Heavy quark production in DIS

(H1/ZEUS combined)

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New Trends in High-Energy Physics, Odessa, Ukraine, May 14

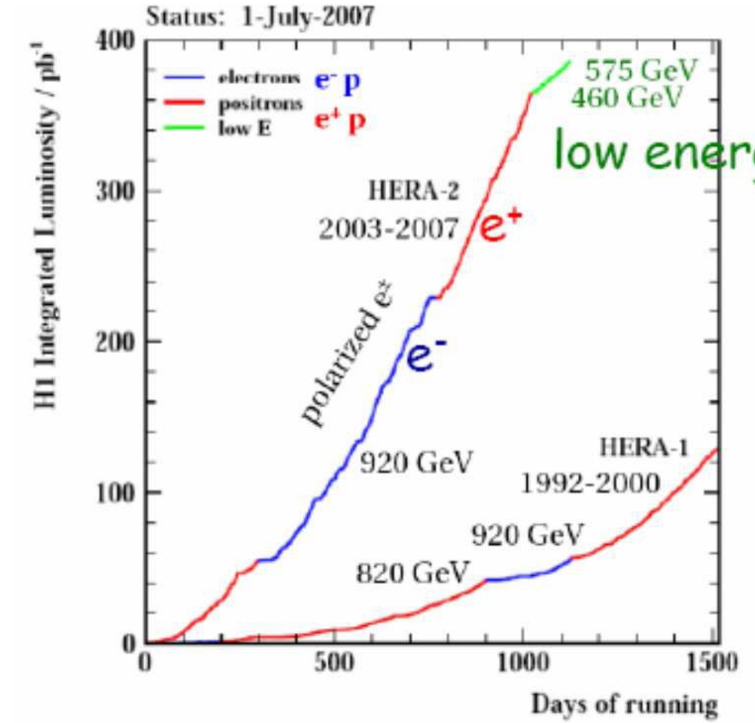
Motivation

- HERA provide important input for tests of QCD
- at HERA heavy-flavour production in DIS proceeds predominantly via the boson-gluon-fusion
- cross section depends strongly on the gluon distribution and heavy-quark mass → this mass provides a hard scale for the applicability of perturbative QCD
- other hard scales are also present in this process: the transverse momenta of the outgoing quarks and the and Q^2 of the exchanged photon.
- The presence of several hard scales complicates the calculation of heavy-flavour production in pQCD

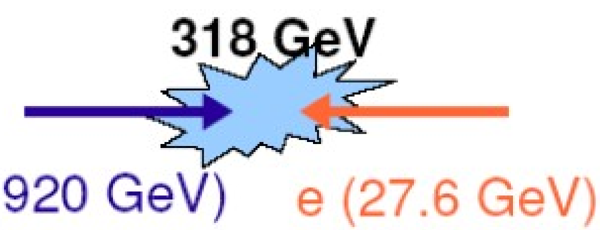
Different approaches have been developed to cope with the multiple scale problem inherent in this process: massive fixed-flavour-number scheme (FFNS) and different implementations of the variable- flavour-number scheme (VFNS)

HERA with two general purpose detectors H1 and ZEUS

1992: Hadron-Electron Ring Accelerator (HERA) @ DESY



HERA:



HERA I: ~ 130 pb^{-1} (physics)

HERA II: ~ 380 pb^{-1}(physics)

Collected ~0.5 fb-1 of integrated luminosity by each experiment

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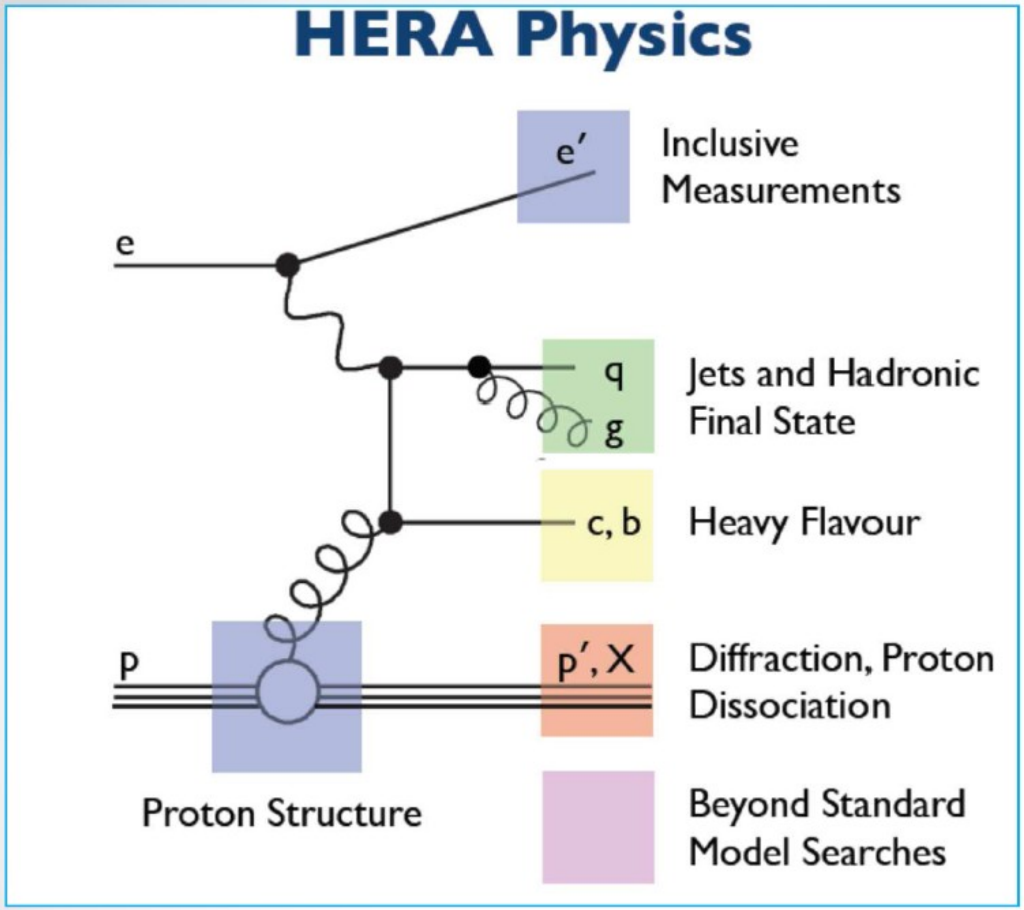
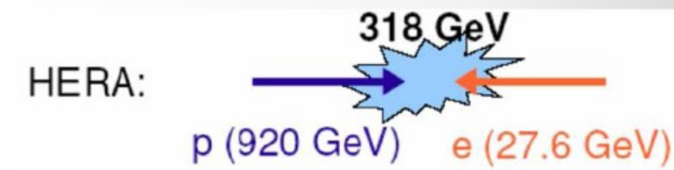




- *located* at Hamburg, Germany;
- *operated during* 1992-2007;
- *Two data-taking periods*:
  - ➡ HERA I (92-00)
  - ➡ HERA II (03-07)

HERA operated with 4 different proton beam energies (Ep):

HERA II:

- **920 GeV** - High Energy Run (HER);
- **575 GeV** - Middle Energy Run (MER);
- **460 GeV** - Low Energy Run (LER);

HERA I:

