Heavy quark production in pp at the LHC

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Outline

1. Heavvy quarks in pQCD
2. Hadroproduction of heavy quarks: Theory
3. Applications
4. Predictions for the LHC
5. Summary

Heavy quarks in pQCD

A quark h is heavy $:\Leftrightarrow m_h \gg \Lambda_{\rm QCD} \sim 250$ MeV

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

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	$\Lambda_{\rm QCD}/m_t \sim 0.001$	$\alpha_s(m_t^2) \sim 0.11$

- 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 ($\Gamma \propto m_t^3$):
  $\Gamma \simeq \Gamma(t \to bW) \simeq \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2 \simeq 1.76 \text{ GeV } (\frac{m_t}{175 \text{ GeV}})^3$

Requirements:

(1) $\mu \ll m$: Decoupling of heavy degrees of freedom

(2) $\mu \gg m$: IR-safety

(3) $\mu \sim m$: Correct threshold behavior

Problems:

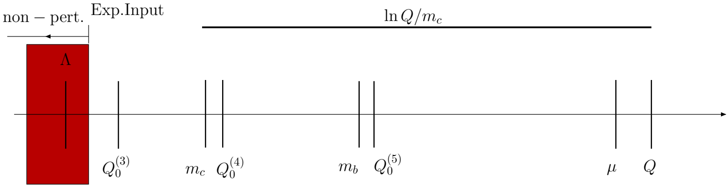
- Multiple hard scales: m_c, m_b, m_t, μ
- Mass-independent factorization/renormalization schemes like $\overline{\text{MS}}$
- A single $\overline{\text{MS}}$ scheme cannot meet requirements (1) and (3) (is unphysical).

Way out: Patchwork of $\overline{\text{MS}}$ schemes S^{n_f, n_R}

- Variable Flavor-Number Scheme (VFNS): $S^{3,3} \to S^{4,4} \to S^{5,5}$
- Fixed Flavor-Number Scheme (FFNS): $S^{3,3} \to S^{3,4} \to S^{3,5}$ (3-FFNS)
- **Masses reintroduced** by backdoor: threshold corrections (=matching conditions)

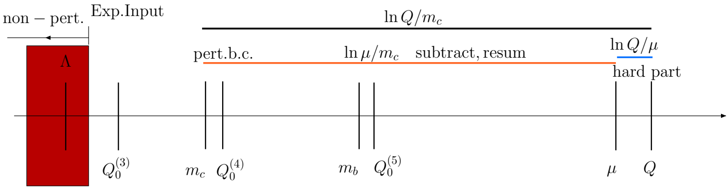
3-FFNS/Fixed Order:

- No charm PDF! Of course need exp. Input for u, d, s, g PDFs at scale $Q_0^{(3)}$
- finite collinear logs $\ln Q/m_c$ arise → are kept in hard part (unresummed, in fixed order)
- Requirement (3) naturally satisfied
- Not IR-safe, does not meet requirement (2):
  - Not valid for $Q >> m_c$
  - Can we quantify? Valid for $Q < m_c, 3m_c, 5m_c$?



Variable Flavour Number Scheme (VFNS):

- often large ratios of scales involved: multi-scale problems
  For $Q \gg m_c$: write $\ln Q/m_c = \ln \mu/m_c + \ln Q/\mu$, 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
- $Q < Q_0 : n_f = 3$ no charm PDF, $Q \geq Q_0 : n_f \to n_f + 1$, charm PDF without fit parameters
- IR-safe, satisfies requirement (2); resums colliner logarithms
- Problem: original ZM-VFNS (=massless parton model) only valid for $Q >> m$ (Quantify?)
- GM-VFNS: need extra work to satisfy requirement (3) but then valid for all scales Q! approaches FFNS for $Q \sim m$, approaches ZM-VFNS for $Q >> m$



- GM-VFNS essential for W, Z cross sections at the LHC [see talk by M. Guzzi]
- Most of the most recent global analyses of proton PDFs use a version of a GM-VFNS
  - MSTW08: TR scheme
  - CTEQ6.6/CT10: S-ACOT$_\chi$
  - NNPDF2.1: FONLL
  - HERANPDF1.0: same as MSTW08
  - GJR08, JR09: as GRV in a FFNS
  - CTEQ5,CTEQ6.1,NNPDF2.0,. . . and older: ZM-VFNS
- The various GM-VFN schemes are 'tuned to' the DIS structure functions F_2^c, F_L^c

