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Charm and beauty production (in DIS) at HERA

A. Bertolin INFN (Sezione di Padova)

on behalf of the H1 and ZEUS collaborations

Outline:

ÅHERA, H1 and ZEUS

Åheavy quark production in DIS at HERA

Åcharm DIS cross sections and charm quark mass

Åbeauty quark mass

Åadditional observables for charm

Åconclusions

The HERA collider and the H1 and ZEUS detectors: short introduction

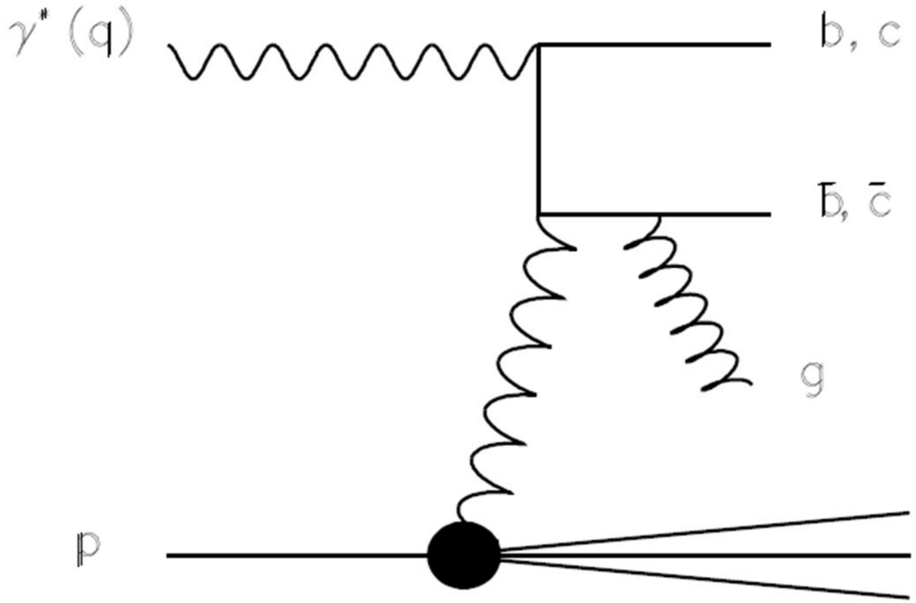
ÅHERA was an *e p* collider, γ *p* center of mass energy was up to 320 GeV (equivalent to a ~ 50 TeV *e* beam on fixed target)

ÅH1 and ZEUS were ~ 4π–coverage multipurpose experiments (calorimetry, tracking, é)

Årunning started in 1992 and ended in 2007 é over time significant detector upgrades: silicon vertex detectors that boosted charm and beauty performances

Åintegrated luminosity: ~ 500 pb^{-1} per experiment, huge for an *e p* collider

Deep Inelastic Scattering (DIS) kinematic variables



referring to the diagram shown above:

Å $Q^2 = -q^2$

virtually of the exchanged γ

Å $x = Q^2 / 2\,P\,q$

fraction of the proton momentum taken by the incoming gluon

Å $y = P\,q / P\,k$

fraction of the electron momentum taken by the incoming γ

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

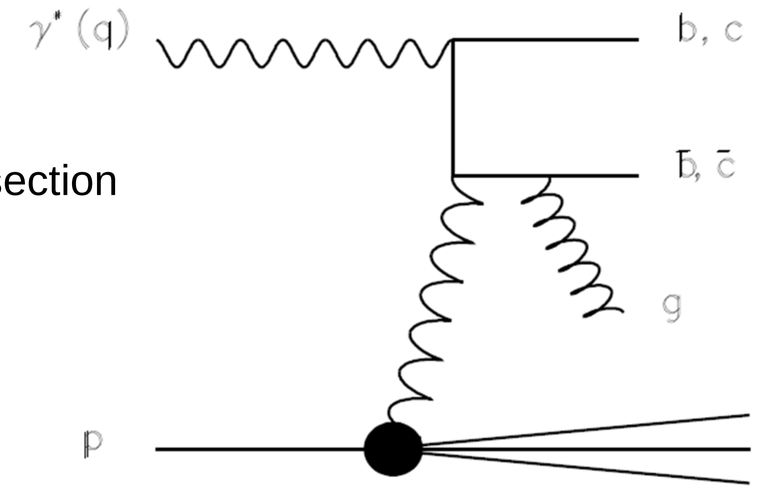
Å DIS regime: $Q^2 > 1$ GeV ^{2}

(photoproduction regime: $Q^2 \sim 0$ GeV^2)

Heavy quark (charm and beauty) production in DIS at HERA

Å important playground for pQCD: the heavy quark mass, m_Q Q=c,b, provides a hard scale that allows pQCD calculations to be made
Å dominant heavy quark production process in DIS: boson gluon fusion

cross section = gluon density ⊗ hard sub-process cross section



$m_Q(\mu)$
$\alpha_S(\mu)$
...
$\mu = Q^2$ or $f(Q^2, p_T{}^2,$ é $)$

hottest questions for pQCD:
Å how accurate is the prediction of the hard sub-process cross section ?
Å if you plug in the gluon density from inclusive DIS measurements do you get the right results for the heavy quark cross sections ?
Å is the running of the charm and beauty quark masses as expected ?

