# *Open heavy-flavour hadroproduction at NLO in the GM-VFN scheme*

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CERN, 3 December 2010

# OUTLINE

# Overview

- One-particle inclusive production of heavy hadrons $H = D, B, \Lambda_c, \ldots$
- General-Mass Variable Flavour Number Scheme (GM-VFNS): [1]
  - Collinear logarithms of the heavy-quark mass $\ln \mu/m_h$ are subtracted and resummed
  - Finite non-logarithmic $m_h/Q$ terms are kept in the hard part/taken into account
  - Scheme guided by the factorization theorem of Collins with heavy quarks [2]

Ongoing effort to compute all relevant processes in the GM-VFNS at NLO:

- Available:
  - $e^+ + e^- \to (D^0, D^+, D^{\star +}) + X$: FFs [3]
  - $\gamma + \gamma \to D^{\star +} + X$: direct process [4]
  - $\gamma + \gamma \to D^{\star +} + X$: single-resolved process [5]
  - $\gamma + p \to D^{\star +} + X$: direct process [6]
  - $\gamma + p \to D^{\star +} + X$: resolved process [7]
  - $p + \bar{p} \to (D^0, D^+, D^{\star +} D_s^+, \Lambda_c^+, B^0, B^+) + X$ [1]

[1] B.K.,Kramer,Schienbein,Spiesberger, PRD71(2005)014018; EPJC41(2005)199; PRL96(2006)012001; PRD77(2008)014011
[2] Collins, PRD58(1998)094002
[3] Kneesch,B.K.,Kramer,Schienbein, NPB799(2008)34
[4] Kramer,Spiesberger, EPJC22(2001)289; [5] EPJC28(2003)495; [6] EPJC38(2004)309
[7] B.K.,Kramer,Schienbein,Spiesberger, arXiv:0902.3166[hep-ph], EPJC(in press)

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# OVERVIEW -CONTINUED-

Input for the computation: Fragmentation Functions (FFs) into heavy hadrons $H$

- FFs from fits to $e^+e^-$ data from $Z$ factories
- Include also $B$ factories $\rightarrow$ Switch from ZM to GM
- Use initial scale $\mu_0 = m$ (instead of $\mu_0 = 2m$) for consistency with PDFs $\rightarrow$ important for gluon fragmentation

| $H$ | Data | Scheme | Reference |
|---|---|---|---|
| $D^{*+}$ | ALEPH,OPAL | ZM $2m$ | BKK, PRD58(1998)014014 |
| $D^0, D^+, D_s^+, \Lambda_c^+$ | OPAL | ZM $2m$ | KK, PRD71(2005)094013 |
| $D^0, D^+, D^{*+}, D_s^+, \Lambda_c^+$ | OPAL | ZM $m$ | KK, PRD74(2006)037502 |
| $D^0, D^+, D_s^+$ | Belle,CLEO,ALEPH,OPAL | GM $m$ | KKKSc, NPB799(2008)34 |
| $B^0, B^+$ | OPAL | ZM $2m$ | BKK, PRD58(1998)034016 |
| $B^0, B^+$ | ALEPH,OPAL,SLD | ZM $m$ | KKScSp, PRD77(2008)014011 |

Goal:

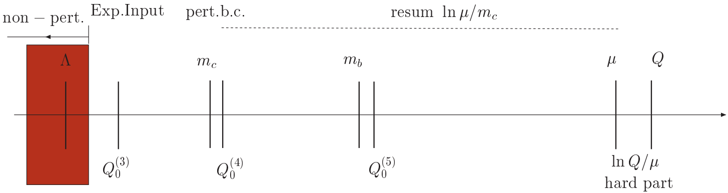
- Test pQCD formalism, scaling violations and universality of FFs in as many processes as possible

# Motivation

## Heavy Quarks and pQCD

Fixed Order Perturbation Theory:

- finite collinear logs $\ln Q/m_c$ arise $\rightarrow$ can be kept in hard part
  Of course need exp. Input for $u, d, s, g$ PDFs at scale $Q_0^{(3)}$




