Recent developments in heavy flavour production

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HERA and the LHC, DESY Hamburg, 12-16 March 2007

Outline

OVERVIEW

Subject of this talk:

- 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:

- $\gamma + \gamma \to D^{\star +} + X$: direct process [3]
- $\gamma + \gamma \to D^{\star +} + X$: single-resolved process [4]
- $\gamma + p \to D^{\star +} + X$ [5,6]
- $p + \bar{p} \to (D^0, D^{\star +}, D^+, D_s^+, \Lambda_c^+) + X$ [1,7]
- $p + \bar{p} \to B^+ + X$ [8]

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[1] Kniehl,G.K.,Schienbein,Spiesberger, PRD71(2005)014018; EPJC41(2005)199
[2] J. Collins, PRD58(1998)094002
[3] G.K.,Spiesberger, EPJC22(2001)289; [4] EPJC28(2003)495; [5] EPJC38(2004)309
[6] Kniehl,G.K.,Schienbein,Spiesberger, to be published,
results compared to H1 data in hep-ex/0608042, submitted to EPJC
[7] Kniehl,G.K.,Schienbein,Spiesberger, PRL96(2006)012001
[8] Kniehl,G.K.,Schienbein,Spiesberger, in prepararion

Overview -continued-

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

- FFs from fits to e^+e^- data from LEP and SLD directly in x-space
- Use new fits with initial scale $\mu_0 = m_h$ (instead of $\mu_0 = 2m_h$)
  $\rightarrow$ important for gluon fragmentation $\rightarrow$ consistency with PDFs

- FFs from fits to $e^+e^- \rightarrow B + X$ data from LEP and SLD

- FFs from fits to $e^+e^- \rightarrow D^*, D, D_s, \Lambda_c$ data from LEP

Work in progress:

- new extraction of FFs for production of D mesons in the GM-VFNS ($\rightarrow$ include low-energy data)

T. Kneesch, Univ. Hamburg

Goal:

- Test pQCD formalism/universality of FFs in as many processes as possible

Motivation

Why heavy flavour production?

Heavy Quarks: $h = c, b, t$

... are interesting:

- $m_h \gg \Lambda_{\rm QCD} \Rightarrow \alpha_s(m_h^2) \propto \ln^{-1}(\frac{m_h^2}{\Lambda^2_{\rm QCD}}) \ll 1$ (asymptotic freedom)
- m_h sets hard scale; acts as long distance cut-off

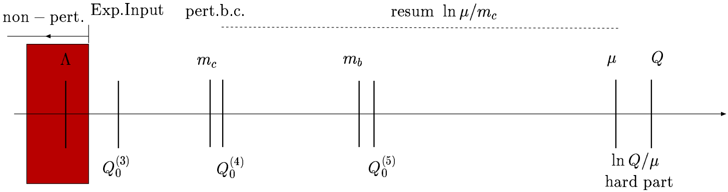
$\Rightarrow$ Perturbation Theory (pQCD) applicable!

Heavy quark production processes are:

- Fundamental elementary particle processes
- Important background to New Physics searches at the LHC

Fixed Order Perturbation Theory:

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

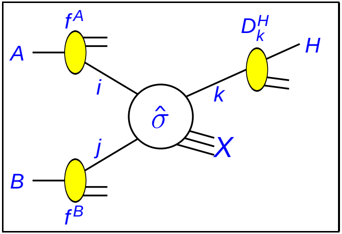


Variable Flavour Number Scheme (VFNS):

- often large ratios of scales involved: multi-scale problems
  For $Q \gg m_h$: write $\ln Q/m_h = \ln Q/\mu + \ln \mu/m_h$, subtract $\ln \mu/m_h$ and resum $\ln \mu/m_h$ (h=b,c)
  by introducing charm and/or bottom PDF (FF) at $Q_0^{(4)} \simeq m_c$ and/or $Q_0^{(5)} \simeq m_b$ using a perturbative boundary condition

$$d\sigma = \sum_{i,j,k} f_i^A(x_1) \otimes f_j^B(x_2) \otimes d\hat{\sigma}(ij \to kX) \otimes D_k^H(z)$$

