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

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What was produced in the center of the collision?

Hot QCD matter
(QGP, CQM, QAP, CGC, ropes, ...)
\[\downarrow\]
Hadronization
(microscopical mech.)
\[\downarrow\]
Final state hadrons

Early models: initial state $\leftrightarrow$ final state
These days: initial state $\rightarrow$ final state
  microscopical mechanisms
(QCD, strong interaction, ... )
$\Rightarrow$ QGP signatures
$\Rightarrow$ Testing QCD
Quark matter formation in heavy ion collisions

Lattice-QCD results at finite density, SU(3), $N_f=2$, $\mu>0$  (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**


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

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

\[
\frac{dN_d}{d^3 P_d} \sim \frac{1}{2!} \int d^3 x_1 d^3 x_2 \ d^3 x'_1 d^3 x'_2 \ \phi^*_d(x_1, x_2) \phi_d(x'_1, x'_2) \ \langle \psi^+(x'_2, t_f) \psi^+(x'_1, t_f) \psi(x_1, t_f) \psi(x_2, t_f) \rangle
\]

**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:** \( \varphi_d(r) = (\pi d^2)^{-3/4} \exp(-r^2/2 d^2) \quad \leftarrow \text{inner structure}!! \)

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

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

**Two-nucleon density matrix**  \( \Rightarrow \) one-particle density matrix:

\( \langle \psi^+(x'_2, t_f) \psi^+(x'_1, t_f) \psi(x_1, t_f) \psi(x_2, t_f) \rangle = \langle \psi^+(x'_2, t_f) \psi(x_2, t_f) \rangle \langle \psi^+(x'_1, t_f) \psi(x_1, t_f) \rangle \)

(at freeze-out the nucleons are uncorrelated)

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

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

**The deuteron spectrum:**

\[
\frac{dN_d}{d^3 P_d} = \frac{3}{(2\pi)^6} \int d^3 r_d d^3 q d^3 r \ D(r,q) f^w_p(q_+, r_+) f^w_n(q_-, r_-)
\]

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, \( q + \bar{q} \Rightarrow M \)

(No constituent quark model, non-relativistic approx.)

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

⇒ asymptotic wave functions do not exist inside deconf. phase !!!!

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

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

--- direct calculation of coalescence matrix elements

\[
M_{12} = \int d^3 x_1 d^3 x_2 \phi_M(|x_1 - x_2|) e^{-ip \cdot x} V_{12}(|x_1 - x_2|) \varphi_q(x_1)\varphi_{\bar{q}}(x_2)
\]

⇒ \( V_{12}(r) \) is an effective coalescence potential:

\[
V_{12} = -\alpha_{\text{eff}} \frac{\langle\lambda_1\lambda_2\rangle}{r}
\]

⇒ many coalescence channels exist (\( \pi, \rho, K, K^*, \phi, ... \))

--- introducing \( 1+2 \rightarrow 3 \) coalescence cross section [e.g. Biro et al, PLB347,1995,6]:

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

⇒ \( a \): Bohr radius

--- quark coalescence rate:

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

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), $N_f=0,2,4$, $\mu=0$ (1990 - ...)

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

[LP, Heinz U., 1996, PRC51,3326]

$\Rightarrow$ Quark and antiquark dominated matter (QAP)
HADRONIZATION $\Leftrightarrow$ 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), $N_f=0,2,4$ $\mu=0$

**Fig. 10.** SU(3), $N_f=0,2,4$ --- $n_u/n_u^0$, $n_d/n_d^0$

**Fig. 11.** SU(3), $N_f=2,4$ --- $R_g(T)$, $R_{q^0}(T)$

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

Attractive potential between (anti-)quarks

Heavy hadron resonances are produced \( \Rightarrow \) decay

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

**Input parameters:** \( P; \langle u \bar{u} \rangle = \langle d \bar{d} \rangle; \langle s \bar{s} \rangle = f_s \ast (\langle u \bar{u} \rangle + \langle d \bar{d} \rangle); \alpha_{\text{eff}} \)
Quark matter formation between $\sqrt{s} = 5 - 200$ A GeV

ALCOR model for quark matter hadronization [Zimányi J., Biró T., L.P.]
Quark matter formation between $\sqrt{s} = 5 - 200$ 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? $\Leftrightarrow$ 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.]

