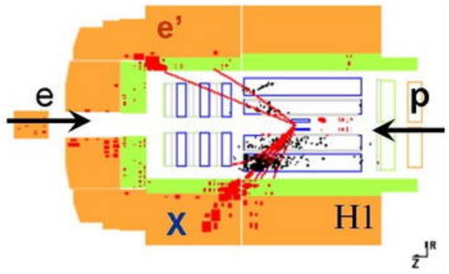
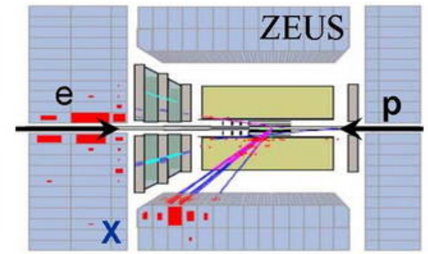
Beauty contribution to the proton structure function and charm results in ep collisions at HERA



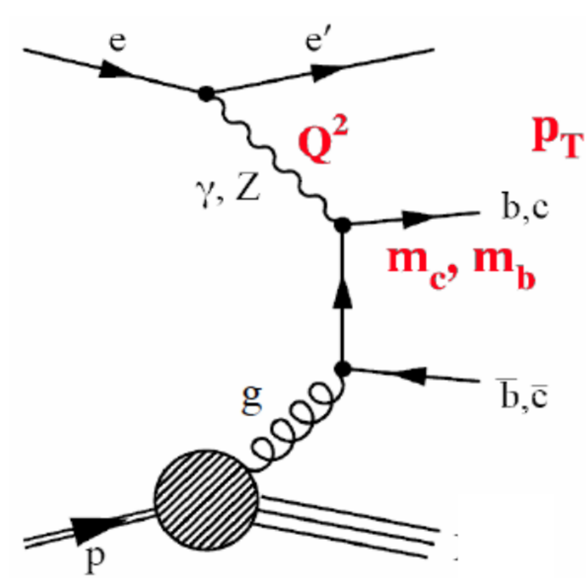


BEAUTY 2014, Edinburgh, 15 July 2014

A. Longhin
INFN-LNF

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

on behalf of the H1 and ZEUS Coll.



Outline

- Deep inelastic scattering:
  - heavy flavours contributions to F_2
  - running masses for beauty and charm
- Photo-production: beauty at low p_T

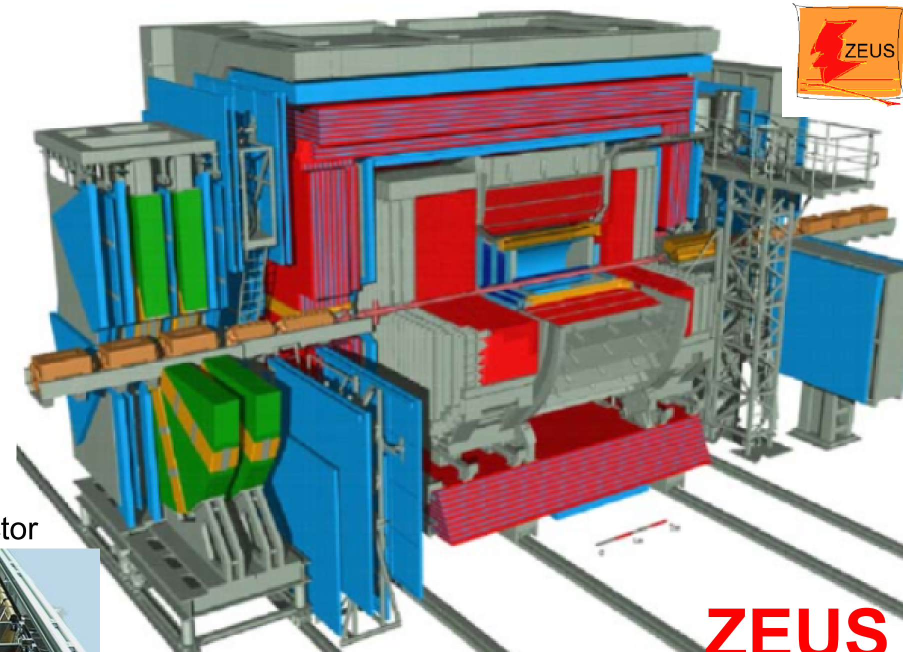
The HERA *ep* collider

$e^{\pm}$ (27.6 GeV) $\leftrightarrow$ p (920 GeV)

$\sqrt{s}$ = 319 GeV

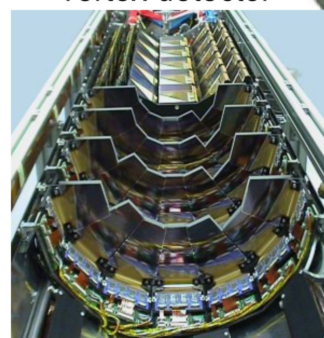
HERA-I: 1992-2000
HERA-II 2002-2007 (improved vtxing, higher *L*)

General purpose experiments: H1, ZEUS
Integrated luminosity: **~0.5 fb^{-1} each**

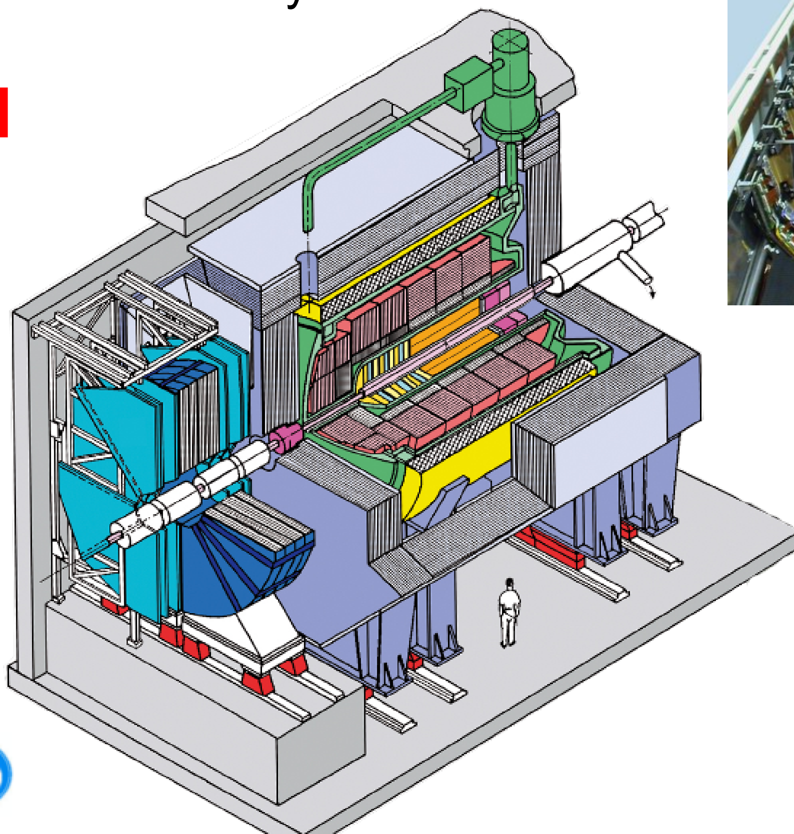


ZEUS

vertex detector



H1

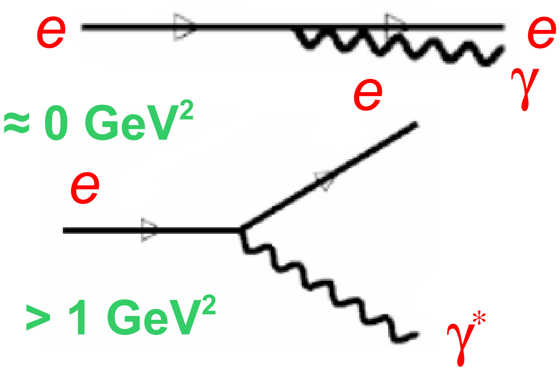


Heavy flavours at HERA

2 **kinematic regimes**

Photoproduction

Deep Inelastic Scattering
(scattered e in the detector)



Kinematic variables

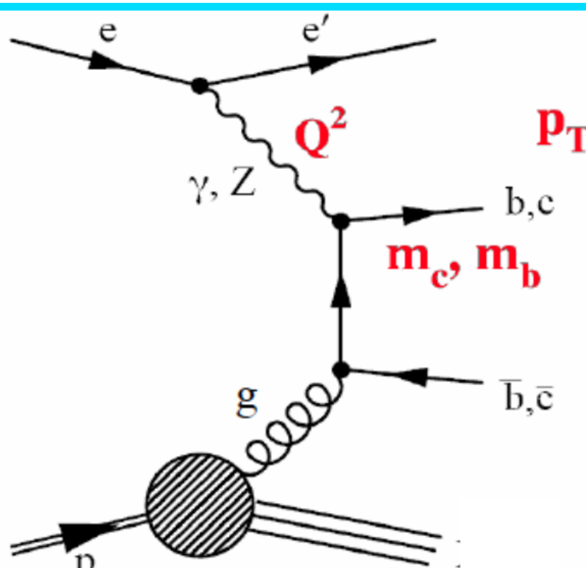
$Q^2 = -q^2 = -(k'-k)^2$ *virtuality of the exchanged γ*

$y = P{\cdot}q/p{\cdot}k$ *fraction of e momentum taken by the γ*

$x = Q^2/2P{\cdot}q$ *fraction of p momentum taken by the struck parton*

***P**: proton 4-momentum*
***k**: electron 4-momentum*

- heavy quarks mainly produced in **Photon-Gluon- Fusion**
- σ(b) : σ(c) : σ(uds) ≈ 1 : 50 : 2000
- Hard scales for perturbative QCD: $m_{c,b}$, p_T, Q^2
  multi-scale problem
- Test pQCD / constrain gluon PDF in the proton

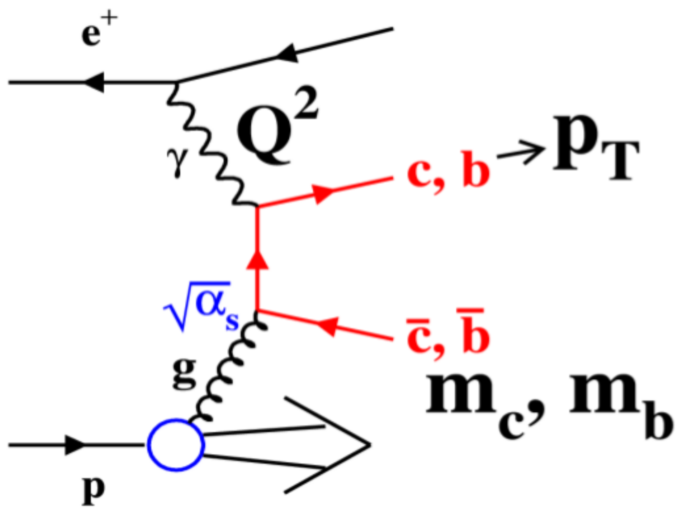


QCD calculations schemes

Multi-hard-scale problem ($m_{b,c}$, p_T, Q^2) → several calculation schemes exist

Massive scheme (FFNS)

Rigorous, fully massive treatment

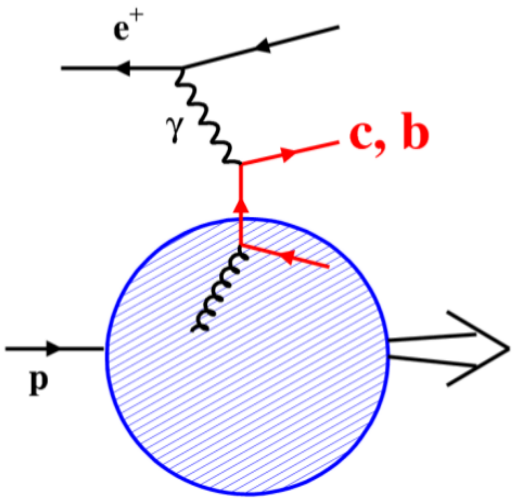


Expected to be valid at scales ~ $m_{b,c}$

Programs exist to calculate fully differential cross sections (HVQDIS, FMNR)

Massless scheme (ZM-VFNS)

Neglects heavy quark masses



Allows resummation of terms proportional to $log(Q^2/m_{b,c}^{\ 2})$

Expected to be valid at scales >>$m_{b,c}$

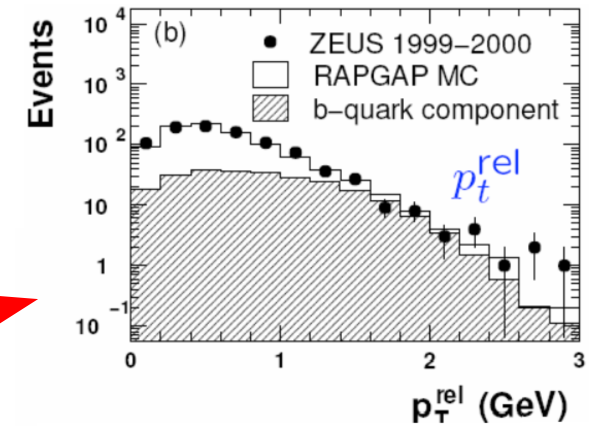
Mixed schemes (GM-VFNS) Employ both FFNS and ZM-VFNS

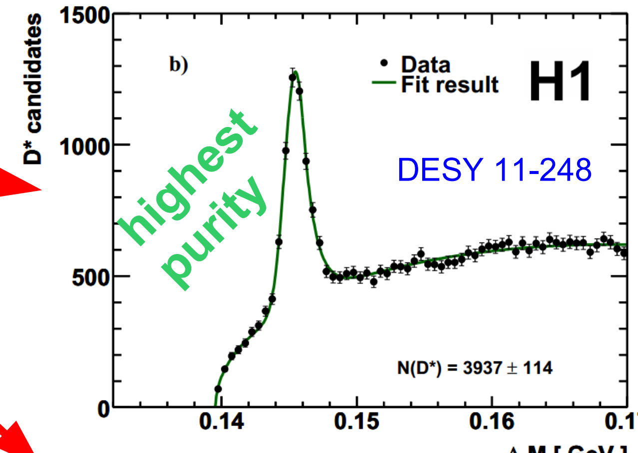
Interpolation ambiguous → various approaches (RT, ACOT etc.) exist

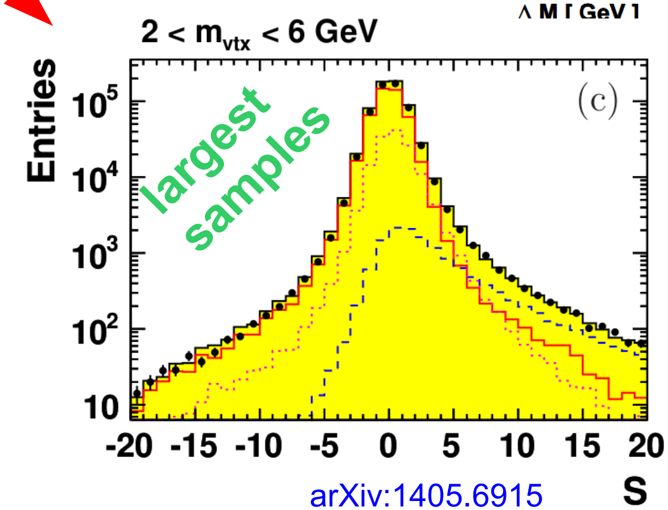
Heavy flavour measurements can help to test and improve the schemes

