Charm production in 400GeV proton collisions

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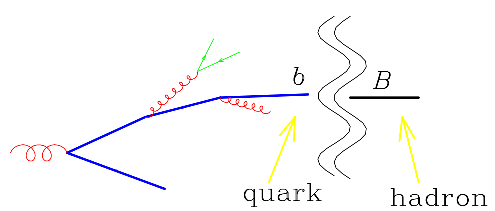
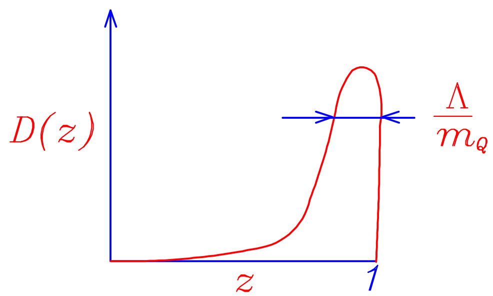
9th SHiP Collaboration Meeting
CERN,23-25 November 2016

Heavy quark production

- In general for bottom and charm production in hadronic collisions one finds large radiative corrections, and thus one expects large unknown higher order terms
- Non perturbative effects (suppressed by powers of Λ/m_Q) play a role (no theory for them)
- Still, understanding to what extent we can trust the theoretical machinery (factorization theorem) is extremely important
- We have to try models and compare with data:

Fragmentation





width of the distribution is $\approx \alpha_s \log p_T/m_Q$

- simple model a la Peterson not justified in hadron collisions

Intrinsic Transverse Momentum

- Assuming that incoming partons have

$$\langle k_T \rangle \sim \Lambda$$

- perturbation theory generates

$$k_T \sim \alpha_S \cdot hard\ scale$$

- Affect transverse momentum of heavy quark pair, its azimuthal correlation and single transverse momentum distribution

Monte Carlo models of hadronization

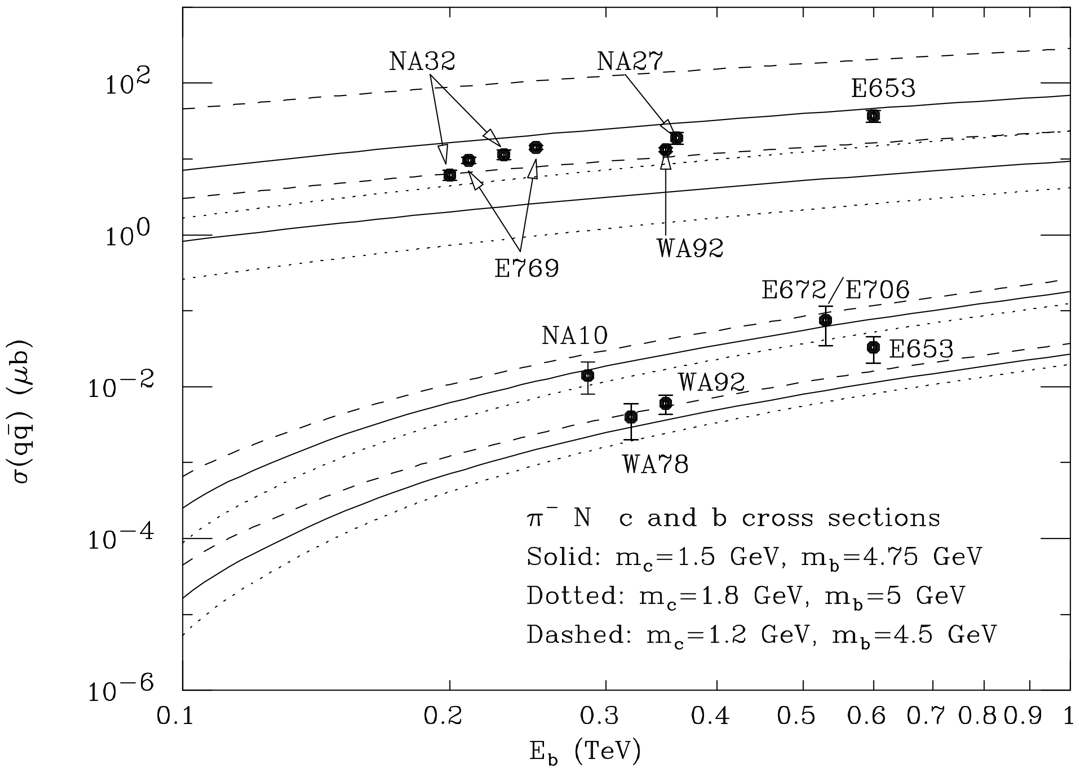
- Much more effects, for example:
  - Color Drag, from projectile remnants
  - leading particle enhancement
  - asymmetries

Total Cross Sections:

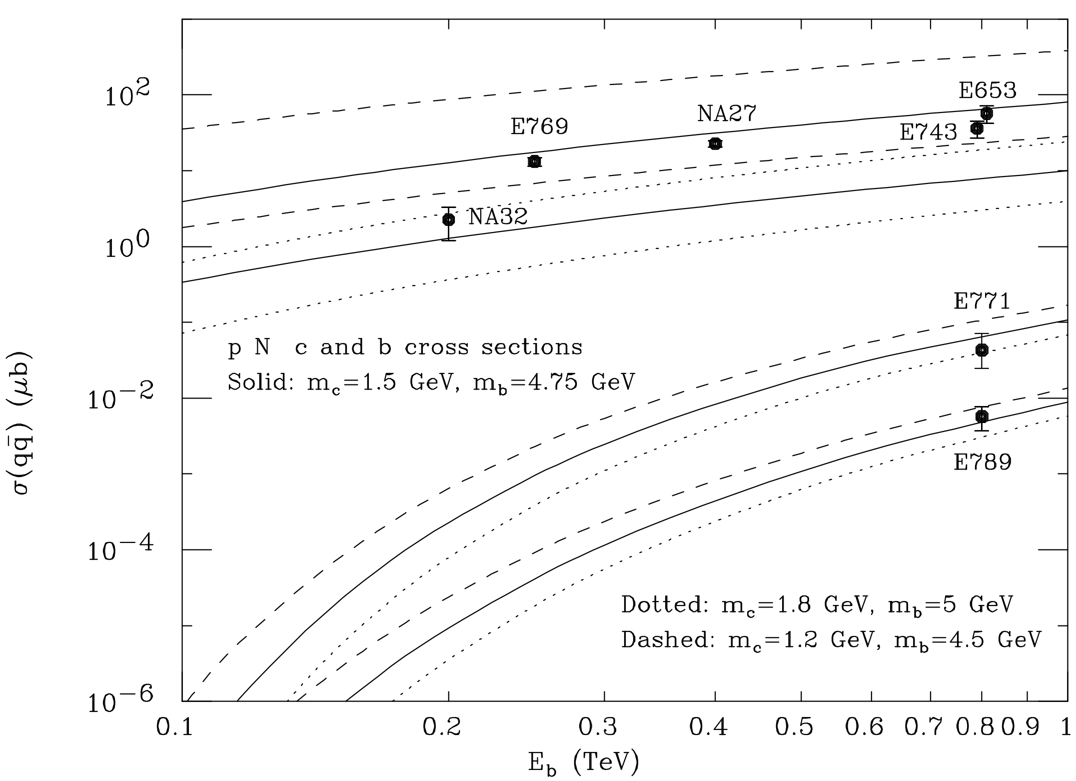
[Frixione et al PR 1997]

$q\bar{q}$ annihilation is the main channel at SHiP energies

$\pi N \to D\,D$



$pN \to D\,D$



	E_b (GeV)	σ (total) or σ_+ ($x_F > 0$) (μb)	$\sigma_{D\bar{D}}$ (μb)	D^+/D^0
pN [Kodama91]	800	$\sigma(D^0/\bar{D}^0) = 38 \pm 3 \pm 13$ $\sigma(D^+/D^-) = 38 \pm 9 \pm 14$	38 ± 10	1.0 ± 0.6
pN [Barlag88]	200	$\sigma_+(D/\bar{D}) = 1.5 \pm 0.7 \pm 0.1$	1.5 ± 0.7	—
pp [Ammar88]	800	$\sigma(D^0/\bar{D}^0) = 22^{+9}_{-7} \pm 5$ $\sigma(D^+/D^-) = 26 \pm 4 \pm 6$	24 ± 6	1.2 ± 0.6
pp [Aguilar88]	400	$\sigma(D^0/\bar{D}^0) = 18.3 \pm 2.5$ $\sigma(D^+/D^-) = 11.9 \pm 1.5$	15.1 ± 1.5	0.7 ± 0.1
pN [Alves96]	250	$\sigma_+(D^0/\bar{D}^0) = 5.6 \pm 1.3 \pm 1.5$ $\sigma_+(D^+/D^-) = 3.2 \pm 0.4 \pm 0.3$	8.8 ± 1.5	0.57 ± 0.22
$\pi^- p$ [Aguilar85a]	360	$\sigma_+(D^0/\bar{D}^0) = 10.1 \pm 2.2$ $\sigma_+(D^+/D^-) = 5.7 \pm 1.6$	12.6 ± 2.2	0.6 ± 0.2
$\pi^- N$ [Barlag91]	230	$\sigma_+(D^0/\bar{D}^0) = 6.3 \pm 0.3 \pm 1.2$ $\sigma_+(D^+/D^-) = 3.2 \pm 0.2 \pm 0.7$	7.6 ± 1.1	0.5 ± 0.2
$\pi^- N$ [Barlag88]	200	$\sigma_+(D^0/\bar{D}^0) = 3.4^{+0.5}_{-0.4} \pm 0.3$ $\sigma_+(D^+/D^-) = 1.7^{+0.4}_{-0.3} \pm 0.1$	$4.1^{+0.6}_{-0.5}$	0.5 ± 0.1
$\pi^- N$ [Kodama92]	600	$\sigma_+(D^0/\bar{D}^0) = 22.05 \pm 1.37 \pm 4.82$ $\sigma_+(D^+/D^-) = 8.66 \pm 0.46 \pm 1.96$	24.6 ± 4.3	0.4 ± 0.1
$\pi^- N$ [Alves96]	210	$\sigma_+(D^0/\bar{D}^0) = 6.3 \pm 0.9 \pm 0.3$ $\sigma_+(D^+/D^-) = 1.7 \pm 0.3 \pm 0.1$	6.4 ± 0.8	0.27 ± 0.06
$\pi^- N$ [Alves96]	250	$\sigma_+(D^0/\bar{D}^0) = 8.2 \pm 0.7 \pm 0.5$ $\sigma_+(D^+/D^-) = 3.6 \pm 0.2 \pm 0.2$	9.4 ± 0.7	0.44 ± 0.06
$\pi^+ N$ [Alves96]	250	$\sigma_+(D^0/\bar{D}^0) = 5.7 \pm 0.8 \pm 0.4$ $\sigma_+(D^+/D^-) = 2.6 \pm 0.3 \pm 0.2$	6.6 ± 0.8	0.46 ± 0.09
$\pi^- N$ [Adamovich96]	350	$\sigma_+(D^0/\bar{D}^0) = 7.78 \pm 0.14 \pm 0.52$ $\sigma_+(D^+/D^-) = 3.28 \pm 0.08 \pm 0.29$	8.8 ± 0.5	0.42 ± 0.05