<table>
<thead>
<tr>
<th></th>
<th>ALCOR 130 AGeV fit</th>
<th>ALCOR 200 AGeV prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>New pairs, $dN_{au}/dy$</td>
<td>250</td>
<td>286</td>
</tr>
<tr>
<td>Strangeness, $f_s$</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>Stopping, in %</td>
<td>3.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Interaction, $\alpha_{eff}$</td>
<td>0.55</td>
<td>0.55</td>
</tr>
</tbody>
</table>

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 -- $\pi^0$

Peripheral coll. $N(\text{bin}) = 12.3 \pm 4$
Central coll. $N(\text{bin}) = 975 \pm 94$

Binary scaling is working
Binary scaling is violated

Jet-quench
Cronin enhancement

$\pi^0$ @ AuAu 200 GeV [70-90%]
$\pi^0$ pp @ 200 GeV [Ncoll(70-90%) scaled]
Uncertainty in $N_{\text{coll}}$ pp scaling

$\pi^0$ AuAu @ 200 GeV [0-10%]
$\pi^0$ pp @ 200 GeV [Ncoll(0-10%) scaled]
Uncertainty in $N_{\text{coll}}$ pp scaling

Jet-quench
Cronin enhancement

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


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

$R_{AA} \neq 0$-10% Central:
- Au+Au $\sqrt{s_{NN}}=200$ GeV
- Au+Au $\sqrt{s_{NN}}=130$ GeV
- Pb+Pb $\sqrt{s_{NN}}=17.3$ GeV

$0.5 \leq R_{AA} \leq 2.5$

Nuclear modification factor:

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

1.5 GeV $< p_T < 6$ GeV: Soft -- hard overlap???
Exciting results from RHIC at $\sqrt{s} = 130$ 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; ...)

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

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

in progress by G. Papp et al. (Budapest)
(hep-ph/0212249)
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 probability to produce a hadron \( h \) with momentum \( z \, p \) from a jet \( c \) with momentum \( p \)

Quark-antiquark pairs from the vacuum

Original quark jet (flavour 'a'

\[ D_c^h(z) = A \, z^\alpha (1 - z)^\beta \]

(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: \( E \Rightarrow E - \Delta E(E,L/\lambda, \mu, ...) \)
'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:** \( E \Rightarrow E - \Delta E(E,L/\lambda, \mu, ...) \) 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 ??

\( 'a' \) ➤ ➤ ➤ matter
(L/\( \lambda \), \( \mu(T) \), ...)}
Hard physics: pion production in AA collision at high- $p_T$

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

\[ E_\pi \frac{d\sigma^{AB}}{d^3 p_\pi} = \int d^2 b d^2 r ~ t_A(\vec{r}) t_B(\vec{b} - \vec{r}) \ E_\pi \frac{d\sigma^{pp}}{d^3 p_\pi} \otimes S(...) \otimes M(...) \otimes Q(...) \]

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, multiscattering, jet-quenching, ...

\[
E_p \frac{d\sigma^{AB}}{d^3 p_p} = \int d^2 b d^2 r \ t_A(\vec{r}) t_B(\vec{b} - \vec{r}) \ E_p \frac{d\sigma^{pp}}{d^3 p_p} \otimes S(...) \otimes M(...) \otimes Q(...) 
\]

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

\[ p_T < 4 \text{ GeV} \]

PQCD underpredicts data by a factor of 10 !!
- even for peripheral collisions
- quenching makes it worst for central coll.
- may agree for \( p_T > 6 \text{ GeV} \) or higher
  (see previous slide for pions)

Problem has already appeared in pp collision:

New production mechanism at intermediate \( p_T \)!
- \( 1.5 \text{ GeV} < p_T < 6 \text{ GeV} \)
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)
Basic coalescence equation: $1 + 2 \rightarrow M$

\[
\frac{dN_M}{d^3P_M} = g_M \int d^3\tau_d d^3\tau_b d^3p_1 d^3p_2 \frac{d}{d^3p} f^w_i(p_1, r_a) f^w_2(p_2, r_b) \\
\delta^3(P_M - p_1 - p_2) \mathcal{F}_M(\vec{r}_a - \vec{r}_b, \vec{p}_1 - \vec{p}_2)
\]

