Charm Enhancement at the LHC?

R. Vogt

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Physics Department, University of California, Davis, CA 95616, USA

Charm Production is a 'Hard' Process

'Hard' processes have a large scale in the calculation that makes perturbative QCD applicable: high momentum transfer, μ^2, high mass, m, high transverse momentum, p_T

Understanding these processes relies on asymptotic freedom to calculate the interactions between two hadrons on the quark/gluon level but the confinement scale determines the probability of finding a particular parton in the proton

This implies factorization between the perturbative hard part and the universal, nonperturbative parton distribution functions

$$\sigma_{AB}(S,m^2) = \sum_{i,j=q,\overline{q},g} \int_{4m_Q^2/s}^{1} \frac{d\tau}{\tau} \int dx_1\, dx_2\, \delta(x_1 x_2 - \tau) \times f_i^A(x_1,\mu_F^2)\, f_j^B(x_2,\mu_F^2)\, \widehat{\sigma}_{ij}(s,m^2,\mu_F^2,\mu_R^2)$$

f_i^A are the parton distributions, either in a proton or a nucleus, determined from fits to data, x_1 and x_2 are the fractional momentum of the hadron carried by partons i and j, $\tau = s/S$

$\widehat{\sigma}_{ij}(s,m^2,\mu_F^2,\mu_R^2)$ is partonic cross section calculable in QCD in powers of α_s^{2+n}: leading order (LO), $n = 0$; next-to-leading order (NLO), $n = 1$ ...

Energy Dependence of 'Best Fit' Total Cross Sections

Best agreement with pp data for MRST HO with $m = 1.2$ GeV, $\mu^2 = 4m^2$ (CTEQ similar) and GRV98 HO with $m = 1.3$ GeV, $\mu^2 = m^2$, extrapolated to higher energy

Lower masses too low for pQCD, higher masses reduce low $\sqrt{S}$ cross section too much to agree with data

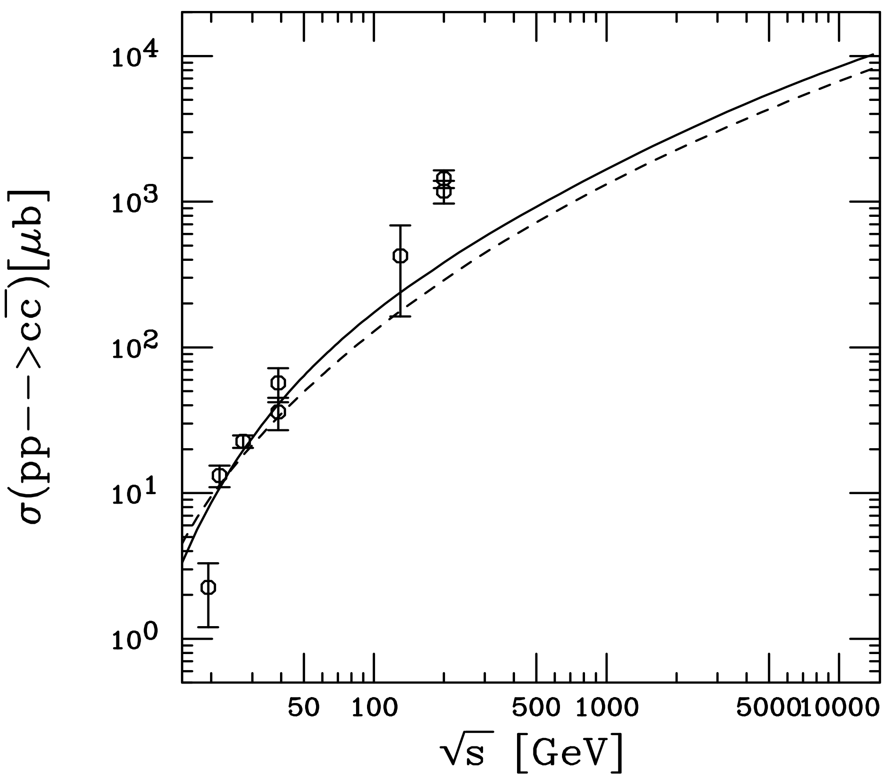

Figure 1: The NLO total $c\bar{c}$ cross sections in pp interactions up to 14 TeV. The curves are MRST HO (central gluon) with $m = 1.2$ GeV and $\mu^2 = 4m^2$ (dashed) and GRV98 HO with $m = 1.3$ GeV and $\mu^2 = m^2$.

Nonlinear Gluon Evolution at Small x?

Global fits to parton distribution functions successfully describe structure function $F_2(x,\mu^2)$ in the "high" x and μ^2 region: $x \geq 0.005$ and $\mu^2 \geq 10$ GeV^2

Problems arise when simultaneously fitting the high and "low" x and μ^2 region: $x \leq 0.005$ and $1.5 \leq \mu^2 \leq 10$ GeV^2

- Fit is not as good
- At low μ^2 the NLO gluon distribution can become negative

Improving the Fit at LO

The LO fit can be improved at low x and μ^2 by including nonlinear corrections to the PDF evolution based on gluon recombination (GLRMQ terms):

$$\frac{\partial(xg(x,\mu^2))}{\partial \ln \mu^2} = \cdots - 3\frac{\alpha_s^2(\mu^2)}{R^2\mu^2}\int_x^1 \frac{dx'}{x'}[x'g(x',\mu^2)]^2$$

$$\frac{\partial(xq(x,\mu^2))}{\partial \ln \mu^2} = \cdots - \frac{1}{10}\frac{\alpha_s^2(\mu^2)}{R^2\mu^2}[xg(x,\mu^2)]^2$$

