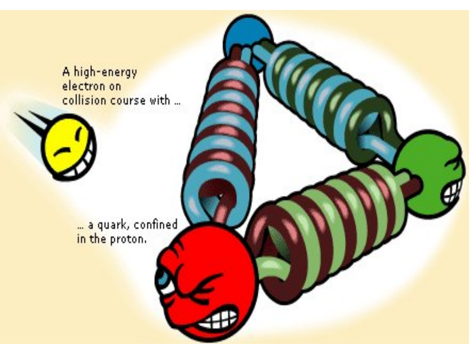
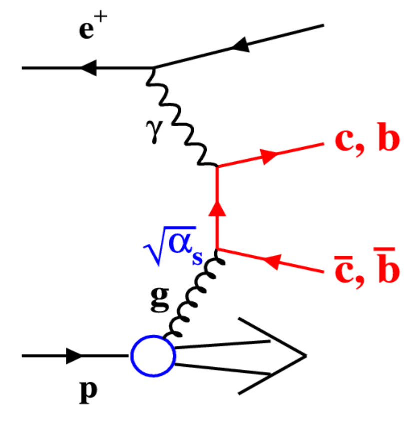
Measurement of beauty and charm production in deep inelastic scattering at HERA and measurement of the beauty-quark mass

To be submitted to JHEP
(results are final)



Outline

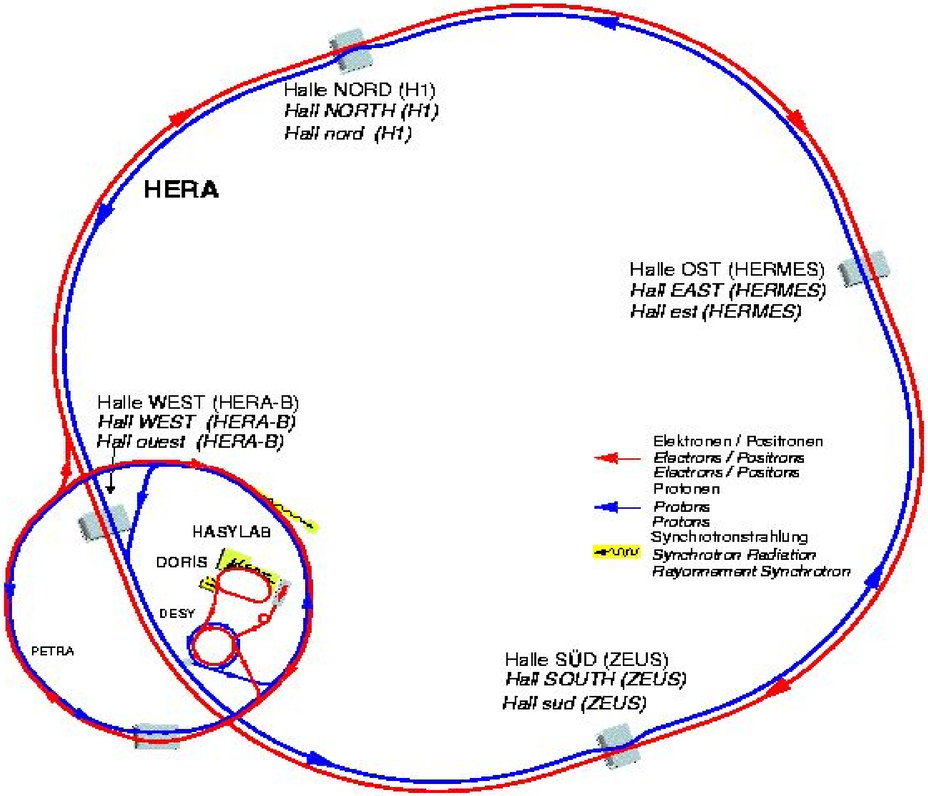
- Heavy flavour physics at HERA
- Experimental procedure
- Results



Vladyslav Libov (DESY)
on behalf of the ***ZEUS collaboration***

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects
Warsaw, 28 April - 2 May 2014

ZEUS experiment at HERA

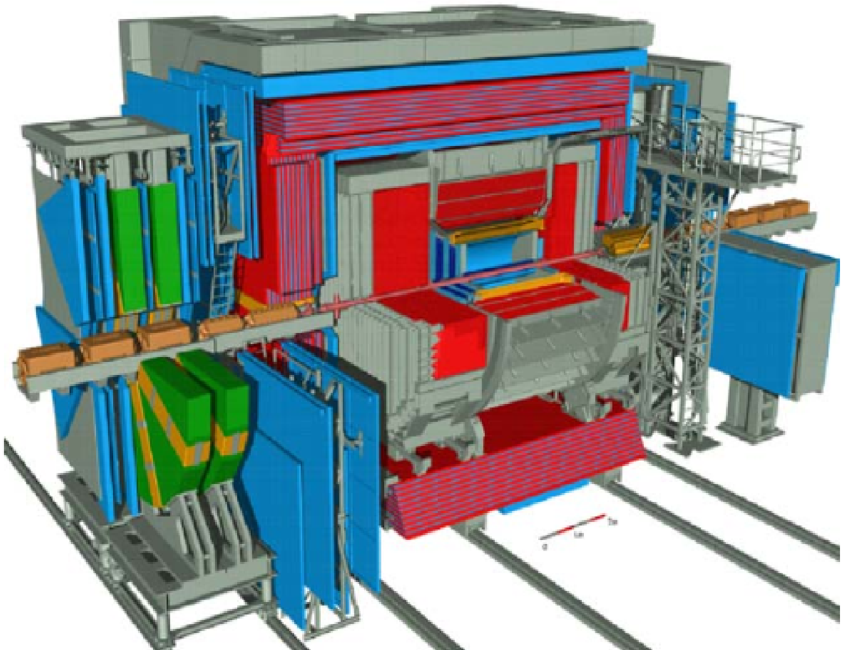


- Protons 920 GeV
- Electrons 27.6 GeV

$$\sqrt{s} = 318 \text{ GeV}$$

- Operational: 1992-2000 (HERA I)

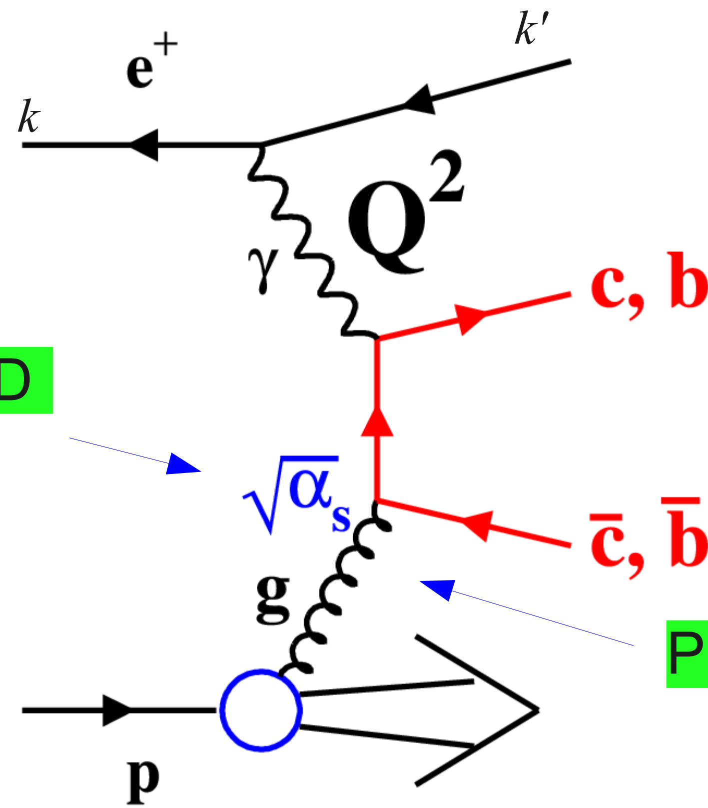
  2003-2007 (HERA II)
- **ZEUS** – general purpose hermetic detector
- Accumulated 0.5 fb^{-1} of data
- This measurement: HERA II (354 pb^{-1})



Heavy flavour physics at HERA

- Beauty and charm quarks are produced in the LO via Boson-Gluon Fusion:

Provides tests of QCD



Sensitive to the quark masses

Probes gluons in the proton

Kinematic variables:

$$Q^2 = -q^2 = -(k-k')^2$$ Photon virtuality

$$x = \frac{Q^2}{2\mathrm{p}\cdot q}$$ Bjorken variable

$$y = \frac{p\cdot q}{p\cdot k}$$ Inelasticity

- Charm contributes up to 30% to inclusive DIS at high Q^2

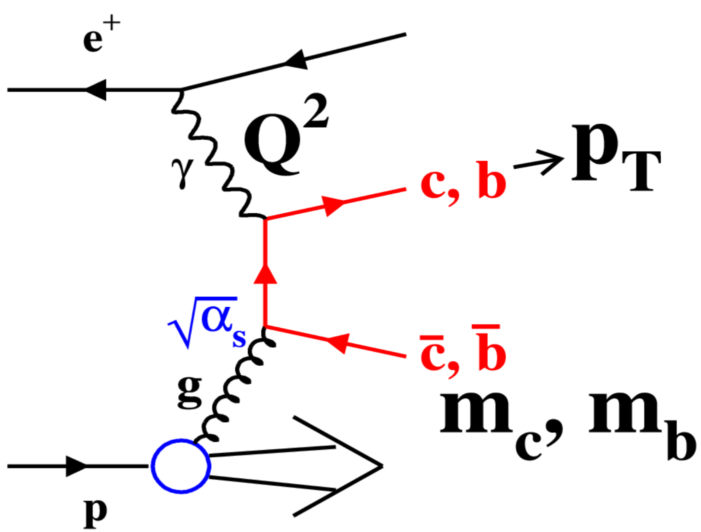
Impact on Parton Density Functions (PDF)!

