The Charm and Beauty quark masses and their running at HERA

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DESY-12-172, EPJ C73 (2013) 2311

DESY-14-083, arXiv:1405.6915

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

for more details on data analysis see talk O. Zenaiev

running of α_s and quark masses

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

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

leading order QCD formulae

- **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

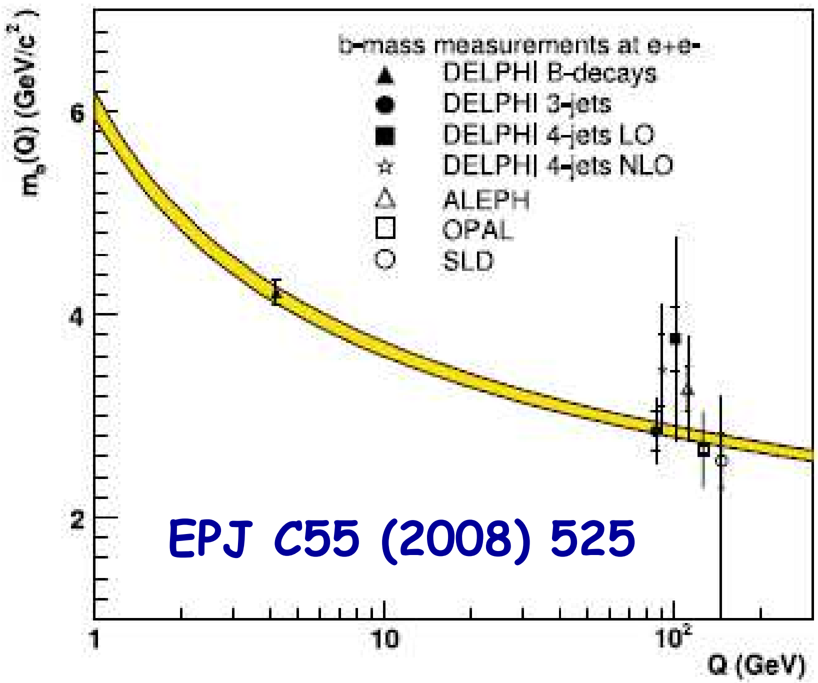


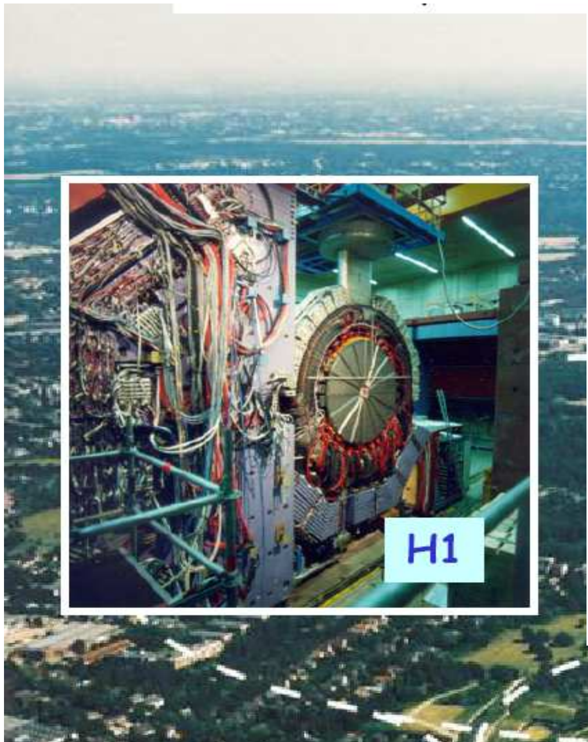
Fig. 6. The energy evolution of the $\overline{MS}$-running b-quark mass $m_b(Q)$ as measured at LEP. DELPHI results from $R_3^{b\ell}$ [7] at the M_Z scale and from semileptonic B-decays [31] at low energy are shown together with results from other experiments (ALEPH [4], OPAL [5] and SLD [6]). The 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])

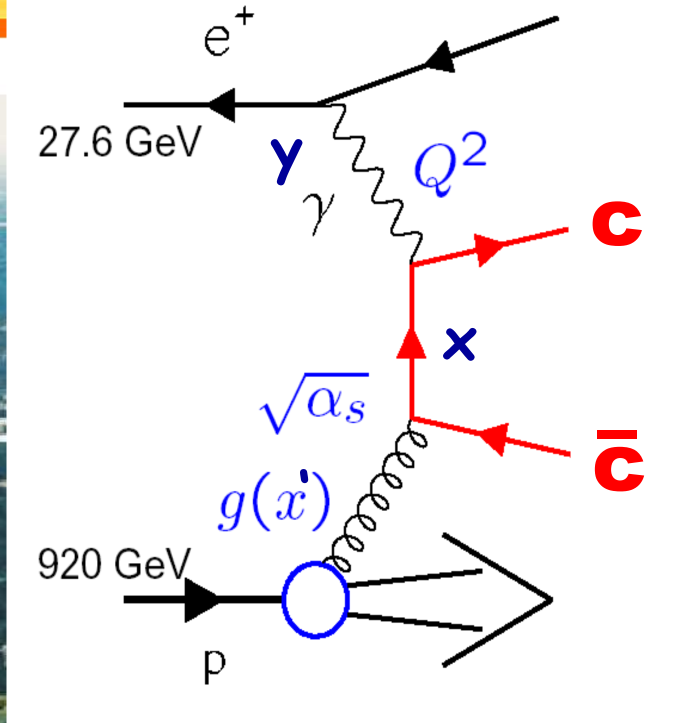
LEP: Z -> bb + gluons, measurement of phase space/ angular distributions

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

charm mass running not explicitly measured (so far)