Distributions

- Data for proton collisions at energies close to 400GeV not available
- several πN experimental results

➡ pion pdf fitted using DY muon pair production

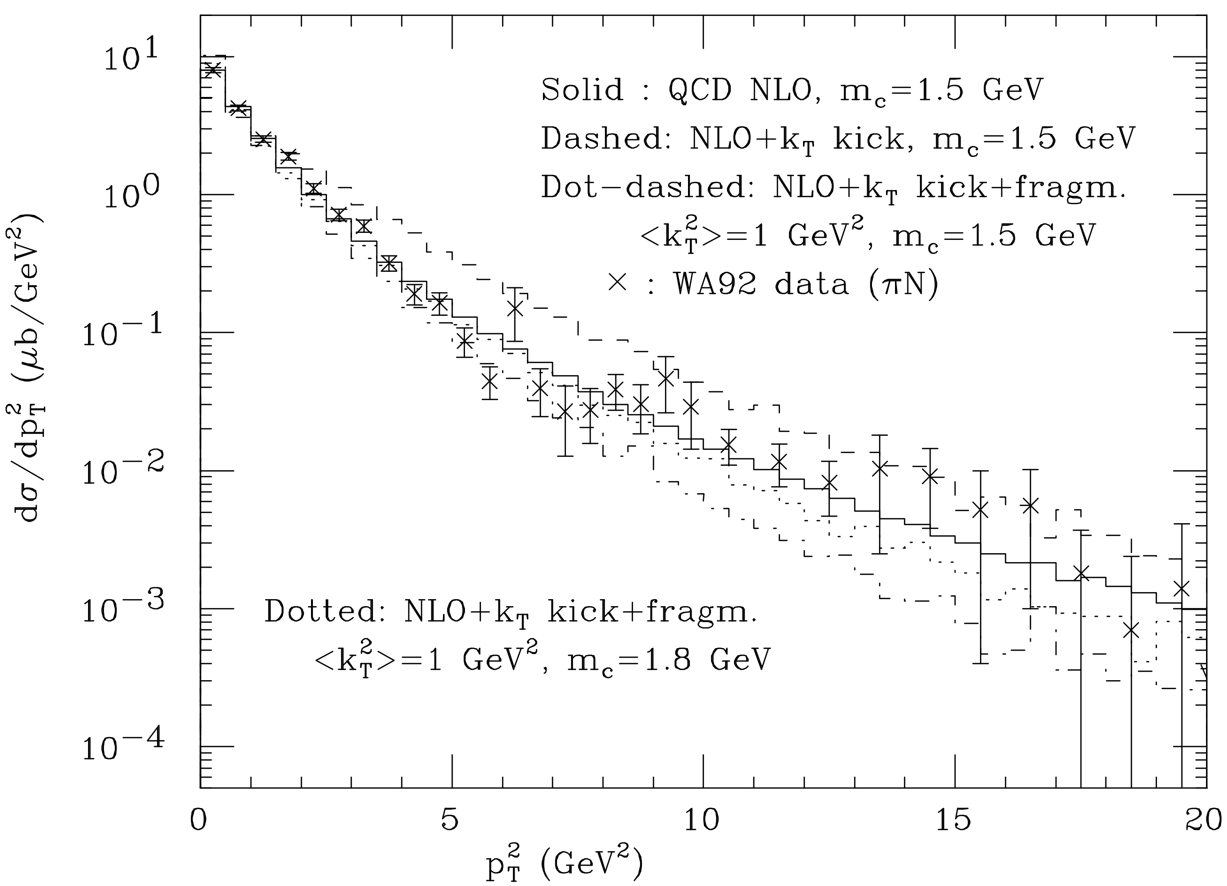
  - NA10 with pions at 196GeV and 286GeV (155k events)
  - E615 with pions at 252GeV (35k events)

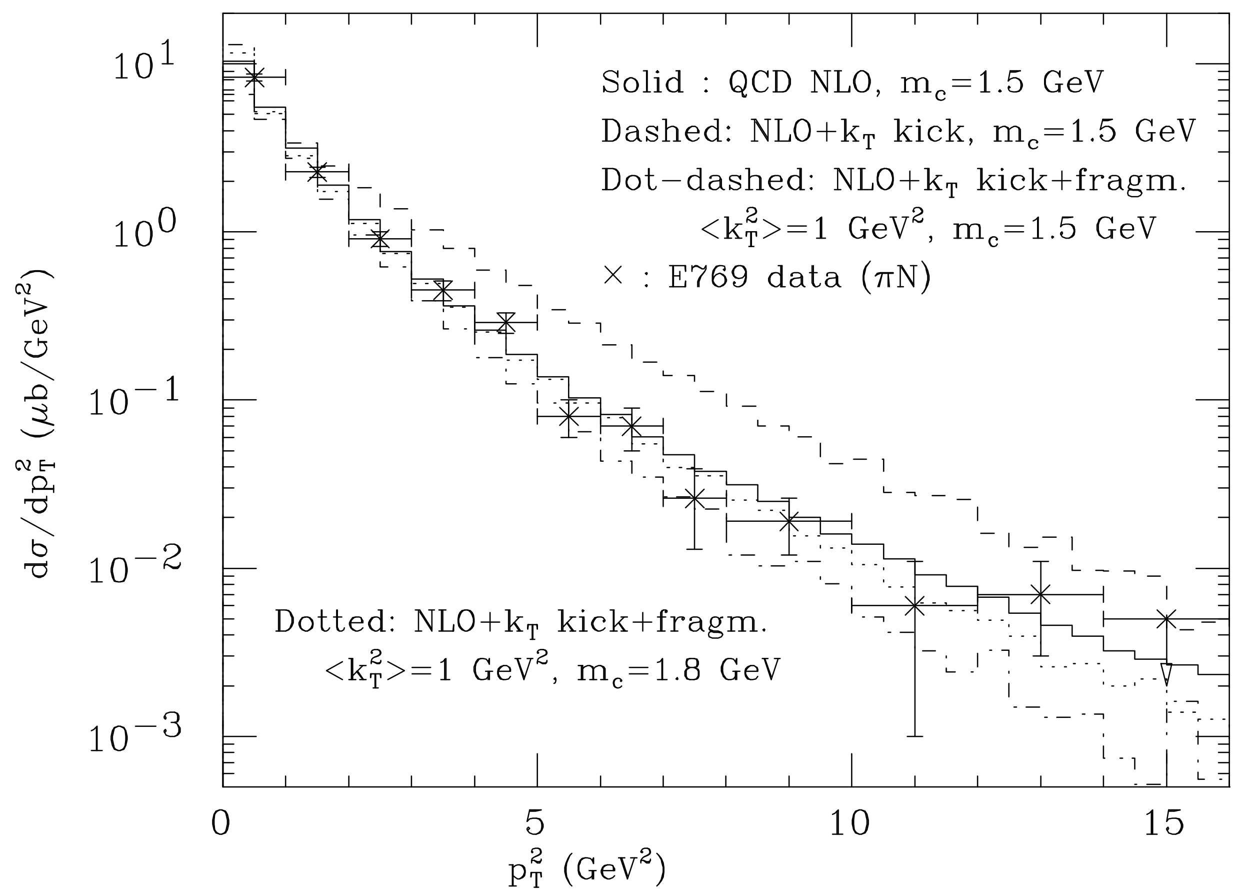
➡ No data available to fit pion pdf at $x \lesssim 0.2$

➡ several sets available that differ for the assumptions on the sea, even using them to estimate pdf uncertainty this could be underestimated

