Open heavy flavour at LHC

Ingo Schienbein
LPSC/Univ. Joseph Fourier

based on work in collaboration with
T. Kneesch, B. Kniehl, G. Kramer, S. Kretzer, F. Olness, H. Spiesberger

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OUTLINE

Overview and Motivation

Quarks heavy $:\Leftrightarrow m_h \gg \Lambda_{\rm QCD} \sim 250$ MeV

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

charm:	$m_c \sim 1.5$ GeV	$\Lambda_{\rm QCD}/m_c \sim 0.17$	$\alpha_s(m_c^2) \sim 0.34$
bottom:	$m_b \sim 5$ GeV	$\Lambda_{\rm QCD}/m_b \sim 0.05$	$\alpha_s(m_b^2) \sim 0.21$
top:	$m_t \sim 175$ GeV	$\Lambda_{\rm QCD}/m_t \sim 0.001$	$\alpha_s(m_t^2) \sim 0.11$

$\Rightarrow$ PERTURBATION THEORY (PQCD) APPLICABLE!

- The smaller the ratio $\Lambda_{\rm QCD}/m_h$, the smaller effects of non-perturbative QCD (such as hadronization)
- Top quark decays before it could hadronize due to its large mass ($\Gamma \propto m_t^3$):
  $\Gamma \simeq \Gamma(t \to bW) \simeq \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2 \simeq 1.76 \text{ GeV } (\frac{m_t}{175 \text{ GeV}})^3$

Extensively studied at e^+e^-, photon–hadron, and hadron–hadron colliders. Why?

Many topics (production and decay of heavy quarks):

- Tests of pQCD
    - Factorization, PDFs, FFs, resummations, higher order calculations
    - $g + g \to b + \bar{b}$: gluon PDF
    - $g + s \to W + c$: strange PDF; $g + c \to \gamma + c$: charm PDF
- Important for new physics
    - Understand production of known heavy objects to find new heavy objects
    - New physics often couples to heavy states
    - Higgs boson discovery
    - Background to new physics
- CKM matrix, $B - \bar{B}$ mixing, CP violation
- Measurement of the spin (top decays before hadronization and the products retain all spin correlations)

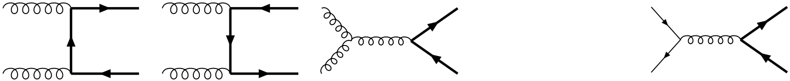
This talk: interested in QCD aspects of open heavy flavour production

- Top quarks: decay before hadronization $\rightarrow$ Not considered here.
- Charm and bottom quarks: hadronize into
  - c and b hadrons: D, B, Λ_c, ... ($\rightarrow$ open heavy flavour)
  - $c\bar{c}$ and $b\bar{b}$ bound states: J/Ψ, Υ, ...

OPEN HEAVY FLAVOUR PRODUCTION :$\Leftrightarrow$ FINAL STATE HADRONS WITH $C \neq 0$ OR $B \neq 0$

Leading order subprocesses:

1. $gg \to Q\bar{Q}$
2. $q\bar{q} \to Q\bar{Q} \quad (q = u, d, s)$



- The gg-channel is dominant at the LHC ($\sim 85\%$ at $\sqrt{S} = 14$ TeV).
- The total production cross section for heavy quarks is finite.
  The minimum virtuality of the t-channel propagator is m^2. Sets the scale in α_s.
  Perturbation theory should be reliable.
- Note: For $m^2 \to 0$ total cross section would diverge.

See M. Mangano, hep-ph/9711337; Textbook by Ellis, Stirling and Webber

Next-to-leading order (NLO) subprocesses:

1. $gg \to Q\bar{Q}g$
2. $q\bar{q} \to Q\bar{Q}g \quad (q = u, d, s)$
3. $gq \to Q\bar{Q}q$, $g\bar{q} \to Q\bar{Q}\bar{q}$ [new at NLO]
4. Virtual corrections to $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$

NLO corrections for $\sigma_{\rm tot}$ and differential cross sections $d\sigma/dp_T dy$ known since long:

- Nason, Dawson, Ellis, NPB303(1988)607; Beenakker, Kuif, van Neerven, Smith, PRD40(1989)54 [$\sigma_{\rm tot}$]
- NDE, NPB327(1989)49; (E)B335(1990)260; Beenakker *et al.*,NPB351(1991)507 [$d\sigma/dp_T dy$]

