

Hadron production from quark coalescence at LHC energies

P. Lévai (RMKI, Budapest)

Last Call for Predictions
CERN, 21 May 2007

Contents:

1. Microscopical mechanisms for hadron productions
2. Coalescence models with massive quarks
3. Data reconstruction at SPS and RHIC energies
4. Predictions for LHC energies
5. Experimental consequences (HMPID, VHMPID detectors)

Hadron production at the microscopical level: [30 years of work !!]

Independent jet fragmentation: $a[\text{parton}] \rightarrow h[\text{hadron}]$

R.D. Field, R.P. Feynman, PRD15(1977)2590, ...

$$E \frac{d\sigma_h}{d^3 p} = \sum_a \int \frac{dz}{z^2} D_{a \rightarrow h}(z) E \frac{d\sigma_a}{d^3 p_a}$$

$D_{a \rightarrow h}(z)$: FFs are determined from e^+e^- collisions

Parton recombination/coalescence/clustering: $a+b \rightarrow h$

K.P. Das, R.C. Hwa, PLB68(1977)459, ...

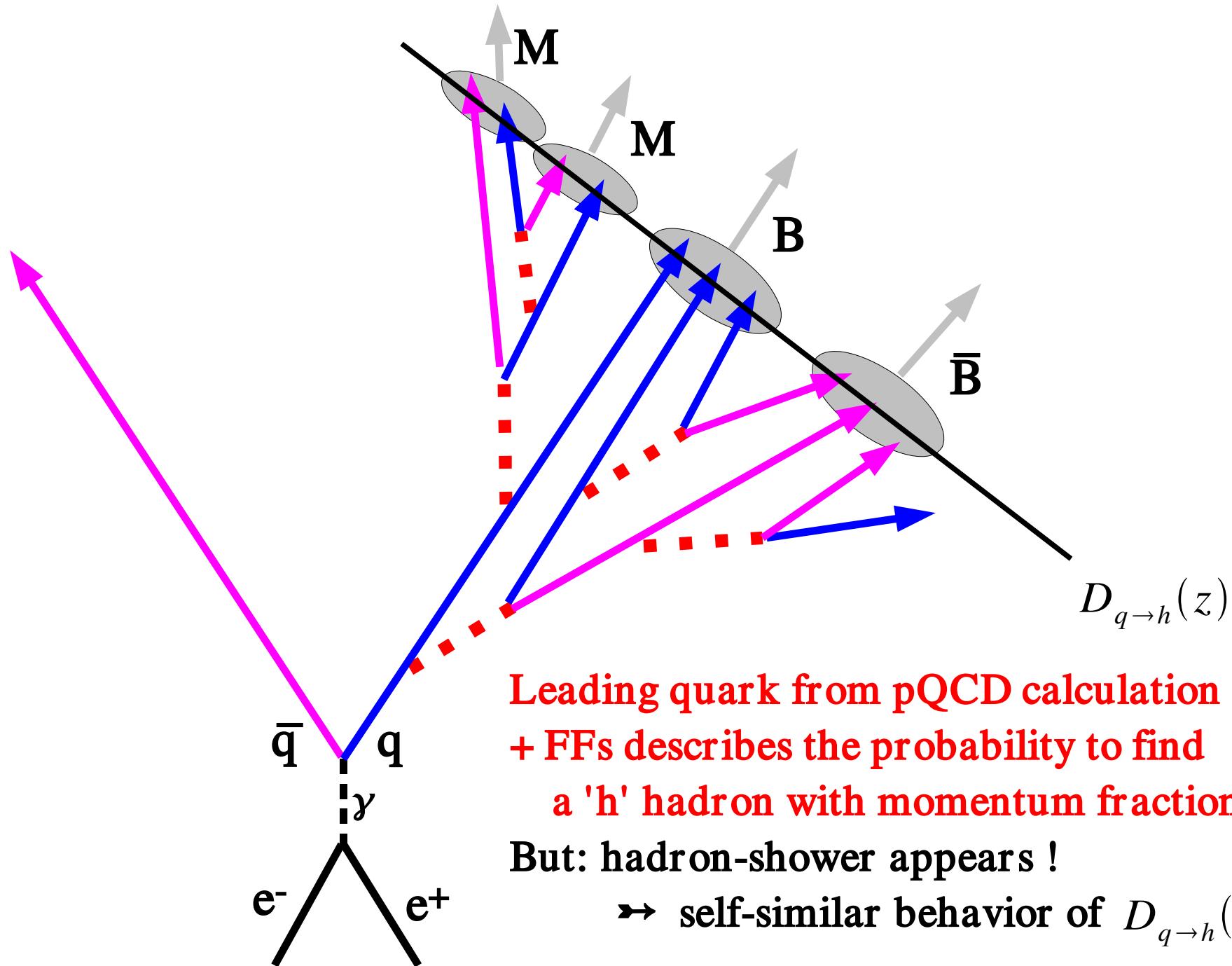
$$E \frac{d\sigma_h}{d^3 p} = \sum_a \int d^3 p_a d^3 p_b E \frac{d\sigma_a}{d^3 p_a} E \frac{d\sigma_b}{d^3 p_b} R(\vec{p}_a, \vec{p}_b, \vec{p}_h) \delta^{(3)}(\vec{p}_a + \vec{p}_b - \vec{p}_h)$$



can be substituted by
'effective' FFs

Momentum distributions +
momentum overlap functions. NO explicit interaction picture ?!

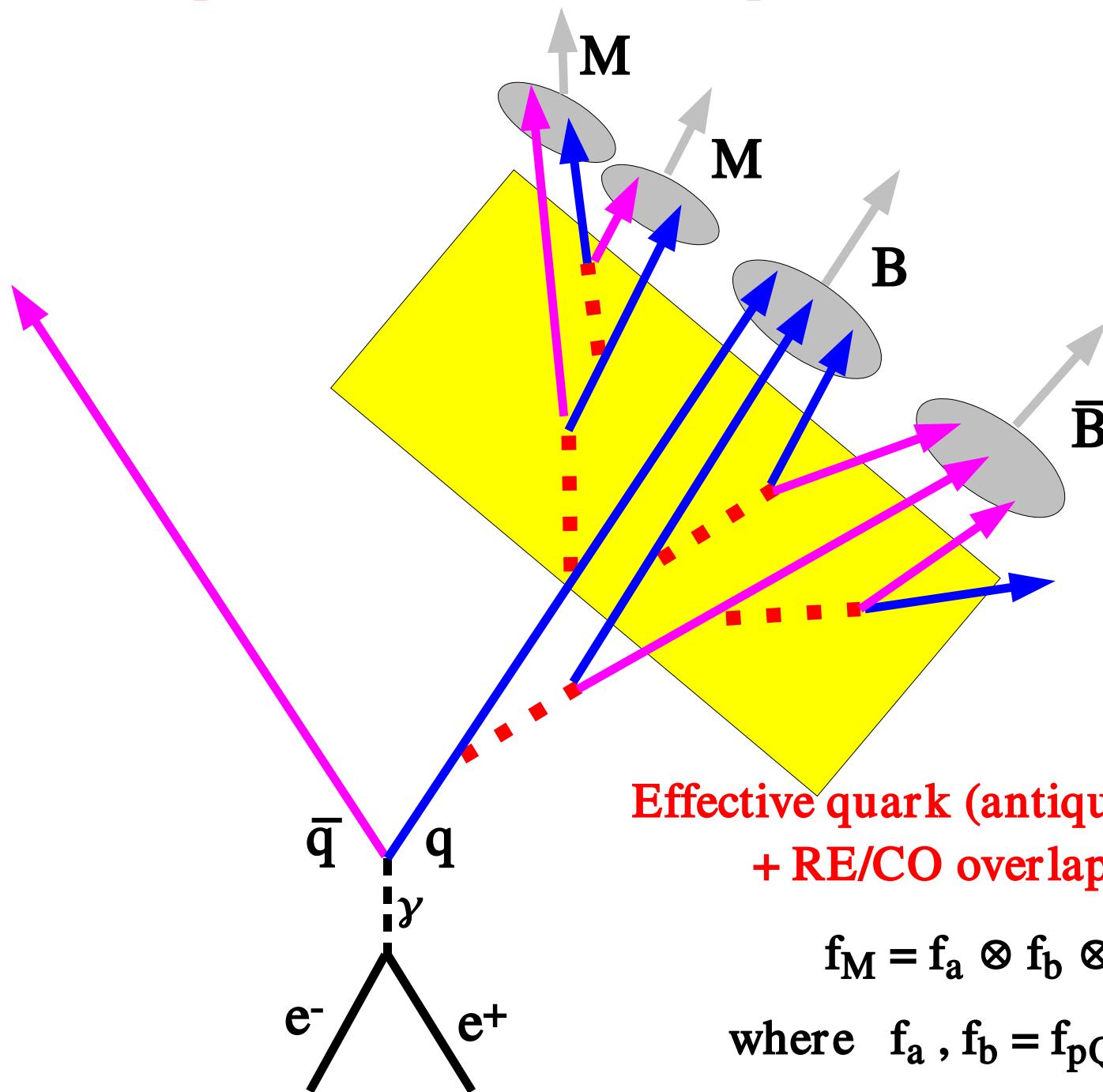
Hadron production at the microscopical level: FF picture



Hadron production at the microscopical level:

