Multiple scattering and p_T-broadening at RHIC energies

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- pp collision: intristic transverse momentum distribution of the partons
- pA collision: extra enhancement of the intristic transverse momentum distribution
- Soft vs. semihard/hard prescattering
- AA collision
- RHIC
- Summary and outlook

Motivation & Program

Heavy Ion Physics: nuclear (collective) effects
search for phenomena beyond a proton-proton collision

This talk:

- Use pQCD ("clear model")
- concentrate on meson (M) production

① Fix perturbative QCD (pQCD) description of

$$p + p \longrightarrow M + X$$

② Search for nuclear effects in

$$p + A \longrightarrow M + X$$

- initial-state scattering,
  Phys. Rev. C61 (2000) R21902.
- final-state radiation
- (anti) shadowing, EMC
- jet-quenching, nucl-th/0012017
- ...

③ Try $A + A$ collisions (at RHIC)

Meson Production in pp collisions in pQCD

Factorization:

$$E_M \frac{d\sigma_M^{pp}}{d^3p} = \sum_{abcd} \int dx_1 dx_2\, f_{a/p}(x_1, Q^2)\, f_{b/p}(x_2, Q^2)$$

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

$f_{a/p}(x, Q^2)$: parton distribution function (PDF)

Q^2 : scale of the pQCD calculation

$D_{M/c}(z_c, \widehat{Q}^2)$: fragmentation function (FF)

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

$\frac{d\sigma}{dt}(ab \to cd)$: differential (partonic)

$\Lambda_{\overline{MS}}$: renormalization scale

Basic elements of a pQCD calculation

- Parton Disribution Functions

GRV LO Glück, Reya, Vogt
Z. Phys. **C53** (1992) 127.

$Q =$ $p_T/2$

$\Lambda =$ 200 MeV

- Fragmentation Functions

BKK LO Binnewies, Kniehl, Kramer
Phys. Rev. **D52**, 4947 (1995)

KKP LO Kniehl, Kramer and Pötter
Nucl. Phys. **B582**, 514 (2000)

$\widehat{Q} =$ $p_T/2z_c$

- Partonic Cross Sections

LO: R.D. Field, *Applications of pQCD*, Addison Wesley, (1989)

Improving pQCD

① Improved NLO calculations:

adjusted (optimized) scale parameters

P. Aurenche *et al.* Eur. Phys. J. **C13**, 347 (2000).

Result: NLO still underestimates data by a factor of 2.

② Additional (non-perturbative) property:

intrinsic k_T

$$dx\ f_{a/p}(x, Q^2) \longrightarrow dx\ d^2k_T\ g(\vec{k}_T)\ f_{a/p}(x, Q^2)$$

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

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

$\langle k_T^2 \rangle$: $= 4\langle k_T \rangle^2/\pi$

Motivation: Heisenberg principle, initial radiation

$p+p \rightarrow \pi^0 + X$ P. AURENCHE et al. HEP-PH/99102...

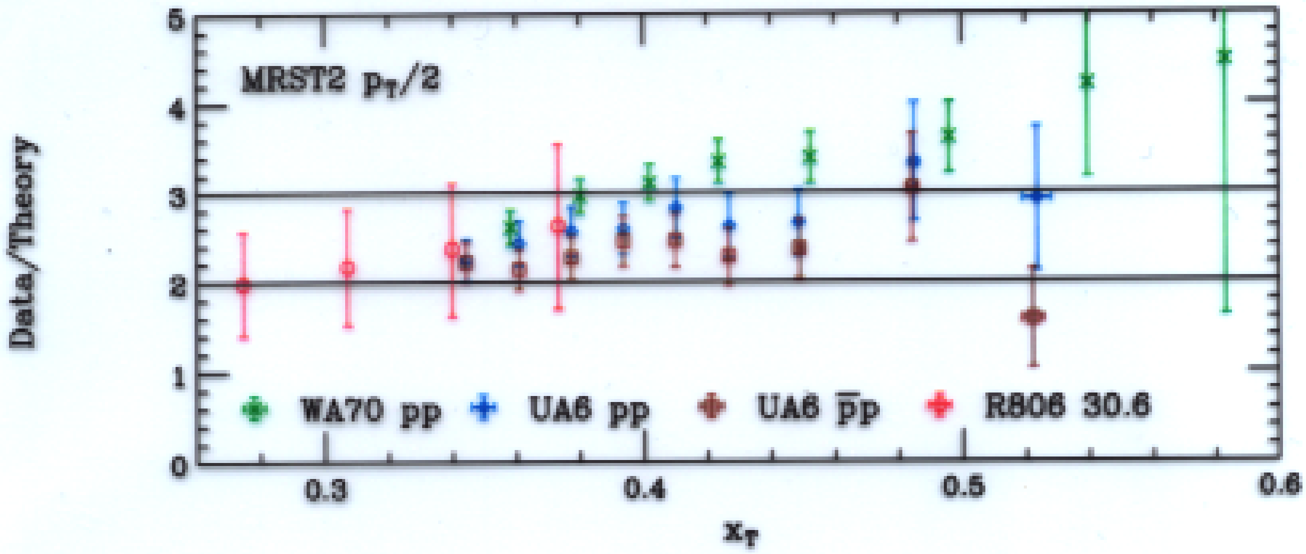


Figure 8: Comparison of WA70, UA6 and ISR π^0 data with NLO prediction based on the MRST2 parton densities. All scales are set equal to $p_T/2$.