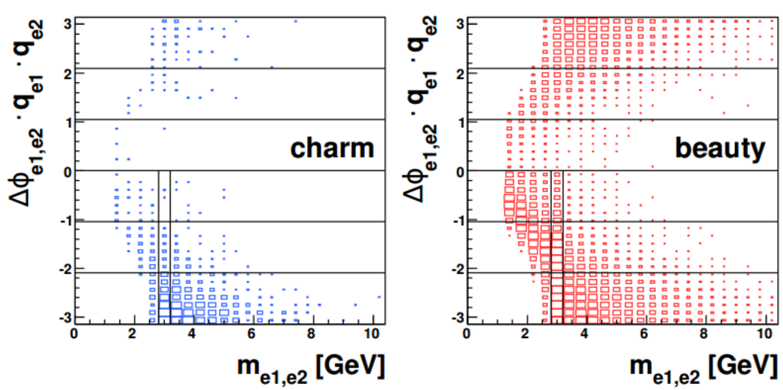
HF tagging at HERA

- **Lepton tagging**: semi-leptonic channels to μ, e (large Branching Ratios)
- p_T^{rel} look for decay leptons with a high transverse momentum w.r.t the jet direction.
- **full reconstruction** of specific decay channels eg. $D^* \rightarrow (K\pi)\,\pi$ (only for charm, no suitable b-decay channels with sufficiently high statistics).
- **Life-time tagging** (displaced vertices and/ or large impact parameters)
- **Secondary vertex mass** tagging: look for high secondary vertex masses
- **"Double" tagging**: μD^*, $\mu\mu$, ee final states









Beauty + charm in DIS

arXiv:1405.6915

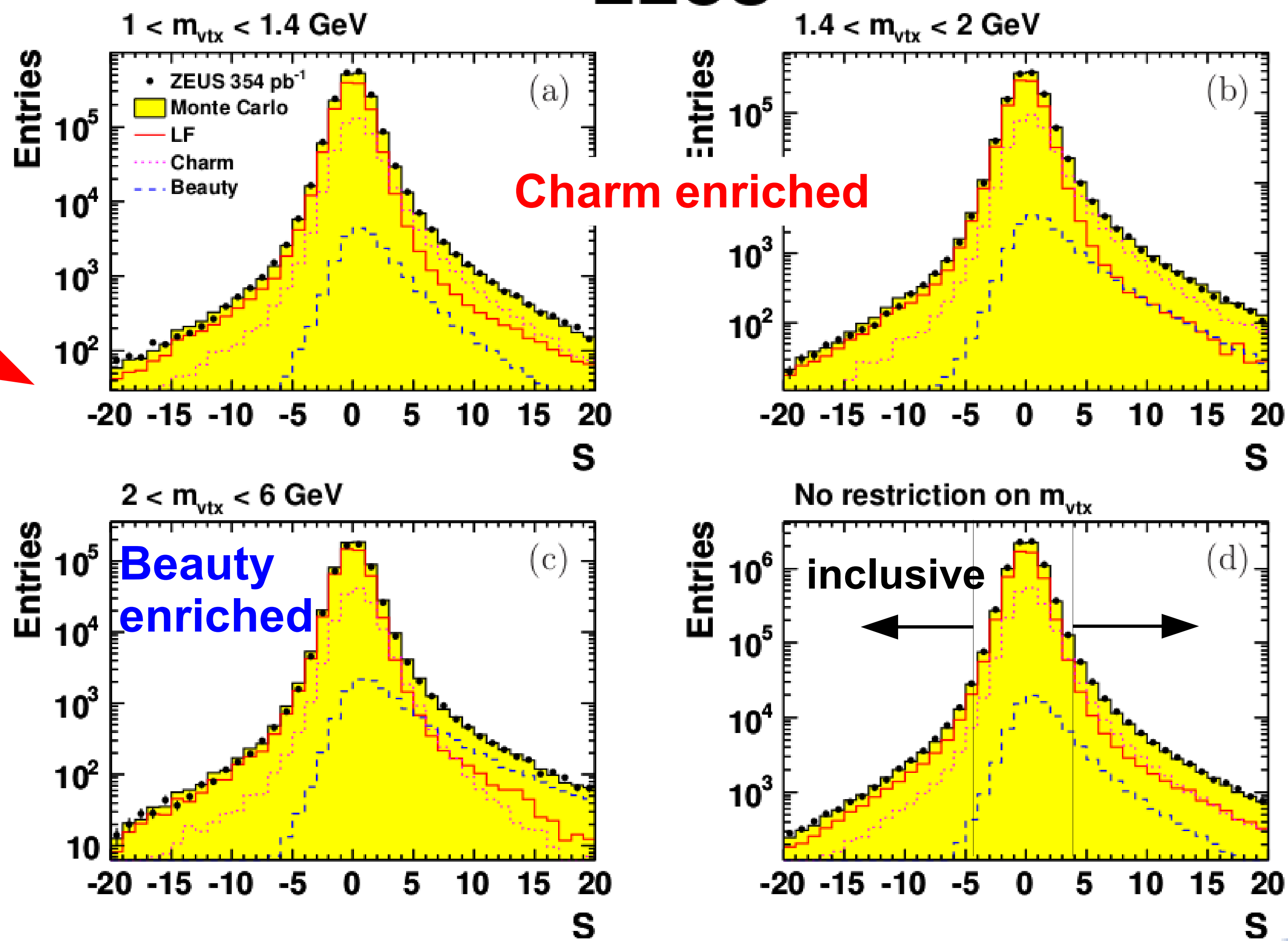
$5 < Q^2 < 1000$ GeV^2
$0.02 < y < 0.7$
$E_T^{jet} > 5$ (4.2) GeV
$-1.6 < \eta_{jet} < 2.2$

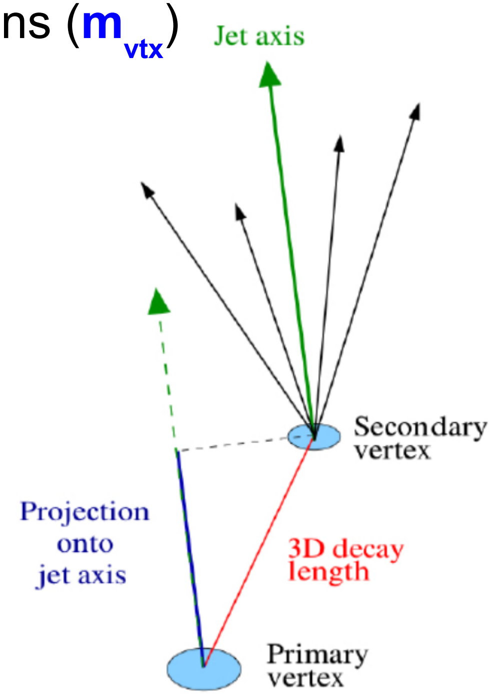
A very recent (May '14) result by ZEUS
No specific decay mode → high statistics
Both charm and beauty

RAPGAP MC for HF,
ARIADNE MC for uds

2^{ry} vertexing on jet tracks with p_T>0.5 GeV

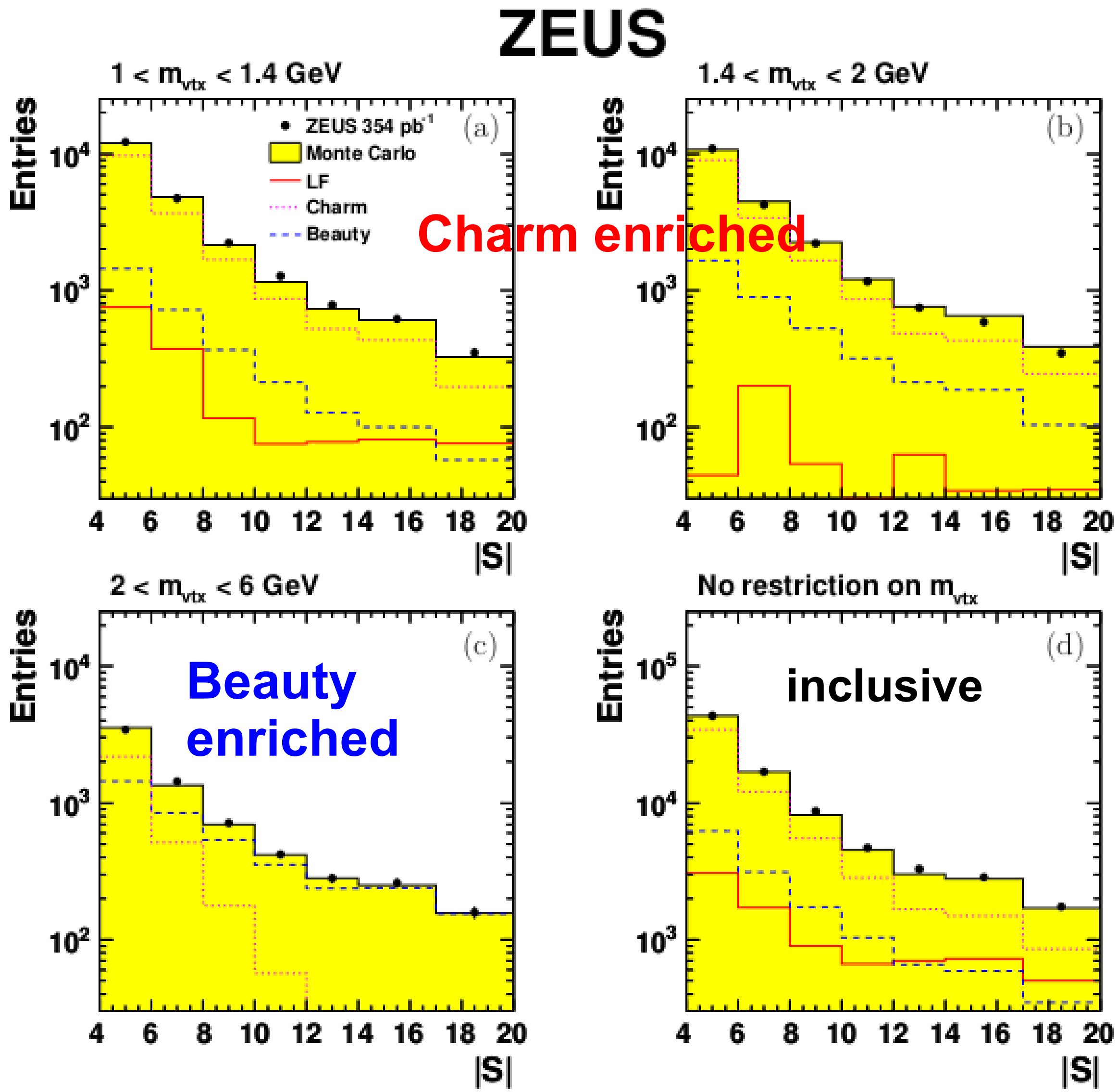
Significance of the decay length projected along the jet-axis (**S**) in three invariant mass bins (**m_{vtx}**)





Charm and beauty asymmetric due to long lifetime
Subtract the symmetric part: **"mirrored significance" → |S|**

Beauty + charm in DIS: signal extraction



Select **|S|>4**

Use the discriminating variables:
→ mirrored significance **|S|**
→ vertex mass $\mathbf{m_{vtx}}$

Simultaneous fit on IS| is performed in these m_{vtx} bins: [1,1.4] [1.4,2] [2,6] GeV

- Light flavour component fixed by unmirrored significance.
- b and c components determined by the fit on a statistical basis in each bin of the considered variable:

- differential x-sections in:
  E_T^{jet}, η^{jet}, x, Q^2
- double differential x-sections:
  $(x, Q^2) \rightarrow F_2^{QQ}$

arXiv:1405.6915

Beauty + charm in DIS: E_T^{jet} x-sections

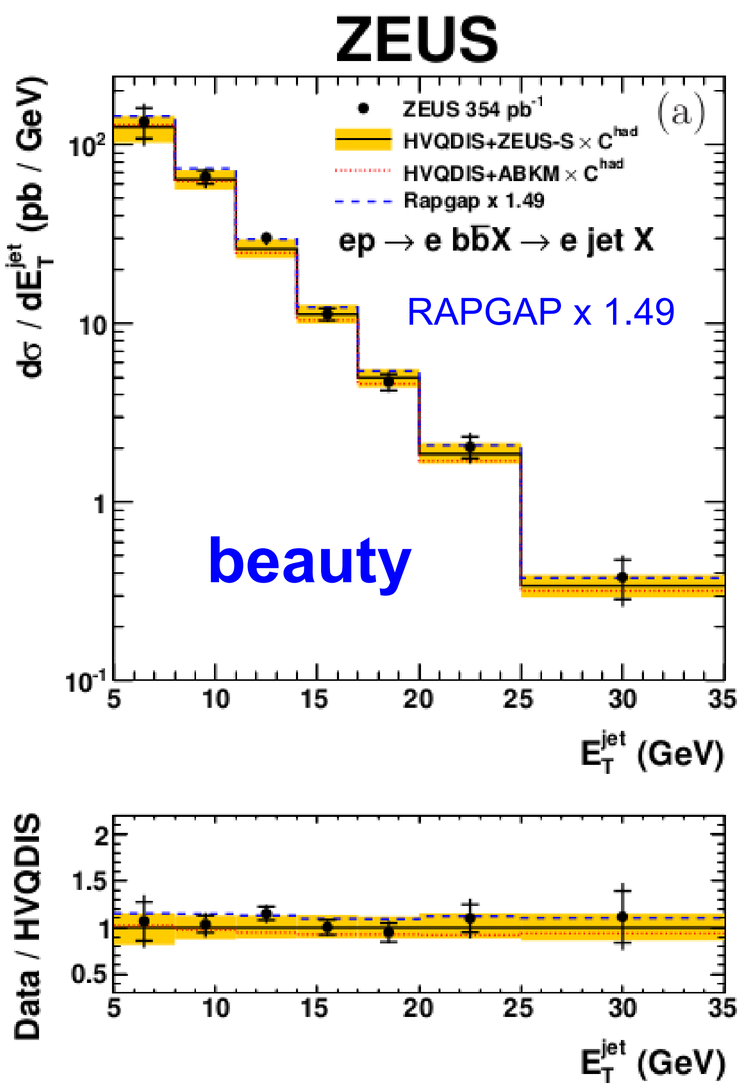
- FFNS NLO, HVQDIS program. **PDFs**: ZEUS-S and ABKM NLO
- $\mu_R=\mu_F=\sqrt{Q^2+4m^2}$. Pole masses 1.5, 4.75 GeV (4.5 for ABKM)
- Hadronic corr. of parton level jets: RAPGAP, QED corr.: HERACLES

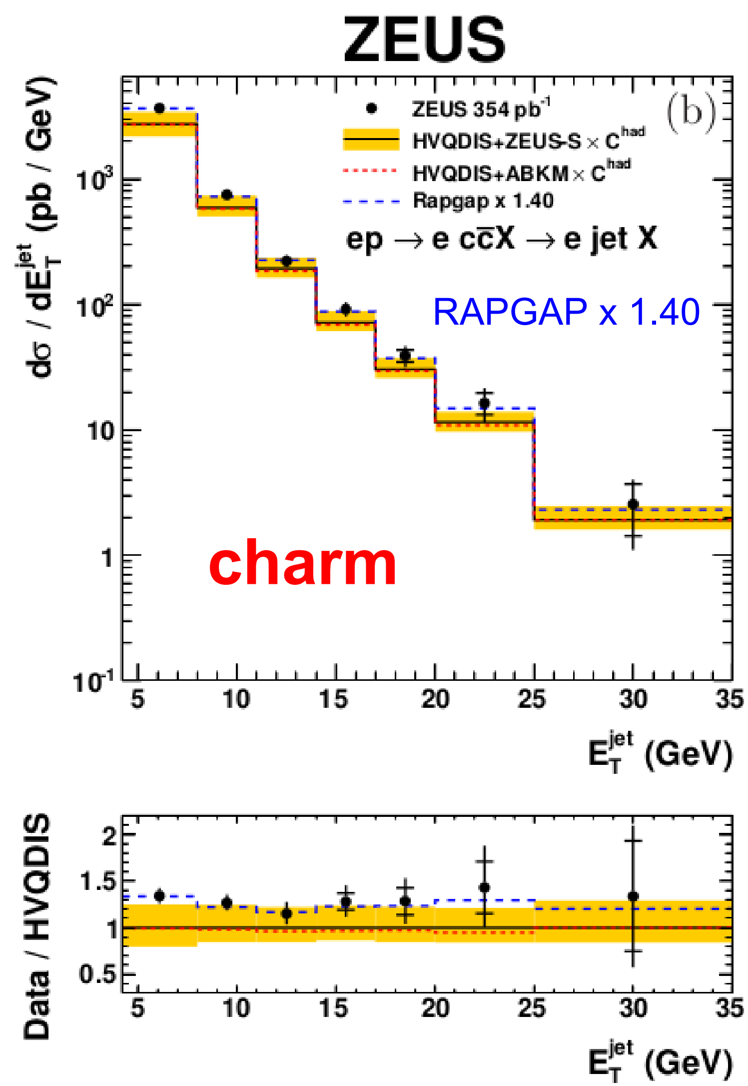
$$\sigma^{\text{had, NLO}} = C^{\text{had}}\sigma^{\text{parton,NLO}}$$

