The Charm and Beauty quark masses and their running at HERA

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for the

ZEUS and H1

collaborations + S. Moch

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EPJ C73 (2013) 2311; H1-prelim-14-071, ZEUS-prel-14-006;

arXiv:1506.06042; JHEP 1409 (2014) 127; arXiv:1506.07519

running of α_s and quark masses

- **α_s running depends on number of coulours N_C and number of quark flavours N_F**

$$\alpha_s(Q^2) = \frac{\alpha_s(Q_0^2)}{1 + \alpha_s\,(11N_C - 2N_F)/12\pi\ \ln(Q^2/Q_0^2)}$$

leading order QCD formulae

- **$\overline{MS}$ quark mass running depends on α_s , e.g.**

$$m_c(\text{pole}) = m_c(m_c)\,(1 + 4/3\ \alpha_s/\pi\,)$$
$$= m_c(Q)\,(1 + \alpha_s/\pi\ (4/3 + \ln(Q^2/m_c^2))$$

- part of gluon field around quark not 'visible' any more when 'looking' at smaller distances/larger energy scales -> **effective mass decreases**

the running b quark mass at LEP

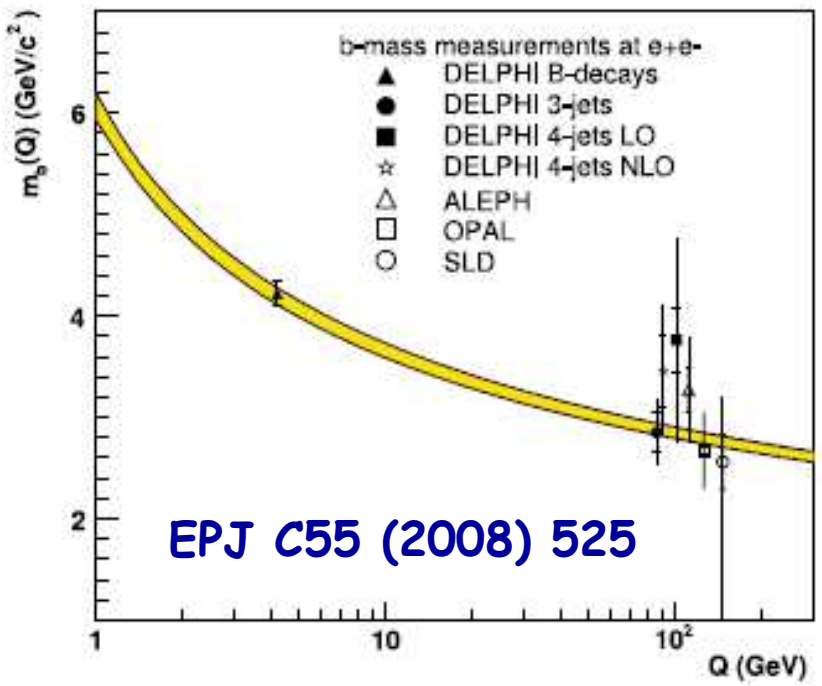


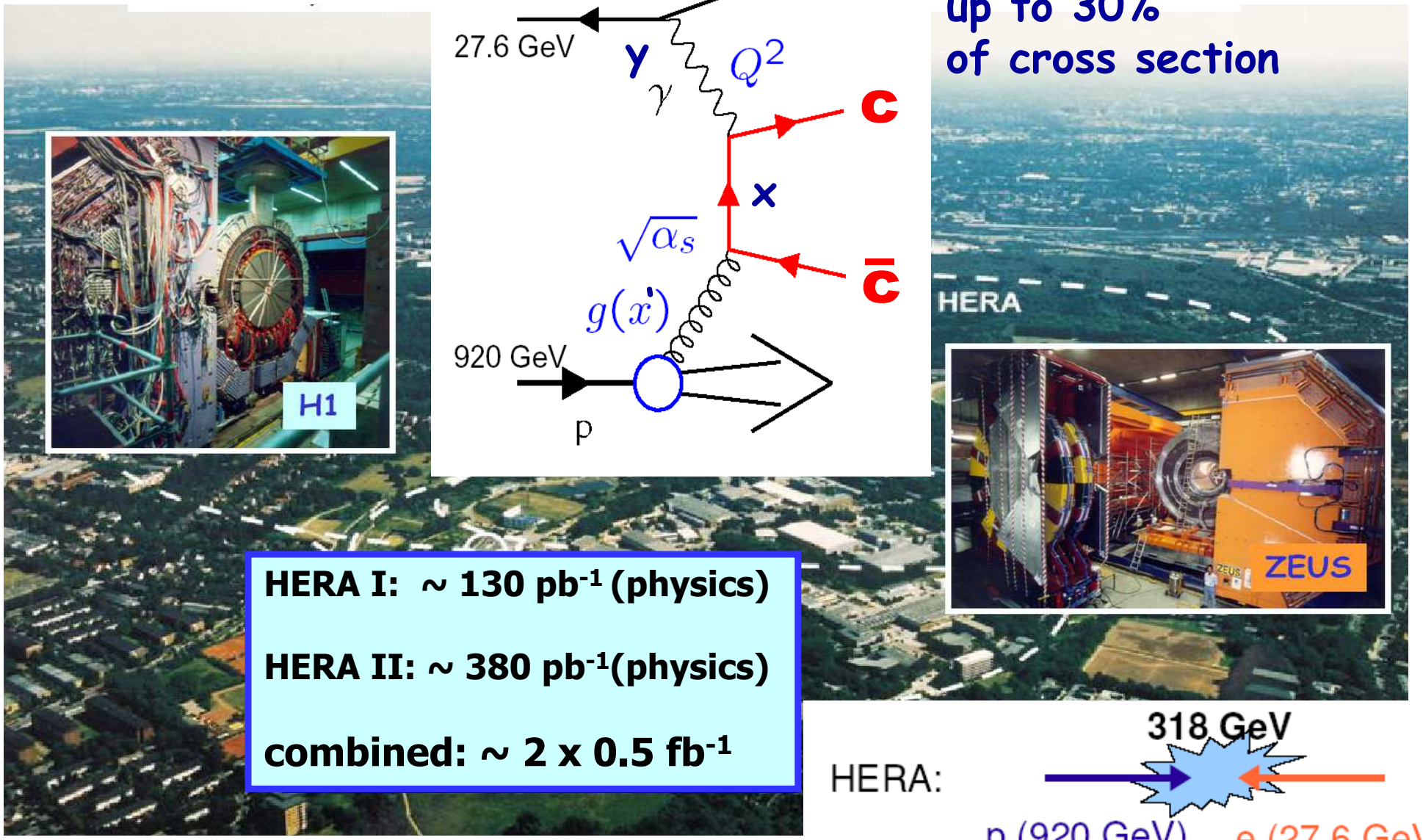
Fig. 6. The energy evolution of the $\overline{MS}$-running b-quark mass $m_b(Q)$ as measured at LEP. DELPHI results from $R_3^{b\ell}$ [7] at the M_Z scale and from semileptonic B-decays [31] at low energy are shown together with results from other experiments (ALEPH [4], OPAL [5] and SLD [6]). The masses extracted from LO and approximate NLO calculations of $R_4^{b\ell}$ are found to be consistent with previous experimental results and with the reference value $m_b(Q)$ (*grey band*) obtained from evolving the average $m_b(m_b) = 4.20 \pm 0.07$ GeV/c^2 from [17] using QCD RGE (with a strong coupling constant value $\alpha_s(M_Z) = 0.1202 \pm 0.0050$ [30])

