F_2^{bb} from the ZEUS HERA-II data

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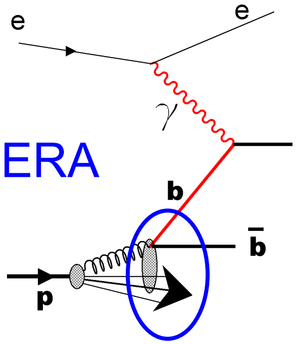
On behalf of the ZEUS collaboration

- Introduction
- Beauty measurements
- Beauty contribution to F_2
- Summary and Conclusions

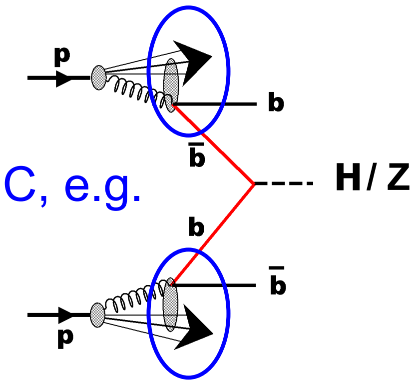
Motivation

- Heavy flavour production in DIS is a test of pQCD providing an additional hard scale M to the momentum transfer of the boson Q and p_t
- Beauty production is of increasing interest for higher energies -> LHC

HERA



LHC, e.g.



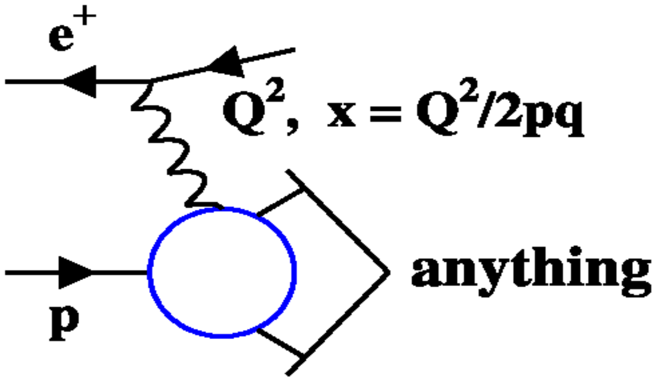
- F_2^{bb} very useful to understand the effect of m_b in different theoretical QCD approaches

Beauty contribution to the proton structure function F_2

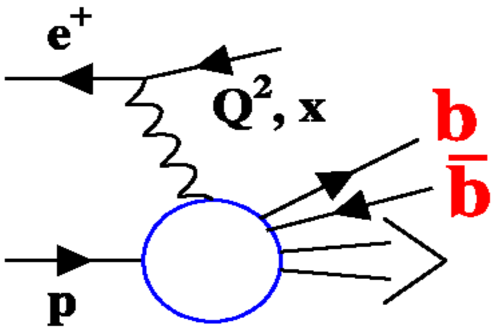
~negligible

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right]F_2(x,Q^2) - y^2 F_L(x,Q^2) + \ldots xF_3\right\}$$

at high Q^2



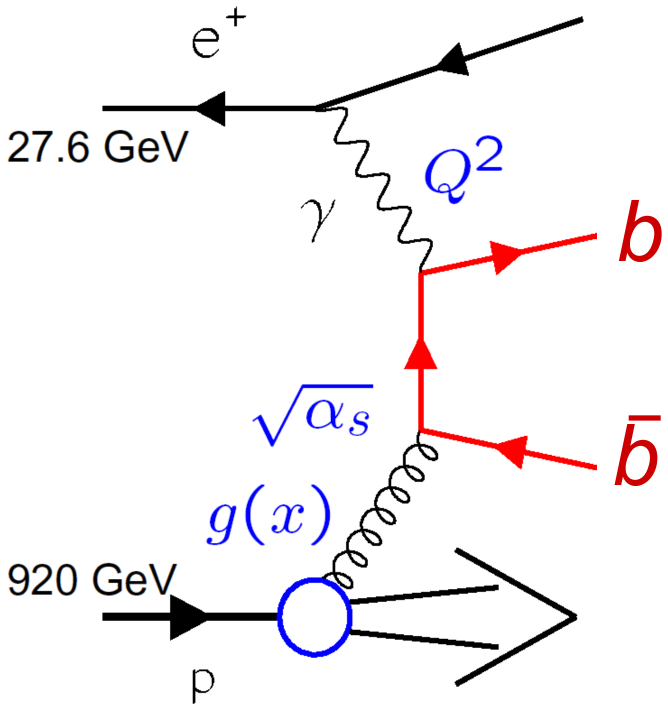
$$\frac{d^2\sigma^{ep}}{dQ^2dx} \propto F_2(x,Q^2)$$



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

Heavy Flavour production mechanism

Dominant process in *ep*-collisions: **Boson-Gluon-Fusion**



Kinematic variables:

$Q^2 = -q^2$ photon virtuality, squared momentum transfer

$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable, for $Q^2 \gg (2m_Q)^2$: momentum fraction of p constituent

Kinematic regime:

- Deep inelastic scattering (DIS): $Q^2 > 1\,\mathrm{GeV}^2$

Multiple scales:

m_b ~ 5 GeV
p_t^b ~ typically few GeV
Q^2 $\gtrsim$ 1 GeV ^{2} in DIS

➡ different pQCD approaches

good testing ground for pQCD

pQCD approximations

Massive scheme:

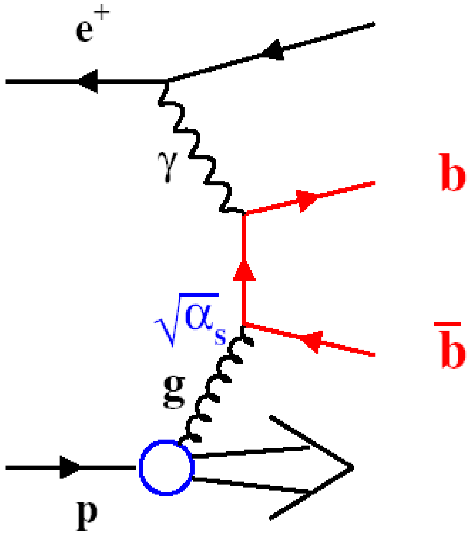
- *b* massive
- neglects $[\alpha_s \ln (Q^2/m_b^2)]^n$
- scale Q^2, m_b, p_t

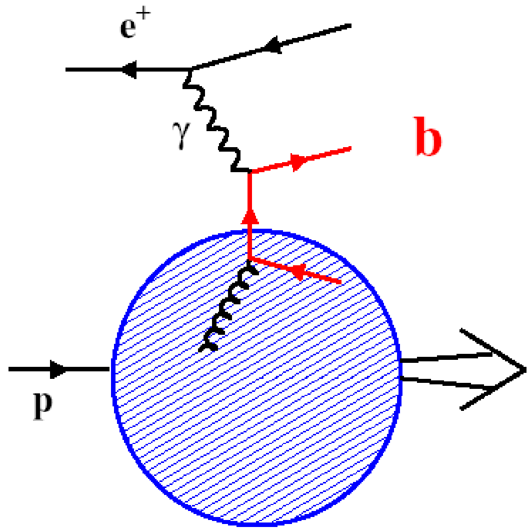
↳ *b* produced perturbatively (not part of the Proton or Photon)