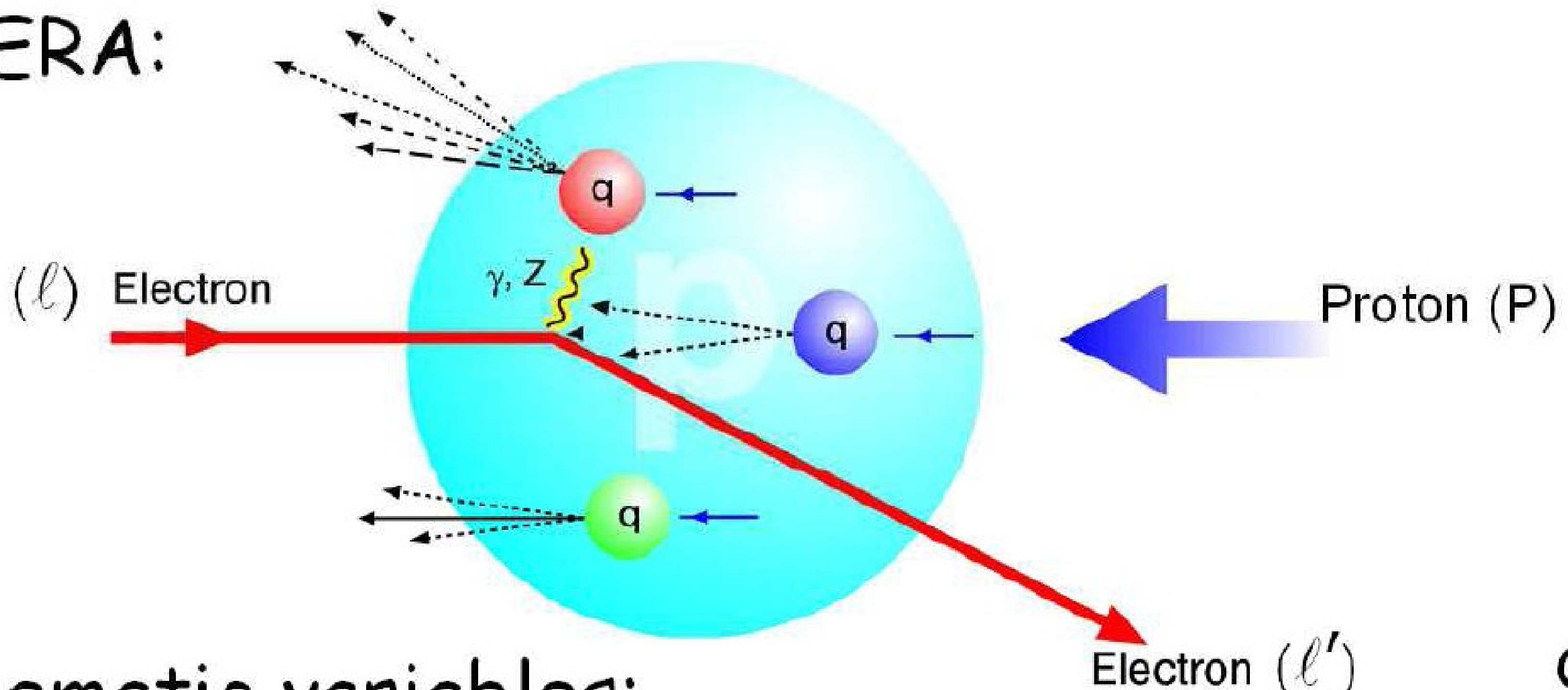
93/98 years - energy **820 GeV**;

and electron beam energy (Ee):27.5 GeV

HERA experiments ZEUS & H1 - one of the best QCD laboratories

Deep inelastic scattering at HERA

HERA:



$$q = \ell - \ell'$$

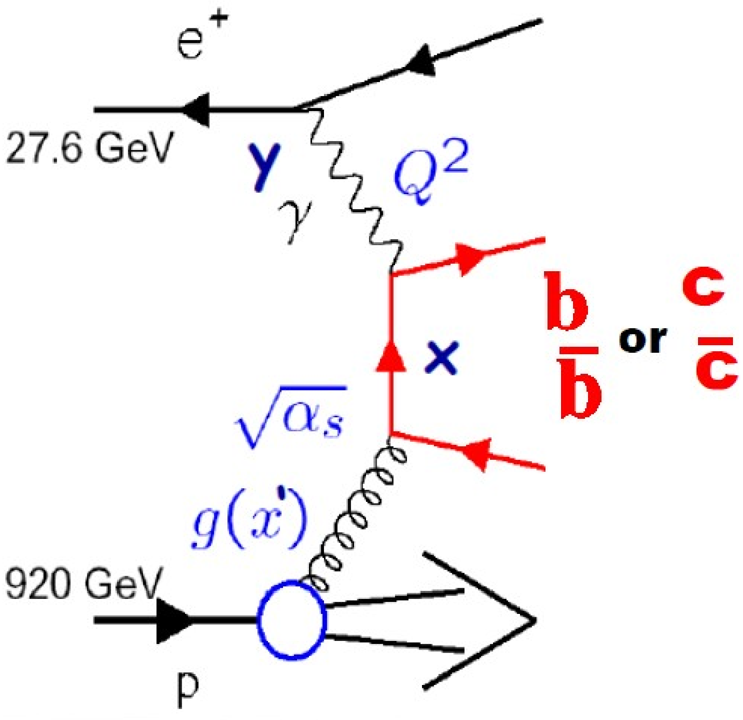
kinematic variables:

$Q^2 = -q^2$	photon (or Z) virtuality, squared momentum transfer
$x = \dfrac{Q^2}{2Pq}$	Bjorken scaling variable, for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent
$y = \dfrac{qP}{\ell P}$	inelasticity, γ momentum fraction (of e)

$Q^2 \lesssim 1\ GeV^2$: photoproduction

$Q^2 \gtrsim 1\ GeV^2$: DIS

Charm and beauty at HERA



- boson-gluon fusion is a dominant process for the charm creation in DIS;
- charm contribution to the inclusive DIS cross section is up to 30% at HERA;
- beauty cross sections much smaller than charm: $\sigma_{cc} \sim 1\ \mu b$ $\sigma_{bb} \sim 10$ nb;
- heavy flavour production sensitive to the gluon density of the proton;
- possibility to test pQCD;
- better understanding of the charm and beauty is one of the key issues for LHC experiments;

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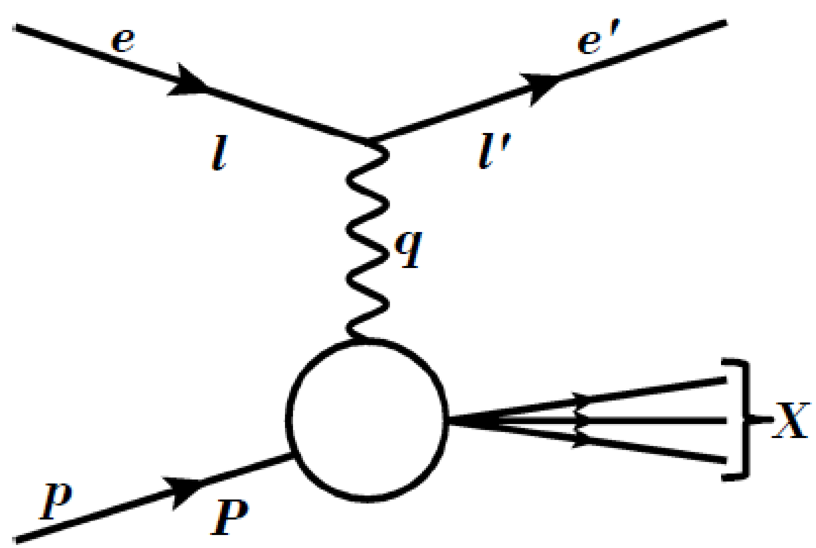
Kinematics:

- Centre-of-mass energy
  $$\sqrt{s} = \sqrt{(l+p)^2}$$
- Momentum transfer
  $$Q^2 = -q^2 = -(l - l')^2$$
- Bjorken x
  $$x = Q^2/2P\cdot q$$
- Inelasticity
  $$y = P\cdot q/P\cdot l$$