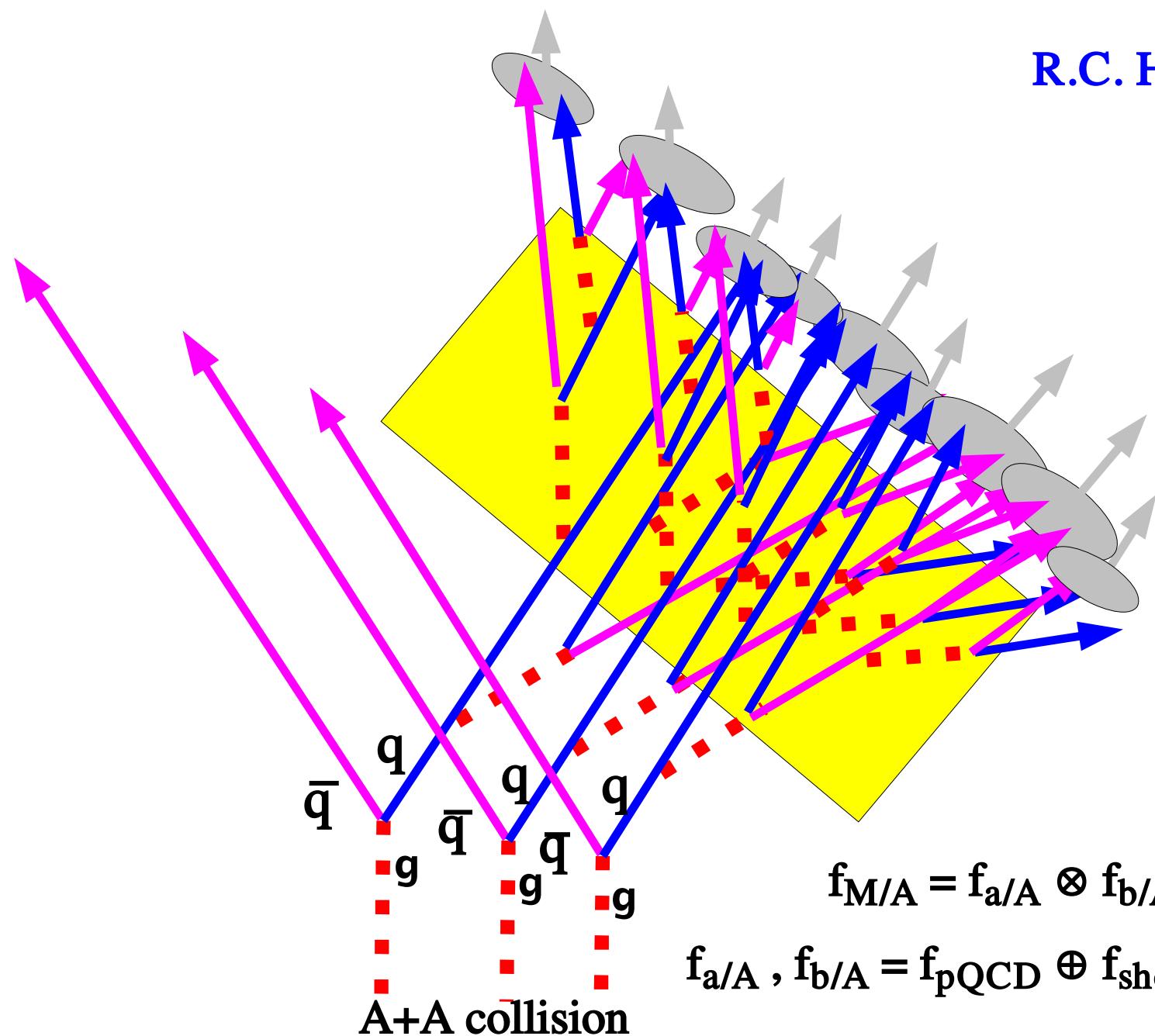
RE/CO picture

Hwa, Yang
Fries, Bass, Müller
Greco, Ko, Lévai



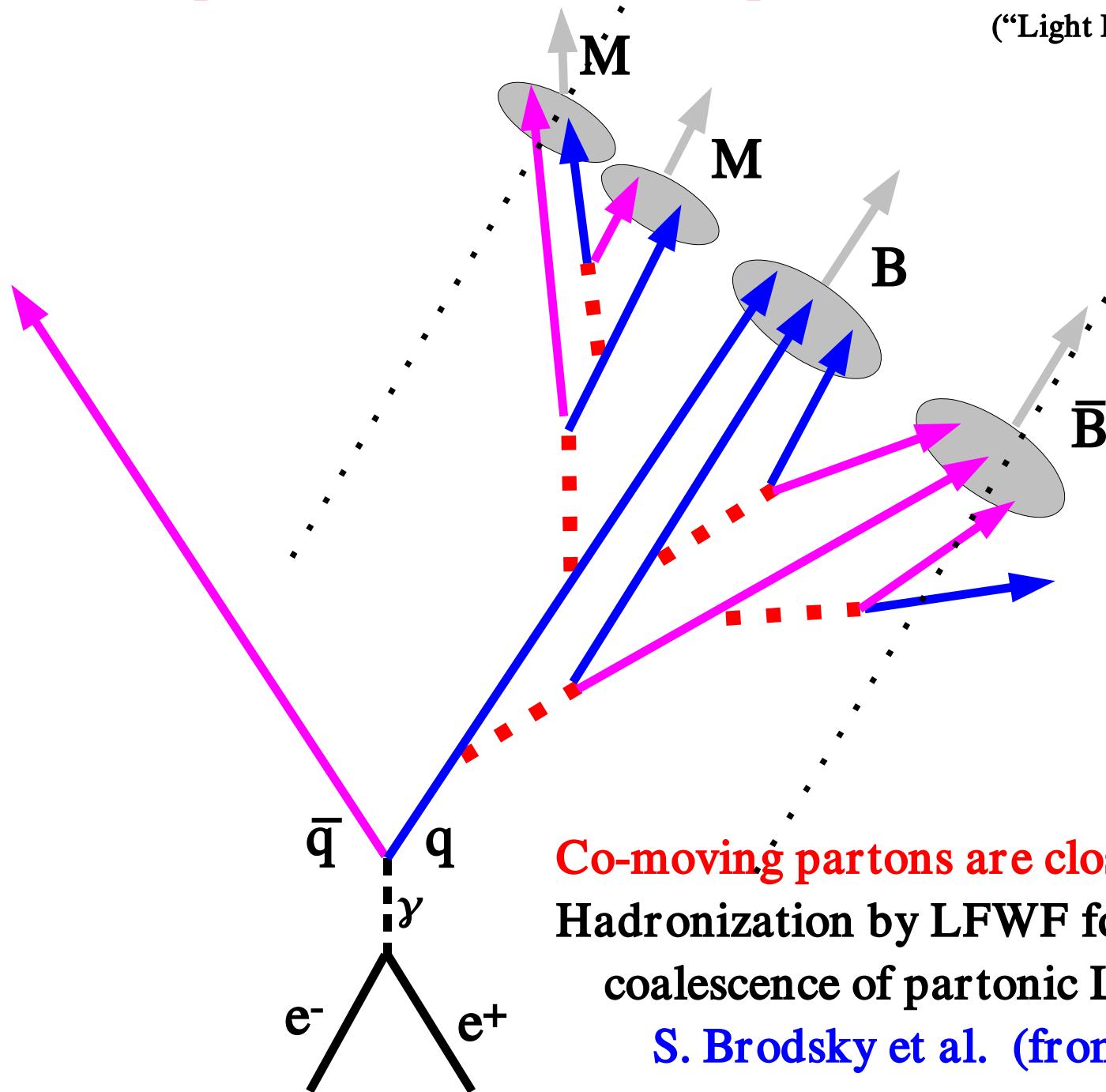
Hadron production at the microscopical level: RE/CO picture in A+A

R.C. Hwa, C.B. Yang



Hadron production at the microscopical level: LFWF picture

("Light Front Wave Function")



Co-moving partons are close to the light-cone
Hadronization by LFWF formalism:
coalescence of partonic LFWFs
S. Brodsky et al. (from 1976 !!!)

Hadron production at the microscopical level: LFWF coalescence

Brodsky, de Teramond, ...

QCD light-front Hamiltonian:

$$H_{LF}^{QCD} |\psi_p\rangle = (P^+ P^- - \vec{P}_T^2) |\psi_p\rangle = M_p^2 |\psi_p\rangle$$

Proton wave function: superposition of the Fock-states

$$|\psi_p\rangle = |uud\rangle + |uudg\rangle + |uudgg\rangle + \dots$$

Wave function with relative momentum coordinates:

$$|\psi_p\rangle = \sum_{n \geq 3} \psi_n^p(x_i, k_{Ti}, \lambda_i)$$

it is encoding the bound state properties in terms of q, g.

Light front Fock state wave functions with angular momentum:

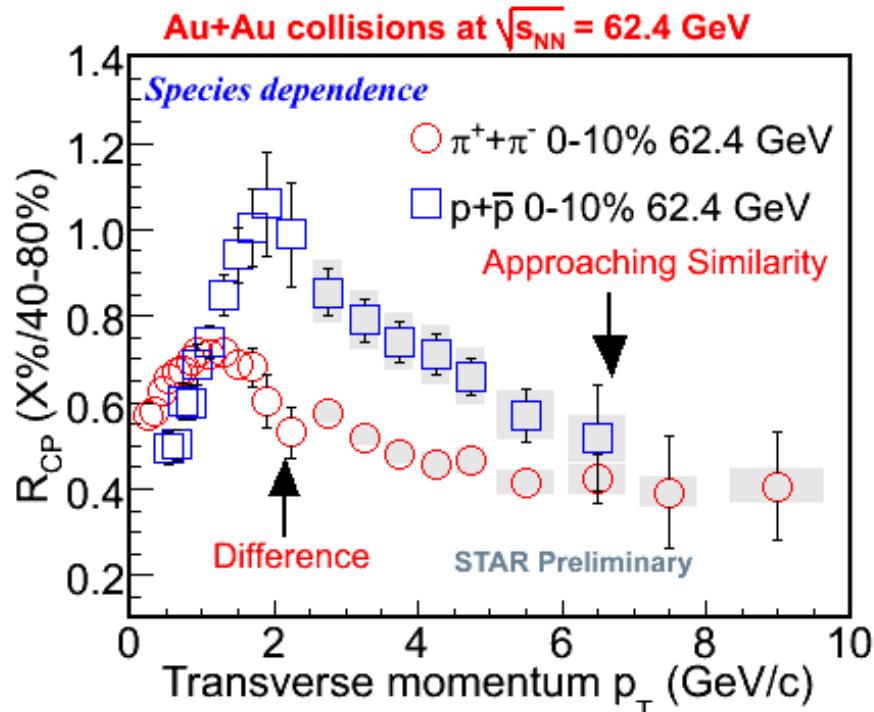
- » conformal properties of the AdS/CFT correspondence !!!
- » baryon resonance spectrum from AdS/CFT correspondence!

