Heavy Flavor Physics at HERA II
Theorical aspects of production

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1. **Motivation**
2. **Heavy quark mass**
3. **Electroproduction of heavy quarks**
4. **Photoproduction of heavy quarks**
5. **Production of onia**
6. **Various**
7. **Conclusions**

Motivation

We know a lot about the heavy quarks c, b, t *an sich* (for the top quark we should do some more verifying)

- that they "exist", and what their masses are
- their spins
- what their charges are under $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$

So we use them now as tools. As such, they are good

- theoretically: since $m > \Lambda_{\mathrm{QCD}}$ they interact mostly perturbatively
- experimentally: they can be "seen" individually.

For electroweak physics, this allows scrutiny of the SM family structure (CKM matrix, $\not{C}$P,...), helps in searching for the Higgs and in determining Yukawa couplings. They are indispensable in searching for BSM physics.

Here we'll concentrate on their importance for...

QCD

Why are we so interested in this theory?

- well-established foundations are simple and elegant
- phrased in terms of confined quanta
- many symmetries (broken, hidden)
- only true (i.e. unbroken) Yang-Mills theory in Nature
- origin of most of the Universe's visible mass
- . . .

Refining our understanding how QCD **works** is, then, a wonderful ambition to have. From precise understanding of its basic interactions, to collective behavior of its quanta, we still have much to learn.

With the upgraded HERA machine and detectors, we will have a unique opportunity to pursue this ambition, using heavy quark observables, in particular their differential production cross sections, as tools.

I will discuss various heavy flavor production models, their theoretical status, and what the post-upgrade data can teach us about them.

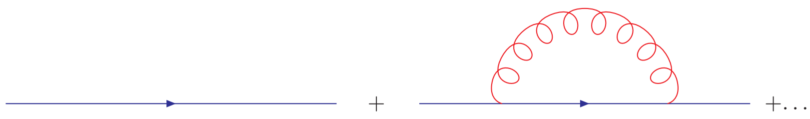
I will concentrate issues relevant to H1 and ZEUS. Nor will I discuss heavy quark production in diffractive cross sections.

Heavy quark mass

The dominant uncertainty of heavy quark production cross sections is often due to the mass. The mass of an unobservable particle requires careful definition, of where there are a variety:

Pole mass M

Higher order corrections to propagating heavy quark:



Summing all self-energy graphs gives full propagator

$$D(p) = \frac{Z}{\not{p} - m - \not{\Sigma}(p)}$$

Pole mass M:

$$M - m - \not{\Sigma}(M) = 0$$

Definition is ok at any finite order (Tarrach '81; Kronfeld '98).

No strong interaction scattering amplitude for actual particles has a pole at the mass of a heavy flavour, due to confinement.

$\Rightarrow$ a pole mass definition has intrinsic ambiguity $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ Smith, Willenbrock '96. Same conclusion from infrared-renormalon analysis

Bigi, Shifman, Uraltsev, Vainshtein '94; Beneke, Braun '94; Smith, Willenbrock '96

$\overline{\mathrm{MS}}$ mass $\bar{m}(\mu)$

View m_{bare}-parameter in QCD Lagrangian ($m_{\mathrm{bare}}\bar{\psi}\psi$) as coupling for two-particle interaction. Renormalize this coupling by only subtracting UV poles $1/\epsilon - \gamma_E + \ln 4\pi$ in higher orders: $m_{\mathrm{bare}} \to \bar{m}(\mu)$.

- it runs, just like $\alpha_s(\mu)$
- no infrared effects $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ involved (hence "short-distance mass")
- $\to$ theoretically "better"

Both definitions in perturbation theory, so can express one in other, now to NNNLO (Cray, Broadhurst, Grafe, Schilcher '90 (NNLO); Chetyrkin, Steinhauser'99,'00; Melnikov, van Ritbergen '00)

$$\begin{aligned}\frac{\bar{m}(\bar{m})}{M} &= 1 + 1.333\left(\frac{\alpha_s(M)}{\pi}\right) \\ &+ (13.44 - 1.041 n_l)\left(\frac{\alpha_s(M)}{\pi}\right)^2 + \ldots + \mathcal{O}(\Lambda_{\mathrm{QCD}})\end{aligned}$$

Other definitions: potential subtracted mass $m_{PS}(\mu_f)$ Beneke '98, $1S$ mass Hoang, Ligeti, Manohar '99.

Some recent results (GeV):

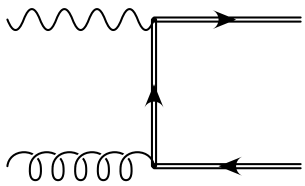
M(c)	$\bar{m}(\bar{m})$	remark
1.87± 0.19	1.53± 0.13	onium Pineda, Yndurain '98
1.33 - 1.40		R(s) Martin, Ryskin, Outhwaite '00
1.7± 0.13	1.23± 0.09	onium Eidemüller, Jamin
M(b)	$\bar{m}(\bar{m})$	
4.97± 0.17	4.26± 0.12	sum rules Beneke, Signer, Smirnov '99
M(t)	$\bar{m}(\bar{m})$	
174.3± 5.1	165± 5	production CDF, D0 '99

There is still considerable uncertainty in the charm mass value. A mass determination at HERA Verkerke '98 (thesis) would be interesting..

In the following, we will implicitly use the pole mass definition.

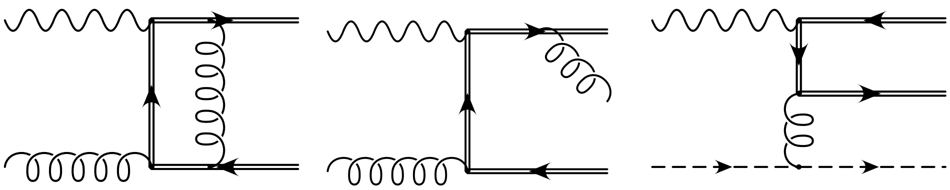
Open heavy quark electroproduction

The HERA data and analyses so far have clearly established the basic (LO) production mechanism: boson-gluon fusion.



