Parton Recombination at all p_T

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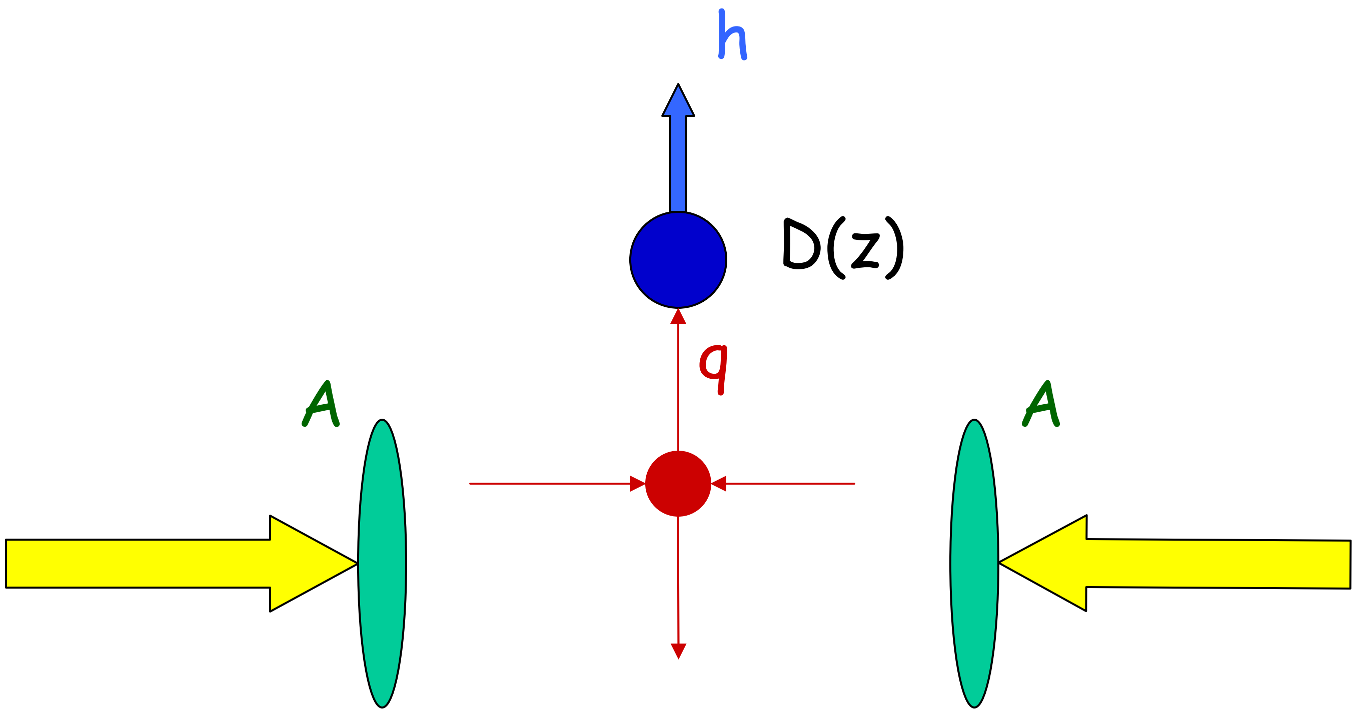
Outline

Why fragmentation is inadequate at intermediate p_T in heavy-ion collisions.

How parton recombination resolves a number of puzzles.

- Shower partons
- Inclusive distributions at all p_T in Au+Au and d+Au collisions (Cronin effect)
- Dihadron correlations
- Forward production in d+Au collisions

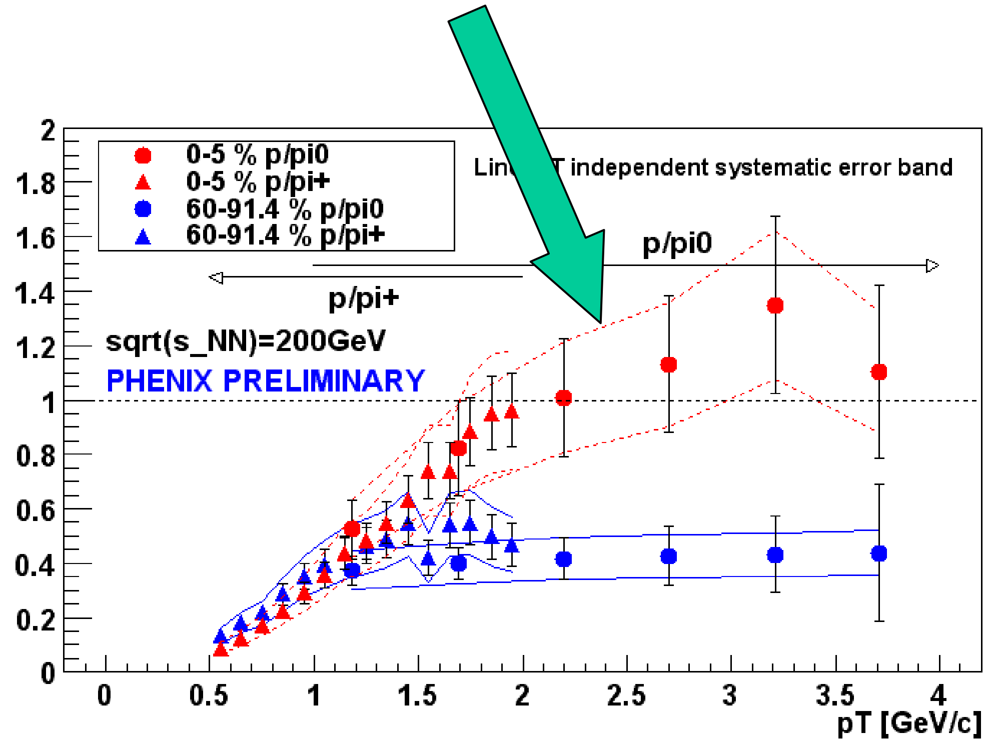
Conventional approach to hadron production at high p_T



There are numerous evidences against this framework: hard scattering × fragmentation in heavy-ion collisions.

Exhibit #1 $R_{p/\pi} > 1$

$R_{p/\pi}$



Not possible in fragmentation model:

$$D_{p/q} << D_{\pi/q}$$

$$\frac{D_{p/q}}{D_{\pi/q}}$$

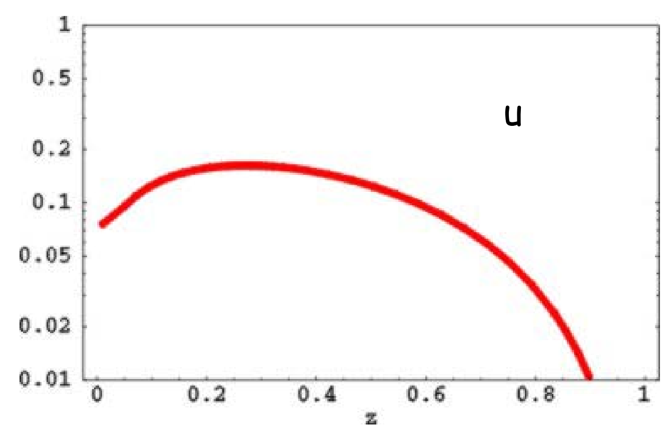
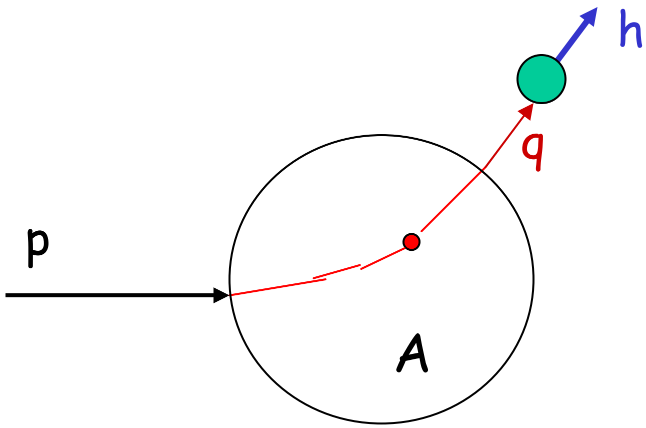


Exhibit #2 in pA or dA collisions

Cronin Effect

Cronin et al, Phys.Rev.D (1975)



$$\frac{dN}{dp_T}(pA \to \pi X) \propto A^{\alpha}, \qquad \alpha > 1$$

k_T broadening by multiple scattering in the initial state.

Unchallenged for ~30 years.

If the medium effect is before fragmentation, then α should be independent of h= π or p