Variable Flavour Number Scheme (VFNS):

- often large ratios of scales involved: multi-scale problems
  For $Q \gg m_c$: write $\ln Q/m_c = \ln Q/\mu + \ln \mu/m_c$, subtract $\ln \mu/m_c$ and resum $\ln \mu/m_c$
  by introducing charm PDF at $Q_0^{(4)} \simeq m_c$ using a perturbative boundary condition

# General-Mass Variable-Flavour-Number Scheme

Two basic approaches:

- Fixed Order Perturbation Theory (FFNS)
- Parton Model (ZM-VFNS)

Interpolating scheme combining the good features:

- Parton Model with quark masses (GM-VFNS, ACOT)

Glossary:

- ZM: Zero Mass
- GM: General Mass
- VFNS: Variable Flavour Number Scheme
- FFNS: Fixed Flavour Number Scheme

Factorization Formula: [1]

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

$Q$: hard scale, $p = 1, 2$

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

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

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[1] J. Collins, 'Hard-scattering factorization with heavy quarks: A general treatment', PRD58(1998)094002

| # | Only light lines | Heavy quark initiated ($m_Q = 0$) | Mass effects: $m_Q \neq 0$ |
|---|---|---|---|
| 1 | $gg \to qX$ | - | $gg \to QX$ |
| 2 | $gg \to gX$ | - | - |
| 3 | $qg \to gX$ | $Qg \to gX$ | - |
| 4 | $qg \to qX$ | $Qg \to QX$ | - |
| 5 | $q\bar{q} \to gX$ | $Q\bar{Q} \to gX$ | - |
| 6 | $q\bar{q} \to qX$ | $Q\bar{Q} \to QX$ | - |
| 7 | $qg \to \bar{q}X$ | $Qg \to \bar{Q}X$ | - |
| 8 | $qg \to \bar{q}'X$ | $Qg \to \bar{q}X$ | $qg \to \bar{Q}X$ |
| 9 | $qg \to q'X$ | $Qg \to qX$ | $qg \to QX$ |
| 10 | $qq \to gX$ | $QQ \to gX$ | - |
| 11 | $qq \to qX$ | $QQ \to QX$ | - |
| 12 | $q\bar{q} \to q'X$ | $Q\bar{Q} \to qX$ | $q\bar{q} \to QX$ |
| 13 | $q\bar{q}' \to gX$ | $Q\bar{q} \to gX$, $q\bar{Q} \to gX$ | - |
| 14 | $q\bar{q}' \to qX$ | $Q\bar{q} \to QX$, $q\bar{Q} \to qX$ | - |
| 15 | $qq' \to gX$ | $Qq \to gX$, $qQ \to gX$ | - |
| 16 | $qq' \to qX$ | $Qq \to QX$, $qQ \to qX$ | - |

⊕ charge conjugated processes

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

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

$\Rightarrow$ Subtraction terms

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

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

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

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

$\to$ allows to use PDFs and FFs with $\overline{\text{MS}}$ factorization $\oplus$ massive short dist. cross sections

- Treat contributions with charm in the initial state 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, Schienbein, PRD58(1998)094035

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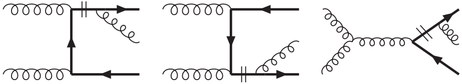
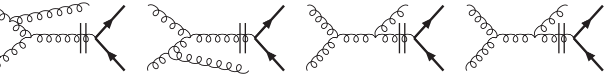
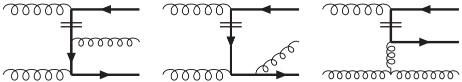
$\mathrm{d}\hat{\sigma}^{(0)}(gg \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



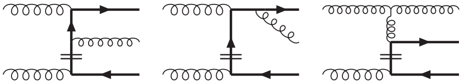
$\mathrm{d}\hat{\sigma}^{(0)}(gg \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



