Heavy flavour production at HERA

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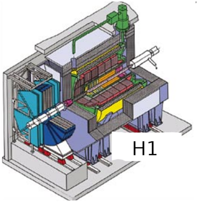
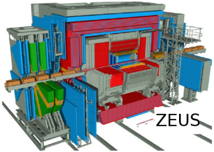
Outline

- Introduction
- Charm combination
- Charm quark mass measurement
- Beauty production and beauty quark mass measurement
- Recent charm measurements and combination of D* production results
- Summary

The HERA *ep* collisions experiments

HERA ring



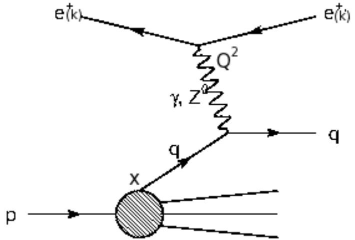


H1 and ZEUS detectors

- HERA accelerator is unique lepton-proton collider
- Was in operation 1992-2007
- $e^{\pm}$ and p were brought to collision with E_p=460-920 GeV (period dependent) and $E_e = 27.6 GeV$

- H1 and ZEUS experiments collected 0.5 fb^{-1} per experiment

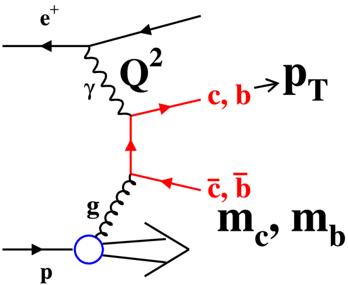
Deep Inelastic Scattering



Deep Inelastic Scattering diagram.
$Q^2 > 1 GeV^2$: DIS;

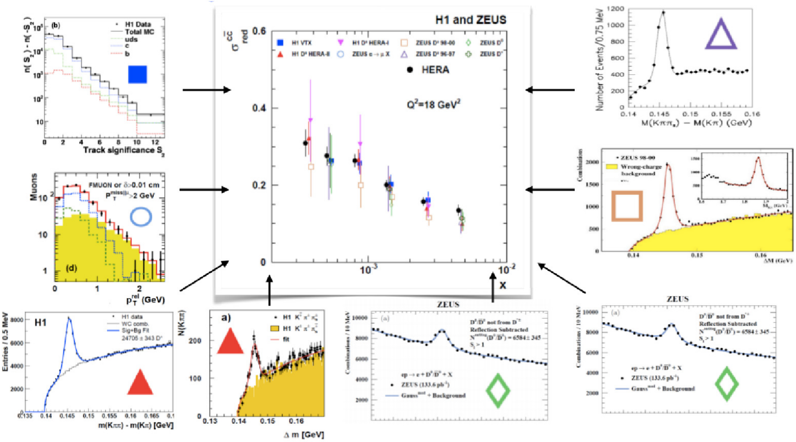
Q^2=-$(k - k')^2$ – photon virtuality,
$x = \frac{Q^2}{2P \cdot (k-k')}$ – Bjorken x
$y = \frac{P \cdot (k-k')}{P \cdot k}$ – inelasticity

Heavy quarks production in *ep* scattering



- At HERA heavy quarks mainly produced by boson-gluon fusion (sensitive to the gluon density in the proton)
- Process involves multiple hard scales (m_q,p_t,Q^2) that results in different approaches to heavy flavours in QCD
- Contribution to total DIS cross section – charm up to 30% and beauty up to 3%.

Charm tagging techniques



Reduced cross section definition

Relation between heavy quarks production cross-section and reduced cross-section is the following :

$$\frac{d\sigma^{q\bar{q}}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[1+(1-y)^2]\sigma^{q\bar{q}}_{red.}(Q^2,x)$$

The heavy quarks measurements are presented in terms of the reduced cross sections that in Neutral Current DIS can be written in term of two structure functions :

