pQCD results on π Production in pp, pA and AA collisions

Gergely Gábor Barnaföldi, Péter Lévai– KFKI RMKI;
Gábor Papp – ELTE University;
George Fái , Yi Zhang – Kent State University.

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(bgergely@rmki.kfki.hu)

Motivation and Program

π Production in pQCD Improved Parton Model

I. Leading Order (LO) Calculations:

(1) $pp \rightarrow \pi + X$ data reproduction at 3 GeV $\leq p_T \leq$ 6 GeV range
calculate intrinsic k_T as baseline

(2) $pA \rightarrow \pi + X$ included known nuclear effects:
Multiple scattering
Shadowing inside the nucleus
k_T broadening $\rightarrow$ Cronin effect

(3) $AA \rightarrow \pi + X$ Further (nuclear) effects :
better pQCD predictions for SPS and RHIC

II. Next-to-Leading Order (NLO) Calculations by K_{jet}:

(1) The definition of $\sqrt{s}$ and p_T dependent K factor

(2) NLO with $K_{jet}(\sqrt{s}, p_T)$ factor

(3) Using "LO Program (I.1)-(I.3)" in NLO frame

III. Compare results of LO and NLO calculations

@ different PDF scales: $Q = p_T/2$ and $Q = p_T$

IV. Summary

The behavior of Cronin effect in our model picture

V. Bibliography

pQCD Improved Parton Model/1 – [LO]

$$E_h \frac{d\sigma_h^{pp}}{d^3p} = \sum_{abcd} \int dx_a \, dx_b \, d^2k_{T,a} \, d^2k_{T,b}, dz_c \times$$
$$\times \quad g(\vec{k}_{T,a}) \, g(\vec{k}_{T,b}) \, f_{a/p}(x_a, Q^2) \, f_{b/p}(x_b, Q^2)$$
$$\times \quad \frac{d\sigma^{ab\to cd}}{d\hat{t}} \, \frac{D_{h/c}(z_c, \widehat{Q}^2)}{\pi z_c^2} \, \hat{s} \, \delta(\hat{s} + \hat{t} + \hat{u}) \quad .$$

$f_{a/p}(x, Q^2)$: Parton Distribution Function (PDF), at scale Q^2

$g(\vec{k}_{T,a})$: Intrinsic 2-dimensional transverse momentum distribution

$D_{h/c}(z_c, \widehat{Q}^2)$: Fragmentation Function (FF), at scale $\widehat{Q}^2$

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

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

pQCD Improved Parton Model/2 – [LO]

PDF: Parton Distribution Functions – LO
GRV – Glück, Reya, Vogt Z.Phys. **C53** 127 (1992)
$Q = p_T/2$, $\Lambda = 200$ MeV

FF: Fragmentation Functions – LO
KKP – Kniehl, Kramer, Pötter Nucl. Phys. **B582** 514 (2000)
$\widehat{Q} = p_T/2z_c$

Intrinsic k_T (Non perturbative) phenomenological assumption :
1 dimensional PDF change to 1+2 dimensional PDF

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

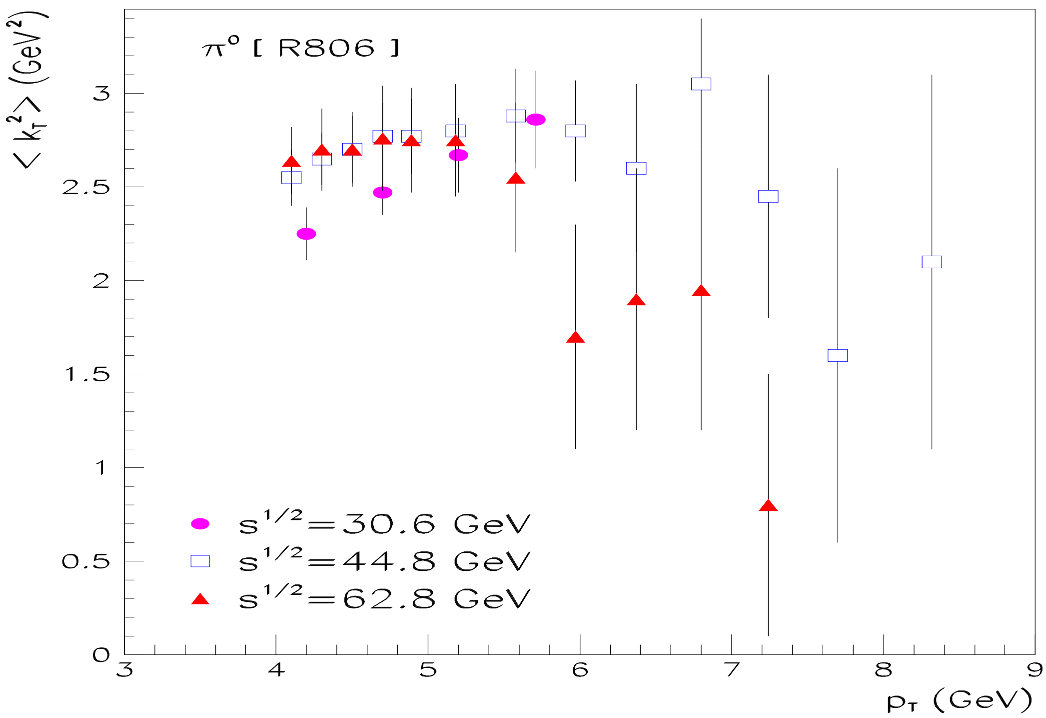
where $g(\vec{k}_T)$ is a Gauss distribution:

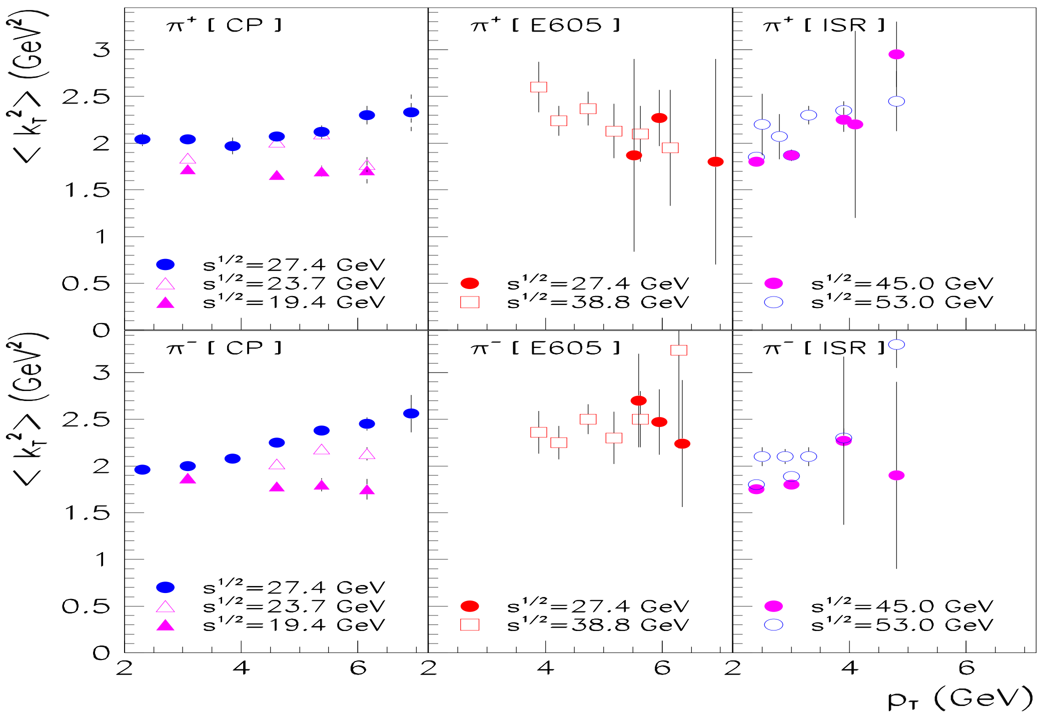
$$g(\vec{k}_T) = \frac{e^{-\vec{k}_T^2/\langle k_T^2\rangle}}{\pi\langle k_T^2\rangle}$$

$$\langle k_T^2\rangle = \frac{4\langle k_T\rangle^2}{\pi}$$

Why is this parametrization good with $\langle k_T^2\rangle$?

