Charm production and charm quark mass determination at HERA

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On behalf of the H1 and ZEUS collaborations

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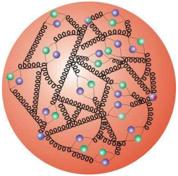
Outline

Disk of Phaistos : 3700 years old,
no success in decoding

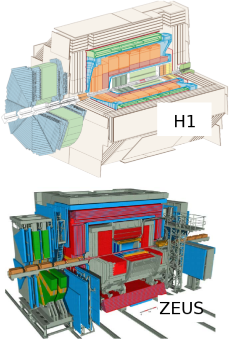


Proton : 14 billions years old,
some success in decoding
structure (also by HERA)

- Charm production at HERA
- Combination and QCD analysis of Charm Data at HERA. Impact on predictions for LHC
- Measurement of Charm quark mass
- New H1-ZEUS D^* visible cross-sections combination
- Summary

The HERA *ep* collisions experiments

HERA ring

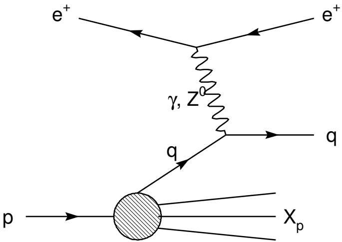


H1 and ZEUS detectors

- 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

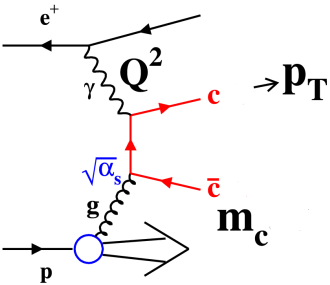
Deep Inelastic Scattering



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

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

Charm production in *ep* scattering



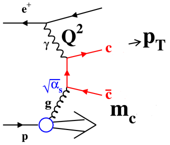
- At HERA Charm mainly produced by boson-gluon fusion (sensitive to the gluon density in the proton)
- Contribution to total DIS cross section – charm up to 30%.

Different Heavy Quark Schemes

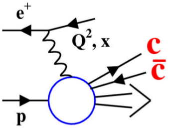
Heavy Quark Scheme in QCD Analysis defines treatment of heavy flavours in perturbative expansion.

- 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 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

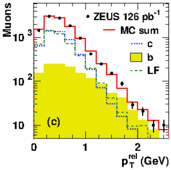


FFNS

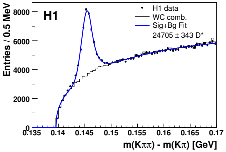


VFNS

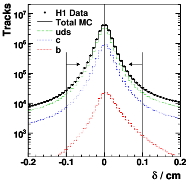
Charm tagging techniques



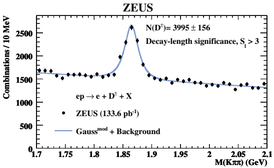
Semi-leptonic decays



Charmed mesons reconstruction



track displacement



Charmed mesons+vertex

Reduced cross section definition

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

$$\sigma_{red}^{c\bar{c}} = F_2^{c\bar{c}} - \frac{y^2}{1+(1-y)^2)} F_L^{c\bar{c}}$$

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

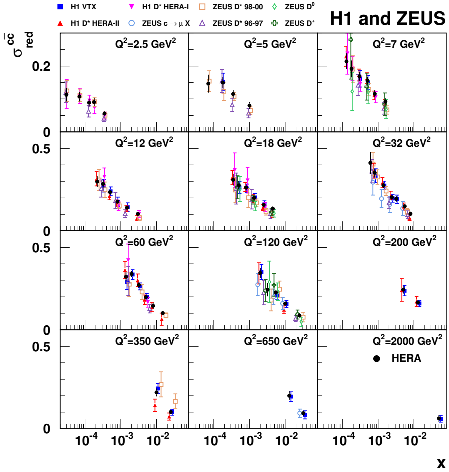
$$\frac{d\sigma^{c\bar{c}}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[1+(1-y)^2]\sigma_{red.}^{c\bar{c}}(Q^2,x)$$

