Open charm hadroproduction and the charm content of the proton

Bernd Kniehl (Hamburg University)
kniehl@desy.de
in collaboration with G. Kramer, I. Schienbein, and H. Spiesberger

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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

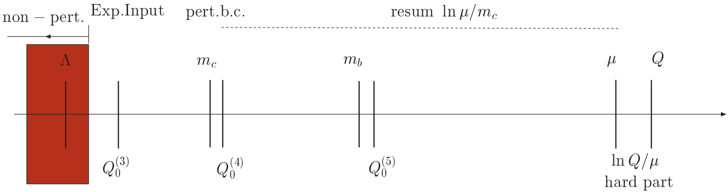
H	Data	Scheme	Reference
D^{*+}	ALEPH,OPAL	ZM $2m$	BKK, PRD58(1998)014014
$D^0, D^+, D_s^+, \Lambda_c^+$	OPAL	ZM $2m$	KK, PRD71(2005)094013
$D^0, D^+, D^{*+}, D_s^+, \Lambda_c^+$	OPAL	ZM m	KK, PRD74(2006)037502
D^0, D^+, D_s^+	Belle,CLEO,ALEPH,OPAL	GM m	KKKSc, NPB799(2008)34
B^0, B^+	OPAL	ZM $2m$	BKK,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

Fixed Order Perturbation Theory:

- finite collinear logs $\ln Q/m_c$ arise → 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, $p = 1, 2$

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

$\oplus$ 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

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

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

$\longrightarrow$ 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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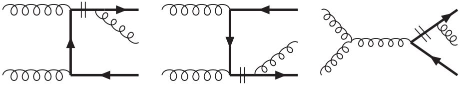
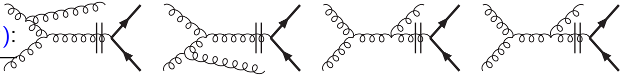
Graphical representation of Subtraction terms for $gg \to Q\bar{Q}g$

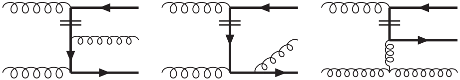
$d\hat{\sigma}^{(0)}(gg \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



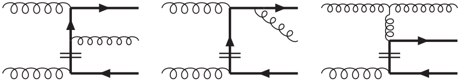
$d\hat{\sigma}^{(0)}(gg \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



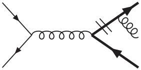
$f^{(1)}_{g\to Q}(x_1) \otimes d\hat{\sigma}^{(0)}(Qg \to Qg)$:



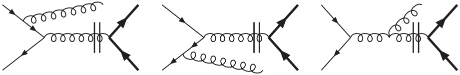
$f^{(1)}_{g\to Q}(x_2) \otimes d\hat{\sigma}^{(0)}(gQ \to Qg)$:



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



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



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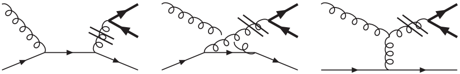

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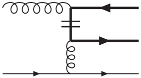

D^0, D^+, D^{*+} FFs with finite-mass corrections [1]

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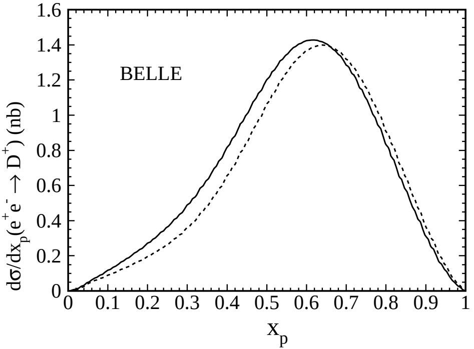
- Use radiator $D_{e^\pm}$ [1]

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



[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
$d\sigma/dx_p$	10.52	D^0, D^+, D^{*+}	CLEO 04
$(1/\sigma_{\text{tot}})d\sigma/dx$	91.2	D^{*+}	ALEPH 00
$(1/\sigma_{\text{tot}})d\sigma/dx$	91.2	D^0, D^+, D^{*+}	OPAL 96,98