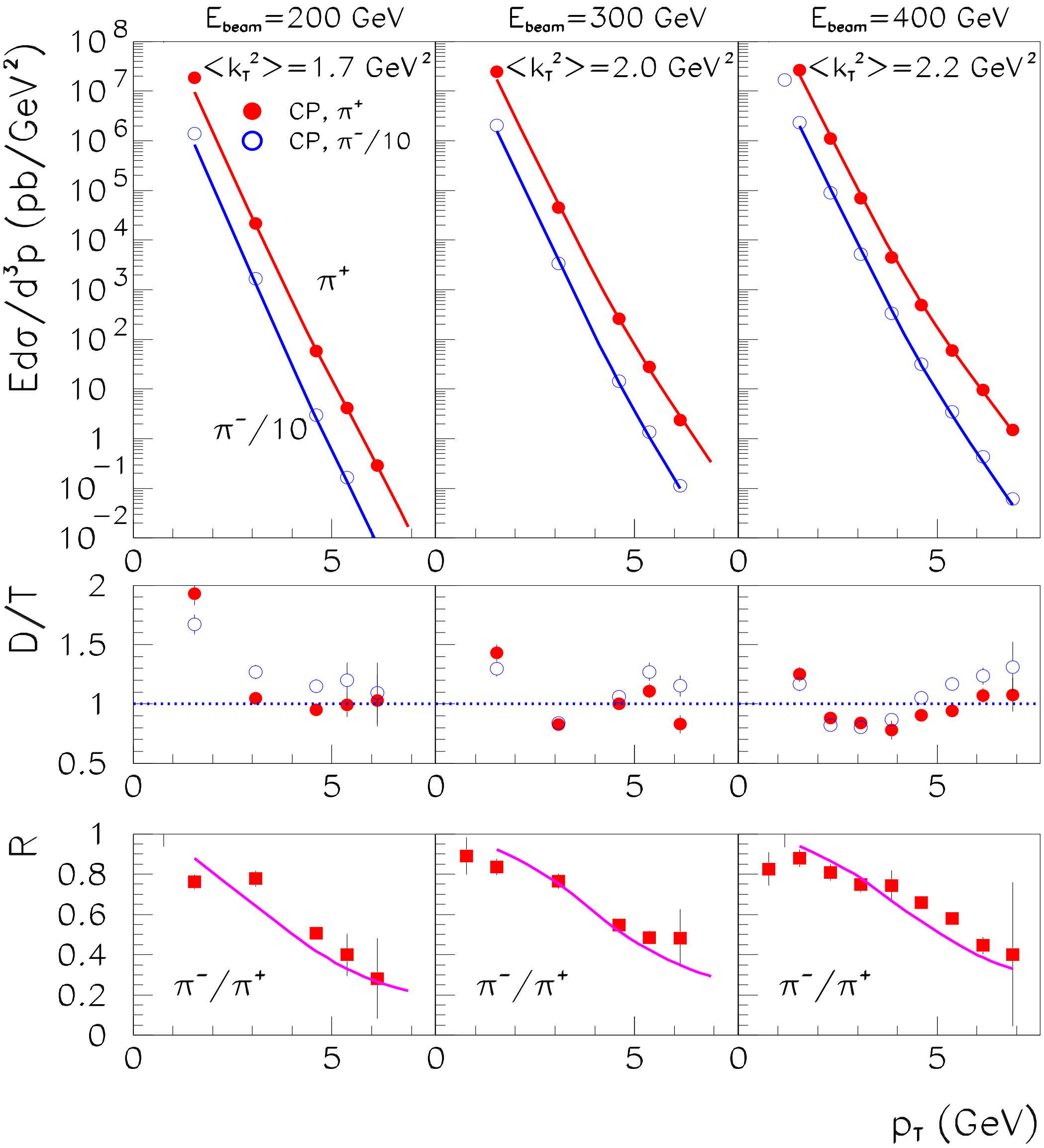
The Intrinsic-k_T as a Function of p_T in Different Experiments at CERN Energies





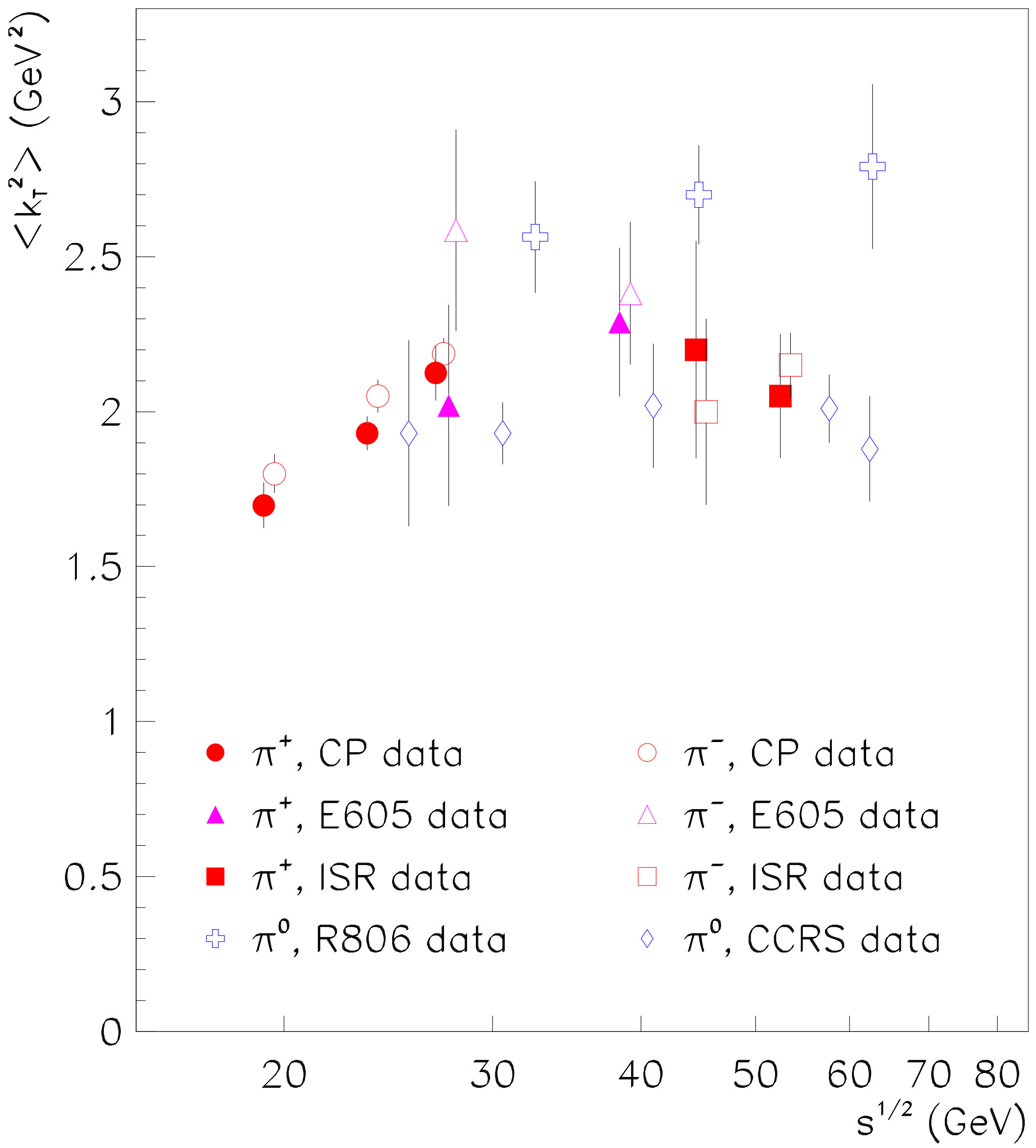
Data: *D. Antreasyan et al., Phys. Rev.* **D19** *764 (1979).*
C. Kourkoumelis et al., Z. Phys. **C5** *95 (1980).*

Charged π Productions, and π^-/π^+ Ratios at Different $\sqrt{s}$ = 19.4 GeV, 23.8 GeV and 27.4 GeV Energies Calculated with Intrinsic-k_T



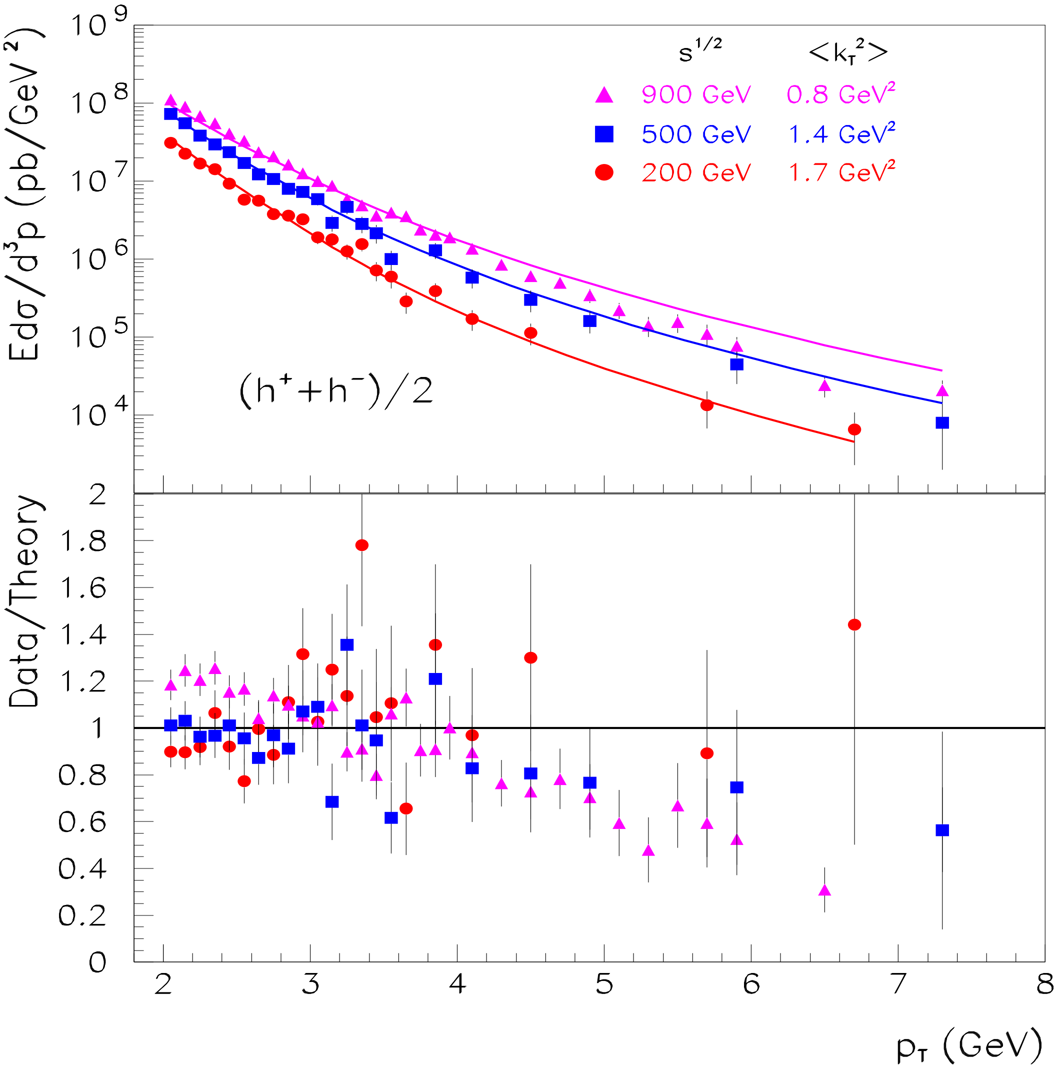
We NEED this INTRINSIC-k_T for good $\pm$ $20-30\%$ agreement with experimental data