$\alpha_p > \alpha_\pi$ ⟺ $R_{CP}^{p}(p_T) > R_{CP}^{\pi}(p_T)$

$$R_{CP}^{p}(p_T) > R_{CP}^{\pi}(p_T)$$

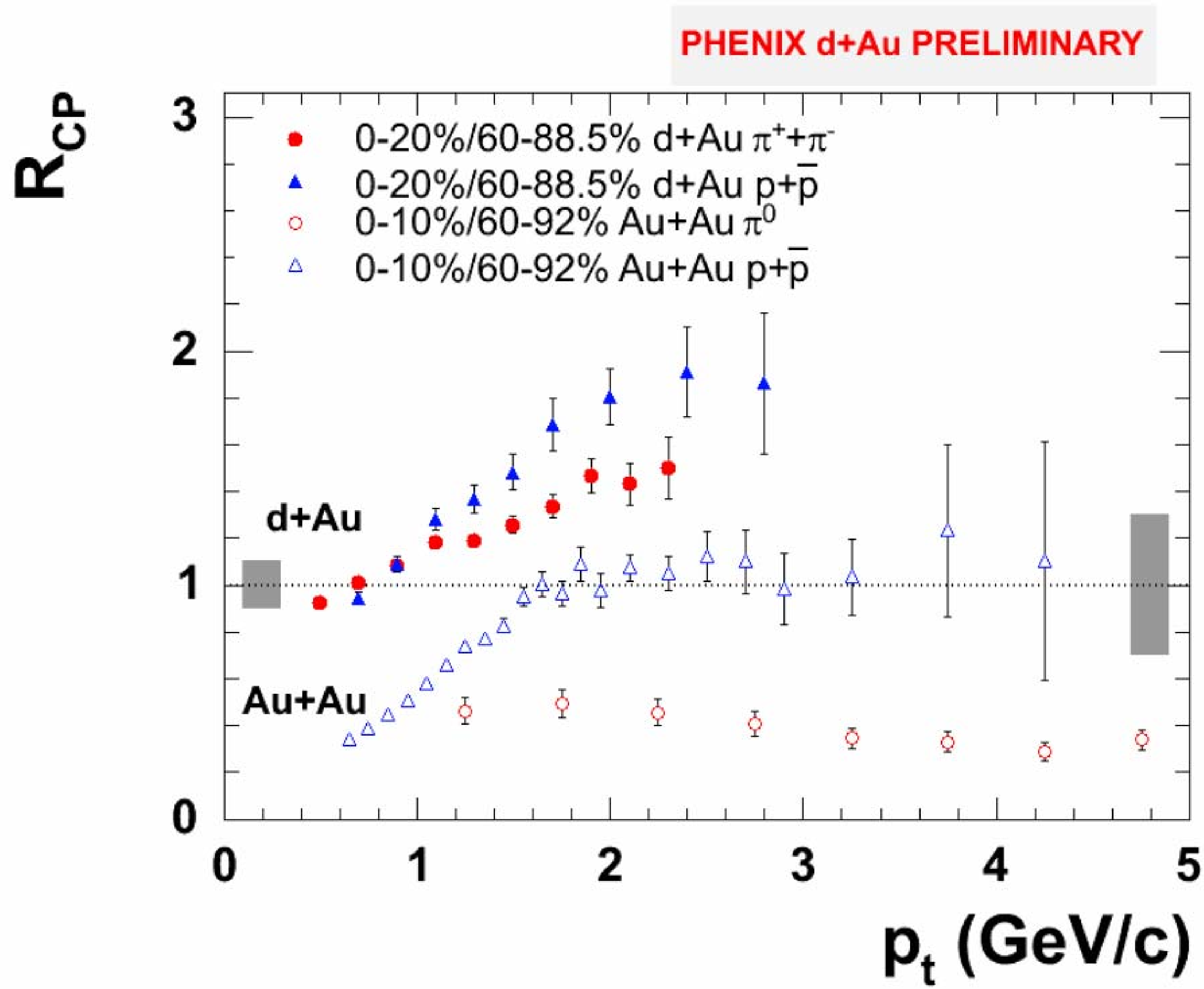


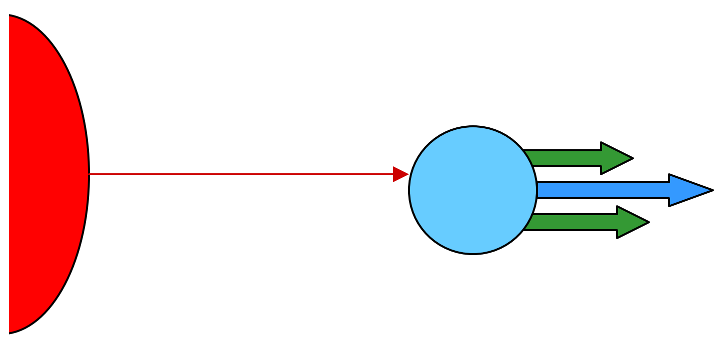
Exhibit #3 Jet structure

Hard parton $\Rightarrow$ jet $\{ \pi(p_1) + \pi(p_2) + \pi(p_3) + \cdots \}$

trigger particle

associated particles

The distribution of the associated particles should be *independent* of the medium if fragmentation takes place in vacuum.



Fuqiang Wang (STAR) Quark Matter 2004

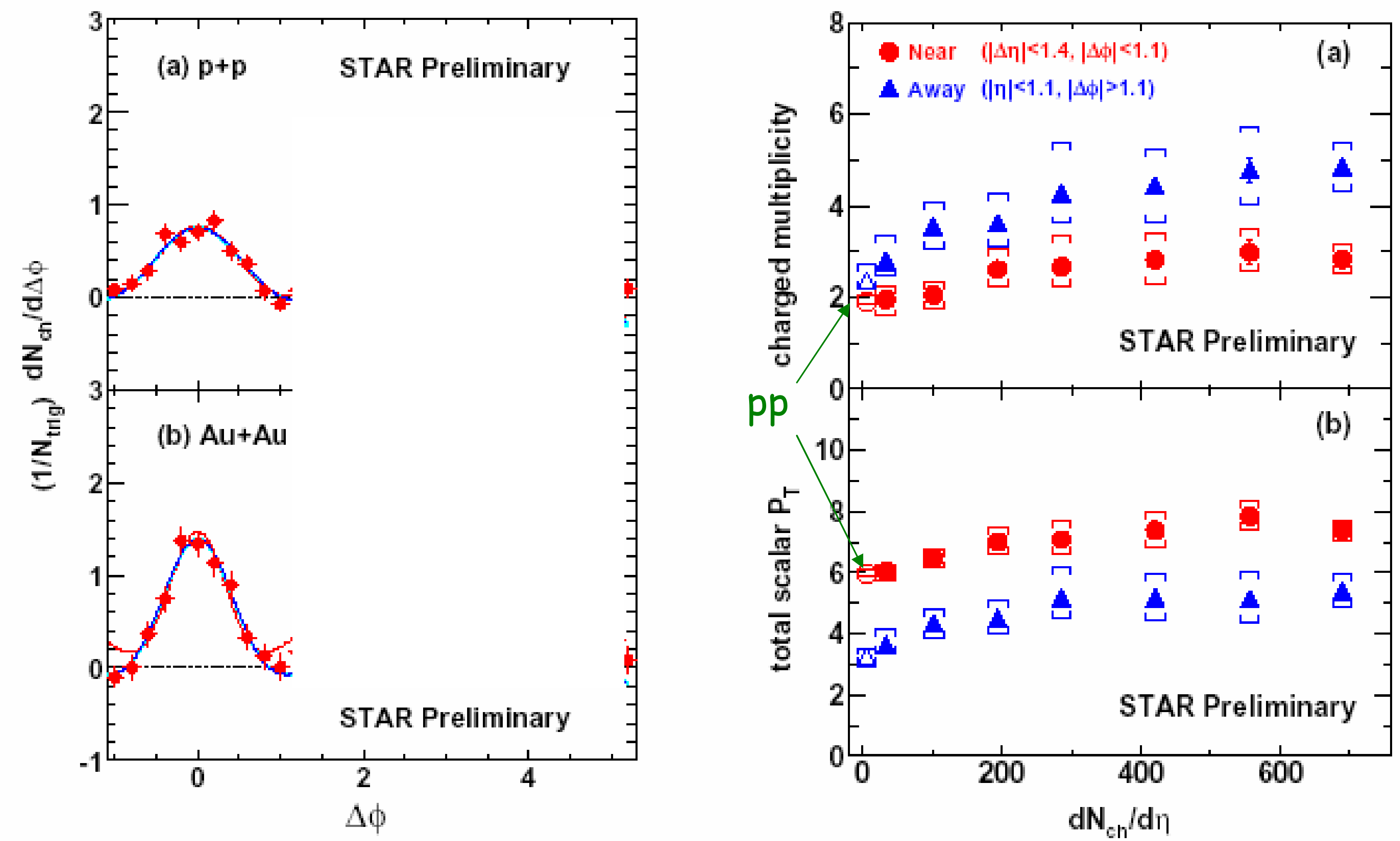
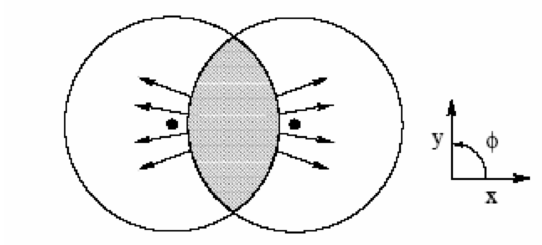


Exhibit #3

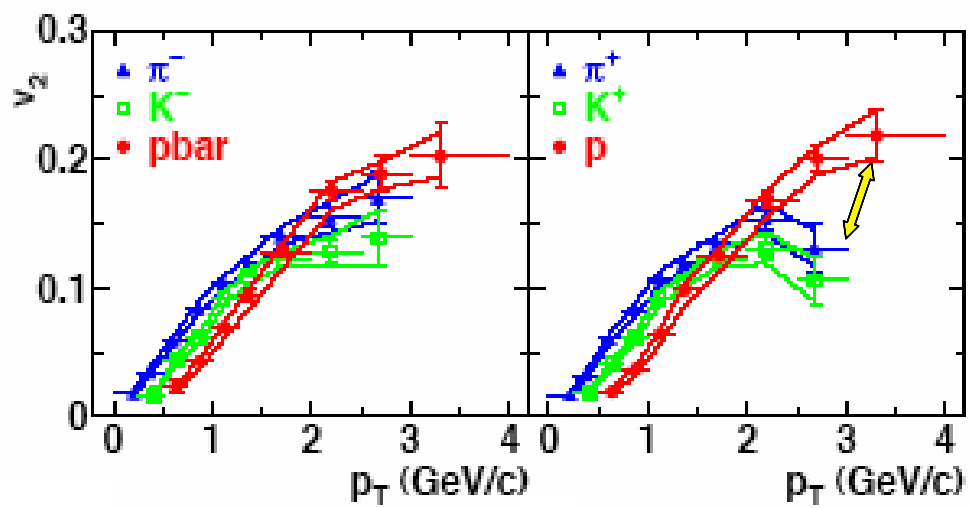
Jet structure for Au+Au collisions is different from that for p+p collisions