$Q^2 > 1$ GeV^2 deep inelastic scattering (DIS)

$Q^2 < 1$ GeV^2 photoproduction (PHP)

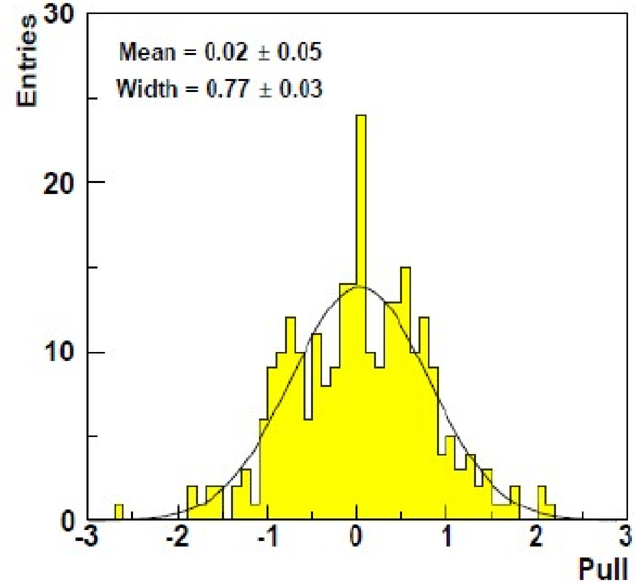


Any two of the variables (Q^2, x, y) define kinematics.

HERA experiments ZEUS & H1 - one of the best QCD laboratories, good job for LHC and future QCD initiatives (EIC, eRICH and LHeC);

Combination of 13 charm+beauty data sets

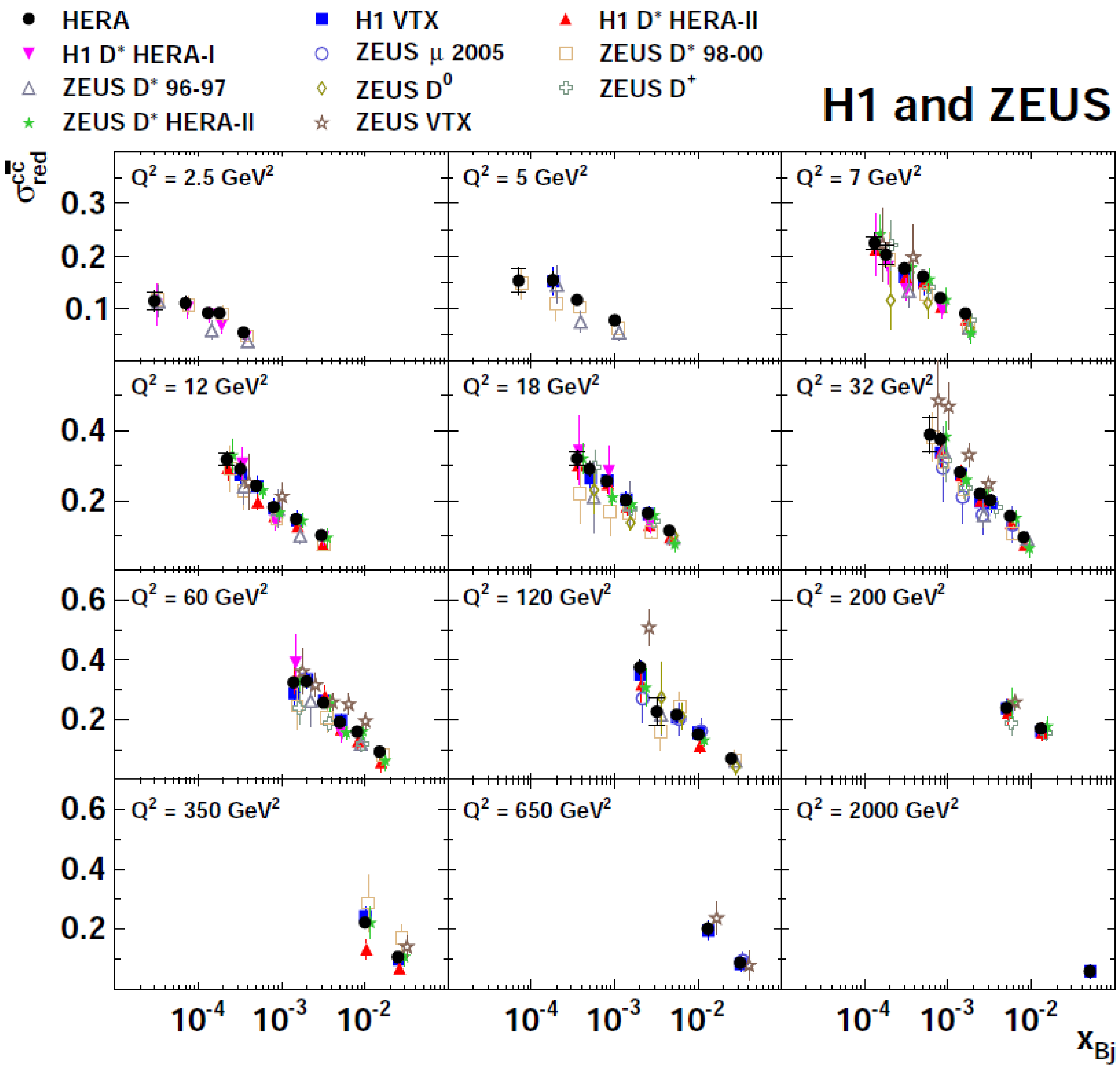
Dataset	Tagging	Q^2 range [GeV^2]	$\mathscr{L}$ [pb^{-1}]	$\sqrt{s}$ [GeV]	N_c	N_b
1 H1 VTX [14]	VTX	5 – 2000	245	318	29	12
2 H1 $D^{*\pm}$ HERA-I [10]	D^{*+}	2 – 100	47	318	17	
3 H1 $D^{*\pm}$ HERA-II (medium Q^2) [20]	D^{*+}	5 – 100	348	318	25	
4 H1 $D^{*\pm}$ HERA-II (high Q^2) [15]	D^{*+}	100 – 1000	351	318	6	
5 ZEUS D^{*+} 96-97 [4]	D^{*+}	1 – 200	37	300	21	
6 ZEUS D^{*+} 98-00 [6]	D^{*+}	1.5 – 1000	82	318	31	
7 ZEUS D^0 2005 [12]	D^0	5 – 1000	134	318	9	
8 ZEUS μ 2005 [13]	μ	20 – 10000	126	318	8	8
9 ZEUS D^+ HERA-II [21]	D^+	5 – 1000	354	318	14	
10 ZEUS D^{*+} HERA-II [22]	D^{*+}	5 – 1000	363	318	31	
11 ZEUS VTX HERA-II [23]	VTX	5 – 1000	354	318	18	17
12 ZEUS e HERA-II [19]	e	10 – 1000	363	318		9
13 ZEUS μ + jet HERA-I [16]	μ	2 – 3000	114	318		11