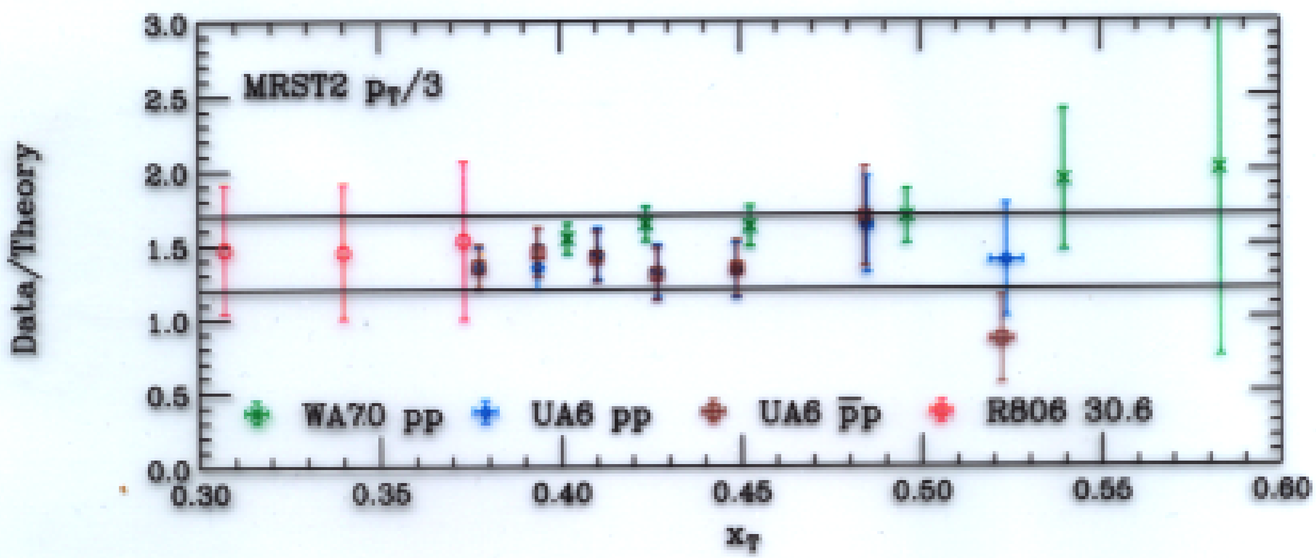


Figure 9: Same as Fig. 8, but for scale choice $p_T/3$.