These terms slow down gluon evolution at low μ^2 relative to normal DGLAP μ^2 evolution

Resulting EHKQS LO PDFs, based on CTEQ5L and CTEQ61L PDFs, shows that slowing down the gluon evolution enhances the gluon distribution at low μ^2 for $x > 3 \times 10^{-5}$ (higher twist important for smaller x)

Charm Production Could Be Enhanced at Small x

Charm production is an excellent probe of nonlinear regime for two reasons:

- low mass, $1.2 \leq m \leq 1.8$ GeV, and thus low μ^2
- production dominated by gluons

Good agreement obtained with total cross sections at NLO for $m = 1.2$ GeV and $\mu^2 = 4m^2$ (MRST and CTEQ parton densities) and $m = 1.3$ GeV and $\mu^2 = m^2$ (GRV98 parton densities)

We use these parameters (changing $\mu^2 \propto m^2$ in total cross section to $\mu^2 \propto m_T^2 = p_T^2 + m^2$ in differential distributions) to calculate charm enhancement with the EHKQS PDFs relative to CTEQ61L

Calculations are for pp only since no nonlinear nuclear PDFs available so far

We take $\sqrt{S} = 5.5$, 8.8 and 14 TeV to reach smallest values of x where effect is greatest (K.J. Eskola, V.J. Kolhinen and R.V., Phys. Lett. **B582** (2004) 157; hep-ph/0403098 with A. Dainese and M. Bondila)

Comparison of EHKQS and CTEQ61L Gluon Distributions

Difference between the two gluon PDFs largest at low x and low μ^2

CTEQ61L range is down to $x_{\rm min} \geq 10^{-6}$ while EHKQS range is to $x_{\rm min} \geq 10^{-5}$, fix both distributions to their values at $x_{\rm min}$ for $x < x_{\rm min}$

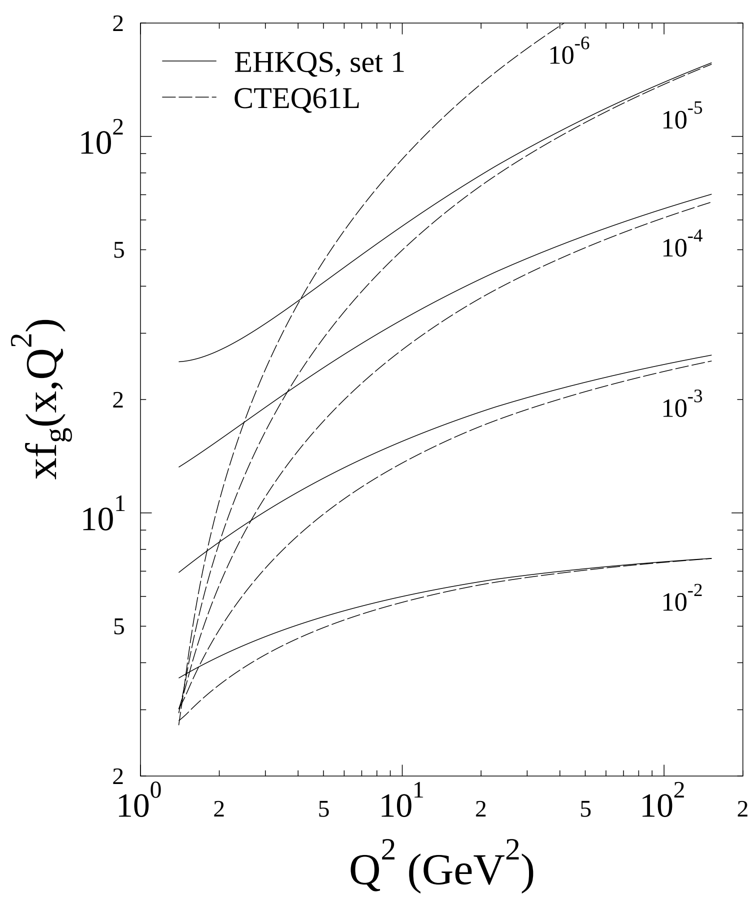

Figure 2: Comparison of the EHKQS set 1 (solid curves) and CTEQ61L (dashed curves) gluon distributions as a function of Q^2 for, from lowest to highest, $x = 10^{-2}$, 10^{-3}, 10^{-4}, 10^{-5} and, for CTEQ61L only, 10^{-6}.

How Does This Translate Into Charm Enhancement? Fixed y Case

Calculate LO $c\overline{c}$ production cross section

$$d\sigma_{pp\to c\overline{c}X}(\mu^2,\sqrt{S}) = \sum_{i,j,k=q,\overline{q},g} f_i(x_1,\mu^2)\otimes f_j(x_2,\mu^2)\otimes d\hat{\sigma}_{ij\to c\overline{c}k}(\mu^2,x_1,x_2)$$

At LO, for fixed p_T, y and y_2, x_1 and x_2 are known precisely

$$\begin{aligned} x_1 &= \frac{2m_T}{\sqrt{S}}(\exp(y)+\exp(y_2)) \\ x_2 &= \frac{2m_T}{\sqrt{S}}(\exp(-y)+\exp(-y_2)) \end{aligned}$$

Calculate ratio of fully differential cross sections as a function of p_T for $y=y_2=0$, $y=2, y_2=0$ and $y=y_2=2$ for $m=1.2$ GeV, $\mu^2=4m_T^2$; $m=1.3$ GeV, $\mu^2=m_T^2$; and $m=1.8$ GeV for $\mu^2=4m_T^2$ and m_T^2

$$R(p_T,y,y_2) \equiv \frac{d^3\sigma(\text{EHKQS})/(dp_T dy dy_2)}{d^3\sigma(\text{CTEQ61L})/(dp_T dy dy_2)}$$

