Forward Production by Parton Recombination

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Forward Physics Workshop
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Outline

- Why fragmentation should not be applied to heavy-ion collisions.
- How parton recombination resolves numerous puzzles.
- Pion production at forward rapidities in d+Au collisions.
- Backward-forward asymmetry ratio

A number of puzzles at high p_T & midrapidity at RHIC

- $R_{p/\pi} \sim 1$ in Au+Au collisions
- $R_{CP}(p) > R_{CP}(\pi)$ in d+Au collisions
- Jet structure in Au+Au different from that in pp
- $v_2(B) > v_2(M)$ in Au+Au collisions

They are puzzling only within the conventional framework of particle production at high p_T:

hard scattering × fragmentation

We show how recombination works at $\eta=0$.

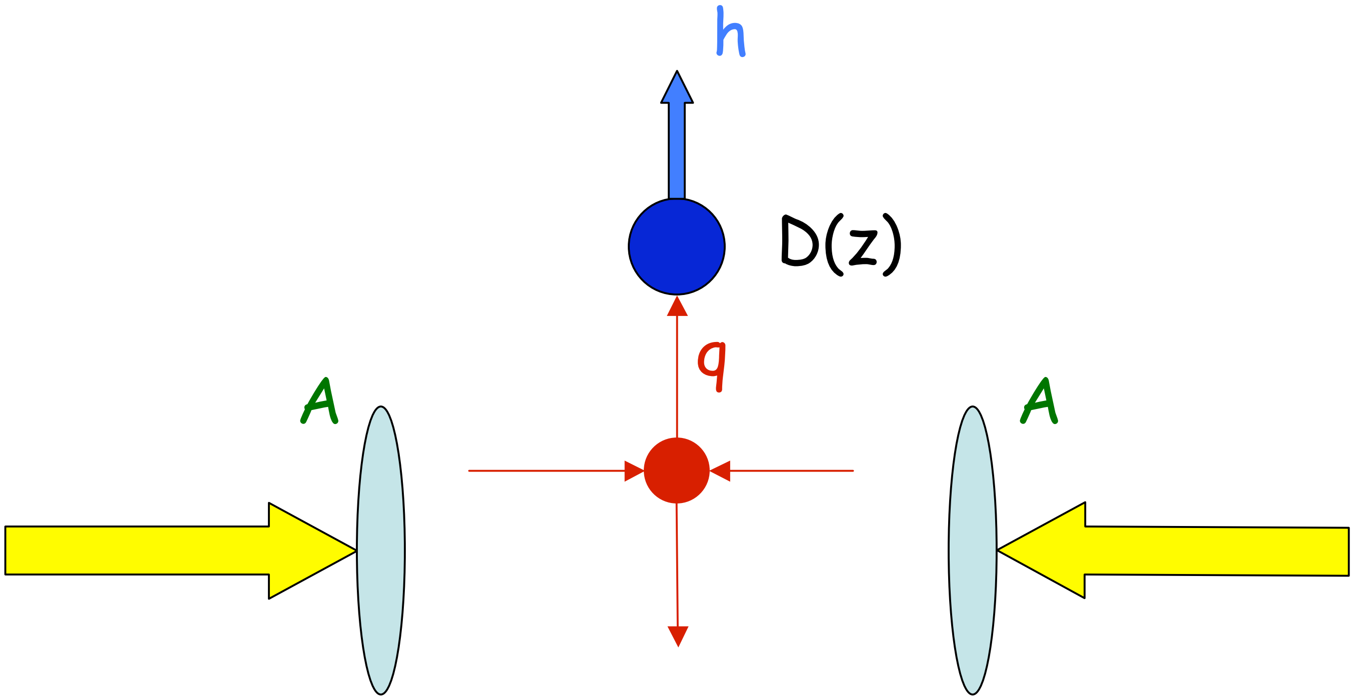
We then extend the same consideration to forward production. Emphasis on hadronization.

- No change of physics from $\eta < 0$ to $\eta > 0$.

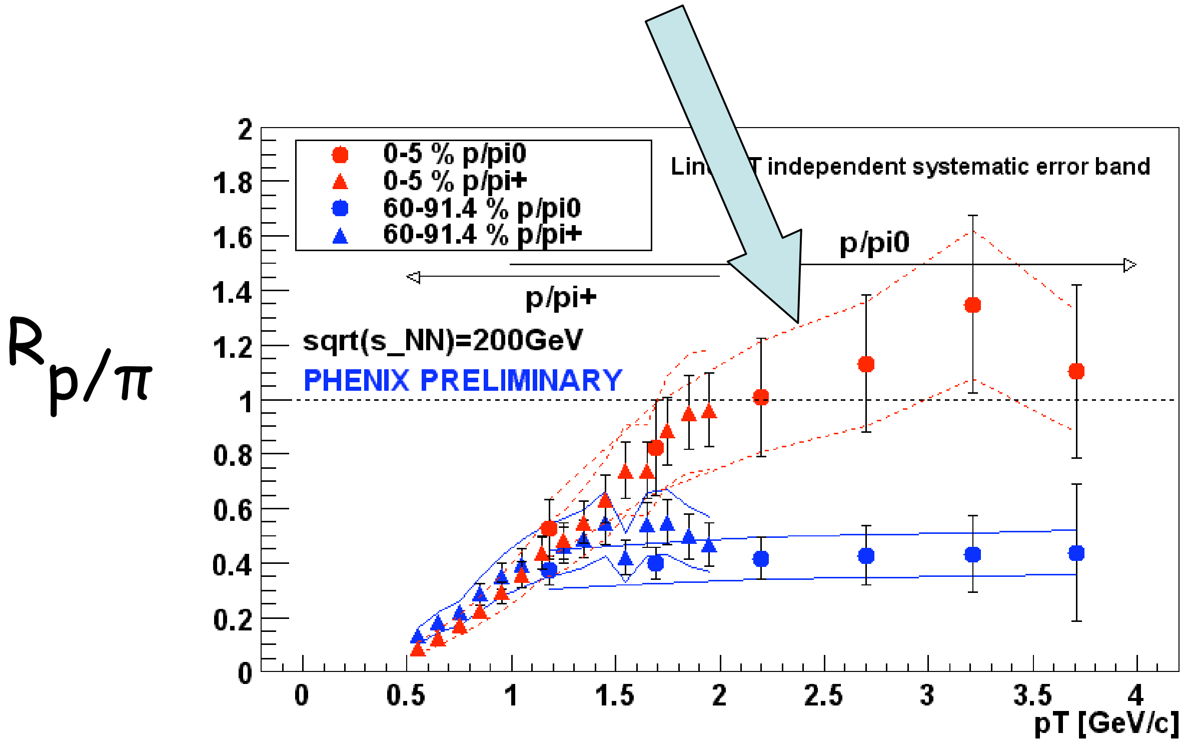
- Whether or not CGC physics is important at $\eta > 0$, it is worth examining what happens if the same physics that is successful at $\eta = 0$ is applied to $\eta > 0$.

- Findings: data on R_{CP} can be well reproduced without new physics.

Conventional approach to hadronization at high p_T

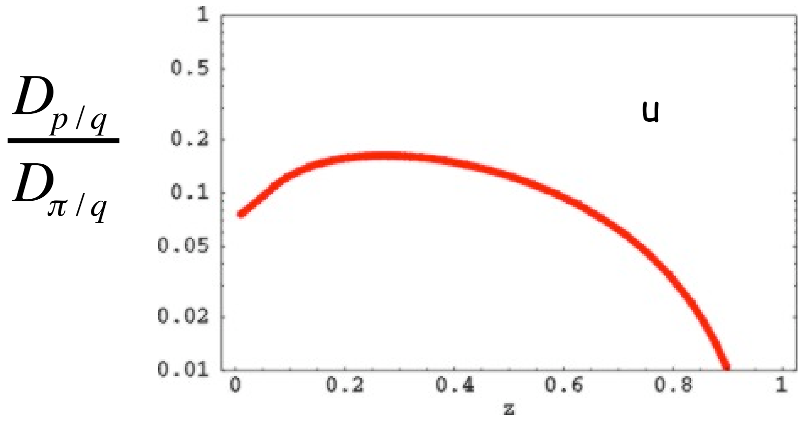


Puzzle #1 $R_{p/\pi} > 1$



Not possible in fragmentation model:

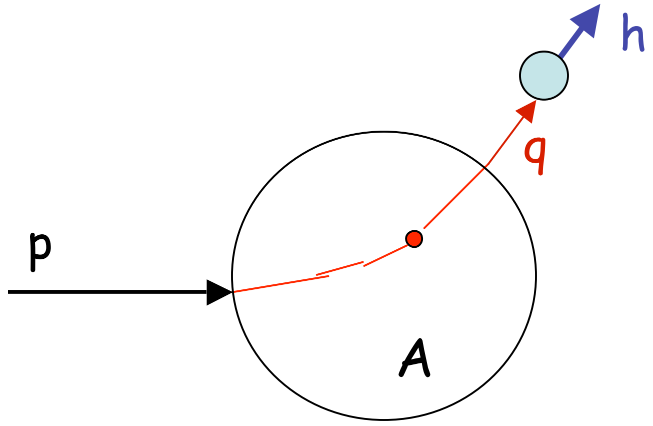
$$D_{p/q} << D_{\pi/q}$$



Puzzle #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.

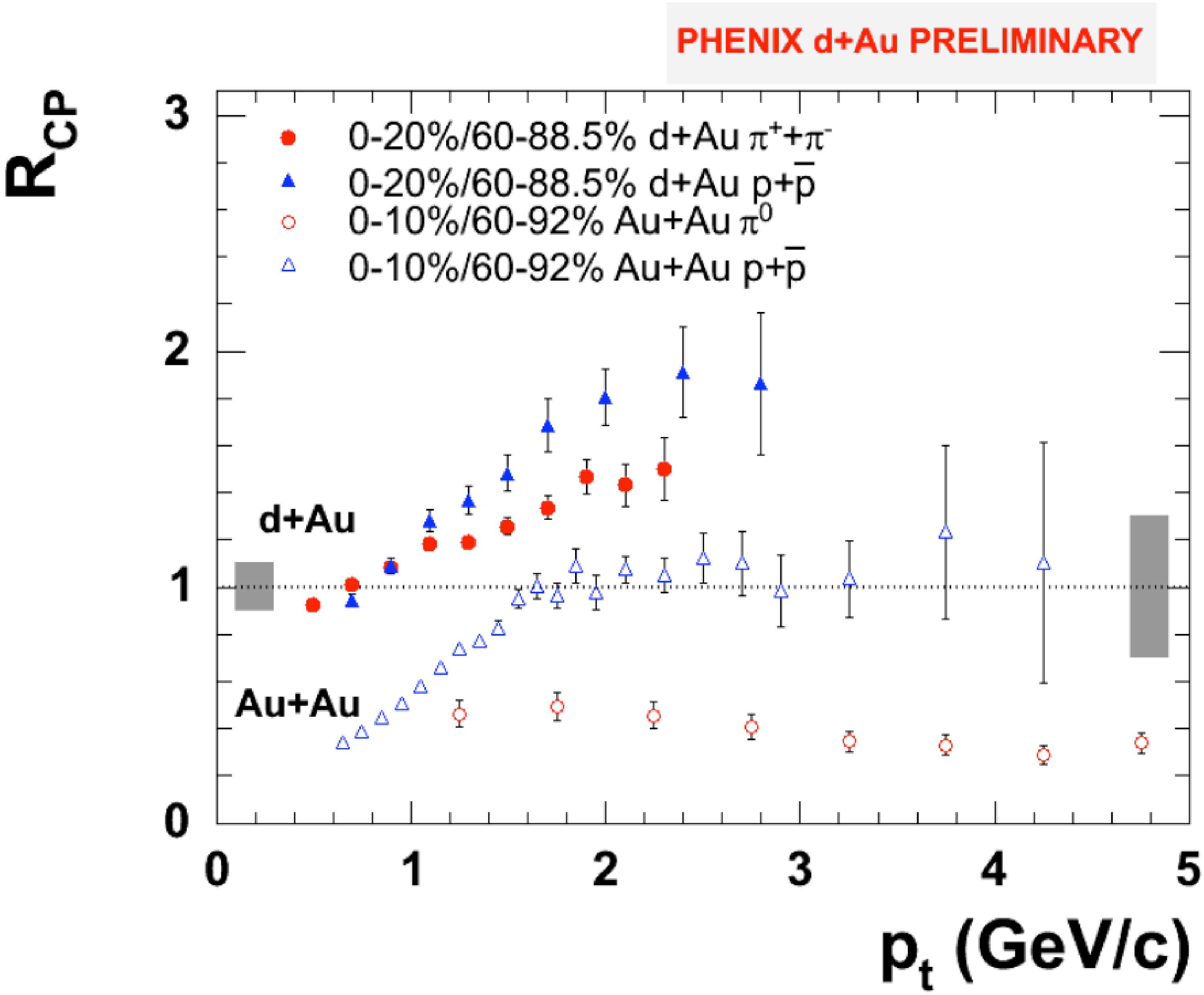
Unchallenged for ~30 years.