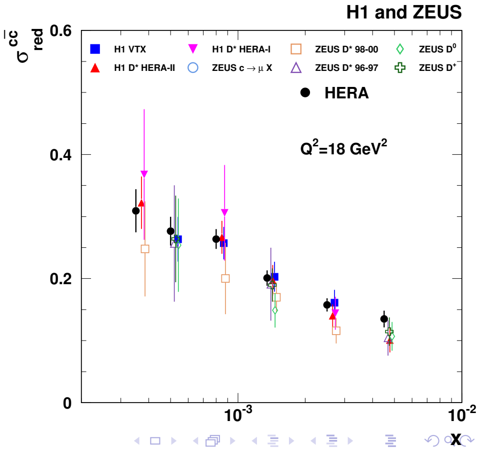
Most measurements are actually measuring visible cross sections with restricted phase space. The extrapolation to full phase space in $p_t(D^*)$ and $\eta(D^*)$ is required :

$$\sigma_{red}^{c\bar{c}}(x,Q^2) = \sigma_{vis,bin}^{c\bar{c}} \frac{\sigma_{red}^{c\bar{c},th}(x,Q^2)}{\sigma_{vis,bin}^{c\bar{c},th}}$$

HERA Charm Data combination

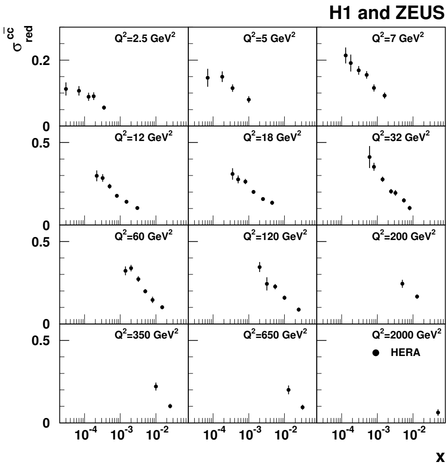
Combination showed good consistency of data with $\frac{\chi^2}{n_{dof}} = 62/103$.
More information in backup.



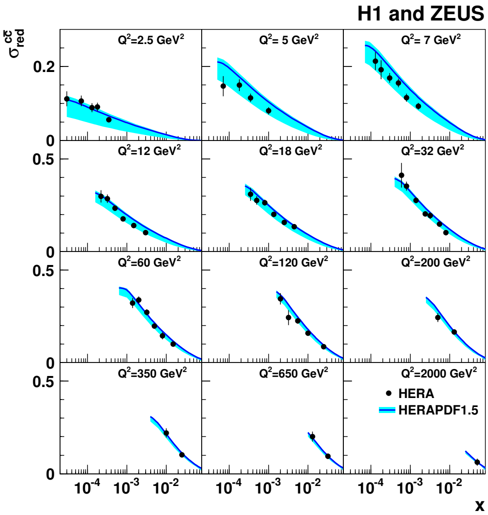


HERA Charm Data combination : Results

155 data points from 9 different measurements were combined to 52 points. With precision about 6% at medium Q^2

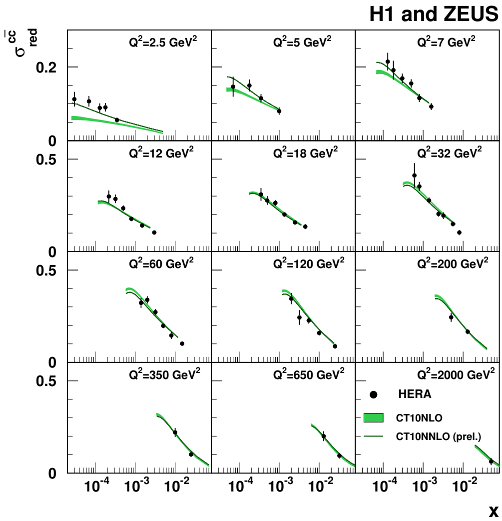


HERAPDF1.5

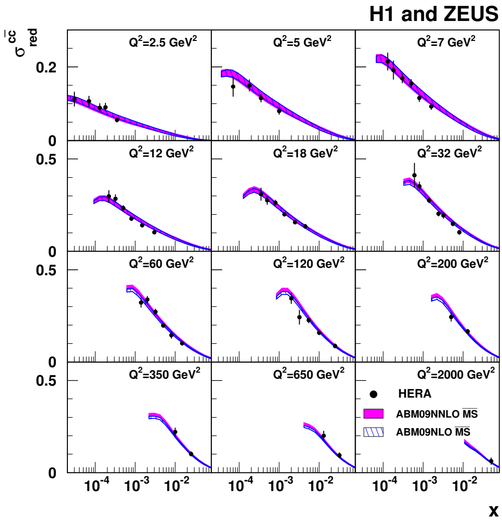


- Good agreement with data
- HERAPDF1.5 obtained with DIS inclusive data only in RT heavy flavour scheme
- Error band mostly corresponds to m_c variation from 1.35 to 1.6 GeV (central value 1.4 GeV).