Exhibit #4

Azimuthal anisotropy



v_2: coeff. of 2nd harmonic in ϕ distribution



$v_2(p) > v_2(\pi)$ at $p_T > 2.5$ GeV/c

Exhibit #5 Backward-forward asymmetry at intermed. p_T

in d+Au collisions

$$\frac{\text{backward}}{\text{forward}}$$

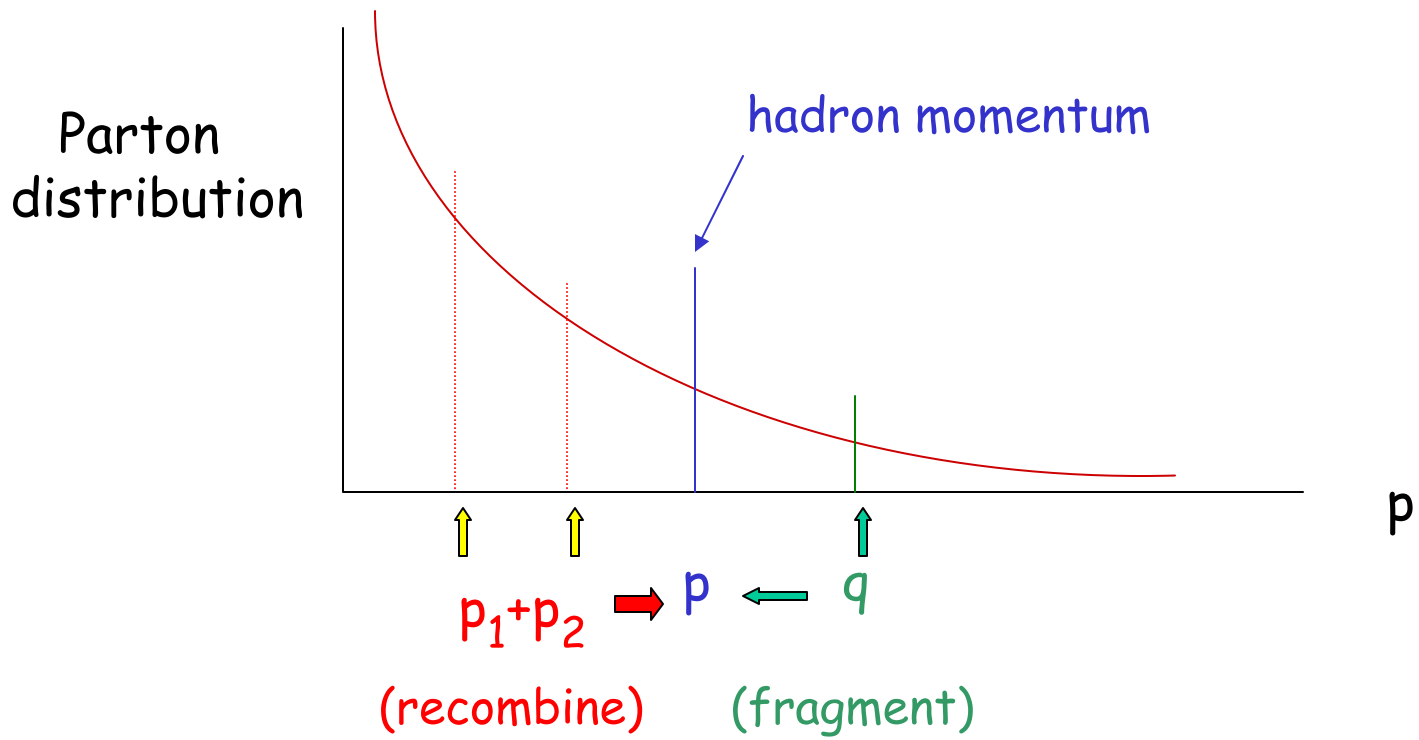
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

The problem:

Fragmentation of hard partons that works so well in leptonic and hadronic processes

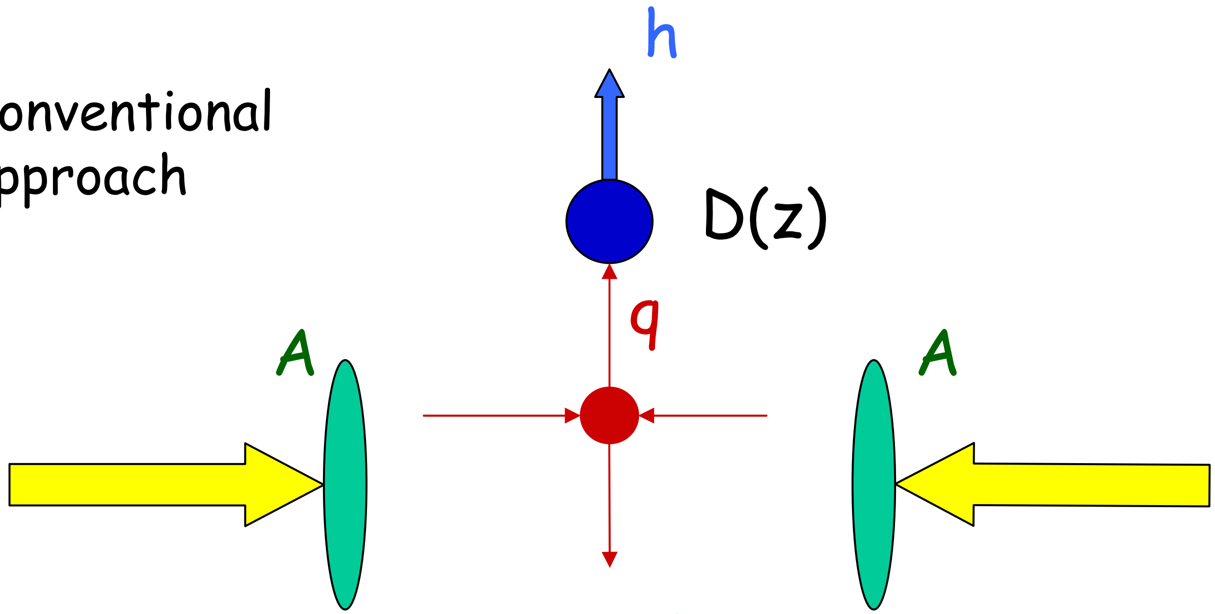
is only one of many components when the hard parton is in the environment of many soft partons, as in heavy-ion collisions.

How can recombination solve the puzzles?

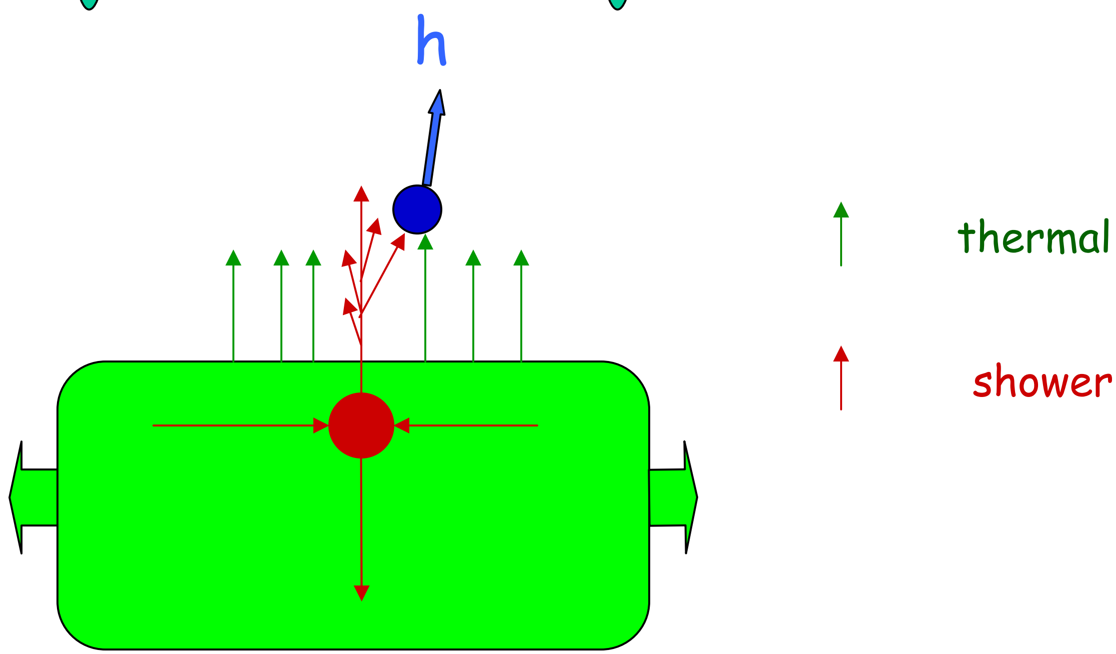


higher yield heavy penalty

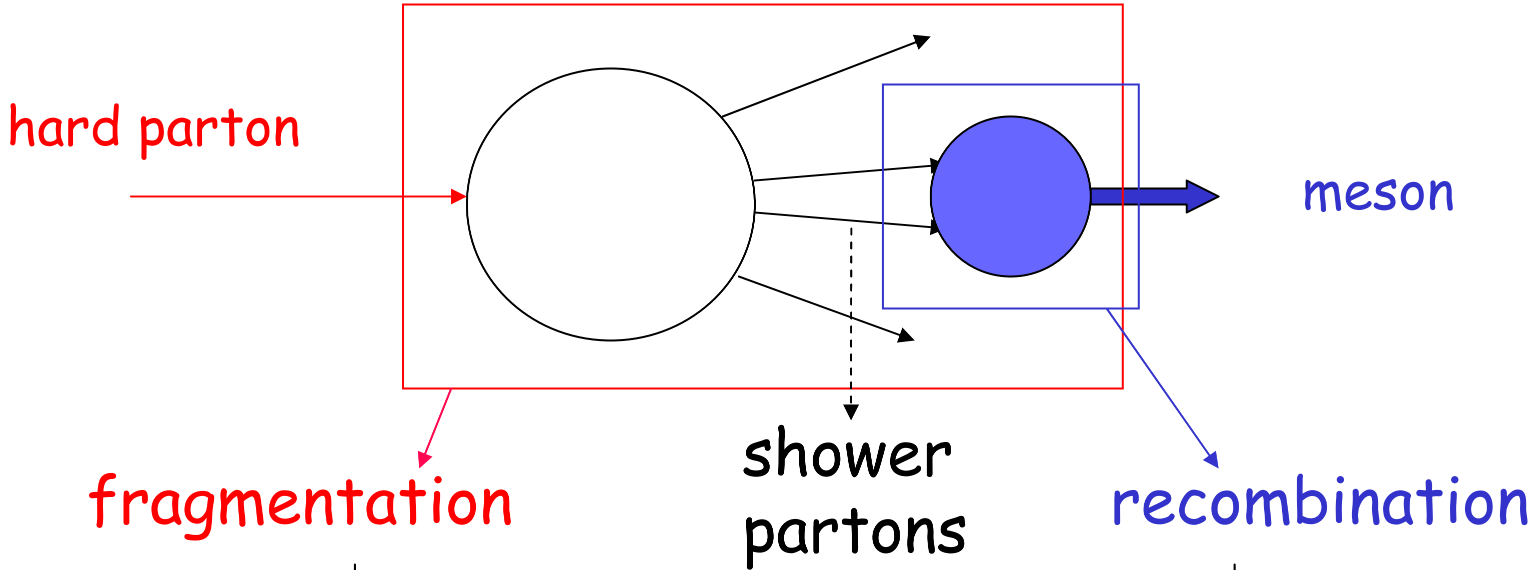
Conventional approach



Thermal-shower recombination



Shower partons in fragmentation process



$$xD_i^h(x) = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} S_i^j(x_1) S_i^{j'}(x_2) R_{jj'}^h(x_1, x_2, x)$$

