DIS'04, 14 - 18 April 2004

Inclusive $D^\star$ Hadroproduction with Massive Quarks

Ingo Schienbein
(DESY)

in collaboration with: B. Kniehl, G. Kramer and H. Spiesberger

---

Outline

- Overview and Motivation
- Heavy Flavour Schemes
- The Calculation
- Numerical Results
- Conclusions and Outlook

Overview and Motivation

Heavy Quarks:

$h = c, b, t$ with $m_h \gg \Lambda_{\rm QCD} \Rightarrow \alpha_s(m_h^2) \propto \ln^{-1}(\frac{m_h^2}{\Lambda^2_{\rm QCD}}) \ll 1$

m_h sets perturbative scale/hard scale; acts as long-distance cut-off

$\Rightarrow$ Heavy Quark Production theoretically interesting:

- application of perturbative QCD (pQCD)
- often other hard scale(s) involved: multi-scale problems
- description of less inclusive observables challenging

$\Rightarrow$ measurement of such processes $\rightsquigarrow$ extensive tests of pQCD

This talk:

- restrict to open charm hadroproduction $p\bar{p} \to D^\star X$
- describe new calculation in a Massive VFNS
  based on the factorization theorem of Collins with heavy quarks [1]
- Related work by G. Kramer and H. Spiesberger:
  - $\gamma\gamma \to D^\star X$: direct process [2]
  - $\gamma\gamma \to D^\star X$: single-resolved process [3]
  - $\gamma p \to D^\star X$: direct process [4]

Main Motivation:

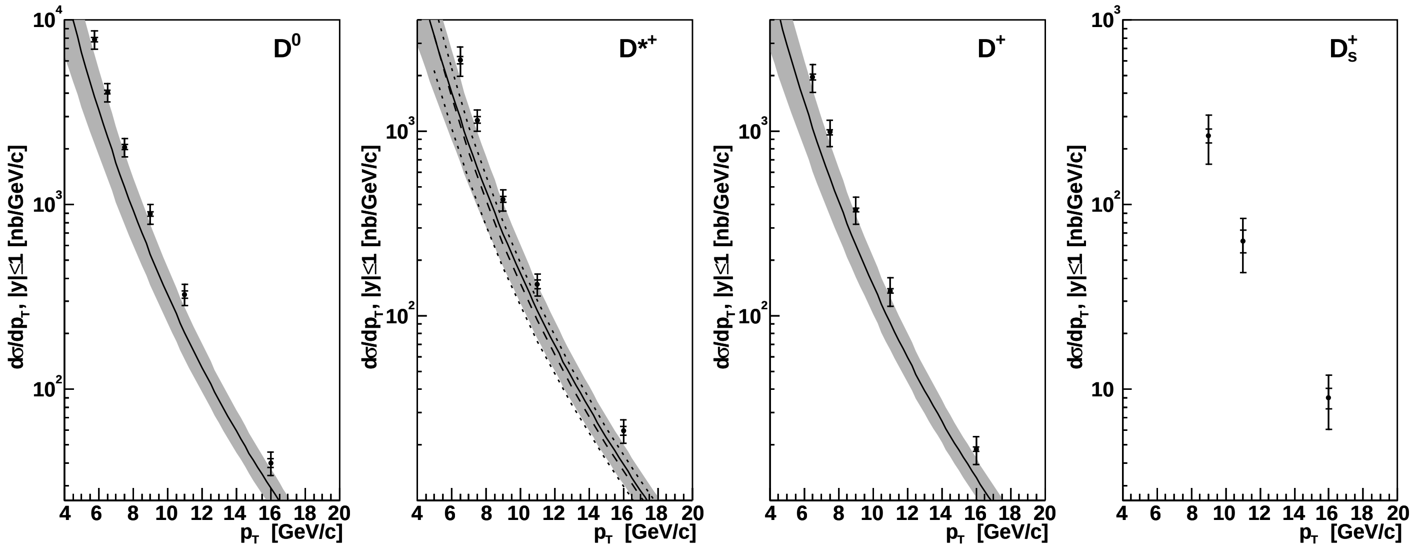
- new/first experimental results for $p\bar{p} \to D^\star X$ from CDF II [5]

---

[1] J. Collins, PRD58(1998)094002
[2] G. Kramer, H. Spiesberger, EPJC22(2001)289; [3] hep-ph/0302081;
[4] hep-ph/0311062
[5] CDF II Coll., D. Acosta et al, PRL91(2003)241804

CDF II data for $p\bar{p} \to DX$ [1]

- $\int_{-1}^{1} \mathrm{d}y \, \frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}y}$ in $\mathrm{nb/GeV}$ vs p_T (at $\sqrt{S} = 1.96$ TeV)
- Theoretical predictions:
  - grey band: 'FONLL' [2]
  - dashed lines: 'massless Kniehl' [3]



Prompt charm (no secondary charm from B decay)

- Data and Theory compatible within errors
- Central values: $\mathrm{Data/Theory} \simeq 2(1.5)$ at low(high) p_T