Sum over all possible subprocesses $i + j \to k + X$



- $d\hat{\sigma}(\mu_F, \mu'_F, \alpha_s(\mu_R), [\frac{m_h}{p_T}])$: hard scattering cross sections, perturbatively computable, free of long-distance physics $\to$ m_h can be kept
- PDFs $f_i^A(x_1, \mu_F)$, $f_j^B(x_2, \mu_F)$: universal, non-perturbative input
  - Direct Photon: $i, j = \gamma$, $f_\gamma^\gamma(x, \mu_F) = \delta(1 - x)$
  - Resolved Photon/Proton: $i, j = g, q, \ldots$ $[q = u, d, s]$
- Fragmentation functions $D_k^H(z, [\mu'_F])$: universal, non-perturbative input $k = h, \ldots$
- Error:
  - light hadrons: $\mathcal{O}((\Lambda/p_T)^p)$ with p_T hard scale, Λ hadronic scale, $p = 1, 2$
  - heavy hadrons: $\mathcal{O}((m_h/p_T)^p)$ if m_h neglected in $d\hat{\sigma}$

Details (which subprocesses, PDFs, FFs; mass terms) depend on the Heavy Flavour Scheme

Heavy Flavour Schemes

Skip Details

Two basic approaches:

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

Interpolating scheme combining the good features:

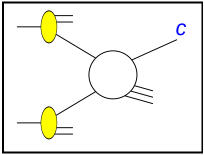
- Parton Model with quark masses (GM-VFNS, ACOT)

Glossary:

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

Fixed Flavour Number Scheme (FFNS)

- $m_c \neq 0$, $n_f = 3$ fixed
- Partons: g, u, d, s
  [NO charm parton; 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 $D_c^H(z)$, describing the hadronisation $c \rightarrow H$ needed to match data;
  $\rightarrow$ not based on factorization theorem (no AP evolution)
  $\rightarrow$ universal?

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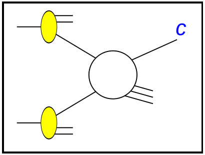

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- $m_c = 0 \rightarrow$ 'Zero Mass'
- Number of active partons depends on scale $\mu_F \rightarrow$ 'VFNS'
  - $\mu_F < m_c$: $n_f = 3$, Partons: g, u, d, s
  - $m_c \leq \mu_F < m_b$: $n_f = 4$, Partons: g, u, d, s, c
  - $m_b \leq \mu_F$: $n_f = 5$, Partons: g, u, d, s, c, b
- Matching conditions at transition scale $Q_0 = m_c$ (similar at m_b): $n_f = 3 \rightarrow n_f = 4$

$$\left.\begin{array}{l}\alpha_s^{(3)} \rightarrow \alpha_s^{(4)} = \alpha_s^{(3)} + \mathcal{O}(\alpha_s^3) \\ f_i^{(3)} \rightarrow f_i^{(4)} = f_i^{(3)} + \mathcal{O}(\alpha_s^2)\end{array}\right\} @\, Q_0 = m_c \qquad \boxed{f_c^{(4)}(x, Q_0^2 = m_c^2) = 0} \text{ pert. b.c.}$$

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

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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 $\rightarrow$ 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}

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  - $m_c \leq \mu_F < m_b$: $n_f = 4$, Partons: g, u, d, s, c
  - $m_b \leq \mu_F$: $n_f = 5$, Partons: g, u, d, s, c, b
- Matching conditions at transition scale $Q_0 = m_c$ (similar at m_b): $n_f = 3 \to n_f = 4$

$$\left.\begin{array}{l} \alpha_s^{(3)} \to \alpha_s^{(4)} = \alpha_s^{(3)} + \mathcal{O}(\alpha_s^3) \\ f_i^{(3)} \to f_i^{(4)} = f_i^{(3)} + \mathcal{O}(\alpha_s^2) \end{array}\right\} @\ Q_0 = m_c \qquad \boxed{f_c^{(4)}(x, Q_0^2 = m_c^2) = 0} \text{ pert. b.c.}$$