known from data (e+e-, μp, …)

can be determined

known from recombination model

Shower parton distributions

$$F_{q\bar{q}'}^{(i)}(x_1, x_2) = S_i^q(x_1) S_i^{\bar{q}'}\left(\frac{x_2}{1-x_1}\right)$$

$$S_i^j = \begin{pmatrix} K & L & L_s \\ L & K & L_s \\ L & L & K_s \\ G & G & G_s \end{pmatrix}$$

(columns: u, d, s; rows: u, d, s, g)

valence

sea

$$K = K_{NS} + L$$

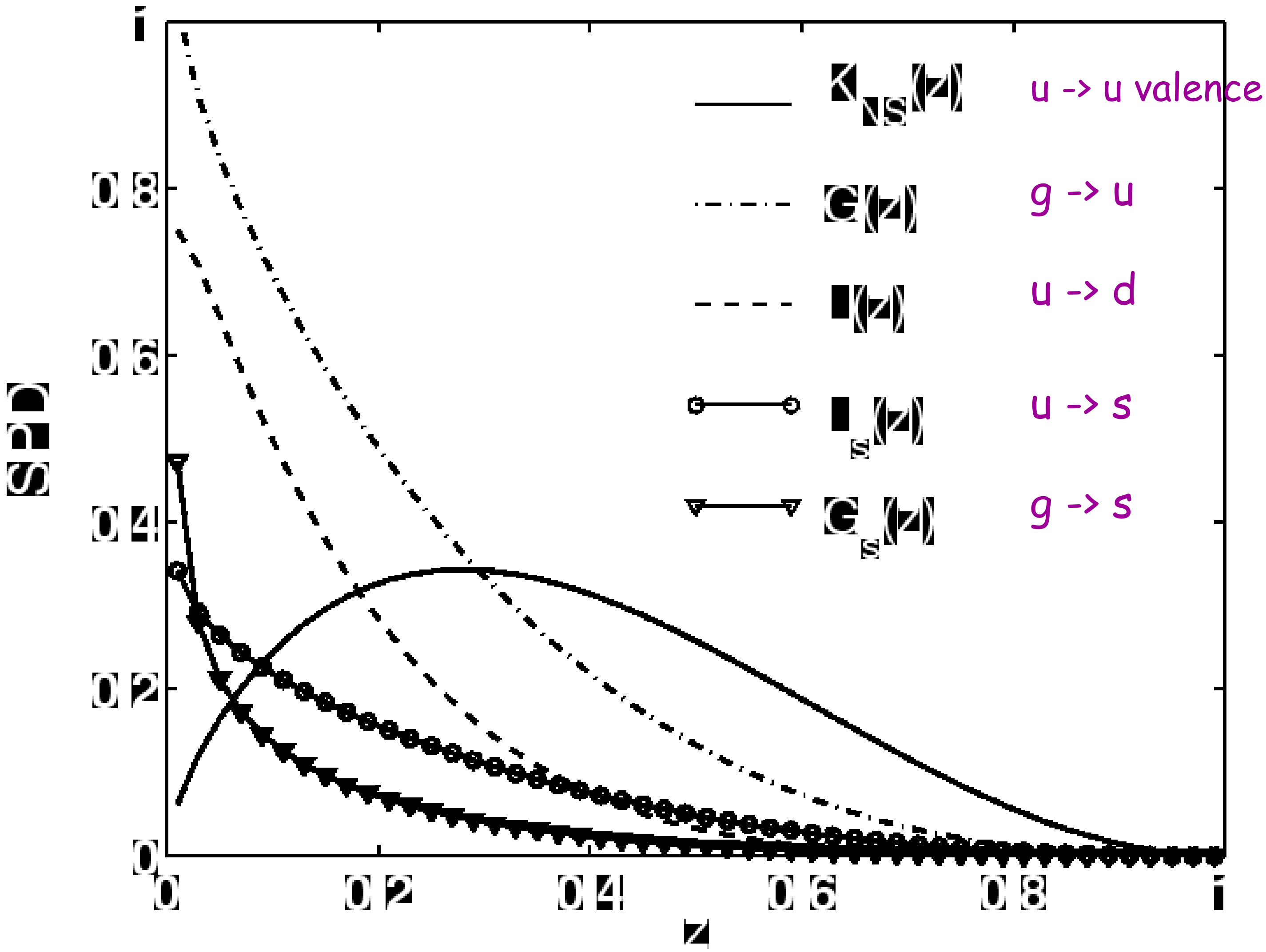
$$S_u^{d,\bar{d},\bar{u},u(sea)} = L$$

$$K_s = K_{NS} + L_s$$

5 SPDs are determined from 5 FFs.

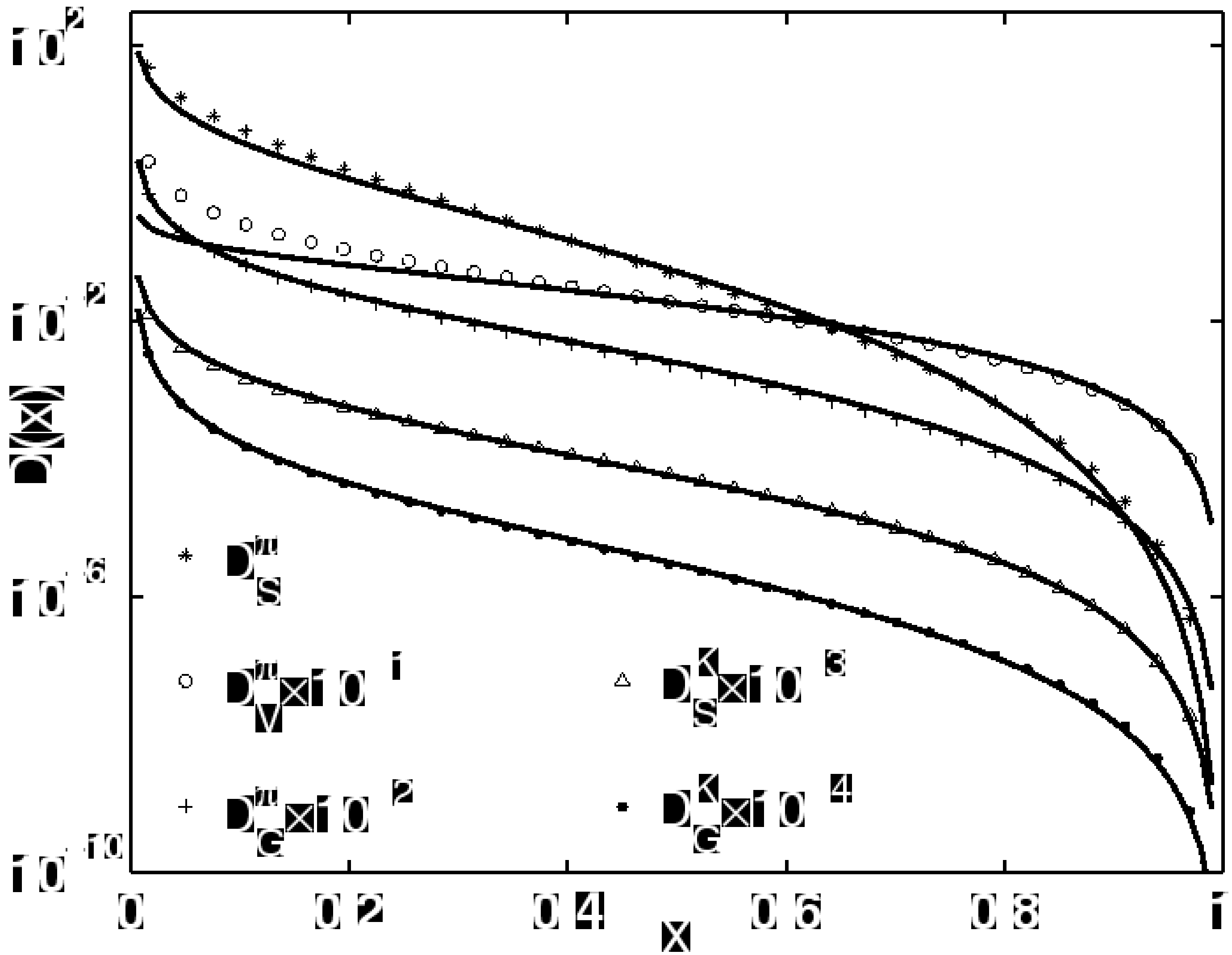
L L	R^π	$\rightarrow$	D^π_{Sea}
K_{NS} L		$\rightarrow$	D^π_V
G G		$\rightarrow$	D^π_G
L L_s	R^K	$\rightarrow$	D^K_{Sea}
G G_s		$\rightarrow$	D^K_G