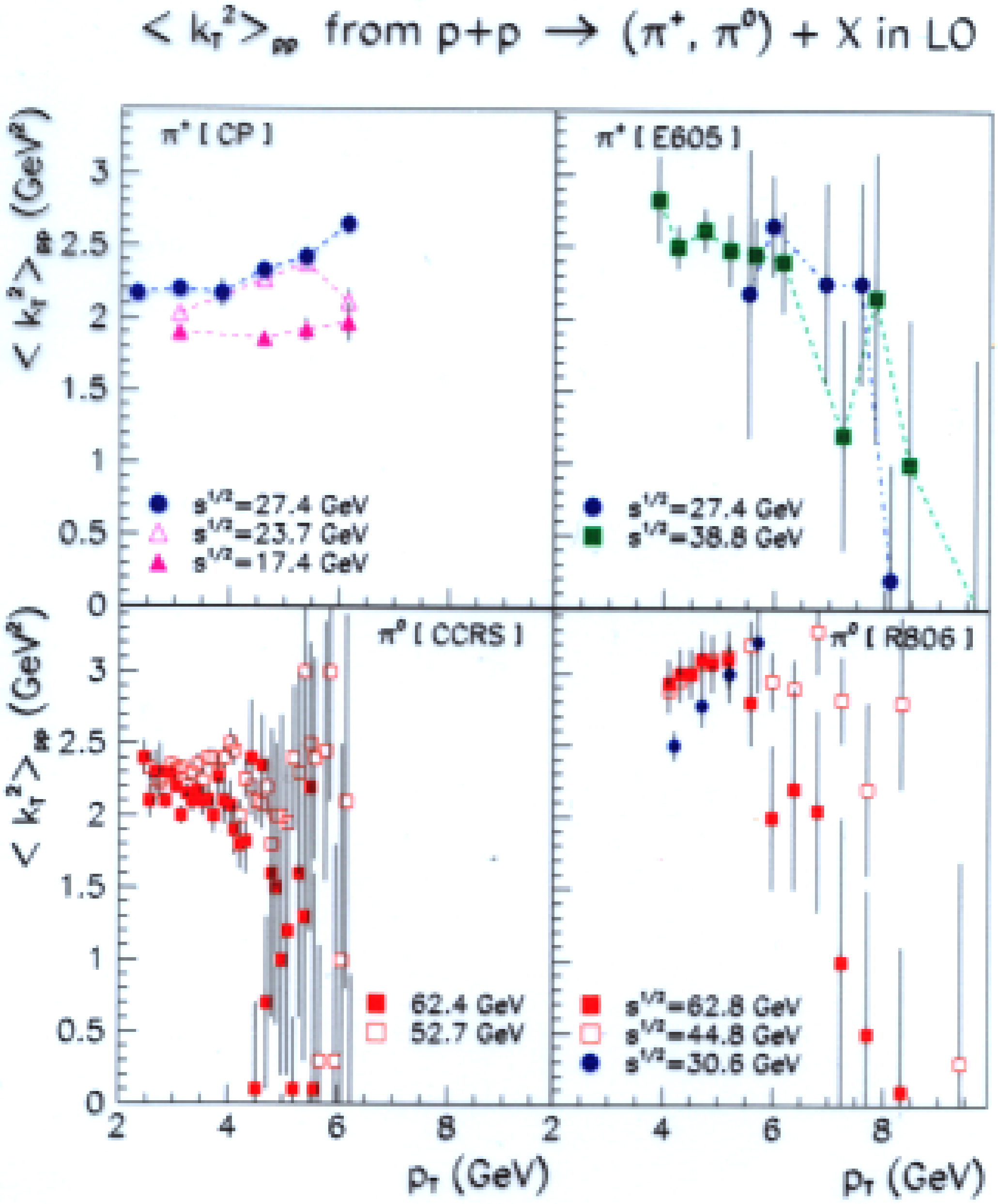
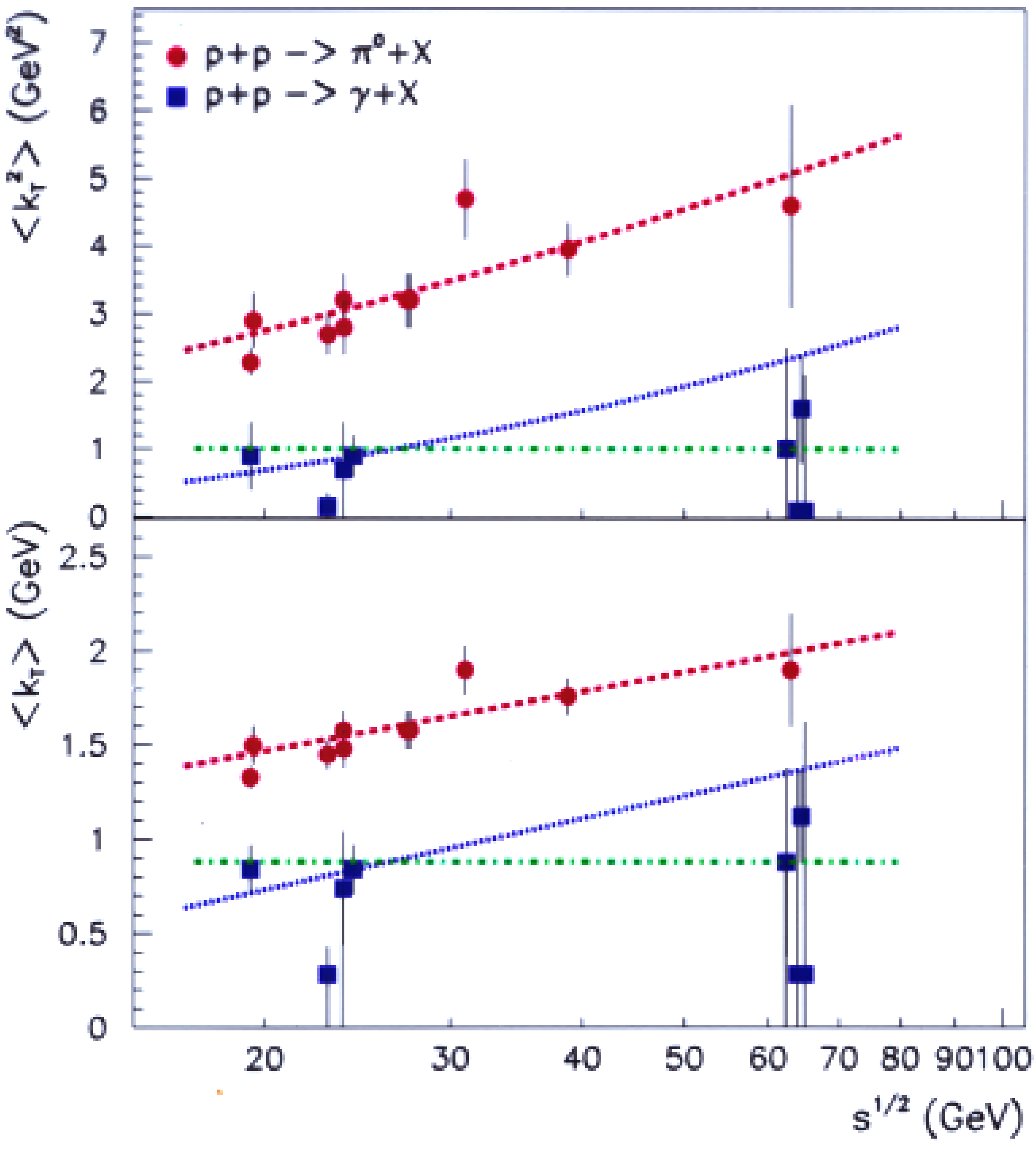
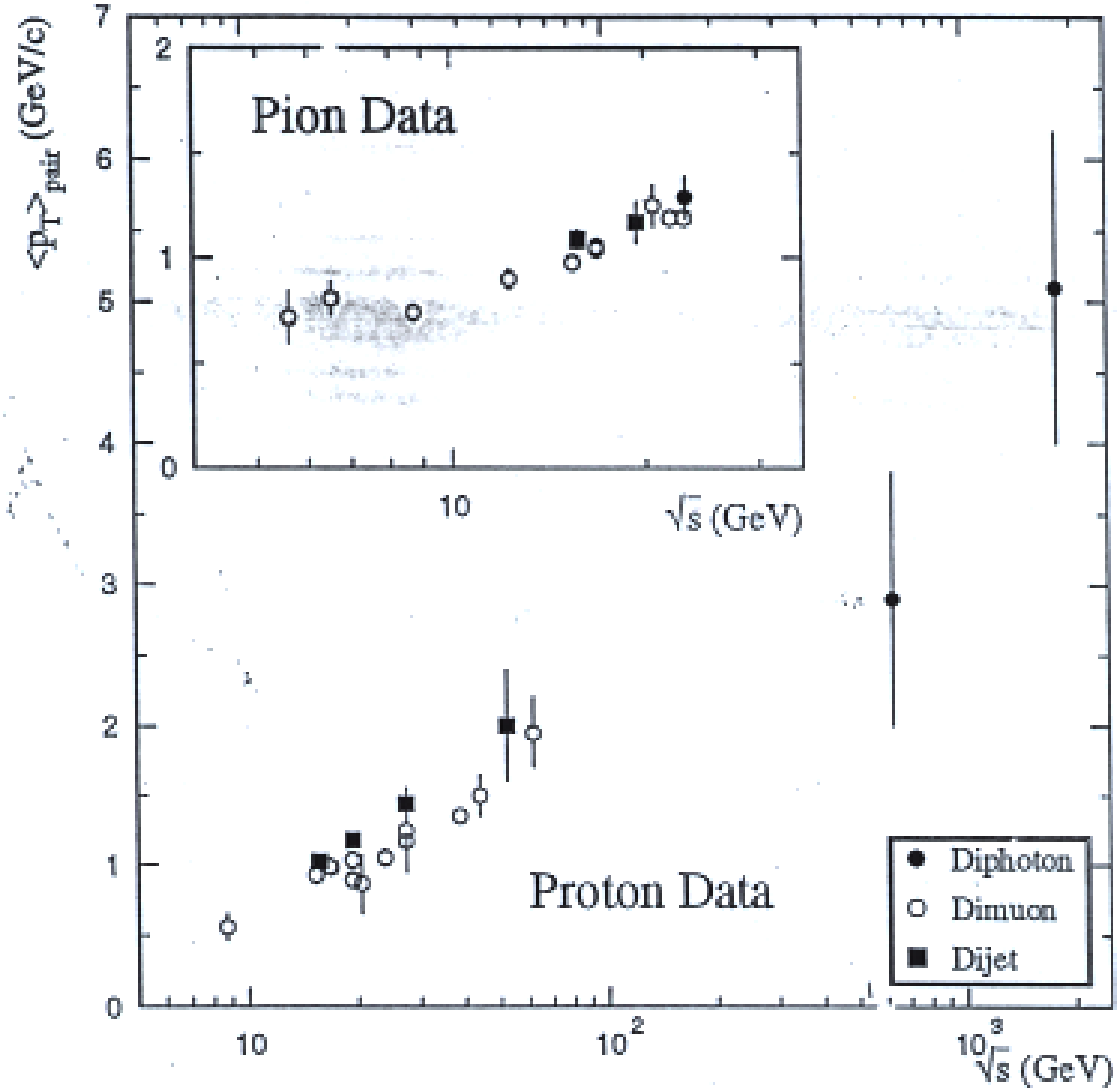