Distributions: p_T^2

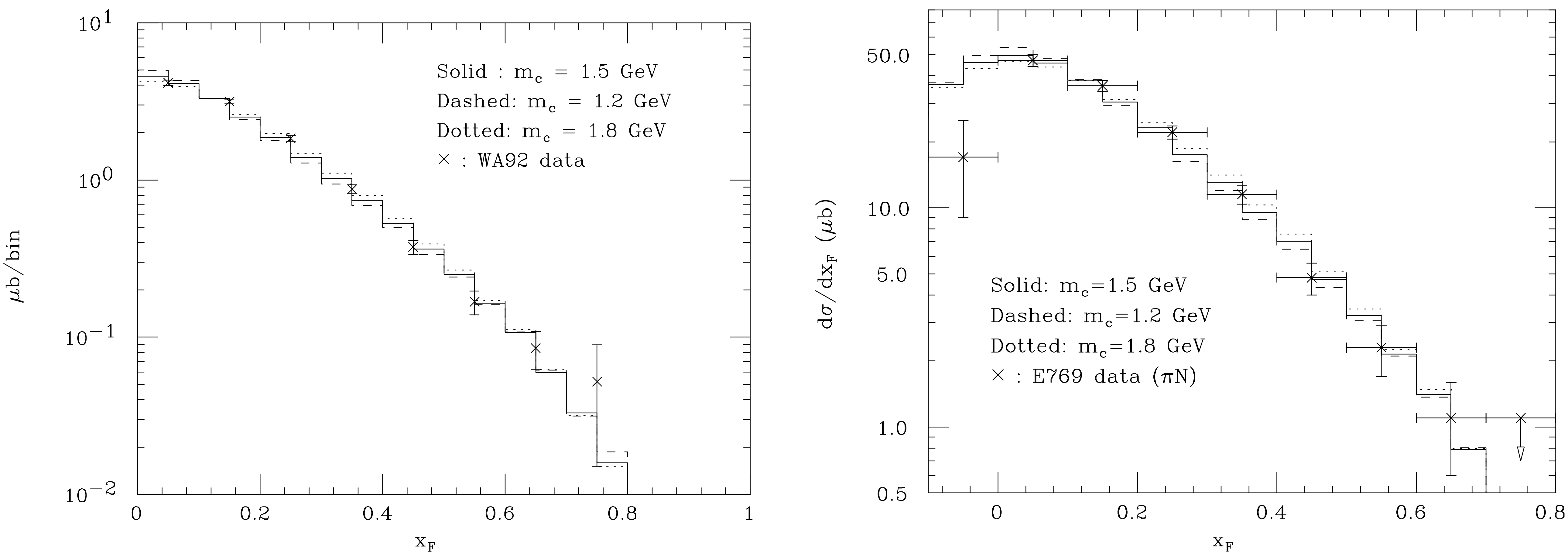
[Frixione et al PR 1997]





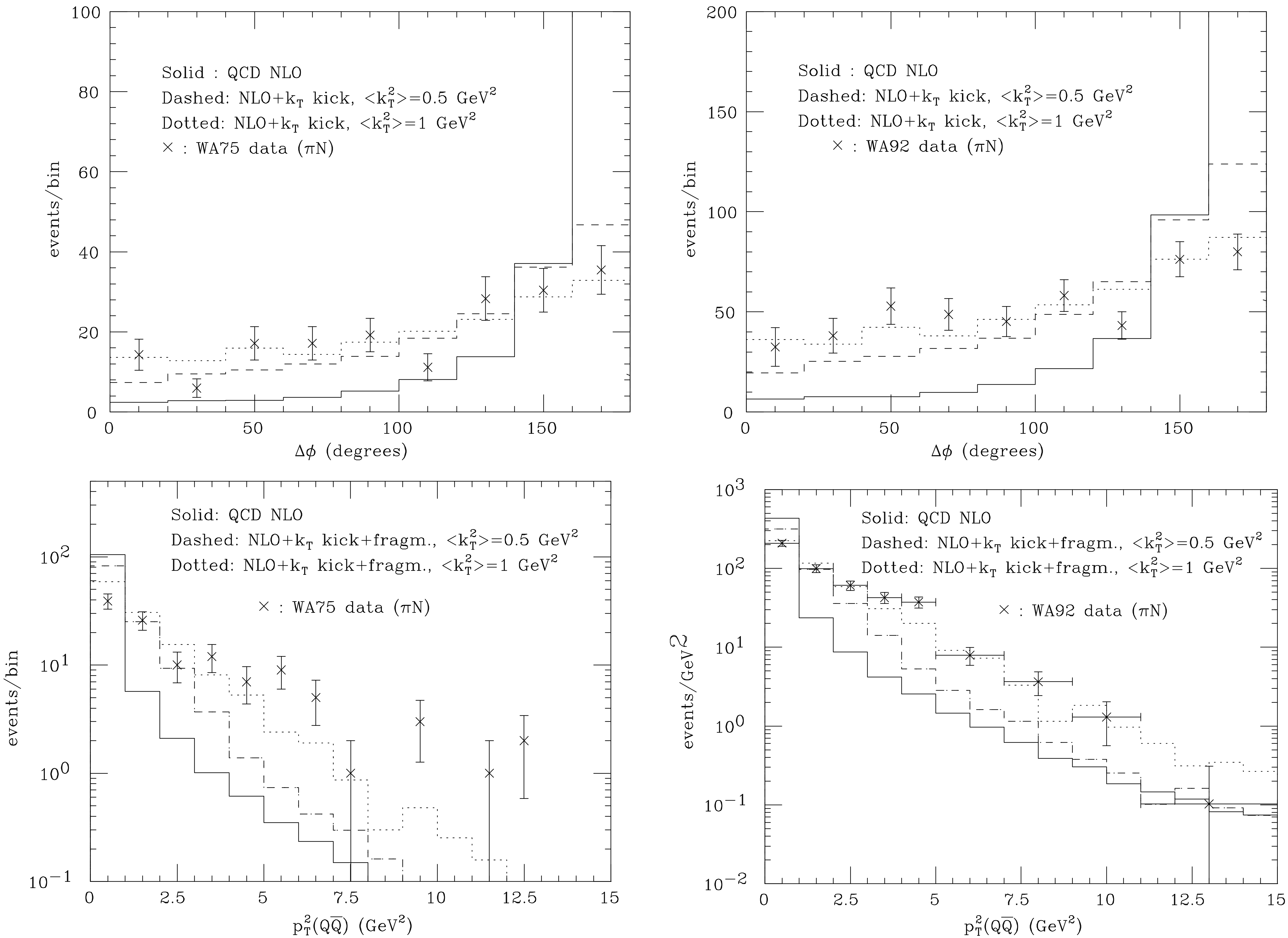
- Large non perturbative corrections
- Intrinsic k_T = 1GeV
- Hadronization via Peterson fragmentation function

Distributions: x_F



- Normalized to data
- Shape in good agreement, insensitive to the charm mass
- Hadronization via Peterson fragmentation function might not be appropriate for x_F distribution in hadronic collisions

