Inclusive photoproduction of D^* mesons at next-to-leading order in the General-Mass Variable-Flavor-Number Scheme

H. Spiesberger
Univ. Mainz

based on work in collaboration with
B. Kniehl, G. Kramer, I. Schienbein

(arXiv:0902.3166)

- Theoretical framework: heavy quark production
  the General-Mass Variable-Flavor-Number Scheme
  for 1-particle inclusive heavy-meson production

- Numerical results for D^* meson production
  in photoproduction at HERA: $\gamma^* p \to D^* X$

- Open charm hadroproduction and the charm content of the proton
  see talk by B. A. Kniehl

Massive or Massless Heavy Quarks?

$m \neq 0 \longrightarrow$

- correct threshold behavior
  no collinear divergences from $c \to c + g$
  but terms $\propto \log(\mu/m)$ with $\mu = Q, p_T, \ldots$
- large corrections at large μ

$m = 0 \longrightarrow$

- mass singularities ($1/\epsilon$-poles instead of $\log m^2$-terms)
  absorbed in PDFs and FFs
- QCD prediction: DGLAP (RG) evolution resums
  large logarithms $\log(\mu/m)$
- more reliable at large μ
- not reliable at heavy quark threshold

Goal: combine massive (low scale) and massless (high scale) calculations

- exploit freedom to choose an appropriate
  factorization scheme

- The problem:
  Conventionally, PDFs and FFs are defined in the $\overline{\mathrm{MS}}$ scheme
  $\overline{\mathrm{MS}}$ scheme is based on a massless calculation
  Massless and massive calculations contain different singularities
  Can not use $\overline{\mathrm{MS}}$ PDFs and FFs in a massive calculation?
- The solution:
  Match massless and massive calculations:

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

The subtracted cross section (in a massive calculation)

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

can be used with $\overline{\mathrm{MS}}$ parton distribution and fragmentation functions

➜ The GM-VFNS (general-mass variable flavor number scheme)

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

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

- collinear logs: $\log(p_T^2/m^2) = \log(p_T^2/\mu^2) + \log(\mu^2/m^2)$, terms with $\log(\mu^2/m^2)$:
  subtracted from hard part and
  absorbed in parton distribution and fragmentation functions
  resummed by DGLAP evolution equations
- Parton distribution functions for g, u, d, s, and c, charm is a parton: $f_c \neq 0$
- VFNS: $f_c = 0$ below, $f_c \neq 0$ above threshold; $\longrightarrow$ GM-VFNS with $m \neq 0$
- technically involved:
  calculation with $m \neq 0$
  terms $\propto (\frac{m}{p_T})^n$ included in the hard scattering cross section
- Fragmentation functions, e.g. for $c \to D^*$: $D_c^{D^\star}(z, \mu_{F'}^2)$ with non-perturbative input and perturbative RG evolution
- large collinear logarithms $\ln \frac{\mu^2}{m^2}$ resummed in evolved $f_c(x, \mu^2)$ and $D_c^{D^\star}(x, \mu^2)$

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

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

$\Rightarrow$ Subtraction terms

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

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

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

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

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

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

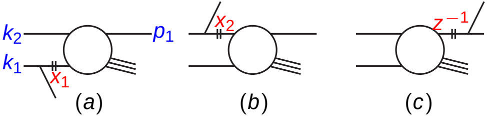
- final state:

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

- Other partonic distribution functions are zero to order α_s

Mele, Nason; Kretzer, Schienbein; Melnikov, Mitov

g and light $q(\bar{q})$
collinear emission
from initial or final state



(a) direct γ
parton a in p

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

(b) resolved γ

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

(c) final state

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

Kniehl, Kramer, Schienbein, HS, EPJC41(2005)199

Subprocesses for photoproduction

- direct photon:
  - dominated by $\gamma + g \to c + \bar{c}$ (LO)
  - at NLO: 1-loop diagrams,
    gluon bremsstrahlung $\gamma + g \to c + \bar{c} + g$
  - also $\gamma + q \to c + \bar{c} + q$ and
  - charm-initiated: $\gamma + c \to g + c$
- resolved photon:
  - gluons, light quarks, and charm in the proton p
  - gluons, light quarks, and charm in the photon γ
- every parton can fragment to the heavy meson:

  fragmentation functions for $c \to D^*$, $g \to D^*$, $q \to D^*$

Applications available for

- $\gamma + \gamma \to D^{*\pm} + X$
  direct and resolved contributions — EPJC22, EPJC28
- $\gamma^* + p \to D^{*\pm} + X$
  photoproduction — EPJC38
  this talk: 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
  talk by B. A. Kniehl: 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

