Recent results on heavy flavour production at HERA

3rd International Conference on New Frontiers in Physics

New Frontiers in Physics

ICNFP 2014

28 July - 6 August 2014, Kolymbari, Crete, Greece

http://indico.cern.ch/event/icnfp2014

Voica Radescu

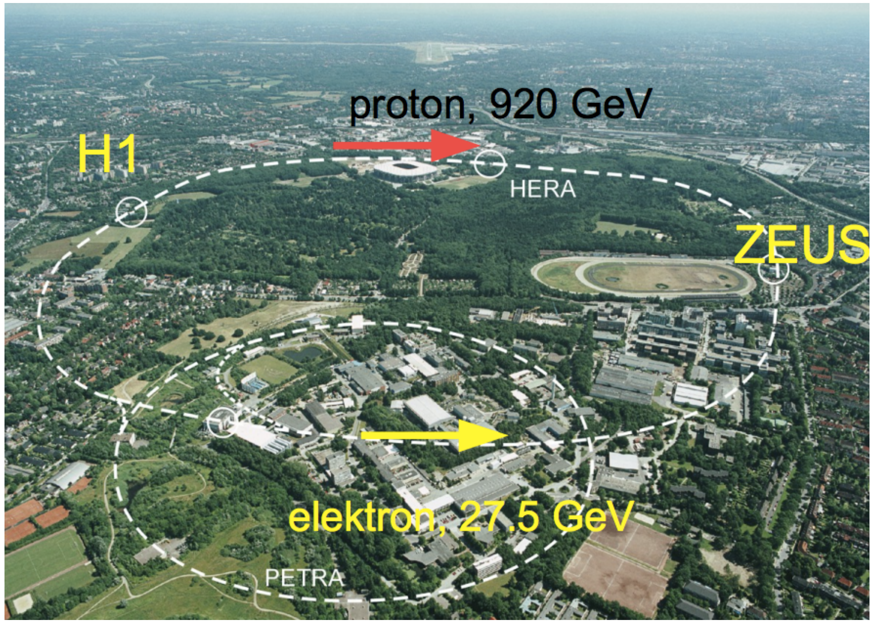
on behalf of the H1 and ZEUS collaborations

OUTLINE:

- Heavy flavour production at HERA
- Charm data combination —> charm mass running
- New charm measurements —> new charm data combination
- Beauty measurement —> beauty mass running
- Summary

HERA ep collider (1992-2007) @ DESY

- **HERA**
  - unique lepton-proton collider
  - Operational:
    - 1992-2000 (HERA I)
    - 2003-2007 (HERA II)
  - Ep=460-920 GeV, Ee = 27.6GeV



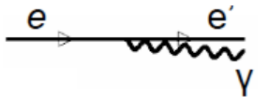
- **H1 and ZEUS collected 0.5/fb per experiment**
- **Rich Physics Program:**
  - proton structure, EW, QCD, diffraction, BSM searches,…

Kinematic variables

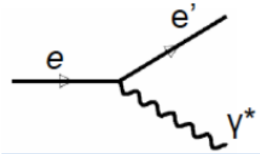
$Q^2 = -q^2 = -(k-k')^2$	Photon virtuality
$x = \dfrac{Q^2}{2p \cdot q}$	Bjorken variable
$y = \dfrac{p \cdot q}{p \cdot k}$	Inelasticity

Two kinematic regimes:

- **Photo-production (PHP)**: $Q^2 < 1$ GeV^2



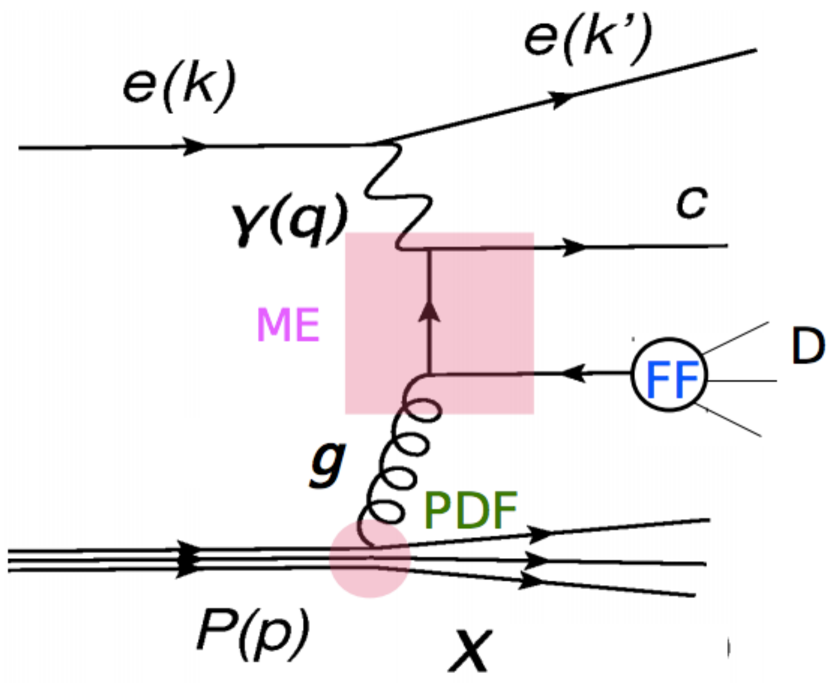
- **Deep Inelastic Scattering (DIS)**: $Q^2 > 1$ GeV^2



Why measure heavy flavour production?

- **Heavy Flavour (HF) production: multi-hard scales pose a challenge for pQCD**
  - m_c, m_b, p_T, Q^2 —> several calculations (schemes) exist
    - Zero-Mass Variable Flavour Number Scheme (ZMVFNS) — massless scheme
    - Fixed Flavour Number Scheme (FFNS) — massive scheme
    - General-Mass Variable Flavour Number Scheme (GM-VFNS) — matched scheme
- **HF production cross section factorise as:** $\sigma^{HQ} = \text{PDF} \otimes \text{ME} \otimes \text{FF}$
- **Measurements of heavy quarks:**
  - are sensitive to the gluon PDF
  - are sensitive to the masses of the heavy quarks
  - are sensitive to the fragmentation process of heavy flavour hardons
- **Measurements allow for tests of pQCD:**
  - QCD LO + Parton shower Monte Carlo generators:
    - Collinear factorisation, DGLAP evolution (PYTHIA, RAPGAP
    - kT factorisation, CCFM evolution (CASCADE).
  - QCD NLO calculations

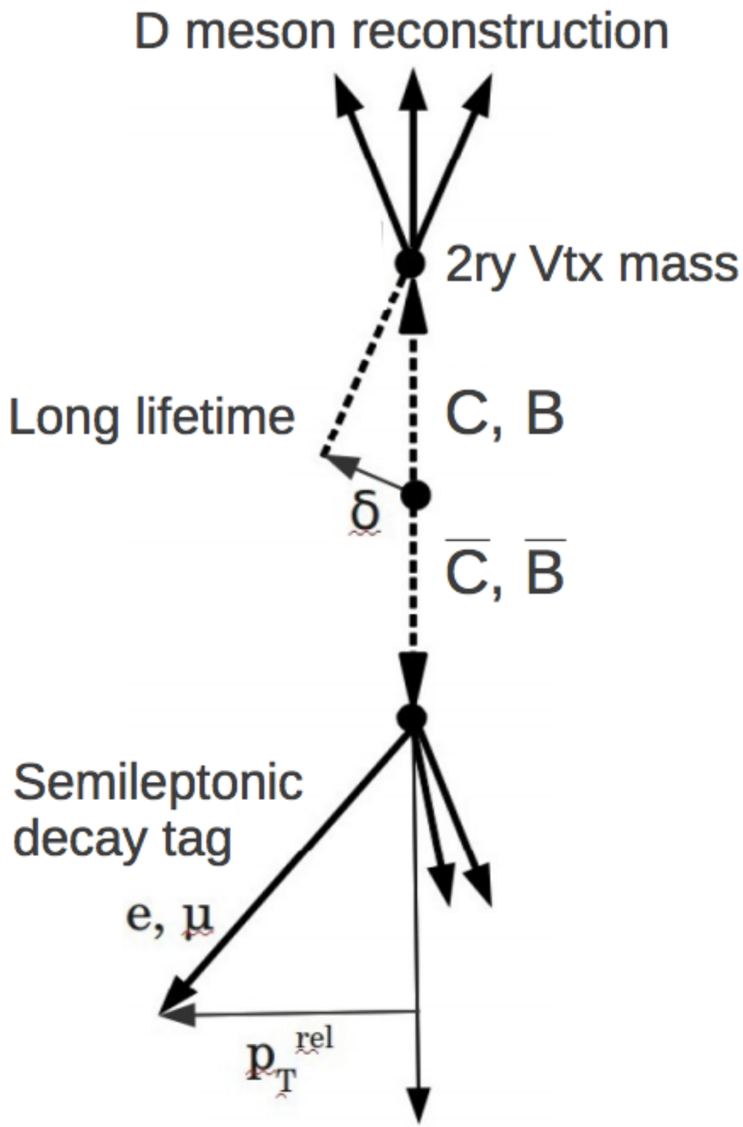
Main process of heavy quark production at HERA is Boson Gluon Fusion



Tagging methods for heavy flavours @ HERA

- **Rates at HERA:**
  - in PHP regime σ(b) : σ(c) ≈ O(0.05%) : O(1%) of σ_{TOT}
  - in DIS regime σ(b) : σ(c) ≈ O(1%) : O(20%) of σ_{TOT}

- **Charm and Beauty Tagging methods:**
  - Full reconstruction:
    - yields best signal-to-background ratio for charm production
    - small BR, phase space of charm production is restricted as all products from decay must be measured.
  - Lepton tagging: Use semi-leptonic b/c decay channels
    - profits from high BR(c,b→ lepton + anything)
    - worse signal-to-background ratio
  - Inclusive life-time info:
    - has the largest phase space coverage
    - life-time tagging: b/c quarks have long lifetimes
    - secondary vertex mass tagging: large masses



Heavy flavour measurements at HERA using different experimental techniques provide complementary handle of systematic uncertainties

HERA Charm Data Combination

EPJC 73 (2013) 2311

- **Best precision achieved when measurements are combined:**
  - Charm Data Combination: chi2/ndof = 62/103
    - 155 data points from 9 different measurements of H1 and ZEUS were combined into 52 points
    - efforts in accounting for correlations of systematic uncertainties between data sets

9 different charm reduced cross sections measurements were combined :

Data Set	Period	Reconstruction	Q^2 [GeV^2]
1) H1 Vertex	HERA I + II	displaced vtx	5–2000
2) H1 D^*	HERA I	D^* decay	2–100
3) H1 D^*	HERA II	D^* decay	5–100
4) H1 D^*	HERA II	D^* decay	100–1000
5) ZEUS D^*	96-97	D^* decay	1–200
6) ZEUS D^*	98-00	D^* decay	1.5–1000
7) ZEUS D^0	2005	D^0 decay	5–1000
8) ZEUS D^+	2005	D^0 decay	5–1000
9) ZEUS μ	2005	semileptonic	20–10000

- **Data combination is performed at the reduced charm cross sections level (as in DIS):**
  - they are obtained from xsec in visible phase space and extrapolated to full space

$$\frac{d^2\sigma^{c\bar{c}}}{dx\, dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} Y_+ \sigma_{red}^{c\bar{c}}(x, Q^2, s)$$