$f^{(1)}_{g\to Q}(x_1) \otimes \mathrm{d}\hat{\sigma}^{(0)}(Qg \to Qg)$:



$f^{(1)}_{g\to Q}(x_2) \otimes \mathrm{d}\hat{\sigma}^{(0)}(gQ \to Qg)$:



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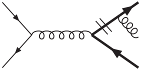

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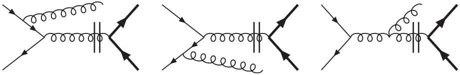

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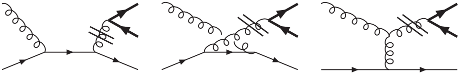

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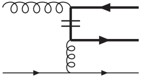

# $D^0, D^+, D^{*+}$ FFs with finite-mass corrections [1]

## Formalism

- $e^+ + e^- \to (\gamma, Z) \to H + X, \qquad H = D^0, D^+, D^{*+}, \ldots$
- $x = 2(p_H \cdot q)/q^2 = 2E_H/\sqrt{s} \qquad \sqrt{\rho_H} \le x \le 1 \quad (\rho_H = 4m_H^2/s)$

$$\frac{d\sigma}{dx}(x,s) = \sum_a \int_{y_{\min}}^{y_{\max}} \frac{dy}{y} \frac{d\sigma_a}{dy}(y,\mu,\mu_f) D_a\left(\frac{x}{y},\mu_f\right)$$

  $d\sigma_a/dy$ at NLO with $m_q = 0$ [2] and $m_q \neq 0$ [1,3]

- $x_p = p/p_{\max} = \sqrt{(x^2 - \rho_H)/(1-\rho_H)} \qquad 0 \le x_p \le 1$

$$\frac{d\sigma}{dx_p}(x_p) = (1-\rho_H)\frac{x_p}{x}\frac{d\sigma}{dx}(x)$$


[1] Kneesch,B.K.,Kramer,Schienbein, NPB799(2008)34

[2] Baier, Fey, ZPC2(1979)339; Altarelli et al. NPB160(1979)301

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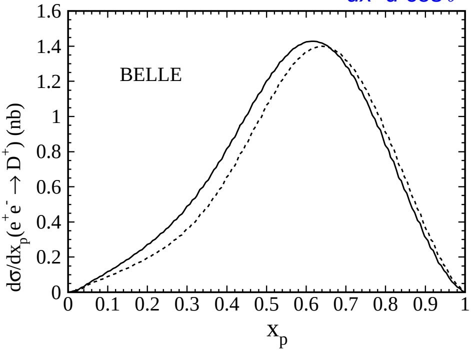
- Use radiator $D_{e^\pm}$ [1]

$$\frac{d\sigma_{\rm ISR}}{dx}(x,s) = \int dx_+\, dx_-\, dx'\, d\cos\theta'\, \delta(x - x(x_+, x_-, x', \cos\theta')) \times D_{e^+}(x_+, s) D_{e^-}(x_-, s) \frac{d^2\sigma}{dx'\, d\cos\theta'}(x', \cos\theta', x_+ x_- s)$$




[1] Kuraev,Fadin, SJNP41(1985)466; Nicrosini,Trentadue, PLB196(1987)551

- Experimental data

| Type | $\sqrt{s}$ [GeV] | H | Collaboration |
|---|---|---|---|
| $d\sigma/dx_p$ | 10.52 | $D^0, D^+, D^{*+}$ | Belle 06 |
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| $(1/\sigma_{\rm tot})d\sigma/dx$ | 91.2 | $D^{*+}$ | ALEPH 00 |
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- Theoretical input
  - $m_c = 1.5$ GeV, $m_b = 5.0$ GeV, $\alpha(m_\Upsilon) = 1/132$, $\alpha_s(m_Z) = 0.1176 \rightsquigarrow \Lambda^{(5)}_{\rm QCD} = 221$ MeV
  - Bowler ansatz [1]

$$D_Q^{H_c}(z, \mu_0) = Nz^{-(1+\gamma^2)}(1-z)^a e^{-\gamma^2/z}$$

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- $\chi^2$/d.o.f.