LEP: Z -> $b\bar{b}$ + gluons, measurement of phase space/ angular distributions

$m_{(Q)} = m_{(Q_0)} (1 - \alpha_s/\pi \ln(Q^2/Q_0^2))$

charm mass running not explicitly measured (so far)

The HERA ep collider and experiments



up to 30%
of cross section

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

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

combined: ~ 2 x 0.5 fb^{-1}

HERA charm data combination

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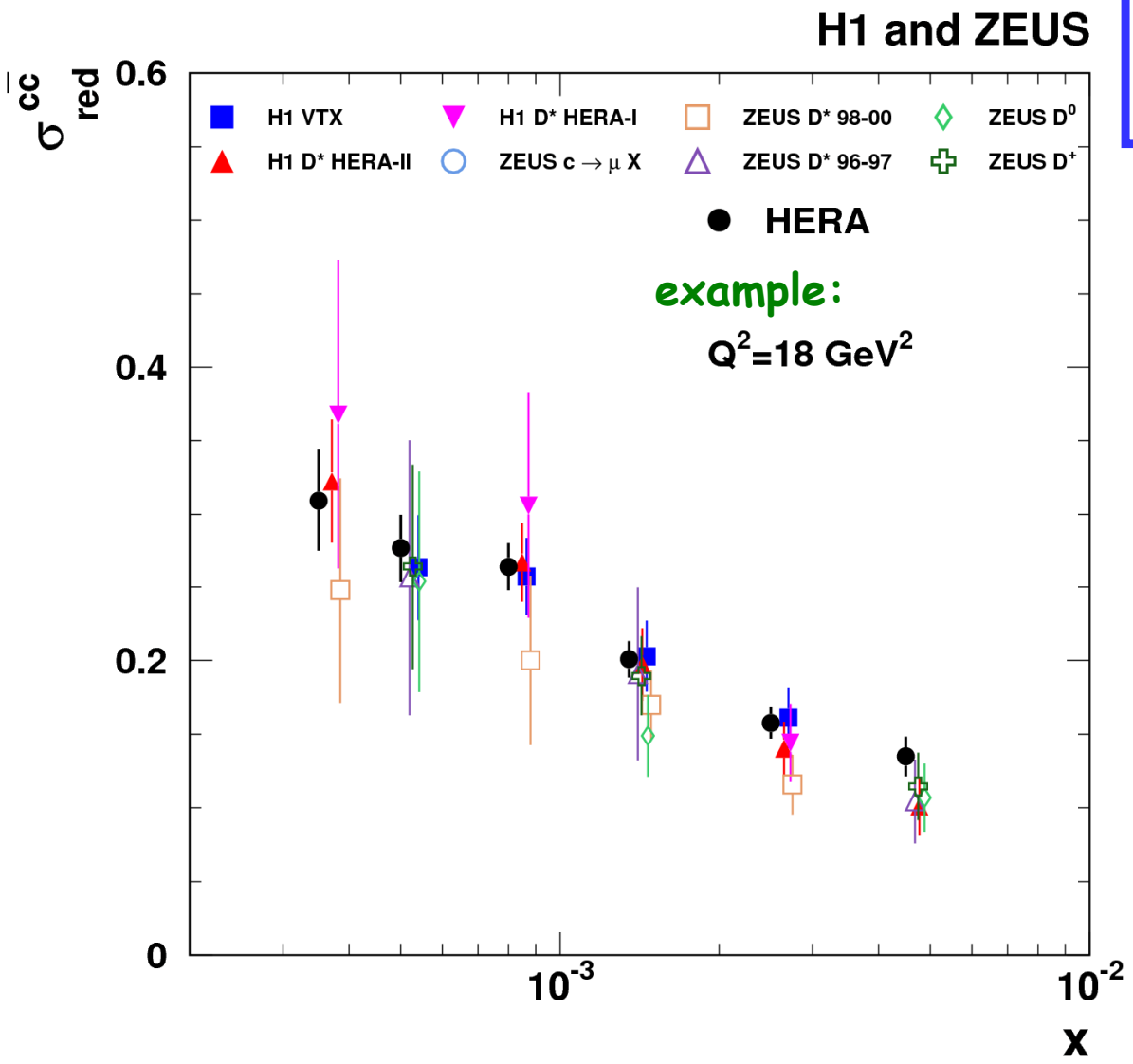
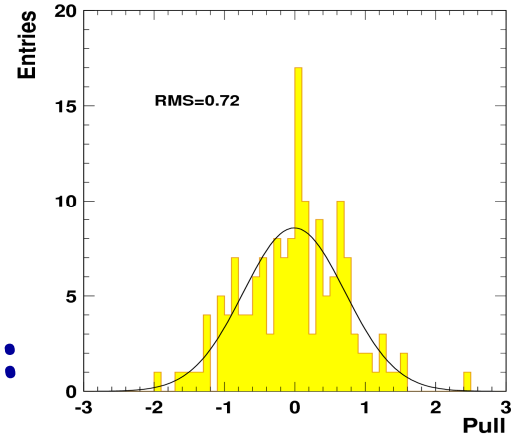
Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right]\sigma_{red}^{c\bar{c}}\right.$$



- 9 data sets (HERA I, HERA II)
- 5 charm tagging methods
- 155 -> 52 data points
- 48 correlated systematic uncertainties