Jets: k_T clustering, long. inv mode. E-recomb. scheme

Theory uncertainty:
μ_R, μ_F x 1/2 and x 2
m_c [1.3,1.7], m_b [4.5,5]
PDFs exp. errors

Reasonable description by FFNS NLO QCD

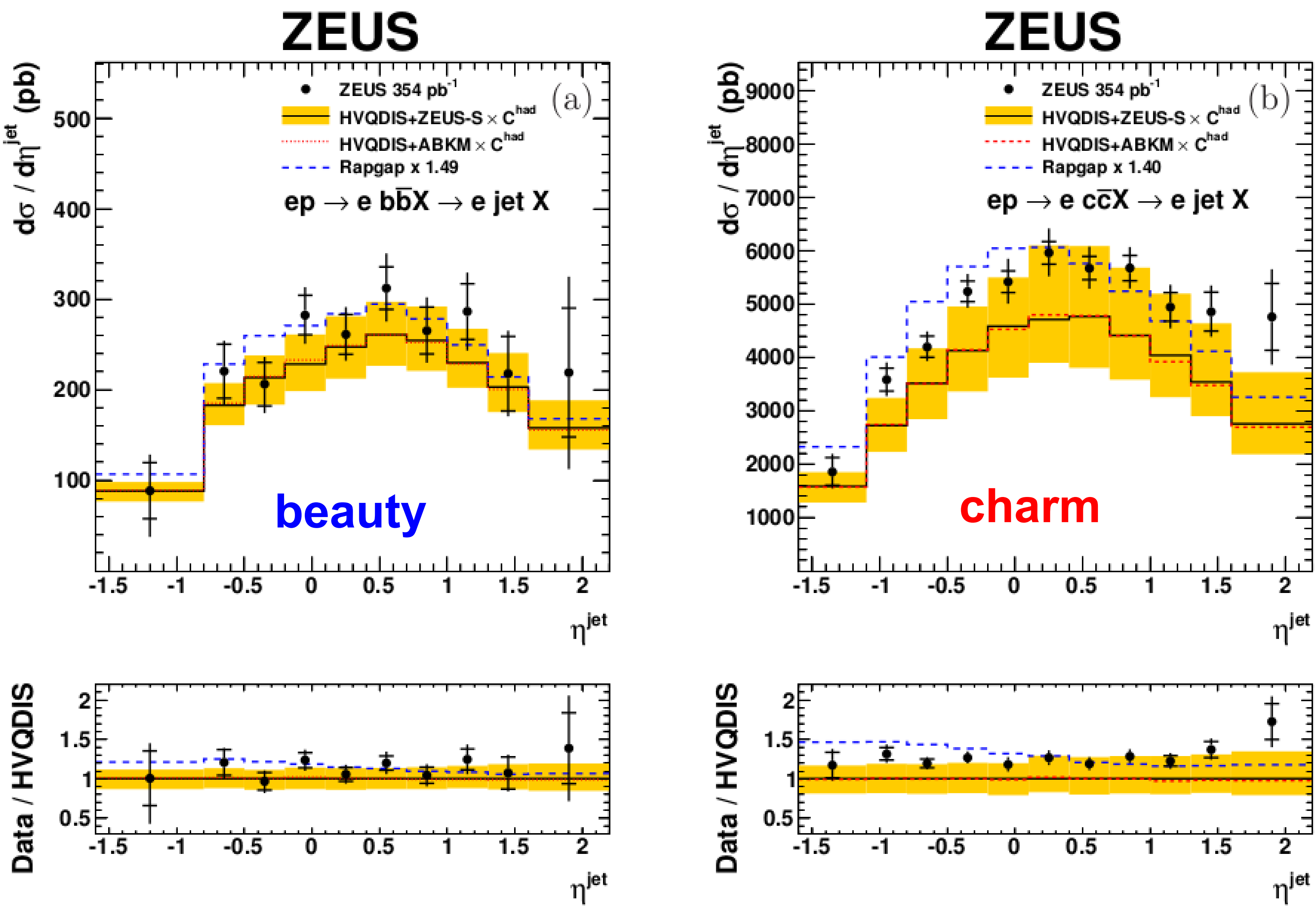




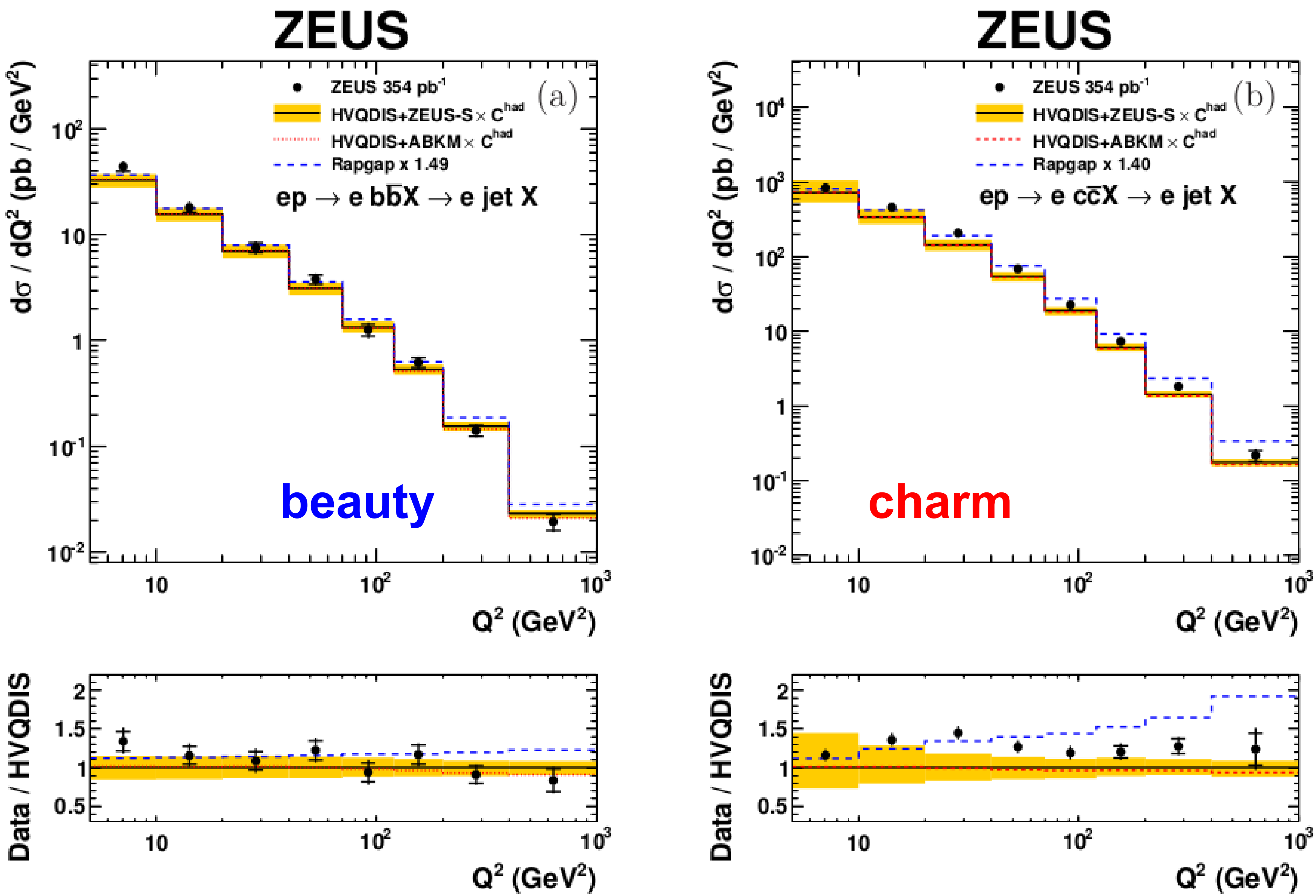
arXiv:1405.6915

Beauty + charm in DIS: η^{jet} x-sections

Reasonable description by FFNS NLO QCD



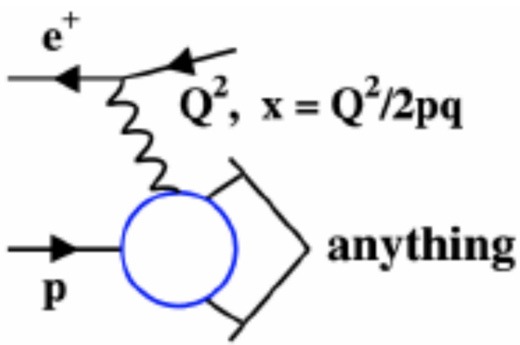
Beauty + charm in DIS: Q^2 cross sections



Reasonable description by FFNS NLO QCD

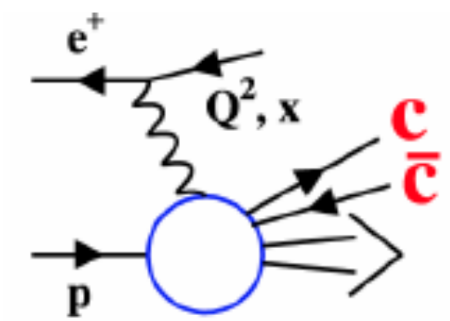
arXiv:1405.6915

$F_2^{Q\bar{Q}}$ (Q=b,c): HQ contributions to the F_2 structure function



$$\frac{d^2\sigma^{ep}}{dx\,dQ^2} \propto F_2(x,Q^2)$$

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\cdot[(1+(1-y)^2)F_2 - y^2 F_L]$$



$$\frac{d^2\sigma^{ep\to c\bar{c}x}}{dx\,dQ^2} \propto F_2^{c\bar{c}}(x,Q^2)$$

$$\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\cdot[(1+(1-y)^2)F_2^{c\bar{c}} - y^2 F_L]$$

NLO-data agreement in the phase space determined by the heavy quark tagging ("visible")
→ extrapolate to the full phase space

$$F_2^{c\bar{c},meas}(x,Q^2) = \sigma_{vis,bin}^{meas}\frac{F_2^{c\bar{c},model}(x,Q^2)}{\sigma_{vis,bin}^{model}}$$

Extrapolation factors (HVQDIS):

b:1 - 1.3 (at low Q^2) (up to 1.7 at high x).

c ~ 2 - 4 (at low Q^2)

"Reduced" cross section
(no assumption on F_L needed)

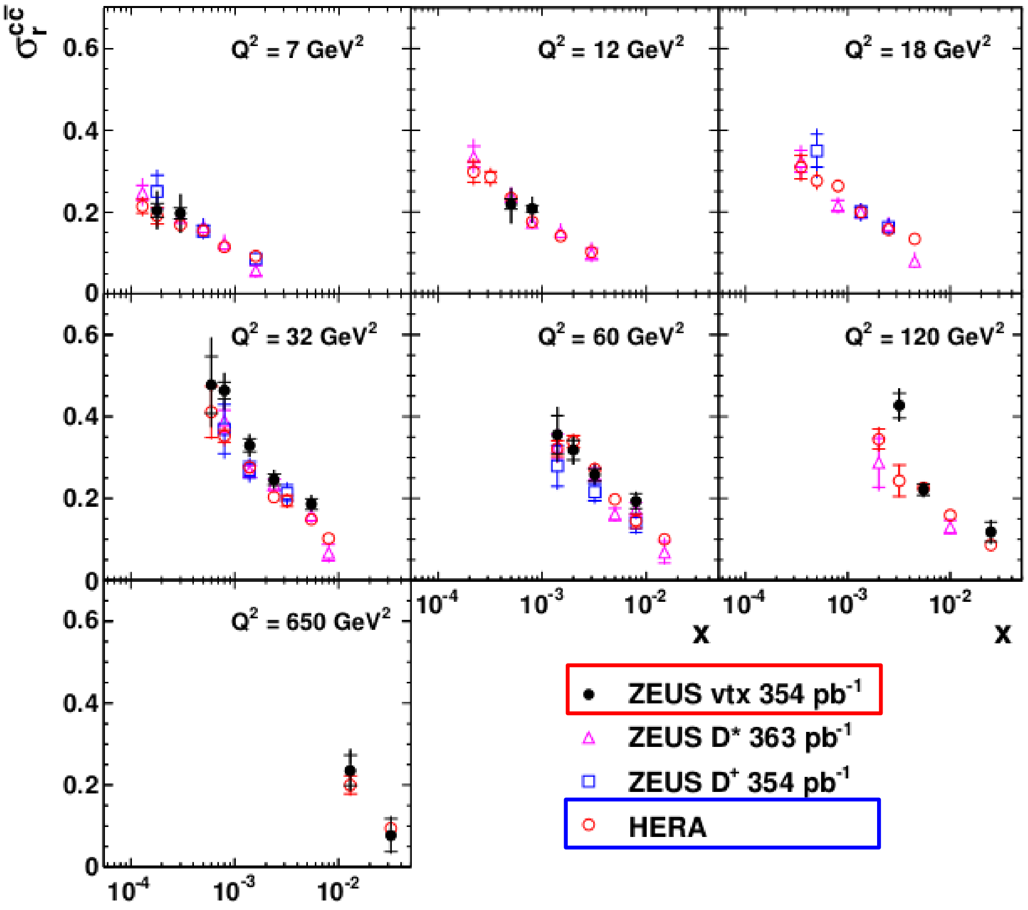
$$\sigma_{\rm red}^{c\bar{c}} = \frac{{\rm d}^2\sigma^{c\bar{c}}}{{\rm d}x{\rm d}Q^2}\cdot\frac{xQ^4}{2\pi\alpha^2(Q^2)\,(1+(1-y)^2)}$$

$$= F_2^{q\bar{q}}(x,Q^2) - \frac{y^2}{1+(1-y^2)}F_L^{q\bar{q}}(x,Q^2)$$

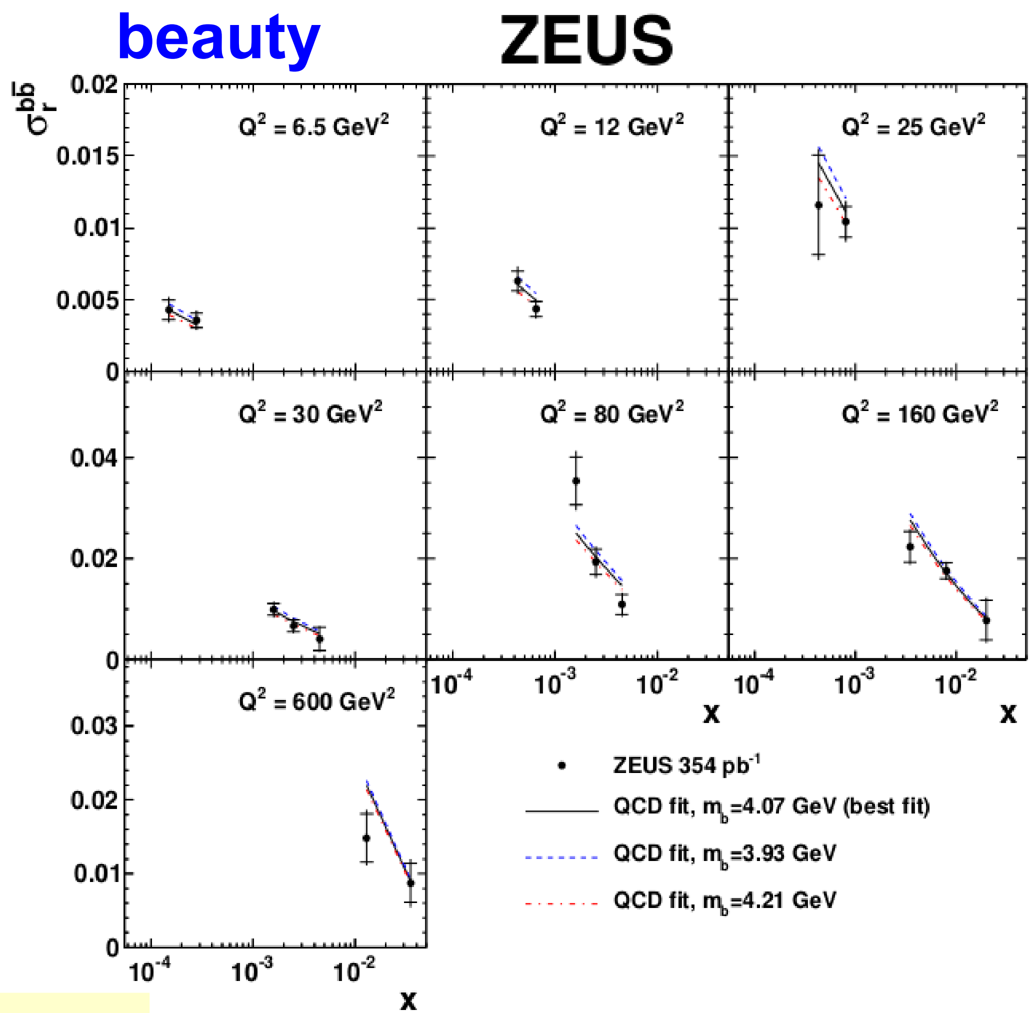
arXiv:1405.6915

Beauty + charm in DIS: $\sigma_r^{Q\bar{Q}}$

charm ZEUS



beauty ZEUS



Comparison of this F_2^{cc} measurement (black) with:

- HERA combined result of 2013 (red, more later on)
- D*, D$^+$ ZEUS recent measurements (blue, magenta, not yet in the combination):

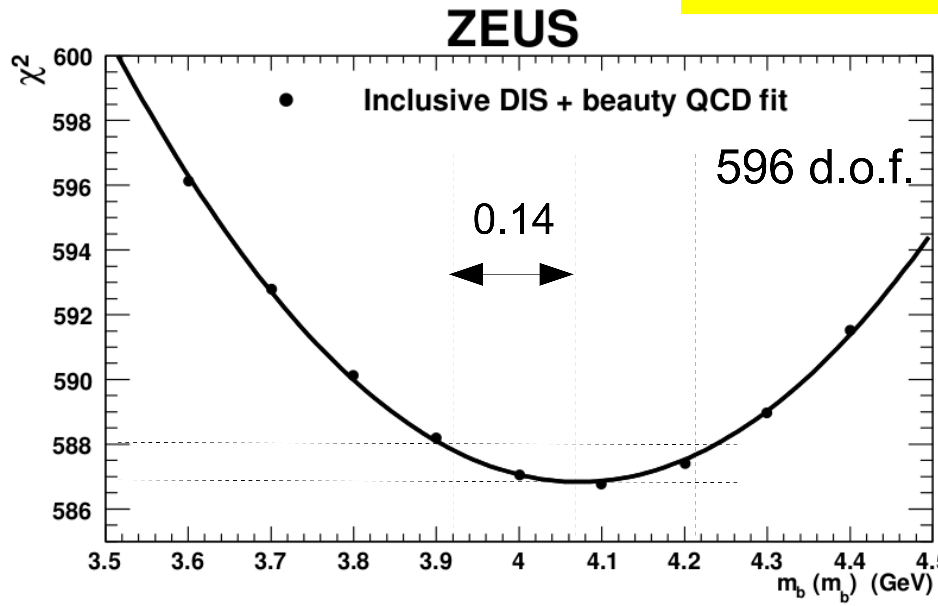
→ **Good agreement and precision**

Most precise F_2^{bb} measurement!

Sensitivity to **m_b**

arXiv:1405.6915

m_b measurement



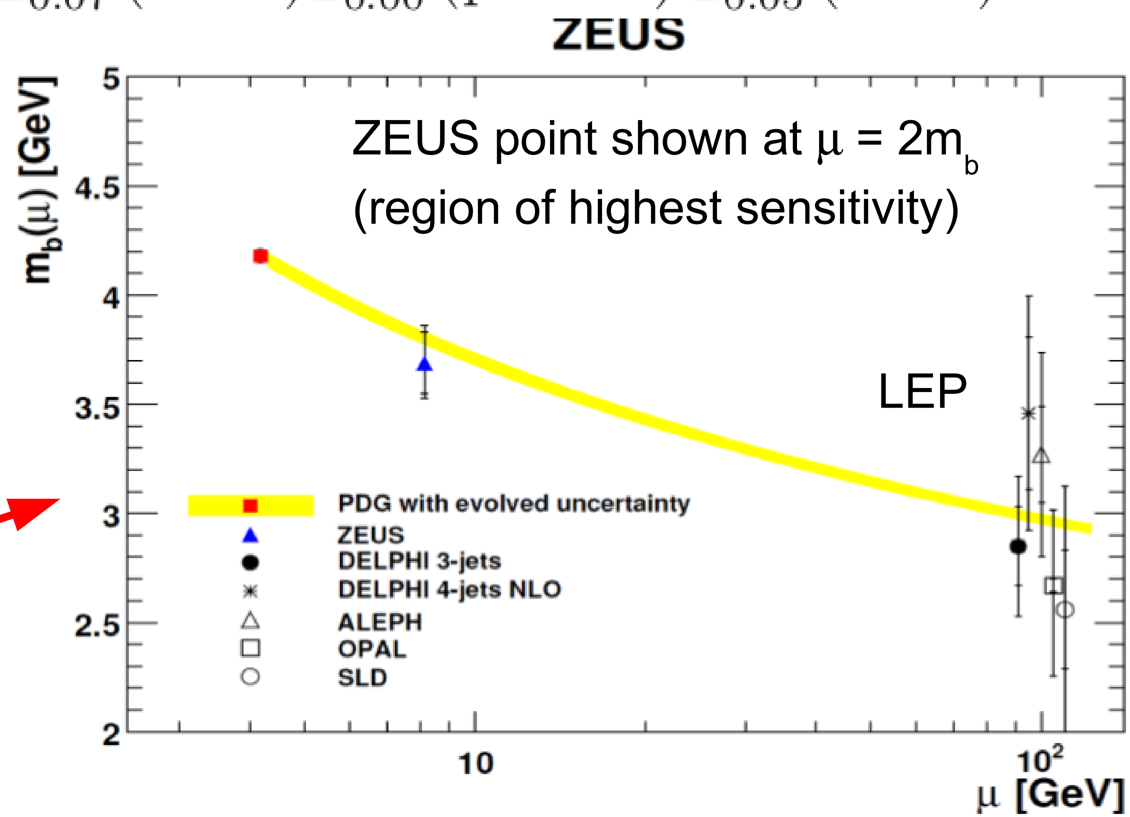
- PDF fit of σ_r^{bb} (17 points χ^2=11.4) and HERA I inclusive DIS under different assumptions of the m_b running mass.
- HERAfitter. FFNS + MSbar scheme. OPENQCDRAD option for evolution.
- No sensitivity using inclusive data only

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

Consistent with W.A.,
$m_b(m_b)$ = (4.18 ± 0.03) GeV

1st measurement
at a hadron collider!

Consistent with running expected from QCD



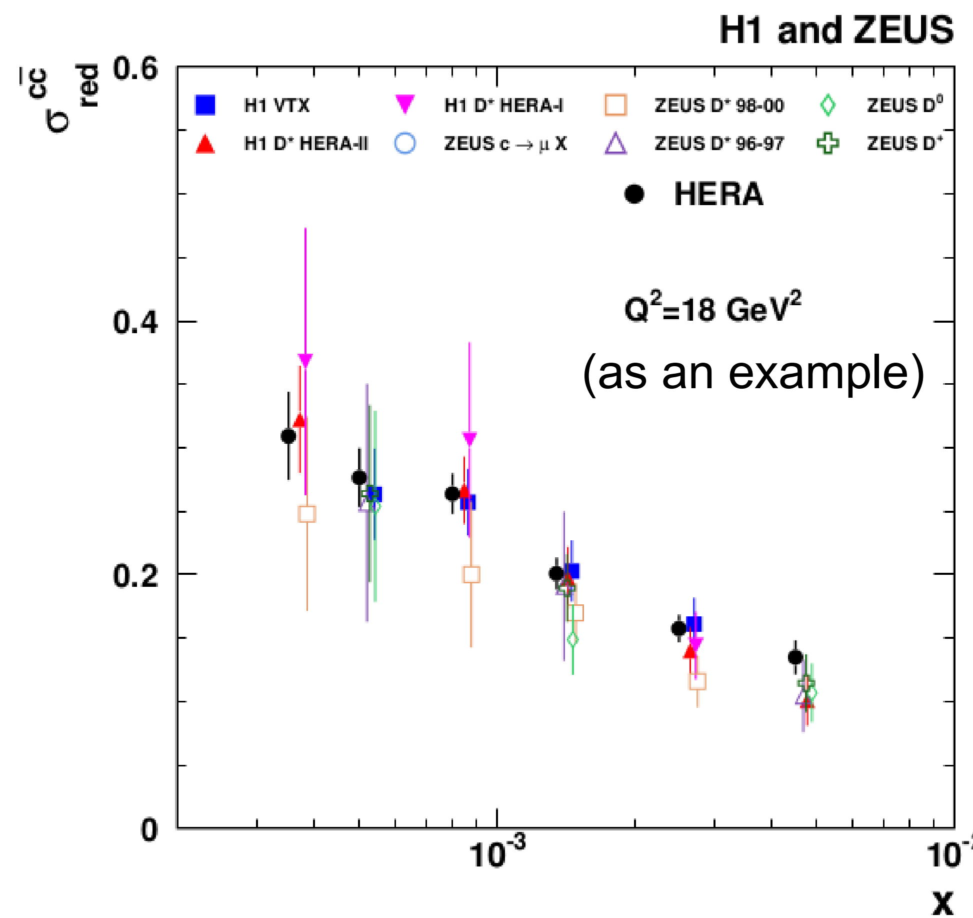
EPJC 73 (2013) 231

Combination of HERA charm analyses

	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

A large variety of tagging techniques complementarity of data-sets → significant gain in the combination

- 155 data points in 52 bins in x-Q^2
- correlations properly accounted for in the combination (black bullets).
- good consistency χ^2 /ndf = 62/103
- 10% uncertainty on average,
- 6% at small x and medium Q^2

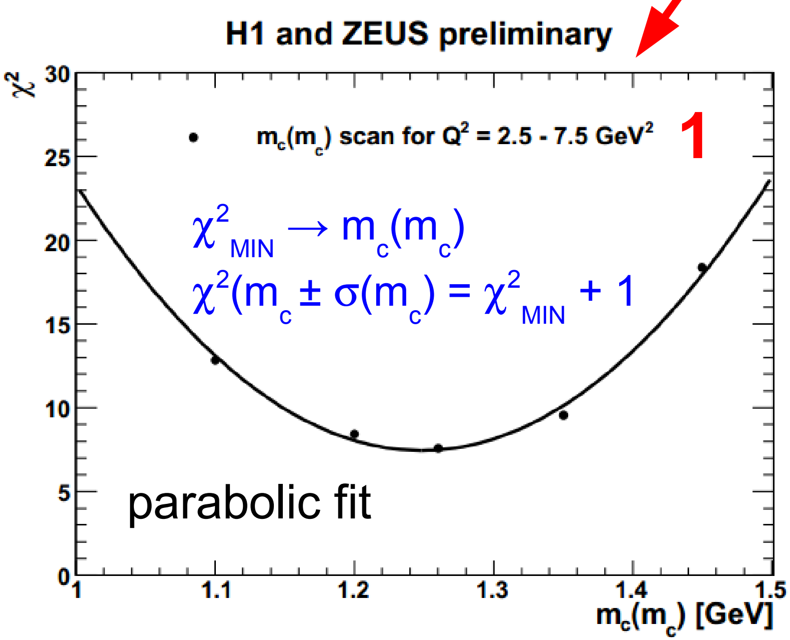


Extraction of m_c in Q^2 bins

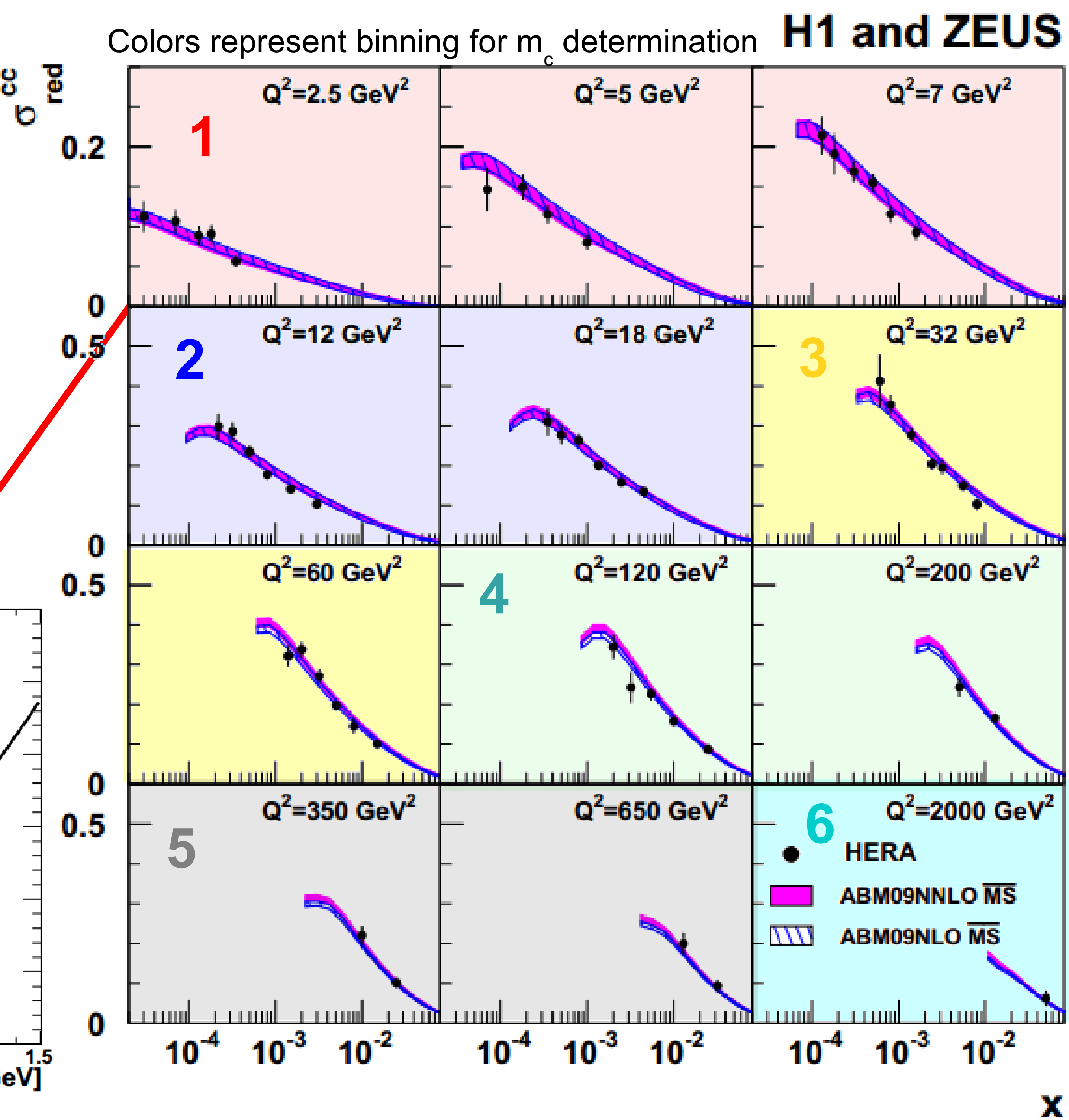
H1-prelim-14-071, ZEUS-prel-14-006

- Combined data compared to ABM predictions in the massive scheme (FFNS) both at NLO and NNLO
- NLO and NNLO are similar
- good description of the data in the whole range
- at small Q^2 m_c is the dominant source of the theory uncertainty