Expect largest enhancement at highest $\sqrt{S}$ and lowest m, μ^2

Factor of Five Enhancement at $\sqrt{S} = 14$ TeV, Best Case

When both m and μ^2 are small, enhancement is largest, between factor of 4 and 5

For larger μ^2, enhancement smaller, factor of 1.5

At central rapidities, no strong dependence on rapidity

Fast decrease with p_T

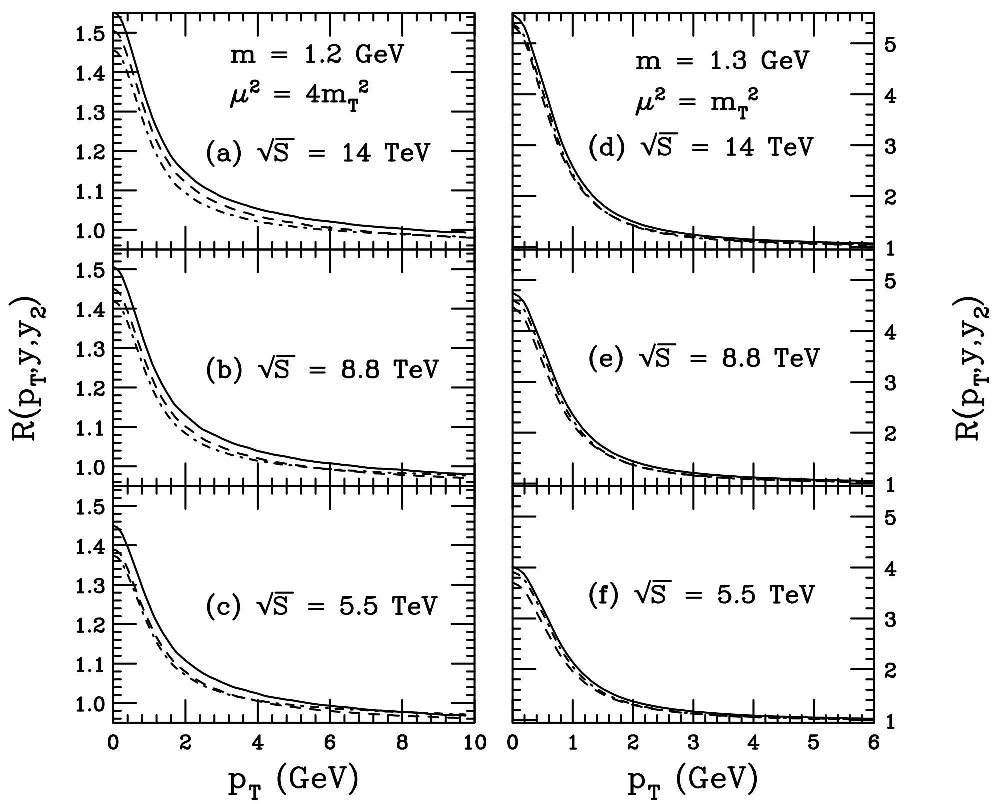

Figure 3: We present $R(p_T, y, y_2)$ for fixed y and y_2 as a function of charm quark p_T at $\sqrt{S} = 14$ TeV, (a) and (d), 8.8 TeV, (b) and (e), and 5.5 TeV, (c) and (f), in pp collisions. The results are shown for $y = y_2 = 0$ (solid curves), $y = 2$ $y_2 = 0$ (dashed) and $y = y_2 = 2$ (dot-dashed). We show $m = 1.2$ GeV and $\mu^2 = 4m_T^2$ on the left-hand side and $m = 1.3$ GeV and $\mu^2 = m_T^2$ on the right-hand side. Note the different scales on the left- and right-hand axes.