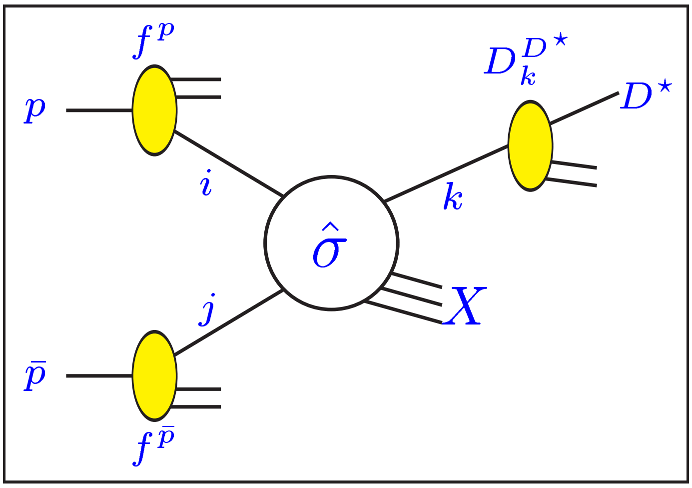
---

[1] CDF II Coll., D. Acosta et al, PRL91(2003)241804

[2] M. Cacciari, P. Nason, JHEP0309(2003)006

[3] B. A. Kniehl, private communication

Theoretical approaches to $p\bar{p} \to D^\star X$ (DGLAP)



Factorization Formula:

$$d\sigma(p\bar{p} \to D^\star X) = \sum_{i,j,k} \int dx_1\ dx_2\ dz\ f_i^p(x_1)\ f_j^{\bar{p}}(x_2)\ \times$$
$$\mathrm{d}\hat{\sigma}(ij \to kX)\ D_k^{D^\star}(z) + \mathcal{O}(\alpha_s^{n+1}, \frac{\Lambda^2}{Q^2})$$

Q: hard scale, e.g., $Q = \max(p_T, m_h)$

- $\mathrm{d}\hat{\sigma}(\mu_{\mathrm{F}}, \mu'_{\mathrm{F}}, \alpha_s(\mu_{\mathrm{R}}), [\frac{m_h}{p_T}])$: hard scattering cross sections free of long-distance physics $\to$ m_h can be kept
- Parton densities of the proton $f_i^p(x_1, \mu_{\mathrm{F}})$:
  $i = g, q, \ldots \quad [q = u, d, s]$
- Parton densities of the anti-proton $f_j^{\bar{p}}(x_2, \mu_{\mathrm{F}})$:
  $j = g, q, \ldots$
- Fragmentation function $D_k^{D^\star}(z, [\mu'_{\mathrm{F}}])$:
  $k = g, q, c \leftarrow$ charm included in the final state

Details depend on the Heavy Flavour Scheme

Conventional Parton Model (ZM-VFNS)

- $m_c = 0 \to$ 'Zero Mass'
- variable number of partons $\to$ 'VFNS'

$$\text{partons} = \begin{cases} g, u, d, s & : \mu_F < Q_0 \\ g, u, d, s + c & : Q_0 < \mu_F \end{cases}$$

$n_f = 3 \to n_f = 4$ in VFNS: finite transformation

$$\left.\begin{array}{l} \alpha_s^{(3)} \to \alpha_s^{(4)} = \alpha_s^{(3)} + \mathcal{O}(\alpha_s^3) \\ f_i^{(3)} \to f_i^{(4)} = f_i^{(3)} + \mathcal{O}(\alpha_s^2) \end{array}\right\} @\ Q_0 = m_c$$

$\boxed{f_c^{(4)}(x, Q_0^2 = m_c^2) = 0}$ pert. boundary condition

- Collinear divergences related to c lines factorized into non-perturbative PDFs and FFs

---

Pro and Contra:

+ large collinear logarithms $\ln \frac{\mu^2}{m_c^2}$ resummed in evolved $f_c(x, \mu^2)$ and $D_c^{D^\star}(x, \mu^2)$ to LL and NLL accuracy

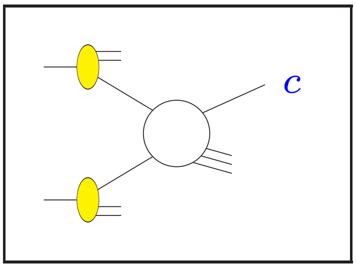
  $\Rightarrow$ $\boxed{\text{good for large } \mu^2 \simeq p_T^2 \gg m_c^2}$

+ Universality of PDFs and FFs guaranteed by factorization theorem $\to$ predictive power, global data analysis

– $(\frac{m_c}{p_T})^n$ terms neglected in the hard part

  $\Rightarrow$ $\boxed{\text{breaks down for } p_T^2 \lesssim m_c^2}$ $\Rightarrow$ No σ_{tot}

Fixed Order (3-FFNS)



- $m_c \neq 0$, $n_f = 3$ fixed
- Partons: g, u, d, s
  (NO charm parton: $f_c = 0$)
  Charm (only) in final state
- collinear logarithms $\ln \frac{s}{m_c^2}$ finite
  $\rightarrow$ No factorization; no conceptual necessity for FFs
  $\rightarrow$ fixed order perturbation theory; no resummation
- Usually c treated in on-shell scheme ($\overline{\mathrm{MS}}_m$)

Pro and Contra:

+ $(\frac{m_c}{p_T})^n$ terms included; correct threshold suppression
  $\Rightarrow$ valid for $0 \leq p_T^2 \lesssim m_c^2$ $\Rightarrow$ σ_{tot} calculable

– fixed order logarithms $\ln \frac{p_T^2}{m_c^2}$ large for $p_T^2 \gg m_c^2$;
  resummation of these large logarithms necessary
  $\Rightarrow$ breaks down for $p_T^2 \gg m_c^2$

– non-perturbative function $D_c^{D^\star}(z)$, describing the
  transition $c \rightarrow D^\star$ needs to be included to match data;
  $\rightarrow$ not based on factorization theorem (no AP evolution)
  $\rightarrow$ universal?