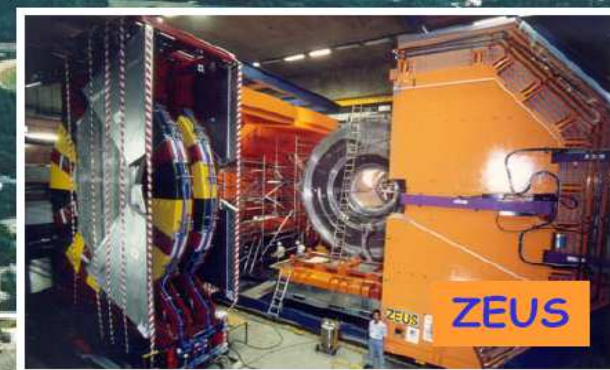
The HERA ep collider and experiments





up to 30% of cross section

HERA



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

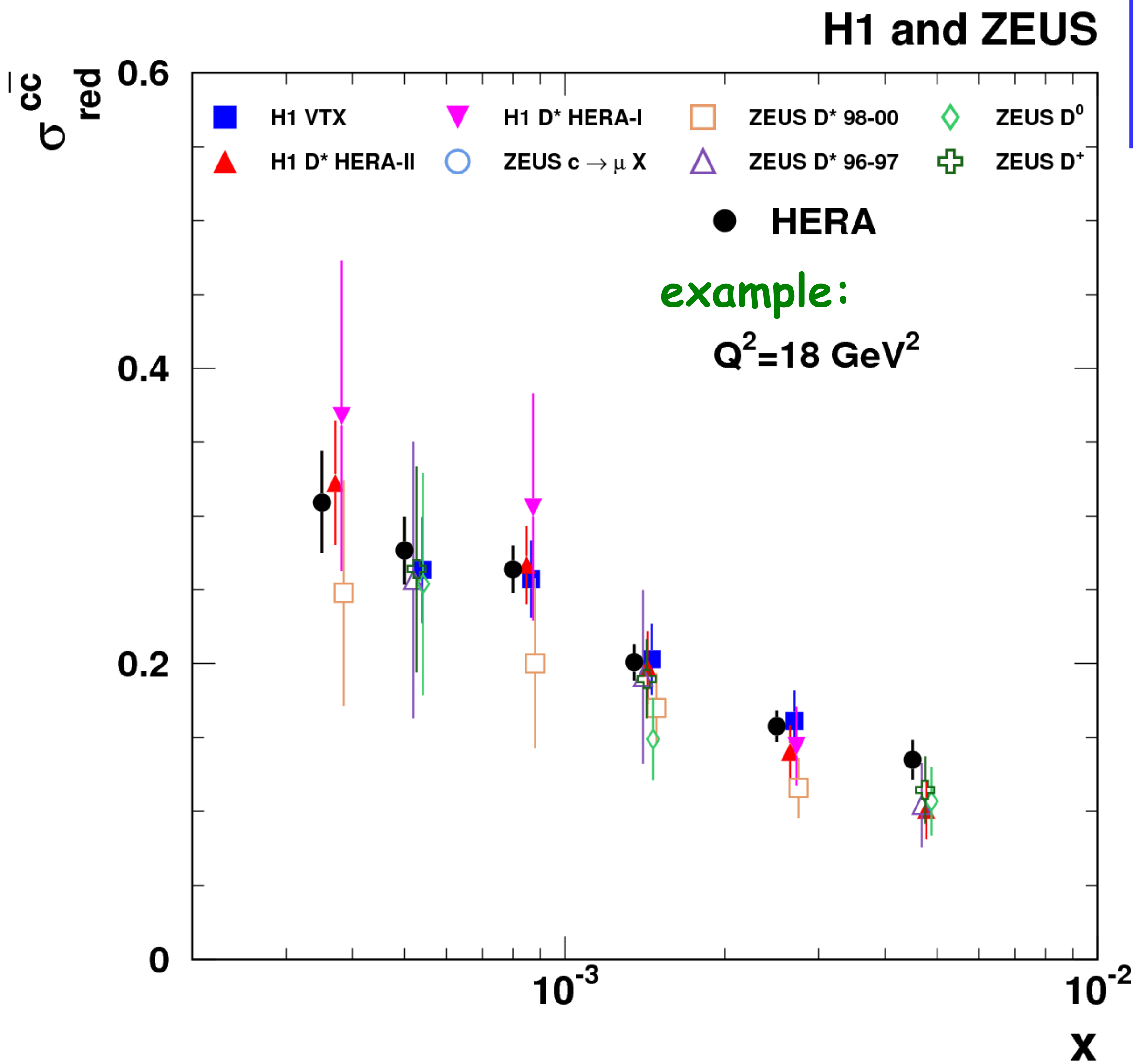
HERA II: ~ 380 pb^{-1}(physics)

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

HERA charm data combination

Measure cross section

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



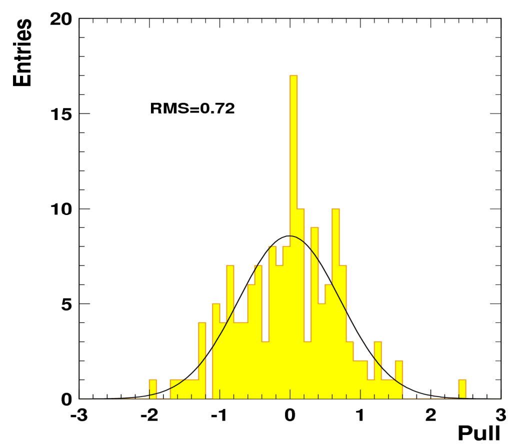
9 data sets
(HERA I, HERA II)

5 charm tagging methods

155 -> 52 data points

48 correlated systematic uncertainties

very good consistency of data:



Combination result

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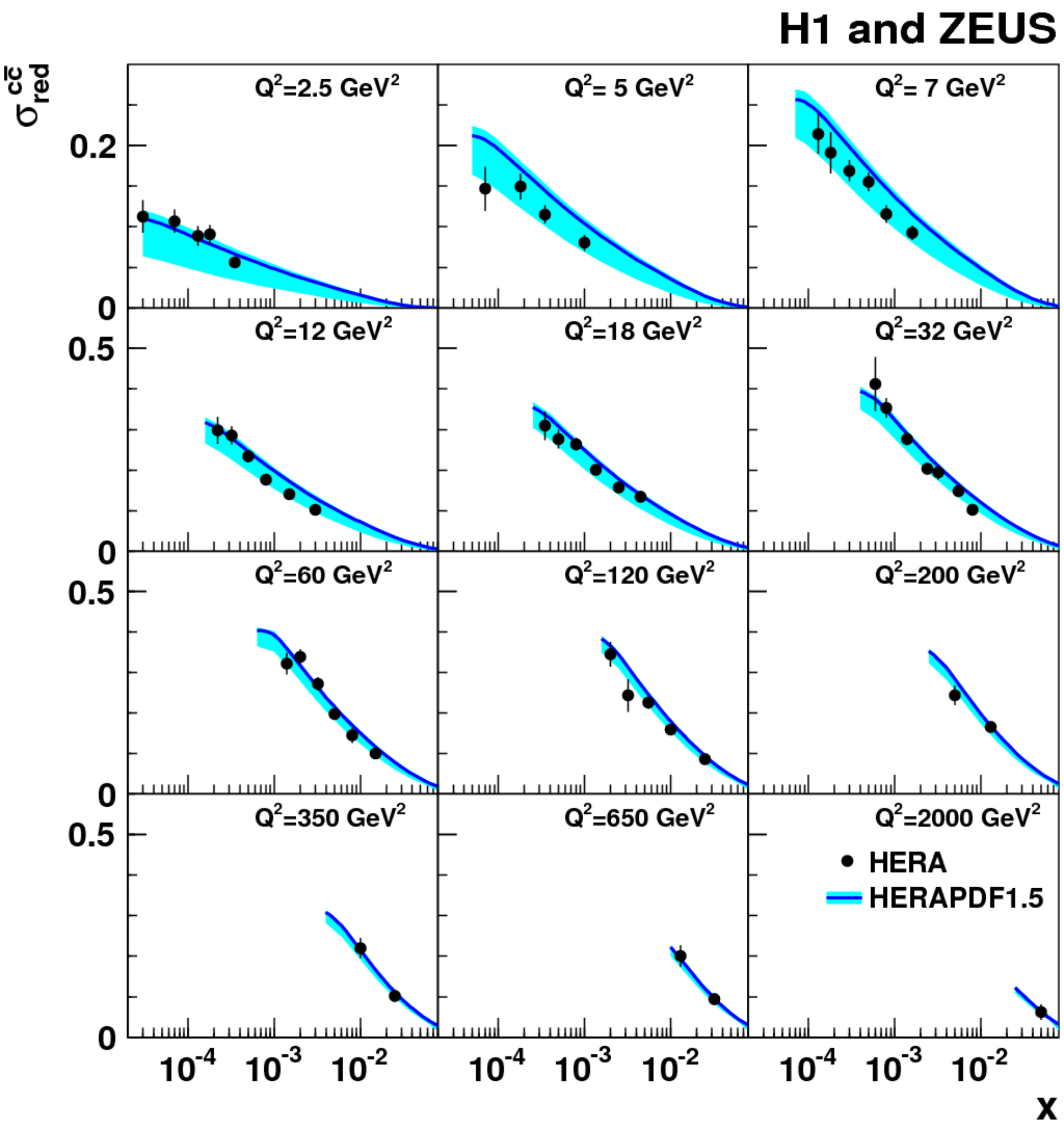
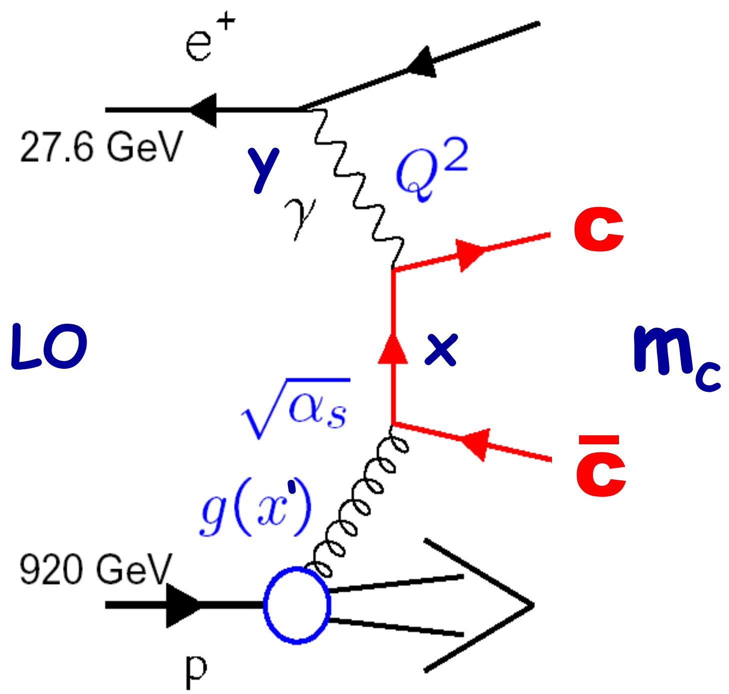