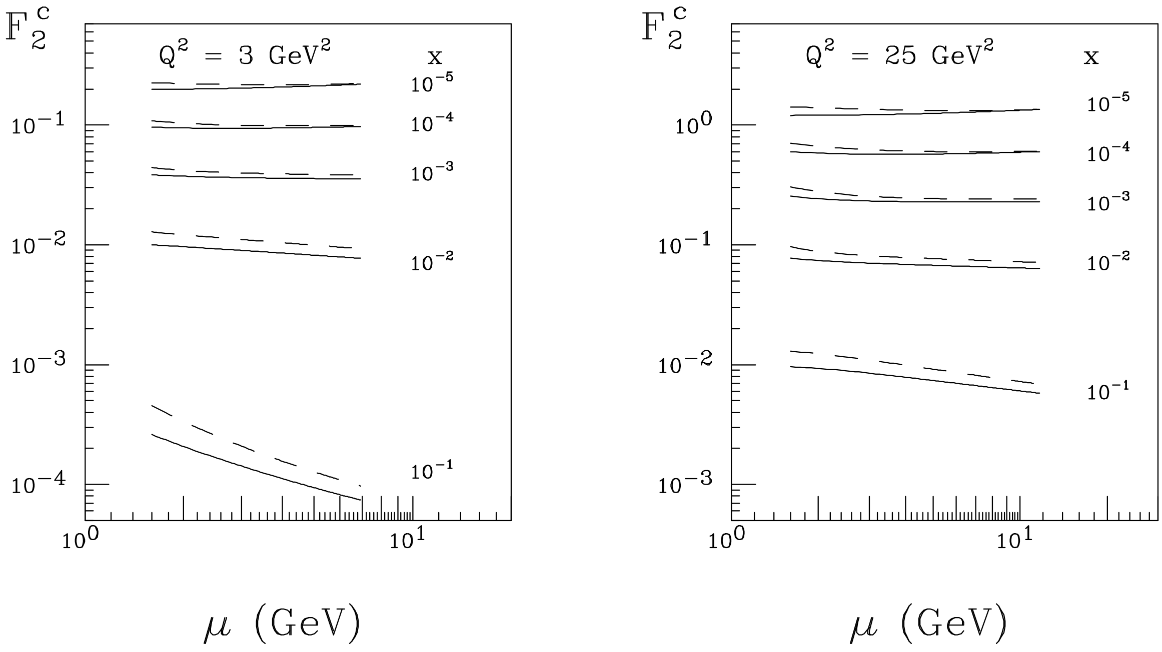
(b)

At NLO one includes radiative and loop graphs, taking care of UV, IR and COL divergences in the standard way.

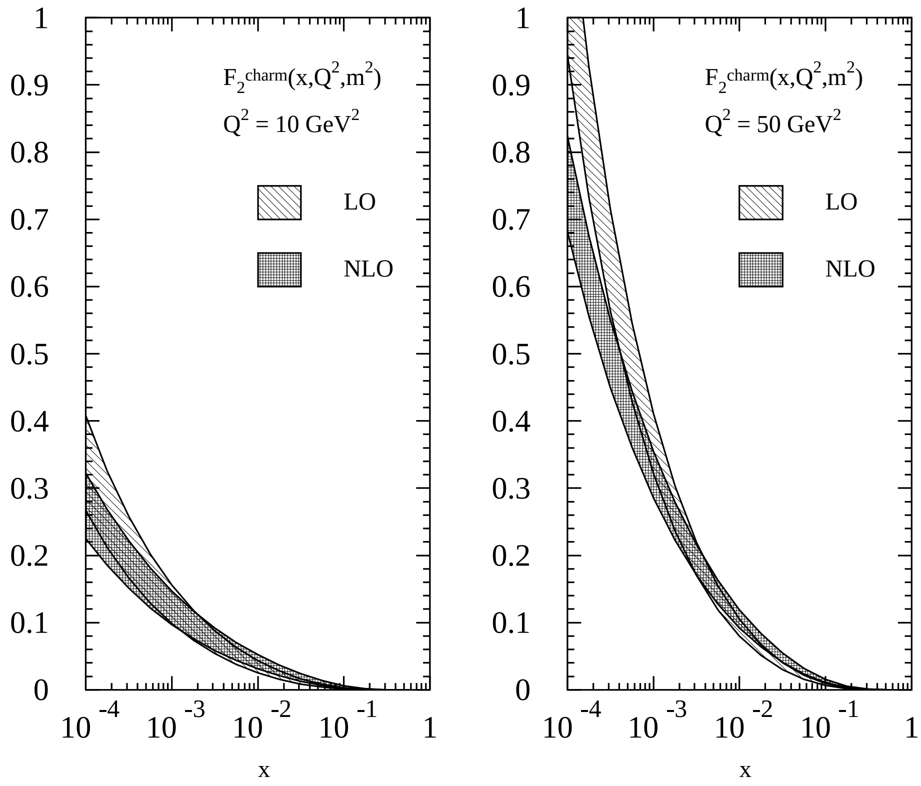


(b) (c) (d)

Initially the QCD corrections to the inclusive and single-particle differential distributions were computed E.L., Riemersma, Smith, v. Neerven '93.