Exemplify results for

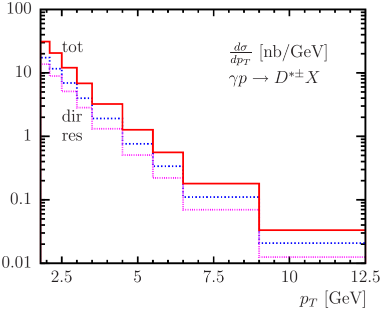
- p_T, η distributions
- photoproduction: $Q^2 \leq 2$ GeV^2
  1.5 GeV $\leq p_T \leq 12.5$ GeV, $|\eta| \leq 1.5$, 100 GeV $\leq W_{\gamma p} \leq 285$ GeV

➜ 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, $|\eta| < 1.5$, $0.02 < y < 0.85$

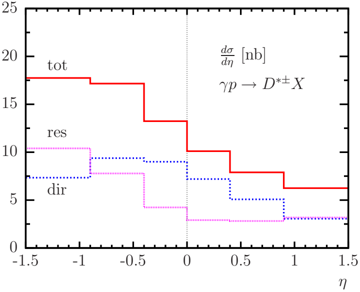
➜ compare with ZEUS data: PLB649

- 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

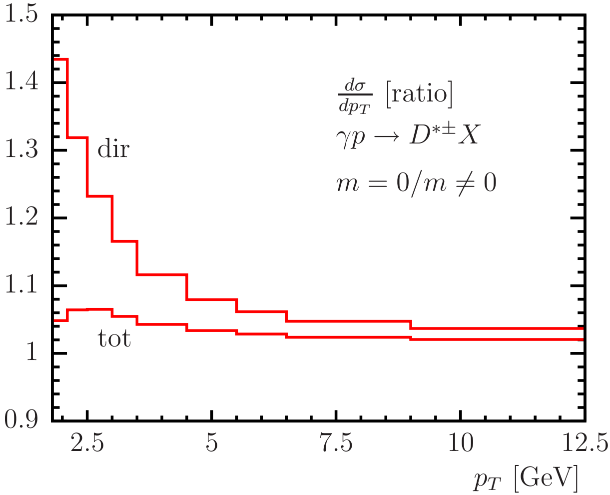


direct and resolved contributions:
p_T distribution

resolved part dominated by charm PDF

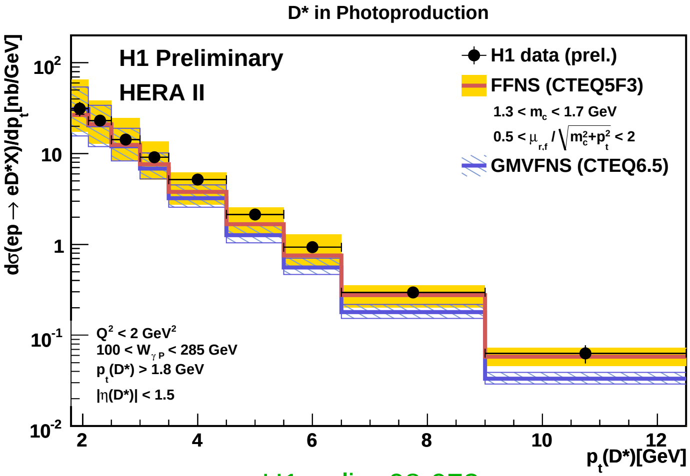