IF THESE SCHEME ARE NOT JUST COOKING RECIPES BUT PQCD FORMALISMS WITH HEAVY QUARKS, THEY SHOULD BE APPLICABLE TO OTHER PROCESSES AS WELL

Hadroproduction of heavy quarks: Theory

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

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
(coeffi cient 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

FFNS/Fixed Order

Start with FFNS = Fixed Order:

- NLO calculation more than 20 years old, very well tested
- Allows to predict the total cross section
- Allows to compute p_T spectrum if $!(p_T >> m)$
  (up to inclusion of a non-perturbative FF which is very hard)

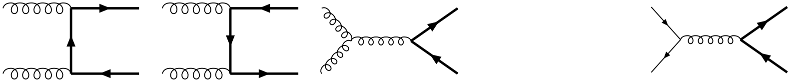
Compare data with best FFNS prediction!

- Find p_T-range where FFNS applicable. Guess: $p_T = 5m$ still ok.
- When need for resummation of $\ln m$ terms visible?
  (Apart from smaller uncertainty band in resummed theory)

AS DESCRIBED BEFORE: GM-VFNS → FFNS FOR $p_T \sim m$

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 fi nite.
  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 $q\bar{q} \to Q\bar{Q}$

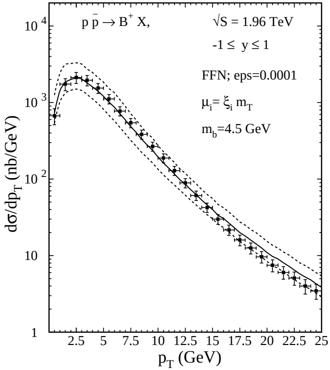
NLO corrections for $\sigma_{\rm tot}$ and differential cross sections $d\sigma/dp_T dy$ known since long:

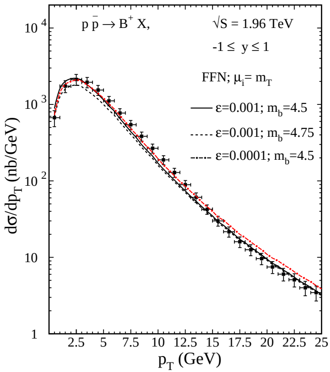
- Nason, Dawson, Ellis, NPB303(1988)607; Beenakker, Kuif, van Neerven, Smith, PRD40(1989)54 [$\sigma_{\rm tot}$]
- NDE, NPB327(1989)49; (E)B335(1990)260; Beenakker *et al.*,NPB351(1991)507 [$d\sigma/dp_T dy$]

Well tested by recalculations and zero-mass limit:

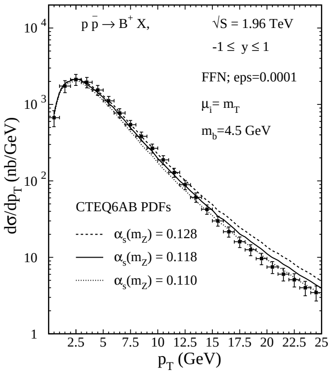
- Bojak, Stratmann, PRD67(2003)034010 [$d\sigma/dp_T dy$ (un)polarized]
- Kniehl, Kramer, Spiesberger, IS, PRD71(2005)014018 [$m \to 0$ limit of diff. x-sec]
- Czakon, Mitov, NPB824(2010)111 [$\sigma_{\rm tot}$, fully analytic]

- $d\sigma/dp_T$ for the process $pp \to B^+X$; Fragmentation $b \to B$ via Peterson-FF
- CTEQ6.1 PDFs (slightly inconsistent)
- Prediction in NLO perturbation theory





p p̄ → B⁺ X,
√S = 1.96 TeV
-1 ≤ y ≤ 1
FFN; μi= mT
ε=0.001; mb=4.5
ε=0.001; mb=4.75
ε=0.0001; mb=4.5
dσ/dpT (nb/GeV)
pT (GeV)



p p̄ → B⁺ X,
√S = 1.96 TeV
-1 ≤ y ≤ 1
FFN; eps=0.0001
μi= mT
mb=4.5 GeV
CTEQ6AB PDFs
αs(mZ) = 0.128
αs(mZ) = 0.118
αs(mZ) = 0.110
dσ/dpT (nb/GeV)
pT (GeV)