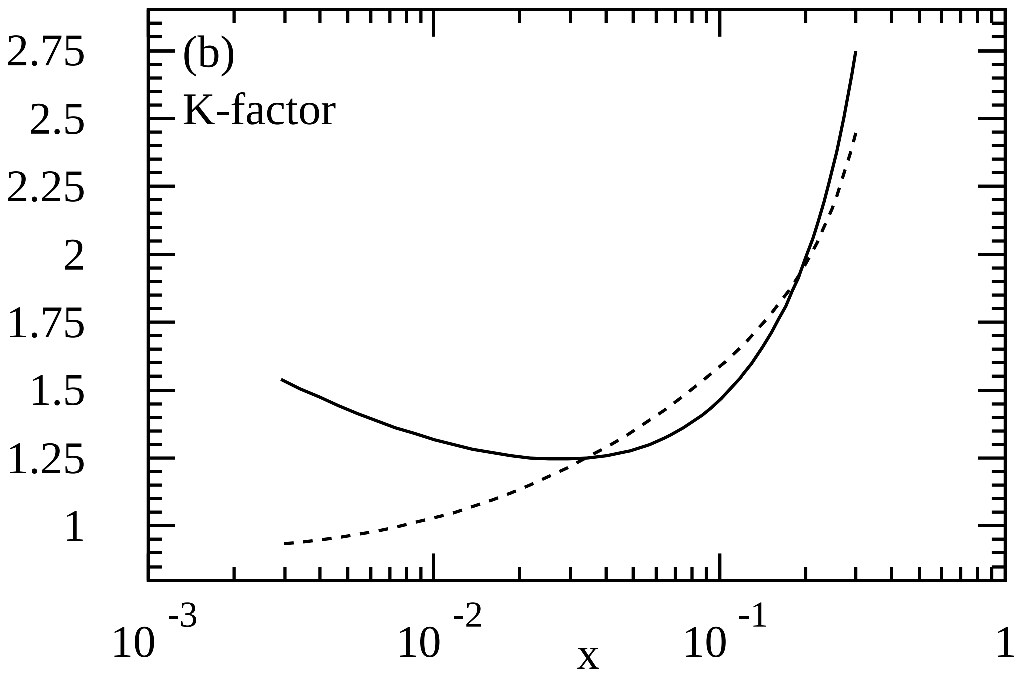


Hardly any scale dependence, especially at smaller x: $\alpha_s(\mu)$ and $g(x,\mu)$ anticorrelated. The dominant uncertainty is due to the charm mass (here 1.3-1.7 GeV)



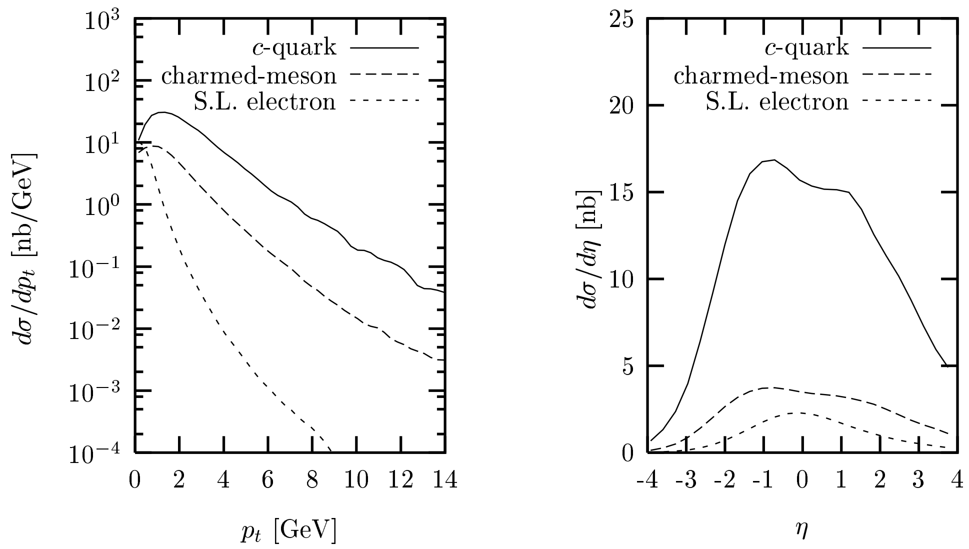
At $x \gtrsim 0.01$ threshold logarithms start to become dominant in higher order corrections. There are analytic results for the threshold-resummed double differential structure functions, and numerical ones for their NNLO expansions E.L., Moch '98.

For $x \simeq 0.1$ corrections sizable



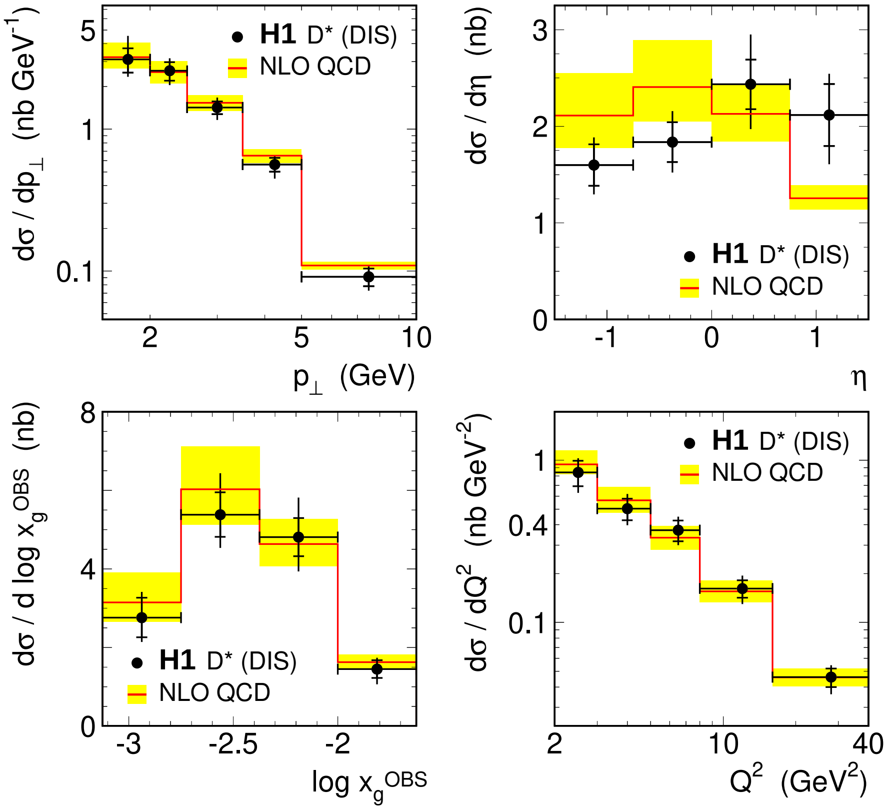
Further work in progress Eynck, E.L., Moch.