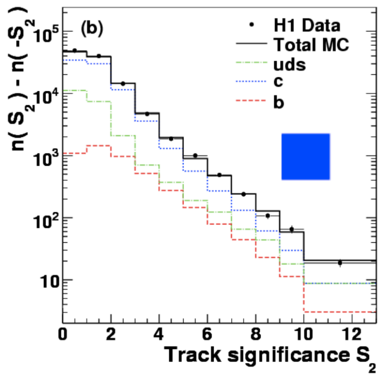
$$\sigma_{red}^{c\bar{c}}(x, Q^2, s) = F_2^{c\bar{c}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x, Q^2)$$

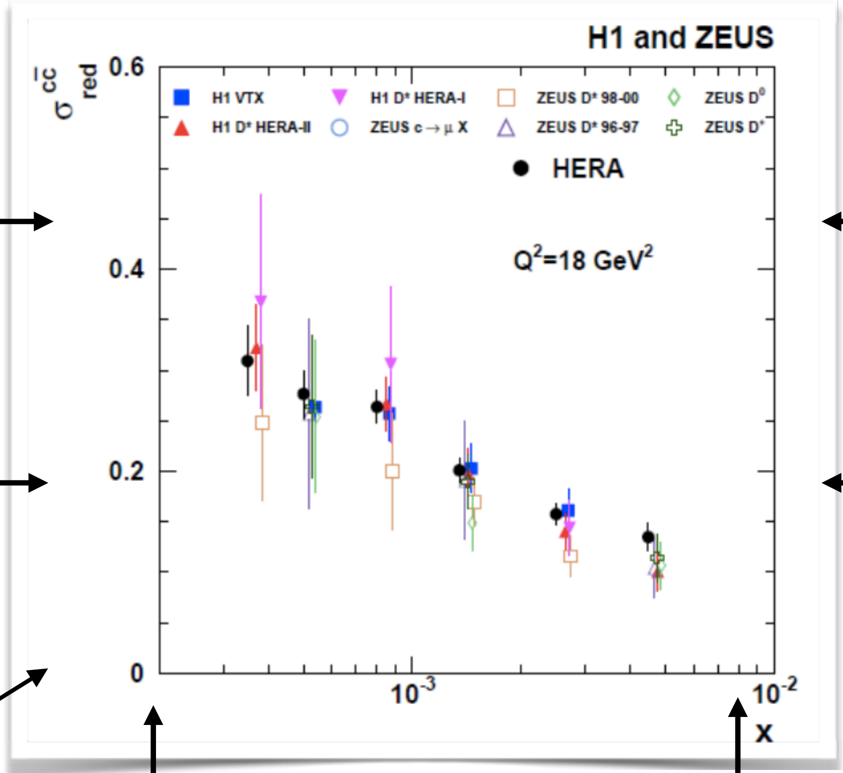
$$\sigma_{red}^{c\bar{c}}(x, Q^2) = \left(\sigma_{vis} - \sigma_{vis}^{beauty}\right)\left(\frac{\sigma_{red,\,HVQDIS}^{c\bar{c}}}{\sigma_{vis,\,HVQDIS}}\right)$$

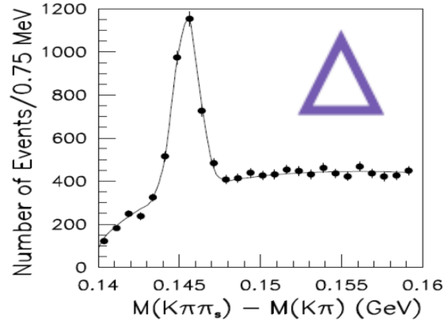
HERA Charm Data Combination

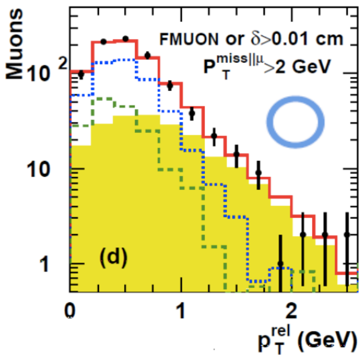
EPJC 73 (2013) 2311

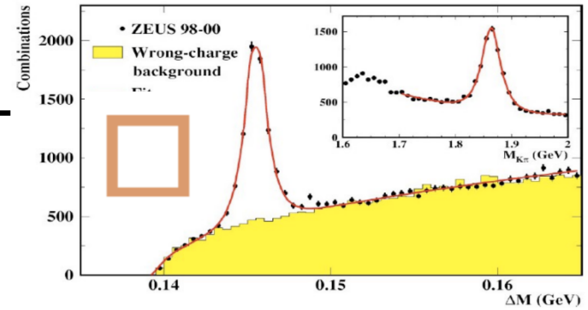
- **Best precision achieved when measurements are combined:**
  - Charm Data Combination: chi2/ndof = 62/103
    - 155 data points from 9 different measurements of H1 and ZEUS were combined into 52 points
    - efforts in accounting for correlations of systematic uncertainties between data sets

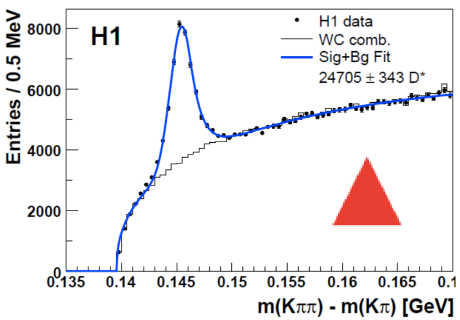


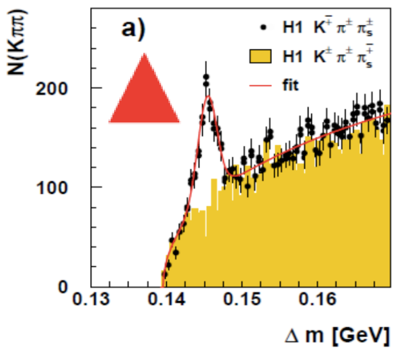


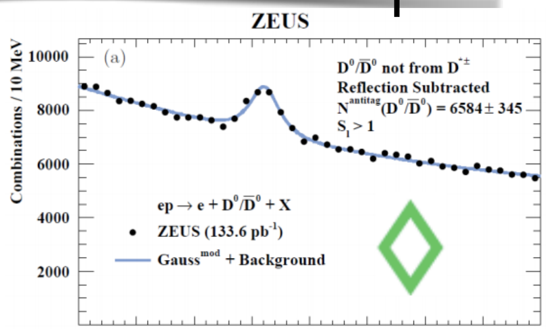


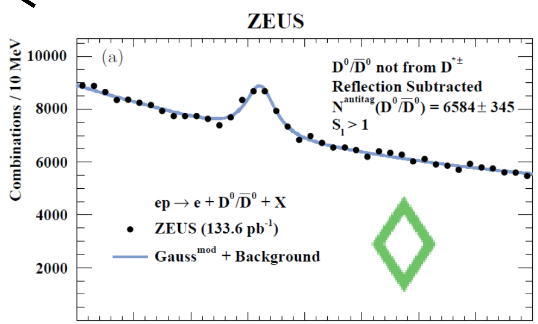








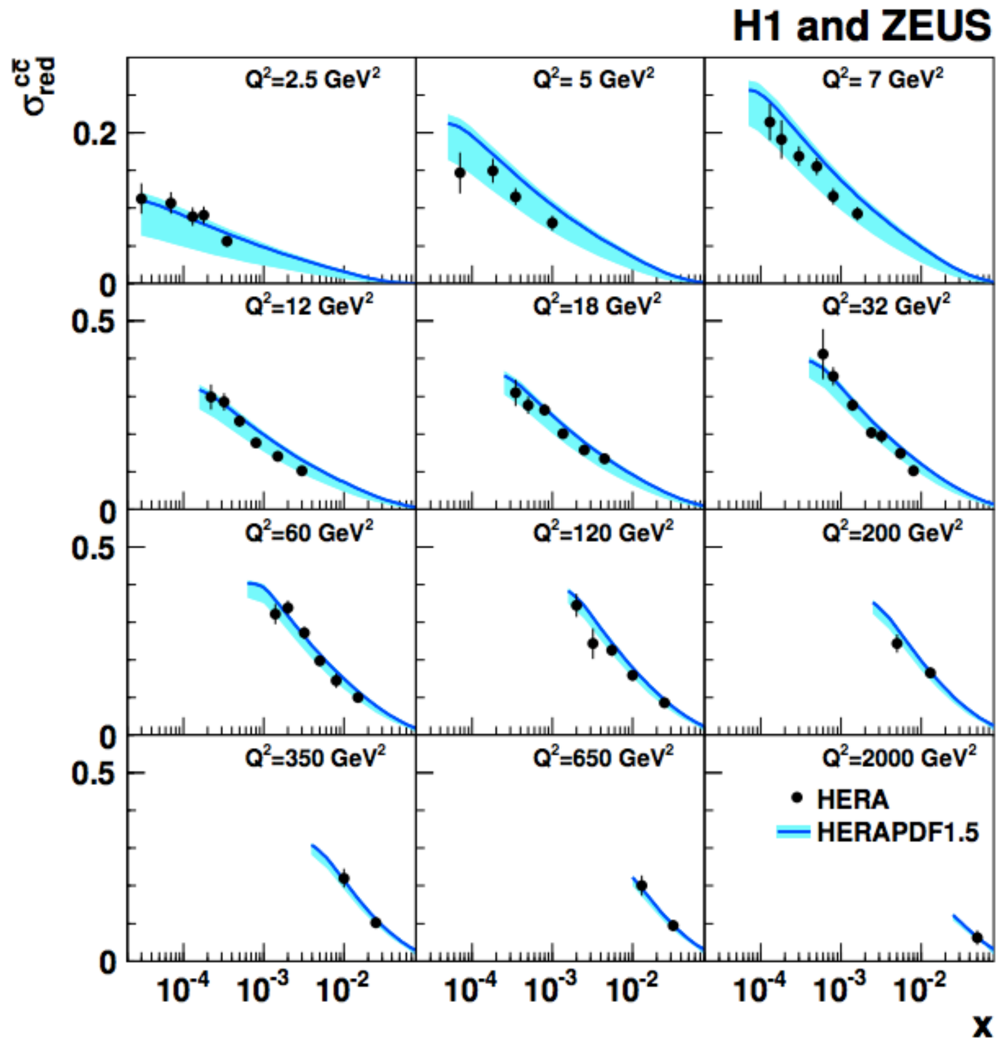




Impact of the Charm Measurements

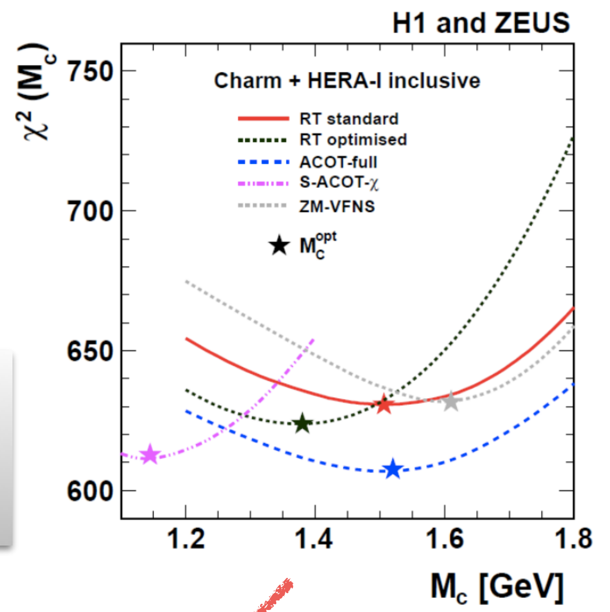
EPJC 73 (2013) 2311

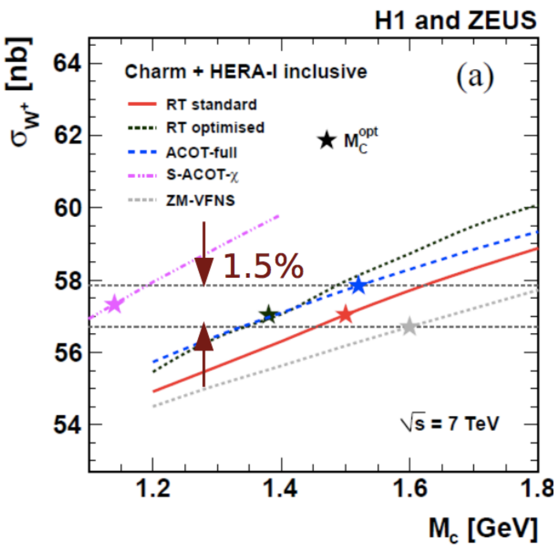
- **Combined data well described by the theory predictions**
  - when M_c is taken at its optimal value
- **The combined charm data used in NLO QCD fits**