Available data and tagging techniques

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

Å two independent experiments

Å a large variety of tagging techniques: inclusive methods using the large lifetime of charmed hadrons, inclusive track lifetime, complete reconstruction of charmed mesons, D^{*+}, charm semileptonic decay, μ

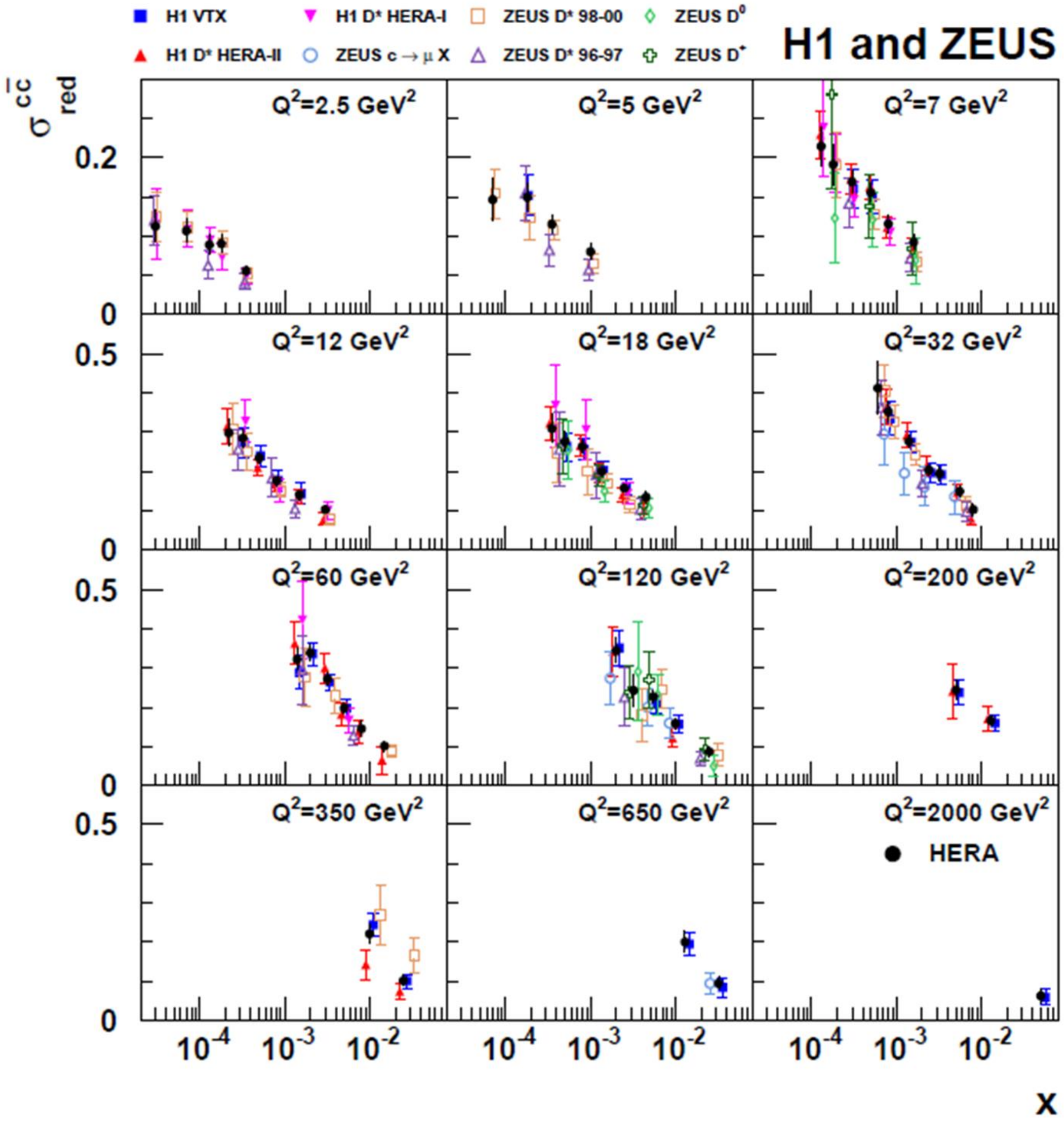
Å a large number of measurements, $\sum N = 155$ data points, in a common grid spanning the x ï Q^2 plane (except for [14] where scaling factors, always smaller than 18 %, have been applied to migrate the original measurements to the closest point of the common grid)

Å developed a combination method taking into account properly correlated and uncorrelated uncertainties (155 data points in 52 bins)

key observable:

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

Combined reduced charm cross section

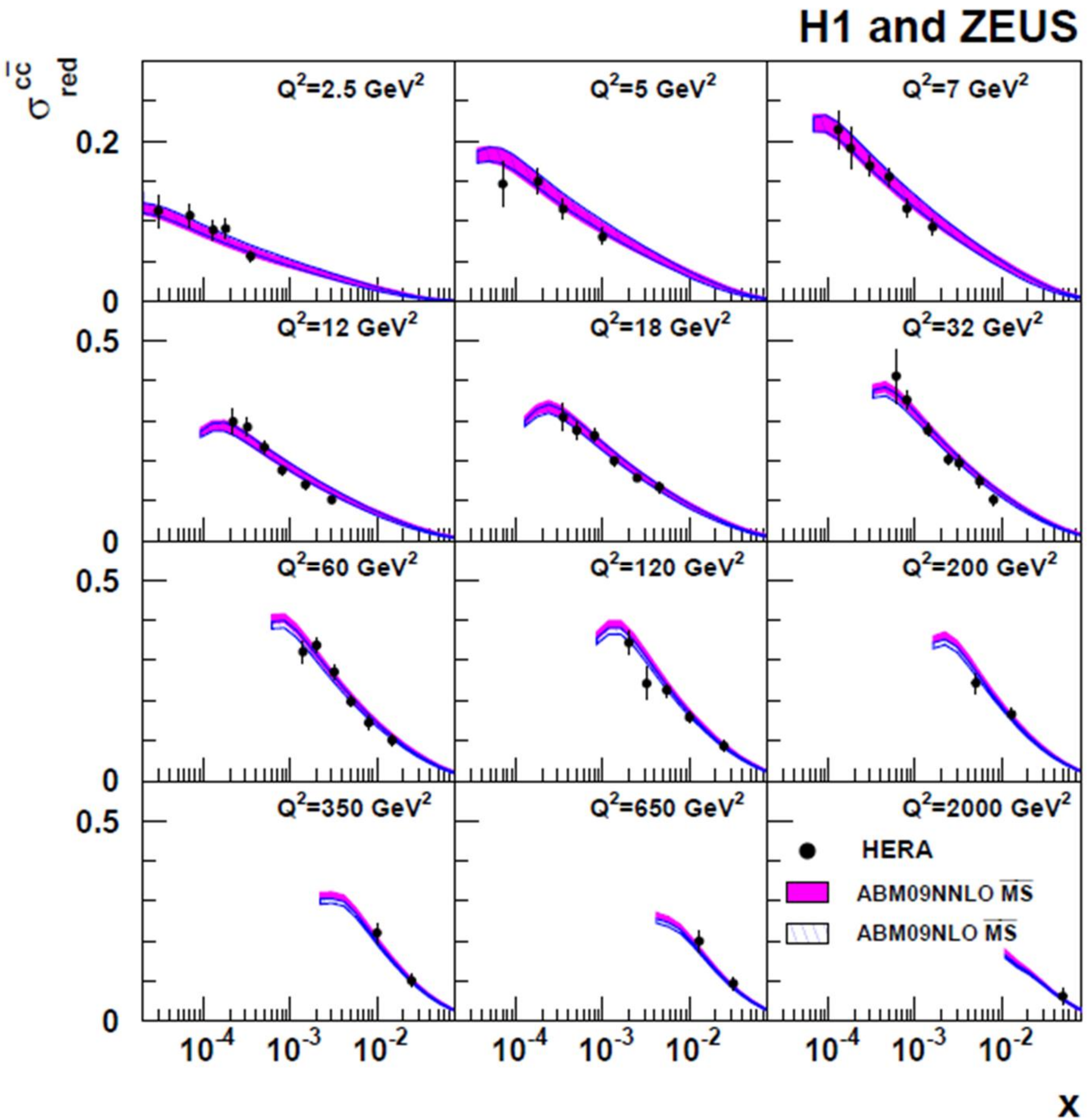


✓ good consistency of data
among the several possible tests
$\chi^2 / \text{ndf} = 62 / 103$

