A Study of D^0 Production from 500 GeV π^-–Nucleon Interactions

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Charm Production from π–N Interactions

1 Incoming hadron parton distributions

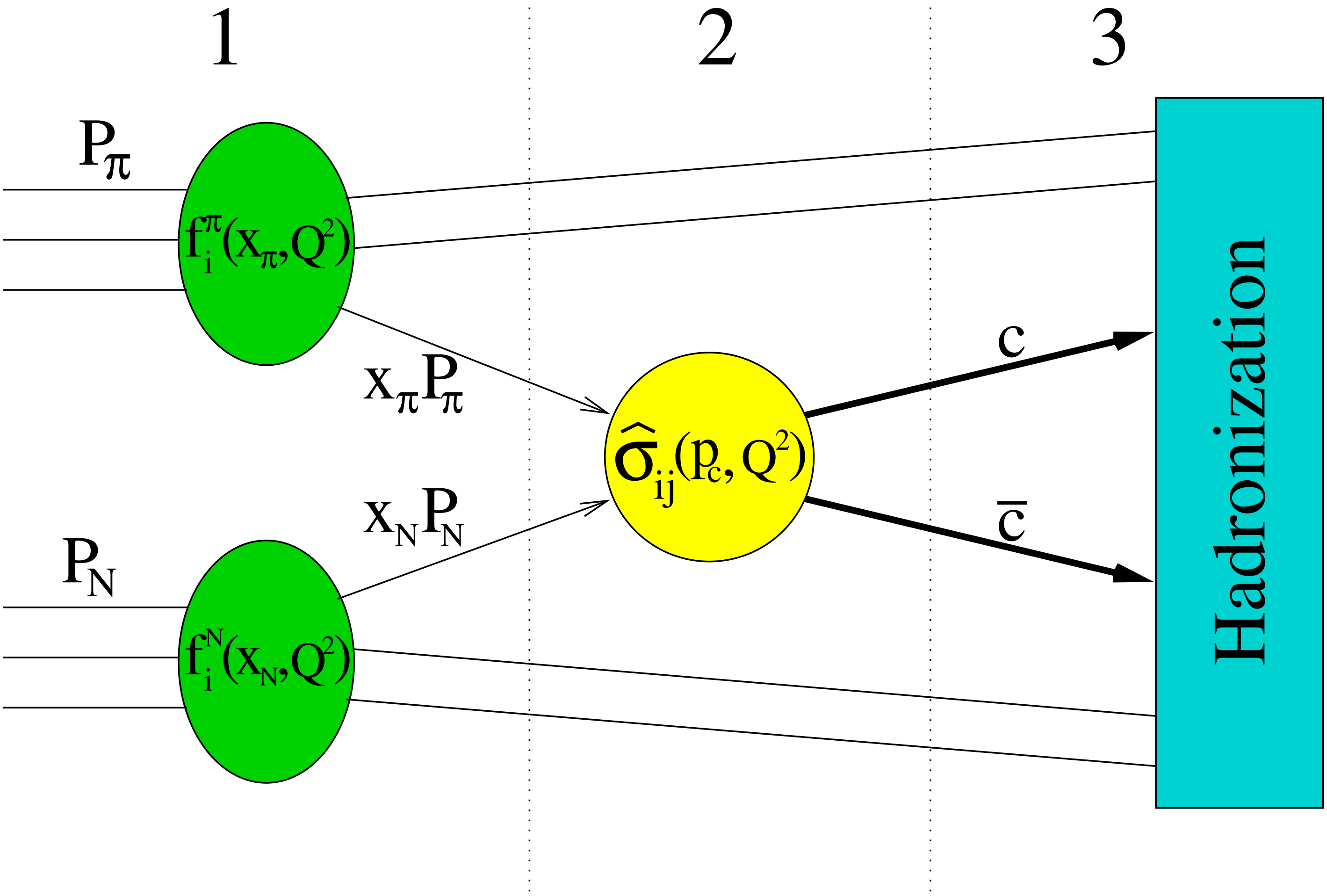
$f_i^A(x_A, Q^2)$ = probability of finding parton type i inside hadron A with momentum fraction x_A.

2 $c\bar{c}$ production from partons

Calculable? by perturbative QCD — $\hat{\sigma}_{ij}(\mathbf{p_c}, Q^2)$.
Scale $= Q^2 \gtrsim m_c^2 \sim (1.5\text{ GeV})^2$.

3 $c\bar{c}$ hadronization (fragmentation) into hadrons

Incalculable by perturbative QCD.
Scale $= Q^2 \sim \Lambda_{QCD}^2 \sim (0.3\text{ GeV})^2$.



MNR NLO vs PYTHIA/JETSET

MNR NLO

- FORTRAN program by Mangano, Nason and Ridolfi (MNR) calculates full next-to-leading order (NLO) (α_s^2 & α_s^3 terms) cross section.
- Independent (Peterson) fragmentation:
  - D meson comes from c quark with scaled momentum.
  - Works for e^+e^- collisions.
  - D meson *must* have less momentum than c quark.

PYTHIA/JETSET

- Monte Carlo event generator with leading order (α_s^2 terms) matrix elements plus parton showers (initial and final state radiation).
- Hadronization is Lund string fragmentation:
  - c quark connected by string to beam/target remnant.
  - String energy used to pop $q\bar{q}$ pairs; used to form hadrons.
  - D meson can have more momentum than c quark.

Adjustable parameters:

- intrinsic k_t of the incoming partons
- mass of the charm quark (m_c)
- factorization and renormalization scale (μ_F & μ_R)
- parton distribution functions
- PYTHIA/JETSET has many more

How to compare to theory

Measure total cross section

- Total cross section = probability of charm particle production.
- Sensitive to charm quark production.

Measure differential cross sections

- Differential cross sections = probability of charm particle production versus kinematic variables.
- Usual, orthogonal, kinematic variables are:
  - Scaled longitudinal momentum = Feynman-x = $x_F = \frac{p^*_L}{p^*_{L max}}$
  - Transverse momentum squared = p_T^2
- Sensitive to all three aspects of charm production (parton distribution functions, c-quark production, and hadronization).

Other possible measurements (not covered)

- Asymmetries
  - cross section difference between particle and antiparticle.
  - ≈0 in pQCD ⇒ measures hadronization.
- Charm-pair correlations
  - Measure correlations between D and $\overline{D}$ in the same event.
  - Transverse correlations sensitive to c-quark production.
  - Longitudinal correlations sensitive to hadronization.

The E791 Experiment

The Spectrometer

- Located in Fermilab's Tagged Photon Laboratory
- Upgrade of photoproduction experiments E516 and E691 and hadroproduction experiment E769
- 6 (17) planes of beam (vertex) silicon strip detectors
- 8 (2) planes of beam (tracking) PWC's
- 35 drift chamber planes in 4 stations
- 2 threshold Čerenkov counters
- 2 analysis magnets (same polarity)
- Electromagnetic and hadronic calorimeters
- Muon system (scintillators behind steel)

Data Sample

- 500 GeV π^- beam on platinum & diamond targets
- Collected 20 billion events on 24,000 8mm tapes during 6 months in 1991
- Hadronic interaction and loose transverse energy requirement in trigger
- Fully reconstructed more than 200,000 charm mesons

Cross Section Measurements

Assume cross section scales linearly with atomic number. This is expected for hard interactions and confirmed by measurements.

