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Charm and Beauty in DIS with muon tags at ZEUS

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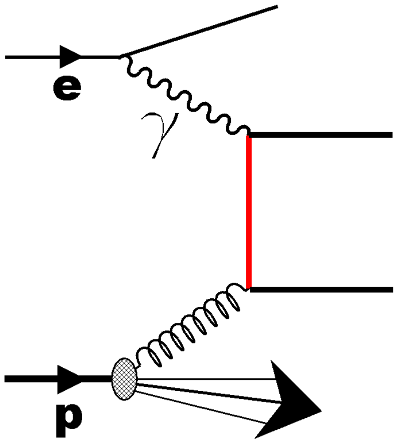
c,b production in DIS

$ep \rightarrow e'Q\bar{Q}X$

QCD test:

- Leading order (LO) boson–gluon fusion (BGF)

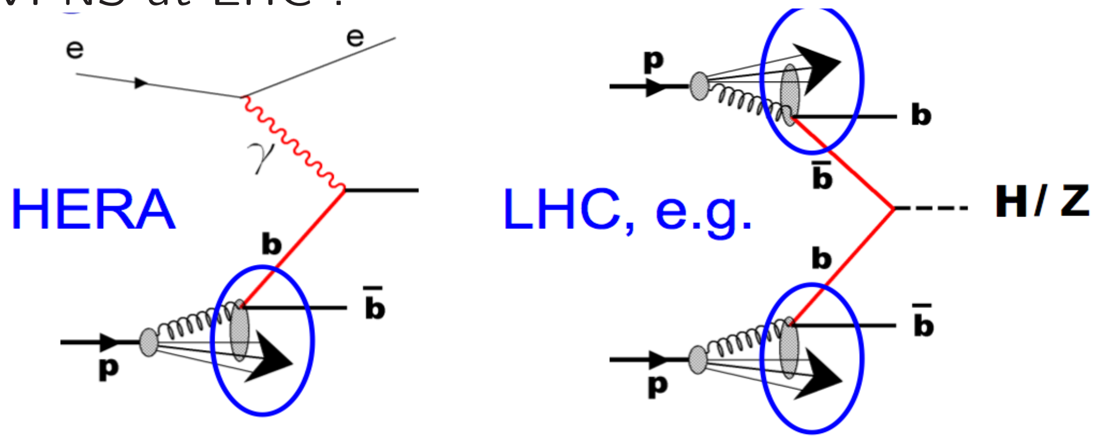


- NLO known since ’90s HVQDIS program
- things complicated by multiple scales (m_Q, Q^2, p_T) e.g. large logs when $Q^2 \gg m_Q^2$

Constraints on PDFs:

- direct access to $g(x)$, rather than via scaling violation as in inclusive DIS
- at $Q^2 \gg m_Q^2$ HQs can be treated as partons: c, b PDFs, variable flavour number scheme (VFNS). Resum effectively large log(Q^2/m^2)
- at $x \ll 1, Q^2 \gg m_c^2$ $c(x), b(x)$ same size of $u(x), d(x), s(x)$

VFNS at LHC :

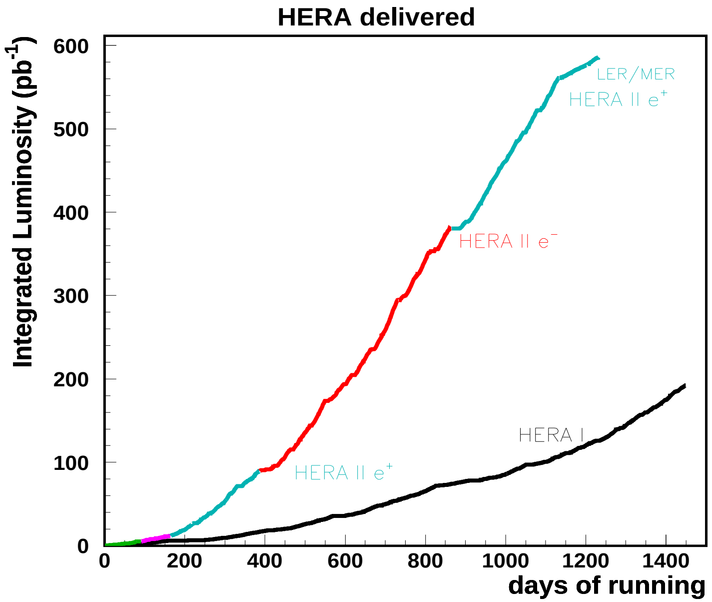


HERA and ZEUS

HERA

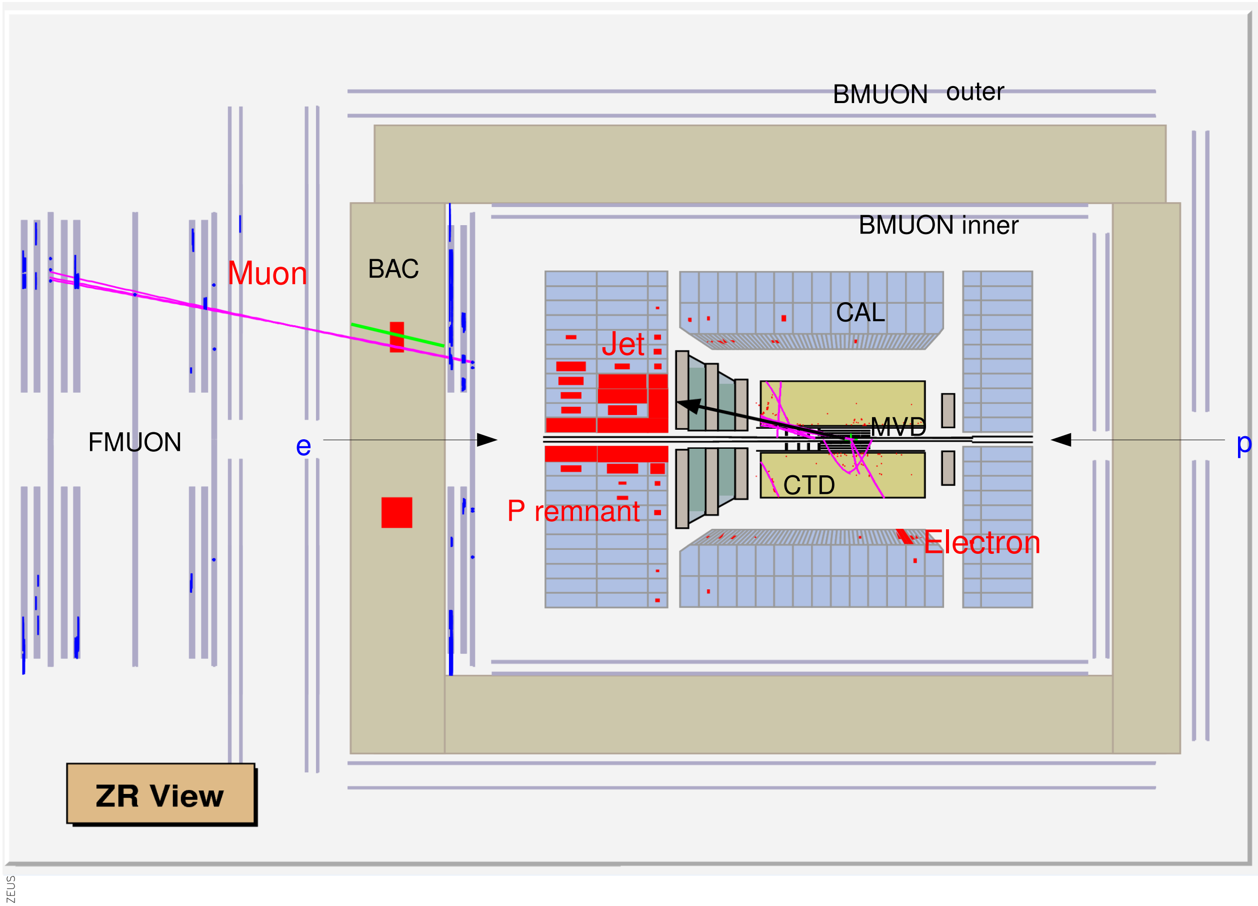
- $E(e^{\pm}) = 27.5\text{GeV}$
  $E(p) = 920\text{GeV}$