Ssmaller Enhancement For Larger Mass

When $m = 1.8$ GeV, best case is only enhancement by factor of two

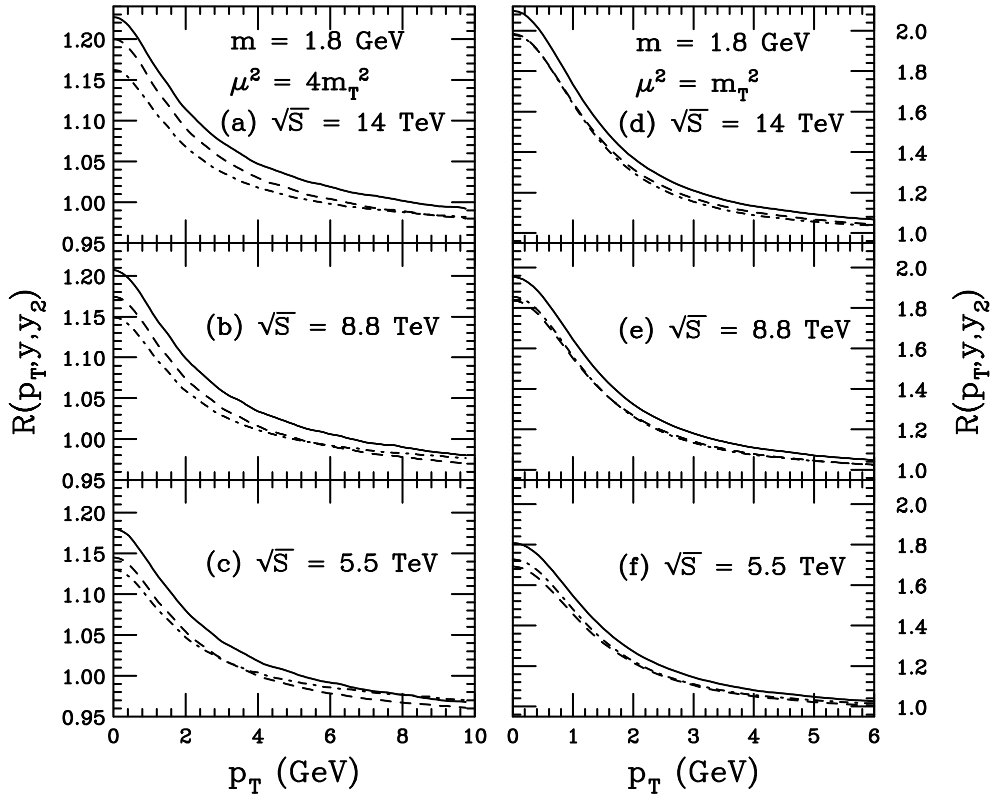

Figure 4: We present $R(p_T, y, y_2)$ for $m = 1.8$ GeV at fixed y and y_2 as a function of charm quark p_T at $\sqrt{S} = 14$ TeV, (a) and (d), 8.8 TeV, (b) and (e), and 5.5 TeV, (c) and (f), in pp collisions. The results are shown for $y = y_2 = 0$ (solid curves), $y = 2$ $y_2 = 0$ (dashed) and $y = y_2 = 2$ (dot-dashed). We show $\mu^2 = 4m_T^2$ on the left-hand side and $\mu^2 = m_T^2$ on the right-hand side. Note the different scales on the left- and right-hand axes.

Charm Enhancement: Integrated Ratios

Integrated ratios smear out x values, reducing enhancement

$$
\begin{aligned}
R(y) &\equiv \frac{d\sigma(\mathrm{EHKQS})/dy}{d\sigma(\mathrm{CTEQ61L})/dy} \\
R(p_T) &\equiv \frac{d\sigma(\mathrm{EHKQS})/dp_T}{d\sigma(\mathrm{CTEQ61L})/dp_T} \\
R(M) &\equiv \frac{d\sigma(\mathrm{EHKQS})/dM}{d\sigma(\mathrm{CTEQ61L})/dM}
\end{aligned}
$$

At large rapidities, $x < 10^{-5}$, making a kink in $R(y)$

Kink occurs because of difference in range of validity of CTEQ61L ($x_{\rm min} = 10^{-6}$) and EHKQS ($x_{\rm min} = 10^{-5}$)

Minimum x reached at smaller y for larger $\sqrt{S}$

Integration Reduces Enhancement

Ratio can drop below unity because $\Lambda_{\rm CTEQ61L} = 0.215$ GeV and $\Lambda_{\rm EHKQS} = 0.192$ GeV so that $\alpha_s^2({\rm EHKQS})/\alpha_s^2({\rm CTEQ61L}) < 1$ at large p_T