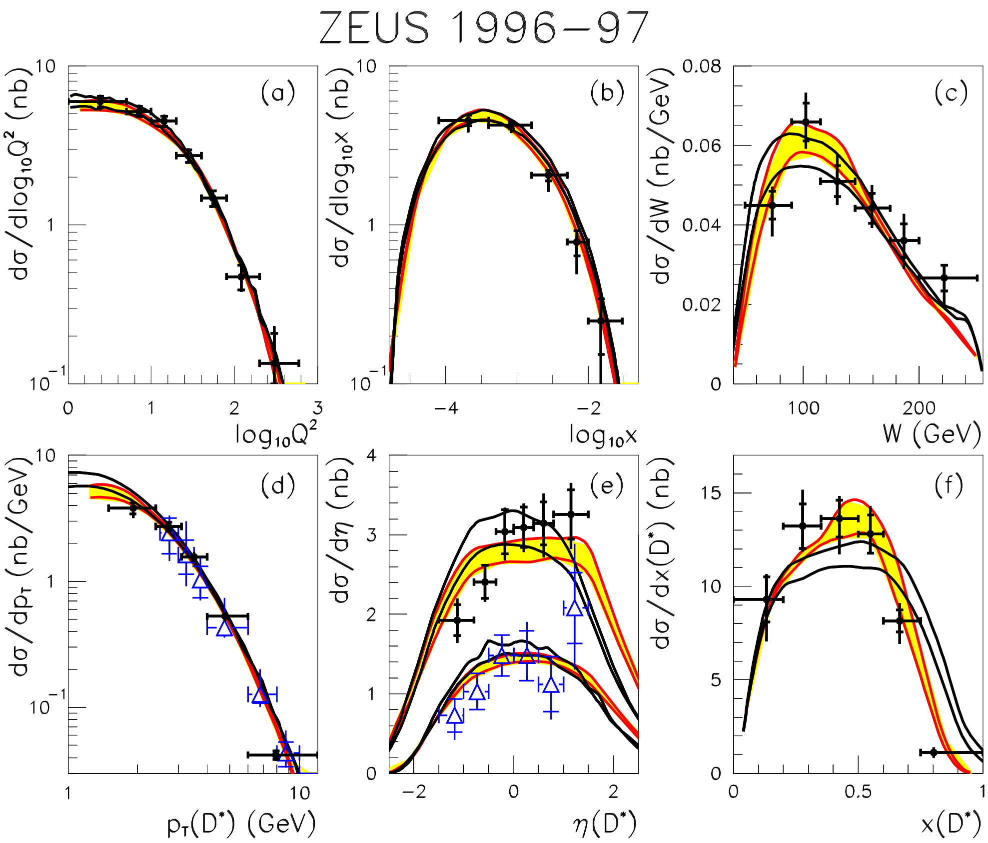
Then, using the same graphs, the fully differential corrections were computed Harris, Smith '95 $\longrightarrow$ HVQDIS NLO Monte Carlo, can compute more differential cross sections, including fragmentation:



Succesful comparison with data so far $\longrightarrow$

At large $\eta(D^*)$ data show some excess. It will be important to clearly establish the robustness of this.


H1 D* (DIS)
NLO QCD
dσ / dp⊥ (nb GeV⁻¹)
p⊥ (GeV)
dσ / dη (nb)
η
dσ / d log x_g^OBS (nb)
log x_g^OBS
dσ / dQ² (nb GeV⁻²)
Q² (GeV²)


ZEUS 1996−97
(a)
(b)
(c)
(d)
(e)
(f)
dσ/dlog₁₀Q² (nb)
log₁₀Q²
dσ/dlog₁₀x (nb)
log₁₀x
dσ/dW (nb/GeV)
W (GeV)
dσ/dp_T (nb/GeV)
p_T(D*) (GeV)
dσ/dη (nb)
η(D*)
dσ/dx(D*) (nb)
x(D*)

All these calculations use a fixed number of light flavours (3 in case of charm), independent of Q. This is a fully consistent scheme. Many other models (VFNS, CCFM, etc) resum classes of logarithms. To seriously test whether NLO is insufficient for certain regions of these cross sections (and thus know which logs are large)

- use NLO precisely (don't fudge with transverse momenta in fragmentation, e.g.)
- rather than emphasize the agreement of another Monte Carlo, it is at least as important to carefully establish the failure of NLO

Example: variable flavor number schemes as an extension of the 3 flavor fixed order approach.

Variable Flavor Number Scheme (VFNS)

There are various flavors of VFNS.

VFNS started out as an appealing but still quite intuitive idea (Aivazis, Olness, Tung '90). Its refinement was slow at first but has accelerated in recent years, spurred by HERA data on DIS charm production.

Question: for DIS charm production, should we use a charm density, or produce charm perturbatively?

The VFNS answer: yes.

- at large Q, logs $\ln(Q/m)$ count as collinear divergences and should be resummed into a charm density
- at small Q, finite m effects are important (threshold) $\rightarrow$ no charm density
- in between, use mixture, and don't double count

The field-theoretic implementation of a VFNS confronts one with the following fundamental issues in QCD

- how does a parton density form in perturbative QCD, and how is it then used?
- how can a heavy flavor mass form thresholds, *and* act as a collinear regulator?
- do factorization theorems allow massive initial partons? Yes Collins '98

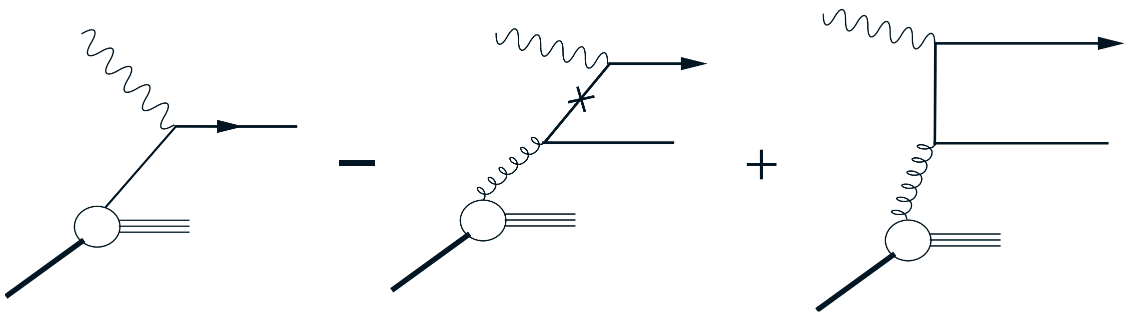
Ingredients for a VFNS

- an PDF set $\{f_i(x,\mu,n_f)\}$ and $\alpha_s(\mu,n_f)$
- a PDF set $\{f_i(x,\mu,n_f+1)\}$ and $\alpha_s(\mu,n_f+1)$, where "+1" stands for the heavy quark
- a matching scale and matching conditions for both
- a set of VFNS coefficient functions
- (a fragmentation function, or jet definition, or shape definition).