- HERA-I: 1992-2000
  HERA-II: 2003-2007



- $\mathcal{L} \simeq 0.5\text{fb}^{-1}$ (ZEUS physics)

DIS event with a muon in ZEUS

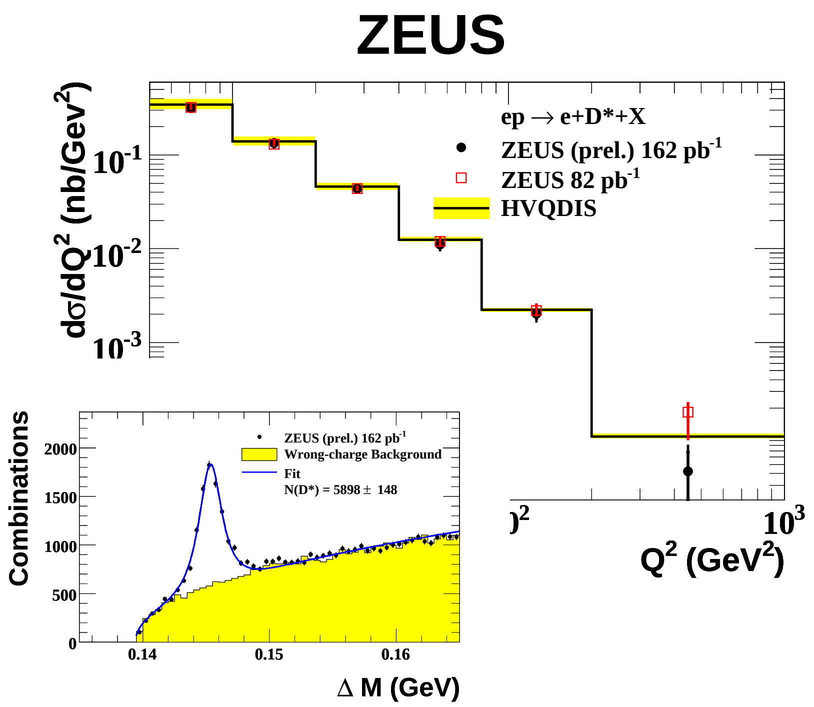


- CAL: uranium-scinitllator calorimeter $e/h = 1$
- CTD: central drift chamber
- MVD: silicon microvertex detector (HERA-II)
- B/R/FMUO: muon chambers
- BAC: backing calorimeter

Charm/beauty tagging

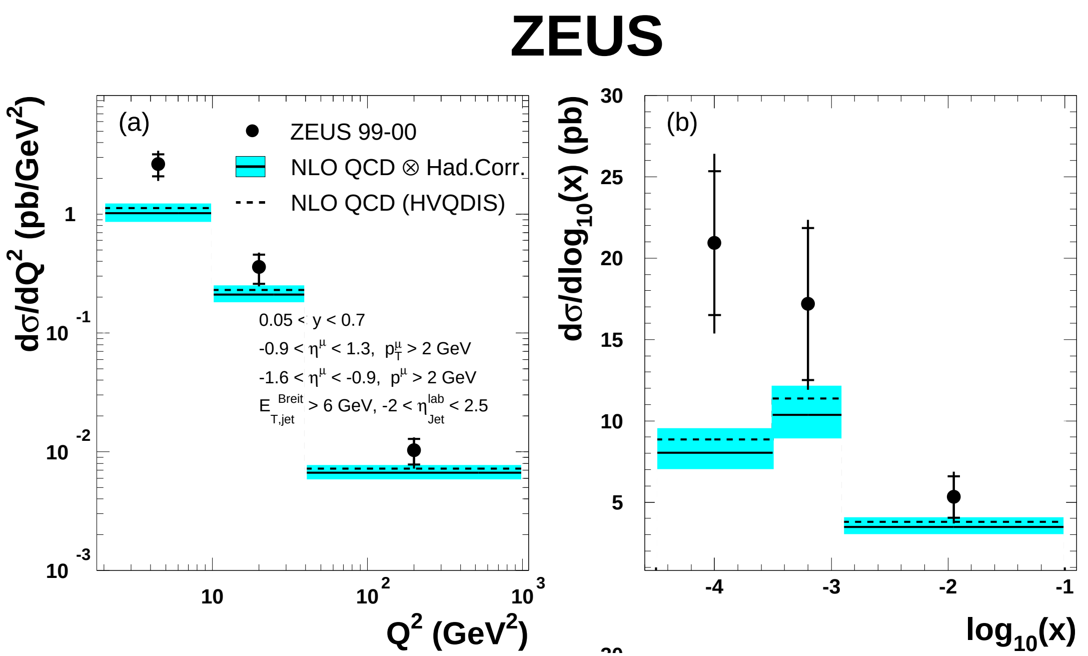
Charm

- charm has been measured from D mesons (ZEUS, H1) or lifetime tagging (H1 only)
- "golden" channel $D^{*+} \to \pi_s^+ (D^0 \to K^- \pi^+)$ statistics limited at large Q^2 $B(c \to D^{*+} \to D^0 \to K^- \pi^+) \simeq 0.6\%$
- SL decays promising at large Q^2 $B(c \to l) \simeq 10\%$



Beauty

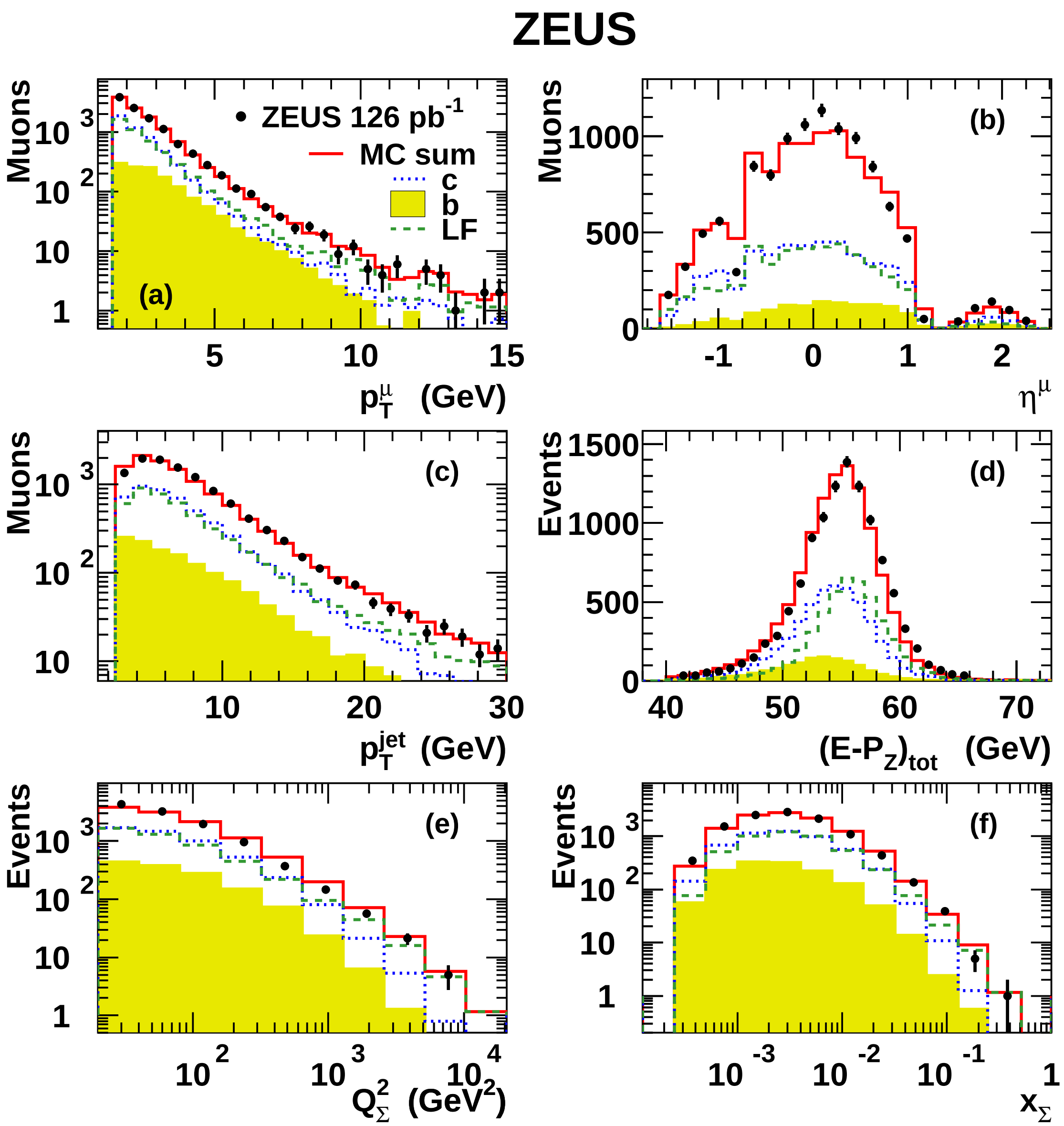
- only few % of all DIS events
- tagged from SL decays (ZEUS, H1) or lifetime tagging (H1 only) $B(b \to l) \simeq 20\%$ (incl. $b \to c \to l$)
- previous muon based results (ZEUS PLB 599(2004)173, H1 EPJC 41(2005)453) focused on high-p_T jets and μs to enhance the b signal
- prev. μ results $\simeq 2$ stand. dev. above NLO at low x, Q^2