Mass treatment in QCD

- Multi-hard-scale problem ($m_{b,c}$, p_T, Q^2) → several calculation schemes exist

Massive scheme (FFNS)

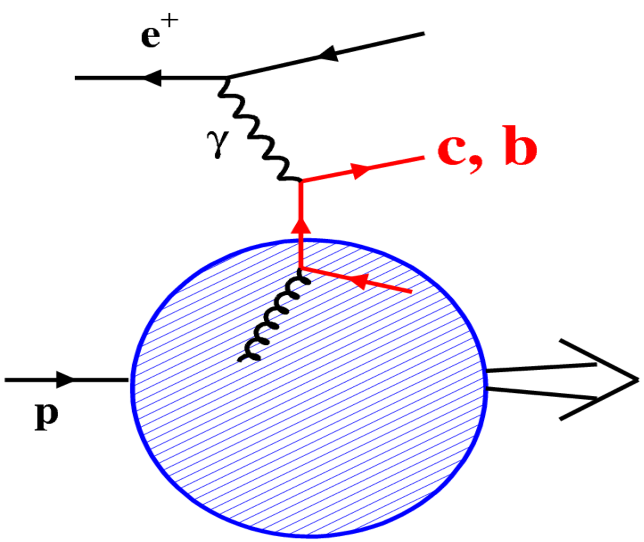
→ Rigorous, fully massive treatment



- Expected to be valid at scales ~ $m_{b,c}$
- Programs exist to calculate fully differential cross sections (HVQDIS, FMNR)

Massless scheme (ZM-VFNS)

→ Neglects heavy quark masses



- Allows resummation of terms proportional to $\log(Q^2/m_{b,c}{}^2)$
- Expected to be valid at scales >>$m_{b,c}$

Mixed schemes (GM-VFNS)

→ Employ both FFNS and ZM-VFNS
- Interpolation is ambiguous → various approaches (RT, ACOT etc.) exist

Heavy flavour measurements can help to test and improve the schemes

Secondary vertex method

Tag: jet + secondary vertex

- Employs long lifetime of ground state hadrons containing charm or beauty quarks
- No specific decay mode requirement → increase in statistics

- Select tracks belonging to a jet
  - p_T(track)>500 MeV
- Fit a secondary vertex
- Project decay length onto a jet axis
- Calculate decay length significance

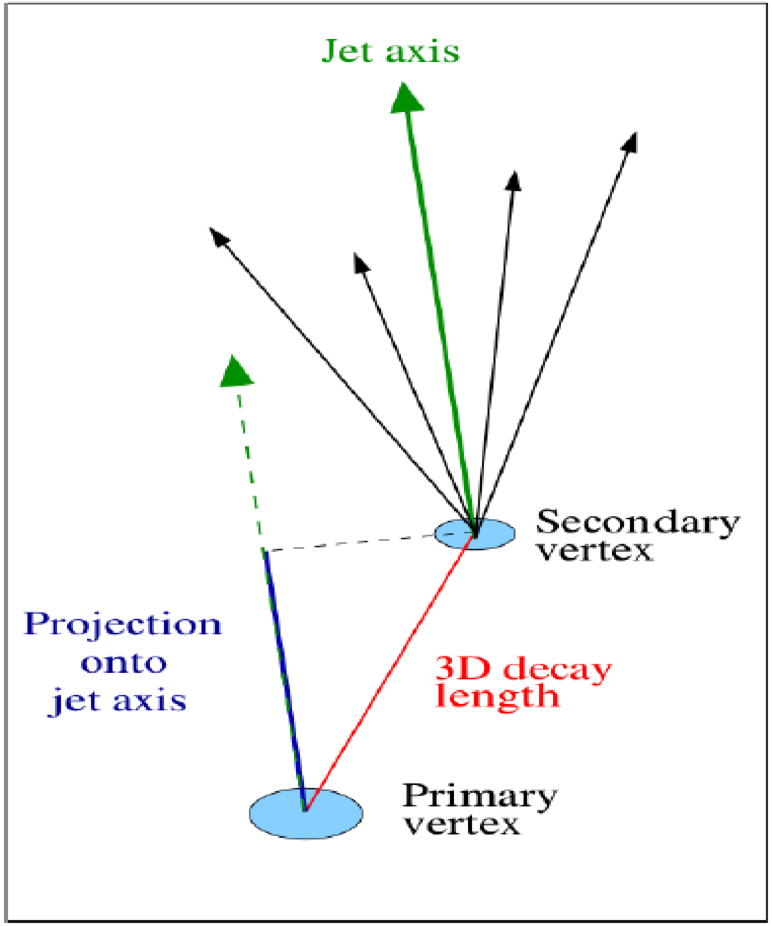
Phase space of the measurement:

$5 < Q^2 < 1000$ GeV^2

$0.02 < y < 0.7$

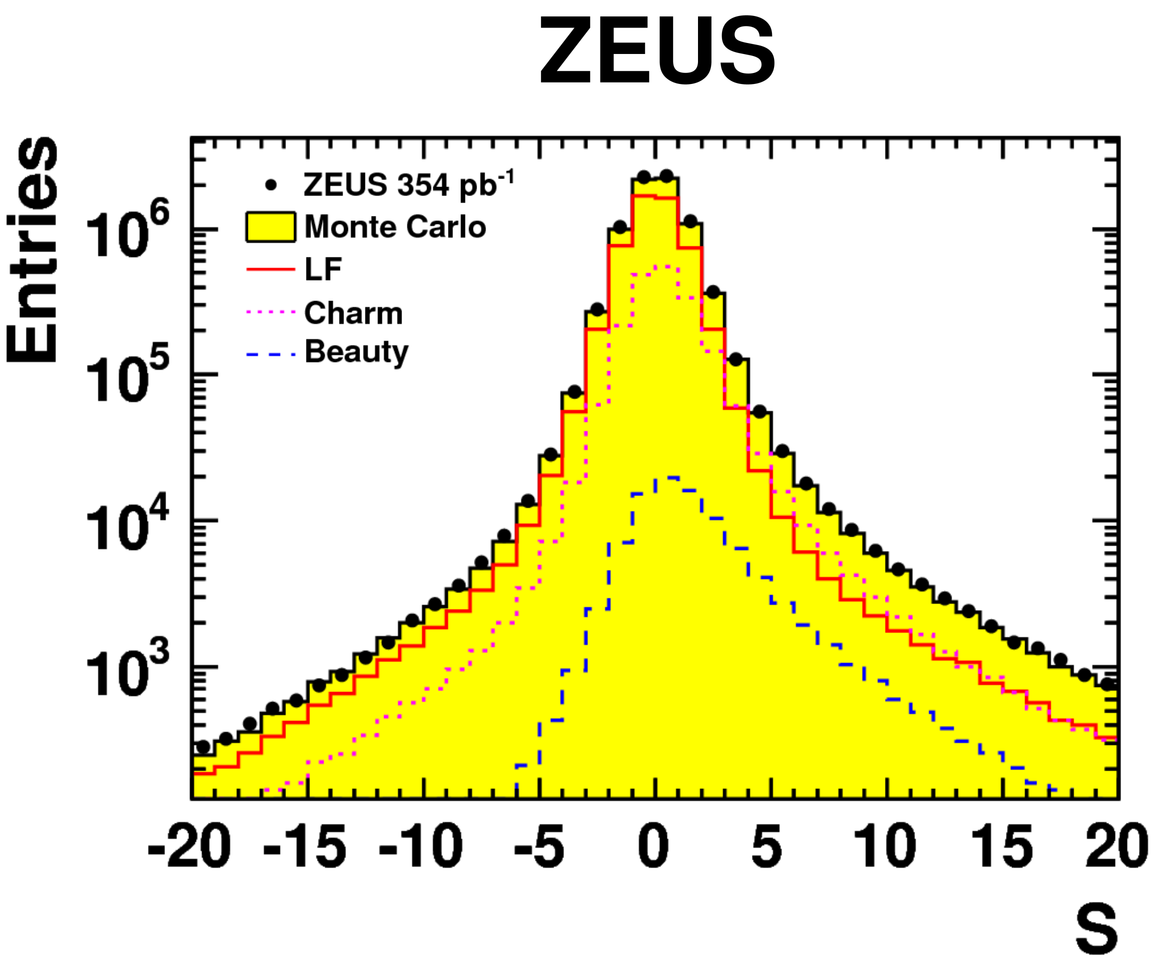
$E_T^{jet} > 5(4.2)$ GeV

$-1.6 < \eta^{jet} < 2.2$



Secondary vertex method (cont'd)

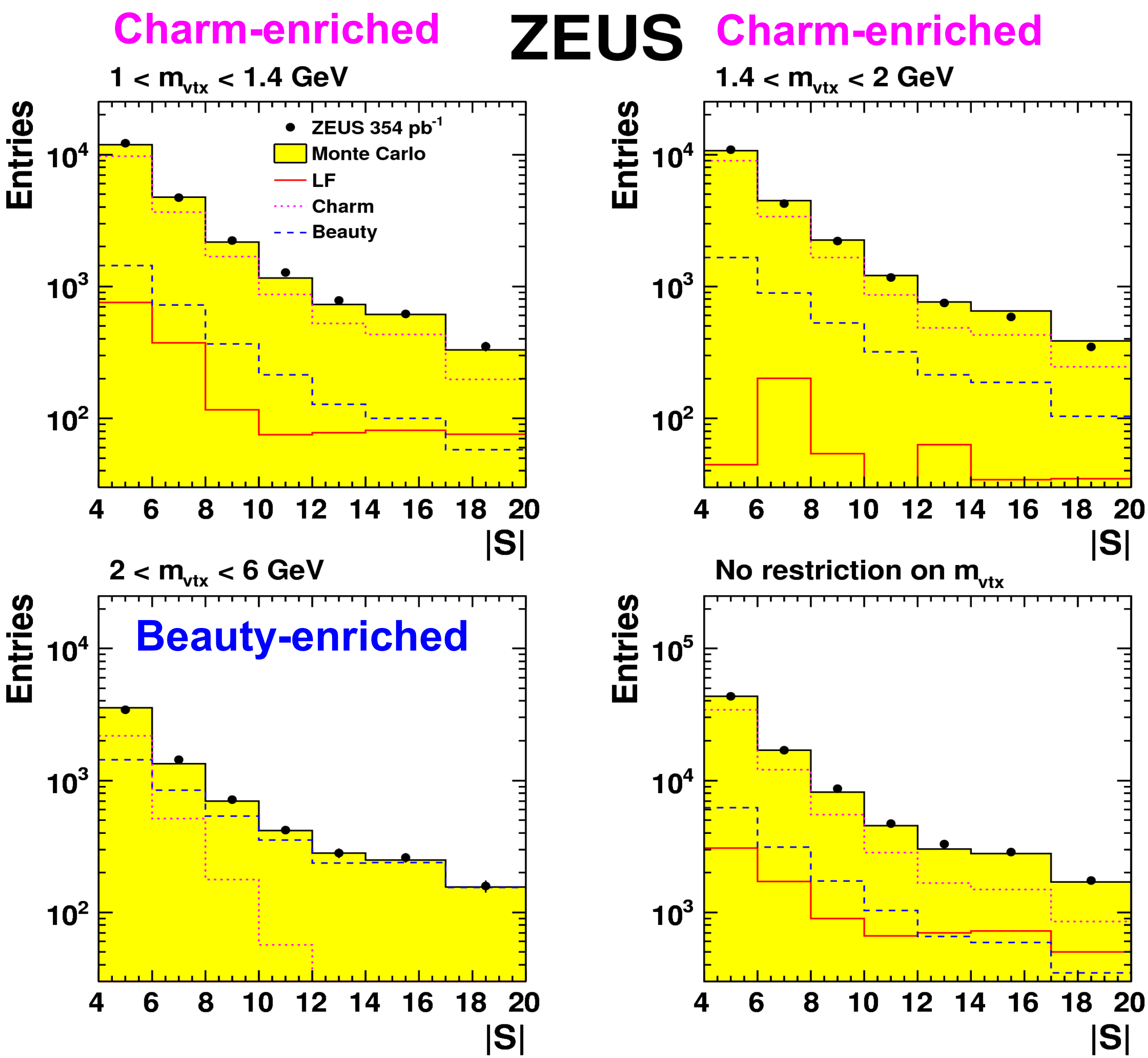
- Decay length significance:



- Charm & Beauty MC: RAPGAP
- Light Flavour (LF) MC: ARIADNE

- Charm and beauty asymmetric due to long lifetime
- Get rid of symmetric part by “mirroring”

Secondary vertex method (cont'd)



- Discriminating variables:
  - → mirrored significance
  - → mass

- Three bins are fitted simultaneously
- Total light flavour normalization is fixed by unmirrored significance

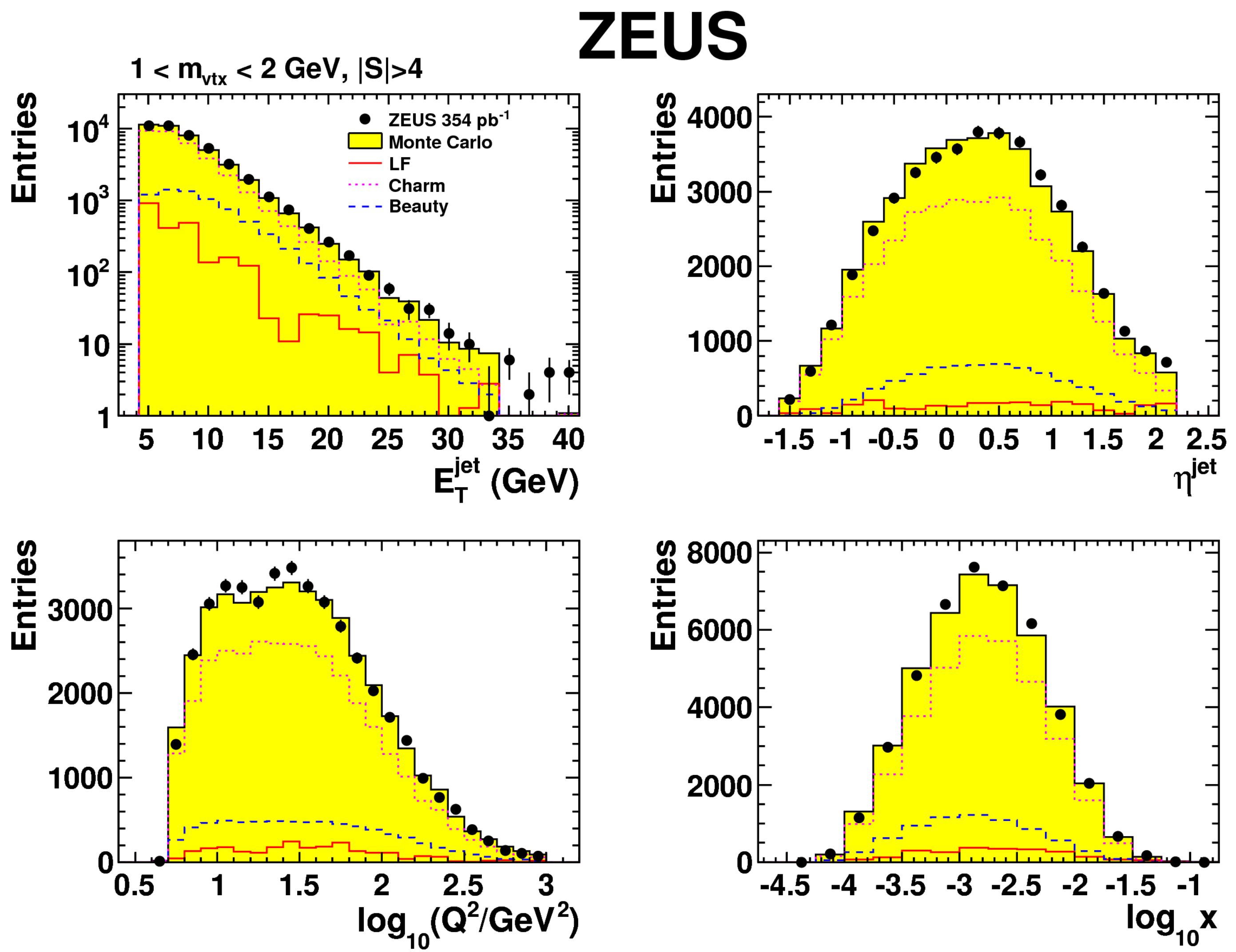
Control distributions (charm)

- **Charm** enrichment:

  S^+-S^->4

  1 < m_{vtx} < 2 GeV

- High purity charm sample!



- Good description of the data by the Monte Carlo

Control distributions (beauty)

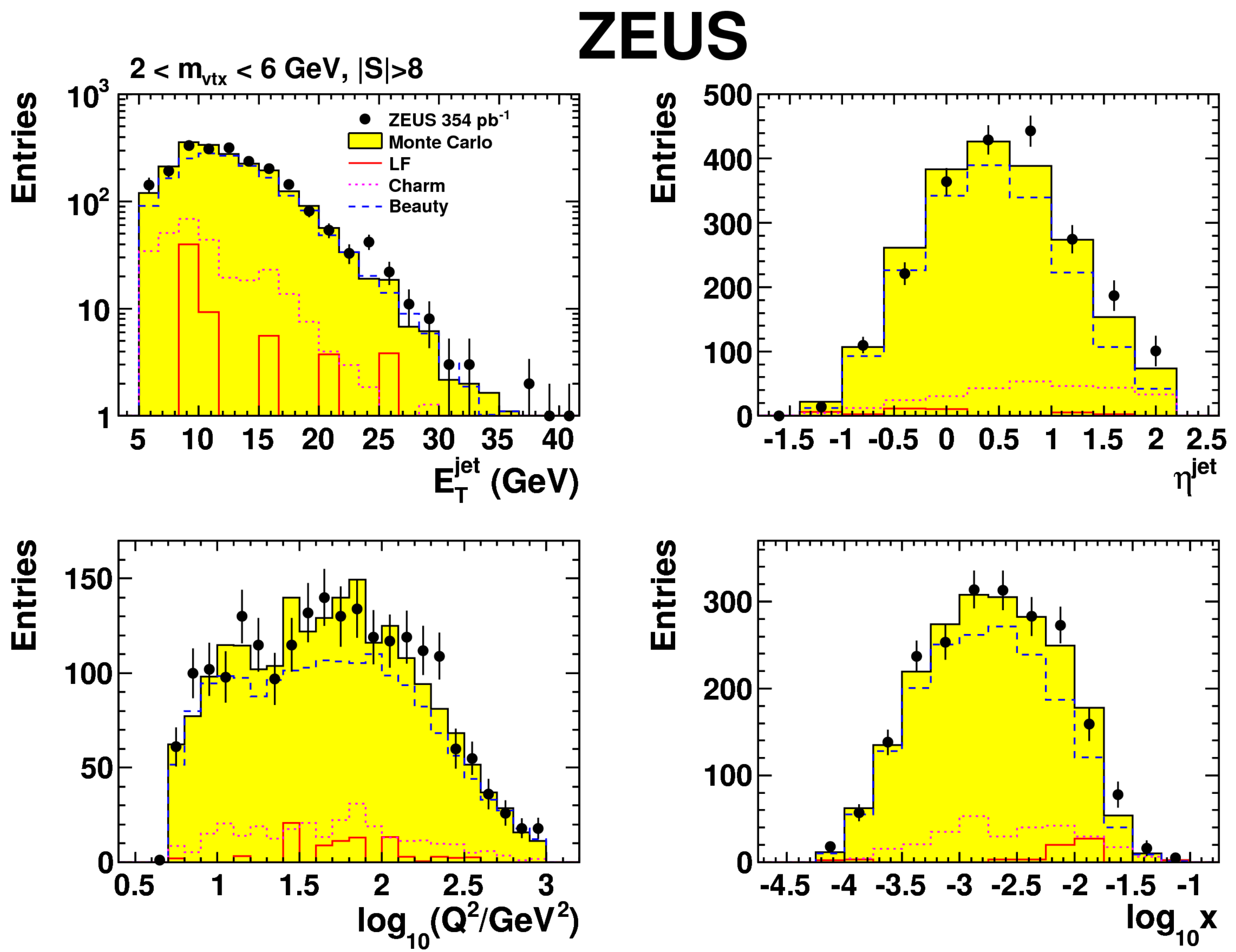
- **Beauty** enrichment:

  S^+-S^->8

  2 < m_{vtx} < 6 GeV

- High purity

  beauty sample!