→ use data to constrain m_c



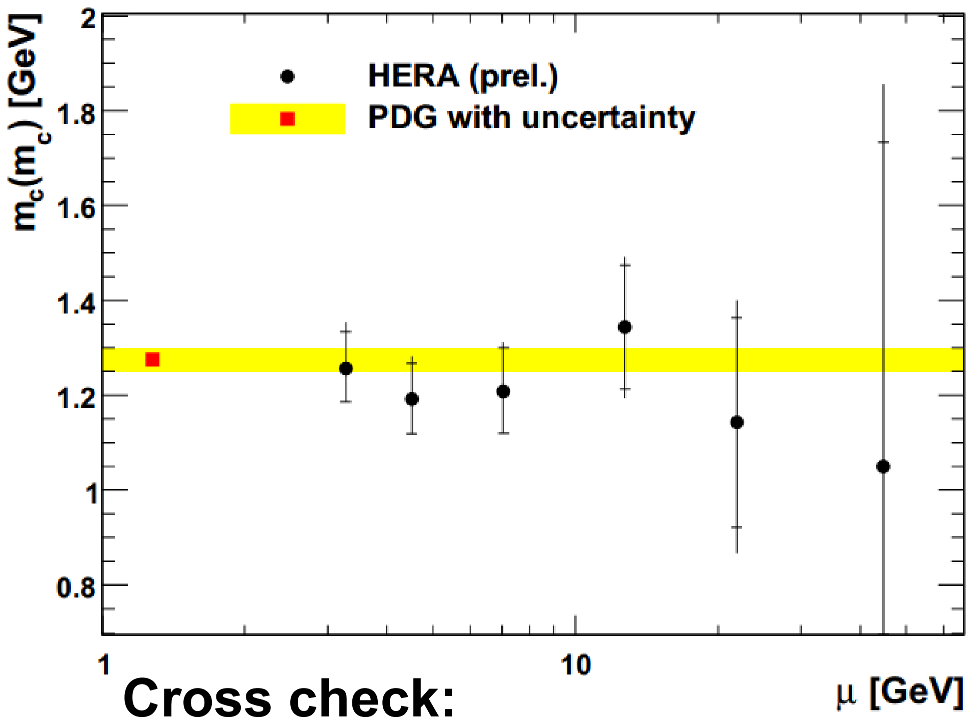
Colors represent binning for m_c determination



Extraction of running m_c

$$\mu = \sqrt{\langle Q^2 \rangle + 4m_c(m_c)^2}$$

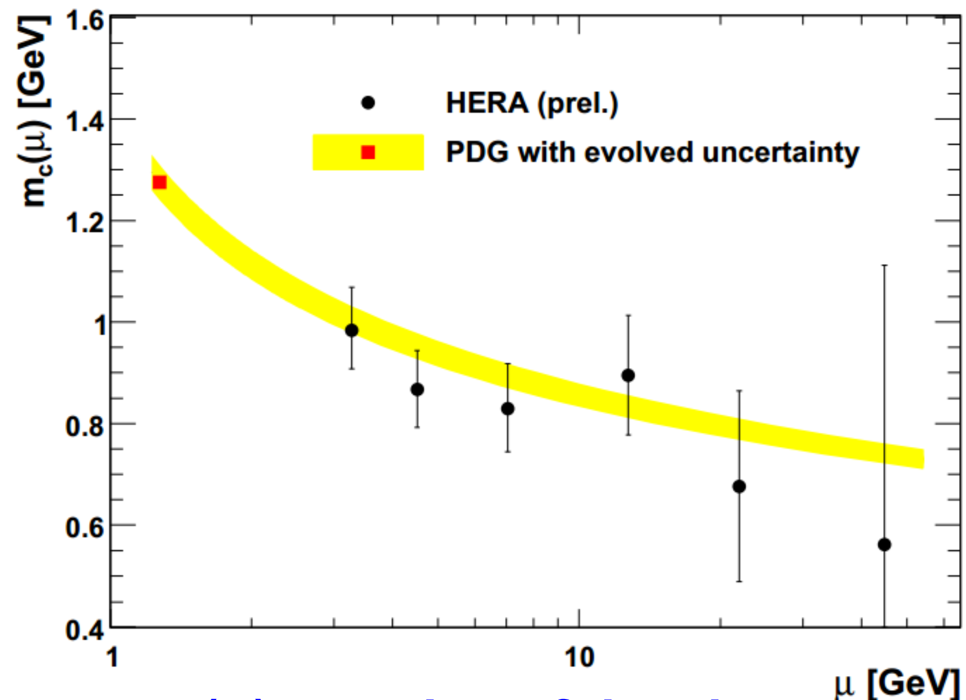
$m_c(m_c)$ vs μ



Cross check:

$m_c(m_c)$ is independent on Q^2

$m_c(\mu)$ vs μ



$m_c(\mu)$: running of the charm quark mass with the scale μ

- Non-trivial consistency check of m_c running in the MSbar renormalisation scheme using sets of data characterised by different hard scales (Q^2 binning).
- m_Q running: available (only for beauty) from LEP now also for charm from HERA

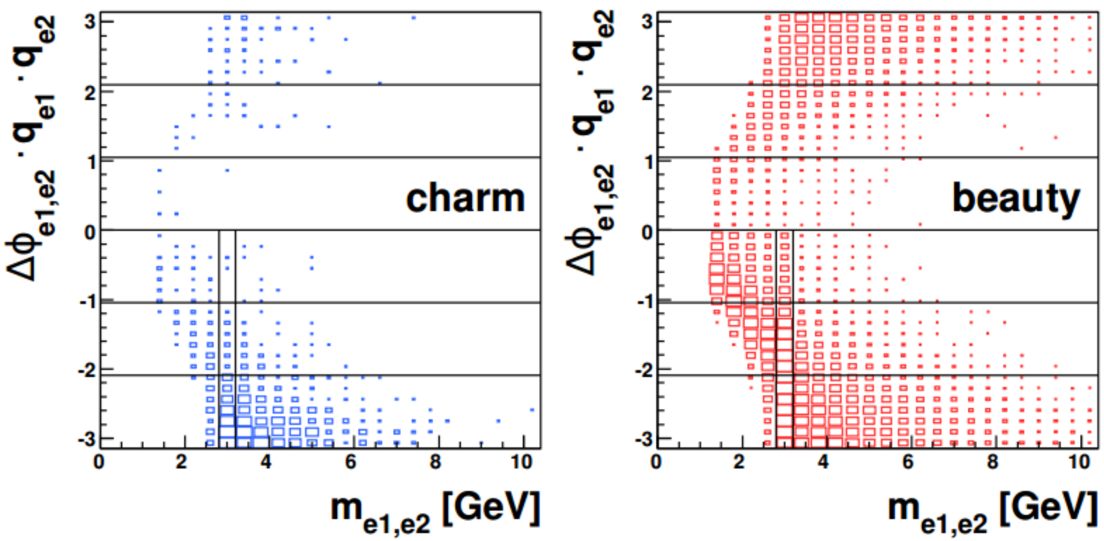
Eur. Phys. J. C72 (2012) 2148

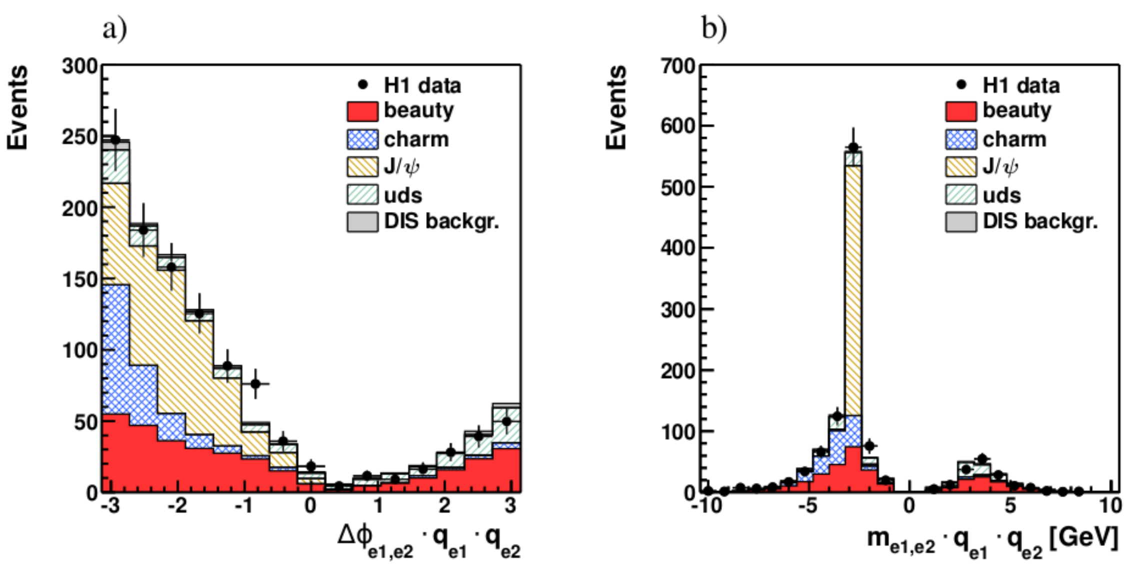
Beauty photoproduction at threshold using di-electrons

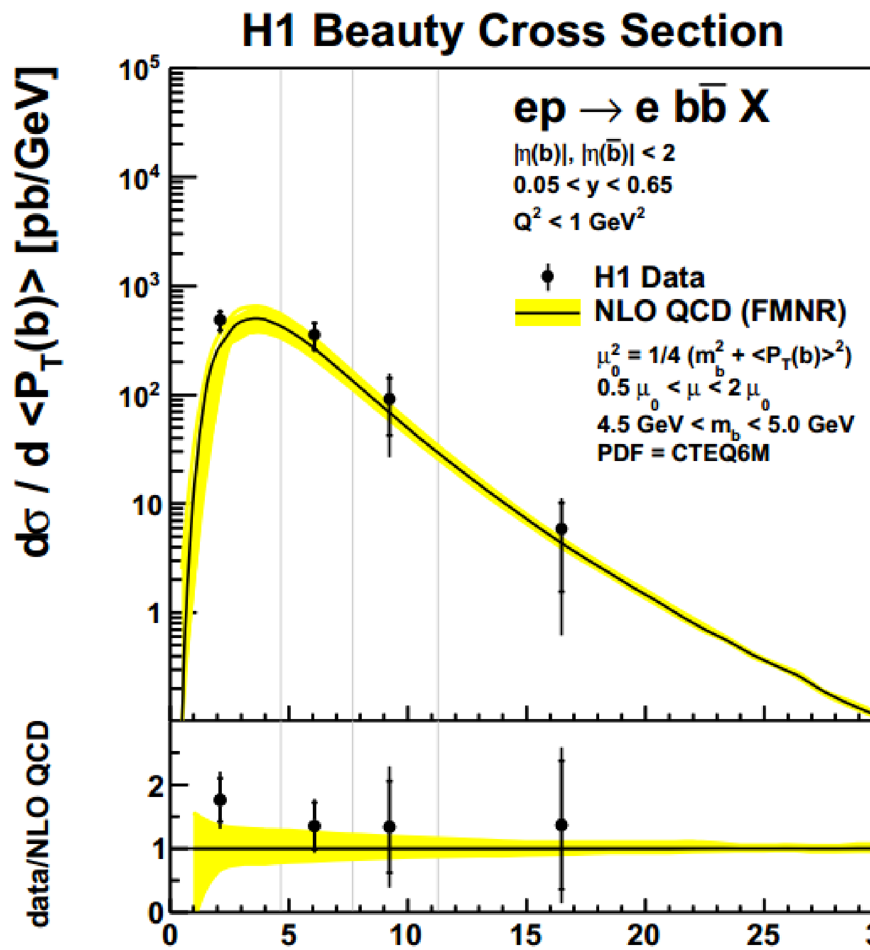
Rich information from angular/charge correlations

Dependence on the e origin: same/different quarks parents, stage in the decay chain

$m_{e1e2}\, q(e_1)q(e_2)$ vs $\Delta\phi_{e1e2}\, q(e_1)q(e_2)$





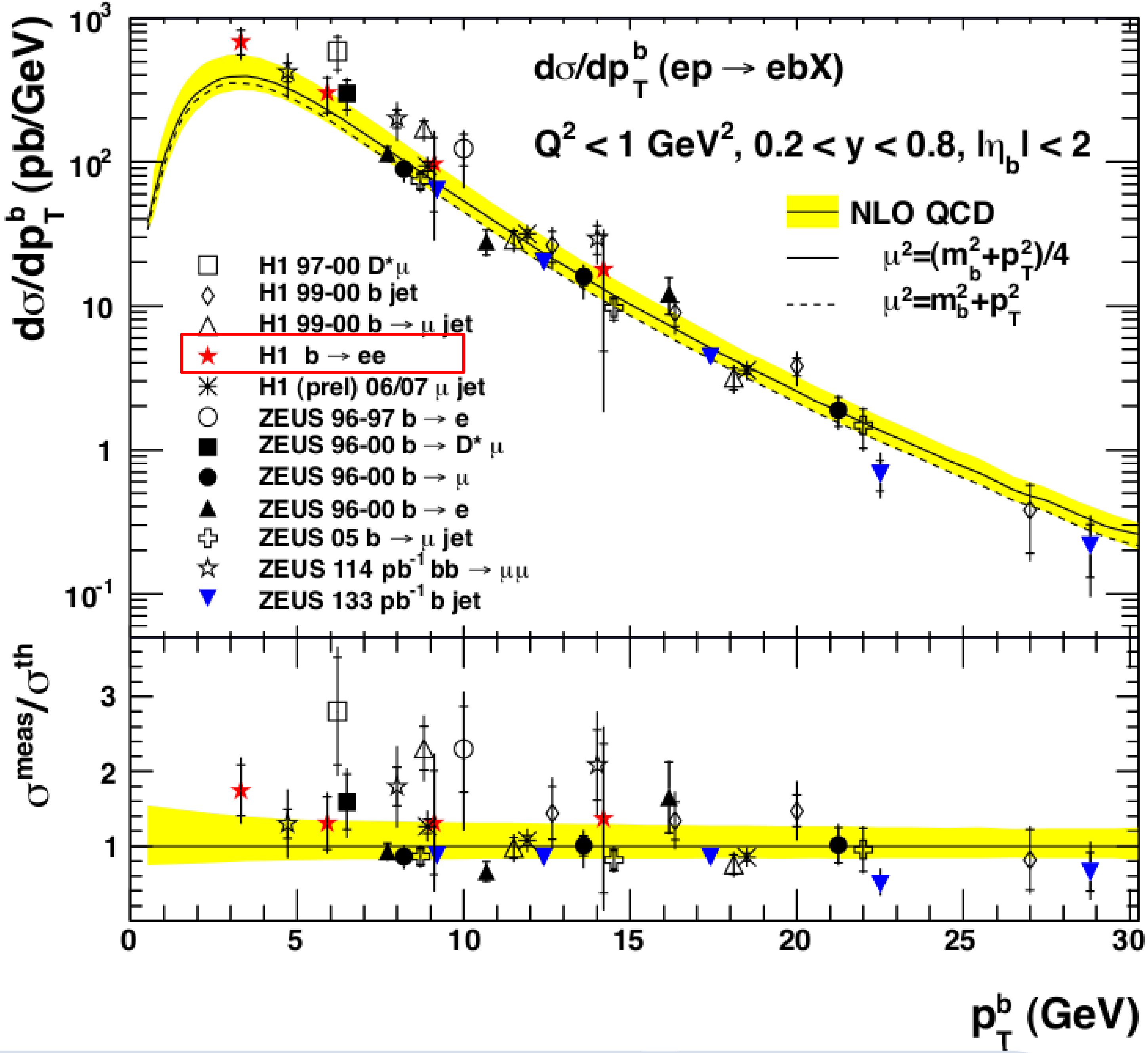


- $1 < p_T(e) < 5$ GeV
- Access to lowest $p_T(b)$ values ever measured in *ep*.
- Data-NLO (FMNR) in agreement.

Overview on beauty photoproduction

Several complementary measurements over a wide $p_T(b)$ range

Generally good agreement between data and NLO calculation (FMNR program).