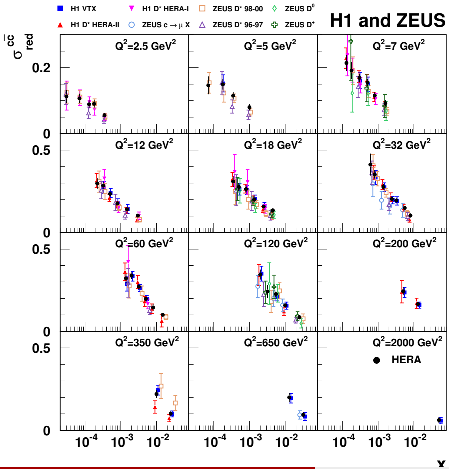
$$\sigma^{q\bar{q}}_{red} = F_2^{q\bar{q}} - \frac{y^2}{1+(1-y)^2}F_L^{q\bar{q}}$$

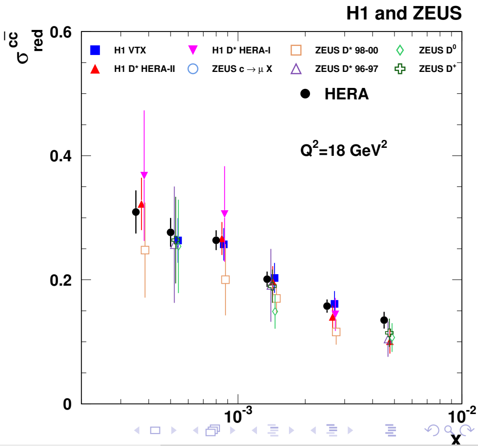
Most measurements are actually measuring visible cross sections with restricted phase space. The extrapolation to full phase space is required using theory (e.q. momentum of D* meson) :

$$\sigma^{q\bar{q}}_{red}(x,Q^2) = \sigma^{q\bar{q}}_{vis,bin}\frac{\sigma^{q\bar{q},th}_{red}(x,Q^2)}{\sigma^{q\bar{q},th}_{vis,bin}}$$

HERA Charm Data combination (Eur. Phys. J. C73 (2013) 2311)

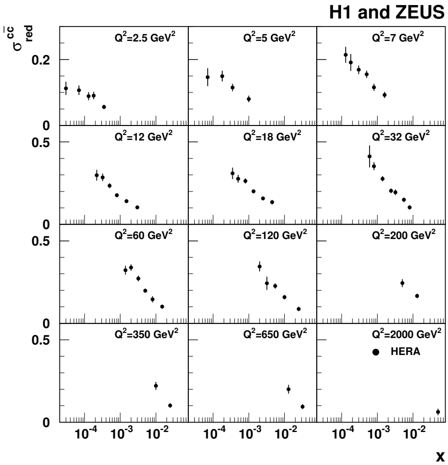
155 data points from 9 different measurements were combined to 52 points.





HERA Charm Data combination : Results

With precision about 6% at medium Q^2

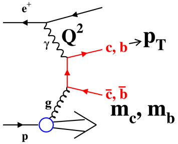


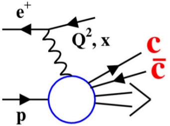
Different Heavy Quark Schemes

Heavy Quark Scheme in QCD Analysis defines treatment of heavy flavours in perturbative expansion.

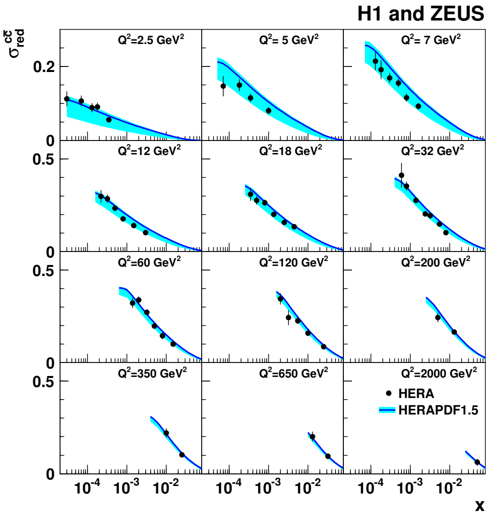
- Zero Mass Variable Flavours Number Scheme (ZMVFMS): all flavours are massless. Fails near $Q^2 = m^2_{HQ}$
- Fixed Flavour Number Scheme (FFNS) (ABM) : heavy quarks are massive, produced in processes equivalent to boson-gluon fusion.
- Generalized Mass VFNS (CTEQ, MSTW, HERAPDF) : number of active flavours depends on Q^2, matching at switching points different for different PDF groups implementations.