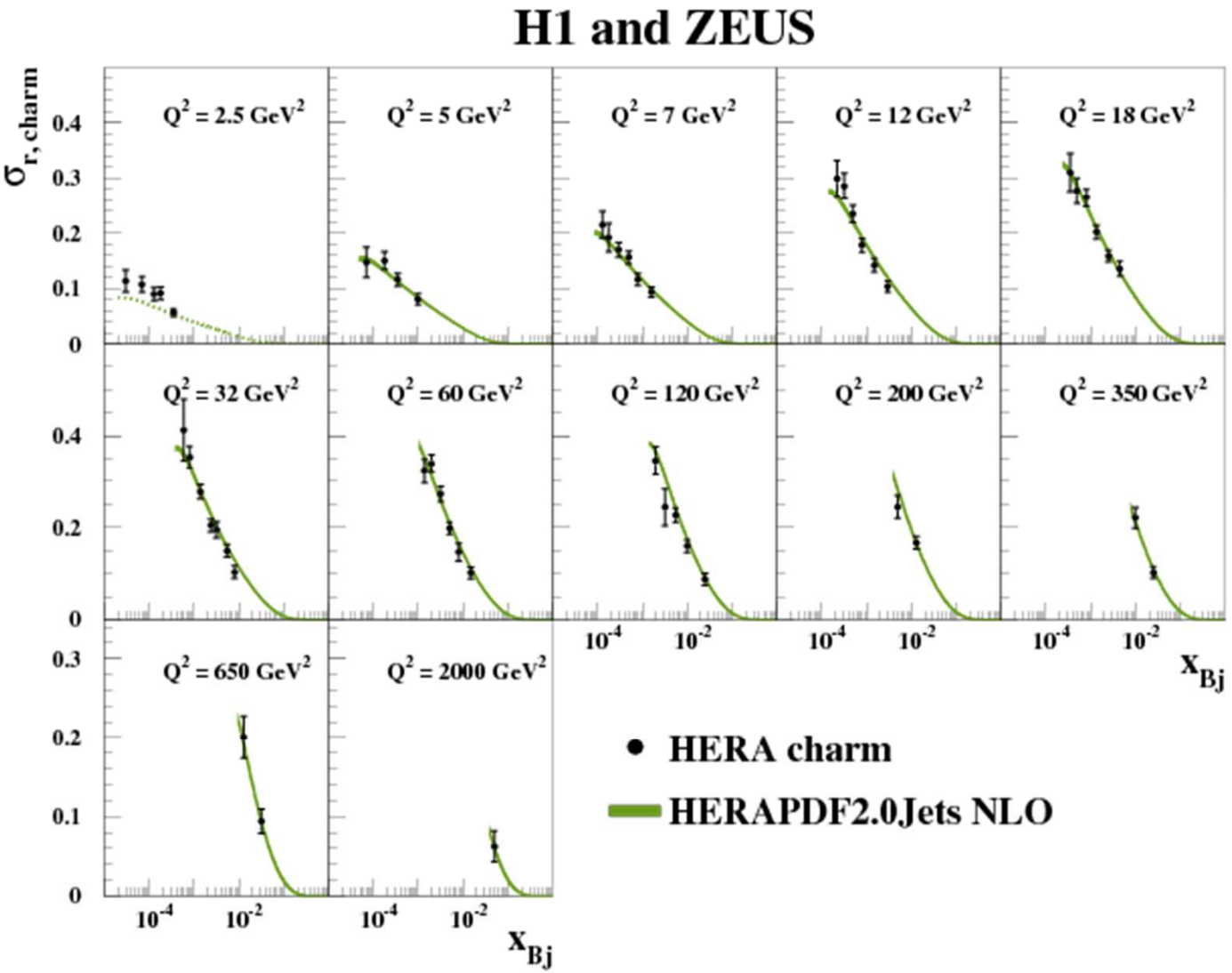


very good selfconsistency of data:

Combination result, HERAPDF

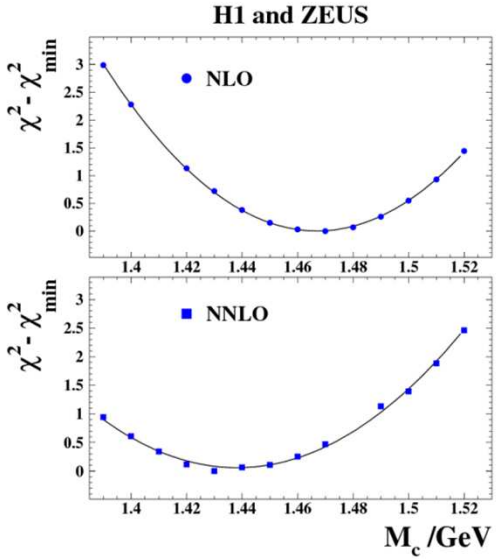
EPJ C73 (2013) 2311, arXiv:1506.06042

also see talks V. Radescu, K. Wichmann

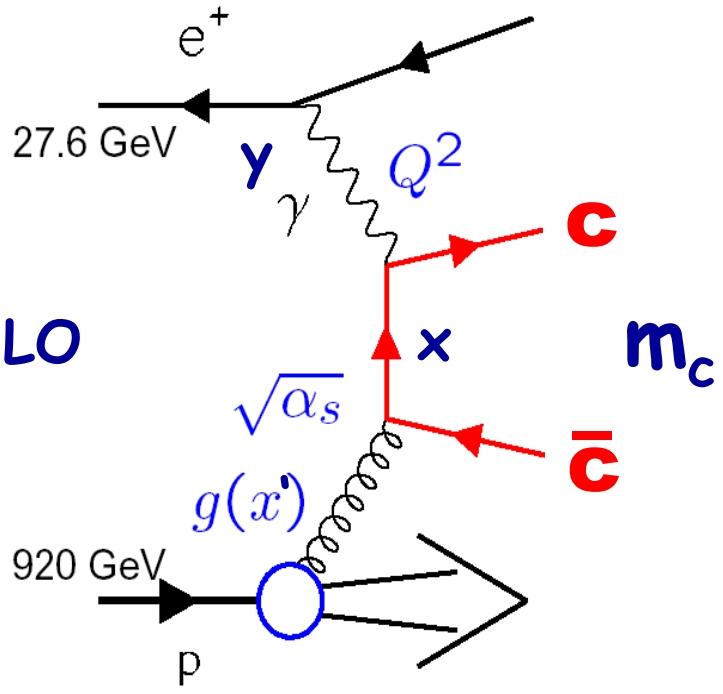


well described using HERAPDF2.0
(and earlier versions)

strong charm mass sensitivity



fixed flavour number scheme (FFNS)



+ NLO (+partial NNLO) corrections,

"natural" scale:
$Q^2 + 4m_c^2$

- 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

comparison to ABM FFNS

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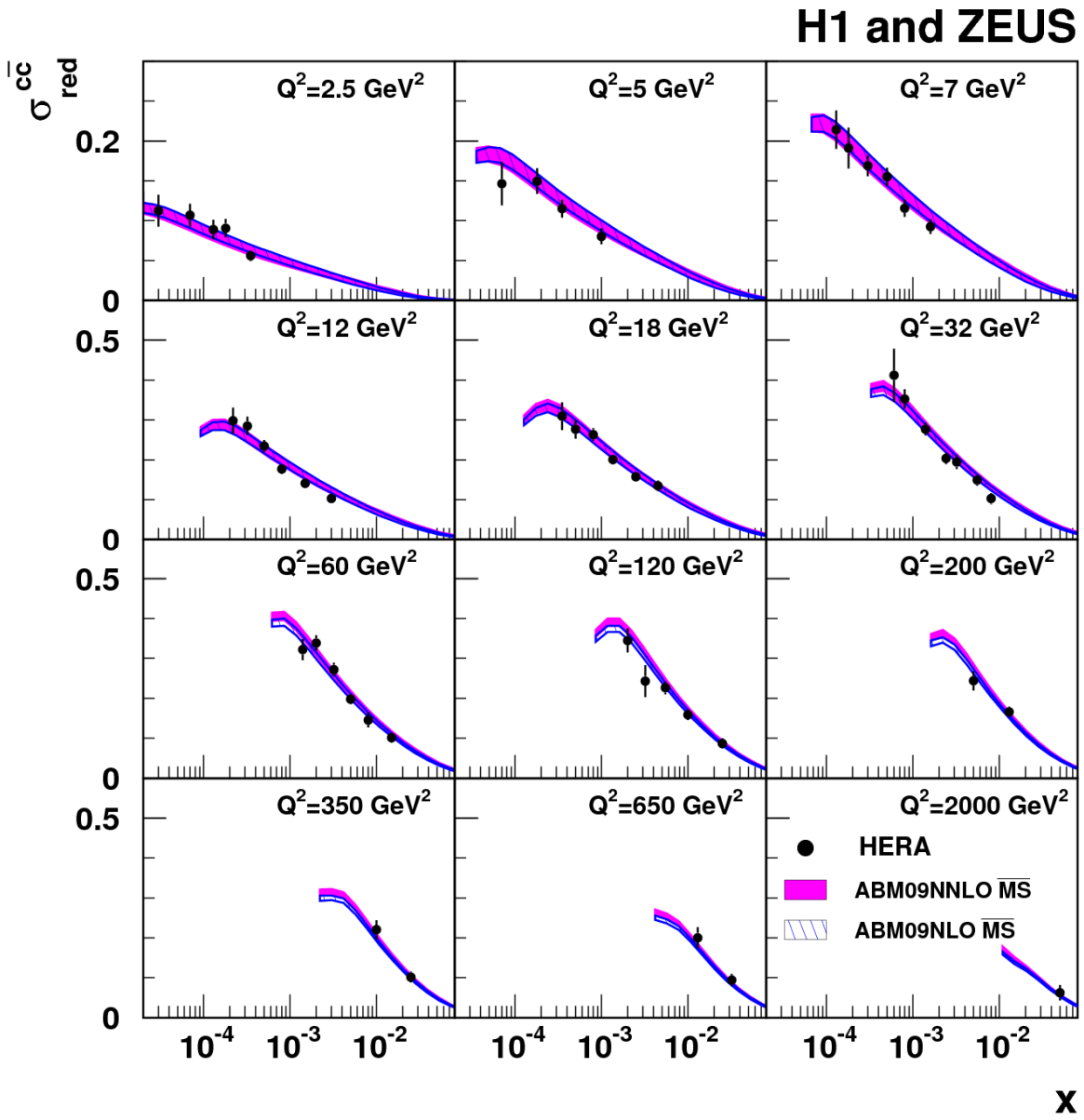

