Masses in perturbative QCD

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based on work in collaboration with

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Theorieseminar Mainz

Outline

Overview and Motivation

QCD: A QFT for the strong interactions

- Statement: Hadronic matter is made of spin-1/2 quarks [$\leftrightarrow SU(3)_{\mathrm{fl}}$]
- Baryons like $\Delta^{++} = |u^\uparrow u^\uparrow u^\uparrow\rangle$ forbidden by Pauli exclusion/Fermi-Dirac stat.
  Need additional colour degree of freedom!
- Local SU(3)-color gauge symmetry:

$$\mathcal{L}_{\mathrm{QCD}} = \sum_{q=u,d,s,c,b,t} \bar{q}(i\not{\partial} - m_q)q - g\bar{q}\not{G}q - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} + \mathcal{L}_{gf} + \mathcal{L}_{ghost}$$

- Fundamental d.o.f.: quark and gluon fields
- Free parameters:
  - gauge coupling: g
  - quark masses: $m_u, m_d, m_s, m_c, m_b, m_t$

QCD: A QFT for the strong interactions

Properties:

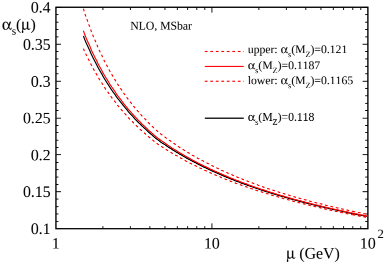
- **Confinement and Hadronization:**
  - Free quarks and gluons have not been observed:
    - A) They are confined in color-neutral hadrons of size $\sim$ 1 fm.
    - B) They hadronize into the observed hadrons.

  - Hadronic energy scale: a few hundred MeV [1 fm $\leftrightarrow$ 200 MeV]
  - Strong coupling large at long distances ($\gtrsim$ 1 fm): 'IR-slavery'
  - Hadrons and hadron masses enter the game

- **Asymptotic freedom:**
  - Strong couling small at short distances: perturbation theory
  - Quarks and gluons behave as free particles at asymptotically large energies

Renormalization of UV-divergences:
Running coupling constant $a_s := \alpha_s/(4\pi)$

$$a_s(\mu) = \frac{1}{\beta_0 \ln(\mu^2/\Lambda^2)}$$



- Gross, Wilczek ('73); Politzer ('73)



Non-abelian gauge theories:
negative beta-functions

$$\frac{da_s}{d\ln\mu^2} = -\beta_0 a_s^2 + \ldots$$

where $\beta_0 = \frac{11}{3} C_A - \frac{2}{3} n_f$

$\Rightarrow$ asympt. freedom: $a_s \searrow$ for $\mu \nearrow$

- Nobel Prize 2004

Asymptotic freedom:

- pQCD directly applicable if **all** energy scales large (hard scales)
- However, usually long-distance contributions to the amplitudes present:
  - emission of soft gluons
  - emission of collinear gluons and quarks

pQCD still useful for two classes of observables:

- IR– and collinear–save observables (insensitive to soft or collinear branching)
- Factorizable observables

Factorization:

- Separate amplitudes into (quantum mechanically) independent factors:
  - Soft parts (long distances/small energies): universal
  - hard parts (short distances/large energies): perturbatively calculable
- Note: Soft parts non-perturbative but universal $\rightarrow$ **Predictive framework**

Parton Model based on QCD factorization theorems:

$$d\sigma = \text{PDF} \otimes d\hat{\sigma} + \text{remainder}$$

- PDF:
  - Proton composed of partons = quarks, gluons
  - Structure of proton described by parton distribution functions (PDF)
  - Factorization theorems provide field theoretic definition of PDFs
  - PDFs universal $\rightarrow$ predictive power
- Hard part $d\hat{\sigma}$:
  - depends on the process
  - calculable order by order in perturbation theory
- Remainder suppressed by hard scale

Original factorization proofs considered massless partons

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

- $m_u, m_d, m_s \lesssim \Lambda_{\rm QCD} \ll m_c, m_b, m_t$
- $m_h \gg \Lambda_{\rm QCD} \Rightarrow \alpha_s(m_h^2) \propto \ln^{-1}(\frac{m_h^2}{\Lambda_{\rm QCD}^2}) \ll 1$ (asymptotic freedom)
- m_h sets hard scale; acts as long distance cut-off $\rightarrow$ pQCD
- Heavy quark production processes are:
  - Fundamental elementary particle processes
  - Important background to New Physics searches at the LHC

How to incorporate heavy quark masses into the pQCD formalism?

Requirements:

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

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

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

Heavy Flavor Schemes

HEAVY FLAVOR SCHEMES

Requirements:

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

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

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

Problem:

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

Way out: Patchwork of $\overline{\mathrm{MS}}$ 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

- charm is not a parton, appears only in final state
- no collinear divergences from $c \to c + g$
  but terms $\propto \log(\mu/m)$ with $\mu = Q, p_T, \ldots$ the hard scale
- Collinear logarithms $\log(\mu/m)$ kept in fixed order perturbation theory

\+ correct threshold behavior

\+ finite charm mass terms m/μ exactly taken into account

– not IR-safe: does not meet requirement (2)

– How to include possible intrinsic charm?

The 3-FFNS should fail when $\alpha_s \ln(\mu/m)$ becomes large [or $a_s \ln(\mu/m)$?]

Phenomenological question: When need to resum collinear log's?
$\to$ Not unambigously answered yet! A lot of handwaving . . .