Heavy flavours treatment and quarks masses are crucial for QCD analysis



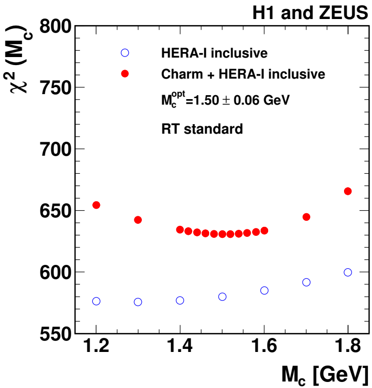


HERAPDF1.5



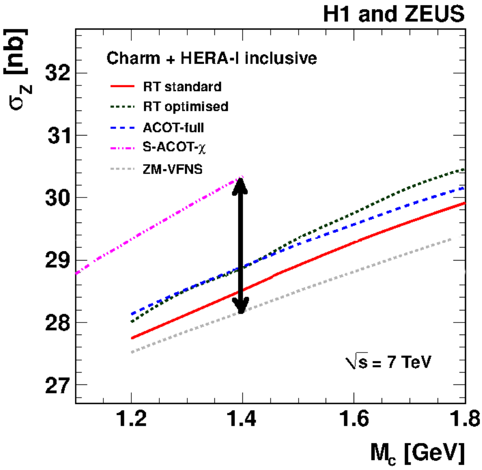
- Good agreement with data
- HERAPDF1.5 obtained with DIS inclusive data only in RT (VFNS) heavy flavour scheme
- Error band mostly corresponds to M_c variation from 1.35 to 1.6 GeV (central value 1.4 GeV) -> data may be used to determine M_c

Testing different heavy quarks schemes: m_c scan



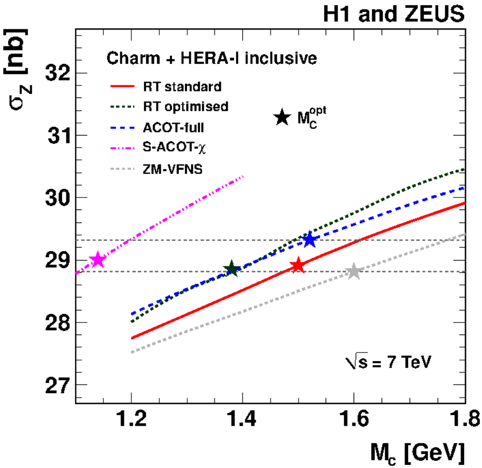
- Adding charm data to HERA inclusive data gives sensitivity to M_c parameter.
- Optimal M_c can be measured with uncertainties determined using $\triangle\chi^2$=1

Testing different heavy quarks schemes: motivation



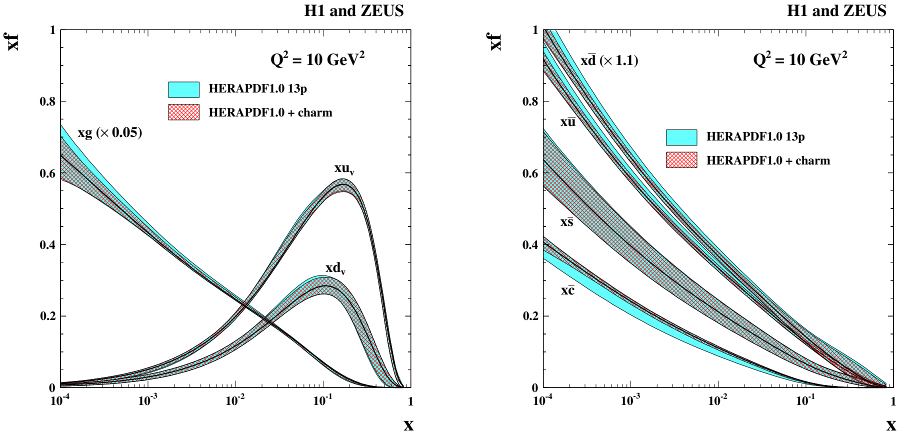
- Due to multiple scale problems there are different heavy flavours schemes. They have significant different predictions with given M_c value for example for $W^{\pm}$, Z production at LHC . (difference due to scheme about 7% !)