| $H$ | VFNS | Belle/CLEO | ALEPH/OPAL | Global |
|---|---|---|---|---|
| $D^0$ | GM | 3.15 | 0.794 | 4.03 |
| | ZM | 3.25 | 0.789 | 4.66 |
| $D^+$ | GM | 1.30 | 0.509 | 1.99 |
| | ZM | 1.37 | 0.507 | 2.21 |
| $D^{*+}$ | GM | 3.74 | 2.06 | 6.90 |
| | ZM | 3.69 | 2.04 | 7.64 |

- Quark mass effects improve global fits and Belle/CLEO fits for $D^0, D^+$, but have no impact on ALEPH/OPAL fits.
- Belle and CLEO data on $D^0, D^{*+}$ moderately compatible.
- OPAL fits for $D^0, D^+$ excellent; ALEPH and OPAL data on $D^{*+}$ moderately compatible.
- Tension between Belle/CLEO and ALEPH/OPAL data.

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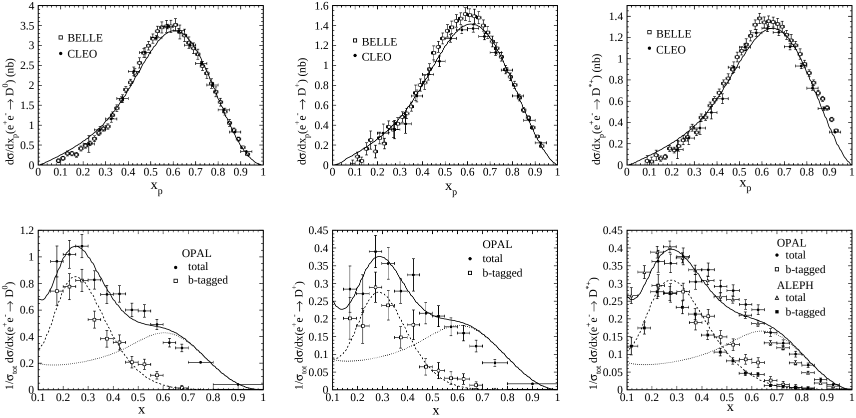
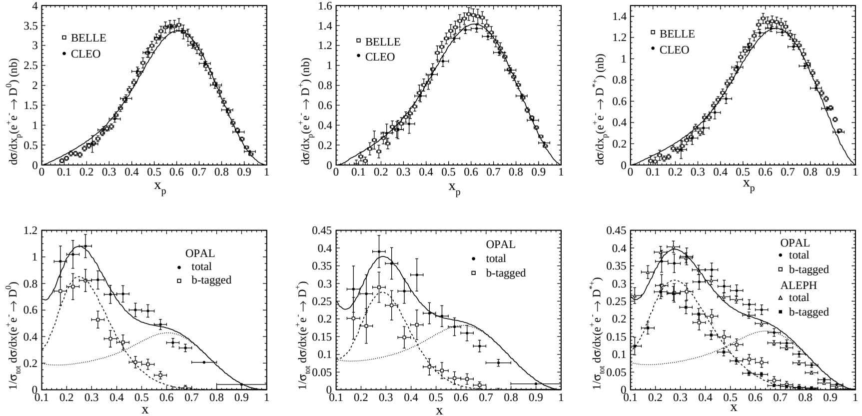



- Belle/CLEO data push $\langle z \rangle_c(m_Z)$ up by 0.03–0.04

# RESULTS: GLOBAL FITS

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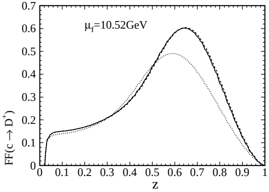
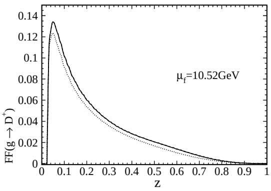
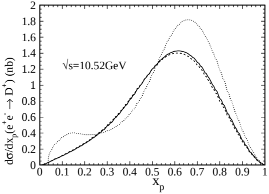



