Jet quenching as a probe of gluon plasma formation

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- Result: agreement with *preliminary* central π^0 PHENIX data sensitive to jet quenching

- pQCD calculation

- nuclear background: multiscattering, shadowing

- nuclear effect in focus: jet quenching

- predicted gluon densities

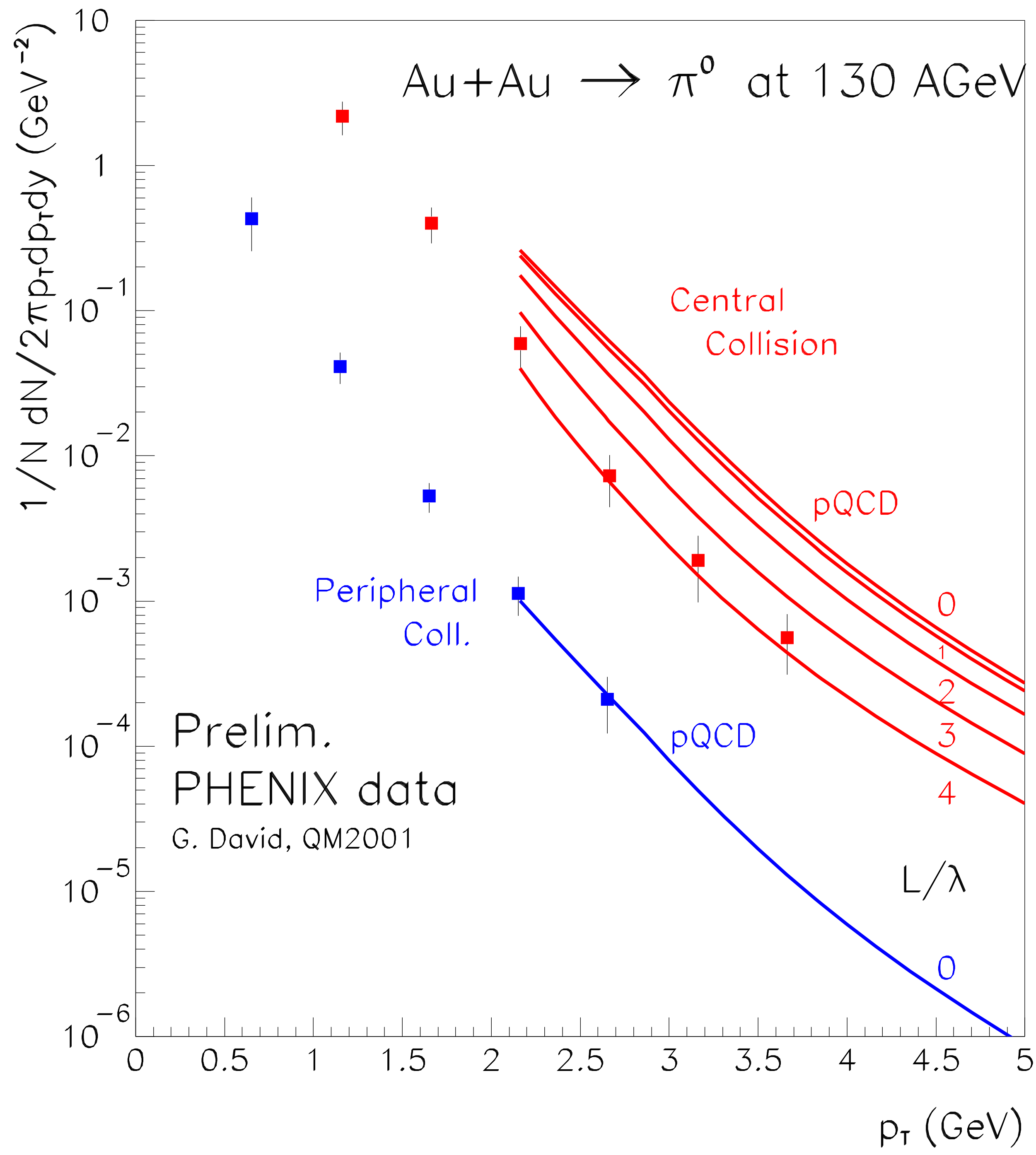


Figure 1: π^0 production in $Au + Au$ collisions, including multiscattering, shadowing, JET QUENCHING, compared to preliminary PHENIX data

Perturbative QCD: Factorization Theorem

$$E_\pi \frac{d\sigma_\pi^{pp}}{d^3p} = \sum_{abcd} \int dx_a dx_b d\vec{k}_{Ta} d\vec{k}_{Tb} dz_c$$

$$\times \quad f_{a/p}(x_a, \vec{k}_{Ta}, Q^2)\ f_{b/p}(x_b, \vec{k}_{Tb}, Q^2)$$

$$\times \frac{d\sigma(ab \to cd)}{d\hat{t}} \frac{D_{\pi/c}(z_c, \widehat{Q}^2)}{\pi z_c^2} \hat{s}\delta(\hat{s}+\hat{t}+\hat{u})$$

$f(x, \vec{k}_T, Q^2)$: 3d parton distribution function (PDF)

Q^2 : scale of the pQCD calculation

$D(z_c, \widehat{Q}^2)$: fragmentation function (FF)

$\widehat{Q}^2$: scale of the parton fragmentation

$\frac{d\sigma}{d\hat{t}}(ab \to cd)$: differential (partonic) cross section

Use leading order (LO) consistently

Scales fixed as $Q = \widehat{Q} = p_T/2$

Partonic cross section: K factor

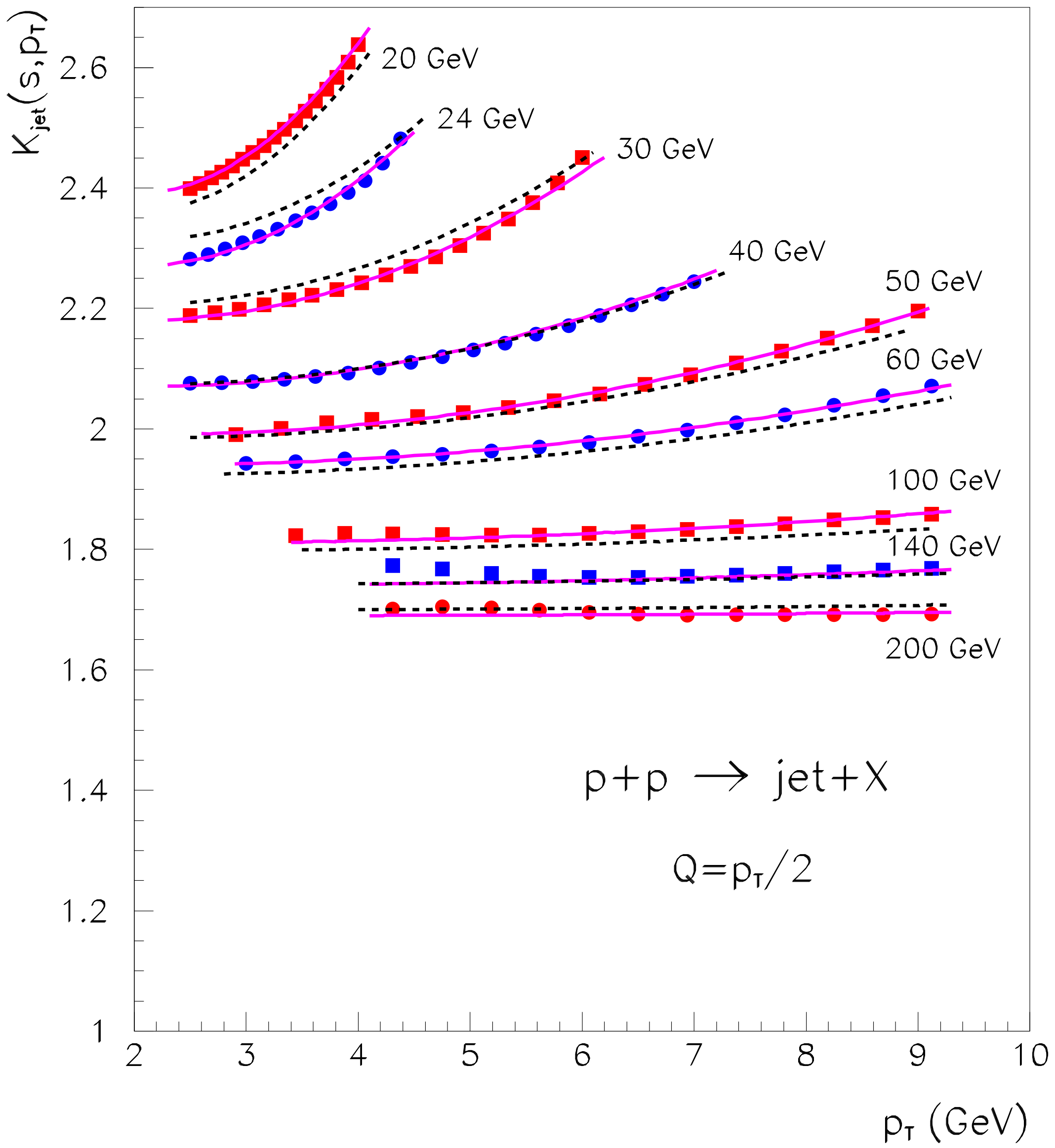


Figure 2: NLO/Born term, JP G, in press, nucl-th/0004066

Three-dimensional PDF: Transverse Momentum

- Observed width of transverse mom. distribution of partons in the proton ($E_{beam} = 400$ GeV)

