New beauty results from HERA

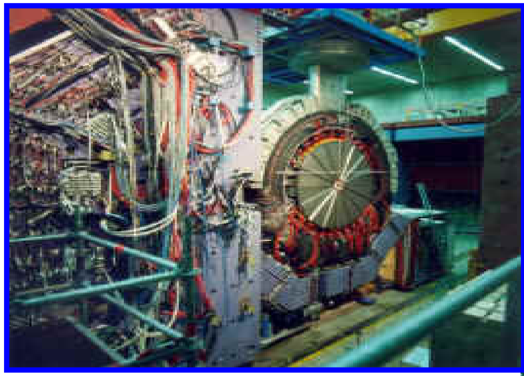
A. Yagües, Humboldt Universität zu Berlin
on behalf of the ZEUS Collaboration

OUTLINE:

- **HERA Collider and ZEUS detector**
- **Heavy quark production at HERA**
- Beauty PHP : dijets + muon
- Beauty PHP: dijets + electron
- Beauty contribution to the proton structure function: F_2^{bb} (DIS)
- Summary and Conclusions

HERA-LHC Workshop
30th October 2007

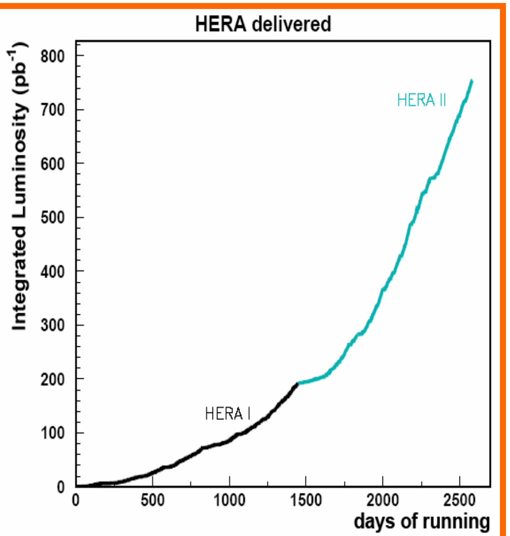
The HERA ep collider:



Delivered luminosity:

190 pb^{-1} 92-00 (HERA I)

560 pb^{-1} 02-07 (HERA II)