Testing different heavy quarks schemes: motivation



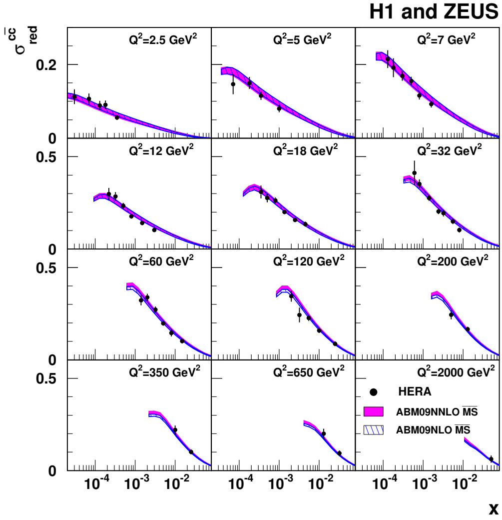
- Optimal M_c value is different for different schemes.
- Uncertainties on W and Z production due to the charm mass using optimal Mc reduced to 1%

HERAPDF improvement with charm data



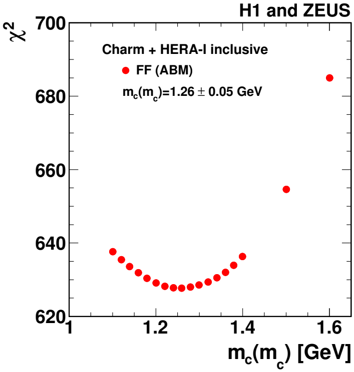
- Charm data reduces uncertainty on gluon and light sea due to better constrained charm-quark mass

ABM FFNS



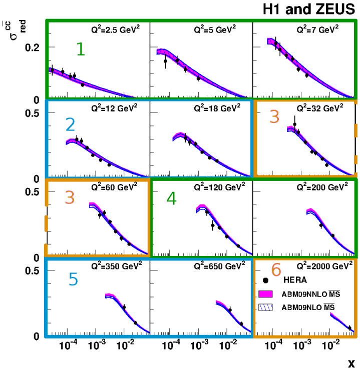
- Good description of data for both NLO and NNLO variants
- Using $\overline{MS}$ mass definition
- Allows to determine $m_c(m_c)$

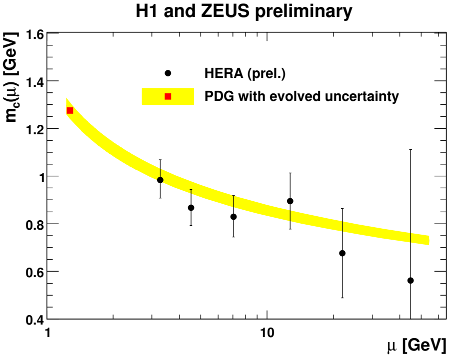
Charm mass measurement



- FFNS gives possibility to determine running charm mass $m_c(m_c)$ in $\bar{MS}$
- Result: $m_c(m_c) = 1.26 \pm 0.05_{exp.} \pm 0.03_{mod.} \pm 0.02_{par.} \pm 0.02_{\alpha s}$ GeV in good agreement with the world average: $m_c(m_c)_{PDG} = 1.275 \pm 0.025$ GeV

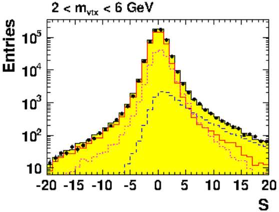
Measurement of the charm quark mass running (ZEUS-prel-14-006 + S.Moch)

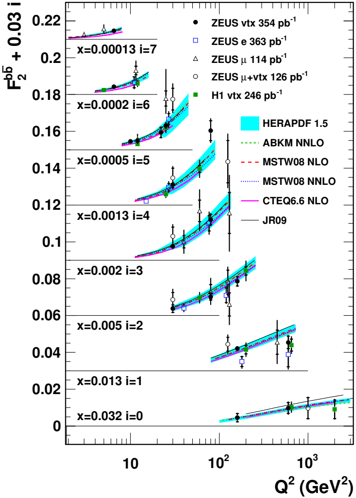




The running of the charm mass in $\bar{MS}$ scheme is measured for the first time, found to be consistent with expectations from QCD