**Heavy (massive) quarks: LFWF formalism reduces to
conventional non-relativistic Schrödinger theory.**

**Hadronization phenomena (coalescence mechanism) can be computed
from LFWF overlap !!!**

| | | | |
|--------|--|--|---|
| Matter | Degrees of freedom | Hadron production | Model descr. |
| QGP | free q,q,g (+B) | Thermal equilibrium fast thermalization (“miracles”) or parton-hadron duality | QCD pQCD |
| wQGP | on-shell massive quasi-q,g $\Gamma_i \sim g^2 T \ln 1/g < m_i \sim g T$ | Thermal equilibrium Quark-coalescence Resonance-production + decay | QCD phenom. QAP, MD |
| sQGP | quasiparticles with mass distribution strong inter \Rightarrow spectral func. $\Gamma_i \approx m_i \sim g T$ | Quark-coalescence qq, qq – correlators | Lattice QCD QCD phenom |
| ssQGP | no quasiparticles (really?) [except high energy jets] or interaction \Rightarrow LFWF form. or strong field dominance | Compactification in higher (effective) dimens. Coalescence Black hole phenomenology | AdS/CFT QAP, <u>Schröd.</u> Gen. relativity |

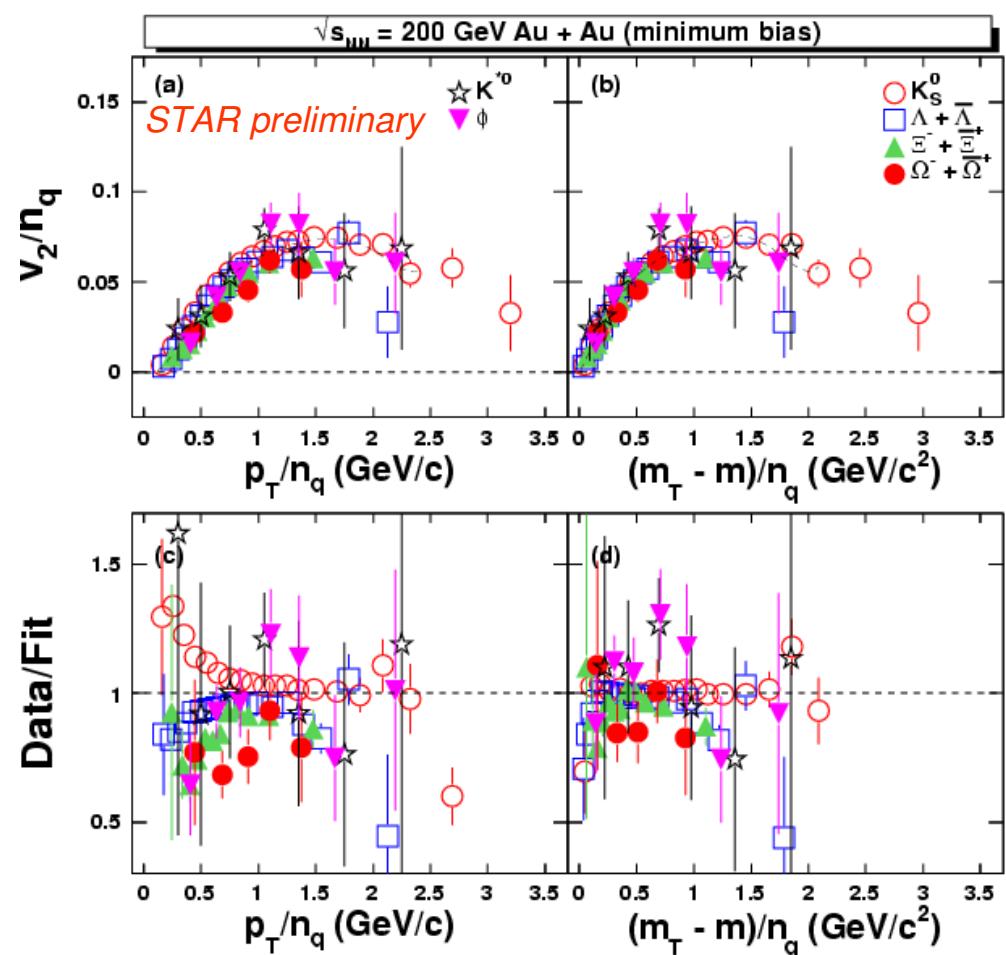
\Rightarrow Simon Wicks's talk



Constituent quark scaling
can be clearly seen in v_2 !

Bulk quark-antiquark matter
around T_c phase transition,
deconfined quark-matter at $T > T_c$!

Recent RHIC results (QM06):
Meson- and baryon-suppressions
are the same at high p_T !
Jet-picture incl. energy loss (pQCD)
is recovered beyond a threshold,
but anomalous B/M ratio at intermed. p_T



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.]

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

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

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:

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

(at freeze-out the nucleons are uncorrelated)

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

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

The deuteron spectrum:

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

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

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

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

\Rightarrow many coalescence channels exist ($\pi, \rho, K, K^*, \phi, \dots$)

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

$$\sigma_{12}(k) = \frac{m_3^2}{4\pi^2} \sqrt{\frac{2m_1 m_2}{(m_1 + m_2)^2}} |M_{12}|^{12} = 16 m_3^2 \sqrt{\pi} \alpha_{eff}^2 \rho^3 \frac{a}{(1 + (ka)^2)^2} \quad \rightarrow a: \text{Bohr radius}$$

$$\text{--- quark coalescence rate: } \langle \sigma_{12} v_{12} \rangle = \frac{\int d^3 P_1 d^3 P_2 f_1(P_1) f_2(P_2) \sigma_{12} v_{12}}{\int d^3 P_1 d^3 P_2 f_1(P_1) f_2(P_2)}$$

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

$m(q) \approx 330 \text{ MeV}, T \approx 175 \text{ MeV} \rightarrow \text{OK}$

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)

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

Newly produced light quark-antiquark pairs

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

Newly produced strange quark-antiquark pairs



Attractive potential between (anti-)quarks

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

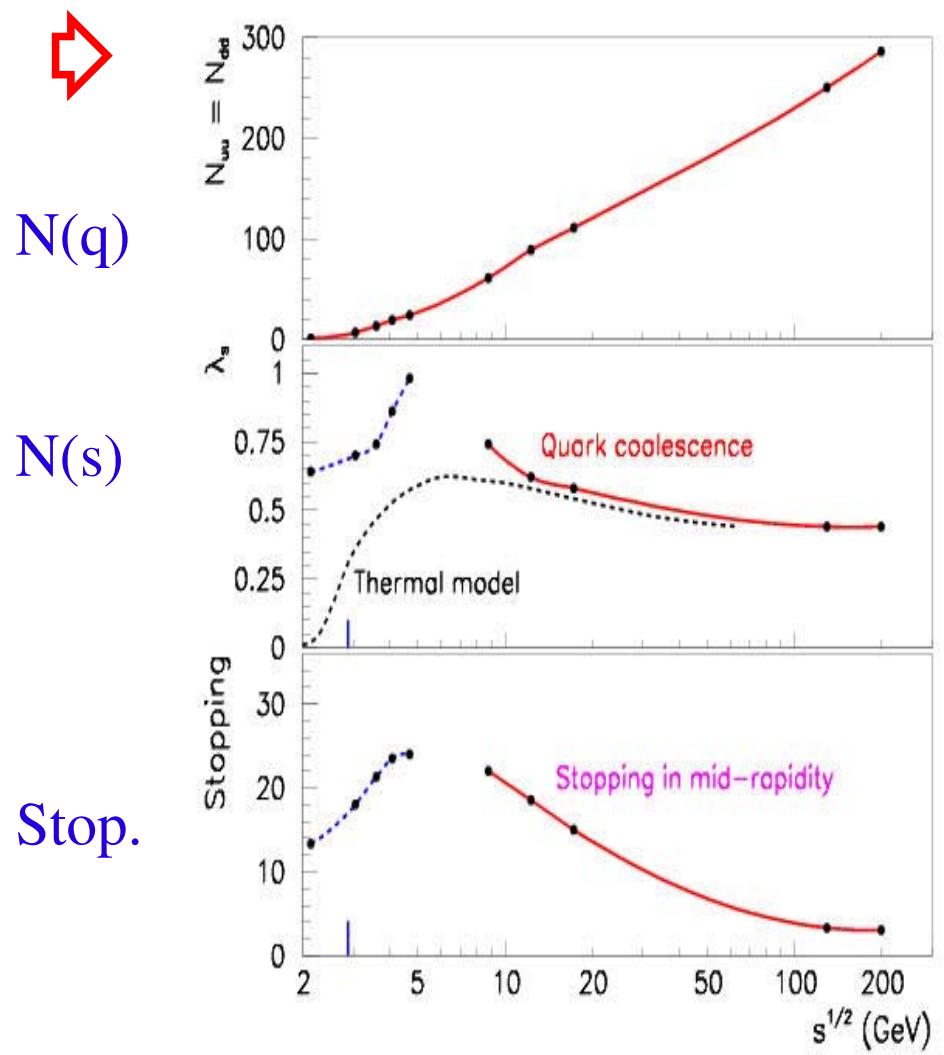
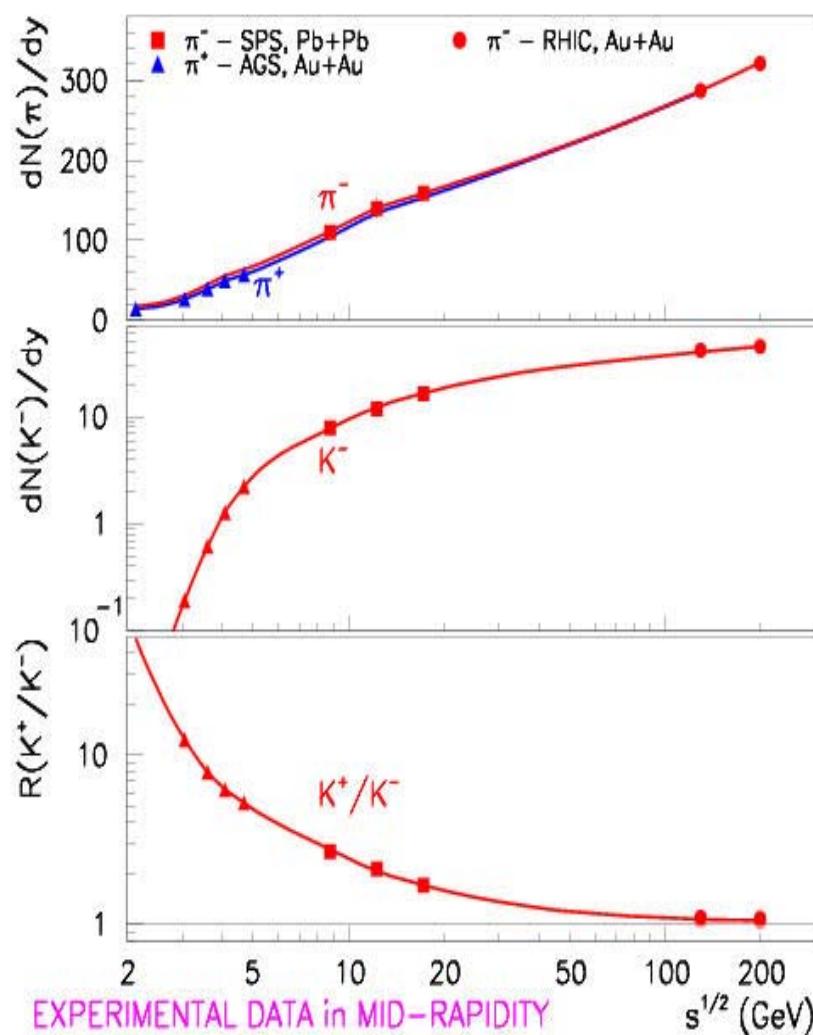
Heavy hadron resonances are produced \rightarrow decay