Massive VFNS

- VFNS with $m_c \neq 0$
- Partons: g, u, d, s, c ($\exists$ charm parton: $f_c \neq 0$)
- collinear $\ln \frac{\mu^2}{m_c^2}$ terms:
  subtracted from hard part (avoid double counting!) and
  resummed by AP evolution equations ($\rightarrow f_c \neq 0$)
- $D_c^{D^\star}(z, {\mu'_{\rm F}}^2)$ evolved

Pro and Contra:

- technically more involved:
  - calculation with $m_c \neq 0$
  - subtraction of collinear parts $\leftrightarrow$ 'IR-safe' hard parts
    Mass factorization with massive regularization
  - kinematics: factorization with massive partons $\rightarrow$
    'ACOT-χ' in DIS

+ large collinear logarithms $\ln \frac{\mu^2}{m_c^2}$ resummed in evolved
  $f_c(x, \mu^2)$ and $D_c^{D^\star}(x, \mu^2)$

+ $(\frac{m_c}{p_T})^n$ included

$\Rightarrow$ good for all p_T: $0 \leq p_T^2 \lesssim m_c^2$ and $p_T^2 \gg m_c^2$

Theoretical predictions for $p\bar{p} \to HX$, ($H = D, B$)

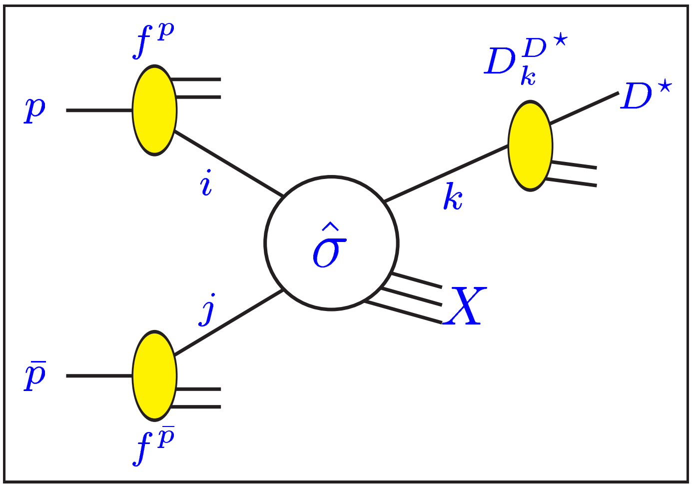
- Fixed Order (massive NLO)
  Nason, Dawson, Ellis, NPB327(1989)49;B335(1990)260(E)
  Ellis, Nason; NPB312(1989)551
  Beenakker, Kuif, van Neerven, Smith, PRD40(1989)54
  Beenakker et al, NPB351(1991)507
  Smith, van Neerven, NPB374(1992)36
  Krämer, Zunft, Steegborn, Zerwas, PLB348(1995)657
  Bojak, Stratmann, PRD67(2003)034010 (un)polarized

- Resummed (massless NLO) [$\to$ main differences: FFs]
  - Cacciari, Greco, NPB421(1994)530
  - 'massless Kniehl':
    Binnewies, Kniehl, Kramer, PRD58(1998)014014
    Kniehl, Kramer, Pötter, NPB597(2001)337

  based on work ($\to$ hard scattering cross sections) by
  Aversa, Chiappetta, Greco, Guillet, NPB327(1989)105

- Interpolations between 'Fixed Order' and 'Resummed' (matched calculations)
  [$\to$ main differences: FFs, Interpolation]
  - 'FONLL' (FO+NLL)
    Cacciari, Greco, Nason, JHEP05(1998)007
    Cacciari, Nason, PRL89(2002)122003; JHEP09(2003)006
  - GM-VFNS (Factorization with massive quarks)
    Olness, Scalise, Tung, PRD59(1998)014506
    Kniehl, Kramer, I.S., Spiesberger

Theoretical basis for $p\bar{p} \to D^\star X$



Factorization Formula: [1]

$$d\sigma(p\bar{p} \to D^\star X) = \sum_{i,j,k} \int dx_1\, dx_2\, dz\, f_i^p(x_1)\, f_j^{\bar{p}}(x_2) \times$$
$$\mathrm{d}\hat{\sigma}(ij \to kX)\, D_k^{D^\star}(z) + \mathcal{O}(\alpha_s^{n+1}, \tfrac{\Lambda^2}{Q^2})$$

