Beauty production in DIS and the measurement of F_2^{bb} at ZEUS

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Motivations

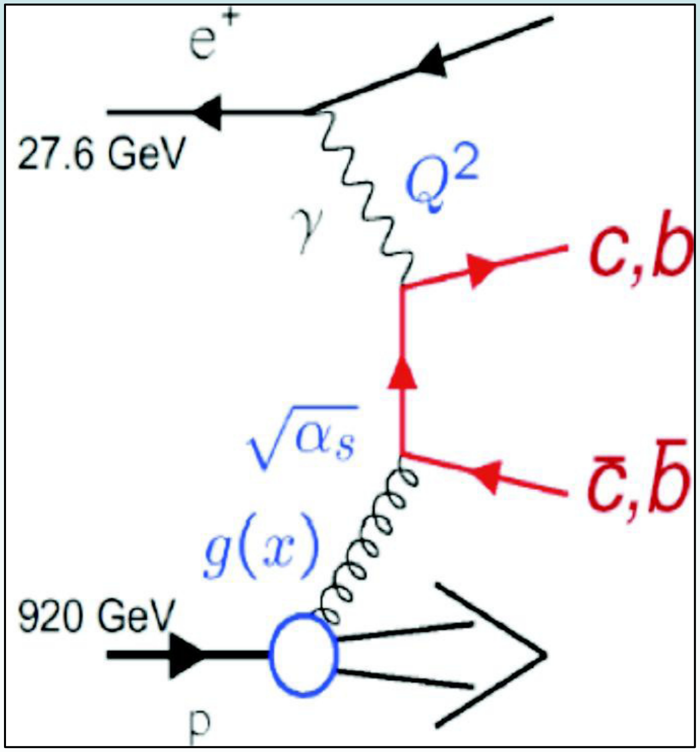
• Heavy flavour production at HERA can be studied for different kinematic regions, from Photoproduction to DIS and for different values of transverse momentum of the heavy quark.

• In DIS regime the heavy quarks are produced mainly by the Boson-Gluon-Fusion process (LO).

• This process is directly sensitive to gluon content inside the proton: possible constraint on g(x) in PDF fits.

• PDFs: F_2^{bb} measurements at high Q^2 important for LHC e.g. *bb->H*

• Important test of pQCD at different scales (M_Q, p^T_Q, Q^2).



Test of theoretical models at NLO

Massive approach (**F**ixed **F**lavour **N**umber **S**cheme): **FFNS**

- c & b massive → full massive matrix elements;
- appropriate for $Q^2 \sim M_Q^2$

DIS : Harris & Smith, HVQDIS fully differential NLO program

→ **c & b produced dynamically in the hard subprocess**

(not part of the proton; 3 active flavours in proton: u, d, s)

Massless approach (**Z**ero **M**ass **V**ariable **F**lavour **N**umber **S**cheme): **ZM-VFNS**

- c & b massless → resums $[\alpha_S \ln (Q^2/M^2_Q)]^n$;
- appropriate for $Q^2 >> M_Q^2$

DIS : only inclusive calculation of F_2^{QQ} available

→ **c & b present in proton**

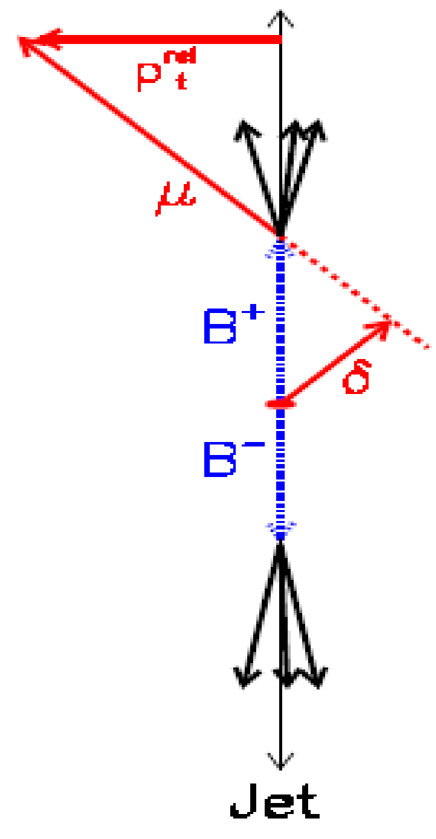
Combined approach (**G**eneralized **M**ass **V**ariable **F**lavour **N**umber **S**cheme): **GM-VFNS**

- **equivalent to massive at small Q^2**
- **equivalent to massless at high Q^2**

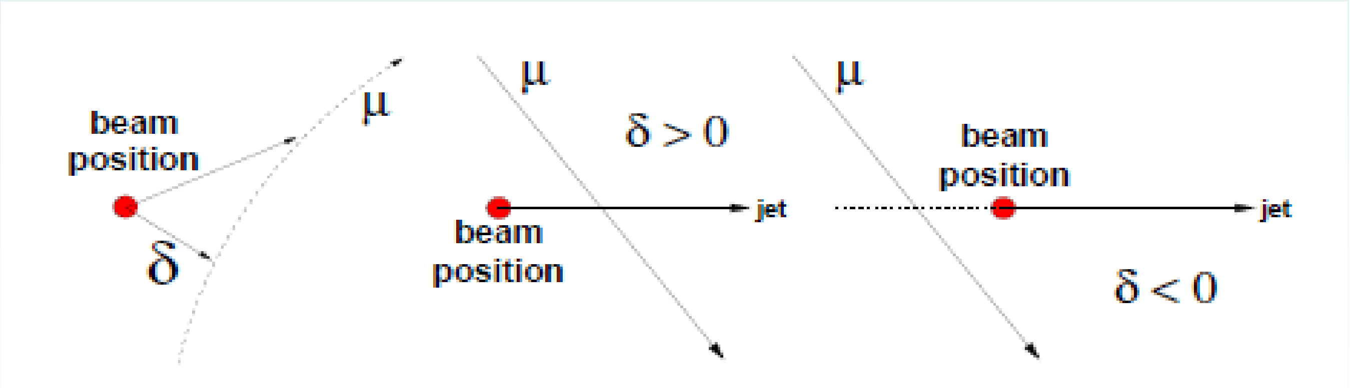
DIS : only F_2^{QQ} available

Beauty at ZEUS.

Beauty fraction in DIS very low (<~1%); by selecting events with muons we can reach a fraction of ~10%. How to distinguish beauty component from charm and light flavour?



- $\mathbf{p_T^{rel}}$: p_T of the muon relative to the associated jet axis
- $\boldsymbol{\delta}$: impact parameter of the muon w.r.t. the "beam spot" in X,Y plane. Sign from muon-jet association.
  → vertex detector with good resolution needed (MVD).



- $p_T^{miss\parallel\mu}$: missing p_T parallel to the muon; sensible to ν from semi-leptonic decay → high resolution hadronic Cal needed.