- Good description of the data by the Monte Carlo

Systematic uncertainties

	Source	Beauty (%)	Charm (%)
δ_1	Event and DIS selection	± 1.4	± 0.8
δ_2	Trigger efficiency	$+2.0$	$+1.0$
δ_3	Tracking efficiency	± 2.0	± 0.5
δ_4	Decay-length smearing	± 1.3	± 1.2
δ_5	Signal extraction procedure	± 0.8	± 0.8
δ_6	Jet energy scale	± 0.7	± 0.9
δ_7	EM energy scale	± 0.3	± 0.1
δ_8	Charm Q^2 reweighting ($\delta_8^{Q^2,c}$)	± 1.7	± 1.8
	Beauty Q^2 reweighting ($\delta_8^{Q^2,b}$)	± 2.9	± 0.4
	Charm η^{jet} reweighting ($\delta_8^{\eta^{\mathrm{jet}},c}$)	$^{+0.3}_{-0.4}$	$^{+1.5}_{-1.0}$
	Beauty η^{jet} reweighting ($\delta_8^{\eta^{\mathrm{jet}},b}$)	$^{+0.7}_{-0.4}$	$^{+0.0}_{-0.1}$
	Charm E_T^{jet} reweighting ($\delta_8^{E_T^{\mathrm{jet}},c}$)	$^{+1.7}_{-1.3}$	$^{+2.2}_{-1.7}$
	Beauty E_T^{jet} reweighting ($\delta_8^{E_T^{\mathrm{jet}},b}$)	$\boxed{^{+5.4}_{-4.2}}$	$^{+0.5}_{-0.6}$
δ_9	Light-flavour asymmetry	± 0.4	± 2.0
δ_{10}	Charm fragmentation function	-0.9	$+1.0$
δ_{11}	Beauty fragmentation function	-3.1	$+0.0$
δ_{12}	BR and fragmentation fractions	$^{+1.8}_{-2.1}$	$\boxed{^{+3.5}_{-2.6}}$
δ_{13}	Luminosity measurement	± 1.9	± 1.9
	Total	$^{+8.0}_{-7.6}$	$^{+6.0}_{-5.1}$

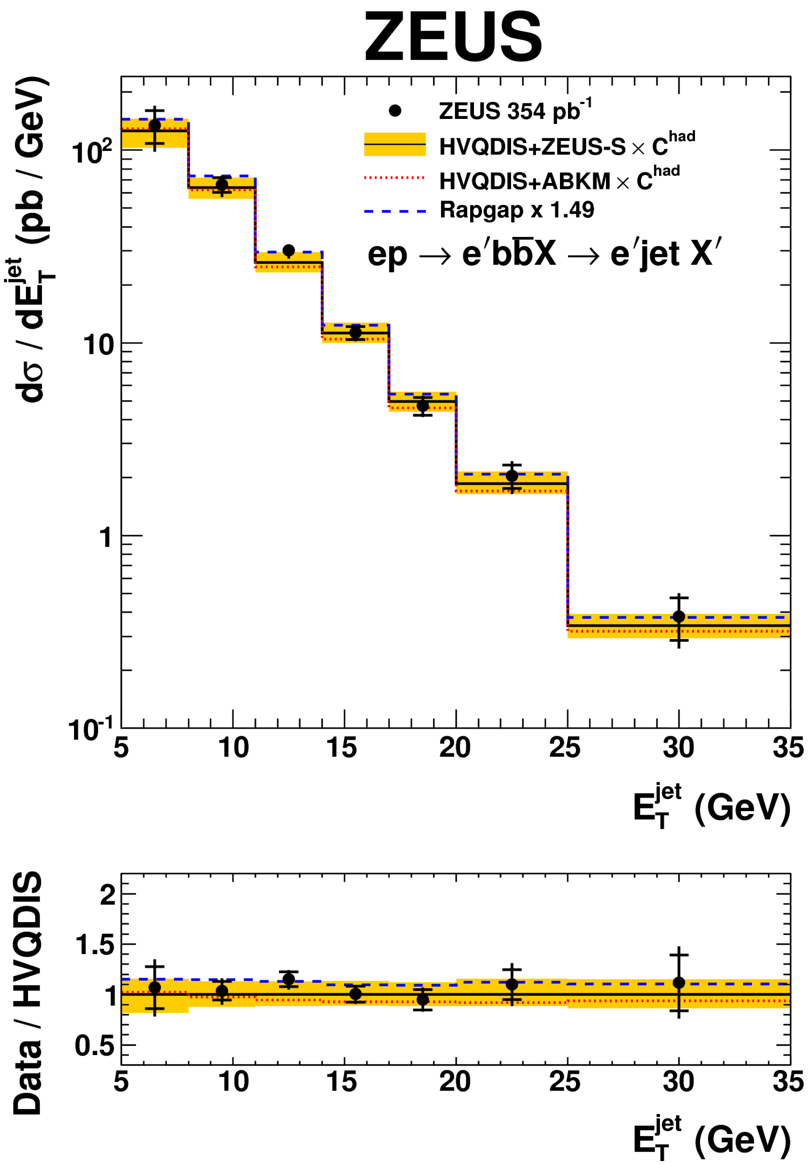
- Control of systemtatics at a few-percent level
- Among the dominant uncertainties:
  → charm: branching ratios and fragmentation fractions knowledge
  → beauty: MC model dependence

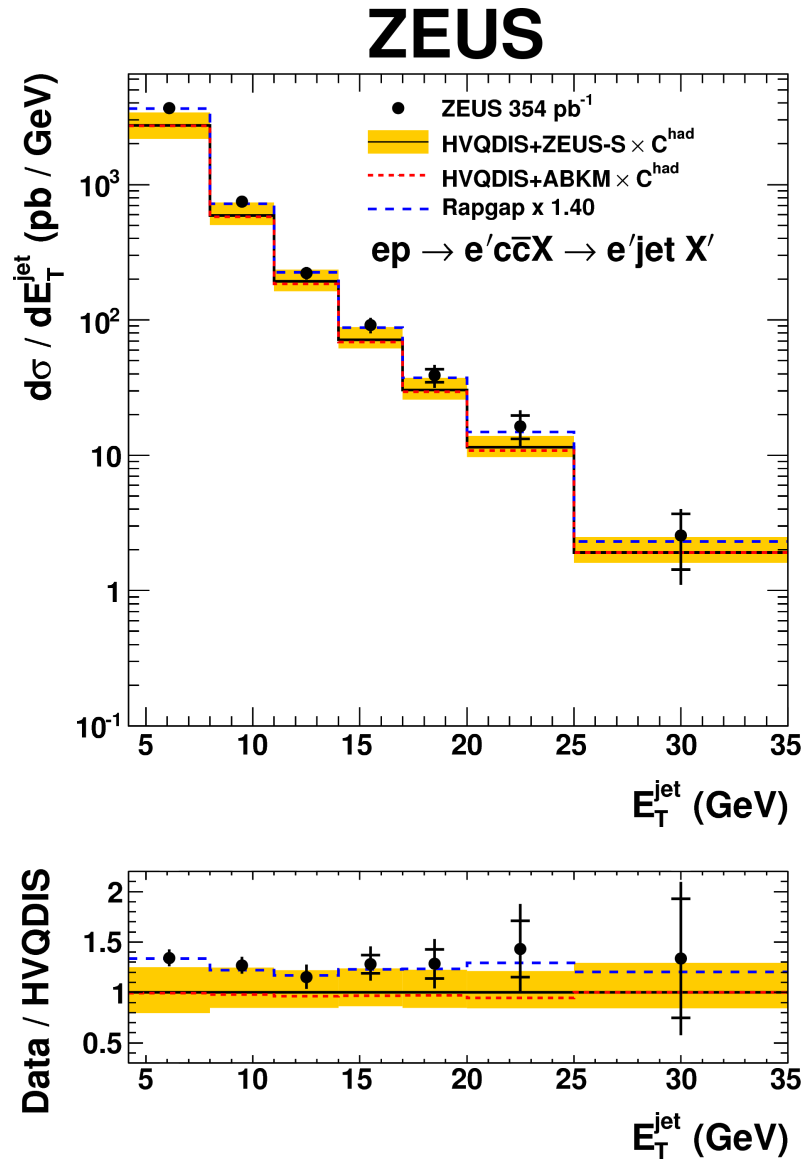
Theory predictions

- HVQDIS program, NLO QCD massive scheme
- ZEUS-S and ABKM NLO PDFs
- $\mu_R = \mu_F = \sqrt{Q^2 + 4m_q^2}$
- Quark pole masses: m_c=1.5 GeV, m_b=4.75 GeV (ABKM PDFs: 4.5 GeV)
- Hadronization corrections obtained with RAPGAP MC
- Uncertainties:
  - μ_R and μ_F varied independently by 0.5 and 2
  - Charm predictions: m_c varied from 1.3 GeV to 1.7 GeV
  - Beauty predictions: m_b varied from 4.5 to 5.0 GeV
  - PDFs varied within uncertainties

Differential cross sections

- Definition: jet cross section in beauty(charm) events
- Corrected to QED Born level using RAPGAP MC