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 defi nition 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.
  Harder FF $\rightarrow$ harder p_T-spectrum
- Larger $\alpha_s(M_Z) \rightarrow$ harder p_T-spectrum
- Mass dependence imortant for $p_T \lesssim m$ (peak) $\rightarrow \sigma_{tot}$
- Only the 4th or 5th Mellin-moment of the FF is relevant for large p_T [M. Mangano]:
  $d\sigma^b/dp_T(b) \simeq A/p_T(b)^n$ with $n \simeq 4, \ldots, 5$ [see talk by F. Arleo]

  $d\sigma^B/dp_T(B) = \int dz/z\, D(z)\, d\sigma^b/dp_T(b)[p_T(b) = p_T(B)/z] =$
  $A/p_T(B)^n \times \int dz\, z^{n-1}\, D(z)$

ZM-VFNS/RS (RS: Resummed)

Next ZM-VFNS/RS which is the baseline for $p_T >> m$

- Again NLO calculation more than 20 years old, very well tested
- Allows to compute p_T spectrum if $p_T >> m$
- Needs scale-dependent FFs for quarks and gluons $D_q^H(z, \mu_F'), D_g^H(z, \mu_F')$
- Same theory used for the computation of inclusive π or K production.

Compare data with best ZM-VFNS prediction!

- Find smallest p_T where ZM-VFNS applicable.
- m/p_T terms neglected.
- Is there an overlapping region where both, FFNS and ZM-VFNS are valid?

As said before: GM-VFNS $\rightarrow$ ZM-VFNS for $p_T >> m$

NLO calculation: [Aversa,Chiappetta,Greco,Guillet,NPB327(1989)105]

1. $gg \to qX$
2. $gg \to gX$
3. $qg \to gX$
4. $qg \to qX$
5. $q\bar{q} \to gX$
6. $q\bar{q} \to qX$
7. $qg \to \bar{q}X$
8. $qg \to \bar{q}'X$
9. $qg \to q'X$
10. $qq \to gX$
11. $qq \to qX$
12. $q\bar{q} \to q'X$
13. $q\bar{q}' \to gX$
14. $q\bar{q}' \to qX$
15. $qq' \to gX$
16. $qq' \to qX$

$\oplus$ charge conjugated processes

One-particle inclusive production in a GM-VFNS

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

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

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

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

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

Fragmentation functions:

- $D_i^H(z, \mu_F') = D_i^Q \otimes D_Q^H$ where:
  - $D_i^Q(z, \mu_F')$: perturbative fragmentation functions of $i = q, g, Q$ into an on-shell heavy quark Q
  - $D_Q^H(z)$: scale-independent, non-perturbative FF describing transition of heavy quark to heavy hadron
- Non-perturbative FF fitted to $e^+e^- \to DX, BX$ data

Applications available for:

- $\gamma^* + p \to D^{*,0,+} + X$
  photoproduction [JHEP0103(2001)006]
- $p + \bar{p} \to (D^0, D^{*\pm}, D^\pm, D_s^\pm, \Lambda_c^\pm) + X$
  good description of Tevatron data [JHEP05(1998)007]
- $p + \bar{p} \to B + X$
  good description of Tevatron data [PRL89(2002)122003,JHEP07(2004)033]
- $p + p \to D, B + X$
  good description of RHIC data [PRL95(2005)122001]

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 $\longrightarrow$ m_h kept
- PDFs $f_i^p(x_1, \mu_F)$, $f_j^{\bar{p}}(x_2, \mu_F)$: $i, j = g, q, c$ $[q = u, d, s]$
- 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	$qq' \to qX$	$Qq \to QX$, $qQ \to qX$	-

$\oplus$ charge conjugated processes

Mass terms contained in the hard scattering coeffi cients:

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

Two ways to derive them:

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

[Kniehl,Kramer,IS,Spiesberger,PRD71(2005)014018]

OR

(2) Perform mass factorization using partonic PDFs and FFs

[Kniehl,Kramer,IS,Spiesberger,EPJC41(2005)199]

- 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 coeffi cient 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:

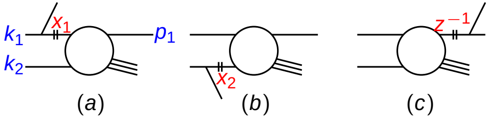

Fig. (a):

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

Fig. (b):

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

Fig. (c):

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

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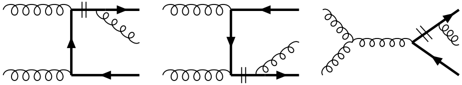
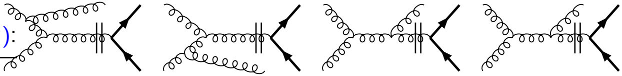
[1] Kniehl, Kramer, I.S., Spiesberger, EPJC41(2005)199

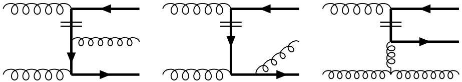
$\mathrm{d}\hat{\sigma}^{(0)}(gg \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



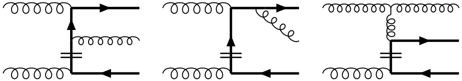
$\mathrm{d}\hat{\sigma}^{(0)}(gg \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



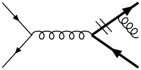
$f^{(1)}_{g\to Q}(x_1) \otimes \mathrm{d}\hat{\sigma}^{(0)}(Qg \to Qg)$:



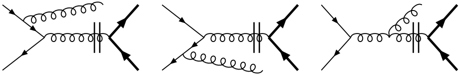
$f^{(1)}_{g\to Q}(x_2) \otimes \mathrm{d}\hat{\sigma}^{(0)}(gQ \to Qg)$:



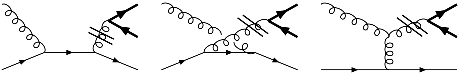
$\mathrm{d}\hat{\sigma}^{(0)}(q\bar{q} \rightarrow Q\bar{Q}) \otimes d^{(1)}_{Q\rightarrow Q}(z)$:



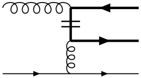
$\mathrm{d}\hat{\sigma}^{(0)}(q\bar{q} \rightarrow gg) \otimes d^{(1)}_{g\rightarrow Q}(z)$:



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



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



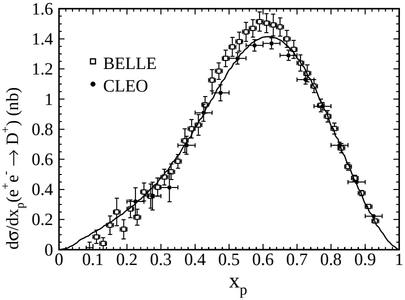
Applications

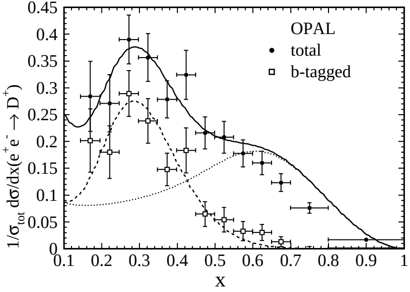
Applications available for

- $\gamma + \gamma \to D^{*\pm} + X$
  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 $e + p \to D + X$

Input parameters:

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





FF for $c \to D^*$
from fitting to e^+e^- data

2008 analysis based on GM-VFNS
$\mu_0 = m$

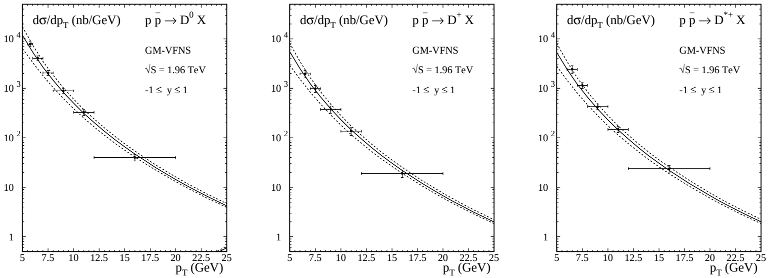
global fit: data from
ALEPH, OPAL, BELLE, CLEO

BELLE/CLEO fit

[KKKS: Kneesch, Kramer, Kniehl, IS
NPB799 (2008)]

tension between low and high energy data sets → speculations about non-perturbative (power-suppressed) terms

