Heavy flavour production at HERA

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on behalf of the H1 and ZEUS collaborations

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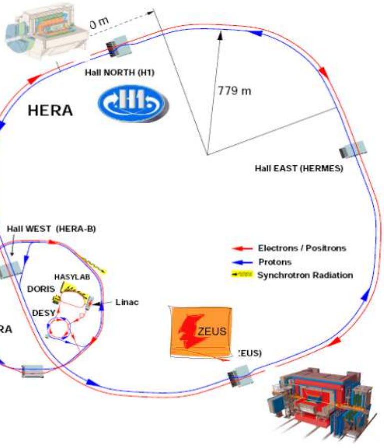
Experimental set-up

HERA Collider

- ep interactions
- $\sqrt{s} = 300 \ldots 318$ GeV

H1 and ZEUS:

- 4π multipurpose detectors
- $\mathcal{L} \sim 500\ \mathrm{pb}^{-1}$ per each experiment



$E_p = 920\,GeV$ $\quad$ $E_e = 27.5\,GeV$

$\sqrt{s} = 318\,GeV$

Kinematics

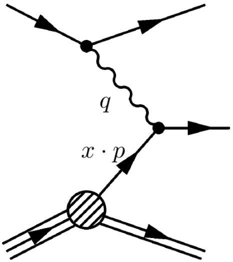
$$Q^2 = -q^2 = -(e - e')^2$$

$$x = \frac{Q^2}{2q \cdot p}$$

$$y = \frac{q \cdot p}{q \cdot e}$$

$$s = (e + p)^2$$

$$Q^2 = sxy$$



Any two of the variables (Q^2, x, y) define kinematics

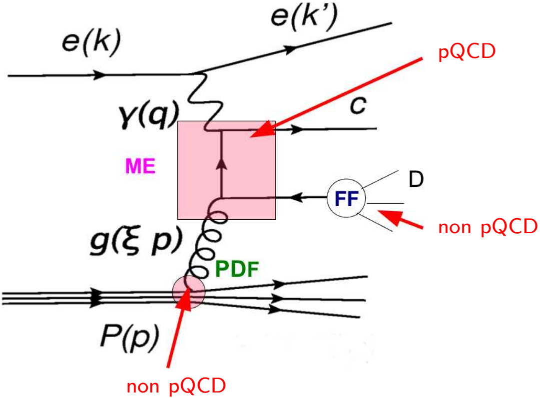
$Q^2 > 1\ GeV^2$ — deep inelastic scattering (DIS)
$Q^2 < 1\ GeV^2$ — photoproduction processes (PHP)

Heavy flavour production in DIS

Test of pQCD (multiple hard scales: Q^2, $p_T(Q)$, m_Q)

Charm and beauty in DIS are predominantly produced via Boson-Gluon Fusion (BGF) process

$$\sigma = \mathbf{PDF} \otimes \mathbf{ME} \otimes \mathbf{FF}$$



Production is directly sensitive to gluon density in the proton and to the quark masses

pQCD approximation of heavy flavour production

Fixed Flavour Number Scheme (FFNS)

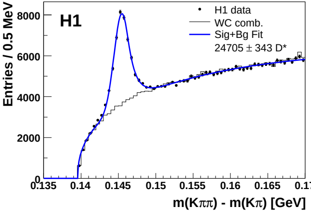
- c,b-quarks are massive $\Rightarrow$ not a part of the proton, produced perturbatively in hard scattering
- valid for $Q^2 \sim m^2_{c,b}$

Zero Mass Variable Flavour Number Scheme (ZMVFNS)

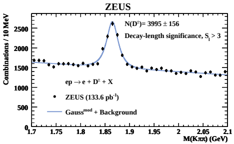
- c,b-quarks are massless $\Rightarrow$ a part of the proton
- valid for $Q^2 >> m^2_{c,b}$

General Mass Variable Flavour Number Scheme (GMVFNS)

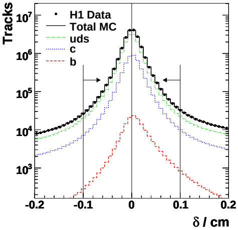
- equivalent to FFNS at low Q^2
- equivalent to ZMVFNS at high Q^2
- not unique (RT, ACOT, ...)