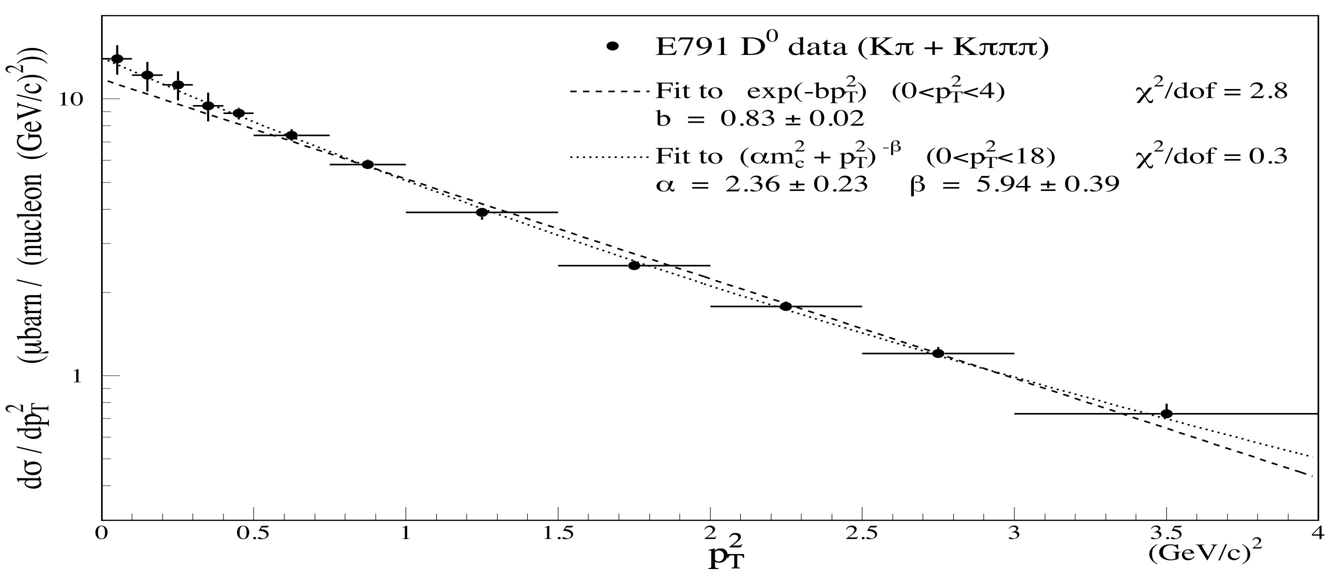
Double differential distributions

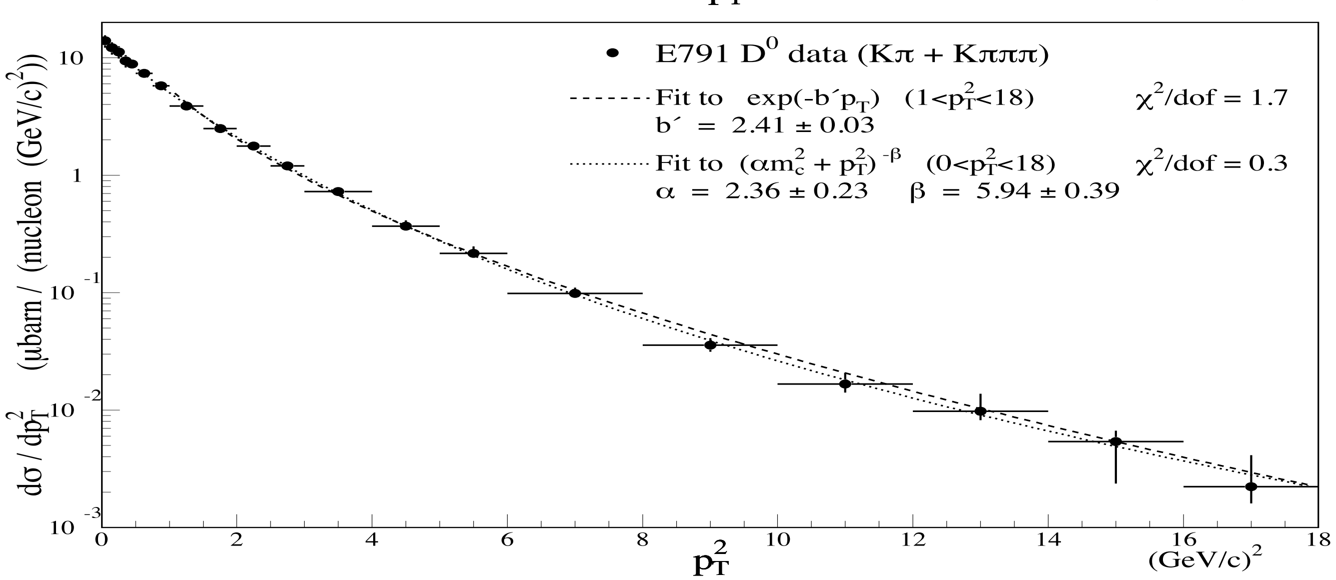


Distributions: E791

- Most precise measurements of diff. distributions
- πN @ 500GeV
- charm is produced at $x \sim 0.1$