Largest enhancement, $R(p_T)$, reduced from 5 to 4.5 in best case

p_T-integrated $R(y)$ only $\sim 1.6 - 1.8$ in best case

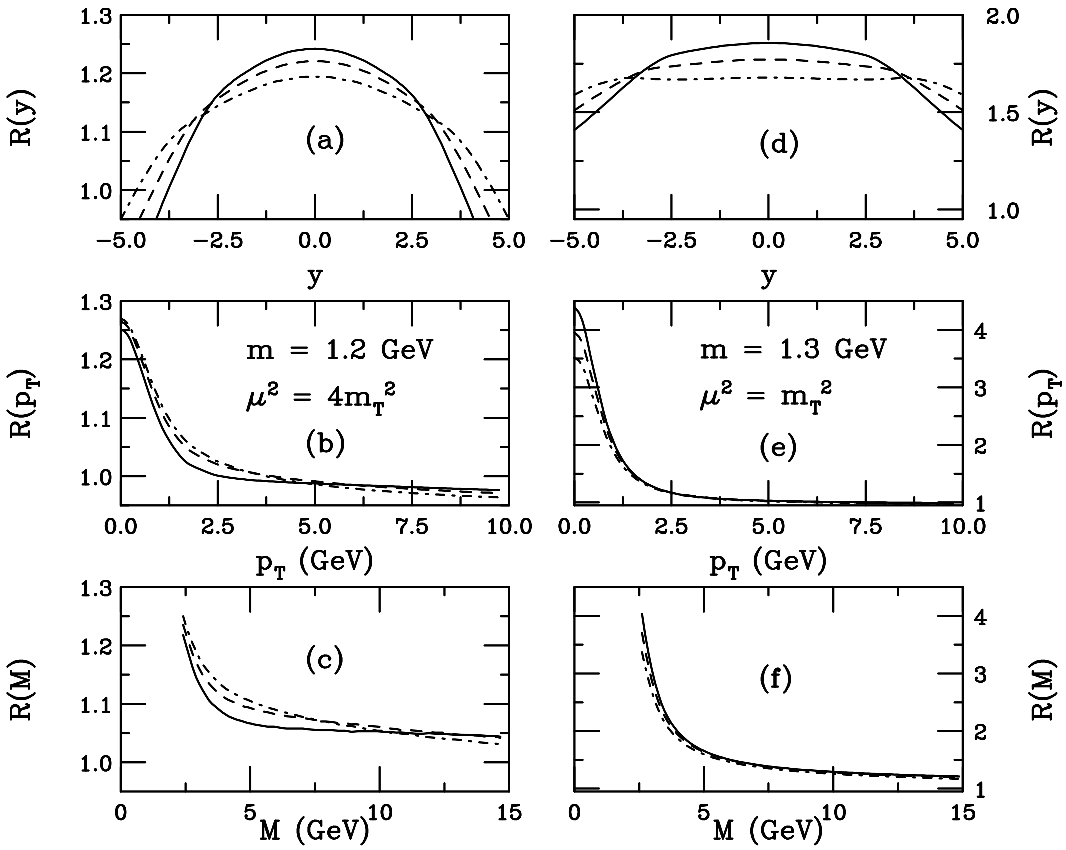

Figure 5: We present $R(y)$, (a) and (d), $R(p_T)$, (b) and (e), and $R(M)$, (c) and (f), in pp collisions at $\sqrt{S} = 14$ (solid), 8.8 (dashed) and 5.5 (dot-dashed) TeV. The left-hand side shows $m = 1.2$ GeV and $\mu^2 = 4m_T^2$, the right-hand side $m = 1.3$ GeV and $\mu^2 = m_T^2$.

Energy Dependence Reversed for $\mu^2 = 4m_T^2$

Individual rapidity distributions rather flat for both scales so contribution to $R(p_T)$ from $x < 10^{-5}$ non-negligible

CTEQ61L gluons larger than EHKQS for $x < 10^{-5}$

Contributions from $x < 10^{-5}$ reduce EHKQS relative to CTEQ61L, largest contribution from highest energy

More clearly seen for $m = 1.8$ GeV

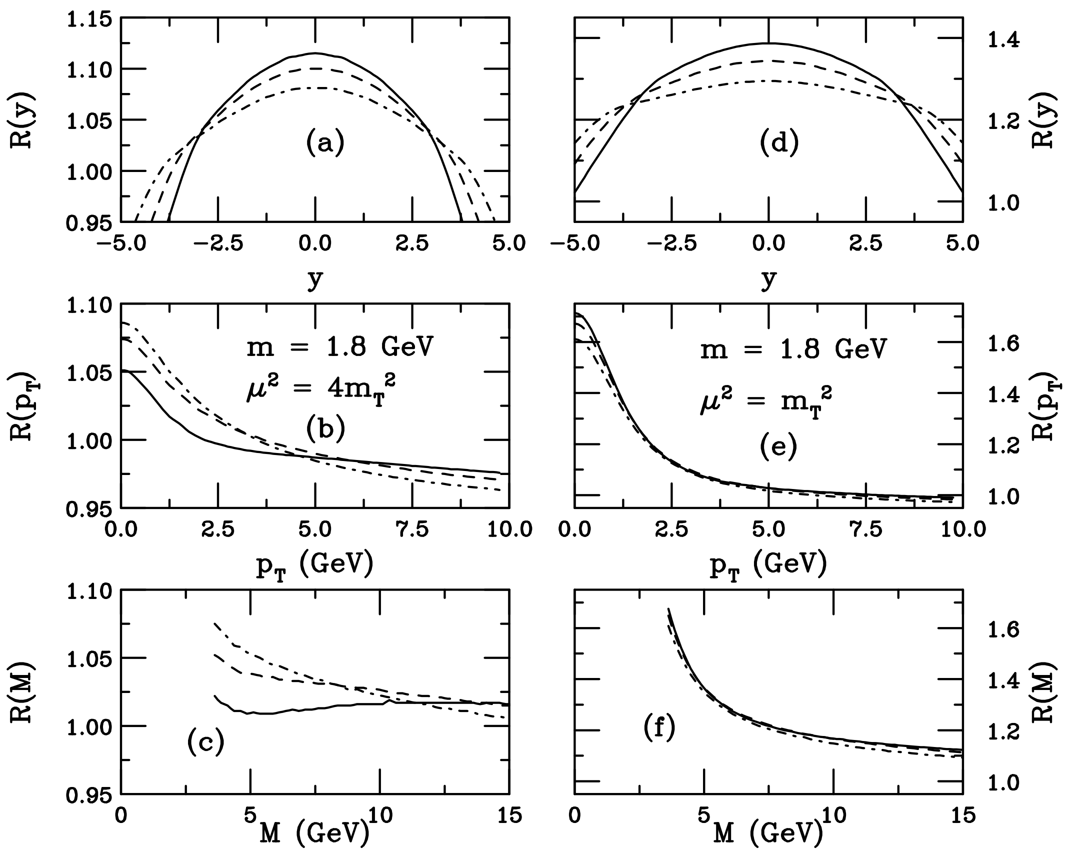

Figure 6: We present $R(y)$, (a) and (d), $R(p_T)$, (b) and (e), and $R(M)$, (c) and (f), in pp collisions at $\sqrt{S} = 14$ (solid), 8.8 (dashed) and 5.5 (dot-dashed) TeV with $m = 1.8$ GeV. The left-hand side shows $\mu^2 = 4m_T^2$, the right-hand side $\mu^2 = m_T^2$.

How to Measure the Enhancement?