$$\langle k_T^2 \rangle \approx 2 \text{ GeV}^2$$

M.D. Corcoran *et al.* PL B **259**, 209 (1991)

- Unintegrated PDFs

Kimber, Martin, Ryskin, hep-ph/0101348

- Gaussian for intrinsic k_T

$$f_{a/p}(x, \vec{k}_T, Q^2) = g(\vec{k}_T)\, f_{a/p}(x, Q^2)$$

$$g(\vec{k}_T) = \frac{\exp(-k_T^2/\langle k_T^2 \rangle)}{\pi \langle k_T^2 \rangle}$$

$\langle k_T^2 \rangle$: 2D width

PDF : GRV Z.Phys C **53**, 127 (1992)

FF : KKP, NP B **597**, 337 (2001)

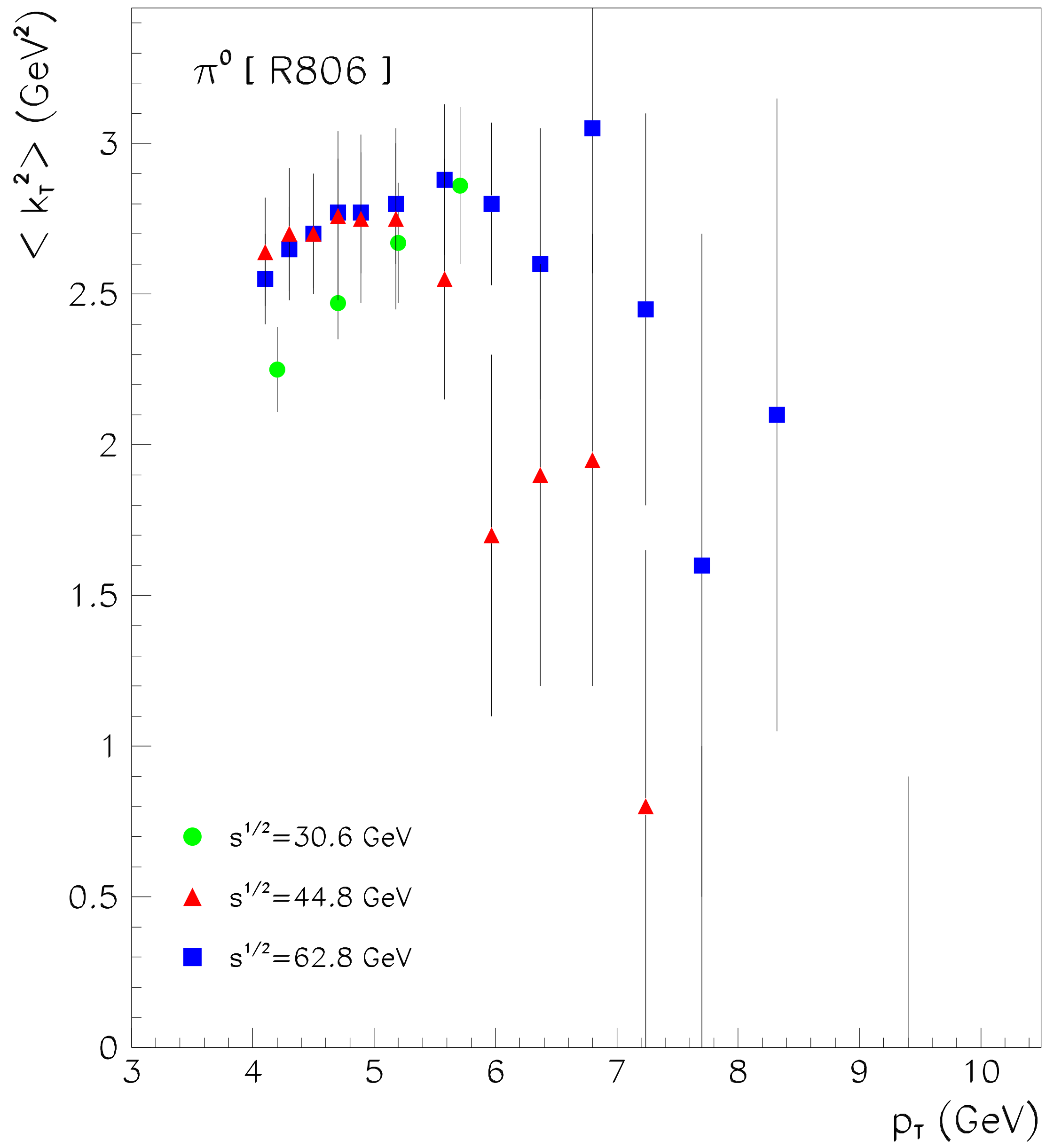