very good description of data in full kinematic range

unambigous treatment of m_c in all terms of calculation

here: $\overline{MS}$ running mass

(similar predictions for pole mass)

measurement of $\overline{MS}$ charm mass

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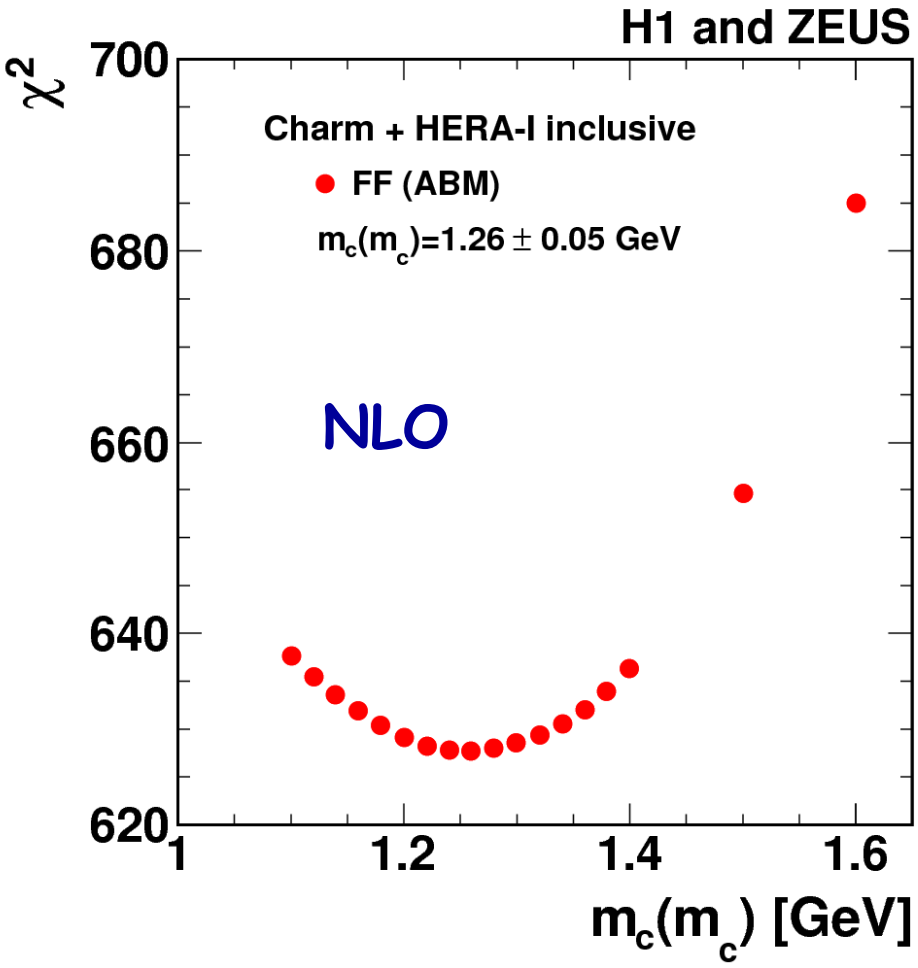


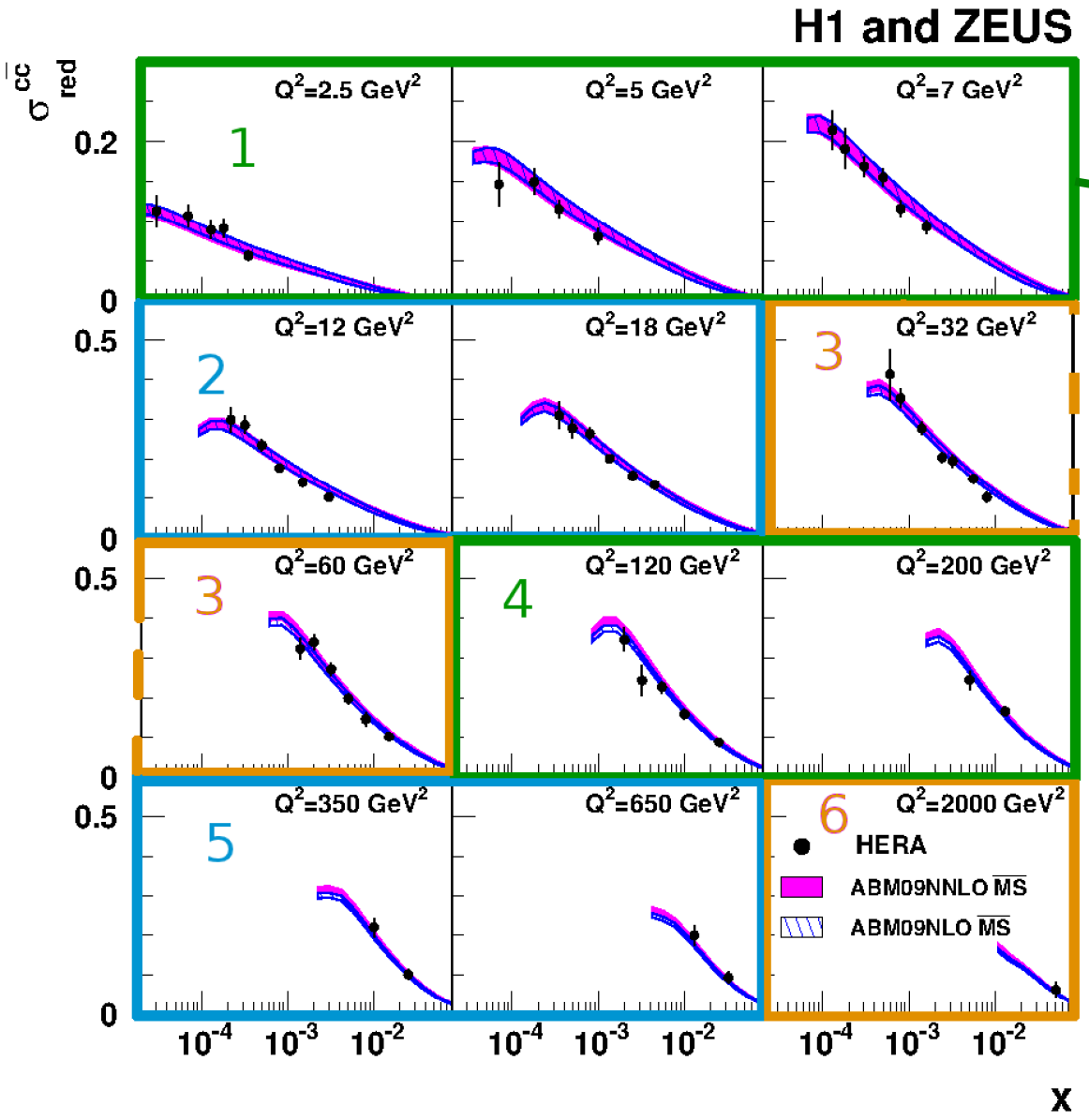
simultaneous fit of combined charm data and inclusive HERA I DIS data