The ALICE detector at the LHC will directly measure D mesons through reconstruction of the $D^0 \to K^- \pi^+$ decay

Detection possible for $p_T^D \to 0$

NLO cross section calculated in way most compatible with the charm enhancement calculated at LO — NLO contribution needed for rate and shape of p_T distribution

We show that enhancement survives hadronization of charm into D mesons

Use NLO calculation to determine rates for statistical uncertainties

Generate “data” from NLO cross section times LO enhancement factor

Check to see if any NLO calculations without enhancement can reproduce the “data”

Calculation of NLO Rate

Inclusive charm hadroproduction cross section

$$d\sigma_{pp\to c\overline{c}X}(\sqrt{s},m_c,\mu_R^2,\mu_F^2) = \sum_{i,j=q,\overline{q},g} f_i(x_1,\mu_F^2)\otimes f_j(x_2,\mu_F^2) \otimes d\hat{\sigma}_{ij\to c\overline{c}\{k\}}(\alpha_s(\mu_R^2),\mu_F^2,m_c,x_1,x_2)$$

$k = 0$ at LO and 0, q, $\overline{q}$ or g at NLO

NLO cross section can be calculated in two ways:

- “standard NLO” — NLO PDFs and two-loop α_s at each order

$$\begin{aligned} d\sigma^{\rm std}_{\rm NLO} &= \sum_{i,j=q,\overline{q},g} f_i^{\rm NLO}(x_1,\mu_F^2)\otimes f_j^{\rm NLO}(x_2,\mu_F^2)\otimes d\hat{\sigma}^{\rm LO}_{ij\to c\overline{c}}(\alpha_s^{\rm 2L}(\mu_R^2),x_1,x_2) \\ &+ \sum_{i,j=q,\overline{q},g} f_i^{\rm NLO}(x_1,\mu_F^2)\otimes f_j^{\rm NLO}(x_2,\mu_F^2)\otimes \sum_{k=0,q,\overline{q},g} d\hat{\sigma}^{\rm NLO}_{ij\to c\overline{c}k}(\alpha_s^{\rm 2L}(\mu_R^2),\mu_F^2,x_1,x_2) \\ &\equiv d\sigma^{\rm 2L}_{\rm LO} + d\sigma_{\mathcal{O}(\alpha_s^3)} \end{aligned}$$

- “alternative NLO” — LO PDFs and one-loop α_s for LO part, NLO PDFs and two-loop α_s for NLO contribution

$$\begin{aligned} d\sigma^{\rm alt}_{\rm NLO} &= \sum_{i,j=q,\overline{q},g} f_i^{\rm LO}(x_1,\mu_F^2)\otimes f_j^{\rm LO}(x_2,\mu_F^2)\otimes d\hat{\sigma}^{\rm LO}_{ij\to c\overline{c}}(\alpha_s^{\rm 1L}(\mu_R^2),x_1,x_2) \\ &+ \sum_{i,j=q,\overline{q},g} f_i^{\rm NLO}(x_1,\mu_F^2)\otimes f_j^{\rm NLO}(x_2,\mu_F^2)\otimes \sum_{k=0,q,\overline{q},g} d\hat{\sigma}^{\rm NLO}_{ij\to c\overline{c}k}(\alpha_s^{\rm 2L}(\mu_R^2),\mu_F^2,x_1,x_2) \\ &\equiv d\sigma^{\rm 1L}_{\rm LO} + d\sigma_{\mathcal{O}(\alpha_s^3)} \end{aligned}$$

Alternative NLO calculation is most compatible with enhancement calculated at LO

Enhancement Factor for ALICE Acceptance

ALICE acceptance for D^0 mesons is in interval $|y| < 1$

Rapidity of undetected c or $\overline{c}$ is integrated away

$$R(p_T, \Delta y) = \frac{\int_{\Delta y} dy \int dy_2 \frac{d^3\sigma(\mathrm{EHKQS})}{dp_T dy dy_2}}{\int_{\Delta y} dy \int dy_2 \frac{d^3\sigma(\mathrm{CTEQ61L})}{dp_T dy dy_2}}$$

Assume that enhancement is same at LO and NLO since no nonlinear evolution calculation exists for NLO — note that the LO and NLO gluon distributions are very different so enhancement factor could change

Enhanced charm p_T distribution at NLO is then

$$R(p_T, \Delta y)\, d\sigma^{\mathrm{alt}}_{\mathrm{NLO}}(\Delta y)/dp_T$$

From Charm to D Enhancement

PYTHIA string fragmentation scheme is used to fragment charm into D mesons

No k_T broadening included, effect small at these energies

Charm quark distribution from PYTHIA is reweigted to match the alternative NLO distribution as