✓ good complementarity of data

✓10 % uncertainty on average,
6 % at small x and medium Q^2

Reduced charm cross section: data vs N(N)LO QCD

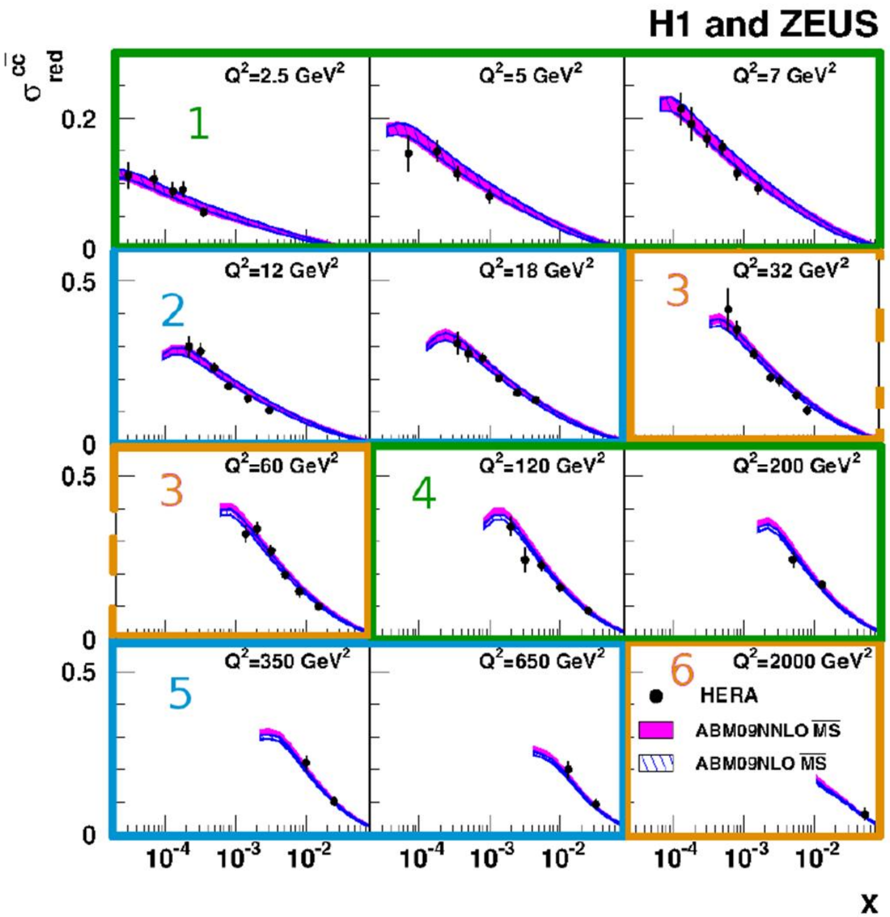


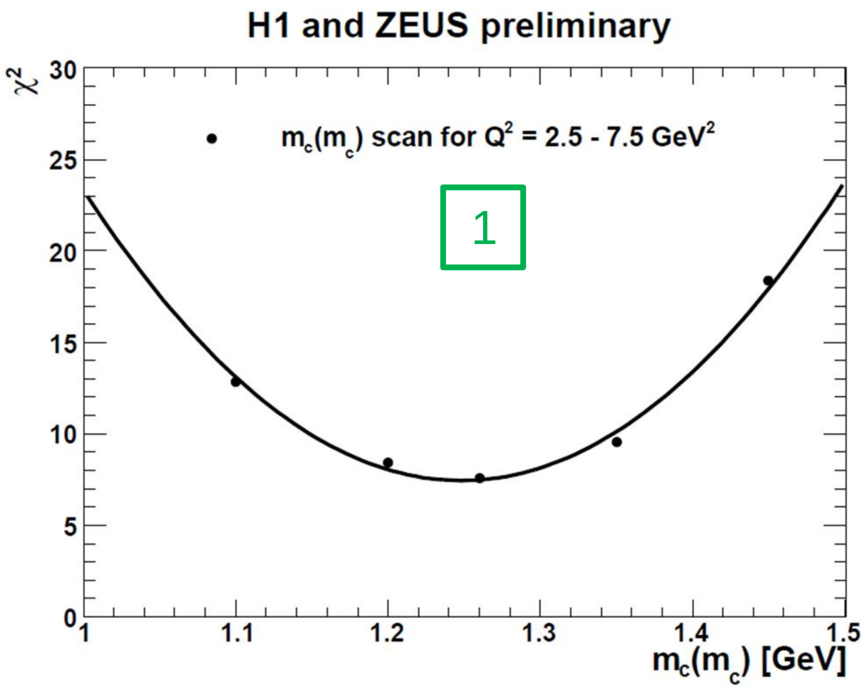
data compared to ABM predictions in the Fixed Flavor Number Scheme at NLO and NNLO

- ✓ NLO and NNLO are similar
- ✓ provide a good description of the data in the whole range
- ✓ at small Q^2 m_c is the dominant source of theoretical uncertainties

so why don't we use these data to constrain m_c ?

Extraction of the charm quark mass

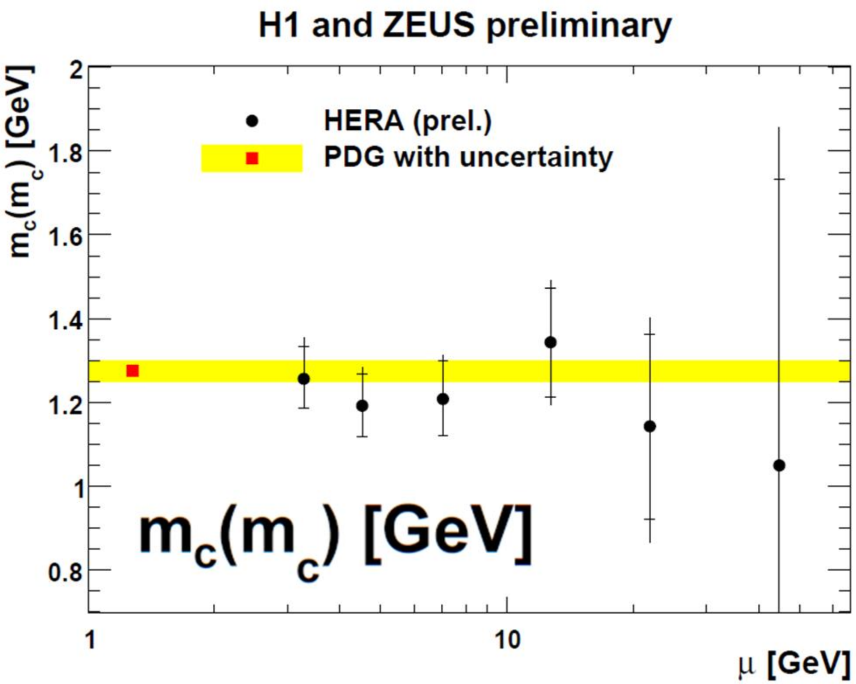




conceptually simple method:
Åwork out an array of FFNS NLO QCD predictions changing CONSISTENTLY $m_c(m_c)$ in the theory
Åfind out, using a χ^2, which $m_c(m_c)$ gives the best description of the data
Åparabolic fit
χ^2_{min}: $m_c(m_c)$, fit uncertainty: $\chi^2_{min} + 1$

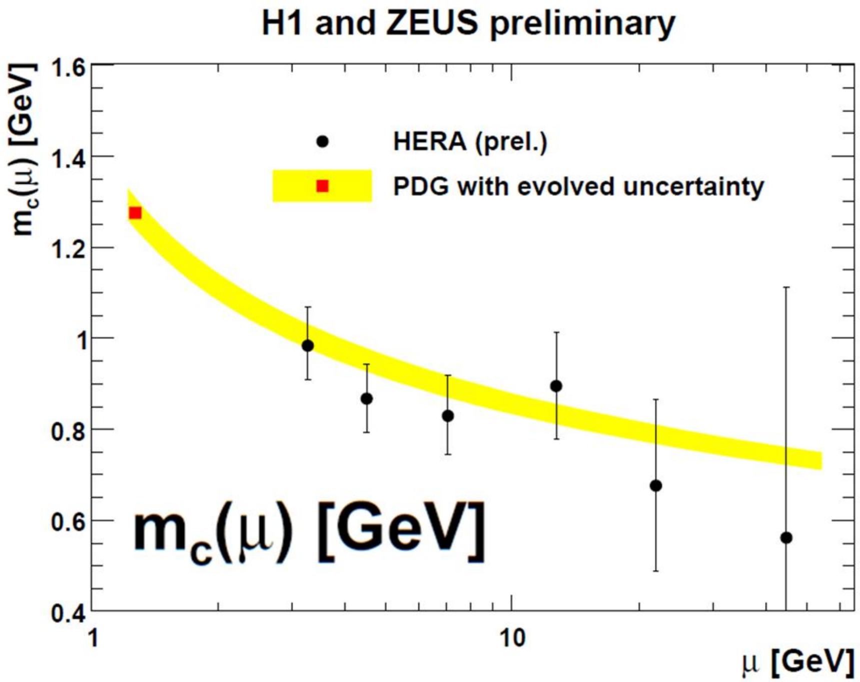
Extraction of the charm quark mass (cont.)

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



does $m_c(m_c)$ depend on which of the 6 data set is being used ?
i.e. does it depends on Q^2 ?