$c \to D^+$ FF



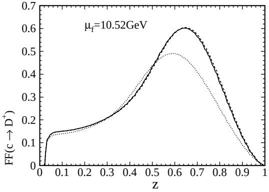

$g \to D^+$ FF



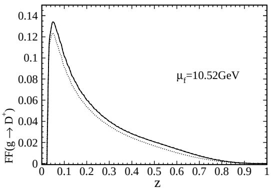

$d\sigma/dx_p$ w/ Belle/CLEO-GM FFs

dotted: $m_c = m_H = 0$
dashed: $m_c = 0 \neq m_H$ (ZM-VFNS)
solid: $m_c \neq 0 \neq m_H$ (GM-VFNS)

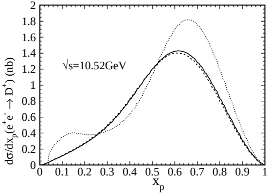
- Hadron mass effects on FFs important, quark mass effects marginal




$c \to D^+$ FF




$g \to D^+$ FF

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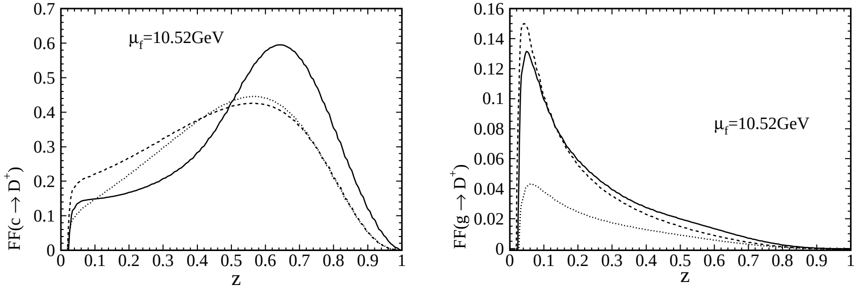
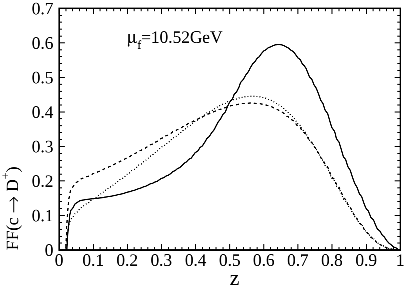


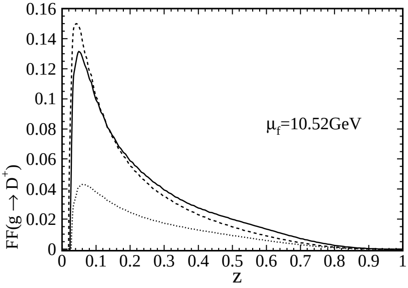

$c \to D^+$ FF $\qquad$ $g \to D^+$ FF

| | | | | | |
|---|---|---|---|---|---|
| dotted: | $m_c = 0 = m_H$ | $\mu_0 = 2m_c$ | Peterson | OPAL | KK 05 |
| dashed: | $m_c = 0 = m_H$ | $\mu_0 = m_c$ | Peterson | OPAL | KK 06 |
| solid: | $m_c \neq 0 \neq m_H$ | $\mu_0 = m_c$ | Bowler | Belle,CLEO,OPAL | KKKSc 08 |

- Strong pull of Belle/CLEO data on $c \to D^+$ FF
- Reduction in $\mu_0$ increases $g \to D^+$ FF