VFNS

- charm is a parton for $\mu \gtrsim m$
- mass singularities absorbed in PDFs (and FFs)
  - if $m = 0$: $1/\varepsilon$ poles $\rightarrow \overline{\mathrm{MS}}$ subtraction
  - if $m \neq 0$: $\log(\mu/m)$ + finite $\rightarrow \overline{\mathrm{MS}}$ subtraction
- QCD prediction: DGLAP (RG) evolution resums large logarithms $\log(\mu/m)$

\+ Requirements (1), (2) satisfied

\+ finite mass terms m/μ can be taken into account: massive VFNS (GM-VFNS) (otherwise: massless VFNS (ZM-VFNS) which is the original parton model)

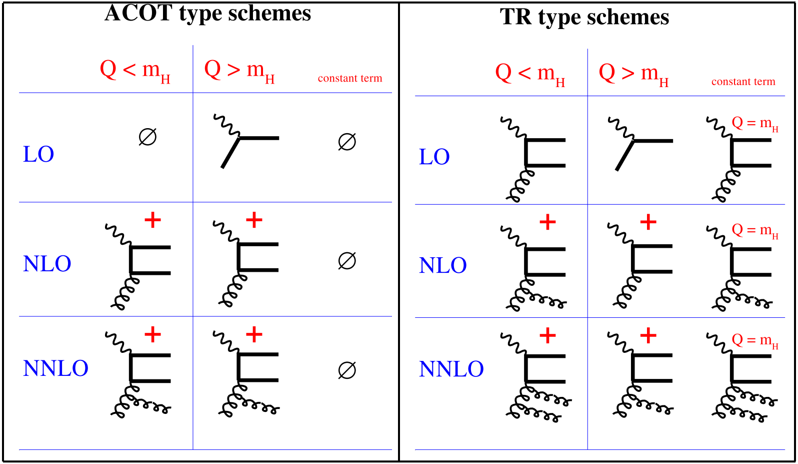
– Requirement (3) **problematic point**:

  - In DIS slow-rescaling prescriptions (ACOT-χ) good approximation of exact threshold kinematics: $c(x) \rightarrow c(\chi)$ where $\chi = x(1 + 4m^2/Q^2)$
  - What to do in hadron–hadron collisions?
  - What to do in 1-particle inclusive production?

- Intrinsic charm natural to incorporate

VFNS

- Factorization proof with massive quarks for inclusive DIS: Collins '98
  Remainder $\sim \mathcal{O}(\Lambda^2/Q^2)$ not $\sim \mathcal{O}(m^2/Q^2)$
- Many incarnations of VFNS (ACOT, ACOT-χ, TR): Freedom to shift finite *m*-terms without spoiling IR-safety
- S-ACOT scheme: incoming heavy quarks massless ($\leftrightarrow$ scheme choice) more complex at NNLO
- Massive quarks can be described by massless evolution kernels ($\leftrightarrow$ scheme choice)
- Matching $n \to n+1$: PDFs, $alpha_s$, masses
- At NLO matching continuous at $\mu = m$: $f_i^{n_f} = f_i^{n_f+1}$
- At higher orders matching discontinuos:
  - for PDFs discontinuous at $\mathcal{O}(\alpha_s^2)$
  - for α_s discontinuous at $\mathcal{O}(\alpha_s^3)$
- Observable discontinuous: $\sigma^{n_f} = \sigma^{n_f+1} + \mathcal{O}(\alpha_s^{K+1})$


ACOT type schemes
$Q < m_H$
$Q > m_H$
constant term
LO
∅
∅
NLO
+
+
∅
NNLO
+
+
∅
TR type schemes
$Q < m_H$
$Q > m_H$
constant term
LO
$Q = m_H$
NLO
+
+
$Q = m_H$
NNLO
+
+
$Q = m_H$

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)

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

- FFs from fi ts 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

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. $qq' \to qX$

Heavy quark initiated ($m_Q = 0$)

1. -
2. -
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. $Qg \to qX$
10. $QQ \to gX$
11. $QQ \to QX$
12. $Q\bar{Q} \to qX$
13. $Q\bar{q} \to gX$, $q\bar{Q} \to gX$
14. $Q\bar{q} \to QX$, $q\bar{Q} \to qX$
15. $Qq \to gX$, $qQ \to gX$
16. $Qq \to QX$, $qQ \to qX$

Mass effects: $m_Q \neq 0$

1. $gg \to QX$
2. -
3. -
4. -
5. -
6. -
7. -
8. $qg \to \bar{Q}X$
9. $qg \to QX$
10. -
11. -
12. $q\bar{q} \to QX$
13. -
14. -
15. -
16. -

$\oplus$ 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 $\overline{\rm MS}$ calculation (Aurenche et al., Aversa et al., ...)

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

  $\Rightarrow$ Subtraction terms

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

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

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

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

  $\to$ allows to use PDFs and FFs with $\overline{\rm MS}$ 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:

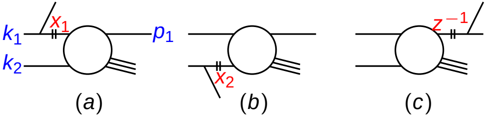

Fig. (a):

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

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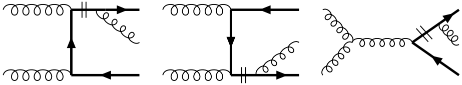
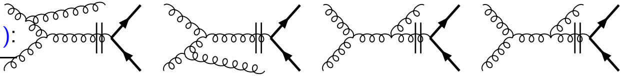
[1] Kniehl, Kramer, I.S., Spiesberger, EPJC41(2005)199

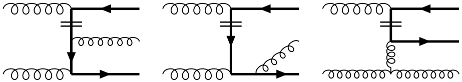
$d\hat{\sigma}^{(0)}(gg \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



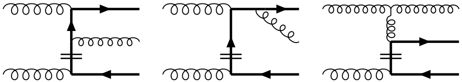
$d\hat{\sigma}^{(0)}(gg \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



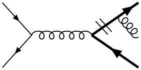
$f^{(1)}_{g\to Q}(x_1) \otimes d\hat{\sigma}^{(0)}(Qg \to Qg)$:



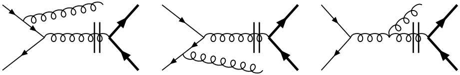
$f^{(1)}_{g\to Q}(x_2) \otimes d\hat{\sigma}^{(0)}(gQ \to Qg)$:



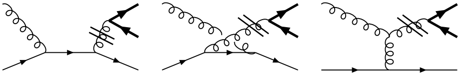
$\mathrm{d}\hat{\sigma}^{(0)}(q\bar{q} \to Q\bar{Q}) \otimes d^{(1)}_{Q\to Q}(z)$:



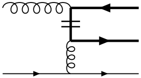
$\mathrm{d}\hat{\sigma}^{(0)}(q\bar{q} \to gg) \otimes d^{(1)}_{g\to Q}(z)$:



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



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



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]

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

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

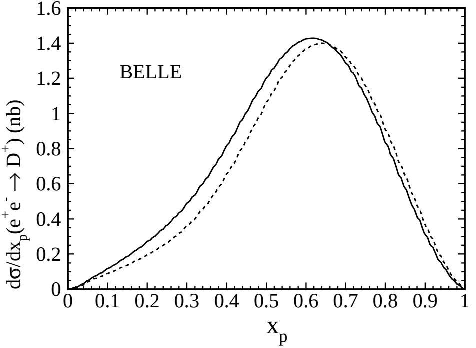
[1] Kneesch,B.K.,Kramer,Schienbein, NPB799(2008)34

[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]

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

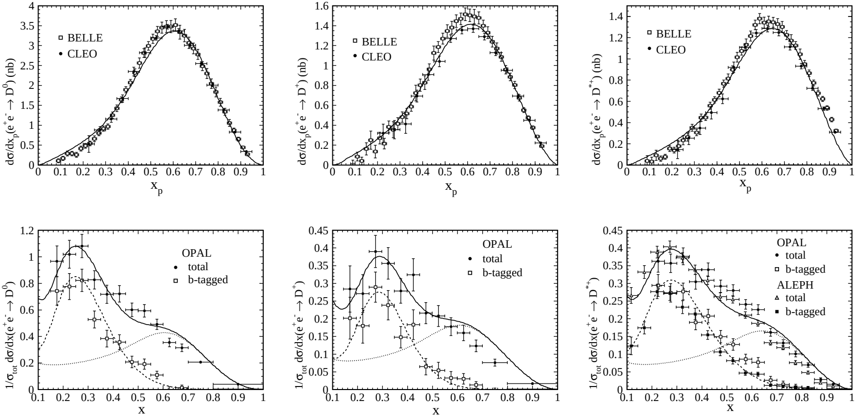
[1] Bowler, ZPC11(1981)169

- χ^2/d.o.f.

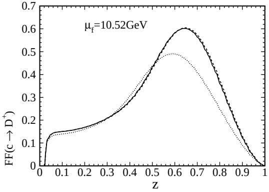
H	VFNS	Belle/CLEO	ALEPH/OPAL	Global
D^0	GM	3.15	0.794	4.03
	ZM	3.25	0.789	4.66
D^+	GM	1.30	0.509	1.99
	ZM	1.37	0.507	2.21
D^{*+}	GM	3.74	2.06	6.90
	ZM	3.69	2.04	7.64

- 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.

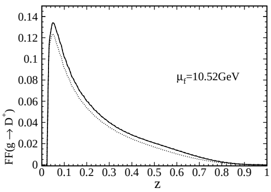
RESULTS: GLOBAL FITS



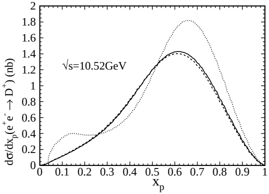
- Belle/CLEO data push $\langle z \rangle_c(m_Z)$ up by 0.03–0.04



$c \to D^+$ FF



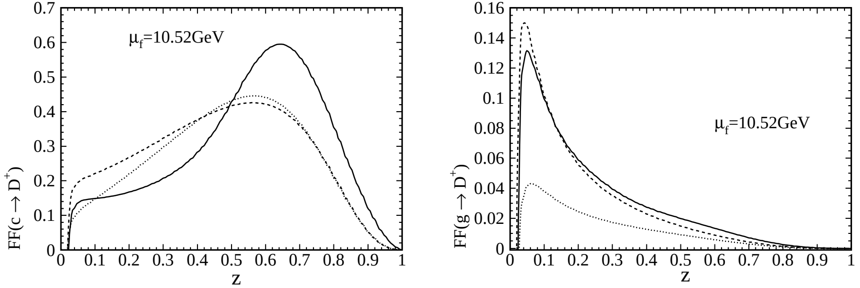
$g \to D^+$ FF



$d\sigma/dx_p$ 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 $\qquad$ $g \to D^+$ FF

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

- Strong pull of Belle/CLEO data on $c \to D^+$ FF
- Reduction in μ_0 increases $g \to D^+$ FF

Applications

Applications available for

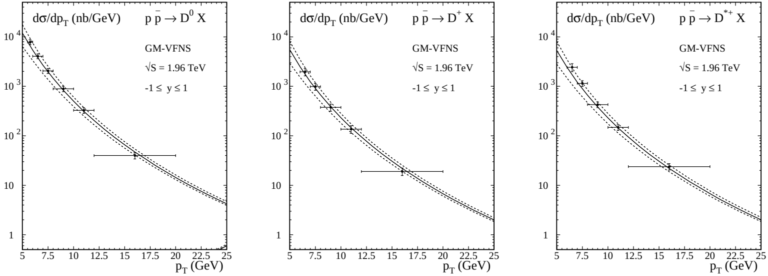
- $\gamma + \gamma \to D^{*\pm} + X$
  direct and resolved contributions — EPJC22, EPJC28
- $\gamma^* + p \to D^{*\pm} + X$
  photoproduction — EPJC38, arXiv:0902.3166 [EPJC]
- $p + \bar{p} \to (D^0, D^{*\pm}, D^\pm, D_s^\pm, \Lambda_c^\pm) + X$
  good description of Tevatron data — PRD71, PRL96, arXiv:0901.4130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