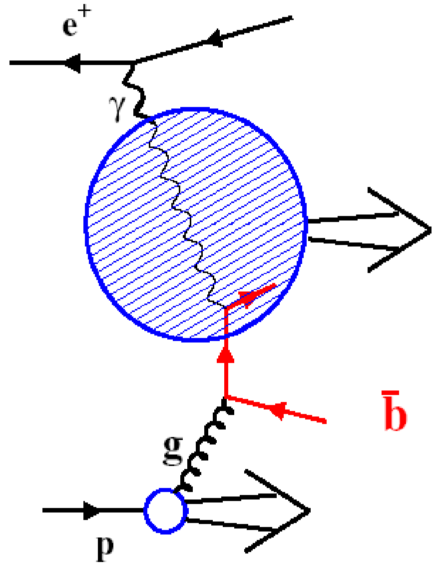
Massless scheme:

- *b* massless
- resums $[\alpha_s \ln (Q^2/m_b^2)]^n$
- scale: Q^2, p_t

↳ *b* also in Proton and Photon







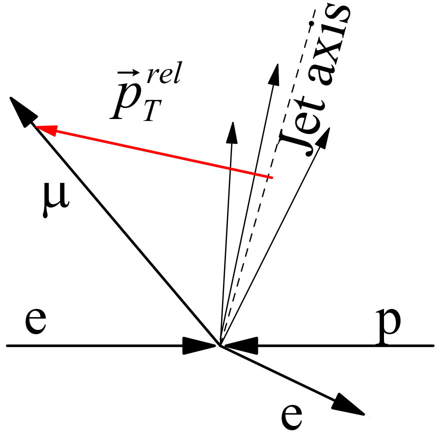
Variable flavour number scheme (VFNS):

- massive at small Q^2
- massless at large Q^2

Beauty identification

Process : $e\,p \rightarrow e\,b\bar{b}\;X \rightarrow e\,\mu\;jet\;X'$

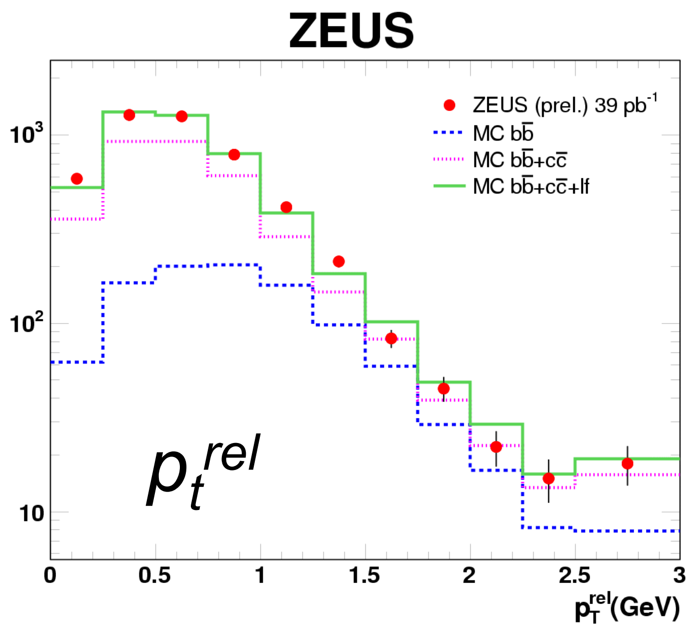
p_t^{rel} method:



p_t^{rel} is the momentum of the muon transverse to the axis of the associated jet (including the muon)

p_t^{rel} spectrum is harder for b than for c

➔ statistical separation using MC



χ^2 fit of b MC against c+lf MC to the data in p_t^{rel}

resulting beauty fraction of about 21%

➔ scale Rapgap-b MC up by a factor 2.49

Cross section

Beauty cross section for the DIS process:

$$e\,p \rightarrow e\,b\bar{b}\;X \rightarrow e\,\mu\;jet\;X'$$

Kinematic range:

$Q^2 > 4$ GeV^2

$0.05 < y < 0.7$

$E^{lab}_{t,jet} > 5$ GeV

$-2 > \eta_{jet} > 2.5$

$p_{t,\mu} > 1.5$ GeV

$-1.6 > \eta_\mu$

Data: $\sigma_{b\bar{b}} = 77.1 \pm 7.8$ (stat.) $\pm^{9.6}_{14.9}$ (sys.) pb

MC (LO+PS): $\sigma_{b\bar{b}} = 31.0$ pb

NLO (HVQDIS): $\sigma_{b\bar{b}} = 32.9 \pm 3.3$ (sys.) pb (2.3σ)

$\mu_{R,F}^2 = p_t^2 + 4m_b^2$ (simultaneous variation: factor 1/4 to 4)

$m_b = 4.75$ GeV (variation: 4.5 GeV to 5 GeV)

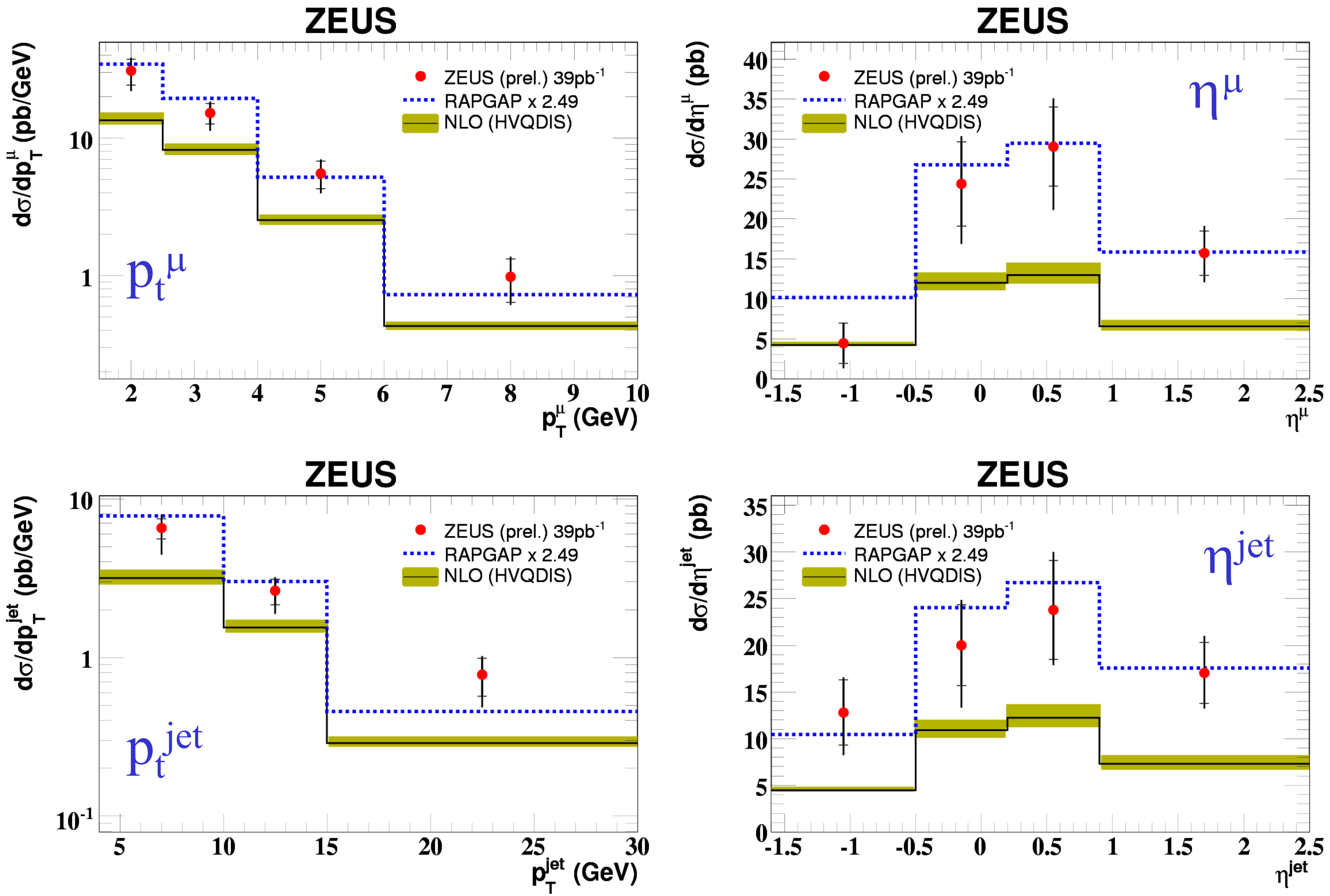
Peterson frag. function $\varepsilon = 0.0035$