Q: hard scale, e.g., $Q = \max(p_T, m_h)$

- $\mathrm{d}\hat{\sigma}(\mu_\mathrm{F}, \mu'_\mathrm{F}, \alpha_s(\mu_\mathrm{R}), \frac{m_h}{p_T})$: hard scattering cross sections free of long-distance physics $\to$ m_h kept
- PDFs $f_i^p(x_1, \mu_\mathrm{F})$, $f_j^{\bar{p}}(x_2, \mu_\mathrm{F})$: $i, j = g, q, c$ $[q = u, d, s]$
- FFs $D_k^{D^\star}(z, \mu'_\mathrm{F})$: $k = g, q, c$

$\Rightarrow$ need short distance coefficients including heavy quark masses

---

[1] Collins, PRD58(1998)094002

Adopted Procedure

- Calculate $m \to 0$ limit of massive 3-FFNS calculation of heavy quark production (at the partonic level) [1]
  Only keep m as regulator in $\ln \frac{m^2}{s}$

  Partonic subprocesses in 3-FFNS:
  - Leading Order (LO):
    1. $gg \to c\bar{c}$
    2. $q\bar{q} \to c\bar{c} \quad (q = u, d, s)$
  - Next-To-Leading Order (NLO):
    1. $gg \to c\bar{c}g$
    2. $q\bar{q} \to c\bar{c}g$
    3. $gq \to c\bar{c}q$ New@NLO

  Limiting procedure non-trivial:
  - Map from PS-slicing to Subtraction method
  - care needed to recover $\delta(1-w)$, $(\frac{1}{1-w})_+$, $(\frac{\ln(1-w)}{1-w})_+$

  Checks:
  - Compare Abelian parts with results in [2]
  - Numerical tests

---

[1] Bojak, Stratmann, PRD67(2003)034010; FORTRAN code provided by I. Bojak

[2] Kramer, Spiesberger, EPJC22(2001)289; hep-ph/0302081

Adopted Procedure –continued–

- Compare $m \to 0$ limit of massive calculation with massless $\overline{\mathrm{MS}}$ calculation [1]

$$\lim_{m\to 0} \mathrm{d}\sigma(m) = \mathrm{d}\hat{\sigma}(\overline{\mathrm{MS}}) + \Delta\mathrm{d}\sigma$$

$\Rightarrow$ Subtraction terms

$$\mathrm{d}\sigma_{\mathrm{SUB}} \equiv \Delta\mathrm{d}\sigma = \lim_{m\to 0} \mathrm{d}\sigma(m) - \mathrm{d}\hat{\sigma}(\overline{\mathrm{MS}})$$

- Subtract $\mathrm{d}\sigma_{\mathrm{SUB}}$ from massive partonic cross section while keeping mass terms

$$\mathrm{d}\hat{\sigma}(m) = \mathrm{d}\sigma(m) - \mathrm{d}\sigma_{\mathrm{SUB}}$$

$\to$ $\mathrm{d}\hat{\sigma}(m)$ short distance coefficient including m

This is nothing but $\overline{\mathrm{MS}}$ mass factorization in a scheme where collinear divergences are massively regularized with help of a quark mass m

$\to$ allows to use PDFs and FFs with $\overline{\mathrm{MS}}$ factorization
$\oplus$ massive short distance cross sections

- Treat contributions with <u>charm in the initial state</u> with $m_c = 0$; $\rightsquigarrow$ scheme choice of practical importance; tiny effect in DIS [2]

---

[1] Aversa, Chiappetta, Greco, Guillet, NPB327(1989)105
[2] Kretzer, I.S., PRD58(1998)094035

List of Subprocesses

Calculation: $\overline{\mathrm{MS}}$-scheme, heavy quark: $m_Q = 0$ [1]

- Red: Heavy quark mass effects included
- Green: Heavy quark initiated: $m_Q = 0$
- Blue: only light lines involved

$gg \to q$	$gg \to Q$	
$gg \to g$		
$qg \to g$	$Qg \to g$	
$qg \to q$	$Qg \to Q$	
$q\bar{q} \to g$	$Q\bar{Q} \to g$	
$q\bar{q} \to q$	$Q\bar{Q} \to Q$	
$qg \to \bar{q}$	$Qg \to \bar{Q}$	
$qg \to \bar{q}'$	$Qg \to \bar{q}'$	$qg \to \bar{Q}$
$qg \to q'$	$Qg \to q'$	$qg \to Q$
$qq \to g$	$QQ \to g$	
$qq \to q$	$QQ \to Q$	
$q\bar{q} \to q'$	$Q\bar{Q} \to q'$	$q\bar{q} \to Q$
$q\bar{q}' \to g$	$Q\bar{q}' \to g$	$q\bar{Q} \to g$
$q\bar{q}' \to q$	$Q\bar{q}' \to Q$	$q\bar{Q} \to q$
$qq' \to g$	$Qq' \to g$	$qQ' \to g$
$qq' \to q$	$Qq' \to Q$	$qQ \to q$