Data sample and selection

ZEUS muon analysis
`arXiv:0904.3487v1 [hep-ex]`

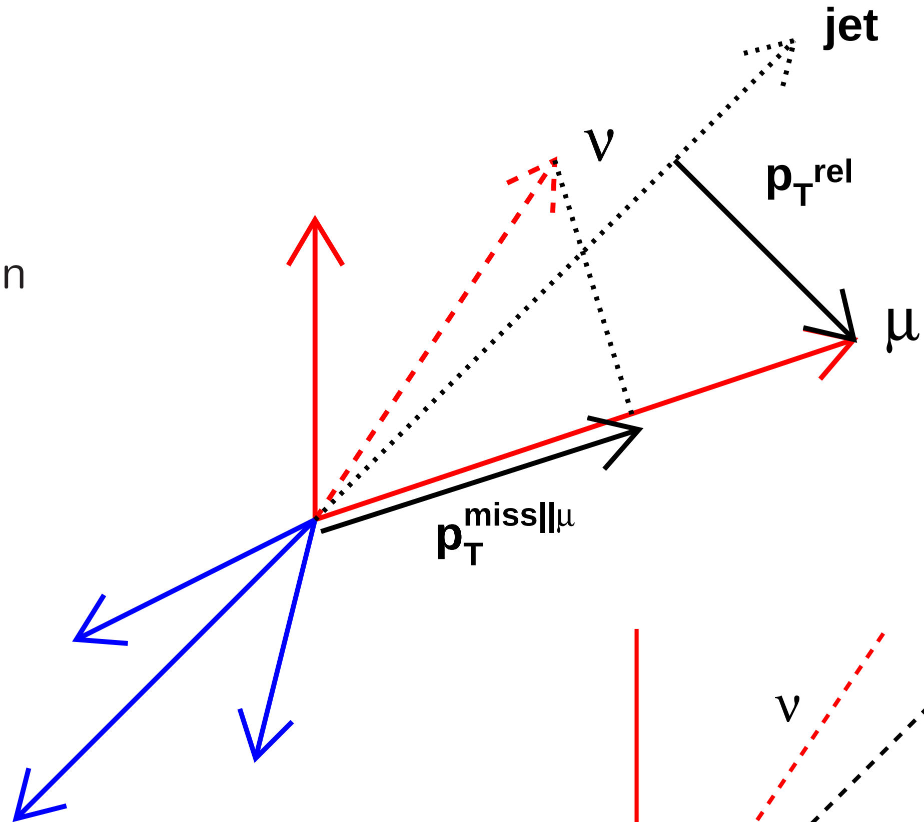
- 2005 data ($\mathcal{L} = 126$ pb^{-1})
  first useful data with MVD
- $Q^2 > 20\text{GeV}^2$, $0.01 < y < 0.7$
- μ: CTD track matched to inner B/RMUON or to FMUON track
  $p_T^\mu > 1.5$ GeV, $-1.6 < \eta^\mu < 2.3$
  (lower p_T^μ than in prev. analyses)
- muon anti-isolation:
  $E^{\text{iso}} > 0.5\text{GeV}$ (cone $R = 1$)
- μ associated to jet with
  $p_T^j > 2.5\text{GeV}$ incl. μ ($\sim 95\%$ eff.)
- muons from b, c decays and "fake" muons from in–flight K, π decays and punch through



total MC:
light flavours (LF): Django (MEPS)
Charm, Beauty: Rapgap (LO BGF + PS)

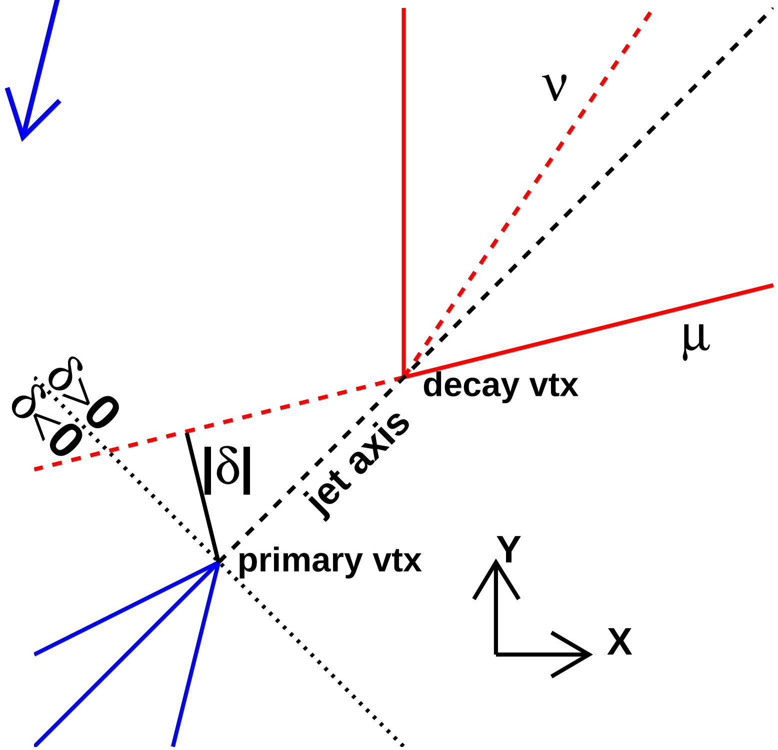
Discriminating variables to separate c, b, LF

- $p_T^{\text{miss}||\mu}$
  total missing p_T in the μ direction
  based on CAL, tracking and μ
  sensitive to ν from SL decays
  mainly distinguishes c, b from LF



- p_T^{rel}
  muon momentum transverse to
  the jet axis
  mainly distinguishes b from c, LF

