Baryon to meson ratio in pp and AA collisions at RHIC and LHC energies

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Heavy Ion Physics at LHC, Workshop
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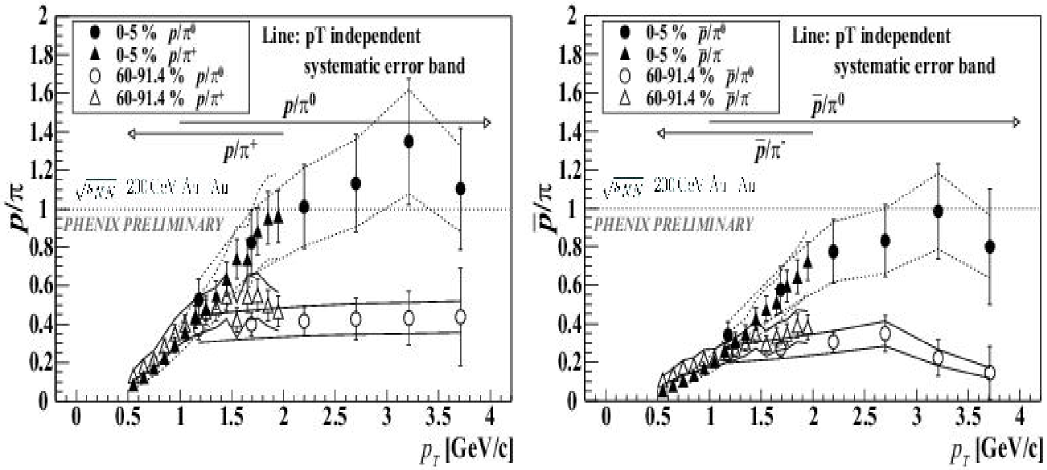
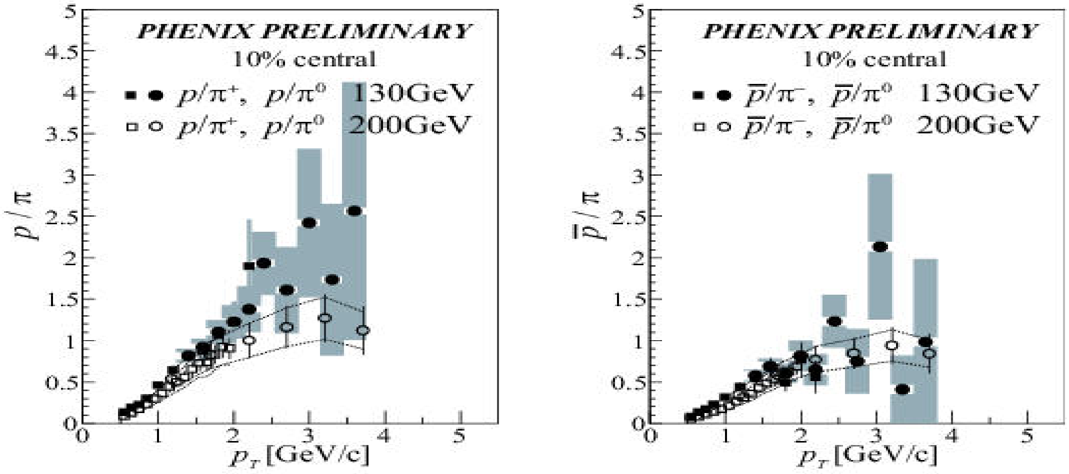
QM02: First results from RHIC at √s = 130 and 200 A GeV -- $p/\pi^+, \bar{p}/\pi^-$

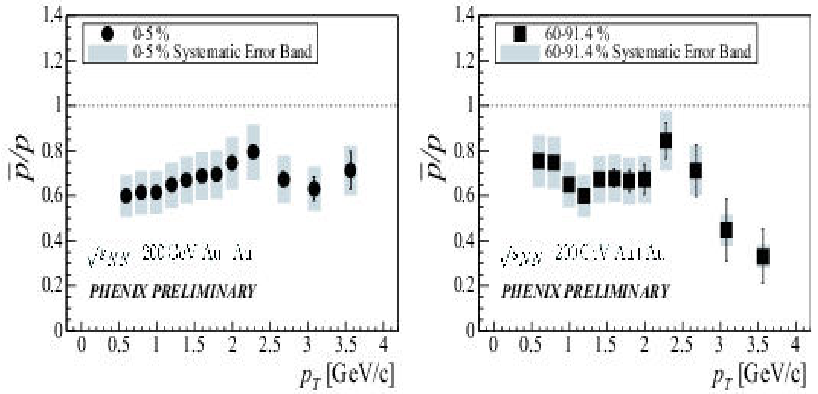
PHENIX Coll., T. Sakaguchi, NPA715(2003)757.





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

Anomalous antiproton (proton) production ??



The birth of "intermediate p_T-region"

Quark coalescence/recombination
(Hwa & Yang; Greco et al; Friese et al.)
See also Chun-Bin Yang's talk !!!

Jet quenching + quark coal. overlap
5 years of activity

1. Hadron production from parton matter:

independent parton fragmentation
vs. parton coalescence

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

Independent jet fragmentation: a[parton] ↣ h[hadron]

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

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

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

Parton recombination/coalescence/clustering: a+b ↣ h

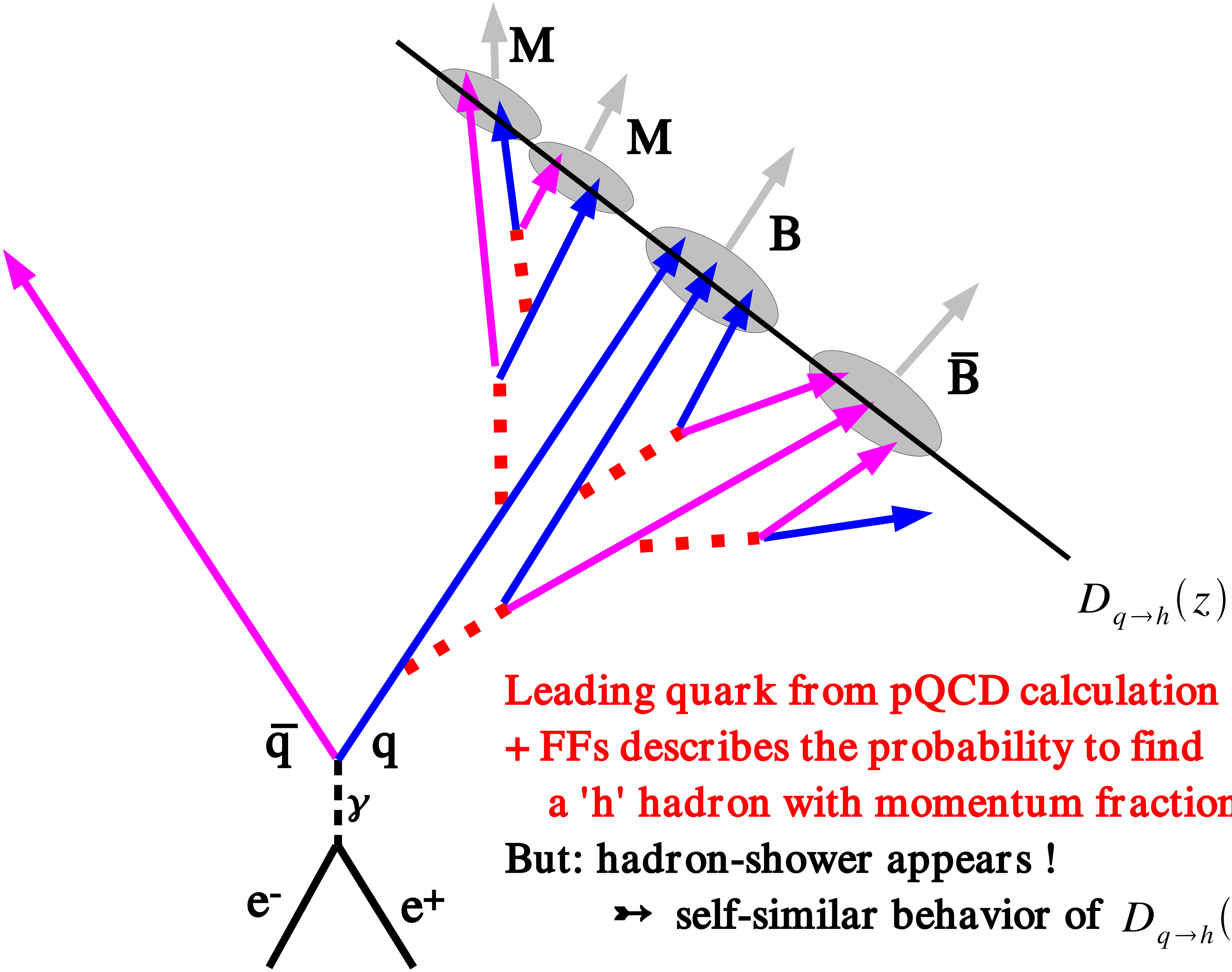
K.P. Das, R.C. Hwa, PLB68(1977)459, ...

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

can be substituted by
'effective' FF (Fragm. Funct)

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

Hadron production at the microscopical level: **FF picture**



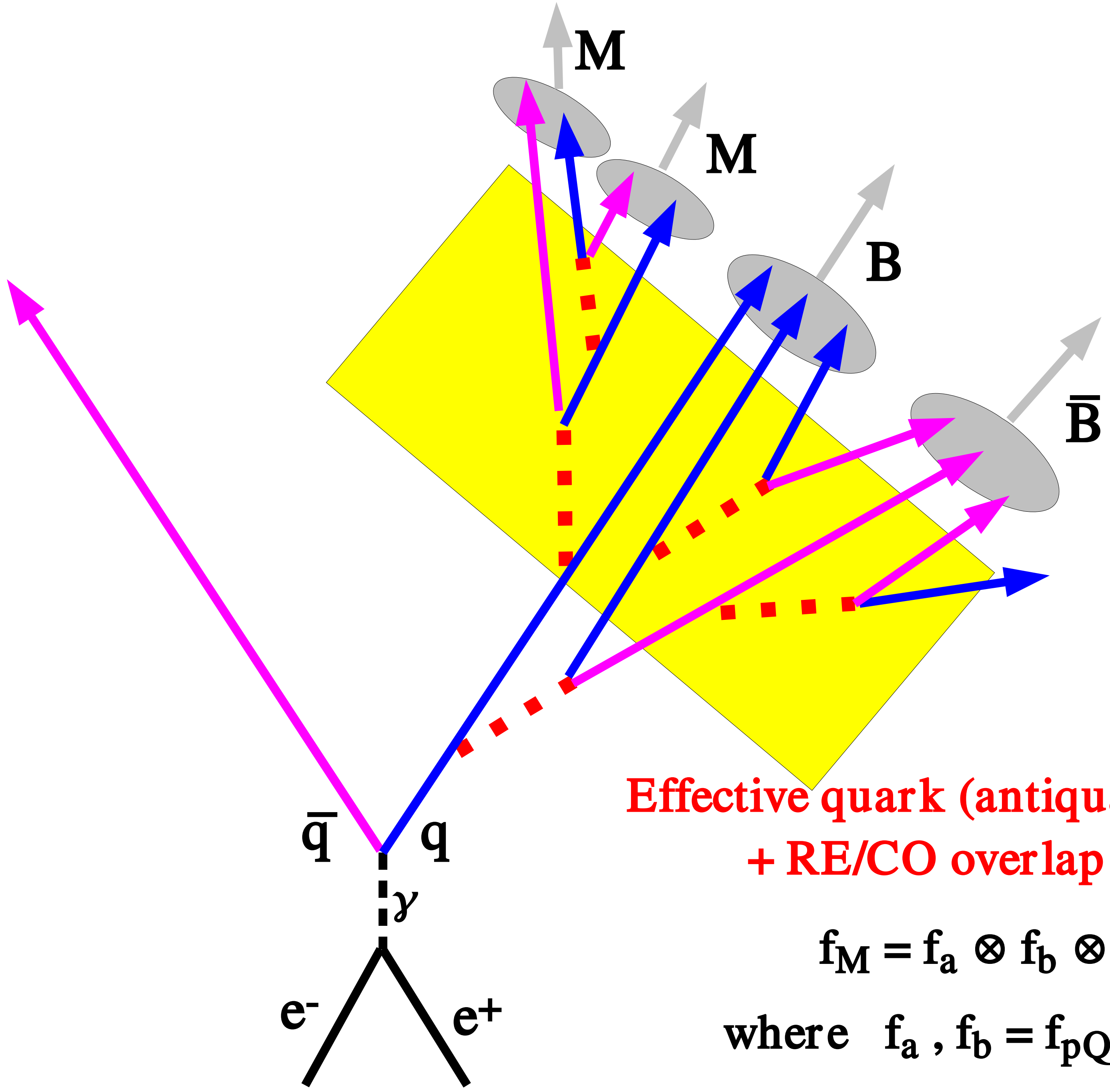
Leading quark from pQCD calculation
+ FFs describes the probability to find
a 'h' hadron with momentum fraction 'z'

But: hadron-shower appears !

↣ self-similar behavior of $D_{q\to h}(z)$

Hadron production at the microscopical level: RE/CO picture

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



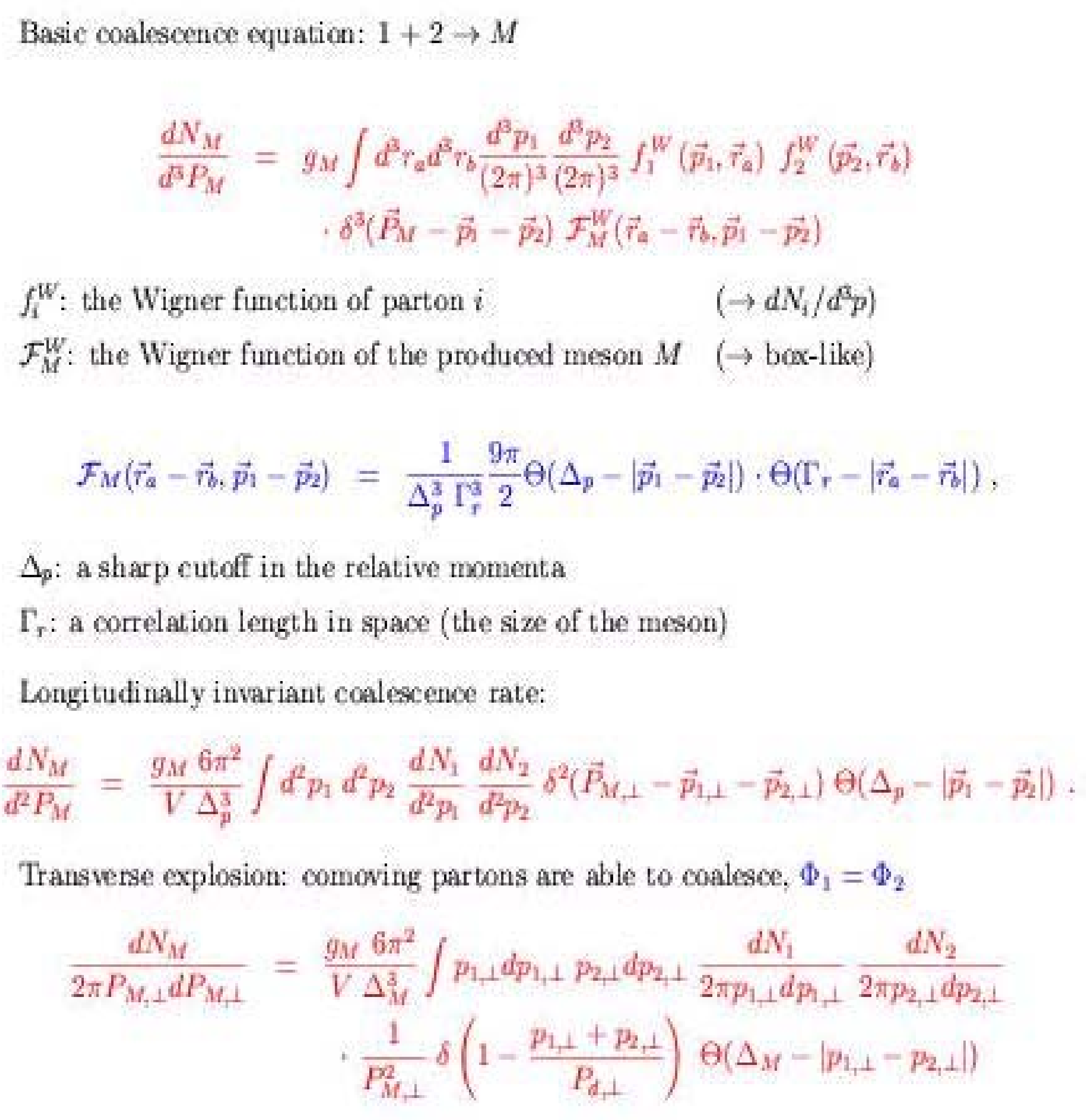
Effective quark (antiquark) distributions + RE/CO overlap functions :

$$f_M = f_a \otimes f_b \otimes R(p_a,p_b)$$

where $f_a\, ,\, f_b = f_{pQCD} \oplus f_{shower}$

For precise calculation: meson production on the basis of RECO

V. Greco, C.M. Ko, P. Levai, PRL90 (2003) 202302.
PRC68 (2003) 034904.



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

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

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

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

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

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,
PRC66 (2002) 064903.
R.J. Fries, B. Muller,
C. Nonaka, S.A. Bass,
PRL90 (2003) 202303.
PRC68 (2003) 044902.