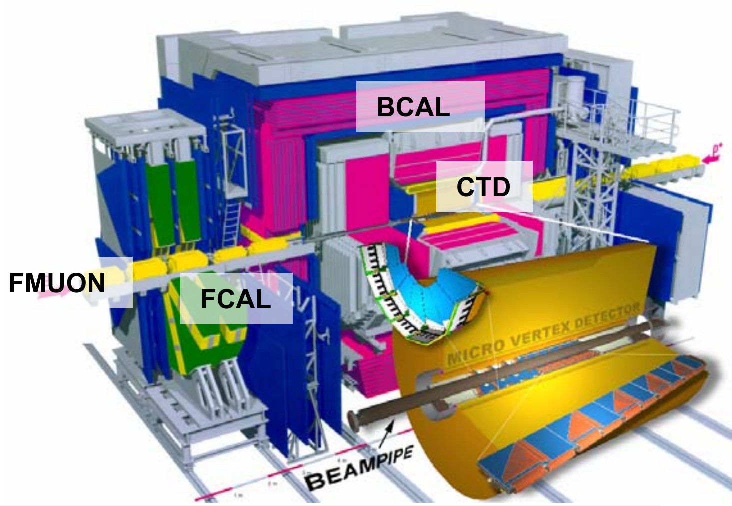


E_p = 920 GeV

E_e = 27.5 GeV

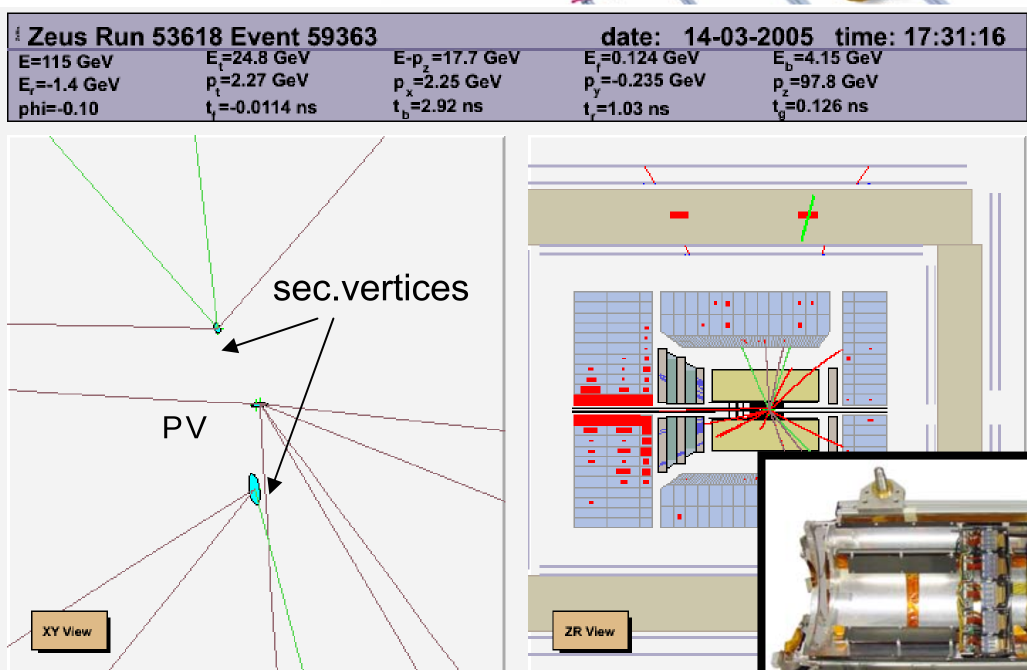
$\sqrt{s}$ ~ 318 GeV

The ZEUS detector:



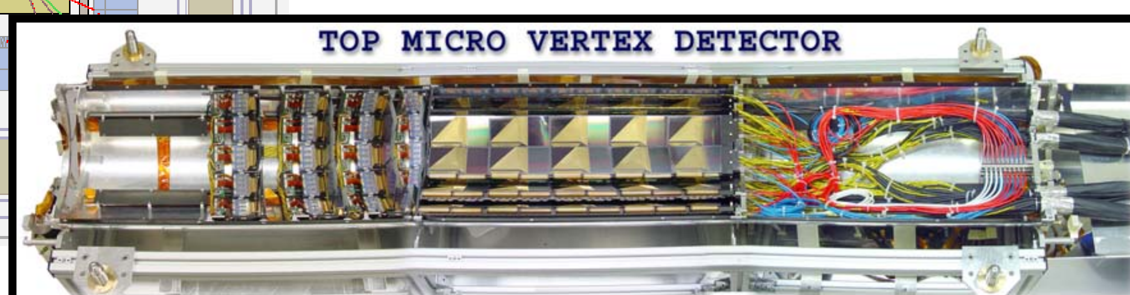
Multi-purpose detector:

- ✓covers almost full solid angle
- ✓ inner tracking detector in 1.5 T magnetic field (superconducting solenoid)
- ✓ uranium-scintillator calorimeter (H1:liquid Argon CAL)
- ✓ muon chambers
- ✓ …