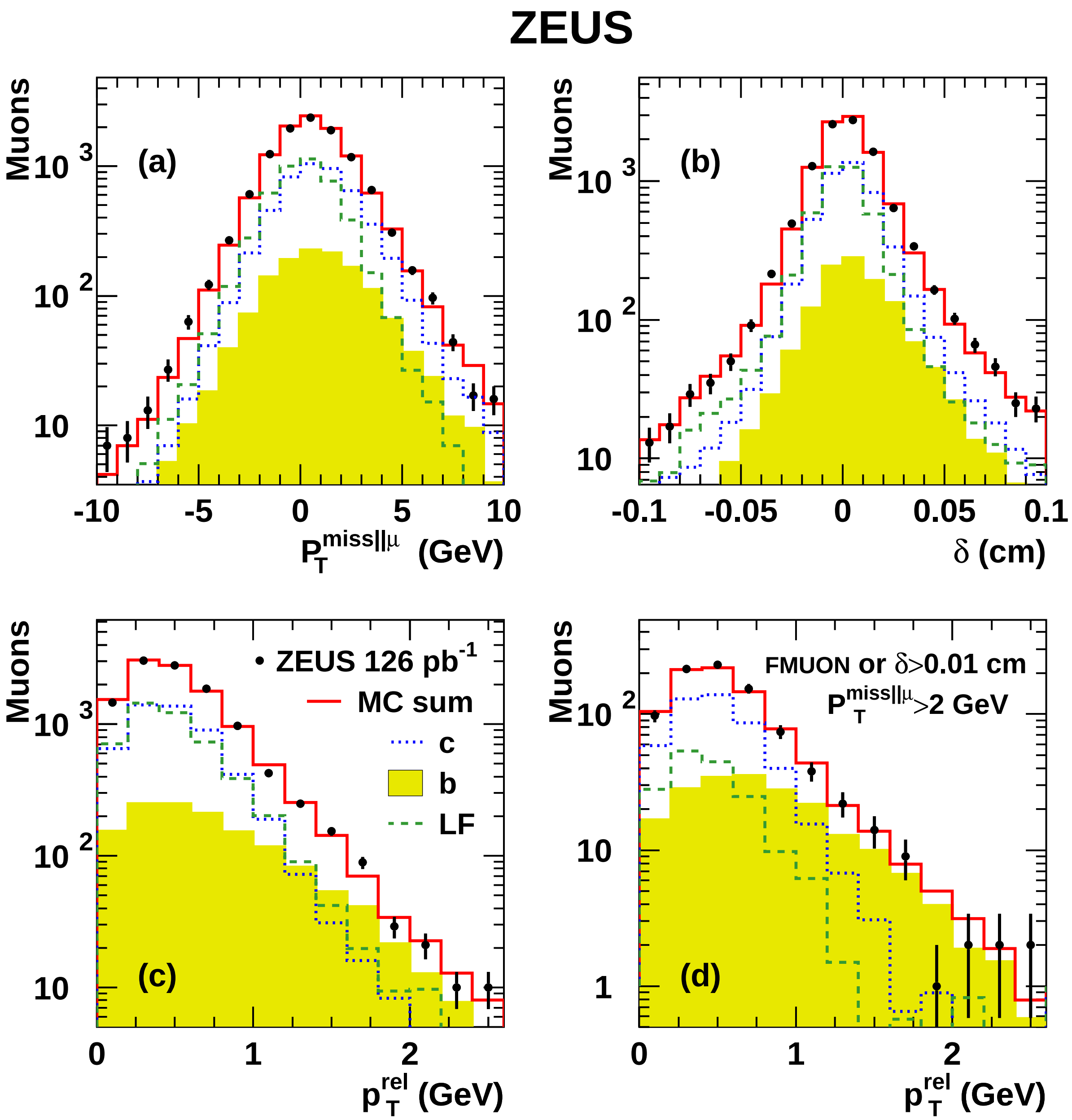
- δ
  signed muon DCA to beam spot
  in X,Y
  sign according to jet direction
  large for μ from secondary vertex
  mainly distinguishes c, b from LF



Determination of c and b content

- MC "templates" corrected using inclusive DIS control samples agree with data
- for $p_T^{\mathrm{miss}||\mu} > 2\mathrm{GeV}$, $\delta > 100\mu\mathrm{m}$ sample dominated by $c(b)$ for $p_T^{\mathrm{rel}} < (>) 1\mathrm{GeV}$
- simultaneous fit of c, b fraction:
  $f_c = 0.456 \pm 0.029(\mathrm{stat.})$
  $f_b = 0.122 \pm 0.013(\mathrm{stat.})$

  (anti)correlation
  $\rho(c, b) = -0.43$



Theoretical predictions

HVQDIS (Harris, Smith) NLO fixed-flavour number scheme (FFNS)

parameters (variations):

- Masses varied in calculation and PDF fit:
  $m_c = 1.5$ (1.2 : 1.7) GeV
  $m_b = 4.75$ (4.5 : 5.0) GeV

- Scales varied independently:
  $\mu_f = \sqrt{Q^2 + 4m_Q^2}$ ($\times 1/2$: $\times 2$)
  $\mu_r = \sqrt{Q^2 + 4m_Q^2}$ ($\times 1/2$: $\times 2$)

- PDF: ZEUS-S FFNS PDF
  varied by its exp. uncertainty

- Peterson's fragmentation:
  $\epsilon_c = 0.055$ (0.04 – 0.12) for D mesons decaying to μ
  (corresponds to 0.034 (0.025 : 0.085) for D^*, covers e^+e^- and ep data at diff. scales)
  $\epsilon_b = 0.0035$ (0.0015 – 0.0055)
  Fragmentation variable: p ($E+p$)

- Decay distributions and branching fractions:
  $D \rightarrow \mu$ from CLEO data; $\mathcal{B}(c \rightarrow \mu) = 0.096 \pm 0.004$
  $b \rightarrow \mu$ from Pythia, checked with Belle, BaBar; $\mathcal{B}(b \rightarrow \mu) = 0.209 \pm 0.004$

Effects of variations added in quadrature

Results

- Visible muon cross sections for
  $Q^2 > 20\text{GeV}^2$, $0.01 < y < 0.7$, $p_T^\mu > 1.5$ GeV, $-1.6 < \eta^\mu < 2.3$
  (corrected to QED Born level):

  $\sigma^c = 164 \pm 10(\text{stat.})\,^{+30}_{-31}(\text{syst.})$ pb
  $\sigma^b = \;\,63 \pm \;\,7(\text{stat.})\,^{+18}_{-11}(\text{syst.})$ pb