$f^w_i$: the Wigner function of parton $i$ \quad ($\rightarrow dN_i/d^3p$)

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

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

$\Delta_p$: a sharp cutoff in the relative momenta

$\Gamma_r$: a correlation length in space (the size of the meson)

Longitudinally invariant coalescence rate:

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

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

\[
\frac{dN_M}{2\pi P_{M,\perp} dP_{M,\perp}} = \frac{g_M 6\pi^2}{V \Delta_M^3} \int \frac{dN_1}{2\pi P_{1,\perp} dP_{1,\perp}} \frac{dN_2}{2\pi P_{2,\perp} dP_{2,\perp}} \\
\frac{1}{P_{M,\perp}^2} \delta\left(1 - \frac{P_{1,\perp} + P_{2,\perp}}{P_{M,\perp}}\right) \Theta(\Delta_M - |P_{1,\perp} - P_{2,\perp}|)
\]
Parton coalescence: baryon production

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

$$
\frac{dN_B}{d^3p_B} = g_B \int d^3\tau_1 \, d^3\tau_2 \, d^3\tau_3 \, \frac{d^3p_1 \, d^3p_2 \, d^3p_3}{(2\pi)^3 \, (2\pi)^3} \, J^W_i(\vec{p}_1, \vec{r}_1) \, J^W_2(\vec{p}_2, \vec{r}_2) \, J^W_3(\vec{p}_3, \vec{r}_3) \cdot \delta^3(\vec{p}_B - \vec{p}_1 - \vec{p}_2 - \vec{p}_3) \, \mathcal{F}^W_B(\vec{\rho}, \vec{\lambda}; \vec{q}_\rho, \vec{q}_\lambda)
$$

$J^W_i$: the Wigner function of parton $i$ \hfill ($\rightarrow dN_i/d^3p$)

$\mathcal{F}^W_B$: the Wigner function of the produced baryon $B$ \hfill ($\rightarrow$ box-like)

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

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

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

Longitudinally invariant coalescence rate:

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

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

$$
\frac{dN_B}{2\pi P_{B,\perp} dP_{B,\perp}} = \frac{g_B \, 36\pi^4}{V^2 \, \Delta_\rho^3} \int \frac{dN_1 \, dN_2 \, dN_3}{d^2p_1 \, d^2p_2 \, d^2p_3} \prod_{i=1,2,3} \frac{dN_i}{2\pi p_{i,\perp} dP_{i,\perp}} \cdot \\
\cdot \frac{1}{P^3_{B,\perp}} \delta \left(1 - p_{1,\perp} + p_{2,\perp} + p_{3,\perp} \right) \prod_{i=1,2,3} \Theta(\Delta_B - |p_{i,\perp} - p_{i+1,\perp}|).
$$
Parton coalescence: initial parton distributions

After quenching:

radiated gluons $\rightarrow$
thermal bath ($T=200$ MeV)

d$E_T$/dy ($y=0$) = 570 GeV

Modification in parton spectra is shifted to higher hadron $p_T$:

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

$p_T(\text{parton}) \Leftrightarrow \frac{p_T(B)}{3}$
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 coalescence: 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
- \( \Delta_p \) momentum window in the coalescence process
Parton coalescence: 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)
- $\Delta_p$ 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

- **MICOR model:** quark-coalescence ($0 < p_T < 4-5$ GeV)
- **p pert. QCD:** independent jet-fragment. ($2 < p_T < 10-20$ GeV)

MICOR model: 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 than $\Lambda$-s with increasing $p_T$

**pQCD**: kaon yield comparable with coalescence rate, $\Lambda$ yield is negligible

**superposition**: $\Lambda/K$ 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 $\sqrt{s} = 130$ and 200 AGeV -- $v_2$

Elliptic flow (anisotropy in momentum space):

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

**Parton coalescence: elliptic flow**

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

### 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 inherited 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 coalescence: elliptic flow

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

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

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

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