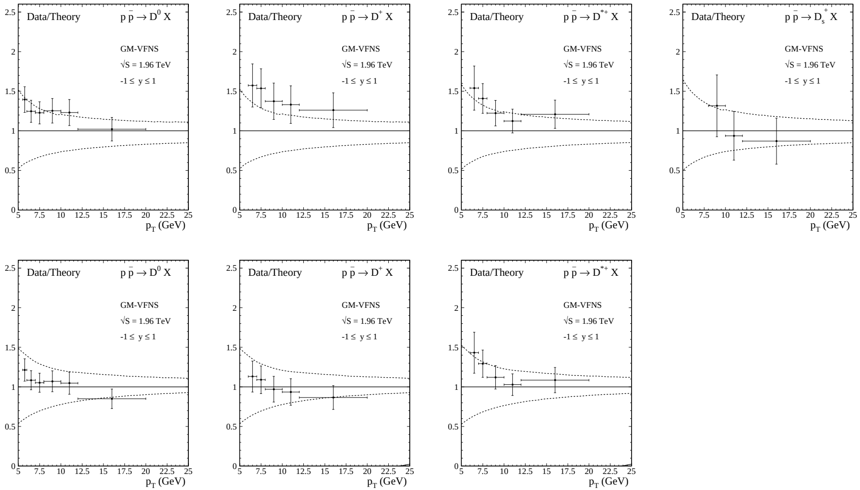
HADROPRODUCTION OF D^0, D^+, D^{*+}, D_s^+
GM-VFNS RESULTS W/ KKKSC FFS [1]



- $d\sigma/dp_T$ [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] Kniehl,Kramer,IS,Spiesberger, arXiv:0901.4130[hep-ph], PRD(to appear)

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



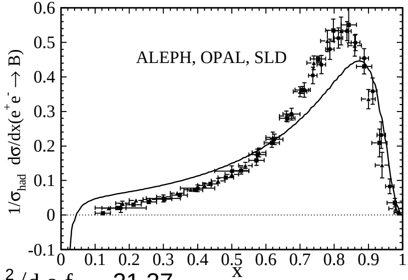
- New KKKSc FFs improve agreement w/ CDF data.

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

HADROPRODUCTION OF B^0, B^+ [1]
NEW FFS FROM LEP1/SLC DATA [2]

Petersen

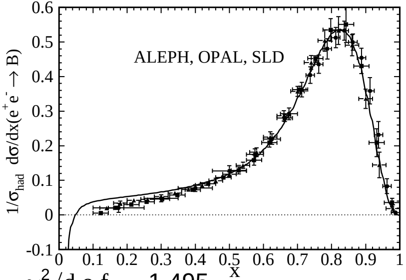
$$D(x, \mu_0^2) = N \frac{x(1-x)^2}{[(1-x)^2 + \epsilon x]^2}$$



χ^2/d.o.f. = 21.37

Kartvelishvili-Likhoded

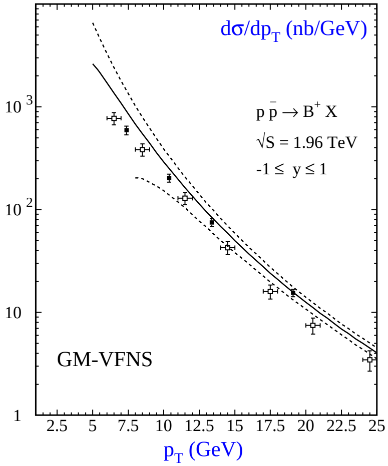
$$D(x, \mu_0^2) = N x^{\alpha}(1-x)^{\beta}$$



χ^2/d.o.f. = 1.495

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

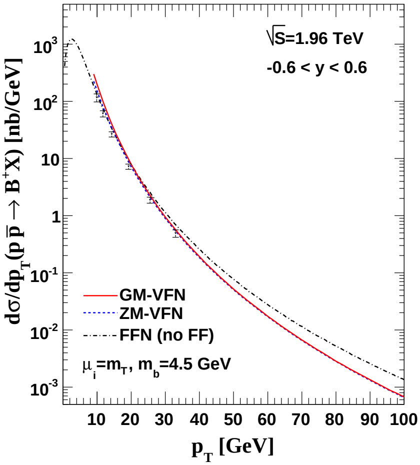
[2] ALEPH, PLB512(2001)30; OPAL, EPJC29(2003)463; SLD, PRL84(2000)4300; PRD65(2002)092006