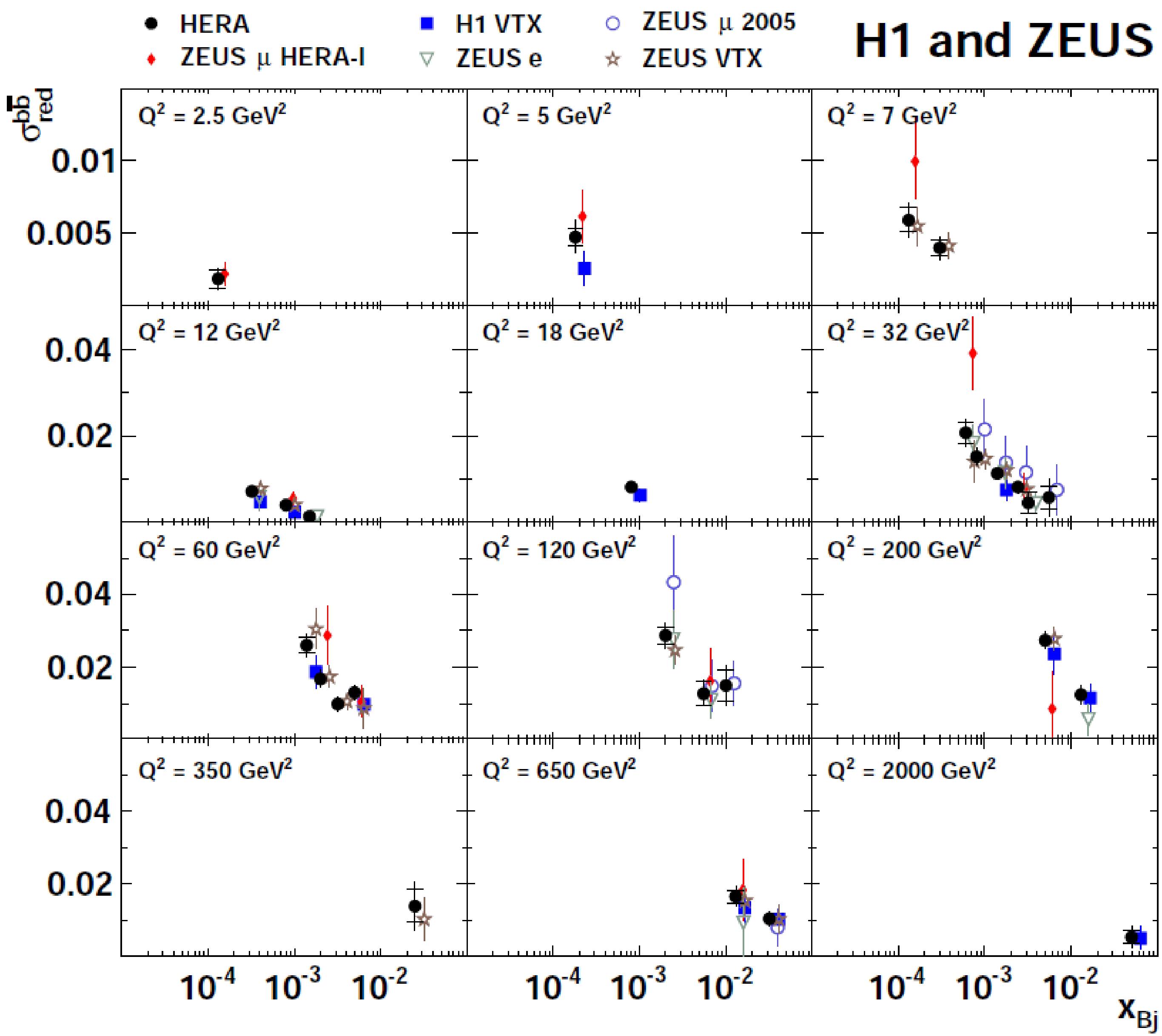
good data consistency:
χ^2= 149/187 dof

3 additional charm datasets w.r.t. EPJ C73 (2013) 2311
beauty combined for the first time account for all systematic correlations between data points, data sets, and between charm and beauty

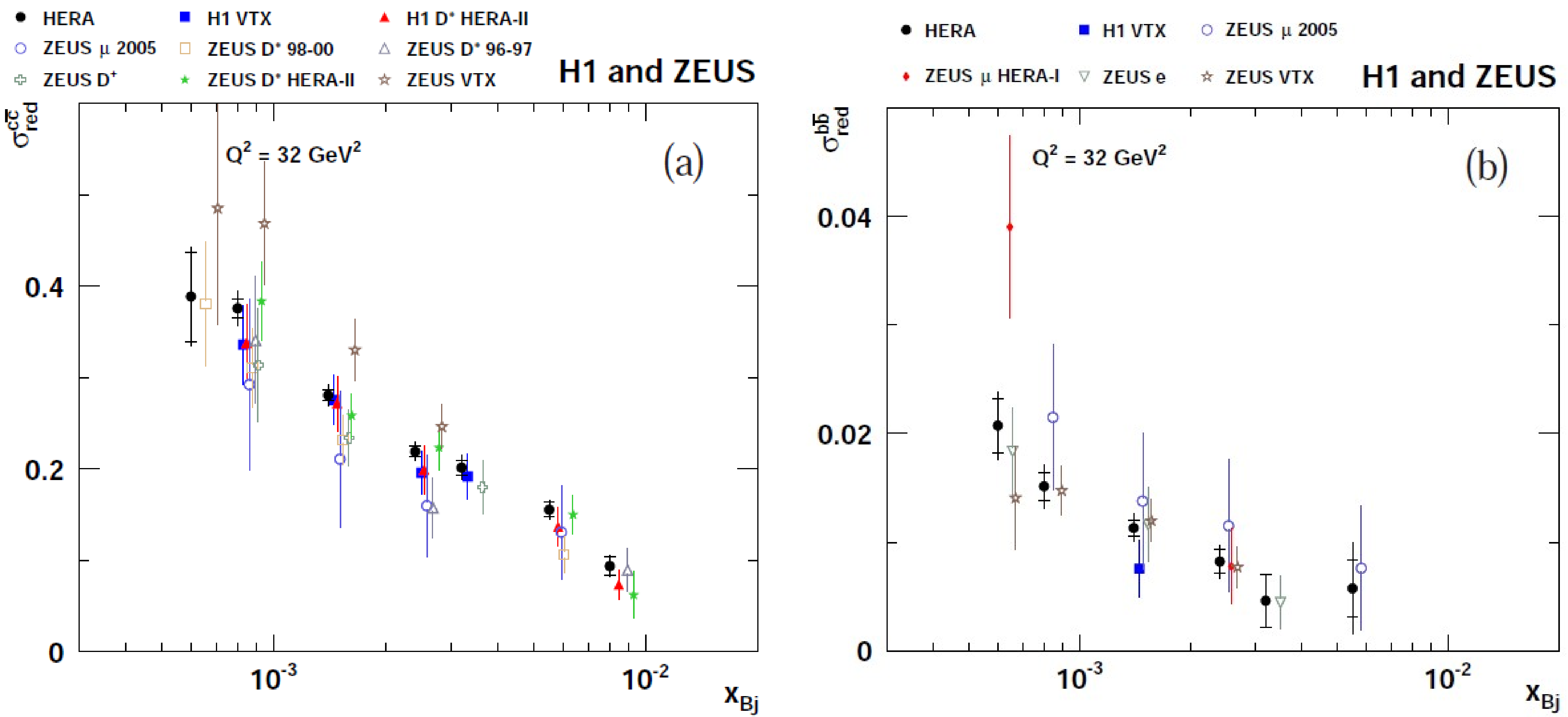
Combined reduced charm production cross sections



