D^* Mesons in Photoproduction at HERA

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

- Theoretical framework: heavy quark production
  the General-Mass Variable-Flavor-Number Scheme
  for 1-particle inclusive heavy-meson production
  cf. talks by F. Olness, R. Thorne (structure functions)

- Numerical results for D^* meson production
  in photoproduction at HERA: $\gamma^* p \rightarrow D^* X$
  cf. talk by K. Lipka (experimental results)

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

$m = 0 \longrightarrow$

- not reliable at heavy quark threshold
- QCD prediction: DGLAP (RG) evolution resums
  large logarithms $\log(\mu/m)$
- more reliable at large μ

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 $\overline{\text{MS}}$ scheme
  $\overline{\text{MS}}$ scheme is based on a massless calculation
  Massless and massive calculations contain different singularities
  Can not use $\overline{\text{MS}}$ PDFs and FFs in a massive calculation?

...details →

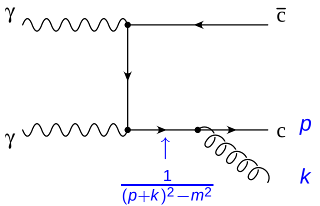
(1) massive calculation $m \neq 0$

example: gluon radiation: $\gamma\gamma \to c\bar{c}g$

$$\int \frac{d^3k}{2k_0} \frac{1}{(p+k)^2 - m^2} = \int \frac{d^3k}{2k_0} \frac{1}{2pk} \longrightarrow$$

$$\int \frac{d\cos\theta}{E - p\cos\theta} = \frac{1}{p} \log\left(\frac{E+p}{E-p}\right) \to \frac{1}{p} \log\left(\frac{E^2}{m^2}\right)$$

using $E = \sqrt{p^2 + m^2} \simeq p + \frac{m^2}{2E}$



NLO corrections contain logarithms $\sim \log \frac{p_T^2}{m^2}$
($\to$ mass singularities, collinear log; associated with initial or final state partons)
Numerically well-defined, but potentially large

(2) calculation with $m = 0$

dimensional regularization ($D = 4 - 2\epsilon$)
$\log(m^2)$-terms correspond to $\frac{1}{\epsilon}$-poles
in dim.reg: coupling $g^2 \to g^2\mu^{2\epsilon}$ and phase space contains $S^{-\epsilon} \to$ terms

$$\frac{1}{\epsilon}\mu^{2\epsilon}S^{-\epsilon} = \frac{1}{\epsilon}\exp\left(\epsilon\left(\ln\mu^2 - \ln S\right)\right) \to \frac{1}{\epsilon}\left(1 + \epsilon\log\frac{\mu^2}{S}\right)$$

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- 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)

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

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: $\mathcal{O}((m_h/p_T)^p)$ if m_h neglected in $d\sigma$

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 $m \neq 0$
- Fragmentation functions, e.g. for $c \rightarrow D^*$: $D_c^{D^*}(z, \mu_{F'}^2)$ with non-perturbative input and perturbative RG evolution

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- technically involved:
  - calculation with $m \neq 0$
  - mass factorization with massive regularization

\+ large collinear logarithms $\ln \frac{\mu^2}{m^2}$ resummed in evolved $f_c(x, \mu^2)$ and $D_c^{D^\star}(x, \mu^2)$

\+ $(\frac{m}{p_T})^n$ included

$\Rightarrow$ good for smaller p_T: $0 < p_T^2 \lesssim m^2$ and $p_T^2 \gg m^2$

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., ...)

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

$\Rightarrow$ Subtraction terms

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

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

  $\Rightarrow$ 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

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- Treat contributions with <u>charm in the initial state</u> 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:

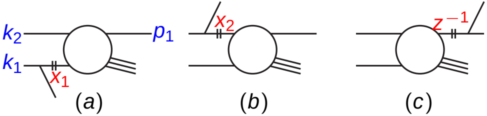
$$d^{(1)}_{g\to Q}(z,\mu^2) = \frac{\alpha_s(\mu)}{2\pi} P^{(0)}_{g\to q}(z) \ln\frac{\mu^2}{m^2}$$

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

- Other partonic distribution functions are zero to this order in 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

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

(b) resolved γ

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

(c) final state

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

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

Subprocesses for photoproduction

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

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

	Light partons	Heavy quark initiated ($m = 0$)	Mass effects: $m \neq 0$
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