Figure 3: Transverse momentum width fitted to π^0 spectra point-by-point

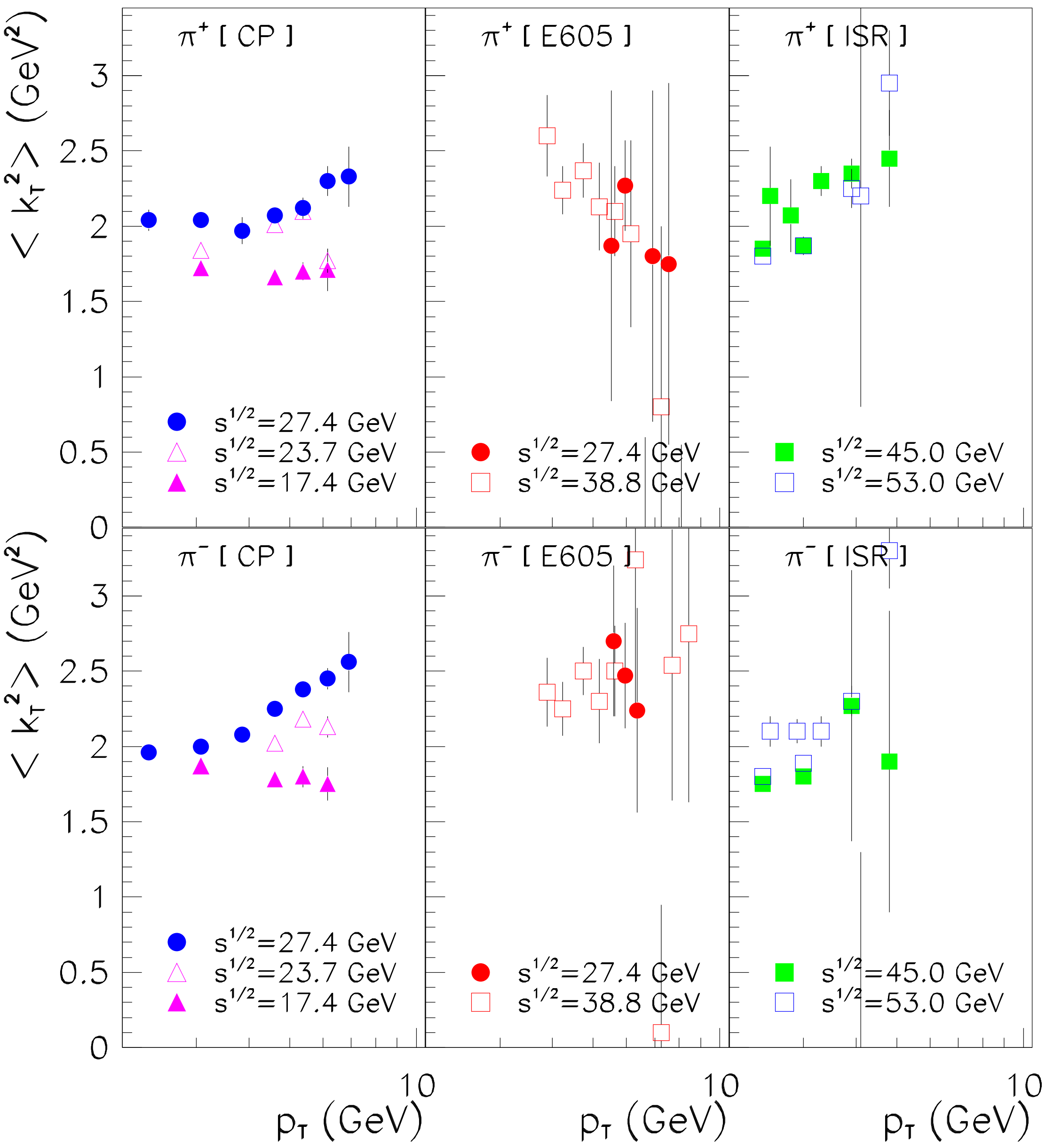


Figure 4: Transverse momentum width fitted to $\pi^{\pm}$ spectra point-by-point

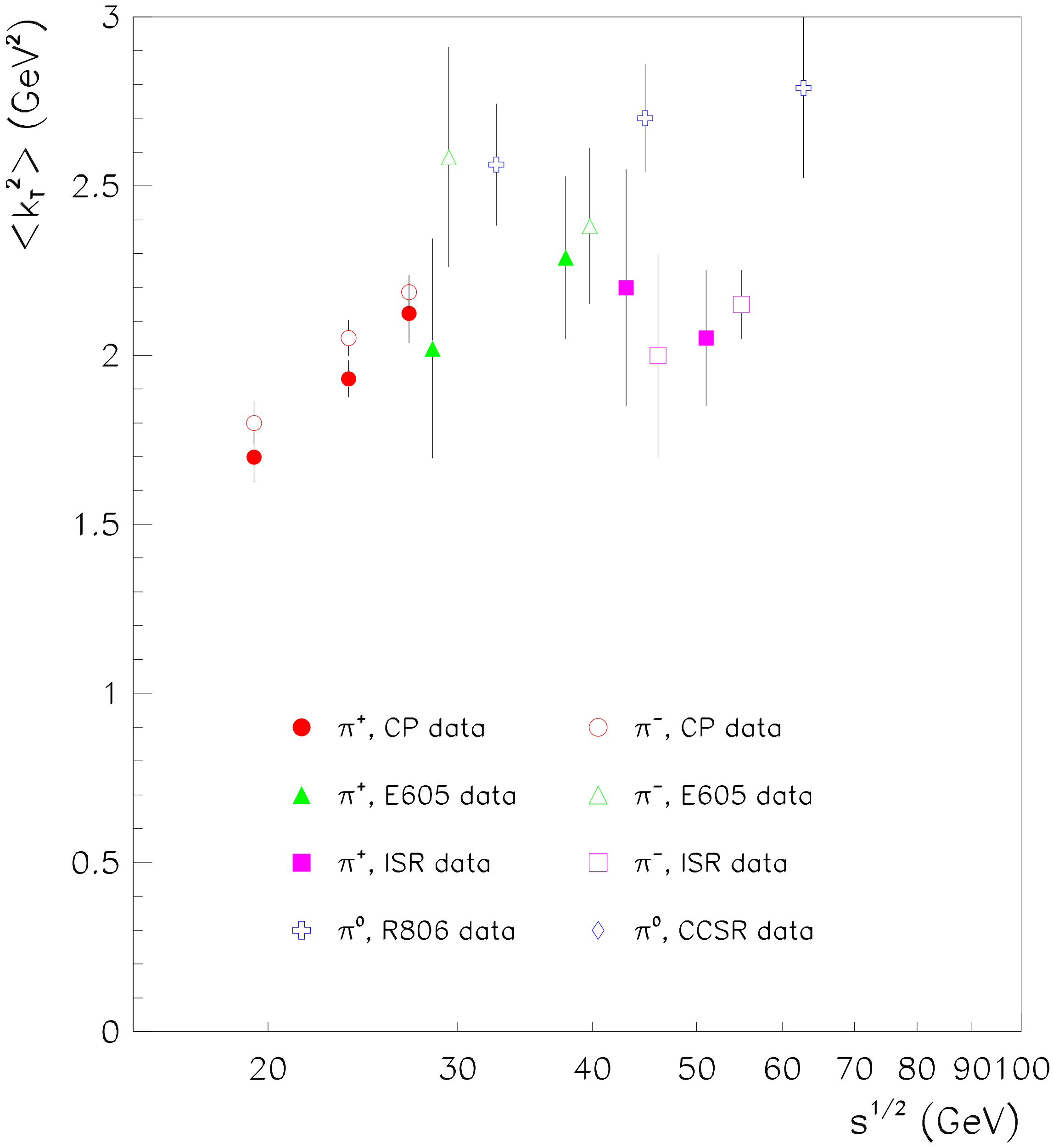


Figure 5: Extracted transverse momentum width as function of energy

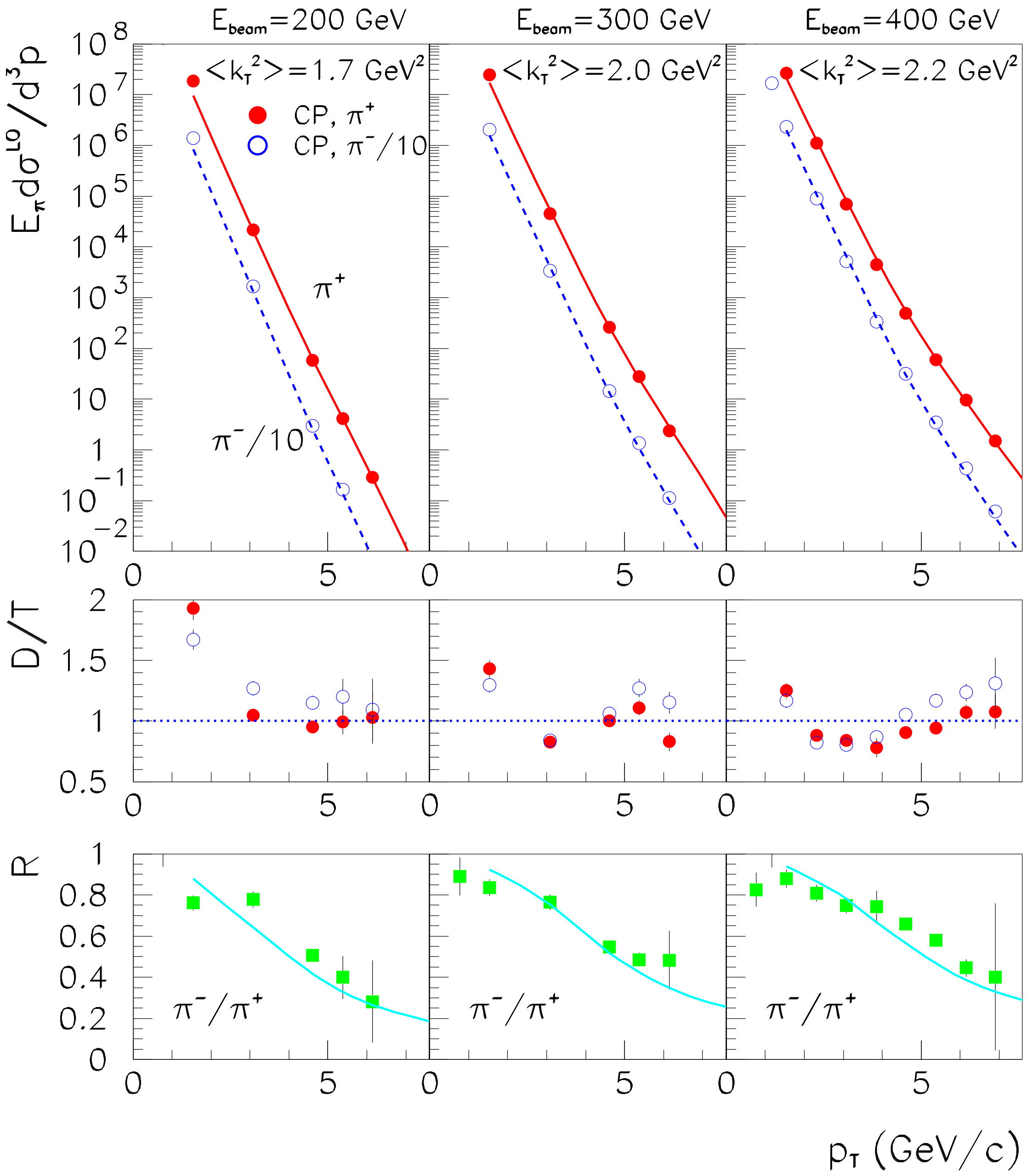


Figure 6: $\pi^{\pm}$ spectra, data/theory ratios, π^-/π^+ ratios

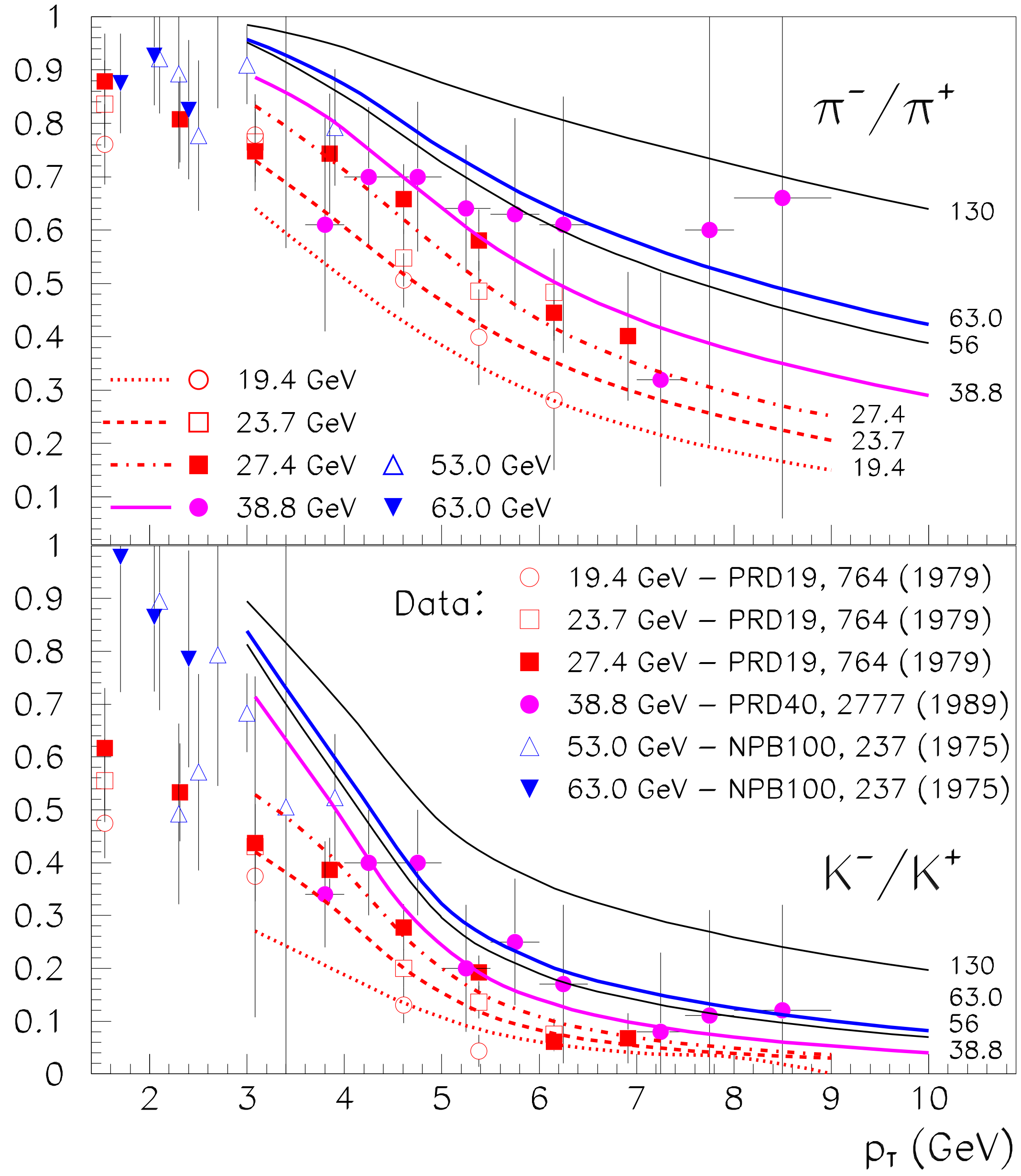


Figure 7: π^-/π^+ and K^-/K^+ ratios in pp collisions

Nuclear effects I: Multiscattering

- Studied in proton-nucleus (pA) collisions
- Cronin effect: enhanced production in pA relative to pp collisions (in a p_T window)

$$\sigma^{pA}/\sigma^{pp} \sim A^{\alpha},\ \alpha > 1$$

D. Antreasyan *et al.* PR D **19**, 764 (1979)
C.N. Brown *et al.* PR C **54**, 3195 (1996)

- Glauber model:

$$E_\pi \frac{d\sigma_\pi^{pA}}{d^3p} = \int d^2b\ t_A(b) E_\pi \frac{d\sigma_\pi^{pp}(\langle k_T^2\rangle_{pA}, \langle k_T^2\rangle_{pp})}{d^3p}$$