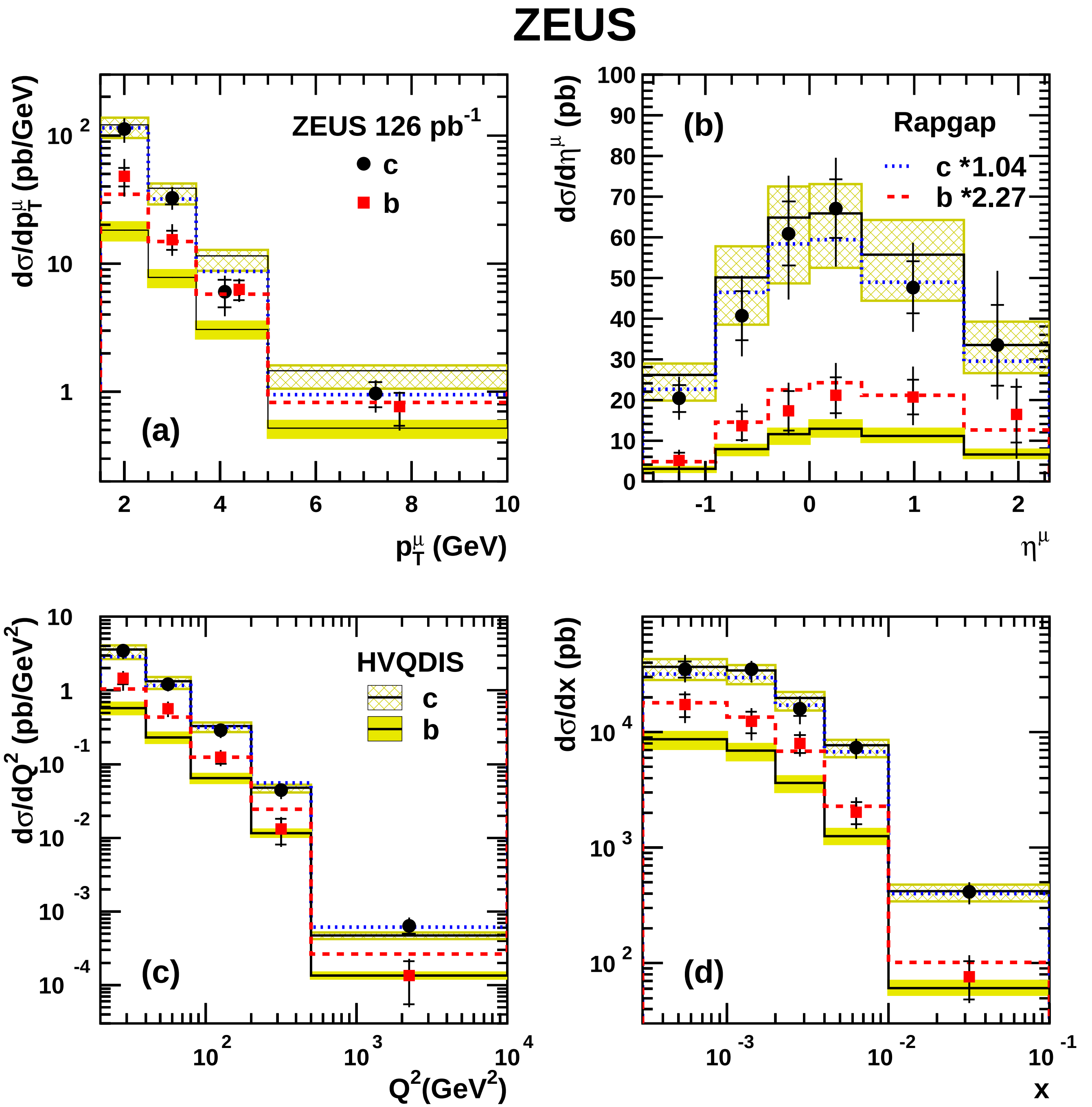
- HVQDIS predictions:
  $\sigma^c(\text{NLO}) = 184^{+26}_{-40}$ pb
  $\sigma^b(\text{NLO}) = \;\,33 \pm 5$ pb

- good agreement with NLO for charm
  2.3 (1.9) standard deviations above central (upper) HVQDIS value for beauty

- Main systematic uncertainties

	$\Delta\sigma^c$	$\Delta\sigma^b$
μ efficiency	5%	5%
$p_T^{\text{miss}\|\|\mu}$ calibration	12%	2%
hadronic energy resolution	2%	7%
δ resolution	3%	11%
p_T^{rel} shape	2%	8%
MC Q^2 and p_T^μ reweight to data	6%	20%
MC $z = (E - P_z(c))/(E - P_z(tot))$ shape rew. to NLO	10%	3%

Differential cross sections



- fit repeated in bins of $p_T^\mu, \eta^\mu, Q^2, x$
- reasonable shape agreement with Hvqdis and Rapgap
- beauty in good agreement with NLO at $Q^2 > 200\text{GeV}^2$

Extraction of $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$

- c and b contribution to F_2 extracted from visible μ cross section in (x, Q^2) bins:

$$F_2^{Q\bar{Q}} = \sigma_\mu \frac{F_2^{Q\bar{Q},\text{theo.}}}{\sigma_\mu^{\text{theo.}}}$$

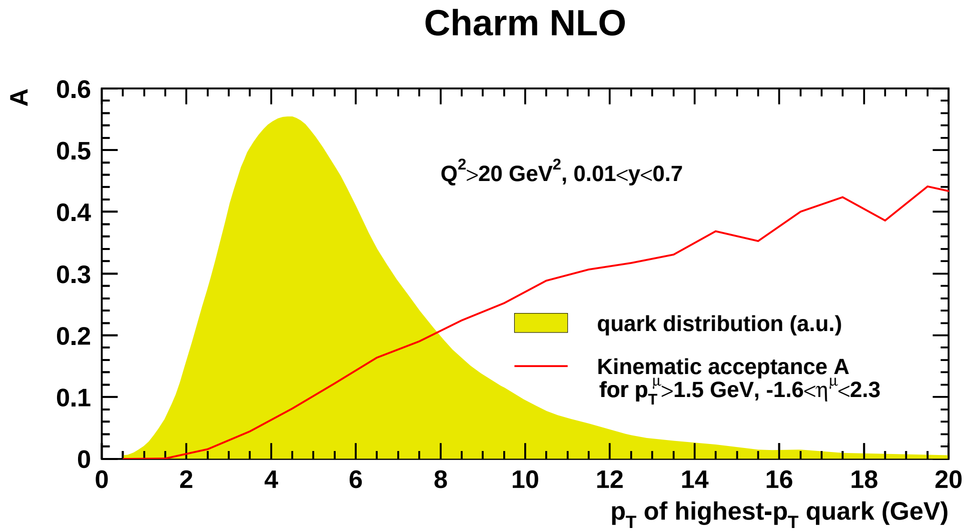
- kinem. acceptance $\mathcal{A}$: fraction of μ in visible phase space

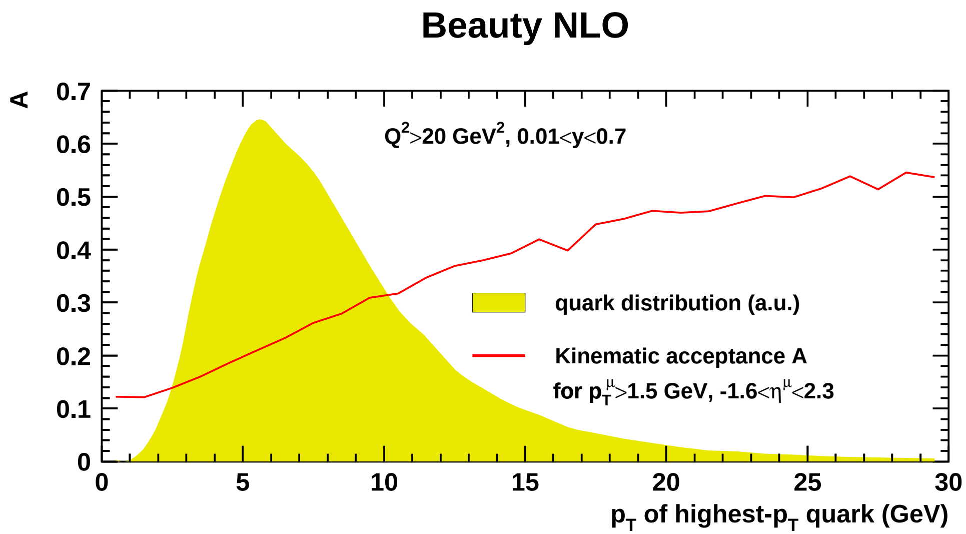
- charm:
  $\mathcal{A} = 10 - 37\%$ for $Q^2 = 30 - 1000\text{GeV}^2$
  $\mathcal{A}$ goes to zero at small quark p_T
  sizeable (i.e. $> 0.25\langle\mathcal{A}\rangle$)
  over 88% of $c\bar{c}$ phase space

  Theor. uncertainty $20 - 10\%$
  for $Q^2 = 30 - 1000\text{GeV}^2$

- beauty:
  $\mathcal{A} = 25 - 42\%$ for $Q^2 = 30 - 1000\text{GeV}^2$
  $\mathcal{A}$ not zero at $p_T^b = 0$:
  sizeable over full $b\bar{b}$ phase space