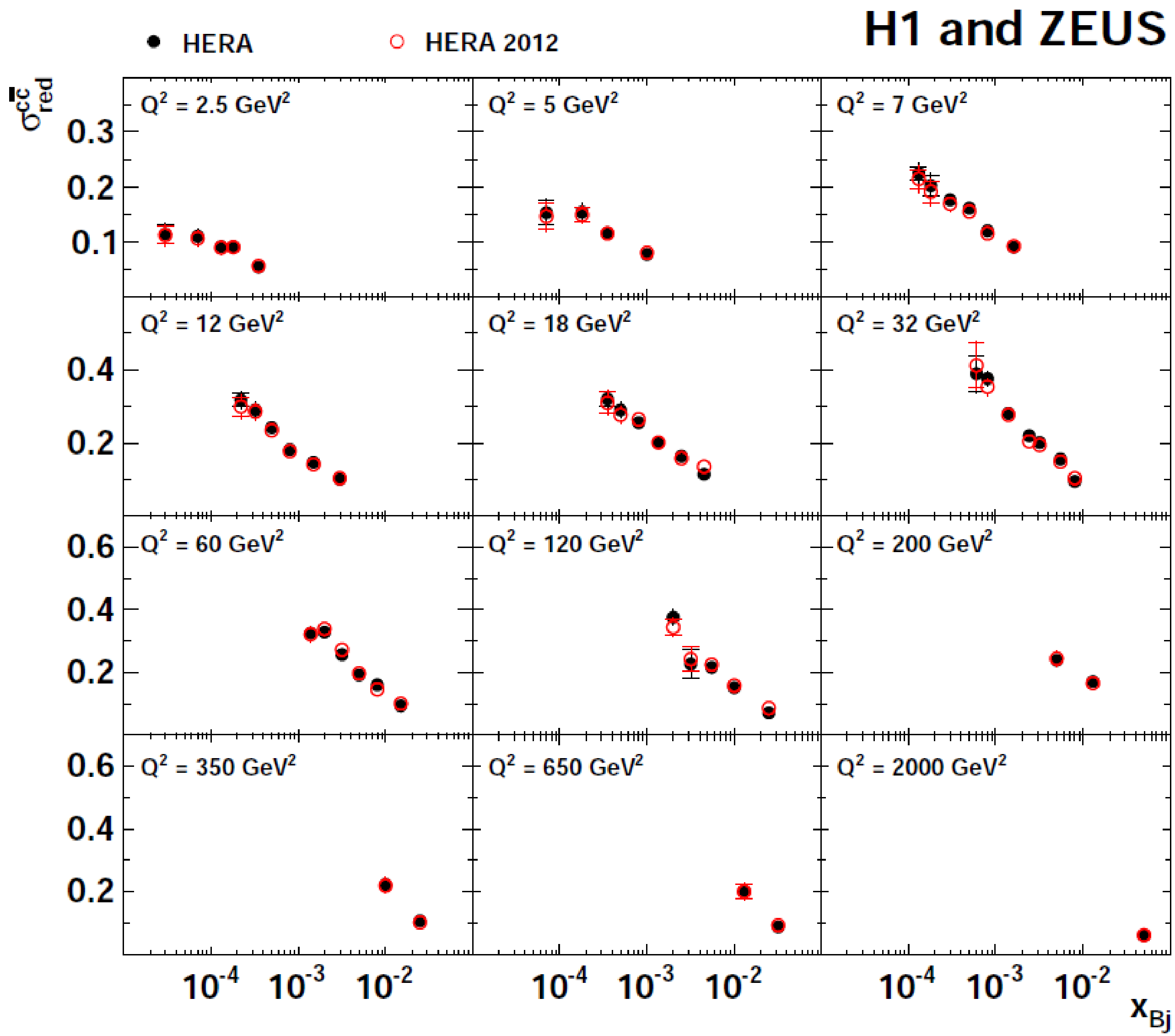
Combined reduced beauty production cross sections



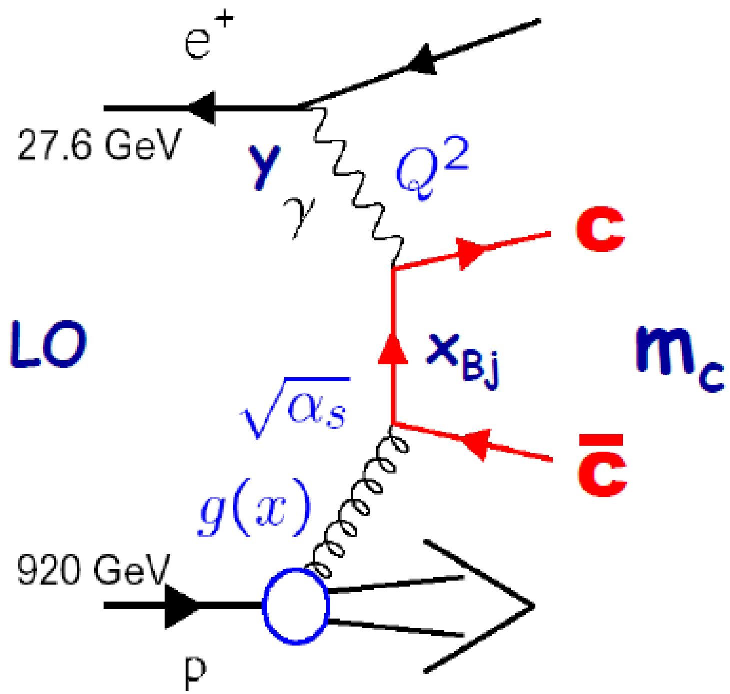
Reduced cross sections as function of x_{Bj} at Q^2=32 GeV^2



Combined reduced (charm) cross sections as a function of x_{Bj} for given values of Q^2



Fixed Flavour Number Scheme (FFNS)