Proton parton distribution: CTEQ5F4 (fixed 4 flavour)

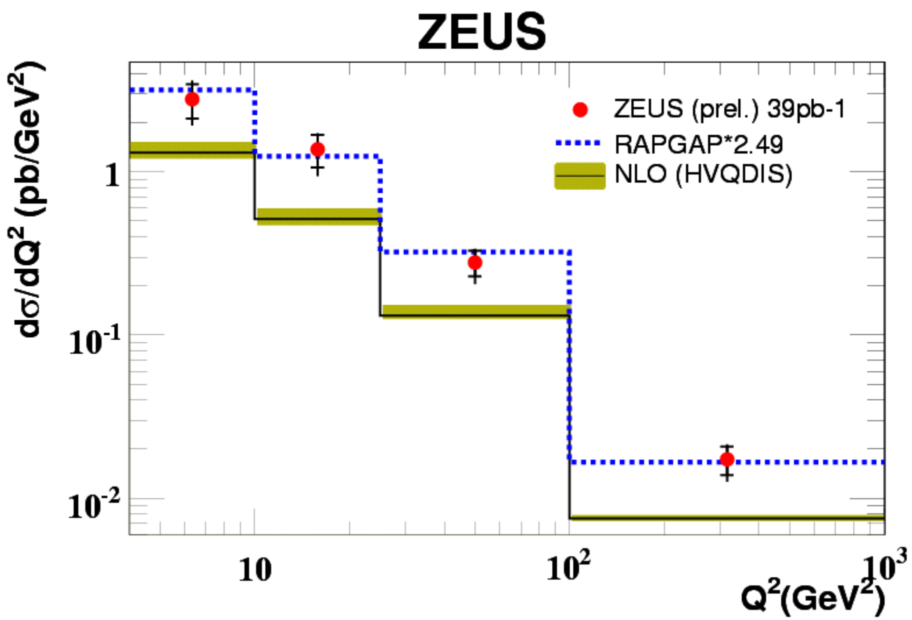
NLO ($\mu = Q^2$): $\sigma_{bb} = 41$ pb

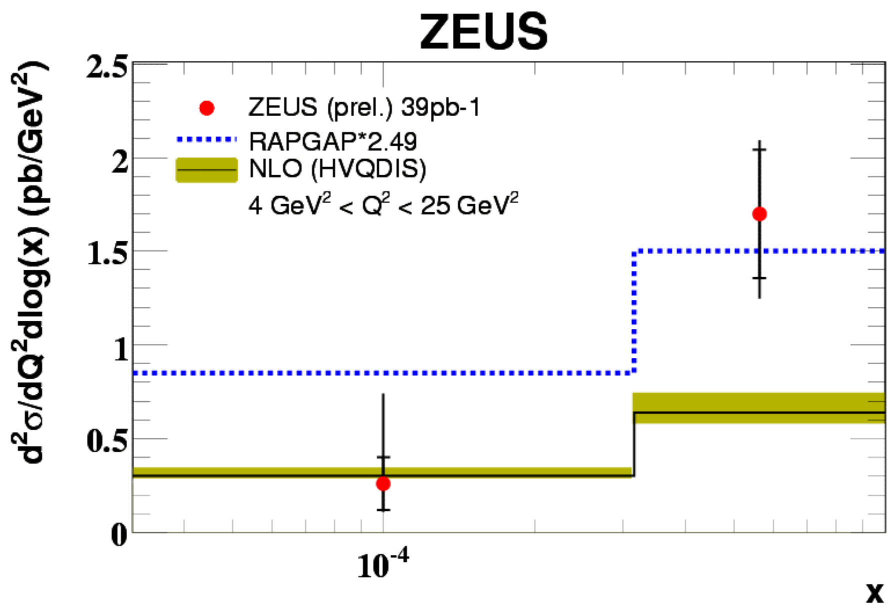
NLO ($\mu = Q^2$; $m_b = 4.3$ GeV) $\sigma_{bb} = 49$ pb

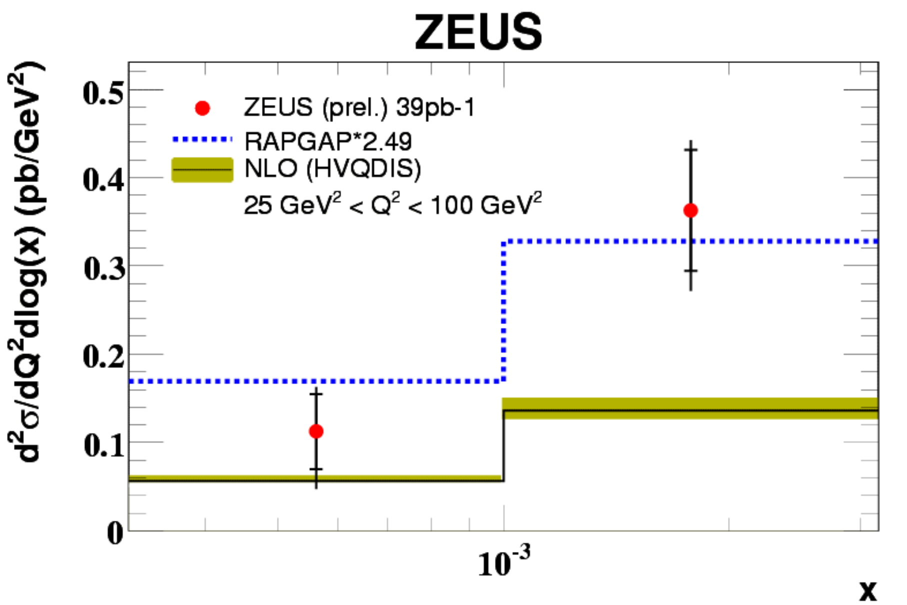
Cross sections in p_t and η

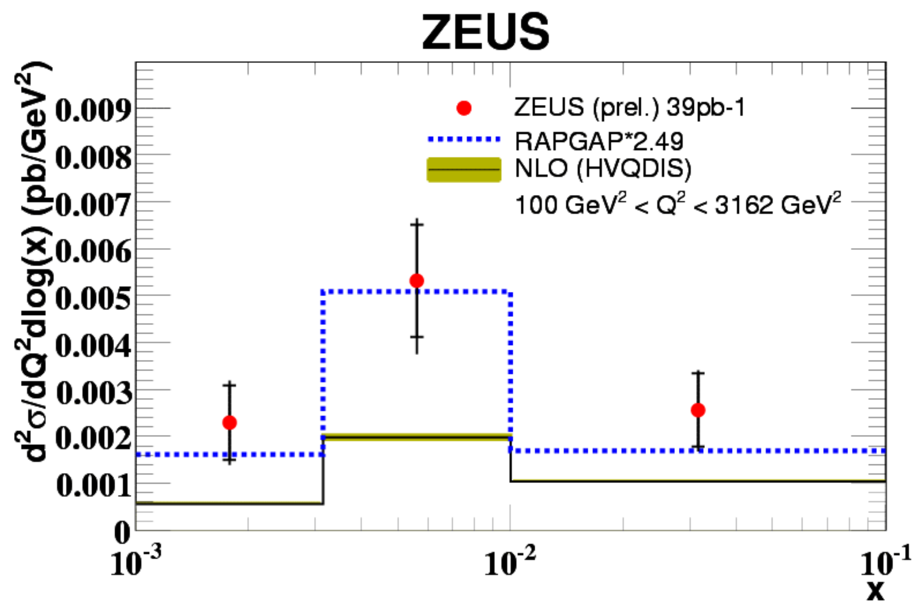


Cross sections in Q^2 and Q^2x









Calculation of

F_2^{bb} = beauty contribution to F_2

„Reduced cross section“ is defined as:

$$\tilde{\sigma}_{NLO}^{b\bar{b}}(x,Q^2) = \frac{d^2\sigma_{NLO}^{b\bar{b}}}{dx\,dQ^2}\frac{xQ^4}{2\pi\alpha^2(1+(1-y)^2)}$$