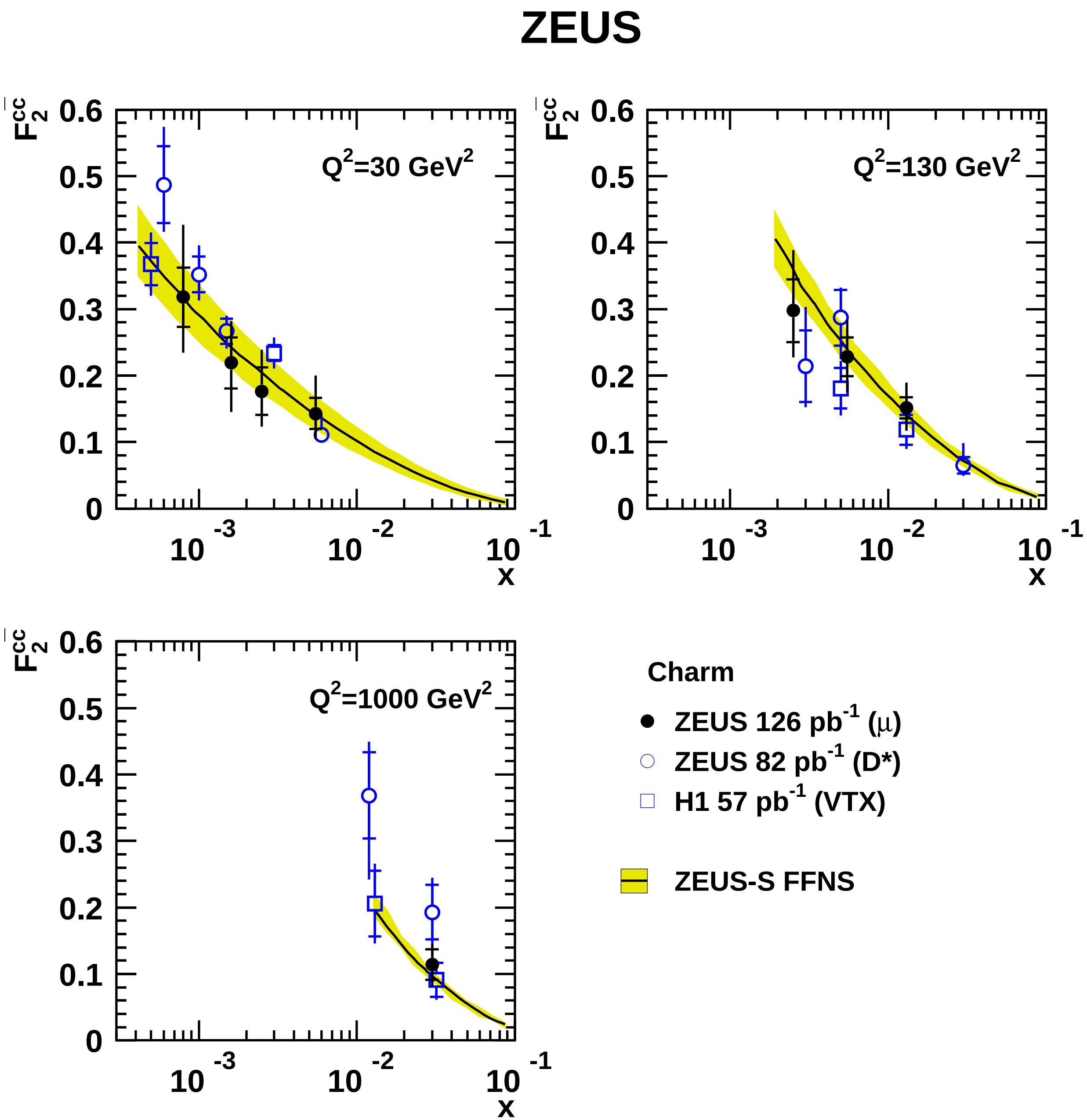
  Theor. uncertainty $5 - 4\%$



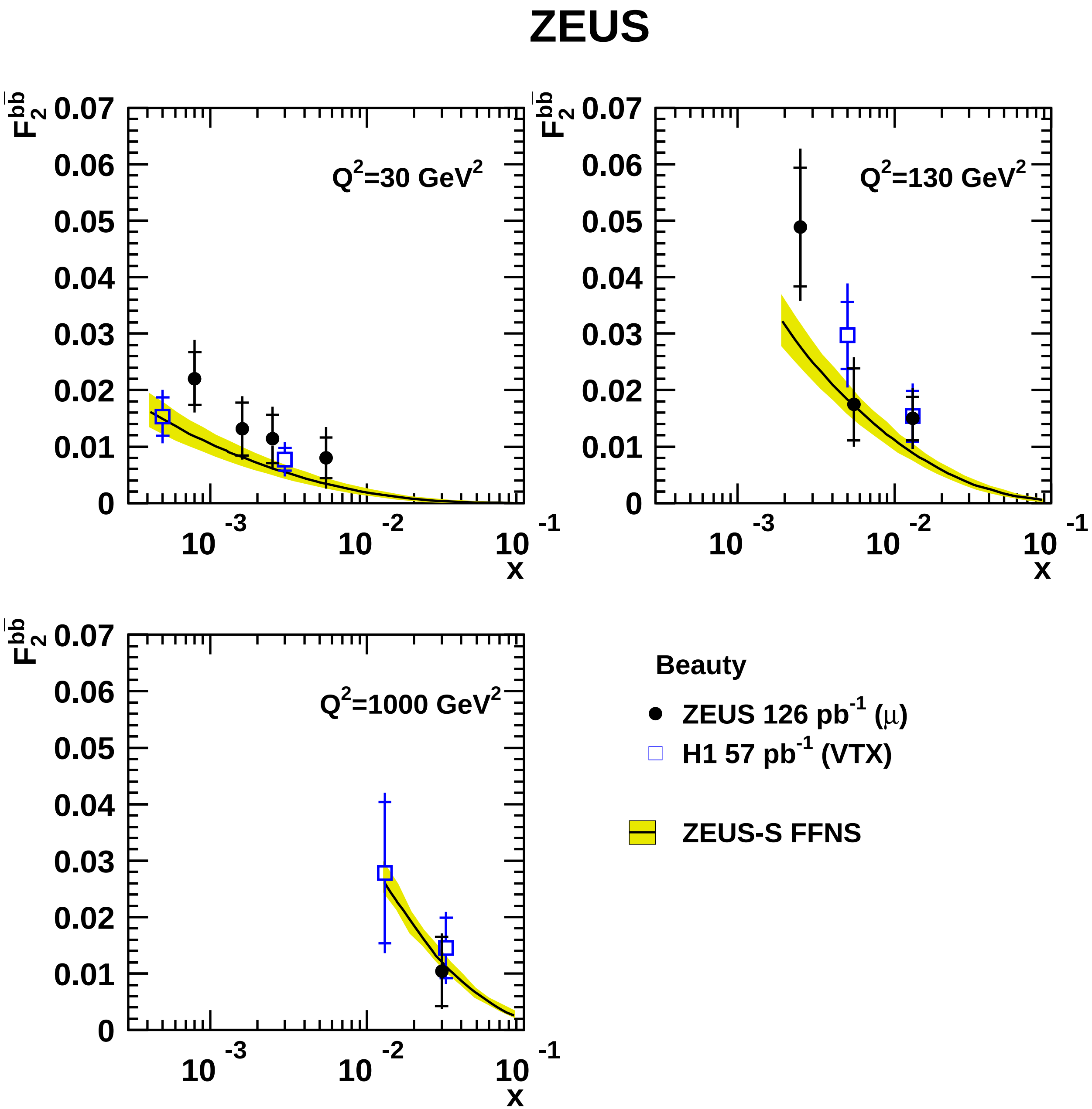


$F_2^{c\bar{c}}$

- good precision at high Q^2
- agreement with other measurements
- agreement with ZEUS-S FFNS band (Hvqdis)