Measure:

$$\sigma(\pi^- N \rightarrow D^0 X) = \frac{N_{prod}(D^0)}{T_N\, N_{\pi^-}} \tag{1}$$

T_N = nucleons/area in target = $\sum_i \rho_i t_i N_A = \sum_i \frac{m_i\, 4}{\pi d_i^2 t_i} t_i N_A = \frac{4N_A}{\pi} \sum_i \frac{m_i}{d_i^2} =$ $1.224 \pm 0.004 \times 10^{-6}$ nucleons/μb.

N_{π^-} = number of incident π^- particles while experiment is live (from scaler).

$N_{prod}(D^0)$ = number of D^0 particles produced = $\frac{N_{rec}(D^0 \rightarrow Kn\pi)}{B(D^0 \rightarrow Kn\pi)\epsilon_{trig}\, \epsilon_{rec}(D^0 \rightarrow Kn\pi)}$.

- $N_{rec}(D^0 \rightarrow Kn\pi)$ = number of reconstructed $D^0 \rightarrow Kn\pi$ decays
- $B(D^0 \rightarrow Kn\pi)$ = $D^0 \rightarrow Kn\pi$ branching ratio from PDG
- ϵ_{trig} = trigger efficiency
- $\epsilon_{rec}(D^0 \rightarrow Kn\pi)$ = $D^0 \rightarrow Kn\pi$ reconstruction efficiency

Total cross section:

$$\sigma(\pi^- N \rightarrow D^0 X) = \frac{N_{rec}(D^0 \rightarrow Kn\pi)}{T_N\, N_{\pi^-}\, B(D^0 \rightarrow Kn\pi)\, \epsilon_{trig}\, \epsilon_{rec}(D^0 \rightarrow Kn\pi)}$$

Differential cross sections:

$$\frac{d\sigma(\pi^- N \rightarrow D^0 X\,;\, x_F)}{d\, x_F} = \frac{N_{rec}(D^0 \rightarrow Kn\pi\,;\, x_F)}{T_N\, N_{\pi^-}\, B(D^0 \rightarrow Kn\pi)\, \epsilon_{trig}\, \epsilon_{rec}(D^0 \rightarrow Kn\pi\,;\, x_F)}$$

$$\frac{d\sigma(\pi^- N \rightarrow D^0 X\,;\, p_T^2)}{d\, p_T^2} = \frac{N_{rec}(D^0 \rightarrow Kn\pi\,;\, p_T^2)}{T_N\, N_{\pi^-}\, B(D^0 \rightarrow Kn\pi)\, \epsilon_{trig}\, \epsilon_{rec}(D^0 \rightarrow Kn\pi\,;\, p_T^2)}$$

Obtaining $N_{rec}(D^0 \to Kn\pi)$

Event Reconstruction

- Make tracks from hits in silicon and wire chambers.
- Get momentum from bend due to magnets.
- Form vertices by combining tracks.
- Calculate invariant mass of secondary vertex.

Event Selection

- Choose D^0 — most produced ground state charm particle.
- Choose $D^0 \to K\pi, K\pi\pi\pi$ — large BR and all-charged decay.
- Loose selection criteria to minimize systematic errors:
  - primary-secondary longitudinal vertex separation greater than 8-11 $\sigma_{\Delta z}$ — best indication of charm
  - secondary vertex out of material by 0-8 σ_z — eliminates secondary interactions
  - p_T of D candidate relative to primary-secondary line-of-flight less than 0.40 GeV/c — ensures well reconstructed D
- Also require:
  - No four-target runs.
  - No events with primary in Pt target – veto problem.
  - No "bad" runs.
  - No runs with missing or inaccurate scaler data.

Signal Measurement

- Fit with Gaussian signal and polynomial background function.
- Normalized mass ($m_n = \frac{m_{Kn\pi} - m_{D^0}}{\sigma_{Kn\pi}}$) provides better signal measurement because it accounts for resolution variations.

Obtaining $\epsilon_{rec}(D^0 \to K n\pi)$

The E791 Monte Carlo

- Uses PYTHIA/JETSET as the event generator.
- Simulates interactions, noise, efficiencies, geometry, *etc.*
- Produces fake data; processed like real data.

Acceptance

- Generate $N_{gen}^{MC}(D^0 \to K n\pi)$ events.
- Reconstruct $N_{rec}^{MC}(D^0 \to K n\pi)$ events.
- $\epsilon_{rec}(D^0 \to K n\pi) = N_{rec}^{MC}(D^0 \to K n\pi) / N_{gen}^{MC}(D^0 \to K n\pi)$
- $\epsilon_{rec}(D^0 \to K n\pi)$ calculated in bins of x_F (p_T^2), integrating over p_T^2 (x_F) and all other variables.
  - Integration is correct procedure *only* if variables being integrated out agree with data *or* have no affect on acceptance.
  - Force agreement by weighting generated *and* reconstructed Monte Carlo.
  - Weight D^0 x_F, D^0 p_T^2, D^0 lifetime, and summed p_T of event.

Obtaining ϵ_{trig}

Source of inefficiency	Efficiency
Interaction trigger	100%
E_T trigger	99.6±0.4%
Trigger vetos	70.3±4.3%
Tape reading/writing	97.6±1.0%
Total	68.3±4.4%

- Interaction trigger required >4.5 minimum ionizing particle (MIP) signal in interaction counter.
- E_T trigger required >3 GeV in calorimeter transverse energy.
- Vetoes required:
  - <2 MIP signal in beam counter
  - <800 GeV in calorimeters
  - No hit in interaction counter within ±78 ns of triggering bucket
- Veto error comes from difference between two measurements.
- Tape reading/writing inefficiency is due to tape failures; error is due to database inconsistencies.