$$\mathcal{W}(p_T) = \frac{dN^c_{\rm NLO}/dp_T}{dN^c_{\rm PYTHIA}/dp_T}$$

Enhancement survives from charm to D but it is lower

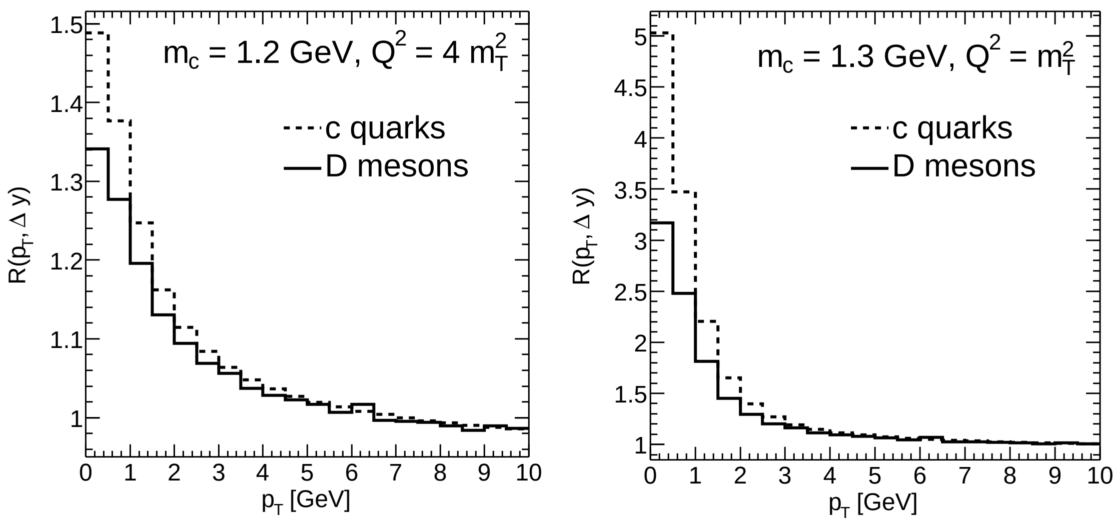

Figure 7: Enhancement factor $R(p_T, \Delta y)$ for charm quarks (dashed histogram) and for D ($\equiv D^+, D^0$) mesons (solid histogram), obtained after PYTHIA string fragmentation. The left-hand side shows the result for $m = 1.2$ GeV and $\mu^2 = 4m_T^2$ while the right-hand side is the result for $m = 1.3$ GeV and $\mu^2 = m_T^2$.

Expected Uncertainties in Measurement

D^0 decay topology, two tracks displaced from the interaction point, distance grows with p_T^D

ALICE can resolve displacement, reducing combinatorics

For our alternative NLO cross section, statistical errors are smaller than systematic up to $p_T^D \simeq 24$ GeV

Error $\propto \sqrt{S(p_T^D)+B(p_T^D)}/S(p_T^D)$
At low p_T^D: $\approx \sqrt{B(p_T^D)}/S(p_T^D) \propto 1/(d\sigma_D/dp_T^D)$ — — — dominated by combinatorics
At high p_T^D: $\approx 1/\sqrt{S(p_T^D)} \propto 1/\sqrt{d\sigma_D/dp_T^D}$ — — — low background

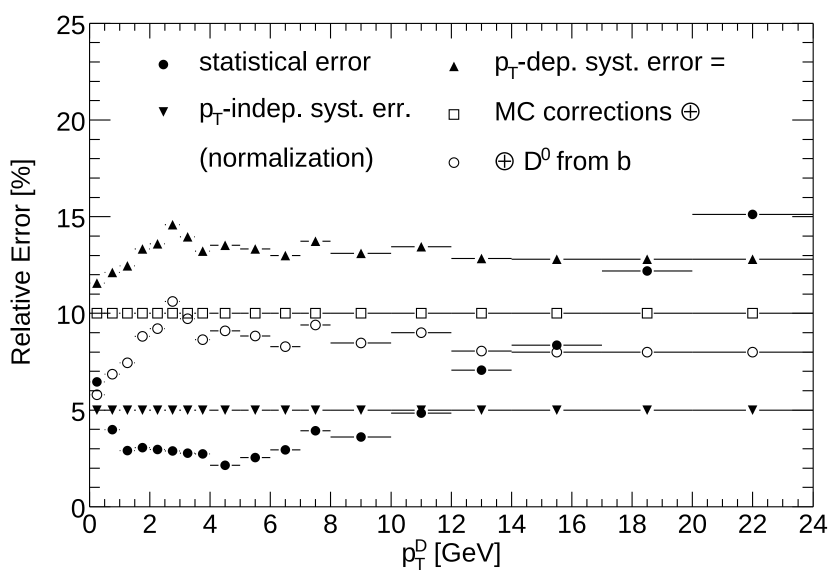

Figure 8: Estimated relative uncertainties on the measurement of the D^0 differential cross section in pp collisions at the LHC with ALICE. Statistical uncertainties correspond to 10^9 minimum-bias pp events (an ≈ 9 month run with a luminosity of $\approx 5 \times 10^{30}$ cm^{-2}s^{-1}).

ALICE "Data" Compared to NLO Cross Sections

D meson "data" from enhancement times alternative NLO cross sections at $\sqrt{S} = 14$ TeV

$d\sigma_{\rm NLO}^{\rm alt} > d\sigma_{\rm NLO}^{\rm std}$ since NLO gluon distribution is smaller at low x for LHC, at fixed-target energies, difference is reduced to difference in α_s evaluations