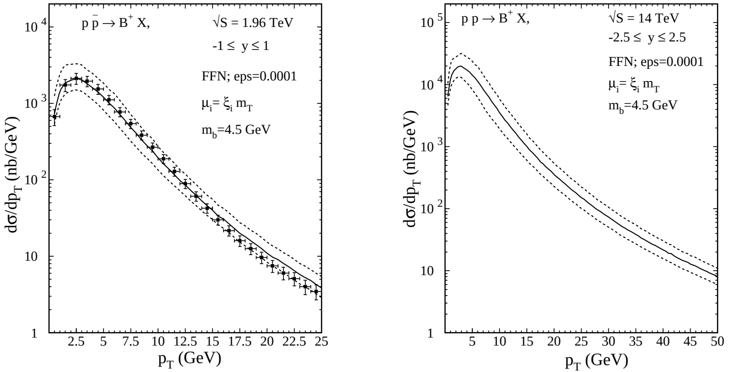
Well tested by recalculations and zero-mass limit:

- Bojak, Stratmann, PRD67(2003)034010 [$d\sigma/dp_T dy$ (un)polarized]
- Kniehl, Kramer, Spiesberger, IS, PRD71(2005)014018 [$m \to 0$ limit of diff. x-sec]
- Czakon, Mitov, NPB824(2010)111 [$\sigma_{\rm tot}$, fully analytic]

Next-to-next-to-leading order (NNLO):

- See, e.g., Bonciani, Ferroglia, arXiv:0909.2980 for an overview

- $d\sigma/dp_T$ for the process $pp \to B^+X$; Fragmentation $b \to B$ via Peterson-FF
- Prediction in NLO perturbation theory



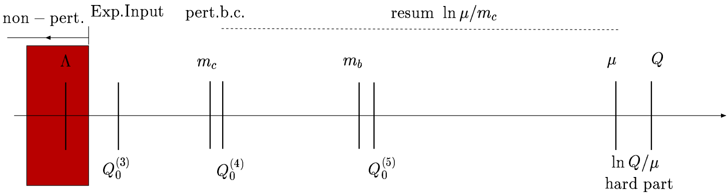
Remarks:

- Fixed order theory in reasonable agreement with Tevatron data up to $p_T \simeq 5m_b$
- At $p_T \lesssim m_b$ factorization less obvious. Depends on definition of convolution variable z: $p_B = zp_b$ or $p_T^B = zp_T^b$ or $p_B^+ = zp_b^+$ or $\vec{p}_B = z\vec{p}_b$
- Less hadronization effects than originally believed: ϵ-parameter small corresponding to a hard fragmentation function.
- Only the 4th or 5th Mellin-moment of the FF is relevant (M. Mangano): $d\sigma^b/dp_T(b) \simeq A/p_T(b)^n$ with $n \simeq 4, \ldots, 5$

  $d\sigma^B/dp_T(B) = \int dz/z\, D(z)\, d\sigma^b/dp_T(b)[p_T(b) = p_T(B)/z] =$
  $A/p_T(B)^n \times \int dz\, z^{n-1}\, D(z)$
- What about $\ln m_b/p_T$ at large $p_T \gg m_b$?

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

Two basic approaches:

- Fixed Order Perturbation Theory (FFNS) $\leftrightarrow$ GRV, nDS
- Parton Model (ZM-VFNS) $\leftrightarrow$ CTEQ5, CTEQ6.1M, MRS, HKN, EKS

Interpolating schemes combining the good features:

- Parton Model with quark masses (GM-VFNS, ACOT) $\leftrightarrow$ CTEQ6.6M, MRST/MSTW, nCTEQ
- FONLL $\leftrightarrow$ NNPDF

Glossary:

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

One-particle inclusive production in a GM-VFNS

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]

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[1] Kniehl,Kramer,IS,Spiesberger, PRD71(2005)014018; EPJC41(2005)199; PRL96(2006)012001; PRD77(2008)014011; arXiv:0901.4130[hep-ph], PRD (in press)
[2] Collins, PRD58(1998)094002
[3] Kneesch,Kniehl,Kramer,IS, NPB799(2008)34
[4] Kramer,Spiesberger, EPJC22(2001)289; [5] EPJC28(2003)495; [6] EPJC38(2004)309
[7] Kniehl,Kramer,IS,Spiesberger, arXiv:0902.3166[hep-ph], EPJC (in press)