Figure 3: The best fit values of $\langle k_T^2 \rangle$ in $pp \to \pi + X$ reactions.



p+p -> π°+X
p+p -> γ+X
<k_T^2> (GeV^2)
<k_T> (GeV)
s^1/2 (GeV)

M. Zielinski,
hep-ph/9811278



1: $\langle p_T \rangle$ of pairs of muons, photons, and jets produced in hadronic collisi

proton nucleus collisions

first try:

The proton-nucleus collision is a superposition of pp collisions proposed by the Glauber model:

$$E_M \frac{d\sigma_M^{pA}}{d^3p} = \sum_{abcd} \int d^2b \, t_A(b)$$

$$\int d^2k_{T_1} d^2k_{T_2} \, g(\vec{k}_{T_1}) g(\vec{k}_{T_2}) \int dx_1 dx_2 \, f_{a/p}(x_1, Q^2)$$

$$\times f_{b/p}(x_2, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \, \frac{D_{M/c}(z_c, \widehat{Q}^2)}{\pi z_c}$$

$t_A(b)$: nuclear thickness function

$$t_A(\vec{b}) = \int dz \; \varrho(\vec{b}, z) \quad .$$

- sharp sphere $\quad t_A(b) = 2\rho_0 \sqrt{R_A^2 - b^2}$
- Gaussian $\quad t_A(b) = \rho_0 \sqrt{\frac{\pi}{\alpha}} \, e^{-\alpha b^2}$
- Woods-Saxon

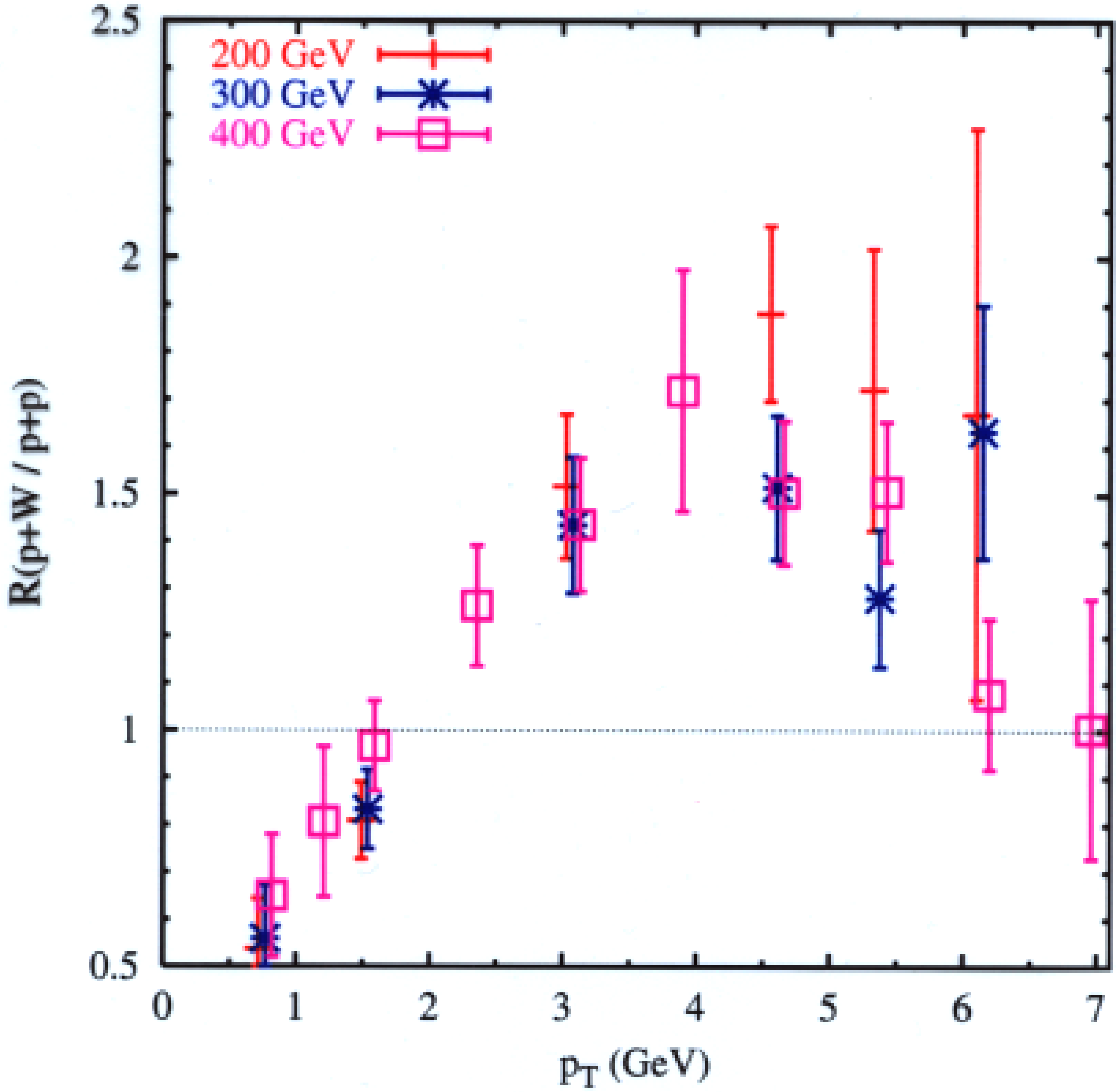


Figure 5: $p + W \to \pi^+ + X$ differential cross section compared to $p+p$ one at $E_{lab} = 200, 300, 400$ GeV. Data is taken from Anreasyan et al., Phys. Rev. **D19**, 764 (1979).