$c \to D^+$ FF

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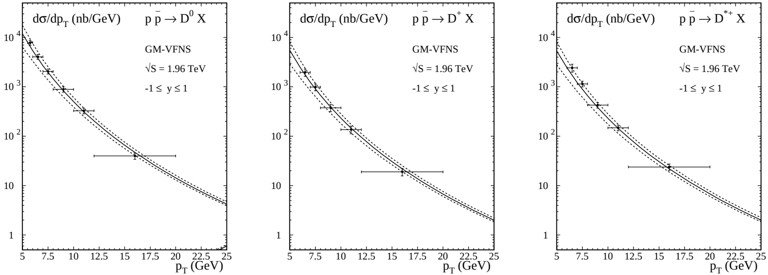
# HADROPRODUCTION OF $D^0, D^+, D^{*+}, D_s^+$

## GM-VFNS RESULTS W/ KKKSC FFS [1]

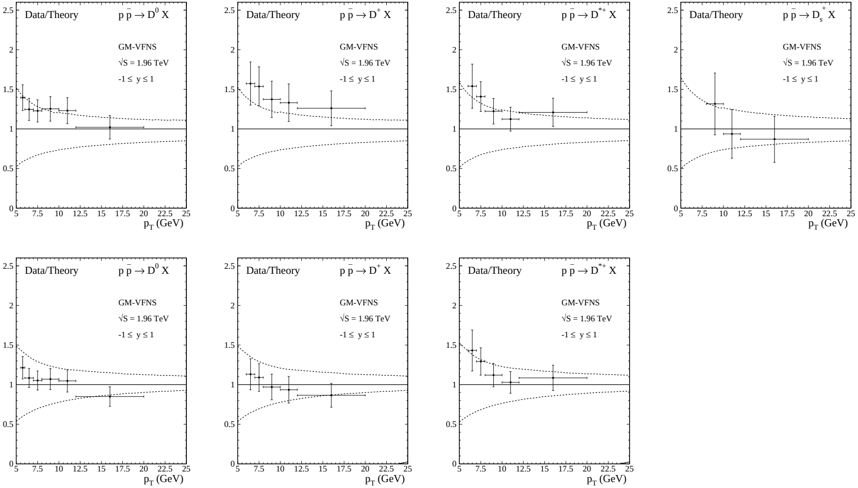



- $d\sigma/dp_T$ [nb/GeV] $|y| \leq 1$ prompt charm
- Uncertainty band: $1/2 \leq \mu_R/m_T, \mu_F/m_T \leq 2$ $\quad (m_T = \sqrt{p_T^2 + m_c^2})$
- CDF data from run II [2]
- GM-VFNS describes data within errors

[1] B.K.,Kramer,Schienbein,Spiesberger, arXiv:0901.4130[hep-ph], PRD(to appear)

[2] Acosta et al., PRL91(2003)241804

# COMPARISON W/ PREVIOUS KK FFS [1]

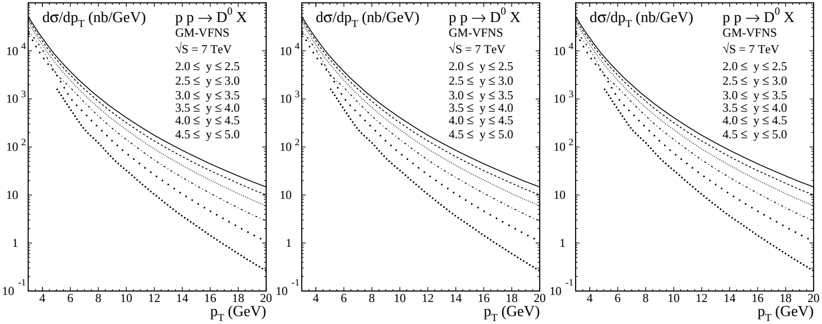



- New KKKSc FFs improve agreement w/ CDF data.