Present status; for $F_{2,L}(\mathrm{charm})$

- field theory of VFNS understood
- implemented to NNLO
- VFNS so far not necessary to describe data

First, low order, implementation, only used Aivazis, Collins, Olness, Tung '94.



All mass dependendence kept in all terms. Further work Amundson, Schmidt, Tung, Wang '00. Simplified scheme: Krämer, Olness, Soper'00.

It gets interesting from NNLO onwards. Required: matching conditions between $\{f_i(x,\mu,n_f),\alpha_s(\mu,n_f)\}$ and $\{f_i(x,\mu,n_f+1),\alpha_s(\mu,n_f+1)\}$. For α_s one has

$$
\begin{aligned}
\alpha_s(\mu,n_f+1) &= \alpha_s(\mu,n_f) + \alpha_s(\mu,n_f)^2\, c_1 \ln\left(\frac{\mu}{m}\right) \\
&+ \alpha_s(\mu,n_f)^3 \left(c_{22} \ln^2\left(\frac{\mu}{m}\right) + c_{21} \ln\left(\frac{\mu}{m}\right) \right. \\
&+ \left. c_{20} \right)
\end{aligned}
$$

(Bernreuther, Wetzel '82; Larin, van Ritbergen, Vermaseren '95; Chetyrkin, Kniehl, Steinhauser '97)

To go from n_f to n_f+1 active flavors in the PDF's, must absorb heavy quark collinear divergences, $\ln^i(\mu/m)$, present in operator matrix elements $A_{ij}(z,\mu/m)$, into $f_i(x,\mu,n_f)$

$$
\begin{aligned}
f_i(x,\mu,n_f+1) &= A_{ij}(\frac{\mu}{m}) \otimes f_j(x,\mu,n_f), \\
j &= q,\bar{q},g, \quad i = q,\bar{q},g,Q
\end{aligned}
$$

$A_{ij}(z,\mu/m)$ calculable (to two loops Buza, Matiounine, (Migneron), Smith, van Neerven ('96),'97,'98.), $f_i(n_f+1)$ are calculable from the $f_i(n_f)$!

Easiest matching scale $\mu = m$. Note: at NNLO $A_{ij}(z,1) \neq 0$!! $\rightarrow$ discontinuity (e.g. *negative* charm density at μ just a little about m $\rightarrow$ greater $f_g(4)$ due to momentum sum rule).

Construction of a VFNS (Buza, Matiounine, Smith, van Neerven '97,'98)

- Take exact $\mathcal{O}(\alpha_s^2)$ calculation (E.L., Riemersma, van Neerven, Smith '93) with a fixed (3) number of flavors

$$F_{2,L,Q}^{\mathrm{EXACT}}(x,Q^2,m^2) = \sum_{i=q,\bar{q},g} C_i^{\mathrm{FF}}(3,\frac{Q}{\mu},\frac{\mu}{m}) \otimes f_i(3,\mu)$$

  Fine for $Q \simeq m$.

- Construct

$$F_{2,L,Q}^{\mathrm{PDF}}(x,Q^2) = \sum_{i=q,\bar{q},g,Q} C_i^{\mathrm{FF}}(4,\frac{Q}{\mu}) \otimes f_i(4,\mu)$$

  with the $f_i(4,\mu)$ construct via the matching conditions. Fine for $Q \gg m$.

- To avoid double counting, construct $Q \gg m$ limit F^{EXACT}, using $A_{ij}(z,Q/m)$.

$$F_{2,L,Q}^{\mathrm{ASYMP}}(x,Q^2,m^2) = \sum_{i=q,\bar{q},g} C_i^{\mathrm{ASYMP}}(3,\frac{Q}{\mu},\frac{\mu}{m})$$

Then define

$$F_{2,L,Q}^{\mathrm{BSMN}} \equiv F_{2,L,Q}^{\mathrm{EXACT}} - F_{2,L,Q}^{\mathrm{ASYMP}} + F_{2,L,Q}^{\mathrm{PDF}}$$

which generalizes the earlier prescription.

Could this be improved upon? Could try to keep finite m/Q effects everywhere (ok to all orders Collins '98).

Implemented by Thorne, Roberts '98, with extra boundary conditions.

Chuvakin, Smith, van Neerven take sum of $F_{2,L,light}^{\mathrm{EXACT}}$ and $F_{2,L,Q}^{\mathrm{EXACT}}$.

Key points

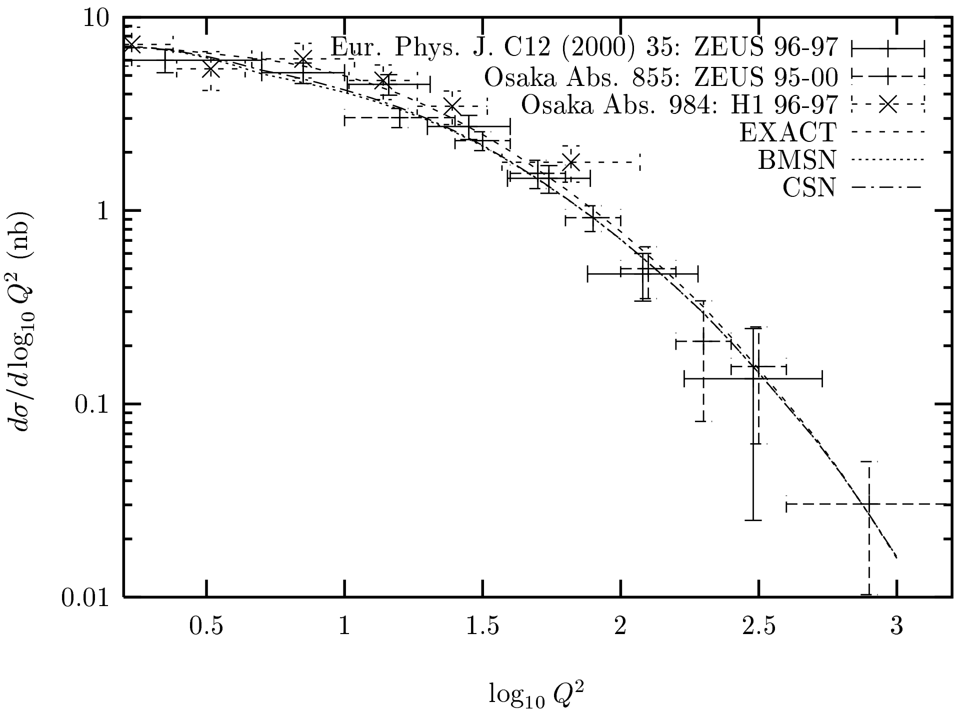
- Consider complete $F_2 = F_2^{\mathrm{heavy}} + F_2^{\mathrm{light}}$
- Move $\ln^i(\mu/m)$ from heavy flavor to light flavor terms, then $f_i(3,\mu) \to f_i(4,\mu)$
- all C_i^{VFNS} can unambigously computed and no m/Q terms dropped