Baryon production on the basis of RECO

G. K. L. PRL90 (2003) 202302

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 $(\to dN_i/d^3p)$

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

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

Δ_ρ, Δ_λ: sharp cutoffs in the relative momenta

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

Longitudinally invariant coalescence rate:

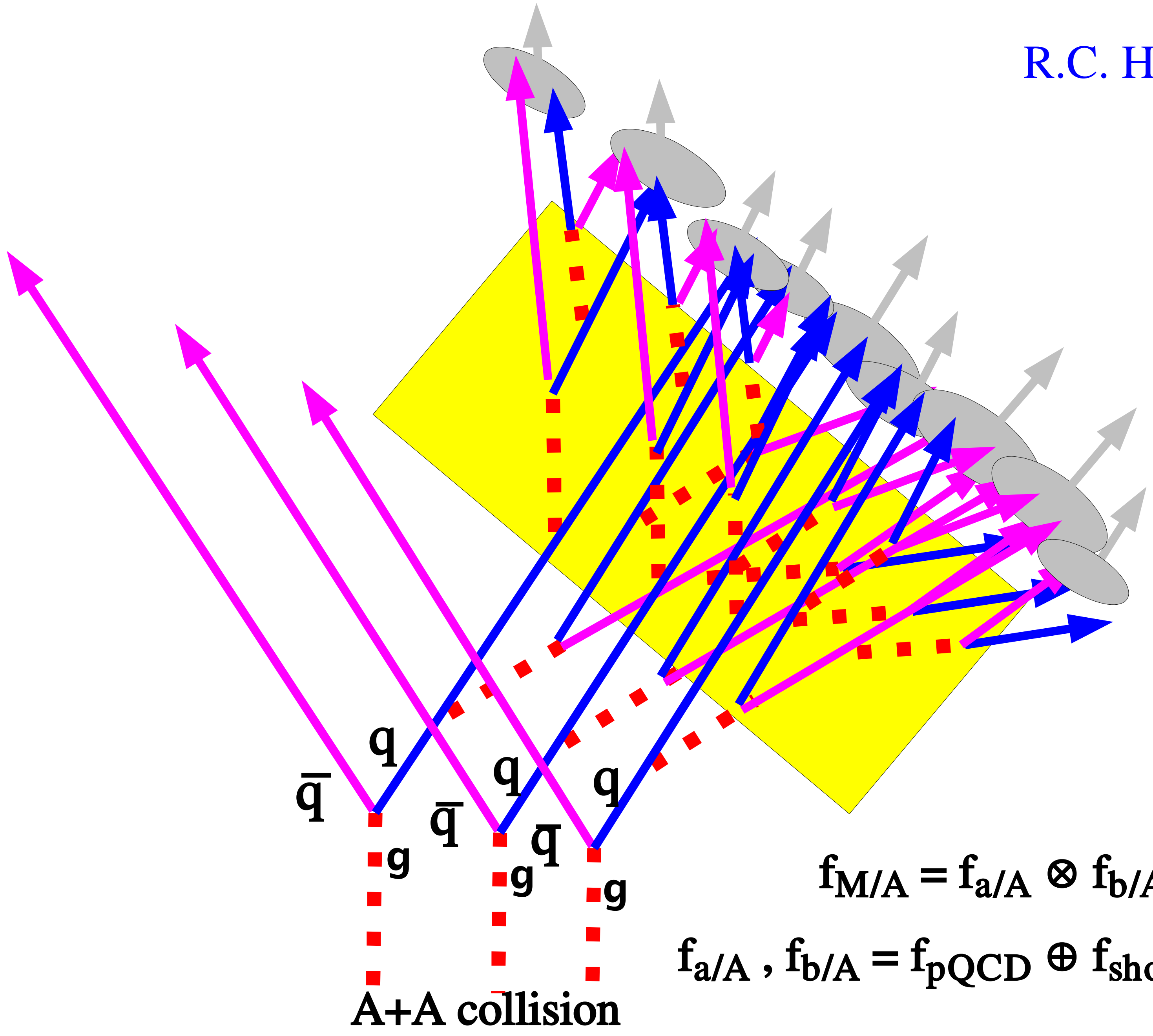
$$\frac{dN_B}{d^2P_B} = \frac{g_B}{V^2}\frac{36\pi^4}{\Delta_\rho^3\,\Delta_\lambda^3}\int d^2p_1\,d^2p_2\,d^2p_3\frac{dN_1}{d^2p_1}\frac{dN_2}{d^2p_2}\frac{dN_3}{d^2p_3}$$
$$\cdot\,\delta^2(\vec{P}_{4,\perp}-\vec{p}_{1,\perp}-\vec{p}_{2,\perp}-\vec{p}_{3,\perp})\;\cdot\;\Theta(\Delta_\rho-|\vec{q}_{\rho,\perp}|)\cdot\Theta(\Delta_\lambda-|\vec{q}_{\lambda,\perp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

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

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

Hadron production at the microscopical level: RE/CO picture - 2

R.C. Hwa, C.B. Yang

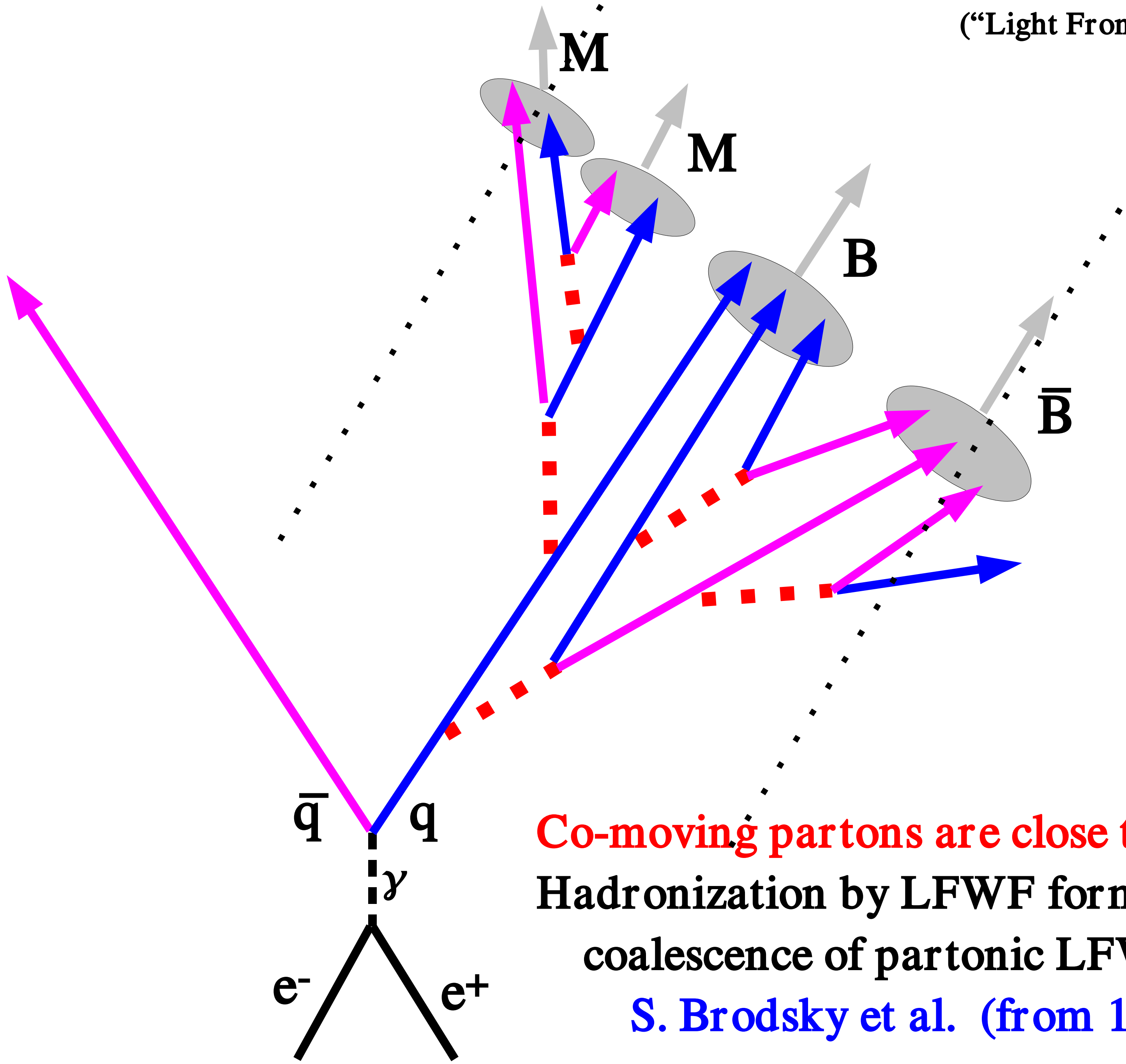


$$f_{M/A} = f_{a/A} \otimes f_{b/A} \otimes R_A(p_a,p_b)$$

$$f_{a/A}\,,\, f_{b/A} = f_{pQCD} \oplus f_{shower} \oplus f_{thermal}$$

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:

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

Proton wave function: superposition of the Fock-states

$$|\psi_p> \;=\; |uud> \;+\; |uudg> \;+\; |uudgg> \;+\; \ldots$$

Wave function with relative momentum coordinates:

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

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 !!!

QUARK COALESCENCE: Schrödinger-picture, comoving frame

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]

⇒ 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

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

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

⇒ many coalescence channels exist (π, ρ, K, K*, ϕ, ...)

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

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

➡ 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**

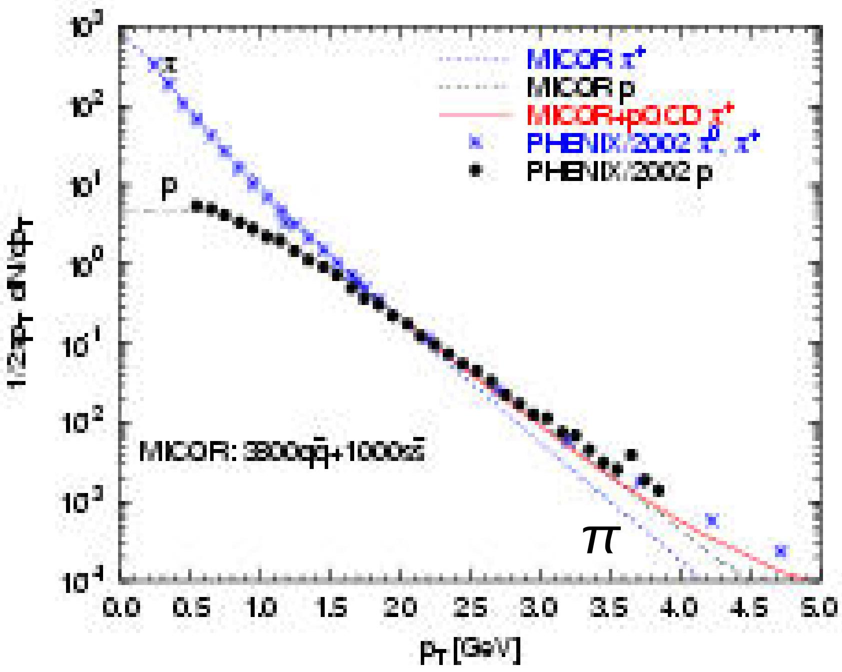
Quark coalescence at low-p_T: MICOR + pQCD model

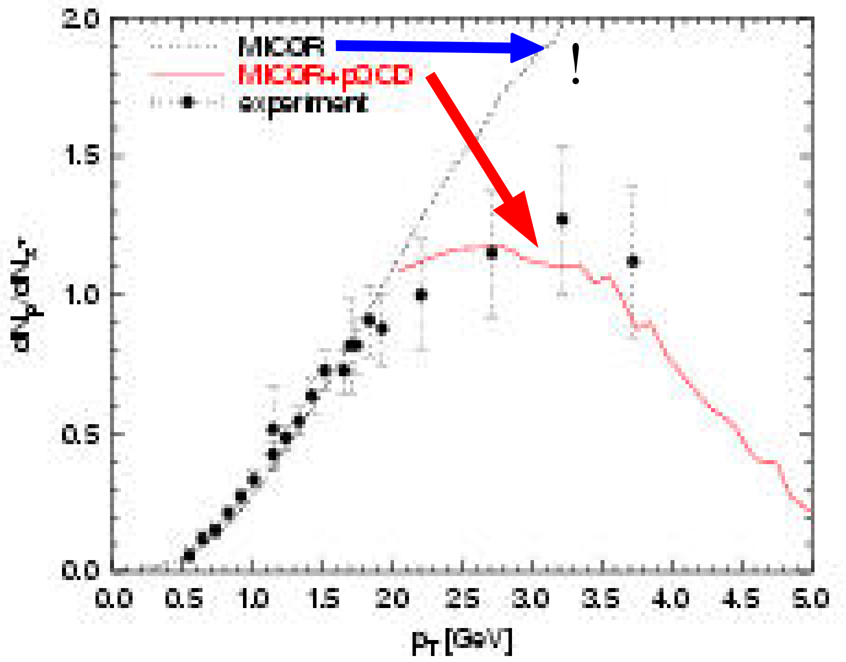
Bulk proton/pion ratio

P. Csizmadia, P.L. '03

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

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

2. Hadron production from quark matter:

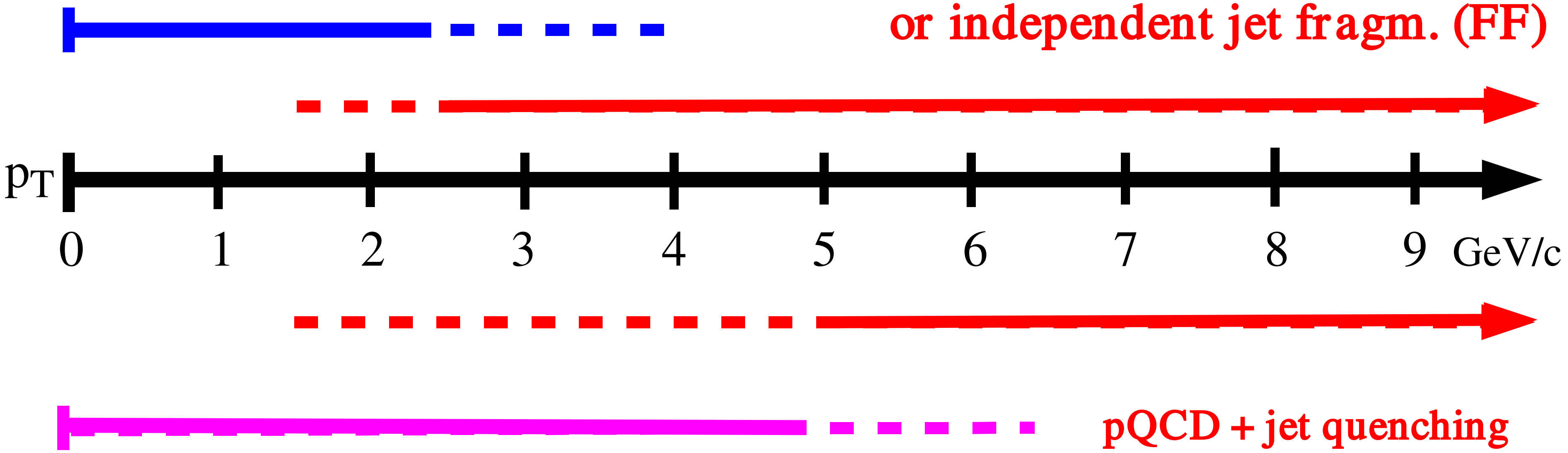
theoretical results
vs. experimental data