ZEUS measurements

HERA- I ZEUS measurement of b in DIS used $\mathbf{p_T^{rel}}$ to distinguish b from c/lf and required an hard jet to increase the b fraction; charm content was taken from other measurements. DESY-04-070, Physics Letters B 599 (2004)

- c and b are extracted simultaneously;
- use also **muon impact parameter** with respect to primary vertex (beamspot) from MicroVertexDetector and $\mathbf{p_T}$ **balance** from neutrinos.

http://arxiv.org/abs/0904.3487

DESY-09-056 zeus-pub-09-003

Beauty & Charm from muons

- New measurement uses first part of HERA II data 2005e → L=126 pb-1

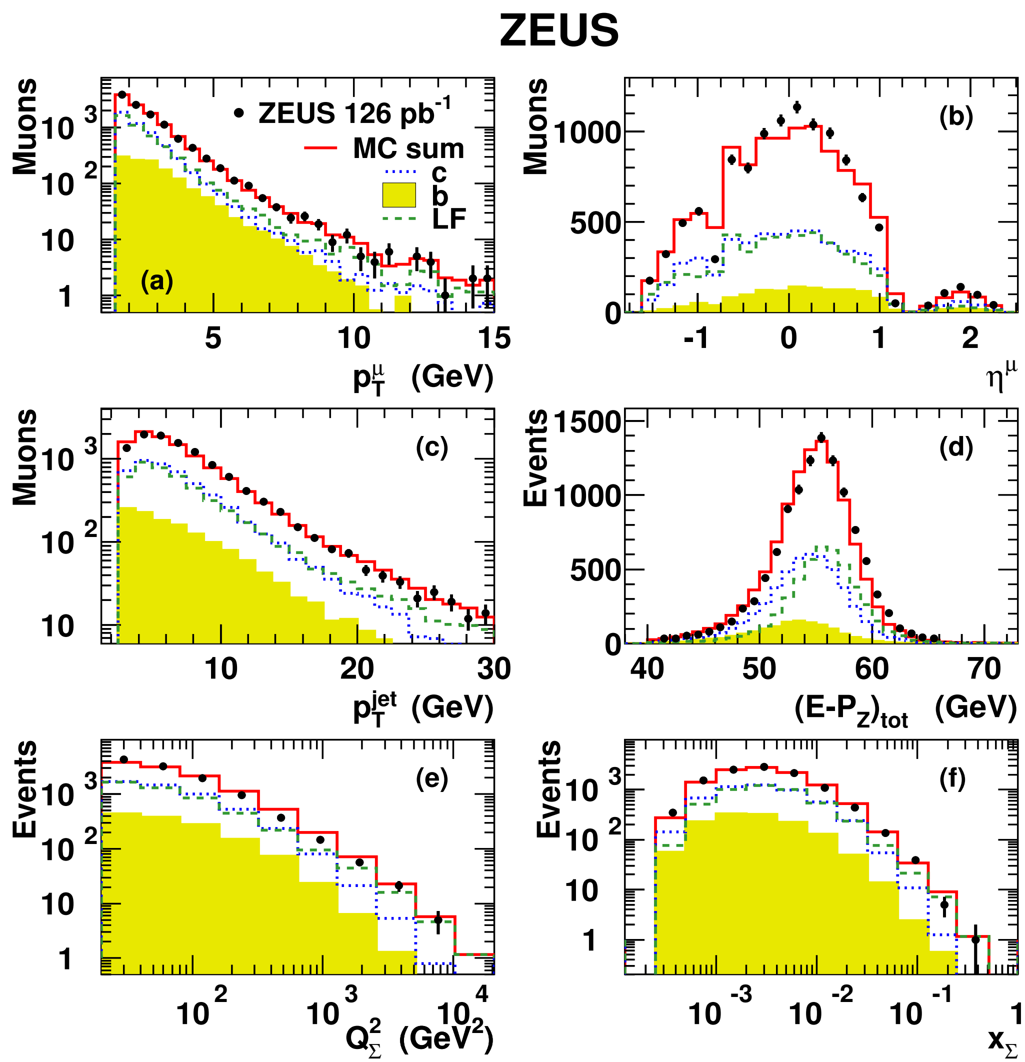
Selection cuts:

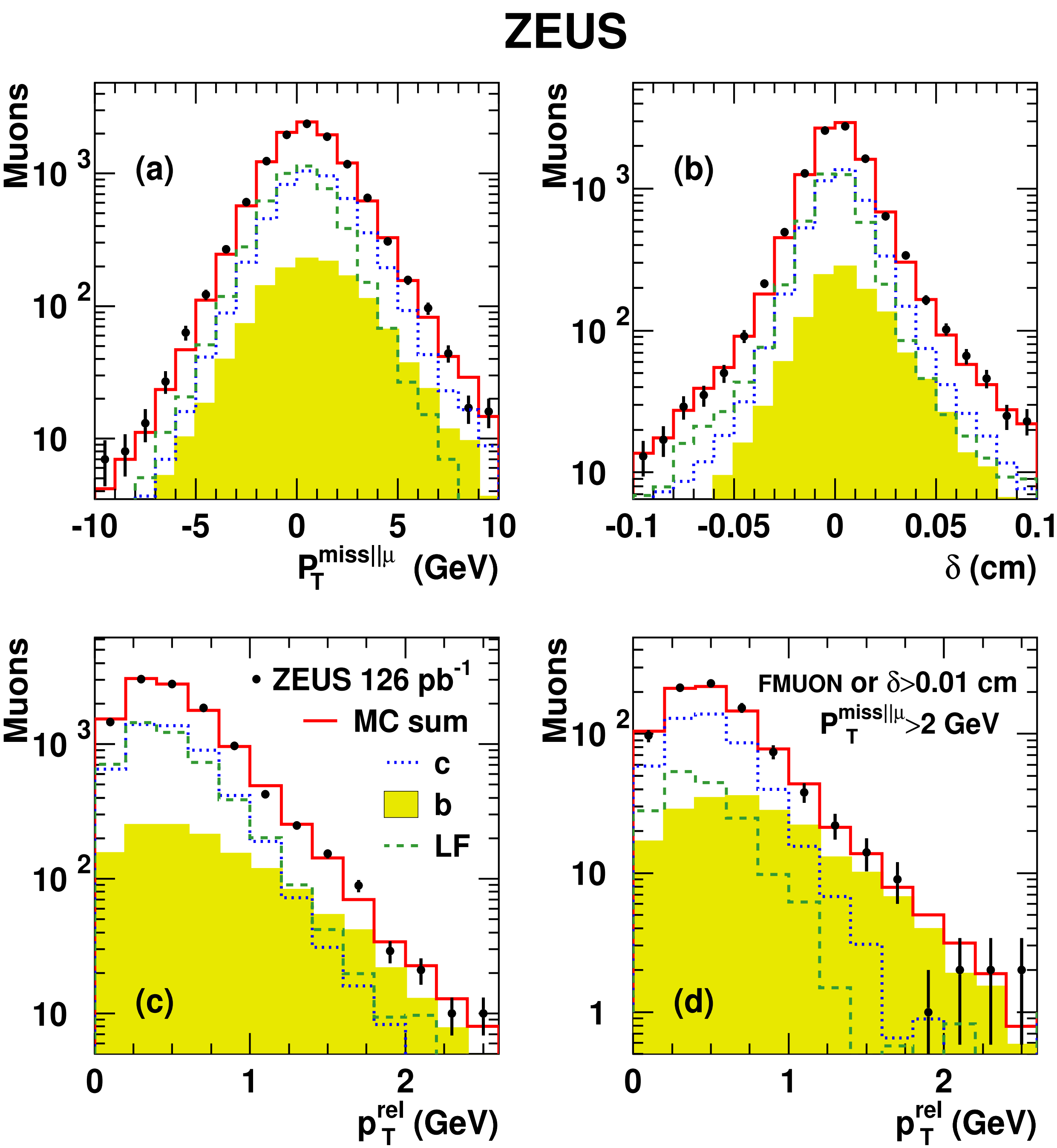
- $Q^2 > 20\ GeV^2$
- $0.01 < y < 0.7$
- $-1.6 < \eta^{\mu} < 2.3$
- $p_T^{\mu} > 1.5$ GeV
- Anti-isolation cut:

  E(cone,R=1) > 0.5 GeV

- jet-mu association required via k_T algorithm, $p_T^{jet} > 2.5$ Gev

Final sample : 11126 MUONS





Fits control plots

- 3D simultaneous fit of discriminating variables sensitive to different aspects of HQ decays.
- MC templates from RAPGAP (charm and beauty) and MEPS (light flavours).
- Background templates for discriminating variables corrected to describe data; inclusive DIS sample has been used.