[1] Aversa, Chiappetta, Greco, Guillet, NPB327(1989)105

Applications available for

- $\gamma + \gamma \to D^{*\pm} + X$
  direct and resolved contributios
- $\gamma^* + p \to D^{*\pm} + X$
  photoproduction, this talk
- $p + \bar{p} \to (D^0, D^{*\pm}, D^\pm, D_s^\pm, \Lambda_c^\pm) + X$
  good description of Tevatron data
- $p + \bar{p} \to B + X$
  works for Tevatron data at large p_T
- work in progress for $e + p \to D + X$

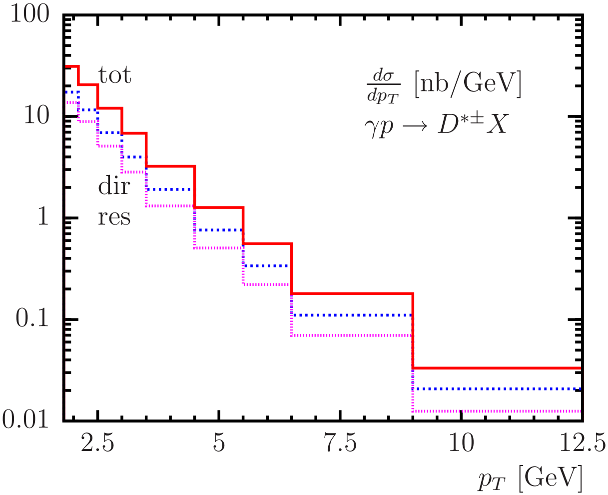
NUMERICAL RESULTS

Exemplify results for

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

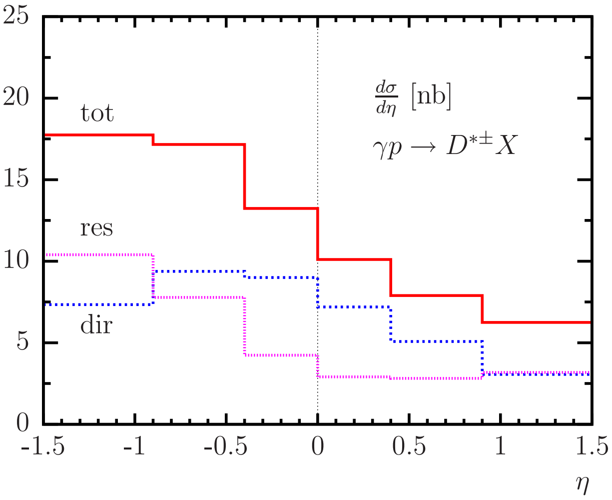
$\rightarrow$ compare with H1 preliminary data