QCD Fits
HERA I+charm

Different calculation schemes prefer different M_c





measurements help reduce uncertainties of predictions for the LHC

Running charm mass $m_c(m_c)$

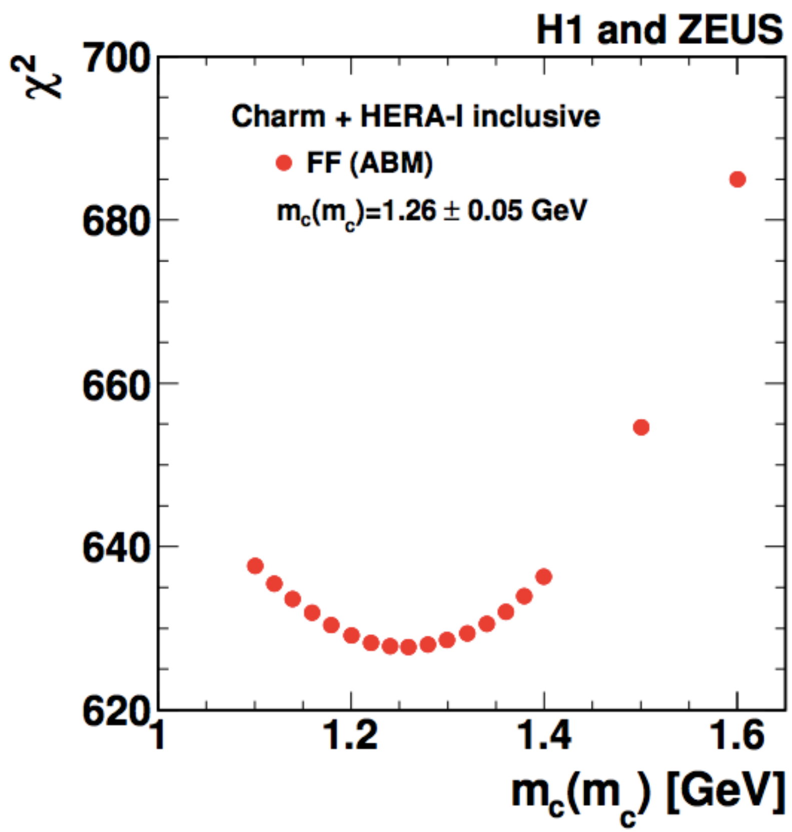
EPJC 73 (2013) 2311

- **Charm combination can also be used in a NLO QCD analysis in FFN scheme to determine the running of charm-quark mass mc(mc) in $\overline{\text{MS}}$:**

$$m_c(m_c) = 1.26 \pm 0.05_{\text{exp}} \pm 0.03_{\text{mod}} \pm 0.02_{\text{param}} \pm 0.02_{\alpha_s} \text{ GeV}$$

  - which is in agreement with the world average extraction:

$$m_c(m_c) = 1.275 \pm 0.025 \text{ GeV}$$



- **This has triggered the question:**

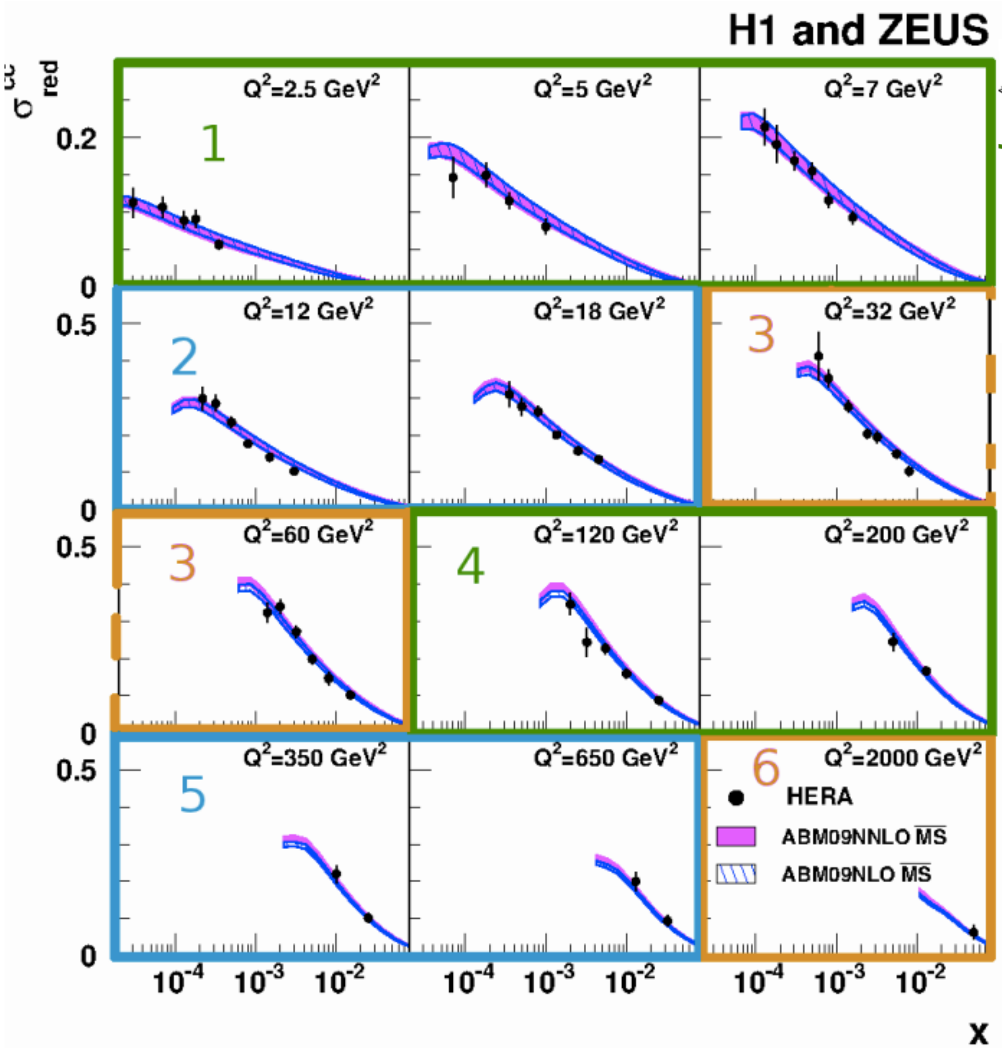
—> how about measuring the running of m_c?

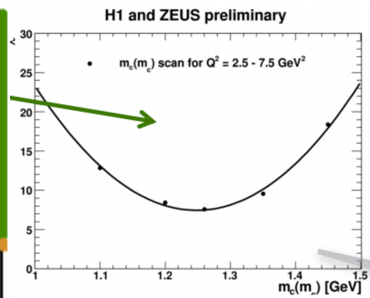
New Measurement of Charm Mass Running

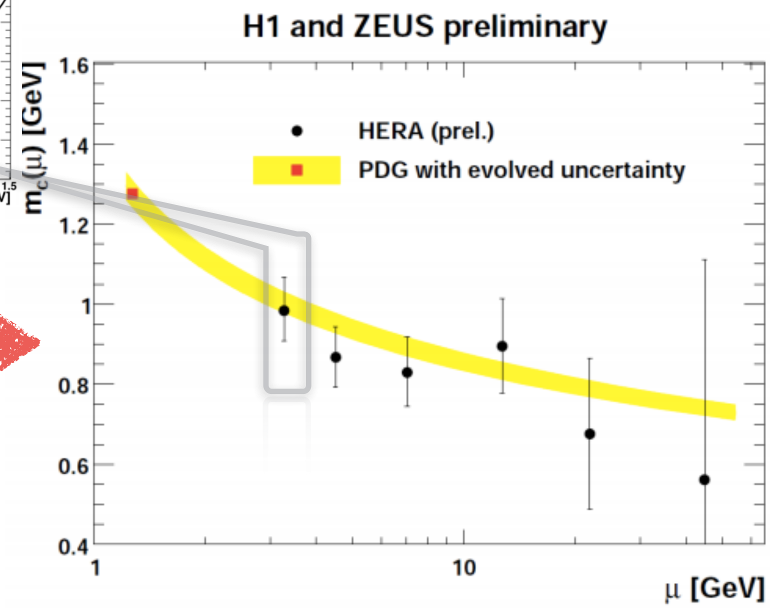
H1-prelim-14-071 ZEUS-prel-14-006 and S. Moch

The running of the charm mass in the $\overline{\mathrm{MS}}$ scheme is measured for the first time from the same HERA combined charm data:

- Extract $m_c(m_c)$ in 6 separate kinematic regions
- Translate back to $m_c(\mu)$ [with $\mu=\sqrt{Q^2+4m_c^2}$] using `OpenQCDrad [S.Alekhin's code].`