ZEUS: NLO QCD predictions for beauty

- The HVQDIS program has been used to evaluate cross sections for heavy quark production at NLO ($O(\alpha_S^2)$) in the Fixed Flavour Number Scheme (the only available).

Quantity	Value	Variation
Renormalisation & Factorisation scale (μ_R, μ_F)	$\mu_R=\mu_F=\sqrt{Q^2+4M_c^2}$	$2\sqrt{Q^2+4M_\chi^2}$ $\frac{1}{2}\sqrt{Q^2+4M_\chi^2}$
Peterson Parameter (ε_b)	**0.0035**	**± 0.002**
Beauty Mass (M_b)	**4.75 GeV**	**± 0.25 GeV**
Input PDF	**Zeus NLO PDF**	**Upper and lower predictions of ZEUS NLO PDF**
Branching Ratio	**0.209**	**± 0.004**

- Biggest uncertainty from $\mathbf{M_B}$ and from μ_R. Uncertainties added in quadr.

Total cross sections

$$Q^2 > 20\,\mathrm{GeV}^2;\ 0.01 < y < 0.7;$$

$$p_T^{\mu} > 1.5\,\mathrm{GeV},\ -1.6 < \eta^{\mu} < 2.3.$$

• Global fractions:

Fc=0.456 ± 0.029 (stat.)

Fb=0.122 ± 0.013 (stat.)

• NLO cross sections:

$\sigma_{c,th} = 184^{+26}_{-40}$ pb

$\sigma_{b,th} = 33^{+5}_{-5}$ pb

• Total cross sections:

$\sigma_c = 164 \pm 10\ \text{(stat.)}\ ^{+30}_{-31}\ \text{(syst.) pb}$

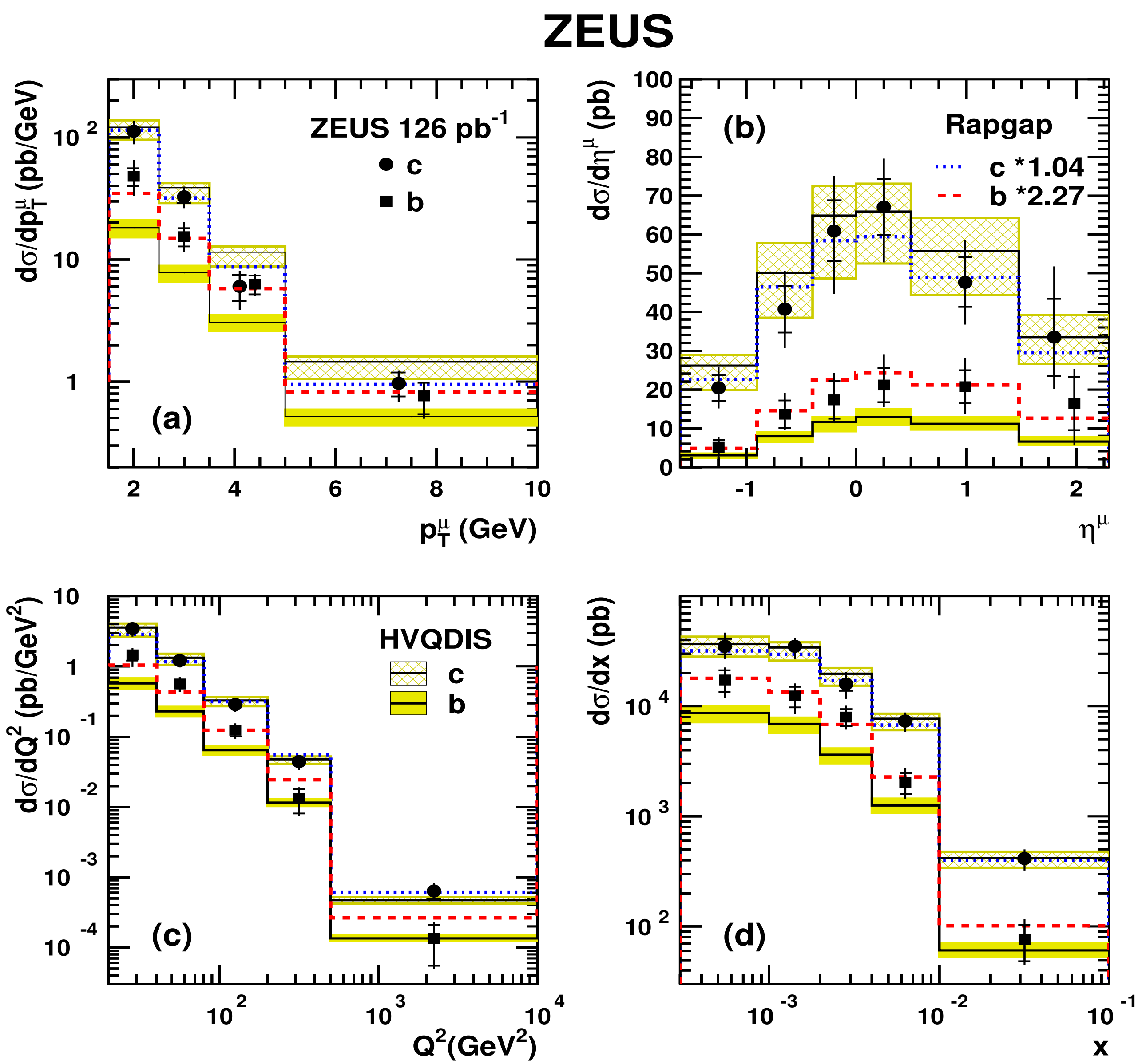
$\sigma_b = 63 \pm 7\ \text{(stat.)}\ ^{+18}_{-11}\ \text{(syst.) pb}$

$\rho_{cb} = -0.43$

- **Main syst. Uncertainties**:

charm: p_T^{miss} calibration, MC model; beauty: δ, p_T^{rel}, MC model

3D fit calculated for each bin of **Q^2, x, p_T^{μ}, eta$^{\mu}$** → differential cross sections.



Differential cross sections

- **charm**: good agreement with HVQDIS and RAPGAP.
- **beauty**: excess at low Q^2 (within ~2σ the significance).