Systematic Errors

Total Forward D^0 Cross Section Errors

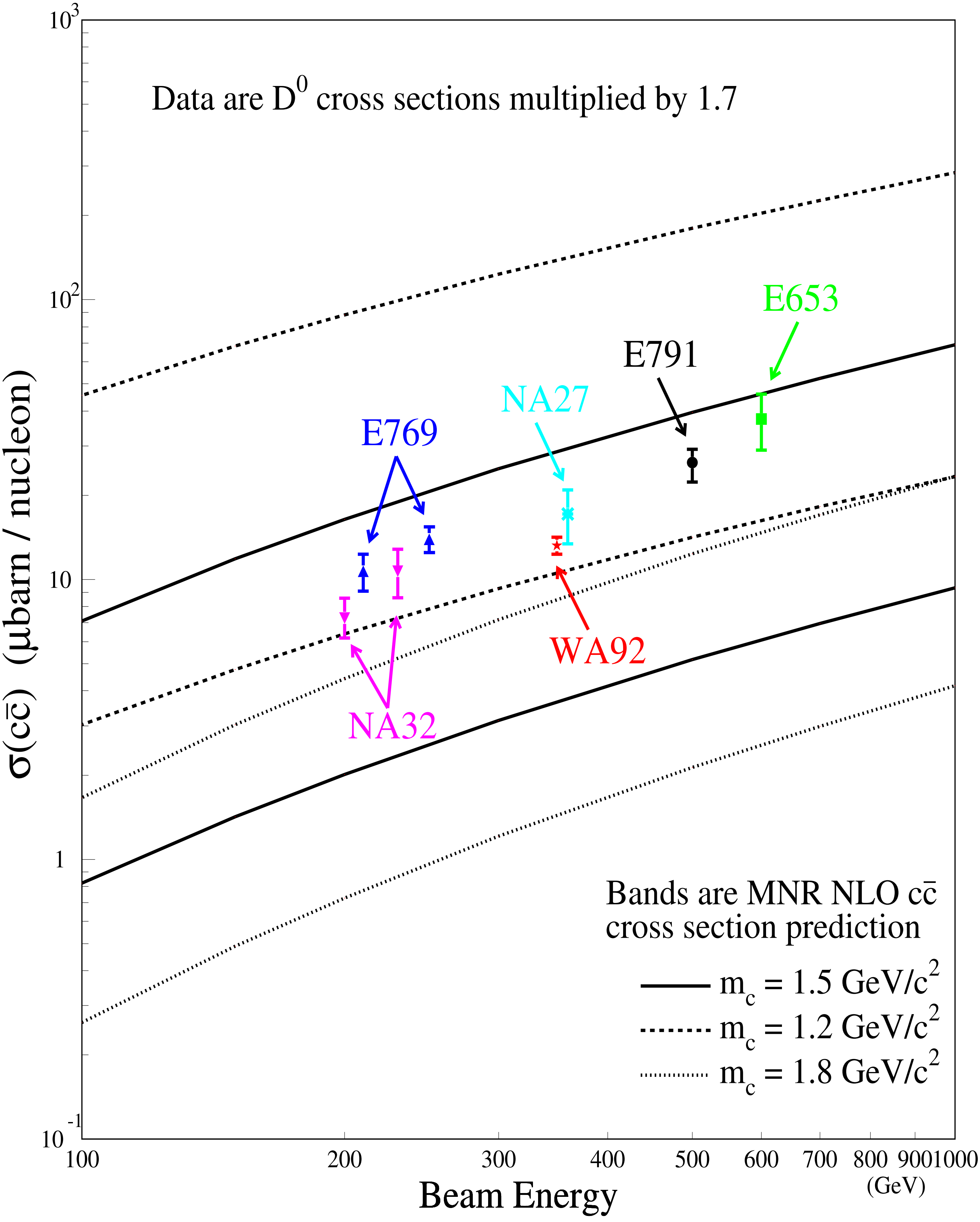
Error source	Relative Error (%)		
	$K\pi$	$K\pi\pi\pi$	D^0
$K\pi$ & $K\pi\pi\pi$ independent errors	$^{+4.1}_{-8.7}$	$^{+5.0}_{-9.6}$	$^{+4.2}_{-7.1}$
Statistics	± 1.0	± 2.8	
SDZ cut efficiency modeling	$^{+0.1}_{-0.0}$	$^{+1.2}_{-0.0}$	
MC background function	$^{+0.0}_{-5.5}$	$^{+0.0}_{-6.0}$	
D^0 signal width in fits	$^{+4.0}_{-4.1}$	$^{+3.9}_{-4.4}$	
Correlated systematic errors			$^{+7.0}_{-10.2}$
Lifetime weighting	$^{+0.6}_{-0.5}$		
MC weighting technique	$^{+0.0}_{-2.3}$		
MC production model	$^{+5.9}_{-5.1}$		
Run weighting	$^{+1.0}_{-2.0}$		
Tracking and vertexing ($K\pi\pi\pi/K\pi$ BR)			± 4.6
Trigger efficiency			± 6.4
T_N measurement			± 0.3
Total forward cross section error			$^{+11.4}_{-14.7}$

MC production model, trigger efficiency, and T_N measurement errors do not affect differential cross section shapes.

Tracking and vertexing errors have little effect on p_T^2 shape.

Total Forward D^0 Cross Section

- Measure by adding up x_F bins >0.
- Find $\sigma(D^0/\overline{D}^0\,; x_F > 0) = 15.4^{+1.8}_{-2.3}$ μbarns/nucleon.
- Must convert D^0 forward cross section to $c\overline{c}$ total cross section.
  - Multiply by 1.6 to account for x_F<0 contribution.
  - Multiply by 2.1 to account for D^+, D_s^+, and Λ_c^+.
  - Divide by 2 to convert from single charm to double charm production.
- All D^0 cross sections multiplied by $\frac{1.6\times 2.1}{2} = 1.7$.
- The data agree remarkably well and show same trend as NLO prediction.
- Data and theory comparison is free of hadronization effects but theoretical uncertainties (due to m_c and μ_R) are large.
- Within the large theoretical errors, the data agree.



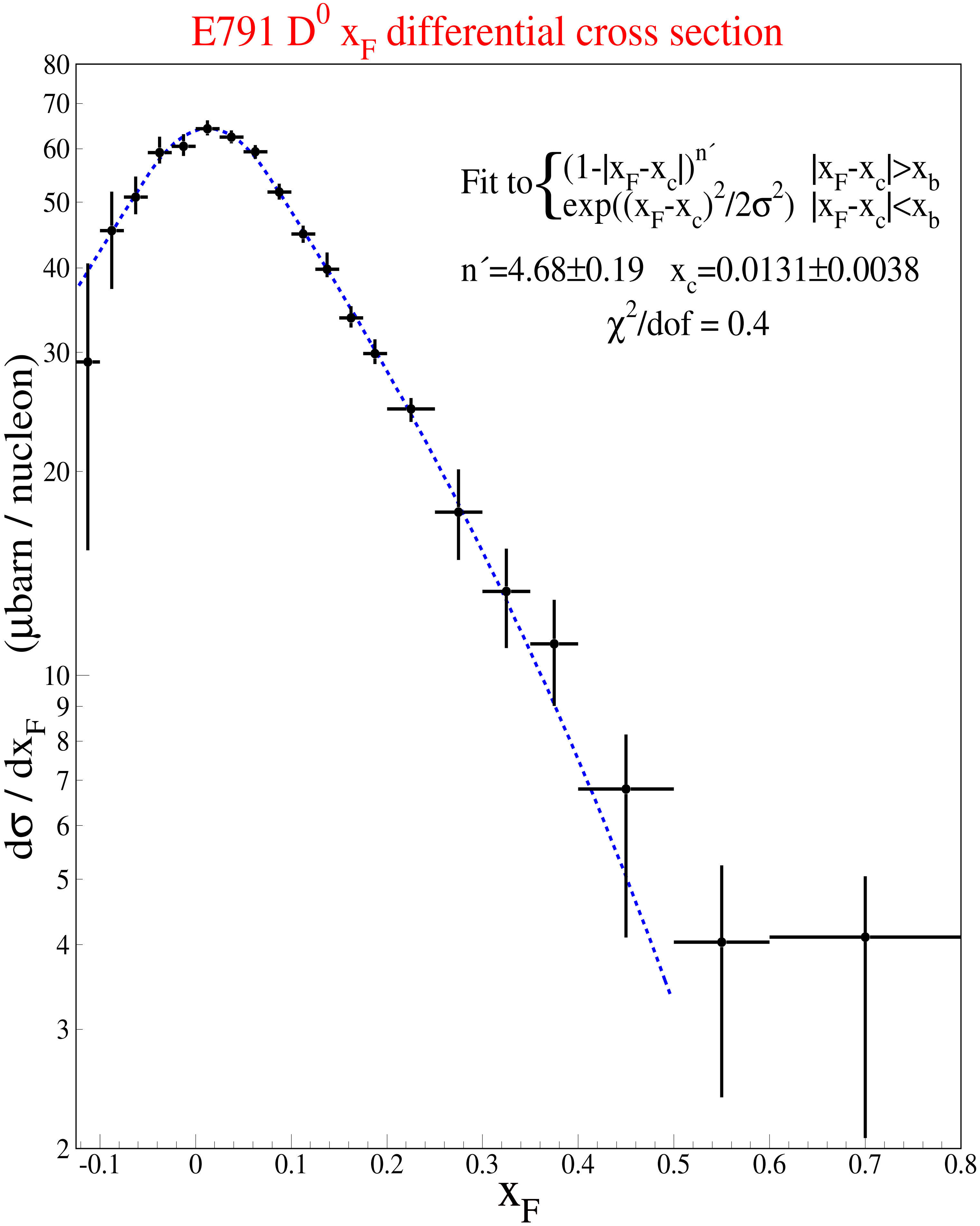
Data are D^0 cross sections multiplied by 1.7
E653
E791
NA27
E769
WA92
NA32
Bands are MNR NLO $c\bar{c}$
cross section prediction
m_c = 1.5 GeV/c^2
m_c = 1.2 GeV/c^2
m_c = 1.8 GeV/c^2
$\sigma(c\bar{c})$ (μbarn / nucleon)
Beam Energy
(GeV)
10^{-1}
1
10
10^2
10^3
100
200
300
400
500
600
700
800
900
1000