CAUTION: $F_{2,L,Q}$ is not IR safe in VFNS.

- near threshold CNS = BMSN = EXACT
- far above threshold CNS = BSMN = PDF
- cancellation very delicate in practice

Can HERA data "see" the need for VFNS, i.e. that NLO is not enough? Study by Chuvakin, Harris, Smith '00:

- NLO describes data very well.
- VFNS scheme result hardly different from NLO Chuvakin, Harris, Smith '00



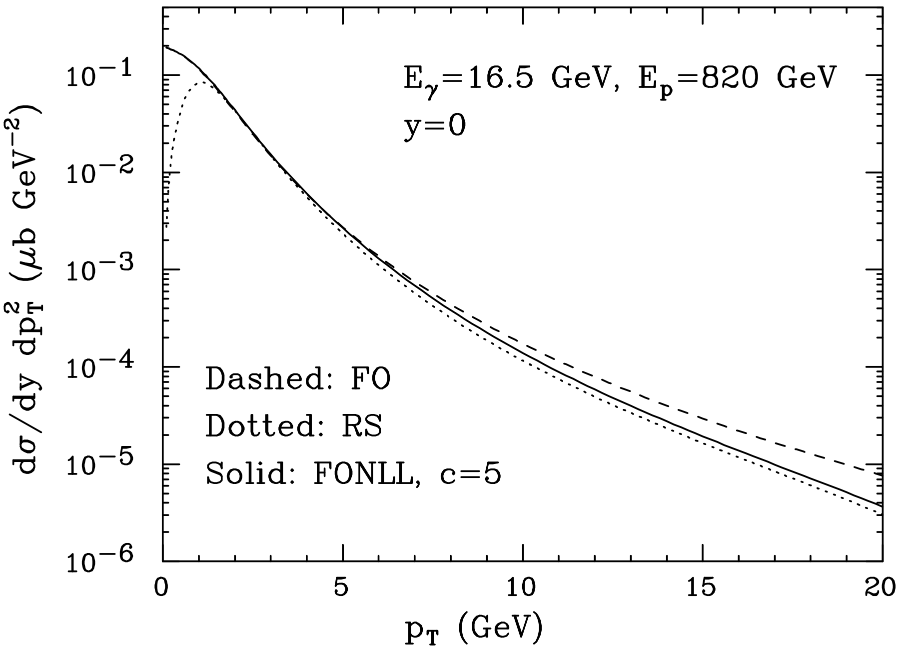
- differences at large x, large Q^2 $\rightarrow$

Open charm photoproduction

Cross section for this reaction is much larger than for electroproduction, but resolved photons contribute

A NLO MC has existed for some time Frixione, Nason, Ridolfi '94. New theoretical work Cacciari, Frixione, Nason '01 construct a VFNS, here called FONLL, for single particle differential distributions, in the sense that

- for $p_T^c \simeq m$: FONLL $\simeq$ NLO
- for $p_T^c \gg m$: FONLL $\simeq$ massless approach ($\ln(p_T/m)$ resummed)



Effect so far marginal (data: $p_T(D^*) \lesssim 10$ GeV), but might be relevant with more data.

Onia production

General aspects of onium production

At issue: the very production mechanism of these “QCD-atoms” itself. There is still a lot to learn about this. Good new review: M. Krämer ’01.

Framework: NRQCD (Non-Relativistic QCD) Bodwin, Braaten, Lepage ’95 , an effective field theory for light quarks, gluons and onia.

Key concepts:

- production ($t \sim 1/m$) and formation ($t \sim 1/mv^2$) time scales well-separated, $\to$ colored $\bar{Q}Q$ channels are open
- (assumes) “standard” factorization into hard scattering and universal non-perturbative factors
- double perturbation expansion, in α_s and v, HQ velocity in onium state (small), multiple scales: $m \gg mv, mv^2, \Lambda$ for power counting

Other models (Color Singlet Model, Color Evaporation Model), not as general, and have severe problems explaining some data