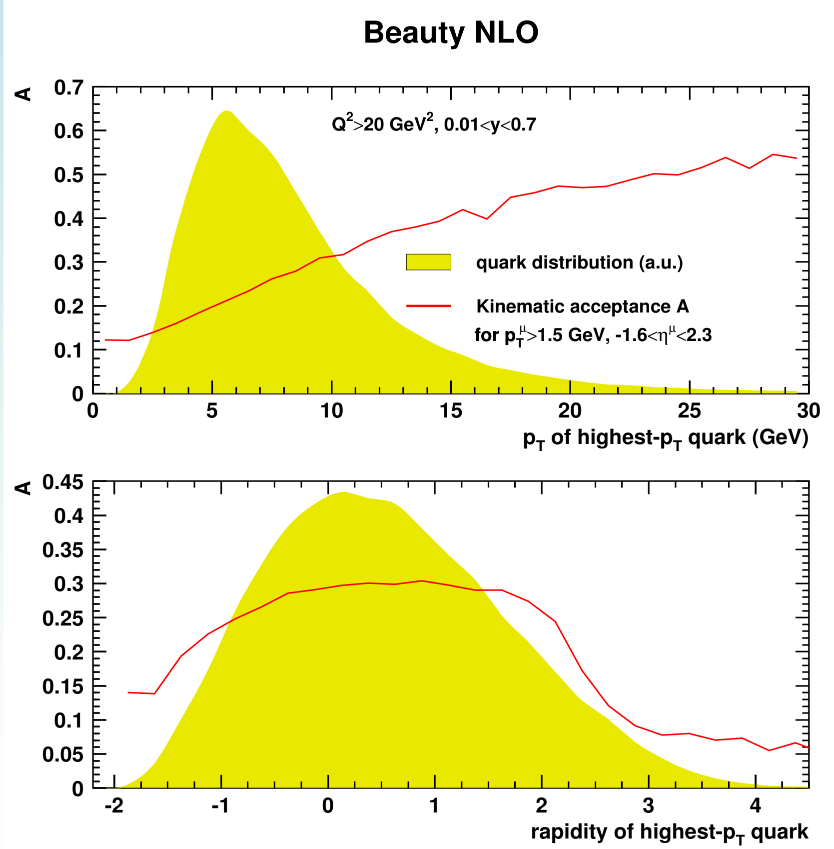
Extraction of F_2^{bb}

$$\frac{d^2\sigma^{q\bar{q}}}{dx\,dQ^2} = \mathcal{K}\left[F_2^{q\bar{q}}(x,Q^2) - \frac{y^2}{Y_+}F_L^{q\bar{q}}(x,Q^2)\right] = \mathcal{K}\,\tilde{\sigma}^{q\bar{q}}(x,Q^2,s)$$

$$\mathcal{K} = Y_+(2\pi\alpha_{em}^2)/(xQ^4) \qquad Y_+ = 1+(1-y)^2$$

$$F_2^{q\bar{q}}(x,Q^2) = \sigma^q \frac{F_2^{q\bar{q},\mathrm{th}}(x,Q^2)}{\sigma^{q,\mathrm{th}}},$$

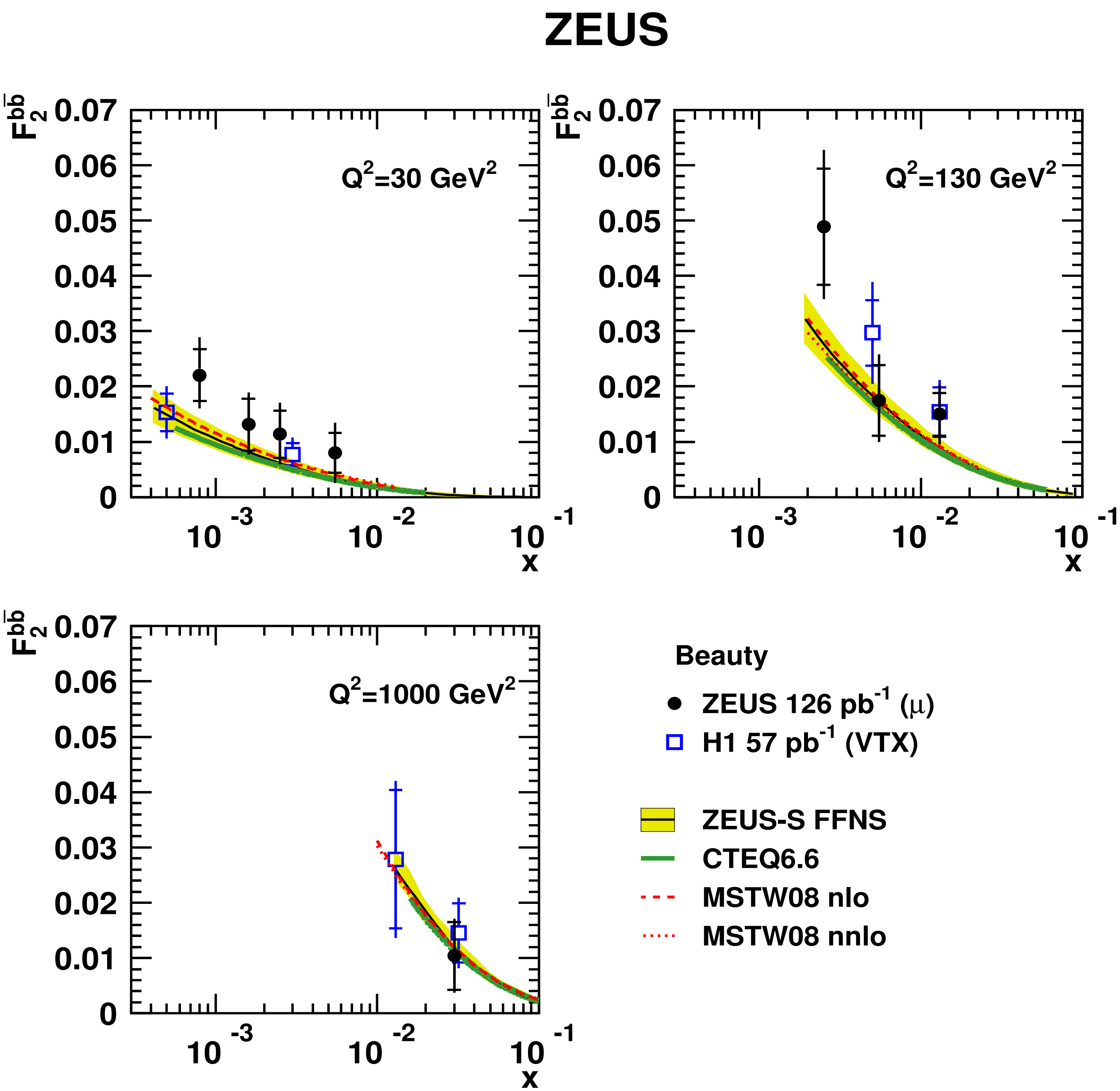
Calculated at NLO in FFNS using HVQDIS



- Extrapolation factor to the full muon phase space.
- Branching ratio q→ **μ.**
- Bin centering.
- Correction for the F_L^{qq} **(1- 4%).**
- QED radiation correction.

$$\langle A\rangle = \left\langle \frac{\#\text{ muons }(p_T>1.5,\ -1.6<\eta<2.3)}{\#\text{muons}}\right\rangle \approx 27\%$$

F_2^{bb} (x):