CT10

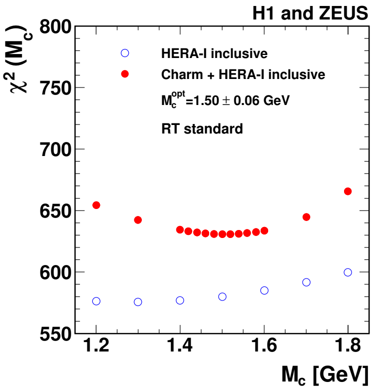


Best agreement with CT10 NNLO variant.



- Good description of data for both NLO and NNLO variants
- Using $\bar{M}S$ mass definition

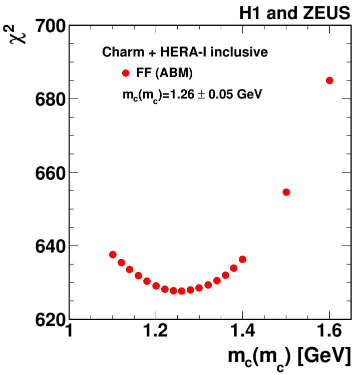
Testing different heavy quarks schemes: m_c scan



- Adding charm data to HERA inclusive data gives sensitivity to m_c parameter.
- Optimal m_c can be measured with uncertainties determined using tolerance $\triangle\chi^2$=1
- Also systemacis due to
  - parametrisation
  - α_s
  - Q^2 of inclusive data
  - evolution starting scale

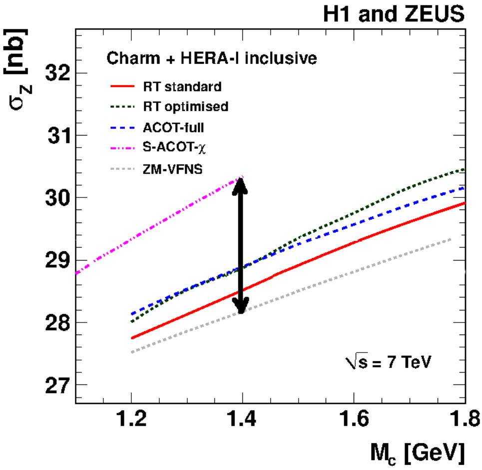
were estimated

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

Testing different heavy quarks schemes: motivation



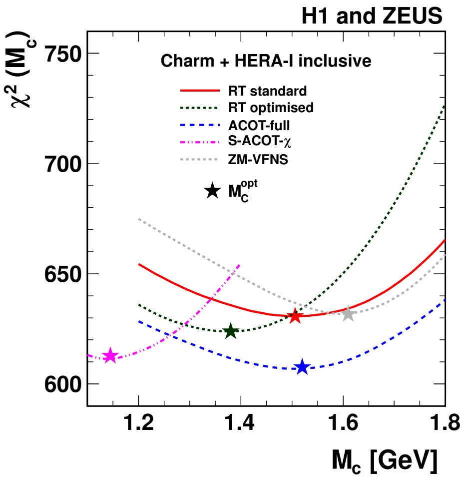
- We need to study different heavy quarks treatment schemes because predictions for example for $W^{\pm}$, Z production at LHC depends on them and charm mass they are using. (difference due to scheme about 7% !)

Testing different VFNS heavy quarks schemes

To test different heavy quarks schemes we need to put them in the same conditions.
For this purpose HERAFitter package was used [herafitter.org] that gives possibility to perform QCD fit of HERA inclusive data together with charm data using different heavy flavour schemes.
Next Variable Flavour Number Schemes were examined :

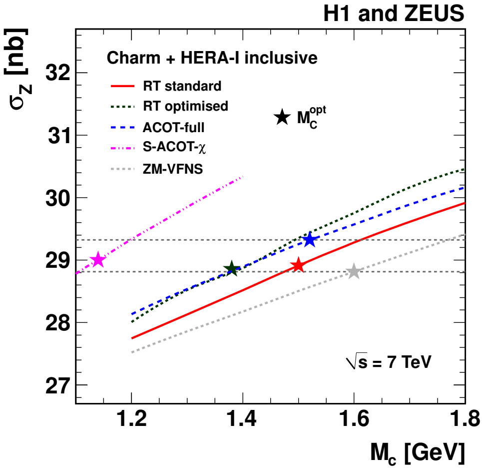
- RT standard [arXiv:0901.0002]
- RT optimized [arXiv:1201.6180]
- ACOT–full [hep-ph/9312319]
- S-ACOT–χ [hep-ph/0110247]
- ZMVFNS [hep-ph/9312319]