The $\sqrt{s}$ Dependence of Intrinsic k_T in Different Experiments at CERN energies



Hadron Production at Higher Energies

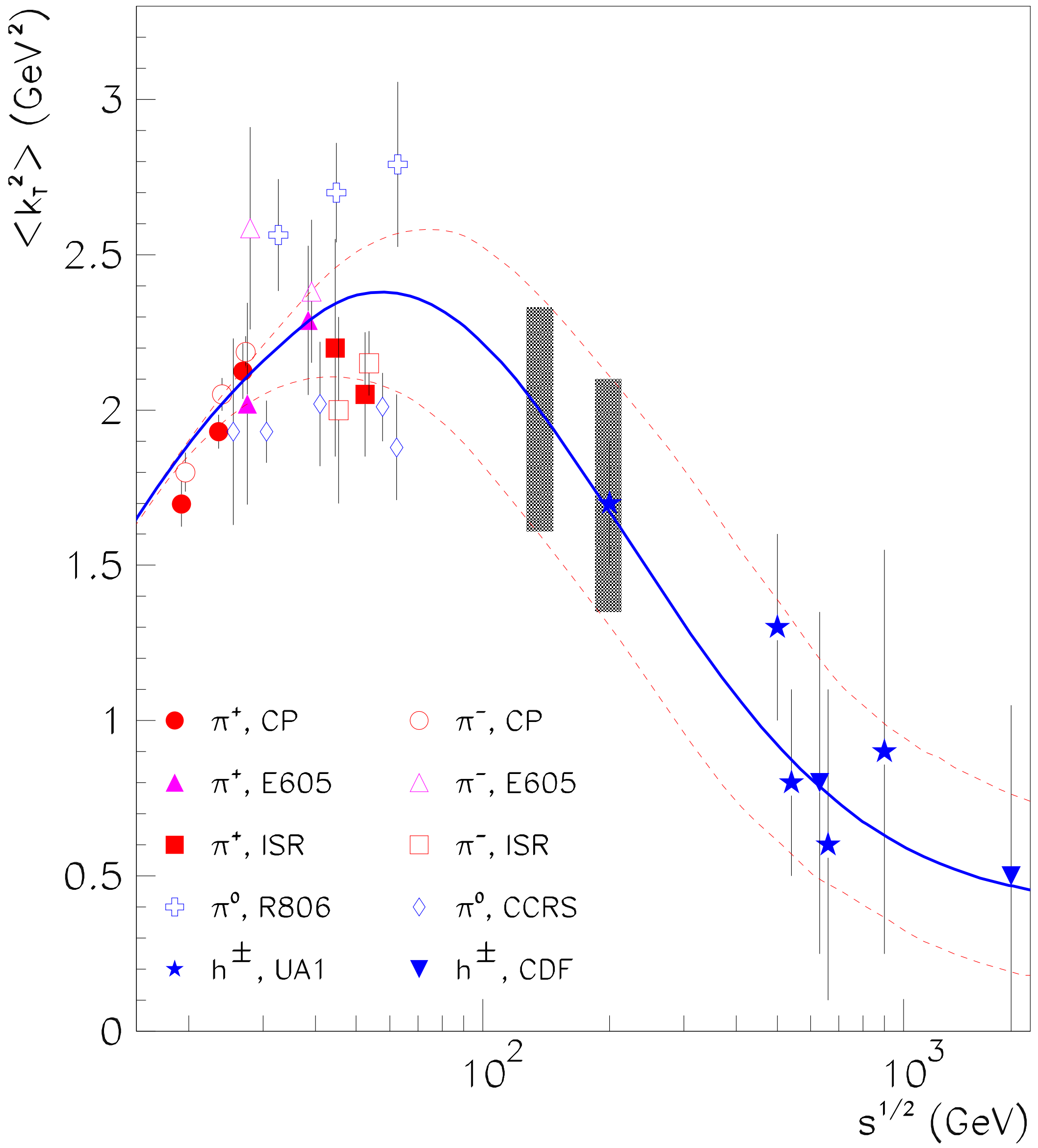
Charged Hadron Production in $p\bar{p}$ Collisions at UA1 Experiment at $\sqrt{s} = 200$ GeV; 500 GeV and 900 GeV Energies



If $\sqrt{s}$ increases then the value of $\langle k_T^2 \rangle$ decreases!

Data: *D. Albajar et al., Nucl. Phys.* **B335** *261 (1990).*

The $\sqrt{s}$ dependence of intrinsic k_T from CERN to Tevatron Energies



pA Collisions – Nuclear Effects/1

Multiple nuclear scattering

- described in proton-nucleus (pA) collisions
- Cronin-effects: increased particle production in 2 GeV $< p_T <$ 6 GeV window

D. Antreasyan *et al.* Phys. Rev. **D19**, 764 (1979)
C.N. Brown *et al.* Phys. Rev **C54**, 3195 (1996)

- Glauber-model (multiple scattering):

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

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

$h(\nu_A(b) - 1)$: number of effective NN collisions
C : (average broadening)^2 / coll.
$t_A(b)$: Nuclear Thickness Functions

$t_A(b) = \int dz \, \rho(b,z)$:
for small A: sharp sphere $t_A(b) = 2\rho_0\sqrt{R_A^2 - b^2}$,
for larger A: Wood−Saxon distribution.

pA Collisions – nuclear effects/2

Shadowing in the nucleus

- PDFs are changed in the nucleus :

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

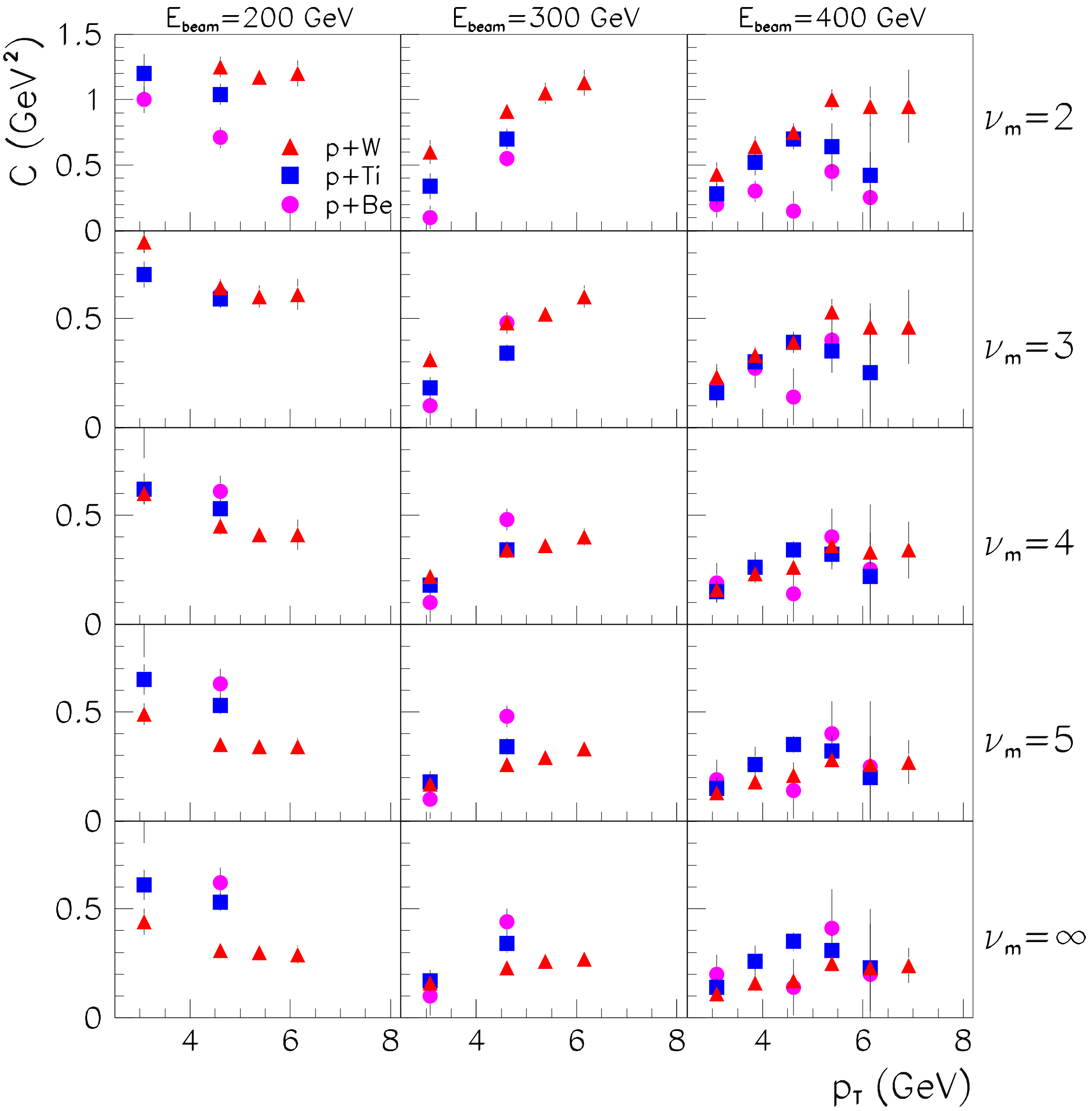
$S_{a/A}(x,b)$: Shadowing function

$$\begin{aligned} S_{a/A}(x) &= 1 + 1.19 \ln^{1/6} A[x^3 - 1.5(x_0 + x_L)x^2 + 3x_0 x_L x] \\ &- \left[\alpha_A - \frac{1.08(A^{1/3}-1)}{\ln(A+1)} \sqrt{x}\right] e^{-x^2/x_0^2} \end{aligned}$$

where $\alpha_A = 0.1(A^{1/3} - 1)$ and $x_0 = 1$, $x_L = 0.7$.