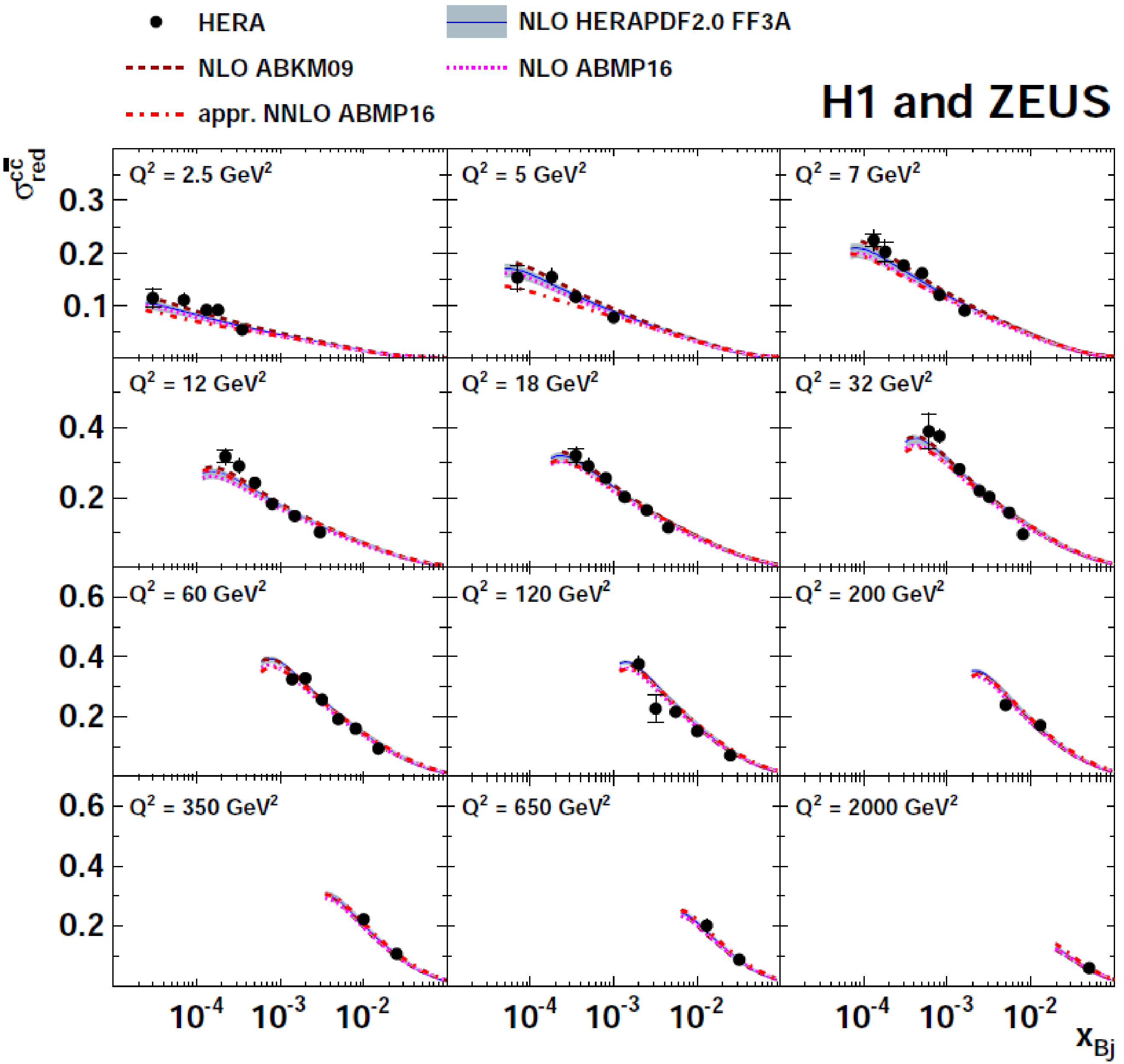


- no charm in proton
- full kinematical treatment of charm mass (multi-scale problem: Q^2, p_T, m_c -> logs of ratios)
- no resummation of logs
- no extra matching parameters

+ NLO (+partial NNLO) corrections,

"natural" scale:
$\mu^2 = Q^2 + 4m_c^2$

Comparison to NLO QCD FFNS predictions (Charm)



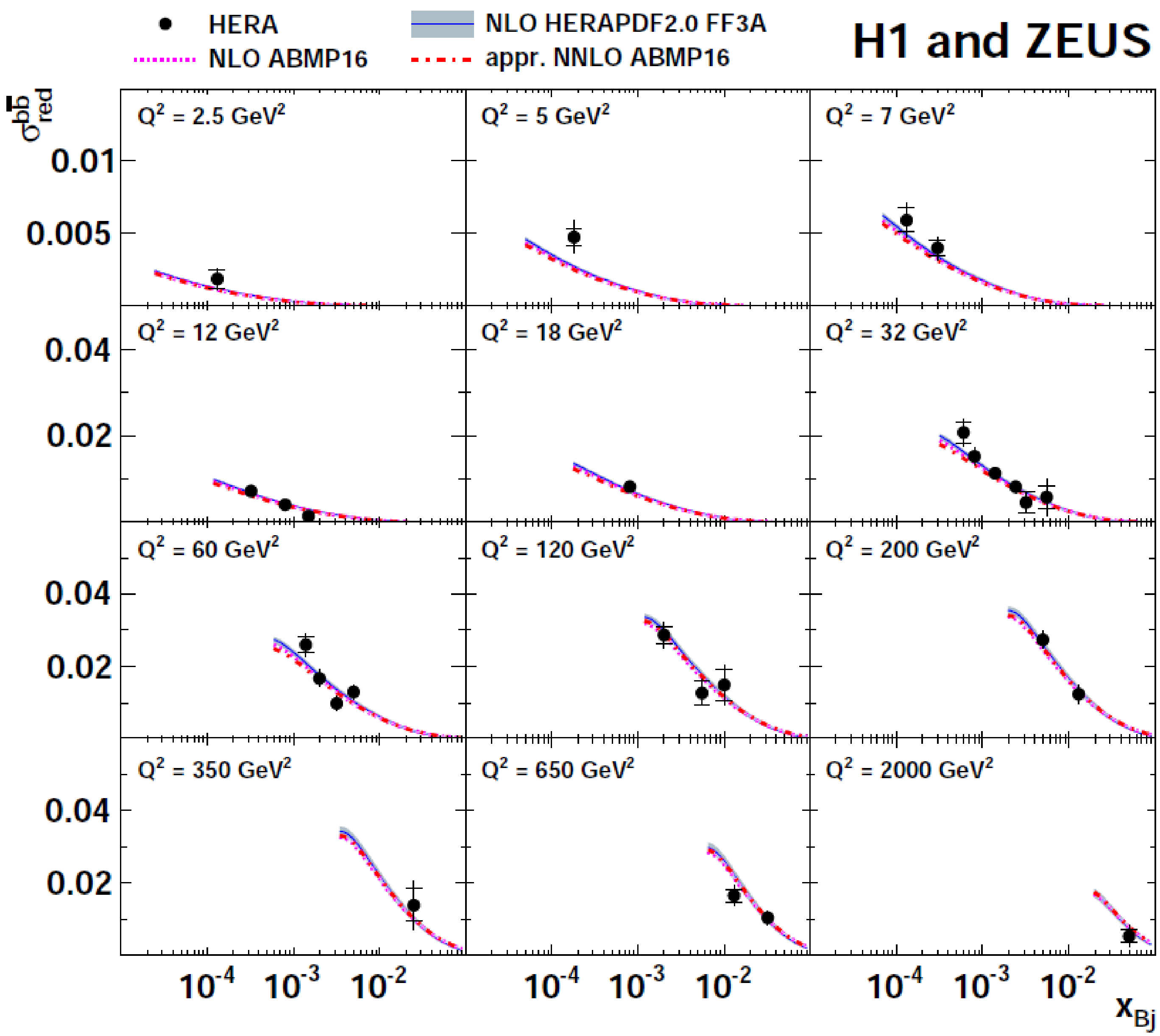
data reasonably described

best: HERAPDF2.0 FF and ABKM09NLO

$\sim 3\sigma$ tension with x_{Bj} slope

appr. NNLO does not improve

Comparison to NLO QCD FFNS predictions (Beauty)