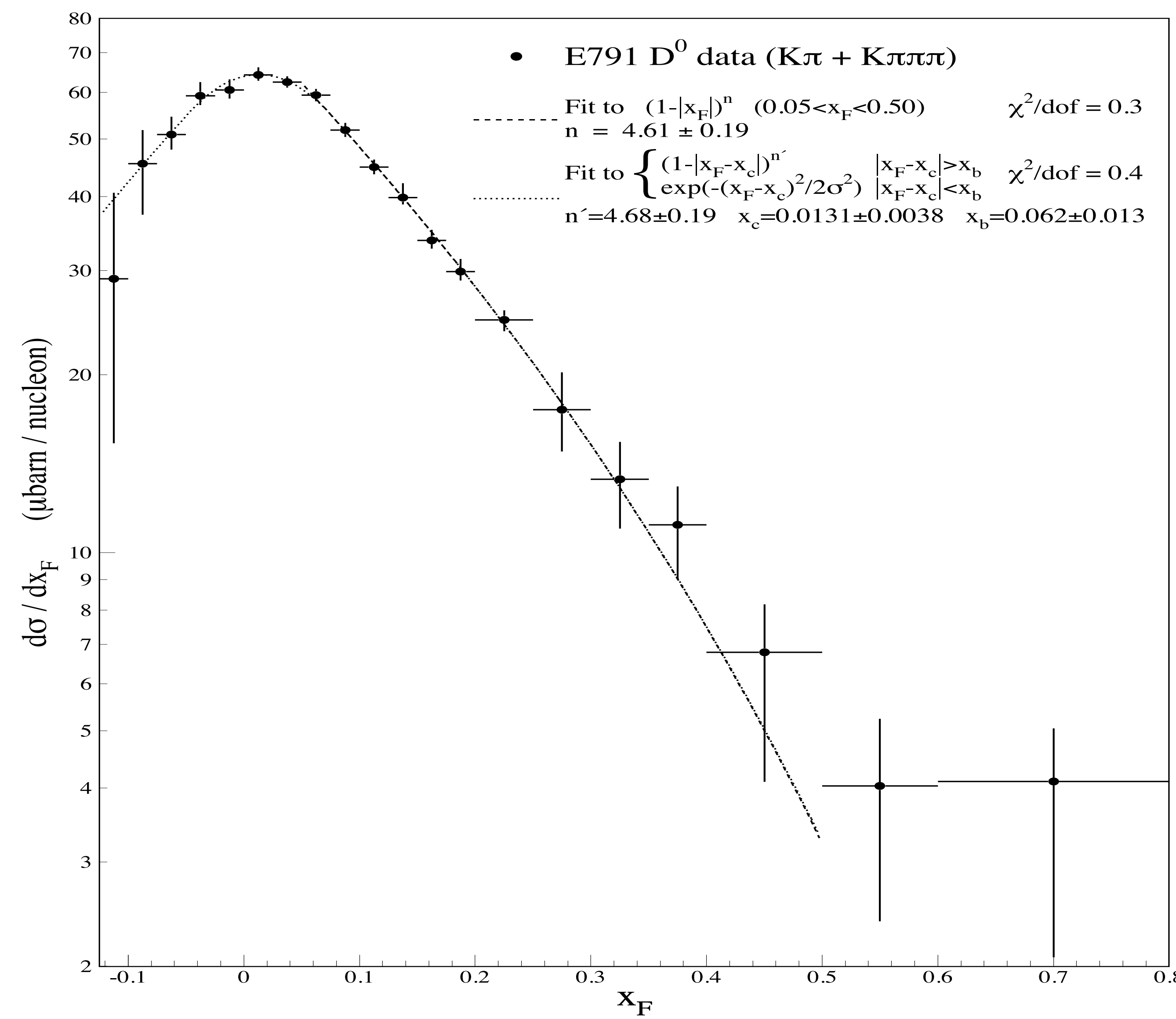
missing +11% -15% on normalization





$$(\alpha m_c^2 + p_T^2)^{-\beta}$$

missing +10% -11% on normalization

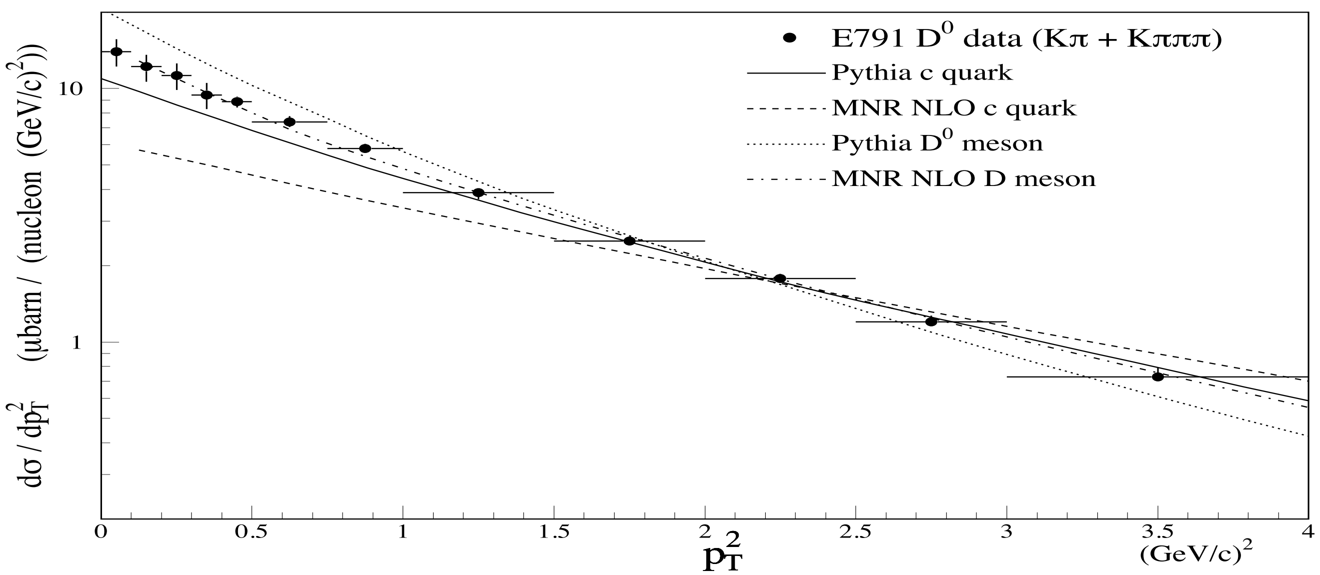


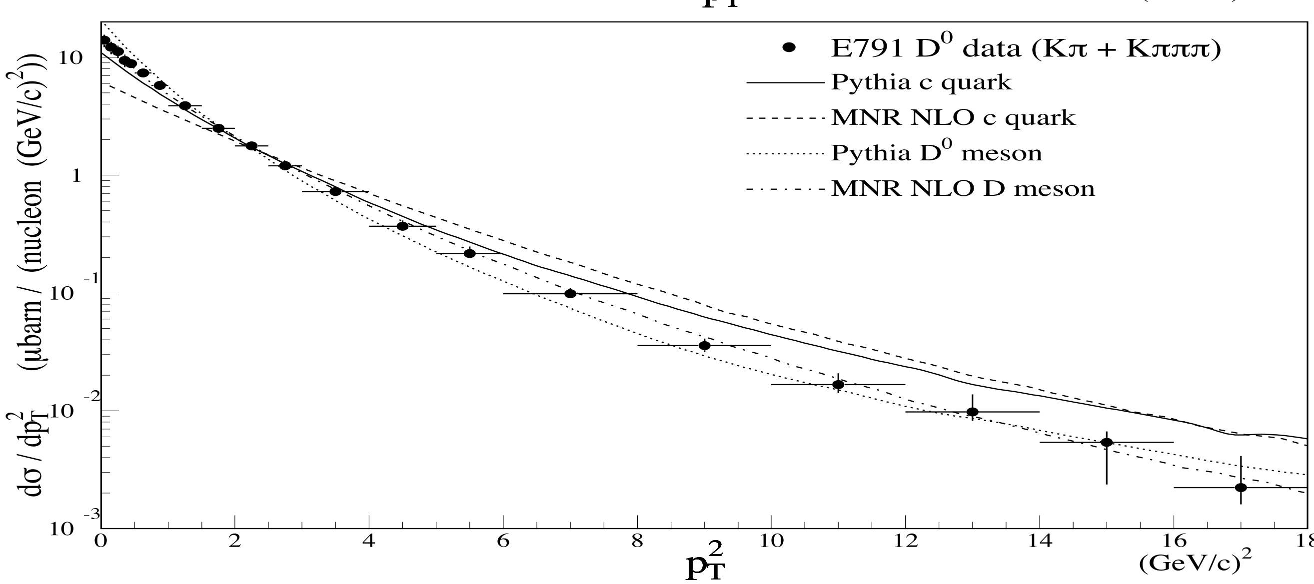
$$(1-|x_F|)^n$$

Distributions: E791

- Most precise measurements of diff. distributions
- πN @ 500GeV
- charm is produced at $x \sim 0.1$!

missing +11% -15% err. on normalization





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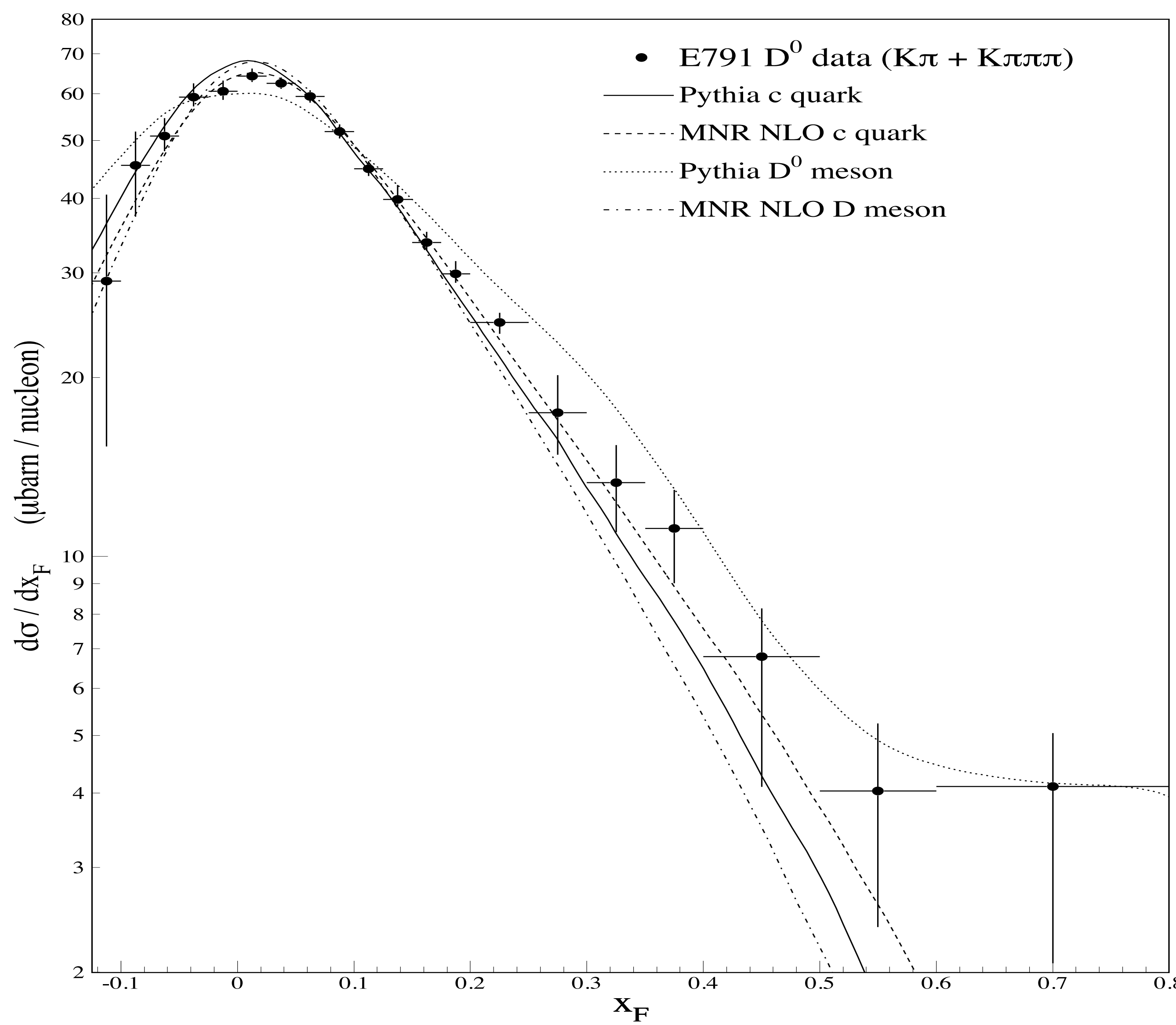


In the prediction MNR NLO D meson:

$$\epsilon = 0.001 \quad \langle k_T^2 \rangle = 1\, GeV^2$$

Data driven simulations

NLO + Parton Shower

- NLO provides important pheno features
- PS resums leading logarithmic enhancement and paired with hadronization models provide full event simulation