Differential D^0 Cross Sections

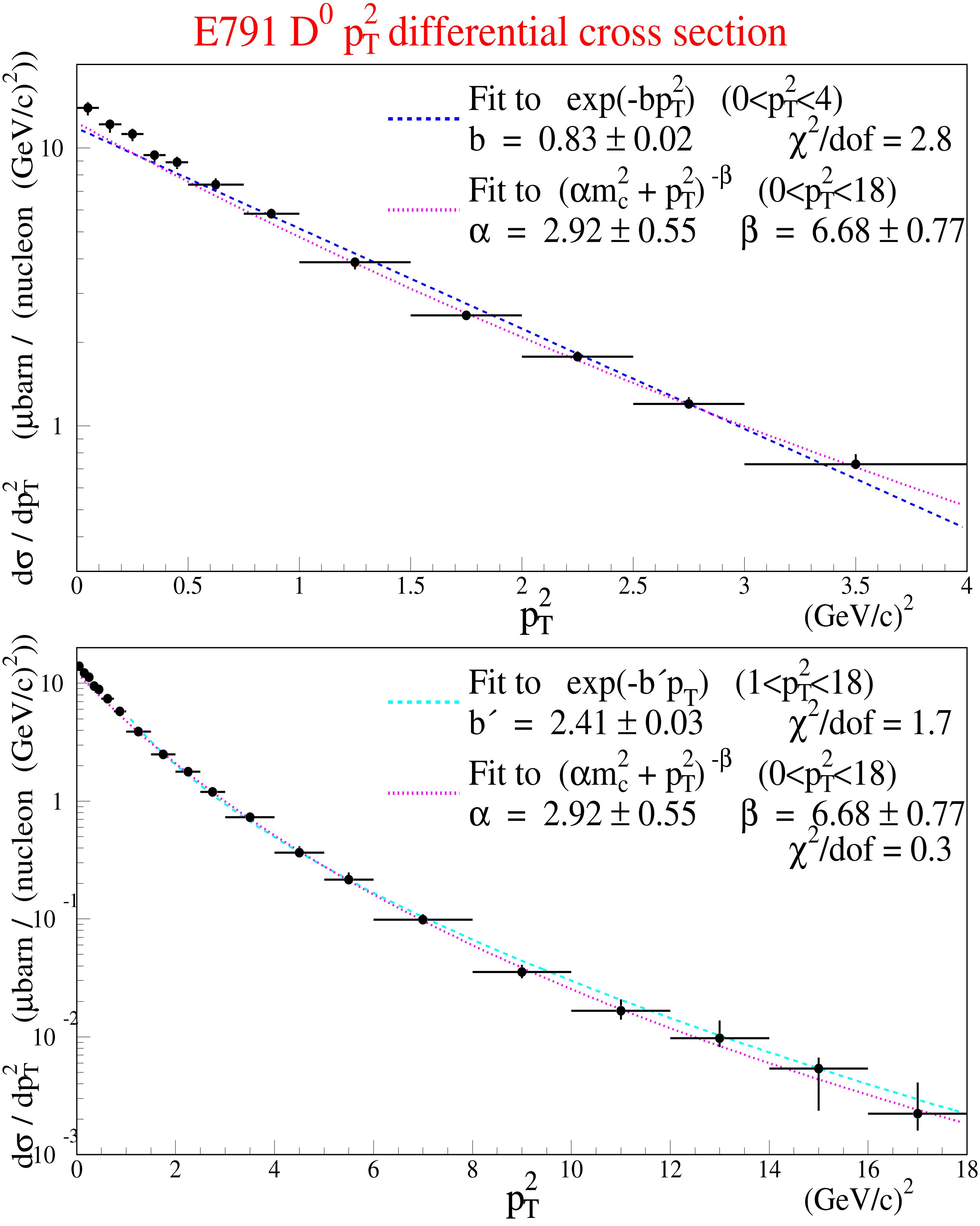
- Shapes of x_F and p_T^2 distributions are sensitive to PDF's, c-quark production, and hadronization.
- High statistics clearly show x_F turnover point which is greater than zero as expected from PDF's.
- p_T^2 data out to 18 (GeV/c)^2.
- Default NLO QCD c quark prediction agrees with data. Implies cancelation of non-perturbative effects.
- Default PYTHIA predicts too much dragging.
- Some discrepancies with recent 350 GeV WA92 data.