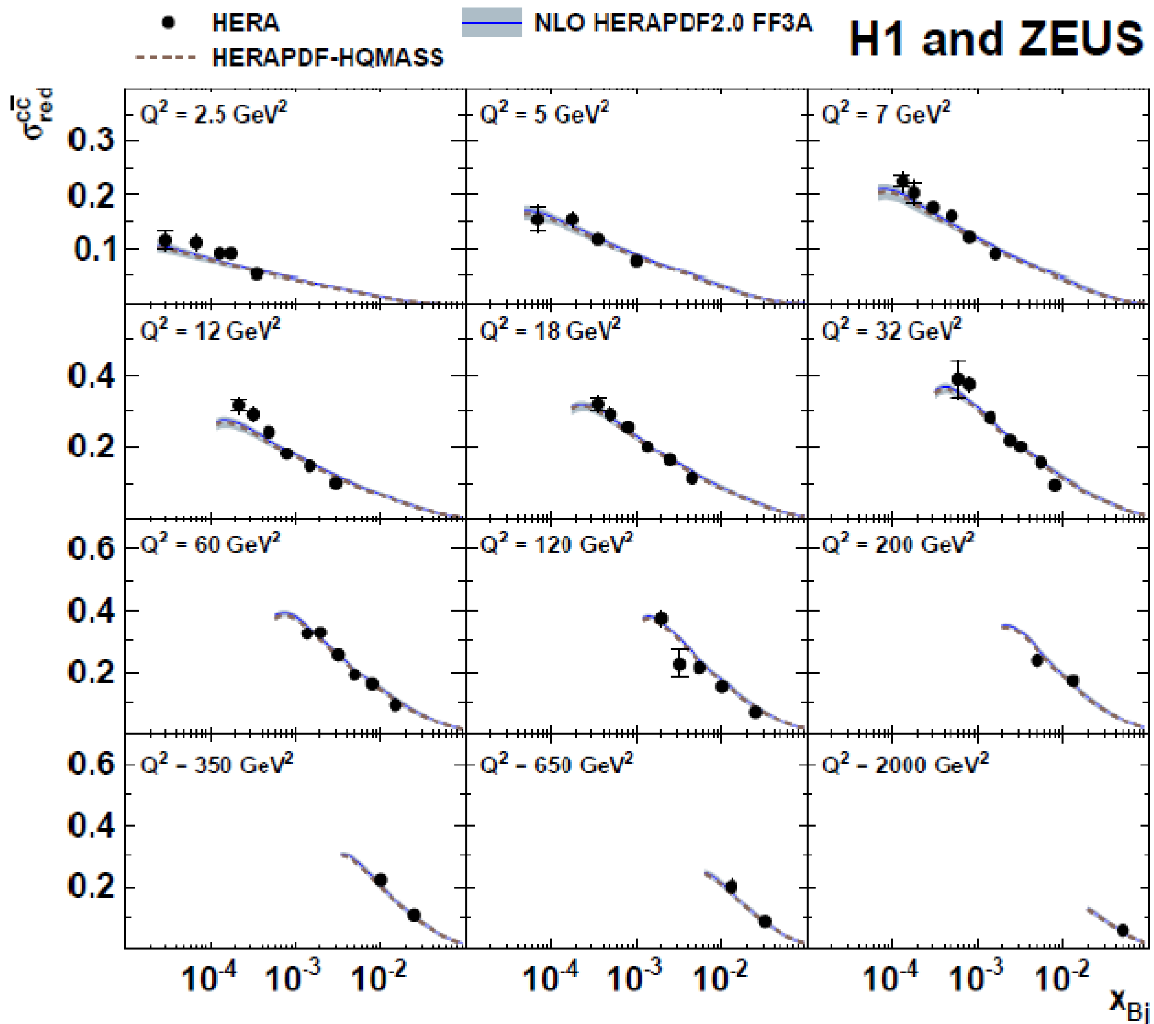


all consistent

QCD fit: charm subset

fully consistent
with HERAPDF2.0 FF3A

uncertainty breakdown
in backup



$m_c(m_c) = 1.29\ ^{+0.05}_{-0.04}\ \text{exp/fit}\ ^{+0.06}_{-0.01}\ \text{mod/scale}\ ^{+0.00}_{-0.03}\ \text{par}$ GeV

PDG: 1.27 ±0.03 GeV (lattice QCD + time-like processes)

Comparison with other $m_c(m_c)$ determinations

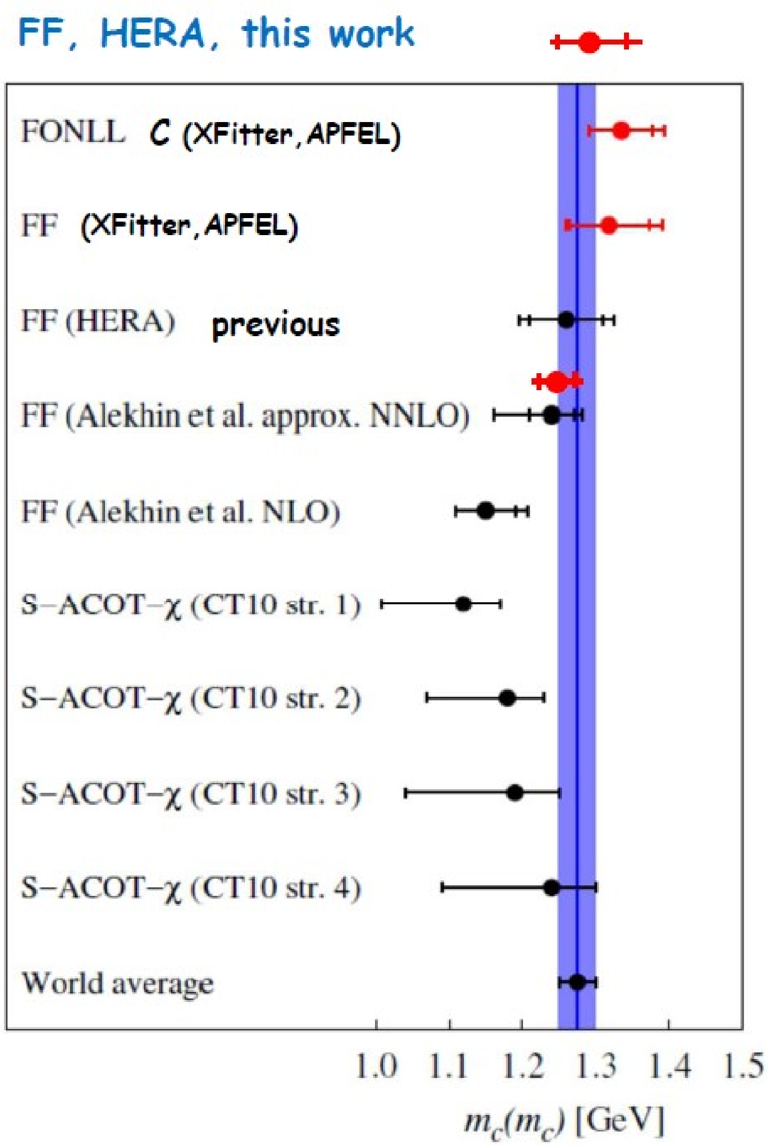
this work:

$m_c(m_c) = 1.29\ ^{+0.05}_{-0.04}\ \text{exp/fit}\ ^{+0.06}_{-0.01}\ \text{mod/scale}\ ^{+0.00}_{-0.03}\ \text{par}$ GeV

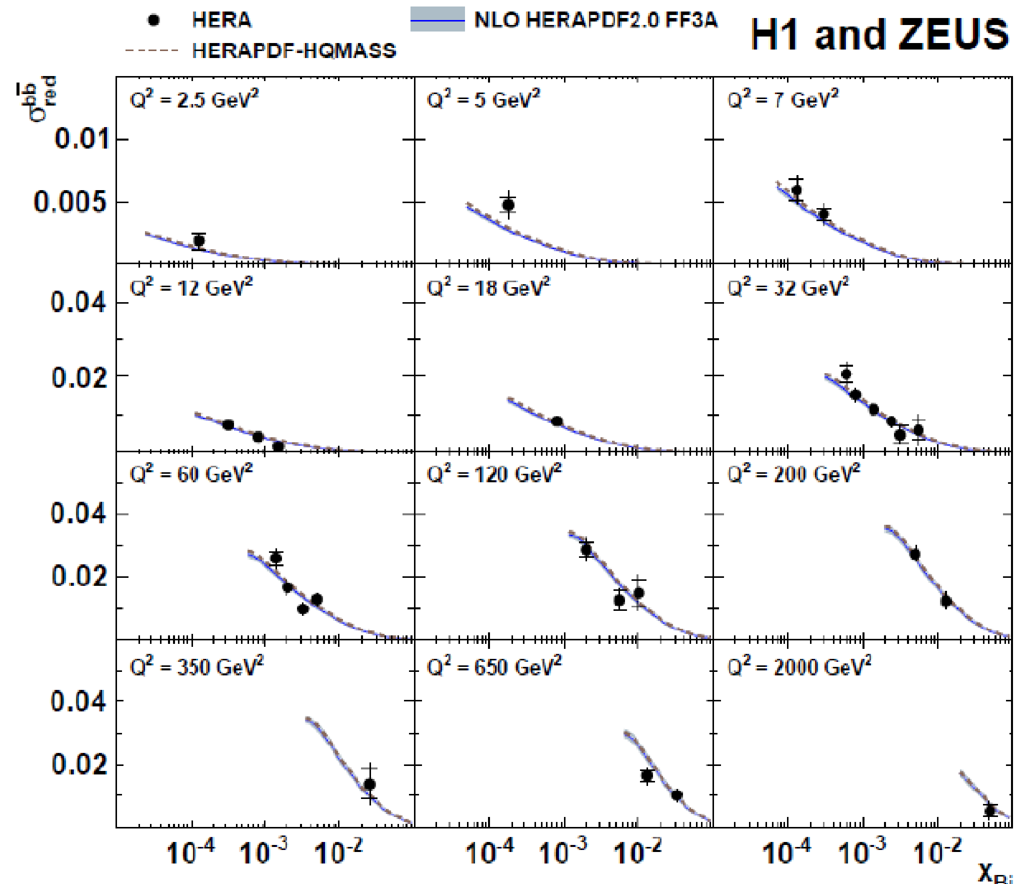
latest ABMP16 result: $m_c(m_c) = 1.252 \pm 0.018 \pm 0.032$ GeV
S. Alekhin et al., arXiv:1701.05383,
Phys. Rev. D96 (2017) 014011