well described using HERAPDF1.5
(fitted from inclusive DIS only)

strong charm mass dependence
(blue band: 1.35->1.6 GeV)

constrains PDFs,
-> talk O. Zenaiev

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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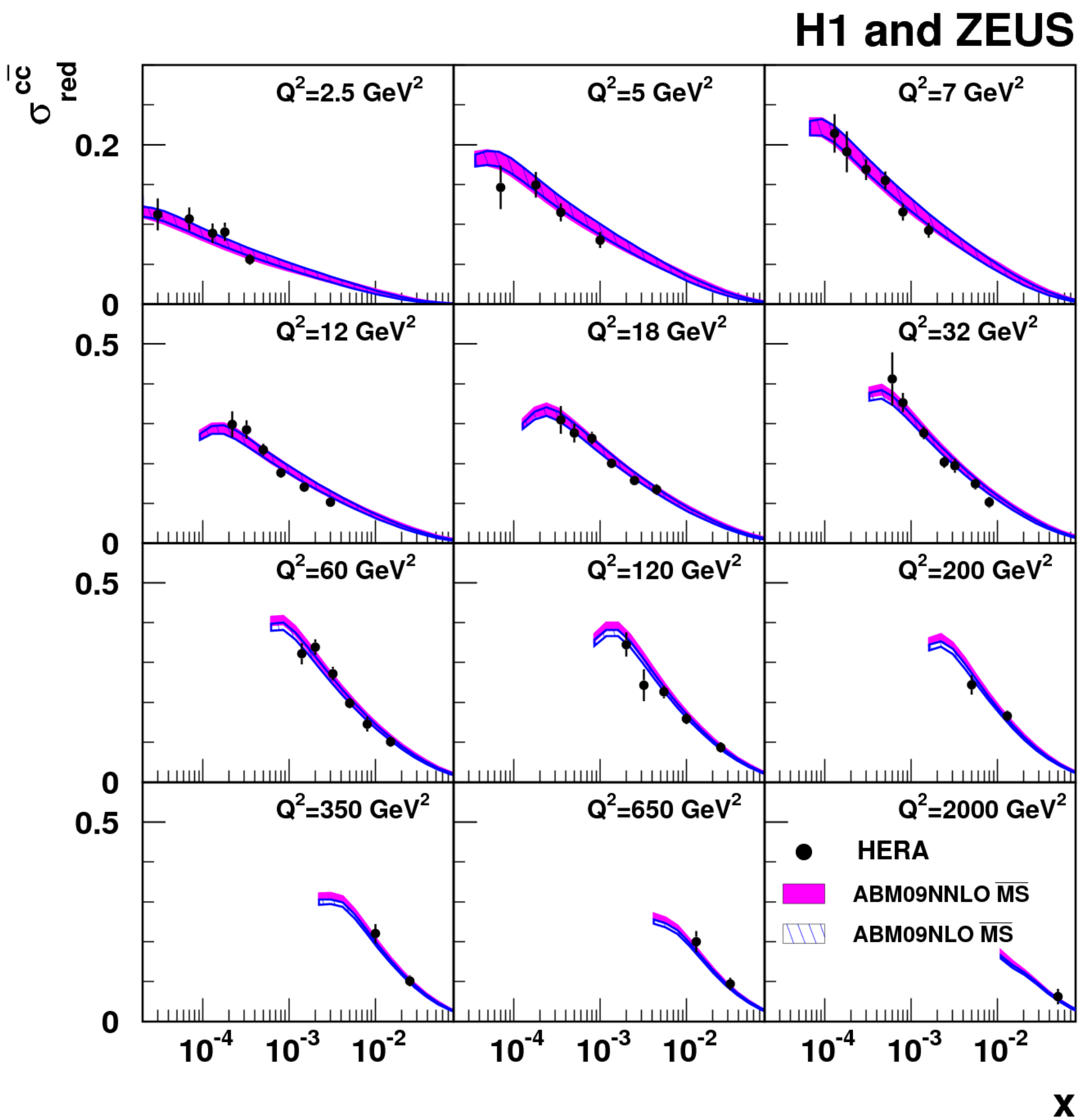