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

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

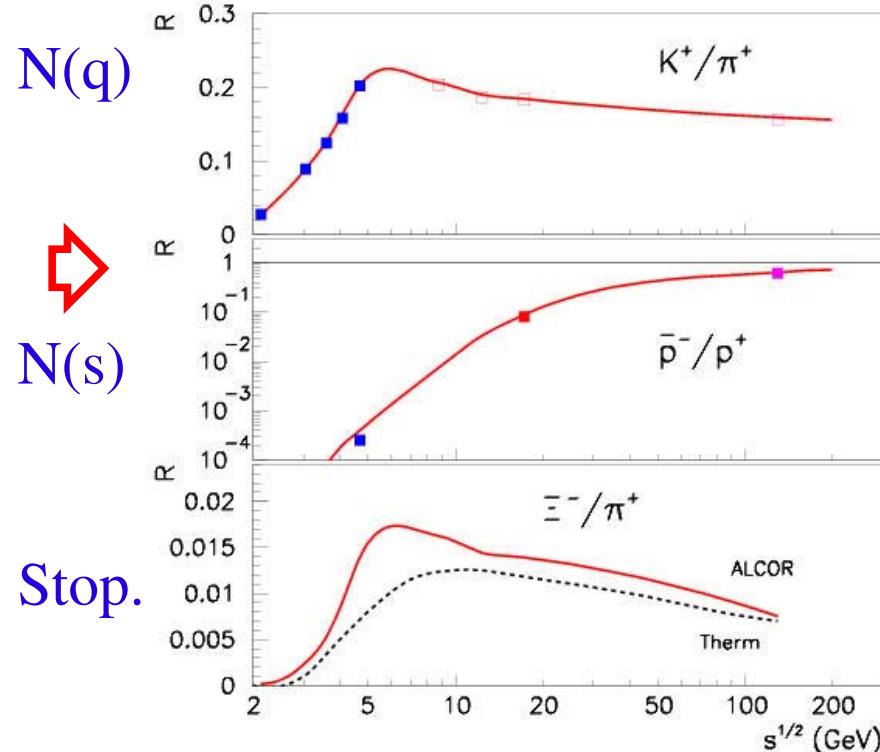
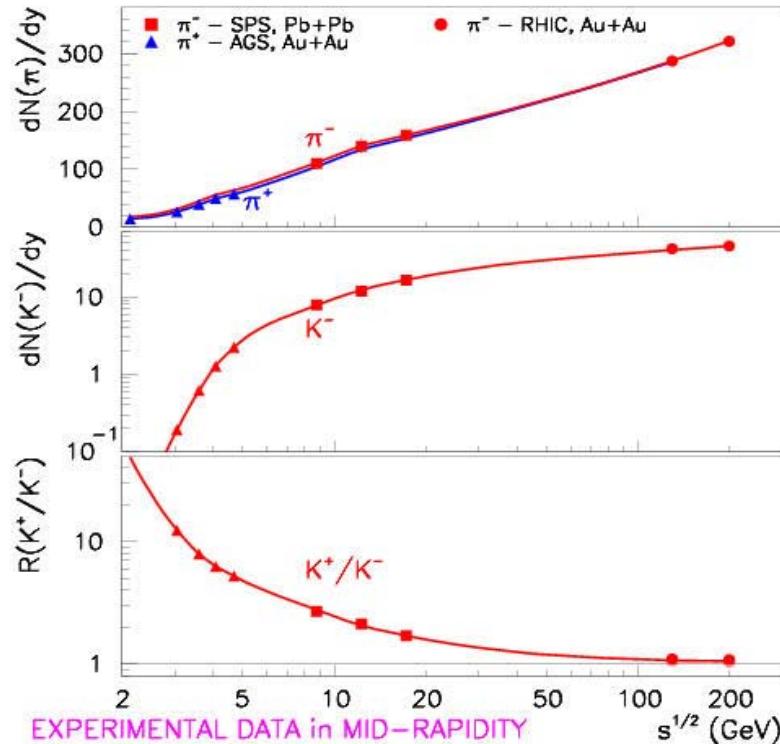
Quark matter formation between $\sqrt{s} = 5 - 200$ A GeV

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



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

What about gluons ? \Leftrightarrow QUARK ANTIQUARK PLASMA (QAP)

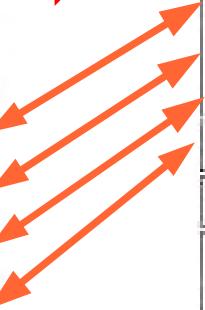
This description is valid for $p_T < 1.5$ GeV (99%)

It is valid at RHIC energy !

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

ALCOR model for quark matter hadronization

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



| Au+Au dN_c/dy | 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 |
| $\langle \Omega^- + \bar{\Omega}^+ \rangle$ | 0.55 ± 0.15 | 0.59 | 0.59 ± 0.14 | 0.72 |
| \bar{p}^-/p^+ | 0.64 ± 0.07 | 0.70 | 0.77 ± 0.05 | 0.76 |
| $\Lambda/\bar{\Lambda}$ | 0.71 ± 0.04 | 0.75 | 0.81 ± 0.07 | 0.810 |
| Ξ^+/Ξ^- | 0.83 ± 0.05 | 0.81 | 0.84 ± 0.06 | 0.86 |
| $\bar{\Omega}^+/\Omega^-$ | 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 |
| $\bar{\Lambda}/h^-$ | 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 | | 0.37 |
| 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)

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

ALCOR model for quark matter hadronization

| | ALCOR 158 GeV fit | ALCOR 80 GeV |
|-------------------------------|-------------------------|-----------------|
| New pairs, $dN_{\bar{u}u}/dy$ | 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 |
| Ξ^+ | 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}^-/\bar{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 |
| Ξ^+/Ξ^- | 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 |
| Ξ^+/π^+ | 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 |

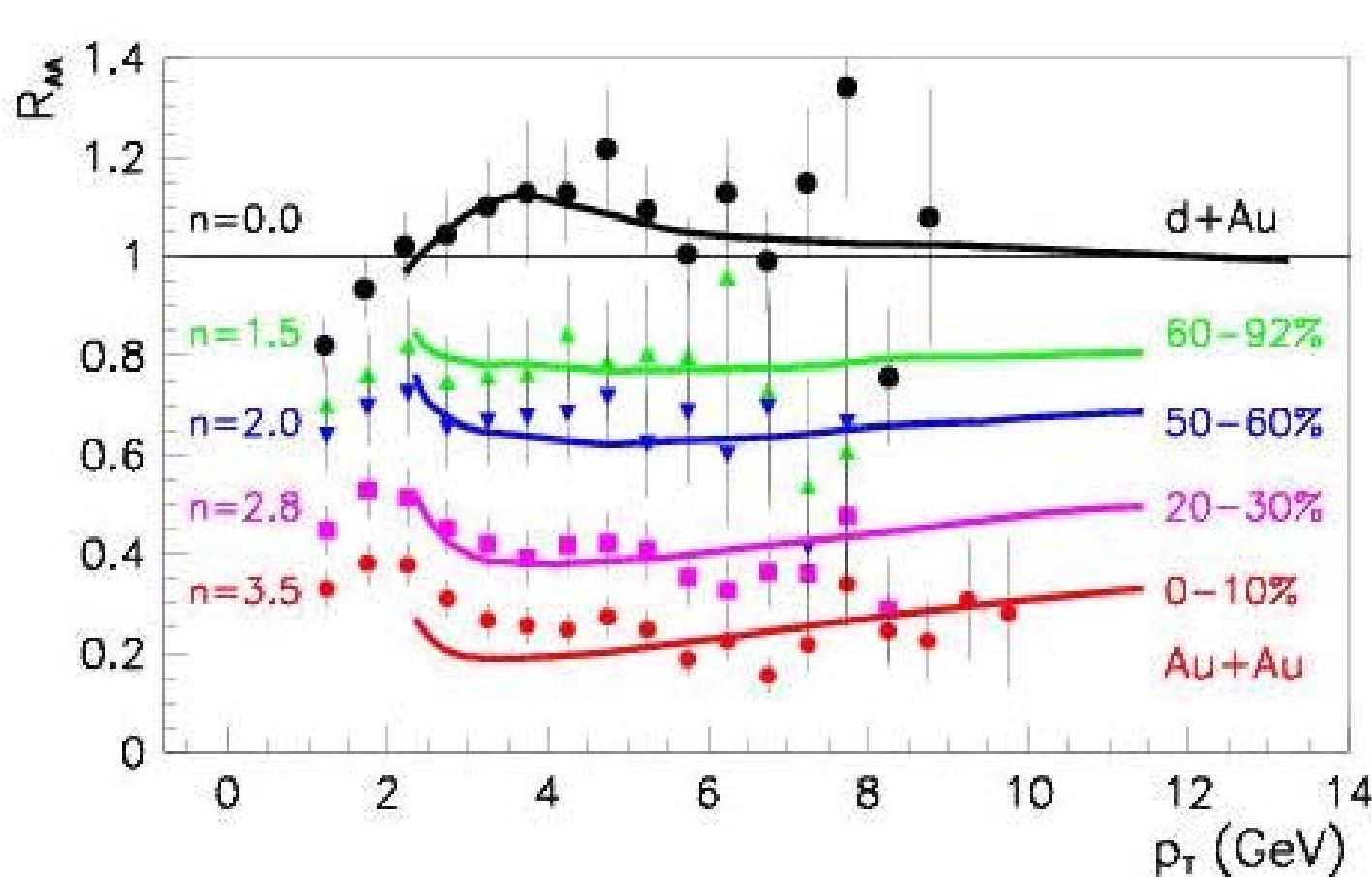
Quark-coalescence:

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

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, ...