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

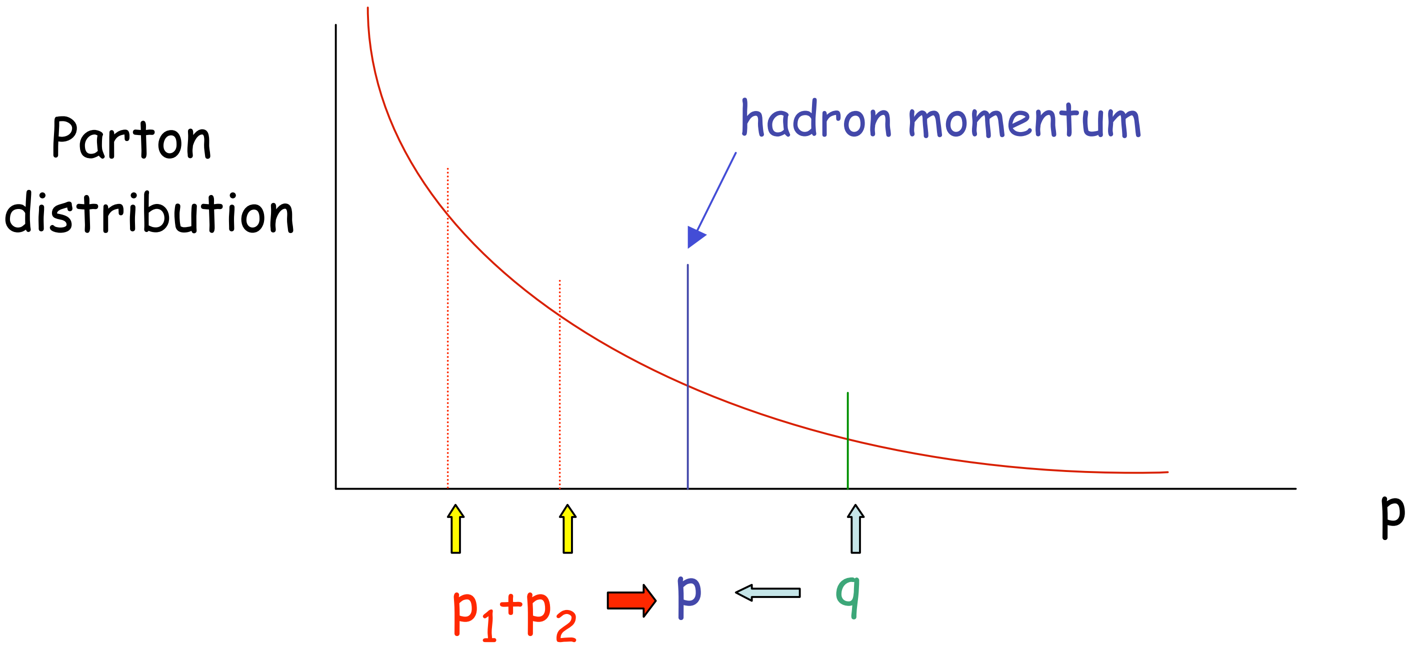
$$\boxed{\alpha_p > \alpha_\pi}$$

RHIC expt (2003)

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



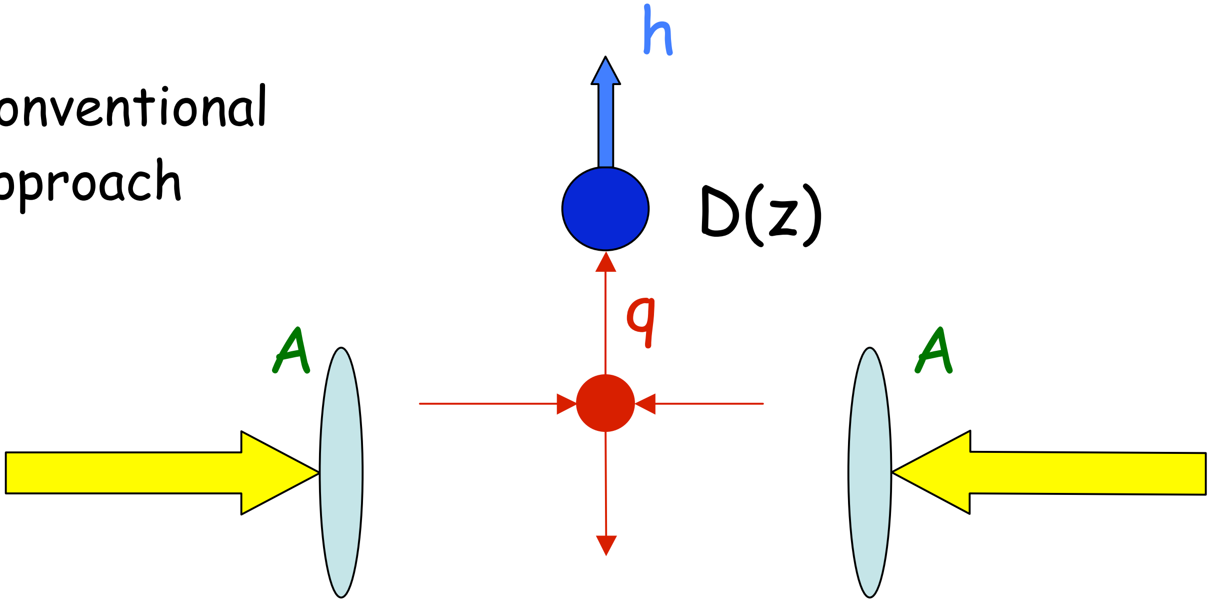
How can recombination solve the puzzles?



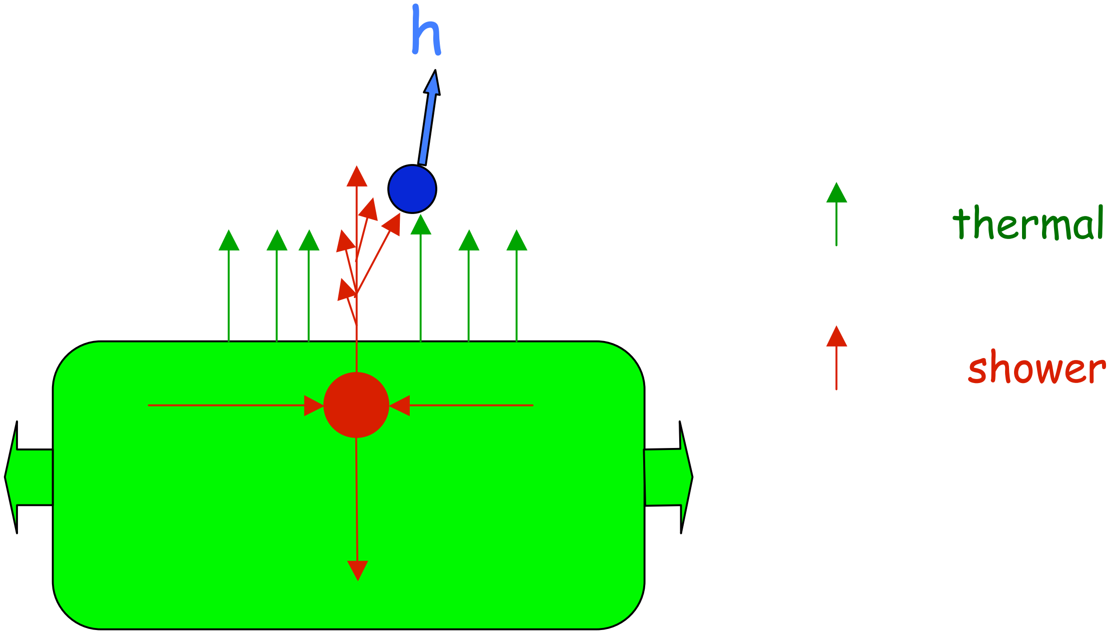
(recombine) (fragment)

higher yield heavy penalty

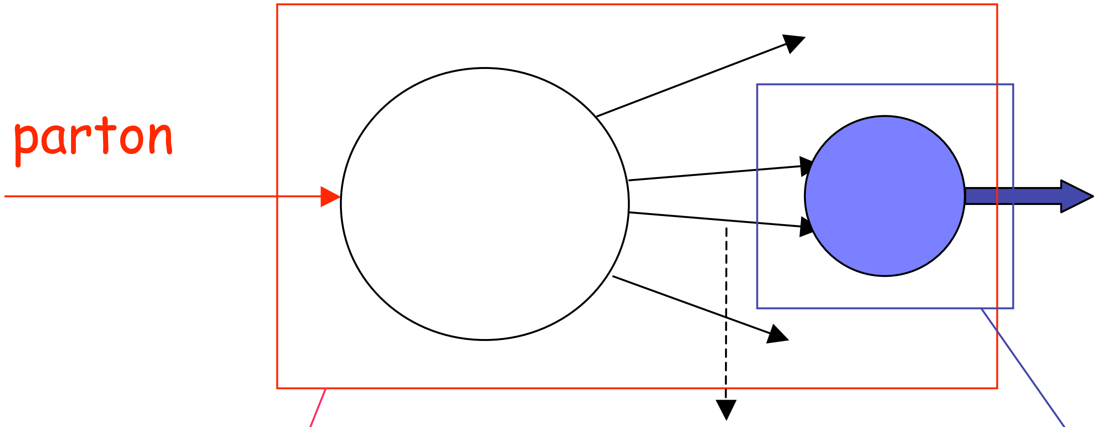
Conventional approach



Thermal-shower recombination



Shower partons



hard parton

meson

fragmentation

shower partons

recombination

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

known from data (e+e-, μp, …)

can be determined

known from recombination model

Shower parton distributions

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

$$S_i^j = \begin{array}{cc} \begin{array}{ccc} \text{u} & \text{d} & \text{s} \end{array} & \\ \begin{pmatrix} K & L & L_s \\ L & K & L_s \\ L & L & K_s \\ G & G & G_s \end{pmatrix} & \begin{array}{c} \text{u} \\ \text{d} \\ \text{s} \\ \text{g} \end{array} \end{array}$$

$$K = \overset{\substack{\text{valence}\\ \downarrow}}{K_{NS}} + L \longleftarrow \text{sea}$$

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

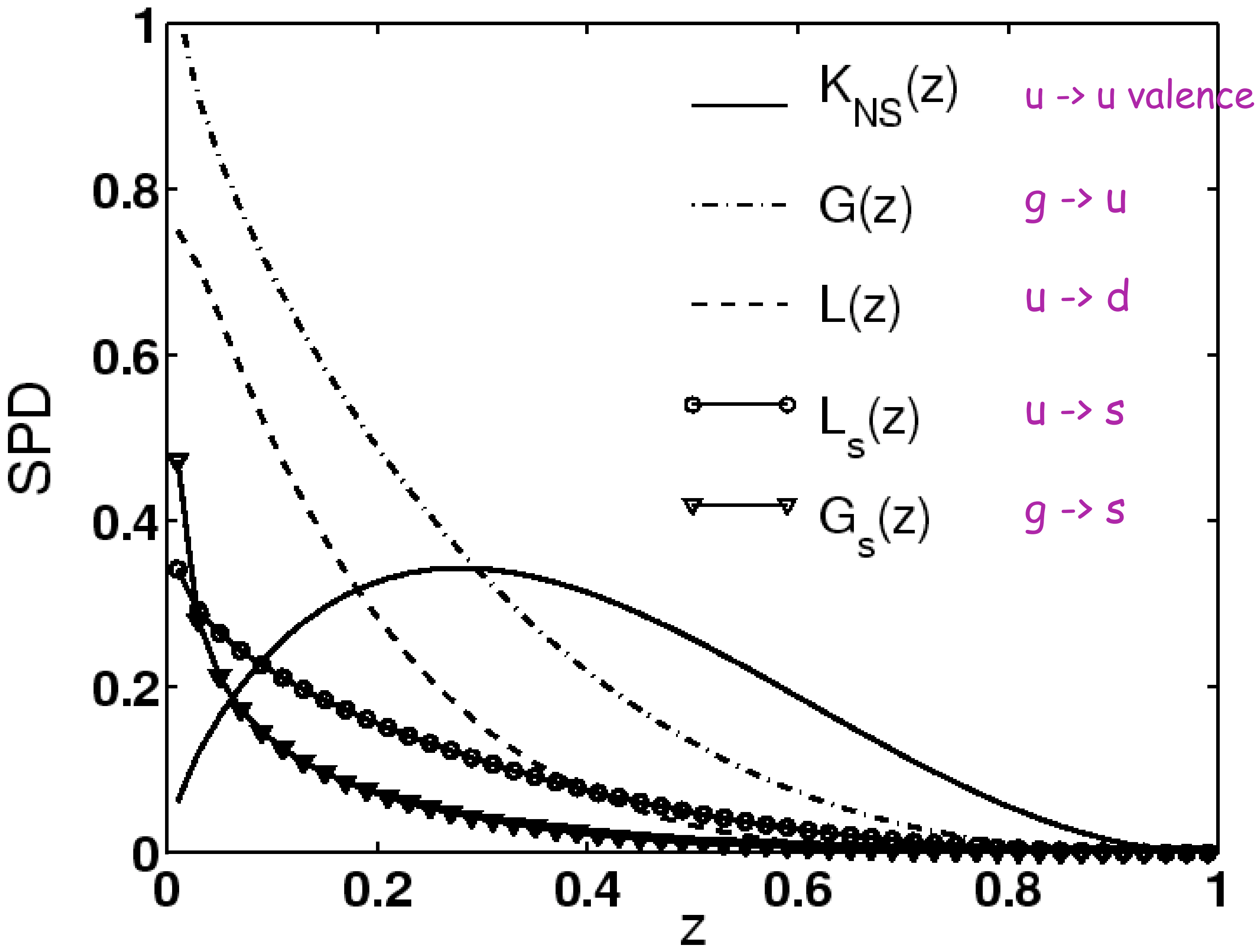
$$K_s = K_{NS} + L_s$$

5 SPDs are determined from 5 FFs.

$$\left.\begin{array}{l} L\ L \\ K_{NS}\ L \\ G\ G \end{array}\right\} R^{\pi} \qquad \begin{array}{l} \rightarrow D^{\pi}_{Sea} \\ \rightarrow D^{\pi}_{V} \\ \rightarrow D^{\pi}_{G} \end{array}$$

$$\left.\begin{array}{l} L\ L_s \\ G\ G_s \end{array}\right\} R^{K} \qquad \begin{array}{l} \rightarrow D^{K}_{Sea} \\ \rightarrow D^{K}_{G} \end{array}$$