Cronin effect:

There is an enhancement in a certain p_T range in the particle production in a pA collision compared to a pp collision.

- ✔ Allow the width parameter $\langle k_T^2 \rangle$ to vary

$$\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C_{all}\, h(\nu_A(b) - 1)$$

$\nu_A(b)$: $\sigma_{NN} t_A(b)$ number of target particles within the channel swept by the projectile

C_{all} : average transverse momentum square imparted per collision

$h()$: "effectivity" function, number of effective contributors

Underlying picture:

- Random soft (pre)collisions change the transverse momentum of the proton before the final collision at the end of the channel.
- Particles are produced in a multiparticle collision event the incoming nucleon colliding on $h(\nu_A(b) - 1) + 1$ target particles.

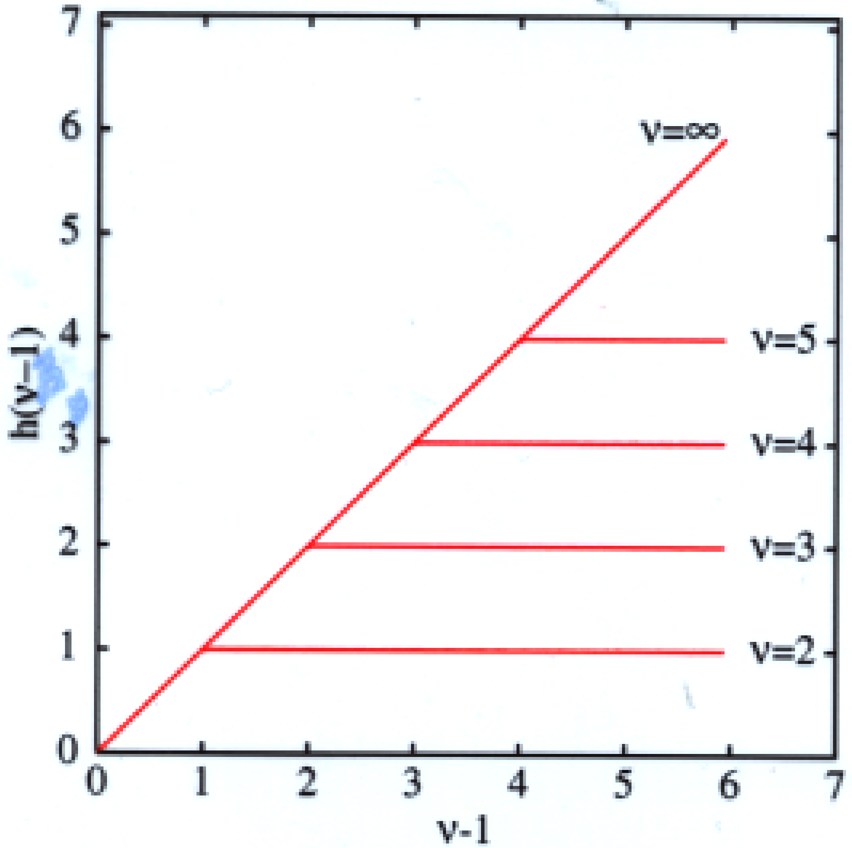
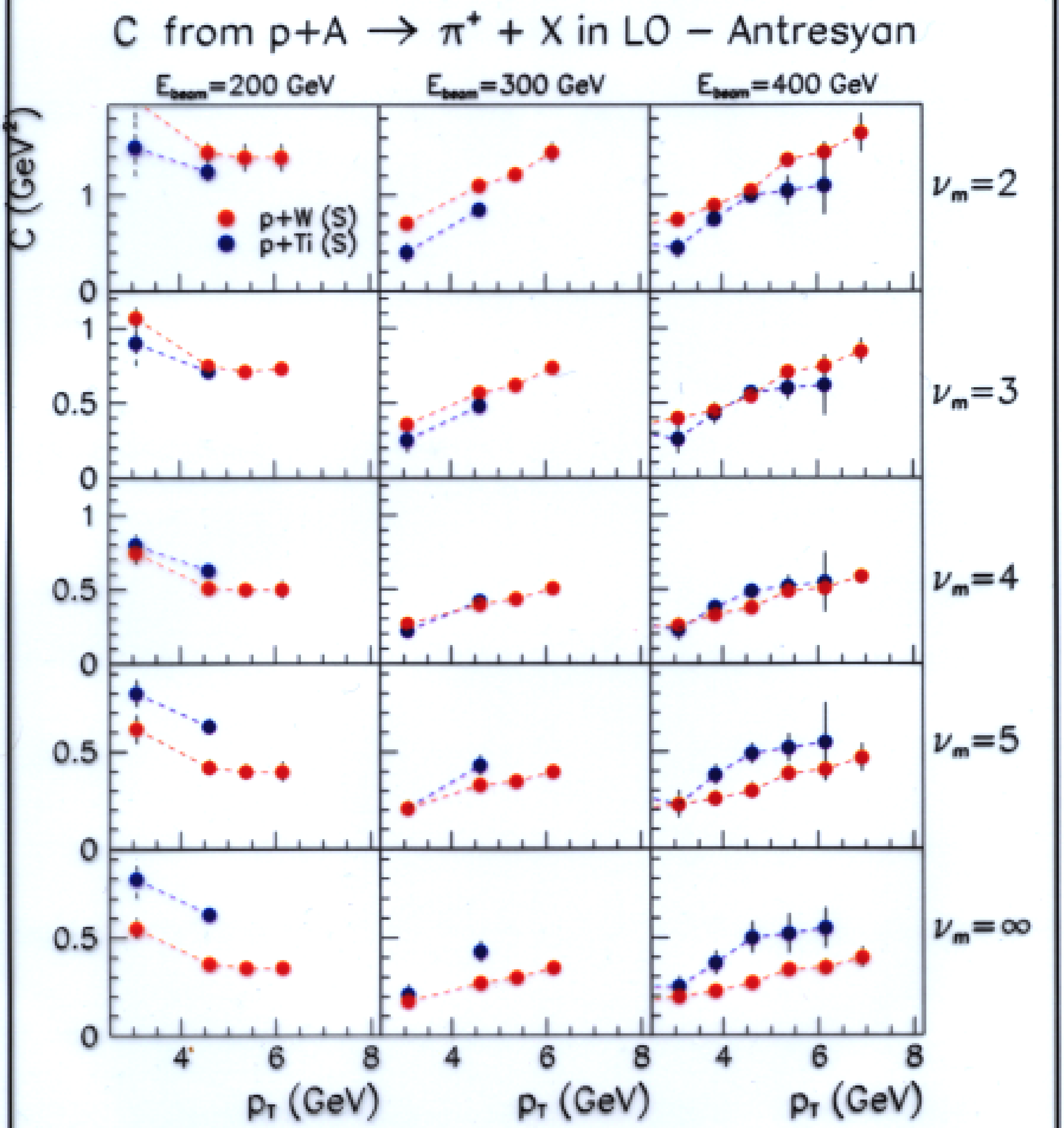


Figure 6: Effective (multi)collision number.