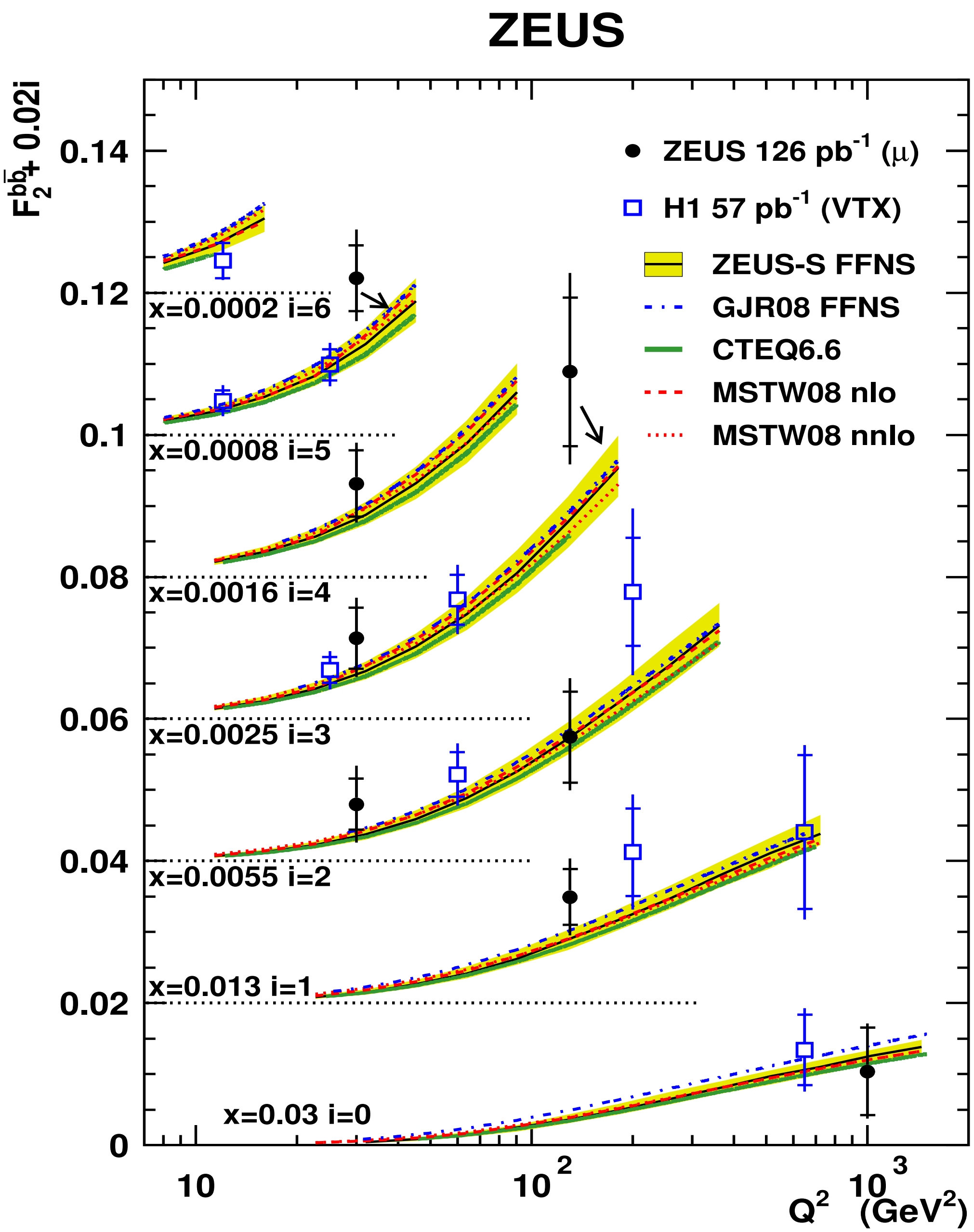


published data

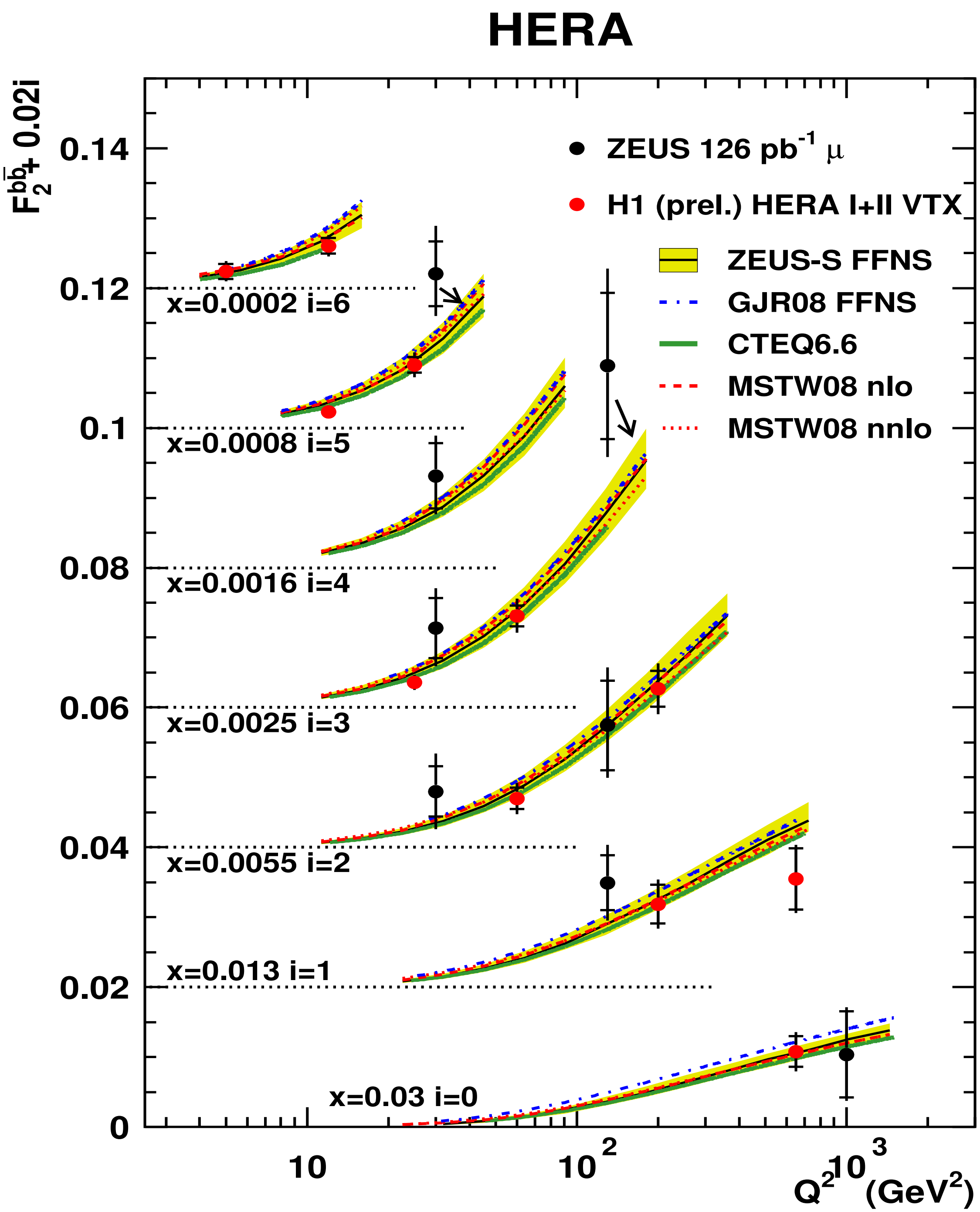
vs

different theories

F_2^{bb} at HERA



- F_2^{bb} determined at ZEUS with part of HERA II data (1/3 lumi) for the first time.
- The published measurements cannot distinguish between different gluon parameterizations.
- ZEUS and H1 measurements are in good agreement.
- Theoretical uncertainty smaller for beauty than for charm.



F_2^{bb} (new prel.)

- F_2^{bb} determined at ZEUS with part of HERA II data (1/3 lumi) for the first time.

- Good agreement between theory and data.

- H1 preliminary points could distinguish between different theories?