Shower Parton Distributions



u -> u valence

g -> u

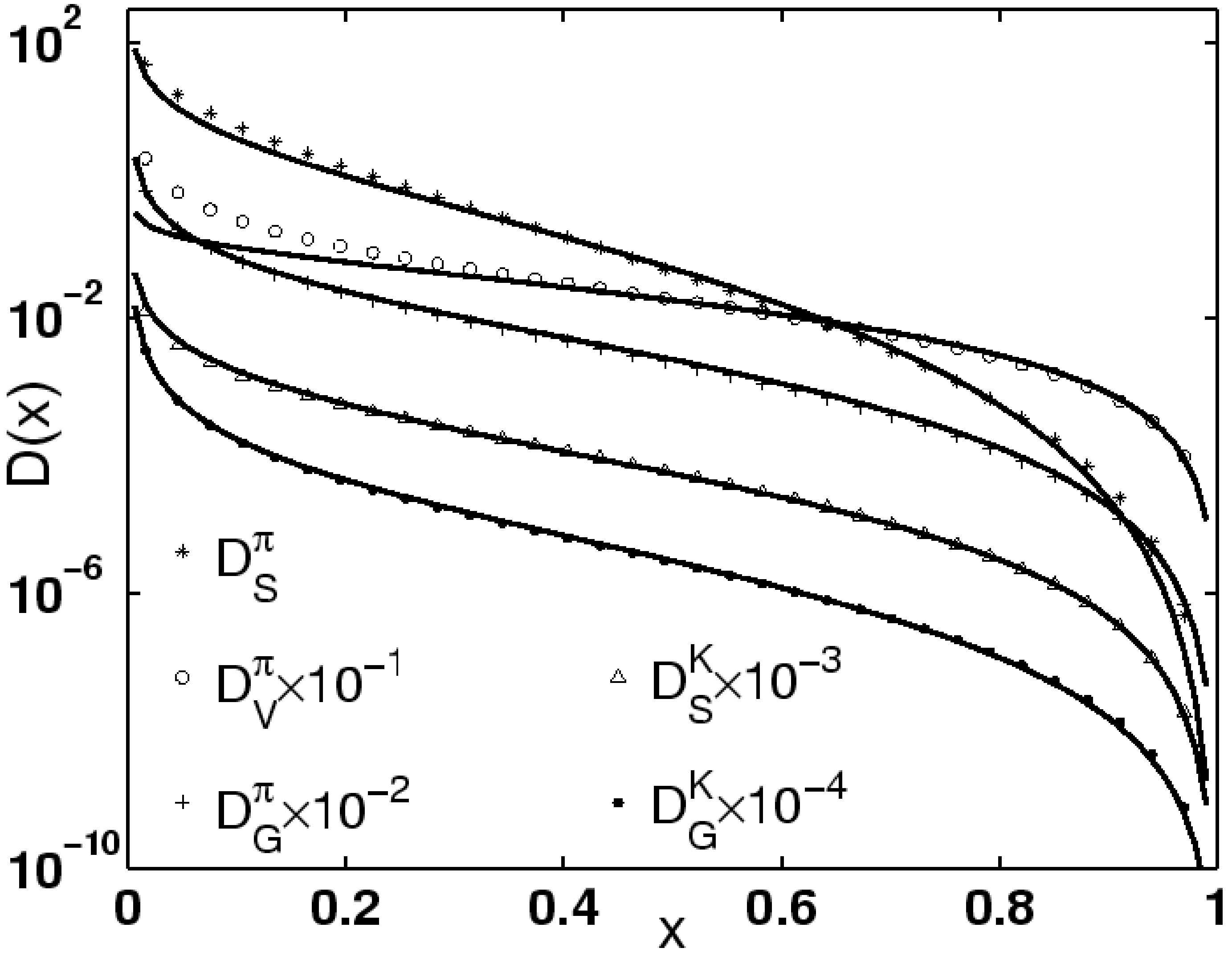
u -> d

u -> s

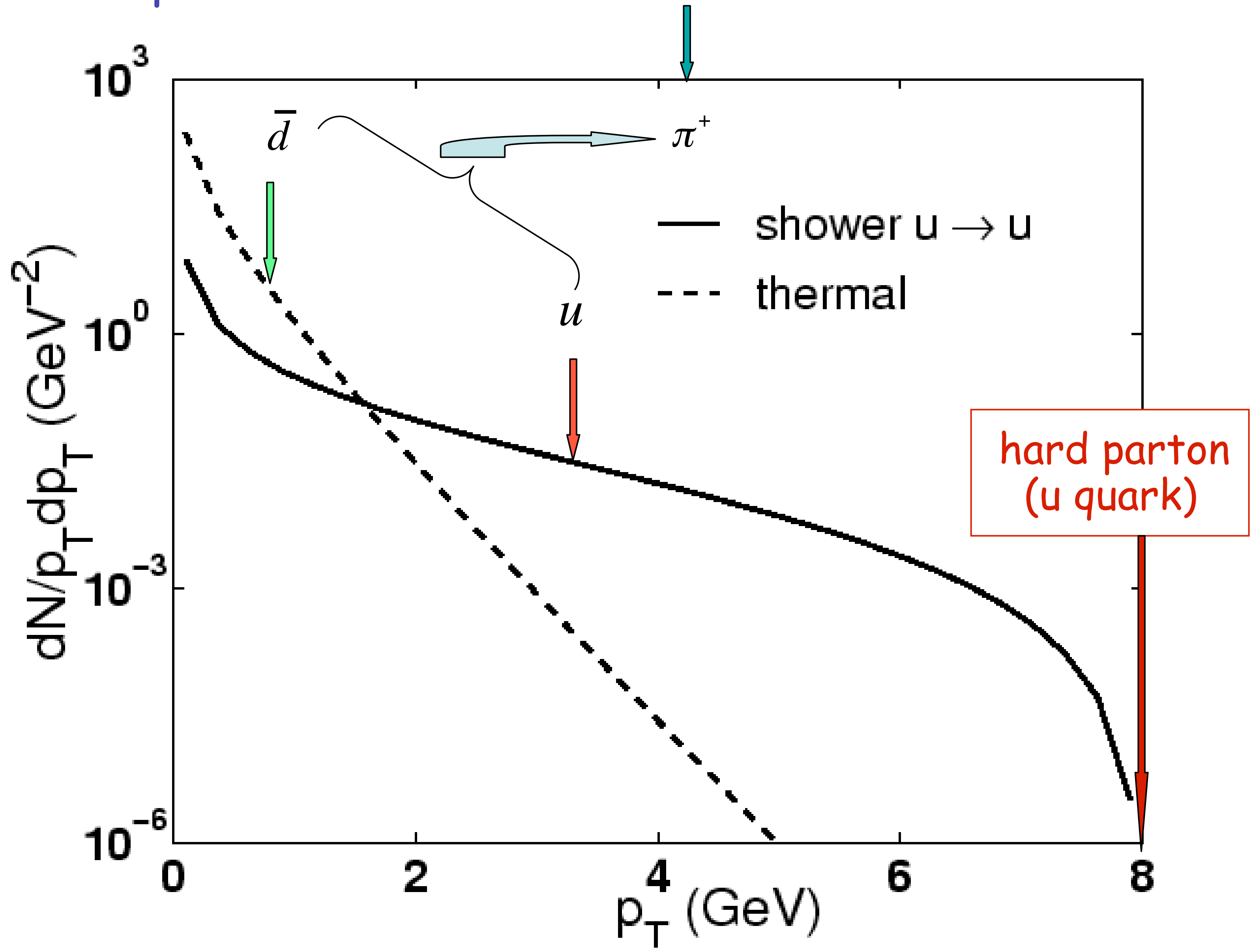
g -> s

Hwa & CB Yang, PRC (2004)

BKK fragmentation functions



An example



hard parton
(u quark)

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)

$$\frac{p_1p_2}{p}\delta(p_1+p_2-p)$$

Pion formation: $q\bar{q}$

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

T thermal

S shower

Proton formation: uud distribution

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

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

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

fraction of hard partons that get out of medium to produce shower

hard parton momentum

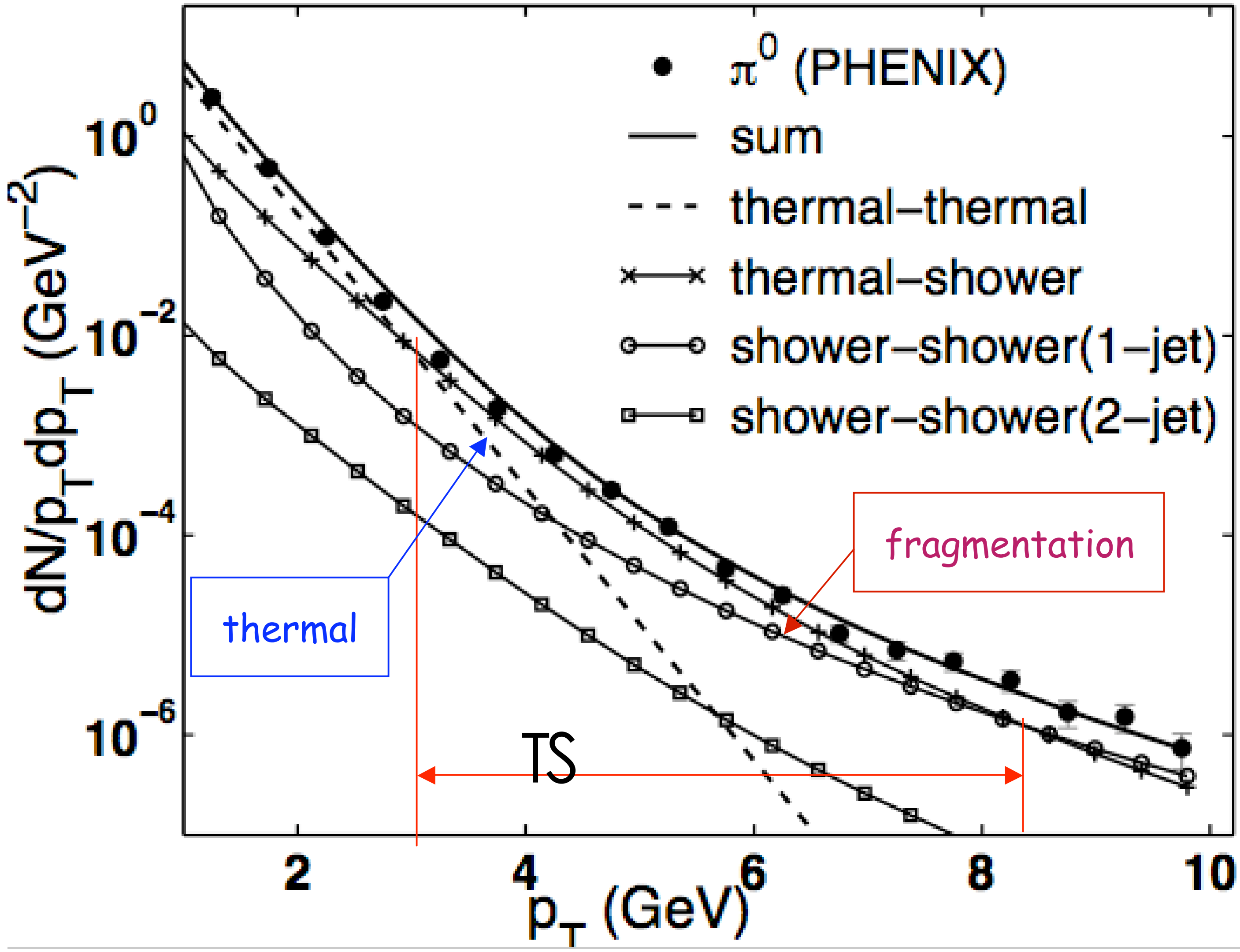
distribution of hard parton i in AuAu collisions