Shower Parton Distributions

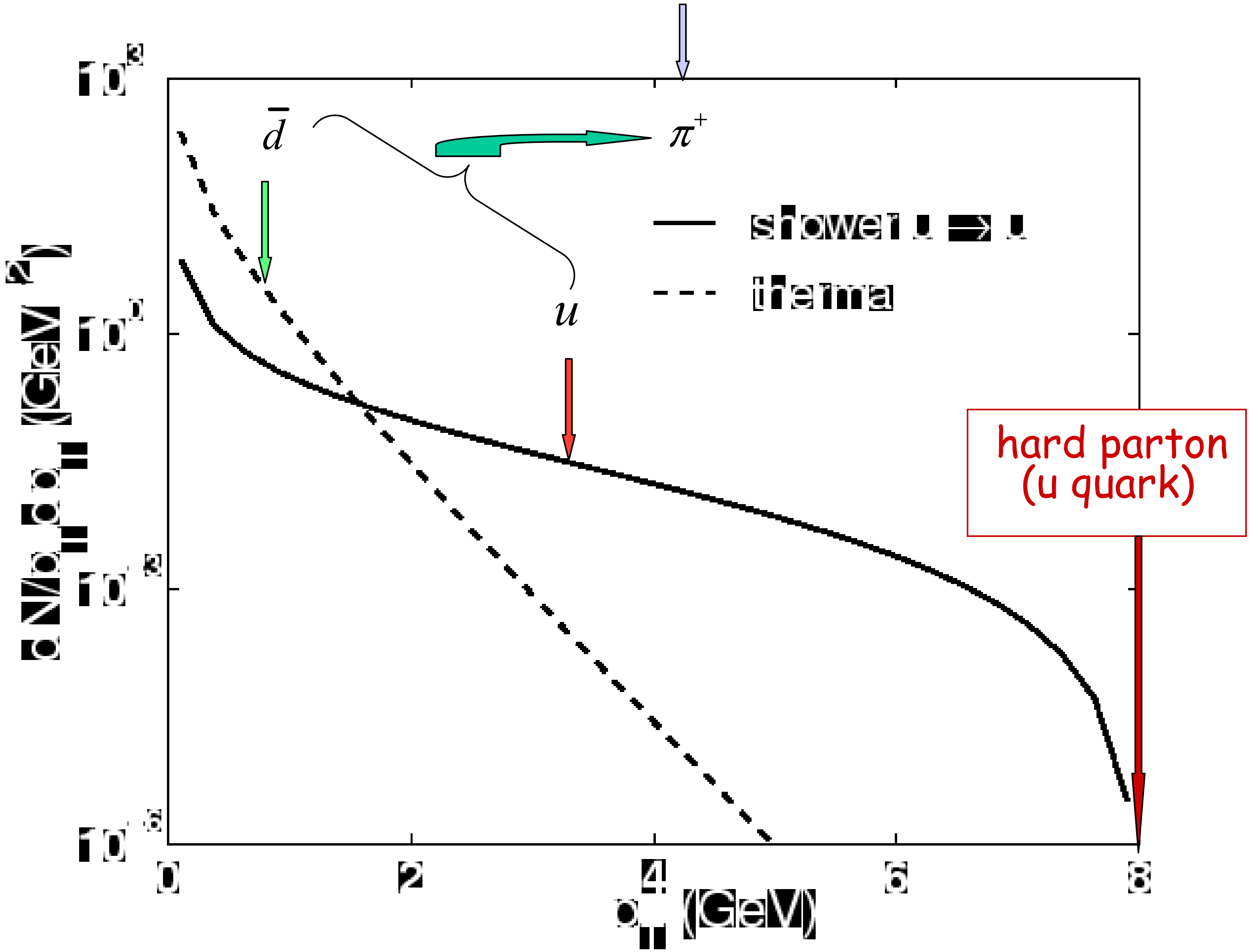


Hwa & CB Yang, PRC (2004).

BKK fragmentation functions



An example



Inclusive distribution of pions in any direction

$$p\frac{dN_\pi}{dp} = \int \frac{dp_1}{p_1}\frac{dp_2}{p_2} F_{q\bar{q}}(p_1, p_2) R_\pi(p_1, p_2, p)$$

Determine **T** by fitting dN_π/dp_T at low p_T (<2GeV/c)

$$\frac{p_1 p_2}{p}\delta(p_1 + p_2 - p)$$

Pion formation: $q\bar{q}$

T thermal

S shower

$F_{q\bar{q}} = \mathrm{TT}$ ➡ **soft pions at low p_T**

Proton formation: uud distribution

$$F_{uud} = \mathrm{TTT} + \mathrm{TTS} + \mathrm{T(SS)}_1 + \boxed{\mathrm{(SSS)}_1}$$ ⬅ fragmentation

Thermal partons

$$\mathrm{T}(p_1) = p_1 \frac{dN_q^{th}}{dp_1} = Cp_1 \exp(-p_1 / T)$$

Determine C and T by fitting low-p_T data on π production

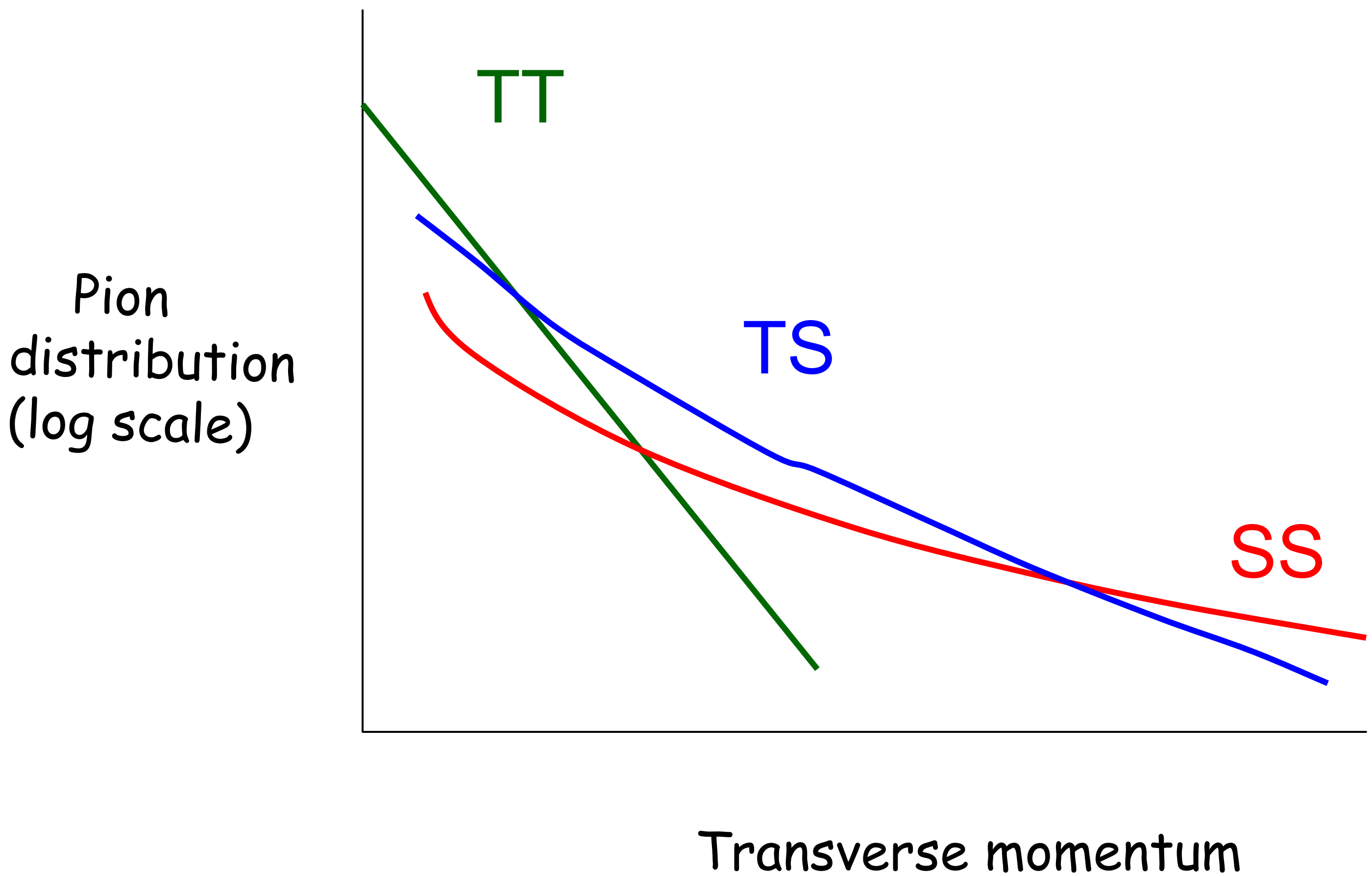
Shower partons

$$\mathrm{S}(p_2) = \xi \sum_i \int dk k f_i(k) S_i^j(p_2 / k)$$

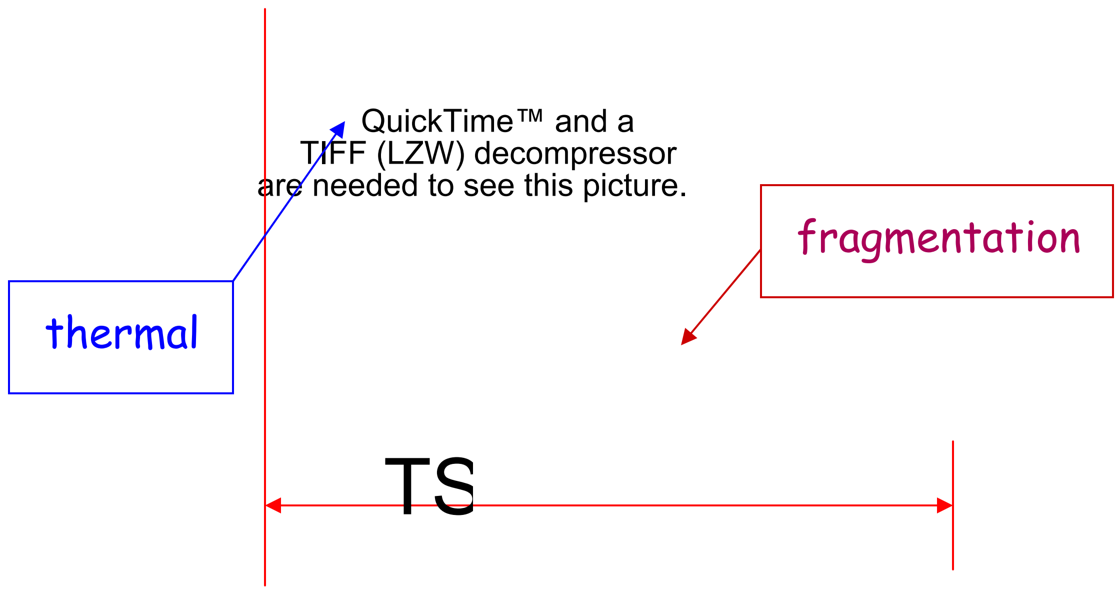
- ξ: fraction of hard partons that get out of medium to produce shower
- k: hard parton momentum
- $f_i(k)$: distribution of hard parton i in AuAu collisions
- S_i^j: SPD of parton j in shower of hard parton i