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



RHIC
200 GeV/N

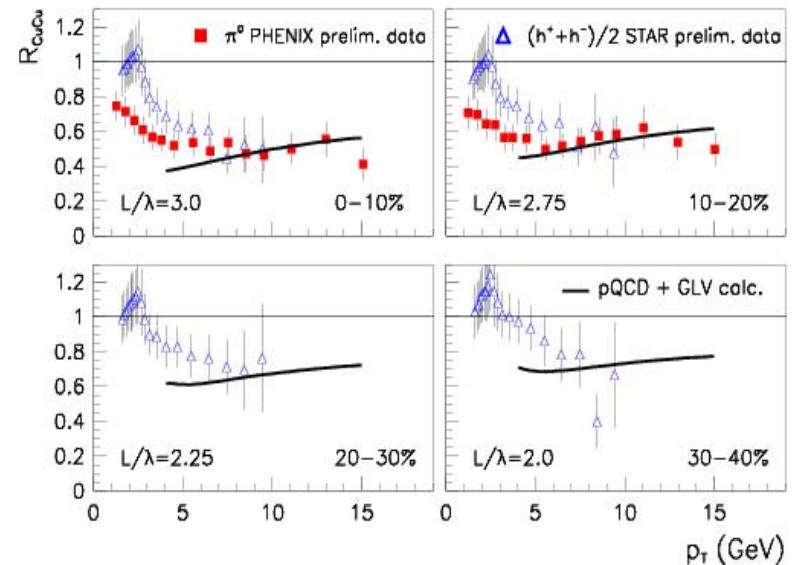
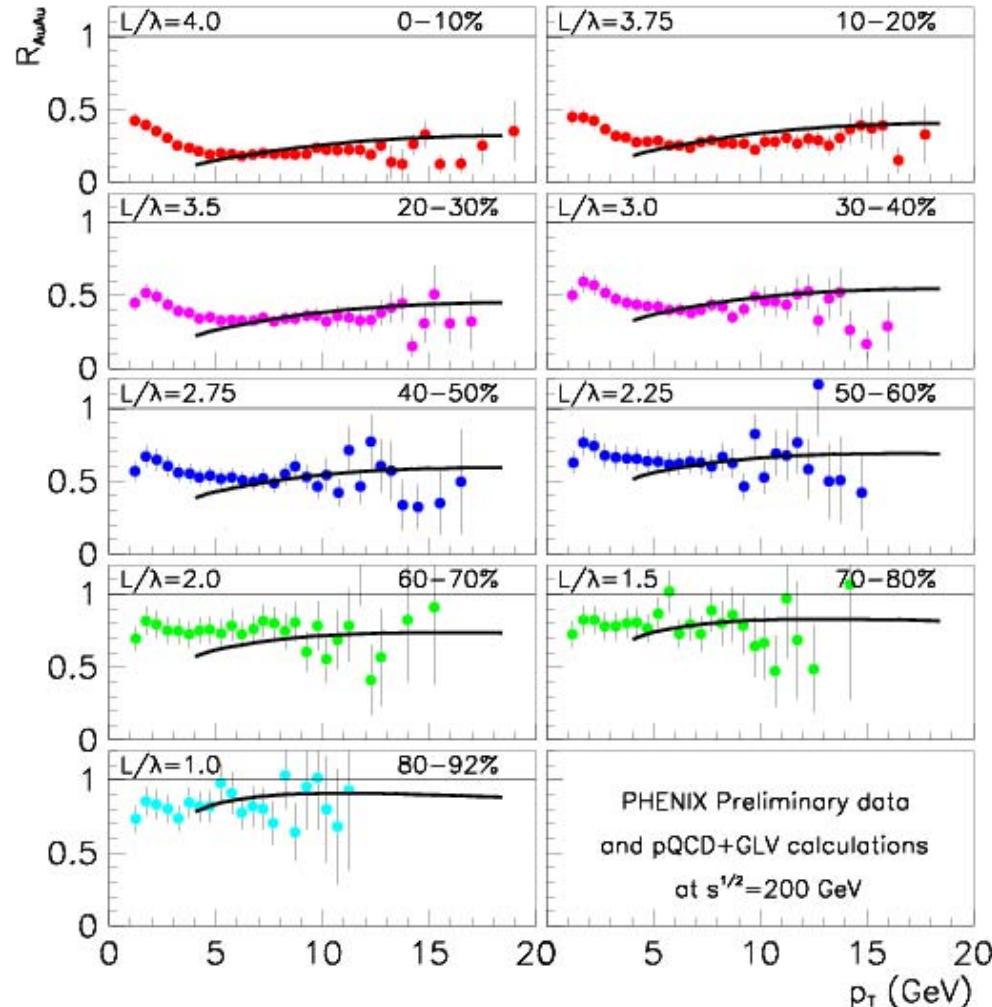
d+Au

Au+Au

$\eta=0$

High p_T pion production in Au+Au and Cu+Cu collisions

G.G. Barnaföldi, P. Lévai, G. Fai, G. Papp, EPJ C49 (2007) 333.

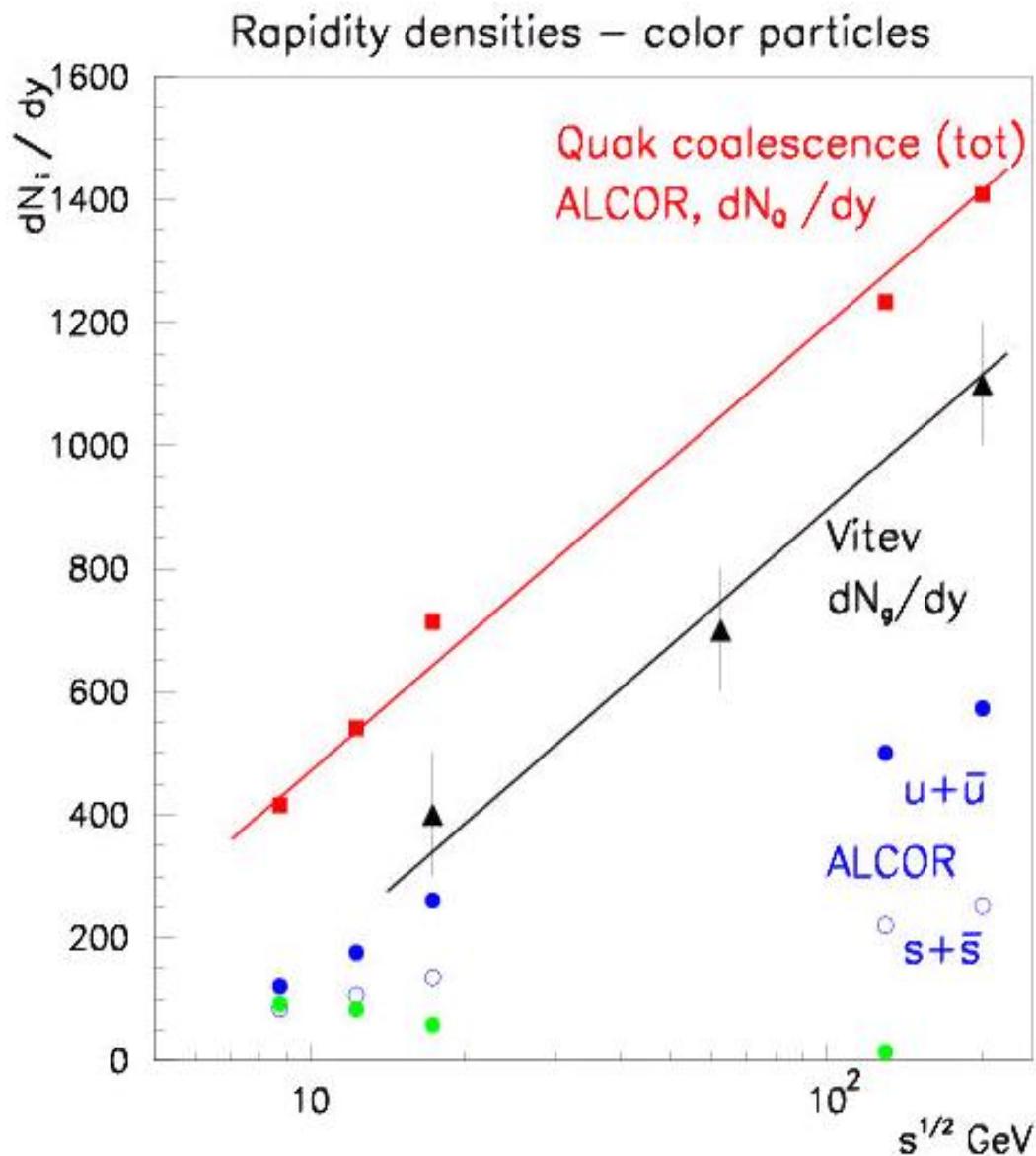


Au + Au collisions

Different centralities are described by different opacities

Cu+Cu collisions

Color particle 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 ± 0.5 |
| 62.4 | 1000 ± 100 | 700 ± 100 | 2.5 ± 0.5 |
| 200.0 | 1400 ± 100 | 1100 ± 100 | 3.5 ± 0.5 |

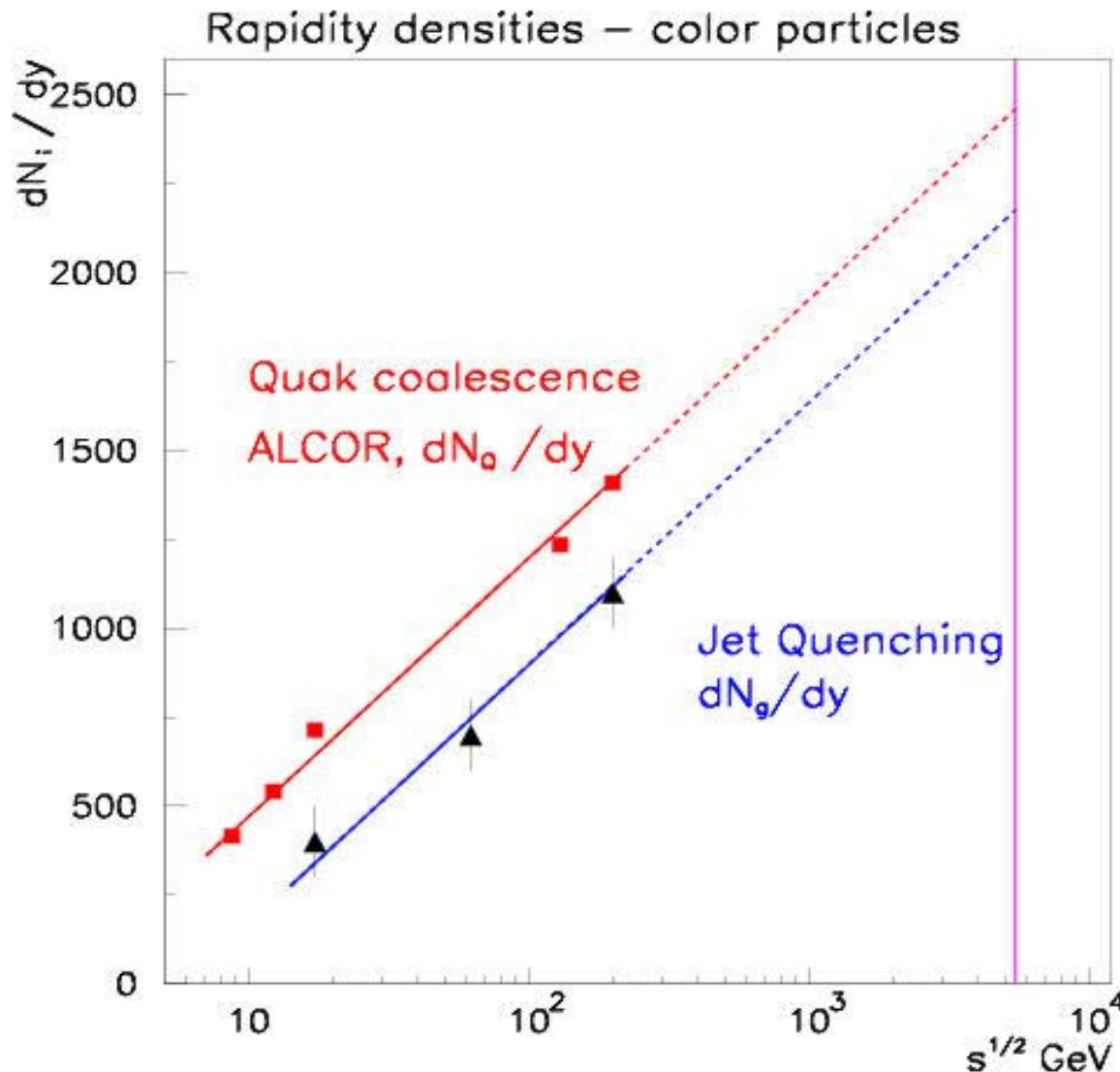
ALCOR I. Vitev P. Levai

Quench: earlier stage

Quark coalescence: later stage

Entropy is OK

Estimate for rapidity density at $y=0$ at LHC energy:



2 times RHIC soft multiplicity
(maybe a liitle bit more)

2 times RHIC opacity:
 $L/\lambda = 8$ at RHIC
(maybe a little bit more)

Linear increase is solid
Saturation: smaller yield
Multiparticle production:
larger yield

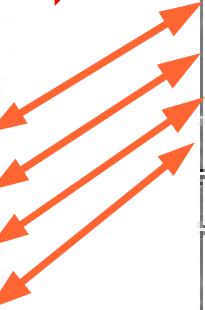
ALCOR results (RHIC) and predictions (LHC) in the mid-rapidity:

| dN/dy (y=0) | 200 GeV | RHIC.data | LHC-I: 5500 AGeV | LHC-II: 5500 AGeV |
|----------------------------|---------|-------------|------------------|-------------------|
| New uu-pairs | 286 | | 500 | 750 |
| f_s (strangeness) | 0.22 | | 0.22 | 0.22 |
| α_s (eff. coupling) | 0.55 | | 0.55 | 0.55 |
| Stopping in y=0 | 3 % | | 1 % | 1 % |
| Total (u+d+s+anti) | 1396 | | 2440 | 3660 |
| | | | | |
| h^\pm | 780 | 780±40 | 1252 | 1830 |
| π^- | 322 | 327±32 | 500 | 724 |
| K^+ | 48 | 51.3± 7.7 | 70 | 99 |
| p^+ | 19 | | 37 | 62 |
| Ξ^- | 2.59 | 2.16±0.09 | 6.42 | 10.7 |
| K^+/π^+ | 0.15 | 0.16±0.02 | 0.14 | 0.14 |
| Ξ^-/π^- | 0.008 | 0.007±0.001 | 0.013 | 0.015 |
| ρ^0/π^0 | 0.22 | 0.20±0.04 | 0.21 | 0.20 |
| ϕ / K^{0*} | 0.37 | | 0.39 | 0.39 |

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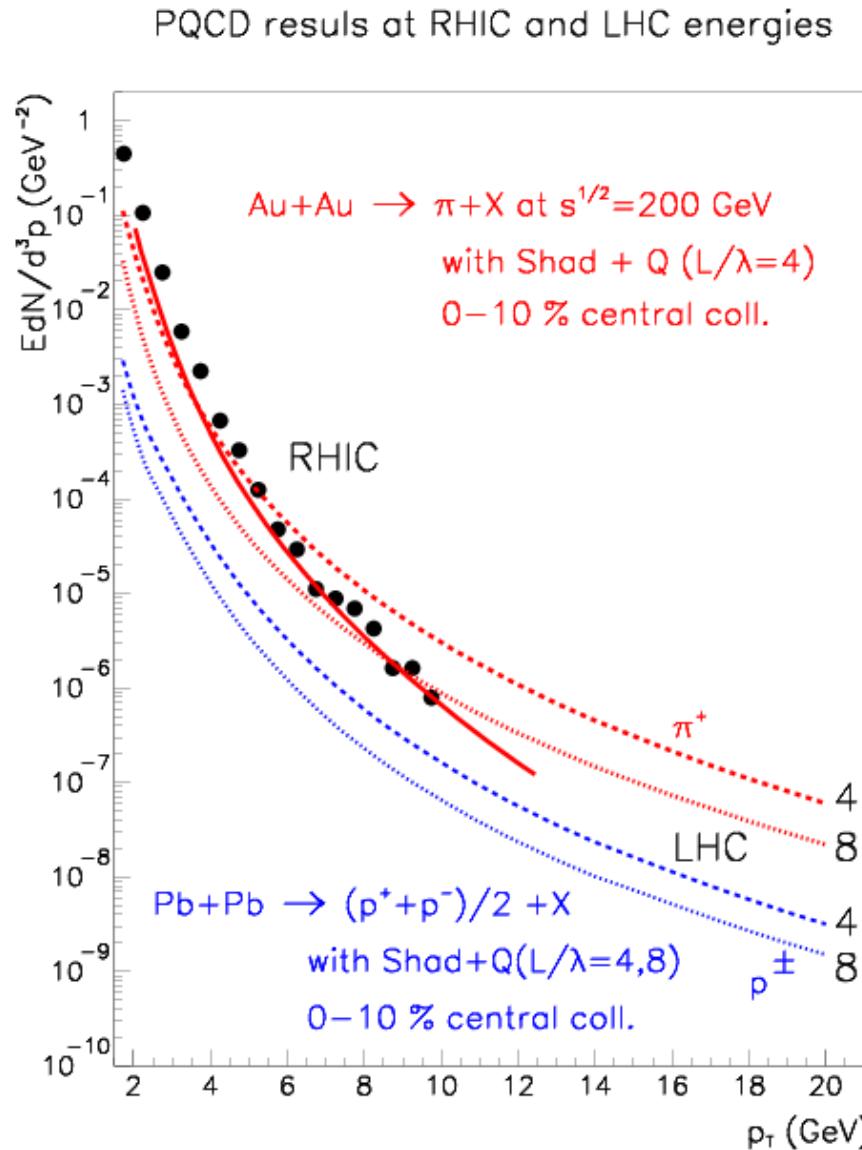


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| ρ^0/π^0 | | 0.22 | 0.20 ± 0.04 | 0.22 |

Quark-coalescence:

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

Summary of the PQCD results for pion and proton production in Au+Au at RHIC and Pb+Pb at LHC energies ($y=0$):