One-particle spectra in central A+A collisions in wide p_T-region:

HADRONIC PARADIGM

Hadron hydrodynamics
(hadron thermo + hadron flow)

pQCD + jet quenching
+ first order phase transition
or parton-hadron duality
or independent jet fragm. (FF)



pQCD + jet quenching
(partons, $2 \to 2$, $2 \to 3$, ...)
+ indep. jet fragm. (FF)

Quark hydrodynamics
(quark thermo + quark flow)
+ coalescence/recombination

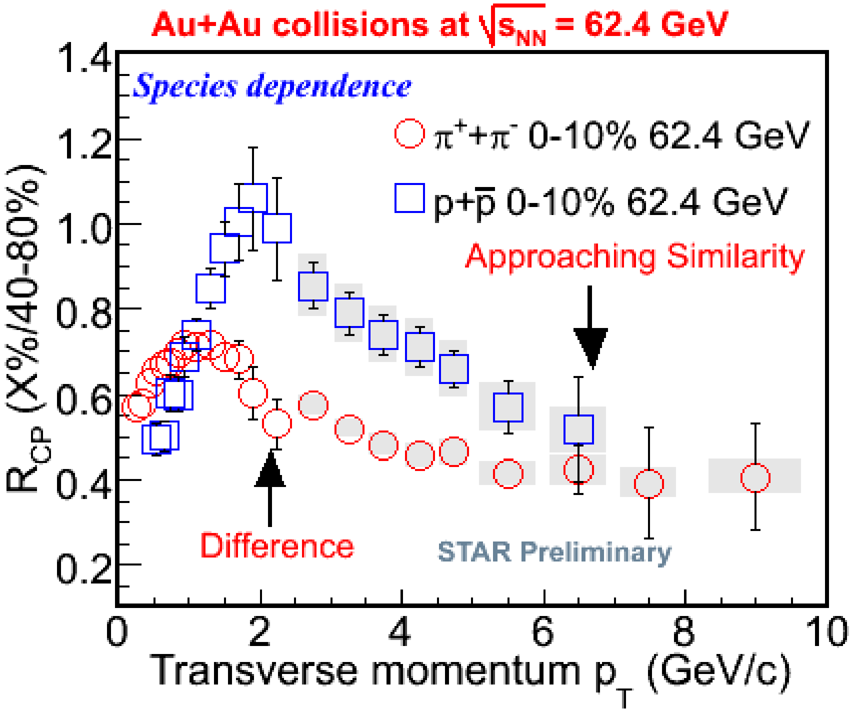
QUARK PARADIGM

Talks from Y.G. Ma, C.M. Ko, C.B. Yang, ...

QM2006 results from RHIC:

Meson- and baryon-suppressions seems to be the same at high p_T .

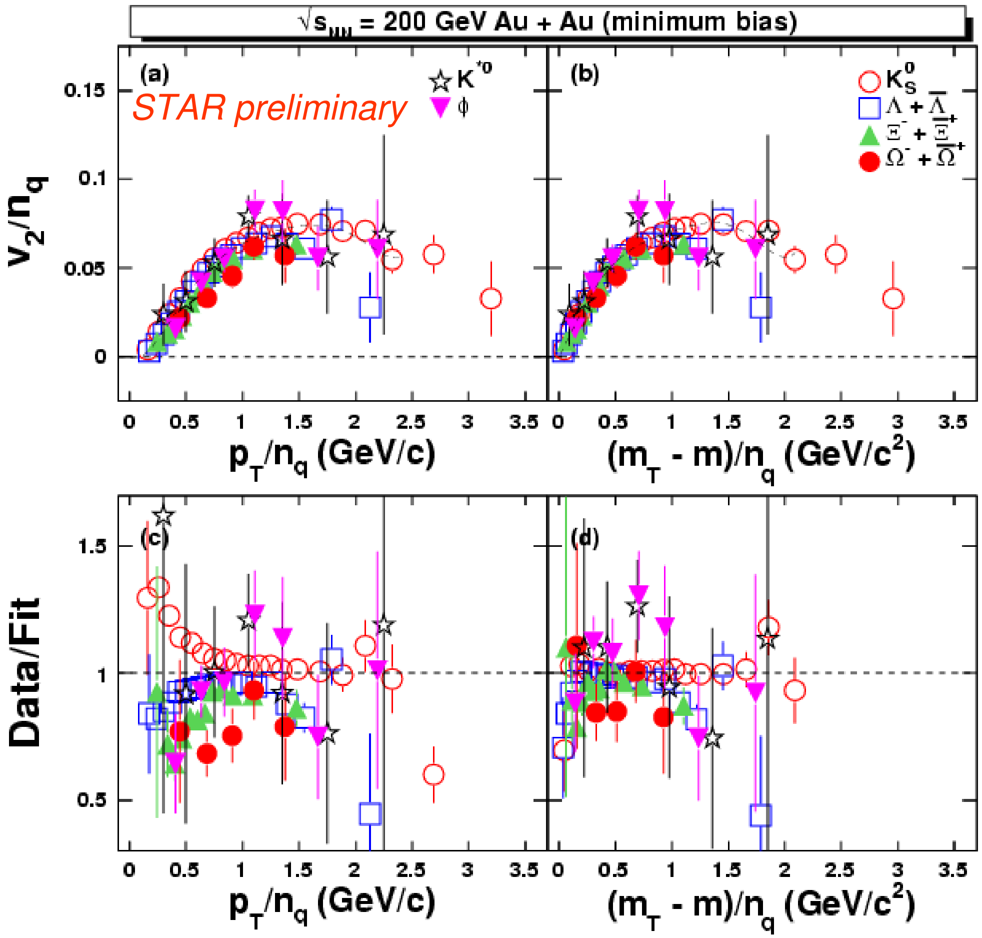
Jet-picture incl. energy loss (pQCD)
is recovered beyond a threshold,
but anomalous B/M ratio at intermed. p_T



Constituent quark scaling can be clearly seen in v_2 !

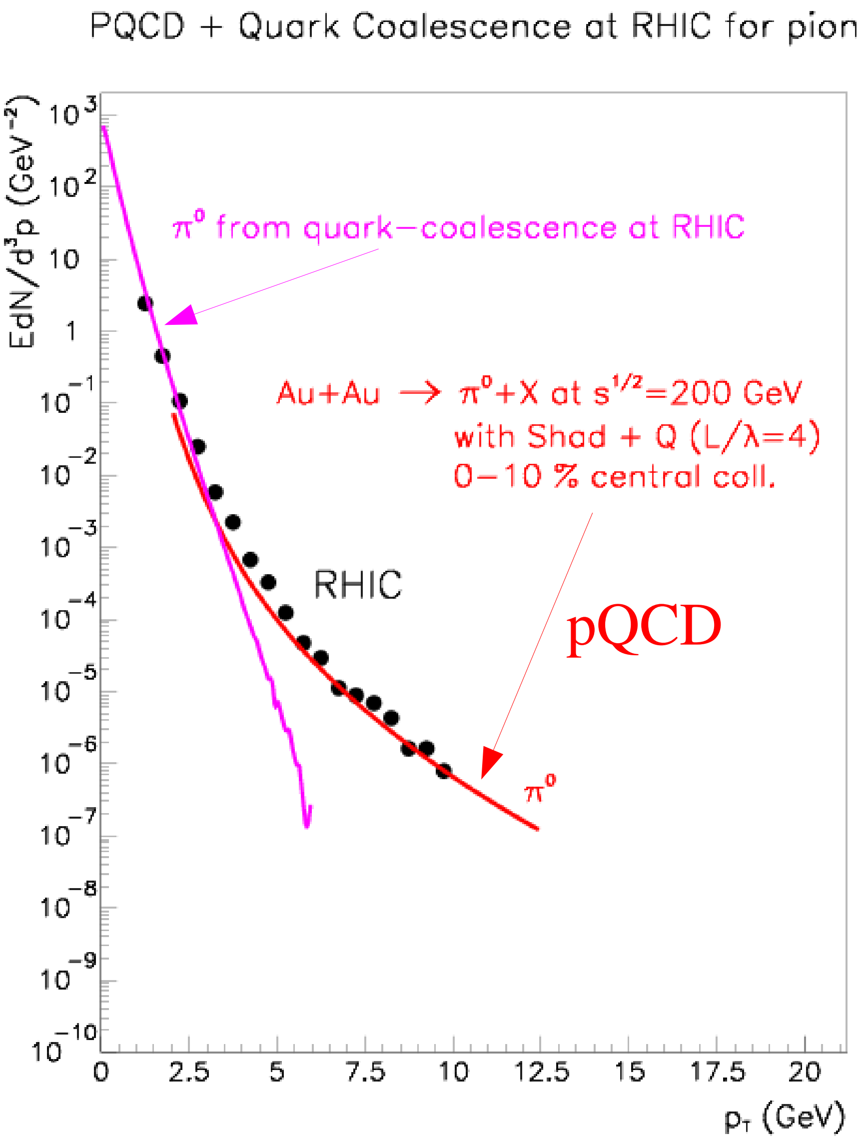
Bulk quark-antiquark matter around T_c phase transition, deconfined quark-matter at $T>T_c$!

Quark-paradigm is supported !!!!

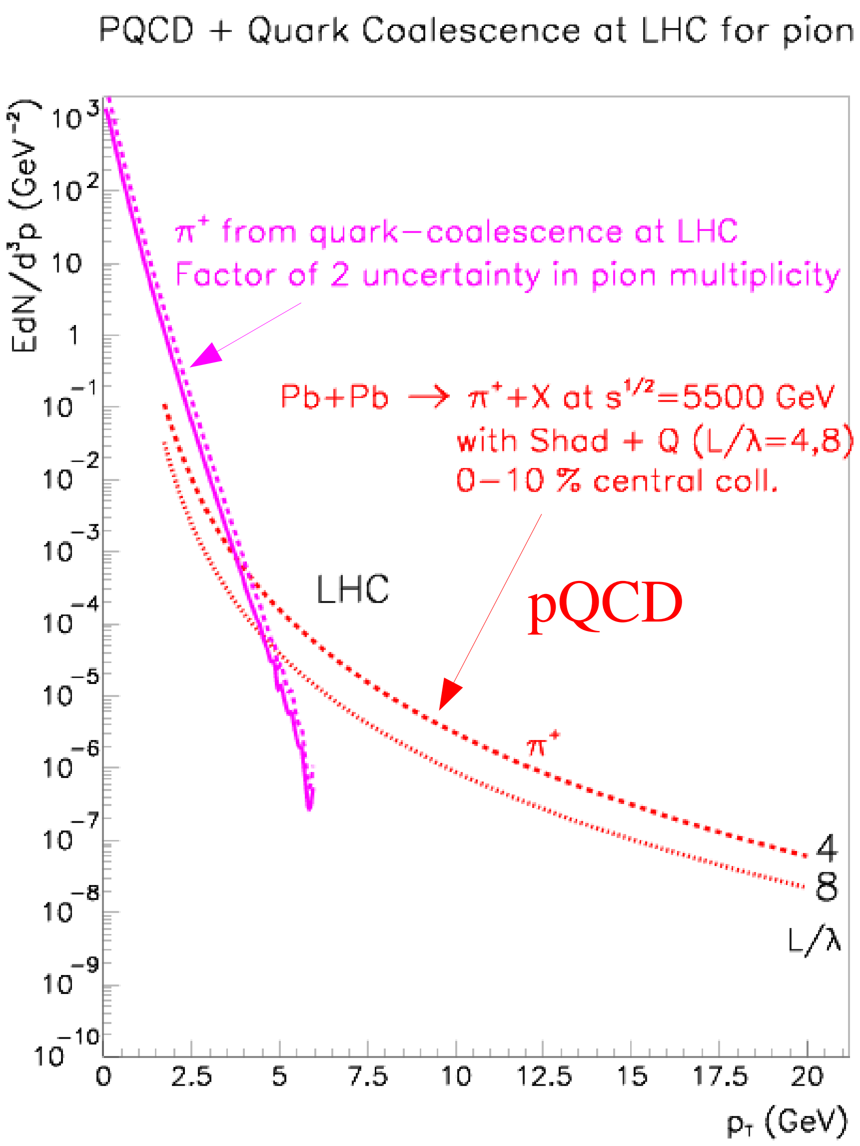


Theoretical results (2005) for pions at RHIC and LHC

(Scaled up RHIC result for coalescence, v_T=0.6.)



PQCD + Quark Coalescence at RHIC for pion



PQCD + Quark Coalescence at LHC for pion

Overlap at p_T = 2.5 - 3 GeV (RHIC)   at 4 ± 1 GeV at LHC

One-particle spectra in central A+A collisions in wide p_T-region:

Proton/pion (B/M) anomaly:

excellent tool to investigate the overlap between
the RECO and pQCD region

RECO details

very phenomenological (so far)

pQCD details

pp baseline (LO, NLO, intrinsic-kT, Sudakov-terms, ...)

fragmentation functions (KKP, AKP, ...; proton, Λ, Ξ, ...)

quenching mechanisms:

--- volume or surface effect

--- radiative and/or collisional energy loss

--- gluons and quarks in hot matter

Many open questions: two-particle correlations may help to answer

Two-particle correlations in pp, pA, AA collisions in wide p_T-region:

1. $\frac{v_2}{n_q}(\frac{E_T}{n_q})$ scaling strongly supports quark RE/CO
   quark number scaling (QNS) at lower pT
   [QNS-breaking at higher pT means pQCD/FF domin.]

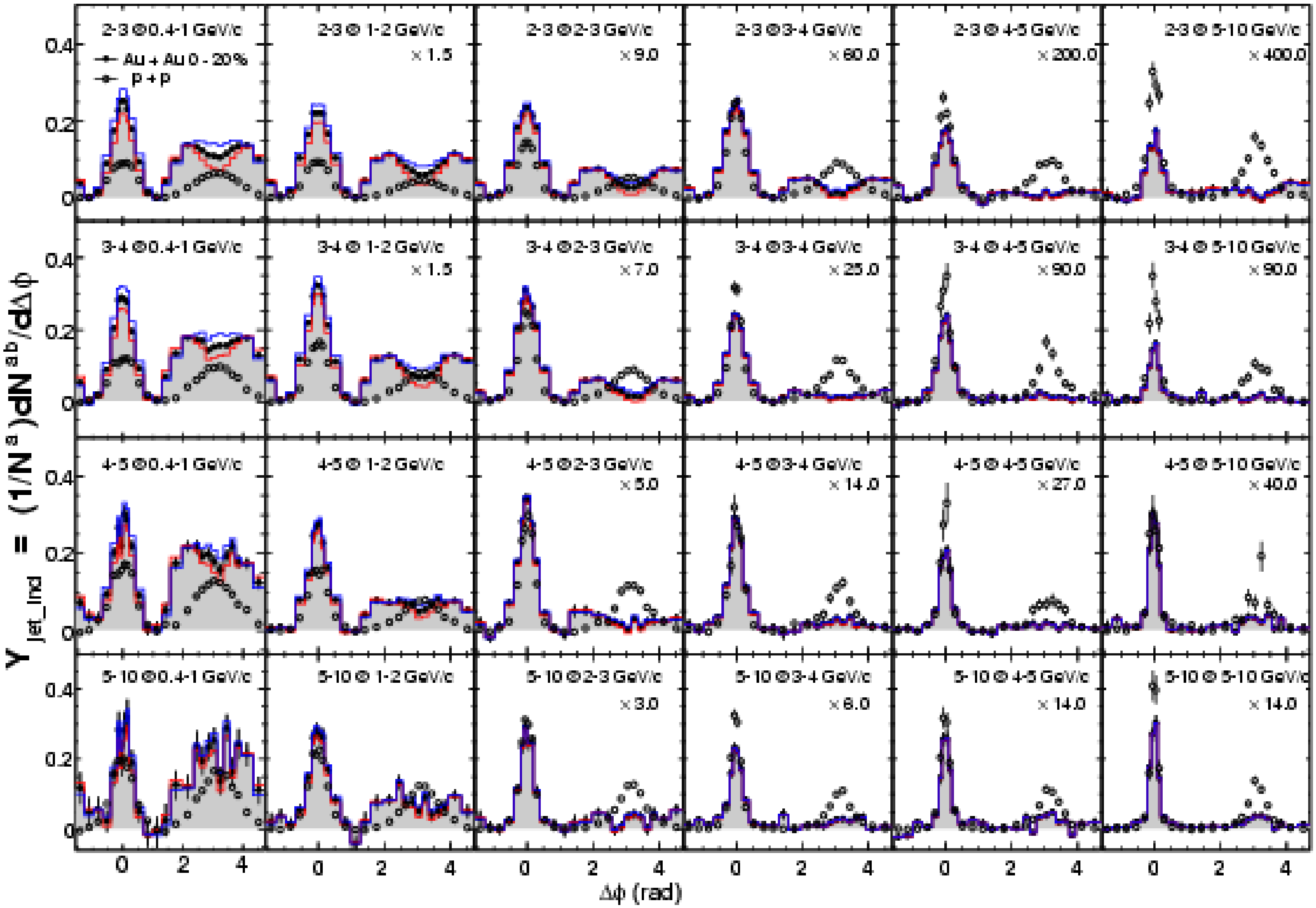
2. Near-side correlations:
   measurable modifications in pp ↣ dAu ↣ AuAu
   indicate in-matter effects for jets ➤➤➤➤ RIDGEOLOGY
   systematic analysis can be performed

3. Away-side correlations:
   strong modifications in pp ↣ dAu ↣ AuAu
   --- double bump structure, Mach-cones, ...
   --- jet-suppression, jet-reapperance, ...
   new ideas are constructed for explanations

Jet-Ridge-Bump: mutual understanding ➤➤ e.g. proton/pion ratio ?