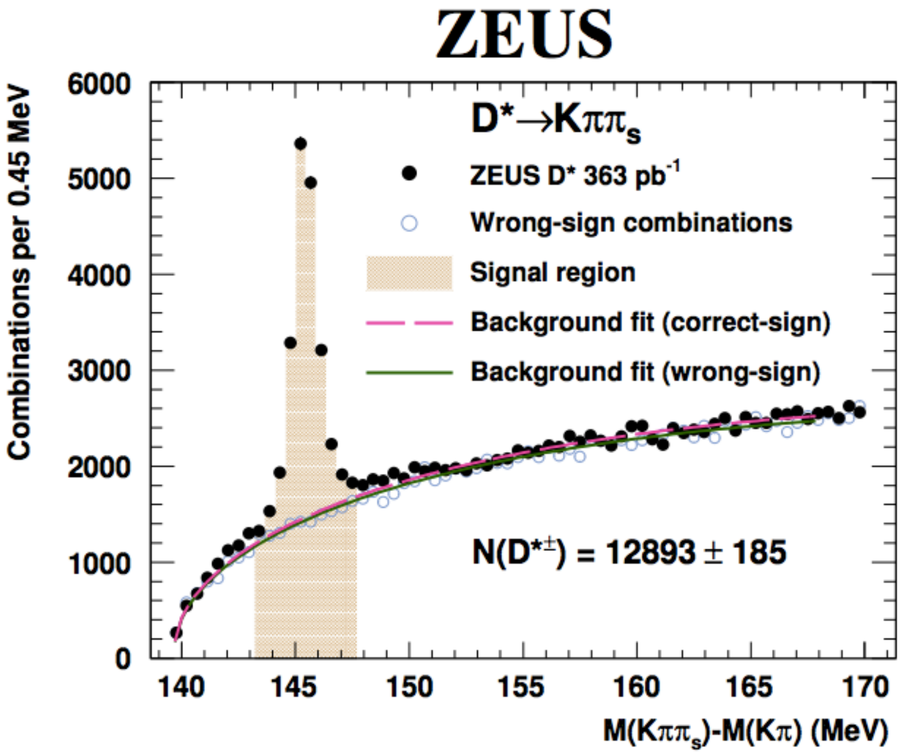


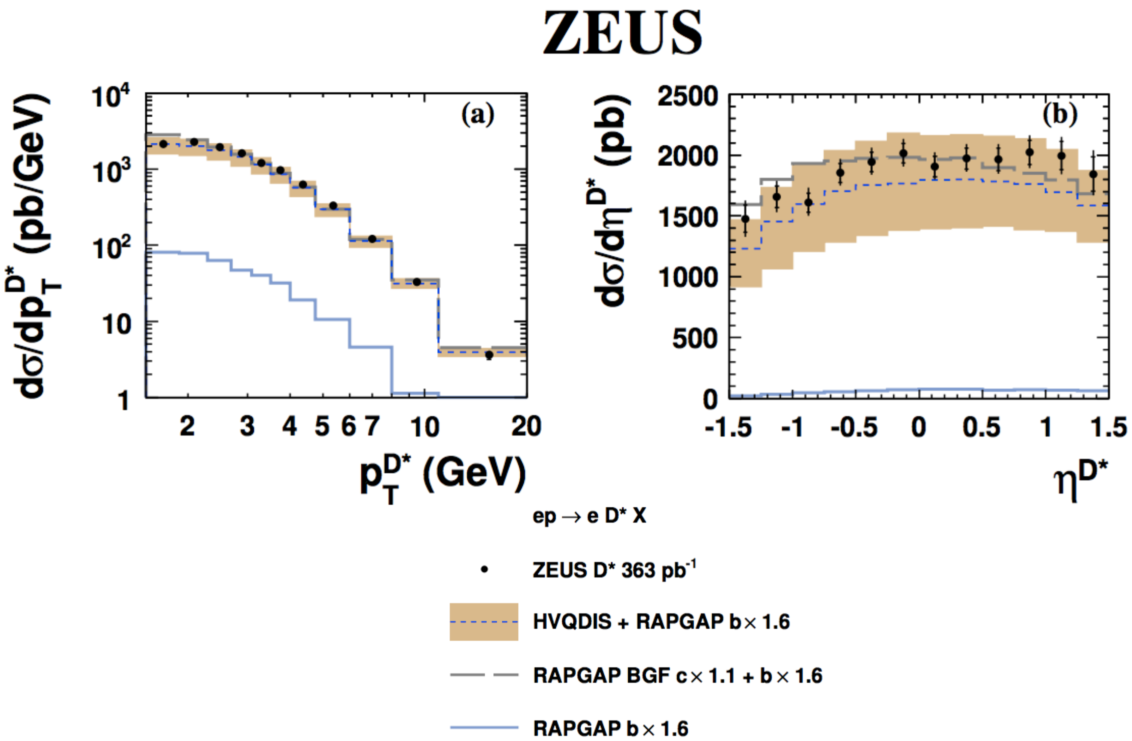
The scale dependence of the mass is consistent with QCD expectations

Recent charm measurements: D* in DIS

JHEP 05(2013) 097

- **The most precise charm DIS measurement from ZEUS from final HERA II data**





- **Well described by massive NLO QCD predictions.**
- **The D* measurements from H1 and ZEUS are combined at the differential level**

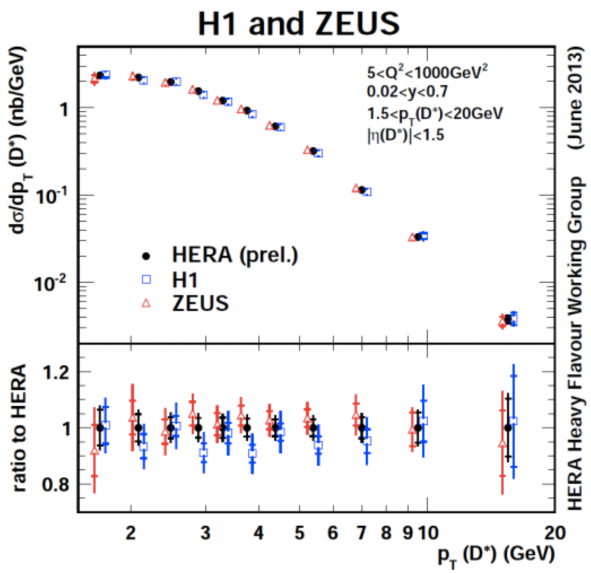
H1 ref: Phys Lett B686 (2010), Eur Phys J C71 (2011)

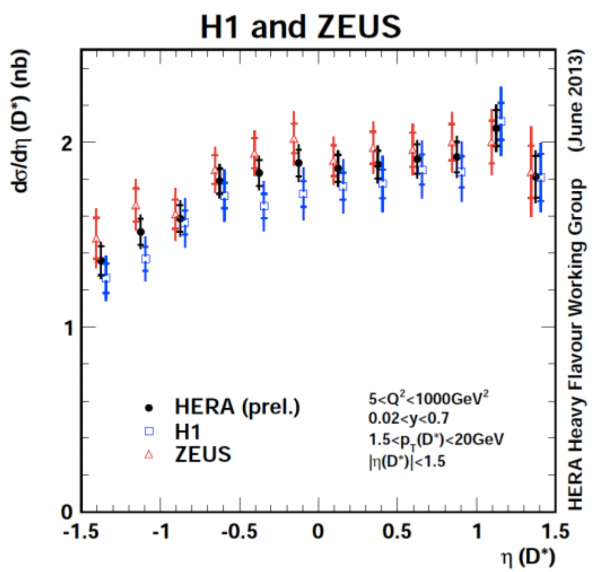
Precise measurements that can be compared directly to QCD predictions without the need of extrapolations corrections

D* Combination

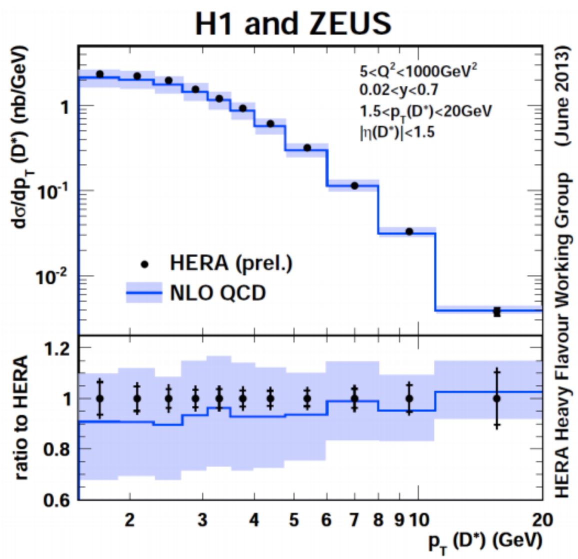
JHEP 02(2014) 106

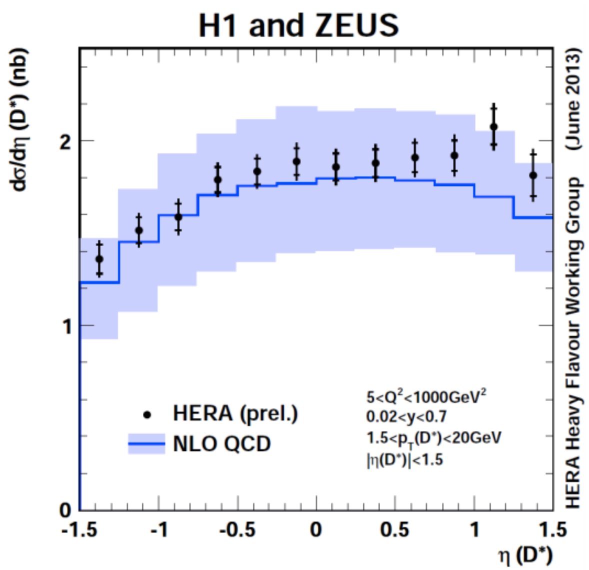
- Good agreement is observed between the H1 and ZEUS measurements —>





- Measurements are compared to NLO QCD theory predictions
  - good agreement is found theory calculations
  - scale variation is dominant uncertainty on predictions