Summary

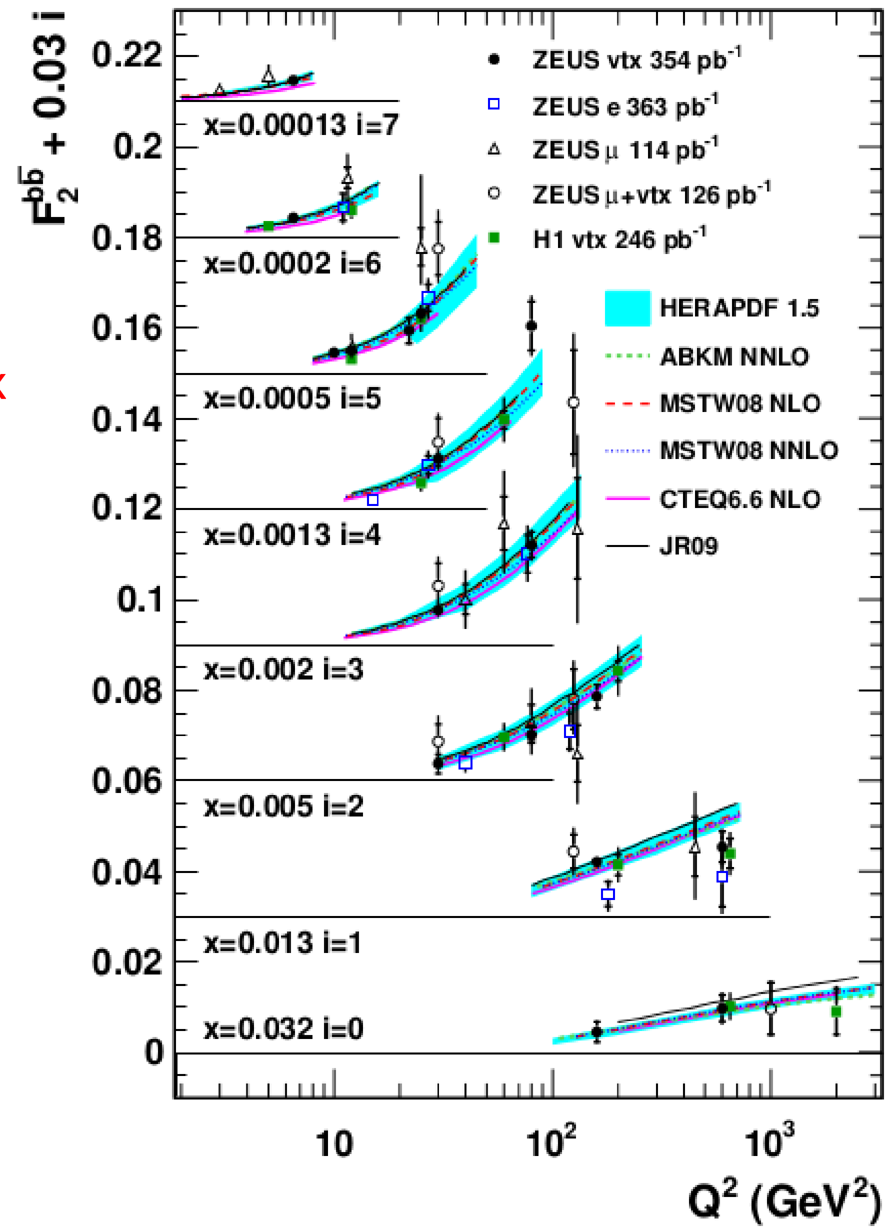
- Heavy flavours at HERA: unique environment to test pQCD (multiple-scale problem), validity of gluon PDFs.

- Accurate measurements with a variety of complementary techniques (HERA combination).

- ZEUS: b and c DIS production w inclusive 2[ry] vtx
  - differential x-sections described by FFNS NLO QCD
  - the most precise ever F_2^{bb}
  - running m_b from a NLO-QCD fit
    - 1[st] time at a hadronic collider

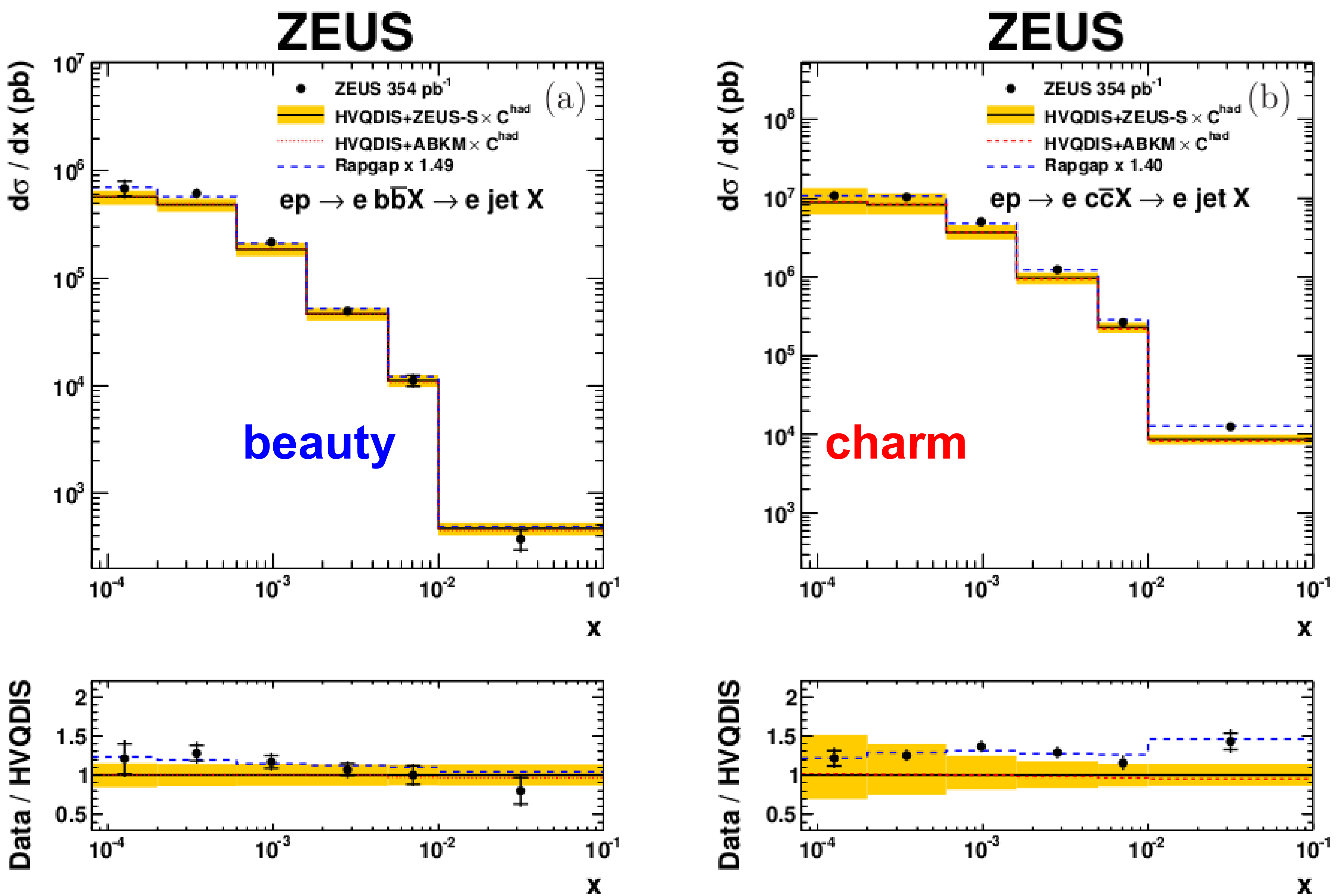
- Combination of HERA results on charm in DIS
  - Most precise measurement of F_2^{cc}
  - Running m_c from a NLO-QCD fit (1[st] time)

- Beauty in photoproduction
  - H1: near threshold production using *ee*
  - Agreement with NLO over a wide $p_T(b)$ range



Beauty + charm in DIS: x cross sections

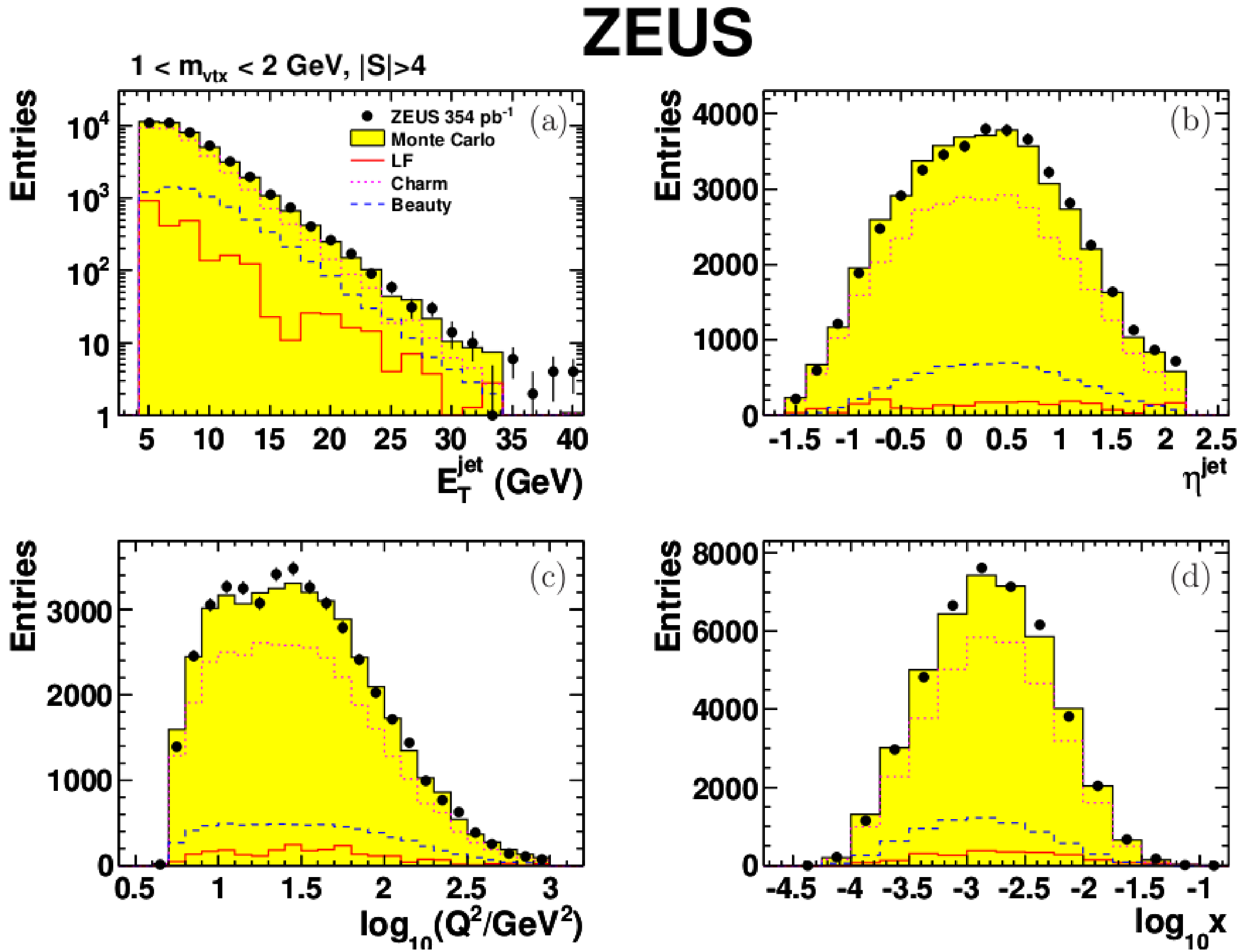
arXiv:1405.6915



Reasonable description by FFNS NLO QCD

Beauty + charm in DIS:
control distributions for the b-enriched sample

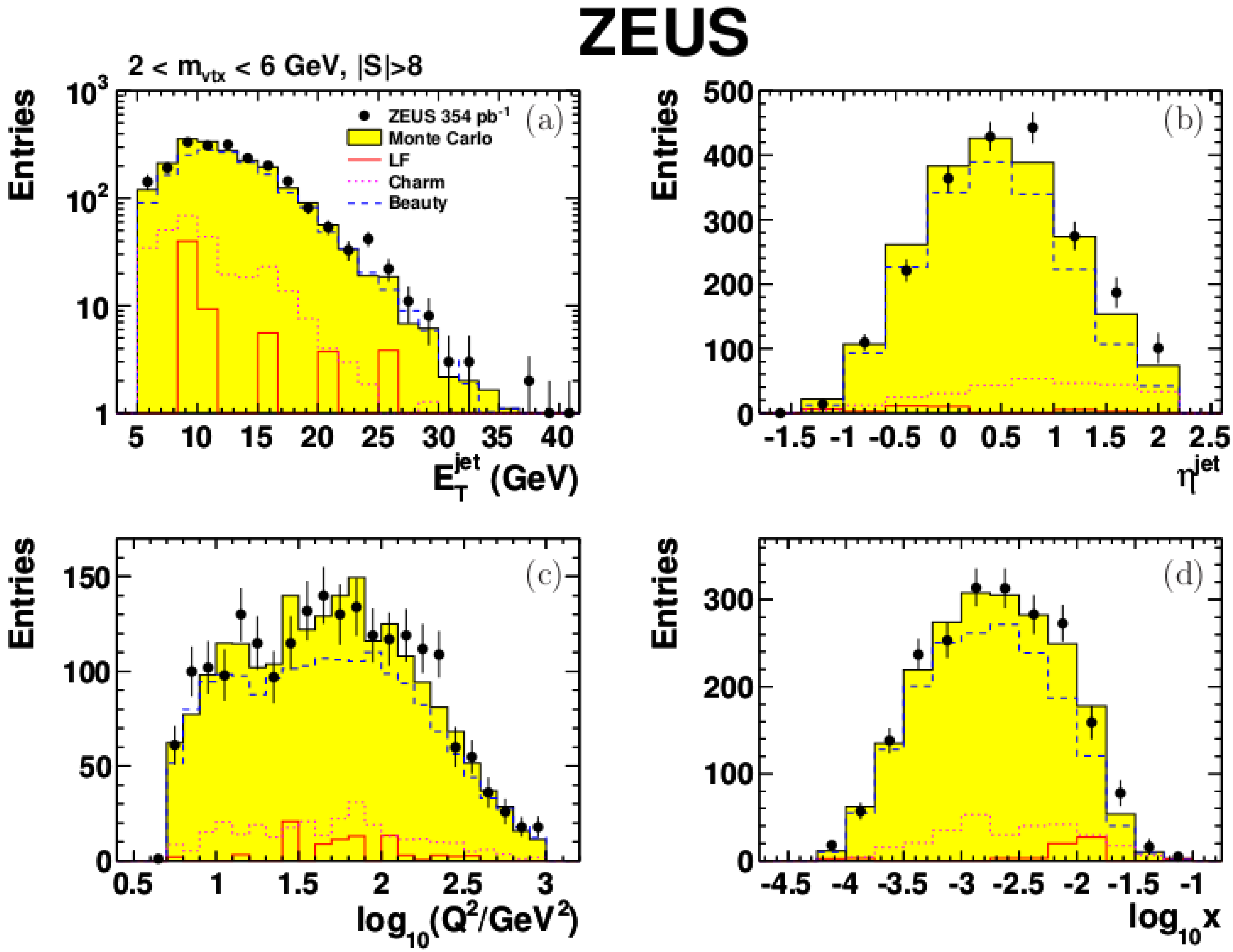
Charm enrichment:
S+-S->4
1 < mvtx < 2 GeV
High purity
charm sample!



Good description of the data by the Monte Carlo

Beauty + charm in DIS:
control distributions for the b-enriched sample

Beauty enrichmen
S+-S->8
2 < mvtx < 6 GeV
High purity
beauty sample!