QM08: Latest results from PHENIX at RHIC energy at √s = 200 A GeV

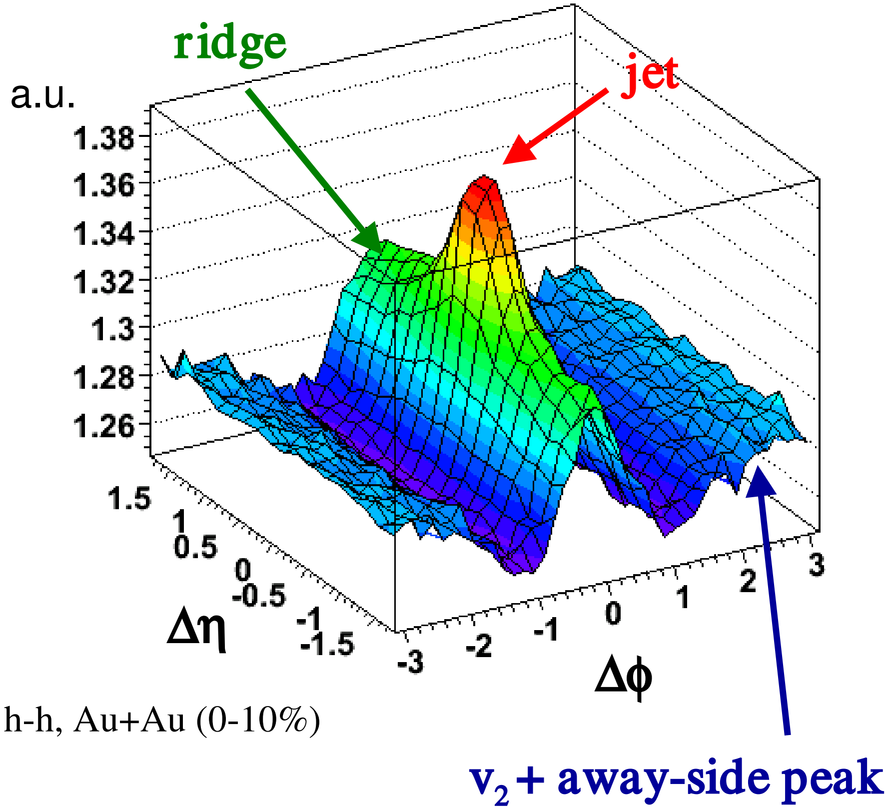
Hadron-hadron correlations   A. Adare et al., arXive: 0801.4545 [hep-ex]



Two-particle correlations: ΔΦΔη

J. Putschke, J.Phys.G34:S679-684,2007

p_T^{trig}=3-6 GeV/c, 1.5 GeV/c <p_T^{assoc}< p_T^{trig}



ridge

jet

v_2 + away-side peak

h-h, Au+Au (0-10%)

- The azimuth angle correlations are extended to Δη
- At near-side the „ridge” appears
- High p_T partons interact with the hot background matter

Armesto et al, PRL 93 (2004)
Majumder et al, hep-ph/0611035
Chiu & Hwa Phys. Rev. C72:034903,2005
S.A. Voloshin, Nucl. Phys. A749, 287 (2005)

- Particle composition (B/M ratio, ...):
  - Peak in AuAu: pp-like
  - Ridge in AuAu: different
- QM'08: C.H CHEN (PHENIX)
  --- ridge is softer than hard scattering (pp)
  --- away shoulder is softer than ridge

Reference: bulk pion and proton production
initial thermal quark distributions (gluons have decayed)
quark coalescence at low-p_T and intermediate-p_T
(MICOR results for RHIC and LHC --- Csizmadia, L.P.)

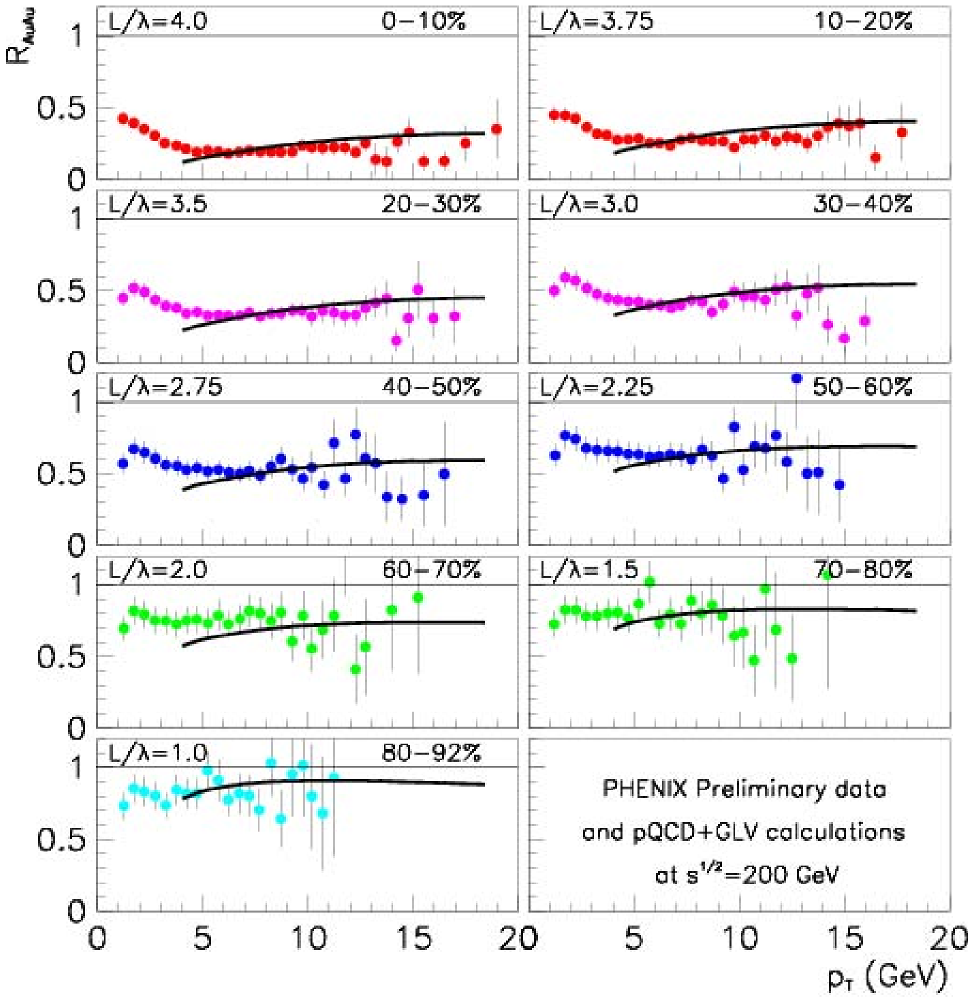
Near-side:
Jet-peak: pQCD with jet-fragmentation

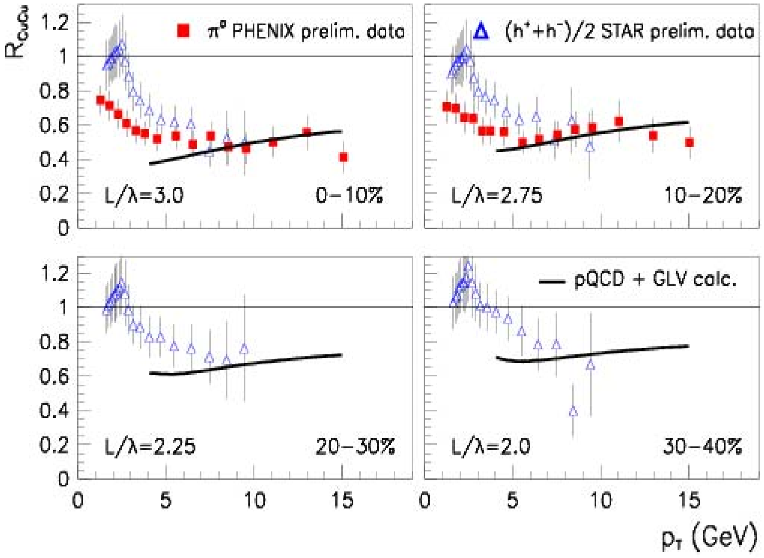
Ridge: ST: shower quark distribution + thermal (anti)quark
STT (or SST) for baryon production

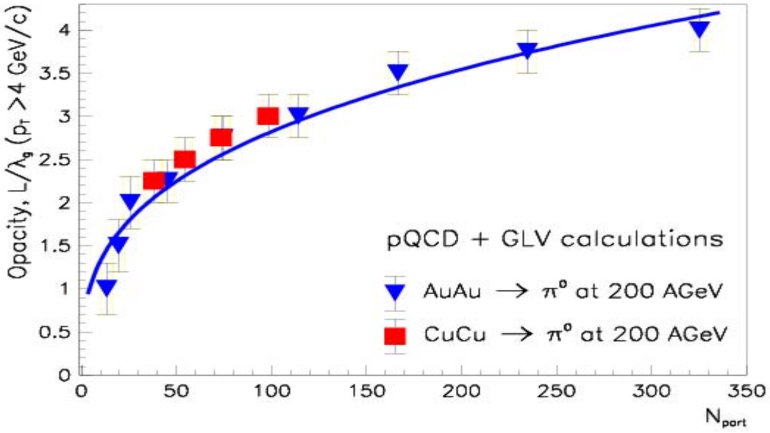
Away-side (just for first approximation):
Bump: TT: thermal quark + thermal antiquark for pion
STT + TTT for baryon production

Bulk pion production at high-p_T at 200 AGeV ($p_T > 5$ GeV)

Au + Au collisions (opacities)   Cu+Cu collisions (opacities)





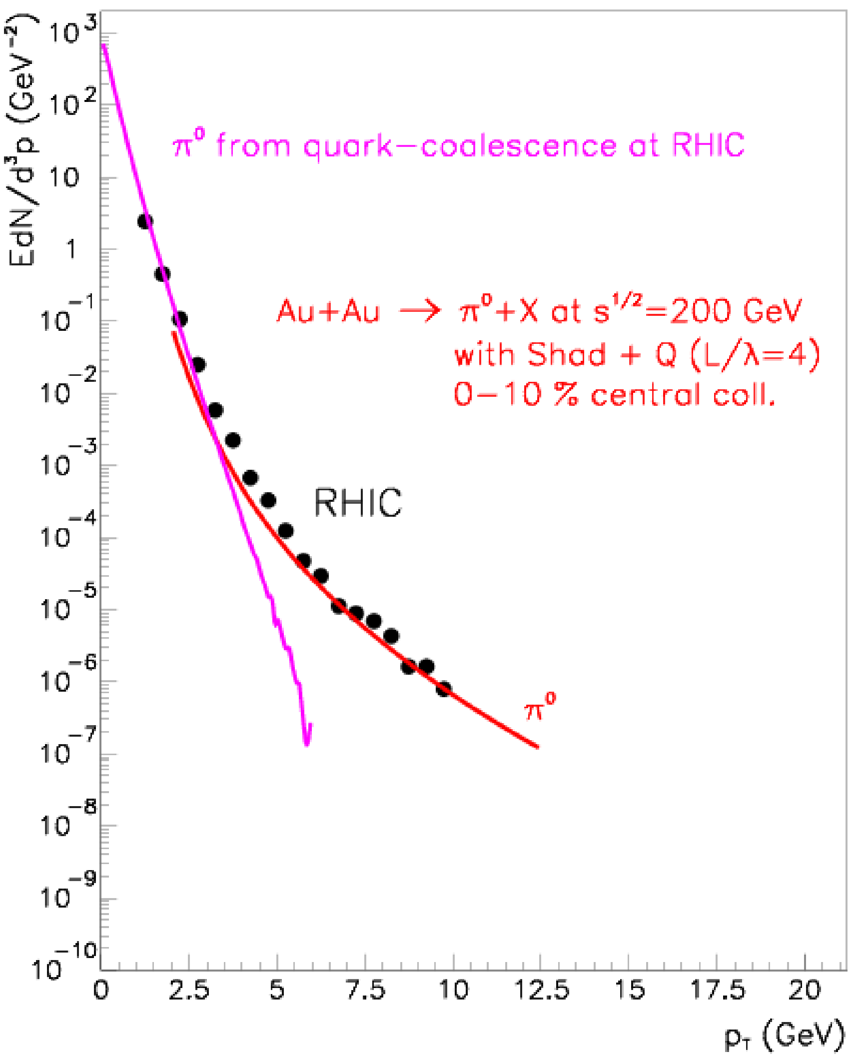


Jet energy loss: volume effect ⇔ $L / \lambda \propto (N_{part})^{1/3}$

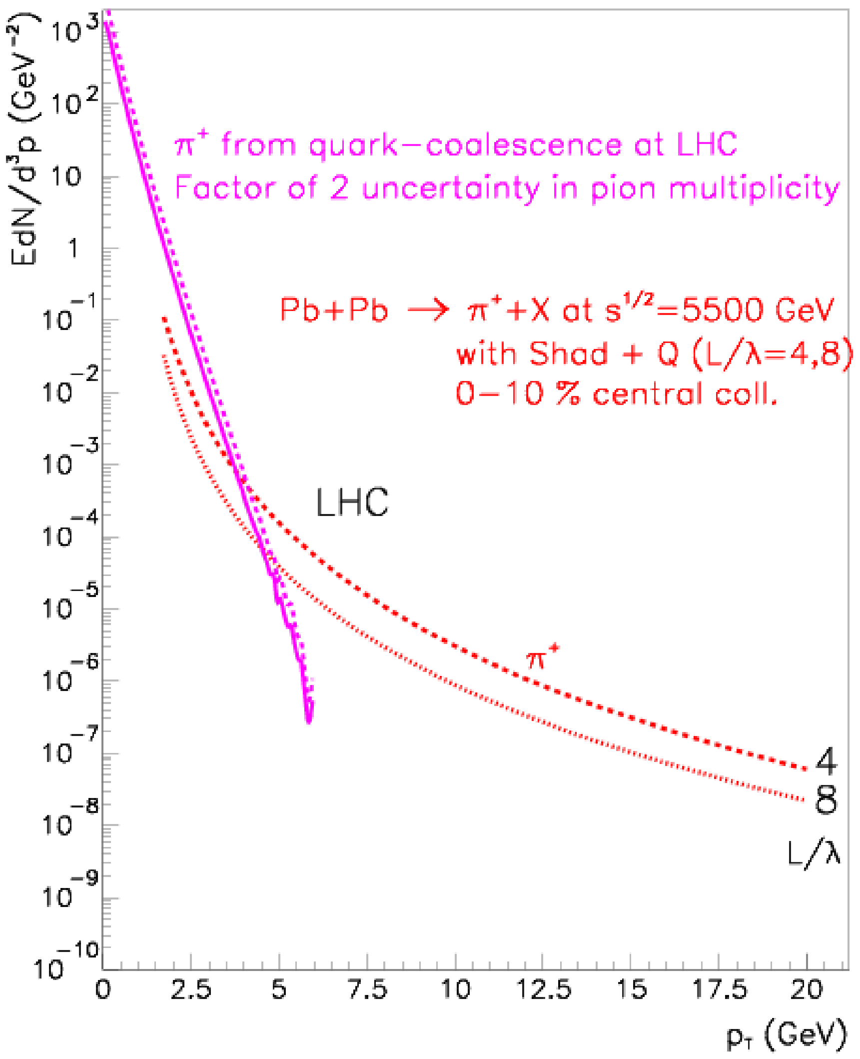
G.G. Barnafoldi et al., Eur. Phys. J C33 (2004) S603.