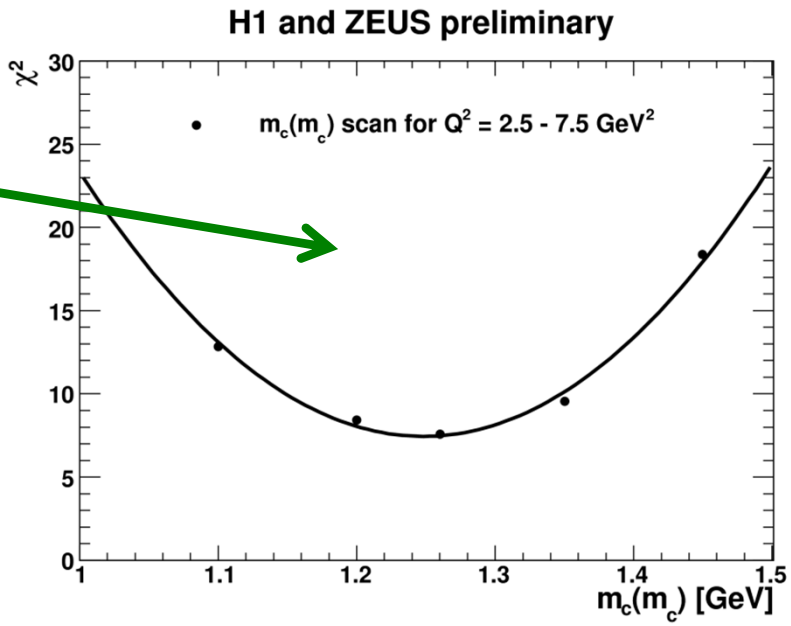
$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{\alpha s}$ GeV

PDG: 1.275 ±0.025 GeV (lattice QCD + time-like processes)

measurement of m_c running

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch





Step 1:
extract $m_c(m_c)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2 + 4m_c^2$

(take log average for central scale)

m_c fit and uncertainties

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch

use appropriate PDF set for each mass (from inclusive DIS data only), fit charm data

using HERAFitter

Fit uncertainty

- Was estimated by taking $\Delta\chi^2 = 1$ (dominant uncertainty)

Parametrisation

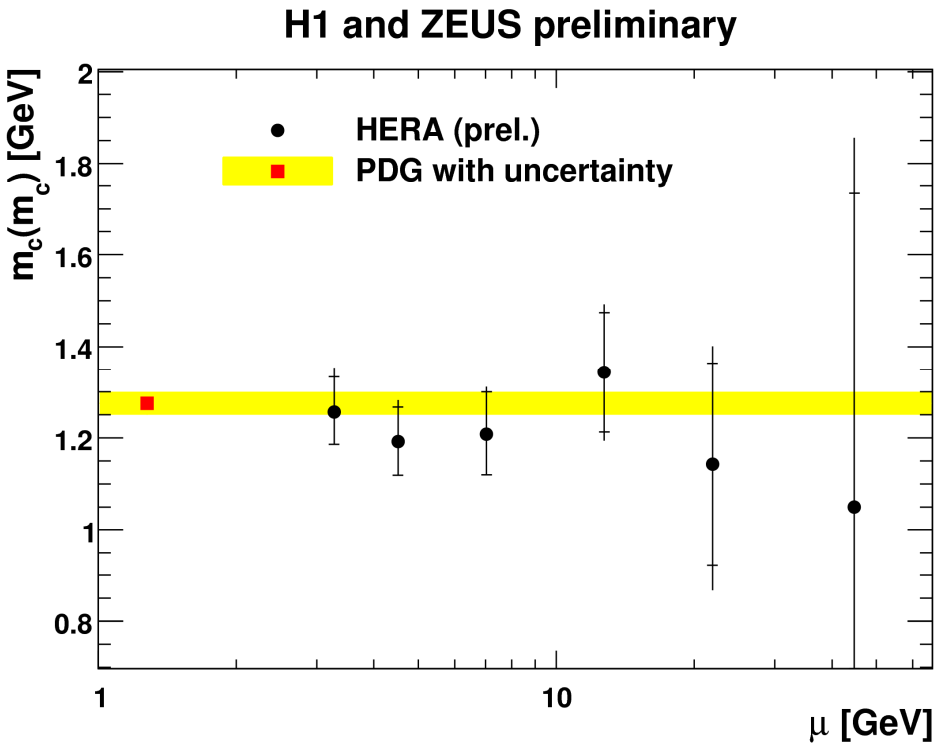
- Adding extra parameter in the PDF parametrisation

Model uncertainty

- Variation of the strangness supression factor
- Lower cut on Q^2 for inclusive data
- The evolution starting scale
- The b-quark mass

Theory

- Variation of α_s
- Variation of the factorisation and renormalization scales of heavy quarks by factor 2