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

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

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

Parton distribution functions:
$f_i^A(x_1, \mu_F)$, $f_j^B(x_2, \mu_F)$
non-perturbative input
long distance
universal

Hard scattering
cross section:
$d\sigma(\mu_F, \mu_F', \alpha_s(\mu_R), [\frac{m_h}{p_T}])$
perturbatively computable
short distance
(coefficient functions)

Fragmentation functions:
$D_k^H(z, [\mu_F'])$
non-perturbative input
long distance
universal

Accuracy:

light hadrons: $\mathcal{O}((\Lambda/p_T)^p)$ with p_T hard scale, Λ hadronic scale, $p = 1, 2$
heavy hadrons: if m_h is neglected in $d\sigma$: $\mathcal{O}((m_h/p_T)^p)$

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

#	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

Mass terms contained in the hard scattering coefficients:

$$d\hat{\sigma}(\mu_F, \mu_{F'}, \alpha_s(\mu_R), \frac{m}{p_T})$$

Two ways to derive them:

(1) Compare massless limit of a massive fixed-order calculation with a massless $\overline{\mathrm{MS}}$ calculation to determine subtraction terms

OR

(2) Perform mass factorization using partonic PDFs and FFs

- Compare limit $m \to 0$ of the massive calculation (Merebashvili et al., Ellis, Nason; Smith, van Neerven; Bojak, Stratmann; ...)
  with massless $\overline{\mathrm{MS}}$ calculation (Aurenche et al., Aversa et al., ...)

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

  $\Rightarrow$ Subtraction terms

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

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

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

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

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

- Treat contributions with charm in the initial state with $m = 0$
- Massless limit: technically non-trivial, map from phase-space slicing to subtraction method

Mass factorization

Subtraction terms are associated to mass singularities:
can be described by
partonic PDFs and FFs for collinear splittings $a \to b + X$

- initial state:

$$f^{(1)}_{g\to Q}(x,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{g\to q}(x) \ln\frac{\mu^2}{m^2}$$

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

$$f^{(1)}_{g\to g}(x,\mu^2) = -\frac{\alpha_s(\mu)}{2\pi}\frac{1}{3}\ln\frac{\mu^2}{m^2}\delta(1-x)$$

- final state:

$$d^{(1)}_{g\to Q}(z,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{g\to q}(z) \ln\frac{\mu^2}{m^2}$$

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

- Other partonic distribution functions are zero to order α_s

Mele, Nason; Kretzer, Schienbein; Melnikov, Mitov

Sketch of kinematics:

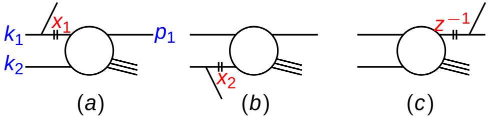

Fig. (a):

$$d\sigma^{\text{sub}}(ab \to QX) = \int_0^1 dx_1\, f^{(1)}_{a\to i}(x_1, \mu_F^2)\, d\hat{\sigma}^{(0)}(ib \to QX)[x_1 k_1, k_2, p_1]$$
$$\equiv f^{(1)}_{a\to i}(x_1) \otimes d\hat{\sigma}^{(0)}(ib \to QX)$$

Fig. (b):

$$d\sigma^{\text{sub}}(ab \to QX) = \int_0^1 dx_2\, f^{(1)}_{b\to j}(x_2, \mu_F^2)\, d\hat{\sigma}^{(0)}(aj \to QX)[k_1, x_2 k_2, p_1]$$
$$\equiv f^{(1)}_{b\to j}(x_2) \otimes d\hat{\sigma}^{(0)}(aj \to QX)$$

Fig. (c):

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

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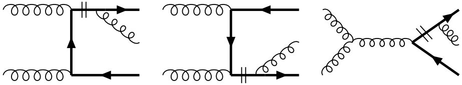
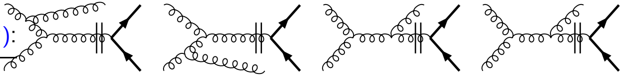
[1] Kniehl, Kramer, I.S., Spiesberger, EPJC41(2005)199