- Double counting of radiative corrections solved with implementation of the MC@NLO and POWHEG methods
- POWHEG master formula:

$$\bar{B}(\mathbf{\Phi}_n) = B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) + \left[\int d\Phi_{\mathrm{rad}} \left[R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1})\right] + \int \frac{dz}{z} \left[G_{\oplus}(\mathbf{\Phi}_{n,\oplus}) + G_{\ominus}(\mathbf{\Phi}_{n,\ominus})\right]\right]^{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n},$$

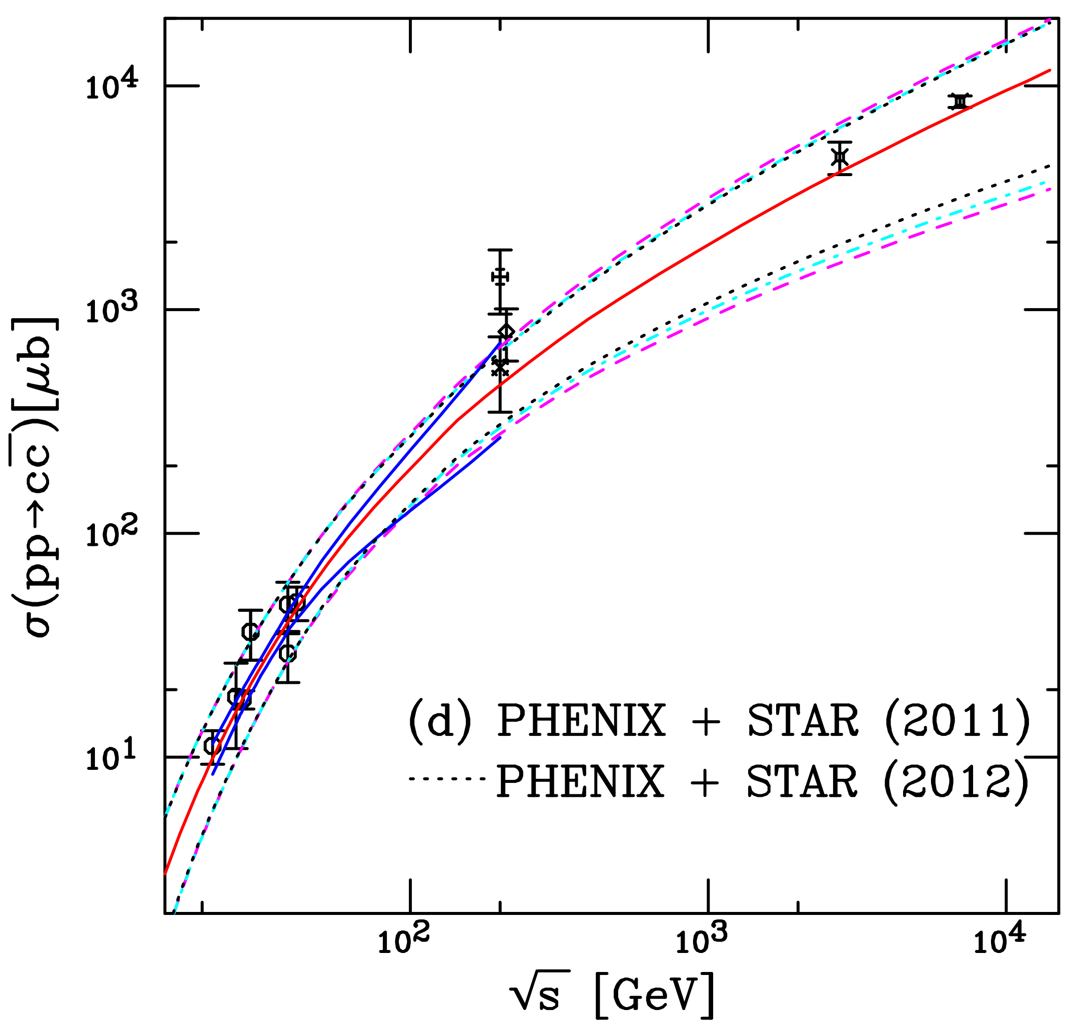
$$\Delta\left(\mathbf{\Phi}_n, p_{\mathrm{T}}\right) = \exp\left\{-\int \frac{\left[d\Phi_{\mathrm{rad}}\, R(\mathbf{\Phi}_{n+1})\, \theta(k_{\mathrm{T}}\left(\mathbf{\Phi}_{n+1}\right) - p_{\mathrm{T}})\right]^{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n}}{B(\mathbf{\Phi}_n)}\right\}$$