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- 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 ($\to f_c \neq 0$)
- $D_c^{D^\star}(z, {\mu'_F}^2)$ 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 $\to$ '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

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Two ways to derive them:

- Massless limit of fixed order calculation
- Mass factorization with massive regularization

Factorization Formula: [1]

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

Q: hard scale, $p = 1, 2$
replace $D^\star$ by B in the case of B production

- $d\hat{\sigma}(\mu_F, \mu_F', \alpha_s(\mu_R), \frac{m_h}{p_T})$: hard scattering cross sections free of long-distance physics $\longrightarrow$ 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

List of Subprocesses: GM-VFNS

	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

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

  Partonic subprocesses in 3-FFNS:(4-FFNS)

  - Leading Order (LO):
    1. $gg \to c\bar{c}$ *resp.* $gg \to b\bar{b}$
    2. $q\bar{q} \to c\bar{c}$ $(q = u, d, s)$ *resp.* $q\bar{q} \to b\bar{b}$ $(q = u, d, s, c)$
  - Next-To-Leading Order (NLO):
    1. $gg \to c\bar{c}g$ *resp.* $gg \to b\bar{b}g$
    2. $q\bar{q} \to c\bar{c}g$ *resp.* $q\bar{q} \to b\bar{b}g$
    3. $gq \to c\bar{c}q$ *resp.* $gq \to b\bar{b}q$ 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] G. K., Spiesberger, EPJC22(2001)289; EPJC28(2003)495

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

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

$\Rightarrow$ Subtraction terms

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

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

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

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

$\longrightarrow$ allows to use PDFs and FFs with $\overline{\mathrm{MS}}$ 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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SUBTRACTION TERMS VIA $\overline{\mathrm{MS}}$ MASS FACTORIZATION: $a(k_1)b(k_2) \to Q(p_1)X$ [1]

Sketch of kinematics:

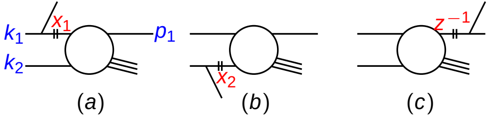

Fig. (a):

$$\mathrm{d}\sigma^{\mathrm{sub}}(ab \to QX) = \int_0^1 \mathrm{d}x_1\, f^{(1)}_{a\to i}(x_1, \mu_F^2)\, \mathrm{d}\hat{\sigma}^{(0)}(ib \to QX)[x_1 k_1, k_2, p_1]$$
$$\equiv f^{(1)}_{a\to i}(x_1) \otimes \mathrm{d}\hat{\sigma}^{(0)}(ib \to QX)$$

Fig. (b):

$$\mathrm{d}\sigma^{\mathrm{sub}}(ab \to QX) = \int_0^1 \mathrm{d}x_2\, f^{(1)}_{b\to j}(x_2, \mu_F^2)\, \mathrm{d}\hat{\sigma}^{(0)}(aj \to QX)[k_1, x_2 k_2, p_1]$$
$$\equiv f^{(1)}_{b\to j}(x_2) \otimes \mathrm{d}\hat{\sigma}^{(0)}(aj \to QX)$$

Fig. (c):

$$\mathrm{d}\sigma^{\mathrm{sub}}(ab \to QX) = \int_0^1 \mathrm{d}z\, \mathrm{d}\hat{\sigma}^{(0)}(ab \to kX)[k_1, k_2, z^{-1} p_1]\, d^{(1)}_{k\to Q}(z, \mu_F'^{\,2})$$
$$\equiv \mathrm{d}\hat{\sigma}^{(0)}(ab \to kX) \otimes d^{(1)}_{k\to Q}(z)$$

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[1] Kniehl, G. K., Schienbein, Spiesberger, EPJC41(2005)199