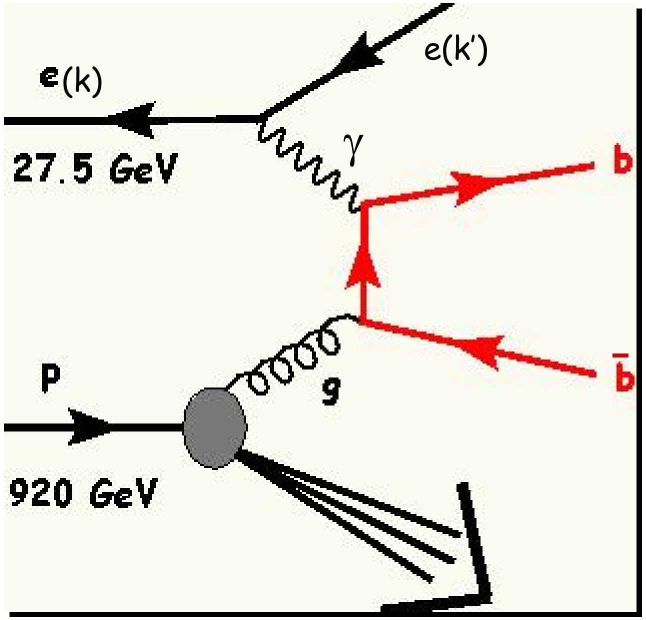
Detector upgraded for HERA II:

Micro Vertex Detector (MVD)



Heavy quark production at HERA

Dominant process: **boson-gluon fusion**



❑ Kinematic Variables:

$Q^2 = -q^2 = (k-k')^2$ Neg. squared momentum transfer (virtuality of exchanged boson)

$s = (k+p)^2 \approx 4E_eE_p$ CM Energy, at HERA $\sqrt{s}$ = 318 GeV

$x = Q^2/2p \cdot q$ Bjorken scaling variable: momentum fraction of parton interacting with lepton in infinite momentum frame (QPM)

$y = p \cdot q / p \cdot k$ Inelasticity: lepton momentum fraction transferred to boson in proton rest frame

❑ Kinematic Regimes:

- **Deep Inelastic Scattering (DIS):** $Q^2 > 1$ GeV^2
- **Photoproduction (PHP):** $Q^2 < 1$GeV^2 ($Q^2 \sim 10^{-3}$, quasi-real γ)

Why study heavy quark production at HERA?:

❖ **Test of perturbative QCD** due to the hard scale given by the heavy quark mass.

❖ **Study of multi-scale problem:** often mass scales compete with other hard scales (p_T, Q^2…) , additional theoretical uncertainties enter.

❖ **Better understanding of structure of the proton**

pQCD approximations:

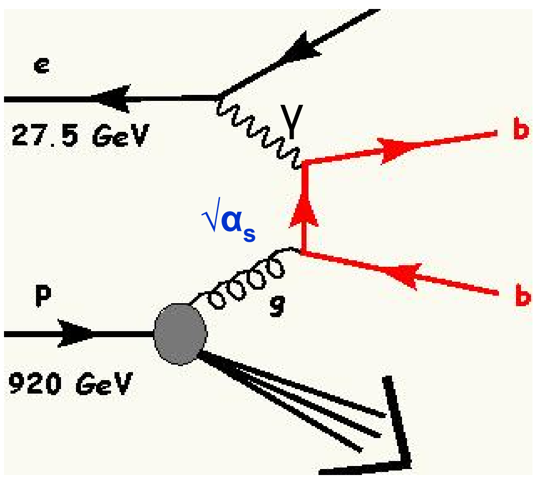
☞assume one dominant hard scale

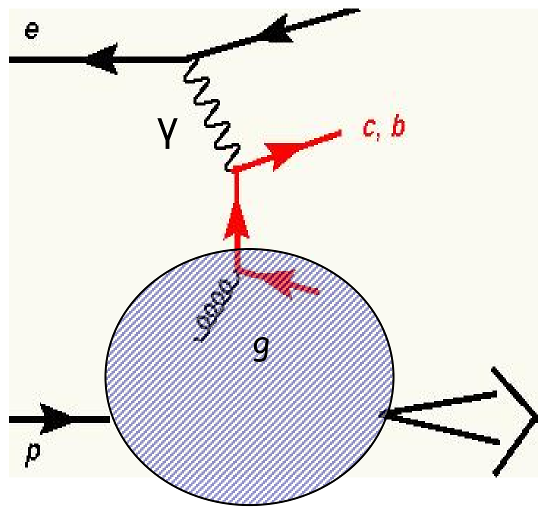
Massive scheme/FO: → m_b

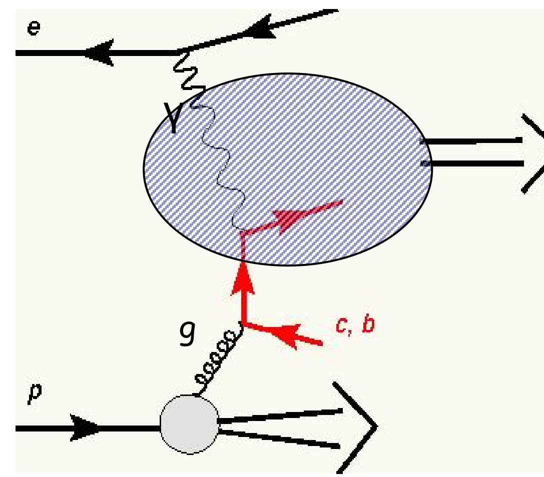
- b massive
- neglects $[\alpha_s \ln(Q^2/m_b^2)]^n$…
- reliable for $p_T \sim m_Q$
- FMNR (PHP) and HVQDIS (DIS)

Massless scheme/NLL: → Q^2, p_T

- b massless
- resums $[\alpha_s \ln(Q^2/m_b^2)]^n$ …
- reliable for $p_T >> m_Q$







Variable schemes (Variable Flavour Number Scheme):

- At small Q^2 → massive, at large Q^2 → massless
- MRST04, CTEQ6HQ…

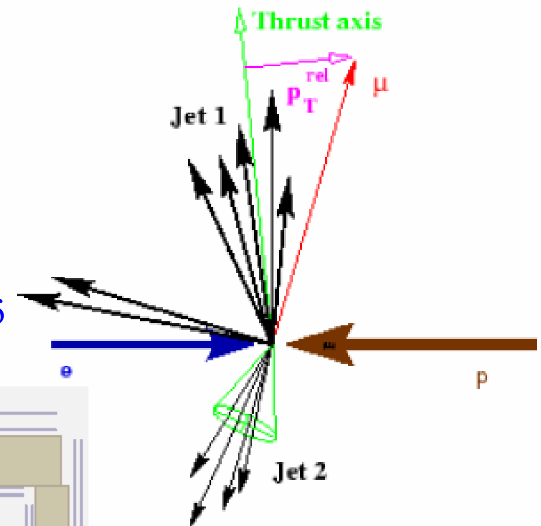
Tagging Beauty with μ+jets (I)

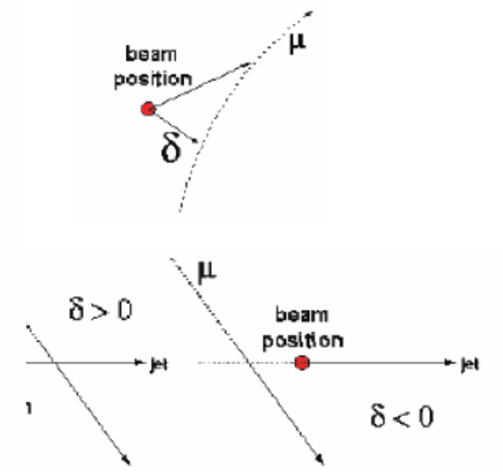
- Semileptonic decay:

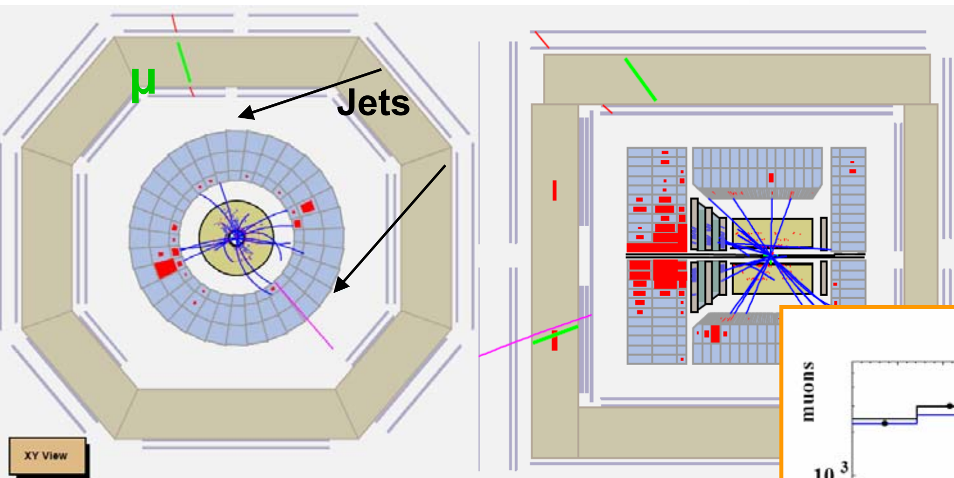
$ep \rightarrow e'bX \rightarrow \mu jjX$

- Separate b from c and uds:

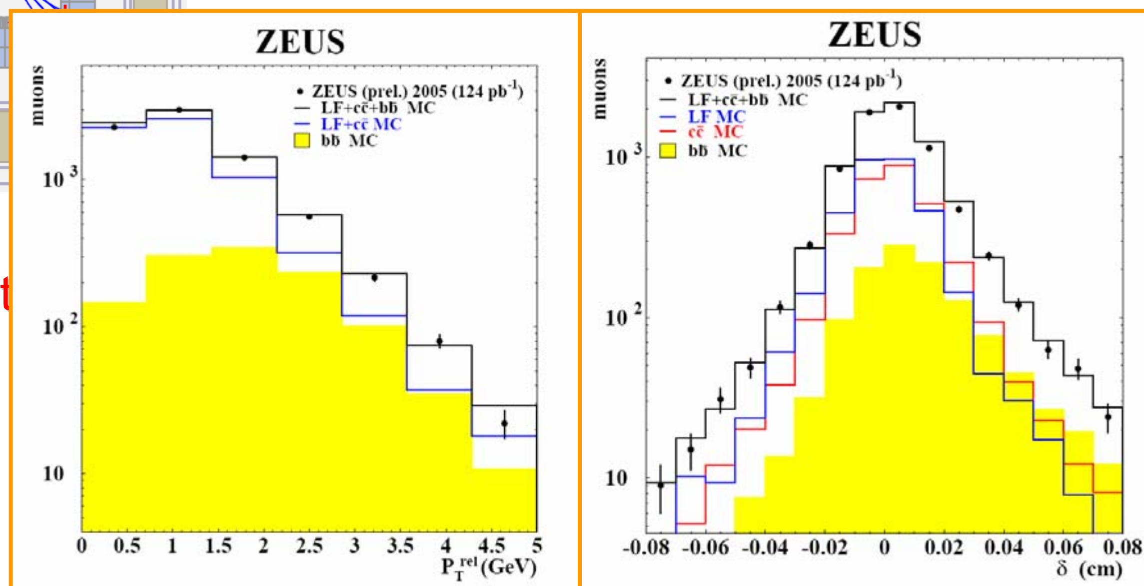
- Large b mass → large muon P_T^{rel}
- Large b lifetime → large muon impact param. δ