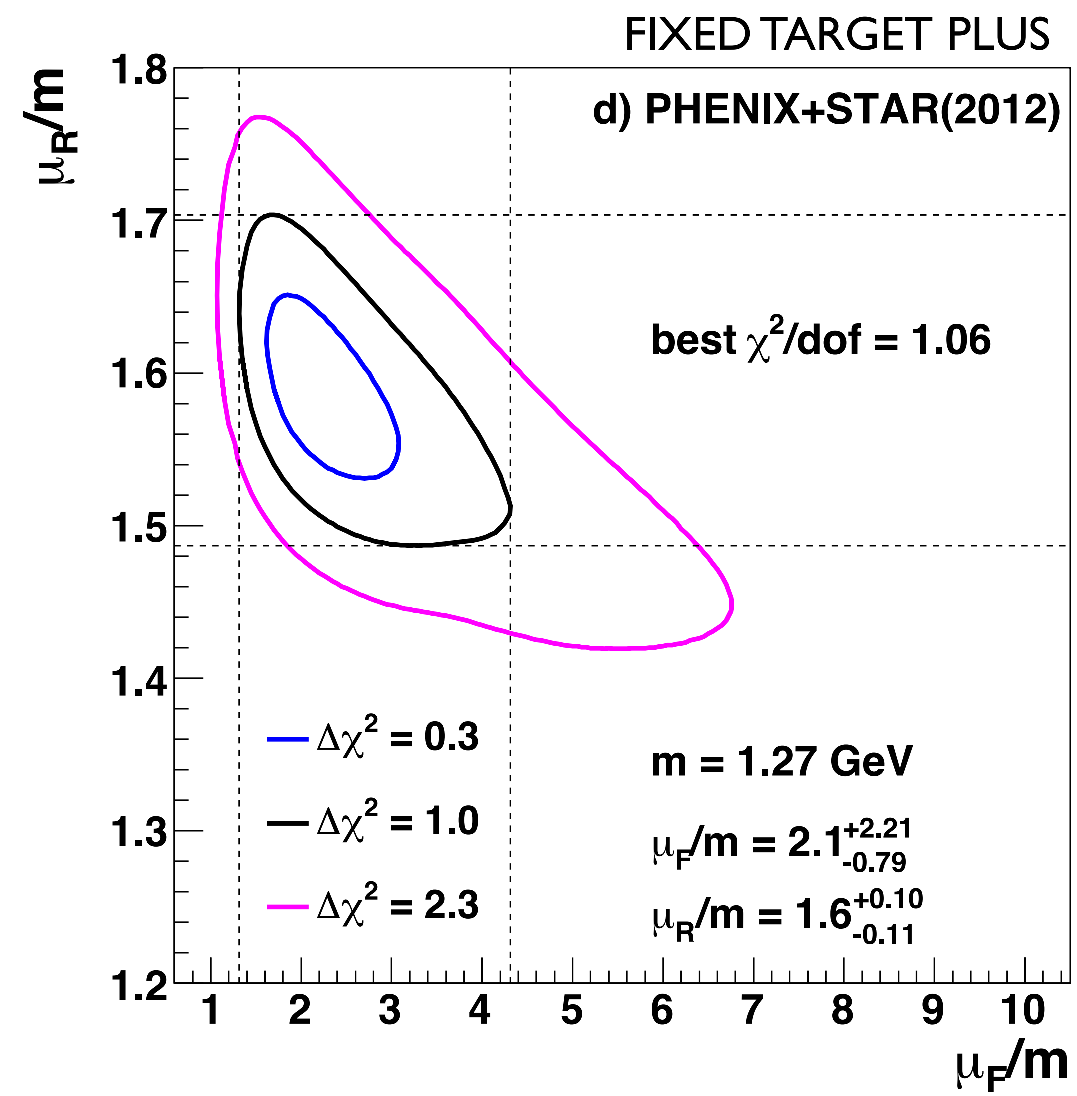
$$d\sigma = \bar{B}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{\Delta\left(\mathbf{\Phi}_n, p_{\mathrm{T}}^{\mathrm{min}}\right) + \Delta\left(\mathbf{\Phi}_n, k_{\mathrm{T}}\left(\mathbf{\Phi}_{n+1}\right)\right) \frac{R\left(\mathbf{\Phi}_{n+1}\right)}{B(\mathbf{\Phi}_n)} d\Phi_{\mathrm{rad}}\right\}_{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n}$$

- In the following we will show results obtained with:
  POWHEG hvq + PYTHIA-6.4.27
- Uncertainties from matching and hadronization could be studied comparing with MC@NLO and linking PYTHIA and HERWIG respectively
- The hvq process with POWHEG can be downloaded from:
  www.powhegbox.mib.infn.it

Tuning Total Cross Sections for proton-proton collisions:

- ✓ Mainly determined by perturbative corrections that have large uncertainty
- ✓ NNLO corrections for heavy quark production available for tt@LHC energies [Czakon et al PRL 2013]
- ✓ Slow convergence expected for charm @ SHiP energies
- ✓ A direct translation between the pole mass and running mass for charm is not possible because of poor convergence of the perturbative series [Marquard et al PRL 2015]
- ✓ We can make use of the data-constrained analysis of the factorization and renormalization scale dependence discussed in [Nelson et al PRC2013] (CT10nlo)





[Nelson et al PRC2013]

E791 Tune for NP effects: setup

- Sutton, Martin, Roberts and Stirling pdf for the pion (PION2, 15% pion momentum carried by the sea)
- Martin, Roberts and Stirling for the proton (HMRSB)
- $\Lambda_{QCD,5}$ = 220MeV
- Default pythia-6.4.27 (no kT-kick in PYTHIA)

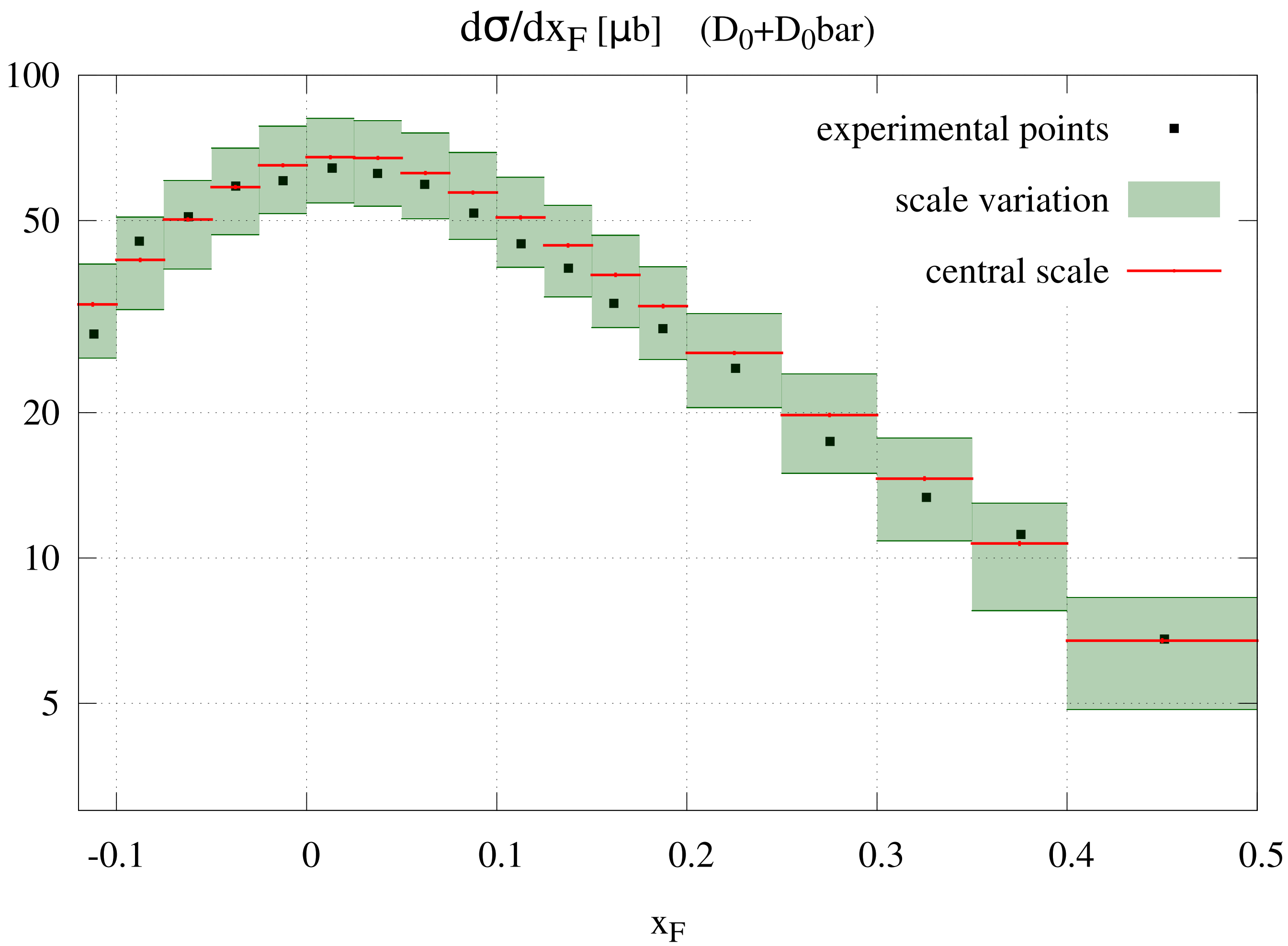
- fixed scales assuming mc=1.37GeV
  - cent. factorization scale 2mc
  - cent. renormalization scale 1.5mc
  - perturbative uncertainty evaluated changing the fac. scale among 2mc to 4mc and the ren. scale among 1.25mc and 2mc