Bulk Pions at RHIC and LHC

(Scaled up RHIC result for coalescence, v_T=0.6.)

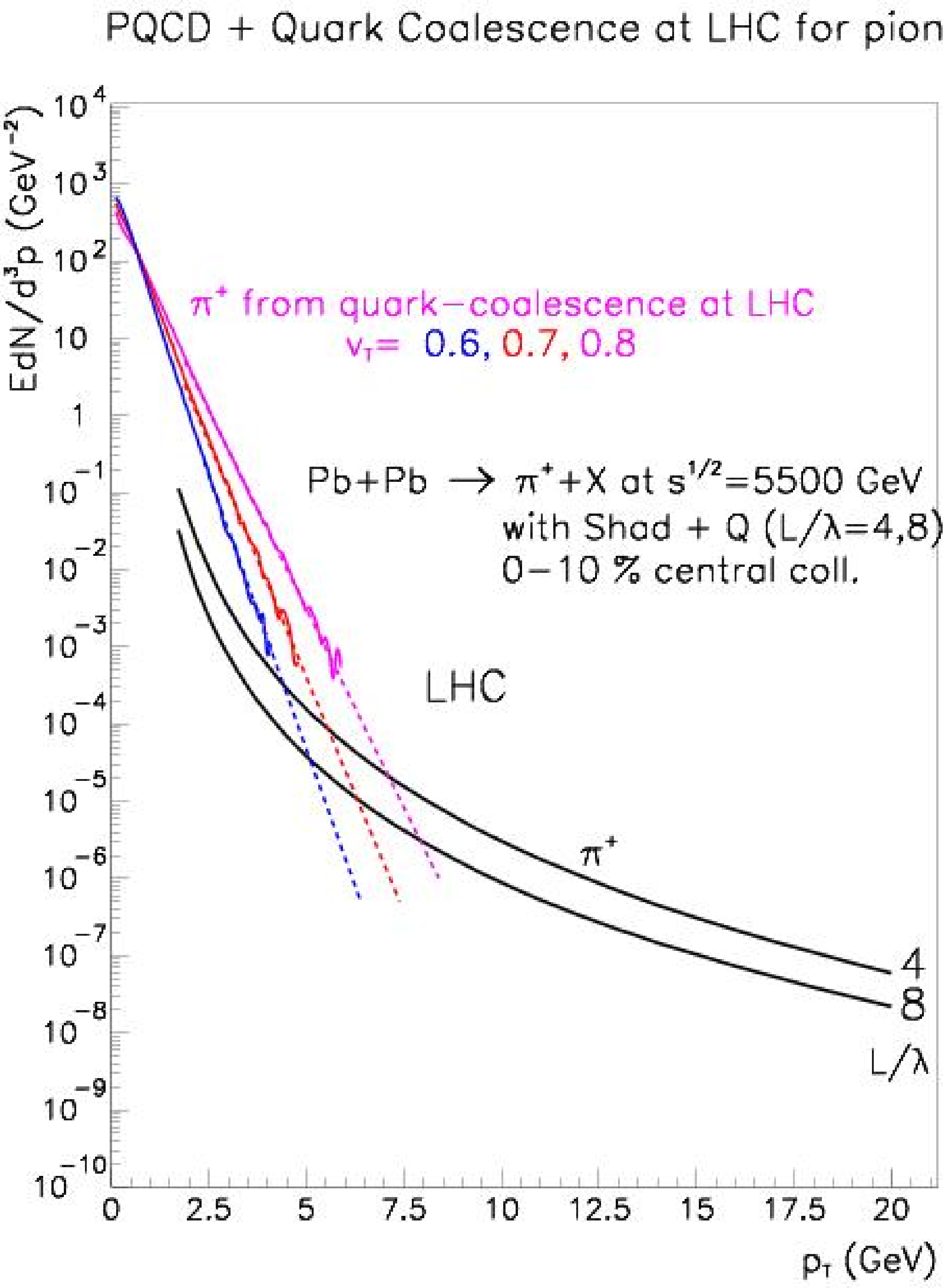


PQCD + Quark Coalescence at RHIC for pion



PQCD + Quark Coalescence at LHC for pion

Overlap at p_T = 2.5 - 3 GeV (RHIC) at 4 ± 1 GeV at LHC



Bulk pions at LHC:
(latest calculation)

dN/dy (π^+, y=0) = 631

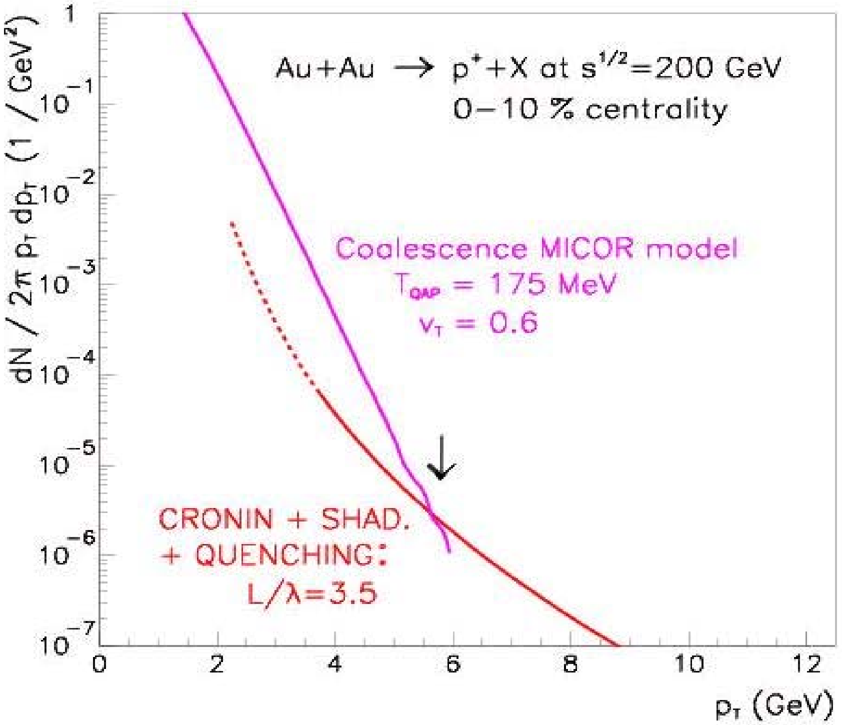
dN/dy (h^-, y=0) = 816

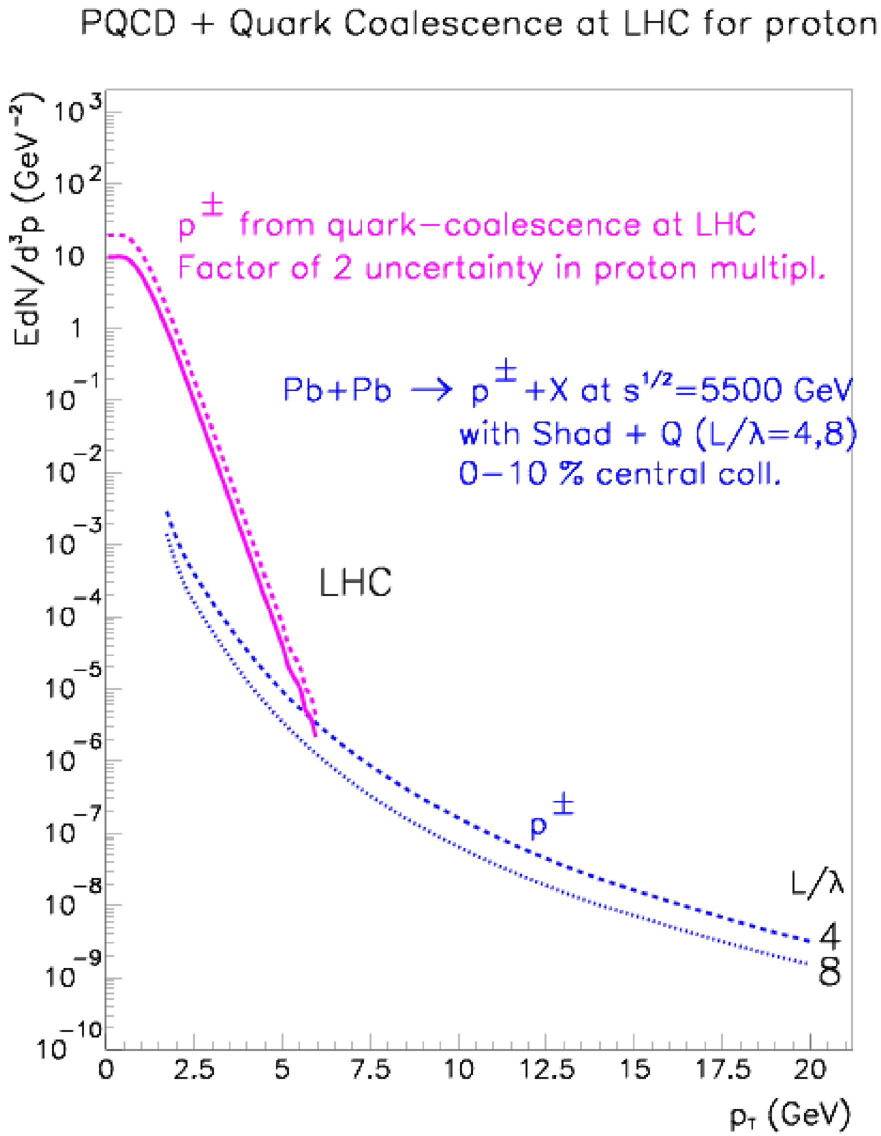
v_T=0.6, 0.7, 0.8

Uncertainty from the transverse flow.

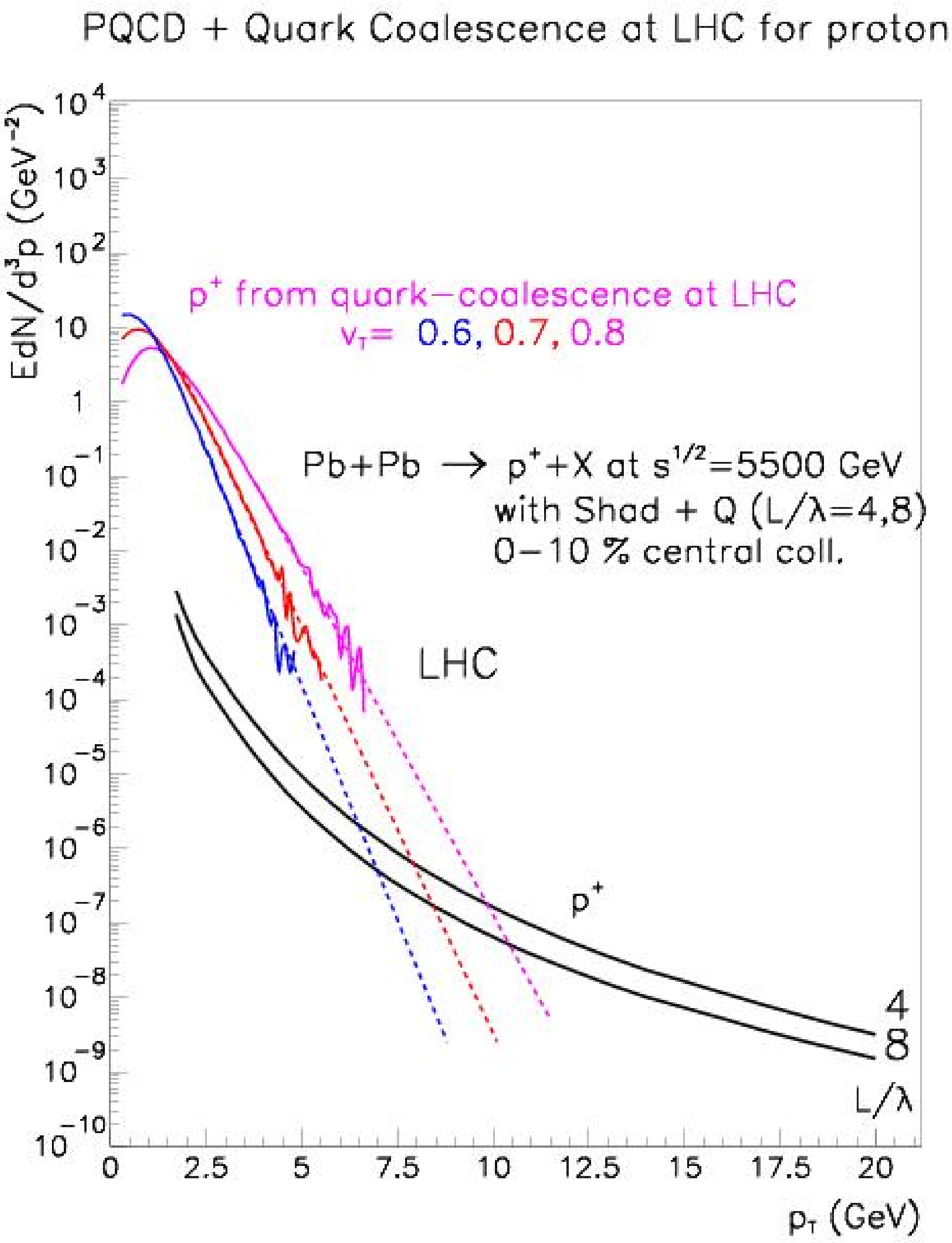
Bulk protons at RHIC and LHC

(Scaled up RHIC result for coalescence, v_T=0.6.)