1. initial state:

$$f^{(1)}_{g\to Q}(x,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{g\to q}(x) \ln\frac{\mu^2}{m^2}$$
$$f^{(1)}_{Q\to Q}(x,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} C_F \left[\frac{1+z^2}{1-z}\left(\ln\frac{\mu^2}{m^2} - 2\ln(1-z) - 1\right)\right]_+ \qquad [2]$$
$$f^{(1)}_{g\to g}(x,\mu^2) = -\frac{\alpha_s(\mu)}{2\pi}\frac{1}{3}\ln\frac{\mu^2}{m^2}\delta(1-x)$$

2. final state:

$$d^{(1)}_{g\to Q}(z,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{g\to q}(z) \ln\frac{\mu^2}{m^2}$$
$$d^{(1)}_{Q\to Q}(z,\mu^2) = C_F \frac{\alpha_s(\mu)}{2\pi} \left[\frac{1+z^2}{1-z}\left(\ln\frac{\mu^2}{m^2} - 2\ln(1-z) - 1\right)\right]_+ \qquad [1,2,3]$$

- Other distributions are zero to this order in α_s
- Analogous for photon splitting: $g \to \gamma$, $\alpha_s \to \alpha$, color factors

[1] Mele, Nason, NPB361(1991)626; Ma, NPB506(1997)329 [$\gamma^\star \to c\bar{c}g$]
[2] Kretzer, Schienbein, PRD58(1998)094035;D59(1999)054004 [$c\gamma^\star \to cg$]
[3] Melnikov, Mitov, PRD70(2004)034027; Mitov, PRD71(2005)054021 [$\mathcal{O}(\alpha_s^2)$]

Existing calculations: (based on DGLAP evolution)

- ZM-VFNS: Binnewies et al.; Cacciari et al.
- FFNS: Frixione et al.
- GM-VFNS:
  - direct part: G. K., Spiesberger
  - resolved part: Kniehl, G. K., Schienbein, Spiesberger (from hadroproduction)

Status:

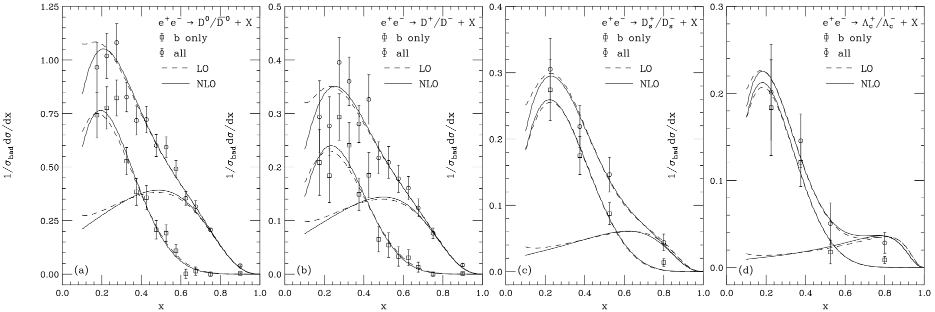
- For comparison of GM-VFNS with preliminary ZEUS data (p_T, y, W, z distributions) see G. K., Spiesberger, EPJC38(2004)309
- Including resolved part in GM-VFNS will help to improve results at small p_T
- New FFs with initial scale $\mu_0 = m_h$ used, results compared with recent H1 data in H1 publication: A. Aktas et al., DESY 06-110, hep-ex/0608042, will be shown below

NUMERICAL RESULTS

Input parameters:

- $\alpha_s(M_Z) = 0.1181$
- $m_c = 1.5\ \mathrm{GeV}, m_b = 4.5\ \mathrm{GeV}$
- PDFs: CTEQ6.1M (NLO)
- FFs: NLO FFs from fi ts to LEP1-OPAL data (*D*-mesons); from fi ts to LEP1-ALEPH and OPAL, SLC-SLD data (*B*-mesons)
- initial scale for evolution: $\mu_0 = m_c$ (*D*-mesons) resp. $\mu_0 = m_b$ (*B*-mesons)
- Default scale choice: $\mu_R = \mu_F = \mu_F' = m_T$ where $m_T = \sqrt{p_T^2 + m^2}$