Conclusions and outlook

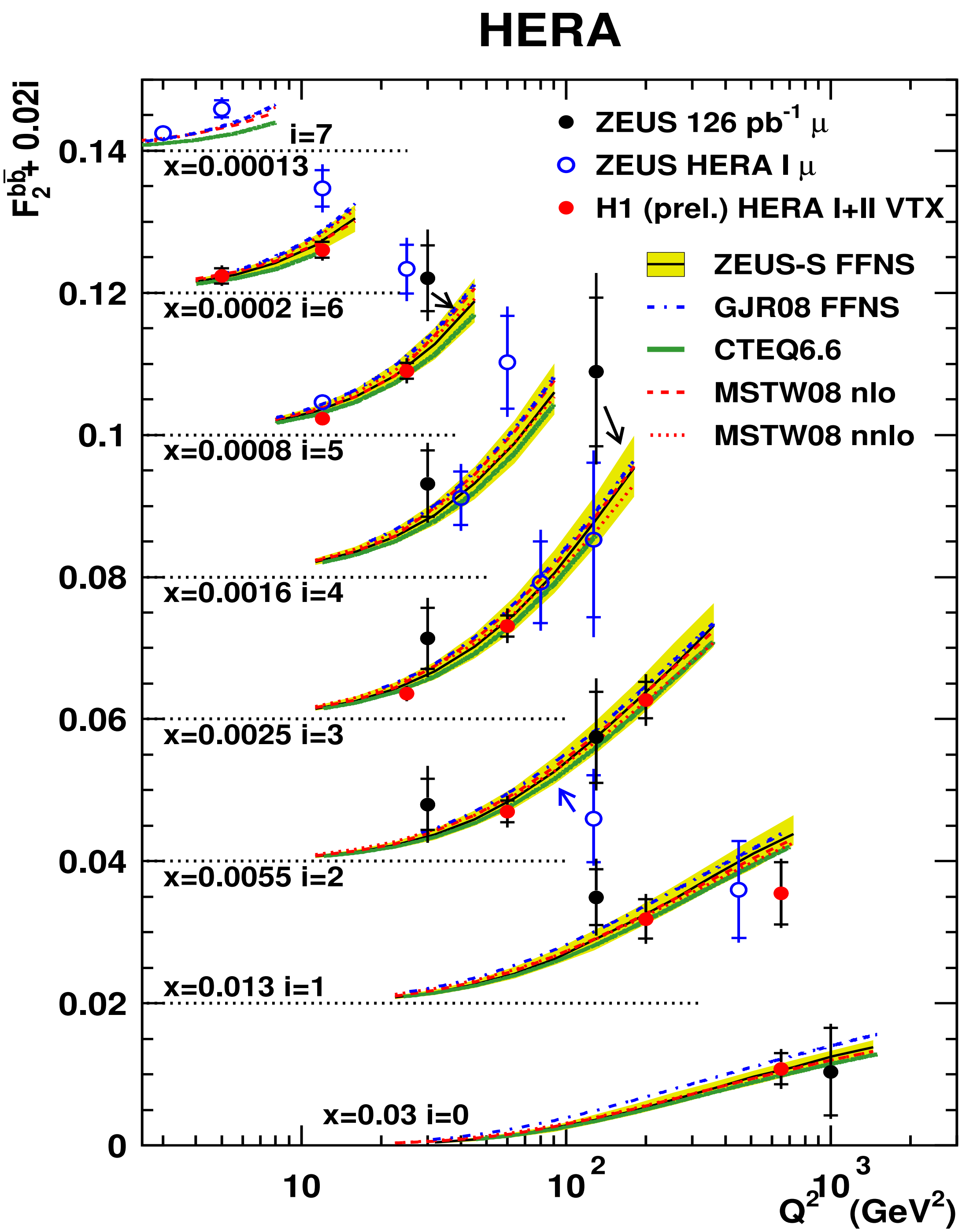
- The beauty contribution to the proton structure functions, F_2, has been measured at ZEUS for the first time with HERAII data using new techniques.

- The two collaborations, ZEUS and H1, using very different methods for the analysis, implying different extrapolations factors, agree on the results.

- The precision of the new measurement is good, specially for higher Q^2 region.

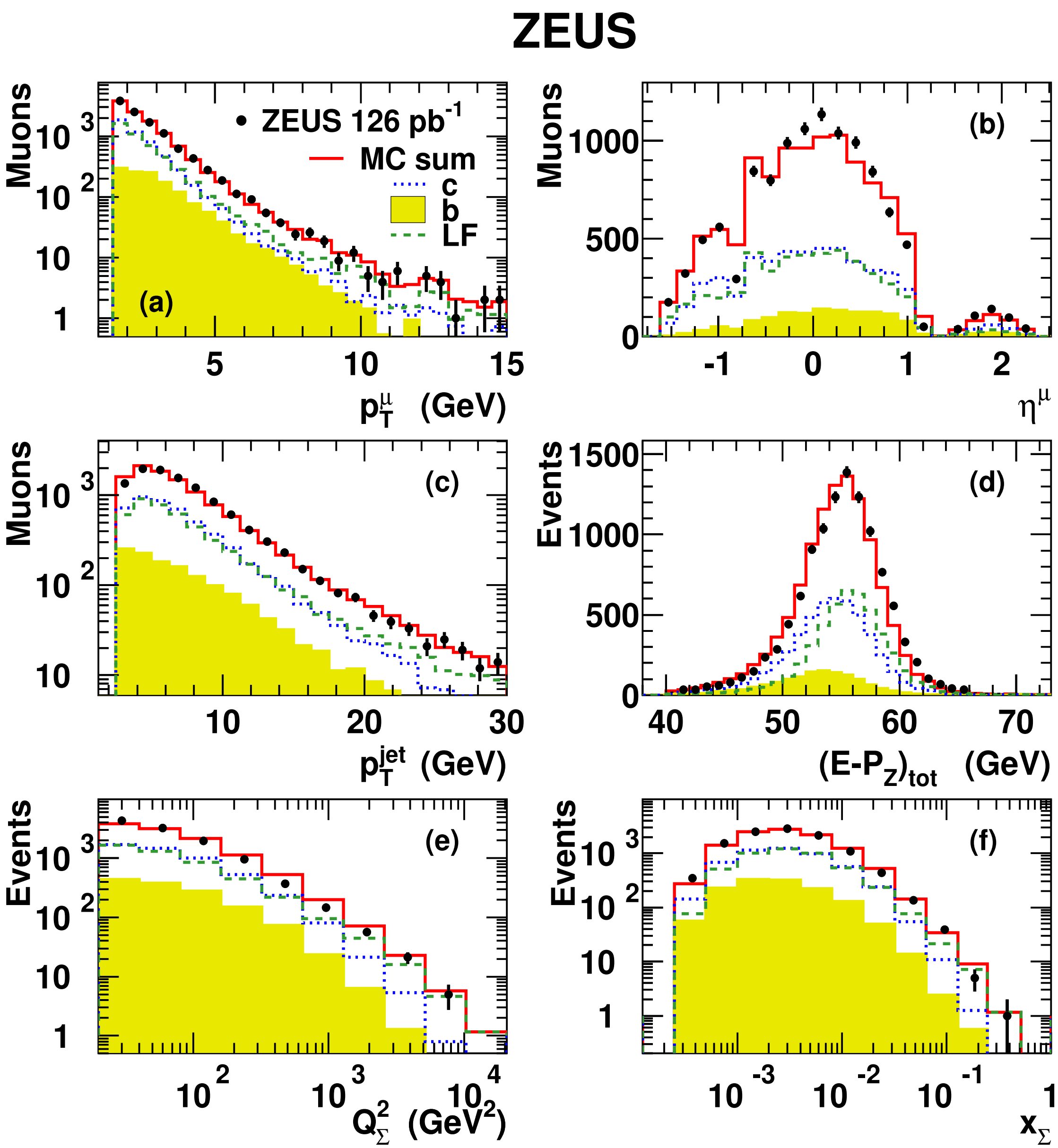
- The use of the whole HERA data sample could really help in constraining the gluon parameterization in the proton.

Backup



F_2^{bb} (publ.+prel.)

- F_2^{bb} determined at ZEUS with part of HERA II data (1/3 lumi).
- Good agreement between theory and data.
- Good precision for high Q^2 point.
- H1 preliminary points could distinguish between different theories?