- dynamic scales assuming mc=1.27GeV
  - central scales and scale variations as above changing mc into $\mu_d = \sqrt{p_T^2 + m_c^2}$

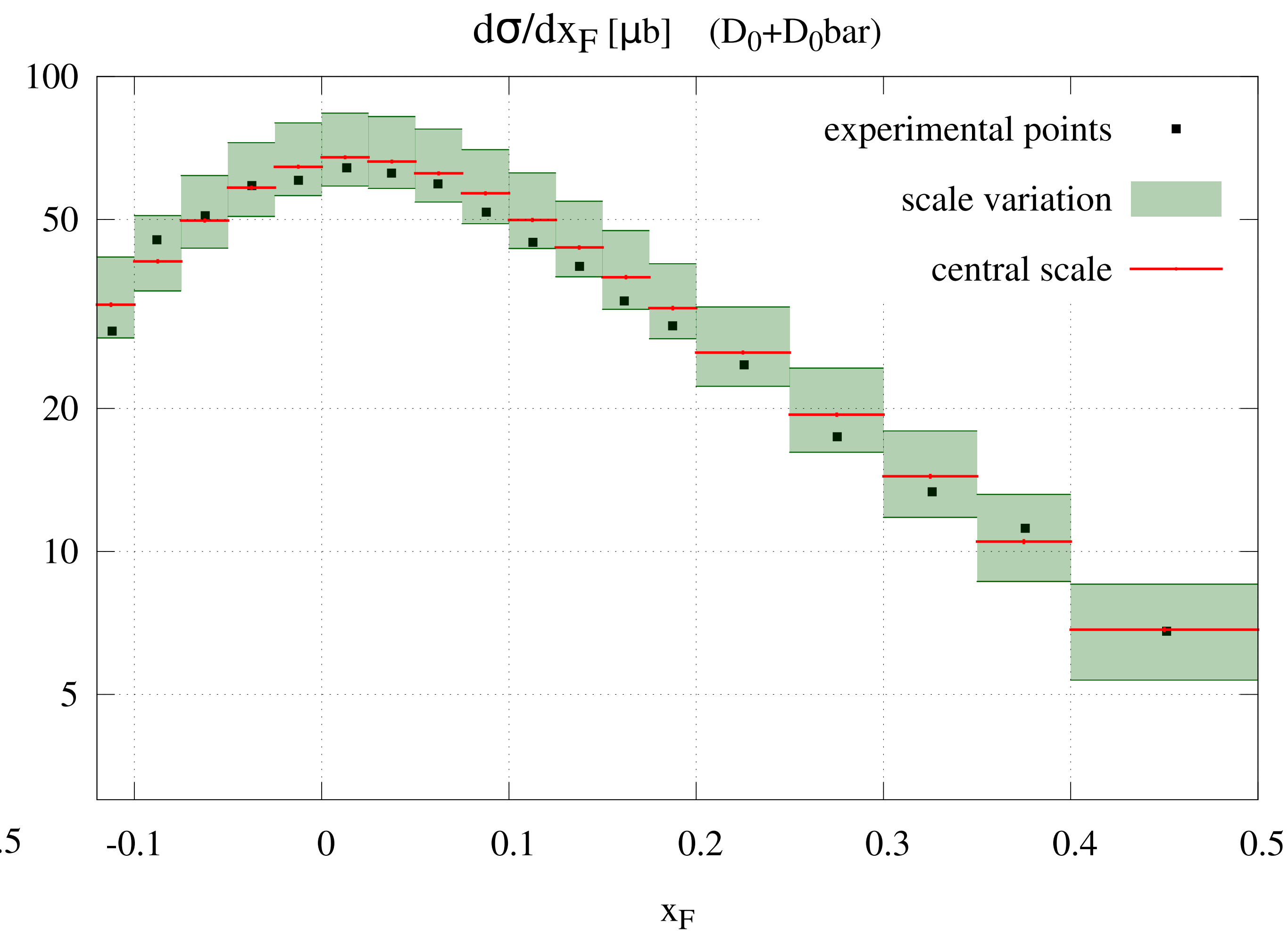
E791 Tune: results

$D_0 + \bar{D}_0$ x$_F$ distribution

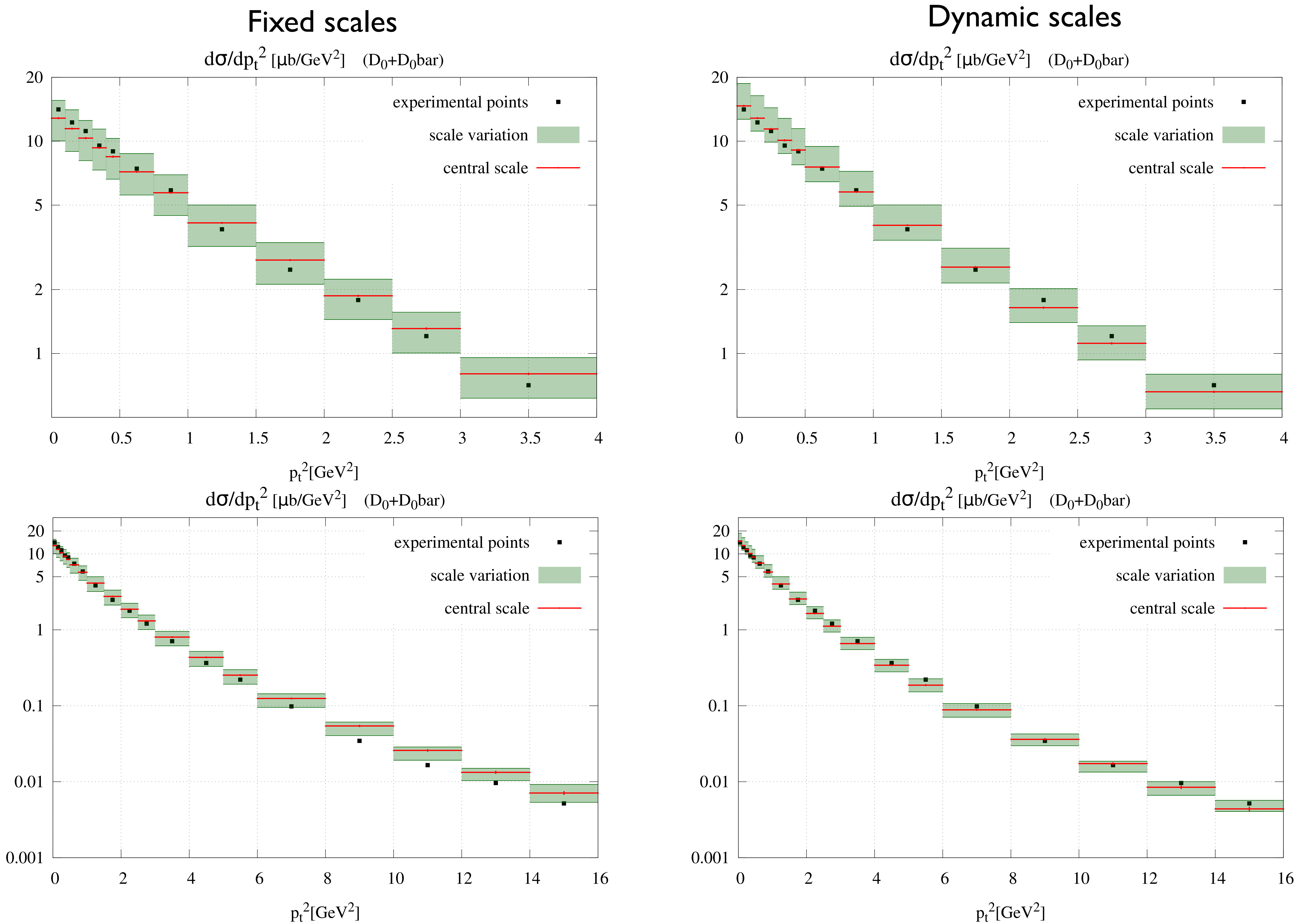
Fixed scales



Dynamic scales



E791 Tune: results $D_0 + \bar{D}_0 \ (x_F > 0)$ p_T^2 distribution

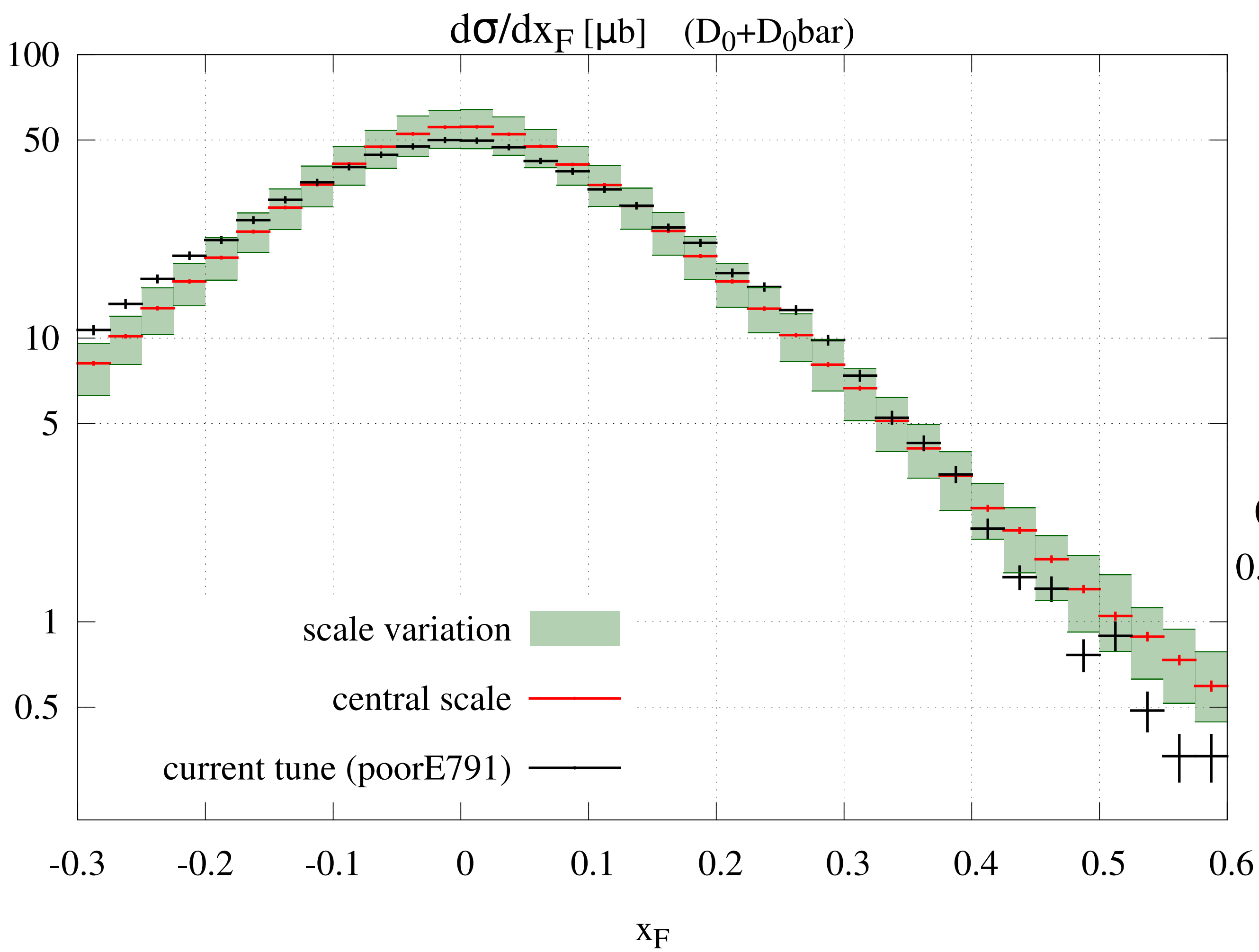


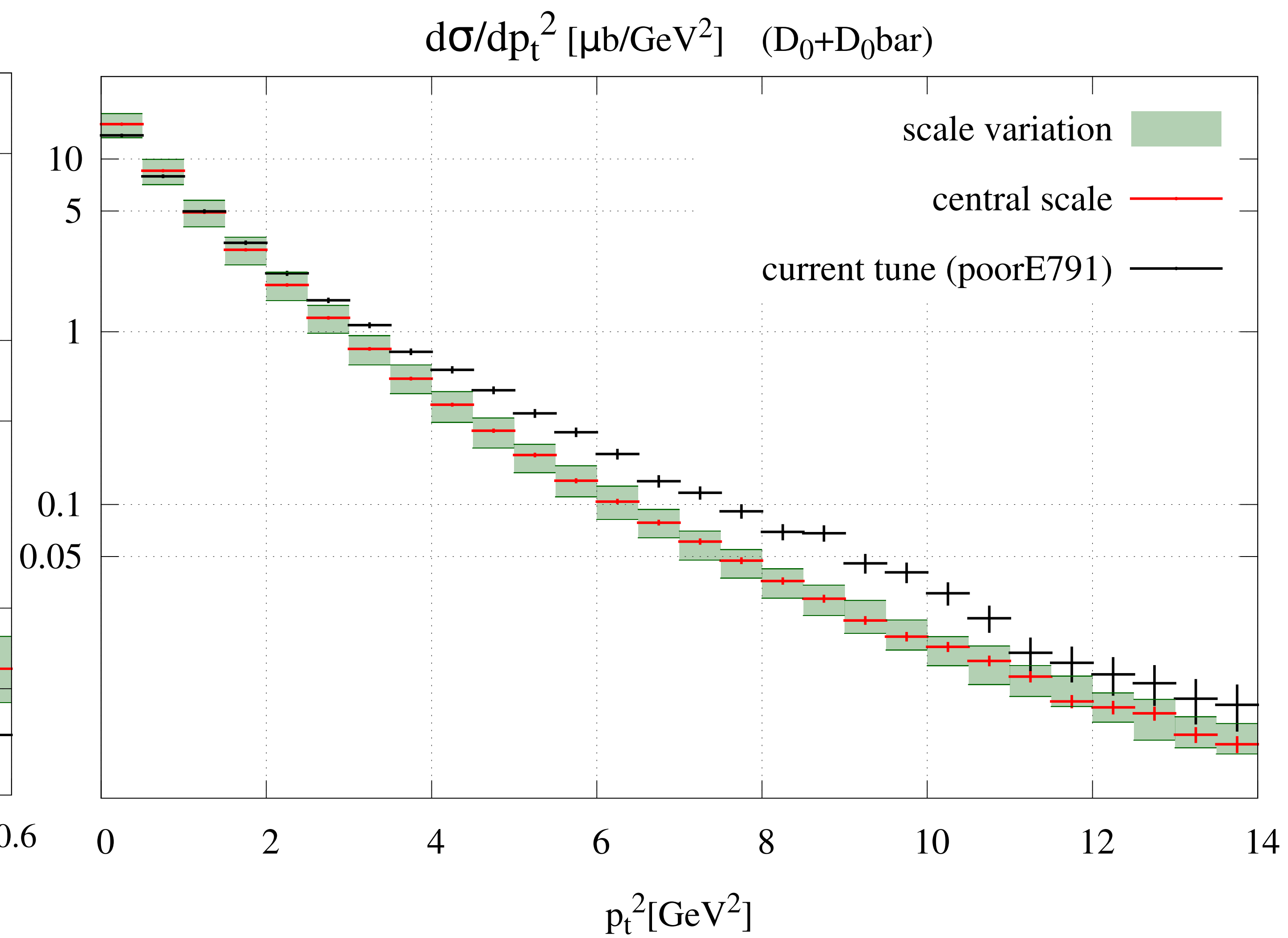
Predictions for proton collisions

SETUP: NLO as in [Nelson et al PRC2013]

- pp collisions with E_b=400GeV
- fixed scales assuming mc=1.27GeV
  - central factorization scale 2mc
  - central renormalization scale 1.6mc
  - perturbative uncertainty evaluated changing the fac. scale among 1.25mc to 4.65mc and the ren. scale among 1.48mc and 1.71mc
  - CT10nlo pdf
- PYTHIA-6.4.27 default plus:
  - MSTP(91)=0 (no primordial kt)

pp collisions @ E_b=400GeV





Conclusions

1. An estimate of the charm rates for SHiP can be obtained tuning the total cross section and the NP effects with available data.

2. Uncertainties remain large because differential distributions for charm production in proton initiated hadron collisions are missing.

3. Charm production pp cross sections at SHiP energies are indeed important to study Non-Perturbative effects (and to understand to what extent the perturbative computation provides qualitative reliable predictions)

    - Note: measurements of D production asymmetries in proton collisions is essential to tune hadronization models that generate asymmetries and can be used to predict charge asymmetries in B production (fake CP violation signal)

4. NLO+PS is the optimal tool to address the task of event simulation

5. I gave an examples of event simulation based on the points 1 and 4

6. w/o measurement a reliable estimate of the uncertainties is hard to get

7. More systematic studies needed!