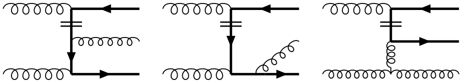
$d\hat{\sigma}^{(0)}(gg \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



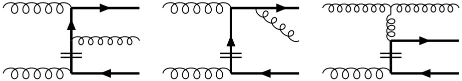
$d\hat{\sigma}^{(0)}(gg \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



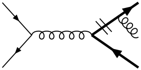
$f^{(1)}_{g\to Q}(x_1) \otimes d\hat{\sigma}^{(0)}(Qg \to Qg)$:



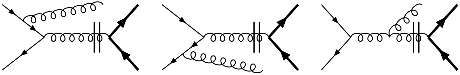
$f^{(1)}_{g\to Q}(x_2) \otimes d\hat{\sigma}^{(0)}(gQ \to Qg)$:



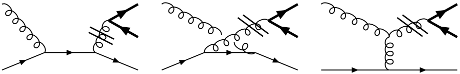
$d\hat{\sigma}^{(0)}(q\bar{q} \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



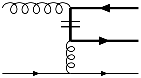
$d\hat{\sigma}^{(0)}(q\bar{q} \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



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



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



Fragmentation Functions in a GM-VFNS

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]

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

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

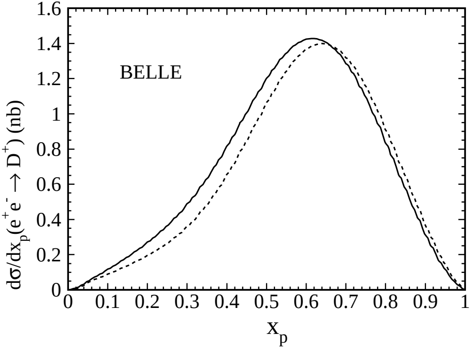
[1] Kneesch,B.K.,Kramer,Schienbein, NPB799(2008)34

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

[3] Nason, Webber, NPB421(1994)473

- 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
$(1/\sigma_{\rm tot})d\sigma/dx$	91.2	D^{*+}	ALEPH 00
$(1/\sigma_{\rm tot})d\sigma/dx$	91.2	D^0, D^+, D^{*+}	OPAL 96,98

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

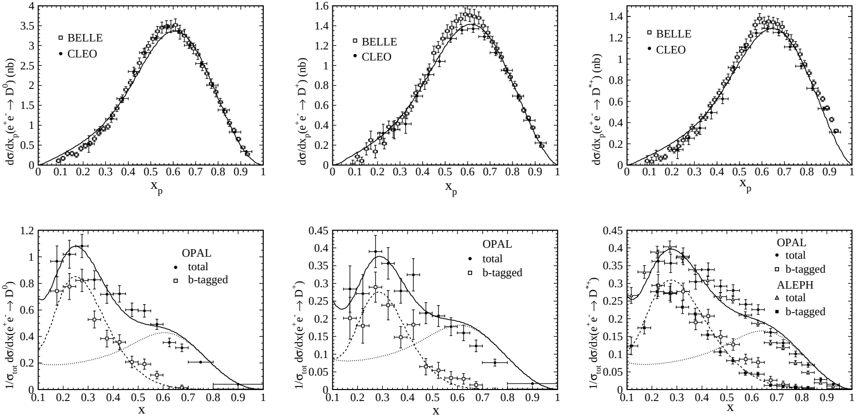
$$D_Q^{H_c}(z,\mu_0) = N z^{-(1+\gamma^2)}(1-z)^a \mathrm{e}^{-\gamma^2/z}$$

[1] Bowler, ZPC11(1981)169

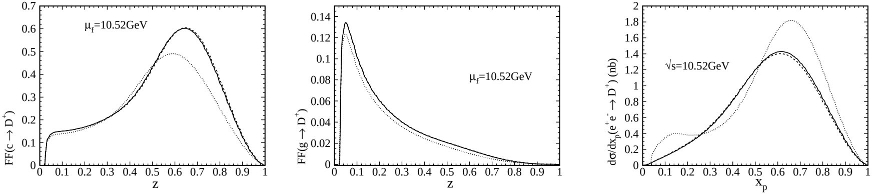
- χ^2/d.o.f.