Fits to $\frac{d\sigma(D^0/\overline{D}^0)}{dx_F} = A(1-x_F)^n$, and $\frac{d\sigma(D^0/\overline{D}^0)}{dp_T^2} = Ae^{-bp_T^2},\ Ae^{-b'p_T}$ yield:

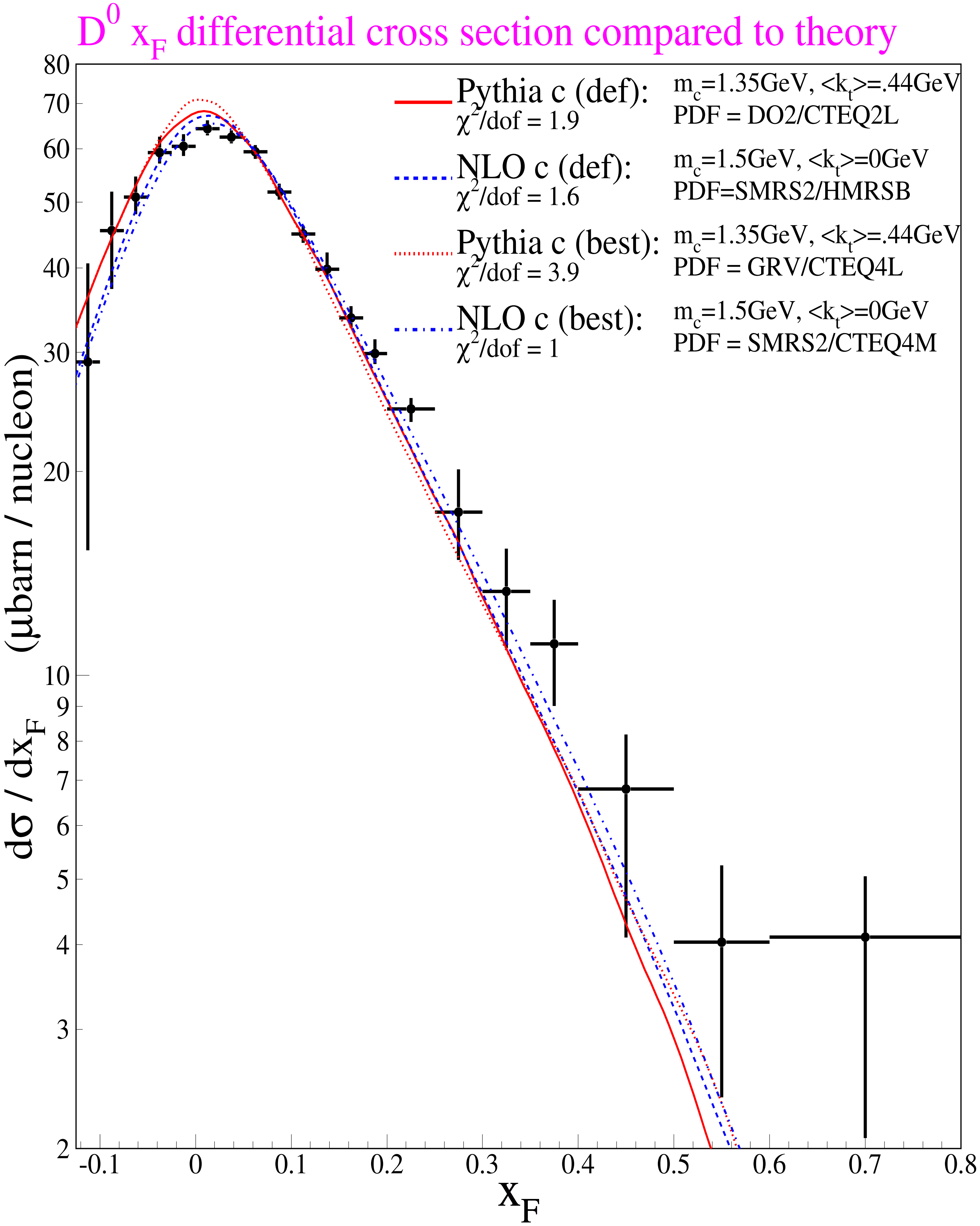
Experiment	E791	WA92	E769
Energy (GeV)	500	350	250
x_F Range	0.05–0.5	0.0–0.8	0.0–0.8
n	4.61±0.19	4.27±0.11	4.03±0.18
p_T^2 Range	0–4	0–7	0–4
b (GeV/c)$^{-2}$	0.83±0.02	0.89±0.02	1.08±0.05
p_T^2 Range	1–18		1–16
b' (GeV/c)$^{-1}$	2.41±0.03		2.74±0.09



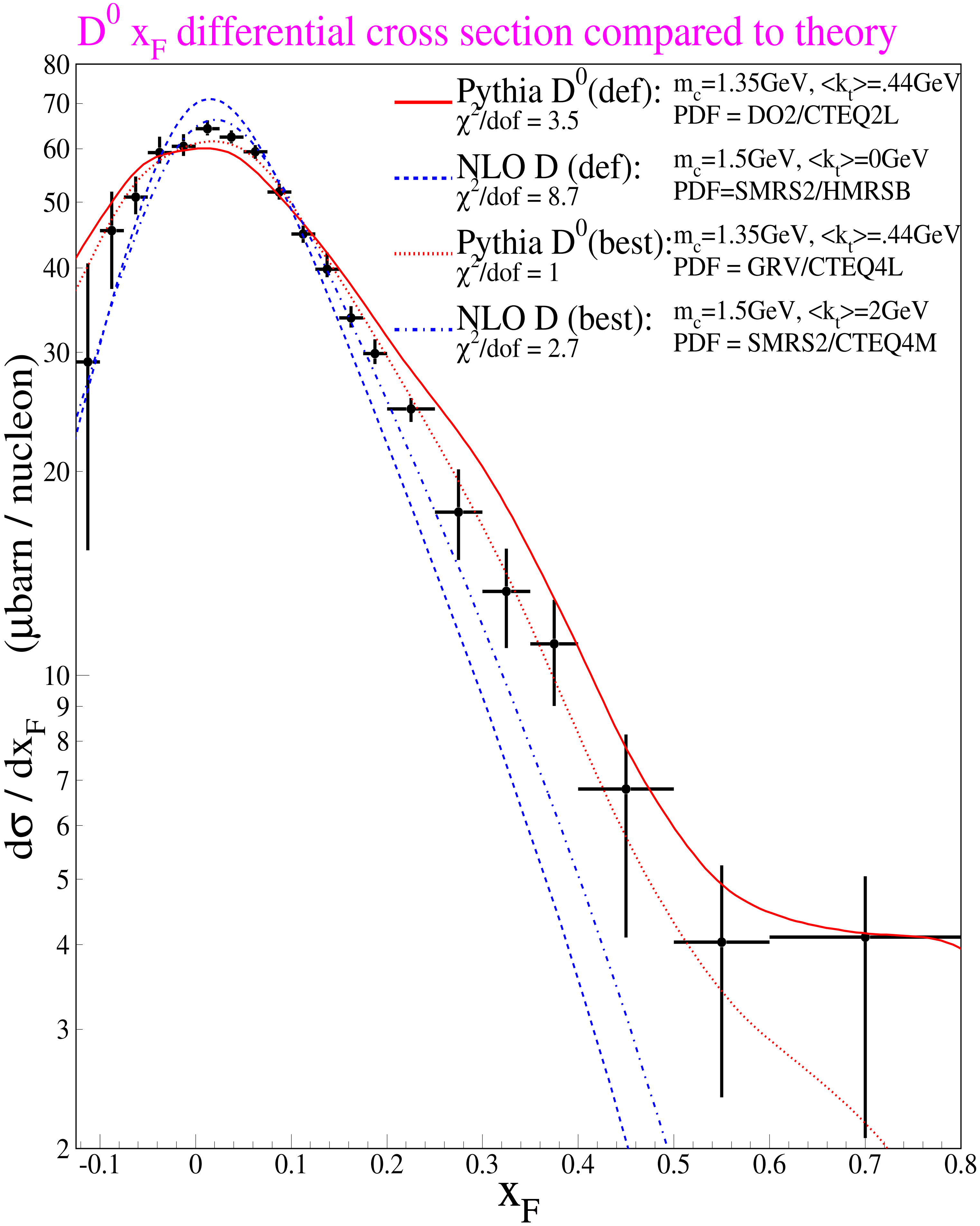
E791 D^0 x_F differential cross section
Fit to $\begin{cases}(1-|x_F-x_c|)^{n'} & |x_F-x_c|>x_b\\ \exp((x_F-x_c)^2/2\sigma^2) & |x_F-x_c|<x_b\end{cases}$
$n'=4.68\pm0.19$ $x_c=0.0131\pm0.0038$
$\chi^2/\text{dof} = 0.4$
$d\sigma / dx_F$ (μbarn / nucleon)
x_F