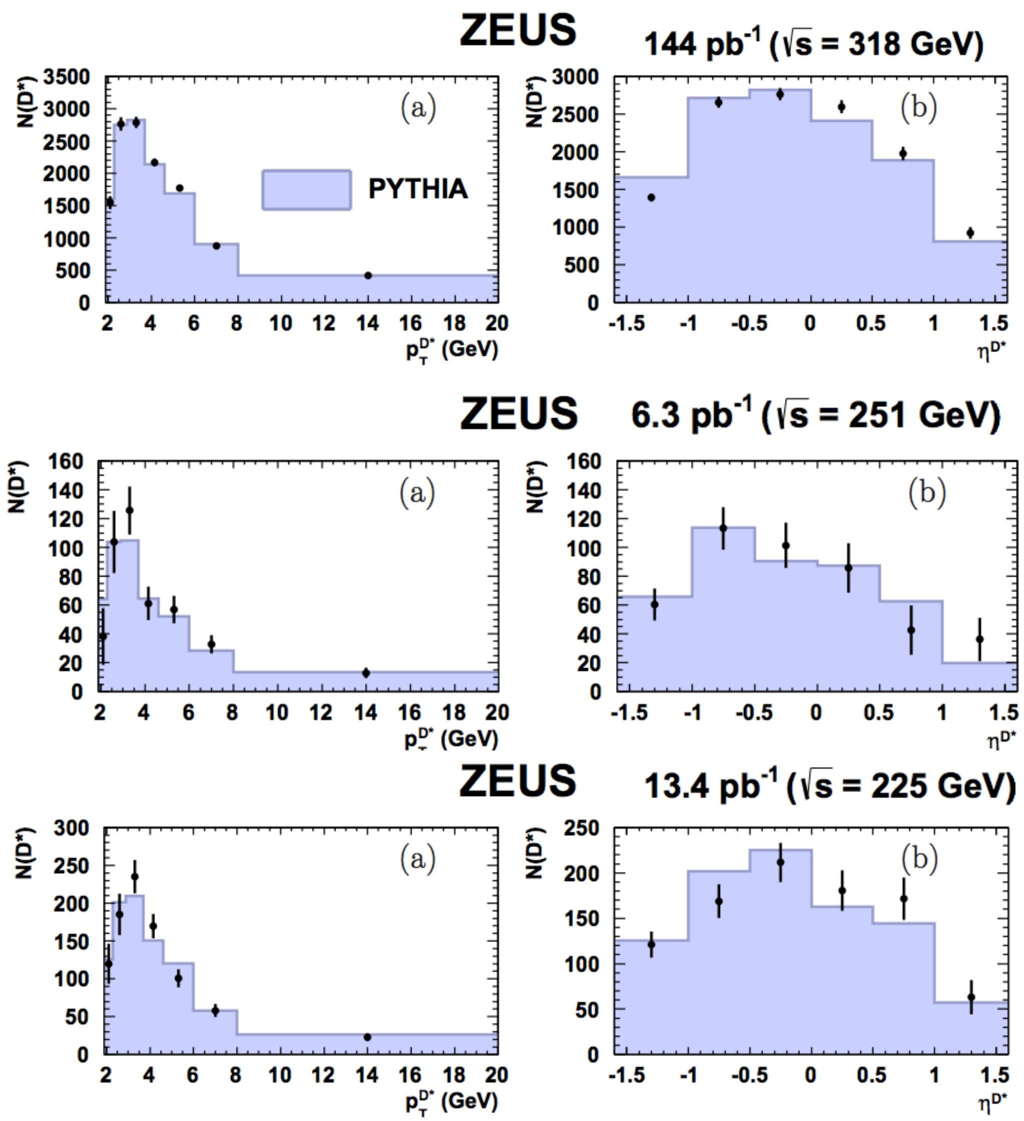


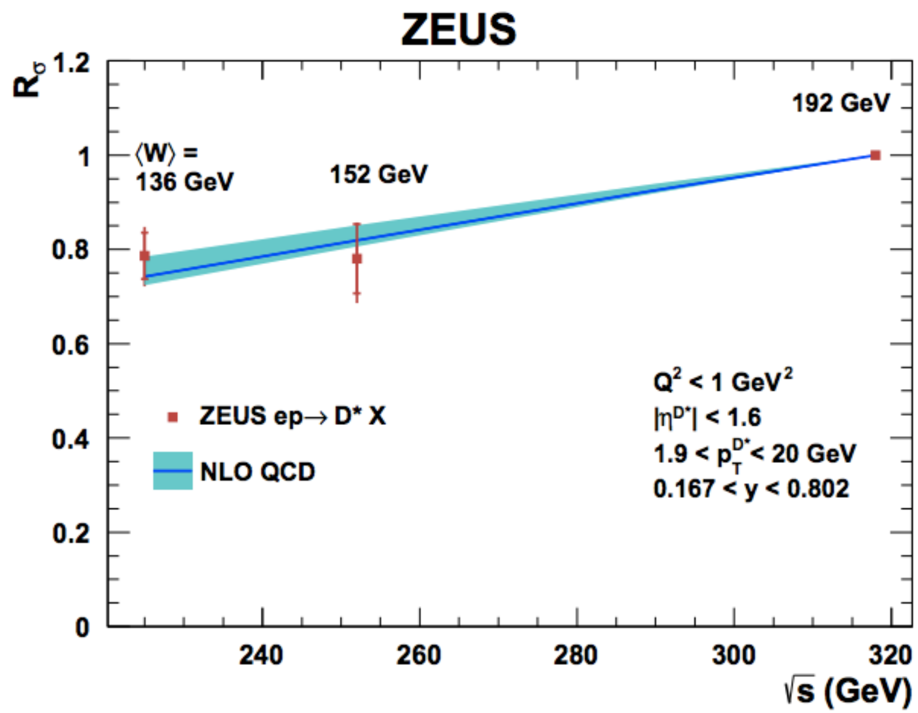


D* Measurement in photo-production

DESY–14–082, arXiv:1405.5068

- **Measurement of D* photo-production at different centre-of-mass energies at HERA**
  - $\sqrt{s}$ =318(HER), 251(MER) and 225(LER) GeV
  - D* visible photo-production measurements normalised to the high-statistics measurement at $\sqrt{s}$ = 318.



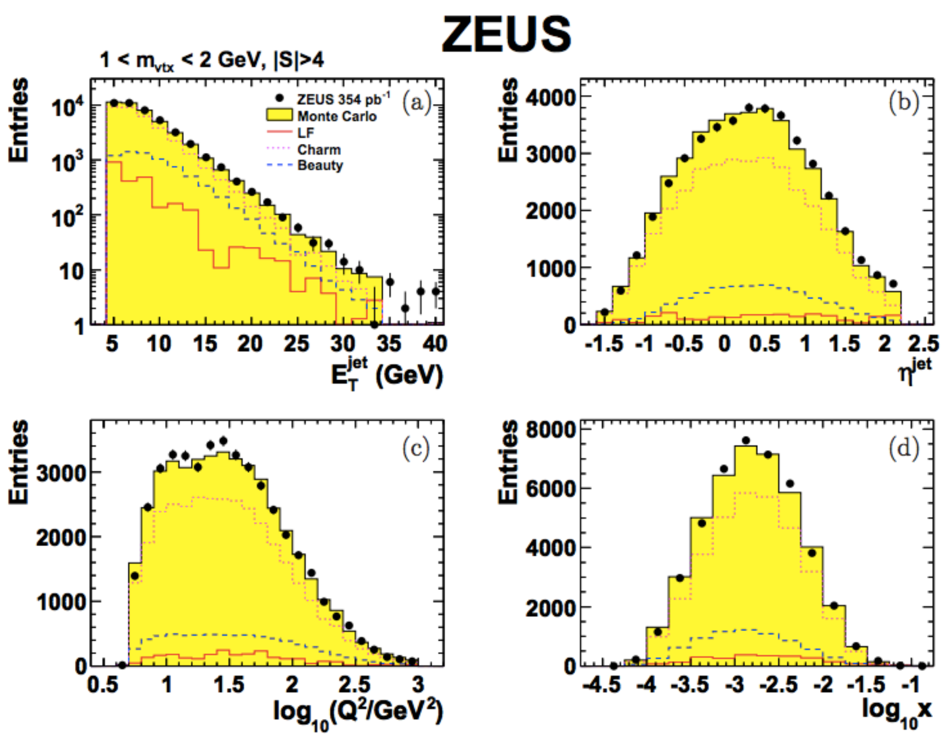


- **The cross sections for the MER and LER sample are significantly smaller than the cross section for the HER data.**
- **The NLO QCD predictions well describe measured energy dependence**

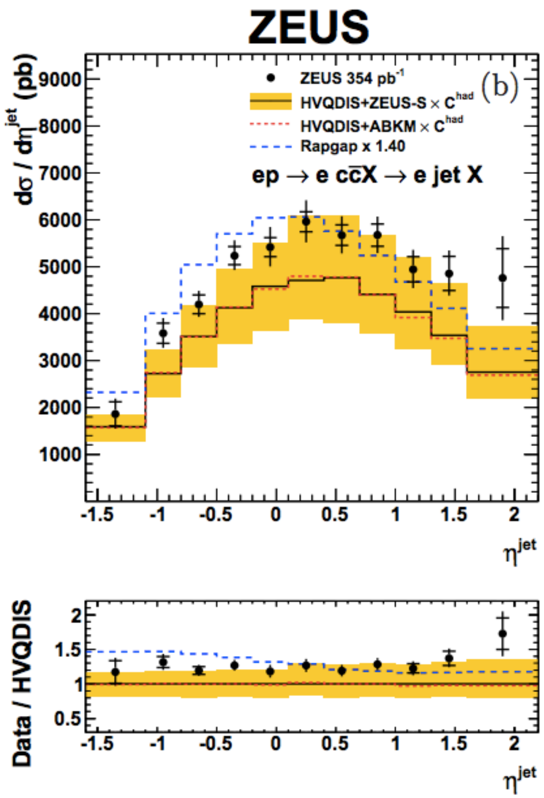
New Charm measurements from LifeTime-Tagging (vtx)

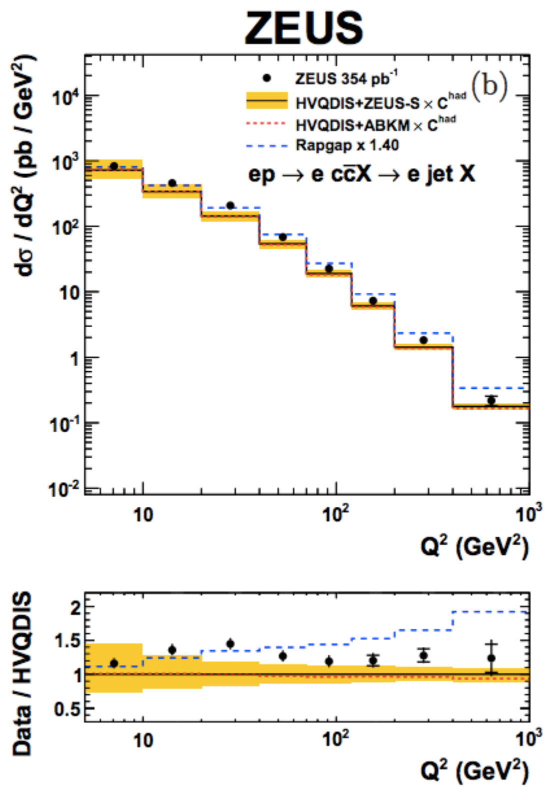
DESY-14-083 arXiv:1405.6915

- **Independent from D*data: D^+ and secondary vertices+lifetime tag:**
- **New measurement in the kinematic span of $5 < Q^2 < 1000$ GeV^2 and L=354/pb**
  - exploiting the long lifetimes of the weakly decaying b and c hadrons and their large masses
  - The single differential cross sections were obtained vs of E_T^{jet}, η^{jet}, Q^2 and x
- **The measurements are compared to HVQDIS NLO QCD and RAPGAP predictions**



- charm enriched sample

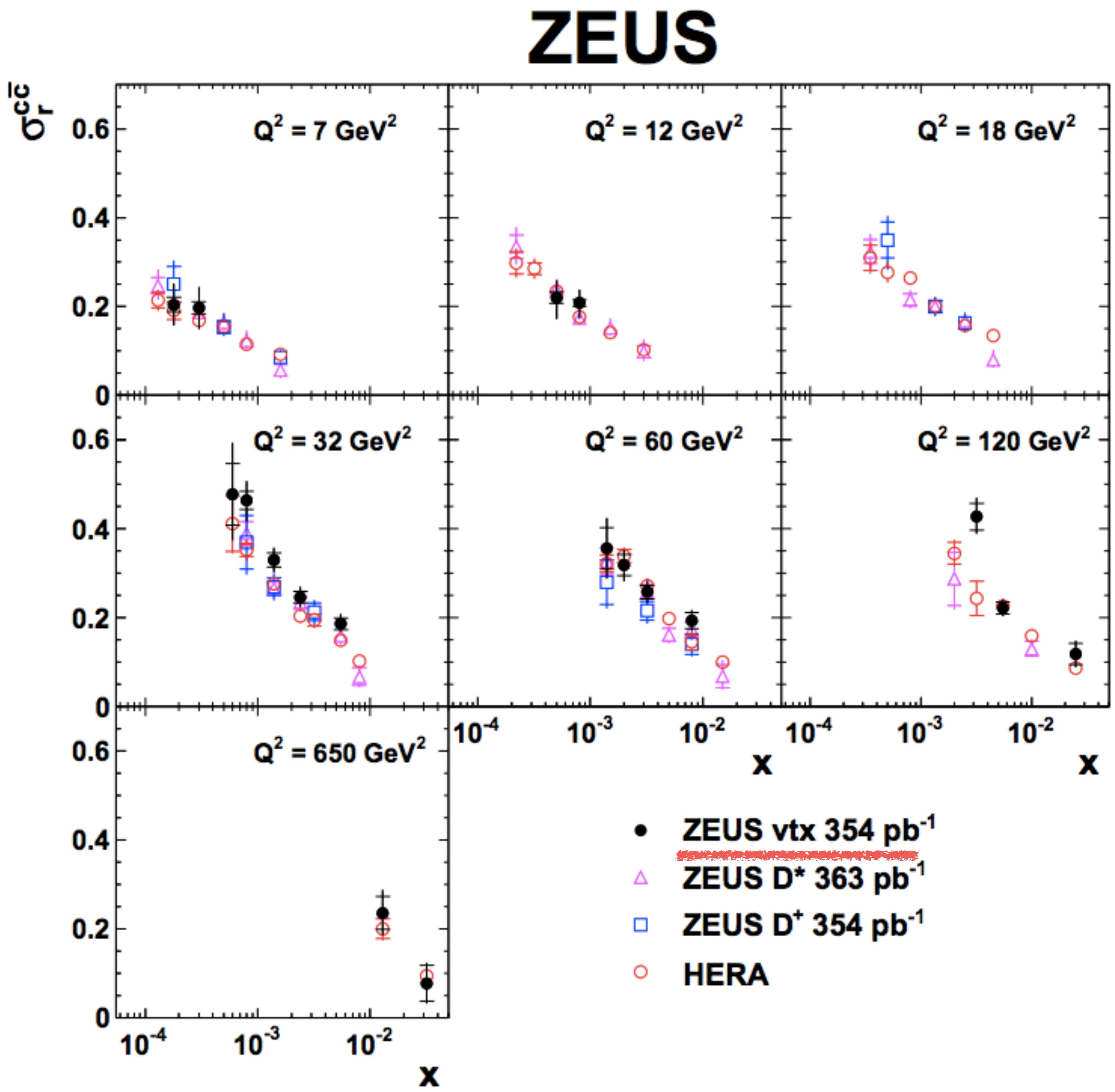




Good description of the data by the massive NLO QCD predictions.