$5 < Q^2 < 1000$ GeV^2

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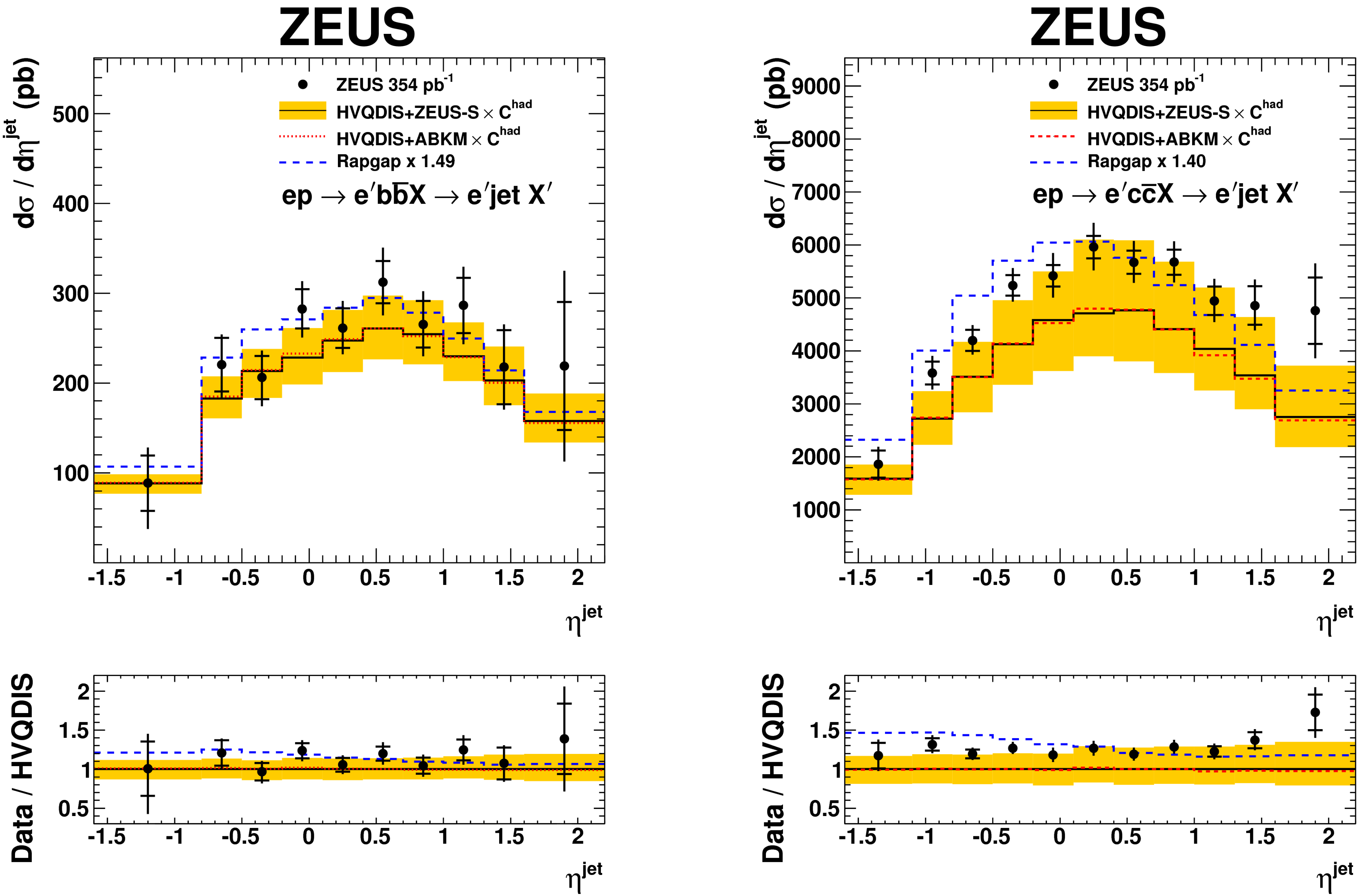
$E_T^{jet} > 5(4.2)$ GeV

$-1.6 < \eta^{jet} < 2.2$

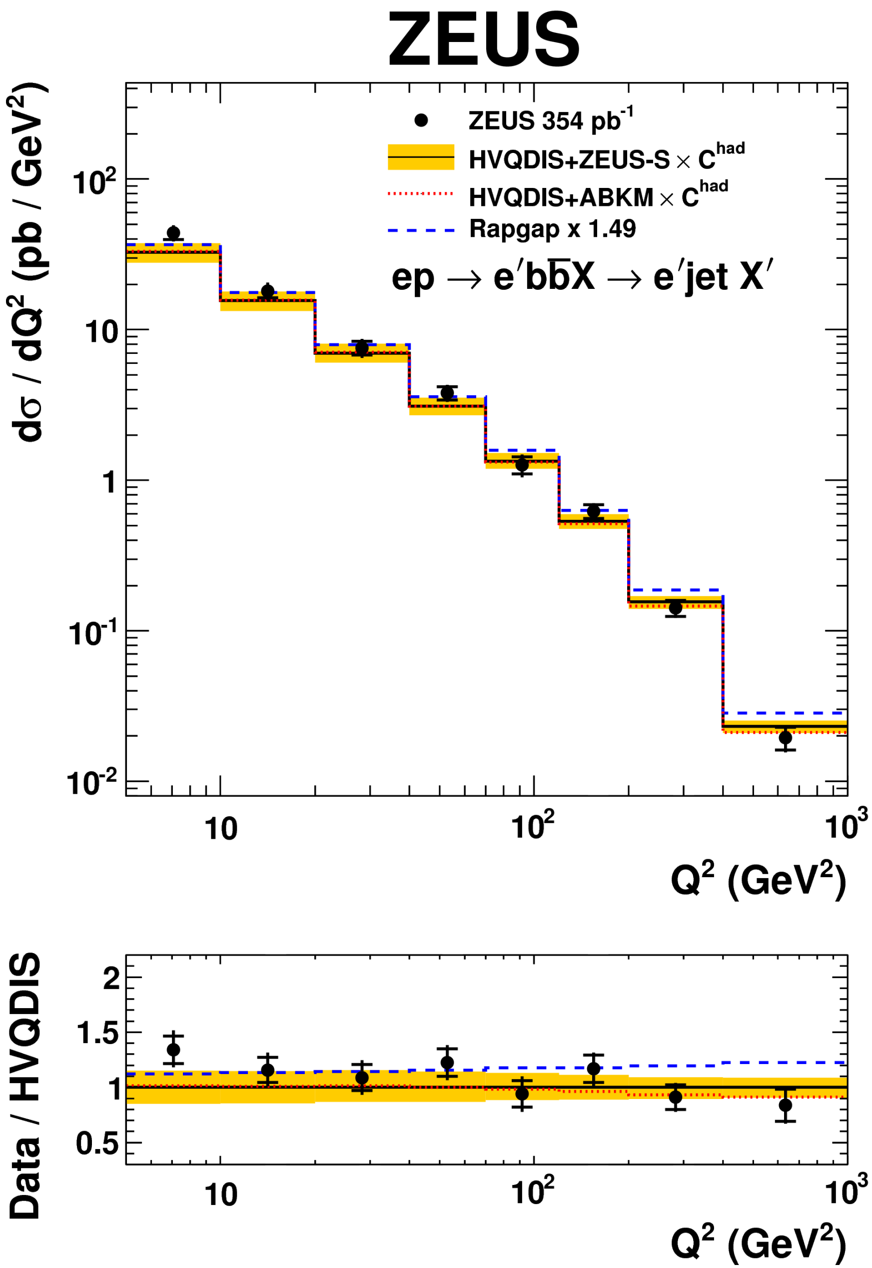
Reasonable description by FFNS NLO QCD

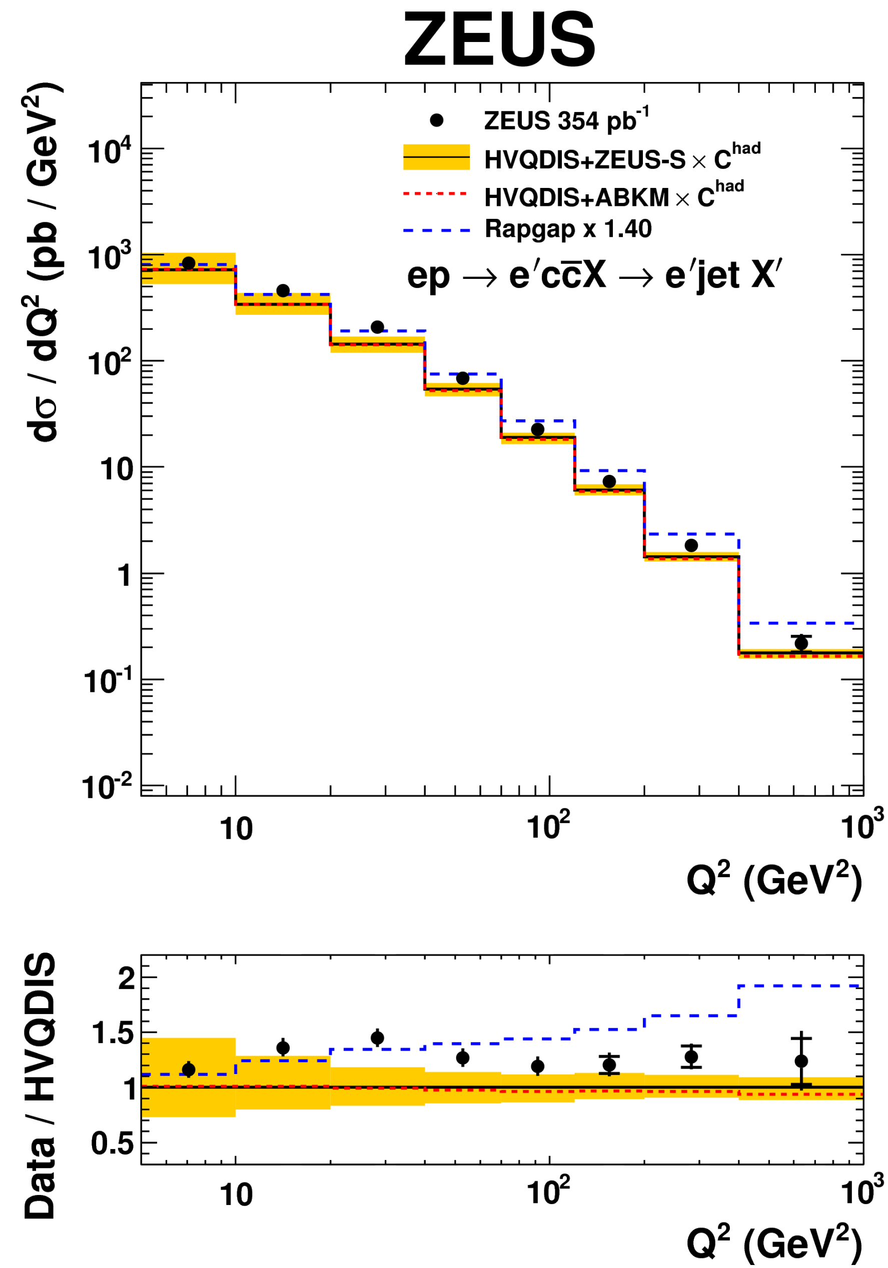
Differential cross sections



Reasonable description by FFNS NLO QCD

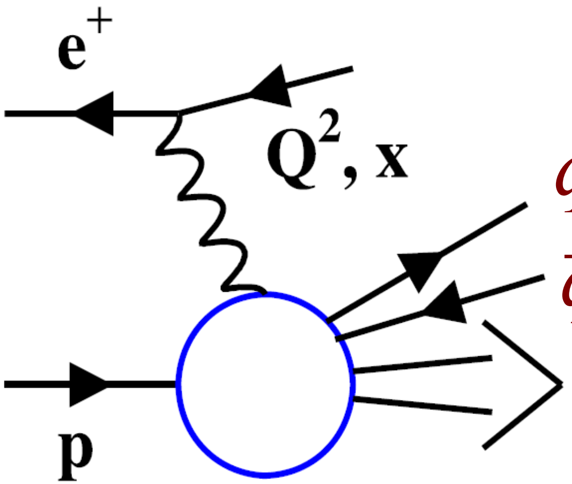
Differential cross sections





Reasonable description by FFNS NLO QCD

Inclusive production



$$q = c, b$$
$$\bar{q} = \bar{c}, \bar{b}$$

- Charm/beauty contribution to the proton structure function F_2:

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

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

- Reduced charm cross sections:

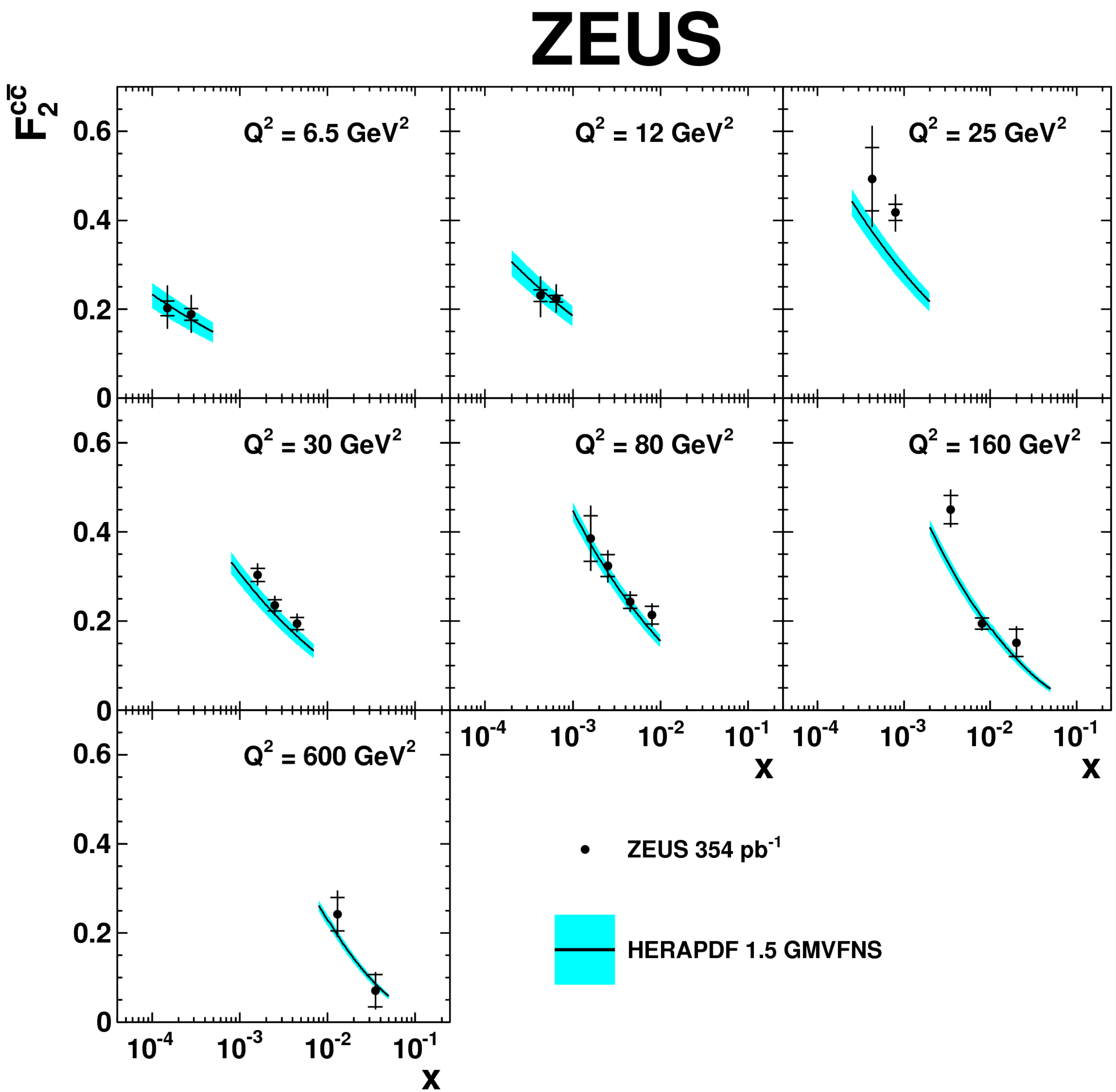
$$\sigma_r^{q\bar{q}} = \frac{xQ^4}{2\pi\alpha^2\left(1+(1-y)^2\right)}\frac{d^2\sigma^{ep\to q\bar{q}x}}{dQ^2\,dx} = F_2^{q\bar{q}}(x, Q^2) - \frac{y^2}{1+(1-y)^2}F_L^{q\bar{q}}$$

- NLO QCD* used to extrapolate from *visible* double-differential cross-sections to *full phase space*:

$$F_{2,meas}^{q\bar{q}}(x_i, Q_i^2) = \frac{\sigma_{meas,i}}{\sigma_{HVQDIS,i}} F_{2,HVQDIS}^{q\bar{q}}(x_i, Q_i^2)$$

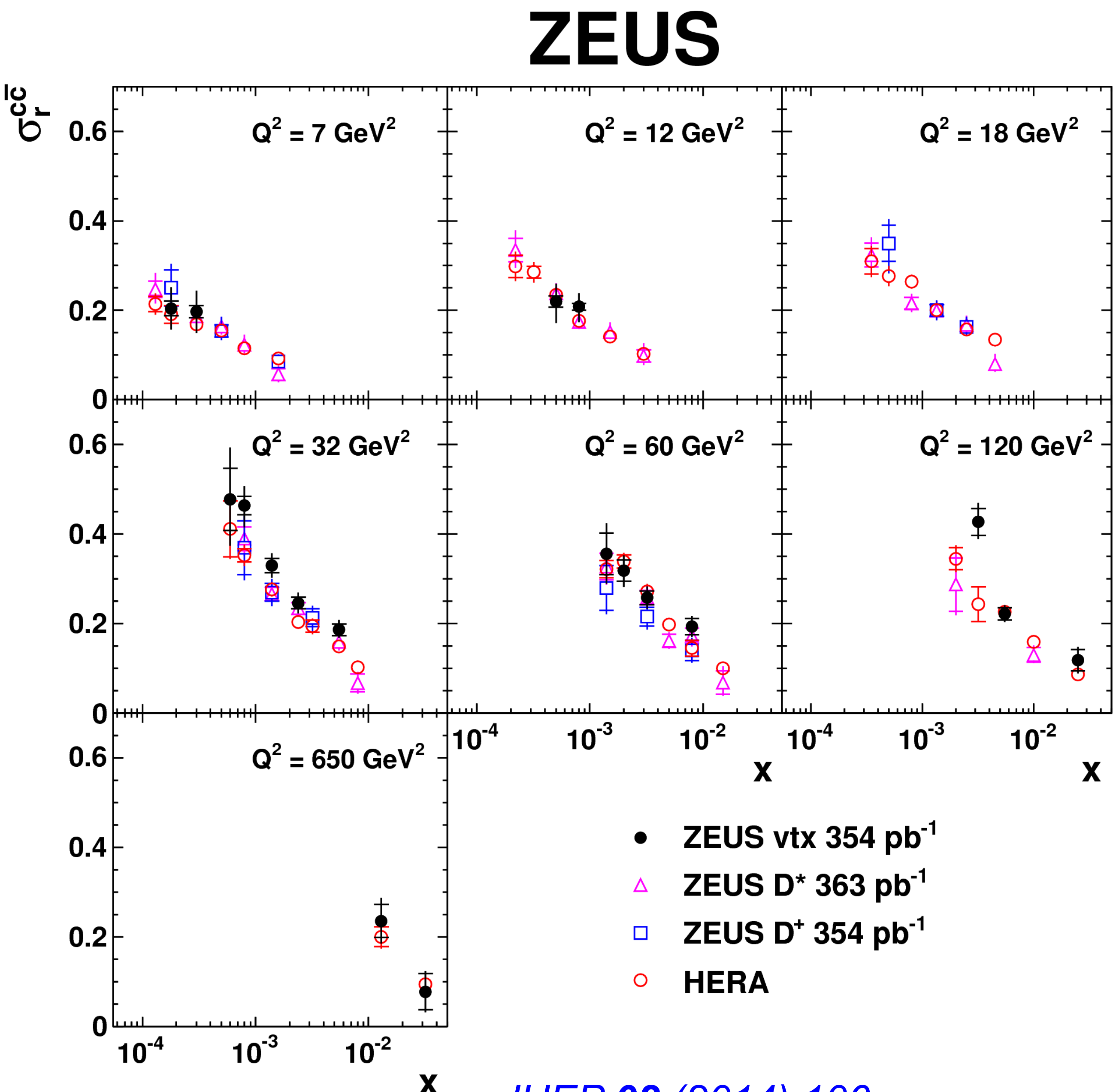
* PDF and parameter choices are consistent with *Eur. Phys. J.* ***C73*** *(2013) 2311*

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



- Good agreement with NLO QCD predictions
- Large extrapolation uncertainties at low Q^2 due to jet E_T cut