- 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

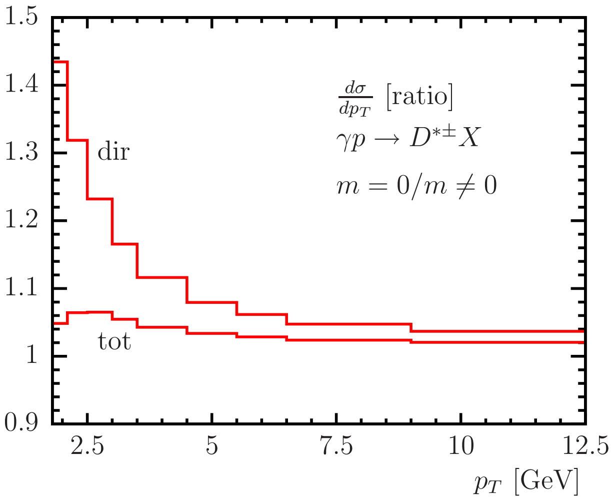


direct and resolved contributions:
p_T distribution

resolved part dominated by charm PDF

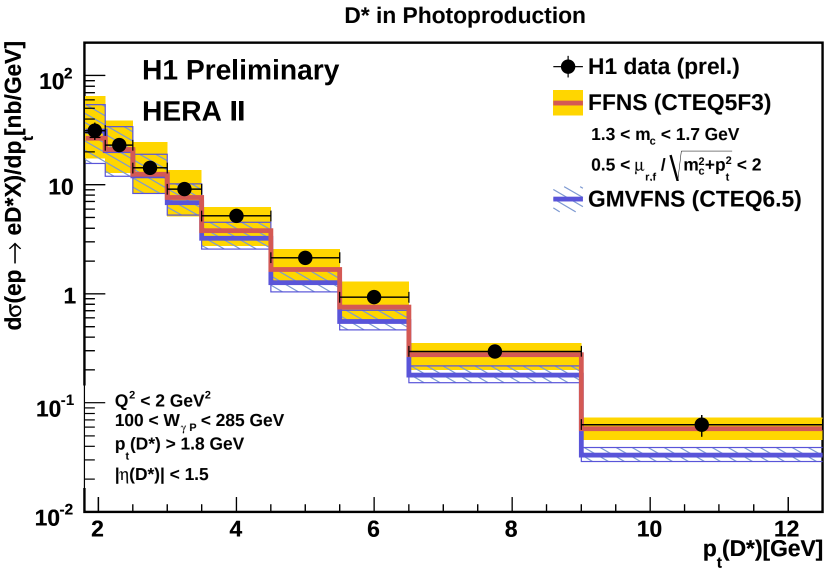


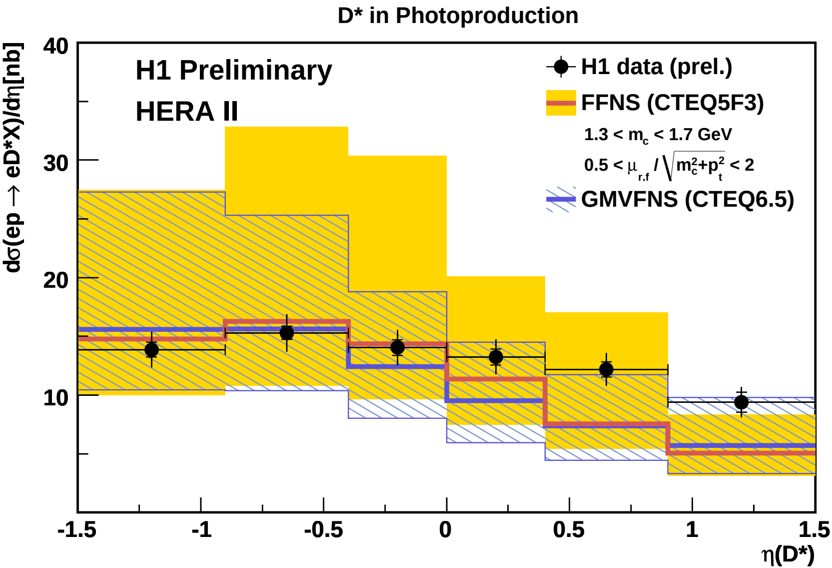
direct and resolved contributions:
η distribution