previous results summarized in
V. Bertone et al., arXiv:1605.01946,
JHEP 1608 (2016) 050 :

scheme	$m_c(m_c)$ [GeV]
FONLL (this work)	$1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$
FFN (this work)	$1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$
FFN (HERA) [9]	$1.26 \pm 0.05(\text{exp}) \pm 0.03(\text{mod}) \pm 0.02(\text{param}) \pm 0.02(\alpha_s)$
FFN (Alekhin *et al.*) [24]	$1.24 \pm 0.03(\text{exp})^{+0.03}_{-0.02}(\text{scale})^{+0.00}_{-0.07}(\text{th})$ (approx. NNLO)
	$1.15 \pm 0.04(\text{exp})^{+0.04}_{-0.00}(\text{scale})$ (NLO)
S-ACOT-χ (CT10) [29]	$1.12^{+0.05}_{-0.11}$ (strategy 1)
	$1.18^{+0.05}_{-0.11}$ (strategy 2)
	$1.19^{+0.06}_{-0.15}$ (strategy 3)
	$1.24^{+0.06}_{-0.15}$ (strategy 4)
World average [53]	1.275 ± 0.025



QCD fit: beauty subset



fully consistent with HERAPDF FF3A

new: $m_b(m_b) = 4.05\ ^{+0.10}_{-0.11}$ exp/fit $^{+0.09}_{-0.03}$ mod/scale $^{+0.00}_{-0.03}$ par GeV

ZEUS: $m_b(m_b) = 4.07 \pm 0.14_{\text{exp/fit}}$ $^{+0.08}_{-0.08}$ mod/scale $^{+0.05}_{-0.00}$ par GeV

PDG: 4.18 ± 0.03 GeV (lattice QCD + time-like processes)

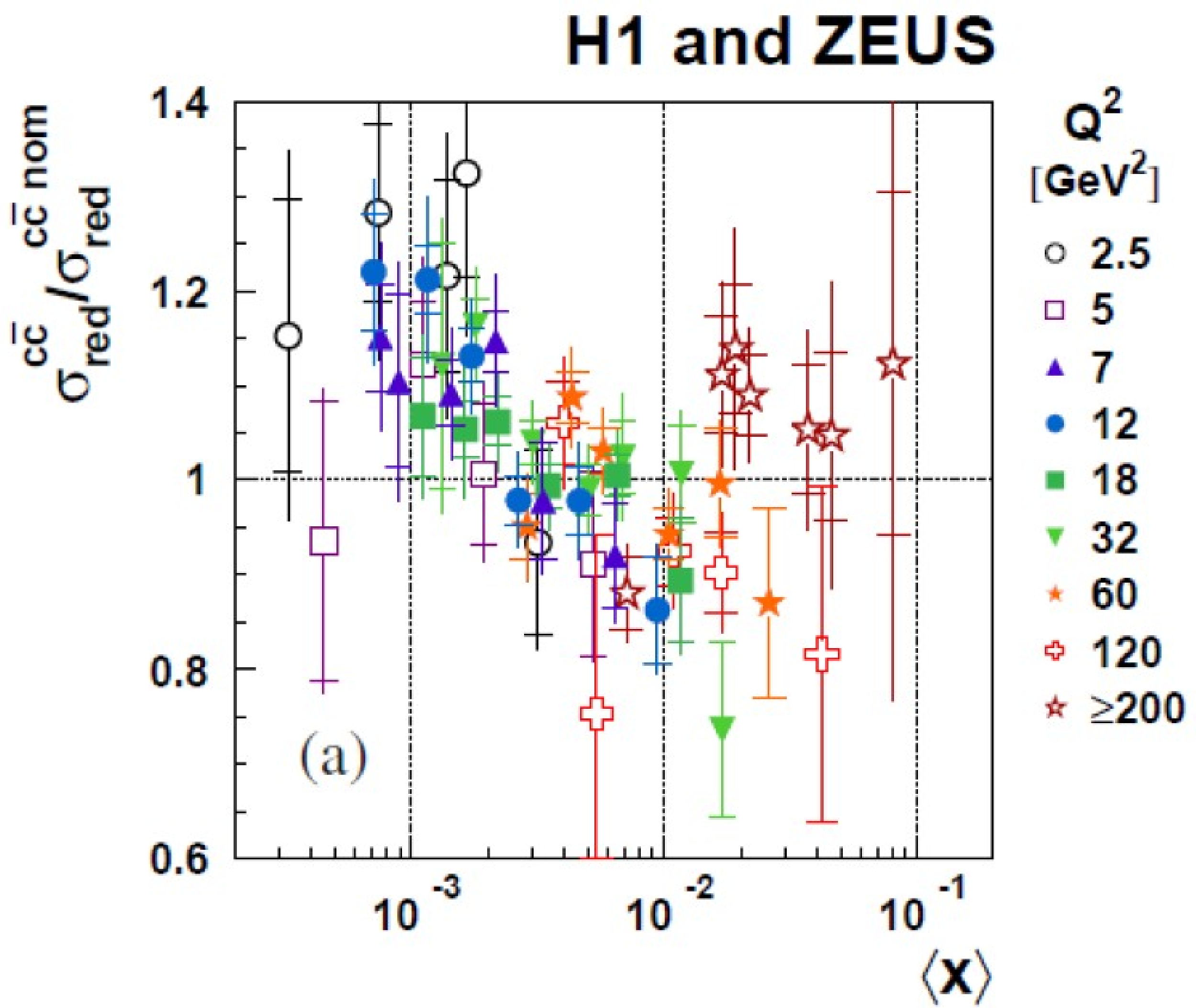
QCD fit: charm x slope

plot **data/fit**
vs. <x> of
incoming partons
(rather than x_{Bj})
for each data point

LO: $x = x_{\rm Bj} \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)$

<x> calculated at **NLO**
using HVQDIS

-> common <x> trend
for all Q^2



Summary

- Final HERA charm and beauty data in DIS have been combined including all correlations. Charm precision improved by ~20%, beauty combined for the first time
- Data are reasonably described by FFNS predictions (NLO better than approx. NNLO), but show ~3σ tension in x slope w.r.t inclusive
- QCD fit of inclusive, charm and beauty data (simultaneous fit of PDFs, m_c and m_b in FFNS at NLO) yields (in agreement with world average and previous measurements):

$$m_c(m_c) = 1290\ ^{+46}_{-41}(\mathrm{exp/fit})\ ^{+62}_{-14}(\mathrm{mod})\ ^{+3}_{-31}(\mathrm{par})\ \mathbf{MeV}$$

$$m_b(m_b) = 4049^{+104}_{-109}(\mathrm{exp/fit})^{+90}_{-32}(\mathrm{mod})\ ^{+1}_{-31}(\mathrm{par})\ \mathbf{MeV}$$

- *More detailed studies of x slope tension -> can not be solved by varying the gluon density, or adding higher orders, or resumming log 1/x terms, within the respective pQCD frameworks*