where

$$\langle k_T^2\rangle_{pA} = \langle k_T^2\rangle_{pp} + C\ h_{pA}(b)$$

$h(b)$: number of effective NN collisions

C : average increase in width/ NN collision

$t_A(b)$: nuclear thickness function

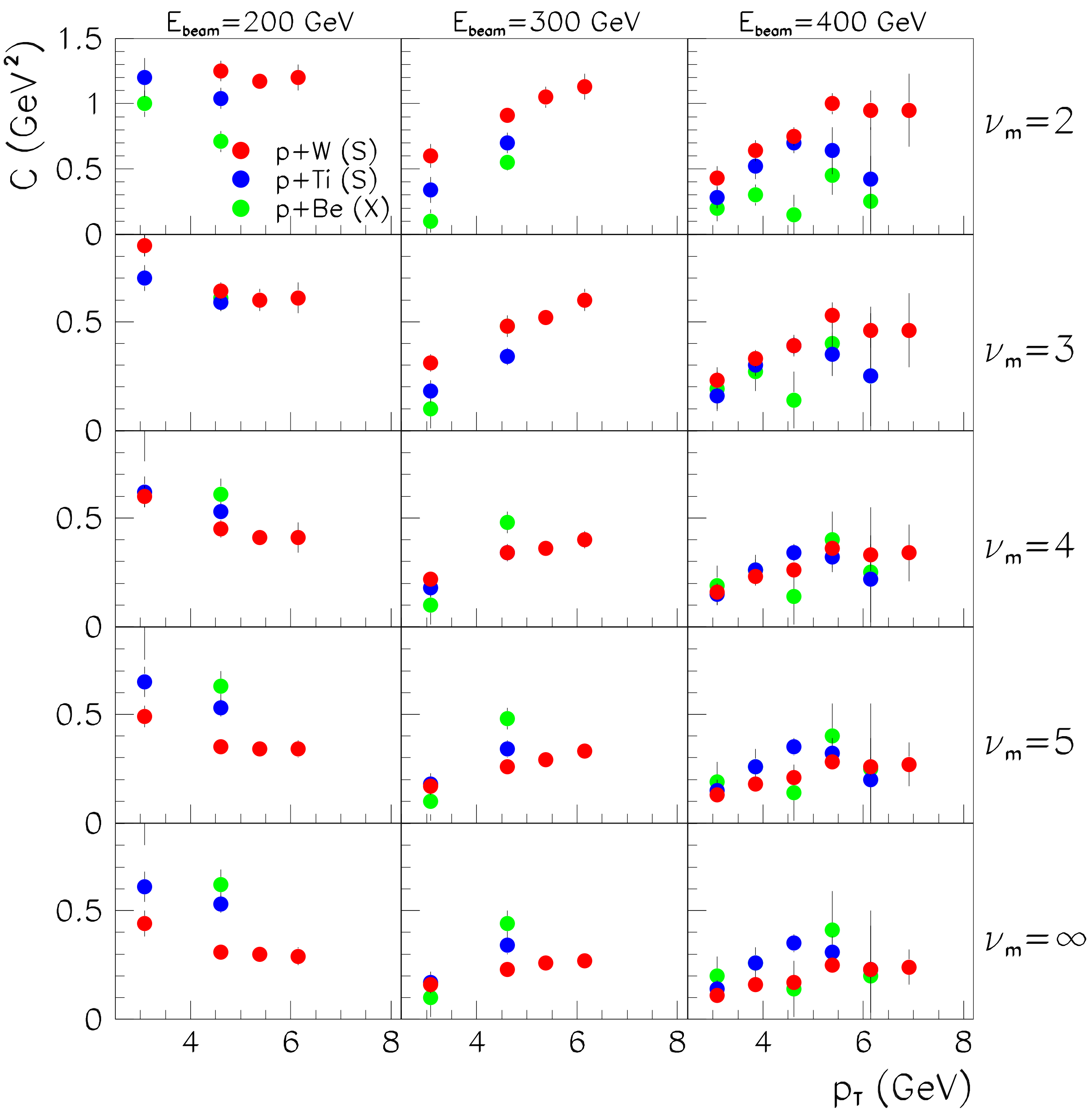


Figure 8: Best fit values of C for Be, Ti, W

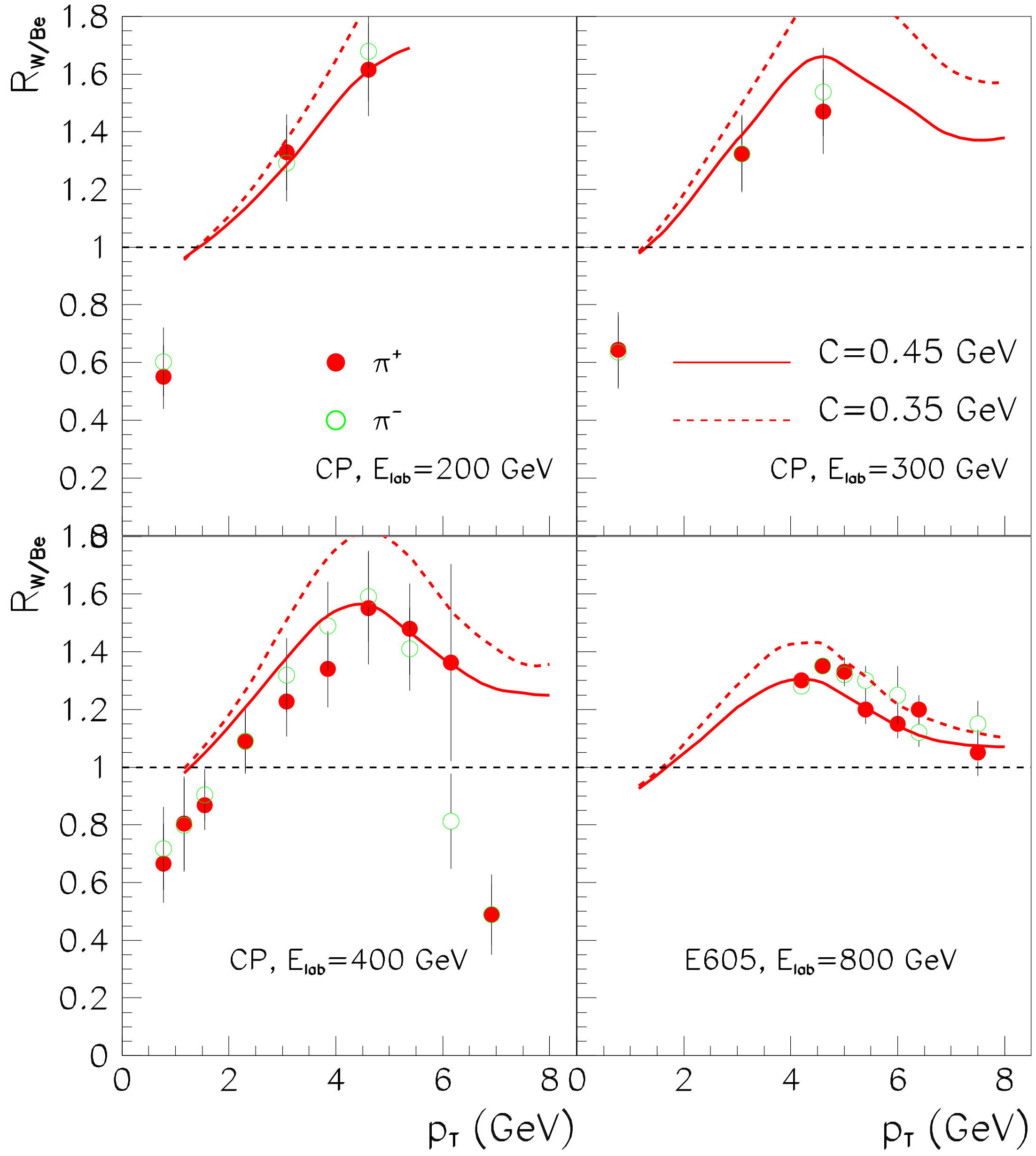


Figure 9: Normalized W/Be cross section ratios

Nuclear effects I: Shadowing

PDFs modified in nuclear environment

$$f_{a/p} \longrightarrow S_{a/A}(x,b)\left[\frac{Z}{A} f_{a/p} + \left(1-\frac{Z}{A}\right) f_{a/n}\right]$$

$S_{a/A}(x,b)$: shadowing factor

Several parameterizations:

- HIJING

  Wang and Gyulassy, PR D **44**, 3501 (1991)

- EKS

  Eskola *et al.*, EPJ C **9**, 61 (1998)

Nuclear effects II: Jet quenching

Jets suffer energy loss $\Delta E(E, L)$ in dense matter

- energy loss in free space ("self quenching")
- different quenching for quark and gluon jets

$$\Delta E \propto C_R = \begin{cases} 4/3 & \text{quarks} \\ 3 & \text{gluons} \end{cases}$$

- assume static QGP
  note, however, dynamical evolution of QGP in nucleus-nucleus (AB) collisions: 1d, 3d, ...

  Gyulassy, Vitev, Wang, PRL **86**, 2537 (2001)

- expansion in opacity $\bar{n} = L/\lambda$
  L : length jet travels in medium
  λ : mean free path

  Gyulassy, Levai, Vitev NP B **594**, 371 (2001)

Nuclear effects II: Jet quenching

- Use average energy loss in AB collisions dominated by single-gluon radiation

$$E_\pi \frac{d\sigma_\pi^{AB}}{d^3p} = \int d^2b\, d^2r\, t_A(b) t_B(|\vec{b}-\vec{r}|)$$
$$\times \sum_{abcd} \int dx_a dx_b d\vec{k}_{Ta} d\vec{k}_{Tb} dz_c$$
$$\times f_{a/A}(x_a, \vec{k}_{Ta}, Q^2)\; f_{b/B}(x_b, \vec{k}_{Tb}, Q^2)$$
$$\times \frac{d\sigma}{d\hat{t}} \frac{z_c^*}{z_c} \frac{D_{\pi/c}(z_c^*, \widehat{Q}^2)}{\pi z_c^2} \hat{s}\delta(\hat{s}+\hat{t}+\hat{u})$$

where $\quad p_c^* = p_c - \Delta E \longrightarrow z_c^* = z_c / (1 - \Delta E/p_c)$

- Note: fluctuations reduce suppression $\longrightarrow$ rescale opacity

Nuclear effects II: Jet quenching

Two limits:

- "thick plasma" $\bar{n} \gg 1$ BDMS

  R. Baier *et al.* NP B **531**, 403 (1998)

$$\frac{\Delta E}{L} = \frac{C_R \alpha_s}{4} \frac{L}{\lambda_g} \mu^2 \ln \frac{E}{\mu} \frac{2}{\mu L}$$

  μ : screening scale

- "thin plasma" $\bar{n} \approx 1$ GLV

  Gyulassy, Levai, Vitev, PRL **85**, 5535 (2000)

$$\frac{\Delta E}{L} = \frac{C_R \alpha_s}{N(E)} \frac{L}{\lambda_g} \mu^2 \ln \frac{E}{\mu}$$