✓ no



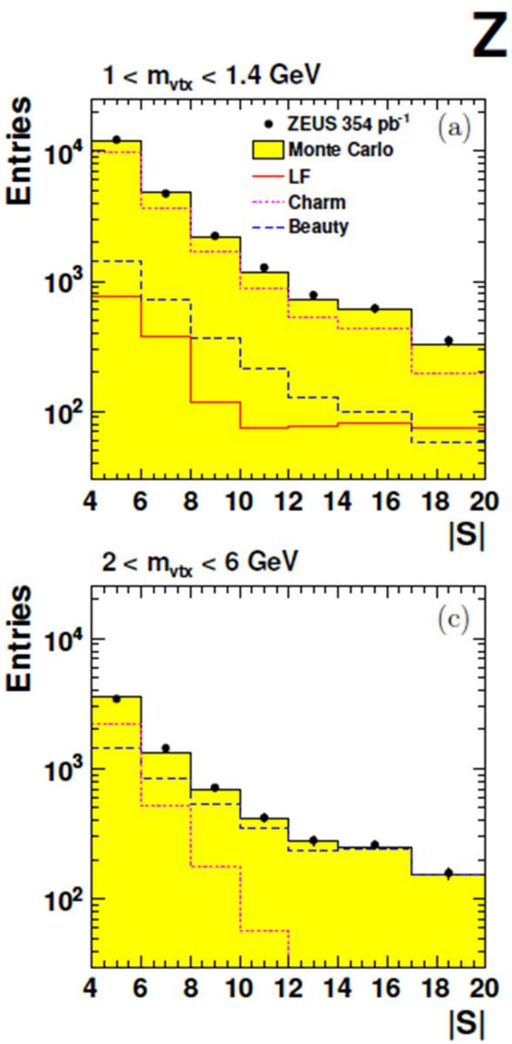
final result: running of the charm quark mass with the scale μ

m_Q running was available only for beauty from LEP data

✓ thanks to HERA now available also for charm !

✓ be aware that at large scales, $M_{Z/W}$ or M_{top}, charm can be significantly lighter than you would naively expect !!!

Can we do the same for beauty ?



Å DIS selection:

Å5 < Q^2 < 1000 GeV^2

Å0.02 < y < 0.7

Å > 0 jet(s):

ÅE^{jet}_T > 4

Å-1.6 < η^{jet} < 2.2

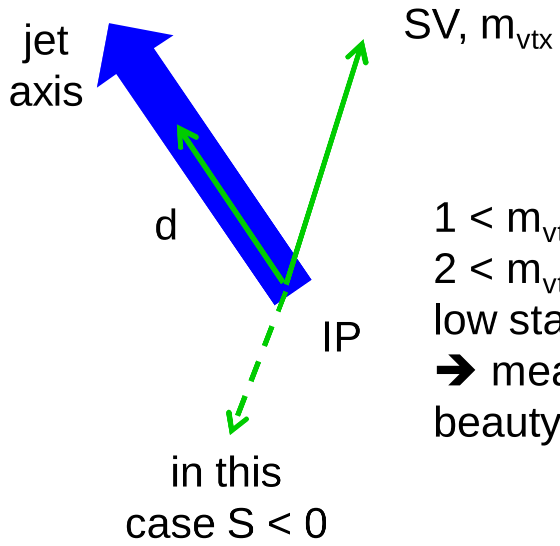
Å heavy flavor(s) separation:

ÅS = d / δd,

$S^{>0}$ - $S^{<0}$ and

finally take |S|

Åm_{vtx}

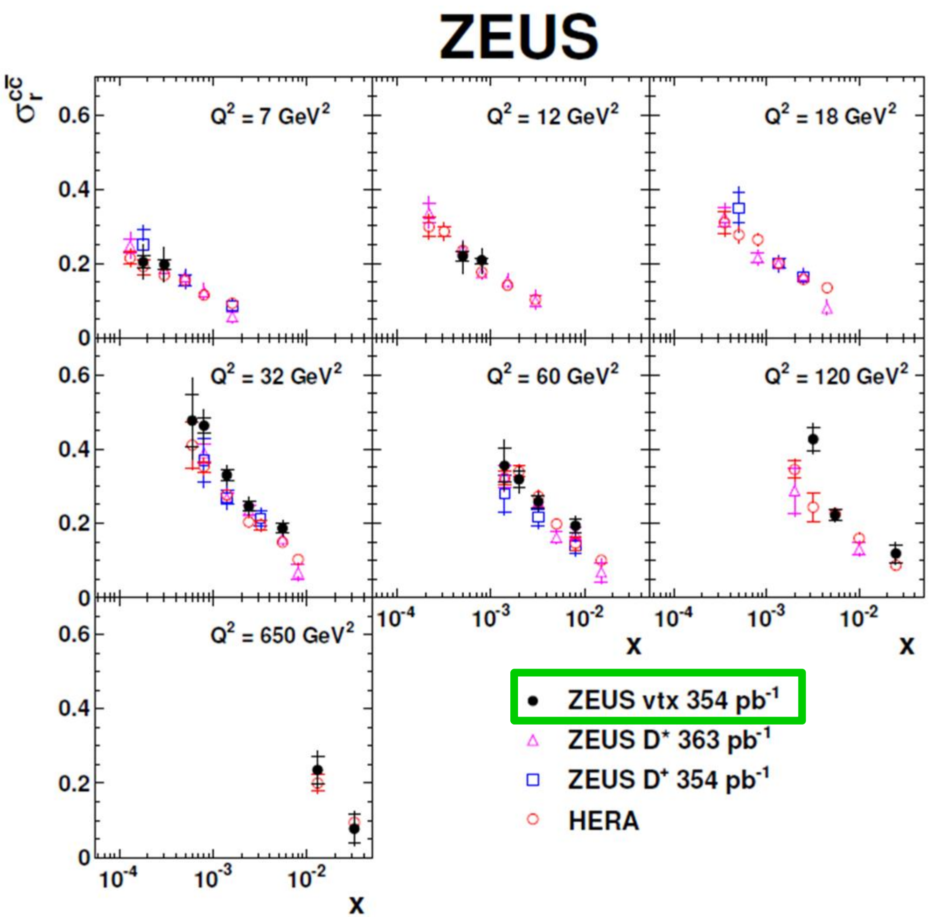


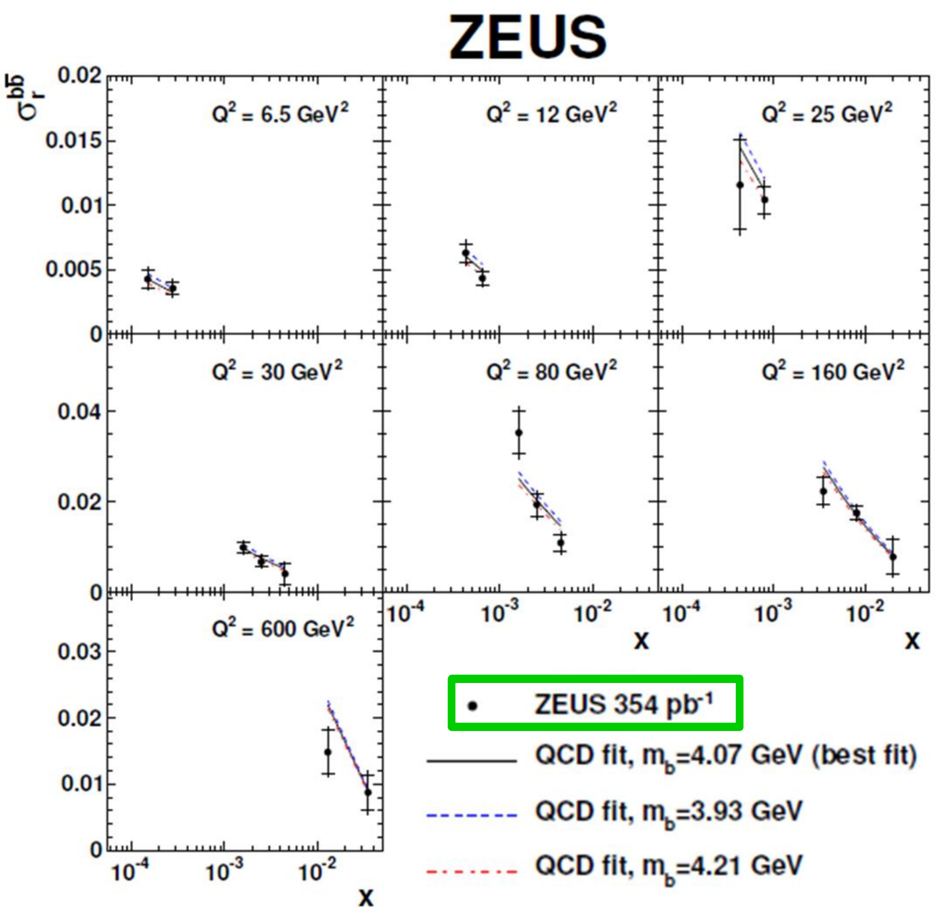
1 < m_{vtx} < 2 GeV: mostly charm

2 < m_{vtx} < 6 GeV && |S| > 8: mostly beauty but low stat.