C from p+A → π⁺ + X in LO – Antresyan
E_beam=200 GeV
E_beam=300 GeV
E_beam=400 GeV
C (GeV²)
p+W (S)
p+Ti (S)
ν_m=2
ν_m=3
ν_m=4
ν_m=5
ν_m=∞
p_T (GeV)
p_T (GeV)
p_T (GeV)

Nucleus Nucleus collisions

Some more integrals to perform

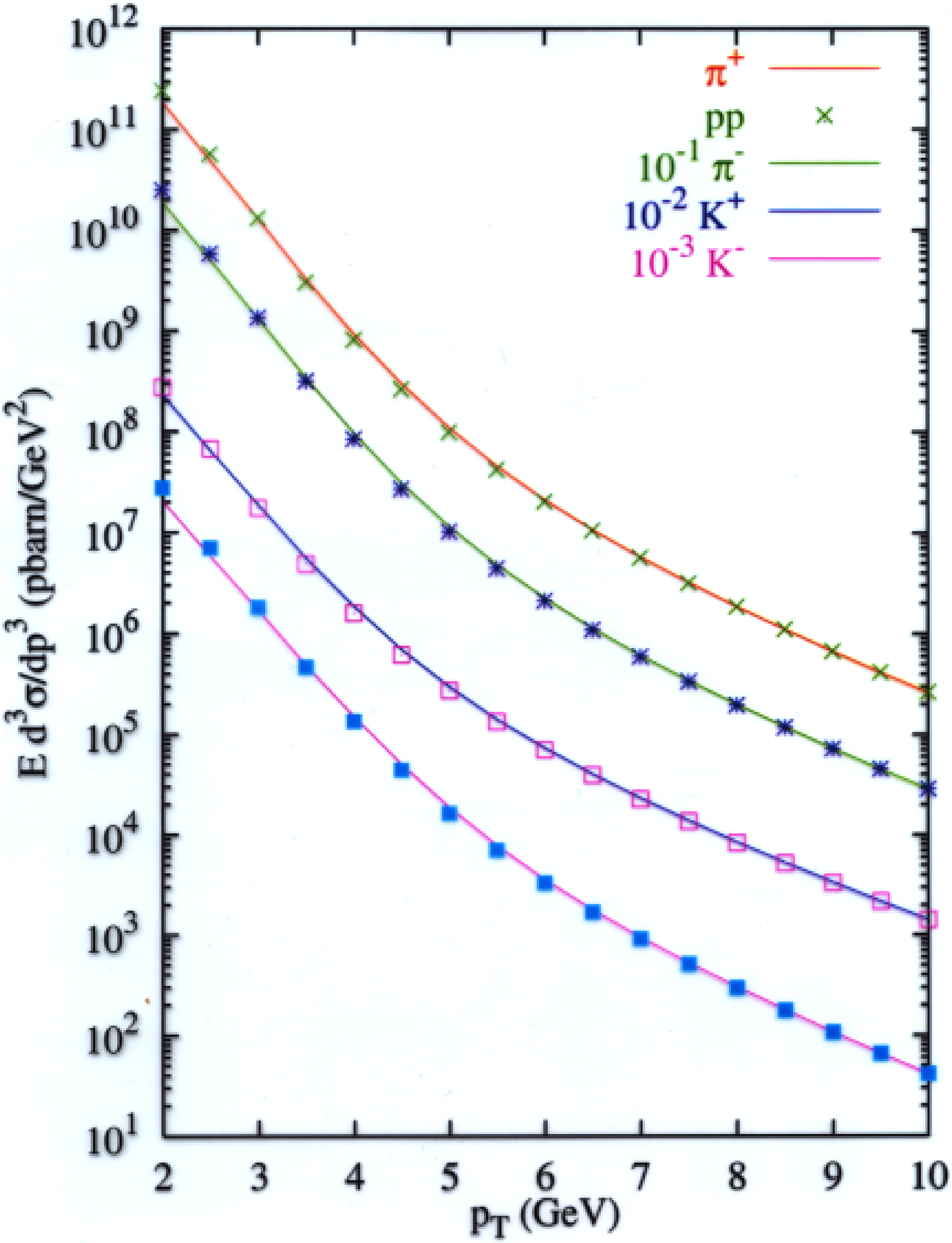
$$E_\pi \frac{d\sigma_\pi^{AA}}{d^3p} = \sum_{abcd} \int d^2b\, d^2r\; t_A(\vec{b})\, t_B(\vec{b}-\vec{r}) \ldots$$

with centrality cut, $b \leq b_{max}$.