-> outer error bar

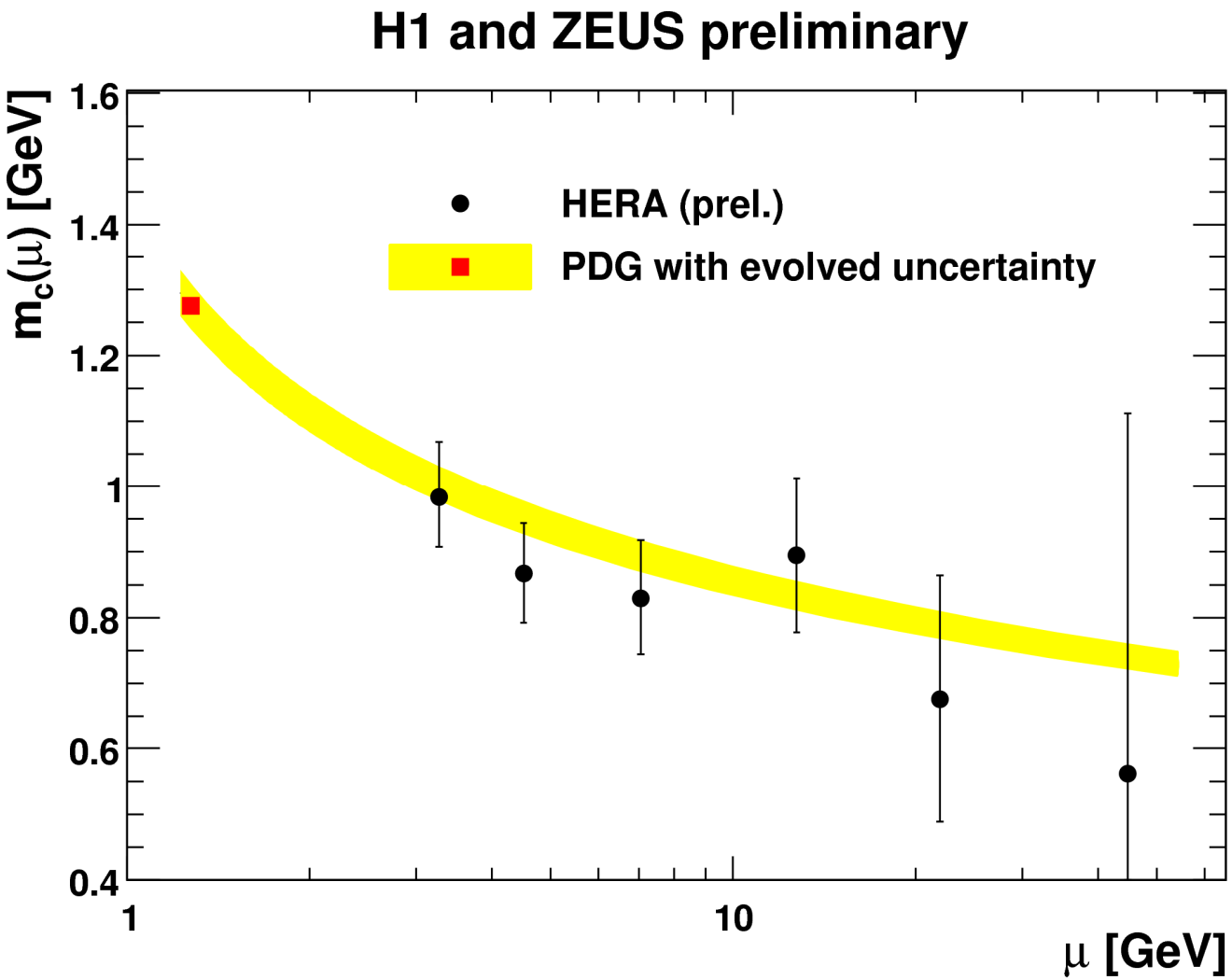
sensitivity to $m_c(m_c)$ decreases with increasing scale $\mu^2 = Q^2+4m_c^2$

'in reality', have measured $m_c(\mu)$ at each scale

the running charm quark mass

H1-prelim-14-071, ZEUS-prel-14-006, + S. Moch

translate back to $m_c(\mu)$ using LO formula consistent with NLO $\overline{MS}$ QCD fit (OpenQCDrad, Alekhin et al.)



running mass concept in QCD is self-consistent !

m_b from reduced beauty cross section

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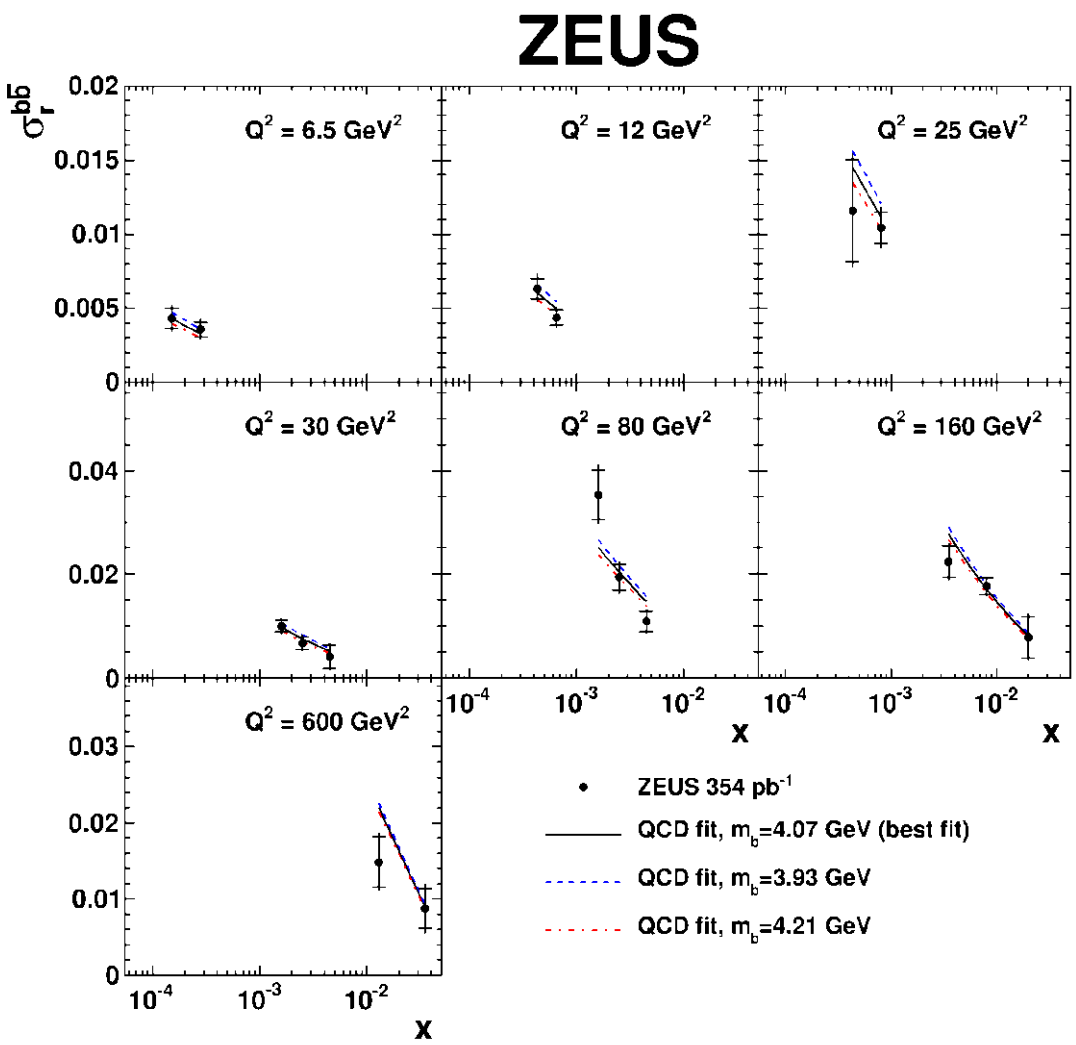
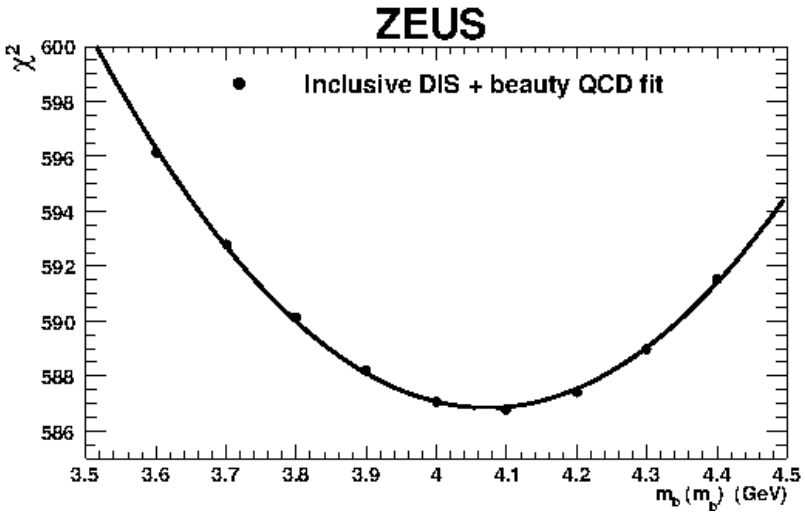