Main variables control plots

A $_{c(b)}$ varies
from ≈ **23% (16%)**
to ≈ 35% (25%)
for p_T^{μ} < or > 2.5GeV

All systematic uncertainties/1

1. B/RMUON efficiency: it was varied by its uncertainty of on average ±5% $(\mp 5, \mp 5)\%$;
2. FMUON efficiency: it was varied by ±20% $(\mp 2, \mp 5)\%$;
3. "false muon" probability: it was varied within the corresponding uncertainty $(^{-3}_{+4}, \mp 1)\%$;
4. global energy scale: it was varied by ±2% $(^{-4}_{+5}, ^{-3}_{+2})\%$;
5. calibration of $p_T^{\mathrm{miss}||\mu}$: it was evaluated by varying the hadronic transverse momentum in the MC by ±0.1 GeV, as allowed by the transverse momentum balance in the control sample $(\pm 12, ^{-2}_{+1})\%$;
6. hadronic energy resolution: it was varied in the MC by ±5% as allowed by the transverse momentum balance in the control sample $(^{+1}_{+2}, \mp 7)\%$;
7. simulation of the tails of $p_T^{\mathrm{miss}||\mu}$: the fits were redone in the restricted range $|p_T^{\mathrm{miss}||\mu}| < 5\,\mathrm{GeV}$ $(0, -6)\%$;
8. resolution on δ: the smearing applied to the MC was varied by ±25% as allowed by the control sample $(^{-3}_{+2}, ^{+11}_{-9})\%$;
9. p_T^{rel} shape of LF and charm: it was evaluated by varying the p_T^{rel} correction by ±50% $(\mp 1.5, ^{+8}_{-5})\%$;

Charm

Beauty

All systematic uncertainties/2

10. hadronic energy flow near the muon: it was evaluated by varying the cut on $E^{\rm iso}$ by $^{+0.50}_{-0.25}$ GeV $(0,^{-1}_{0})$%;
11. jet fragmentation: the cut on $p_T^{\rm jet}$ was varied by ± 0.5 GeV $(\pm 2.5,^{-3.5}_{+2.5})$%;
12. charm SL decay spectrum: the reweighting to the CLEO model was varied by ± 50%, $(^{-4}_{+3},^{+3}_{-2})$%;
13. MC model dependence: RAPGAP was reweighted to reproduce the measured differential cross sections in Q^2 or in p_T^{μ} and the largest deviation from the nominal cross section was taken $(+6,+20)$%;
14. higher order effects: this uncertainty was evaluated by varying the HQ distribution before parton showering in RAPGAP by the difference between NLO and leading order, as evaluated with HVQDIS $(^{+6}_{-10},^{+2}_{-3})$%;
15. MVD efficiency: the efficiency of the cut on the number of MVD hits was varied by its uncertainty $(\mp 3,\mp 3)$%;
16. CTD siumlation: tracks were required to pass ≥ 4 superlayers in the B/RMUON region and to have ≥ 7 hits in the FMUON region $(+1,0)$%;
17. integrated luminosity: measurement uncertainty $(\mp 2.6,\mp 2.6)$%.

Charm

Beauty

Total systematic uncertainty

C B

$(^{+18}_{-19},^{+28}_{-17})$%

Theoretical models used

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)

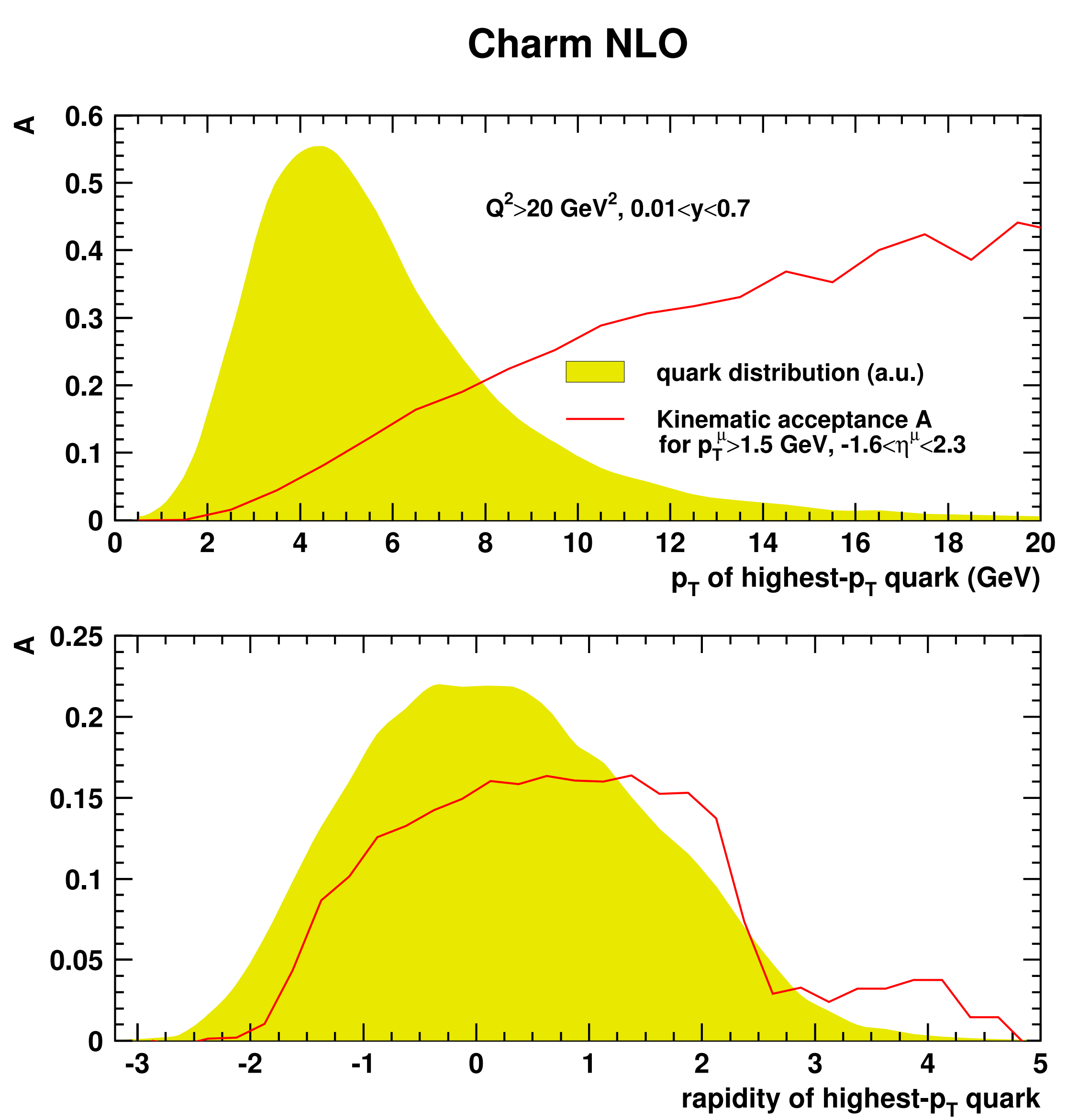
- grid from authors
- NLO: $O(\alpha_s)$
- $\mu_r = Q$, $\mu_F = \sqrt{Q^2 + m^2}$ $(\sqrt{Q^2 + 4m^2 alsoavail.})$
- $m_c = 1.3$ GeV, $m_b = 4.5$ GeV