very good description of data in full kinematic range

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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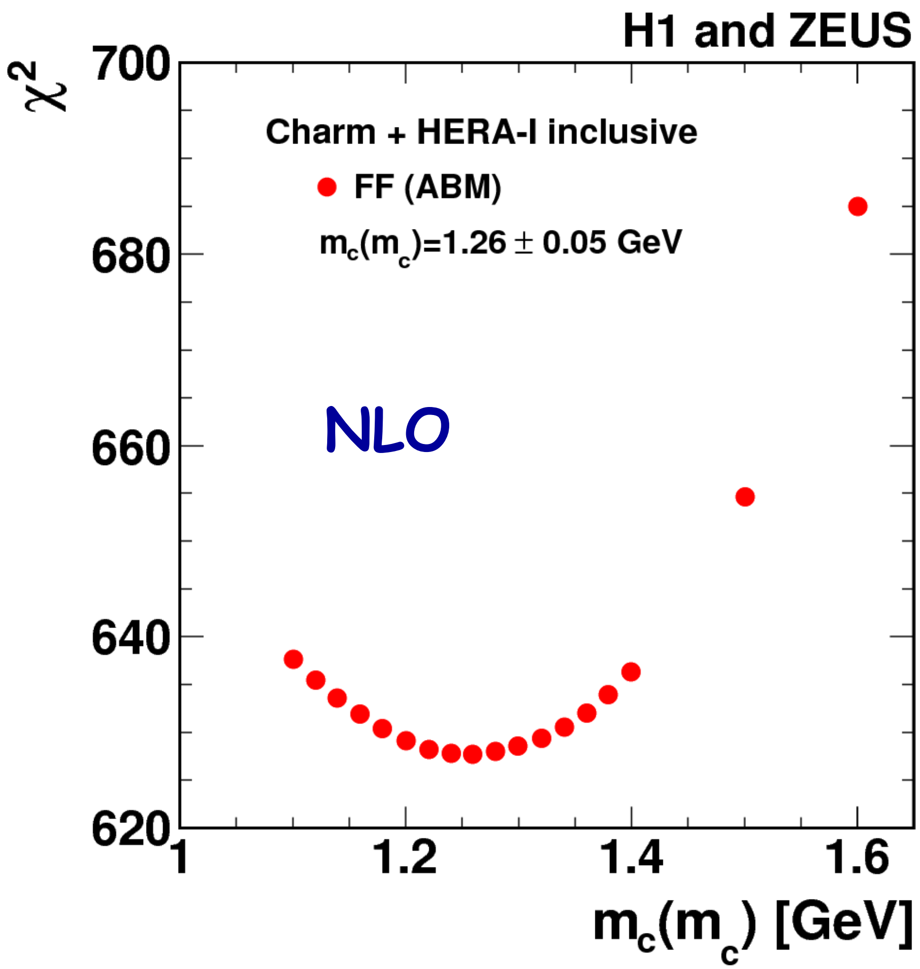

simultaneous fit of combined charm data and inclusive HERA I DIS data

$m_c(m_c)$ = 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

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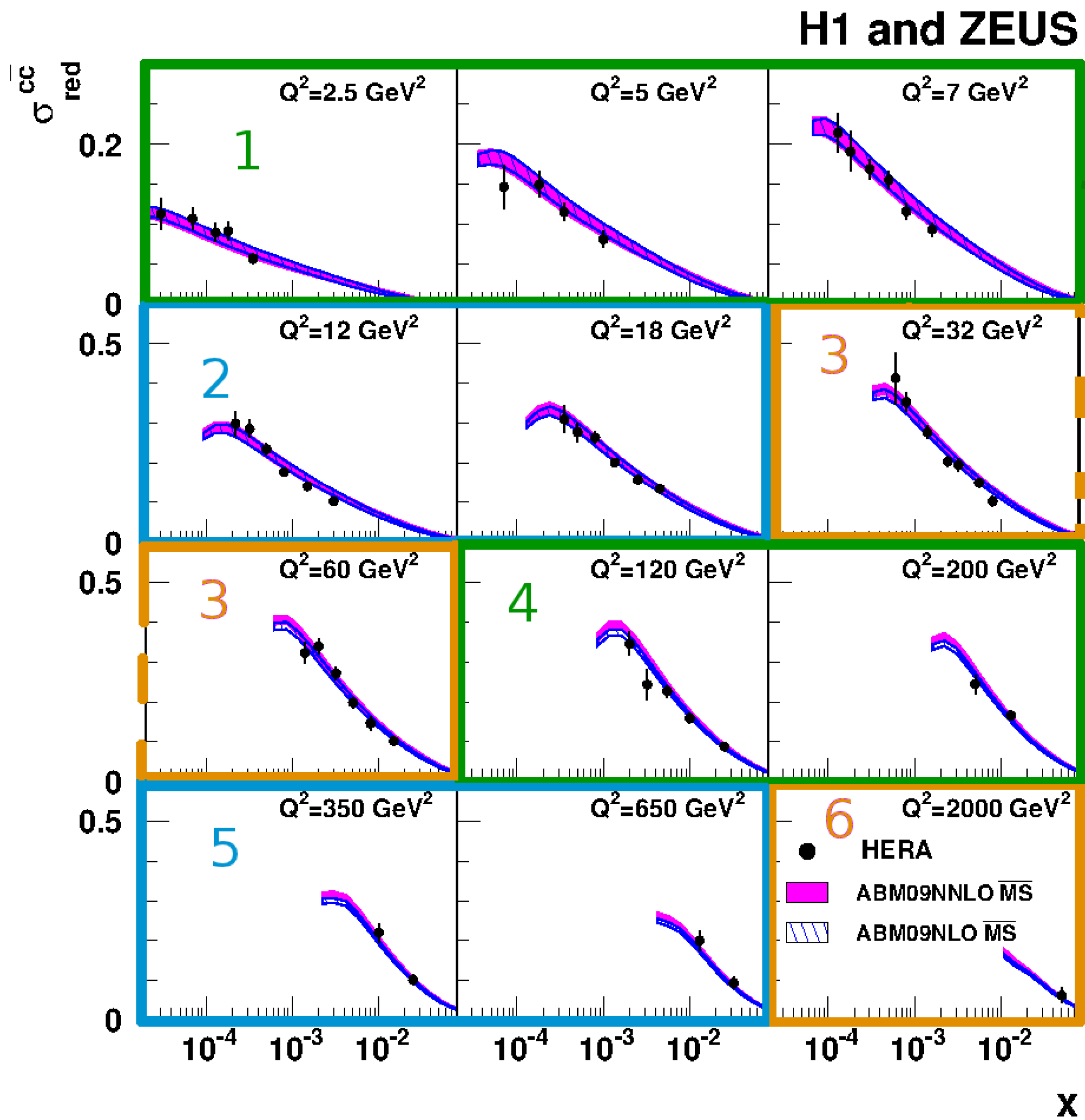
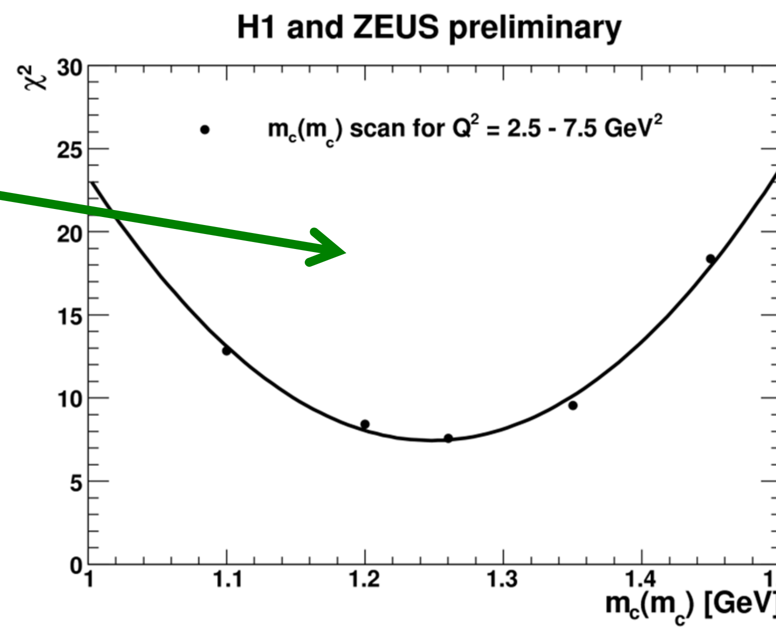




Step 1:
extract $m_c(m_c)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2+4m_c^2$