$\int dk k f_i(k) S_i^j(p_2/k)$: calculable

ξ = 0.07

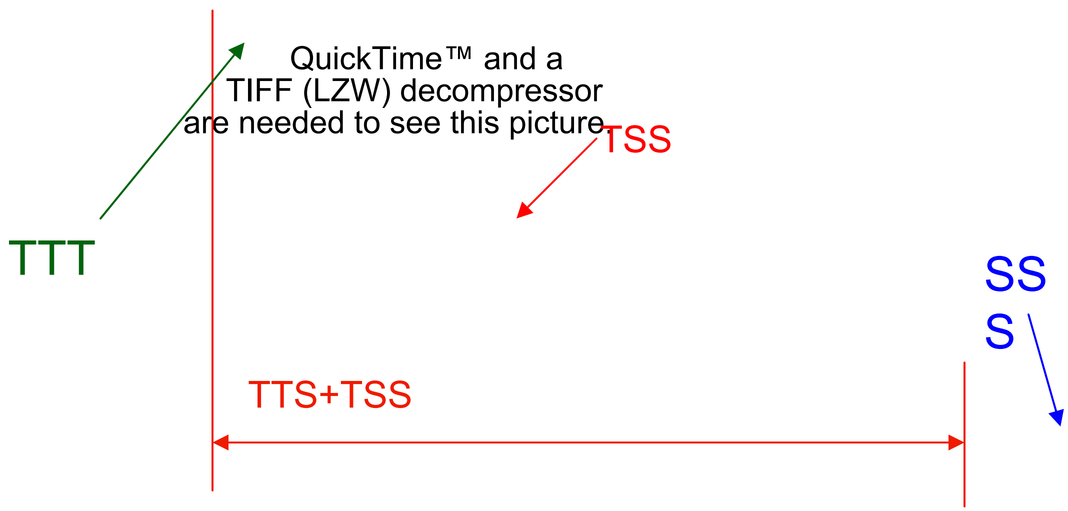

TT
TS
SS
Pion distribution (log scale)
Transverse momentum

π production in AuAu central collision at 200 GeV



Hwa & CB Yang, PRC70, 024905 (2004)

Proton production in AuAu collisions



Puzzle #1 Proton/pion ratio

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

resolved

Hwa & CB Yang, PRC70, 024905 (2004)

Compilation of $R_{p/\pi}$ by R. Seto (UCR)

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

All in recombination/
coalescence model

Duke: Fries, Mueller, Nonaka, Bass, PRL90,202303(2003);PRC68,044902(2003).
TAM: Greco, Ko, Levai, PRL,90,202302(2003); PRC68,034904(2003).

d+Au collisions

Pions

$\xi = 1$

soft-soft

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

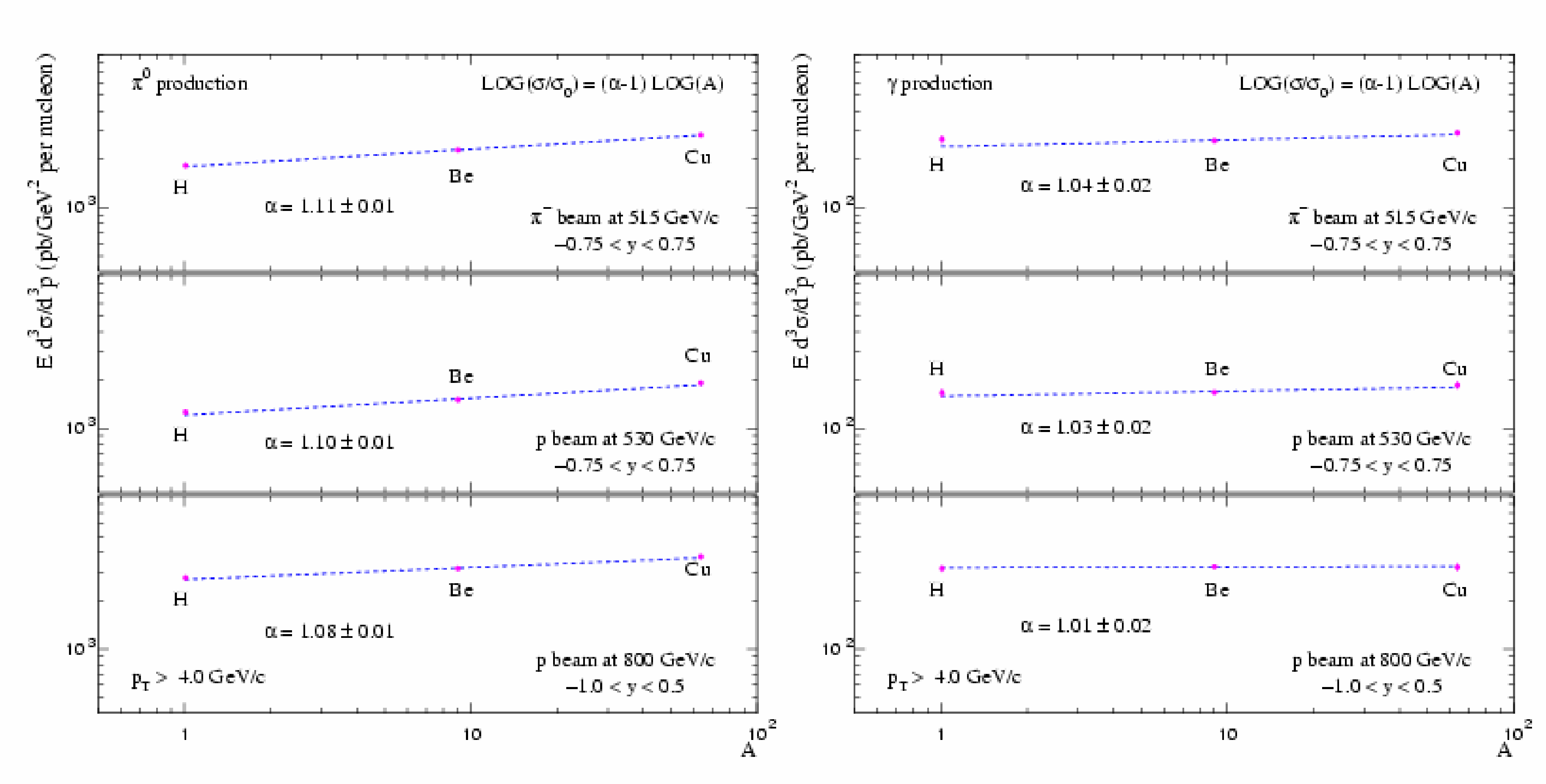
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

★ No p_T broadening by multiple scattering in the initial state.

Medium effect is due to thermal (soft)-shower recombination in the final state.

Hwa & CB Yang, PRL 93, 082302 (2004)

π^0, γ production in p+A collisions



π^0: α = 1.1 **γ: α = 1.0**

Proton

Thermal-shower recombination is NOT negligible.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Thermal-shower recombination is negligible.

Nuclear Modification Factor

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Puzzle #2

resolved

$$R_{CP}^{p} > R_{CP}^{\pi}$$

because 3q → p, 2q → π

Jet Structure

Exhibit #3 Jet structure in Au+Au
different from that in p+p collisions

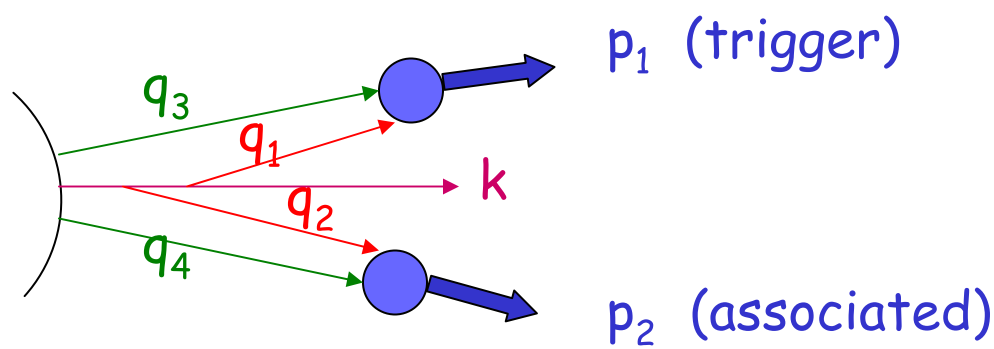
A simple consequence of TS recombination being more important in Au+Au collisions than in p+p collisions.

Consider dihadron correlation in the same jet
on the near side.

Trigger at $4 < p_T < 6$ GeV/c

p+p: mainly SS ⟷ fragmentation
Au+Au: mainly TS

Associated particle



$$\xi \sum_i \int dk\, k f_i(k) \begin{pmatrix} S(q_1)T(q_3)R(q_1,q_3,p_1) \\ S(q_2)T(q_4)R(q_2,q_4,p_2) \end{pmatrix}$$

⟶ trigger

⟶ associated

There are other contributions as well.

trigger		associated	
(TS)	+	[TS]	
(TS)	+	[SS]	
(SS)	+	[TS]	
(SS)	+	[SS]	← too small for Au+Au
			but the only term for p+p

Associated particle distribution

(TS)[TS] →

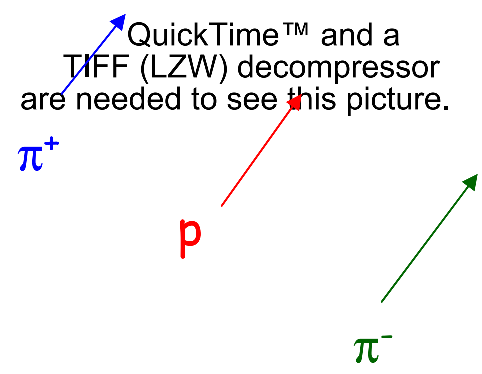
} π^+

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

(TS)[SS]+(SS)[TS]

(SS)[SS] for p+p collisions much lower

Associated particle distribution in central Au+Au collisions



Hwa & Yang, PRC (2004)

Centrality dependence of associated-particle dist.