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



A becomes sizeable when $A\ >\ 0.25\ \langle A\rangle$

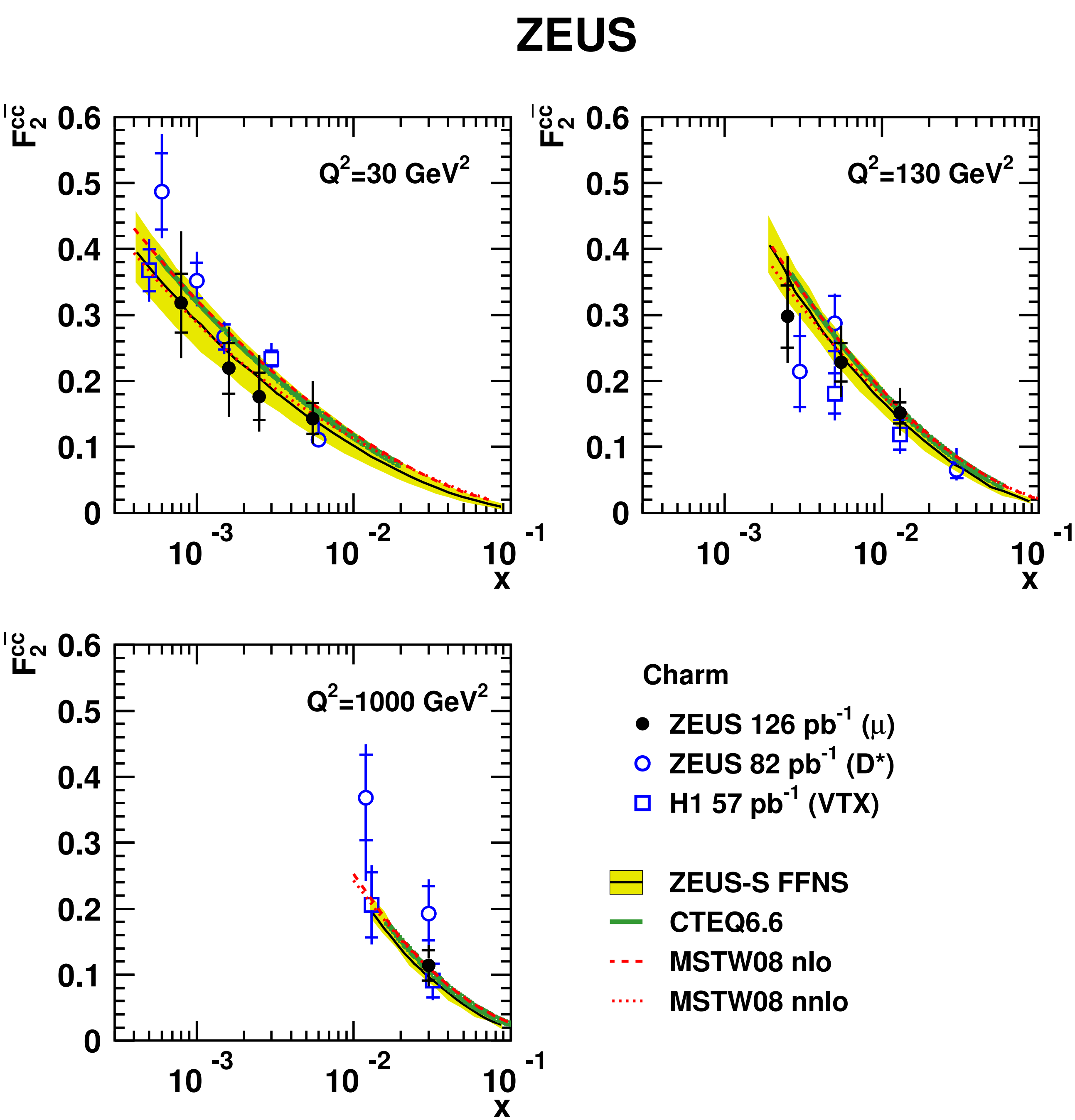
For charm:

$\langle A\rangle \sim 13\%$

⇩

One of the quarks with $p_T > 3$ GeV and $-1.5 < \eta < 2.5$

F_2^{cc} (x):

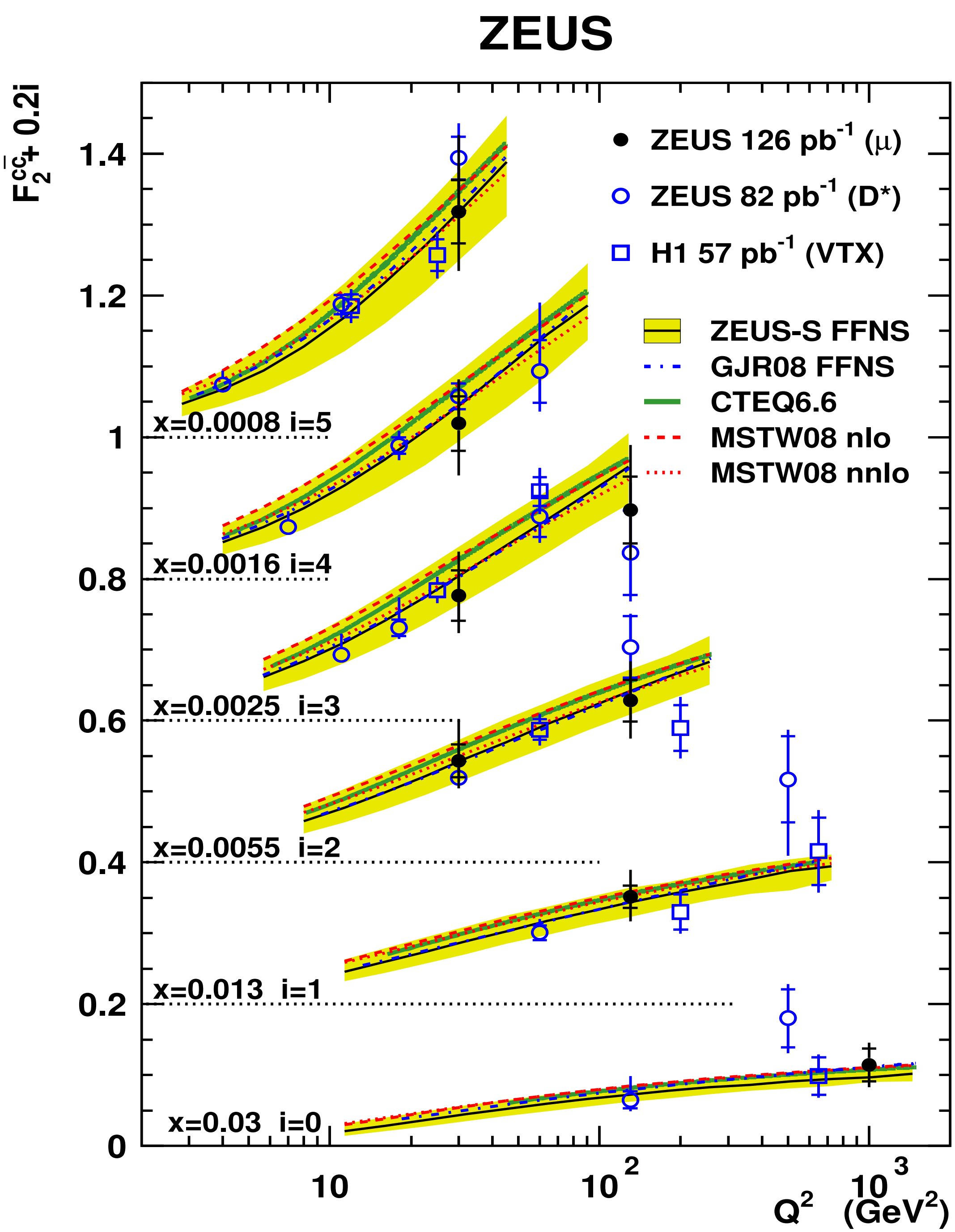


published data

vs

different theories

F_2^{cc} (publ.+prel.)



Adding NNPDF