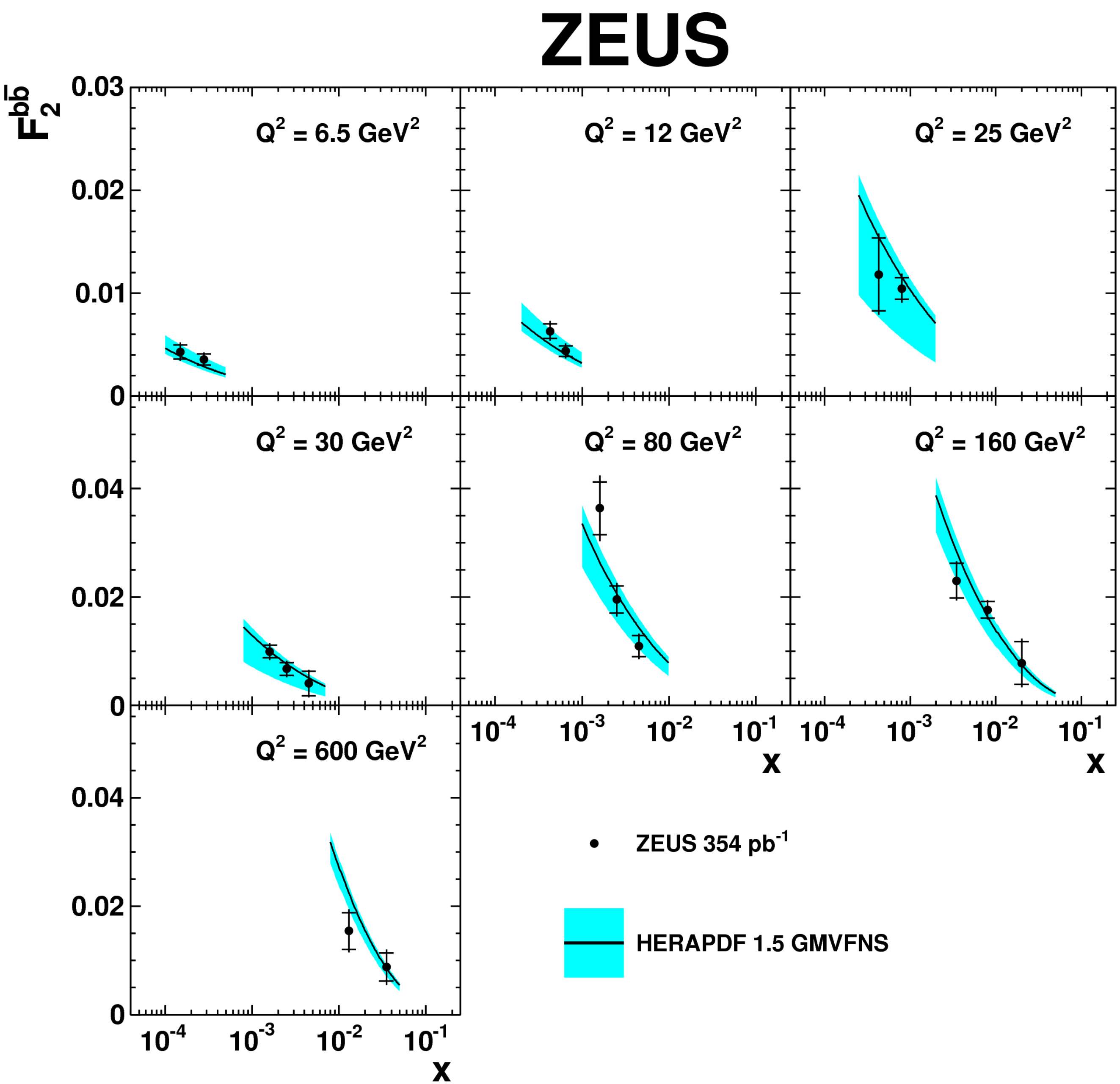
$\sigma_r^{c\bar{c}}$



- Swum in x,Q^2 using NLO QCD to match the previous measurements
- Consistent with HERA combined results, and with the new measurements not yet included in the combination
- Good precision – together with other new results will contribute to the next charm combination round

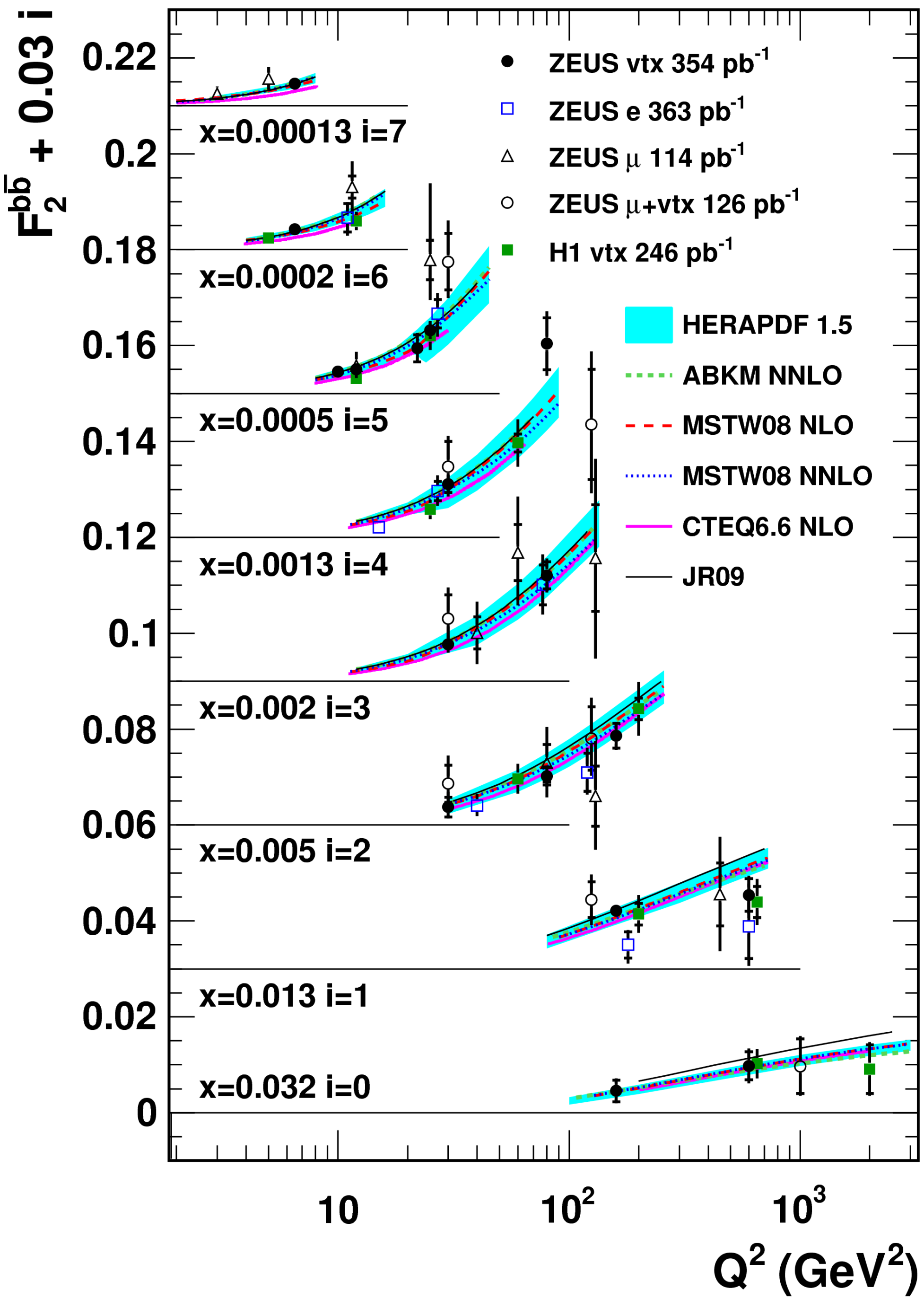
JHEP ***02*** *(2014) 106*
JHEP ***05*** *(2013) 023*
Eur. Phys. J. ***C73*** *(2013) 2311*

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



- Good agreement with NLO QCD predictions

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

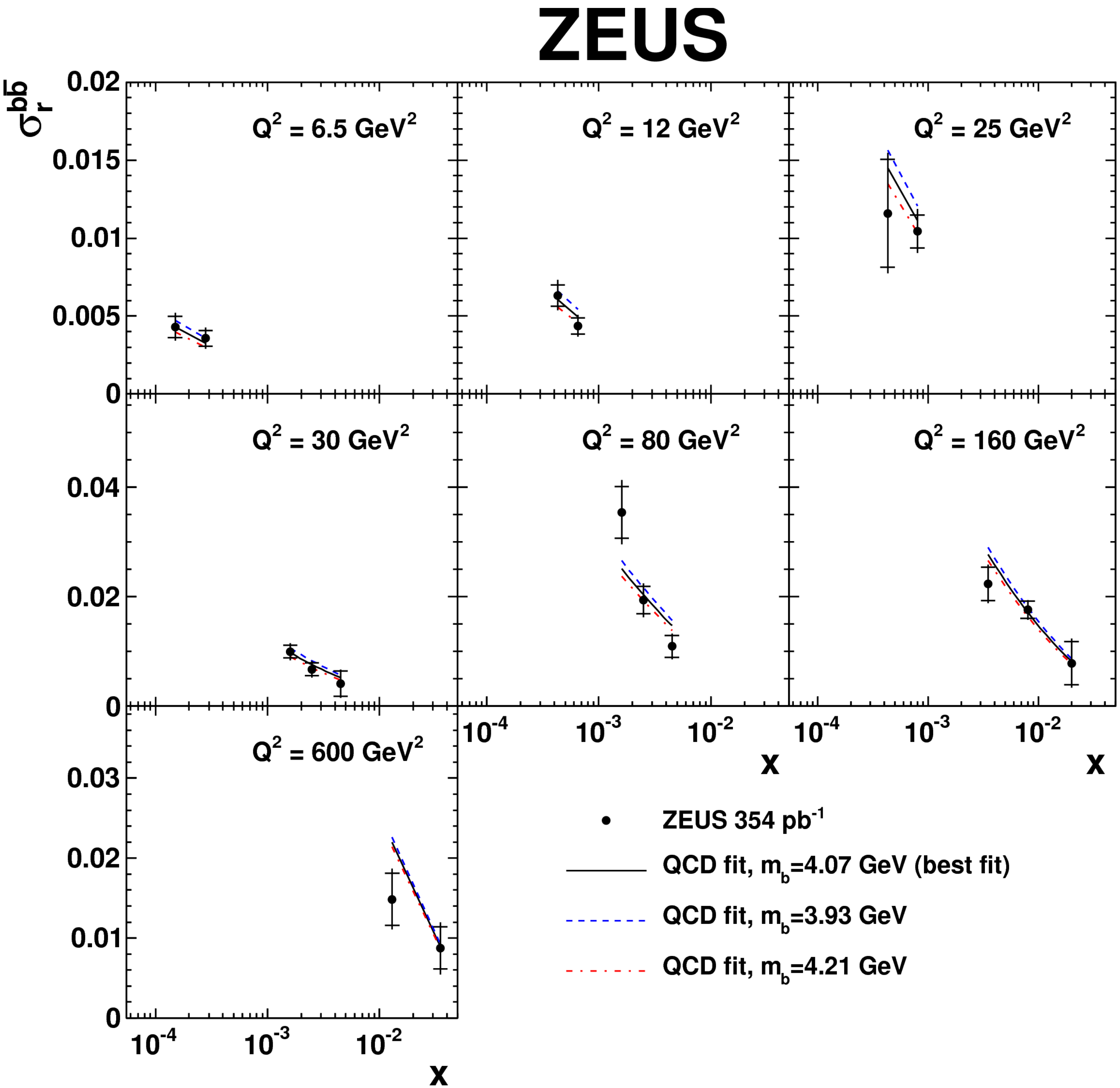


- Swum in x,Q^2 using NLO QCD to match previous results
- Consistent with existing measurements
- Agrees to QCD predictions in various schemes
- Most precise measurement in a wide range of Q^2