Cross section calculated using HVQDIS+CTEQ5F4 for a tiny bin around (x,Q^2)

Expected to be compatible with calculations by Riemersma *et al.* used for F_2^{cc}

Neglecting the small contribution from F_L, the reduced cross section is equal to F_2:

$$\tilde{\sigma}^{b\bar{b}}(x,Q^2) = F_2^{b\bar{b}} - \frac{y^2}{1+(1-y)^2}F_L^{b\bar{b}}$$

neglected

HVQDIS: B. W. Harris, *Electroproduction of Heavy Quarks at NLO*, Proceedings of American Physical Society, Division of Particles and Fields, Minneapolis, 1996

F_2^{bb} measurement

The reduced cross section for data is the reduced cross section of the NLO multiplied by the ratio of data to NLO in a x,Q^2 bin:

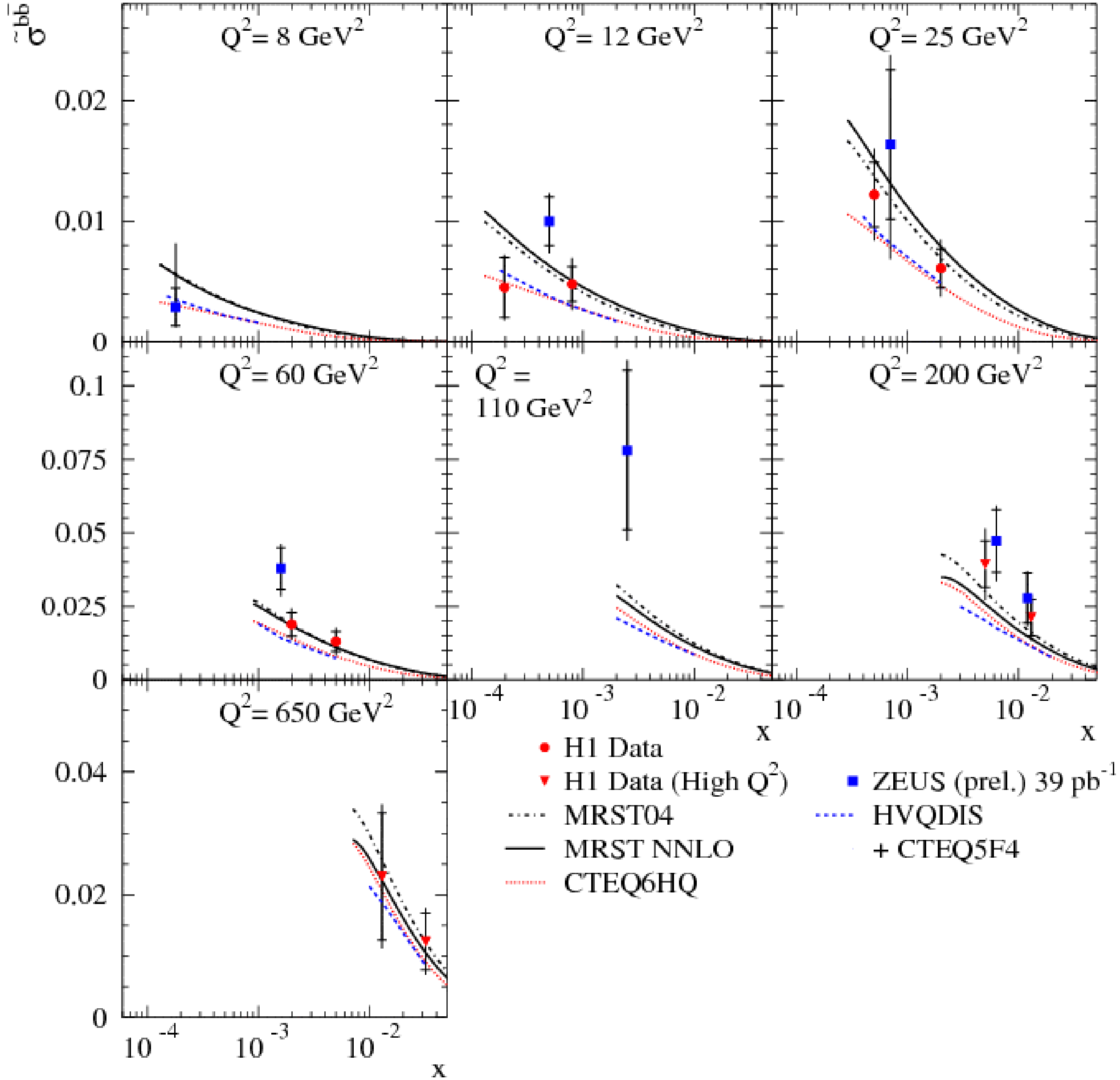
$$\tilde{\sigma}^{b\bar{b}}_{data}(x,Q^2) = \tilde{\sigma}^{b\bar{b}}_{NLO}(x,Q^2)\frac{\mathrm{d}^2\sigma^{b\bar{b}\to\mu}_{data}}{\mathrm{d}x\,\mathrm{d}Q^2}\Bigg/\frac{\mathrm{d}^2\sigma^{b\bar{b}\to\mu}_{NLO}}{\mathrm{d}x\,\mathrm{d}Q^2}$$

Cross section for
$e\,p \to e\,b\bar{b}\,X \to e\,\mu\,jet\,X'$

NLO using HVQDIS with same settings as for $\tilde{\sigma}^{b\bar{b}}$ (but requiring SL decay to μ and jet)

H1 uses the impact parameter method to measure F_2^{bb} and F_2^{cc} with an inclusive charm and beauty sample of $57pb^{-1}$:
H1 Collab., A. Aktas et al., Eur. Phys. J. C45 (2006) 23-33

F_2^{bb} at ZEUS and H1



ZEUS data lie above H1 data but compatible within errors.

Large spread between theory predictions.