$F_2^{b\bar{b}}$ structure function (arXiv:1405.6915v1)

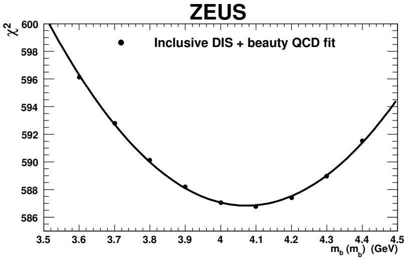


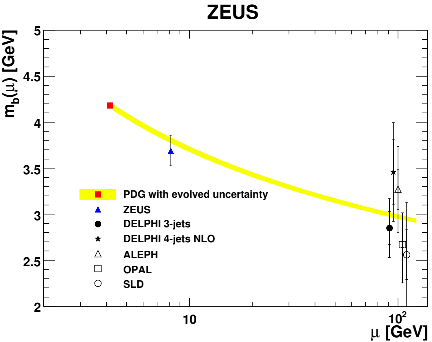


- $5 < Q^2 < 1000$ GeV^2
- $1.5{\times}10^{-4} < x < 0.035$

At least 1 jet with invariant mass of charged tracks associated with secondary vertices and decay-length significance

running b quark mass



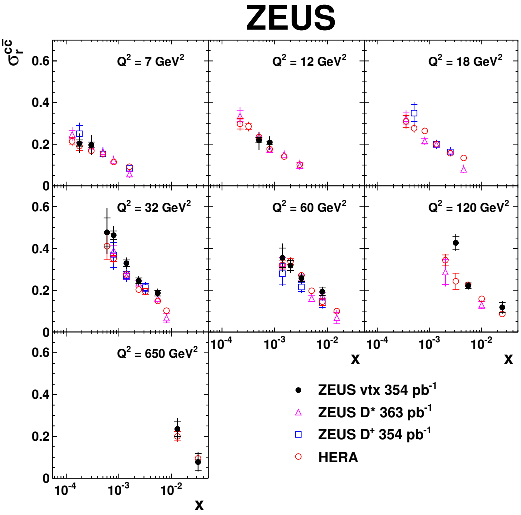


NLO FFNS fit used to extract the b quark mass in $\overline{MS}$ scheme

ZEUS : $m_b(m_b) = 4.07 \pm 0.14 \,^{+0.01}_{-0.07}$ (mod.) $^{+0.05}_{-0.00}$ (param.) $^{+0.08}_{-0.05}$ (theo.)

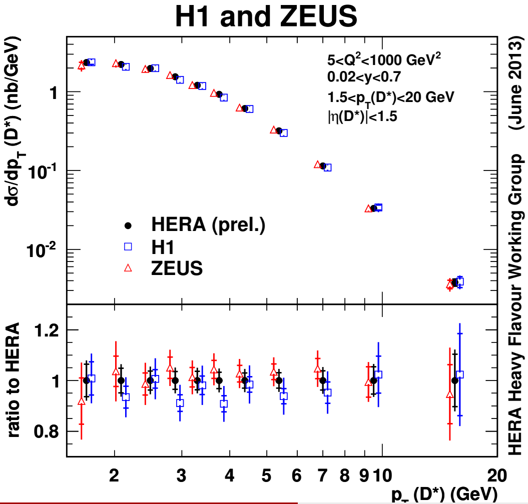
PDG: $m_b(m_b) = 4.18 \pm 0.03$ GeV

Recent charm measurements



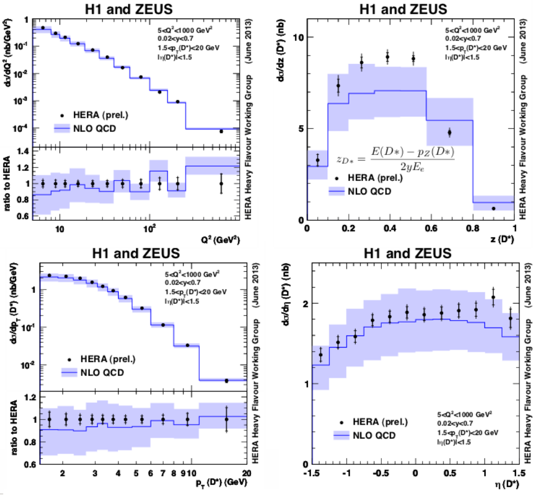
- Two new measurements from ZEUS were published recently : D^+ (JHEP 05 (2013) 023) and D^* (JHEP 05 (2013) 097) – good agreement with combination of HERA data