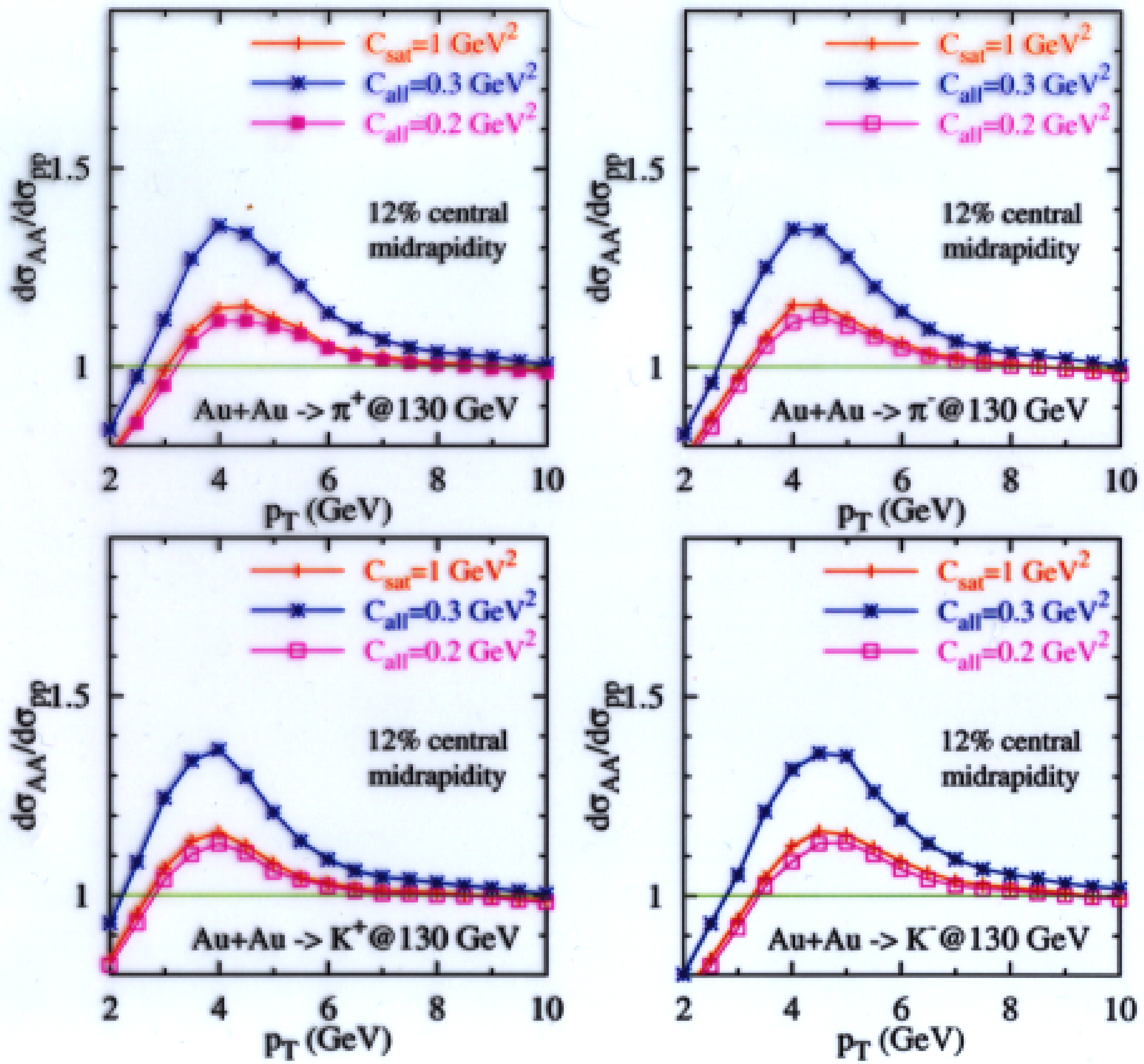
✎ extra nuclear enhancement takes places both for target and projectile nucleons.

✎ Calculations for RHIC are performed selecting the most central events with $b_{max} = 3fm$, corresponding to $\sim$ 12% of most central events.

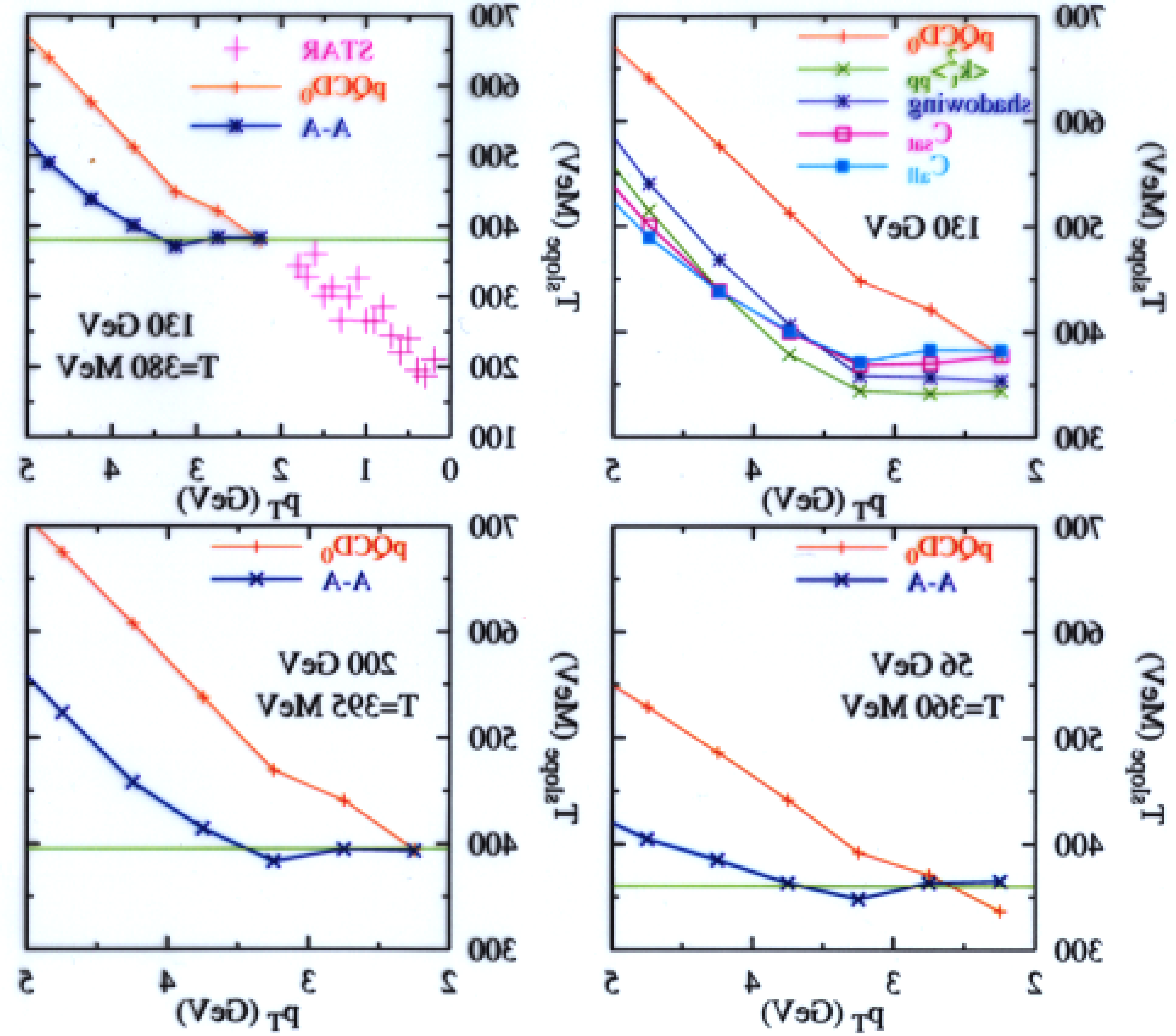
slope parameter: $\frac{Ed\sigma}{d^3p} \propto e^{-m_t/T}$