direct and resolved contributions:
η distribution

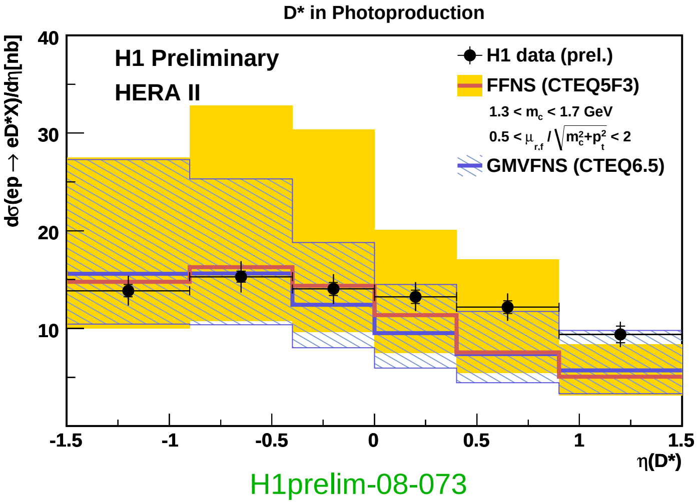


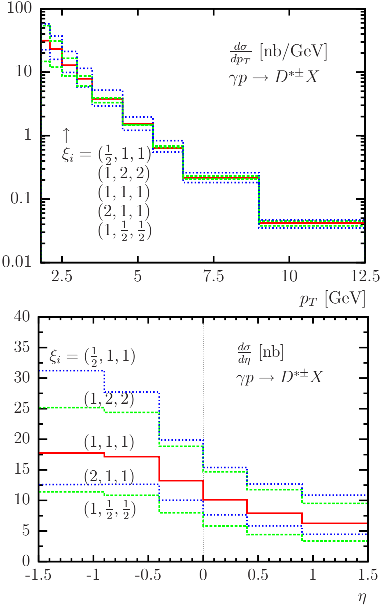
ratio of cross sections:
$\sigma(m = 0)/\sigma(m \neq 0)$

mass effects
suppressed in σ_{tot}



H1prelim-08-073


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)
dσ(ep → eD*X)/dη[nb]
η(D*)
40
30
20
10
-1.5
-1
-0.5
0
0.5
1
1.5
H1prelim-08-073



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

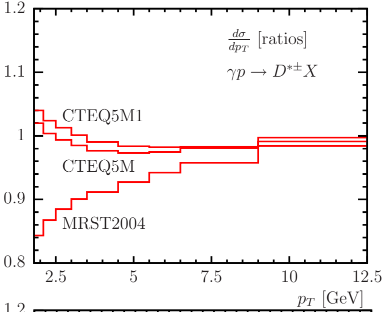
renormalization scale: R
factorization scales:
F: initial state (PDF)
F': final state (FF)

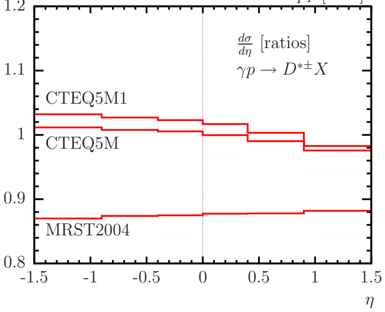
variation by factor 2 up/down:

$+84/-53\,\%$ 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

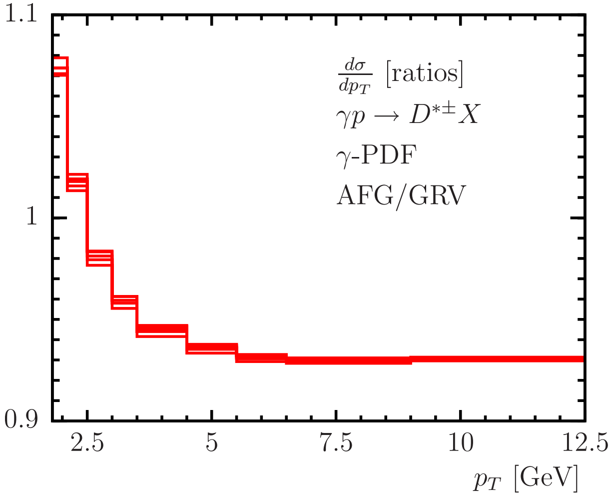




ratio of cross sections normalized to CTEQ6.5

largest influence from varying PDF input at small p_T

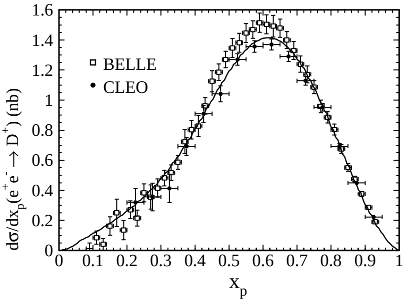
but small compared to scale uncertainty

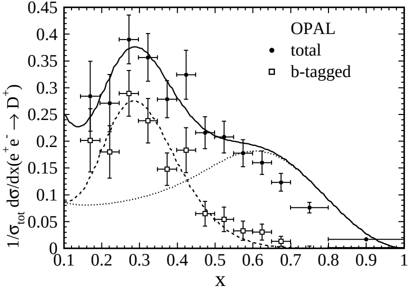


ratio of cross sections

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

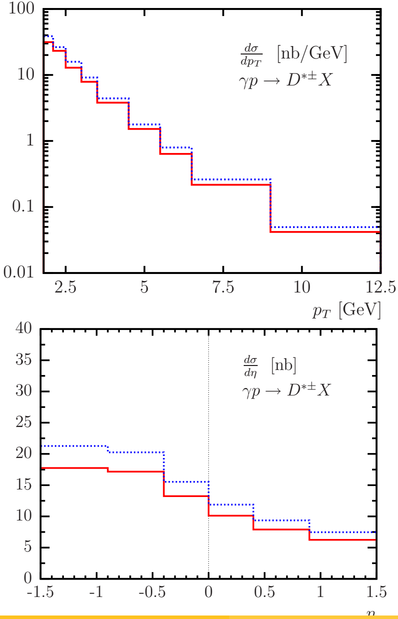
2008 analysis based on GM-VFNS
$\mu_0 = m$

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

BELLE/CLEO fit

KKKS: Kneesch, Kramer, Kniehl, Schienbein, NPB799 (2008)

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

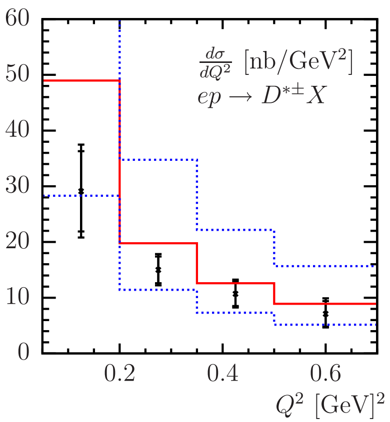


uncertainties from
$c \longrightarrow D^*$ FF:

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

BELLE/CLEO fit

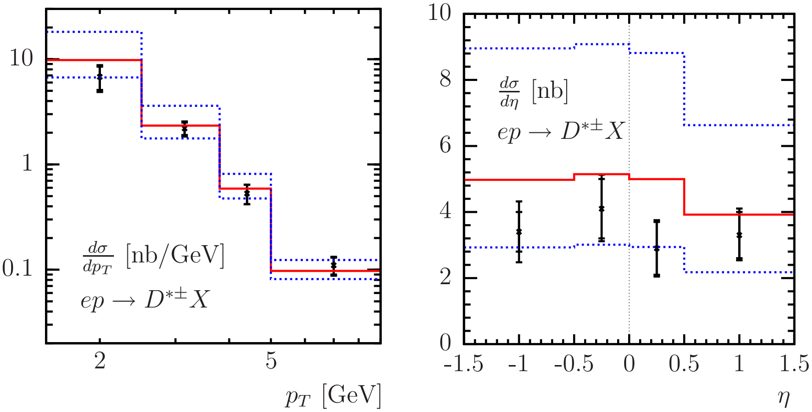
Kneesch, Kramer, Kniehl,
Schienbein, NPB799 (2008)



$0.05 < Q^2 < 0.7$ 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

Summary

- The General-Mass Variable-Flavor-Number Scheme:
  a theoretical framework for one-particle inclusive heavy quark production

  resummed large logarithms in universal PDFs and FFs

  mass terms fully kept at $O(\alpha_s)$

- Numerical results for D^* meson production in photoproduction and low-Q^2 *ep* scattering at HERA

  more results available for $\gamma\gamma$, $p\bar{p}$, pp collisions, also B-meson production,

  more to come: DIS

see the talk by B. A. Kniehl on

Open charm hadroproduction and
the charm content of the proton

(this session, 17:15)