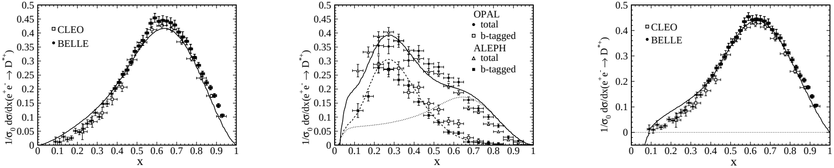
- $(1/\sigma_{\rm tot})d\sigma/dx$, ZM-VFNS
- $\mu_R, \mu'_F = \sqrt{S}$
- Fit to LEP1 data from OPAL [2]



[1] Kniehl, G. K., PRD71(2005)094013

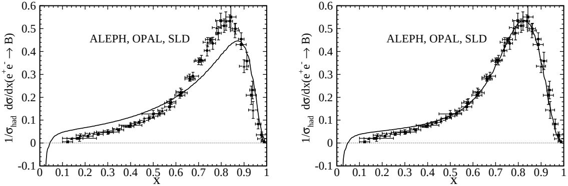
[2] Alexander et al.,OPAL Collaboration, ZPC72(1996)1

- $(1/\sigma_{\rm tot}){\rm d}\sigma/{\rm d}x$, GM-VFNS, $\mu_R, \mu'_F = \sqrt{S}$
- Corrected for photon radiation in the initial state
- Fit to data from BELLE and CLEO [2], combined fit, compared to ALEPH and OPAL data from LEP1 [3]
- Bowler parametrisation [4]: $D_c^{D^*}(x,\mu^2) = N(1-x)^\alpha x^{-(1+\gamma^2)} \exp(-\gamma^2/x)$ at $\mu = m_c$



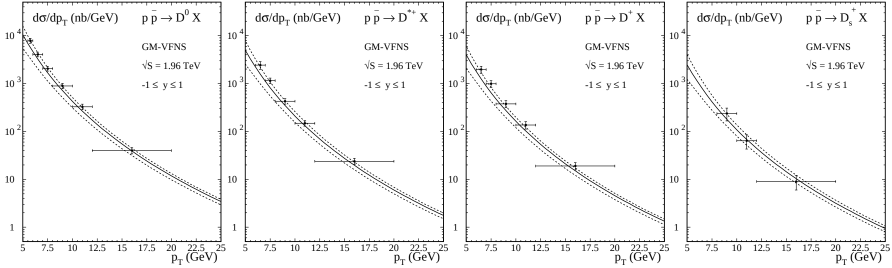
[1] Kneesch, Kniehl, G. K., to be published
[2] Seuster et al., BELLE Collaboration, PRD73 (2006) 032002; M. Artuso et al., CLEO Collaboration, PRD70 (2004) 112001
[3] K. Ackerstaff et al., OPAL Collaboration, EPJC1 (1998) 439; R. Barate et al., ALEPH Collaboration, EPJC16 (2000) 597
[4] M. G. Bowler, Z.Phys. C11 (1981)

- $(1/\sigma_{\rm tot})d\sigma/dx$, ZM-VFNS
- $\mu_R, \mu'_F = \sqrt{S}$
- Fit to LEP1 data from ALEPH [2], OPAL [3] and SLC data from SLD [4]
- Full points: ALEPH, squares: OPAL, triangles: SLD
- Left figure: Peterson ansatz, right figure: power ansatz
- Starting scale $\mu = m_b$ in both
- Peterson can not, power can describe the data



[1] Kniehl, G. K., Schienbein, Spiesberger, to be published
[2] Heister et al., ALEPH Collaboration, Phys. Lett. B512 (2001) 30
[3] Abbiendi et al., OPAL Collaboration, EPJ C29 (2003) 463
[4] Abe et al., SLD Collaboration, Phys. Rev. D65 (2002) 092006, D66 (2002) 079905(E)