  $N(E)$: energy-dependent numerical factor

$$\Delta E / E \approx const.$$

Numerical calculations with

$$\alpha_s = 0.3 \quad \mu = 0.5\,\mathrm{GeV} \quad \lambda_g = 1\,\mathrm{fm}$$

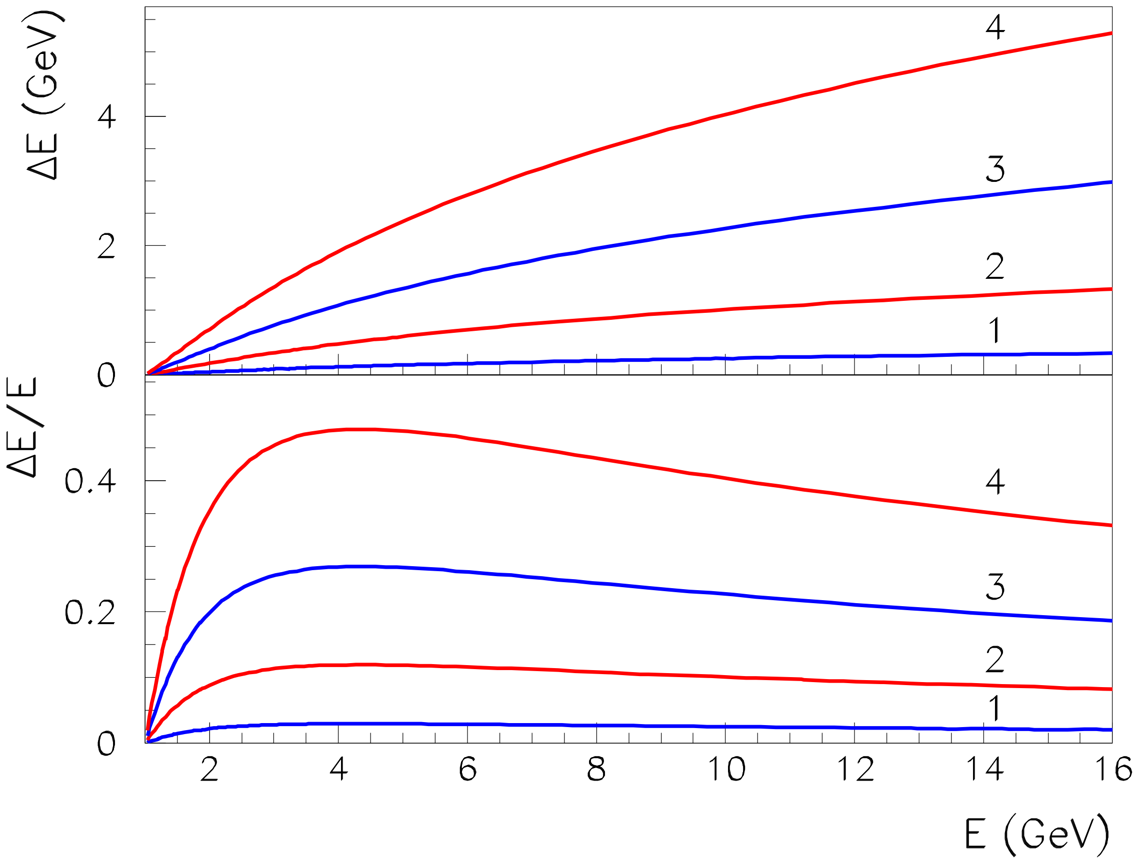


Figure 10: GLV absolute and relative energy loss of a gluon jet at different opacities $\bar{n} = L/\lambda_g$ =1,2,3,4