- Theoretical input
  - $m_c = 1.5$ GeV, $m_b = 5.0$ GeV, $\alpha(m_\Upsilon) = 1/132$, $\alpha_s(m_Z) = 0.1176 \rightsquigarrow \Lambda^{(5)}_{\text{QCD}} = 221$ MeV
  - Bowler ansatz [1]

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

[1] Bowler, ZPC11(1981)169

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- χ^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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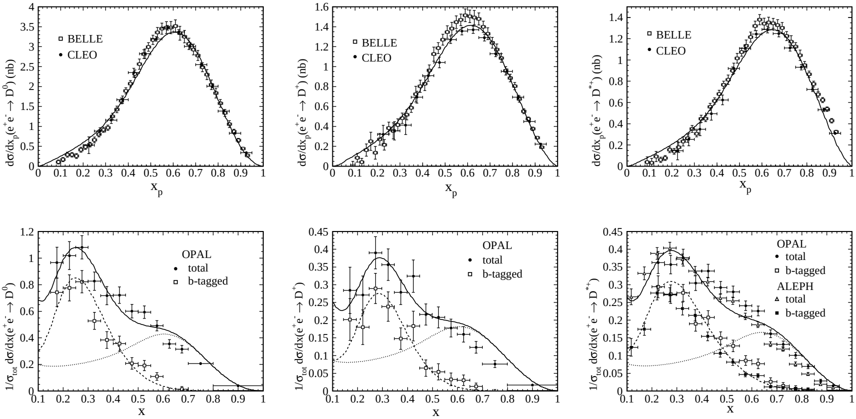
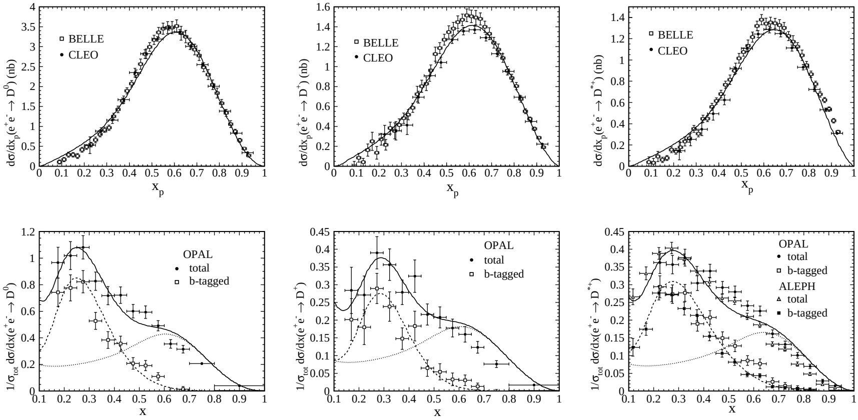


- Belle/CLEO data push $\langle z \rangle_c(m_Z)$ up by 0.03–0.04



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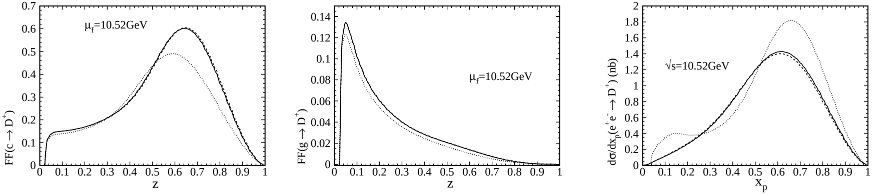

$c \longrightarrow D^+$ FF $\qquad$ $g \longrightarrow D^+$ FF $\qquad$ $d\sigma/dx_p$ w/ Belle/CLEO-GM FFs

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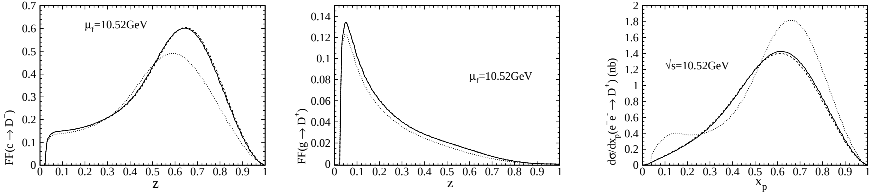
dashed: $m_c = 0 \neq m_H$ (ZM-VFNS)
solid: $m_c \neq 0 \neq m_H$ (GM-VFNS)