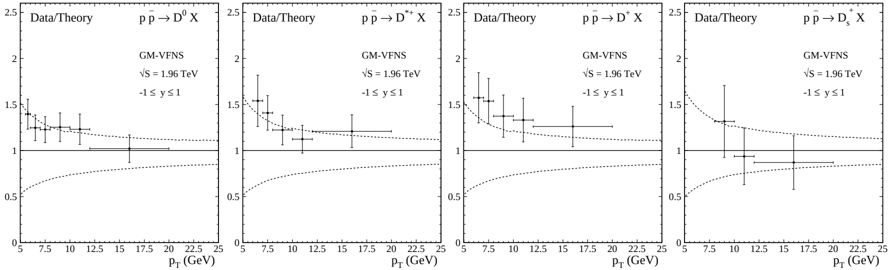
- $d\sigma/dp_T$ (nb/GeV), $|y| \leq 1$, GM-VFNS
- Uncertainty band: independent variation of $\mu_R, \mu_F, \mu_F' = \xi m_T$, $\xi \in [1/2, 2]$



- Data described by QCD within errors
- New PDFs with intrinsic charm content by Pumplin et al., [3], could be tested with these data

[1] Kniehl, G.K, Schienbein, Spiesberger,PRL96(2006)012001; [2] Acosta et al, PRL91(2003)241804 [3] Pumplin, Lai, Tung, MSY-HEP-070101, hep-ph/0701220

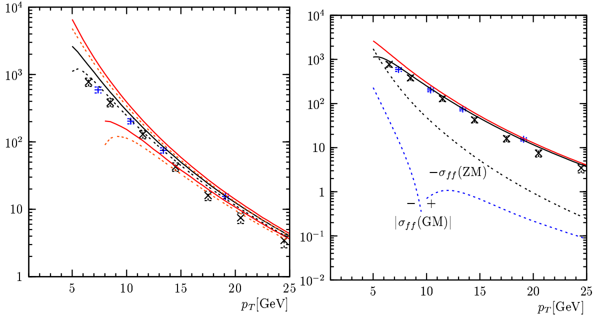
- $d\sigma/dp_T$ (nb/GeV), $|y| \leq 1$, GM-VFNS
- Uncertainty band: independent variation of $\mu_R, \mu_F, \mu'_F = \xi m_T$, $\xi \in [1/2, 2]$



- Prompt charm data (no secondary charm from B decay) from CDF in run II
- Data and Theory compatible within errors
- Central values: Data/Theory $\simeq 1.5 - 1.2$

[1] Kniehl, G.K., Schienbein, Spiesberger,PRL96(2006)012001; [2] Acosta et al, PRL91(2003)241804

- $d\sigma/dp_T$ (nb/GeV), $|y| \leq 1$, GM-VFNS, four massless flavours, one massive
- Fragmentation function fitted to e^+e^- *data*
  $D_b^{B^\pm}(x) = Nx^\alpha(1-x)^\beta$ *at* $\mu = m_b = 4.5\mathrm{GeV}$
- $\mu = \xi m_T,\ \xi_R = 1,\ central : \xi_I = \xi_F = 1,\ lower : \xi_I = \xi_F = 0.5,\ upper : \xi_I = \xi_F = 2$

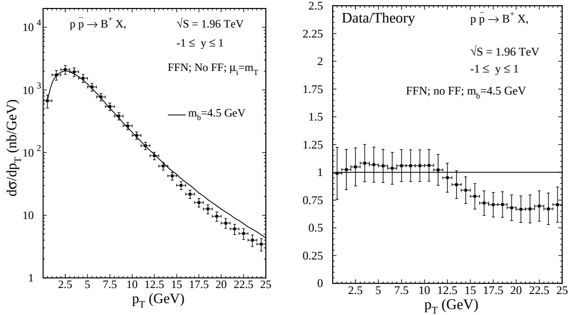


- Data described well by GM-VFNS in range of applicability: $p_T \gtrsim 10$ GeV, no agreement for small p_T
- GM-VFN (full lines) approaches ZM-VFN (dashed lines) at large p_T