SPD of parton j in shower of hard parton i

$\boxed{\xi = 0.07}$

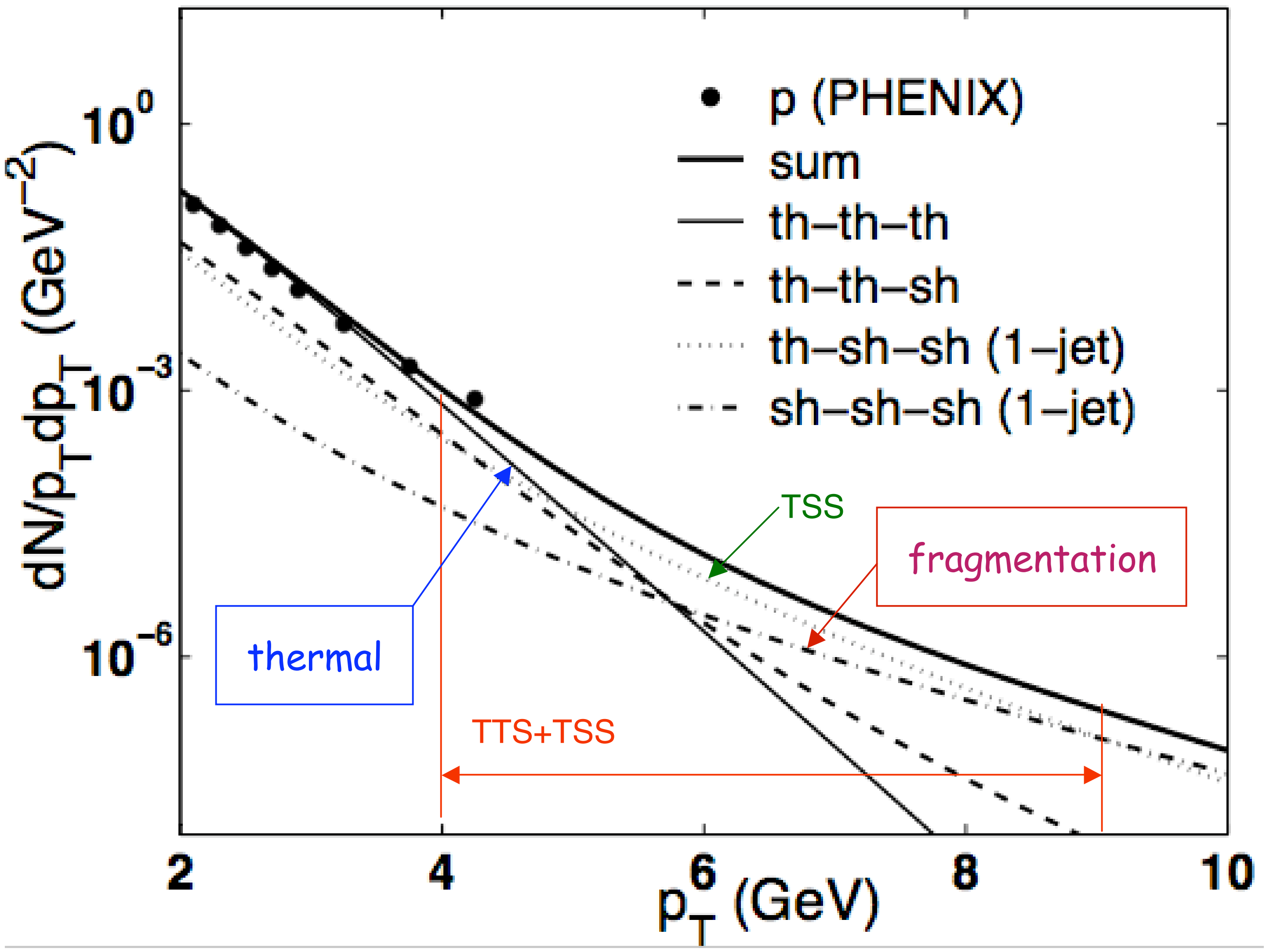
calculable

π production in AuAu central collision at 200 GeV

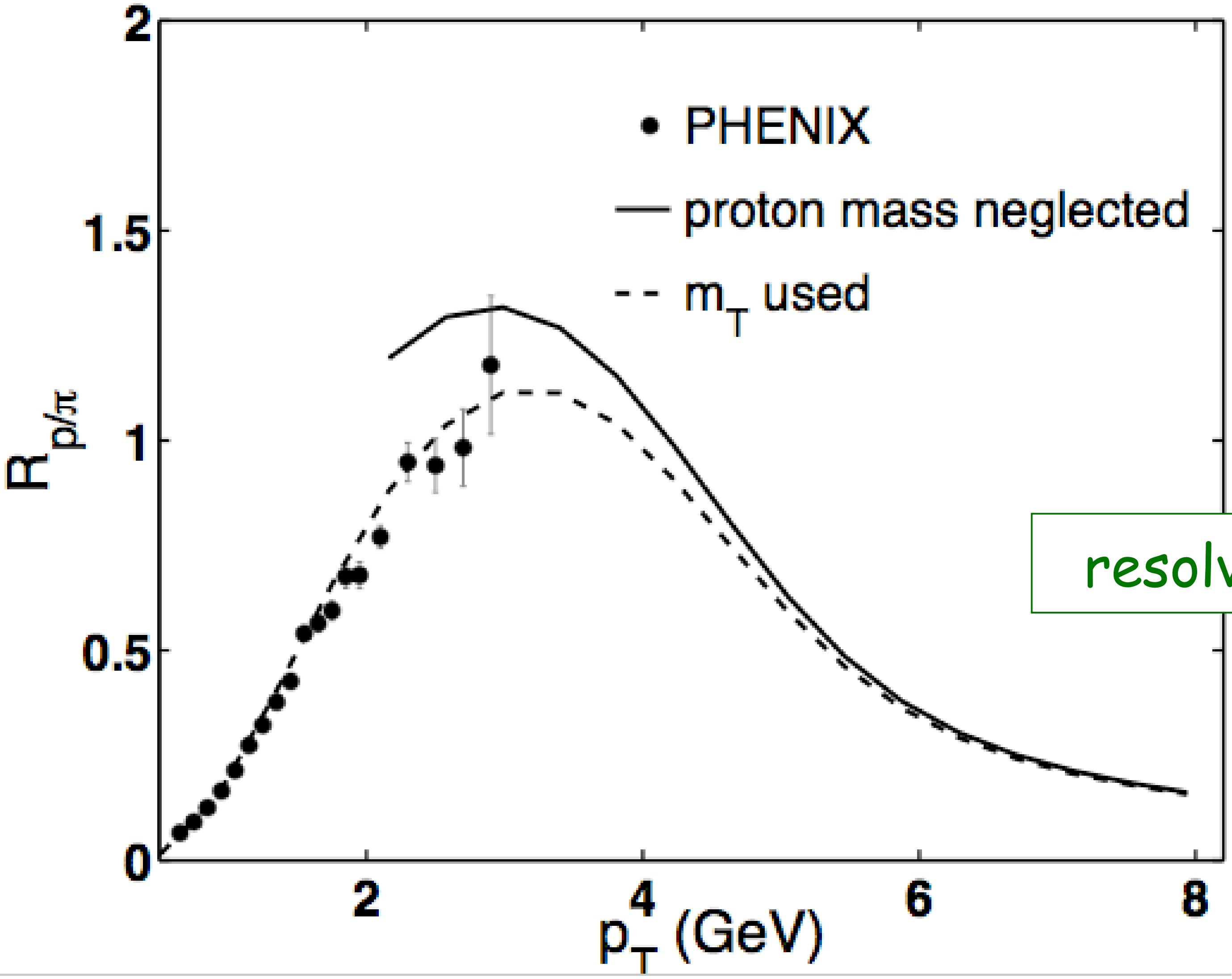


Hwa & CB Yang, PRC<u>70</u>, 024905 (2004)

Proton production in AuAu collisions



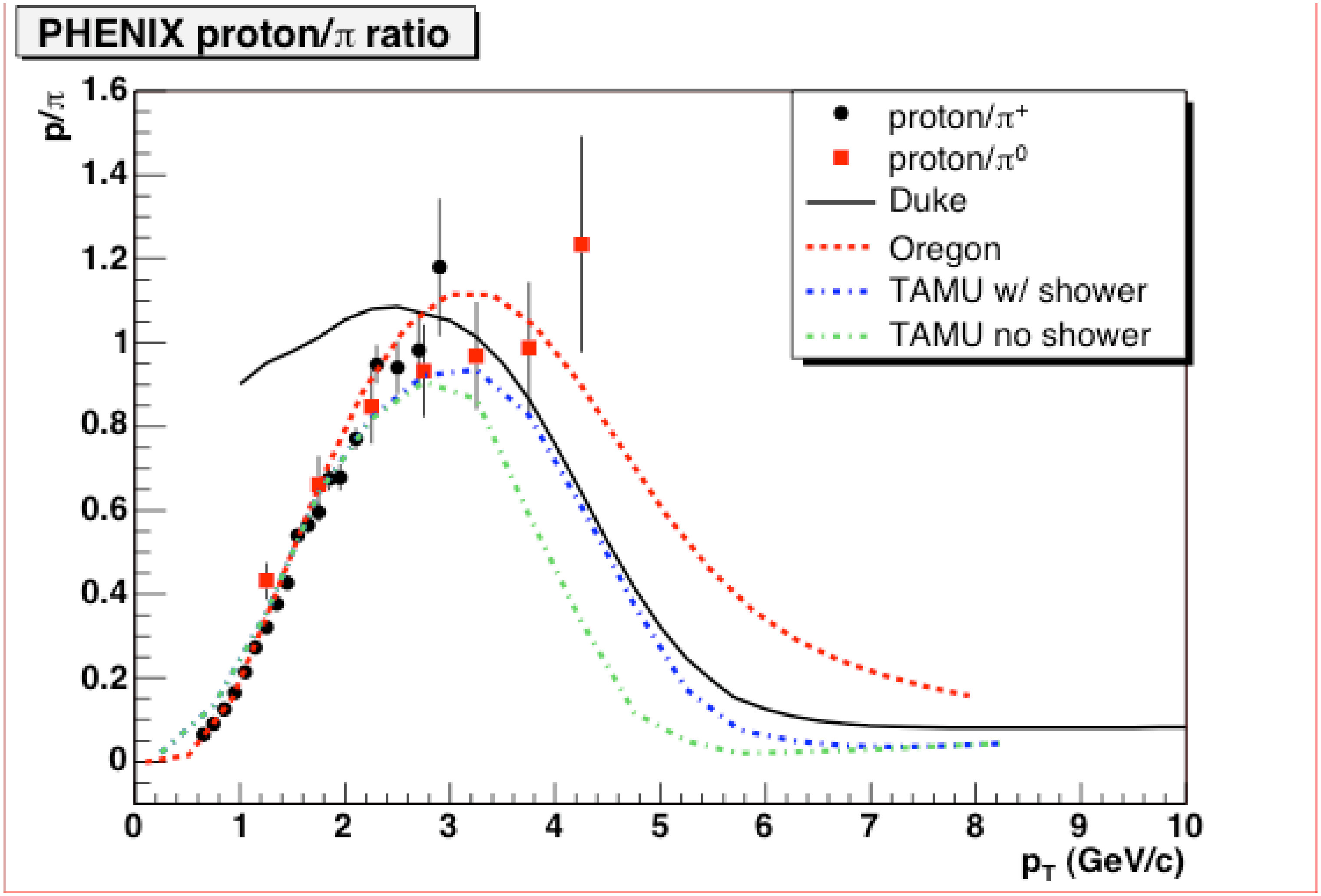
Puzzle #1 Proton/pion ratio



resolved

Hwa & CB Yang, PRC70, 024905 (2004)

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

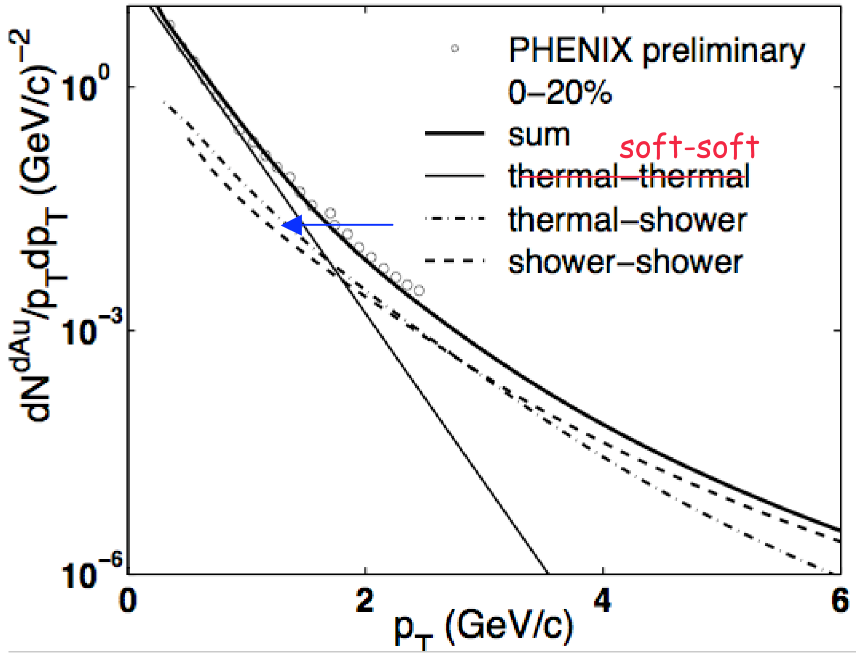


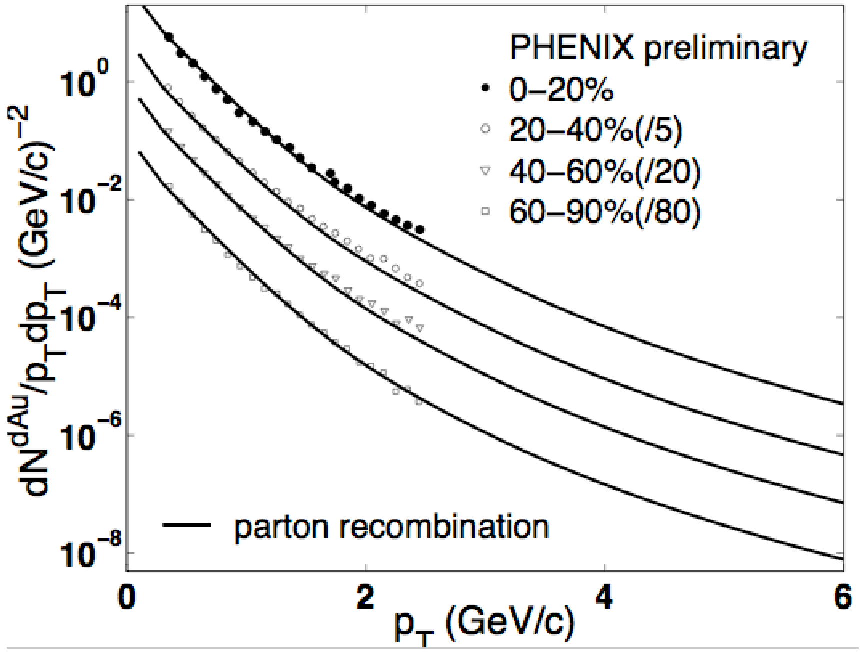
Duke: Fries, Mueller, Nonaka, Bass, PRL90,202303(2003);PRC68,044902(2003).
TAM: Greco, Ko, Levai, PRL,90,202302(2003); PRC68,034904(2003).

d+Au collisions

Pions

$\xi = 1$



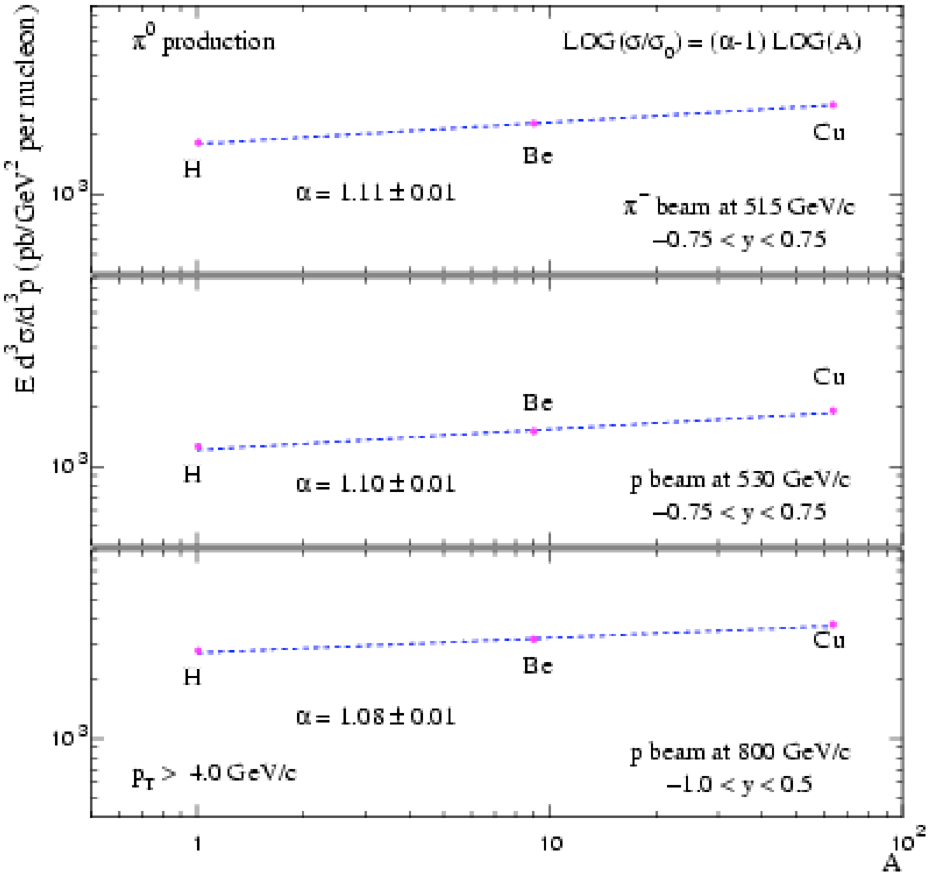


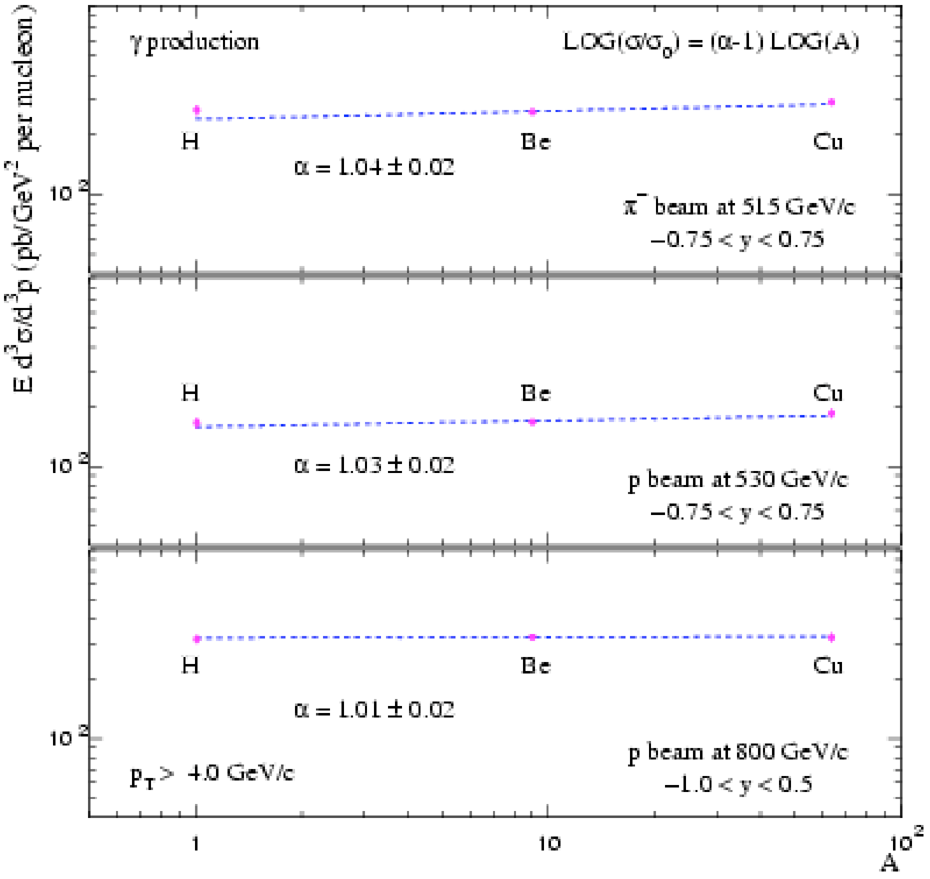
☆ No p_T broadening by multiple scattering in the initial state.