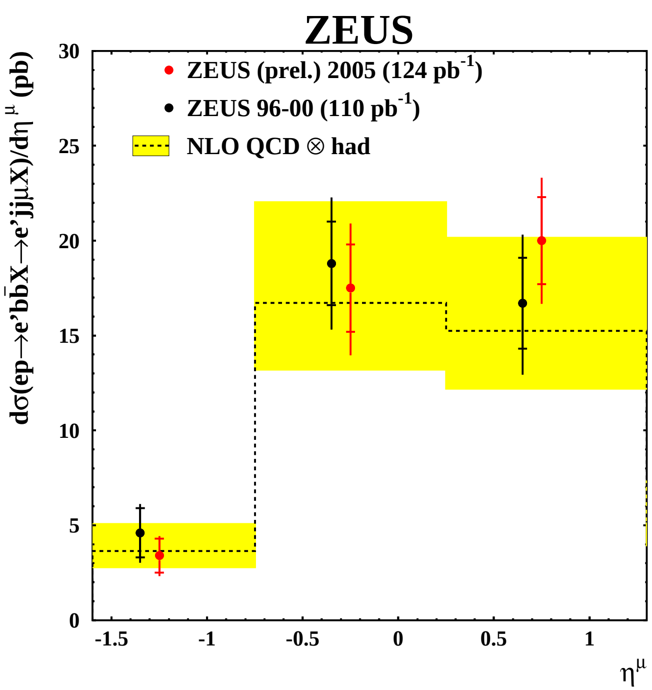


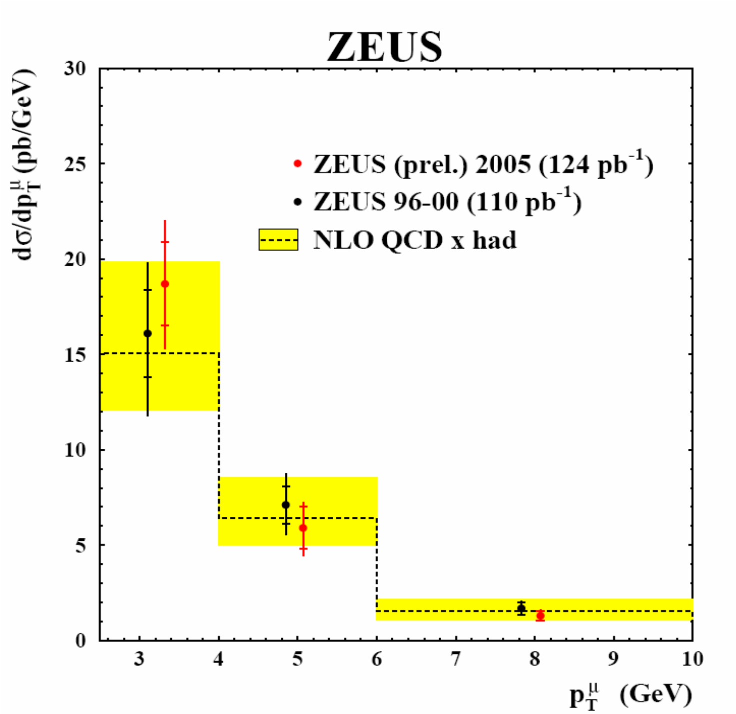


→ Simultaneous 2-dim P_T^{rel} and δ fit
(enhanced statistics
and reduced syst.errors)



Tagging Beauty with μ+jets (II)