[1] Acosta et al, CDF Collaboration, PRD 71 (2005) 034016 (black points);
Abulencia et al., CDF Collaboration, hep-ex/0612015, (blue points)

COMPARISON WITH CDF II DATA FOR $p\bar{p} \to B^+X \to J/\Psi X'$ [1]

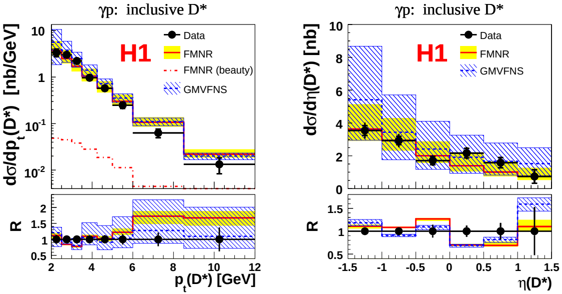
- $d\sigma/dp_T$ (nb/GeV), $|y| \leq 1$, FFN scheme, four massless flavours, one massive
- No fragmentation function: $D_b^{B^\pm}(x) = N\delta(1-x)$, N determined by $BR(b \to B) = 0.397$
- Theory well known since 1988



- Data described well by FFNS theory in range of applicability: $p_T \lesssim 10$ GeV, disagreement for large p_T

[1] Acosta et al, CDF Collaboration, PRD 71 (2005) 034016
[2] Nason et al., NPB 303 (1988); B 327 (1989) 49; B 335 (1989) 260(E); Beenacker et al., PRD 40 (1989) 54; NPB 351 (1991) 507

- $d\sigma/dp_T$ (nb/GeV), $|y| \le 1.5$, FFN scheme and GM-VFN scheme, both three massless flavours, one massive
- Fragmentation function forGM-VFNS: $D_c^{D^{*\pm}}(x) = Nx^{\alpha}(1-x)^{\beta}$ $b \to D^*$ and Peterson $c \to D^*$
- Theory FFN [2] GM-VFN [3]



- Data described by FFNS and GM-VFNS theory, GM-VFNS large scale variation for small p_T, $p_T \sim 2$ GeV

[1] Aktas et al, H1 Collaboration, DESY 06-110, hep-ex/0608042
[2] Frixione, Nason, Ridolfi, NPB 454 (1995) 3
[3] Kniehl, G. K., Schienbein, Spiesberger, to be published

- In this talk:
  Discussion of one-particle inclusive production of heavy quarks in the GM-VFNS
- Available at NLO in the GM-VFNS:
  - $\gamma\gamma \to HX$
  - $\gamma p \to HX$
  - $p\bar{p} \to HX$
- General expectation:
  - Improvement at $p_T \gg m_h$ due to updated FFs (and PDFs)
  - Mass effects: Improve agreement with (HERA) data for $p_T \gtrsim m_h$
  - Mass effects: Reduced factorization scale dependence

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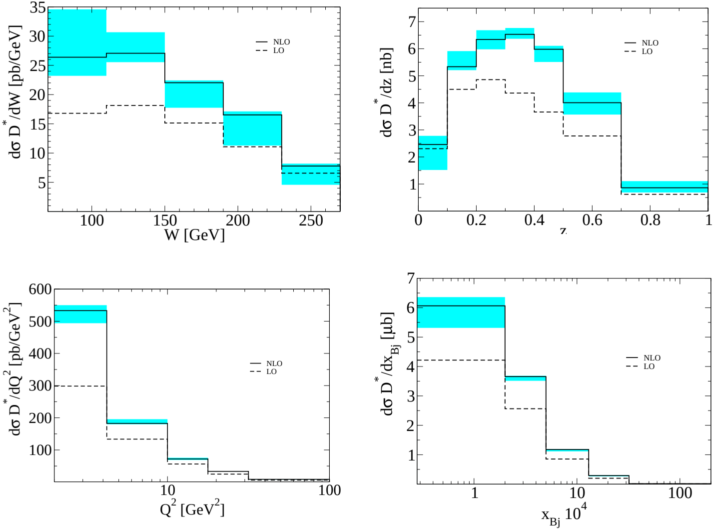
Backup Slides


dσ D* /dW [pb/GeV]
W [GeV]
NLO
LO
dσ D* /dz [nb]
z
NLO
LO
dσ D* /dQ² [pb/GeV²]
Q² [GeV²]
NLO
LO
dσ D* /dx_Bj [μb]
x_Bj 10⁴
NLO
LO