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



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solid: $m_c \neq 0 \neq m_H$ (GM-VFNS)

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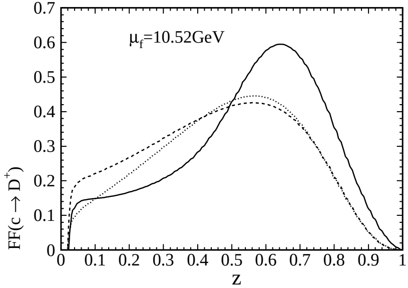
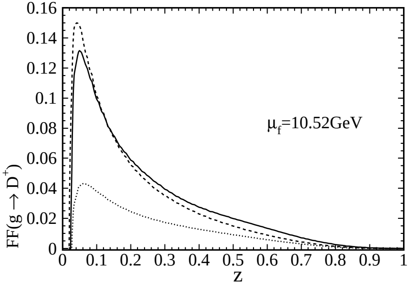


$c \to D^+$ FF



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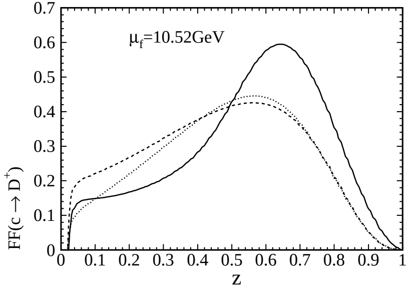

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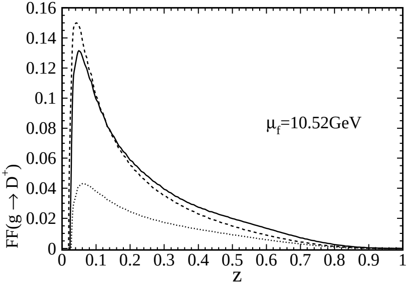

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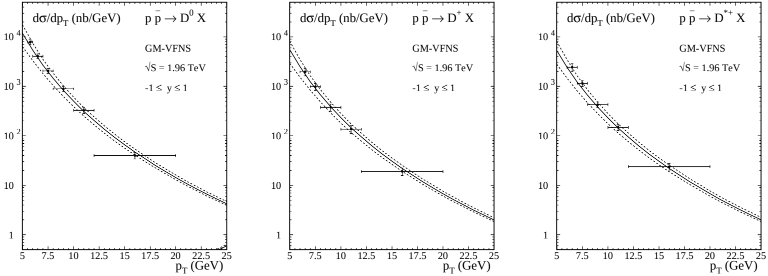
HADROPRODUCTION OF D^0, D^+, D^{*+}, D_s^+

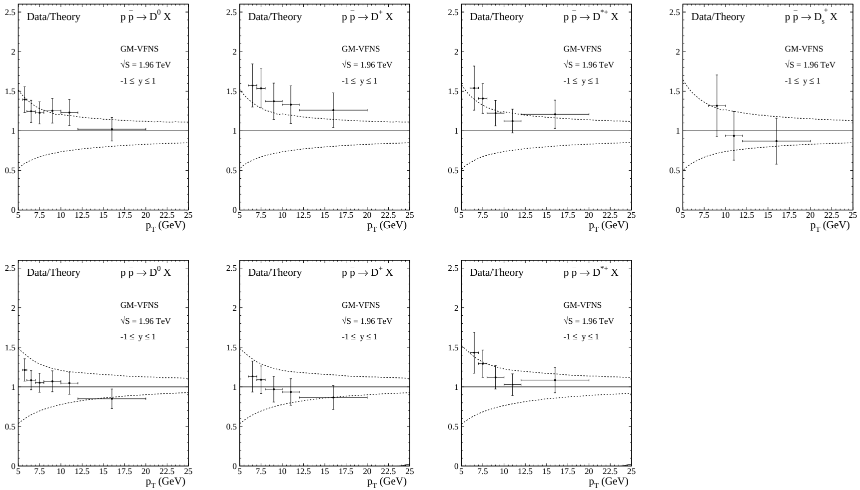
GM-VFNS RESULTS W/ KKKSC FFS [1]



- $d\sigma/dp_T$ [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



- New KKKSc FFs improve agreement w/ CDF data.