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]
10²
10
1
10⁻¹
10⁻²
2
4
6
8
10
12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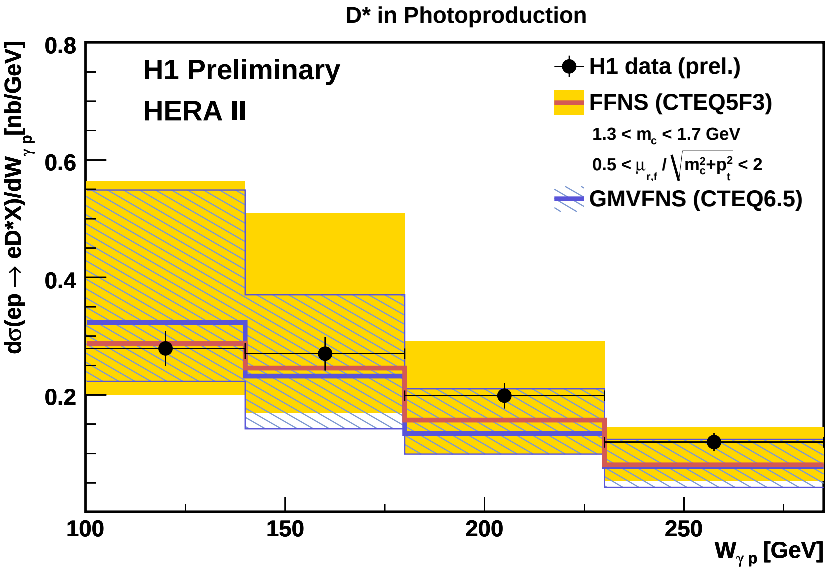
FFNS (CTEQ5F3)
1.3 < m_c < 1.7 GeV
0.5 < μ_r,f / √(m_c²+p_t²) < 2
GMVFNS (CTEQ6.5)
dσ(ep → eD*X)/dη[nb]
η(D*)
40
30
20
10
-1.5
-1
-0.5
0
0.5
1
1.5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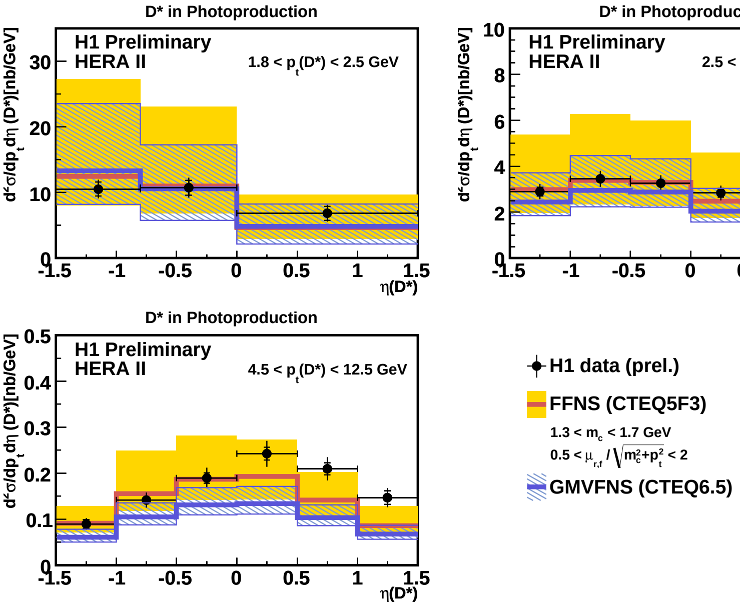
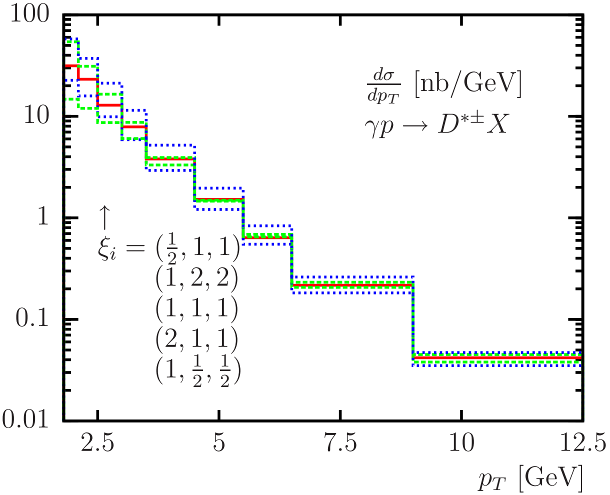
H1 data (prel.)
FFNS (CTEQ5F3)
1.3 < m_c < 1.7 GeV
0.5 < μ_r,f / √(m_c^2+p_t^2) < 2
GMVFNS (CTEQ6.5)
dσ(ep → eD*X)/dW_γp [nb/GeV]
W_γp [GeV]
0.8
0.6
0.4
0.2
100
150
200
250



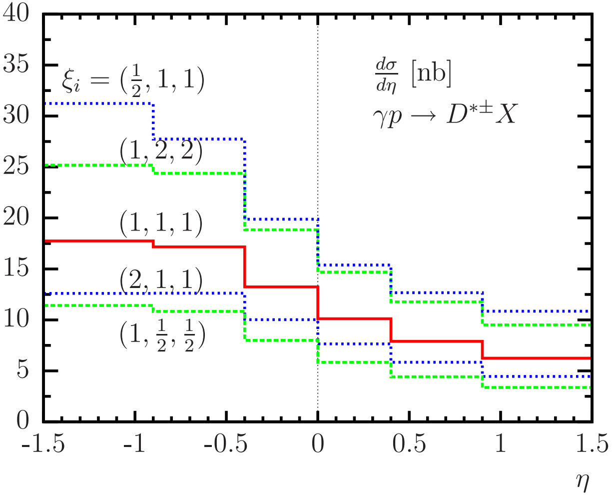
D* in Photoproduction
H1 Preliminary
HERA II
1.8 < p_t(D*) < 2.5 GeV
d²σ/dp_t dη (D*)[nb/GeV]
η(D*)
D* in Photoproduction
H1 Preliminary
HERA II
2.5 < p_t(D*) < 4.5 GeV
D* in Photoproduction
H1 Preliminary
HERA II
4.5 < p_t(D*) < 12.5 GeV
H1 data (prel.)
FFNS (CTEQ5F3)
1.3 < m_c < 1.7 GeV
0.5 < μ_r,f / √(m_c²+p_t²) < 2
GMVFNS (CTEQ6.5)