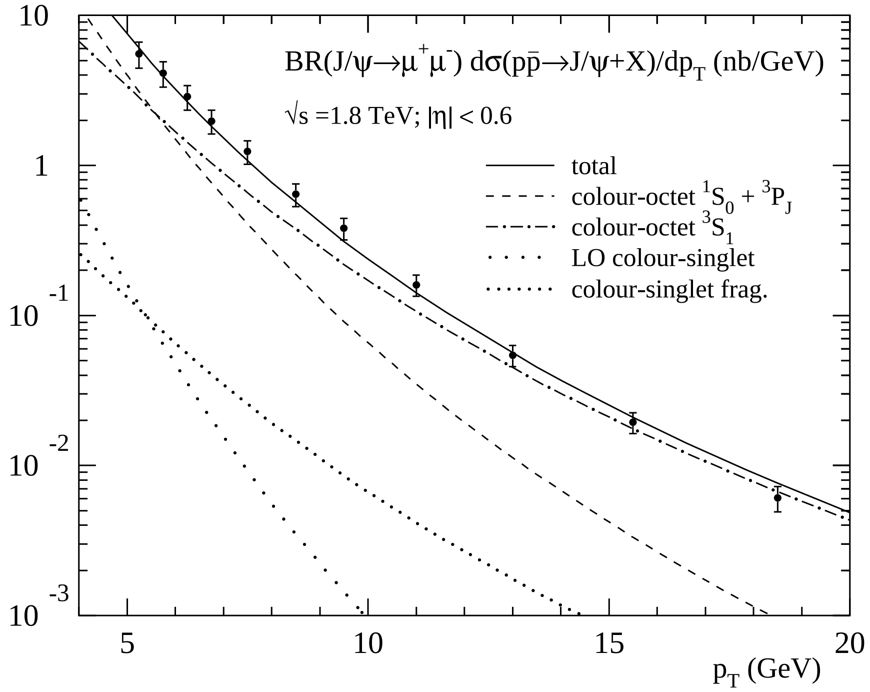
Onium leptoproduction cross section, e.g., in NRQCD:

$$d\sigma(l + p \to \psi(P,\lambda) + X) \quad = \quad \sum_i f_i \otimes \sum_n d\sigma(l + i \to Q\bar{Q}[n] + X)\langle O_n^{\psi(\lambda)}\rangle$$

Sum over all allowed states, labeled by ${}^{2S+1}L_J$ and by color $(\underline{1}, \underline{8}, \ldots)$ Onium binding encoded in process-independent, non-perturbative $\langle O[\underline{n}, {}^{2S+1}L_J]\rangle$, ordered in powers of α_s and v.

Two strong arguments for NRQCD:

- gigantic discrepancy between onia p_T spectra at the Tevatron, and the prediction of the CS model, can be accommodated by having open colored channels Braaten, Fleming '95 . [NRQCD not only framework that can get this right]



- Unlike CS model, NRQCD has no uncancelled infrared divergence in P-wave onium production and decay

How to test NRQCD further?

▷ Determine size of $\langle O^H[\underline{n},{}^{2S+1}L_J]\rangle$ in other reactions. But sizable sensitivity to

- higher orders, low p_T physics
- initial state radiation Cano-Coloma, Sanchis-Lozano '97; Kniehl, Kramer, '99).

▷ $J/\psi, \psi'$ polarization at the Tevatron at large p_T Cho, Wise '94; Beneke, Krämer, '97. Dominant process: fragmentation of gluon (octet) at large p_T into ${}^3S_1^{(8)}$ $c\bar{c}$ state. Standard NRQCD power counting: binding then does not flip spin.

Angular behavior of onium $\rightarrow$ 2 leptons

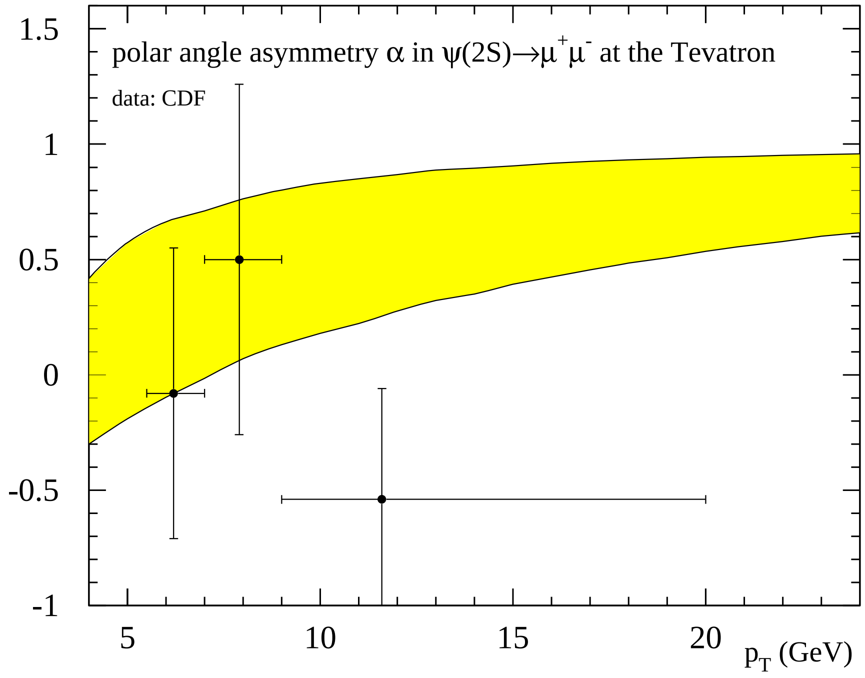
$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos^2\theta$$

with

- $\alpha = 0$: unpolarized
- $\alpha = 1$: transversely polarized
- $\alpha = -1$: longitudinally polarized

So NRQCD predicts $\alpha \rightarrow 1$ as p_T increases.

CDF measurement for direct J/ψ:



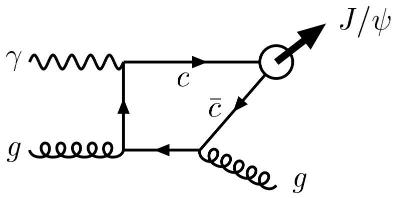
Does not look so good. . .

- matrix elements not well known enough?
- v not small for charmonia, power counting not right $\longrightarrow$ spin-flips not suppressed? Beneke '97; Fleming, Leibovich, Rothstein '00
- higher-twist?