$Q^2 < 1\,GeV^2$

$0.2 < y < 0.8$

$p_T^{\mu} > 2.5$ GeV

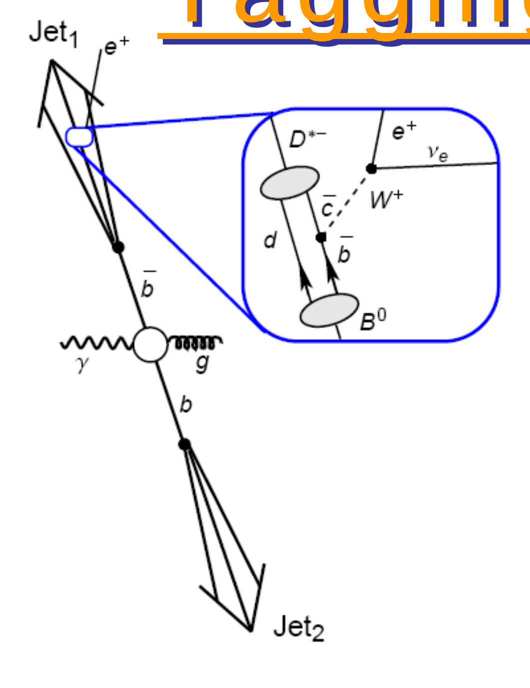
$-1.6 < \eta_{\mu} < 2.3$

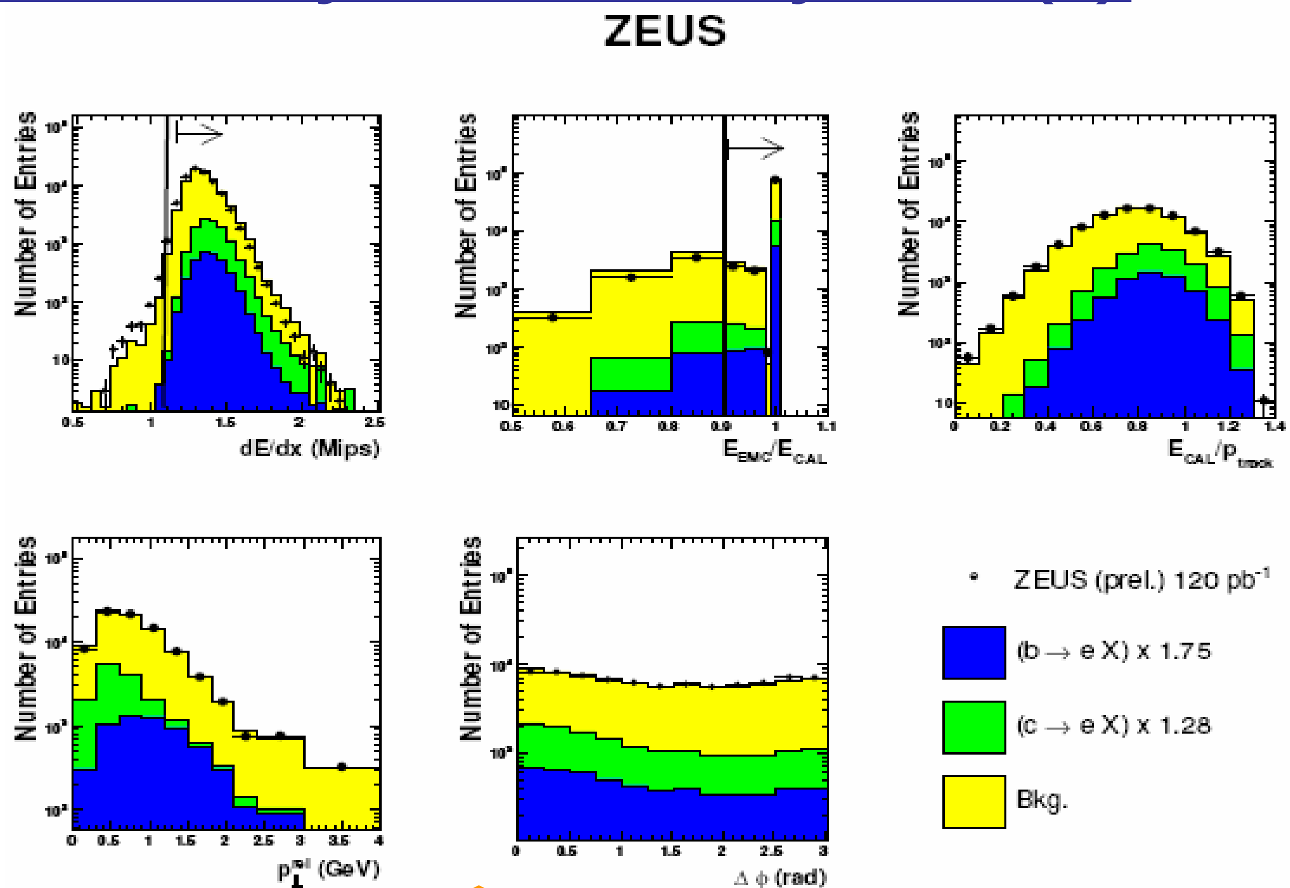
$p_T^{jet} > 7(6)$ GeV

$|\eta^{jet}| < 2.5$

- Compatible with previous measurements
- NLO calculations provide reasonable good description of data