Good description of the data by the Monte Carlo

Beauty + charm in DIS: systematics

	Source	Beauty (%)	Charm (%)
δ_1	Event and DIS selection	± 1.4	± 0.8
δ_2	Trigger efficiency	$+2.0$	$+1.0$
δ_3	Tracking efficiency	± 2.0	± 0.5
δ_4	Decay-length smearing	± 1.3	± 1.2
δ_5	Signal extraction procedure	± 0.8	± 0.8
δ_6	Jet energy scale	± 0.7	± 0.9
δ_7	EM energy scale	± 0.3	± 0.1
δ_8	Charm Q^2 reweighting $(\delta_8^{Q^2,c})$	± 1.7	± 1.8
	Beauty Q^2 reweighting $(\delta_8^{Q^2,b})$	± 2.9	± 0.4
	Charm $\eta^{\rm jet}$ reweighting $(\delta_8^{\eta^{\rm jet},c})$	${}^{+0.3}_{-0.4}$	${}^{+1.5}_{-1.0}$
	Beauty $\eta^{\rm jet}$ reweighting $(\delta_8^{\eta^{\rm jet},b})$	${}^{+0.7}_{-0.4}$	${}^{+0.0}_{-0.1}$
	Charm $E_T^{\rm jet}$ reweighting $(\delta_8^{E_T^{\rm jet},c})$	${}^{+1.7}_{-1.3}$	${}^{+2.2}_{-1.7}$
	Beauty $E_T^{\rm jet}$ reweighting $(\delta_8^{E_T^{\rm jet},b})$	${}^{+5.4}_{-4.2}$	${}^{+0.5}_{-0.6}$
δ_9	Light-flavour asymmetry	± 0.4	± 2.0
δ_{10}	Charm fragmentation function	-0.9	$+1.0$
δ_{11}	Beauty fragmentation function	-3.1	$+0.0$
δ_{12}	BR and fragmentation fractions	${}^{+1.8}_{-2.1}$	${}^{+3.5}_{-2.6}$
δ_{13}	Luminosity measurement	± 1.9	± 1.9
	Total	${}^{+8.0}_{-7.6}$	${}^{+6.0}_{-5.1}$

Control of systemtatics at a few-percent level

Among the dominant uncertainties:

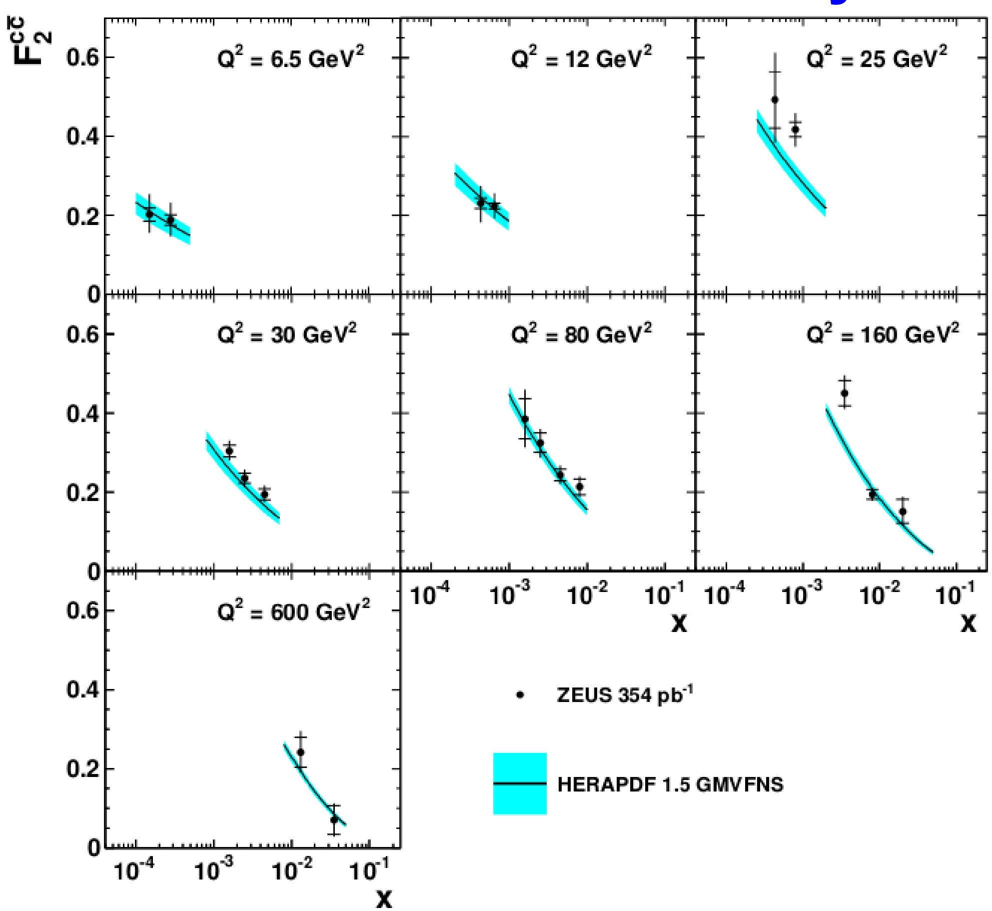
→ charm: branching ratios and fragmentation fractions knowledge

→ beauty: MC model dependence

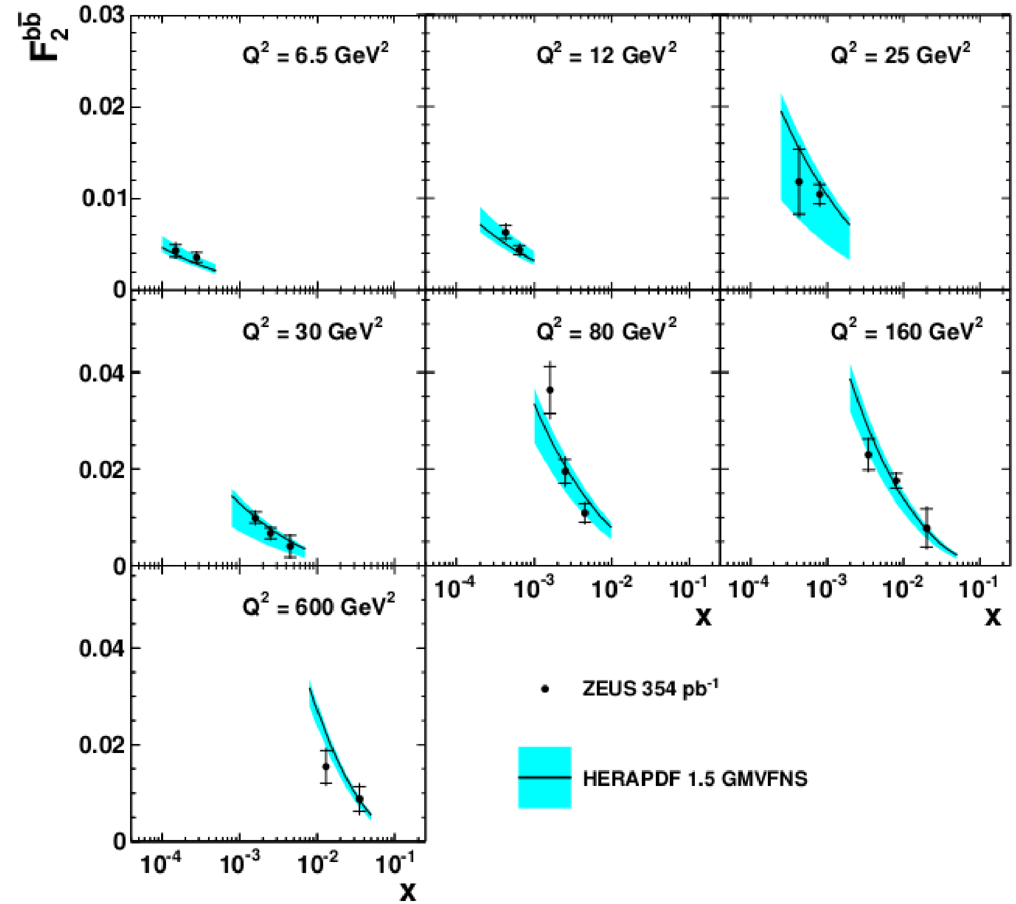
arXiv:1405.6915

Beauty + charm in DIS: F_2^{QQ}

ZEUS beauty



ZEUS charm



H1-prelim-13-171
ZEUS-prel-13-002

D* combined cross sections

DIS selection:
$5 < Q^2 < 1000\ \mathrm{GeV}^2$
$0.02 < y < 0.7$
D^* ($K\pi\pi_s$) selection:
$1.5 < p_T(D^*) < 20$ GeV
$|\eta(D^*)| < 1.5$

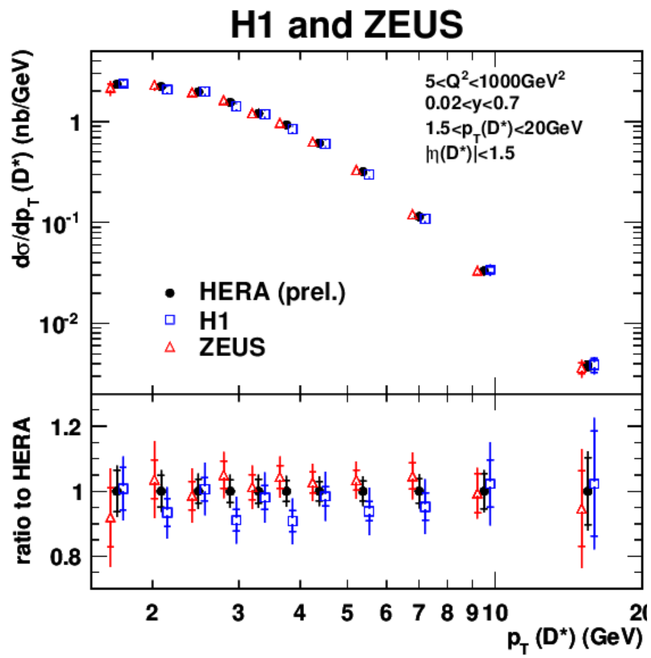
3 % beauty contribution

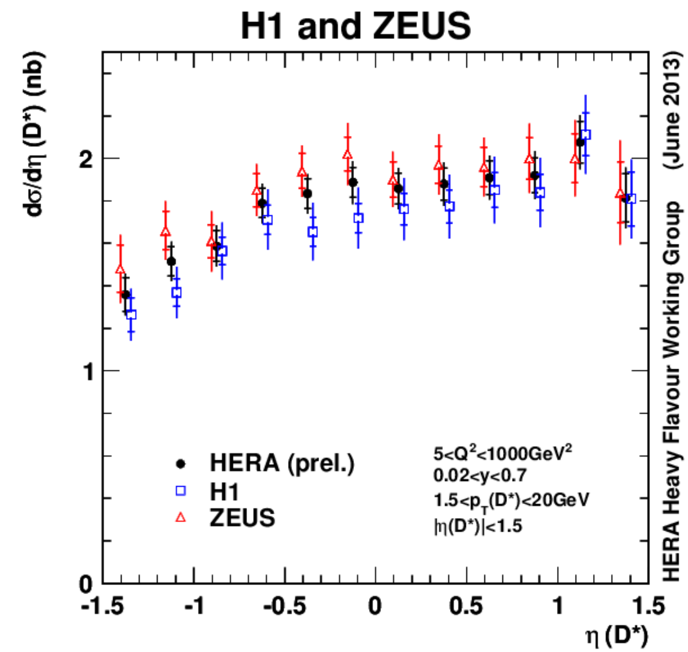
Correlations properly accounted for in the combination.

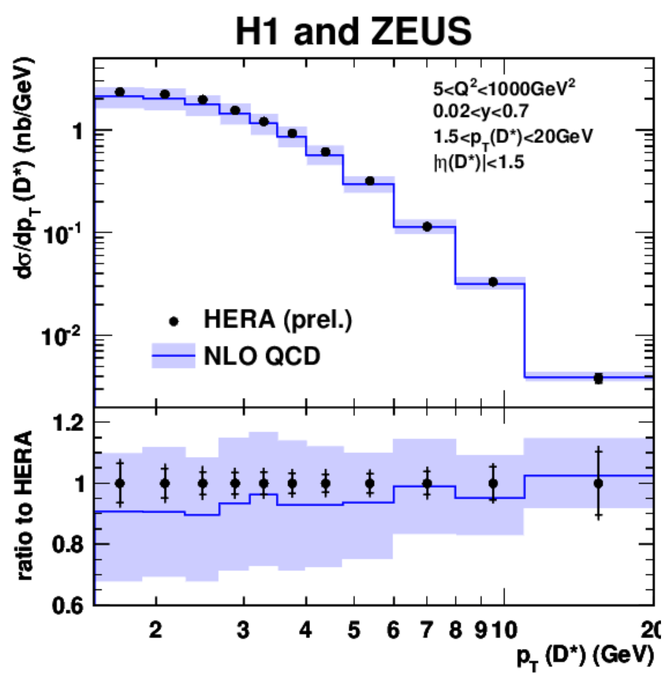
FFNS NLO QCD
$m_c(m_c)$=1.5 GeV
HERAPDF1.0

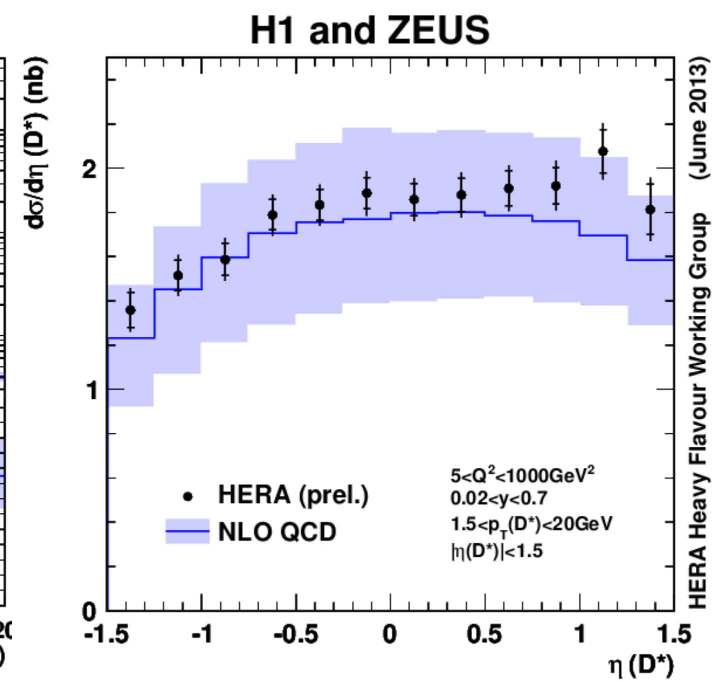
NLO has large normalization uncertainties.

It describes the data rather well (also for z, Q^2, y, in backup slides)









m_b theory errors

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

Model uncertainty: The model choices include an assumption on the strangeness fraction, f_s, the minimum Q^2 used in the data selection, $Q^2_{\min}$, and Q^2_0, the starting value for the QCD evolution. These were treated exactly as in the charm-quark mass fit [34]. Table 20 lists the choices and variations and their individual contributions to the model uncertainty attributed to the model choices.

PDF parameterisation uncertainty: The parameterisation of the PDFs is chosen as for the charm-quark mass fit [34], including the "flexible" parameterisation of the gluon distribution. An additional uncertainty is estimated by freeing three extra PDF parameters D_{u_v}, $D_{\bar{D}}$ and $D_{\bar{U}}$ in the fit which allow for small shape variations in the u_v, $\bar{U}$ and $\bar{D}$ parton distributions [34]. The effect is given in Table 20.

Fit uncertainty: For the beauty data, all uncertainties from Tables 12, 13 (experimental and 18 (extrapolation), and the statistical uncertainty, as summarised in Table 1(were accounted for in the fit. Following the discussion in Section 4, an uncertaint of 100 % on $\Delta^{\text{had}} = C^{\text{had}} - 1$ (Table 6) was introduced as an additional uncorrelate uncertainty. The uncertainties arising from the default PDF parameterisation [34 including the so-called "flexible" gluon parameterisation, are implicitly part of th fit uncertainty.

The statistical uncertainties and the uncertainties δ_1, δ_2, δ_4^{core}, δ_5 and δ_{12} from Tables and 13 were treated as uncorrelated, while all other uncertainties, including thos from luminosity and from Table 18, were treated as point-to-point correlated. Th "multiplicative" uncertainty option [96] from HERAFitter was used. In the case c asymmetric uncertainties, the larger was used in both directions. The uncertaintie of the inclusive data were used as published. Since the inclusive data were take during the HERA I phase and the beauty data during the HERA II phase, the tw sets of data were treated as uncorrelated.