"Golden channel"
$D^{*\pm} \to D^0(\to K^\mp\pi^\pm)\pi_s^\pm$



Lifetime tagging of weak decays



Inclusive lifetime tagging

	Data set	Tagging method	Q^2 range [GeV^2]	N	$\mathcal{L}$ [pb^{-1}]
1	H1 VTX [14]	Inclusive track lifetime	5 – 2000	29	245
2	H1 D^* HERA-I [10]	D^{*+}	2 – 100	17	47
3	H1 D^* HERA-II [18]	D^{*+}	5 – 100	25	348
4	H1 D^* HERA-II [15]	D^{*+}	100 – 1000	6	351
5	ZEUS D^* (96-97) [4]	D^{*+}	1 – 200	21	37
6	ZEUS D^* (98-00) [6]	D^{*+}	1.5 – 1000	31	82
7	ZEUS D^0 [12]	$D^{0,\mathrm{no}D^{*+}}$	5 – 1000	9	134
8	ZEUS D^+ [12]	D^+	5 – 1000	9	134
9	ZEUS μ [13]	μ	20 – 10000	8	126

Charm combination

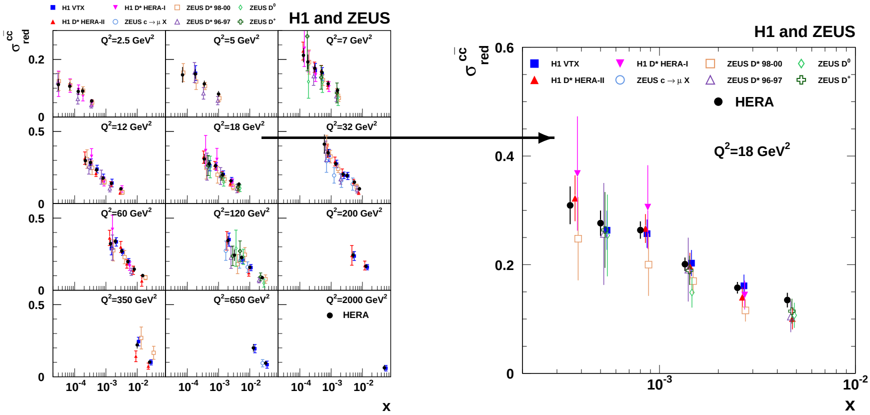
[EPJ C73 (2013) 2311]

- Combination done in terms of $\sigma_{red}^{c\bar{c}} = \frac{d^2\sigma^{c\bar{c}}}{dxdQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2(Q^2)(1+(1-y)^2)}$
- $\sigma_{red}^{c\bar{c}}$ are measured in a fiducial phase space $\Rightarrow$ extrapolated to the full phase space with FFNS NLO predictions $\Rightarrow$ extrapolation uncertainties
- Two experiments $\Rightarrow$ independent statistical uncertainties
- Different tagging techniqes $\Rightarrow$ independent systematical uncertainties
- **Significant reduction of both statistical and systematic uncertainties in the combination**

Questions one can ask:

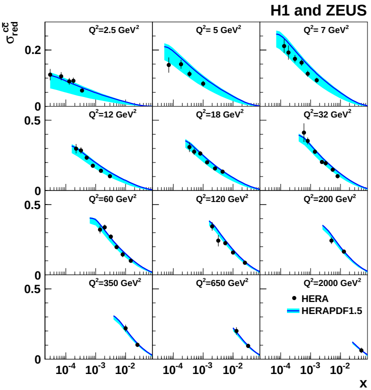
- How well GMVFNS works?
- How well FFNS works?
- How well the charm mass and PDFs can be constrained?

Charm combination: data

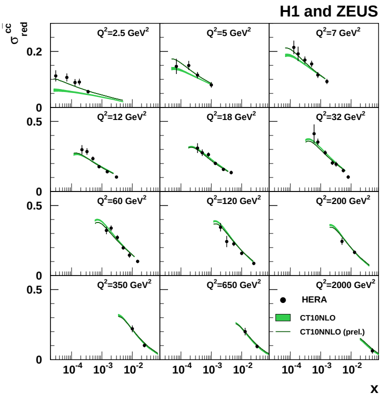


- $\chi^2/NDoF = 62/103 \Rightarrow$ good consistency of the input data
- Significant improvement of precision in the combination!