Testing different heavy quarks schemes: m_c scan



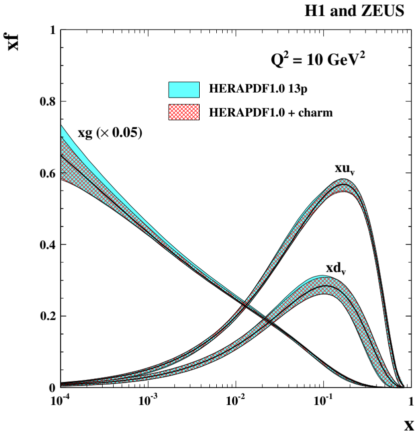
- Different schemes have different optimal m_c values
- Best χ^2 for HERA data gives ACOT–full, but the best fit to HERA charm data is from RT standard.

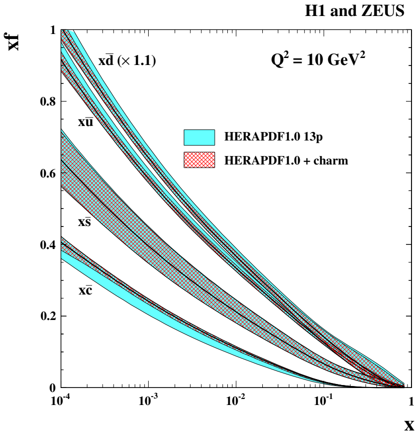
Testing different heavy quarks schemes



- Using optimal m_c value for each scheme reduces difference due to choice of scheme to 2%

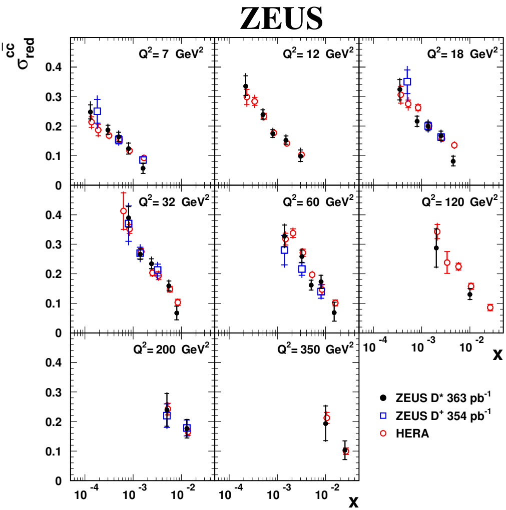
HERAPDF improvement with charm data





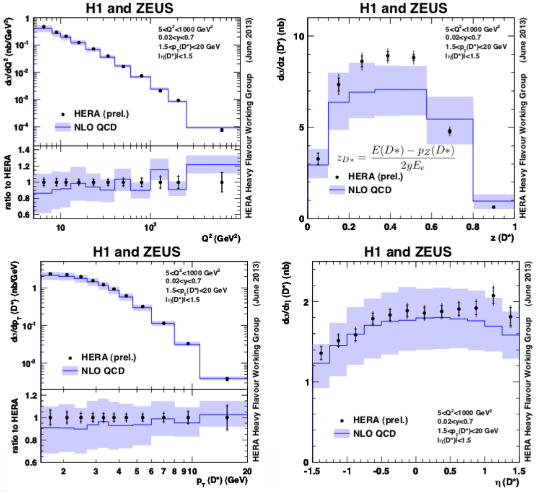
- Charm data reduces uncertainty on gluon and light sea due to better constrained charm-quark mass

New charm results from HERA



- Two new measurements from ZEUS were published recently : D^{+} and D^{*} – good agreement with combination
- **Visible cross sections** from new D^{*} measurement were combined with H1 results.

Combined D* differential cross sections



$$z_{D*} = \frac{E(D*) - p_Z(D*)}{2yE_e}$$

- 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 DIS charm data have been combined: significant uncertainties reduction achieved, combination good described by NLO QCD predictions
- Combined charm data included in QCD analysis :
  - Running mass of charm quark in $\bar{MS}$ determined in FFNS at NLO, in good agreement with PDG world average
  - 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
- 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.