◂ go back

$$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0})\mathrm{G}(\mathrm{m}, \mathrm{p_T}) \text{ with}$$
$$G(m, p_T) = \frac{p_T^2}{p_T^2 + 25m^2}$$

$$\text{GM-VFNS} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0})\tilde{\mathrm{G}}(\mathrm{m}, \mathrm{p_T}) \text{ with}$$
$$\tilde{G}(m, p_T) = 1$$

FO: Fixed Order; FOM0: Massless limit of FO; RS $\equiv$ ZM-VFNS: Resummed

- Both approaches interpolate between FO and ZM-VFNS
  - FONLL: obvious;
  - GM-VFNS: matching with FO at quark level (see Olness,Scalise,Tung,PRD59(1998)014506)
- Factor $\tilde{G}(m, p_T)$ follows from calculation; $\tilde{G}(m, p_T) = 1 \leftrightarrow$ S-ACOT scheme
- Different point-of-view: GM-VFNS finally needs PDFs and FFs in this scheme.
- Numerical comparisons interesting and should be done!

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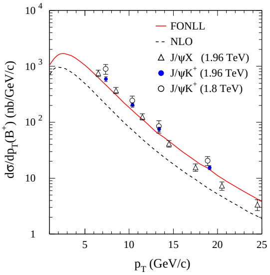
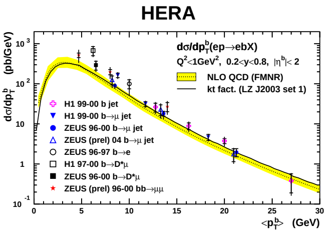


FIG. 10: Measurements of the B^+ differential cross section ($|y^{B^+}| \leq 1$) at the Tevatron are compared to the NLO and FONLL theoretical predictions (see text). The result of this experiment (•) is shown together with those of (△) Ref. [30] and (○) Ref. [9]; the result of Ref. [9] has been increased by 10% to account for the expected increase of the cross section from $\sqrt{s} = 1.8$ to 1.96 TeV [1].

26

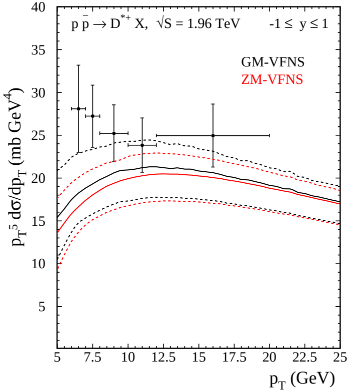
COMPARISON OF FO THEORY WITH DATA FOR $\gamma p \rightarrow bX$ [1]



[1] Brugnera, Contribution to the proceedings of HQL06, Munich, hep-ex/0701027

$p\bar{p} \to D^{\star+}X$

- Results with old FFs with initial scale $\mu_0 = 2m_c$
- Uncertainty band: independent variation of $\mu_R, \mu_F, \mu'_F = \xi m_T, \xi \in [1/2, 2]$



- In this example still $p_T > 3m_c$
- Mass effects bigger for small μ_R (large $\alpha_s(\mu_R)$)

STRONG COUPLING CONSTANT

- PDG'04: $\alpha_s(M_Z) = 0.1187 \pm 0.0020$
- CTEQ6M PDFs: $\alpha_s(M_Z) = 0.118$; MRST03 $\alpha_s(M_Z) = 0.1165$;
- $d\sigma(p\bar{p} \to DX) \propto \alpha_s^2(1 + \alpha_s K)$