Charm combination: comparison to GMVFNS



RT scheme, inclusive DIS data only

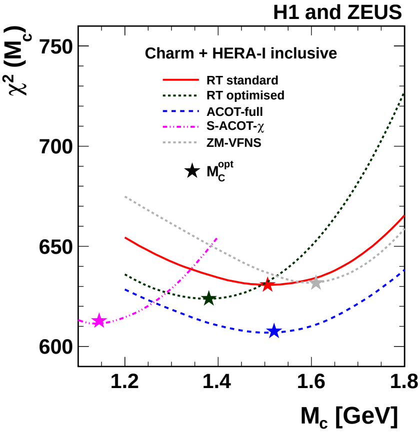


ACOT scheme

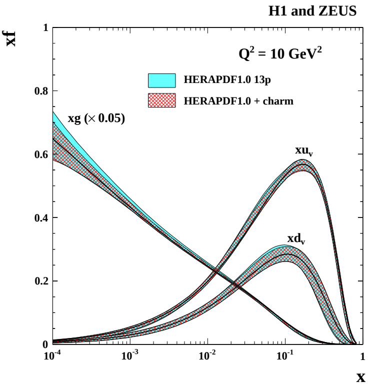
- Charm data are well described by two variants of GMVFNS
- Large uncertainty band for HERAPDF1.5 dominated by M_c variation

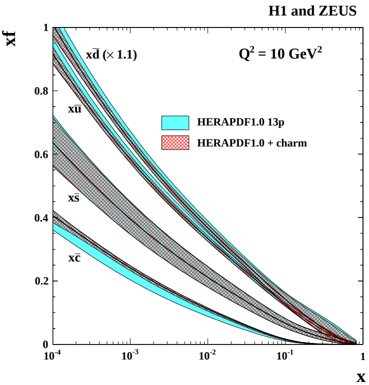
Charm combination: M_c^{opt}

- Different variants of GMVFNS prefer different M_c^{opt} parameters
- For RT scheme
  $M_c^{opt} = 1.50 \pm 0.06(exp) \pm 0.06(mod) \pm 0.01(param) \pm 0.03(\alpha_s)\ GeV$
  $\Rightarrow$ well constraint w.r.t default $1.35 < M_c^{opt} < 1.65\ GeV$



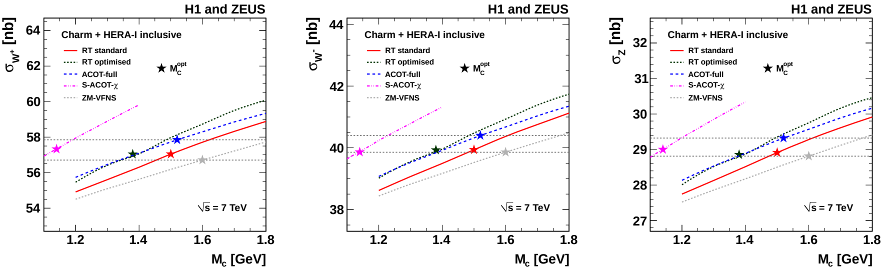
Charm combination: impact on PDFs





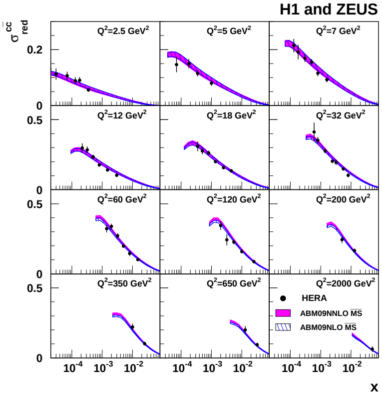
- Charm data stabilise the sea flavour composition
- Additional reduction of the uncertainties due to constraint M_c^{opt}

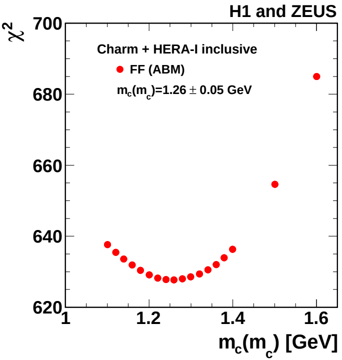
Charm combination: impact on LHC predictions



Impact on the $W^{\pm}$ and Z production at the LHC:

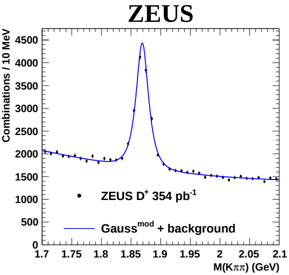
- Significant spread ($\sim 6\%$) if one uses different schemes with fixed M_c
- ... but much reduced ($< 2\%$) if an appropriate M_c^{opt} used for each of the schemes

