Further data are needed in the region 3 GeV $< p_T <$ 6-8 GeV at RHIC

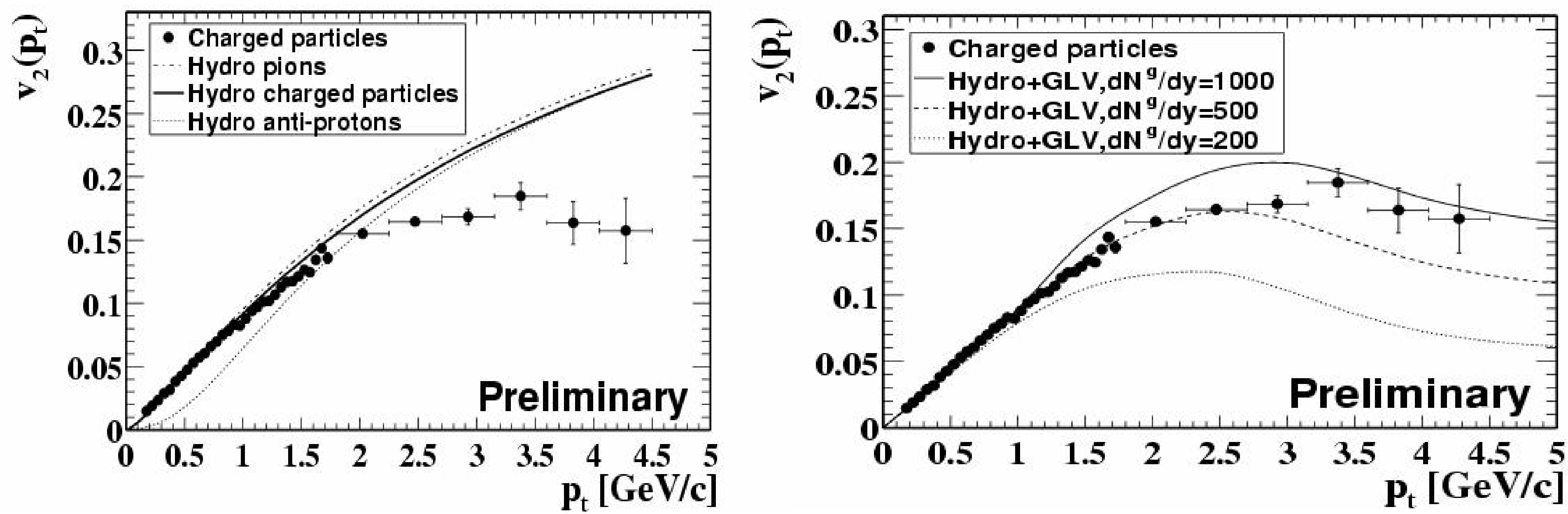
Exciting results from RHIC at √s = 130 and 200 AGeV -- v_2

Elliptic flow (anisotropy in momentum space):

$$v_2(p_T) = \langle \cos(2\phi) \rangle_{p_T} \equiv \frac{\int_{-\pi}^{\pi} d\phi\ \cos(2\phi)\ \frac{d^3N}{dy\, p_t\, dp_t\, d\phi}}{\int_{-\pi}^{\pi} d\phi\ \frac{d^3N}{dy\, p_t\, dp_t\, d\phi}}$$

STAR data at 130 A GeV

(Nucl.Phys. A698 (2002) 193-198)



Parton colescence: elliptic flow

D.Molnar, S.A. Voloshin, (nucl-th/0302014)

Quark coalescence:

$$\frac{dN_B}{d^2p_\perp}(\vec{p}_\perp) = C_B\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/3)\right]^3$$
$$\frac{dN_M}{d^2p_\perp}(\vec{p}_\perp) = C_M\left[\frac{dN_q}{d^2p_\perp}(\vec{p}_\perp/2)\right]^2$$

where the coefficients C_M and C_B are the probabilities for $q\bar{q} \to meson$ and $qqq \to baryon$ coalescence.

Anisotropic flow.
In the coalescence region, meson and baryon elliptic flow

$$v_{2,M}(p_\perp) \approx 2v_{2,q}(\frac{p_\perp}{2}), \qquad v_{2,B}(p_\perp) \approx 3v_{2,q}(\frac{p_\perp}{3}) .$$

If partons have only elliptical anisotropy, i.e., $dN_q/p_\perp dp_\perp d\Phi = (1/2\pi)dN_q/p_\perp dp_\perp[1 + 2v_{2,q}\cos(2\Phi)]$, then

$$v_{2,B}(p_\perp) = \frac{3v_{2,q}(p_\perp/3)}{1+6v_{2,q}^2(p_\perp/3)}$$
$$v_{2,M}(p_\perp) = \frac{2v_{2,q}(p_\perp/2)}{1+2v_{2,q}^2(p_\perp/2)} .$$

Coalescence region:

Starting from a mutual p_T spectra for quarks to produce mesons and/or baryons

☞ if elliptic flow exist for quarks then it will be herited for in different ways for mesons and for baryons

$$v_{2,B}(p_T) > v_{2,M}(p_T)$$

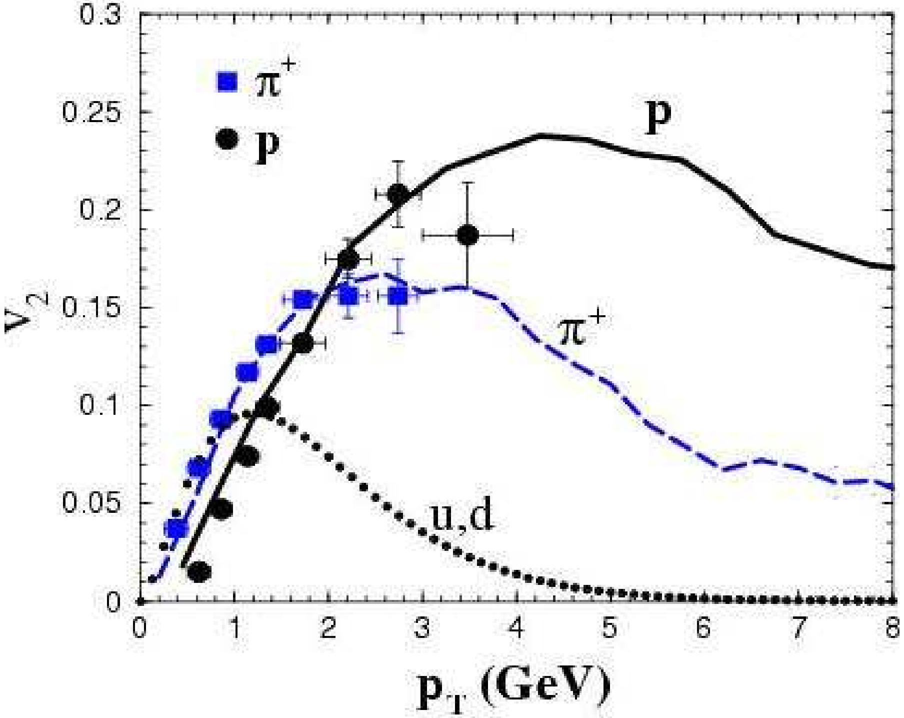
☞ different flows for
different quark flavours :
splitting in hadronic v_2

$$v_{2,p} > v_{2,\lambda}$$

Parton colescence: elliptic flow

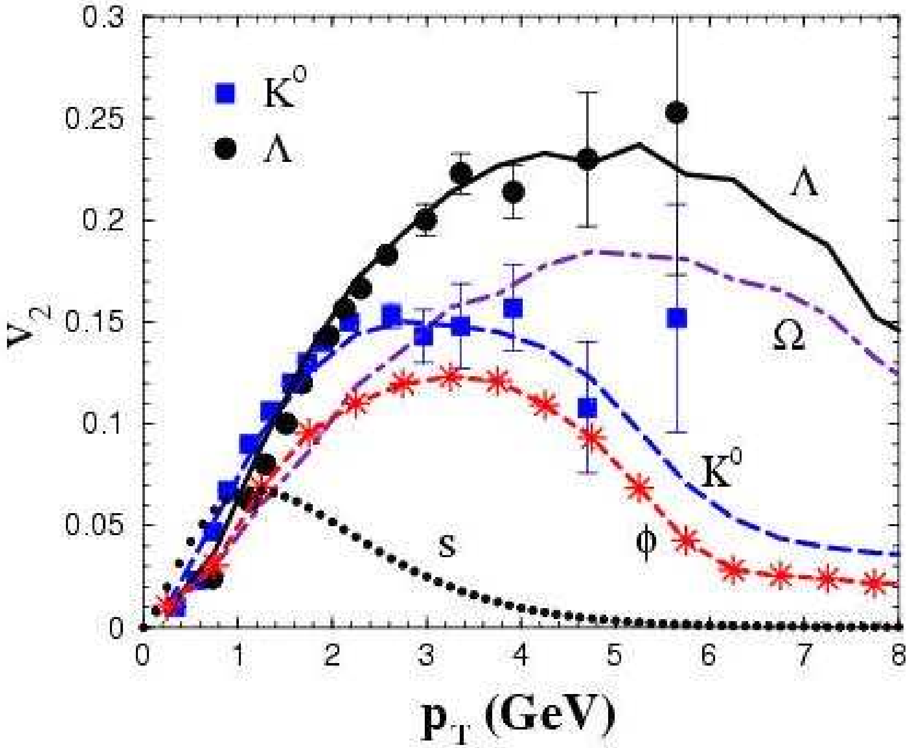
V. Greco, C.M. Ko, P. Levai (nucl-th/0305024)

Data: S. Esumi (PHENIX), nucl-ex/0210012



$$v_{2,p}(p_T) > v_{2,\pi}(p_T)$$

Data: R. Snellings (STAR), nucl-ex/0305001



$$v_{2,\lambda}(p_T) > v_{2,K}(p_T)$$