Diagrams for inelastic photoproduction:

(a) leading-order colour-singlet:

direct γ: $\gamma + g \to c\bar{c}[^3S_1^{(1)}] + g$ resolved γ: $g_\gamma + g \to c\bar{c}[^3S_1^{(1)}] + g$



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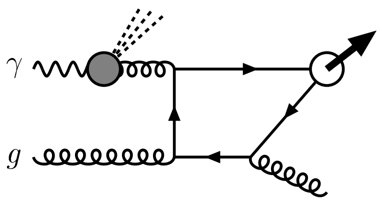

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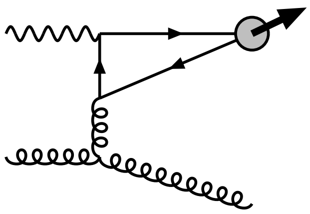
(b) inelastic colour-octet:

direct γ: $\gamma + g \to c\bar{c}[^1S_0^{(8)}, {}^3P_J^{(8)}] + g$ resolved γ: $g_\gamma + g \to c\bar{c}[^3S_1^{(8)}] + g$



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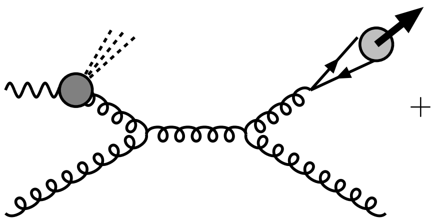
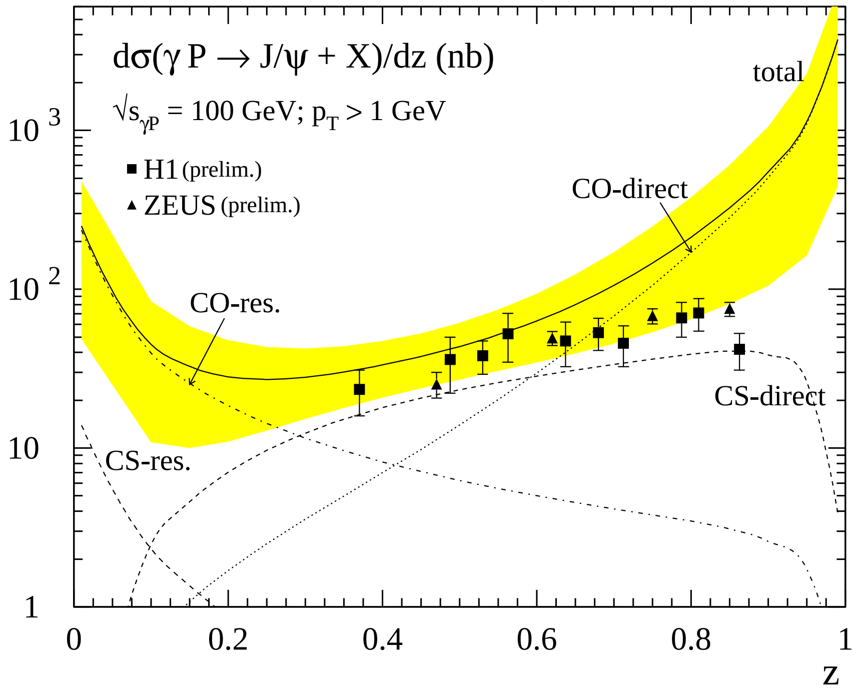


$+\ldots$

Onium production at HERA

NLO corrections Krämer '96 for colour-singlet production very important. For colour-octet only inclusive NLO known Maltoni, Mangano, Petrelli '98.

Comparison with H1 and ZEUS data: ($z = E_{J/\psi}/E_\gamma$ in proton rest frame)



Too much colour-octet at large z, but there the model is too sensitive to soft gluons Beneke, Rothstein, Wise '97; Beneke, Schuler, Wolf '00. Need harder p_T cut on J/ψ (i.e. more data) to make large z region useful. Note also sensitivity fo α_S and m_c variations.

NRQCD LO deep-inelastic production of J/ψ is cleaner than photoproduction, and has $\langle O^{J\psi}[8,^1S_0,^3P_0]\rangle$ sensitivity Baier, Rück; Körner et al '82; Fleming, Mehen '98; Yuan, Chao '00. Preliminary H1 data seem to favor not much colour-octet, but future data will be very useful.

How can the upgraded HERA collider help?

In general, many and wide distributions (in z, p_T, Q^2, ...) possible, as well as good polarization data $\rightarrow$ all weighted sums of operator matrix elements $\rightarrow$ sensitive tests. In particular

- access to resolved processes
- production of spin-singlet η_c, h_c, sensitive to colour-octets
- $J/\psi + \gamma$ production, sensitive to colour-octets
- bottomonium

The HERA upgrade, together with the Tevatron upgrade (and a continuing theory upgrade), should vastly improve our understanding of making onia in QCD.

Various

CCFM (Ciafaloni-Catani-Fiore-Marchesini)

Formalism resums small-x logarithms, while also incorporating large x DGLAP logarithms in evolution, via evolution kernel for unintegrated (k_T dependent) parton densities

$$P_{gg}(z, q^2, k_T^2) = \frac{\alpha_s(q_T^2)}{(1-z)_+} + \frac{\alpha_s(k_T^2)}{z}\Delta(z, q^2, k_T^2)$$

Implemented e.g. in CASCADE Monte Carlo Jung, Salam programs. Interestingly

- it gives sizable enhancement at large pseudorapidity
- it gives sizable enhancement to the Tevatron b-cross section

But Lönnblad DIS01 it is very sensitive to subleading effects

$$P_{gg}(z) = \frac{1}{(1-z)_+} + \frac{1}{z} - 2 + z(1-z)$$

$\rightarrow$ further theoretical development underway.

Polarized charm production

Photoproduction: NLO available Bojak, Stratmann '98; Contogouris, Merebashvili,Grispos '00

Electroproduction: LO available only (NLO in progress), threshold-resummed calculation available Eynck, Moch '00

Future photoproduction data should help determine polarized gluon density at smallish x values Frixione, Ridolfi '96

Charged current heavy quark production

Theory well-developed to $O(\alpha_s^2)$ Gottschalk; Glück, Kretzer, Reya; Kramer, Lampe, partly to $O(\alpha_s^2)$ Buza, van Neerven. Awaits new data.

Conclusions

- In electro- and photoproduction of open charm, it is possible and very worthwhile to rigorously test NLO (let it fail!)
- Electro- and photoproduction of bottom quarks is very well-behaved theoretically, and very worthwhile to rigorously test NLO (let it fail!)
- Theorists should "refine" calculations beyond (N)LO (NNLO, various resummations), use/produce PDF's with errors. . .
- Close interaction (H1, ZEUS, theorist, Tevatron,..) and careful work essential for consistent study and interpretation of post-upgrade data