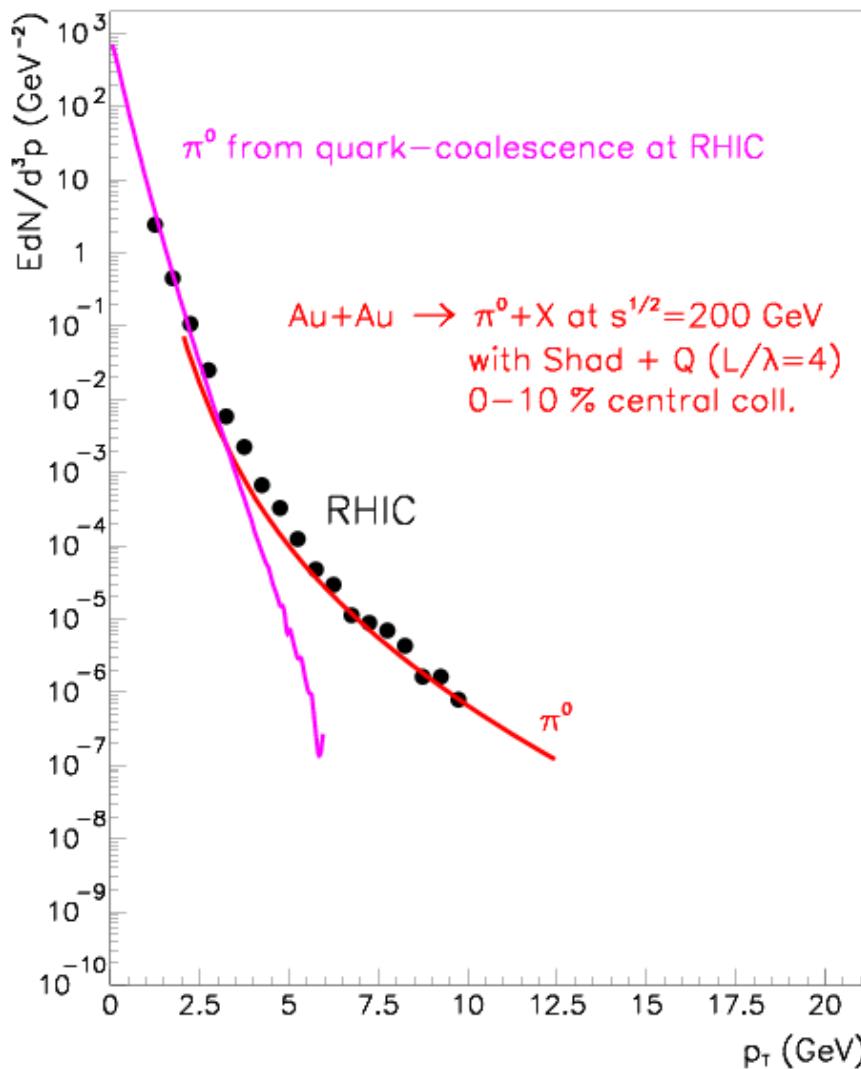
➡ Predictions

See GG Barnaföldi's
talk next week

Pions at RHIC and LHC from the ALCOR/MICOR + pQCD

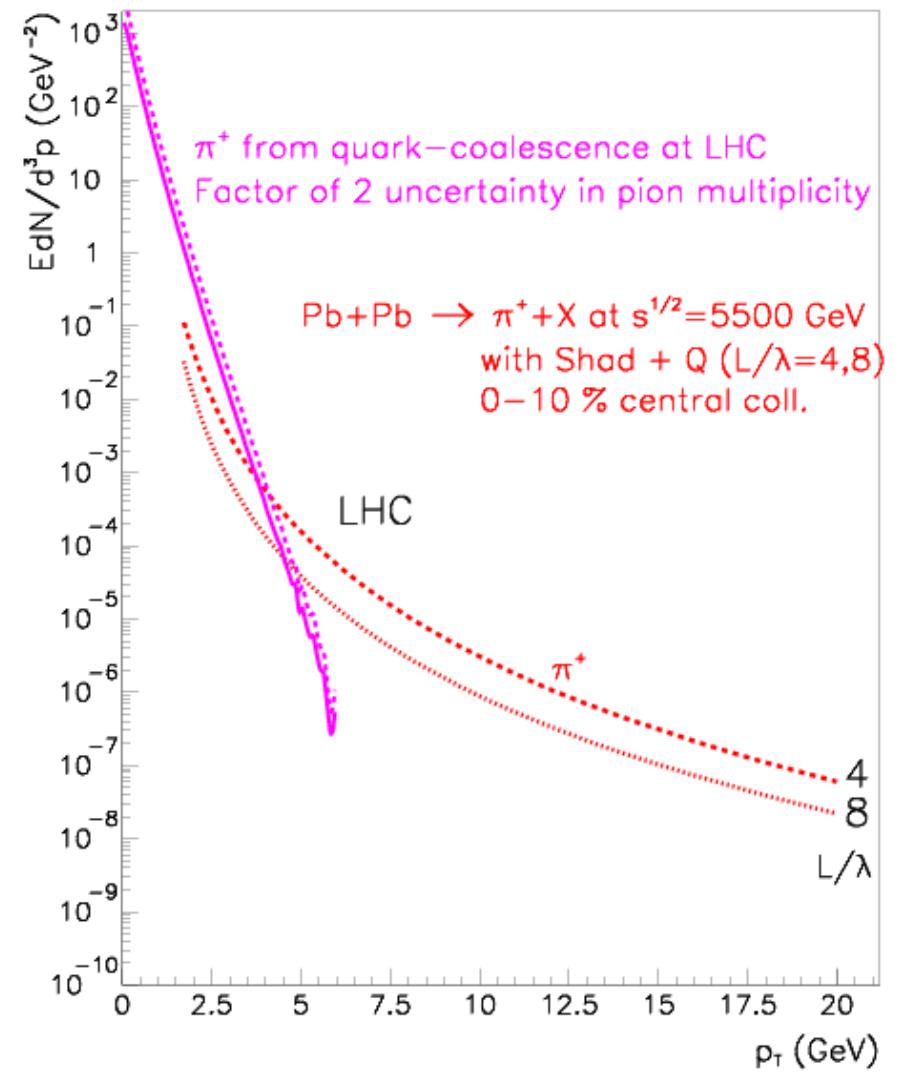
(Coalescence results at $v_T=0.6$.)

PQCD + Quark Coalescence at RHIC for pion



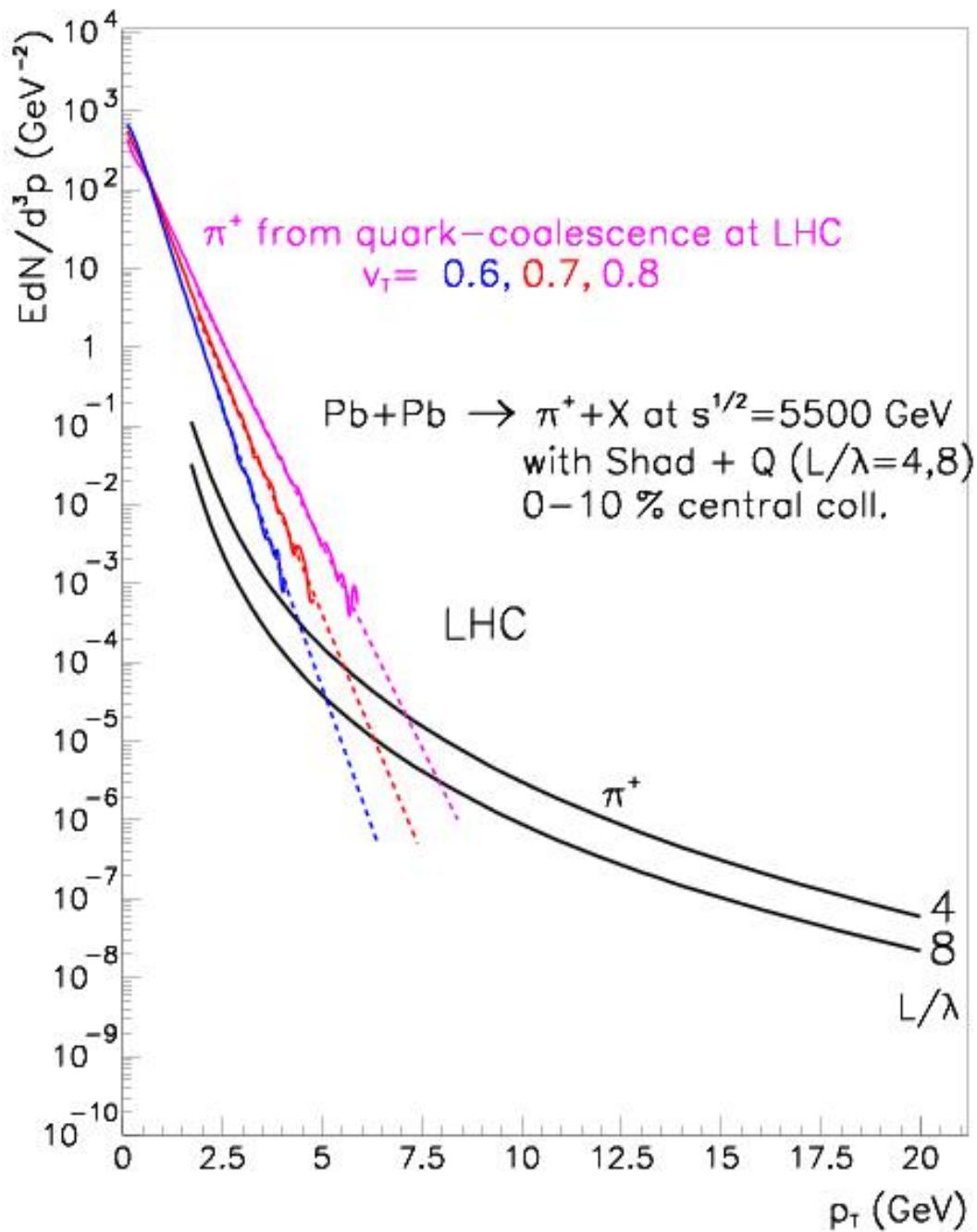
Overlap at $p_T = 2.5 - 3$ GeV (RHIC)

PQCD + Quark Coalescence at LHC for pion



at 4 ± 1 GeV at LHC

PQCD + Quark Coalescence at LHC for pion



Pions at LHC:
 (latest calculation)

$$dN/dy (\pi^+, y=0) = 500$$

$$dN/dy (h^-, y=0) = 625$$

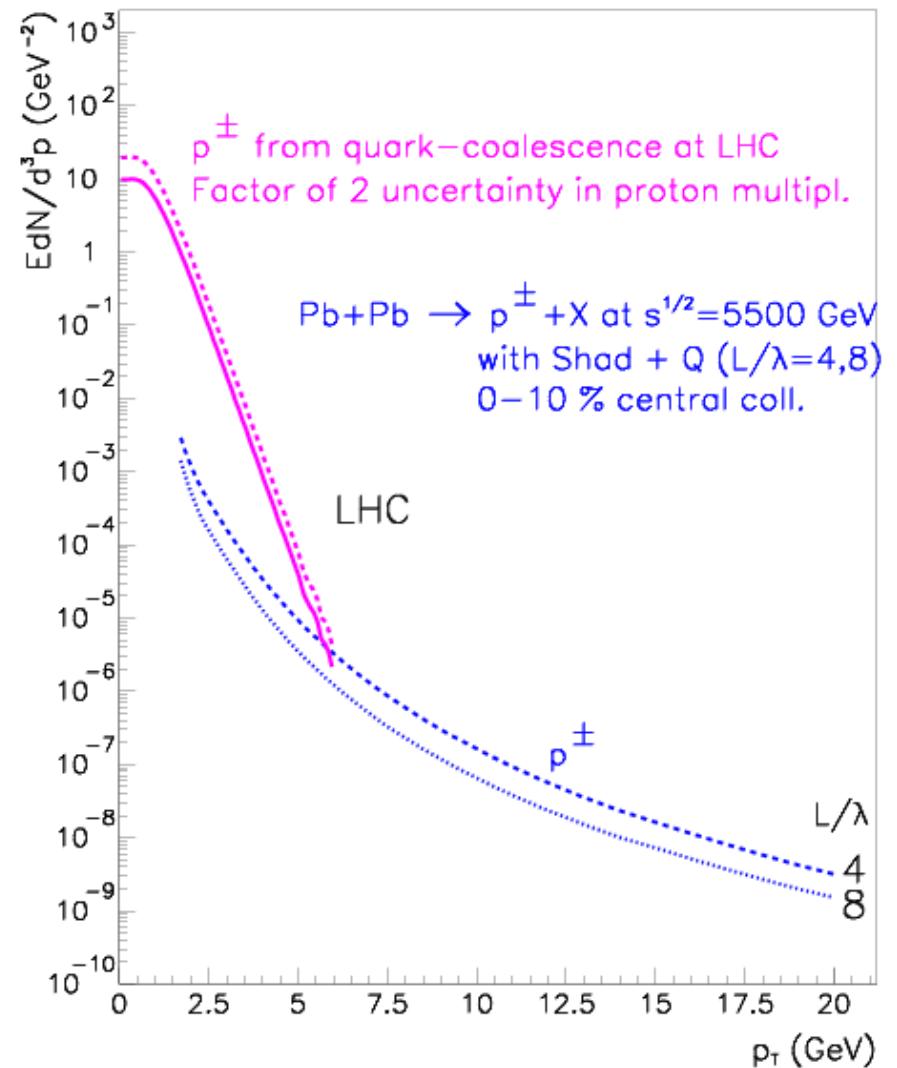
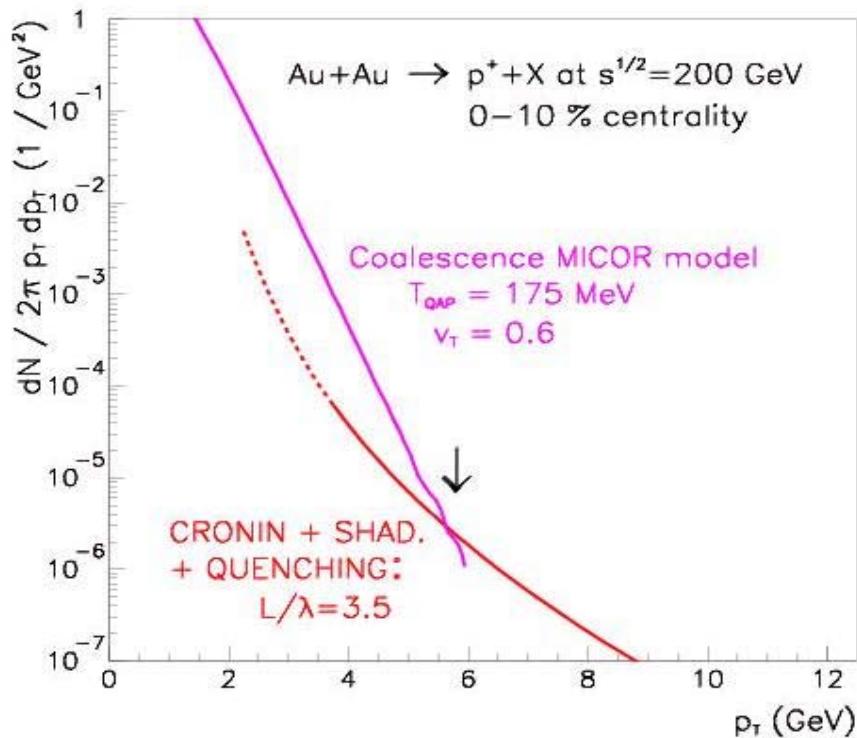
$$v_T = 0.6, 0.7, 0.8$$

Uncertainty from the
 transverse flow.