uncertainty evaluation
similar to charm running case

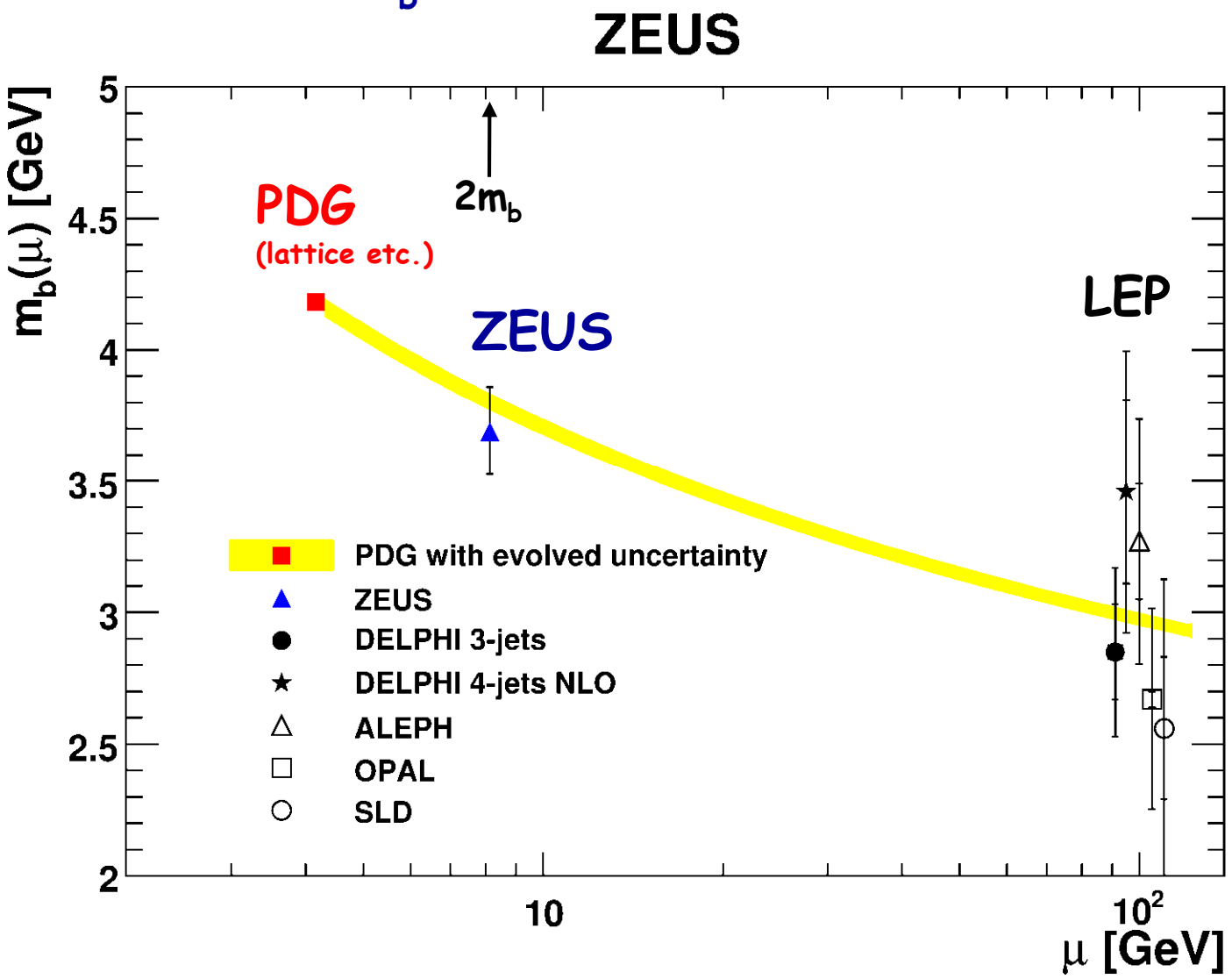
$m_b(m_b) = 4.07 \pm 0.14_{fit}\ ^{+0.01}_{-0.07\ mod}\ ^{+0.05}_{-0.00\ par}\ ^{+0.08}_{-0.05\ th}$ GeV

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

the running beauty quark mass

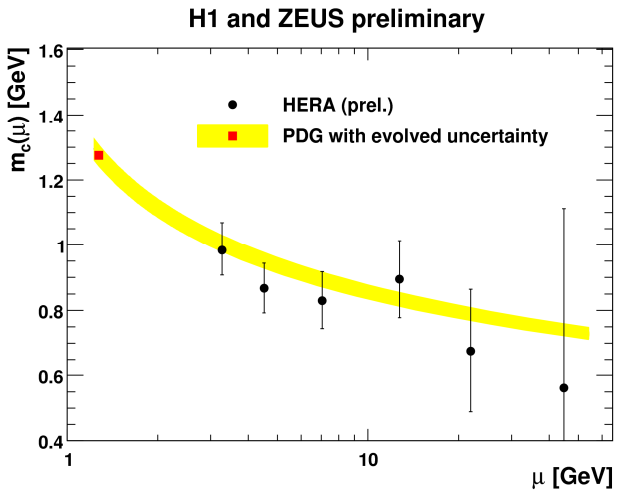
arXiv:1506.07519

translate back to $2m_b$



Summary and conclusions

- **HERA DIS charm data have been combined**
  (except most recent, see talk J. Hladky)
  very good consistency, reduced uncertainties



- **well-described by NLO QCD in FFNS**
  -> measure charm mass

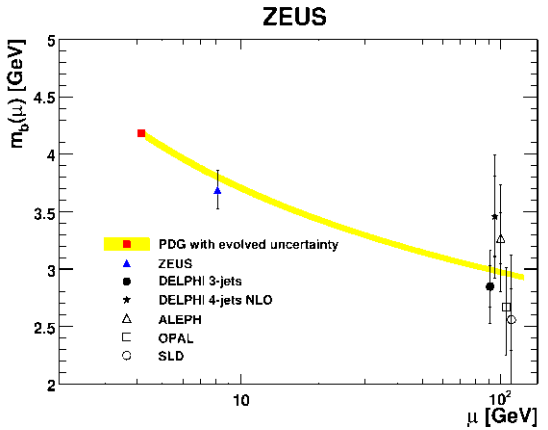
$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{\alpha s}$ GeV

- **split data into subsets spanning different scales**
  -> first measurement of charm mass running (QCD consistency check)

- **ZEUS DIS beauty data well described by NLO QCD**
  -> measure beauty mass

$m_b(m_b) = 4.07 \pm 0.14_{fit}\ ^{+0.01}_{-0.07\ mod}\ ^{+0.05}_{-0.00\ par}\ ^{+0.08}_{-0.05\ th}$ GeV