Distributions

Ratios

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Au+Au central
d+Au peripheral

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

p+p

d+Au central
d+Au peripheral

Exhibit #3 Jets in Au+Au and in p+p are very different.

Dihadron correlation with soft parton correlation

Fries, Bass, Mueller, nucl-th/0407102

(1) soft-soft recombination X soft-soft recom
(2) fragmentation X fragmentation
(3) soft-hard recom X fragmentation

No shower partons

(1) + (2) with 8% scaled soft parton correlation

Comparable associated particle yields for meson and baryon triggers

Meson trigger   Baryon trigger

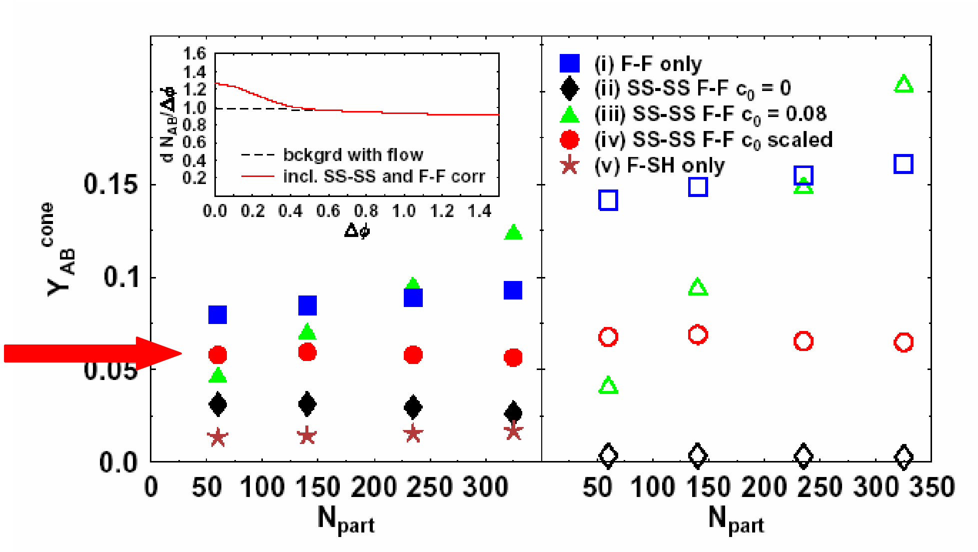
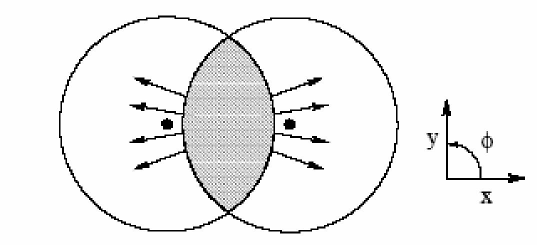
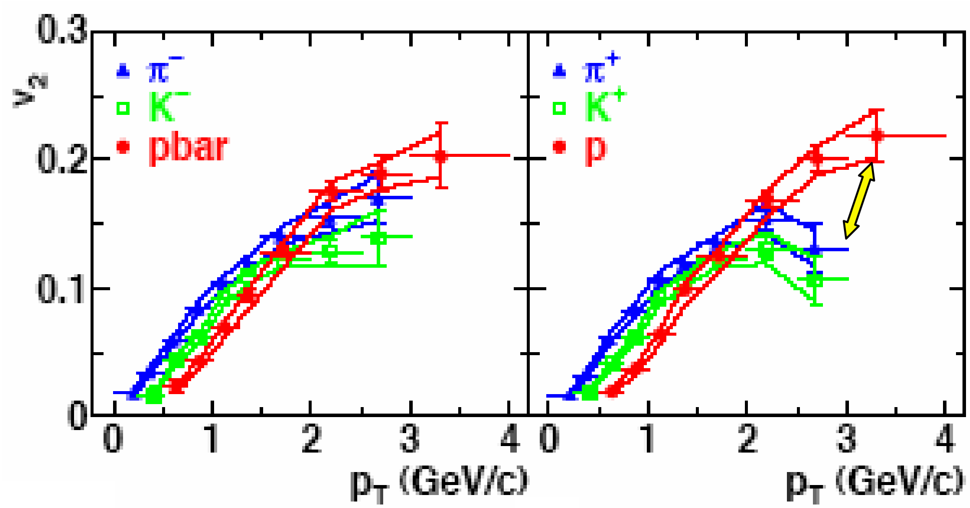


Exhibit #4

Azimuthal anisotropy



v_2: coeff. of 2nd harmonic of ϕ distribution



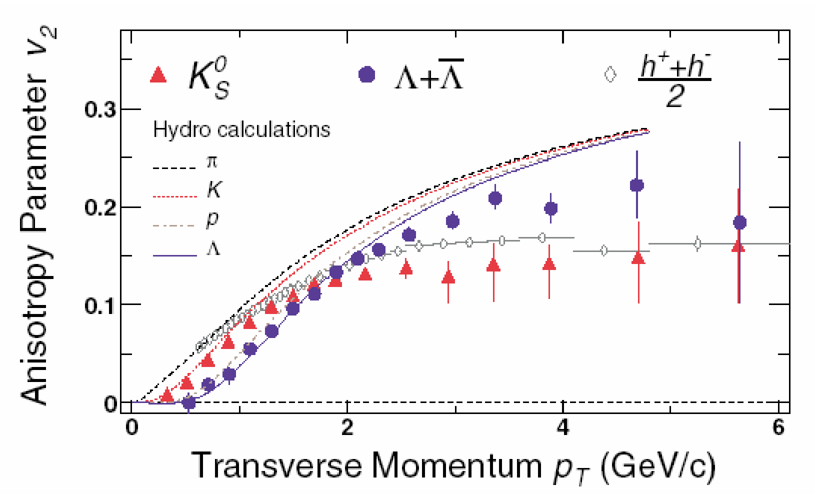
PHENIX,
PRL 91 (2003)

$v_2(p) > v_2(\pi)$ at $p_T > 2.5$ GeV/c

Molnar and Voloshin, PRL 91, 092301 (2003).

<u>Parton coalescence</u> implies that $v_2(p_T)$ scales with the number of constituents

STAR data



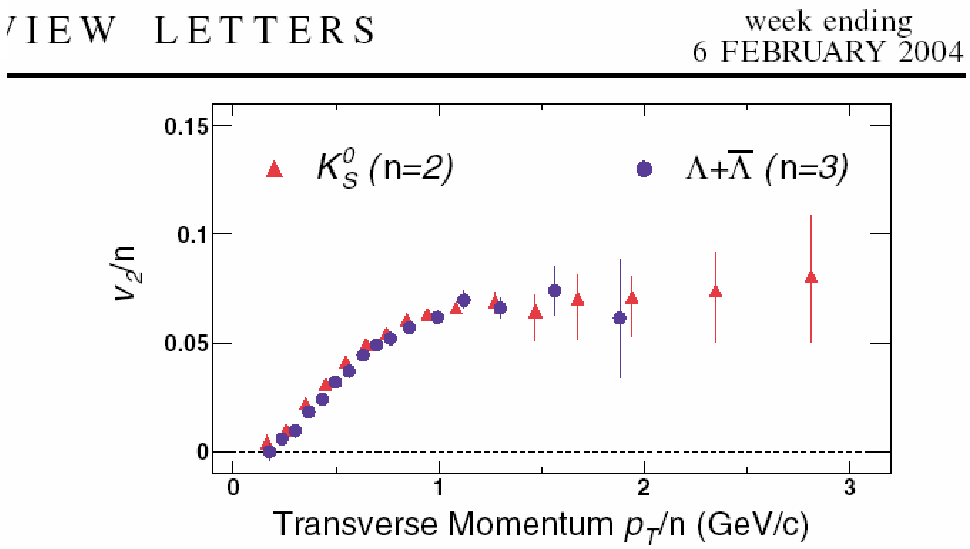


Exhibit #5 Forward-backward asymmetry at intermed. p_T

in d+Au collisions

$$\frac{\text{backward}}{\text{forward}}$$

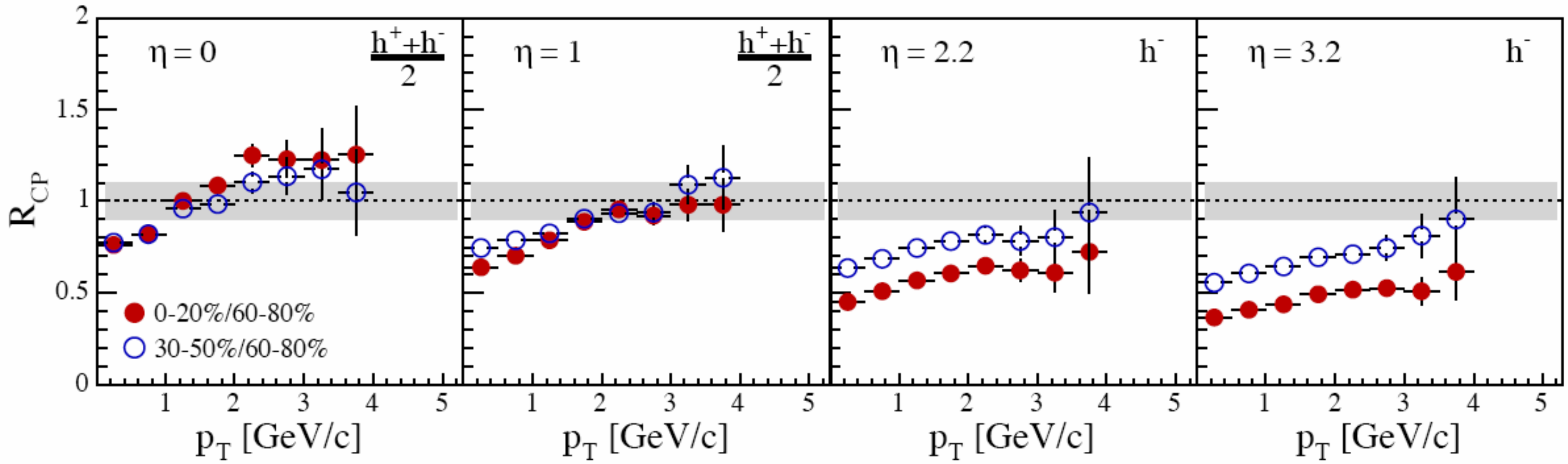
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

STAR preliminary data

Rapidity dependence of R_{CP} in d+Au collisions

BRAHMS

nucl-ex/0403005



$R_{CP} < 1$ at $\eta=3.2$ → Central more suppressed than peripheral collisions

This can be understood in terms of parton recombination.