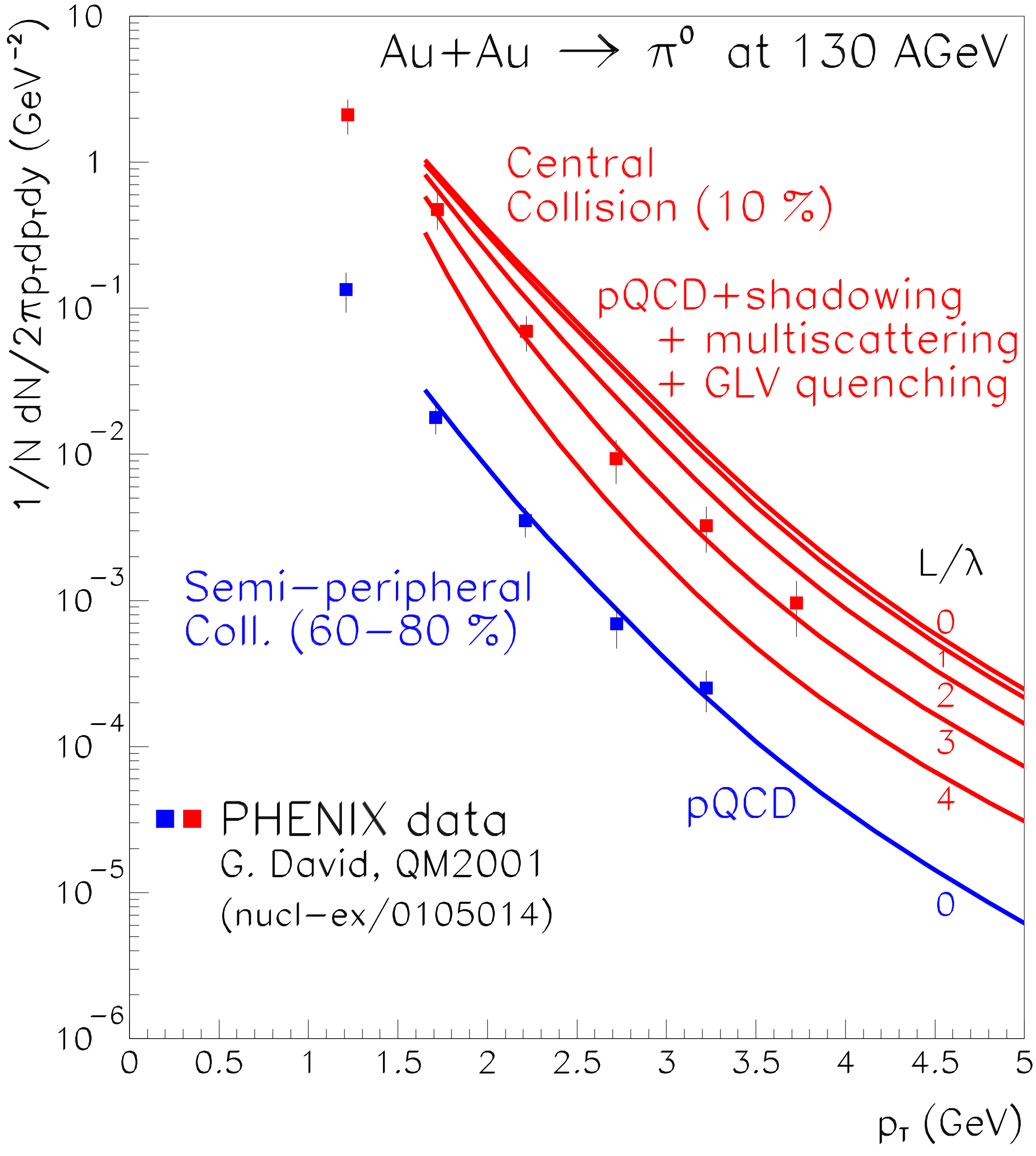


Figure 11: π^0 production in $Au + Au$ collisions

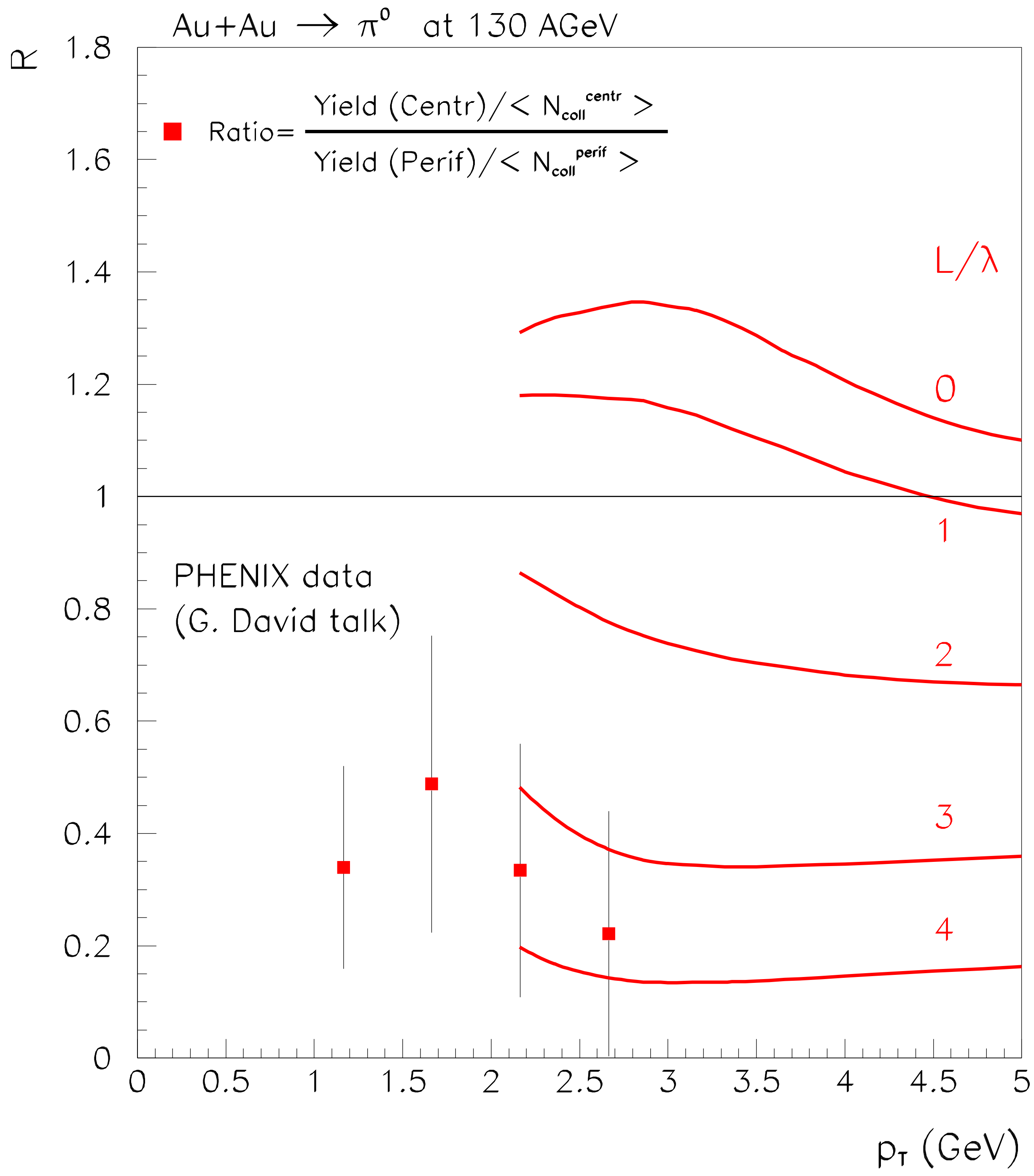


Figure 12: Central/peripheral pion yield ratios normalized by the number of binary collisions, N_{coll} =857 and 5.5, respectively

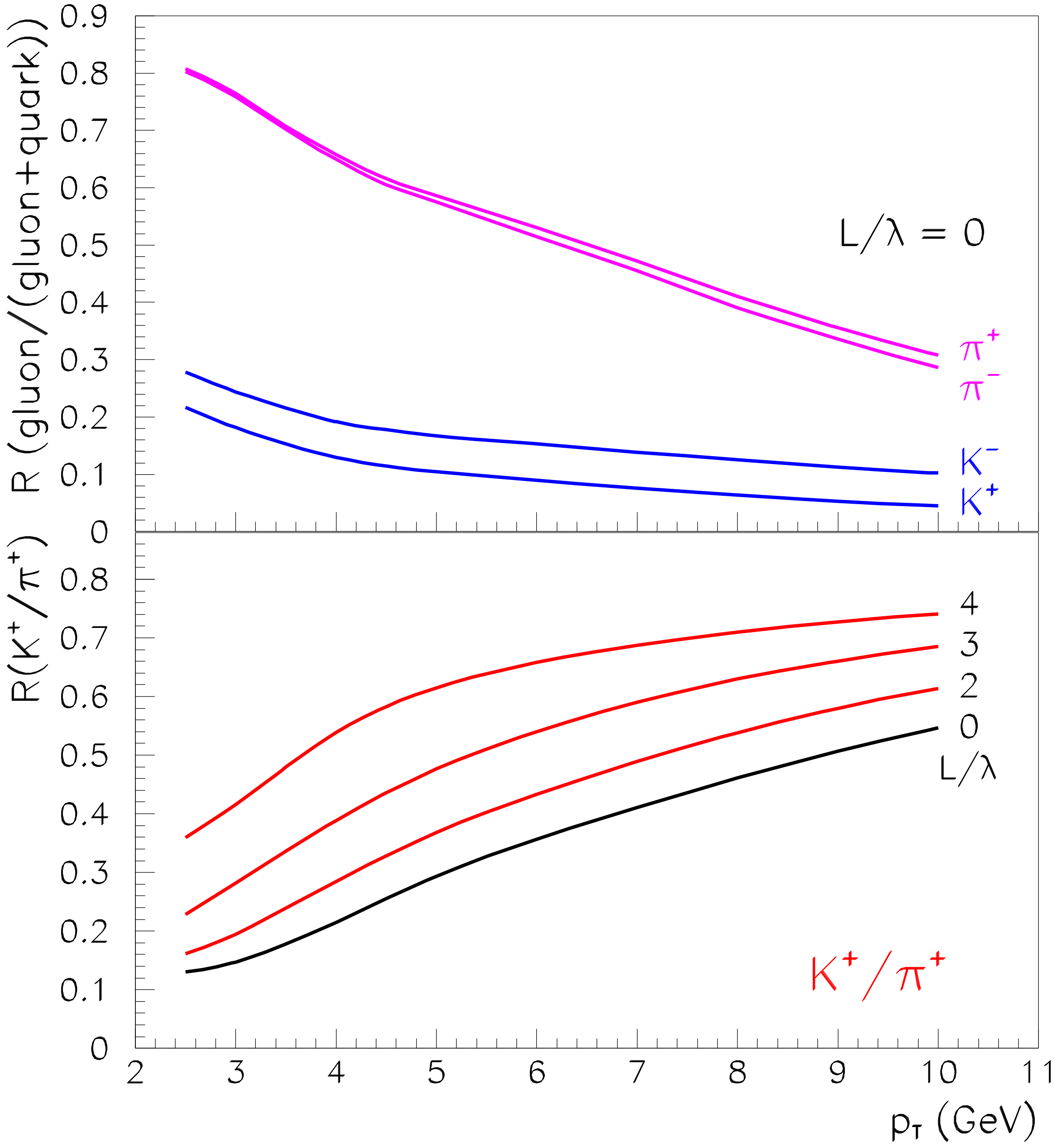


Figure 13:

Upper panel: Pion and kaon (relative) production yields from quark and gluon jets at $\sqrt{s}$ =130 AGeV.

Lower panel: Effect of jet quenching on K/π ratios in $Au + Au$ collisions at $\sqrt{s}$ =130 AGeV.