(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

Fit uncertainty

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

Parametrisation

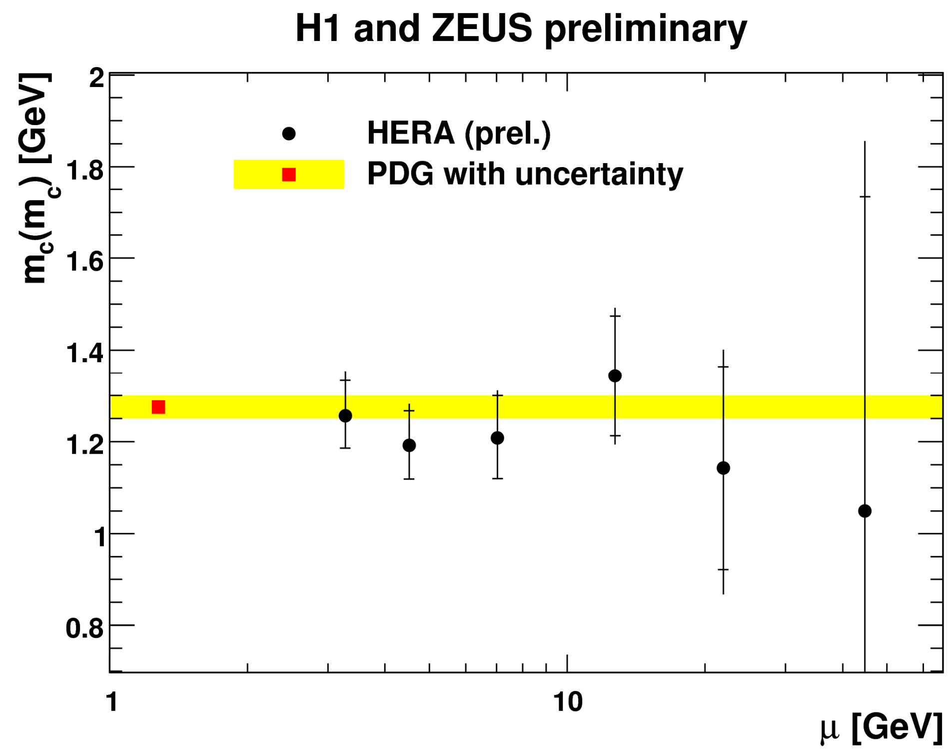
- Adding extra parameter in the PDF parametrisation

Model uncertainty

- Variation of the strangeness 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



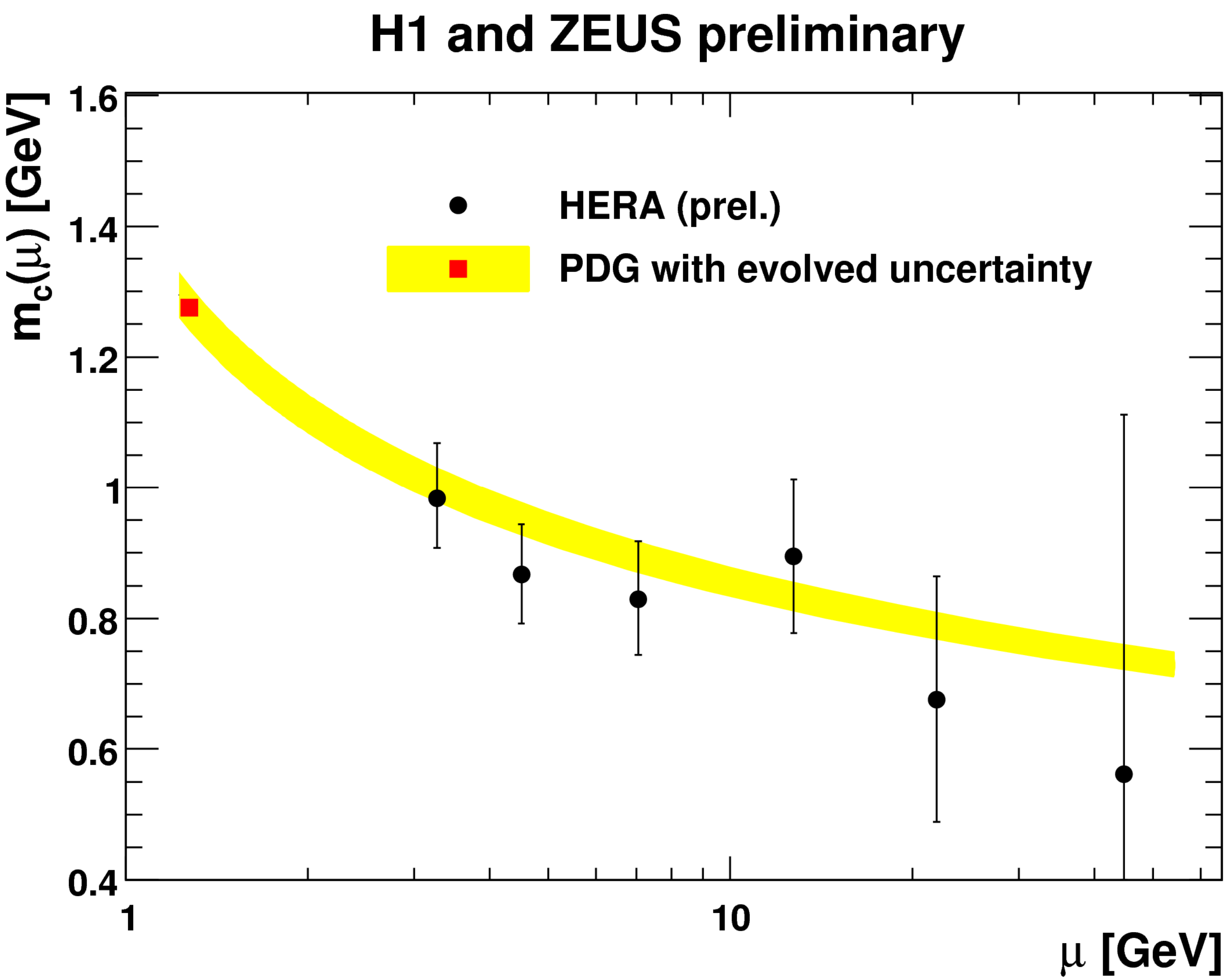
sensitivity to $m_c(m_c)$ decreases with increasing scale $\mu^2 = Q^2+4m_c^2$

'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 !