Charm data from D+, D*,second. vertex comparison

DESY-14-083 arXiv:1405.6915



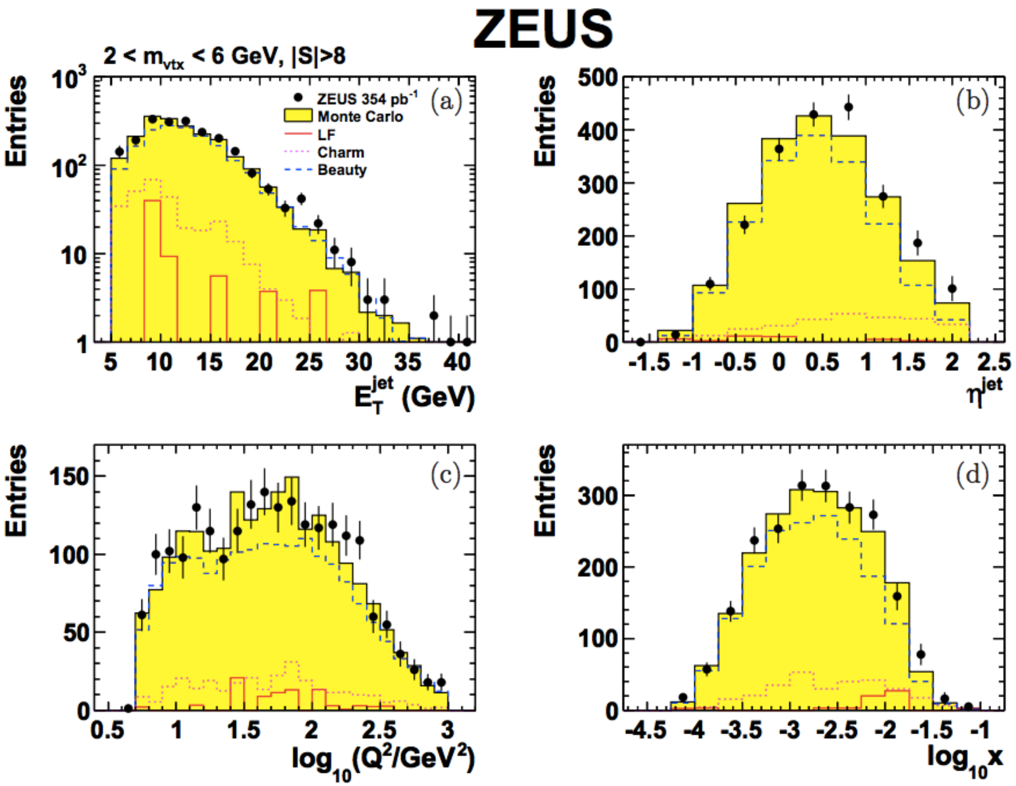
$$\frac{d\sigma^{c\bar{c}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot [1+(1-y)^2] \cdot \sigma_{red}^{c\bar{c}}$$

- **The new data are precise and independent from the previous combination.**
- **The new measurements are in agreement with previous measurements at HERA.**

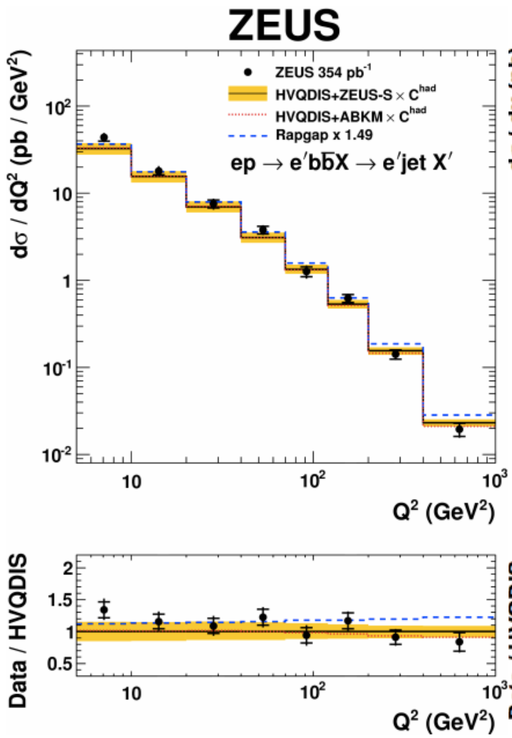
New Beauty in DIS from LifeTime-Tagging

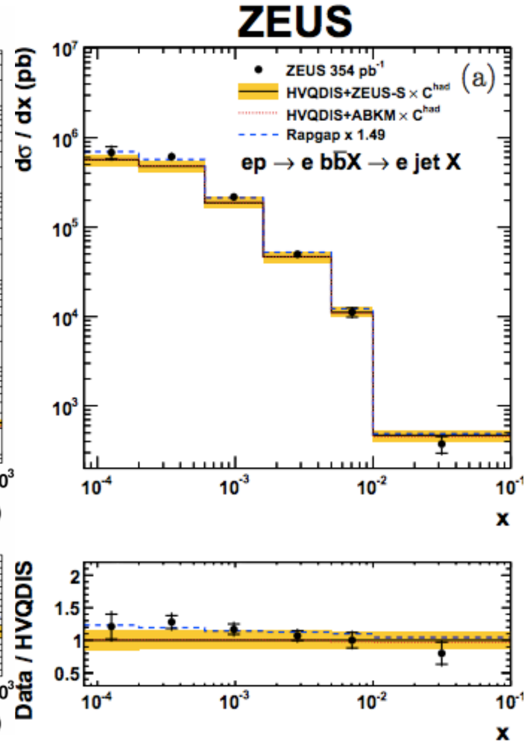
DESY-14-083 arXiv:1405.6915

- **New measurement in the kinematic span of $5 < Q^2 < 1000$ GeV^2 and L=354/pb**
  - exploiting the long lifetimes of the weakly decaying b and c hadrons and their large masses
  - measurement was not restricted to any particular final state —> substantially increased statistics
  - Differential cross sections as functions of E_T^{jet}, η^{jet}, Q^2 and x were determined.



- beauty enriched sample



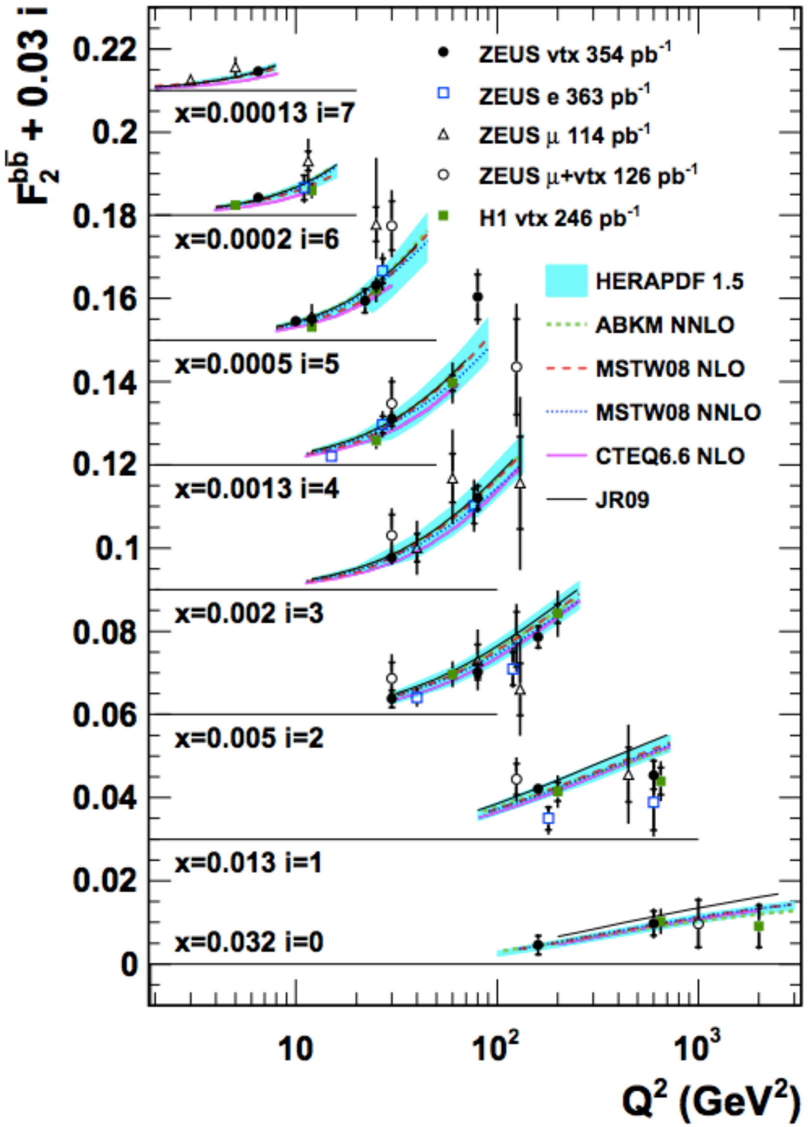


Good description of the data by the massive NLO QCD predictions.