➔ measure both and separate charm and beauty statistically

Reduced charm and beauty cross sections

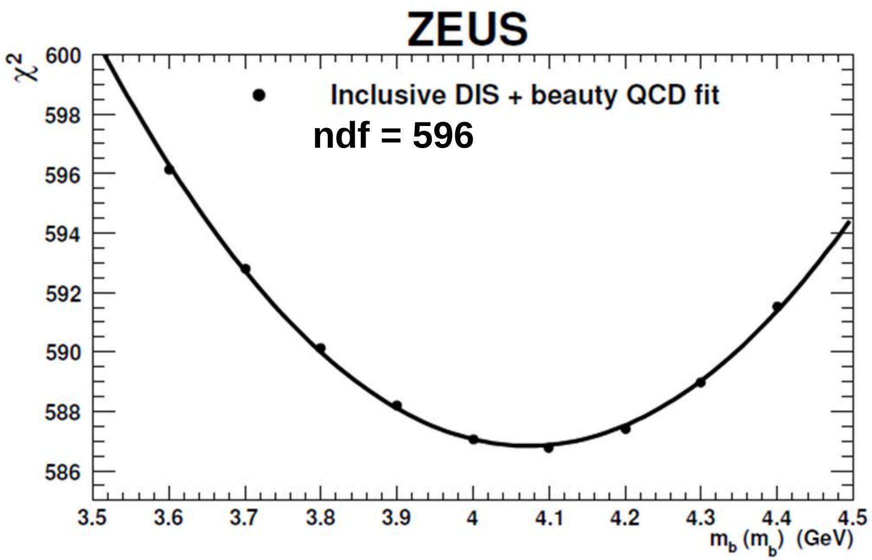


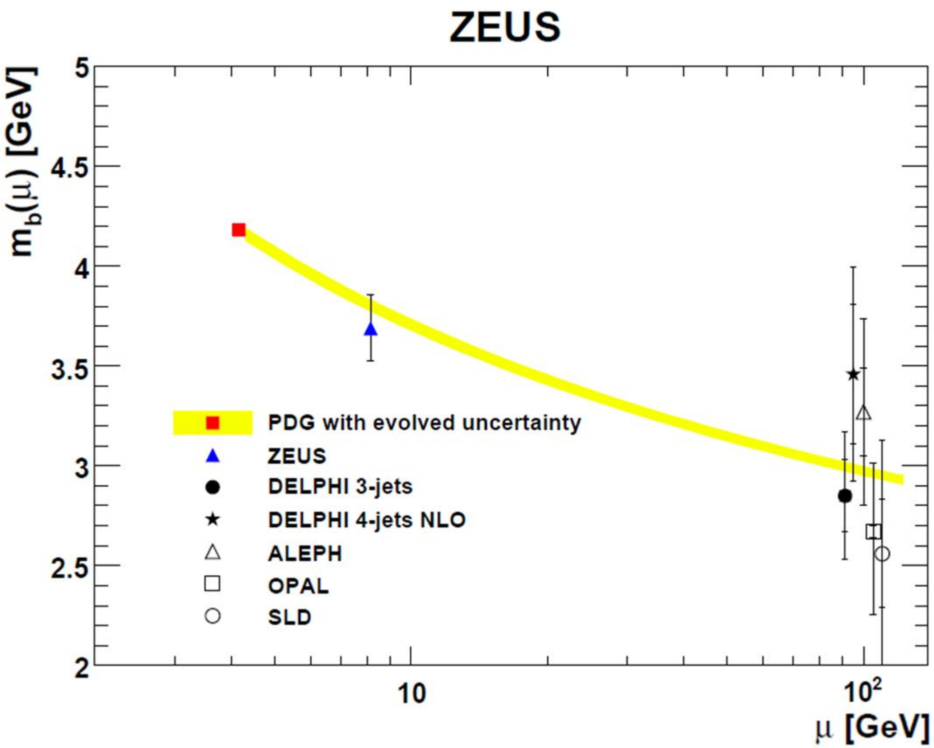


results for **charm** compared to:
Å2 ZEUS D* measurement
Åa HERA charm combination
✓ good agreement with different methods

results for **beauty** compared to:
Å3 NLO QCD predictions obtained
for different $m_b(m_b)$
which value best matches the data ?

Extraction of the beauty quark mass





beauty quark mass fit

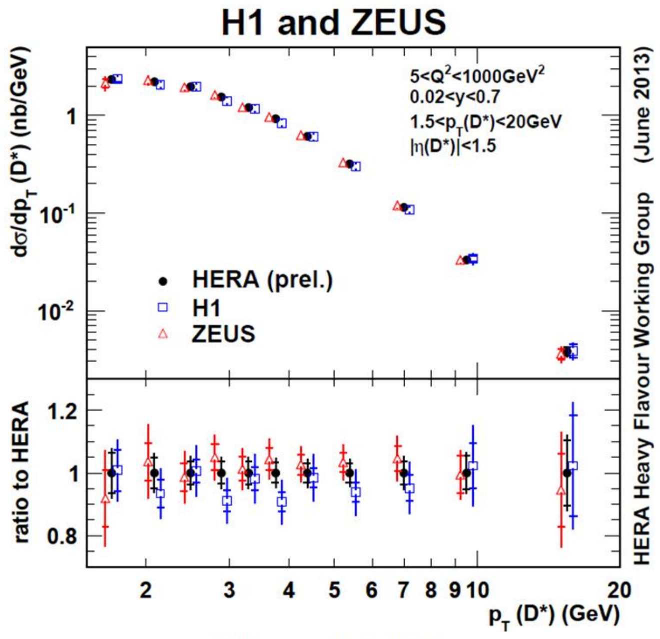
input:
- reduced beauty cross section
- inclusive DIS data

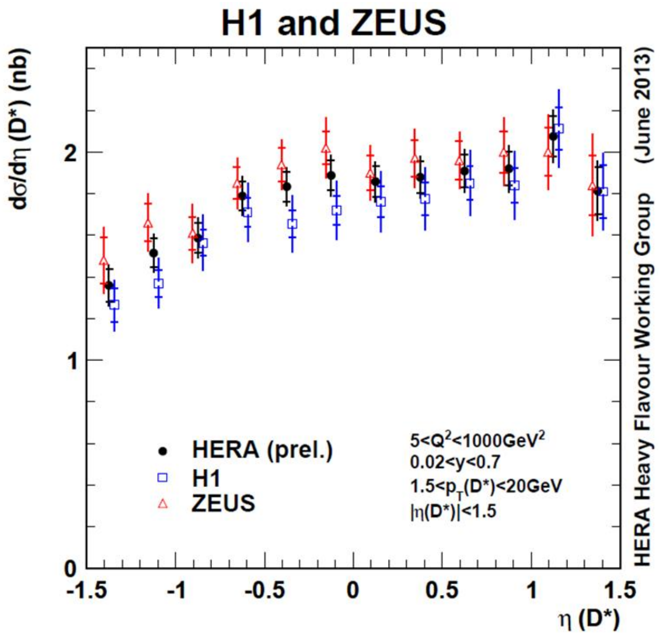
fitted quantities:
- $m_b(m_b)$
- parton densities

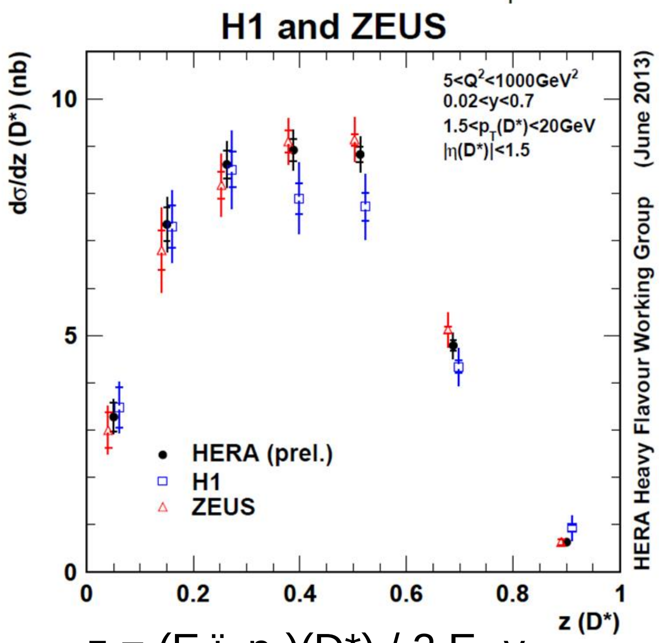
✓ ZEUS + LEP + SLD proof the running of m_b
✓ ZEUS uncertainties are very competitive
✓ be aware that at large scales, $M_{Z/W}$ or M_{top}, beauty can be significantly lighter than you would naively expect !!!