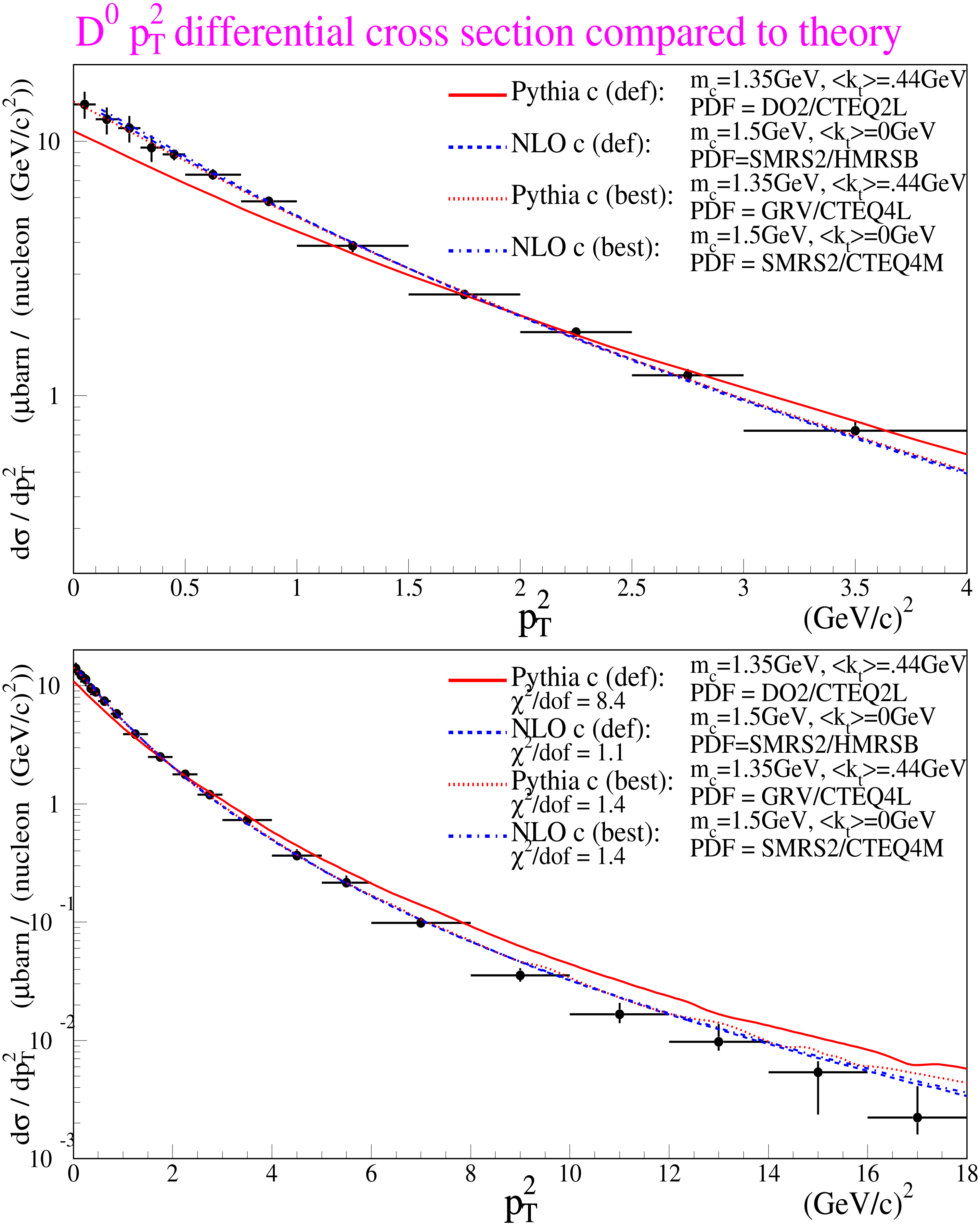
E791 D^0 p_T^2 differential cross section
Fit to $\exp(-bp_T^2)$ $(0<p_T^2<4)$
$b = 0.83 \pm 0.02$ $\chi^2/dof = 2.8$
Fit to $(\alpha m_c^2 + p_T^2)^{-\beta}$ $(0<p_T^2<18)$
$\alpha = 2.92 \pm 0.55$ $\beta = 6.68 \pm 0.77$
$d\sigma / dp_T^2$ $(\mu barn / (nucleon (GeV/c)^2))$
p_T^2 $(GeV/c)^2$
Fit to $\exp(-b' p_T)$ $(1<p_T^2<18)$
$b' = 2.41 \pm 0.03$ $\chi^2/dof = 1.7$
Fit to $(\alpha m_c^2 + p_T^2)^{-\beta}$ $(0<p_T^2<18)$
$\alpha = 2.92 \pm 0.55$ $\beta = 6.68 \pm 0.77$
$\chi^2/dof = 0.3$
$d\sigma / dp_T^2$ $(\mu barn / (nucleon (GeV/c)^2))$
p_T^2 $(GeV/c)^2$