beauty in DIS at HERA

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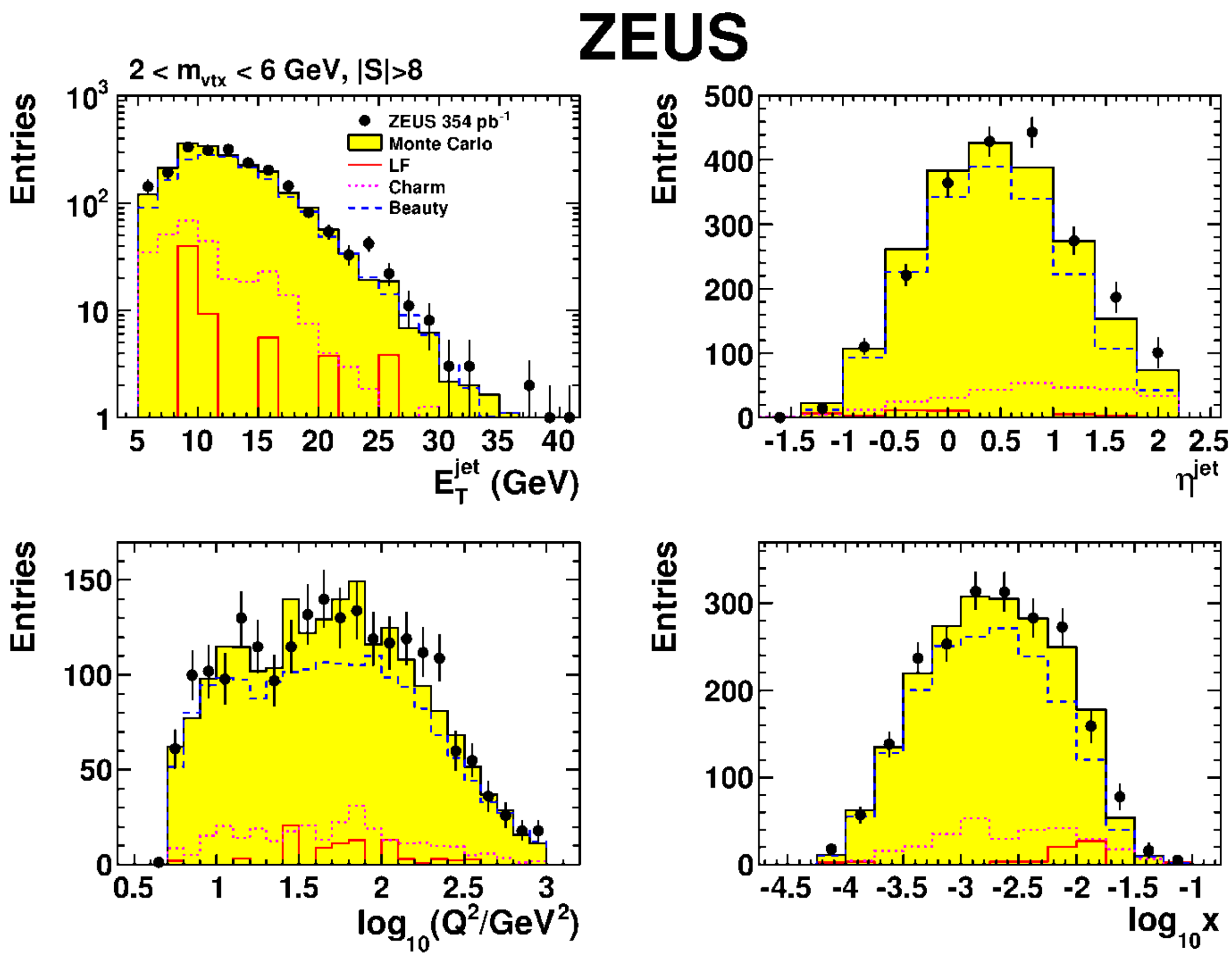
beauty cross section at HERA much smaller than charm, can use lifetime information (micro-vertex detector)

->
beauty-enriched sample

(more in talk
O. Zenaiev)



m_b from reduced beauty cross section

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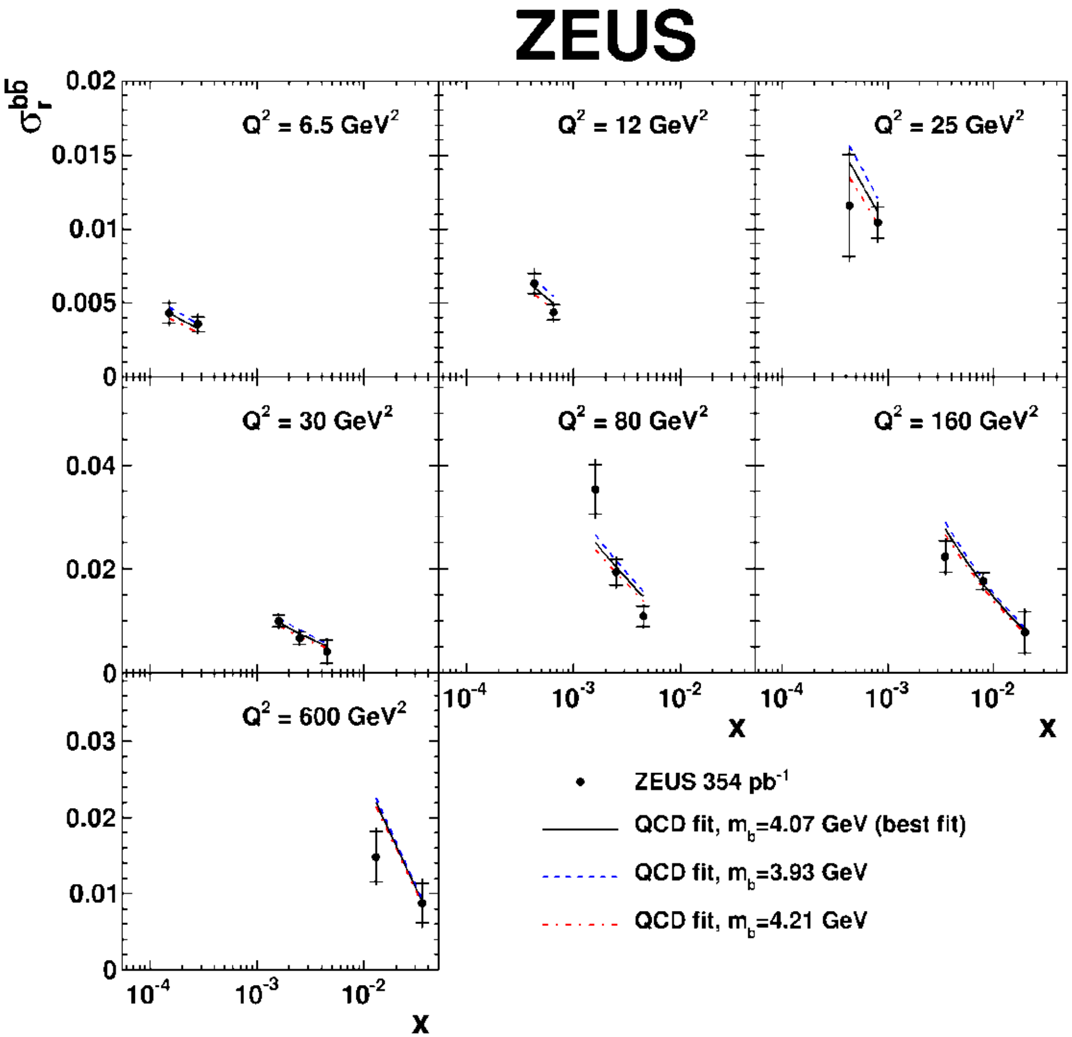
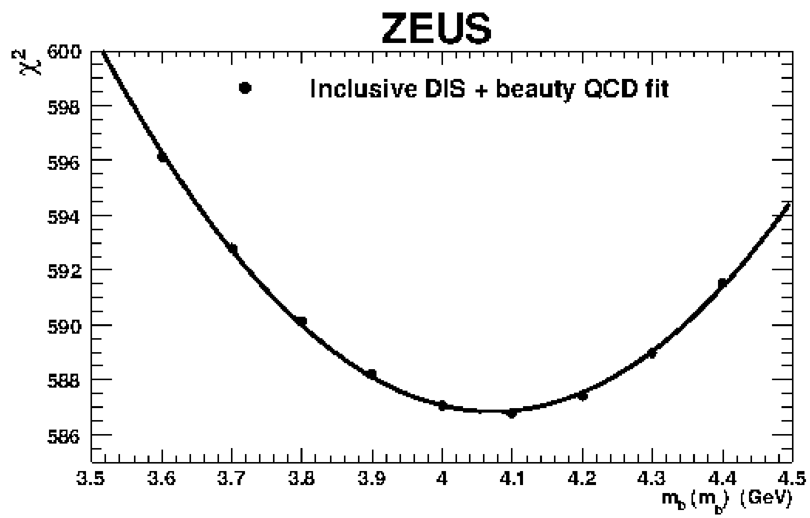