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

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

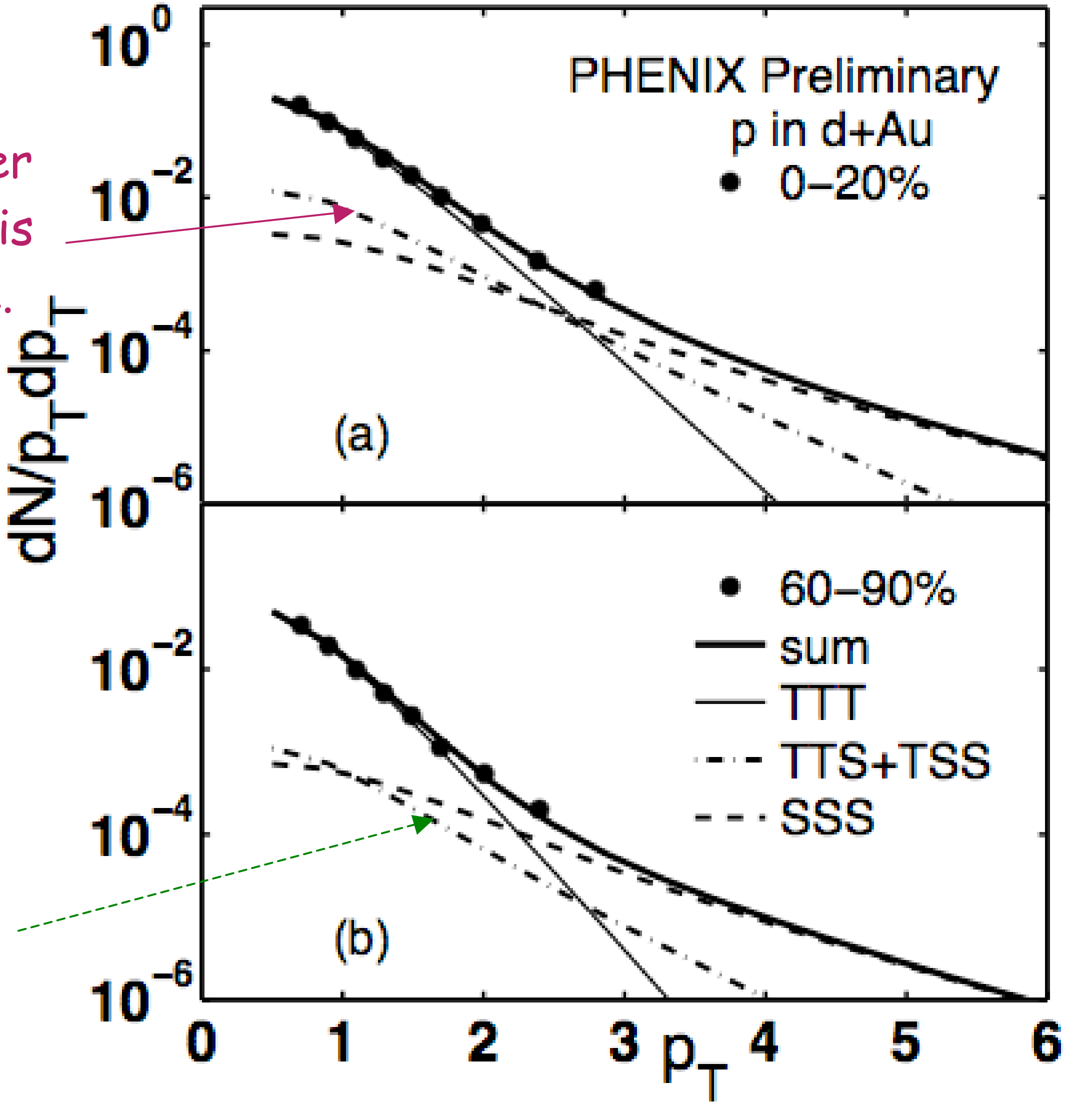
π^0, γ production in p+A collisions





π^0: _ = 1.1 **γ: _ = 1.0**

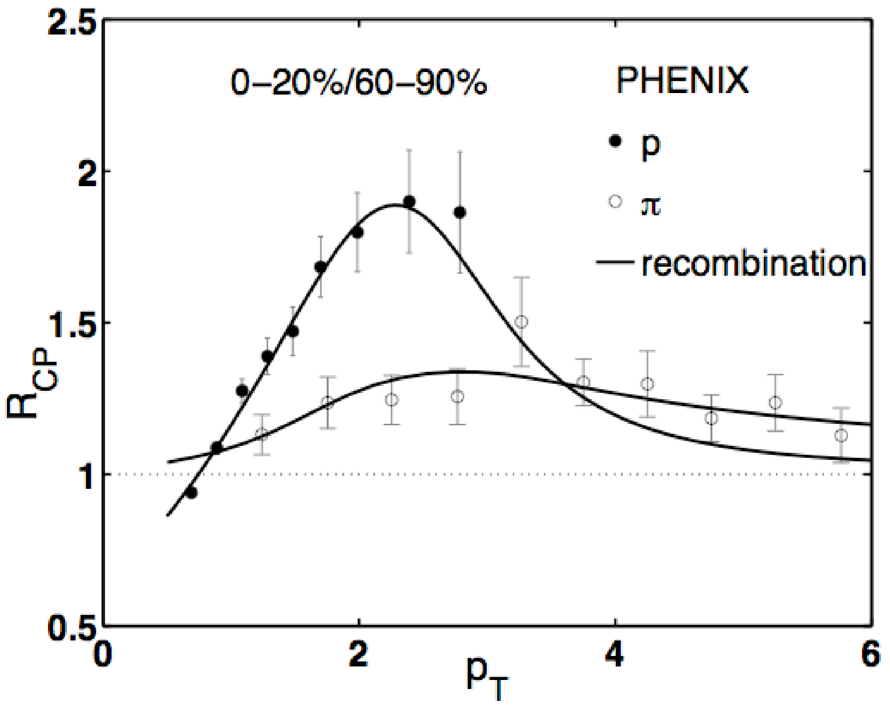
Proton



Thermal-shower recombination is <u>NOT</u> negligible.

Thermal-shower recombination is negligible.

Nuclear Modification Factor



Puzzle #2

resolved

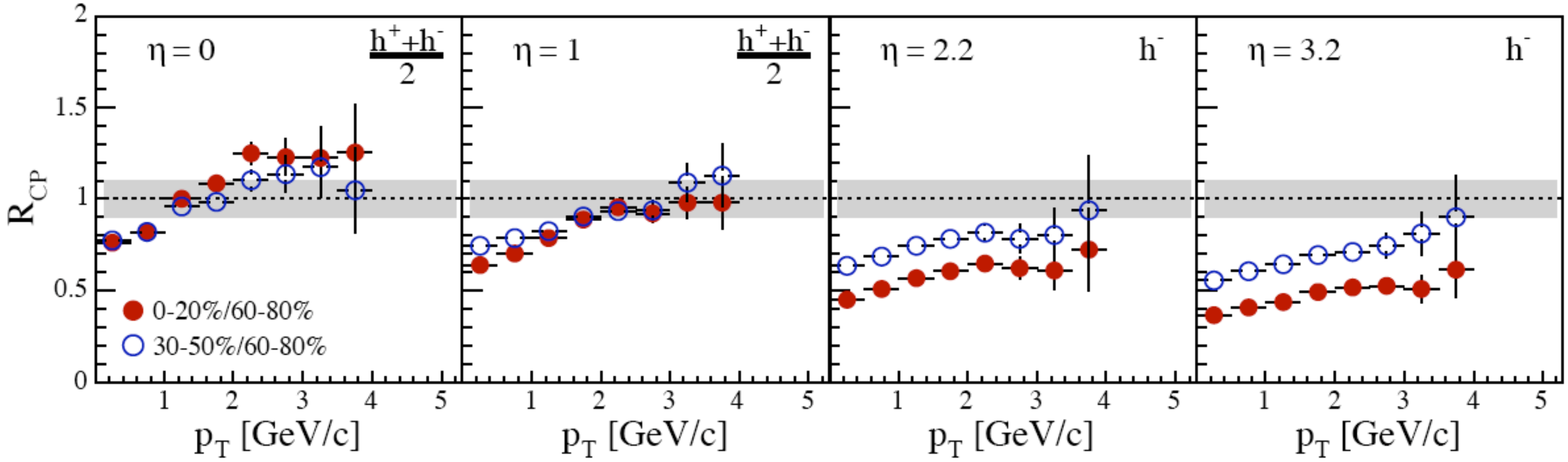
$$\boxed{R^{p}_{CP} > R^{\pi}_{CP}}$$

because 3q → p, 2q → π

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

BRAHMS

nucl-ex/0403005



$R_{CP} < 1$ at η=3.2 ⟹ Central more suppressed than peripheral collisions

Let’s see how this can be understood by parton recombination.

Forward production in d+Au collisions

Soft component: $\mathrm{T}(p_1) = p_1 \frac{dN_q^{soft}}{dp_1} = Cp_1 \exp(-p_1/T)$

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

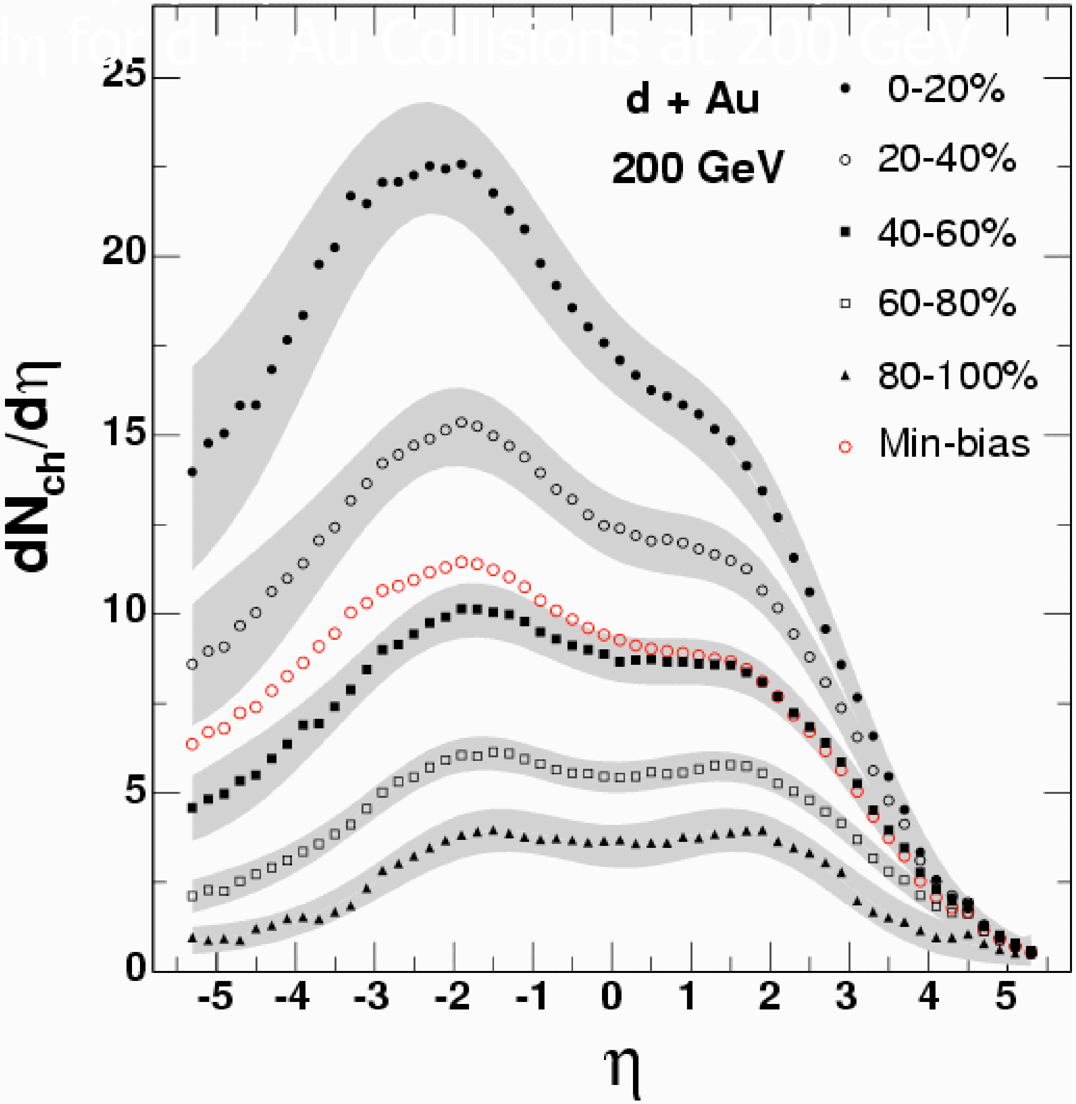
$C(\beta,\eta)$

for all β and η

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

trality (Impact Parameter) Dependence
dη for d + Au Collisions at 200 GeV

PHOBOS Preliminary

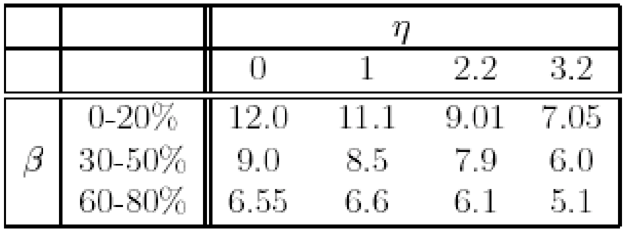


$\therefore \quad C(\beta,\eta)$ can be calculated.