New Beauty in DIS from LifeTime-Tagging

DESY-14-083 arXiv:1405.6915

- **Inclusive jet cross sections in beauty and charm events are used to:**
  - The good agreement of the data and NLO calculations in the visible phase (given by the heavy quark tagging) allow to extrapolate to the full phase space and to measure F2bb (and identical F2cc) :



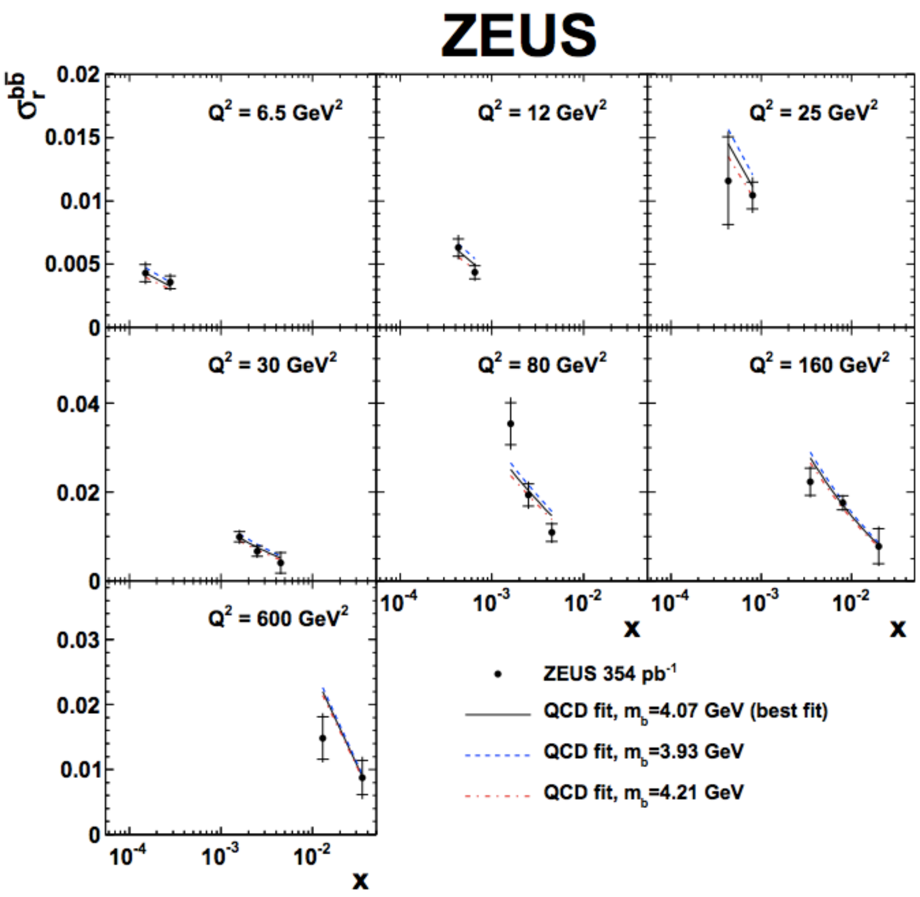
$$\frac{d\sigma^{b\bar{b}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot \left[\left(1+(1-y)^2\right) \cdot F_2^{b\bar{b}} - y^2 \cdot F_L^{b\bar{b}}\right]$$

- **The new measurement is the most precise determination of F_2b from ZEUS**
- **Data are in good agreement and well described by fixed-order (massive) and variable-flavour (mixed) NLO and NNLO QCD calculations**

Running beauty mass $m_b(m_b)$

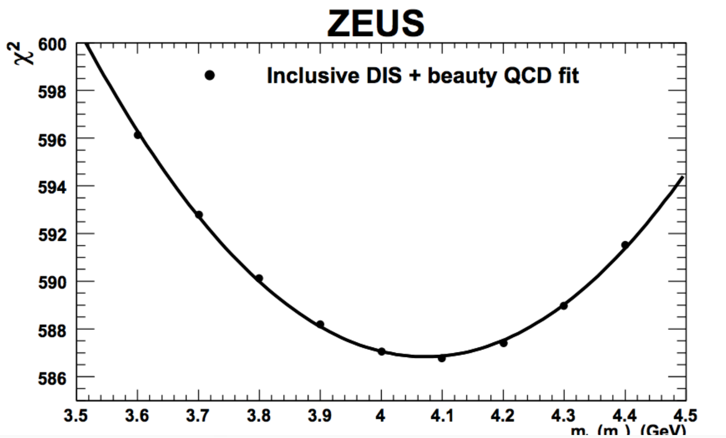
DESY-14-083 arXiv:1405.6915

- **The value of the running beauty mass is obtained in a similar manner as for $m_c(m_c)$:**
  - **chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the $\overline{\text{MS}}$ scheme.**



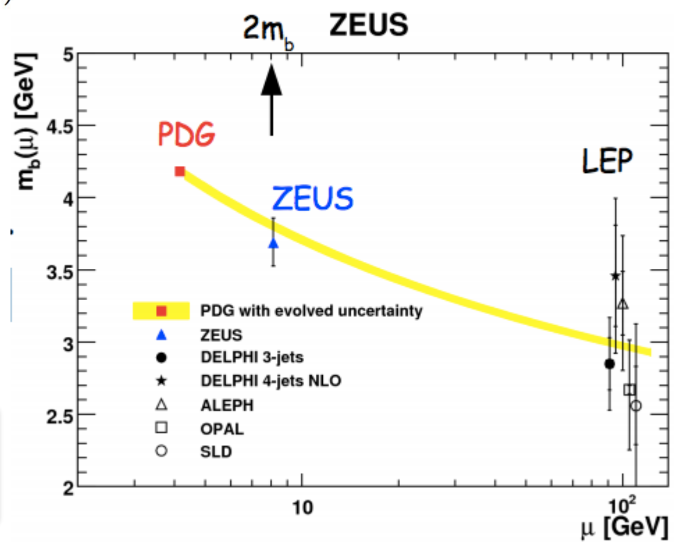
QCD Fits

HERA I+beauty



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

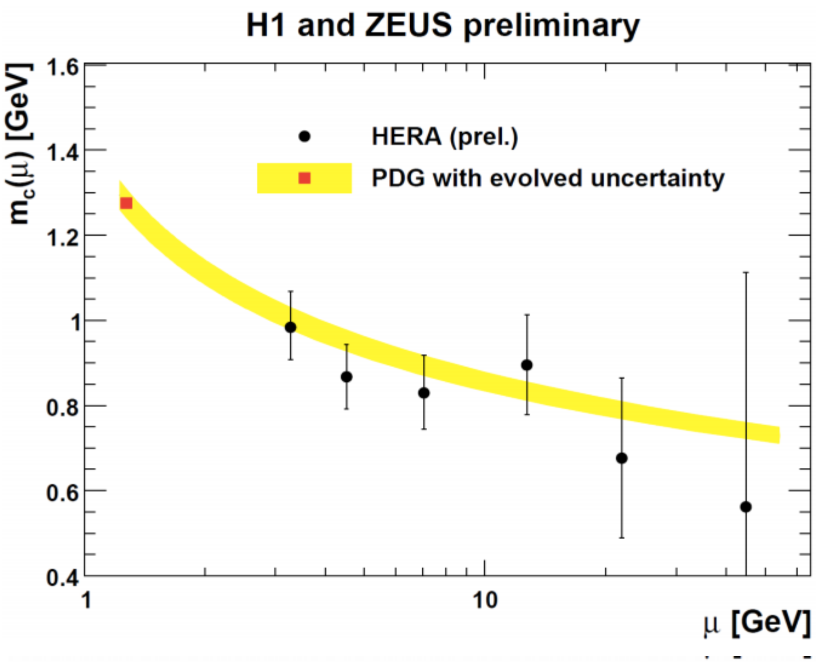
$$m_b(m_b) = (4.18 \pm 0.03)\ \text{GeV}$$ —>PDG2012

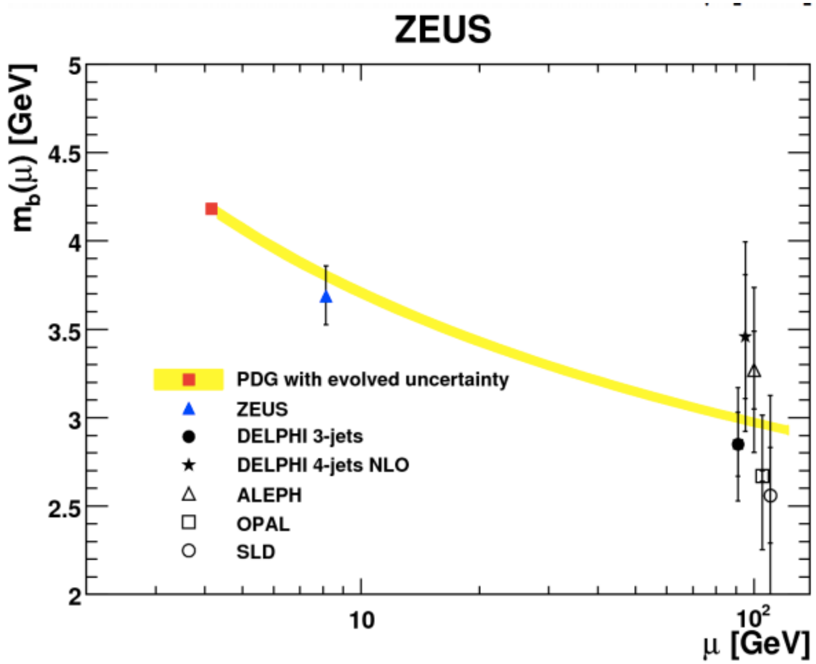


The extracted $\overline{\text{MS}}$ beauty-quark mass is in agreement with PDG average and LEP results.

Summary

- **Most HERA DIS charm data were combined:**
  - consistent data sets extracted using different methods
  - data are well described by QCD predictions
  - running charm mass determined: $m_c(m_c) = 1.26 \pm 0.06$ GeV
- **First measurement of the charm-mass running.**
- **New charm measurements for D* are combined at the visible phase space level**
  - awaiting for theory improvements
- **New measurement in photo-production exploiting different centre of mass energy.**
- **New beauty-jet measurement + lifetime taging in DIS by ZEUS:**
  - one of the most precise beauty measurements at HERA
  - beauty mass measured: $m_b(m_b) = 4.07 \pm 0.17$ GeV.





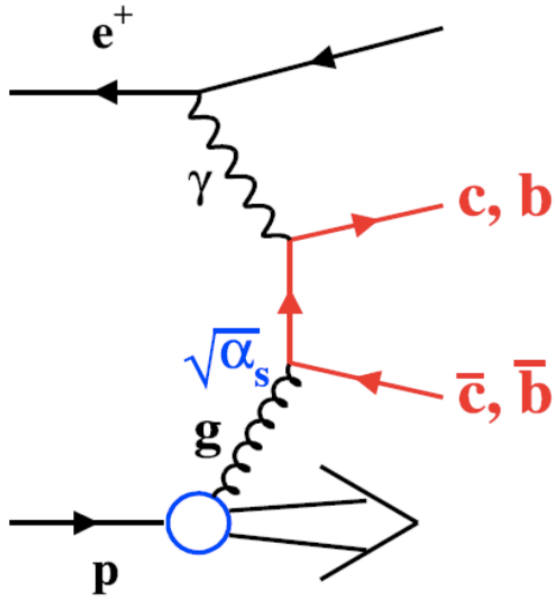
Thank you!

Extra Material

Why measure heavy flavour production?