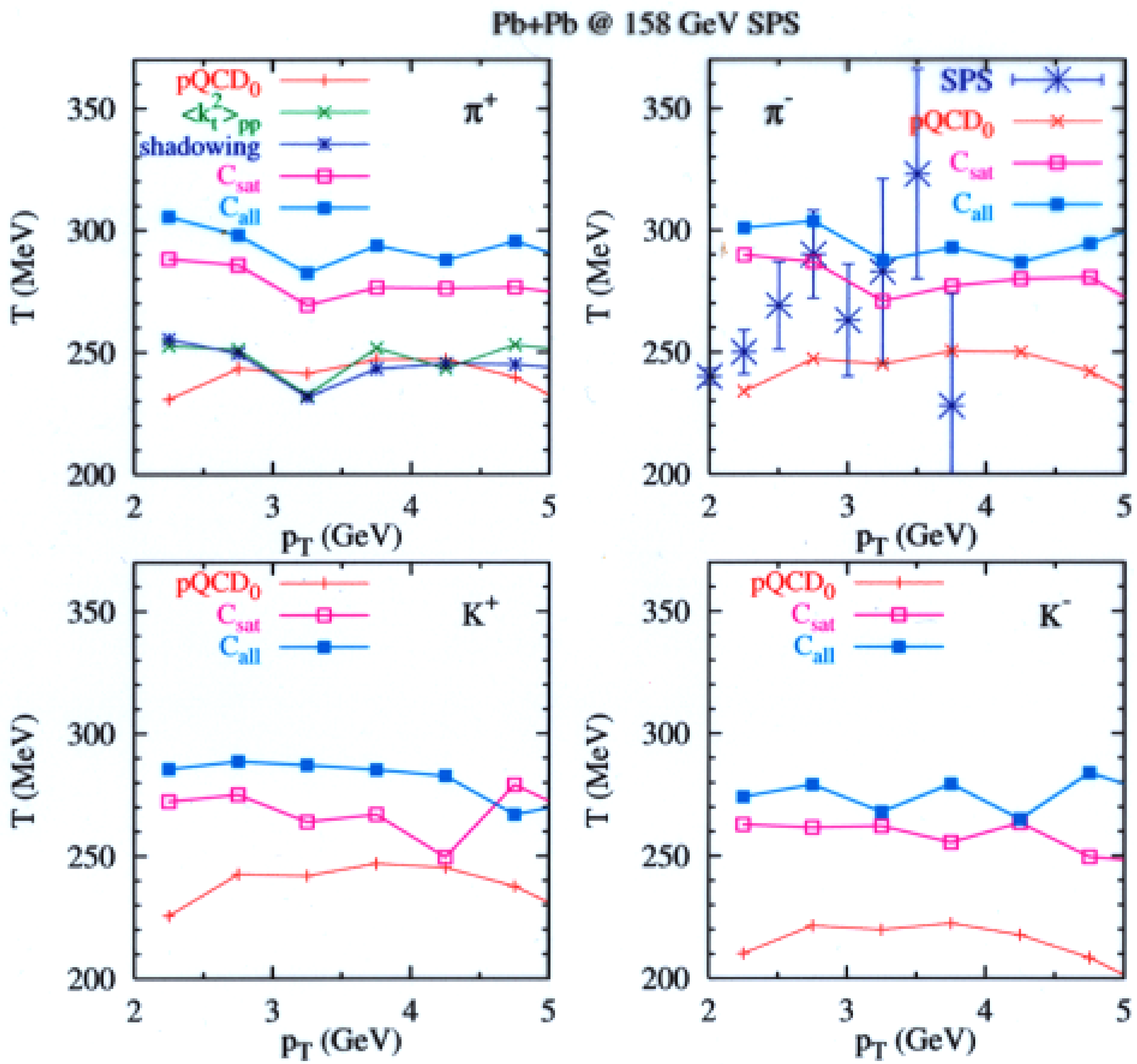
π+
pp
10-1 π-
10-2 K+
10-3 K-
E d3σ/dp3 (pbarn/GeV2)
pT (GeV)



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



130 GeV
T=380 MeV
STAR
pQCD0
A-A
130 GeV
pQCD0
<k_t^2>pp
shadowing
C_sat
C_all
200 GeV
T=395 MeV
56 GeV
T=360 MeV
T_slope (MeV)
p_T (GeV)


Pb+Pb @ 158 GeV SPS
pQCD0
<kt2>pp
shadowing
Csat
Call
π+
SPS
π-
K+
K-
T (MeV)
pT (GeV)
200
250
300
350
2
3
4
5

Summary

- Proper pQCD description of (photon and) pion production in hadron-hadron collisions in the p_T range 2–8 GeV requires the introduction of intrinsic transverse momentum distribution of the partons.

- In proton-nucleus collisions the average intrinsic transverse momentum of the projectile increases due to the nuclear environment.

- The increase in the average intrinsic transverse momentum is described best assuming a scattering of the incoming proton on maximum few (≈ 3) target nucleons.

- pQCD shows an exponential slope in particle production in the range $p_T = 2 - 4\,GeV$ with a slope parameter $T \approx 350 - 400\,MeV$, which is highly insensitive to the exact mechanism of nuclear enhancement.

- Nuclear multiscattering effects are balanced by shadowin at RHIC energies in nucleus-nucleus collisions.

- Nuclear multiscattering effects may be understood better from
  - p - p data
  - p - A systematic analysis (from light to heavy nuclei)