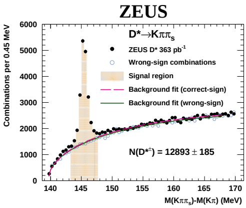


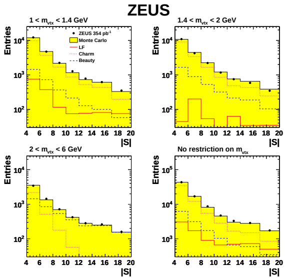


- Charm data are well described by FFNS
- Measured running mass $m_c(m_c) = 1.26 \pm 0.05(exp) \pm 0.03(mod) \pm 0.02(param) \pm 0.02(\alpha_s)\ GeV$ agrees with world average $m_c(m_c) = 1.275 \pm 0.025\ GeV$ (based mainly on lattice calculations)

Additional charm measurements



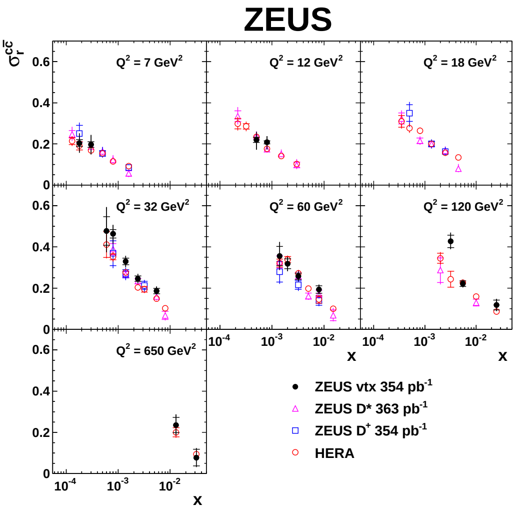




Recently did a few more charm measurements:

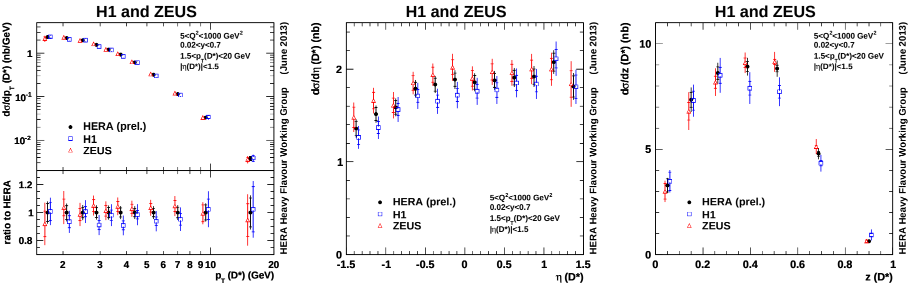
- ZEUS $D^{\pm}$ [JHEP 05 (2013) 023]
- ZEUS D^{*} [JHEP 05 (2013) 097]
- ZEUS D^{*} (PHP) [arXiv:1405.5068]
- ZEUS inclusive lifetime tagging [arXiv:1405.6915] (charm + beauty!)

ZEUS new measurements: charm



- Data are consistent with the HERA charm combination and have competitive precision
- $\Rightarrow$ can improve the combination!

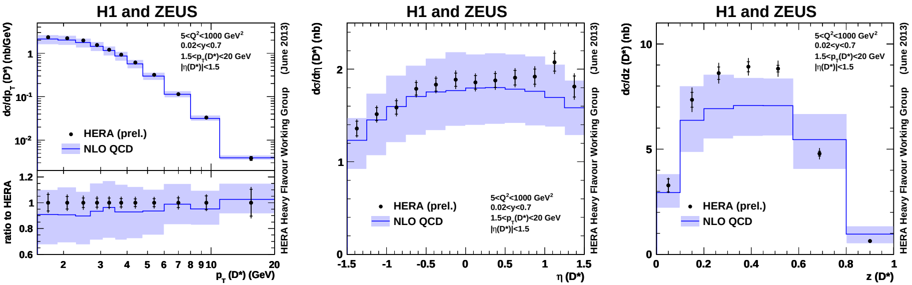
H1ZEUS combination: D^* visible cross sections



Advantages of the D^* visible cross sections combination:

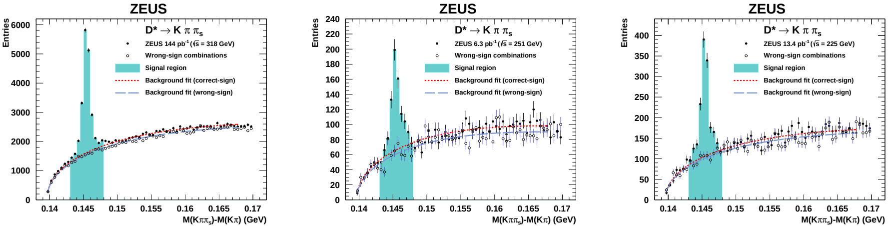
- Directly measured quantities in very similar phase space and bins $\Rightarrow$ neglibly small extrapolation uncertainties
- New observables are available:
  - $p_T(D^*)$
  - $\eta(D^*) = -ln(tan\frac{\theta(D^*)}{2})$
  - $z(D^*) = (E(D^*) - p_Z(D^*))/(2E_e y)$

H1ZEUS combination: D^* visible cross sections



- Well described by FFNS NLO convoluted with FF measured by H1 and ZEUS
- Data are more precise than theory
- $\Rightarrow$ NNLO and improved fragmentation are wanted!

ZEUS D* in PHP



- ZEUS, 2006 / 2007 years;
- Photoproduction ($Q^2 < 1$ GeV^2)
- Phase Space:

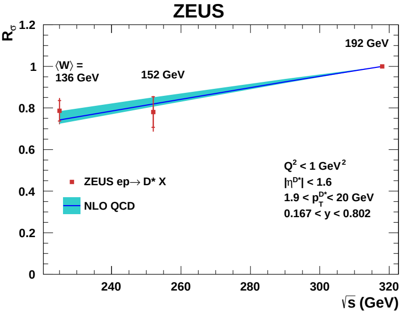
$130 < W_{HER} < 285$ GeV
$103 < W_{MER} < 225$ GeV
$92 < W_{LER} < 201$ GeV

$0.167 < y < 0.802$

$1.9 < p_T(D^*) < 20$ GeV

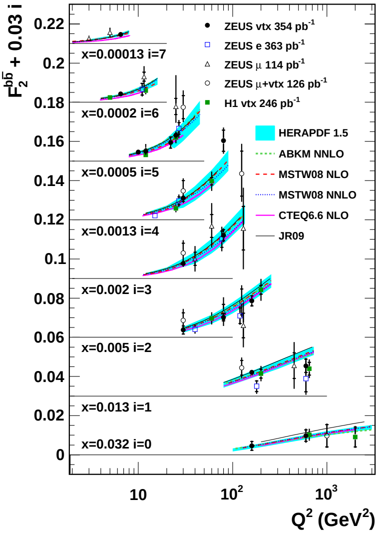
$|\eta(D^*)| < 1.6$

$$W^2 = (q + p)^2$$



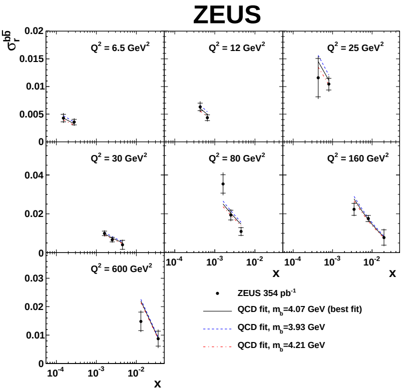
NLO QCD predictions (FMNR) well describe measured energy dependence — might be usefull for future *ep* colliders

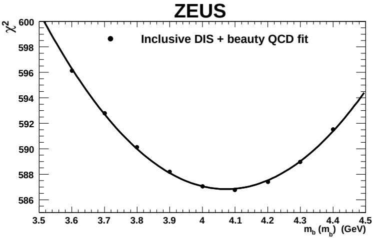
ZEUS lifetime tagging: beauty



- Beauty data are well described by FFNS and GMVFNS approaches

ZEUS lifetime tagging: beauty





- Beauty data are well described by FFNS
- Measured running mass $m_b(m_b) = 4.07 \pm 0.14(exp)^{+0.01}_{-0.07}(mod)^{+0.05}_{-0.00}(param)^{+0.08}_{-0.05}(theo)\ GeV$ agrees with world average $m_b(m_b) = 4.18 \pm 0.03\ GeV$

Summary

- HERA charm combination:
  - precise data for testing pQCD and different treatment of heavy quarks
  - stabilises sea composition of PDFs
  - accurate measurement of $m_c(m_c)$
- New charm measurements to be added to the combination
- Combination of D^* visible cross sections:
  - combination of most precise charm measurements
  - neglible theory uncertainties
  - shows that more advanced theory is really needed
- D* in PHP: measured dependence on $\sqrt{s}$
- Beauty production measured and $m_b(m_b)$ extracted as well