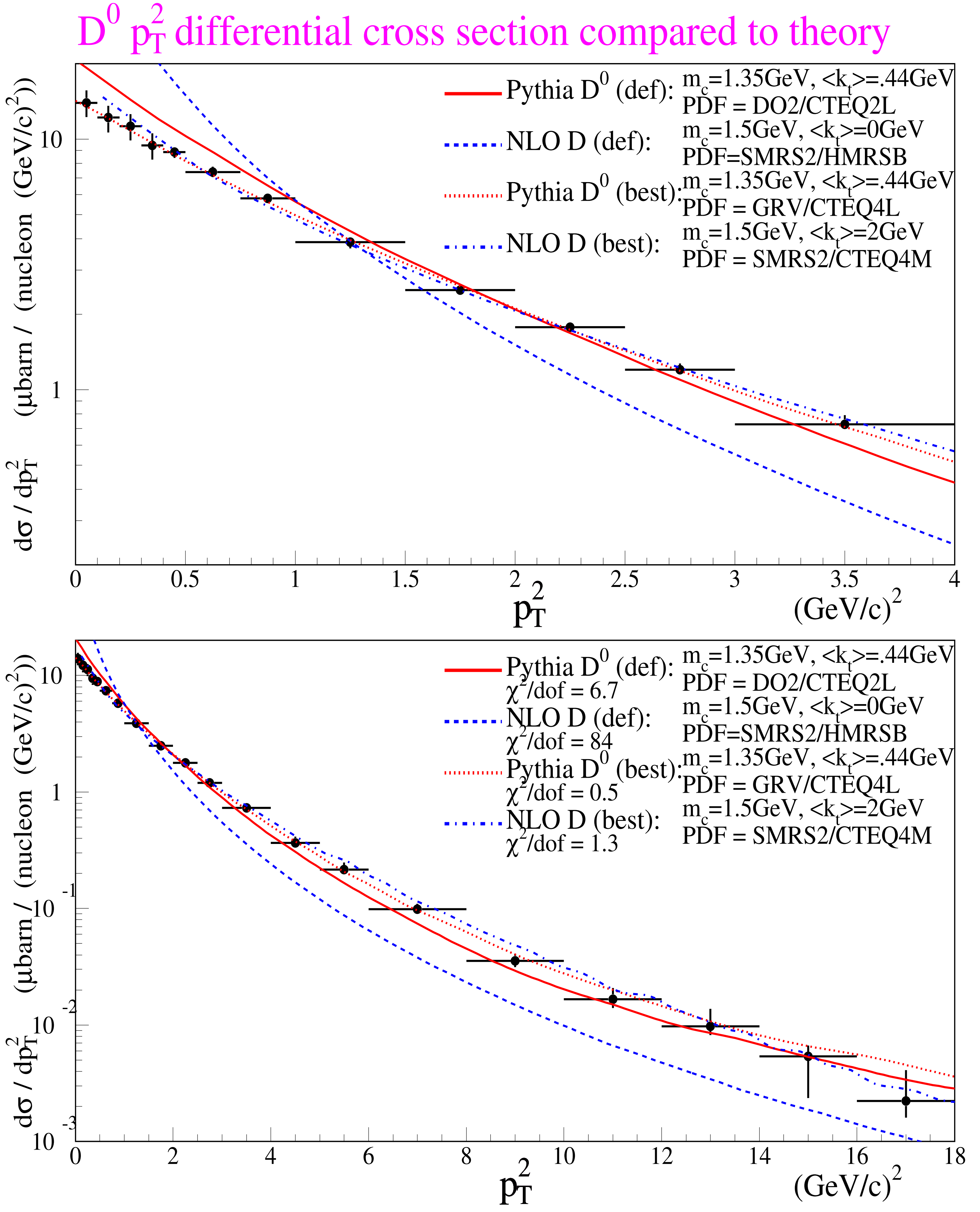


D0 xF differential cross section compared to theory
Pythia c (def): χ2/dof = 1.9
mc=1.35GeV, <kt>=.44GeV
PDF = DO2/CTEQ2L
NLO c (def): χ2/dof = 1.6
mc=1.5GeV, <kt>=0GeV
PDF=SMRS2/HMRSB
Pythia c (best): χ2/dof = 3.9
mc=1.35GeV, <kt>=.44GeV
PDF = GRV/CTEQ4L
NLO c (best): χ2/dof = 1
mc=1.5GeV, <kt>=0GeV
PDF = SMRS2/CTEQ4M
dσ / dxF (μbarn / nucleon)
xF

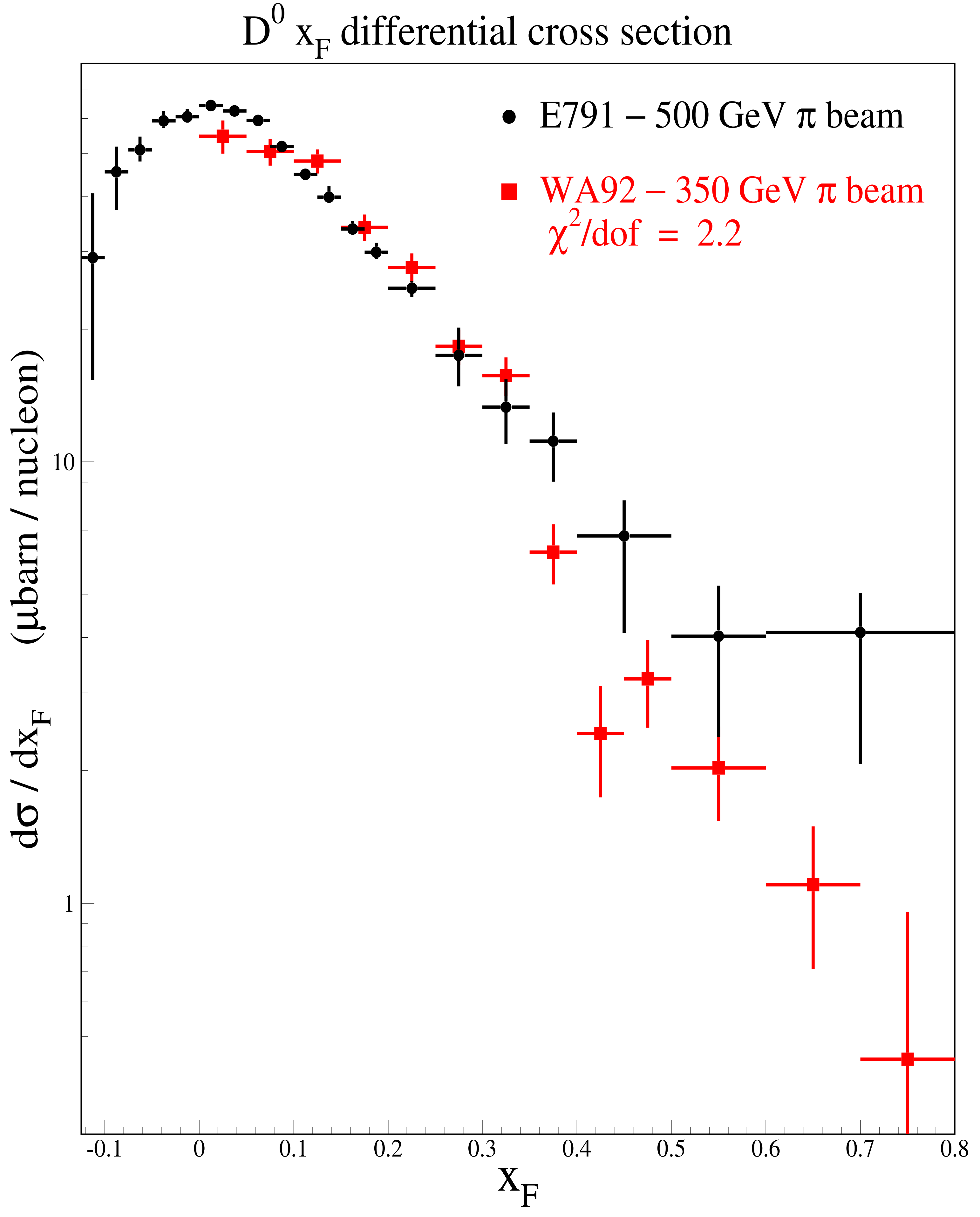


D^0 x$_F$ differential cross section compared to theory
Pythia D^0(def): χ^2/dof = 3.5
m$_c$=1.35GeV, <k$_t$>=.44GeV
PDF = DO2/CTEQ2L
NLO D (def): χ^2/dof = 8.7
m$_c$=1.5GeV, <k$_t$>=0GeV
PDF=SMRS2/HMRSB
Pythia D^0(best): χ^2/dof = 1
m$_c$=1.35GeV, <k$_t$>=.44GeV
PDF = GRV/CTEQ4L
NLO D (best): χ^2/dof = 2.7
m$_c$=1.5GeV, <k$_t$>=2GeV
PDF = SMRS2/CTEQ4M
dσ / dx$_F$ (μbarn / nucleon)
x$_F$