Numerical Results

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 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 $m_T = \sqrt{p_T^2 + m^2}$

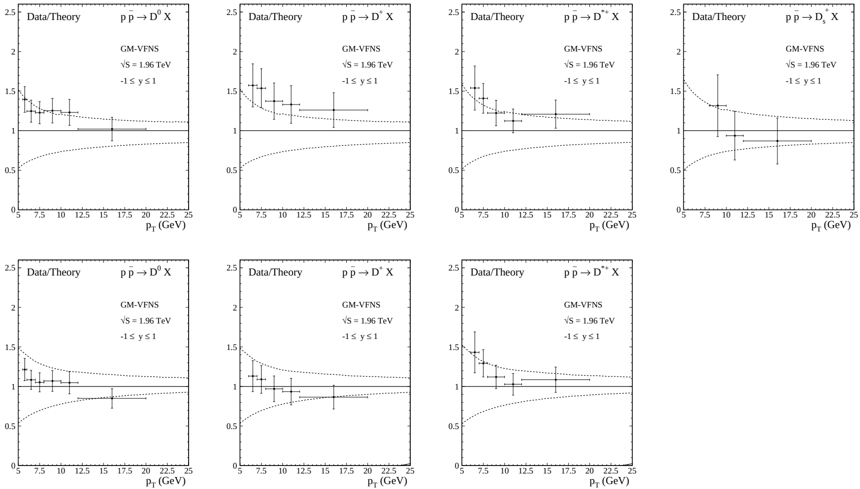
HADROPRODUCTION OF D^0, D^+, D^{*+}, D_s^+
GM-VFNS RESULTS W/ KKKSC FFS [1]



- $d\sigma/dp_T$ [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

- c, $\overline{c}$, b, $\overline{b}$ PDFs relatively weakly constrained by global QCD analyses
- Knowledge important
  - inherently: fundamental structure of the nucleon
  - phenomenologically: signifi cant 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 fi xed-order pQCD
  - theoretical: heavy-quark d.o.f. perturbatively calculable
  - practical: lack of clearly identifyable experimental constraints

- 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]

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

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

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

$$\int_0^1 \mathrm{d}x\, x[c(x) - \overline{c}(x)] = 0$$

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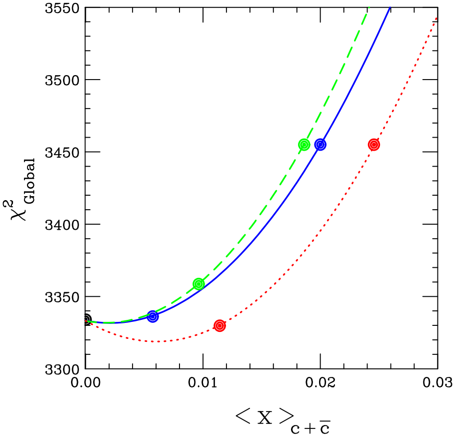
[1] Brodsky, Hoyer, Peterson, Sakai, PLB93(1980)451

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

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

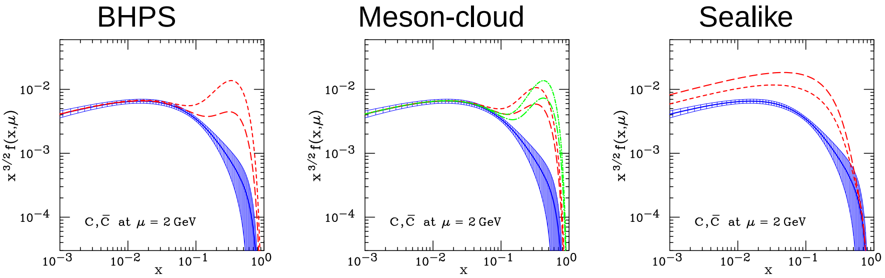


CTEQ.6.5C*n*

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

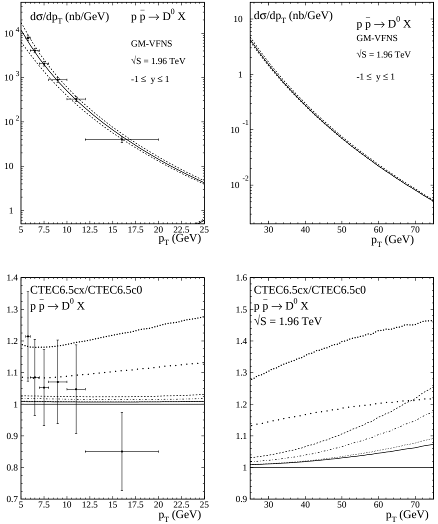
After evolution from $\mu_0 = 1.3$ GeV to $\mu = 2$ GeV.



$n = 0$ 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.



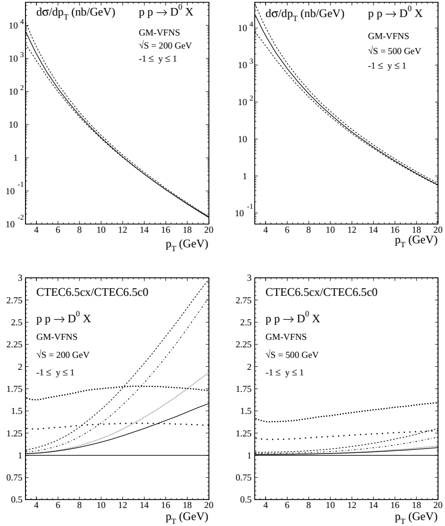
Acosta et al. (CDF Collaboration), PRL91(2003)241804

$(\mathrm{d}\sigma/\mathrm{d}p_T)(p\bar{p} \to D^0 + X)$

$\sqrt{s} = 1.96$ 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
$|y| < 1$