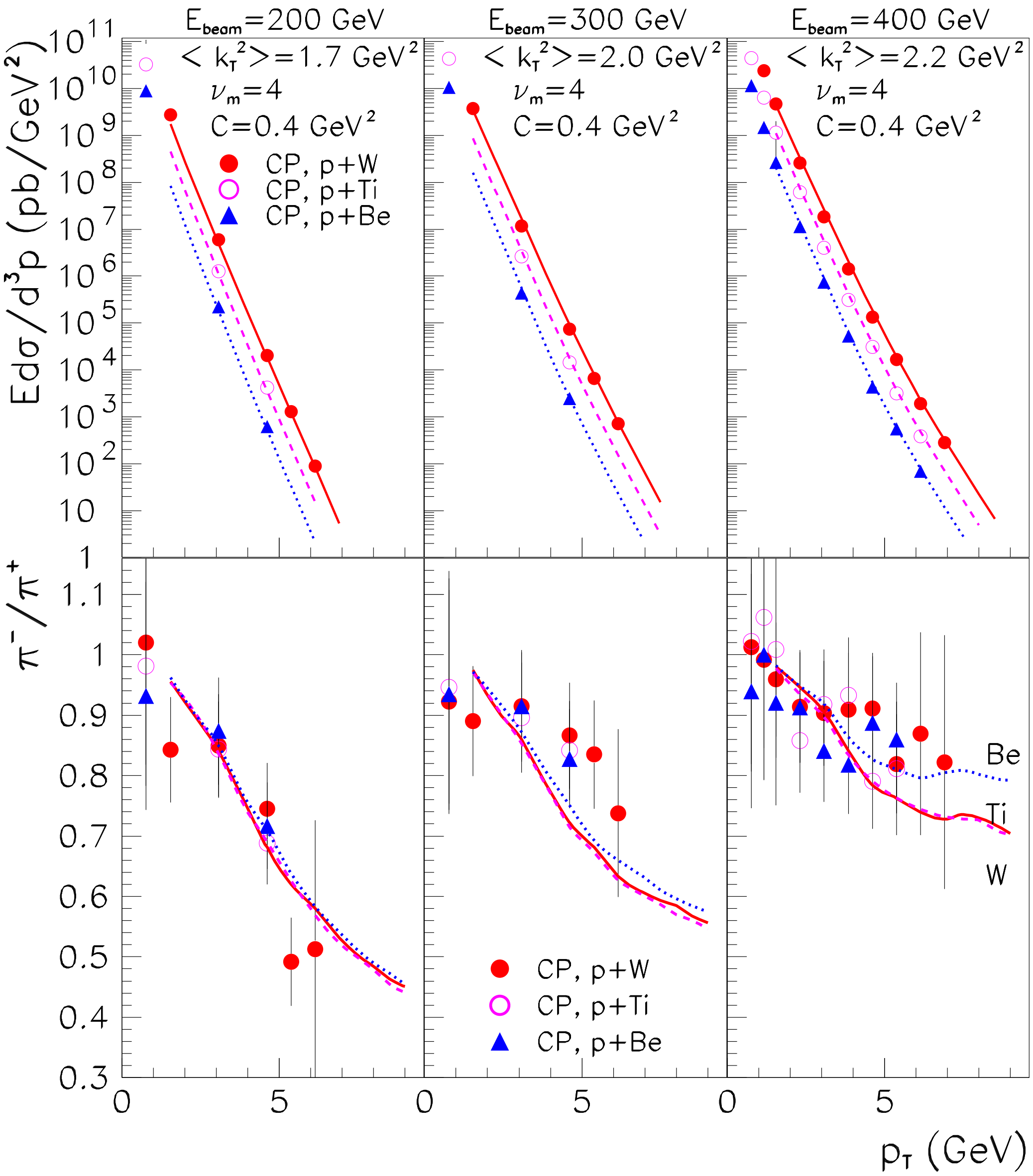
Wang and Gyulassy, Phys. Rev **D44**, 3501 (1991)
Eskola *et al.*, Eur. Phys. Jour. **C9**, 61 (1998)

The p_T and ν_m Dependence of C-factor in $p + Be$, $p + Ti$ and $p + W$ Collisions at $\sqrt{s} = 19.4$ GeV, 23.8 GeV and 27.4 GeV



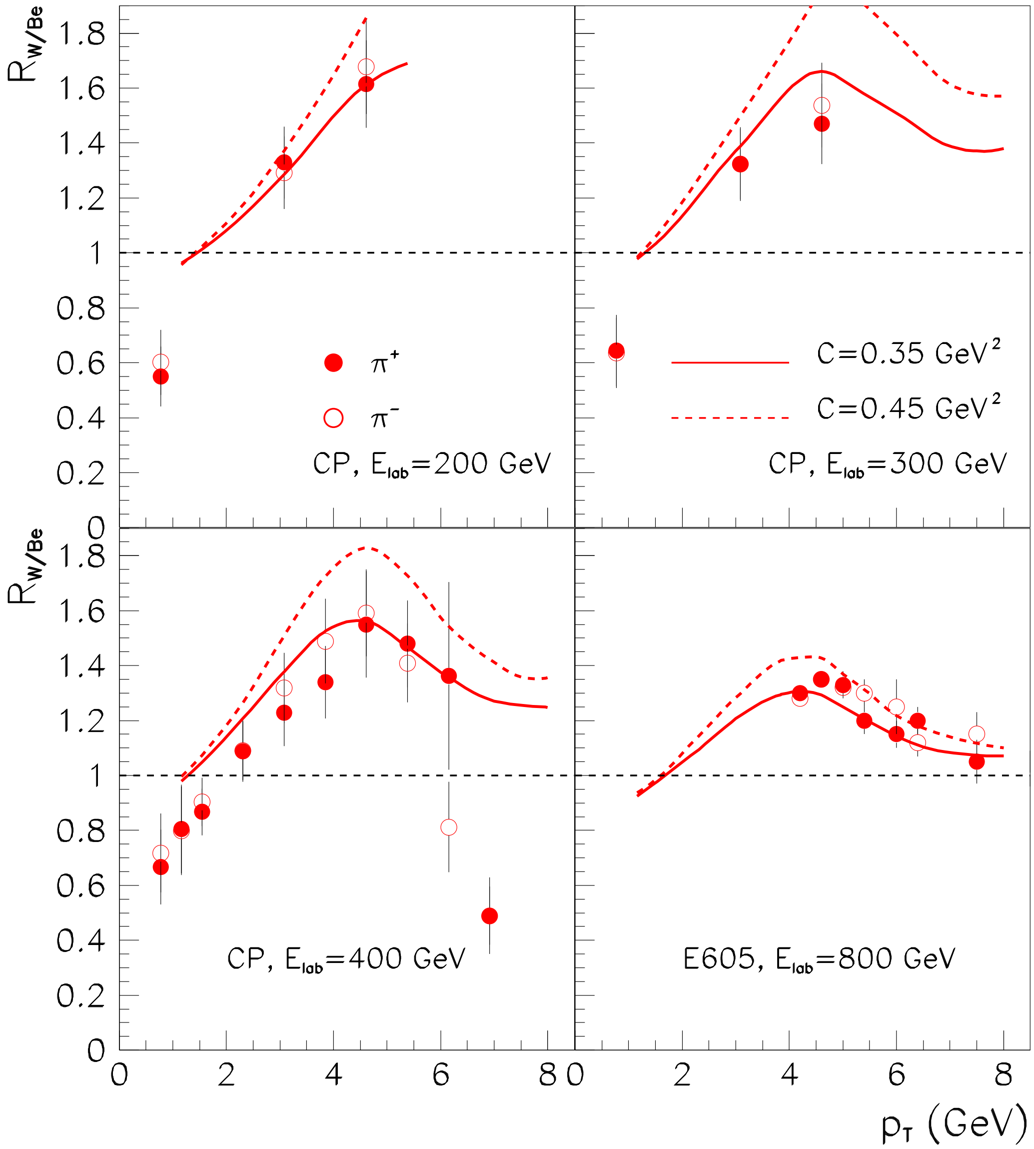
The best agreement with experiment if $C = 0.4 \pm 0.05$ and $\nu_m = 4$