Overlap at p_T = 5 - 6 GeV (RHIC)   at 6± 1 GeV at LHC

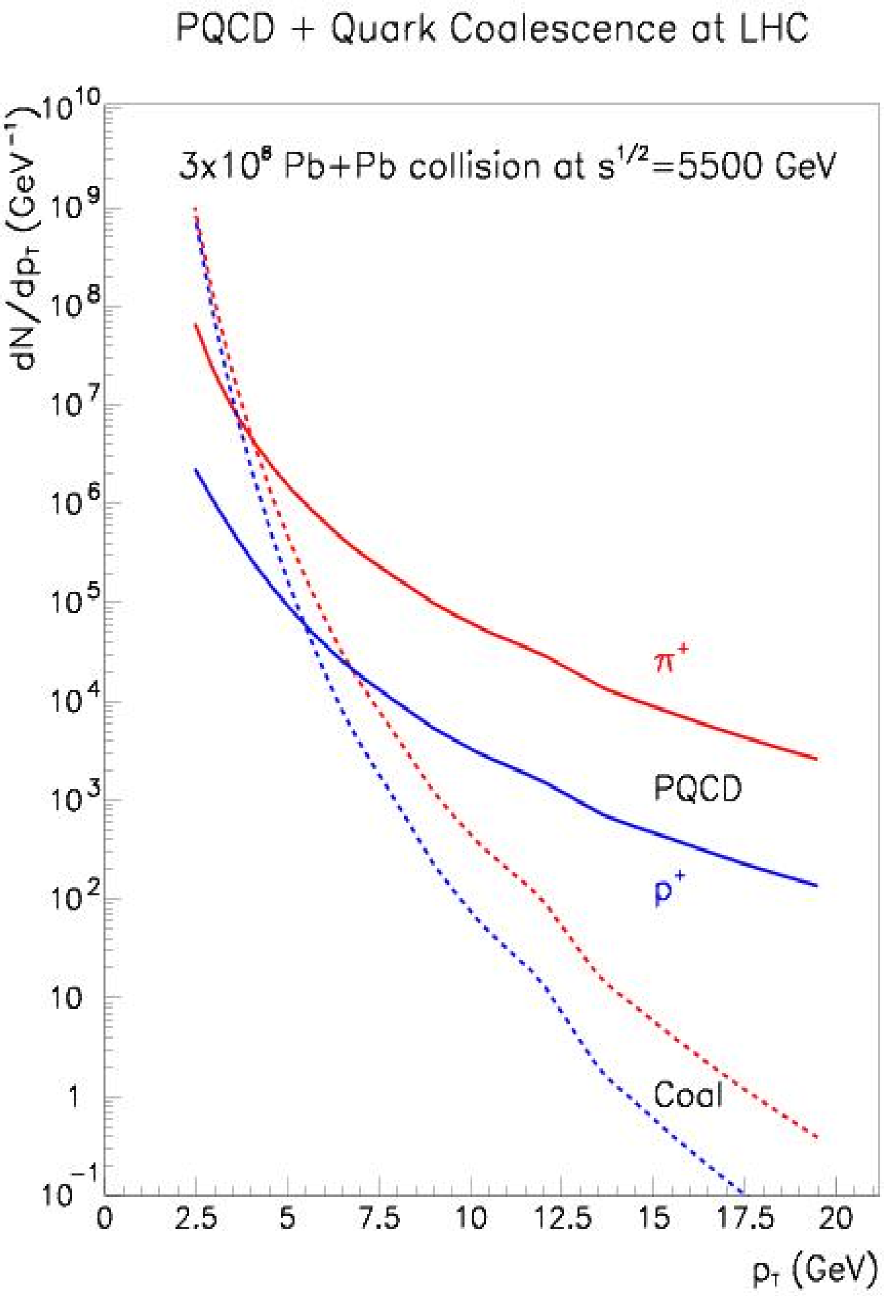


Bulk protons at LHC:
(latest calculation)

$dN/dy\ (p^+, y=0) = 68.6$
$dN/dy\ (h^-, y=0) = 816$

v_T=0.6, 0.7, 0.8

Uncertainty from the transverse flow.

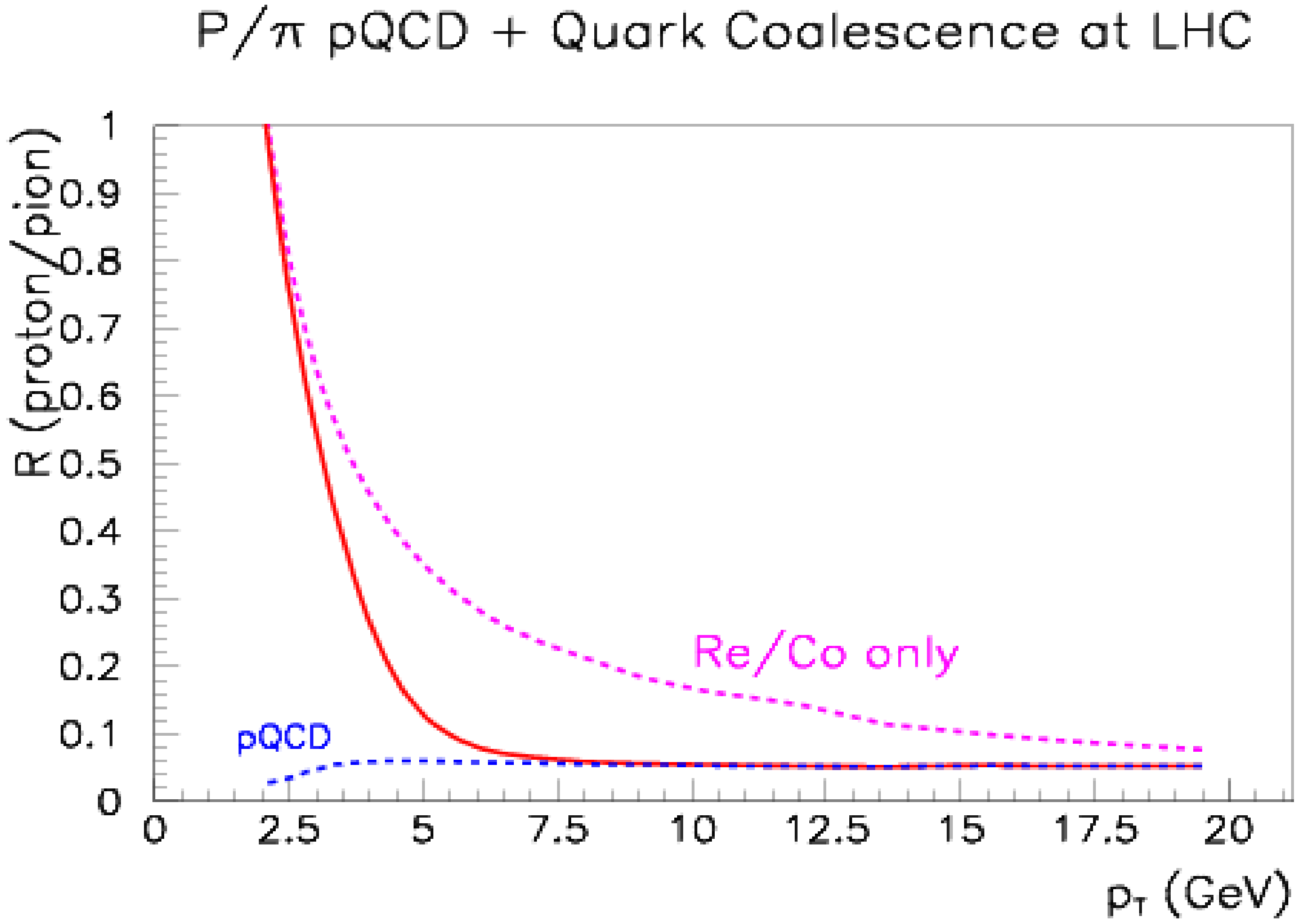


“1 year” at LHC:
absolute yields for
bulk pion and proton
(v_T=0.7)

What are the wanted
proton/pion ratios ?

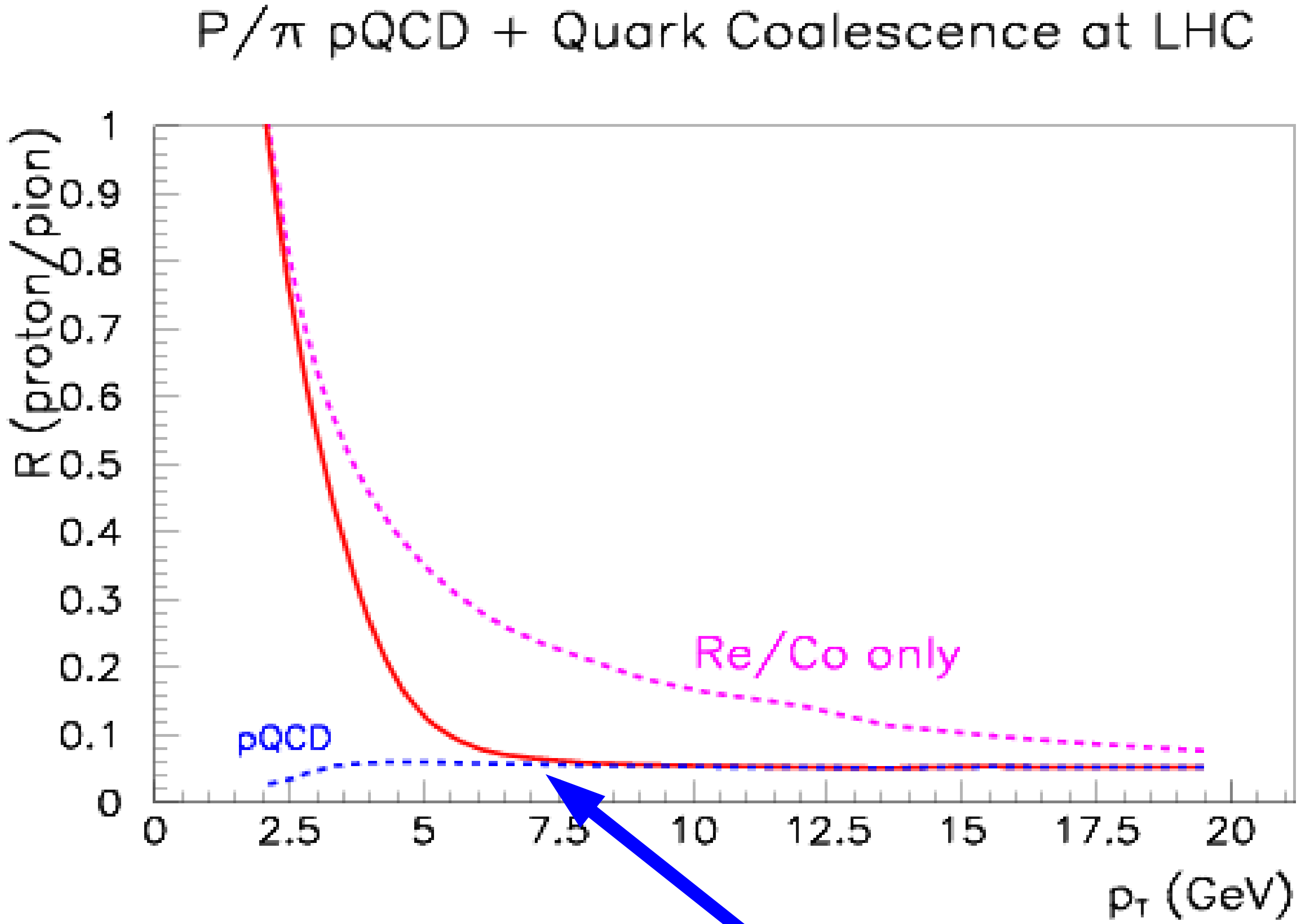
Bulk proton/pion ratio at intermediate-p_T:

MICOR + pQCD model



Jet proton/pion ratio at intermediate-p_T:

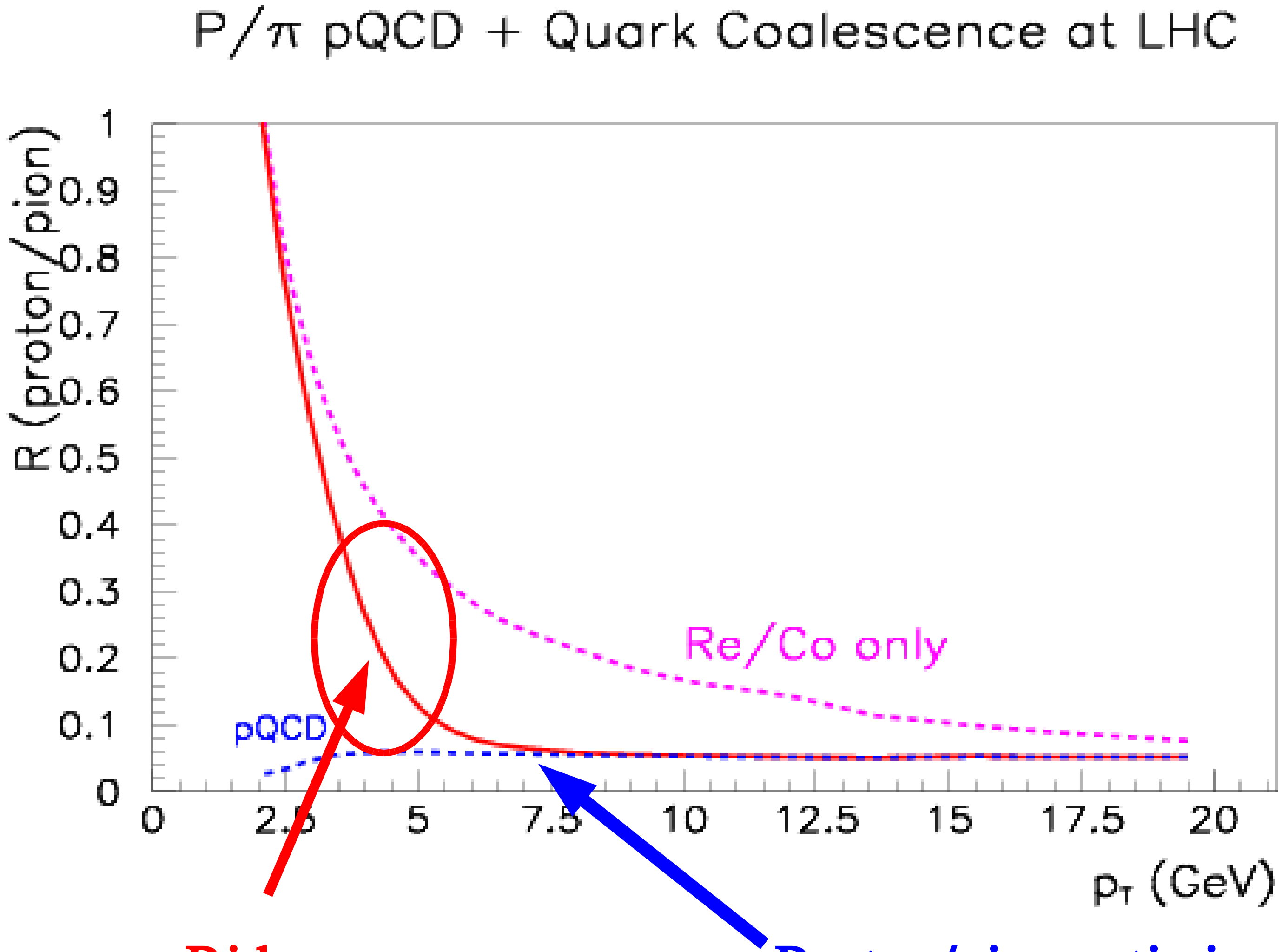
pQCD model



Proton/pion ratio in near-side jet

Ridge proton/pion ratio at intermediate-p_T:

ReCo+pQCD model

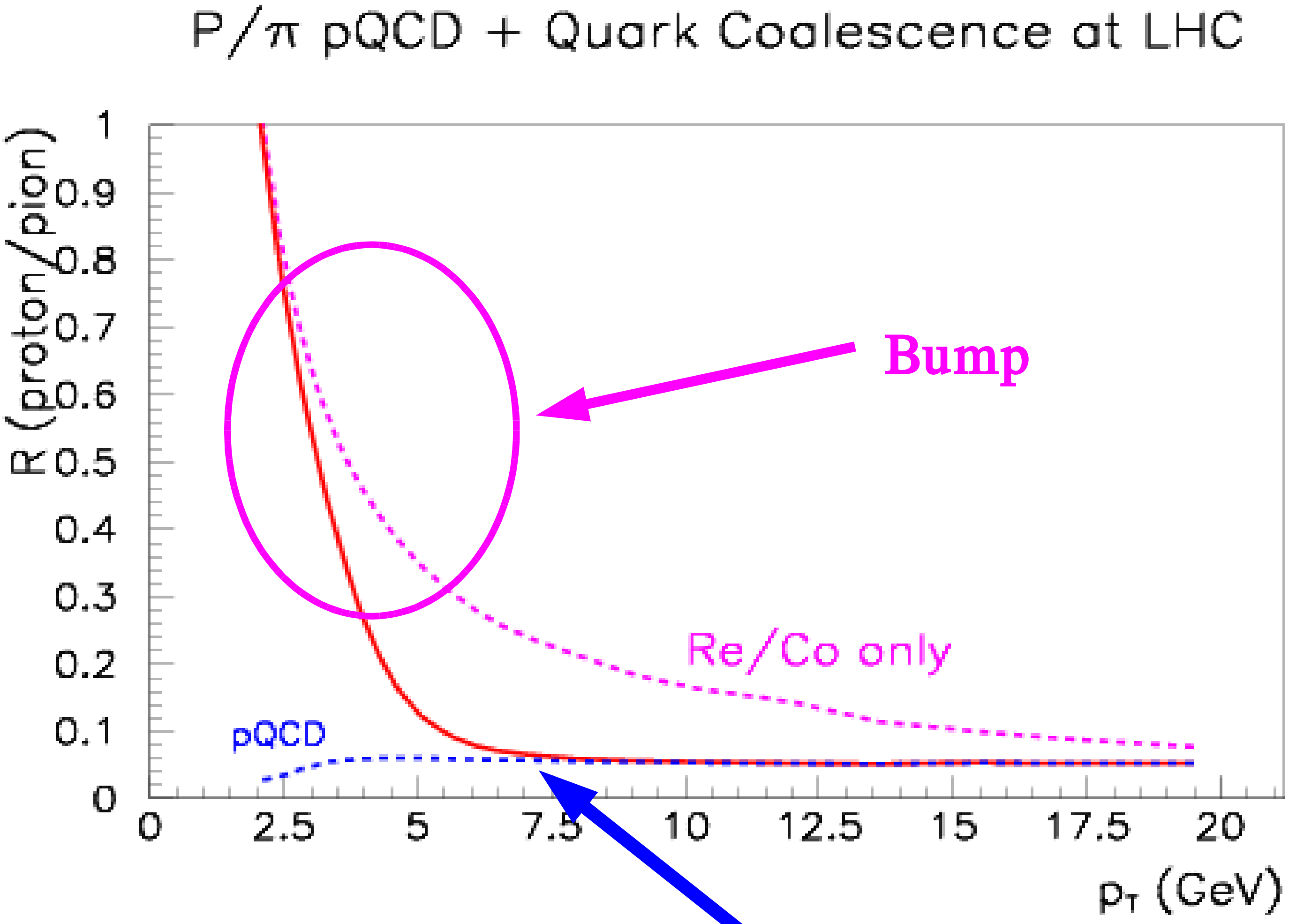


Ridge

Proton/pion ratio in near-side jet

Bump proton/pion ratio at intermediate-p_T:

ReCo+pQCD model

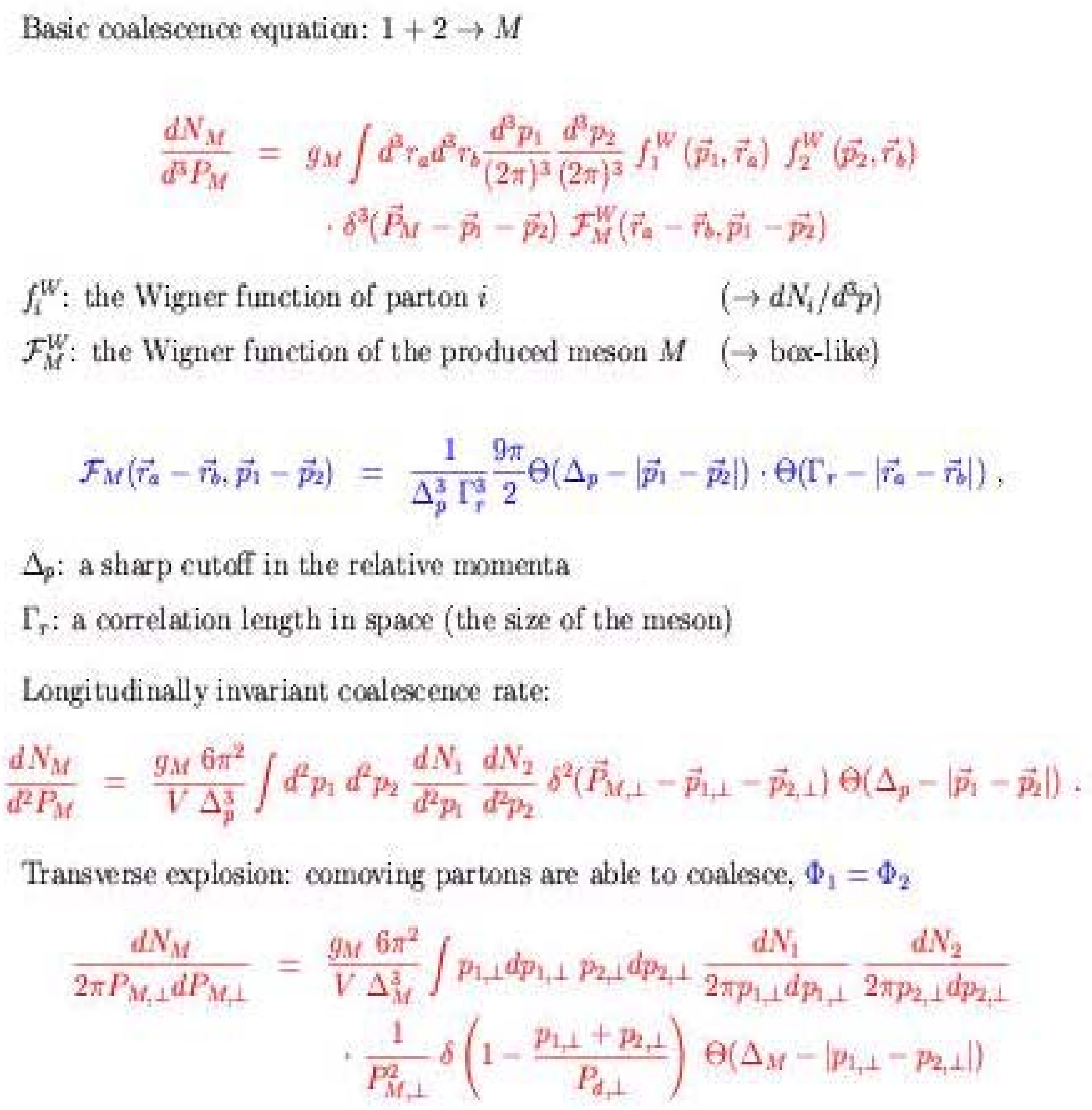


Bump

Proton/pion ratio in near-side jet

For precise calculation: meson production on the basis of RECO

V. Greco, C.M. Ko, P. Levai, PRL90 (2003) 202302.
PRC68 (2003) 034904.



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,
PRC66 (2002) 064903.
R.J. Fries, B. Muller,
C. Nonaka, S.A. Bass,
PRL90 (2003) 202303.
PRC68 (2003) 044902.

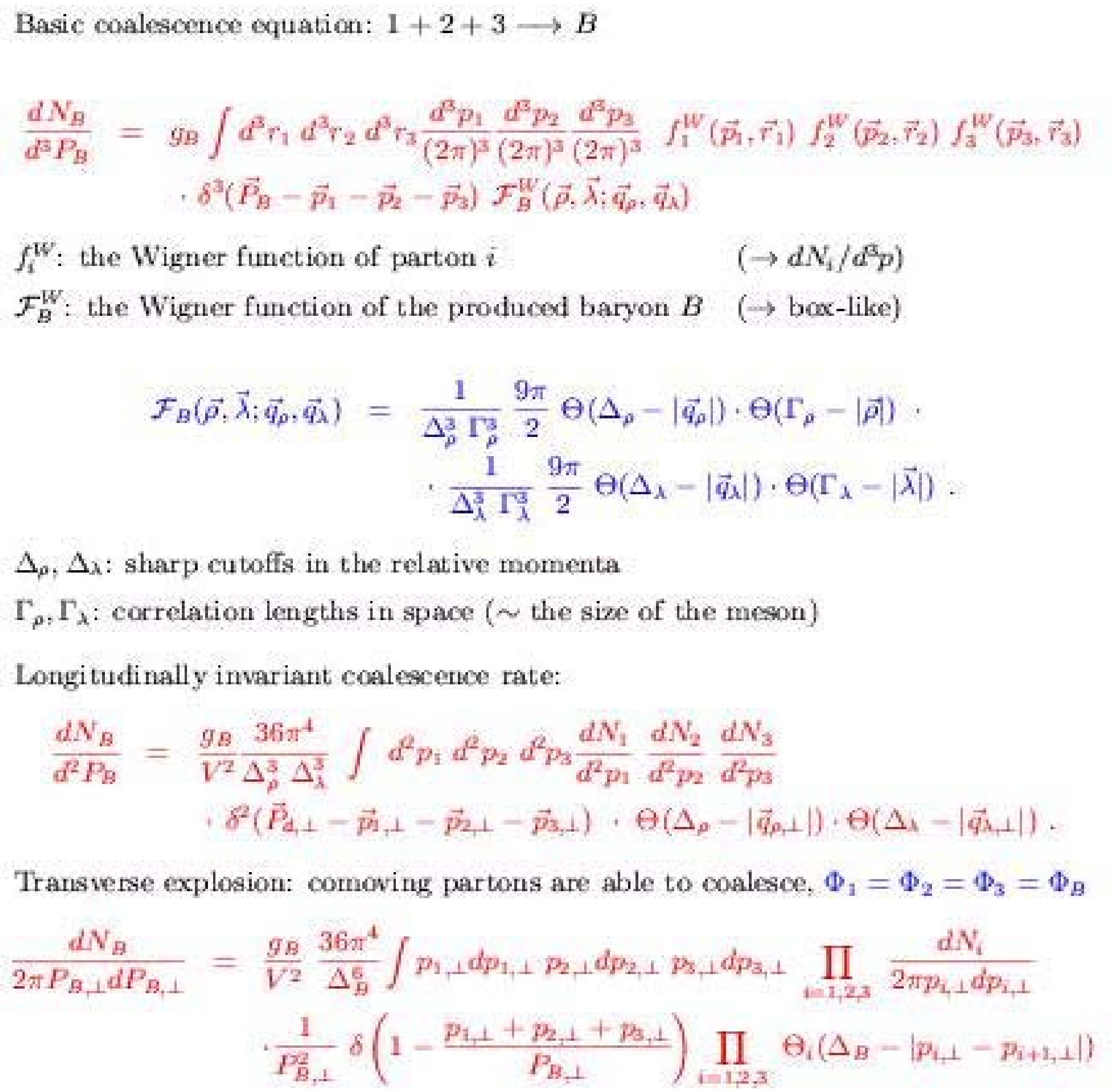
Ridge: M=S+T:

f_1 : pQCD shower

f_2 : thermal

Baryon production on the basis of RECO

G. K. L. PRL90 (2003) 202302



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 $(\rightarrow dN_i/d^3p)$

$\mathcal{F}_B^W$: the Wigner function of the produced baryon B $(\rightarrow$ 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:

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

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

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

Ridge: B = S+T+T

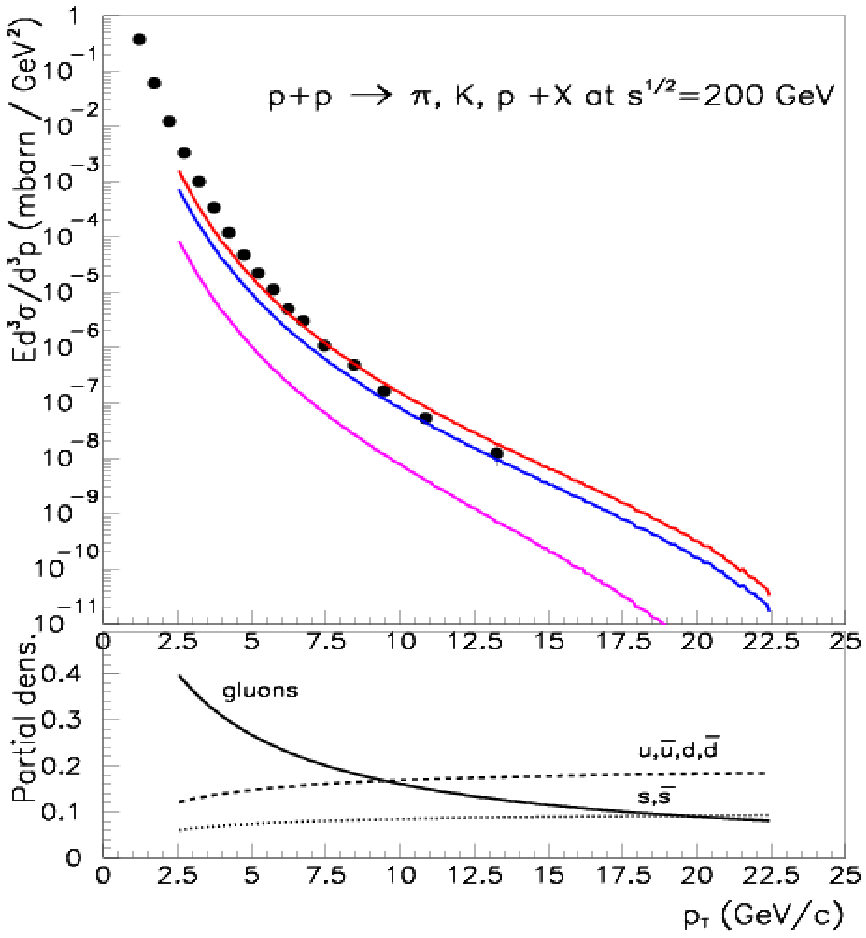
f_1 : pQCD shower

f_2 : thermal

f_3 : thermal

But what are the "pQCD shower" distributions ???

Model: first FF step ↣ leading hadron spectra
remnant partons + one FF step ↣ associated hadrons
leading + associated ↣ final hadron spectra



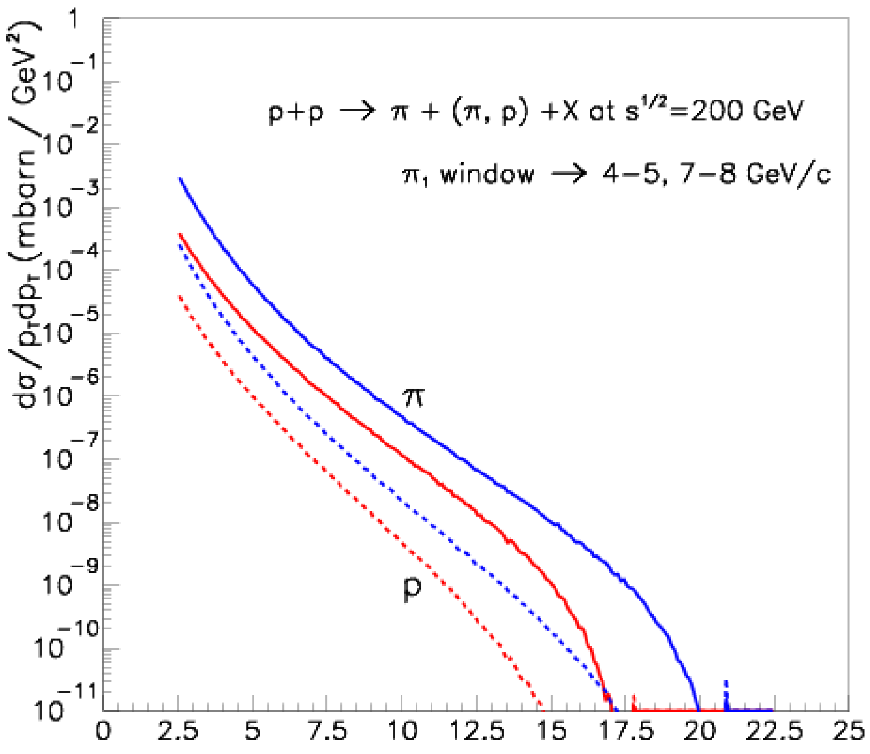
This model can work:
pion, kaon, proton
one-particle spectra

Two-particle correlation:
(M-B, B-aB correlation)

Independent fragmentation:
no flavour,
no charge,
no baryon-number
correlation

Near-side h-h correlation in p-p collision

Leading particle is pion in the pT windows: 4-5 GeV/c & 7-8 GeV/c



Momentum distribution for "associated" hadrons:

pions in windows 1 and 2
(full blue and red line)

protons in windows 1 and 2
(dashed blue and red line)

Further works are needed.
How to check it ?

\+ influence of quenching !!!

Why intermediate-pT region (p_T = 3-10 GeV/c) is important ?