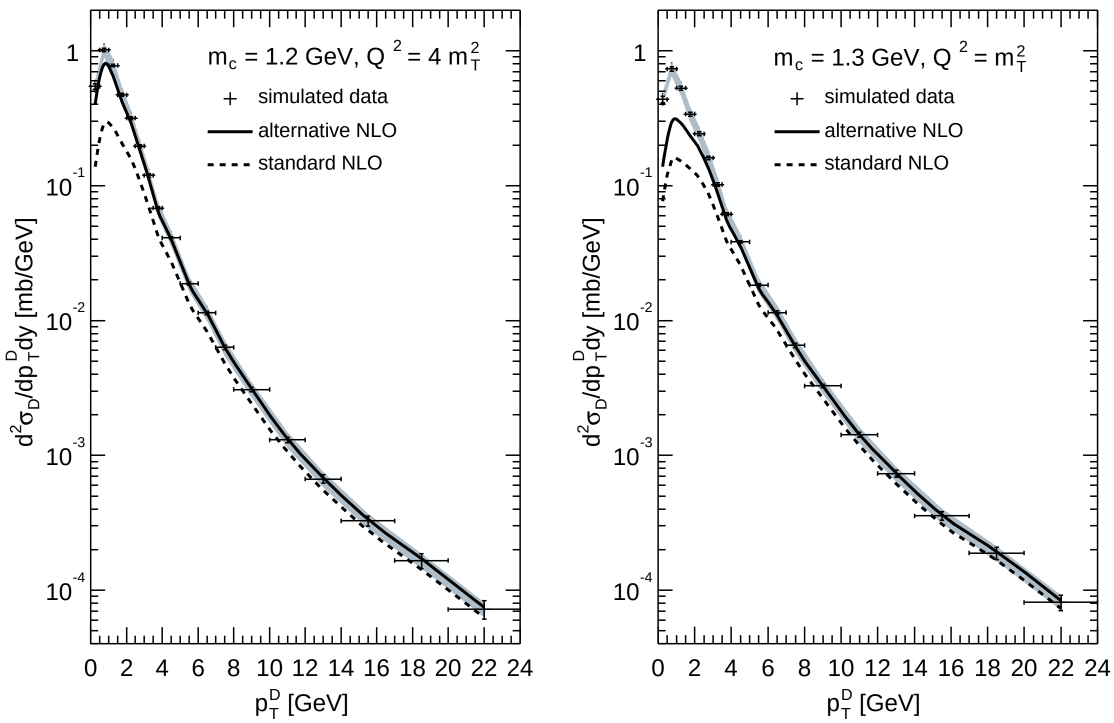

Figure 9: Comparison of the simulated ALICE data generated from $R(p_T, \Delta y) d\sigma_{\rm NLO}^{\rm alt}$ with the alternative (solid) and standard (dashed) NLO calculations. The effect of string fragmentation is included in the "data" points as well as in the curves. The left-hand side shows the result for $m = 1.2$ GeV and $\mu^2 = 4m_T^2$ while the right-hand side is the result for $m = 1.3$ GeV and $\mu^2 = m_T^2$. The error bars on the data represent the statistical error and the shaded band represents the p_T-dependent systematic error. The 5% normalization error is not shown.

Data/Theory Ratios Show Enhancement Can Be Detected

For $m = 1.2$ GeV and $\mu^2 = 4m_T^2$, only better description of "experimental" ratio is with $m = 1.1$ GeV, too small

For $m = 1.3$ GeV and $\mu^2 = m_T^2$, lower mass and higher scale solutions have wrong curvature

Result seems rather independent of PDF

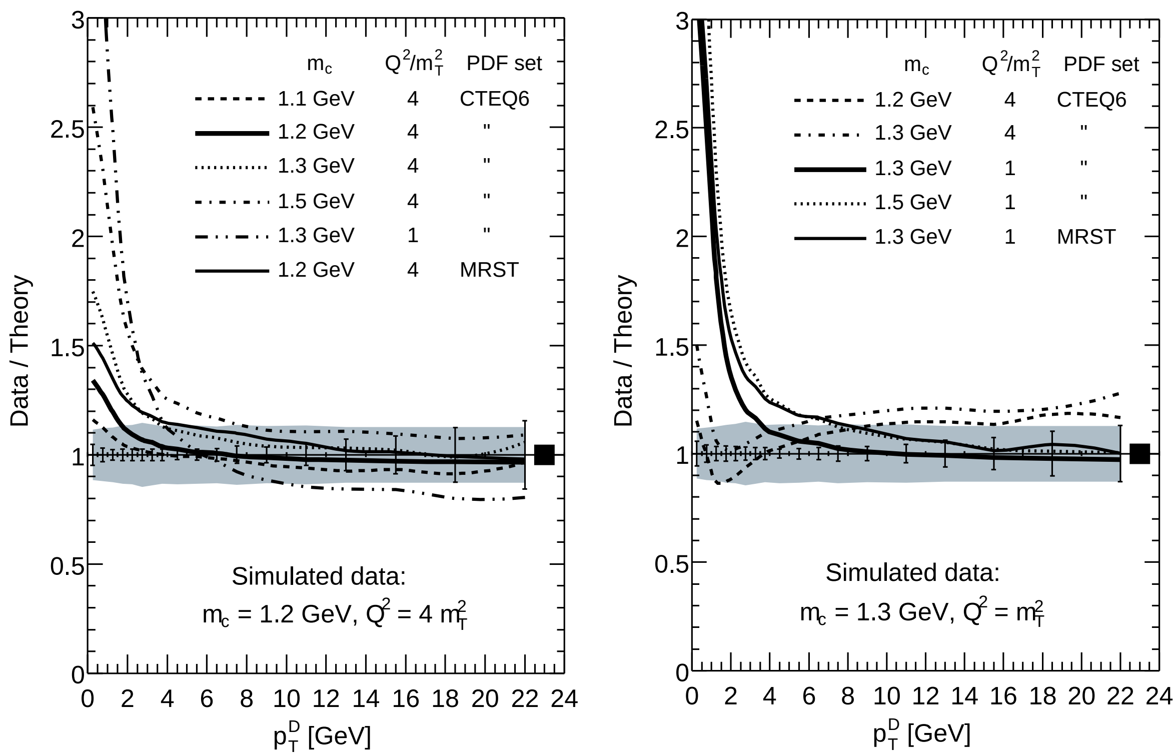

Figure 10: Ratio of the generated ALICE data relative to calculations of the alternative NLO cross sections with several sets of parameters and PYTHIA string fragmentation. The left-hand side shows the result for $m = 1.2$ GeV and $\mu^2 = 4m_T^2$ while the right-hand side is the result for $m = 1.3$ GeV and $\mu^2 = m_T^2$.

Summary

Nonlinear terms in PDFs lead to recombination of gluons and thus to enhanced gluon distributions at low x and Q^2

Enhanced gluon distributions have important effect on charm production, increases LO charm cross section at low p_T by up to a factor of five

Remaining uncertainties are importance of recombination terms at NLO and difference between protons and nuclei

Effect survives hadronization to D mesons and can be detected by ALICE through low p_T^D D^0 reconstruction