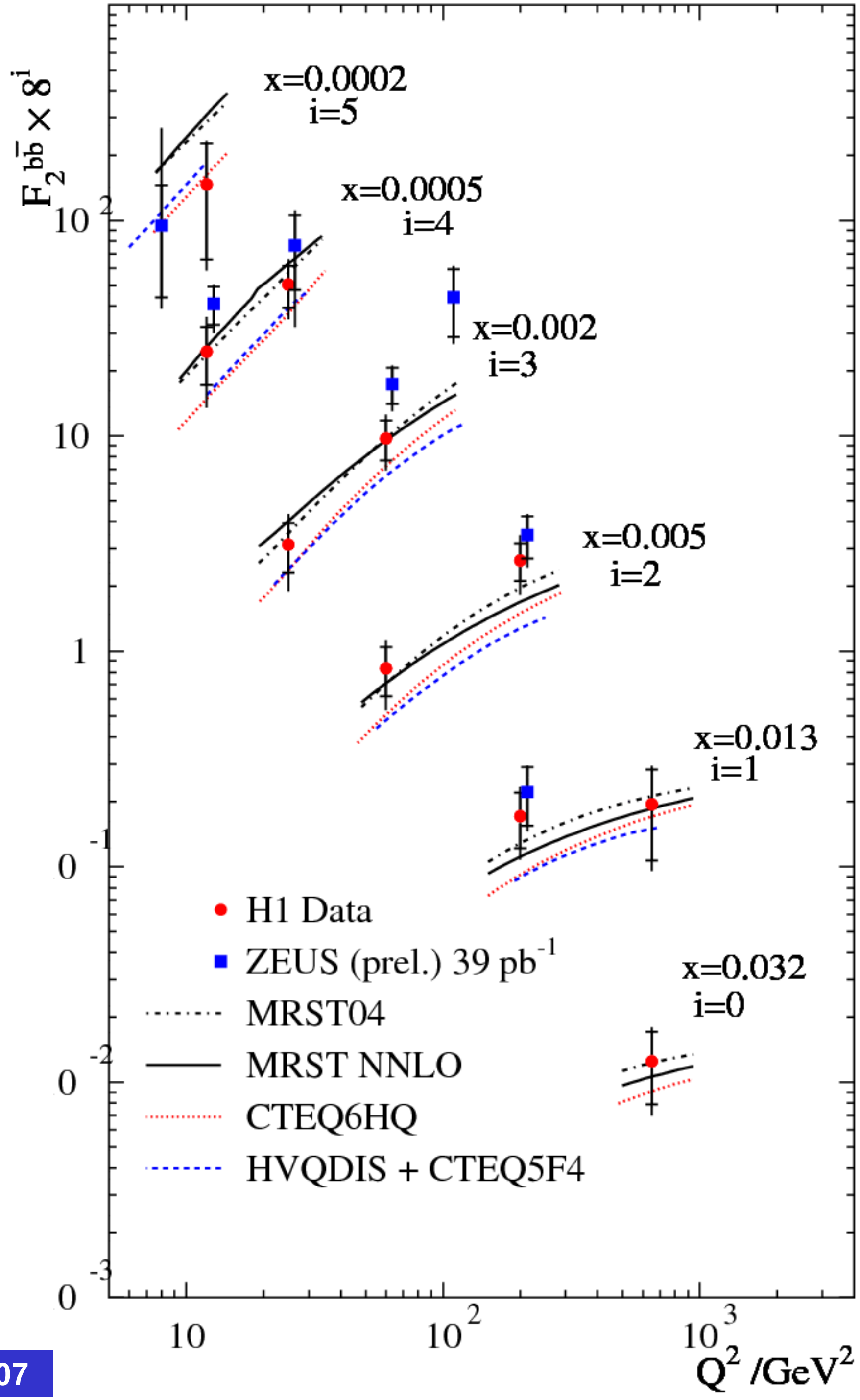
ZEUS: 39 pb^{-1}

H1: 57.4 pb^{-1}

Theory predictions except HVQDIS+CTEQ5F4 provided by P.D.Thompson, hep-ph/0703103

ZEUS data point at Q^2=200GeV^2; x=0.13 is shifted to lower x value to be separated from the H1 point

F_2^{bb} vs. Q^2



Same ZEUS data. Some points are recalculated for other values of x to be comparable with H1 data and theory curves.

Some ZEUS data point are shifted to higher Q^2 values to be separated from the H1 point

PDF Schemes and Parameters

PDF	Order	Scheme, Nf	μ^2	M_b(GeV)
MRST04	α_s^2	VFNS	Q^2	4.3
MRST NNLO	α_s^3	VFNS	Q^2	4.3
CTEQ6HQ	α_s^2	VFNS	Q^2	4.5
HVQDIS+CTEQ5F4	α_s^2	FFNS, 4	$p_t^2+4M^2$	4.75
CTEQ5F3	α_s^2	FFNS, 3	Q^2	4.5
MRST FF	α_s^2	FFNS, 3	Q^2	4.3
CTEQ6.5	α_s^2	VFNS	Q^2+M^2	4.5

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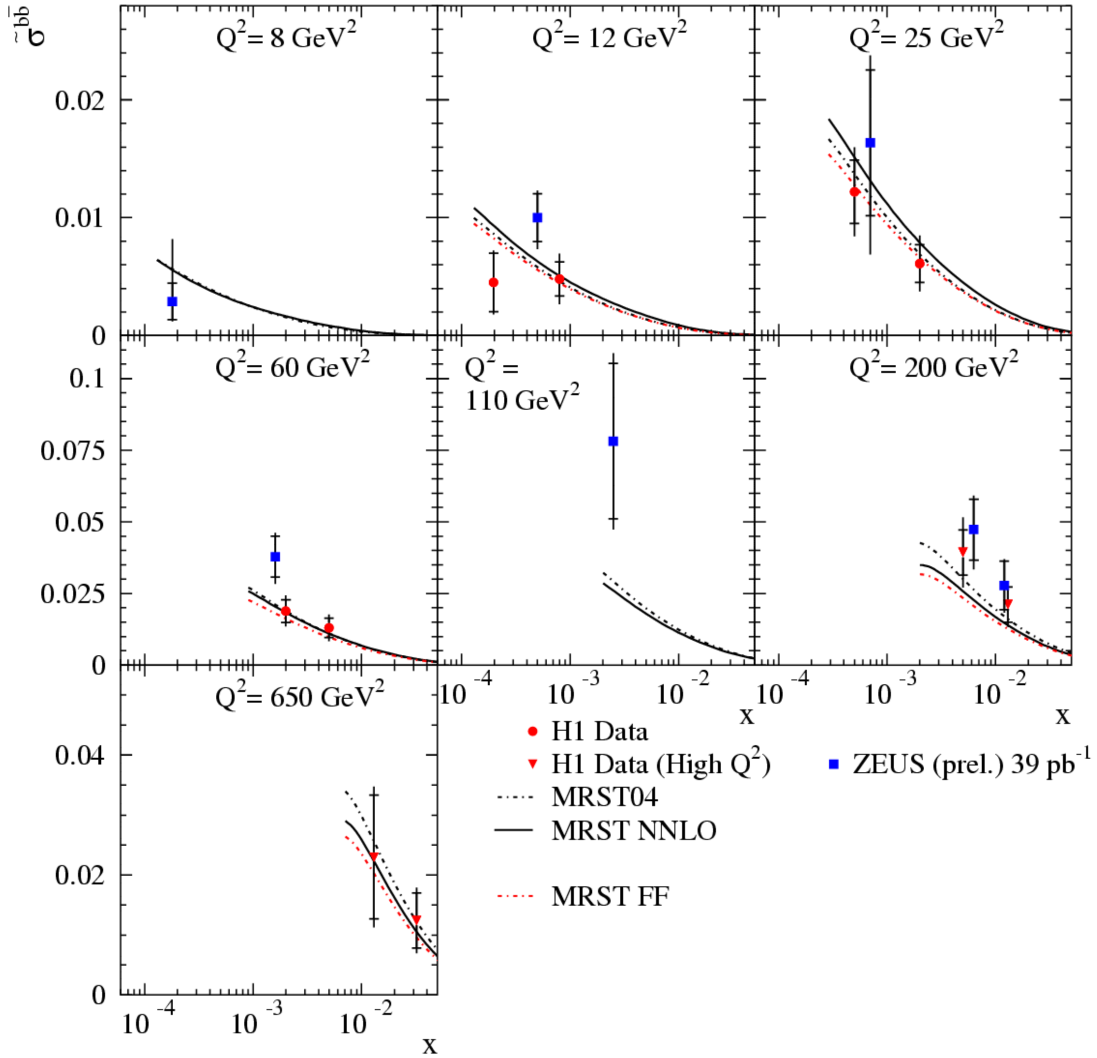
FFNS vs. VFNS and NLO vs. NNLO