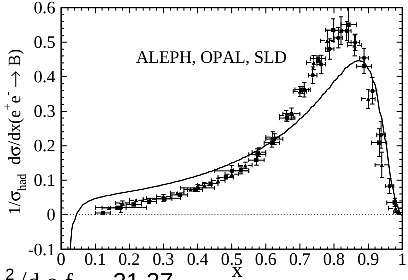
IC Model	moderate	marginal
BHPS	solid	dashed
Meson-cloud	densely dotted	dot-dashed
Sealike	scarsely dotted	dotted

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

NEW FFS FROM LEP1/SLC DATA [2]

Petersen

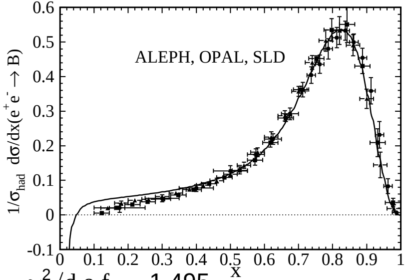
$$D(x,\mu_0^2) = N\frac{x(1-x)^2}{[(1-x)^2+\epsilon x]^2}$$



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

Kartvelishvili-Likhoded

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



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

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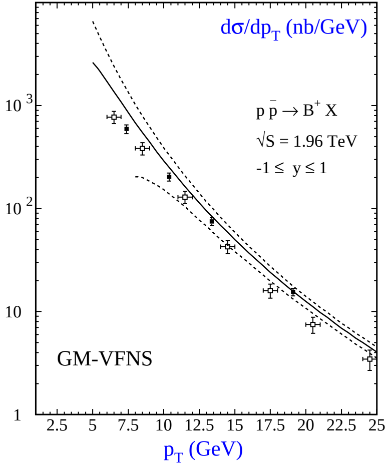
[1] Kniehl,Kramer,IS,Spiesberger,PRD77(2008)014011

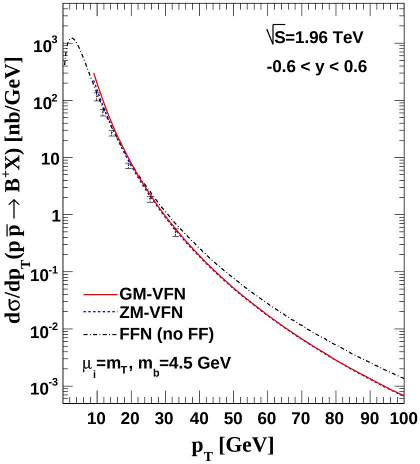
[2] ALEPH, PLB512(2001)30; OPAL, EPJC29(2003)463; SLD, PRL84(2000)4300; PRD65(2002)092006



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

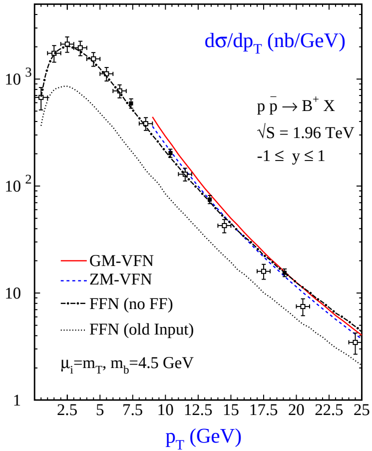
[1] CDF, PRD71(2005)032001

[2] CDF, PRD75(2007)012010



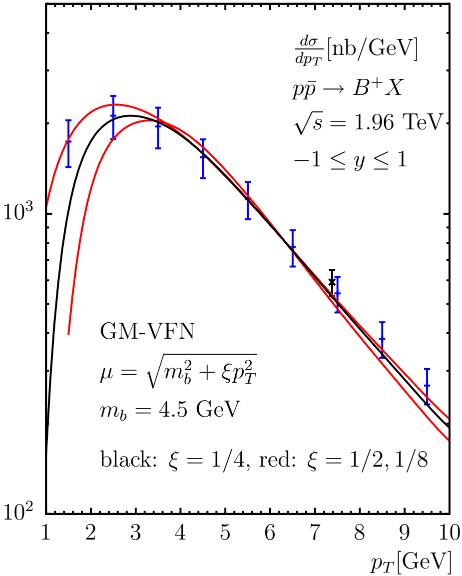
- CDF II (preliminary) [1]
- $\mu_R = \mu_F = m_T$
- for $p_T \gg m_b$:
  - GM-VFN merges w/ ZM-VFN
  - FFN breaks down
- data point in bin [29,40] favors GM-VFN

[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
  - $\Lambda^{(5)}_{\overline{\rm MS}} = 227$ 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 $\mu_F \xrightarrow{p_T\to 0} m_Q = \mu_0$
- $G(m, p_T) \equiv 1$ in contrast to FONLL

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

NUMERICAL RESULTS

Exemplify results for

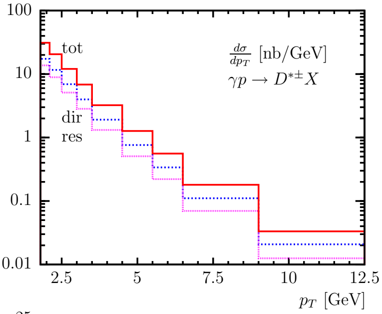
- p_T, η distributions
- photoproduction: $Q^2 \leq 2$ GeV^2
  1.5 GeV $\leq p_T \leq$ 12.5 GeV, $|\eta| \leq 1.5$, 100 GeV $\leq W_{\gamma p} \leq$ 285 GeV

➜ compare with H1 preliminary data: H1prelim-08-073

- $e^{\pm}p$ at low Q^2: $0.05 < Q^2 < 0.7$ GeV^2,
  $1.5 < p_T < 9.0$ GeV, $|\eta| < 1.5$, $0.02 < y < 0.85$