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

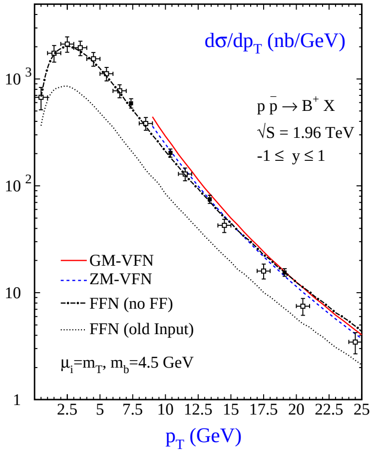
[1] CDF, PRD71(2005)032001

[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

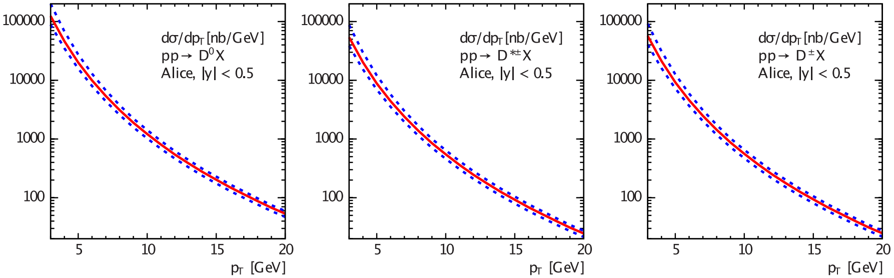
[1] Kraus, FERMILAB-THESIS-2006-47; Annovi, FERMILAB-CONF-07-509-E



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

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

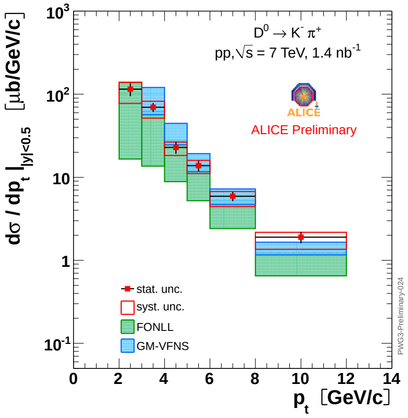
Predictions for the LHC

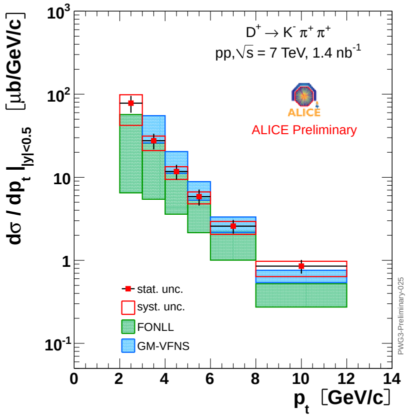


- pp collisions, $\sqrt{S} = 7$ TeV
- CTEQ6.5 PDF, KKKSc FF, $m_c = 1.5$ GeV
- Results for $D^0 + \bar{D}^0$, $D^{\star +} + D^{\star -}$, $D^+ + D^-$
- Error bands: Varying μ_R by factors 2 up and down
  (Except for very small p_T this gives maximal variation in the cross section)

PRELIMINARY ALICE RESULTS FOR D^0 AND D^+

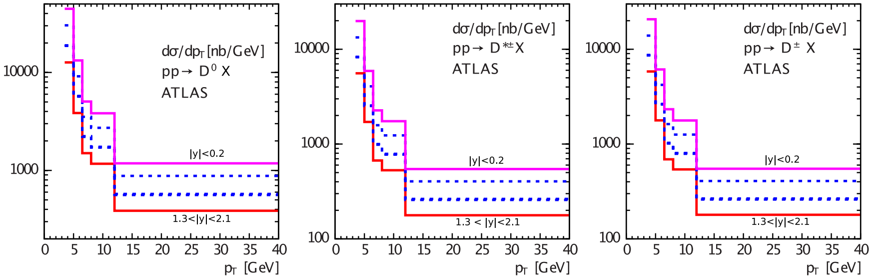
- Presented by A. Dainese at LHC Physics Day, 3. Dec. 2010