π^+ Spectra and π^-/π^+ Ratios in $p + Be$, $p + Ti$ and $p + W$ Collisions, at $\sqrt{s} = 19.4$ GeV, 23.8 GeV and 27.4 GeV



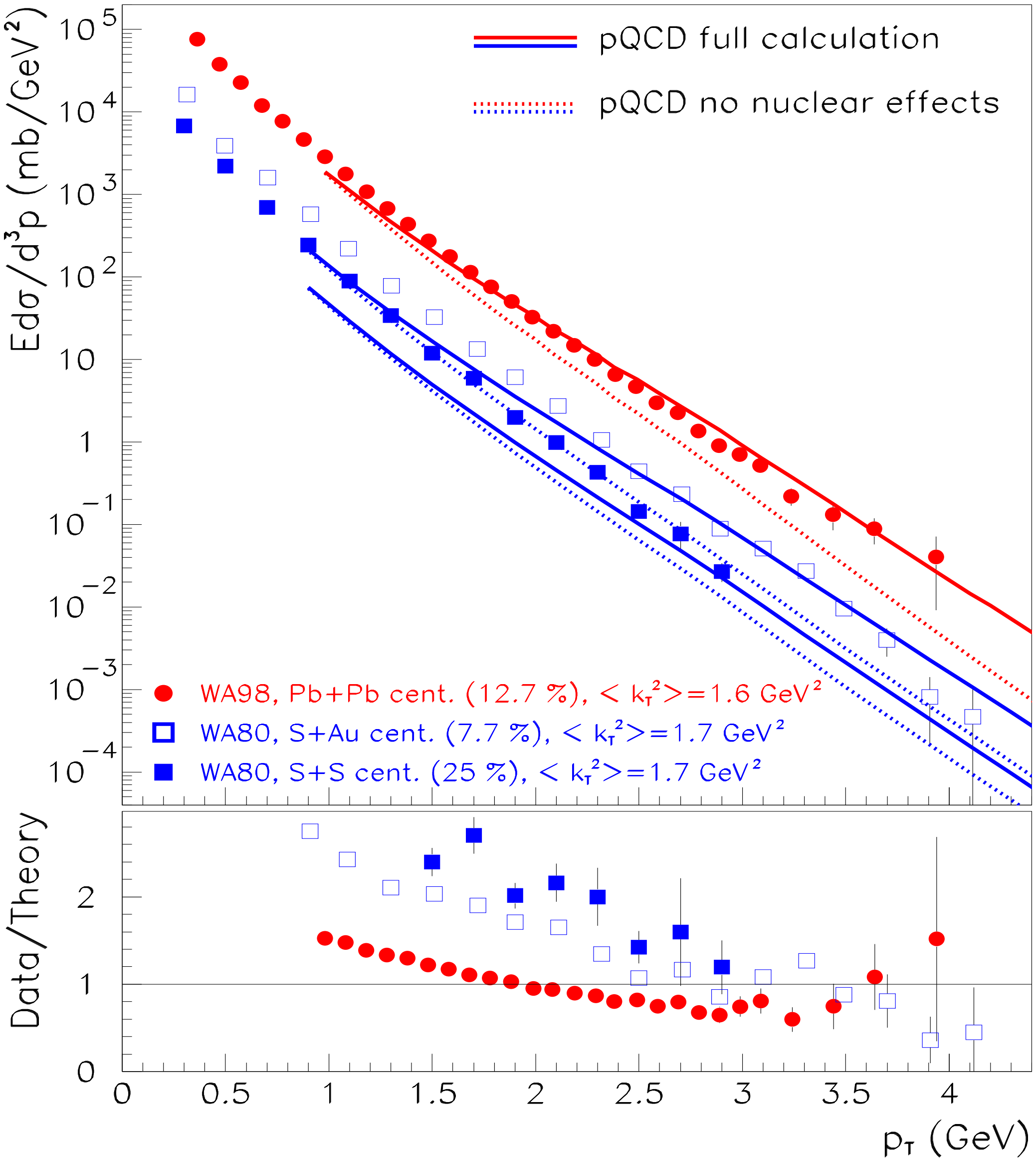
$C = 0,4 \pm 0,05$ **and** $\nu_m = 4$

Cronin effect (on presented W/Be ratios) at $\sqrt{s} = 19.4$ GeV, 23.8 GeV, 27.4 GeV and 38.8 GeV



!!! THIS WILL BE IMPORTANT !!!

Central AB Collisions: WA80 and WA98 Experiments at $\sqrt{s} = 19.4$ GeV and $\sqrt{s} = 17.3$ GeV



$\pm 30 - 40\%$

NLO Calculations with $K_{jet}(\sqrt{s}, p_T, Q)$

$$E_h \, \frac{d\sigma_h^{pp}}{d^3p} = \sum_{abcd} \int dx_a \, dx_b \, d^2k_{T,a} \, d^2k_{T,b}, dz_c \times$$
$$\times \quad g(\vec{k}_{T,a}) \, g(\vec{k}_{T,b}) \, f_{a/p}^{NLO}(x_a, Q^2) \, f_{b/p}^{NLO}(x_b, Q^2)$$
$$\times \quad \left[K_{jet}(\sqrt{s}, p_T, Q) \, \frac{d\sigma_{Born}^{ab\to cd}}{d\hat{t}} \right] \frac{D_{h/c}^{NLO}(z_c, \widehat{Q}^2)}{\pi z_c^2} \, \hat{s} \, \delta(\hat{s} + \hat{t} + \hat{u}) \, .$$

NLO Cross-section:

Parton Distribution Functions (PDF) at $Q = p_T$
MRTS-98, Martin et al: Eur.Phys.J. **C4** (1998) 463

2-Dimensional PDFs are Gaussian
parameterized by new values of intrinsic k_T

Fragmentation Functions (FF) at $\hat{Q} = p_T/2z_c$
KKP, Kniehl-Kramer-Pötter: Nucl.Phys. **B597** (2001) 337

K_{jet} factor analysis:

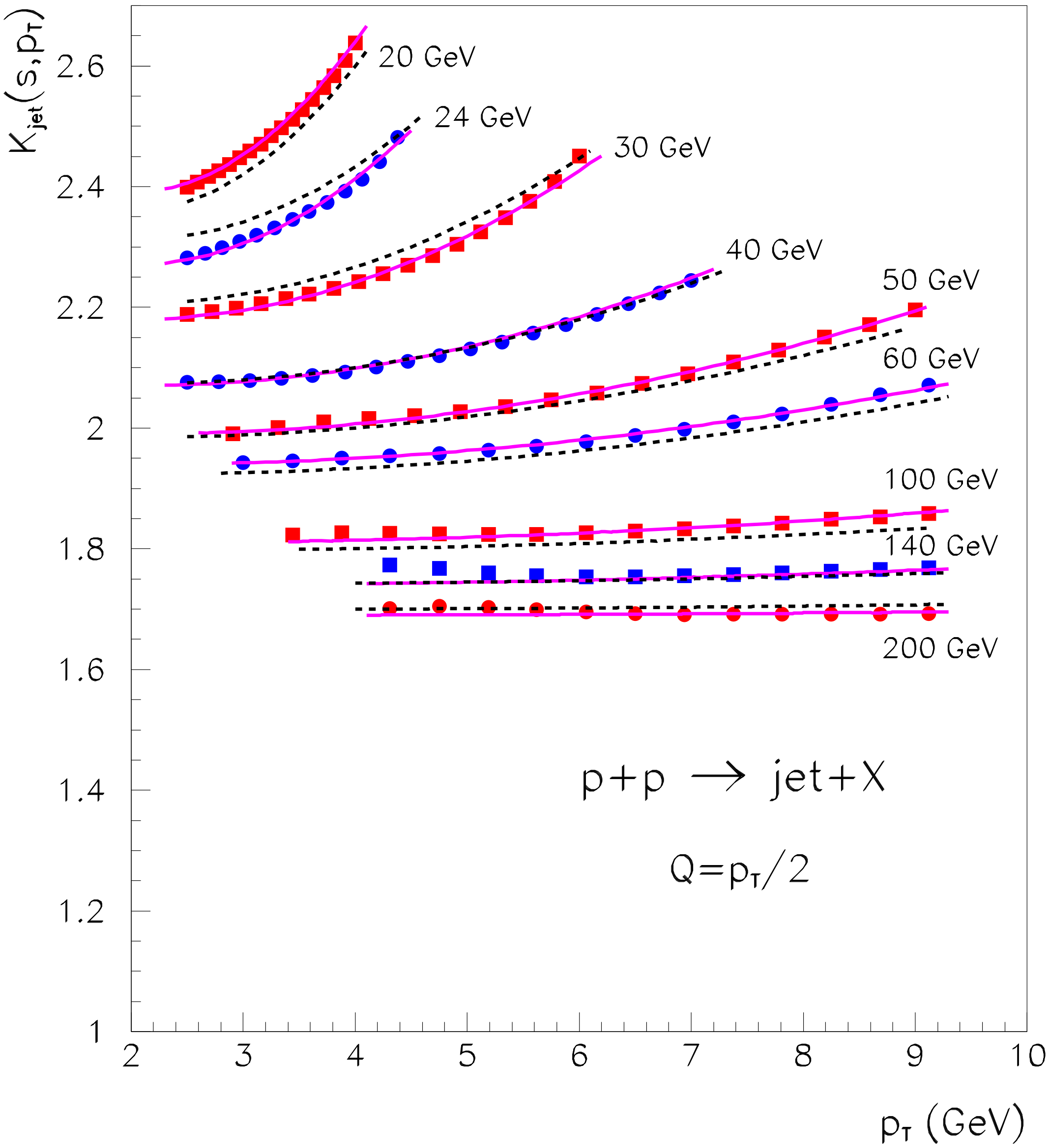
Naive "K factor" $= \frac{NLO}{LO}$, but K_{jet} depends on $\sqrt{s}$, p_T and Q

$K_{jet}(\sqrt{s}, p_T, Q)$ calculated in model of EKS
Ellis-Kunszt-Soper: PR **D40** (1989) 2188.