Protons at RHIC and LHC from the ALCOR/MICOR + pQCD

(Coalescence results with $v_T=0.6$.)

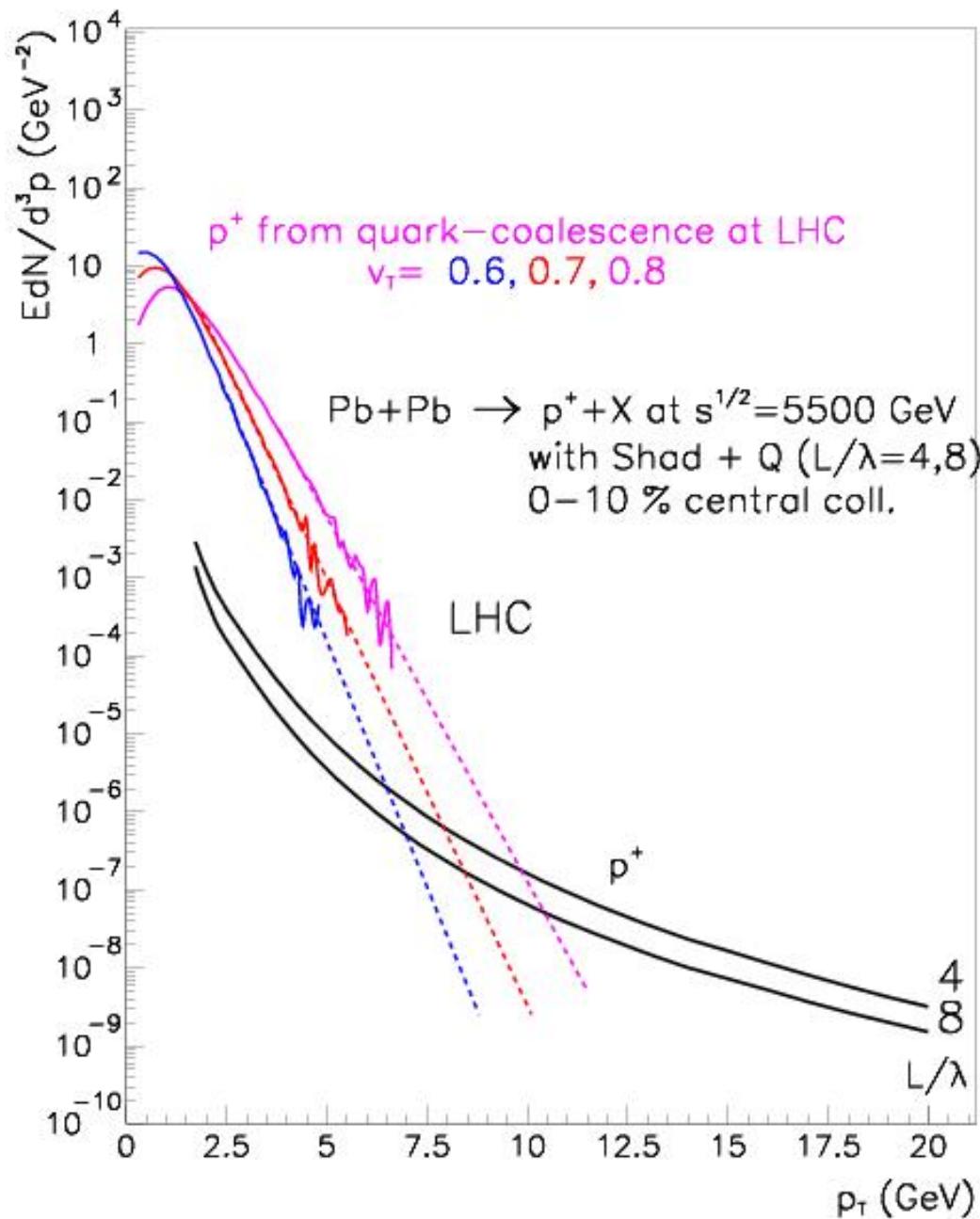
PQCD + Quark Coalescence at LHC for proton



Overlap at $p_T = 5 - 6 \text{ GeV}$ (RHIC)

at 6 ± 1 GeV at LHC

PQCD + Quark Coalescence at LHC for proton



Protons at LHC:
 (latest calculation)

$$dN/dy (p^+, y=0) = 70$$

$$dN/dy (h^-, y=0) = 625$$

$$v_T = 0.6, 0.7, 0.8$$

Uncertainty from the transverse flow.

How to measure and identify these hadrons at LHC ?

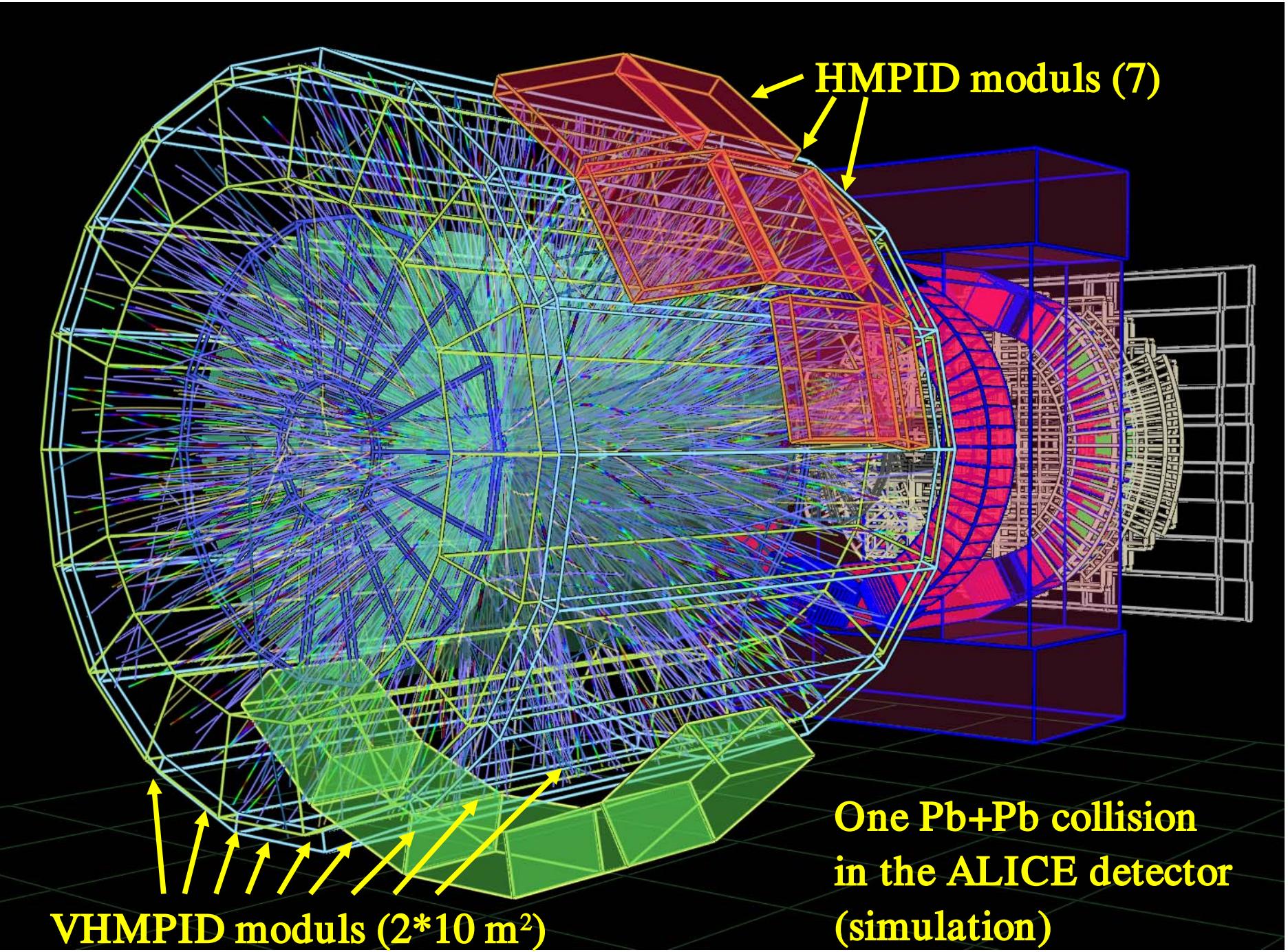
ALICE detectors:

TPC+TOF+ rdE/dx: up to $p_T = 10\text{-}12 \text{ GeV}/c$
(separation in a statistical way)

HMPID: pions up to $p_T=3 \text{ GeV}$
protons up to $p_T=5 \text{ GeV}$
(event by event)

VHMPID: (planned: R&D at CERN, Bari, Budapest, Mexico, Moscow)
up to $p_T=10\text{-}15 \text{ GeV}$ (depending on 'n')
(event by event)
hadron correlation with HMPID, EMCAL
high- p_T triggerig !

What about deuteron, triton, ... ? (D. di Bari)



Summary:

1. Hadronization descriptions are very “phenomenological”
2. Coalescence models are very successful at SPS and RHIC
3. Predictions can be made for LHC energies
for hadron production in a large p_T window
4. ALICE experiment can measure these hadrons
(TPC+TOF; HMPID, VHMPID detectors)

What can be done more?

5. Hadron coalescence ($p+n \rightarrow d, \dots$) - how does it work at RHIC ?
Predictions for deuteron, triton, and heavier nuclei at LHC