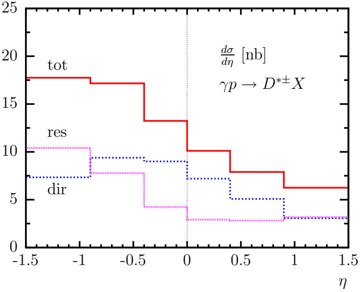
➜ compare with ZEUS data: PLB649

- charm mass: $m = 1.5$ GeV
- α_s at NLO with $\Lambda^{\overline{\mathrm{MS}}}_{N_f=4} = 0.328$ GeV, i.e. $\alpha_s(M_Z^2) = 0.1180$
- independent choice of renormalization and factorization scales:
  $\mu_i = \xi_i \sqrt{p_T^2 + m^2}$, $i = R, F, F'$, default: $\xi_i = 1$
- PDFs: proton: CTEQ6.5, photon: GRV
- fragmentation functions: KKKS 2008

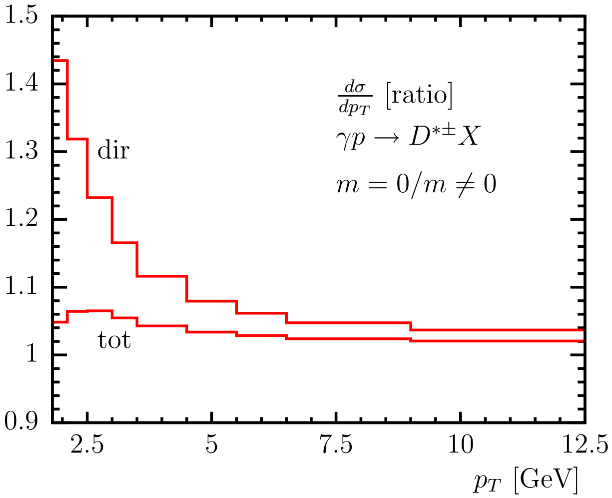


direct and resolved contributions:
p_T distribution

resolved part dominated by charm PDF

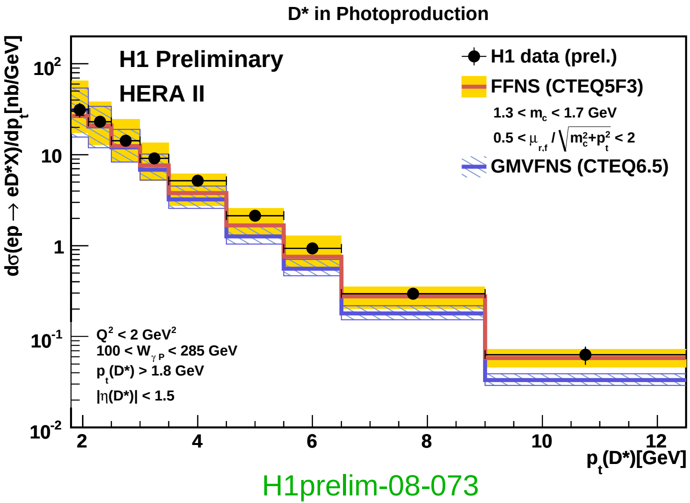


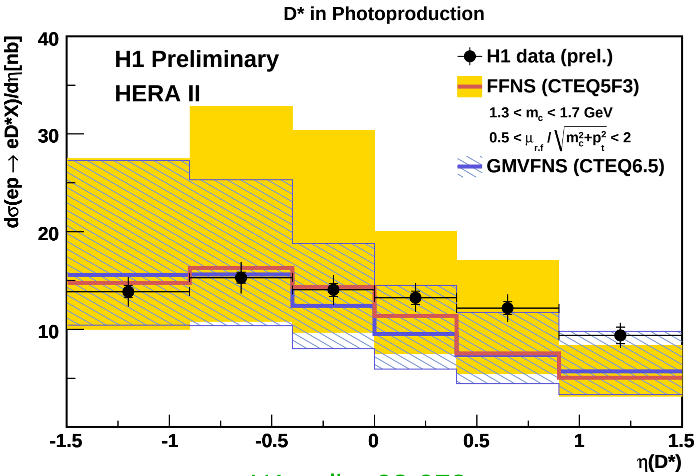
direct and resolved contributions:
η distribution



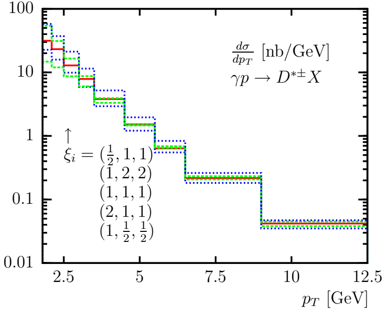
ratio of cross sections:
$\sigma(m = 0)/\sigma(m \neq 0)$

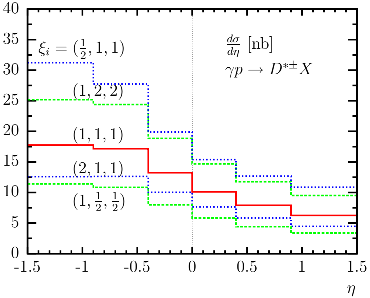
mass effects
suppressed in σ_{tot}


D* in Photoproduction
H1 Preliminary
HERA II
H1 data (prel.)
FFNS (CTEQ5F3)
1.3 < m_c < 1.7 GeV
0.5 < μ_r,f / √(m_c²+p_t²) < 2
GMVFNS (CTEQ6.5)
Q² < 2 GeV²
100 < W_γP < 285 GeV
p_t(D*) > 1.8 GeV
|η(D*)| < 1.5
dσ(ep → eD*X)/dp_t [nb/GeV]
p_t(D*)[GeV]
H1prelim-08-073