Soft partons: $$\mathrm{T}(p_1) = p_1 \frac{dN_q^{soft}}{dp_1} = Cp_1 \exp(-p_1/T)$$

Normalization $C(\beta,\eta)$ decreases with increasing η
and increasing β

Table 1: Values of $C(\beta,\eta)$ in $(\mathrm{GeV}/c)^{-1}$



		η			
		0	1	2.2	3.2
β	0-20%	12.0	11.1	9.01	7.05
	30-50%	9.0	8.5	7.9	6.0
	60-80%	6.55	6.6	6.1	5.1

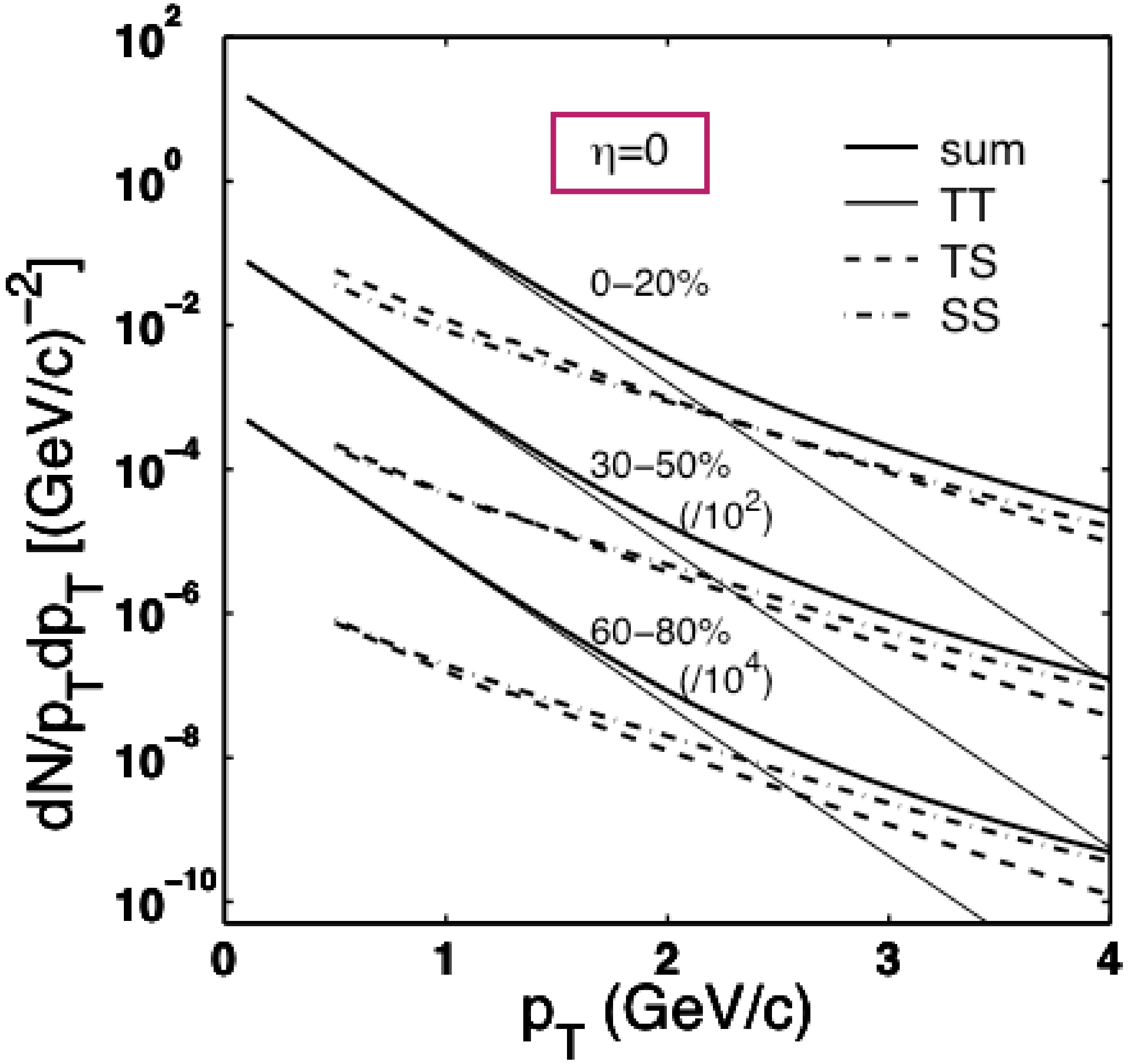
Inverse slope T should also decrease:

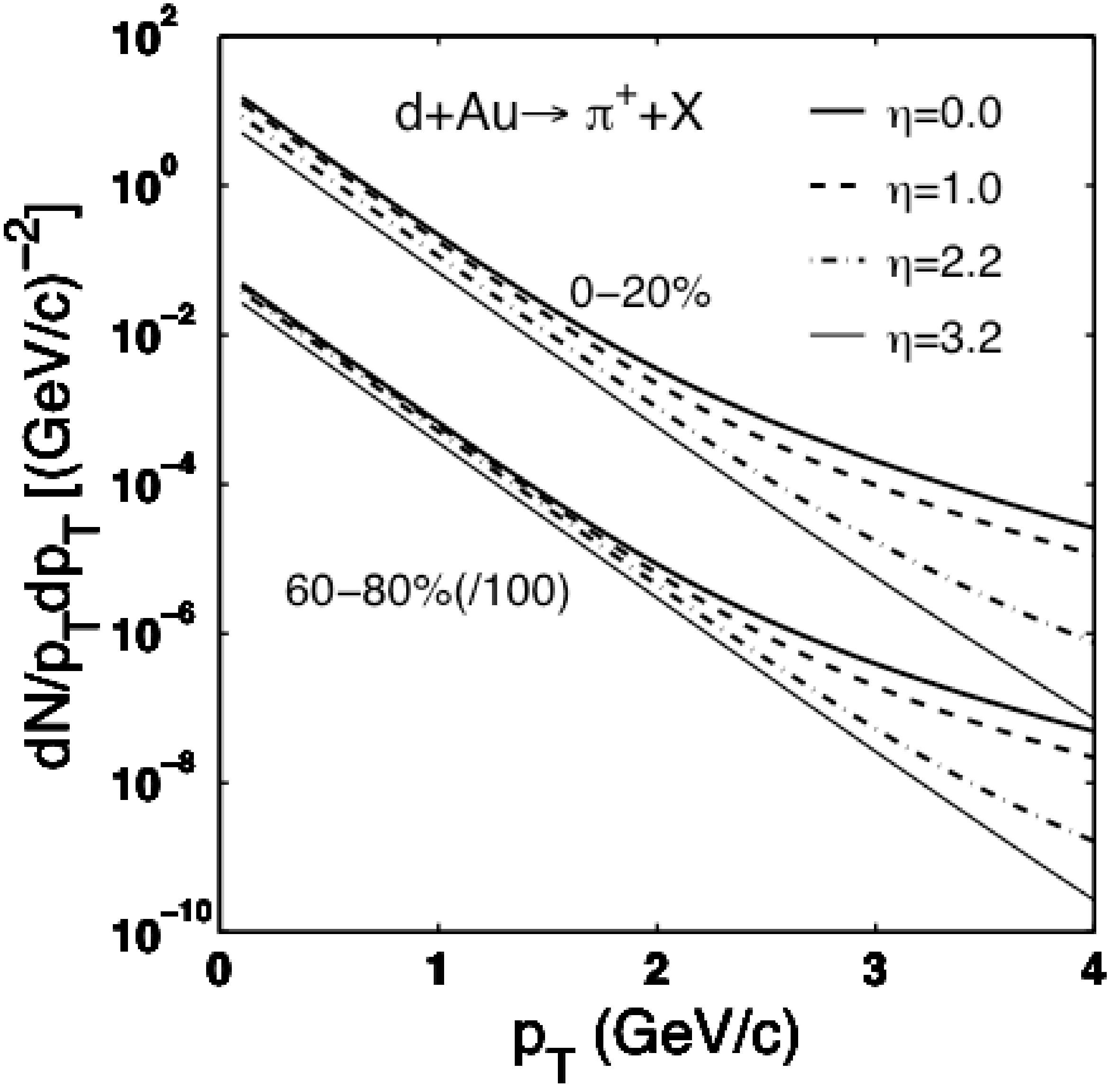
$$T(\beta,\eta) = T_0(1-\varepsilon\beta\eta)$$

T_0 known from η=0: 0.208 GeV/c

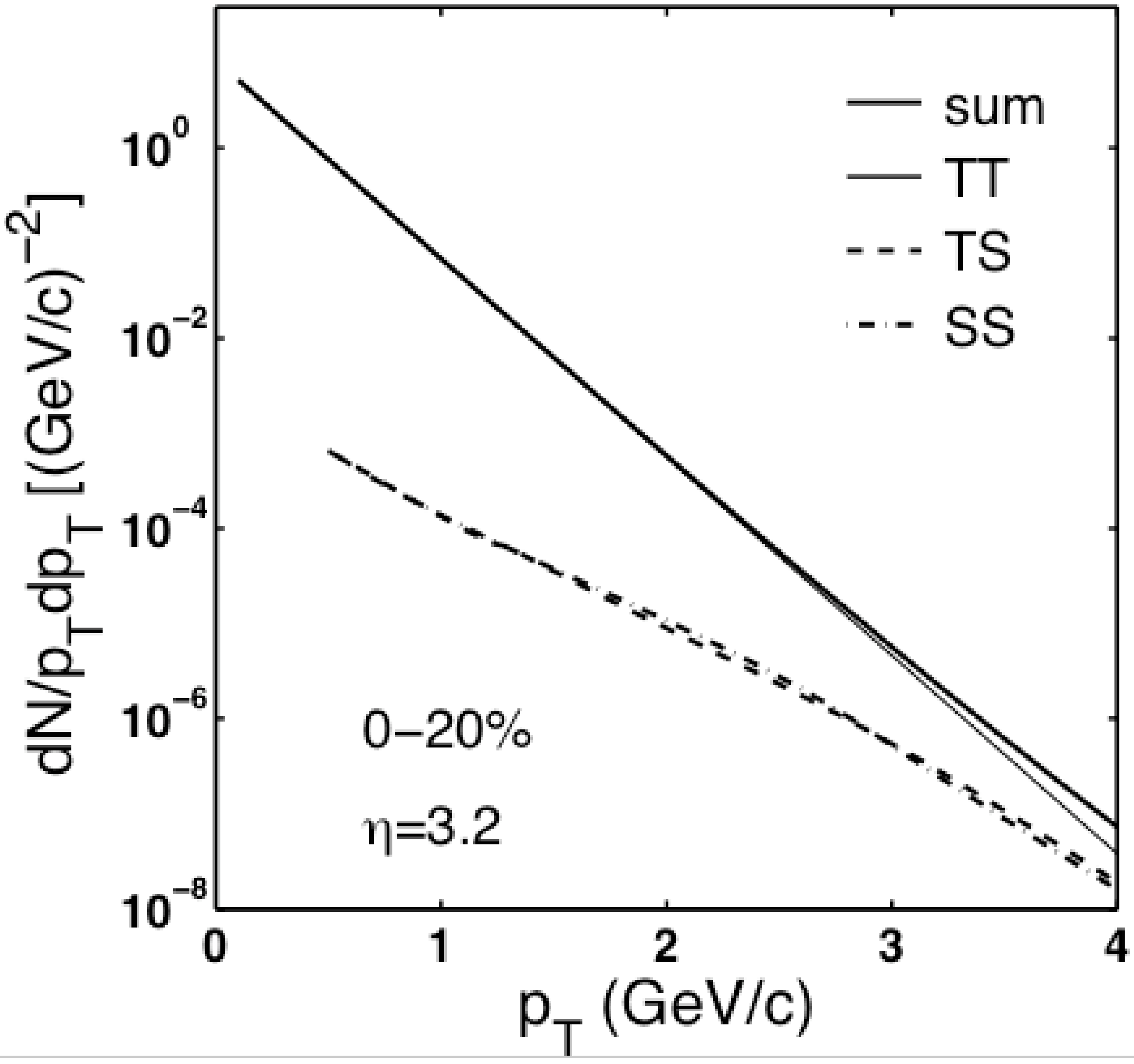
ε is the only parameter

(we let ε=0 initially.)

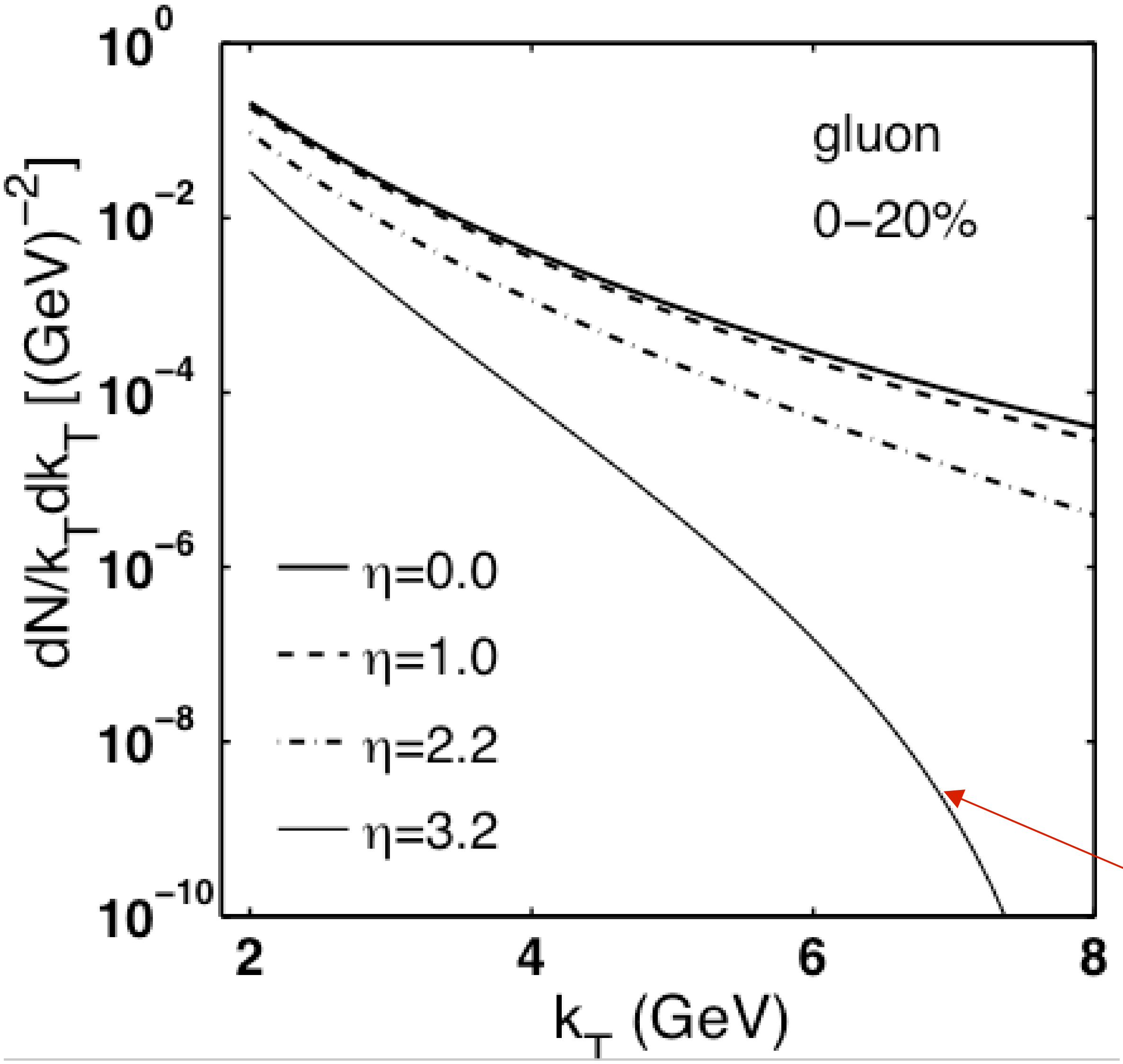

η=0
sum
TT
TS
SS
0–20%
30–50%
(/10^2)
60–80%
(/10^4)
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0
1
2
3
4
dN/p$_T$dp$_T$ [(GeV/c)$^{-2}$]
p$_T$ (GeV/c)



Hwa, Yang, and Fries (to appear)



sum
TT
TS
SS
0–20%
η=3.2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
1
2
3
4
dN/p_Tdp_T [(GeV/c)$^{-2}$]
p_T (GeV/c)



LO minijet calculation

CTEQ5 pdf

EKS98 shadowing

Strong damping due to kinematical limit

No multiple scattering in the initial state.