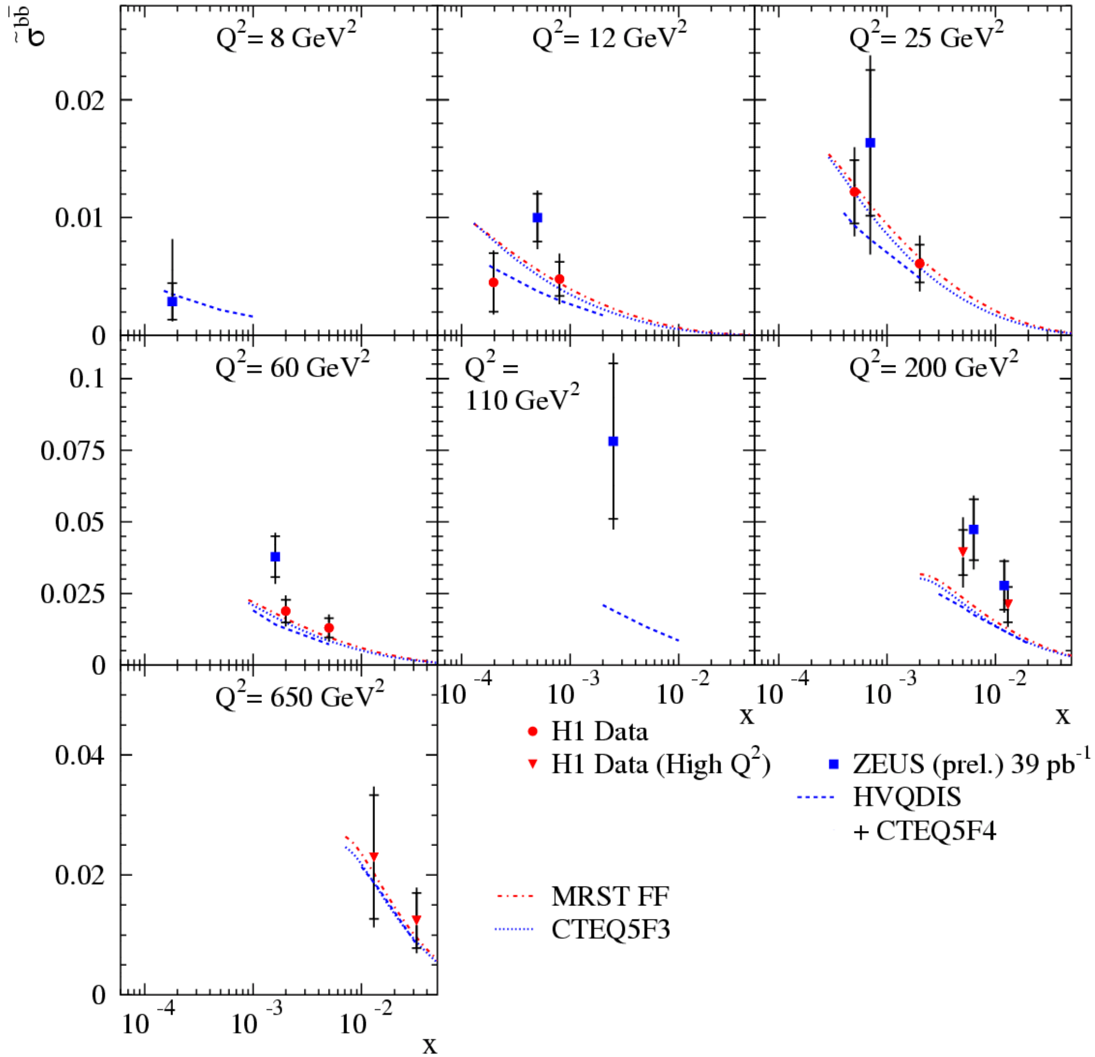
MRST FF close to MRST04 (VFNS) (both scale = Q^2)

=> differences NOT dominated by FFNS vs. VFNS scheme

MRST04 (NLO) close to MRST NNLO (both VFNS, scale Q^2)

=> differences NOT dominated by NNLO vs. NLO

MRST vs. CTEQ gluons and scale



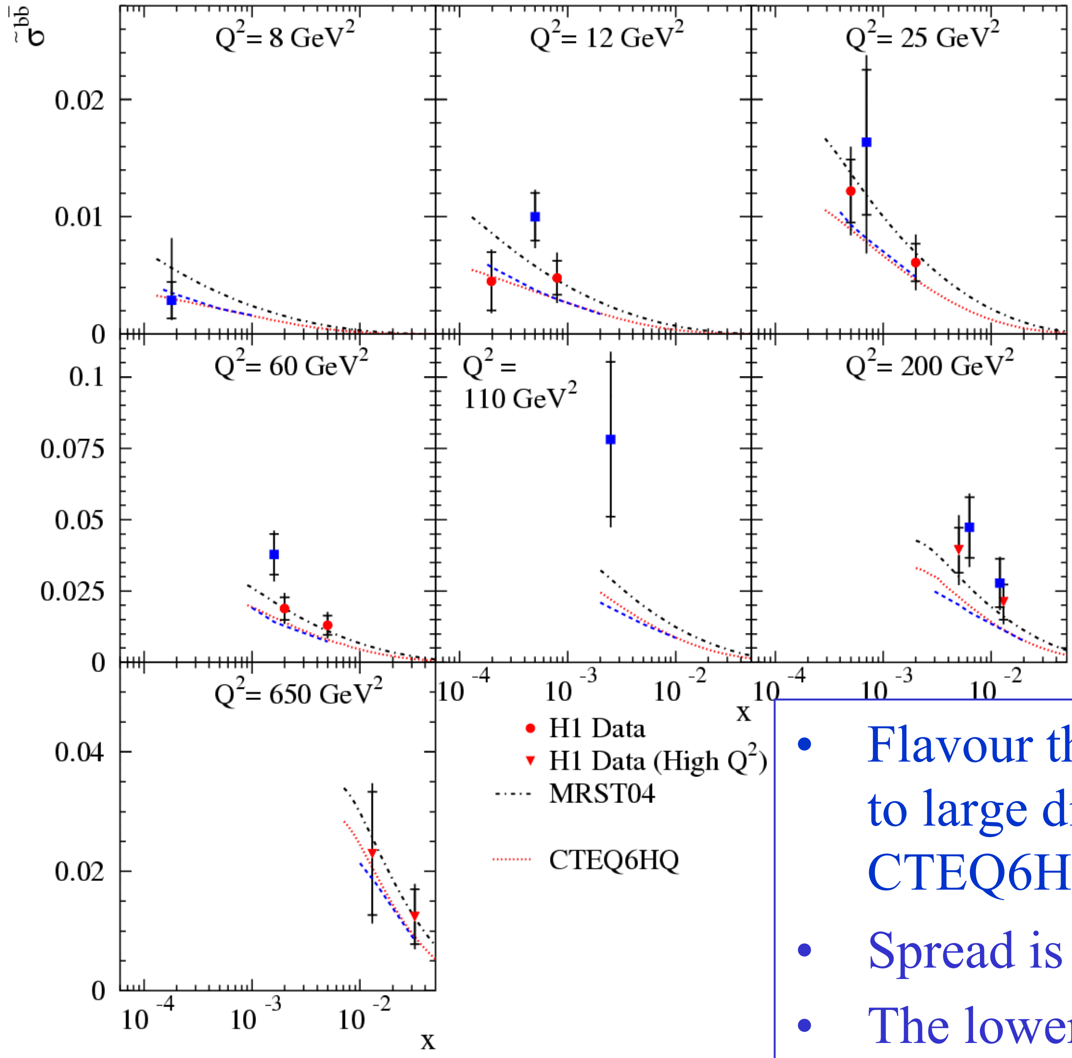
MRST FF very close to CTEQ5F3 (also FFNS) (both scale = Q^2)