Jet quenching at RHIC

Remarks:

- constant $dE/dx = 0.25$ GeV/fm also fits preliminary PHENIX data similarly

  X.-N. Wang, QM2001 Proceedings

- jet quenching effect on flow $\quad v_2(p_T)$

  X.-N. Wang, PR C **63**, 054902 (2001)
  I. Vitev, RHIC Workshop, LBNL, May 2001

- connection to gluon densities
  transport coefficient

$$\frac{\mu^2}{\lambda_g} \quad \propto \quad \frac{dN_g}{dy}$$

$$L/\lambda_g \approx 3-4 \quad \longleftrightarrow \quad \frac{dN_g}{dy} \approx 400-500$$

e

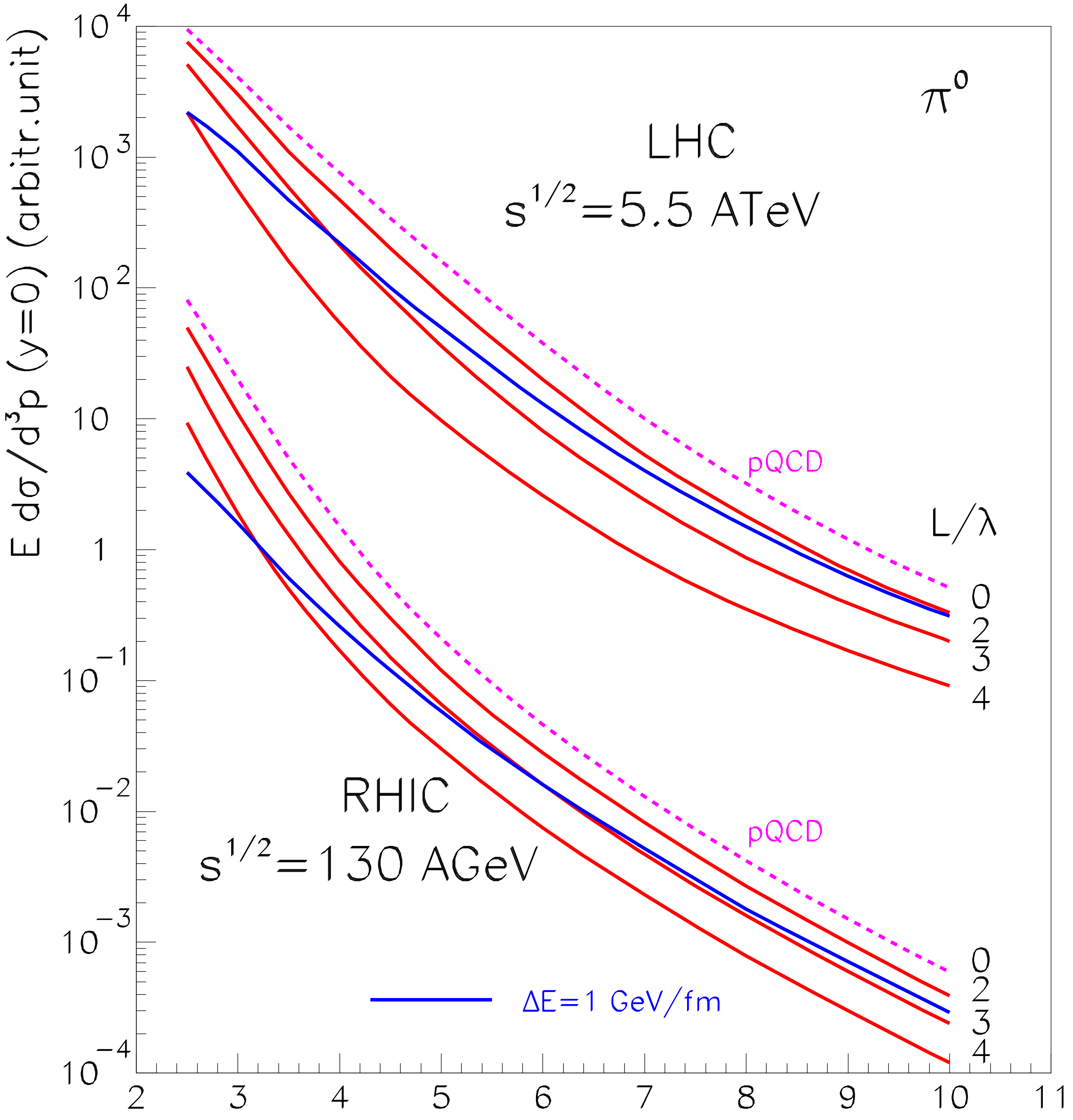


Figure 14: Effect of jet quenching on π^0 yields at RHIC and LHC

Conclusions

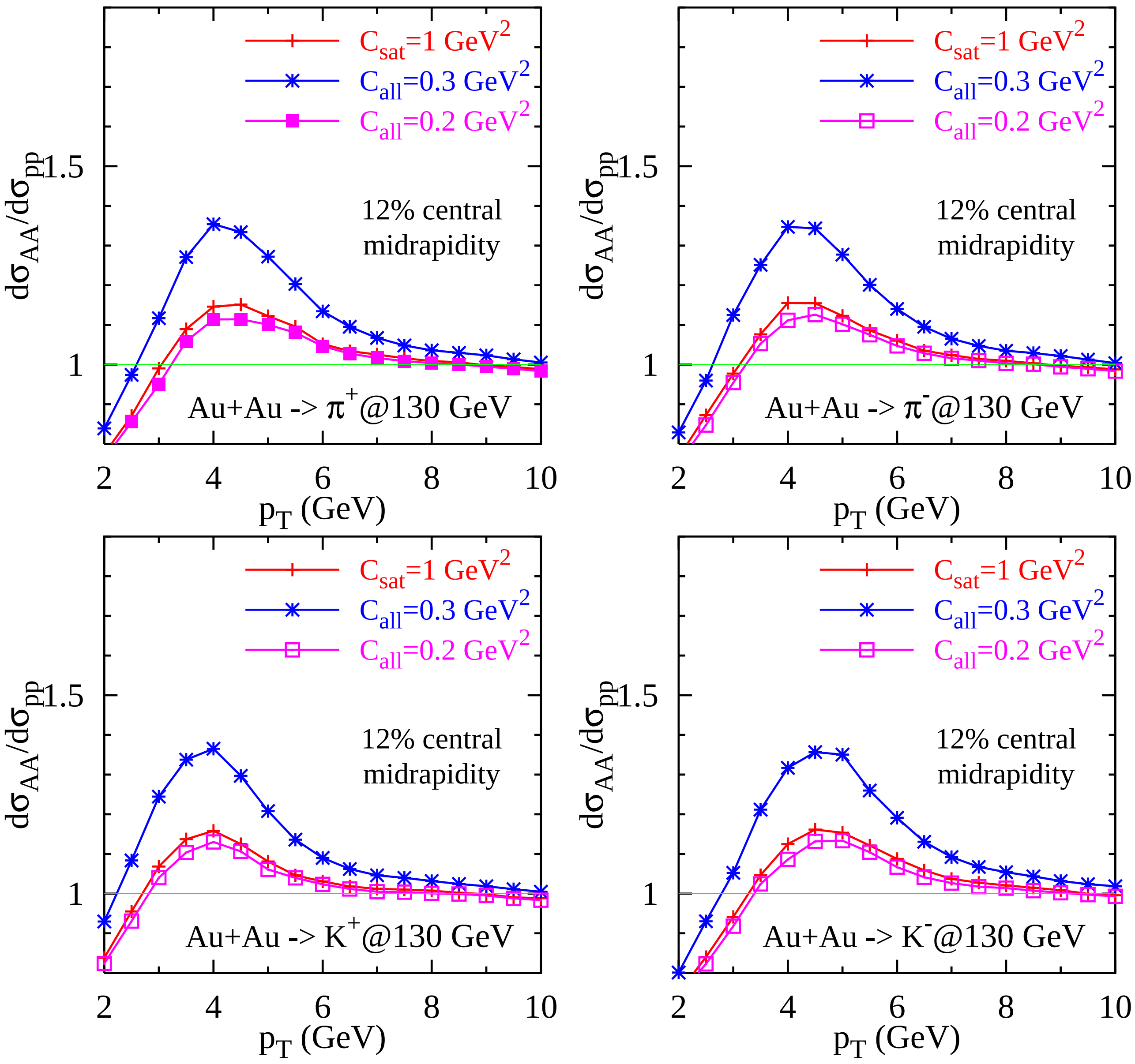
- perturbative QCD calculation augmented by intrinsic transverse momentum provides a reasonable description of available pp and pA data

- model can be used as a basis for studying jet quenching in AA collisions at RHIC

- agreement with preliminary PHENIX data with average static opacity of $\bar{n} \approx 3 - 4$, corresponding to $\frac{dN_g}{dy} \approx 400 - 500$ (dense gluon plasma)

- sensitivity of agreement with data makes jet quenching a promising probe of the density of colored scattering centers

- need for dynamical calculations



C_sat=1 GeV^2
C_all=0.3 GeV^2
C_all=0.2 GeV^2
dσ_AA/dσ_pp
12% central
midrapidity
Au+Au -> π^+@130 GeV
Au+Au -> π^-@130 GeV
Au+Au -> K^+@130 GeV
Au+Au -> K^-@130 GeV
p_T (GeV)