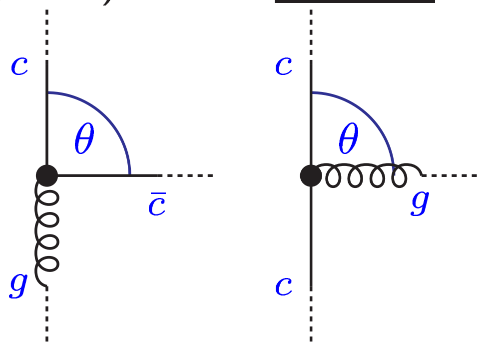
$\oplus$ charge conjugated processes

[1] Aversa, Chiappetta, Greco, Guillet, NPB327(1989)105

$\overline{\text{MS}}$ mass factorization

Recap some facts:

- 'Mass divergences' ($\equiv$ 'Collinear divergences'): internal propagator on-shell ($\rightarrow$ long-distance propagation) due to collinear emission of particles



collinear ($\theta \approx 0$)

- Mass factorization:
  Collinear divergences subtracted / absorbed into PDFs (FFs)

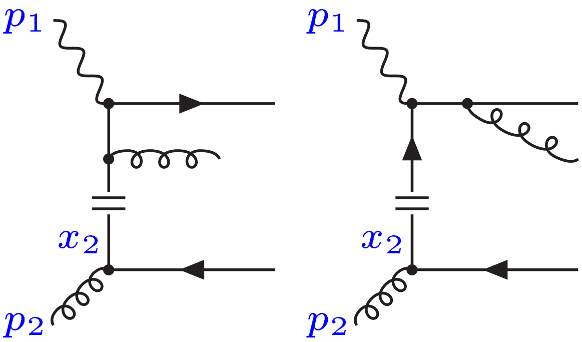
- along with the poles finite terms can be subtracted
  $\rightarrow$ different factorization schemes; here $\overline{\text{MS}}$ scheme

- even for the same factorization scheme the subtraction terms do depend on the regularization procedure

- $\overline{\text{MS}}$ fact. scheme defined using dimensional regularization $[m_c = 0]$
  $\rightarrow$ collinear poles occur as $\frac{1}{\epsilon}$ poles $\rightarrow$ Example

- Heavy Quark Production:
  Natural to use the heavy quark mass m as collinear regulator;
  $\rightarrow$ collinear poles occur as $\ln \frac{s}{m^2}$ poles
  The massive $\overline{\text{MS}}$ subtraction terms $\sigma_{\text{SUB}}(\mu_{\text{F}}, m)$ are identified by: $\lim_{m \to 0} \left(\sigma(m) - \sigma_{\text{SUB}}(m)\right) \stackrel{!}{=} \hat{\sigma}(\overline{\text{MS}})$

Example:



$\rightsquigarrow \mathrm{d}\sigma_{\mathrm{SUB}}({\mu_{\mathrm{F}}}^2, \mu^2)$

$$= \int_0^1 \mathrm{d}x_2 \; G^1_{cg}(x_2) \mathrm{d}\hat{\sigma}^{(0)}_{\gamma c \to cg}(p_1, x_2 p_2) \equiv G^1_{cg}(x_2) \otimes \mathrm{d}\hat{\sigma}^{(0)}_{\gamma c \to cg}$$

with $[n = 4 - 2\epsilon]$

$$G^1_{cg}(x, {\mu_{\mathrm{F}}}^2, \mu^2) = \frac{\alpha_s(\mu^2)}{2\pi} \Big[P^{(0)}_{cg}(x) \big(-\tfrac{1}{\epsilon} + \gamma_E - \ln 4\pi\big) \big(\tfrac{\mu^2}{{\mu_{\mathrm{F}}}^2}\big)^\epsilon + \underbrace{g^1_{cg}(x)}_{\overline{\mathrm{MS}}=0} \Big]$$

Remarks:

- $p_1, x_2 p_2 \to \hat{s}, \hat{t}, \hat{u} \to \delta(\hat{s} + \hat{t} + \hat{u}) \Rightarrow x_2 = x_2(s, t, u)$
- (usually) $\mathrm{d}\hat{\sigma}^{(0)}$ in n dimensions
- $\underbrace{\ln \frac{s}{\mu^2}}_{-\frac{1}{\epsilon}(\mu^2/s)^\epsilon} \quad \underbrace{- \ln \frac{{\mu_{\mathrm{F}}}^2}{\mu^2}}_{\mathrm{SUB}} = \underbrace{\ln \frac{s}{{\mu_{\mathrm{F}}}^2}}_{\to \mathrm{hard}}$

Generally:

$$G^1_{ij}(x, {\mu_{\mathrm{F}}}^2, \mu^2) = \frac{\alpha_s(\mu^2)}{2\pi} \Big[P^{(0)}_{ij}(x) \big(-\tfrac{1}{\epsilon} + \gamma_E - \ln 4\pi\big) \big(\tfrac{\mu^2}{{\mu_{\mathrm{F}}}^2}\big)^\epsilon + \underbrace{g^1_{ij}(x)}_{\overline{\mathrm{MS}}=0} \Big]$$

Massive $\overline{\rm MS}$ mass factorization

Subtraction term: (as before)

$$d\sigma^1_{\rm SUB}({\mu_{\rm F}}^2, \mu^2) = G^1(x) \otimes d\hat{\sigma}^{(0)} \,,\; d\hat{\sigma}^{(0)} \otimes D^1(z)$$

with universal functions $G^1_{ij}(x, {\mu_{\rm F}}^2, \mu^2)$ and $D^1_{ij}(x, {\mu_{\rm F}}^2, \mu^2)$