Earlier analysis at scale $Q = p_T/2$
G.G. Barnaföldi et al: JP **G27 (2001) 1767**

New analysis at scale $Q = p_T$
G.G. Barnaföldi et al: *in preparation*

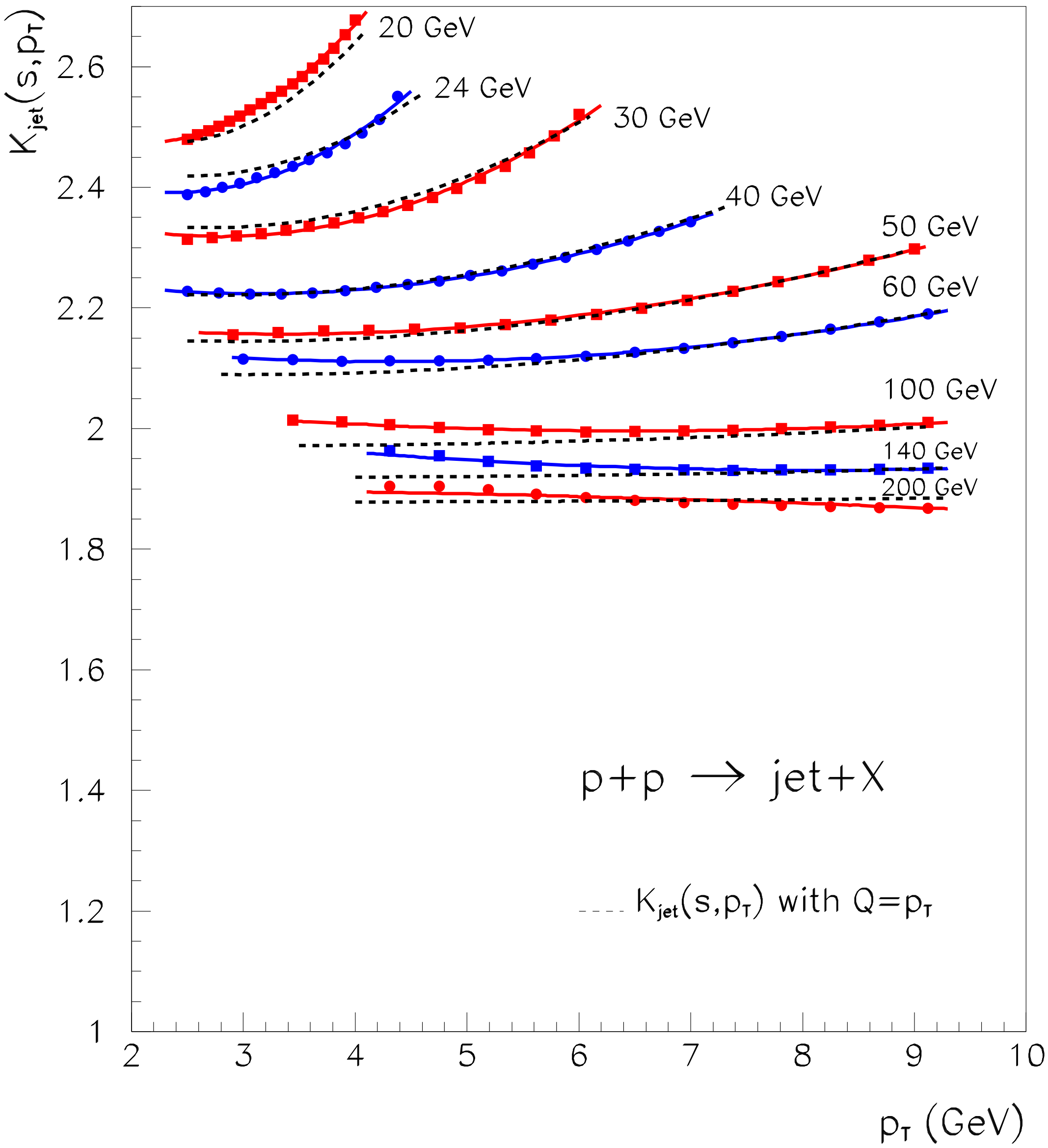
Function of $K_{jet}(\sqrt{s}, p_T, Q)$ at $Q = p_T/2$



$$K_{jet}(s, p_T) = 1.6 + \frac{20.}{\sqrt{s}} - \frac{24.}{(\sqrt{s} - 10.)^2}\, p_T + \frac{6.}{(\sqrt{s} - 10.)^2}\, p_T^2. \quad (1)$$

G.G. Barnaföldi et al: JP **G27 (2001) 1767**

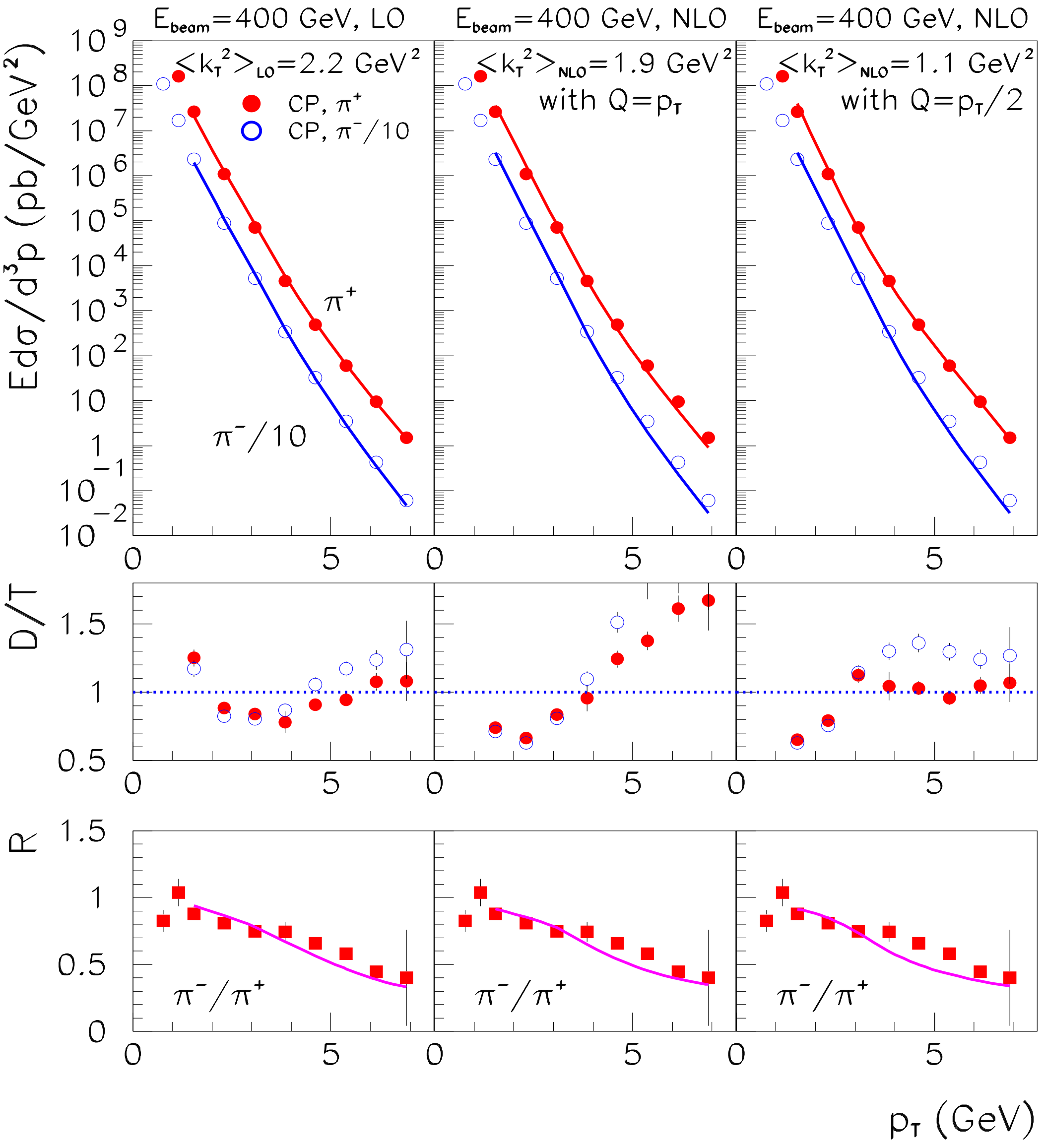
Function of $K_{jet}(\sqrt{s}, p_T, Q)$ at $Q = p_T$



$$K_{jet}(s, p_T) = 1.79 + \frac{20.}{\sqrt{s}} - \frac{45.}{(\sqrt{s} - 7.)^2}\, p_T + \frac{7.}{(\sqrt{s} - 9.)^2}\, p_T^2. \quad (2)$$