[1] B.K.,Kramer, PRD74(2006)037502

# NLO GM-VFNS PREDICTIONS FOR THE LHC

## LHCB CONDITIONS




- Inputs: CTEQ6.5 PDFs, KKKSc FFs [1]
- Uncertainty band: $1/2 \leq \mu_R/m_T, \mu_F/m_T \leq 2 \quad (m_T = \sqrt{p_T^2 + m_c^2})$


[1] Kneesch,B.K.,Kramer,Schienbein, NPB799(2008)34

# SUMMARY

- GM-VFNS (cf. ACOT scheme) with non-perturbative FFs provides rigorous theoretical framework for global analysis of inclusive heavy-hadron production:
  - full mass dependence
  - scaling violations and universality of FFs
  - no spurious $x \to 1$ problems to be fixed
  - no ad-hoc weight functions, no hidden theoretical errors
- Processes available at NLO:
  - $e^+e^- \to H + X$
  - $\gamma\gamma \to H + X$ direct, singly and doubly resolved
  - $\gamma p \to H + X$ direct and resolved
  - $p\bar{p}, pp \to H + X$
- New $D^0, D^+, D^{*+}$ FFs w/ mass effects from Belle, CLEO, ALEPH, and OPAL data
- $D$ (and $B$) hadroproduction predictions in good agreement w/ CDF data
  - Mass effects positive and moderate

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- Up-to-date NLO GM-VFNS predictions for $D^0$, $D^\pm$, $D^{*\pm}$ and $D_s^\pm$ hadroproduction at LHC available upon request
- Just specify $D$-meson species and $p_T$ and $y$ bins
- Same for $B$ hadrons

# SUMMARY (CONT.)

- Up-to-date NLO GM-VFNS predictions for $D^0$, $D^\pm$, $D^{*\pm}$ and $D_s^\pm$ hadroproduction at LHC available upon request
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- Up-to-date NLO GM-VFNS predictions for $D^0$, $D^\pm$, $D^{*\pm}$ and $D_s^\pm$ hadroproduction at LHC available upon request
- Just specify $D$-meson species and $p_T$ and $y$ bins
- Same for $B$ hadrons

$$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0}) \times G(m, p_T)$$

- FO: *fixed order*; FOM0: *massless limit* thereof; RS: *resummed*
- shift $p_T \to m_T$ in $(\mathrm{RS} - \mathrm{FOM0})$
- $G(m, p_T) = \dfrac{p_T^2}{p_T^2 + c^2 m^2}$ with $c = 5$ to suppress $(\mathrm{RS} - \mathrm{FOM0})$ being *abnormally large* for $m_T < 5m$
- NB: $G(m, p_T) = 4\%, 14\%, 26\%$ for $p_T/m = 1, 2, 3$
- convolute $(\mathrm{RS} - \mathrm{FOM0})$ with perturbative $q \to Q$ and $g \to Q$ FFs subject to DGLAP evolution in $\mu_F$
- convolute FONLL with non-perturbative $\mu_F$-independent $Q \to X_c$ FF of form [2] $D_{\mathrm{NP}}(x) = \mathrm{Norm.} \times \frac{1}{1+c}[\delta(1-x) + cN_{a,b}^{-1}(1-x)^a x^b]$ with $N_{a,b} = \int_0^1 \mathrm{d}x\,(1-x)^a x^b$

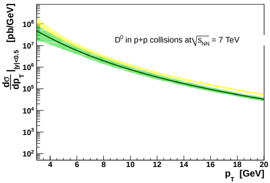
[1] Cacciari,Greco,Nason, JHEP05(1998)007; Cacciari,Nason, PRL89(2002)122003

[2] Cacciari,Nason,Oleari, JHEP04(2006)006

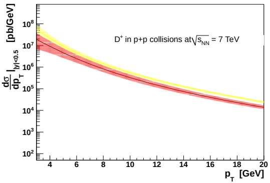
# GM-VFNS vs. FONLL

## *D* mesons at ALICE

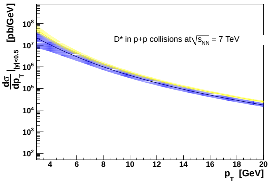
$(D^0 + \overline{D}^0)/2$




$(D^+ + D^-)/2$




$(D^{*+} + D^{*-})/2$

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- FONLL inputs: ?

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