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.



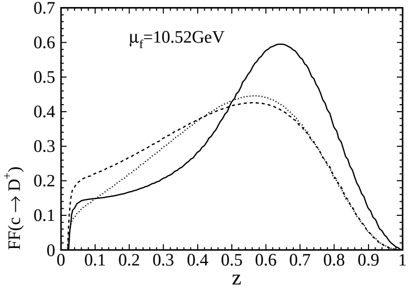
- Belle/CLEO data push $\langle z \rangle_c(m_Z)$ up by 0.03–0.04



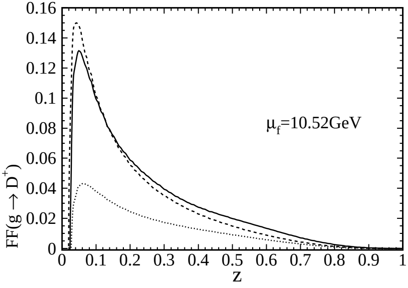
$c \to D^+$ FF　　$g \to D^+$ FF　　$d\sigma/dx_p$ w/ Belle/CLEO-GM FFs

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

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 μ_0 increases $g \to D^+$ FF

Applications

Applications available for

- $\gamma + \gamma \to D^{*\pm} + X$
  direct and resolved contributions EPJC22, EPJC28
- $\gamma^* + p \to D^{*\pm} + X$
  photoproduction EPJC38, arXiv:0902.3166 [EPJC]
- $p + \bar{p} \to (D^0, D^{*\pm}, D^{\pm}, D_s^{\pm}, \Lambda_c^{\pm}) + X$
  good description of Tevatron data PRD71, PRL96, arXiv:0901.4130
- $p + \bar{p} \to B + X$
  works for Tevatron data at large p_T PRD77
- work in progress for $e + p \to D + X$

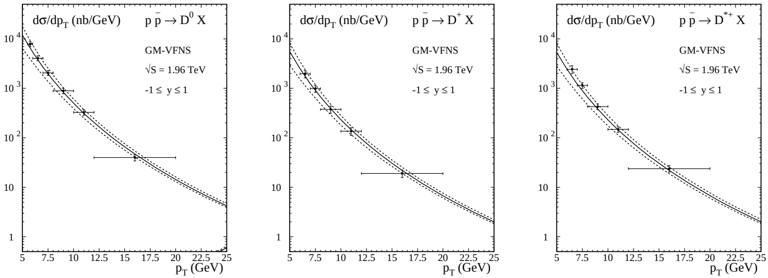
Numerical Results

<u>Input parameters:</u>

- $\alpha_s(M_Z) = 0.1181$
- $m_c = 1.5\ \mathrm{GeV}, m_b = 5\ \mathrm{GeV}$
- PDFs: CTEQ6M (NLO)
- FFs: NLO FFs from fits to LEP-OPAL data,
  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 $m_T = \sqrt{p_T^2 + m^2}$

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

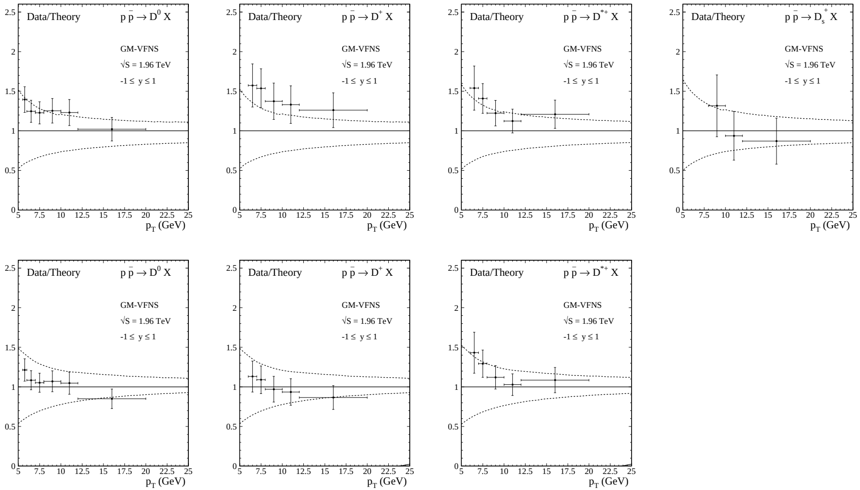
GM-VFNS RESULTS W/ KKKSC FFS [1]



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

[1] Kniehl,Kramer,IS,Spiesberger, arXiv:0901.4130[hep-ph], PRD(to appear)

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



- New KKKSc FFs improve agreement w/ CDF data.