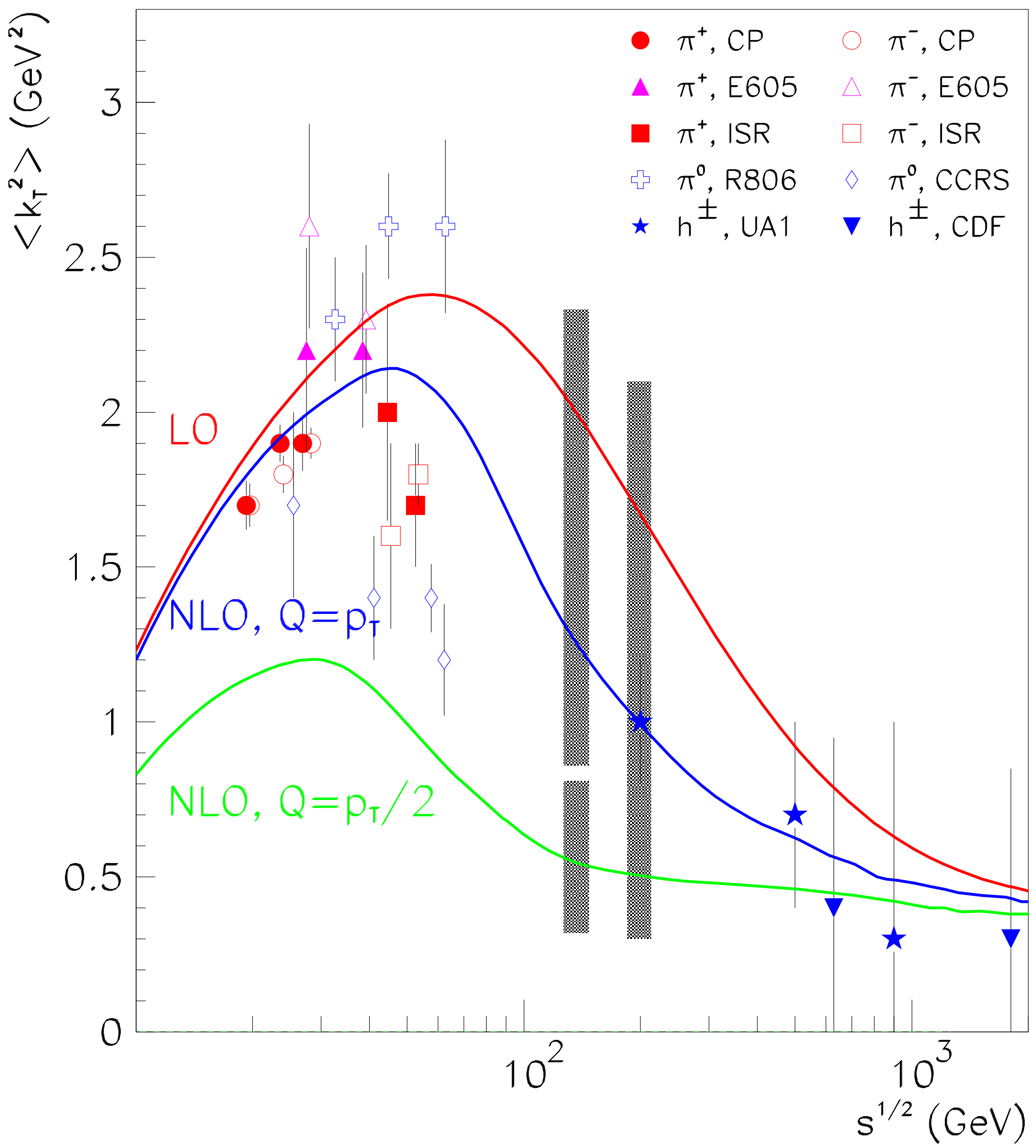
G.G. Barnaföldi et al: *in preparation*

Charged π Productions, and π^-/π^+ Ratios at $\sqrt{s} = 27,4$ GeV Calculated with Different $\langle k_T^2 \rangle$ and PDF scale: $Q = p_T, p_T/2$

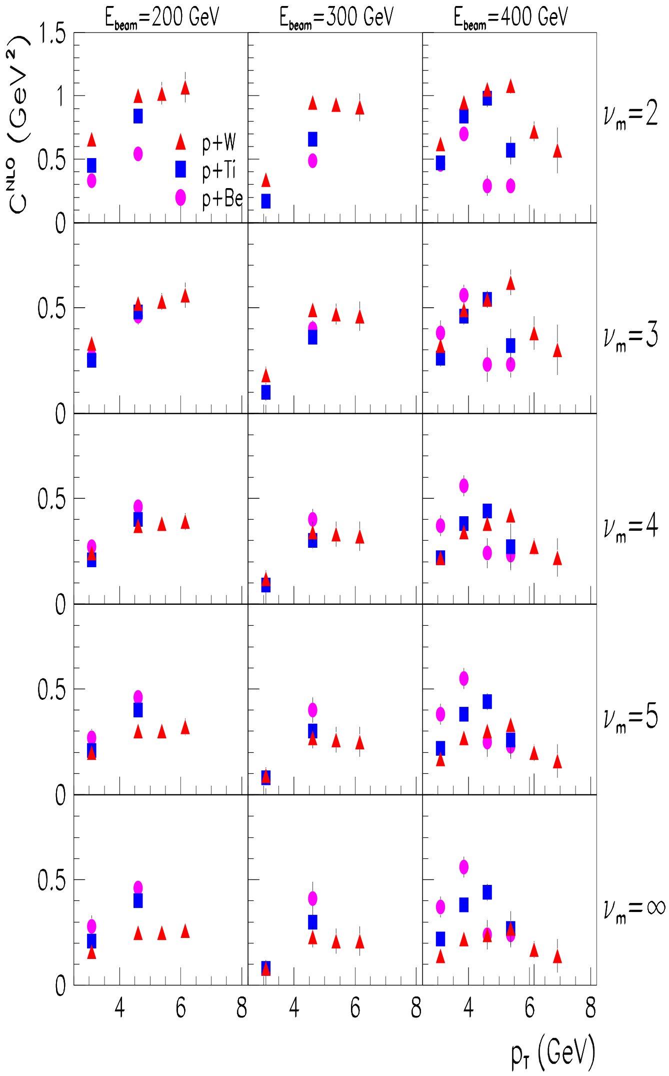


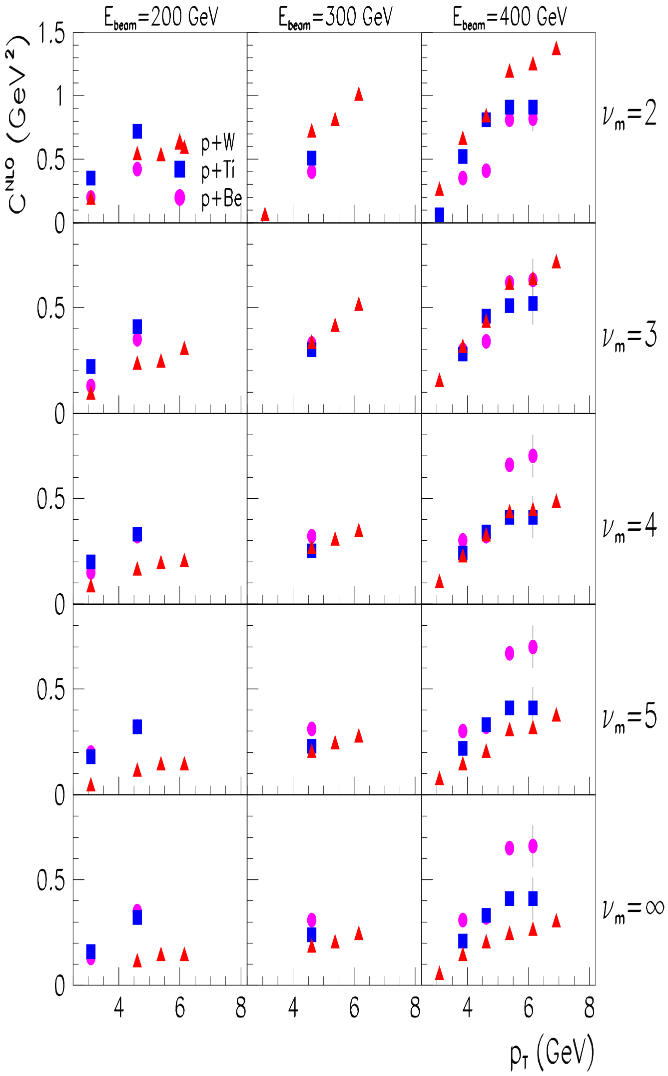
$$\langle k_T^2 \rangle^{LO}_{Q=p_T/2} > \langle k_T^2 \rangle^{NLO}_{Q=p_T/2} \quad \textbf{BUT} \quad \langle k_T^2 \rangle^{LO}_{Q=p_T/2} \approx \langle k_T^2 \rangle^{NLO}_{Q=p_T}$$

$\sqrt{s}$ Dependence of Intrinsic-k_T in Different pp and $p\bar{p}$ Experiments from CERN to Tevatron Energies both LO and NLO



The p_T and ν_m Dependence of C-factor in $p+Be$, $p+Ti$ and $p+W$ collisions at $\sqrt{s}=19.4$ GeV, 23.8 GeV and 27.4 GeV – calculated NLO with scale $Q=p_T/2$ (left) and $Q=p_T$ (right)