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

Additional observables in the charm case







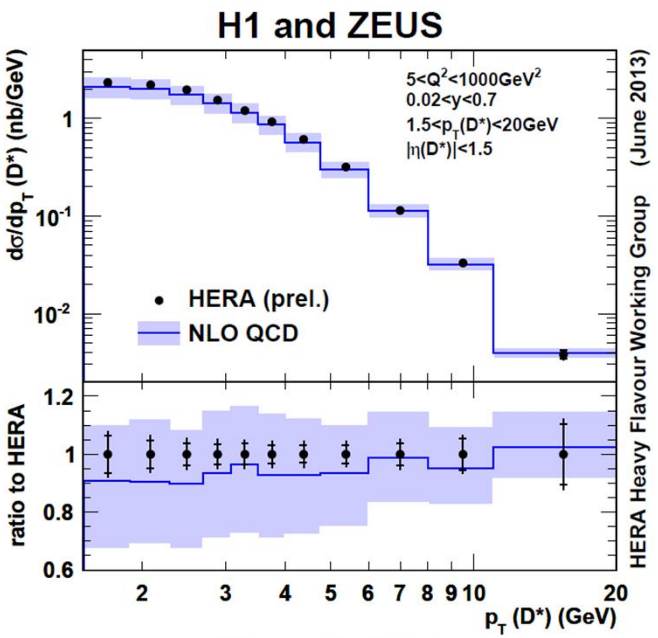
z = (E ï p_z)(D*) / 2 E_e y

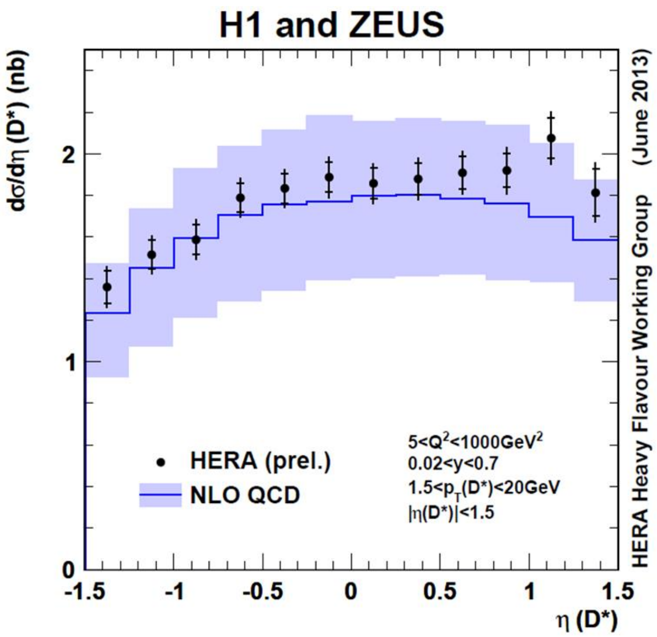
DIS selection:
Å5 < Q 2 < 1000 GeV 2
Å0.02 < y < 0.7
D* (K π π_s) selection:
Å1.5 < p t (D*) < 20 GeV
Å|η(D*)| < 1.5

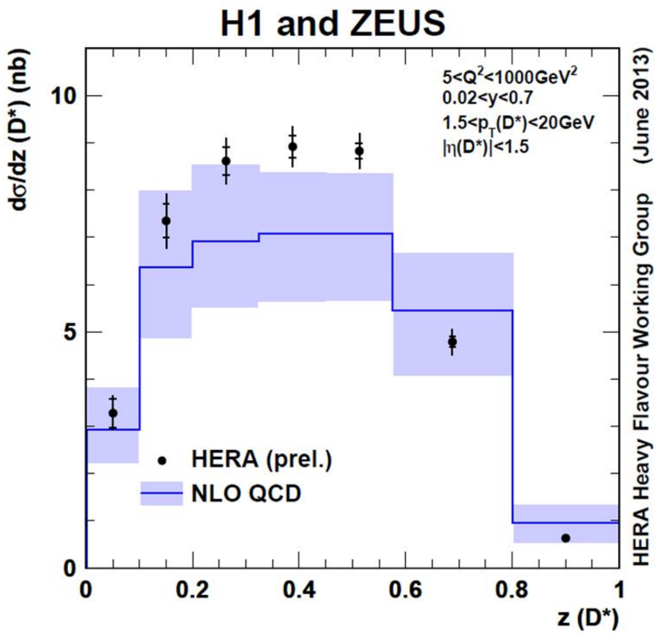
3 % beauty contribution

combination treating consistently correlated and uncorrelated uncertainties

Additional observables in the charm case: data vs NLO QCD







combined data are compared to FFNS NLO QCD predictions ($m_c(m_c)$=1.5 GeV, HERAPDF1.0)

NLO predictions:
✓ describe the data rather well
✓ are affected by large normalization uncertainties
✓ can be further improved in some aspects

Conclusions

Åaccurate charm and beauty cross section measurements have been performed by the H1 and ZEUS collaborations

Åsame measurements are performed using different experimental techniques: each technique has its own advantages and disadvantages

Å$m_c(m_c)$ extracted for the first time and running clearly measured

Å$m_b(m_b)$ extracted as well

Åcharm data are significantly more precise than NLO predictions which suffers from large scale variation uncertainties é **we need NNLO for charm !!!**

Åhave already started to combine:

_ different experimental techniques

_ H1 and ZEUS results

to achieve the best accuracy not only for cross section measurement ! see $m_c(m_c)$!