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

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

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

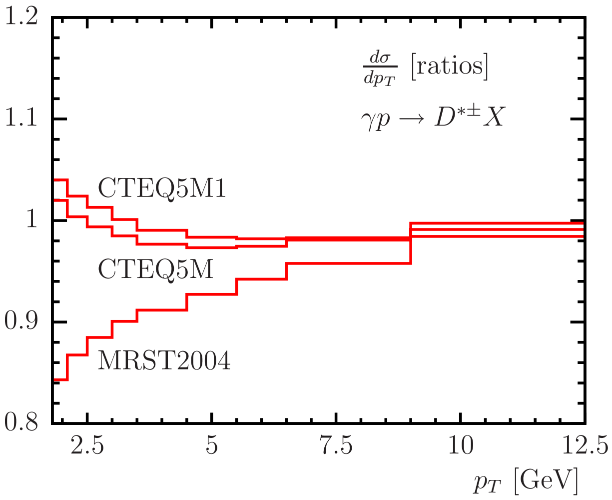


scale dependence: rapidity distribution

Large scale uncertainties at small p_T $\rightarrow$
need further improvements:

- matching of $3 \leftrightarrow 4$ flavor schemes
- threshold behaviour of charm-initiated subprocesses

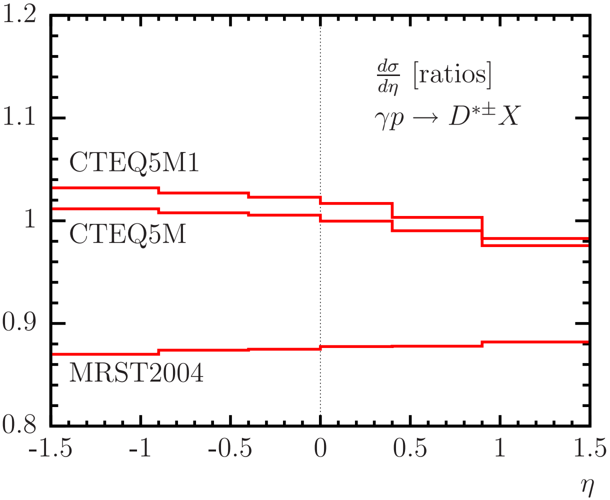
... work in progress



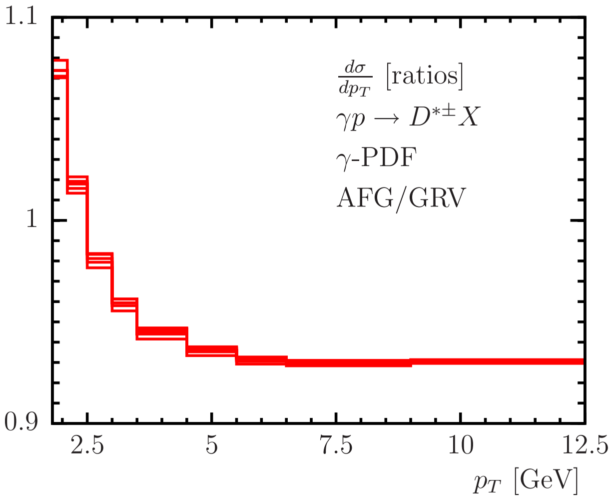
ratio of cross sections normalized to CTEQ6.5