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

- c, $\overline{c}$, b, $\overline{b}$ PDFs relatively weakly constrained by global QCD analyses
- Knowledge important
  - inherently: fundamental structure of the nucleon
  - phenomenologically: significant for physics at Tevatron II and LHC, e.g. charm, bottom, single-top, Higgs production etc.
- Global QCD analyses usually adopt *radiatively generated* HQ PDFs:
  - $f_Q(x, \mu_0) \equiv 0$ at $\mu_0 = m_Q$ for $Q = c, b$
  - completely determined by gluon and light-quark d.o.f. via QCD evolution
  - properly resums collinear logs of m_Q appearing in fixed-order pQCD
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Intrinsic charm in the proton

Generalities (cont.)

- Room for additional, genuinely non-perturbative, intrinsic component with $f_Q(x, \mu_0) \neq 0$
- Especially for charm because $m_c \gtrsim m_p \rightsquigarrow$ *intrinsic charm* (IC)
- Constrain/determine IC through general global analysis with $m_Q \neq 0$ and comprehensive experimental inputs, such as extension of CTEQ6.5 [1]
- Consider 3 representative IC models: BHPS, meson-cloud, sealike
- Open charm hadroproduction as a laboratory to probe IC [2]

[1] Pumplin,Lai,Tung, PRD75(2007)054029

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

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1. BHPS model [1]
   - Invokes light-cone Fock space picture of nucleon structure
   - states with heavy quarks suppressed by off-shell distance $(p_T^2 + m^2)/x \rightsquigarrow$ large x preferred
   - Predicts $c(x) = \overline{c}(x)$
   - $c(x,\mu_0) = \overline{c}(x,\mu_0) = Ax^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$
   - A controls magnitude of IC, characterized by

$$\langle x \rangle_{c+\overline{c}} = \int_0^1 \mathrm{d}x\, x[c(x) + \overline{c}(x)]$$

2. Meson-cloud model [2]
   - Another light-cone model $\rightsquigarrow$ large x preferred
   - IC from virtual $uudc\overline{c}$ components, e.g. $\overline{D}^0 \Lambda_c^+$
   - Predicts $c(x) \neq \overline{c}(x)$
   - $c(x,\mu_0) \approx Ax^{1.897}(1-x)^{6.095}, \qquad \overline{c}(x,\mu_0) \approx \overline{A}x^{2.511}(1-x)^{4.929}$
   - $A/\overline{A}$ determined by quark number sum rule $\int_0^1 \mathrm{d}x[c(x) - \overline{c}(x)] = 0$

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3. Sealike model [3]
   - Purely phenomenological scenario
   - Assume $c(x,\mu_0) = \overline{c}(x,\mu_0) \propto \overline{u}(x,\mu_0) + \overline{d}(x,\mu_0)$ at $\mu_0 = m_c$ w/ overall mass suppression
   - IC interchangable w/ light sea-quark components $\rightsquigarrow$ softer x spectrum

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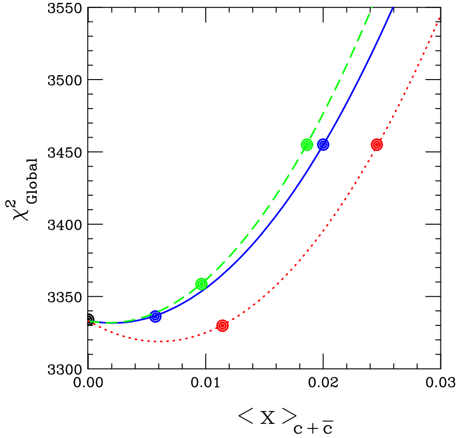
[1] Brodsky, Hoyer, Peterson, Sakai, PLB93(1980)451