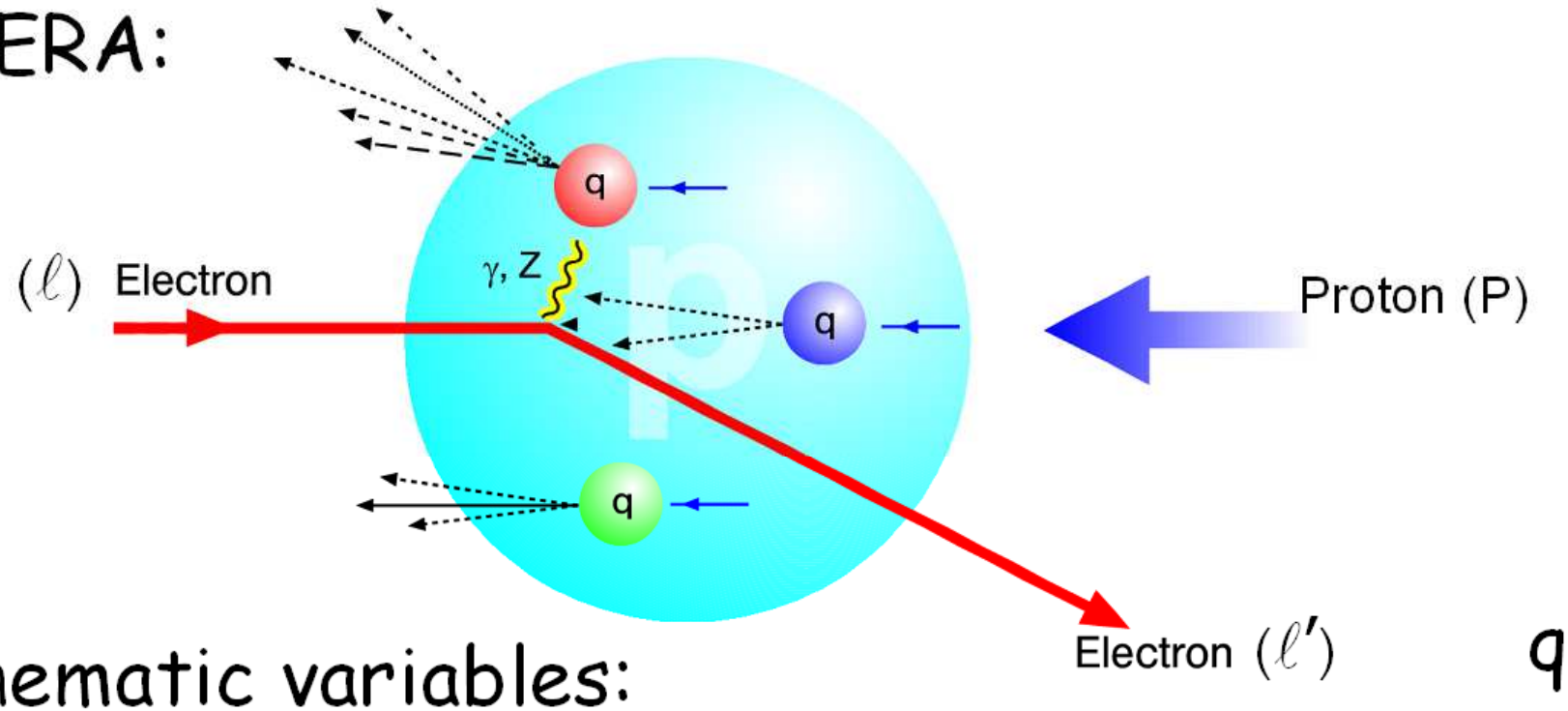
- **compare to PDG and LEP**
  -> beauty mass running consistent with QCD



Backup

Deep Inelastic ep Scattering at HERA

HERA:



kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

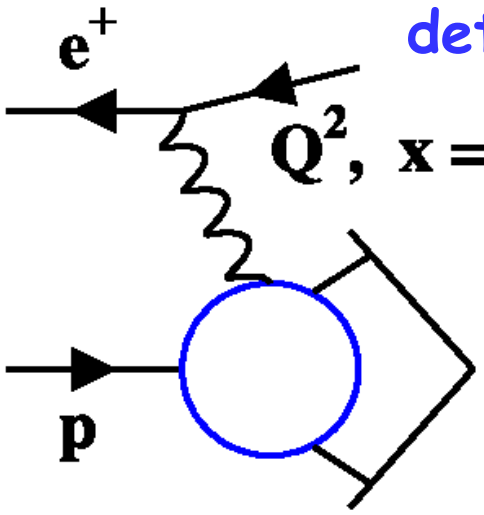
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ inelasticity,
γ momentum fraction (of e)

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

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

Heavy flavour contributions to F_2

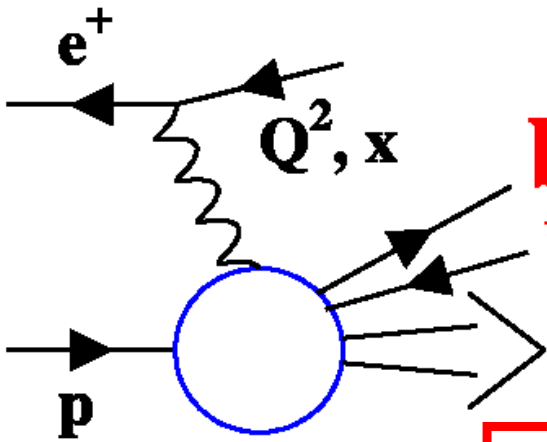


detect ⟷

Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} \cong \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right]F_2(x,Q^2)\right.$$

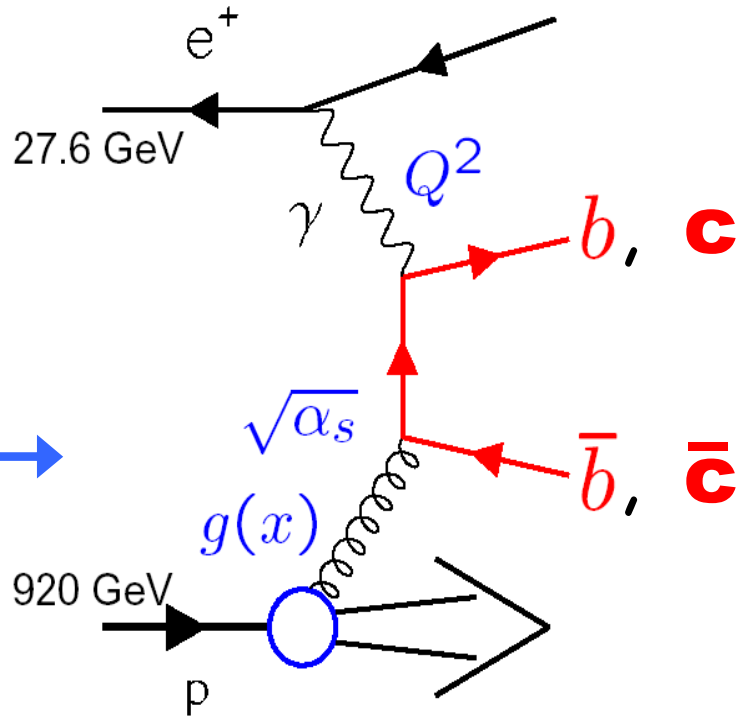
flavour tagging ↓



b b̄ or **c c̄**

-> $F_2^{b\bar{b}}$, $F_2^{c\bar{c}}$

QCD ⟷



beauty in DIS at HERA

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beauty cross section at HERA much smaller than charm, can use lifetime information (micro-vertex detector)

->

beauty-enriched sample