largest influence from varying PDF input at small p_T

but small compared to scale uncertainty



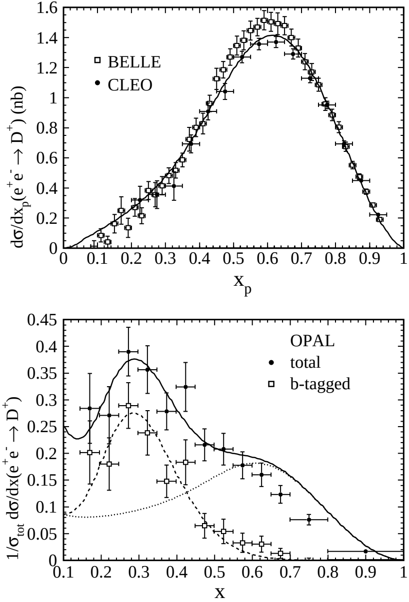
PDF input:
rapidity distribution



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

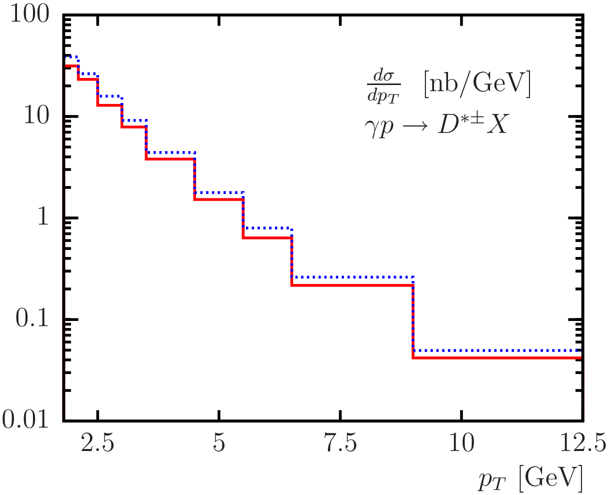
2008 analysis based on GM-VFNS
$\mu_0 = m$

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

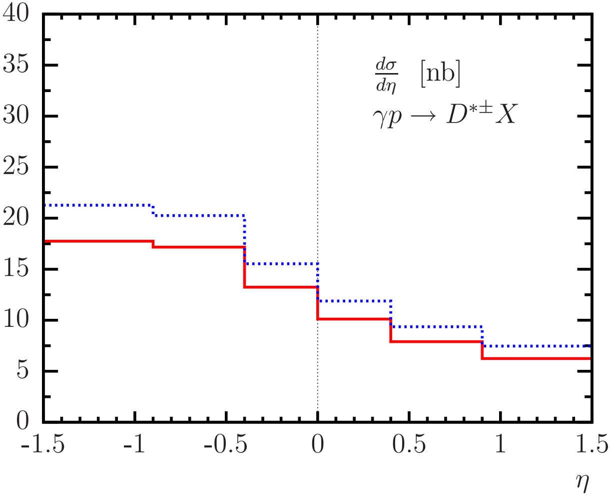


uncertainties from
$c \to D^*$ FF:

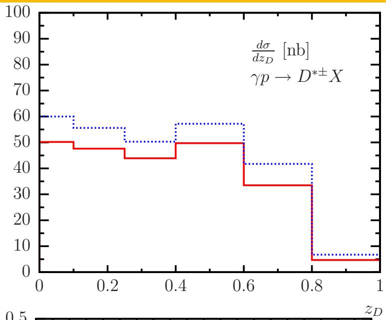
global fit: data from
ALEPH, OPAL, BELLE, CLEO

BELLE/CLEO fit

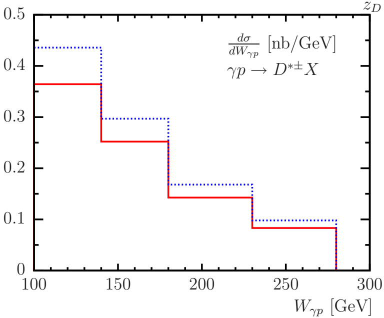
Kneesch, Kramer, Kniehl,
Schienbein, NPB799 (2008)



FF input:
rapidity distribution



inelasticity
$z_D = E(D^*)/E(\gamma^*)$
(in p rest frame)



$\gamma^* p$ cms energy: $W_{\gamma p}$

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 at HERA

  more results available for $\gamma\gamma$, $p\bar{p}$, pp collisions, more to come: DIS