ndf = 596

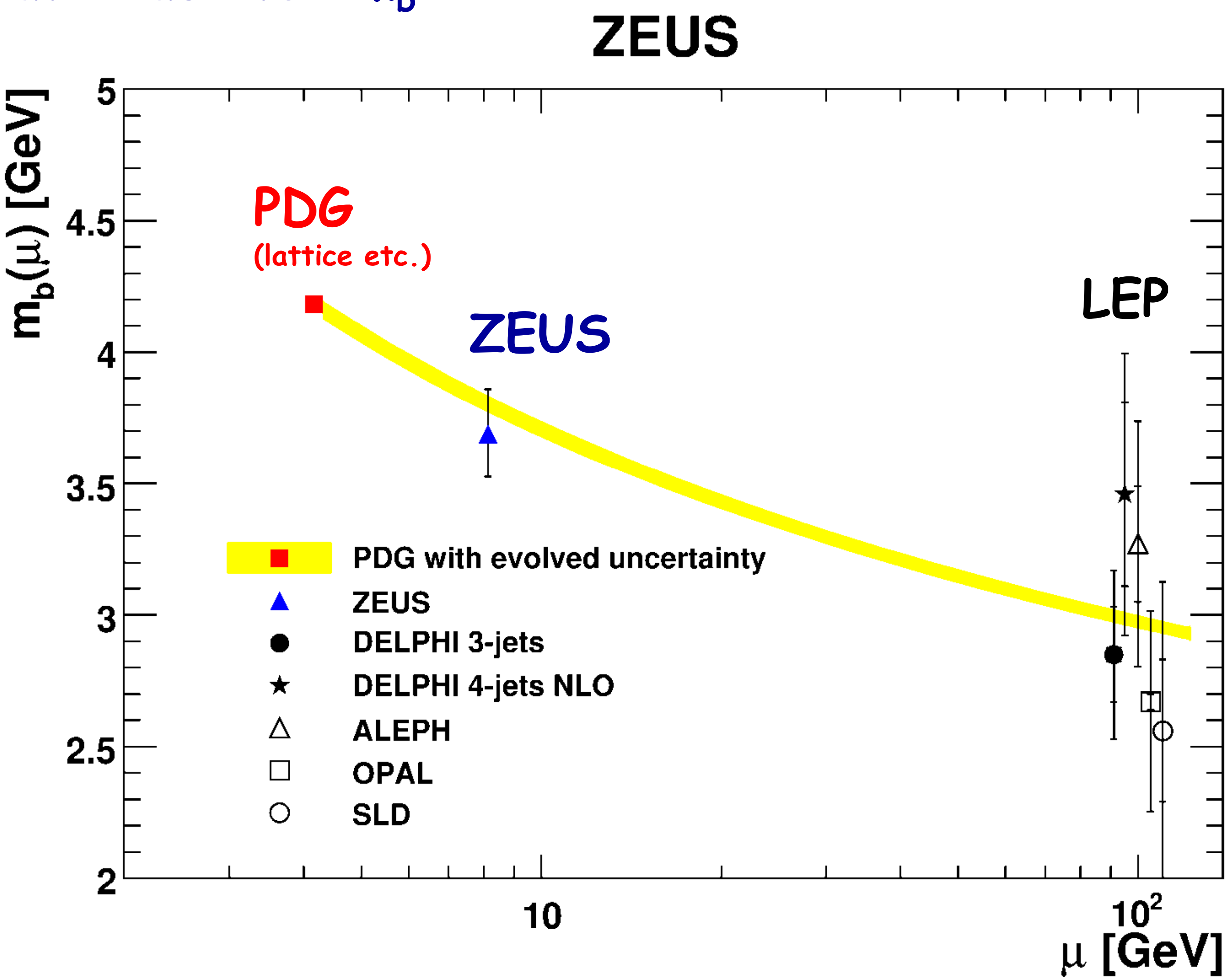
uncertainty evaluation
similar to charm running case

$m_b(m_b)$ = 4.07 ±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

translate back to $2m_b$



Outlook

- so far, only HERA charm data have been combined;
  combination of beauty data could further improve b mass result, and constrain b mass running from HERA data

- $m_b/\surd s_{HERA} \sim m_t/\surd s_{LHC}$
  m_t has sizeable QCD+electroweak corrections
  m_c, m_b have QCD corrections only
  -> learn how to deal with QCD part of t quark mass running at LHC,
  and how to disentangle it from electroweak part ?

- reinterpret running of quark masses as running of corresponding Higgs Yukawa couplings !?

Summary and conclusions

- HERA DIS charm data have been combined
  (except most recent, see talk O. Zenaiev)
  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)

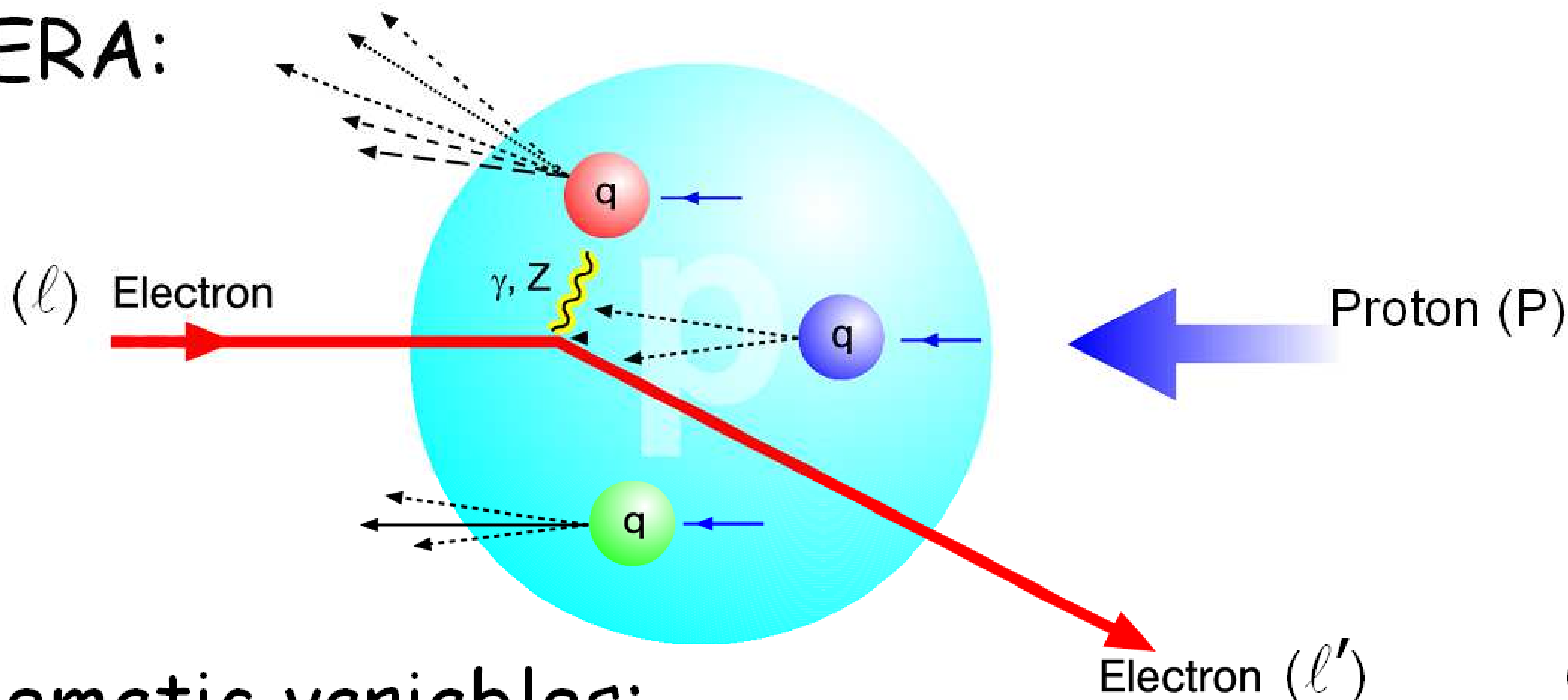
- ZEUS DIS beauty data well described by NLO QCD
  -> measure beauty mass
  $m_b(m_b) = 4.07 \pm 0.14_{fit} {}^{+0.01}_{-0.07\ mod} {}^{+0.05}_{-0.00\ par} {}^{+0.08}_{-0.05\ th}$ GeV