Forward production in d+Au collisions

Same hadronization process as at η=0.

Soft component: $T(p_1) = p_1 \frac{dN_q^{soft}}{dp_1} = C p_1 \exp(-p_1/T)$

Pion distribution $\left.\frac{dN_\pi^{soft}}{p_T dp_T d\eta}\right|_{\eta=0} = \frac{C^2}{6}\exp(-p_T/T)$

C(β,η)

Notation:

Centrality 0-20% → β = 0.1

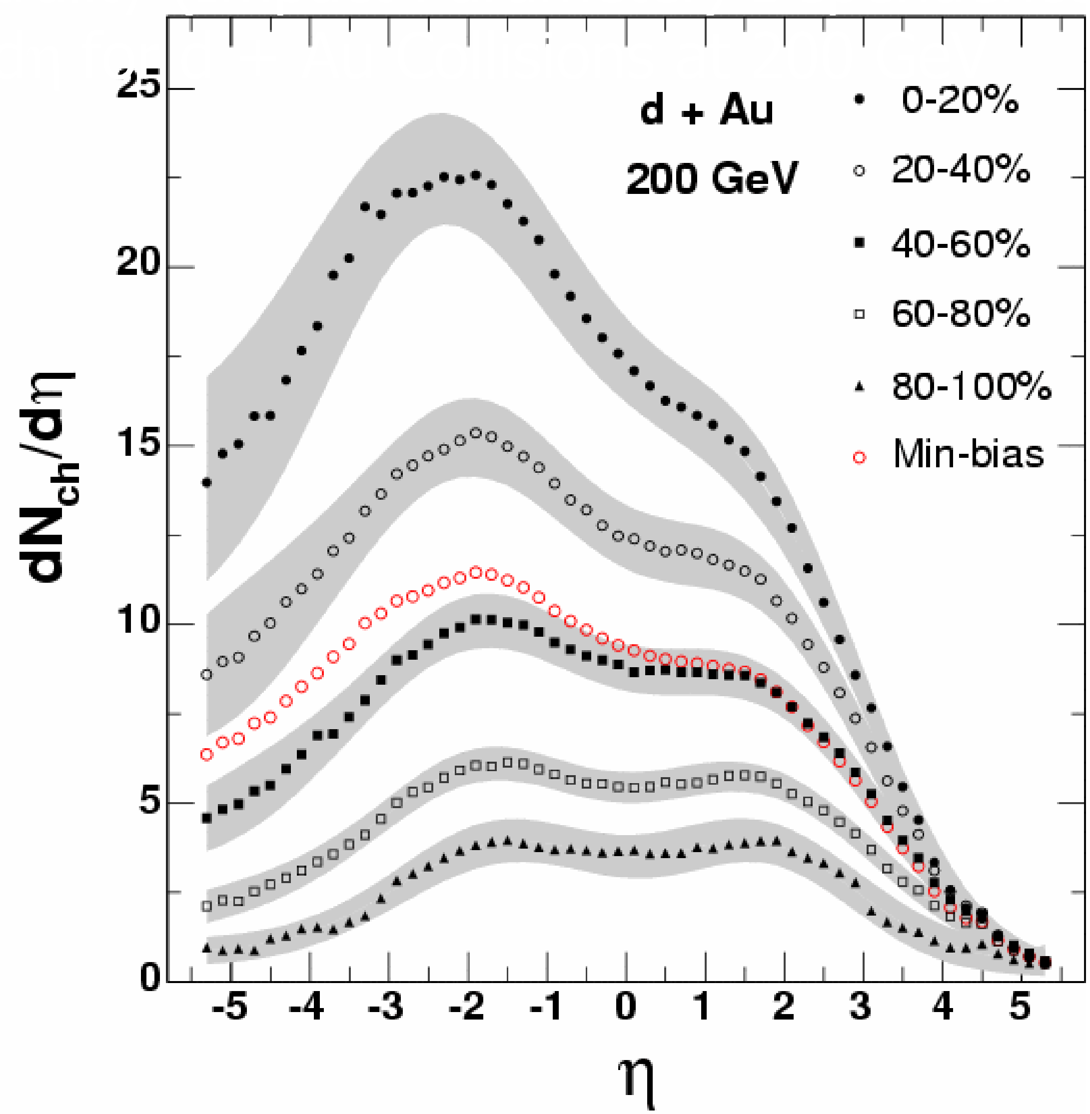
60-80% → 0.7

$C(\beta,\eta)$

for all β and η

$$C(\beta,\eta) = C(\beta,0)\left[\frac{dN_{ch}/d\eta(\beta)}{dN_{ch}/d\eta|_{\eta=0}(\beta)}\right]^{1/2}$$

Preliminary



$\therefore \quad C(\beta,\eta)$ can be calculated.

Our prediction on the π+ spectra for $0 \leq \eta \leq 3.2$, $0.1 \leq \beta \leq 0.7$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Hwa, Yang, and Fries,
nucl-th/0410111

T=constant, no free parameter

No new physics, e.g. gluon saturation, explicitly.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Include β and η dependences of T (one free parameter) and momentum degradation

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

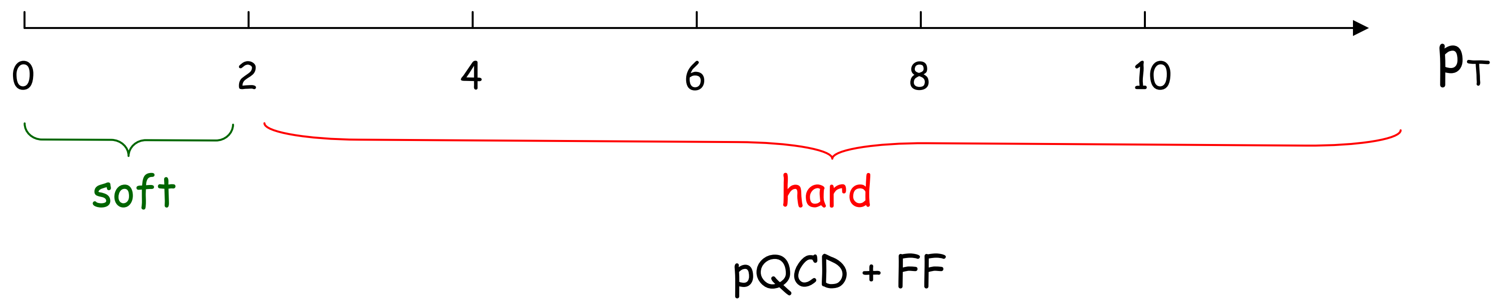
Hwa, Yang, Fries, nucl-th/0410111

Without any more free parameters

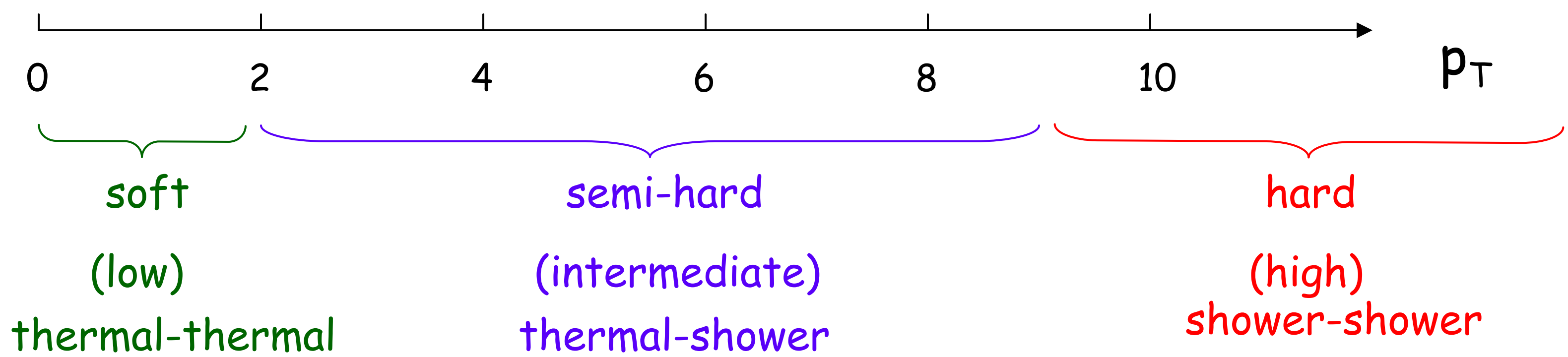
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Summary

Traditional picture



More realistic picture



All anomalies at intermediate p_T can be understood in terms of recombination of

thermal and shower partons

Recombination is the hadronization process.

At $p_T > 9$ GeV/c fragmentation dominates, but it can still be expressed as shower-shower recombination.

Hence, parton recombination at all p_T.

Conclusion in one sentence

Due to the soft parton environment in heavy-ion collisions at RHIC,

hadronization by thermal-shower recombination

dominates all phenomena on particle production at intermediate p_T

for all centralities and all rapidities.

All of the work presented

was done in collaboration with

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