Hard (IR safe) cross sections $\hat{\sigma}$:

$$d\hat{\sigma}^{(1)} = d\sigma^1 - d\sigma^1_{\rm SUB}$$

Setting $\mu_{\rm F} = \mu$, massive regularized, $\overline{\rm MS}$:

1. initial state:

$$G^1_{cg}(x, \mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{cg}(x) \ln \frac{\mu^2}{m_c^2}$$

$$G^1_{cc}(x, \mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{cc}(x) \ln \frac{\mu^2}{m_c^2}$$

$$G^1_{gg}(x, \mu^2) = \frac{\alpha_s(\mu)}{2\pi} \ln \frac{\mu^2}{m_c^2} \delta(1-x)$$

2. final state:

$$D^1_{cg}(z, \mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{cg}(z) \ln \frac{\mu^2}{m_c^2}$$

$$D^1_{cc}(z, \mu^2) = C_F \frac{\alpha_s(\mu)}{2\pi} \left[\frac{1+z^2}{1-z}\left(\ln \frac{\mu^2}{m_c^2} - 2\ln(1-z) - 1\right)\right]_+ [1,2]$$

- other distributions are zero to this order
- analogous for photon splitting: $g \to \gamma$, $\alpha_s \to \alpha$

---

[1] Mele, Nason, NPB361(91)626; [2] Kretzer, I.S., PRD59(99)054004

Numerical Results

$$\int_{-1}^{1} \mathrm{d}y \, \frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}y}$$

for

$$p + \bar{p} \to (gg \to c) \to D^\star + X$$

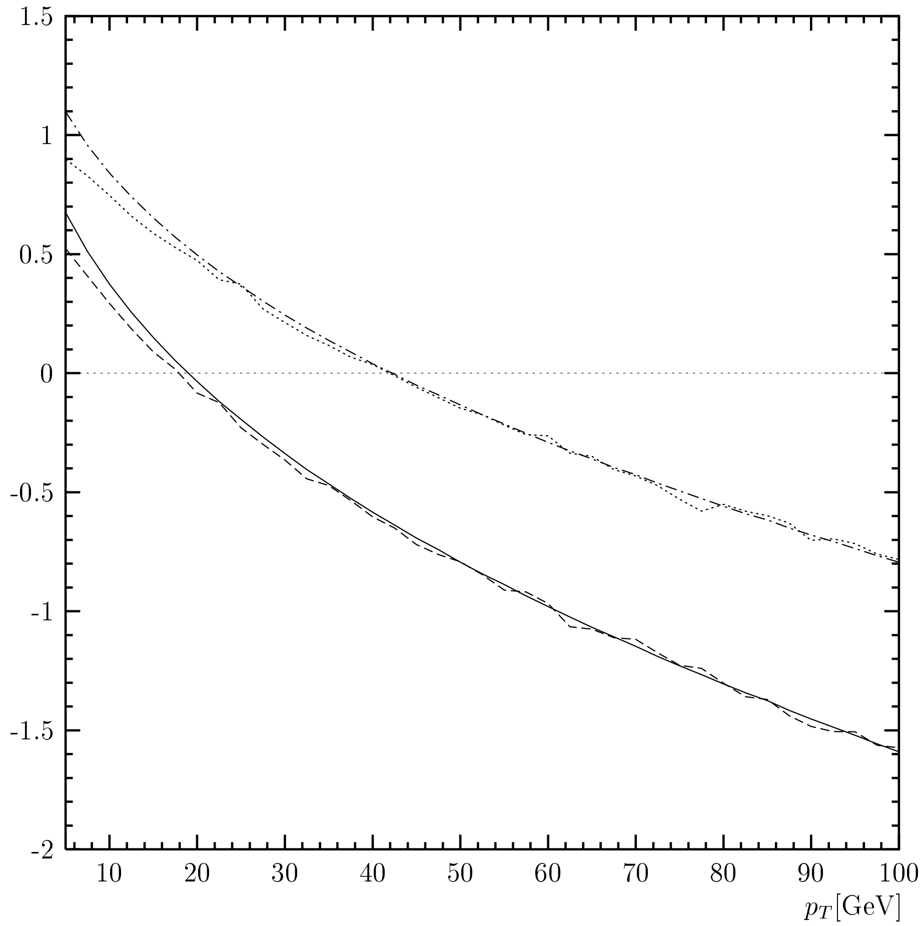
at the Tevatron

Input parameters:

- $E_p = 980 \text{ GeV} \to \sqrt{S} = 1960 \text{ GeV}$
- Show results for: $5 \text{ GeV} < p_T < 100 \text{ GeV}$
- PDFs: CTEQ6M (NLO), CTEQ6L (LO)
- FFs: NLO OPAL
- $\alpha_s(M_Z) = 0.118$
- $\mu_\mathrm{R} = \mu_\mathrm{F} = \mu'_\mathrm{F}$