H1prelim-08-073





$\mu_i = \xi_i \sqrt{p_T^2 + m^2}$
for $i = R, F, F'$

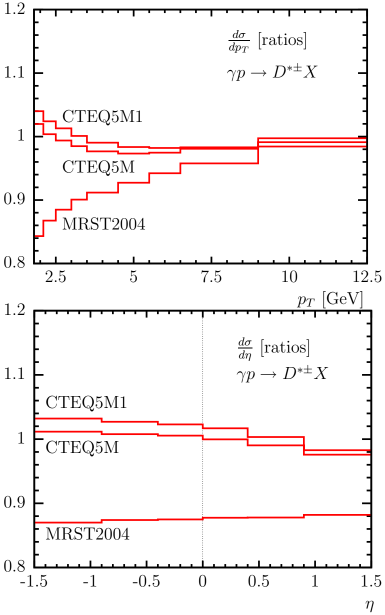
renormalization scale: R
factorization scales:
F: initial state (PDF)
F': final state (FF)

variation by factor 2 up/down:

$+84/-53\,\%$ at *low* p_T
$+13/-16\,\%$ at *high* p_T

large scale uncertainties
at small p_T
determines scale uncertainty for all η

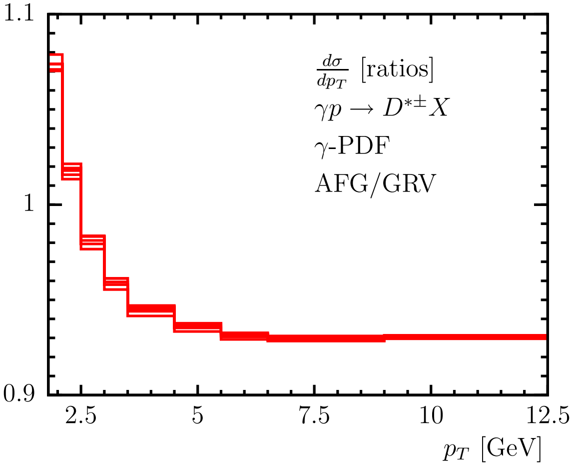
➜ improvement: matching to $N_f = 3$,
threshold for c-initiated
subprocesses



ratio of cross sections normalized to CTEQ6.5

largest influence from varying PDF input at small p_T

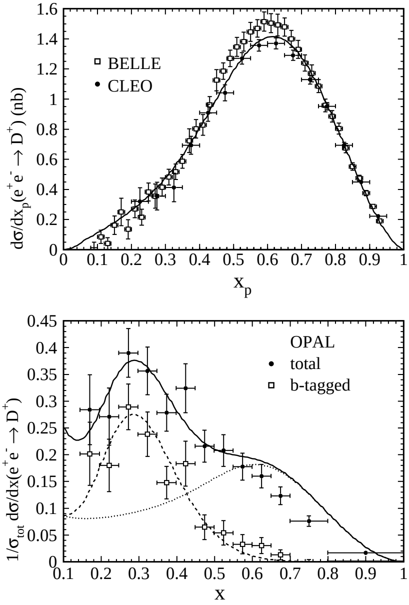
but small compared to scale uncertainty



ratio of cross sections

uncertainties
from γ PDF input
slightly smaller

default: GRV
compared with AFG:
Aurenche, Fontannaz,
Guillet, EPJC44 (2005)
5 sets (low/high μ_0^2, soft/hard
non-perturbative gluon)



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

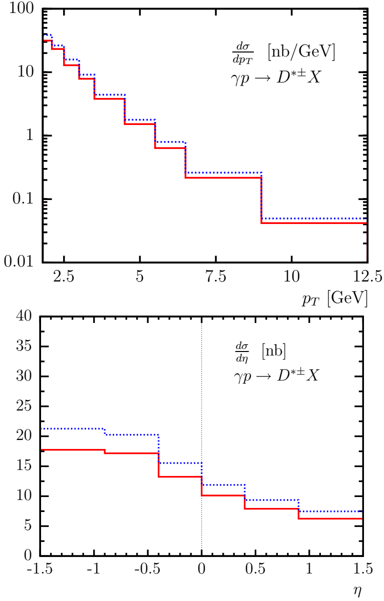
2008 analysis based on GM-VFNS
$\mu_0 = m$

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

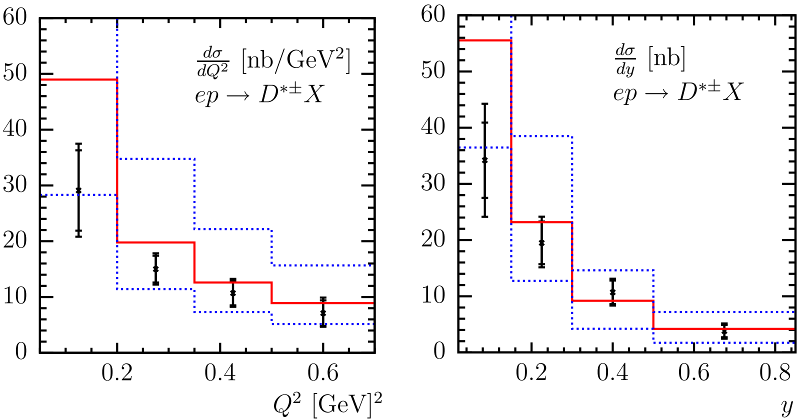


uncertainties from $c \longrightarrow D^*$ FF:

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

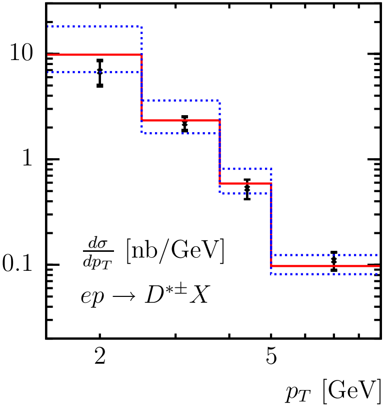
BELLE/CLEO fit

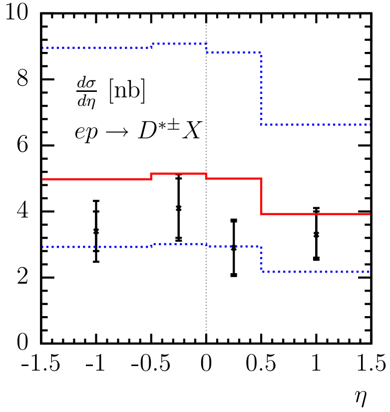
Kneesch, Kramer, Kniehl, IS NPB799 (2008)