1. π, (K,) p yields in this p_T region (one-particle spectra)

understanding RHIC data, proton/pion anomaly

challenge for theory: soft + quark coalescence + pQCD
particle production mechanisms
deeper knowledge on FF
jet energy loss, flavor dependence

2. Near-side hadron-hadron correlations (two-particle spectra)

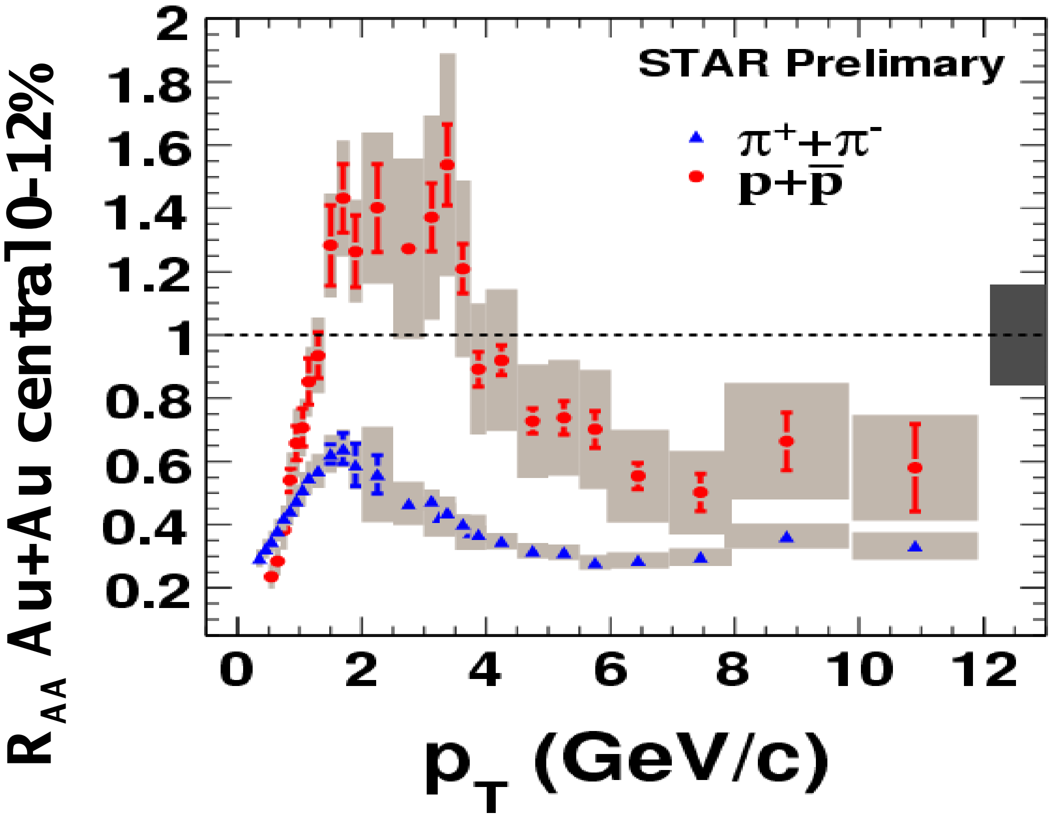
B-M (π-p) and B-B (p-$\bar{p}$) correlations at RHIC
Parton-showers, dFFs (D_B*D_M, D_B*$D_{\bar{B}}$, or D_{BM}, ... ?)
Triple-, 4-particle FFs ? In-matter modifications?
Jet energy loss: volume or surface effect?

3. Only after the answers of the above problems:

Away-side hadron-hadron correlations
which is complicated, includes further effects:
size; influence of k_T-imbalance; in-matter effects; ...

WARNING: latest nuclear suppression factor for pions and protons

Bedanga (STAR), QM2008, Jaipur



p_T = 8-12 GeV/c

↣ pQCD region

FF functions:

Pions from quarks

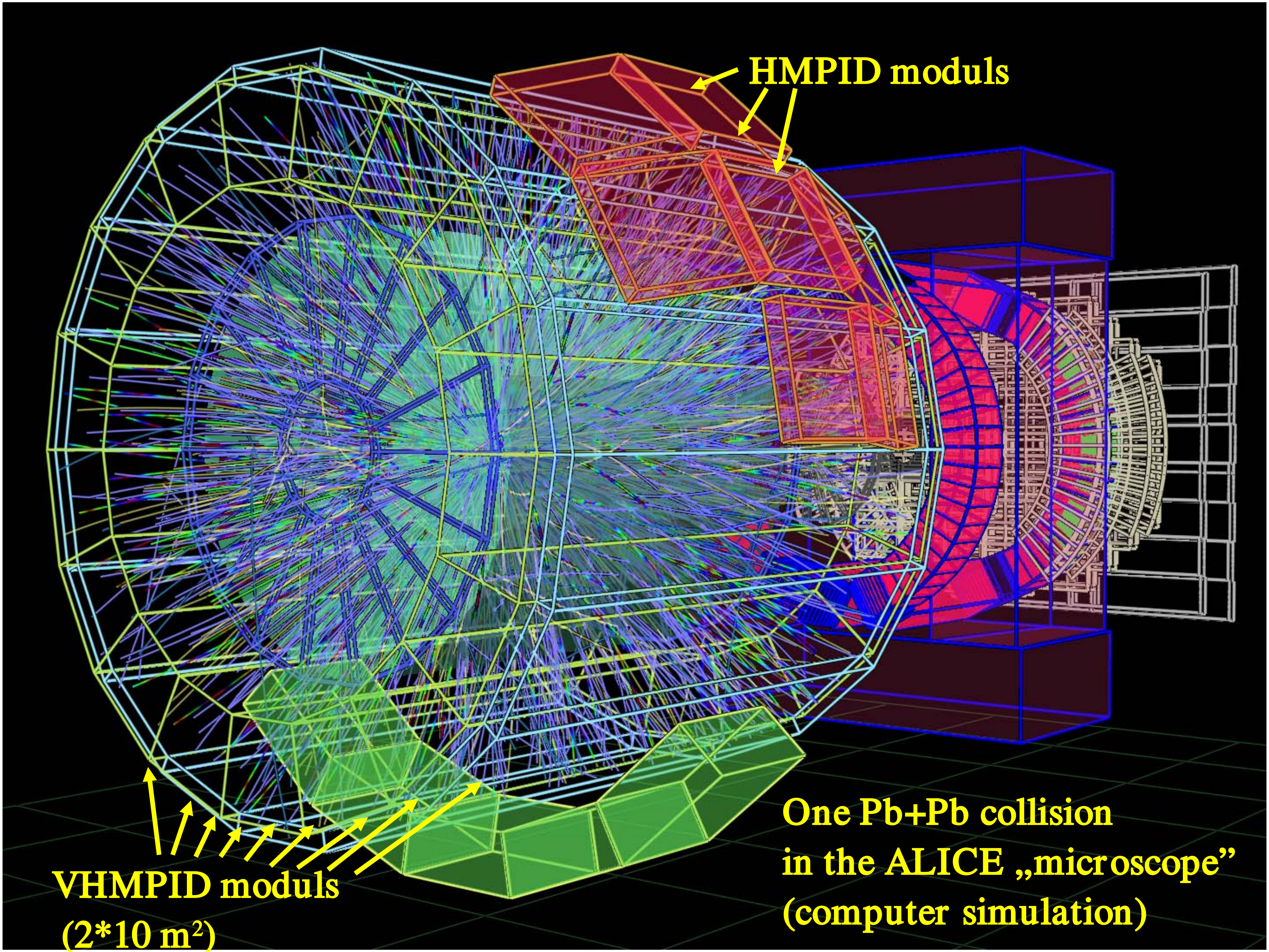
Protons from gluons

Energy loss (quenching):

Gluon/quark = C_A/C_F

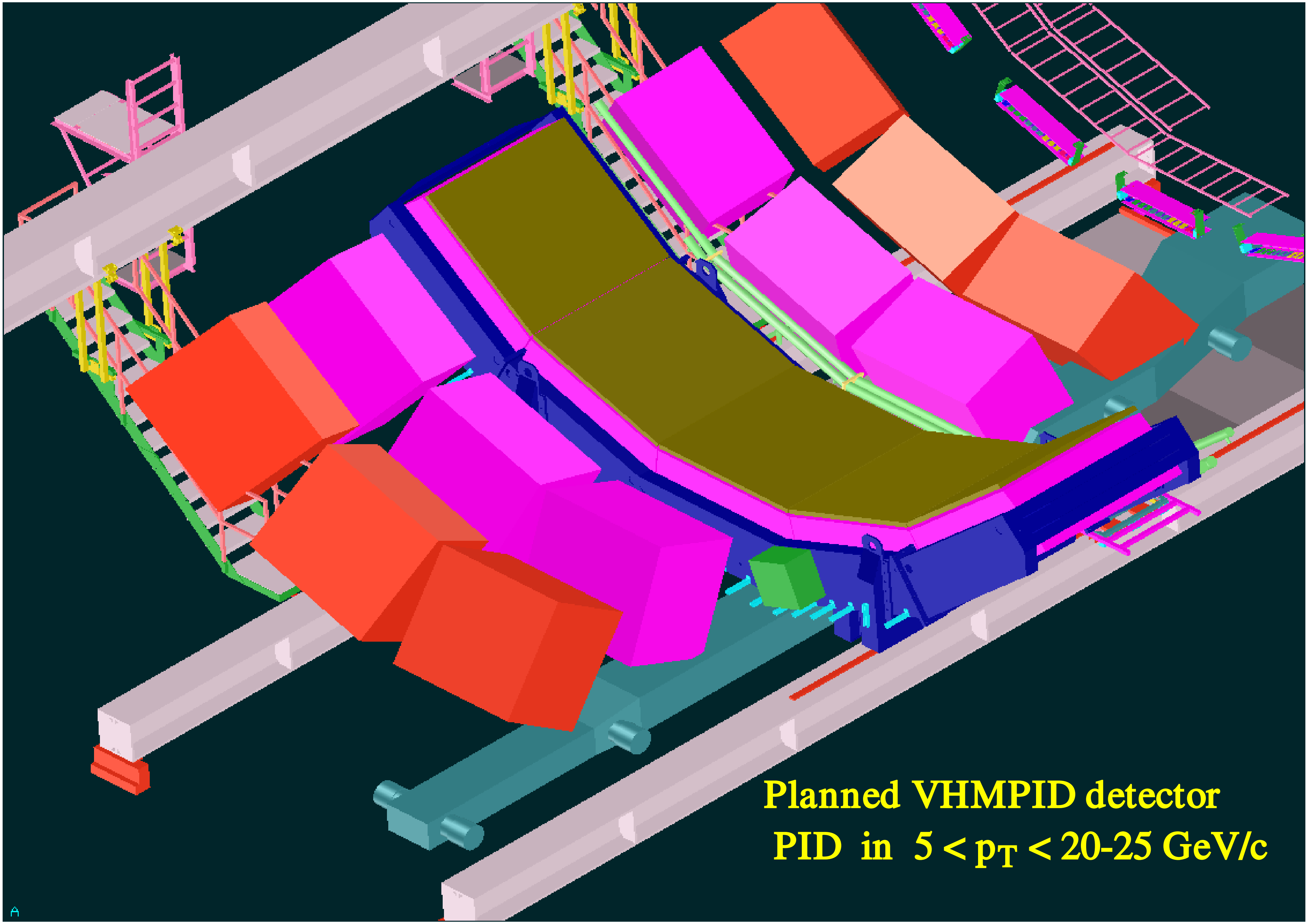
= 3 / 1.33 = 2.25

Why pions are suppressed more than protons ????



One Pb+Pb collision
in the ALICE „microscope"
(computer simulation)

Aim: 6+6 VHMPID moduls around the PHOS detector (kb. 2x10 m²) – 2010/11



Planned VHMPID detector

PID in $5 < p_T < 20\text{-}25$ GeV/c

Conclusions:

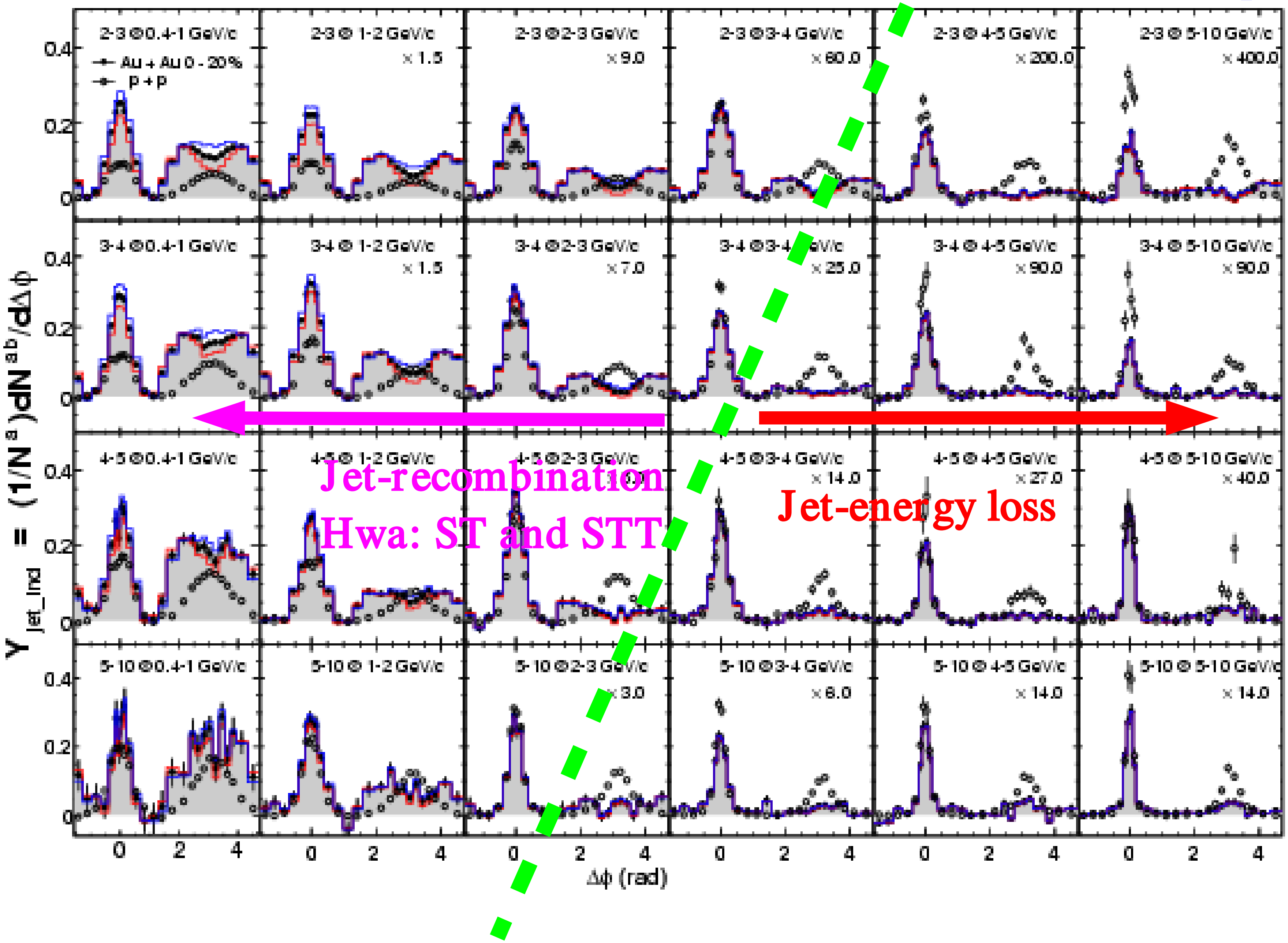
1. Soft/hard overlap: intermediate -p_T region
   Precise measurement is the key point for understanding hadron production mechanisms;

2. Two-particle correlations:
   near-side correlation is simpler but not trivial.
   AuAu collisions vs pp collisions at RHIC-200:
   enhancement at lower-p_T and suppression at high-p_T;
   in-matter effects are seen in near-side correlations
   Quenching is volume effect !!!
3. Proton-pion anomaly in near-side correlations in Au+Au coll.
   in-matter effects in the ridge – challenging for theory

4. Surprise may come in the $5 < p_T < 20$ GeV/c region at LHC !!!??
   ➣➣ TPC + TOF + TRD
   ➣➣ ALICE HMPID ➣➣➣ ALICE VHMPID detectors

QM08: Latest results from PHENIX at RHIC energy at √s = 200 A GeV

Hadron-hadron correlations   A. Adare et al., arXive: 0801.4545 [hep-ex]



Jet-recombination

Hwa: ST and STT

Jet-energy loss