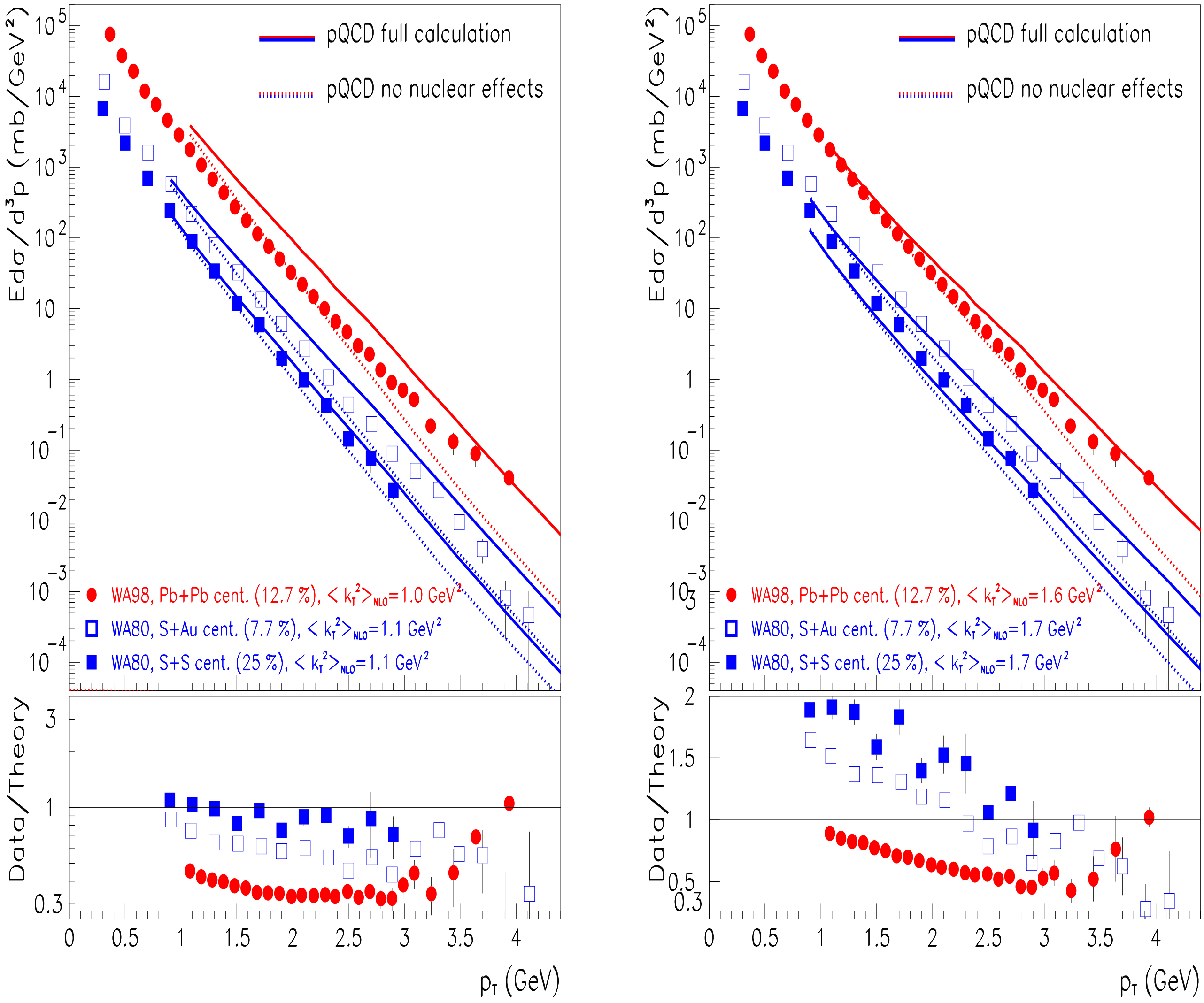




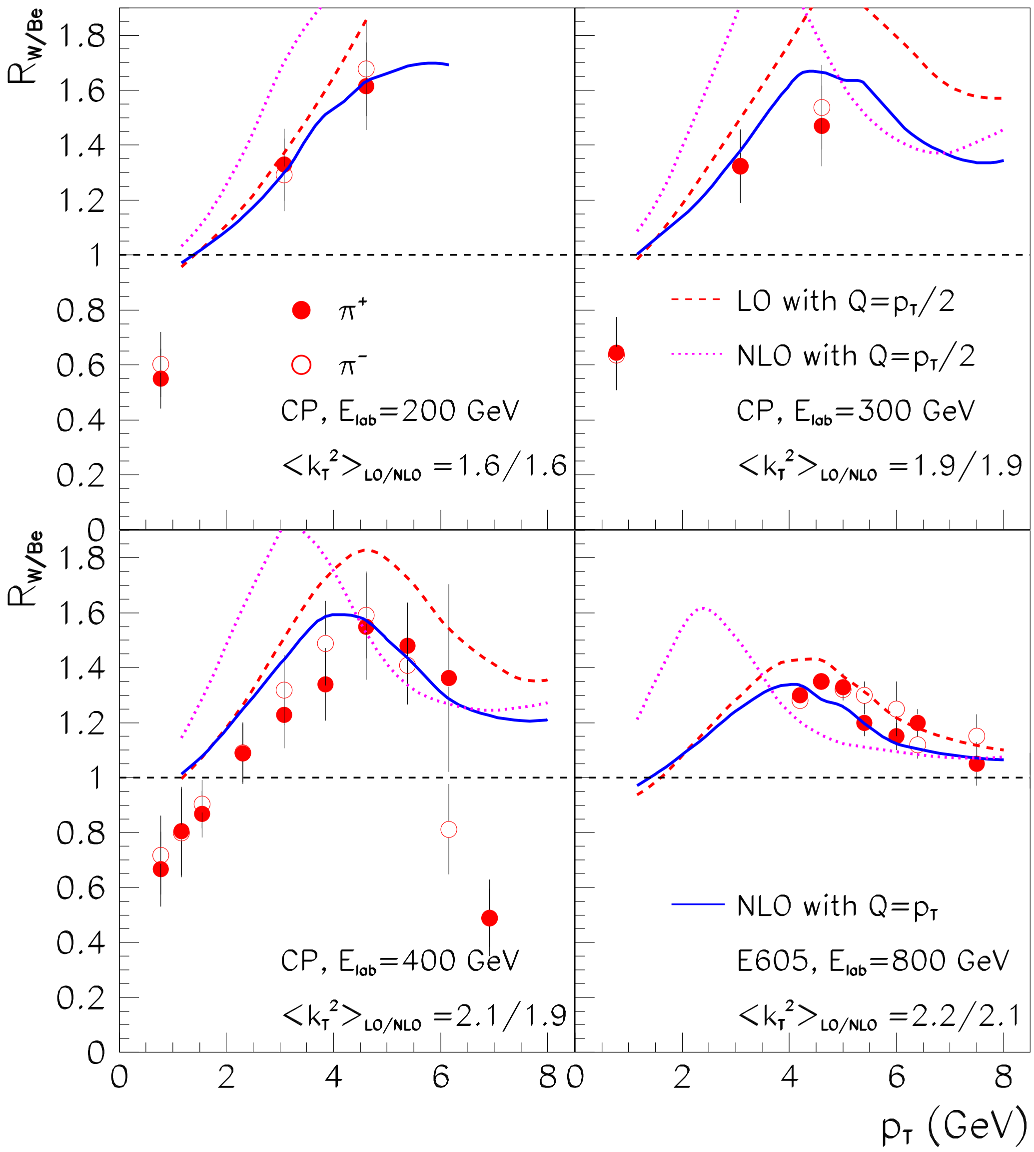
$Q=p_T/2$
$C=0.4\pm0.05$ **and** $\nu_m=4$

$Q=p_T$
$C=0.3\pm0.1$ **and** $\nu_m=4$ **?**

Central AB Collisions calculated in NLO for WA80 and WA98 Experimental Setup at $\sqrt{s} = 19.4$ GeV and $\sqrt{s} = 17.3$ GeV Scales: $Q = p_T/2$ (left) and $Q = p_T$ (right)



Cronin-effect (presented on W/Be ratios) at $\sqrt{s} = 19.4$ GeV, 23.8 GeV, 27.4 GeV and 38.8 GeV in NLO Calculations



Best agreement with experimantal data at: $\nu = 3 - 4$, $C = 0.3 - 0.4$ GeV^2 and scale is: $Q = p_T$!

Summary – Conclusions

Parton model extended with intrinsic k_T)

I. Leading Order Calculations

(1) pp data were reproduced

$\Longrightarrow$ π productions within $\pm 20 - 30\%$ errors
after introducing intrinsic k_T

(2) pA data were reproducing (Cronin effect) :

– shadowing (PDFs change in nucleus)

– multiple scattering

$\Longrightarrow$ k_T-broadening: C-factor and ν_m

$\Longrightarrow$ reproduction with $\pm 10 - 20\%$ errors

(3) Predictions for AA collisions at high-p_T :

– difference from data at SPS: $\sim$ 30 – 40%

$\Longrightarrow$ new nuclear effects (jet quenching?)

II. Next-to-Leading Order Calculations

(1) This talk: $K_{jet}(\sqrt{s}, p_T)$, but soon: full NLO

(2) Scale differences modify intrinsic-k_T

$\Longrightarrow$ Reproducing Cronin peak is crucial!!!

Bibliography

G.G. Barnaföldi; P. Lévai; G. Papp; G. Fai; Y. Zhang

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Phys. Rev **C65** (2002) 034903 *hep-ph/0109233*