$F_2^{b\bar{b}}$

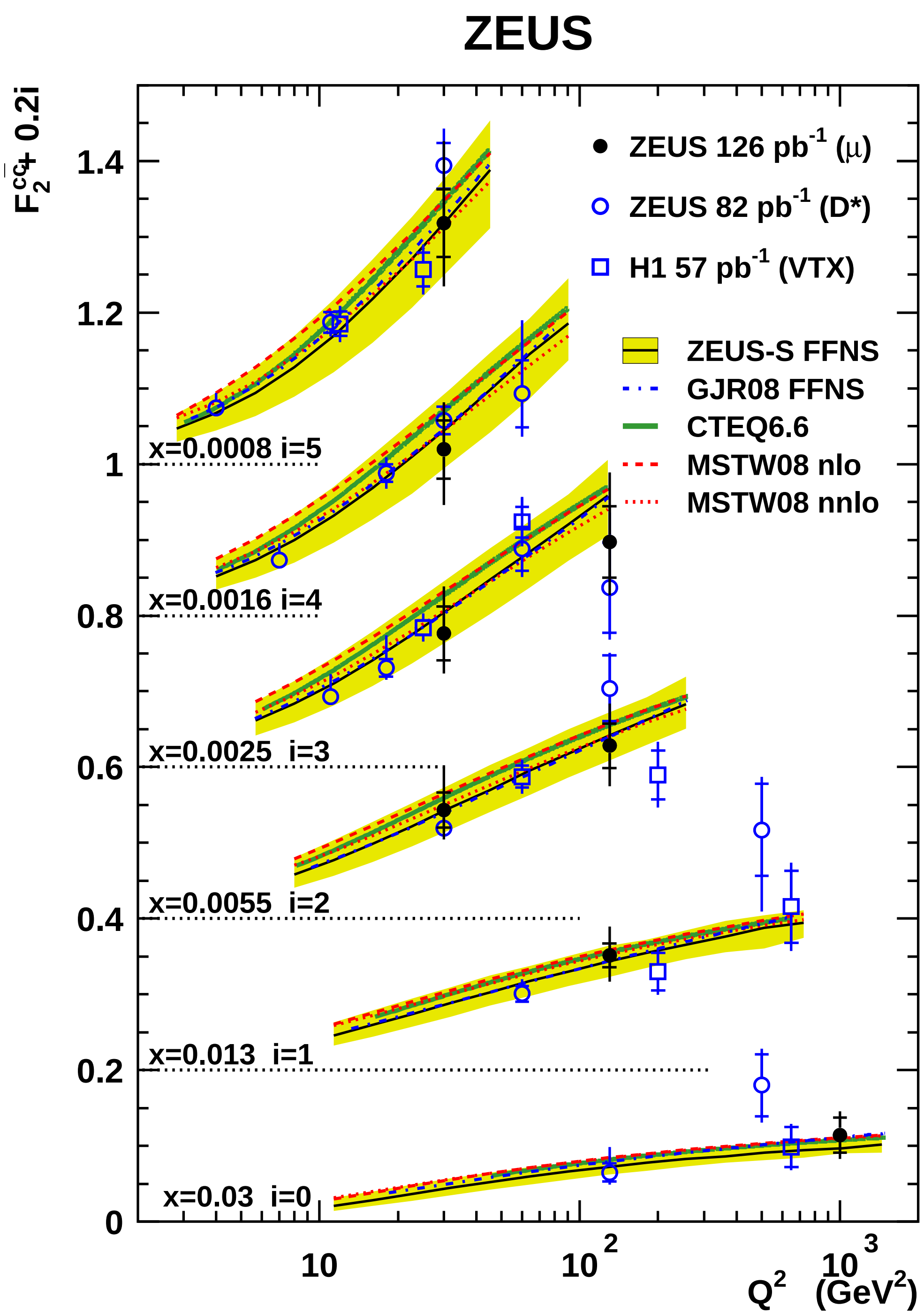


- agreement with other measurements
- consistent with with ZEUS-S FFNS band

$F_2^{c\bar{c}}$ vs Q^2

- other theor. curves:
  - GJR08 (FFNS)
  - CTEQ6.6 NLO (GM-VFNS)
  - MSTW08 NLO (GM-VFNS)
  - MSTW08 NNLO
  - ...
  - ...

- all theories very similar and within uncertainty of ZEUS-S FFNS



$F_2^{b\bar{b}}$ vs Q^2, all HERA data

- H1 (prel.) VTX all HERA data
  - agreement with ZEUS μ data
  - no excess at $Q^2 \sim 30\text{GeV}^2$

- other theor. curves:
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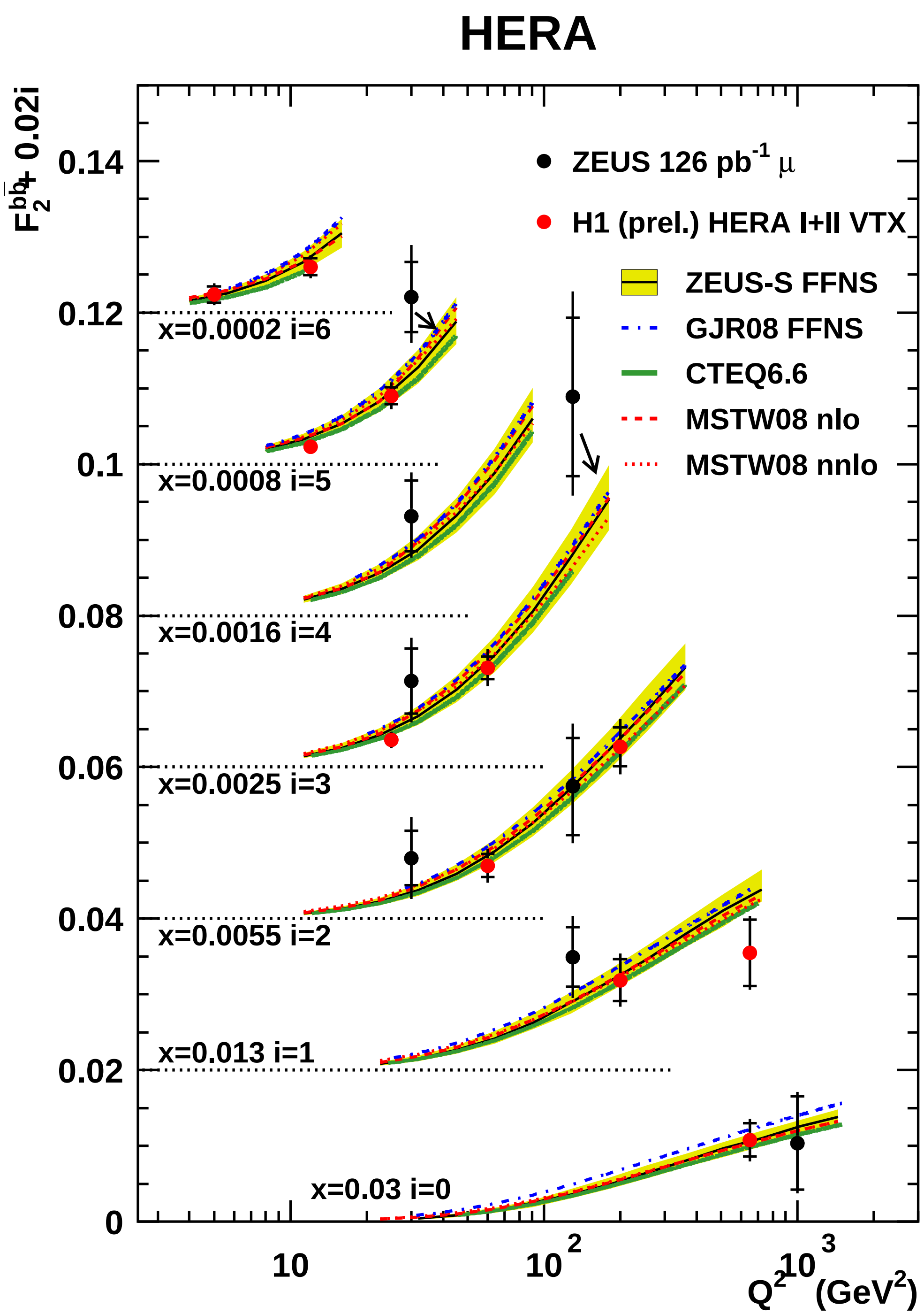