$0.05 < Q^2 < 0.7$ GeV^2 ZEUS PLB649

scales at $\mu_{R,F} = \xi_{R,f}\sqrt{p_T^2 + m^2}$ varied by factor 2 up and down



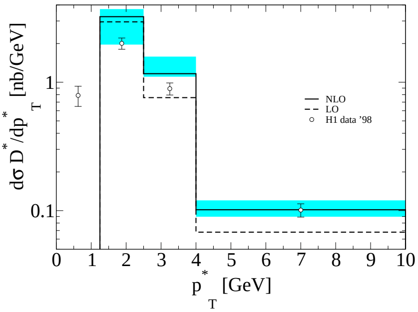


$0.05 < Q^2 < 0.7$ GeV^2 ZEUS PLB649

scales at $\mu_{R,F} = \xi_{R,f}\sqrt{p_T^2 + m^2}$ varied by factor 2 up and down

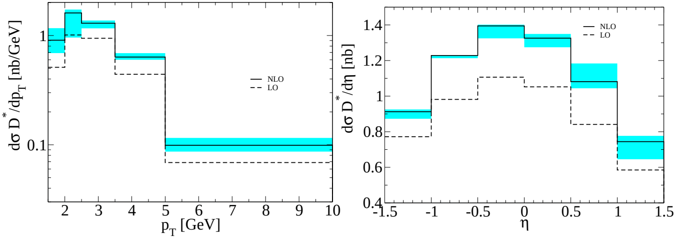
uncertainty for all η dominated by smallest p_T

- Phase Space: $2 < Q^2 < 100\ \mathrm{GeV}^2$, $0.05 < y < 0.7$,
  $1.5 \leq p_{T,Lab}(D^\star) \leq 15\ \mathrm{GeV}$, $|\eta_{Lab}(D^\star)| < 1.5$,



- ${\mu_R}^2 = {\mu_F}^2 = {\mu'_F}^2 = \xi \frac{Q^2 + (p_T^*)^2}{2}$
- Uncertainty band: variation of $\xi \in [1/2, 2]$

- Phase Space: $2 < Q^2 < 100\ \mathrm{GeV}^2$, $0.05 < y < 0.7$,
  $1.5 \leq p_{T,Lab}(D^\star) \leq 15\ \mathrm{GeV}$, $|\eta_{Lab}(D^\star)| < 1.5$,
- Additional Cut: $p_T^*(D^*) > 2\ \mathrm{GeV}$ ($\gamma^* p$-CMS)



- ${\mu_R}^2 = {\mu_F}^2 = {\mu_F'}^2 = \xi \frac{Q^2 + (p_T^*)^2}{2}$
- Uncertainty band: variation of $\xi \in [1/2, 2]$

▸ More distributions

- Discussion of 1-particle inclusive production of heavy quarks in a massive VFNS (GM-VFNS)
- Available at NLO in the GM-VFNS:
  - $\gamma\gamma \to HX$
  - $\gamma p \to HX$
  - $p\bar{p} \to HX$
- Work in progress:
  - $ep \to HX$
- Generell 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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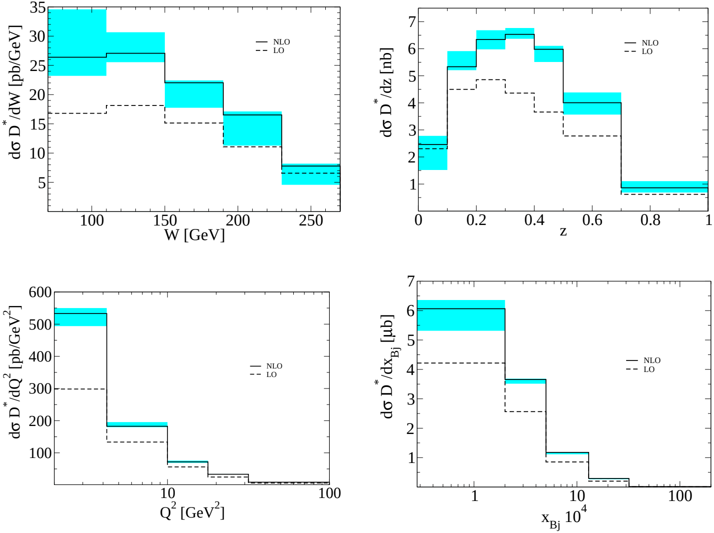
Backup Slides


35
30
25
20
15
10
5
100
150
200
250
W [GeV]
dσ D* /dW [pb/GeV]
NLO
LO
7
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1
z
dσ D* /dz [nb]
NLO
LO
600
500
400
300
200
100
10
100
Q² [GeV²]
dσ D* /dQ² [pb/GeV²]
NLO
LO
7
6
5
4
3
2
1
1
10
100
x_Bj 10⁴
dσ D* /dx_Bj [μb]
NLO
LO

◂ go back

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

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

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

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

back to schemes

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

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

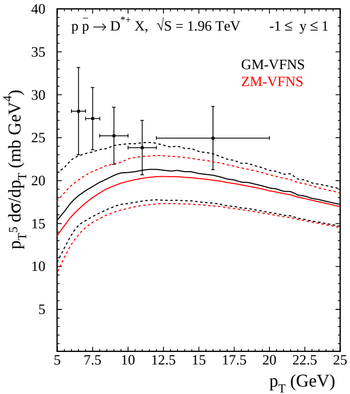
$$\text{GM-VFNS} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0})\tilde{\mathrm{G}}(\mathrm{m}, \mathrm{p_T}) \text{ with}$$
$$\tilde{G}(m, p_T) = 1$$

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!

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

- 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 $\alpha_s(M_Z) = 0.1165$;
- $d\sigma(p\bar{p} \to DX) \propto \alpha_s^2(1 + \alpha_s K)$