Multi-hard scales: a challenge for pQCD

- mc, mb, pT, Q2 —> several calculations (schemes) exist
  - Zero-Mass Variable Flavour Number Scheme (ZMVFNS) — massless schei
    - all flavours massless
    - valid at Q2>>mc2, mb2
  - Fixed Flavour Number Scheme (FFNS) — massive scheme
    - heavy quark produced perturbatively
  - General-Mass Variable Flavour Number Scheme (GM-VFNS)
    - matched scheme across the heavy quark thresholds
      —> heavy quarks masses more a tuning parameter.
    - different variants exists (as used in global PDFs: Thorne-Roberts, ACOT, FONLL)

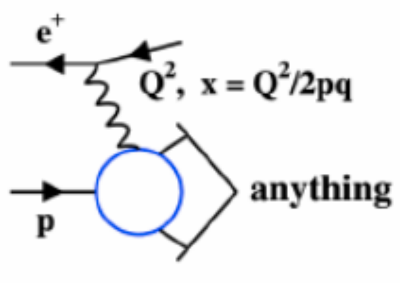


σ^{HQ} = PDF ⊗ ME ⊗ FF

F_2^{bb} and F_2^{cc} contributions to the proton structure function F_2

- F_2 structure function of the proton:

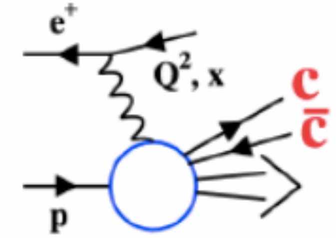
$$\frac{d^2\sigma}{dx\,dQ^2}=\frac{2\pi\alpha^2}{x\,Q^4}\cdot[(1+(1-y)^2)F_2-y^2F_L]$$



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

- F_2^{cc} structure function of the proton:
(identical for F_2^{bb})

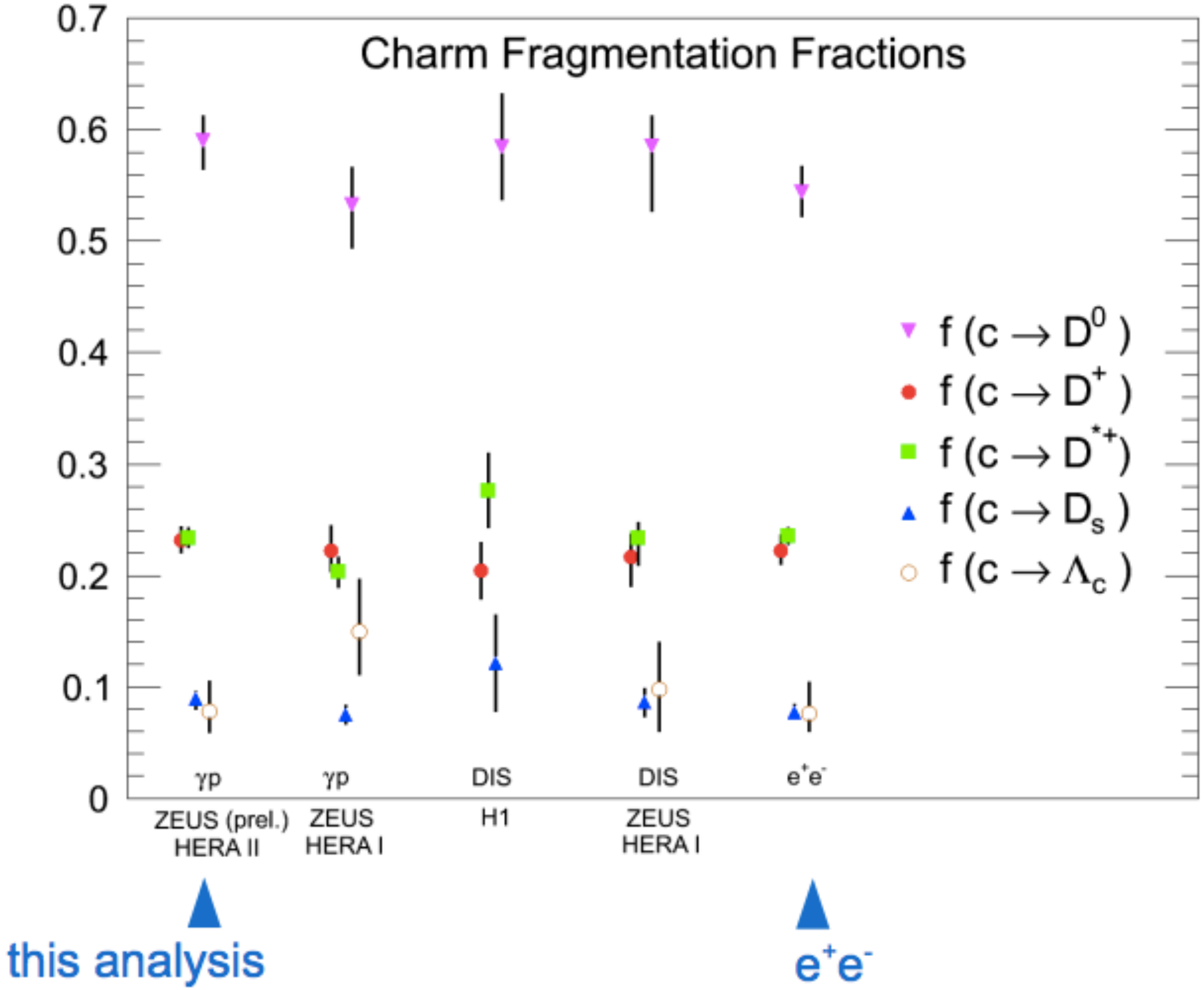
$$\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2}=\frac{2\pi\alpha^2}{x\,Q^4}\cdot[(1+(1-y)^2)F_2^{c\bar{c}}-y^2F_L^{c\bar{c}}]$$



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

- The good agreement of the data and NLO calculations in the visible phase (given by the heavy quark tagging) allow to extrapolate to the full phase space and to measure F_2^{cc} (and identical F_2^{bb}) :

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



ZEUS-prel-12-003

- Charm fragmentation universality confirmed.

Running of heavy quark masses

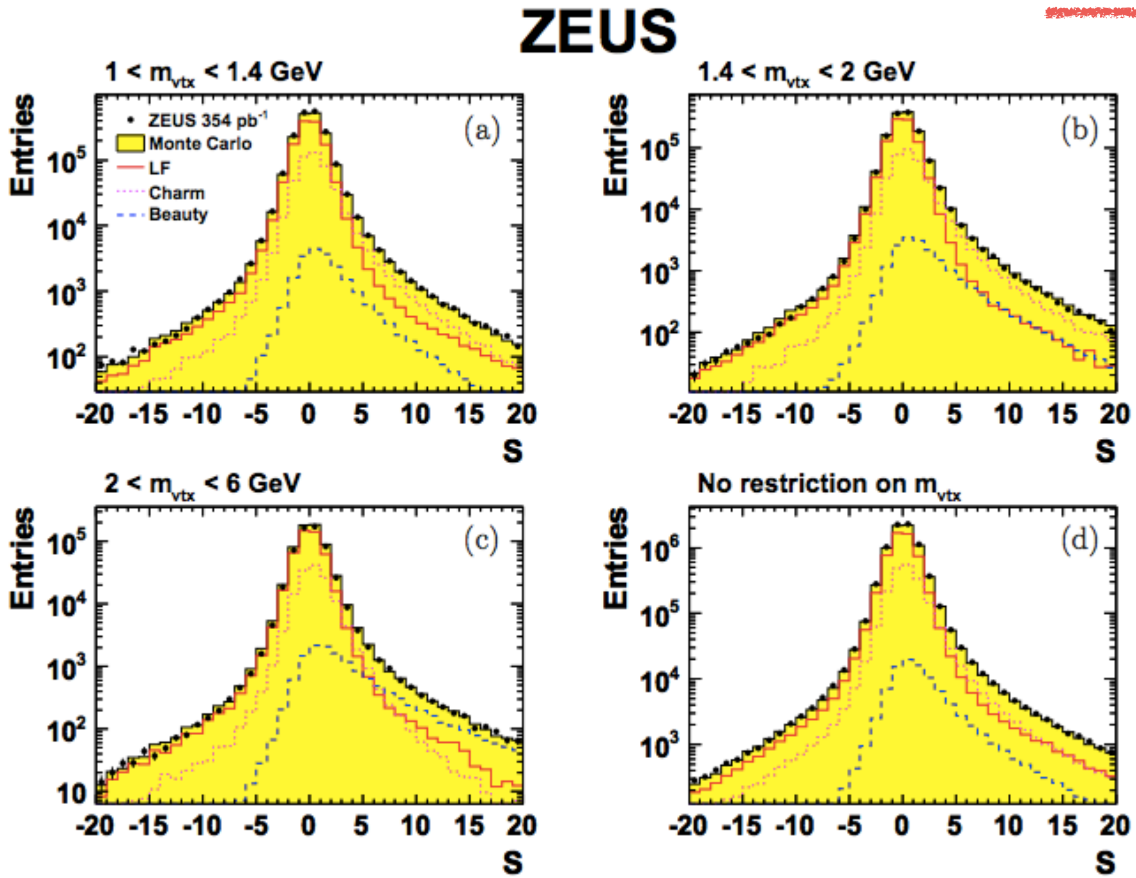
- Quark mass running depends on α_s:

    - leading order QCD formulae:
    - **$m_c(pole) = m_c(m_c)\,(1 + 4/3\,\alpha_s/\pi) = m_c(Q)\,(1 + \alpha_s/\pi\,(4/3+\ln(Q^2/m_c^2))$**

- Charm mass running not explicitly measured (so far)

beauty from charm

mirror it



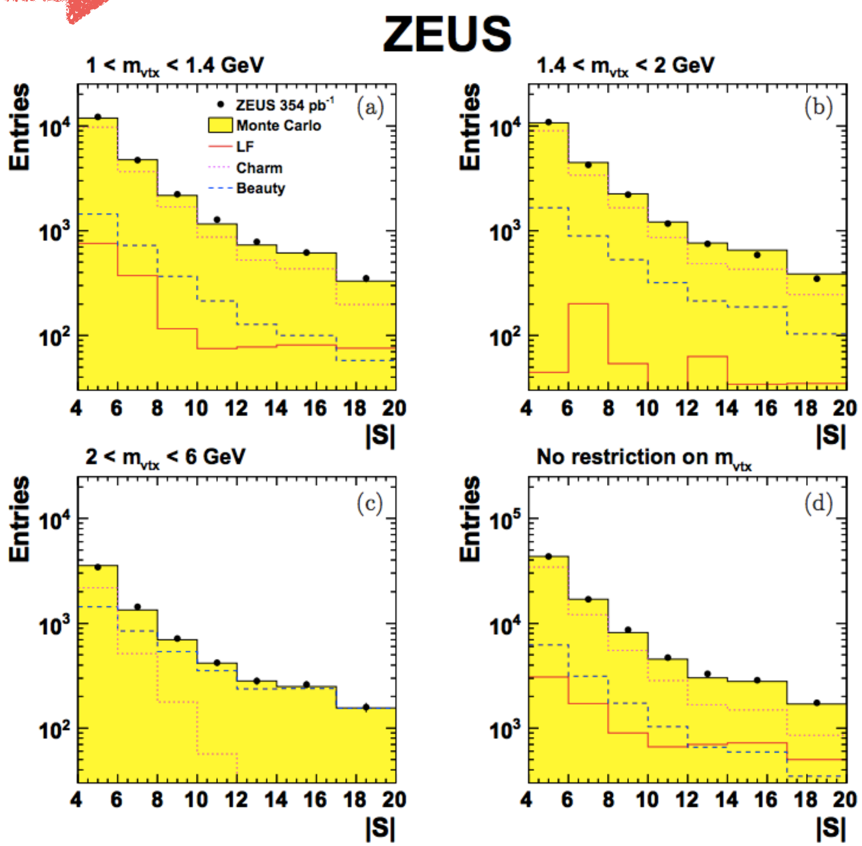


Figure 1: *Distributions of the decay-length significance, S, for (a) $1 < m_{vtx} < 1.4\,\mathrm{GeV}$, (b) $1.4 < m_{vtx} < 2\,\mathrm{GeV}$, (c) $2 < m_{vtx} < 6\,\mathrm{GeV}$ and (d) no restriction on m_{vtx}. The data are compared to the sum of all MC distributions as well as the individual contributions from the beauty, charm and light-flavour (LF) MC subsamples. All samples were normalised*