→ **Can we make use of it?**

Beauty quark mass measurement

- $\sigma_r^{b\bar{b}}$ are sensitive to the beauty quark mass (mostly from low Q^2)

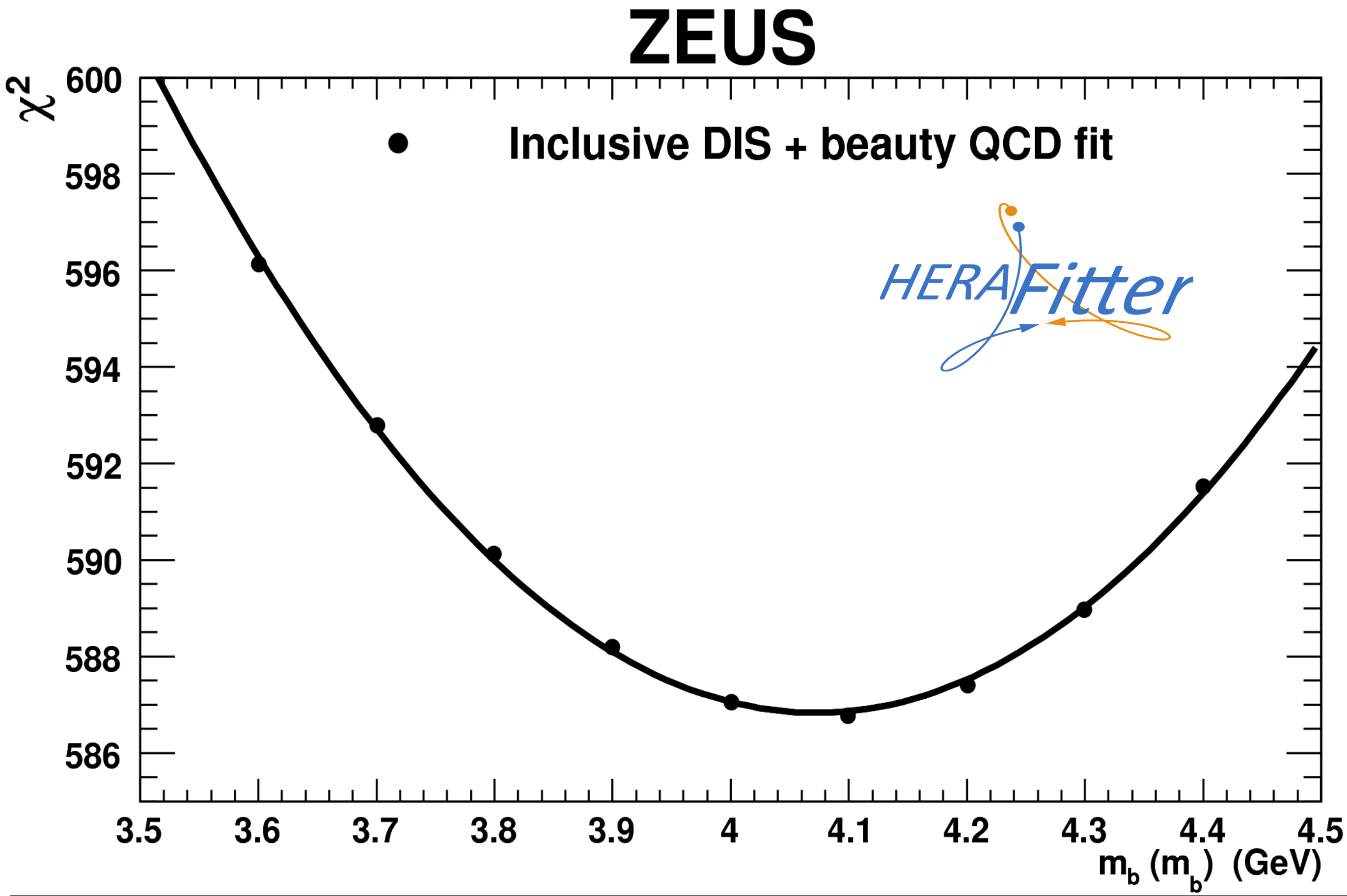


(next slide for more details on predictions)

→ Can be used for a measurement!

Beauty quark mass measurement

- A PDF fit of $\sigma_r^{b\bar{b}}$ (together with HERA I inclusive DIS) is performed using different values of the beauty quark running mass



- FFNS + $\overline{\mathrm{MS}}$ scheme as implemented in OPENQCDRAD
- Beauty data clearly provide sensitivity to m_b!

See talk by A. Gizhko (WG5) for more details on the technique

Result:

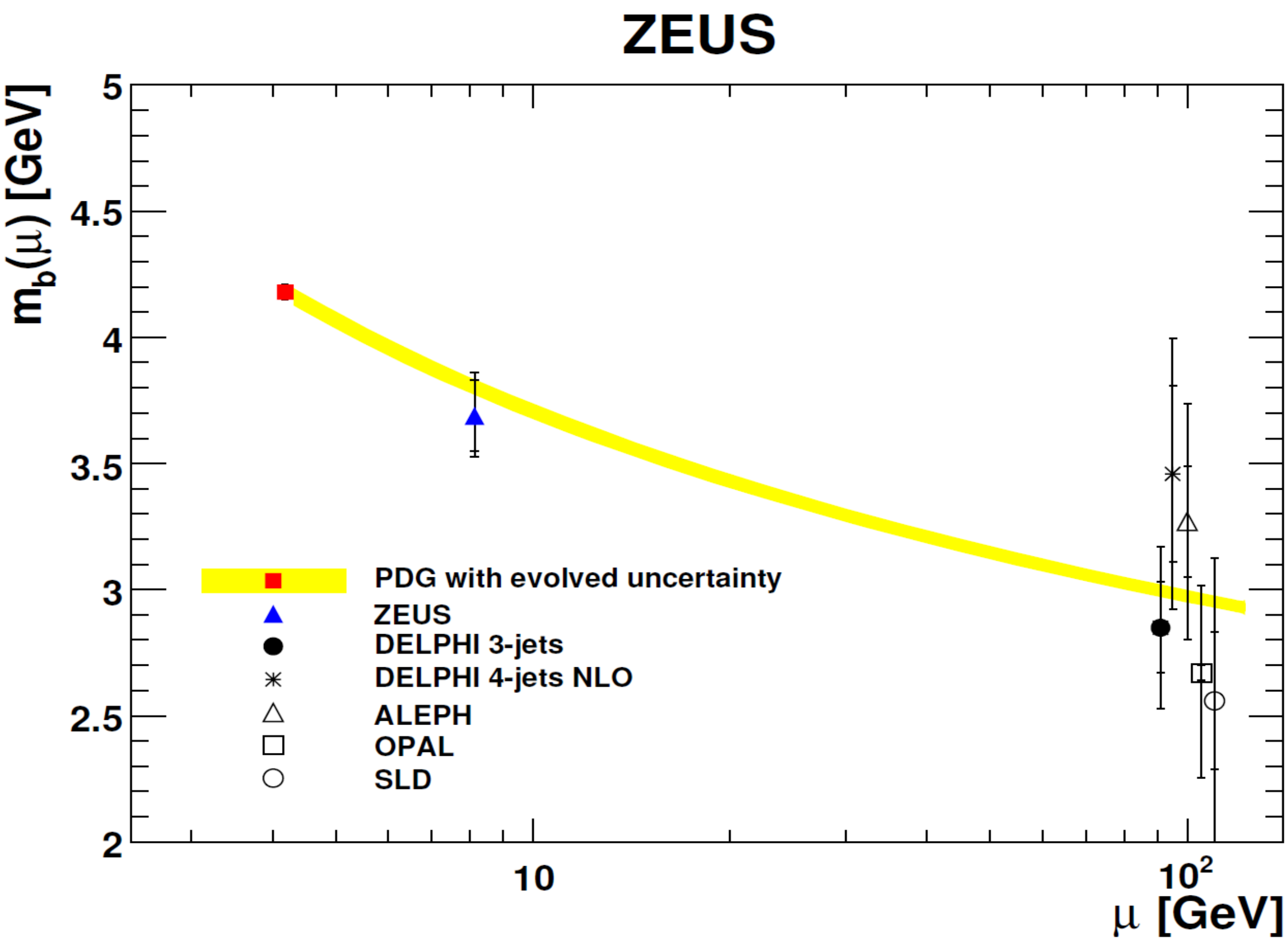
$$m_b(m_b) = 4.07 \pm 0.14\,(\text{fit})^{+0.01}_{-0.07}\,(\text{mod.})^{+0.05}_{-0.00}\,(\text{param.})\,^{+0.08}_{-0.05}\,(\text{theo.})\ \text{GeV}$$

Value consistent with world average

First measurement of m_b at a hadron collider

Beauty quark mass running

- Let's compare to the measurements at different scales



→ The ZEUS measurement is shown at the scale of $2m_b$ (region of highest sensitivity of the data)

Consistent with running expected from QCD

Summary

- Heavy flavour measurements at HERA provide unique means to test pQCD, validity of gluon PDFs, multiple-scale problem and are sensitive to quark masses

- Beauty and charm production was measured with inclusive secondary vertex method

- Differential cross-sections are reasonably described by NLO QCD (HVQDIS program)
- Charm and beauty contributions to the proton structure function were determined
- Beauty: most precise $F_2^{b\bar{b}}$ measurement!
- Running beauty mass was determined from a QCD fit

Thanks for your attention!