=> differences NOT dominated by MRST vs. CTEQ gluon

CTEQ5F3 (scale = Q^2) noticeably larger than HVQDIS+CTEQ5F4 (scale = $p_T^2+4m^2$) at low Q^2, similar at high Q^2 (both FFNS)

=> scale choice makes important difference

MRST VFNS vs. CTEQ VFNS



MRST04 much larger than CTEQ6HQ everywhere (both VFNS, scale = Q^2)

=> flavour threshold treatment within VFNS = source of large (largest?) uncertainties

- Flavour threshold treatment within VFNS leads to large differences between MRST and CTEQ6HQ
- Spread is also due to the different scale μ
- The lower b mass in MRST and CTEQ6 increases the F_2^{bb} predictions at low Q^2 (agreement at the HERA-LHC workshop to use 4.75 GeV in the future for all PDFs)

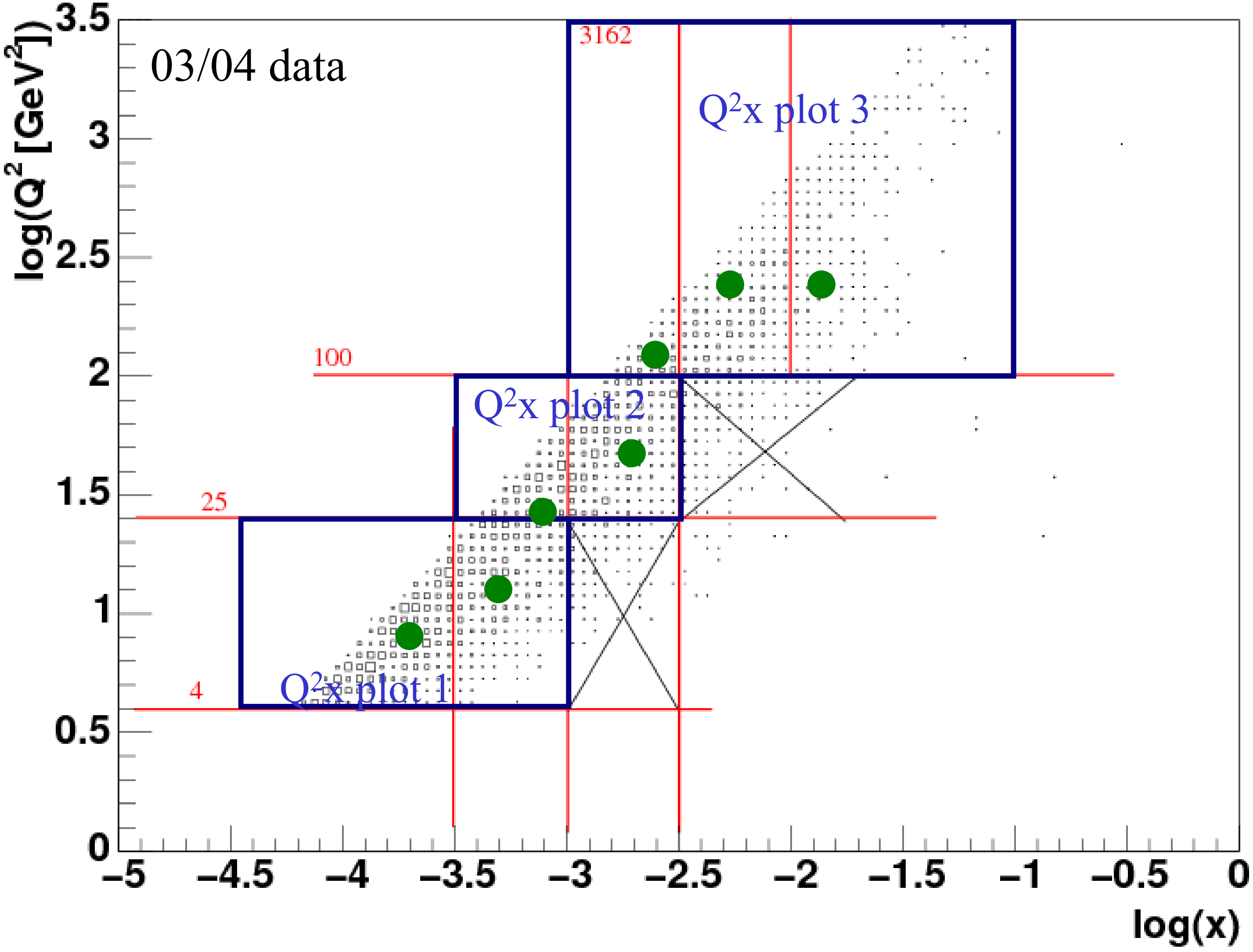
details see talk R. Thorne, HERA-LHC meeting

Summary and Outlook

- First measurement of F_2^{bb} at ZEUS (39 pb^{-1}),
  ~10 times more data to come -> much reduced errors
- Results agree with H1's using a very different method to obtain F_2^{bb} but similar uncertainties (both statistical and systematical)
- NLO predictions consistent with data (within large spread)
- Measurement of F_2^{bb} at high Q^2 will allow validation of b-PDF for Tevatron/LHC