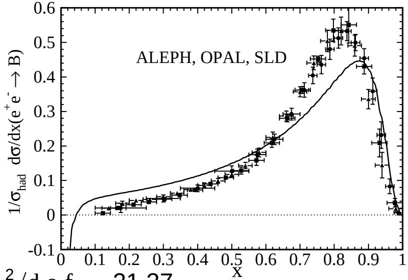
[1] Kniehl,Kramer, PRD74(2006)037502

HADROPRODUCTION OF B^0, B^+ [1]

NEW FFS FROM LEP1/SLC DATA [2]

Petersen

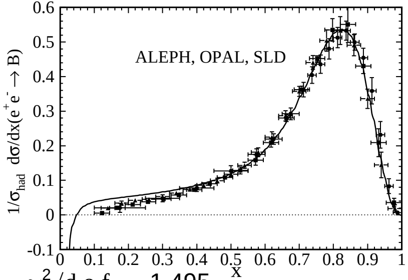
$$D(x, \mu_0^2) = N \frac{x(1-x)^2}{[(1-x)^2 + \epsilon x]^2}$$



$\chi^2/\text{d.o.f.} = 21.37$

Kartvelishvili-Likhoded

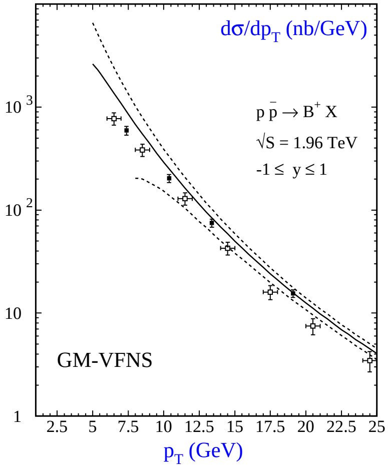
$$D(x, \mu_0^2) = N x^{\alpha} (1-x)^{\beta}$$



$\chi^2/\text{d.o.f.} = 1.495$

[1] Kniehl,Kramer,IS,Spiesberger,PRD77(2008)014011

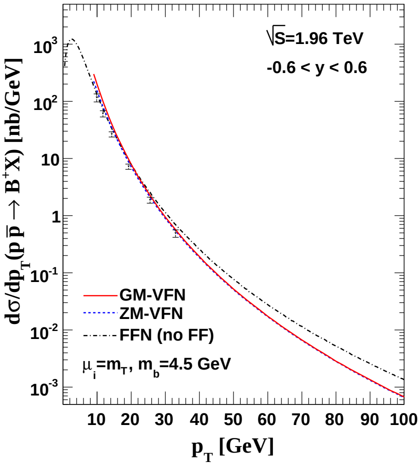
[2] ALEPH, PLB512(2001)30; OPAL, EPJC29(2003)463; SLD, PRL84(2000)4300; PRD65(2002)092006



- CDF (1.96 TeV):
  - open squares $J/\psi X$ [1]
  - solid squares $J/\psi K^+$ [2]
- CTEQ6.1M PDFs
- $m_b = 4.5$ GeV
- $\Lambda_{\overline{\mathrm{MS}}}^{(5)} = 227\ \mathrm{MeV} \rightsquigarrow \alpha_s^{(5)} = 0.1181$
- $1/2 \leq \mu_R/m_T, \mu_F/m_T, \mu_R/\mu_F \leq 2$ $(m_T = \sqrt{p_T^2 + m_b^2})$