Combined D* differential cross sections (H1prel-13-171, ZEUS-prel-13-00)



- **Visible cross sections** from new D^* measurement were combined with H1 results for single-differential and double-differential cross-sections to reduce uncertanties, especially systematics

Combined D* differential cross sections (H1prel-13-171, ZEUS-prel-13-00)



- Recently combined H1 and ZEUS measurements of visible D^* production cross-sections gives possibility to use them for fragmentation models study and further theory constraints
- Predictions were obtained in NLO QCD (HVQDIS) with Kartvelischwili fragmentation using HERAPDF 1.0 FFNS.

Summary

HERA providing new heavy flavour results using all measured data to test QCD and constraint it

- Optimal charm mass parameter in PDF for different VFNS determined, improves predictions of $W^{\pm}$ and Z cross sections at the LHC
- charm data reduces uncertainties on gluon and sea quarks PDFs
- Running mass of charm quark in $\bar{MS}$ determined in FFNS at NLO, in good agreement with PDG world average
- Consistency check of charm quark mass running performed
- New precise measurements of beauty production in DIS with high statisctics using secondary vertices. Measured b quark mass in $\bar{MS}$ scheme showed good agreement with PDG value
- Differential cross sections of D^{*} mesons at HERA combined, challenge to the theory and fragmentation models

Testing different PDFs

Having such precise combined data gives a possibility to test different available PDFs on a market.

Theory	Scheme	Ref.	$F_{2(L)}$ def.	m_c [GeV]	Massive ($Q^2 \lesssim m_c^2$)	Massless ($Q^2 \gg m_c^2$)	$\alpha_s(m_Z)$ ($n_f = 5$)	Scale	Included charm data
MSTW08 NLO	RT standard	[28]	$F_{2(L)}^c$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108	Q	[1, 4–6, 8, 9, 11]
MSTW08 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
MSTW08 NLO (opt.)	RT optimised	[31]			$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108		
MSTW08 NNLO (opt.)					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
HERAPDF1.5 NLO	RT standard	[55]	$F_{2(L)}^c$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.1176	Q	HERA inclusive DIS only
NNPDF2.1 FONLL A	FONLL A	[30]	n.a.	$\sqrt{2}$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.119	Q	[4–6, 12, 13, 15, 18]
NNPDF2.1 FONLL B	FONLL B		$F_{2(L)}^c$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$			
NNPDF2.1 FONLL C	FONLL C		$F_{2(L)}^c$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
CT10 NLO	S-ACOT-χ	[22]	n.a.	1.3	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.118	$\sqrt{Q^2 + m_c^2}$	[4–6, 8, 9]
CT10 NNLO (prel.)		[56]	$F_{2(L)}^{c\bar{c}}$	1.3 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
ABKM09 NLO	FFNS	[57]	$F_{2(L)}^{c\bar{c}}$	1.18 ($\overline{\text{MS}}$)	$\mathcal{O}(\alpha_s^2)$	-	0.1135	$\sqrt{Q^2 + 4m_c^2}$	for mass optimisation only
ABKM09 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	-			

Available predictions differs by many parameters such as :heavy flavour scheme, perturbative order, masses, PDF assumptions, values of $\alpha_s(M_z)$

HERA Charm Data combination : datasets

9 different charm reduced cross sections measurements were combined :

.	Data Set	Period	Reconstruction	Q^2 [GeV^2]
•	1) H1 Vertex	HERA I + II	displaced vtx	5–2000
•	2) H1 D^*	HERA I	D^* decay	2–100
•	3) H1 D^*	HERA II	D^* decay	5–100
•	4) H1 D^*	HERA II	D^* decay	100–1000
•	5) ZEUS D^*	96-97	D^* decay	1–200
•	6) ZEUS D^*	98-00	D^* decay	1.5–1000
•	7) ZEUS D^0	2005	D^0 decay	5–1000
•	8) ZEUS D^+	2005	D^0 decay	5–1000
•	9) ZEUS μ	2005	semileptonic	20–10000

Full references in the paper.