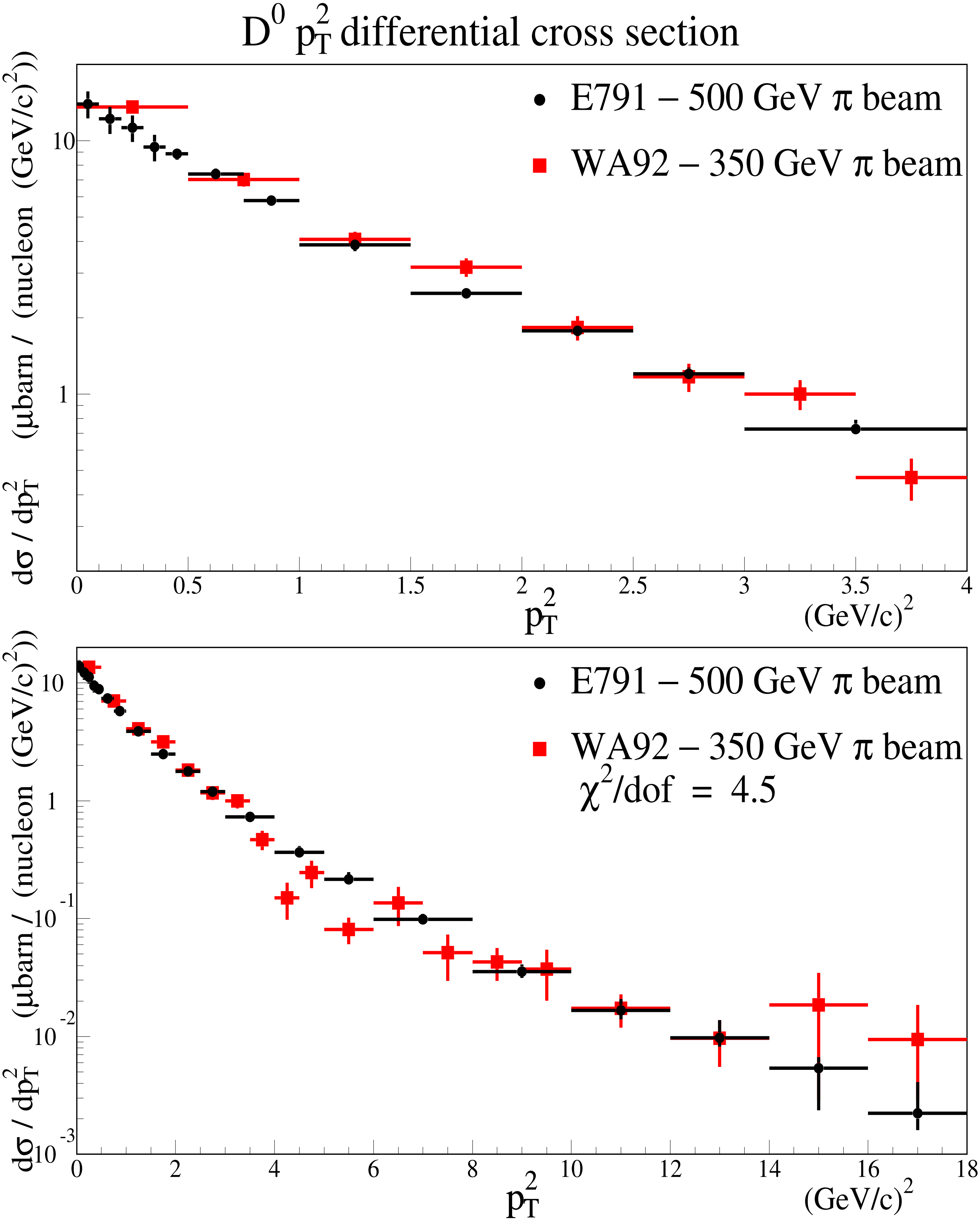

D0 pT2 differential cross section compared to theory
Pythia c (def):
mc=1.35GeV, <kt>=.44GeV
PDF = DO2/CTEQ2L
NLO c (def):
mc=1.5GeV, <kt>=0GeV
PDF=SMRS2/HMRSB
Pythia c (best):
mc=1.35GeV, <kt>=.44GeV
PDF = GRV/CTEQ4L
NLO c (best):
mc=1.5GeV, <kt>=0GeV
PDF = SMRS2/CTEQ4M
dσ / dpT2 (μbarn / (nucleon (GeV/c)2))
pT2
(GeV/c)2
Pythia c (def):
χ2/dof = 8.4
NLO c (def):
χ2/dof = 1.1
Pythia c (best):
χ2/dof = 1.4
NLO c (best):
χ2/dof = 1.4



D0 pT2 differential cross section compared to theory
Pythia D0 (def): mc=1.35GeV, <kt>=.44GeV PDF = DO2/CTEQ2L
NLO D (def): mc=1.5GeV, <kt>=0GeV PDF=SMRS2/HMRSB
Pythia D0 (best): mc=1.35GeV, <kt>=.44GeV PDF = GRV/CTEQ4L
NLO D (best): mc=1.5GeV, <kt>=2GeV PDF = SMRS2/CTEQ4M
χ2/dof = 6.7
χ2/dof = 84
χ2/dof = 0.5
χ2/dof = 1.3
dσ / dpT2 (μbarn / (nucleon (GeV/c)2))
pT2 (GeV/c)2



D0 xF differential cross section
E791 – 500 GeV π beam
WA92 – 350 GeV π beam
χ2/dof = 2.2
dσ / dxF (μbarn / nucleon)
10
1
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
xF



D^0 p_T^2 differential cross section
$d\sigma / dp_T^2$ (μbarn / (nucleon (GeV/c)^2))
p_T^2
(GeV/c)^2
E791 – 500 GeV π beam
WA92 – 350 GeV π beam
χ^2/dof = 4.5

Conclusions

- Still no chinks in the QCD armor.
- The data basically agree with previous experiments.
- The data provide information which can help select theories and/or parameters.
  - Modern PDF's are preferred.
  - Peterson fragmentation requires very large intrinsic k_t ($\gtrsim$ 2 GeV/c) to work.
  - Lund string fragmentation can work.
- Large theoretical uncertainties imply no single result can uniquely determine the physics of charm production.
- Synthesizing all E791 results and results from other experiments might provide a coherent picture.