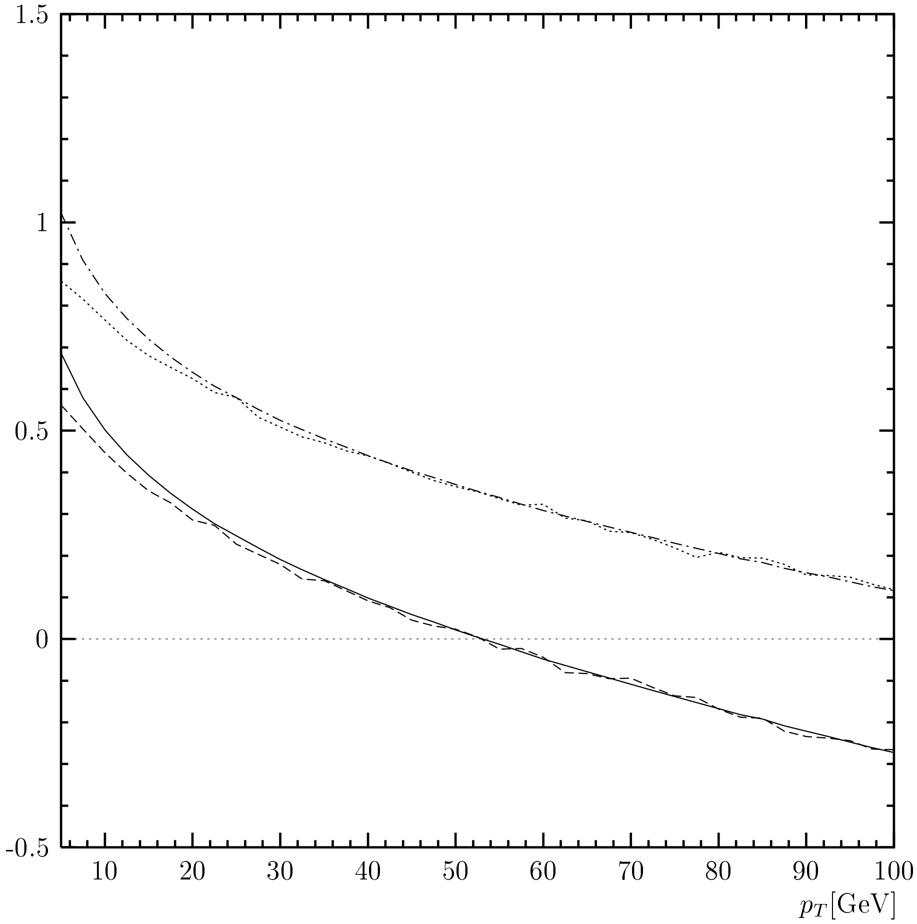
(LO+NLO)/LO(m=0) vs p_T (Abelian Part)

- $p\bar{p} \to (gg \to c) \to D^\star + X$, Abelian Part
- $\mu_\mathrm{F} = \mu'_\mathrm{F} = \mu_\mathrm{R} = m$



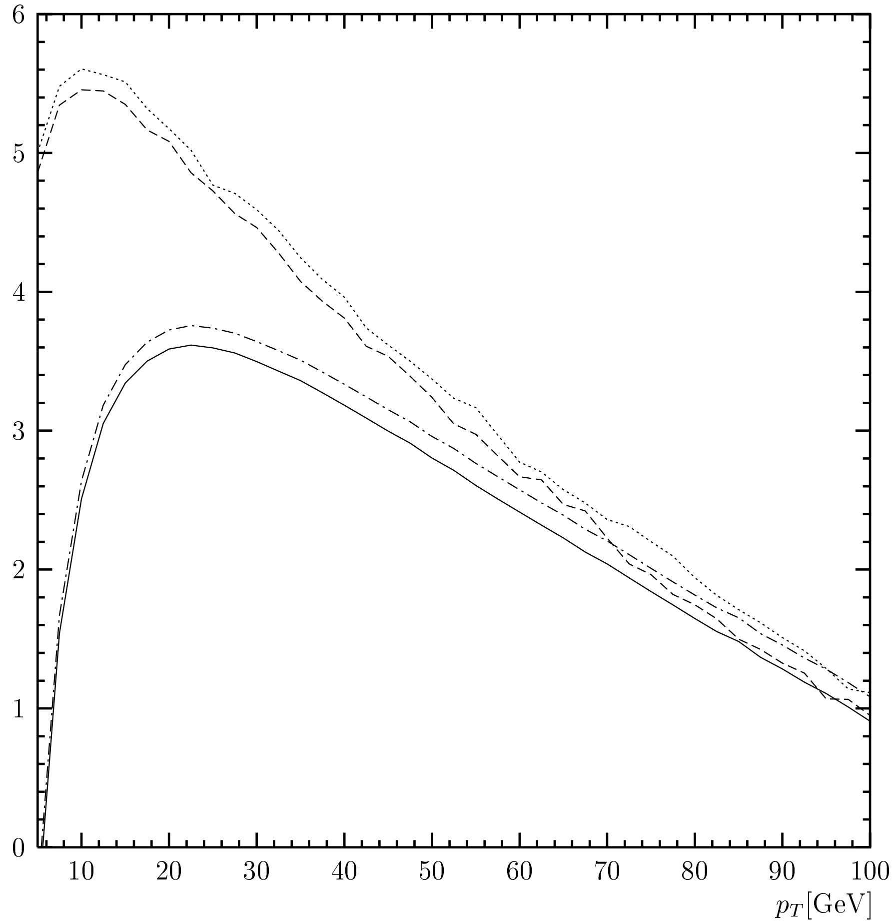
(LO+NLO)/LO(m=0) vs p_T (Abelian Part)