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

Backup

Deep Inelastic ep Scattering at HERA

HERA:



$q = \ell - \ell'$

kinematic variables:

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

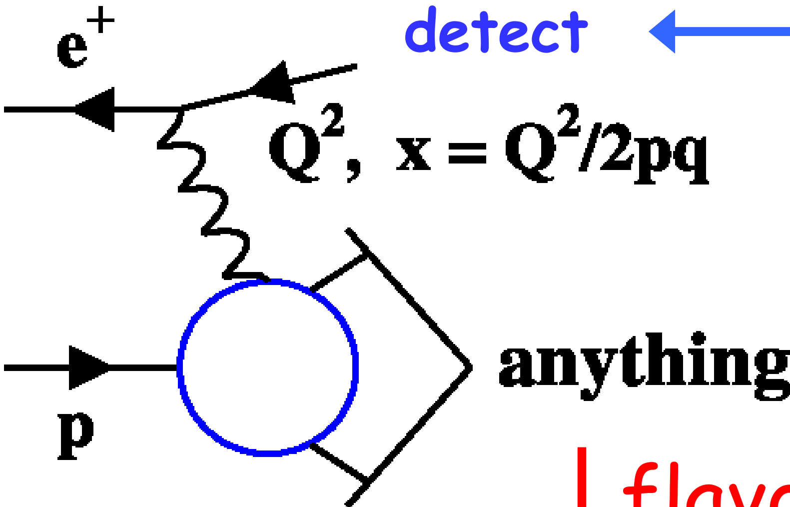
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ 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

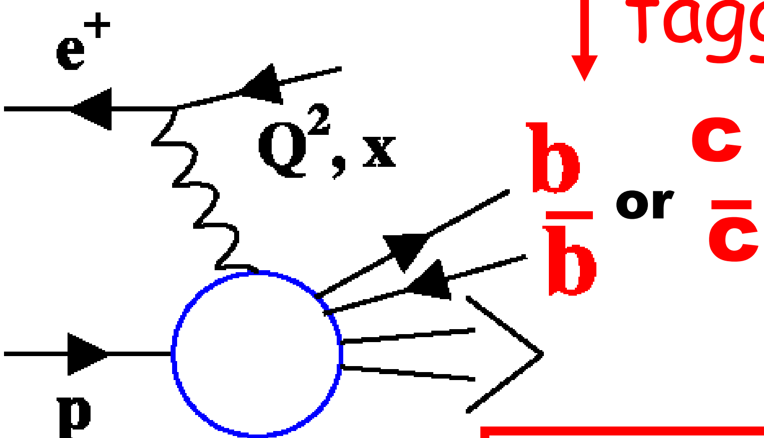


detect ⟷

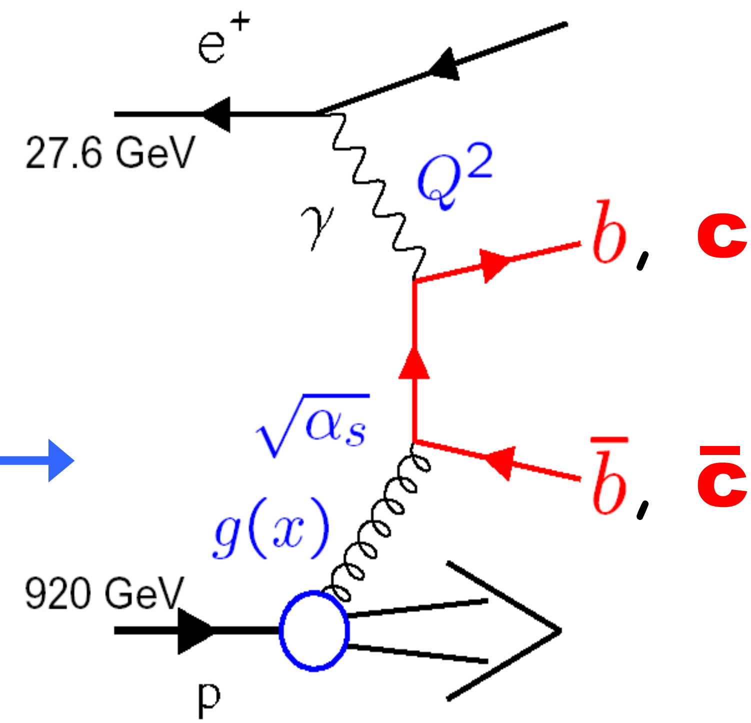
Measure cross section

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

flavour tagging ↓



QCD ⟷



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

Quark mass definitions

Pole quark mass

- Based on (unphysical) concept of quark being a free parton
- Pole mass is ambiguous up to corrections of $O(\Lambda_{QCD})$

Running quark mass ($\overline{MS}$)

- $\overline{MS}$ (minimal subtraction scheme) mass definition $m(\mu_R)$ realizes running mass (scale dependence)
- renormalization group equation (mass anomalous dimension γ)

$$\left(\mu_R^2 \frac{\delta}{\delta \mu_R^2} + \beta(\alpha_s) \frac{\delta}{\delta \alpha_s}\right) m(\mu_R) = \gamma(\alpha_s) m(\mu_R)$$

Measurement of the charm quark mass running

From $m_c(m_c)$ it was translated back to $m_c(\mu)$ by 1-loop formula :

$$m_c(\mu) = m_c(m_c)\frac{\left(\frac{\alpha_s(\mu)}{\pi}\right)^{\frac{1}{\beta_0}}}{\left(\frac{\alpha_s(m_c)}{\pi}\right)^{\frac{1}{\beta_0}}}$$

Where β_0 for N_f=3 is $\frac{9}{4}$
$\mu = \sqrt{Q^2 + 4m_c^2}$,
This formula is the same that is used in the QCD fit (OpenQCDRad).
[arXiv:hep-ph/0004189]
Q^2 was chosen to be log average between Q^2 of used bins

Charm mass measurement

- χ^2 mass scan had been performed by fitting charm data in FFNS ABM($\overline{MS}$) scheme (OPENQCDRAD program) using HeraFitter package with following setup:
  - FFNS ABM (running mass)
  - Evolution starting scale set to Q_0=1.4 GeV^2
  - PDF parametrisation with 13 parameters
  - H12011 χ^2 function definition
  - $\alpha_s(M_z)$=0.105
  - Data below $Q^2 = 3.5\ GeV^2$ removed
  - $m_b(m_b)$ was set to 4.75
  - Renormalization and factorization scale was set to $\sqrt{Q^2 + 4m_q^2}$