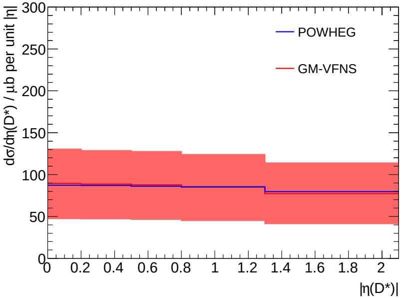
- pQCD predictions (FONLL, GM-VFNS) compatible with data

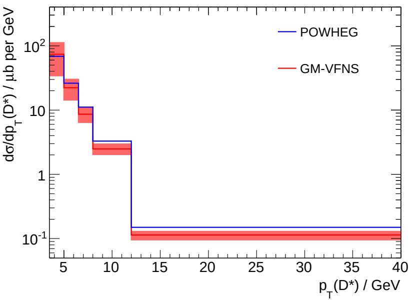
GM-VFNS predictions for D^0, $D^{\star\pm}$, $D^\pm$ production at ATLAS



- *pp* collisions, $\sqrt{S} = 7$ TeV
- CTEQ6.6 PDF, KKKS06 FF, $m_c = 1.5$ GeV
- Rapidity bins (top to bottom):
  $|\eta| < 0.2$, $0.2 < |\eta| < 0.5$,$0.5 < |\eta| < 0.8$,$0.8 < |\eta| < 1.3$, $1.3 < |\eta| < 2.1$
- Results for average $(D^0 + \bar{D}^0)/2$, $(D^{\star+} + D^{\star-})/2$, $(D^+ + D^-)/2$

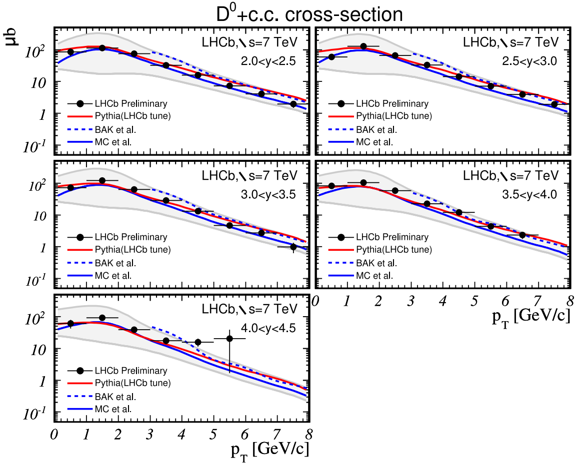
Figures provided by S. Head





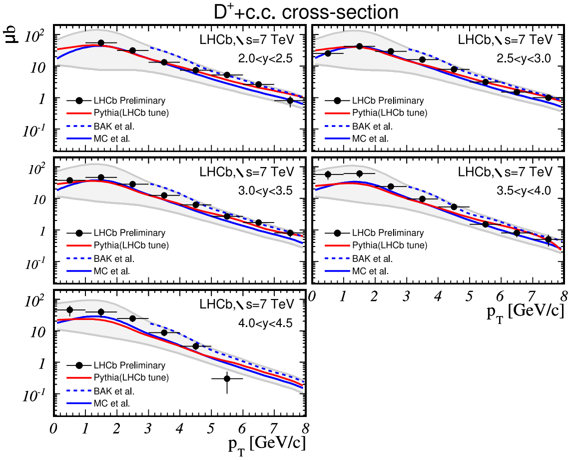
- pp collisions, $\sqrt{S} = 7$ TeV
- CTEQ6.6 PDF, KKKS06 FF, $m_c = 1.5$ GeV
- Left fi gure: $d\sigma/d\eta$ for $3.5 < p_T < 40$
- Right fi gure: $d\sigma/dp_T$ for $0 < \eta < 2.1$
- Results for sum $D^0 + \bar{D}^0$, $D^{\star+} + D^{\star-}$, $D^+ + D^-$
- Independent variation of μ_R and μ_F by a factor two up and down

- Prelim. results ($\mathcal{L} = 1.8$ nb^{-1}), $D^0 \to K^-\pi^+$, Data: 12 % correlated error not shown



- BAK et al.= GM-VFNS: B. Kniehl,G. Kramer,I. Schienbein,H. Spiesberger
- MC et al.= FONLL: M. Cacciari, S. Frixione, M. Mangano, P. Nason, G. Ridolfi