Perturbative scheme and related theory uncertainty: The parameters used for the perturbative part of the QCD calculations also introduce uncertainties; the effects are listed in Table 20. As in previous analyses [34, 94, 95], the $\overline{\text{MS}}$ running-mass scheme [100–102] was chosen for all calculations of the reduced cross sections and the fit because it shows better perturbative convergence behaviour than the pole-mass scheme. In order to allow the low-Q^2 points of the inclusive DIS measurement to be included without the need of additional charm-quark mass corrections, the number of active flavours (NF) was set to three, i.e. the charm contribution was also treated in the fixed-flavour-number scheme. Accordingly, the strong coupling constant was set to $\alpha_s(M_Z)^{\text{NF}=3} = 0.105 \pm 0.002$, corresponding to $\alpha_s(M_Z)^{\text{NF}=5} = 0.116 \pm 0.002$.

The theoretical prediction of the charm contribution to the inclusive DIS data is obtained using the running charm-quark mass obtained from the fit to the combined HERA charm data [34], i.e. $m_c(m_c) = (1.26 \pm 0.06)$ GeV. It was checked that, as expected, using this mass together with the central PDF from the m_b fit, a good description of the combined HERA charm data [34] was obtained. Thus, the charm contribution to the inclusive data should be well described.

The renormalisation and factorisation scales were set to $\mu = \mu_R = \mu_F = \sqrt{Q^2 + 4m^2}$ with $m = 0, m_c, m_b$ for the light quark, charm, and beauty contributions, respectively, and varied simultaneously by a factor two as in previous analyses [94, 95].

Charm data combination method

3.4 Combination method

The combination of the data sets uses the χ^2 minimisation method developed for the combination of inclusive DIS cross sections [32, 34]. The χ^2 function takes into account the correlated systematic uncertainties for the H1 and ZEUS cross section measurements. For an individual data set, e, the χ^2 function is defined as

$$\chi^2_{\text{exp},e}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma_j^{i,e} m^i b_j - \mu^{i,e}\right)^2}{\left(\delta_{i,e,\text{stat}}\,\mu^{i,e}\right)^2 + \left(\delta_{i,e,\text{uncor}}\,m^i\right)^2} + \sum_j b_j^2 \,. \tag{5}$$

Here $\mu^{i,e}$ is the measured value of $\sigma_{\text{red}}^{c\bar{c}}(x_i, Q_i^2)$ at an (x, Q^2) point i and $\gamma_j^{i,e}$, $\delta_{i,e,\text{stat}}$ and $\delta_{i,e,\text{uncor}}$ are the relative correlated systematic, relative statistical and relative uncorrelated systematic uncertainties, respectively. The vector $\boldsymbol{m}$ of quantities m^i expresses the values of the combined cross section for each point i and the vector $\boldsymbol{b}$ of quantities b_j expresses the shifts of the correlated systematic uncertainty sources, j, in units of the standard deviation. Several data sets providing a number of measurements are represented by a total χ^2 function, which is built from the sum of the $\chi^2_{\text{exp},e}$ functions of all data sets

$$\chi^2_{\text{tot}} = \sum_e \chi^2_{\text{exp},e} \,. \tag{6}$$

The combined reduced cross sections are given by the vector $\boldsymbol{m}$ obtained by the minimisation of χ^2_{tot} with respect to $\boldsymbol{m}$ and $\boldsymbol{b}$. With the assumption that the statistical uncertainties are constant and that the systematic uncertainties are proportional to m^i, this minimisation provides an almost unbiased estimator of $\boldsymbol{m}$.

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MSbar running mass ↔ pole mass

$$m_c(Q) = m_{c,\text{pole}}\left[1 - \frac{\alpha_s}{\pi} - \frac{3\alpha_s}{4\pi}\ln\left(\frac{Q^2}{m_c(m_c)^2}\right)\right]$$

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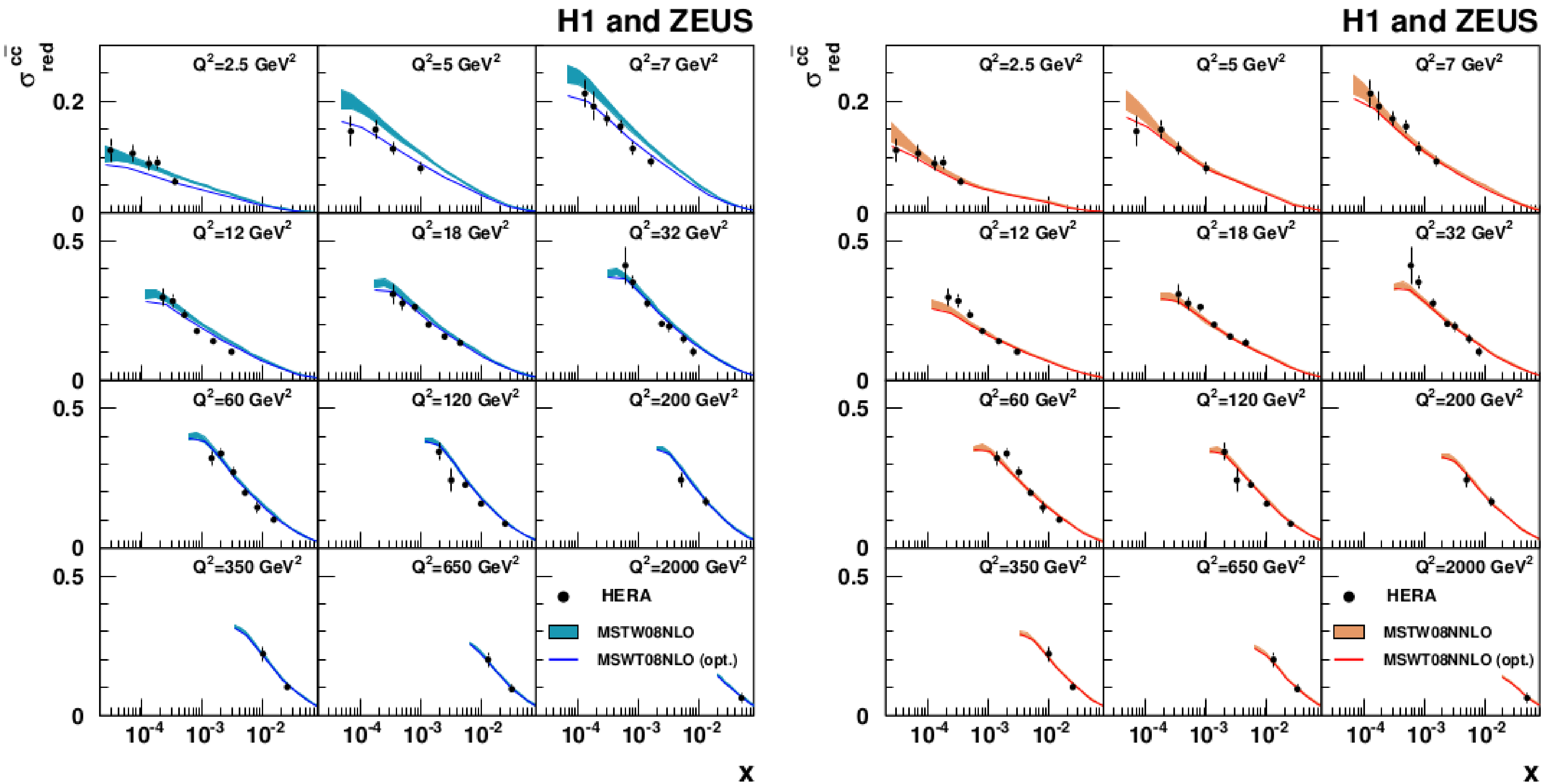
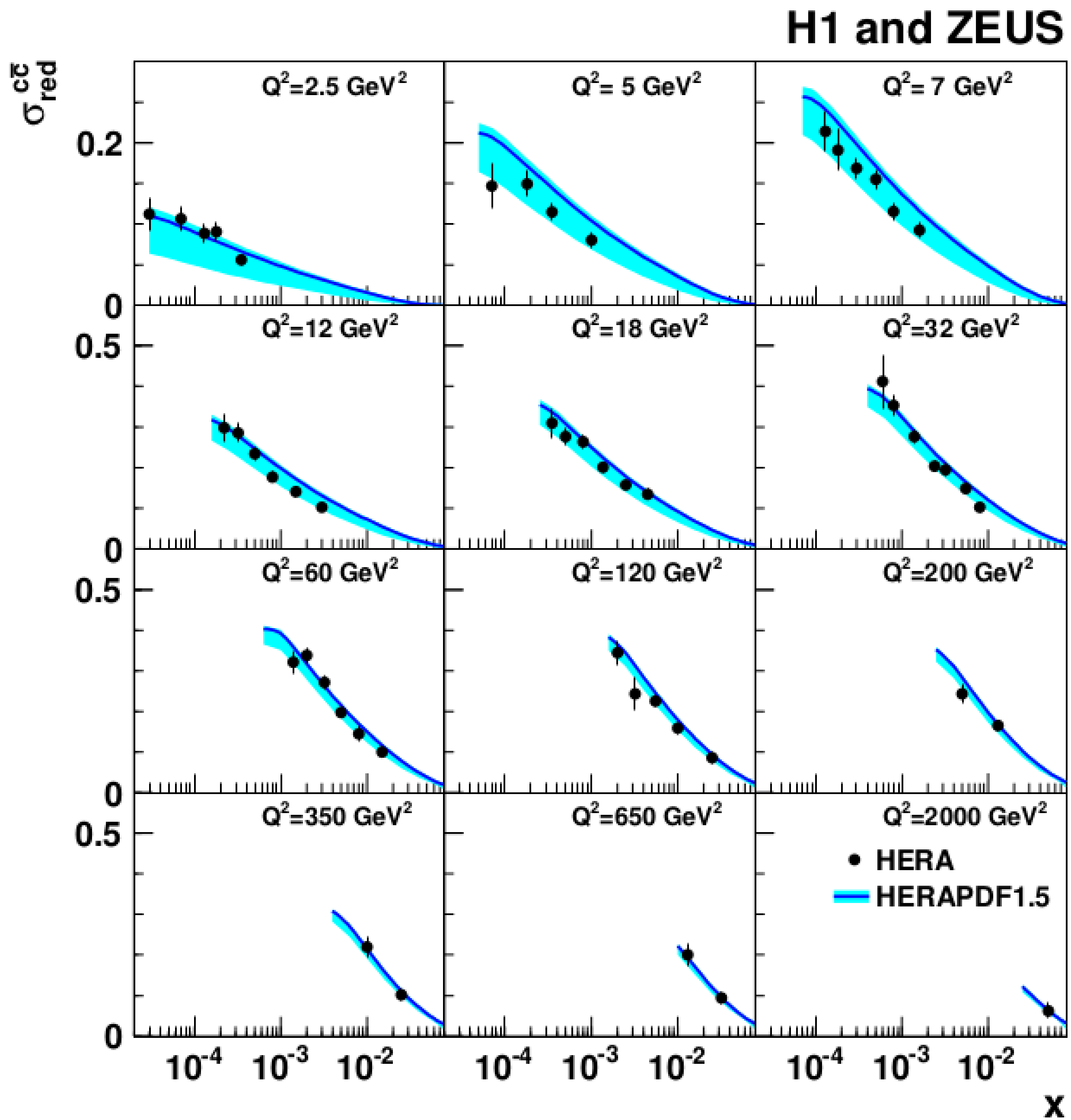
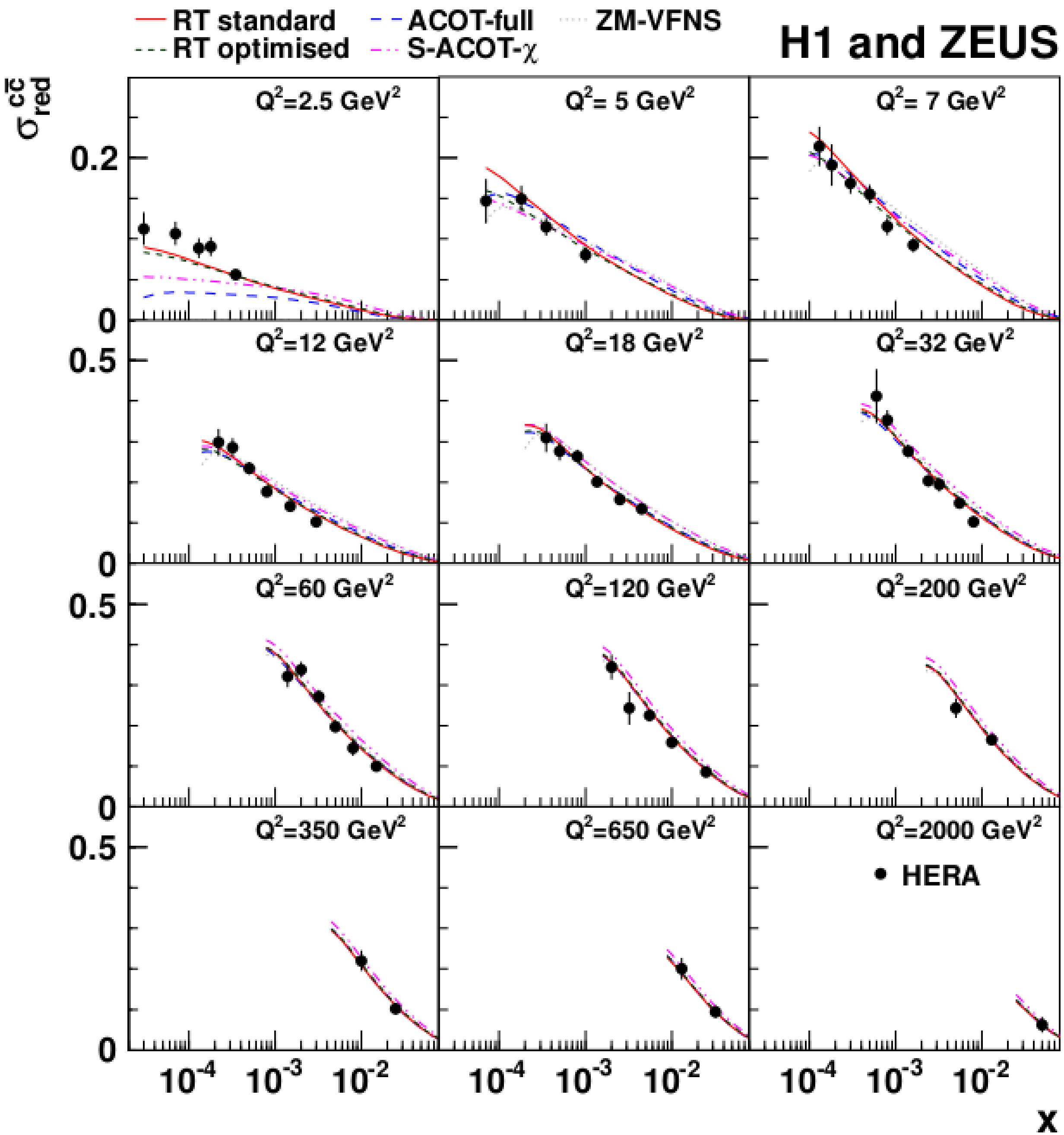



H1 and ZEUS
$\sigma_{red}^{c\bar{c}}$
Q²=2.5 GeV²
Q²= 5 GeV²
Q²= 7 GeV²
Q²=12 GeV²
Q²=18 GeV²
Q²=32 GeV²
Q²=60 GeV²
Q²=120 GeV²
Q²=200 GeV²
Q²=350 GeV²
Q²=650 GeV²
Q²=2000 GeV²
HERA
HERAPDF1.5
0.2
0.5
0
10⁻⁴
10⁻³
10⁻²
x


RT standard
RT optimised
ACOT-full
S-ACOT-χ
ZM-VFNS
H1 and ZEUS
σ red cc̄
Q²=2.5 GeV²
Q²= 5 GeV²
Q²= 7 GeV²
Q²=12 GeV²
Q²=18 GeV²
Q²=32 GeV²
Q²=60 GeV²
Q²=120 GeV²
Q²=200 GeV²
Q²=350 GeV²
Q²=650 GeV²
Q²=2000 GeV²
HERA
0.2
0.5
0
10⁻⁴
10⁻³
10⁻²
x

Eur. Phys. J. C72 (2012) 2148

Beauty photoproduction at threshold using di-electrons