No effects of gluon saturation considered.

(not explicitly)

Since we have calculated the pion spectra at all β and η, we can determine R_{CP}.

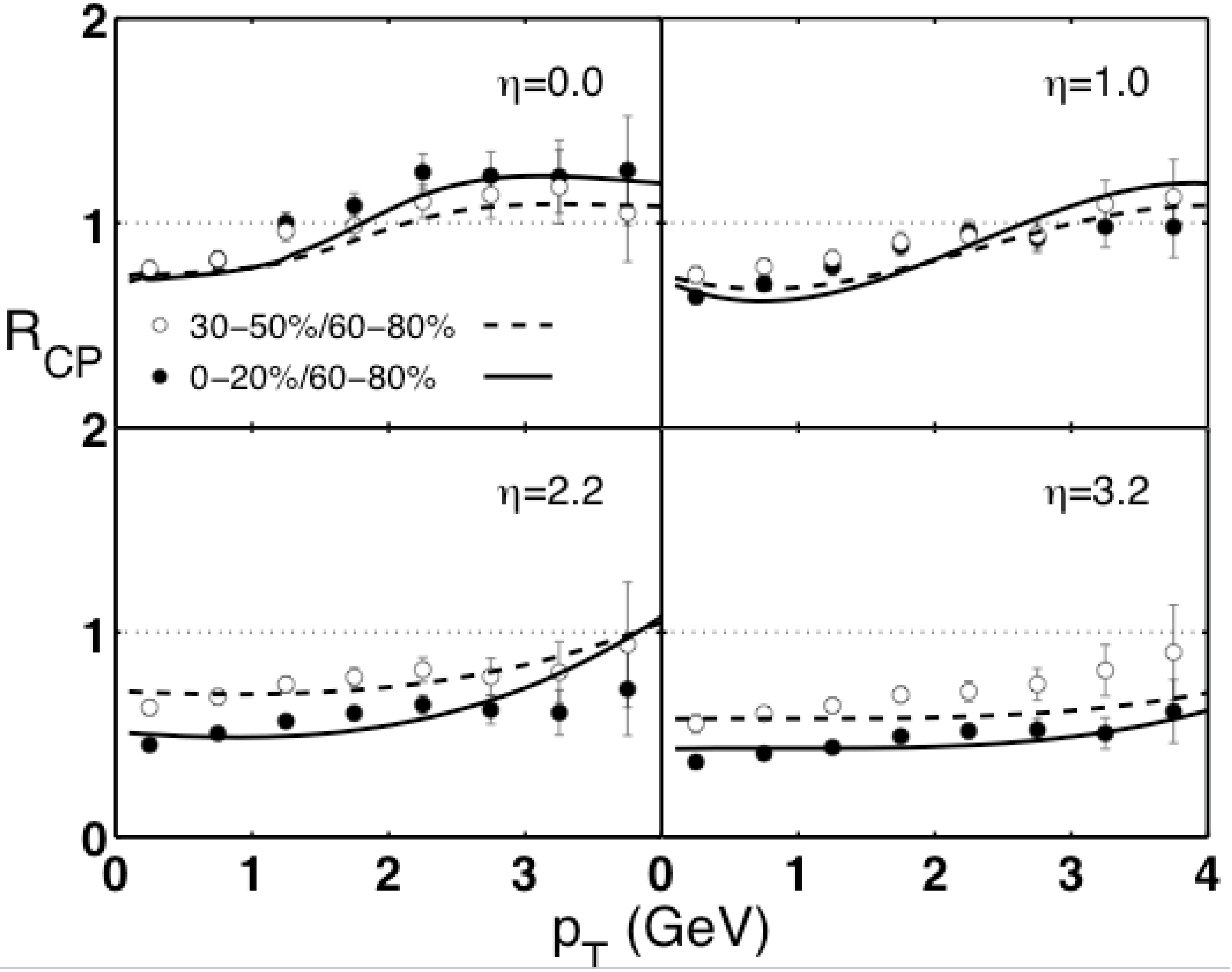
$$R^h_{CP}(p_T) = \frac{\dfrac{dN_h}{dp_T}\dfrac{1}{\langle N_{Coll}\rangle}(central)}{\dfrac{dN_h}{dp_T}\dfrac{1}{\langle N_{Coll}\rangle}(peripheral)}$$

The only adjustable parameter is ε.

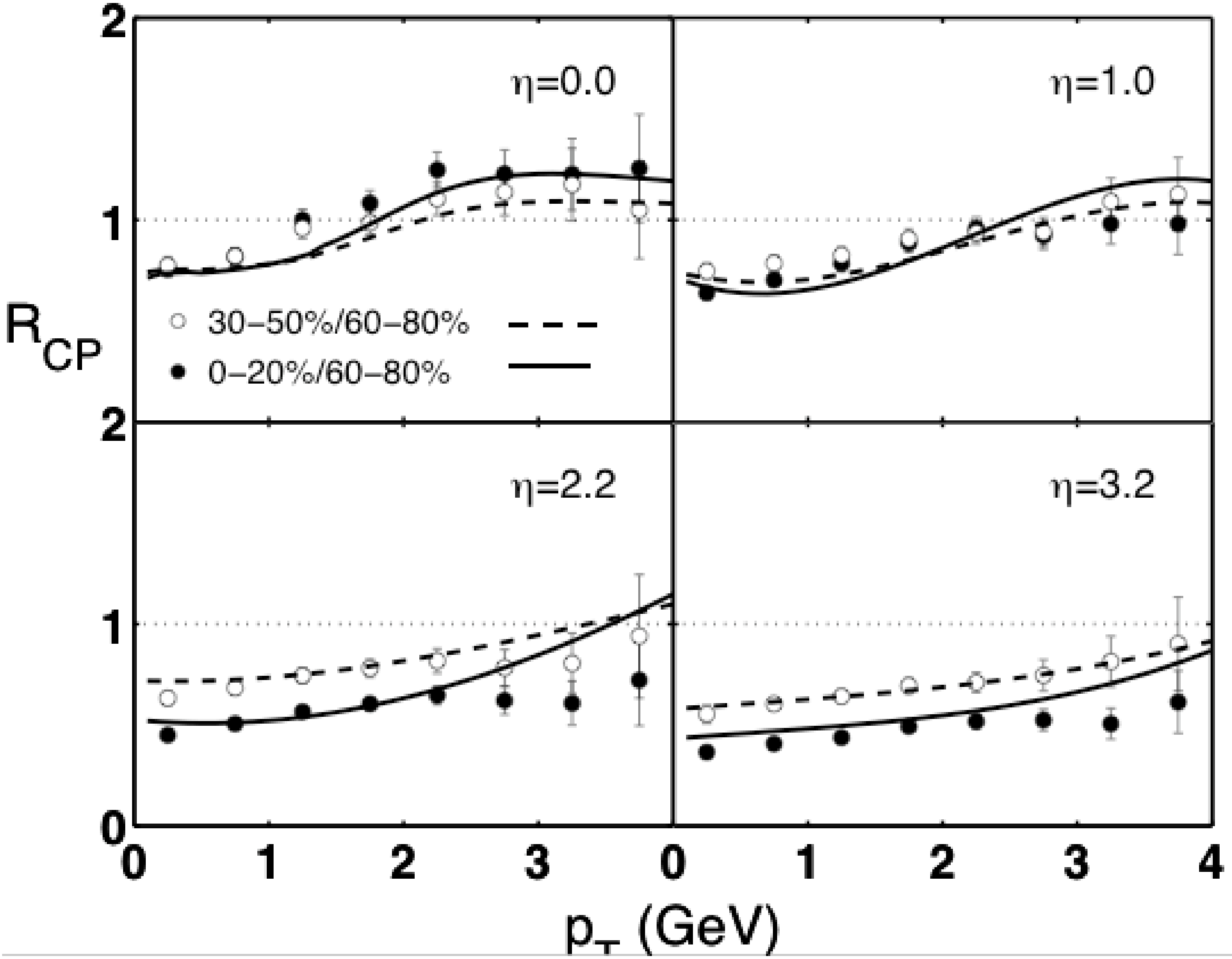
$$T(\beta,\eta) = T_0(1-\varepsilon\beta\eta)$$