- Prelim. results ($\mathcal{L} = 1.8\ \text{nb}^{-1}$), $D^+ \to K^-\pi^+\pi^+$, Data: 14 % correlated error not shown



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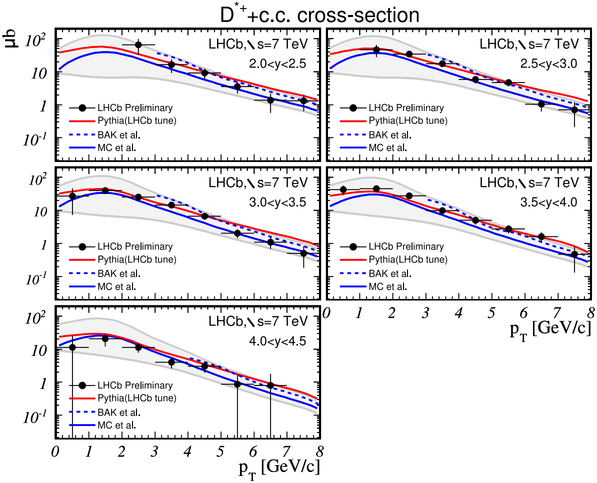
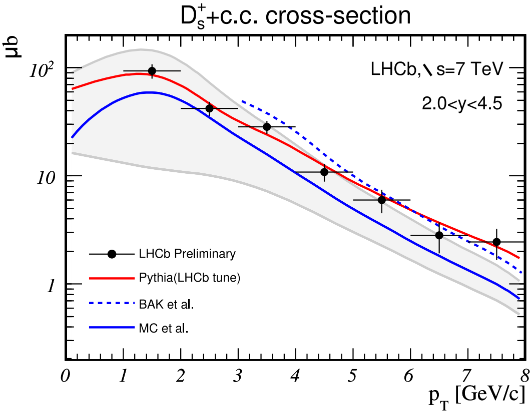
- MC et al.= FONLL: M. Cacciari, S. Frixione, M. Mangano, P. Nason, G. Ridolfi

- Preliminary ($\mathcal{L} = 1.8\ \text{nb}^{-1}$), $D^{\star +} \to (D^0 \to K^- \pi^+)\pi^+$, Data: 14 % corr. error not shown



- BAK et al.= GM-VFNS: B. Kniehl,G. Kramer,I. Schienbein,H. Spiesberger
- MC et al.= FONLL: M. Cacciari, S. Frixione, M. Mangano, P. Nason, G. Ridolfi

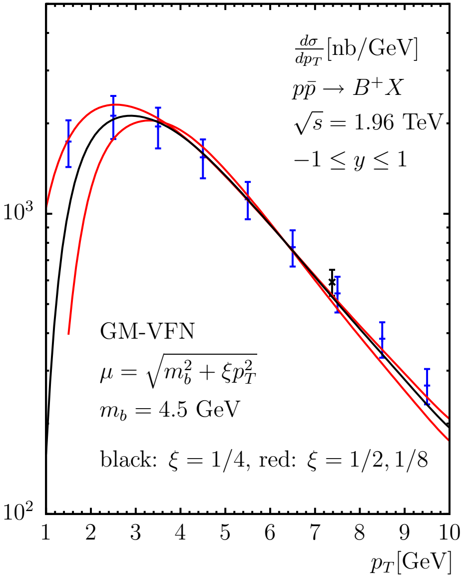
- Preliminary ($\mathcal{L} = 1.8$ nb^{-1}), $D^s \to K^- K^+ \pi^+$, Data: 16 % corr. error not shown



- BAK et al.= GM-VFNS: B. Kniehl,G. Kramer,I. Schienbein,H. Spiesberger
- MC et al.= FONLL: M. Cacciari, S. Frixione, M. Mangano, P. Nason, G. Ridolfi

- Presented an overview of theoretical approaches to hadroproduction of heavy quarks
- Main message: GM-VFNS predictions in good agreement with first LHC data
- Paper in preparation
  - More predictions (GM-VFNS,FFNS) for *D* and *B* mesons
  - Uncertainties
  - Matching to FFNS at small p_T

Backup



- 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 $\mu_F \xrightarrow{p_T\to 0} m_Q = \mu_0$
- $G(m, p_T) \equiv 1$ in contrast to FONLL

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