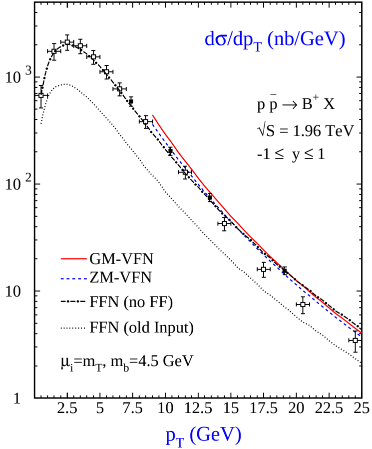
[1] CDF, PRD71(2005)032001

[2] CDF, PRD75(2007)012010



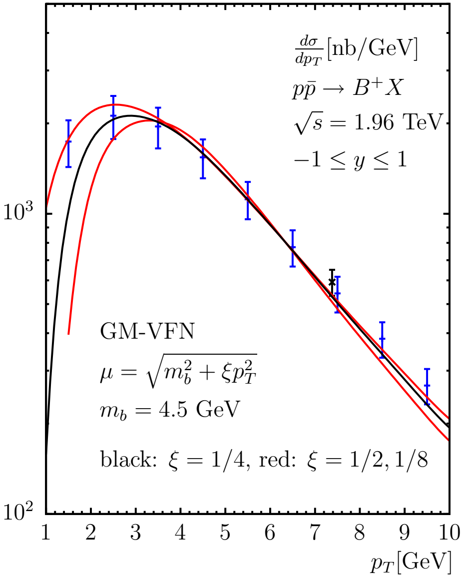
- CDF II (preliminary) [1]
- $\mu_R = \mu_F = m_T$
- for $p_T \gg m_b$:
  - GM-VFN merges w/ ZM-VFN
  - FFN breaks down
- data point in bin [29,40] favors GM-VFN

[1] Kraus, FERMILAB-THESIS-2006-47; Annovi, FERMILAB-CONF-07-509-E



- obsolete FFN as above
- up-to-date FFN evaluated with
  - CTEQ6.1M PDFs
  - $m_b = 4.5$ GeV
  - $\Lambda^{(5)}_{\overline{\rm MS}} = 227\ \mathrm{MeV} \rightsquigarrow \alpha_s^{(5)} = 0.1181$
  - $D(x) = B(b \to B)\delta(1-x)$ with $B(b \to B) = 39.8\%$

[1] Kniehl,Kramer,IS,Spiesberger,PRD77(2008)014011



- evaluate $d\hat{\sigma}^{(1)}_{\rm ZM}(Q + g/q \to Q + X)$ @ LO to match $f^{(1)}_{g\to Q} \otimes d\hat{\sigma}^{(0)}(Q + g/q \to Q + g/q)$
- evaluate $d\hat{\sigma}^{(0)}(gg/q\overline{q} \to Q\overline{Q}) \otimes d^{(1)}_{Q\to Q}$ w/ $m_Q \neq 0$ to match $d\hat{\sigma}^{(1)}_{\rm GM}(gg/q\overline{q} \to Q/\overline{Q} + X)$
- impose $\theta(\hat{s} - 4m_Q^2)$ on massless kinematics
- choose $\mu_F^2 = m_Q^2 + \xi p_T^2$ so that $\mu_F \overset{p_T\to 0}{\longrightarrow} m_Q = \mu_0$
- $G(m, p_T) \equiv 1$ in contrast to FONLL

[1] Kniehl,Kramer,IS,Spiesberger,in preparation

- Discussion of 1-particle inclusive hadroproduction of heavy quarks in a massive VFNS (GM-VFNS)
- Available at NLO in the GM-VFNS:
  - $\gamma\gamma \rightarrow HX$
  - $\gamma p \rightarrow HX$
  - $p\bar{p} \rightarrow HX$
- Work in progress:
  - $ep \rightarrow HX$
  - Matching to the fixed order theory at small p_T
  - Updated predictions for the LHC (latest FFs, PDFs)

Backup Slides

FONLL = FO+NLL [1]

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

FO: Fixed Order; FOM0: Massless limit of FO; RS: Resummed

$$G(m, p_T) = \frac{p_T^2}{p_T^2 + 25m^2}$$

$$\Rightarrow \mathrm{FONLL} = \begin{cases} \mathrm{FO} & : \quad p_T \lesssim 5m \\ \mathrm{RS} & : \quad p_T \gtrsim 5m \end{cases}$$

[1] Cacciari, Greco, Nason, JHEP05(1998)007

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

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

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!