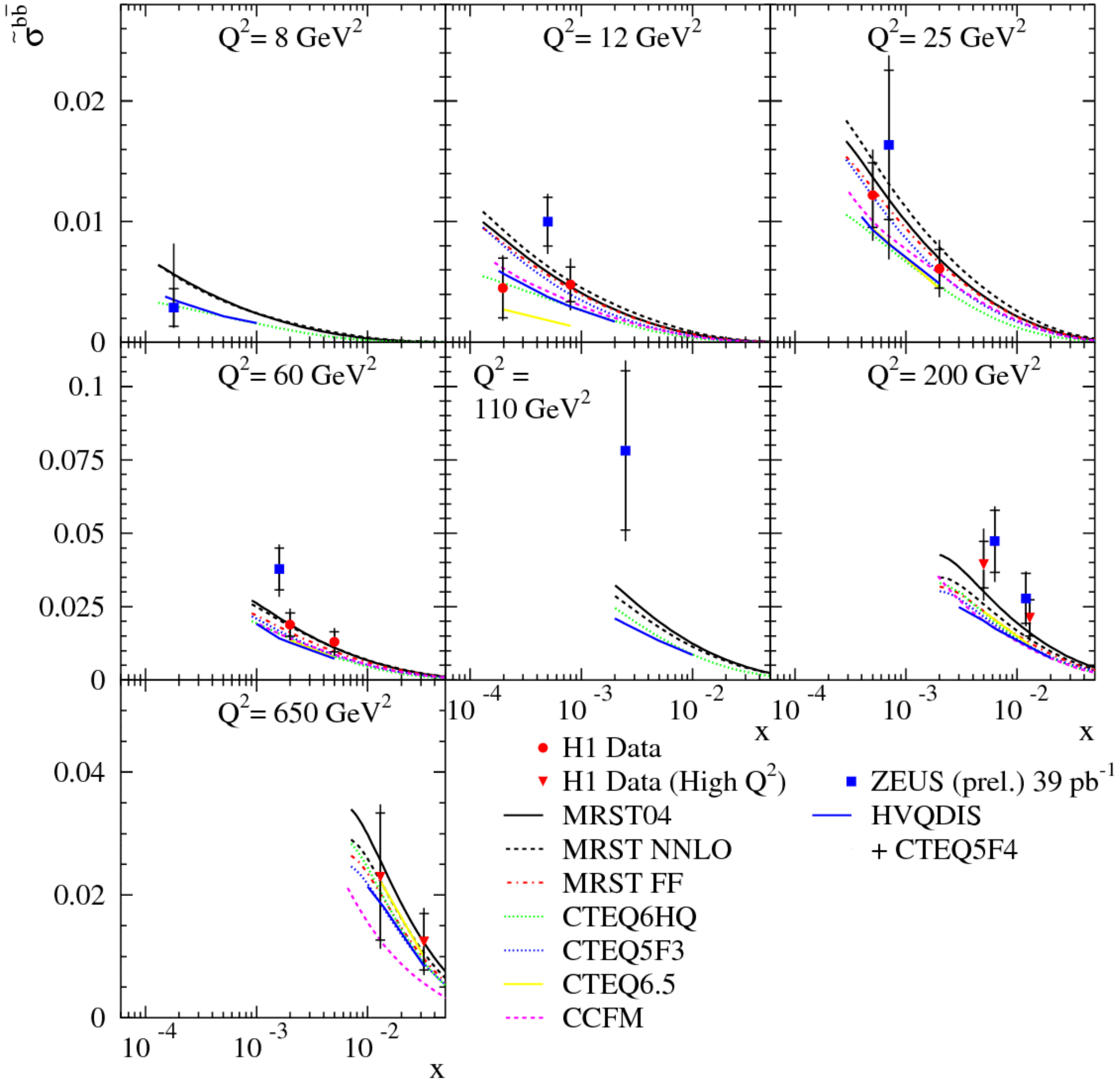
BACKUP

Kinematic plane (ZEUS)



- (x,Q2) values chosen for F_2^{bb} to compare with H1's results

F_2^{bb} at ZEUS and H1



Same plot as before, but with additional theory curves.

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Theory predictions except HVQDIS+CTEQ5F4 provided by P.D.Thompson, hep-ph/0703103

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NLO calculations

The calculation of the NLO QCD visible cross section predictions proceeds in three steps:

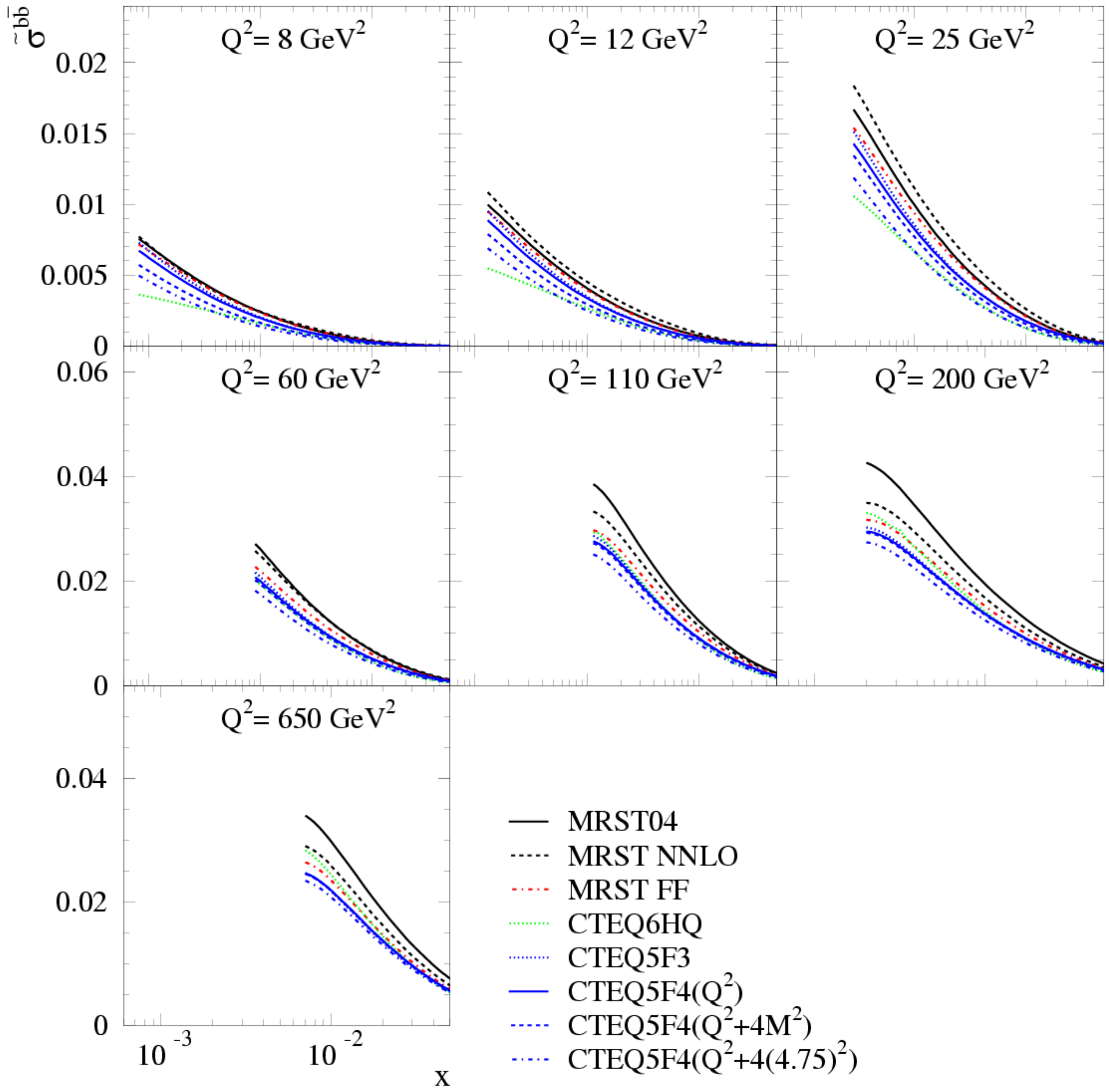
- HVQDIS (B.Harris, J.Smith, hep-ph/9503484):
  $\gamma^*g \rightarrow bb$, $\gamma^*g \rightarrow bbg$, $\gamma^*q \rightarrow bbq$, etc. (pointlike only)
  using CTEQ5F4 (FFNS) PDF

- Fragmentation of the **b-quark** into a **B-meson**
  (Peterson function with ε=0.0035)

- Semileptonic decay of the B-meson

  (Muon momentum spectrum extracted from RAPGAP, including primary and secondary muons)

CTEQ5F4 with different scales



F_2^{bb} using different scales for CTEQ5F4:

Q^2

Q^2+4M^2 (M=4.5GeV)

Q^2+4M^2 (M=4.75 GeV)

large differences at low Q^2 for different masses

Extrapolation to full phase-space

Q^2	Extrapolation factor:
25 GeV^2	~6
110 GeV^2	~4
200 GeV^2	~3

Extrapolation factor excluding branching fraction to μ of 0.3924

Extrapolation factor includes p_t^b and η^b spectrum, fragmentation, and decay kinematics (jet and μ)

Similar to extrapolations for F_2^{cc}

Inclusive lifetime tags

most significant impact parameter S_1

2nd most significant impact parameter S_2