[2] Navarra et al., PRD54(1996)842; Melnitchouk, Thomas, PLB414(1997)134

[3] Pumplin, Lai, Tung, PRD75(2007)054029

Intrinsic charm in the proton

IC from CTEQ6.5 global analysis [1]

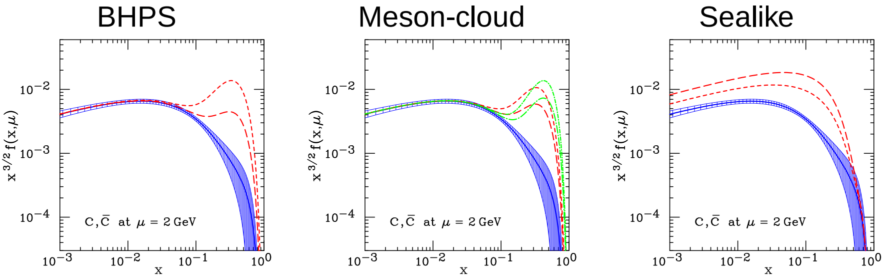


CTEQ.6.5C*n*

n	IC model	$\langle x \rangle_{c+\bar{c}}$
0	Zero IC	0
1	BHPS	0.57%
2		2.0%
3	Meson-cloud	0.96%
4		1.8%
5	Sealike	1.1%
6		2.4%

[1] Pumplin, Lai, Tung, PRD75(2007)054029

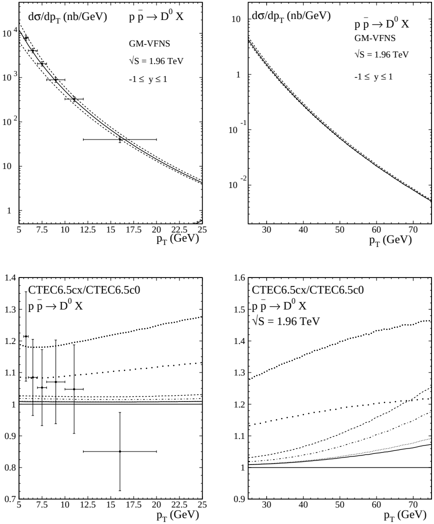
After evolution from $\mu_0 = 1.3$ GeV to $\mu = 2$ GeV.



$n = 0$ blue | $c(\bar{c})$ red (green)

$n = 1(2)$ down (up) | $n = 3(4)$ down (up) | $n = 5(6)$ down (up)

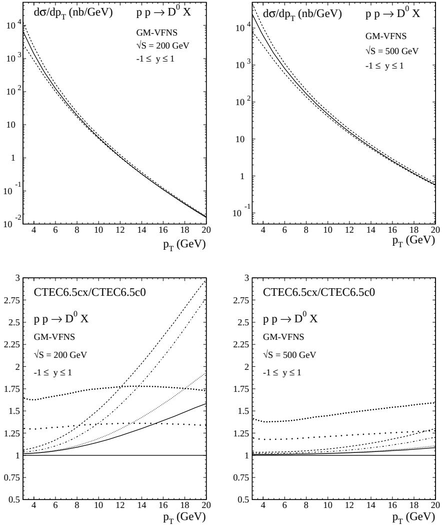
Enhancements get washed out as μ increases.



Acosta et al. (CDF Collaboration), PRL91(2003)241804

$(\mathrm{d}\sigma/\mathrm{d}p_T)(p\overline{p} \rightarrow D^0 + X)$
$\sqrt{s} = 1.96$ TeV
$|y| < 1$

IC Model	moderate	marginal
BHPS	solid	dashed
Meson-cloud	densely dotted	dot-dashed
Sealike	scarsely dotted	dotted



$(\mathrm{d}\sigma/\mathrm{d}p_T)(pp \to D^0 + X)$
$\sqrt{s} = 200, 500$ GeV
$|y| < 1$

IC Model	moderate	marginal
BHPS	solid	dashed
Meson-cloud	densely dotted	dot-dashed
Sealike	scarsely dotted	dotted

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
  - $p\bar{p} \to H + X$
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  - 5.8 pb^{-1} of published CDF II data from Feb.+Mar. 2002 already sensitive to sealike IC
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