- ε = 0
- ε adjusted to fit later

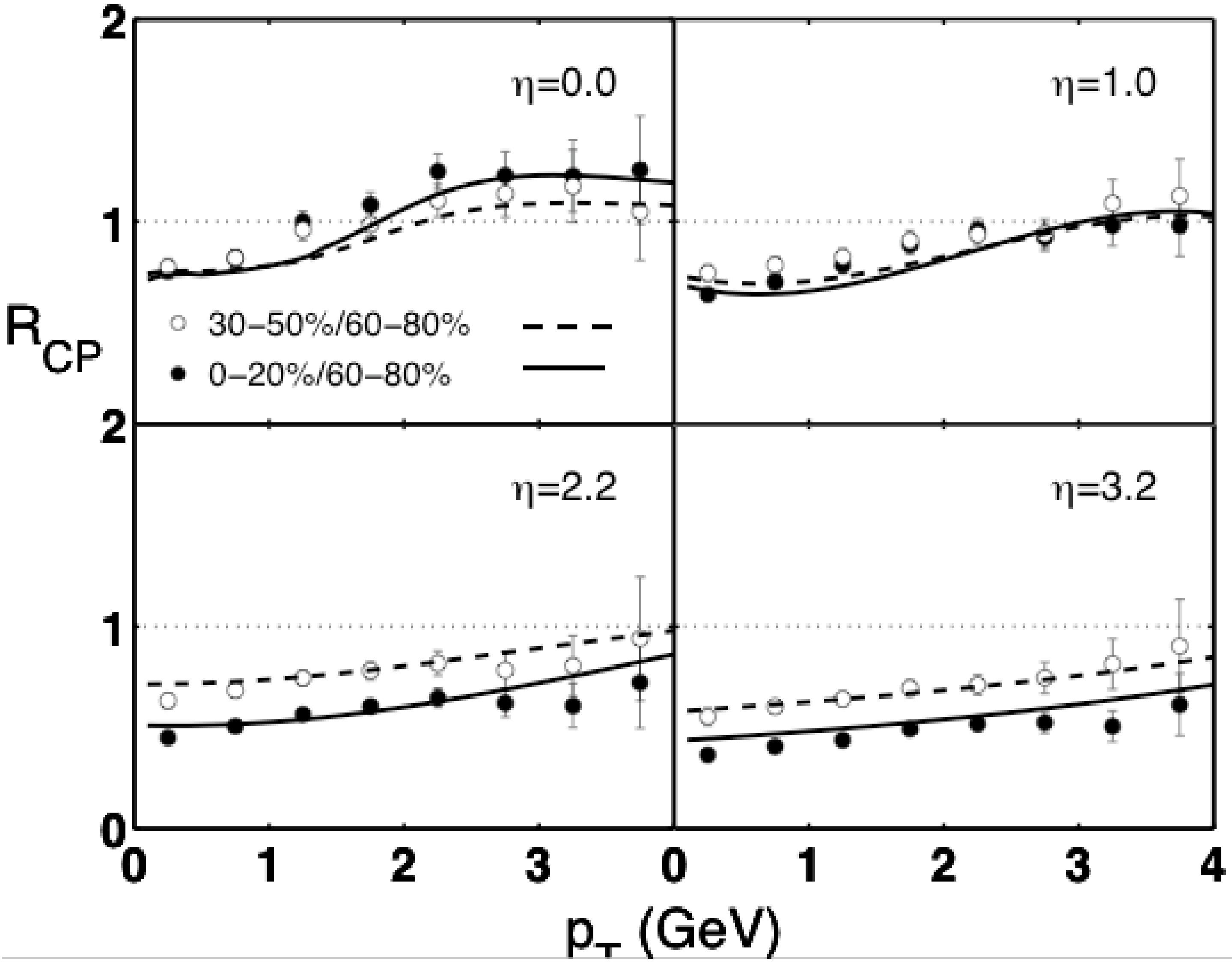
ε=0, T=constant, no free parameter



ε = 0.02 determined by fitting R_{CP} at β=0.4 and η=3.2



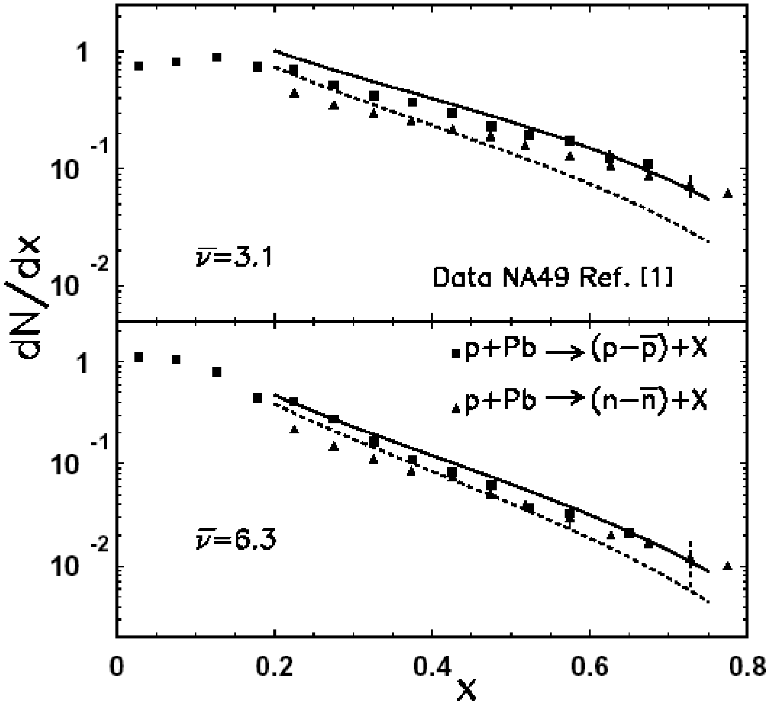
Momentum degradation effect considered



Hwa,
Yang,
Fries

Momentum degradation

“Baryon stopping” in p-A collisions



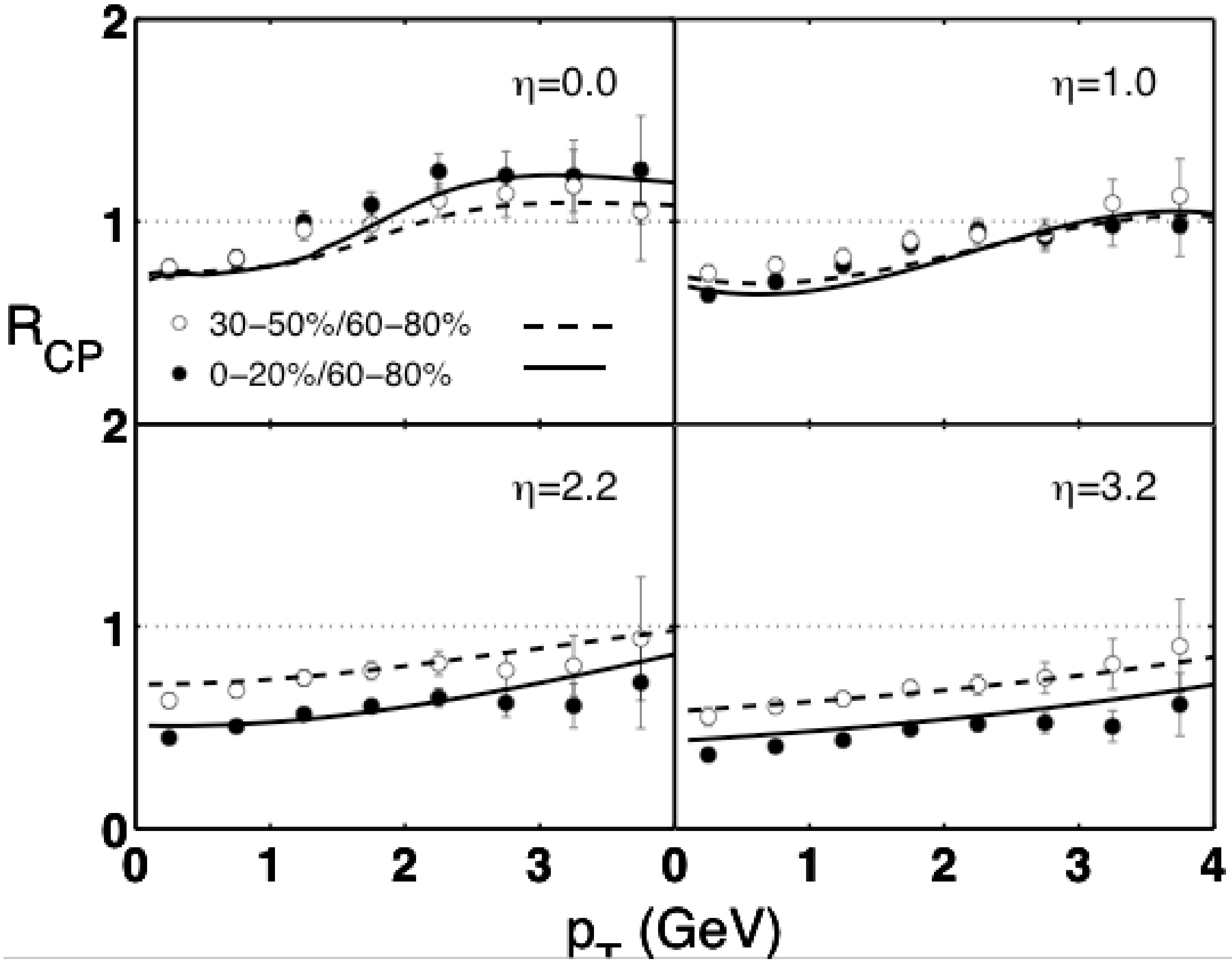
$$\frac{dN_N}{dx_F} \propto \exp[-\Lambda(\nu)x_F]$$

$\Lambda(\nu)$ increases with ν

Corresponds to a suppression factor

$$\zeta(\beta,\eta) = \exp[-\kappa(N_c - 1)\eta]$$

$$\kappa \approx 0.01$$



Hwa,
Yang,
Fries

Little room for any other physics to play a major role unless the neglect of soft partons can be justified.

Suppression of R_{CP} at high η is due mainly to the reduction of the soft parton density at large η.

The slight reduction of T and momentum degradation are minor effects.

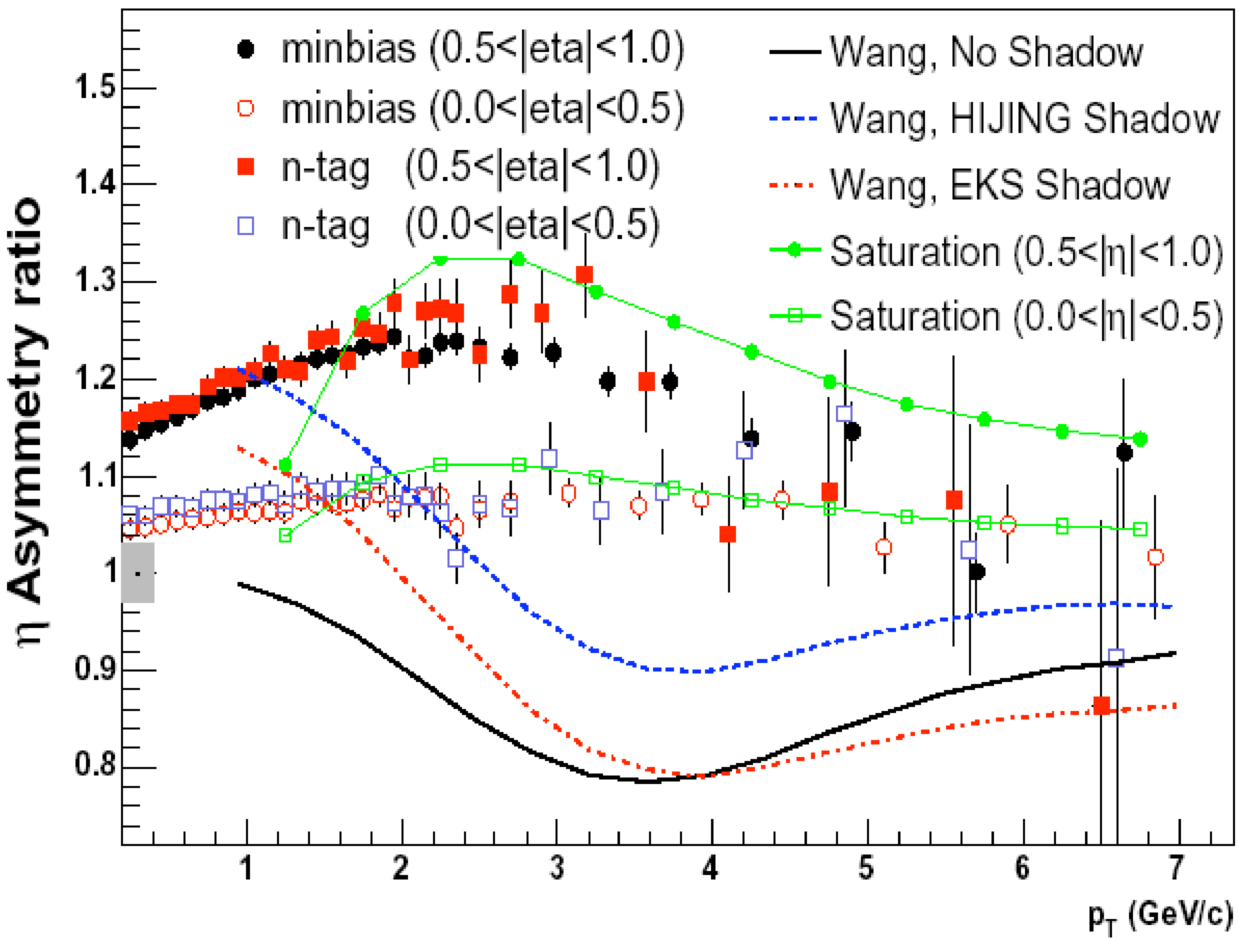
For $\eta=3.2$, and $p_T < 3$ GeV/c, pions are mostly produced by the recombination of soft partons.

We expect protons to have similar behavior.

Backward-forward asymmetry ratio

in d+Au collisions

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



STAR, nucl-ex/0408016

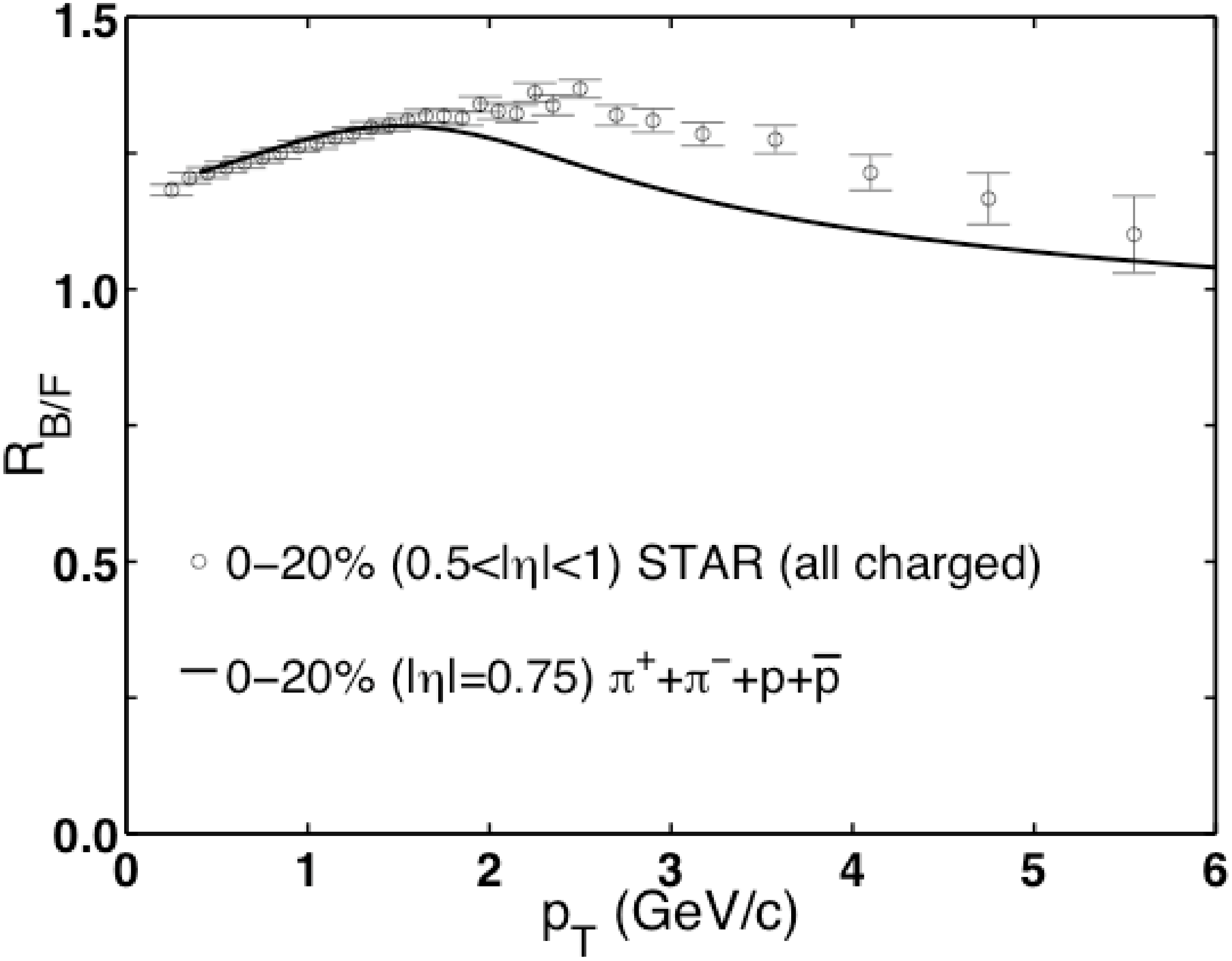
Backward-forward asymmetry

$$R_{B/F}(p_{T,}|\eta|) = \frac{dN_\pi / dp_T d\eta(\eta = -|\eta|)}{dN_\pi / dp_T d\eta(\eta = +|\eta|)}$$

We can do the calculation without any new parameters, using what we have already

C(β,η) and T(β,η)

for β=0-20% and η=±0.75


1.5
1.0
0.5
0.0
$R_{B/F}$
0
1
2
3
4
5
6
p_T (GeV/c)
○ 0−20% (0.5<|η|<1) STAR (all charged)
— 0−20% (|η|=0.75) $\pi^+ + \pi^- + p + \bar{p}$

Conclusion

R_{CP} well reproduced with only the recombination of soft and shower partons.

No change of physics from $\eta<0$ to $\eta>0$.

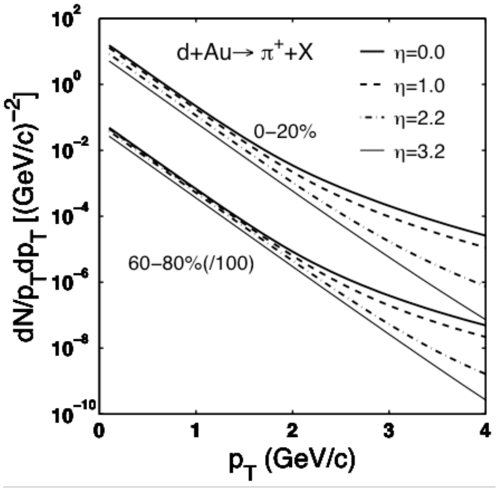
No multiple scattering or gluon saturation put in explicitly.

No conflict between CGC and recombination, only question is where?

Behaviors to check

p_T spectra (a) pions — β, η dependences

(b) protons — If $p/\pi > 0.2$, difficult for fragmentation



Di-hadron correlations

Back-to-back jets

In collaboration with

Chunbin Yang

Hua-zhong Normal University

Wuhan, China

Rainer J. Fries

University of Minnesota