- $p\bar{p} \to (gg \to c) \to D^{\star} + X$, Abelian Part
- $\mu_{\rm F} = \mu'_{\rm F} = \mu_{\rm R} = 2m_T$, ($m_T^2 = m^2 + p_T^2$)



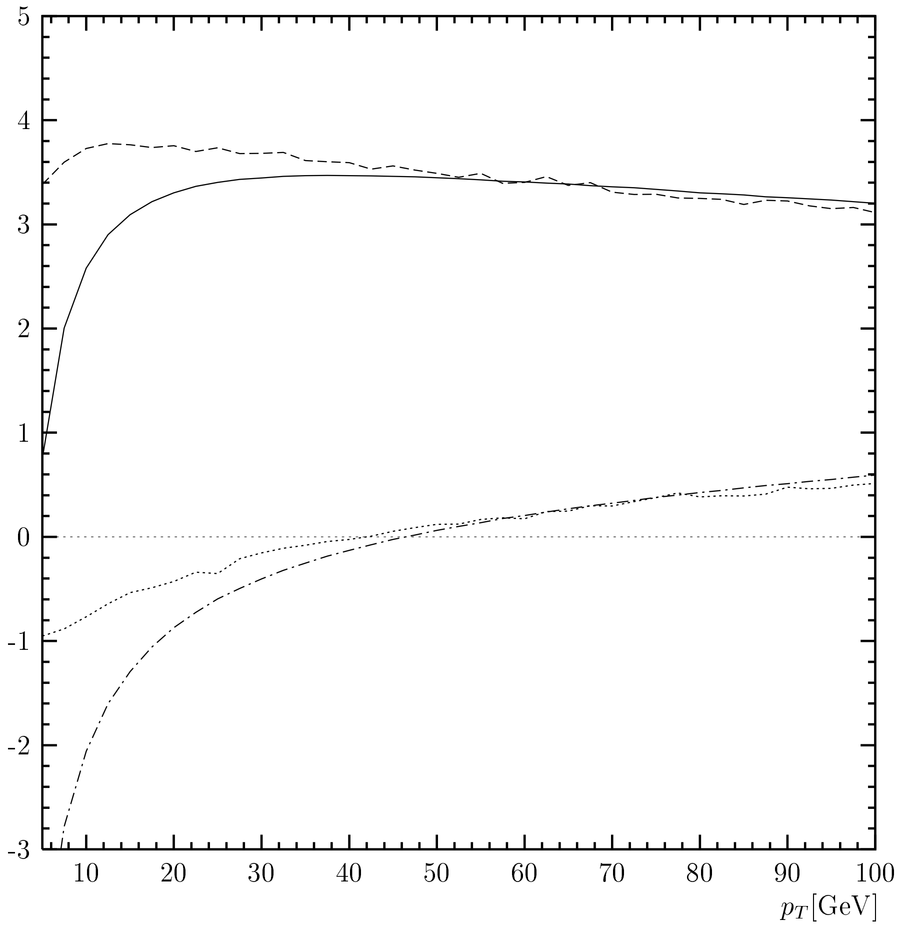
(LO+NLO)/LO(m=0) vs p_T

- $p\bar{p} \to (gg \to c) \to D^\star + X$, Abelian and Non-Abelian
- $\mu_{\mathrm{F}} = \mu'_{\mathrm{F}} = \mu_{\mathrm{R}} = m$



(LO+NLO)/LO(m=0) vs p_T

- $p\bar{p} \to (gg \to c) \to D^\star + X$, Abelian and Non-Abelian
- $\mu_\mathrm{F} = \mu'_\mathrm{F} = \mu_\mathrm{R} = 2m_T$



Conclusions and Outlook

- Massless limit of massive calculation compared with massless $\overline{\mathrm{MS}}$ calculation
  Subtraction terms identified:

$$d\sigma_{\mathrm{SUB}} \equiv \Delta d\sigma = \lim_{m\to 0} d\sigma(m) - d\hat{\sigma}(\overline{\mathrm{MS}})$$

- Short distance coefficients including heavy quark mass m constructed:

$$d\hat{\sigma}(m) = d\sigma(m) - d\sigma_{\mathrm{SUB}}$$

- allows to use PDFs and FFs with $\overline{\mathrm{MS}}$ factorization together with massive short distance cross sections

- Application:
  Framework for $p\bar{p} \to HX$ $(H = D, B)$
  valid for $0 \le p_T^2 \lesssim m_c^2$ and $p_T^2 \gg m_c^2$
  based on Collin's factorization theorem with heavy quarks

Outlook:

- Comparison with Tevatron data for D and B meson production

- Resolved contribution to $\gamma p \to D^\star X$, $\gamma\gamma \to D^\star X$

Paper will appear soon!