Conclusions

- ZEUS measurement of c, b in DIS
  using muons for $Q^2 > 20\text{GeV}^2$

- c,b fractions determined simulatneously using p_T^{rel}, δ and $p_T^{\text{miss}||e}$

- Charm:
  good agreement with NLO
  competitive with D meson measurements at $Q^2 \geq 130\text{GeV}^2$

- Beauty:
  2.3 (1.9) standard deviations above central (upper) NLO prediciton

- large improvment expected by using full HERA II data and improved tracking

BACKUPS

GM-VFNS

FFNS

ZEUS-S

- calclated with HVQDIS
- NLO $O(\alpha_s^2)$
- $m_c = 1.5 \pm 0.2$ GeV, $m_b = 4.75 \pm 0.25$ GeV
- $\mu_0 = \sqrt{4m^2 + Q^2}$, $\mu_0/2 < \mu_F < 2\mu_0$, $\mu_0/2 < \mu_R < 2\mu_0$
- ZEUS-S-FF PDF (with expt. uncert.)

GJR08

(Eur.Phys.J.C (2008) 355)

- grids from authors
- NLO $O(\alpha_s^2)$
- $m_c = 1.3$ GeV, $m_b = 4.2$ GeV
- $\mu_R = \mu_F = m_q$

MSTW08 nlo, nnlo

(arXiv:0901.0002)

- prel. code from authors
- NLO: $O(\alpha_s^2)$ @lowQ^2, . $O(\alpha_s)$ @highQ^2
- NNLO: approx.$O(\alpha_s^3)$@lowQ^2, . $O(\alpha_s^2)$ @highQ^2
- $m_c = 1.4$ GeV, $m_b = 4.75$ GeV
- $\mu_R = \mu_F = Q$

CTEQ6.6

(arXiv:0802.0007)

- grid from authors
- NLO: $O(\alpha_s)$
- $\mu_r = Q$, $\mu_F = \sqrt{Q^2 + m^2}$ ($\sqrt{Q^2 + 4m^2}$ also available)
- $m_c = 1.3$ GeV, $m_b = 4.5$ GeV

ZM-VFNS

NNPDF

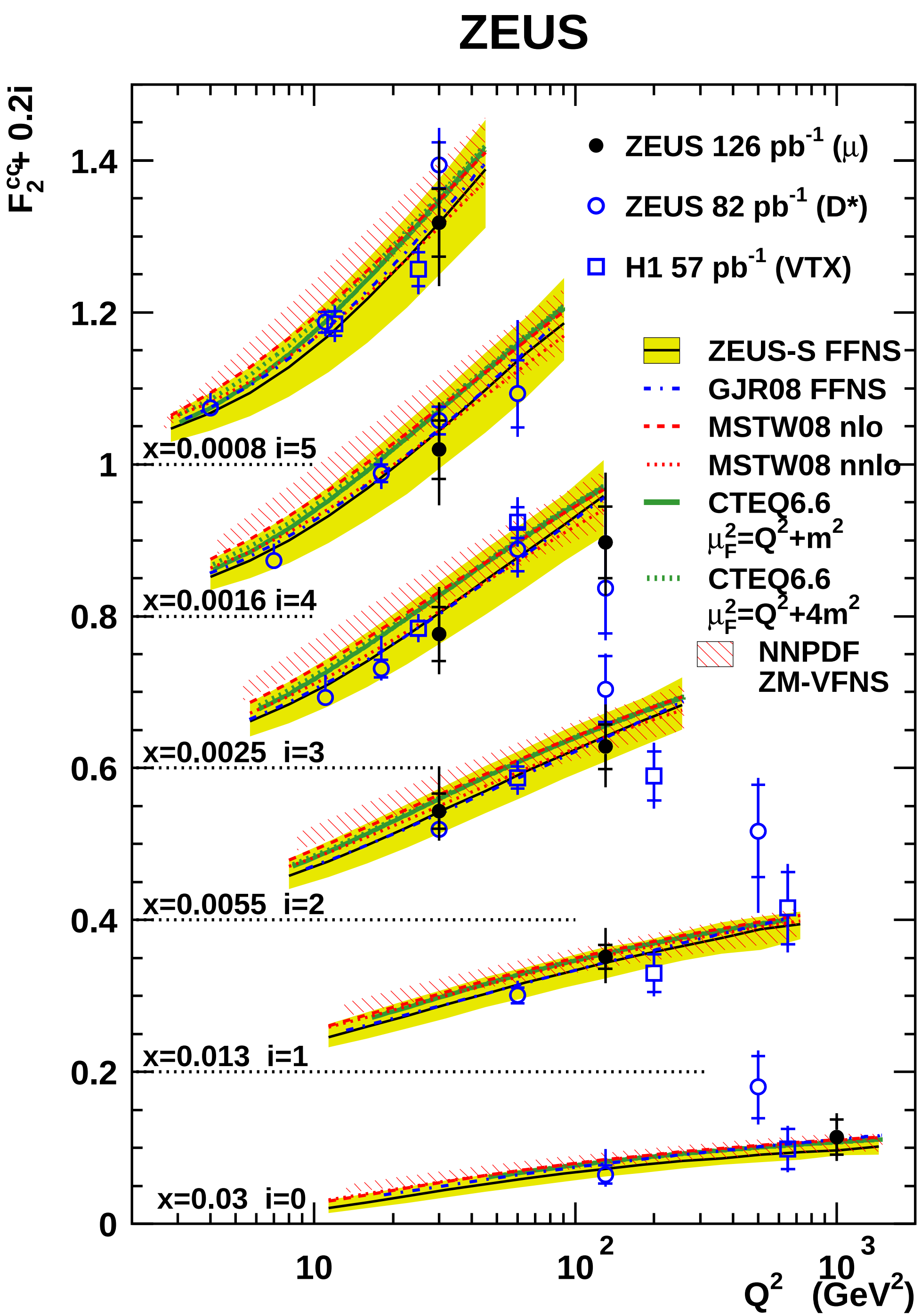
(arXiv:0808.1231)

- grid from authors
- NLO: $O(\alpha_s)$
- $\mu_R = \mu_F = Q$
- $m_c = 1.414$ GeV, $m_b = 4.3$ GeV
- PDF uncertainty

$F_2^{c\bar{c}}$ vs Q^2

- other theor. curves:
  - GJR08 (FFNS)
  - CTEQ6.6 NLO $\mu_F = \sqrt{Q^2 + m^2}$
  - CTEQ6.6 NLO $\mu_F = \sqrt{Q^2 + 4m^2}$
  - MSTW08 NLO (GM-VFNS)
  - MSTW08 NNLO
  - NNPDF 1.0 (ZM-VFNS)

- ZM-VFNS still describes charm in this Q^2 range



$F_2^{b\bar{b}}$ vs Q^2, all HERA data

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  - MSTW08 NLO (GM-VFNS)
  - MSTW08 NNLO
  - NNPDF 1.0 (ZM-VFNS)

- ZM-VFNS badly fails for beauty
  two CTEQ scales differ at low Q^2