Tagging Beauty with e+jets (I)





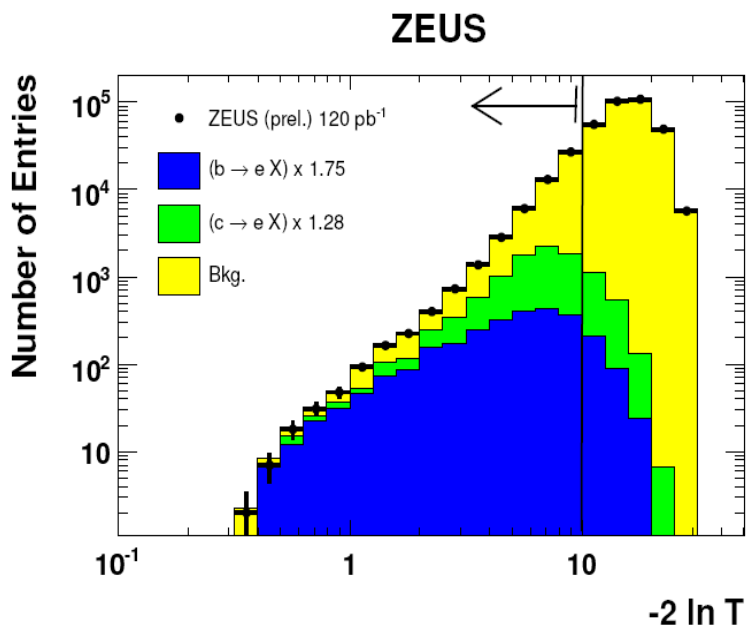
- **Semileptonic decay:**

ep→e'bX→e'jj+eX

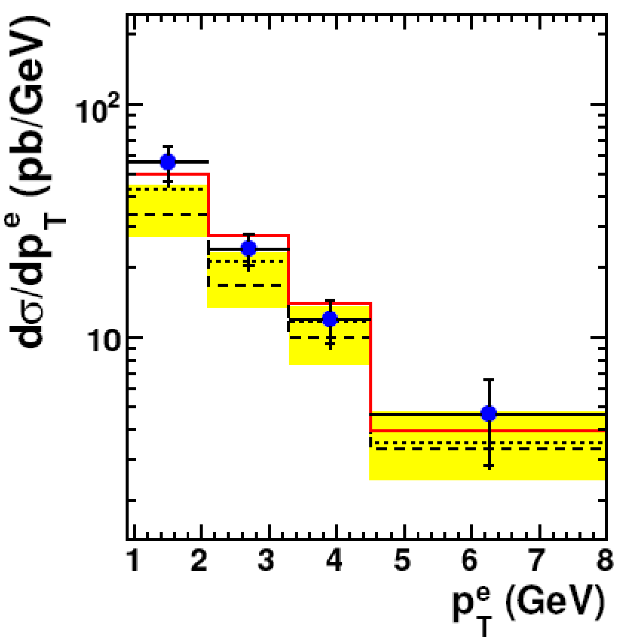
- **b-fraction extracted from likelihood fit using variables sensitive to e$^-$ identification and semileptonic decays**

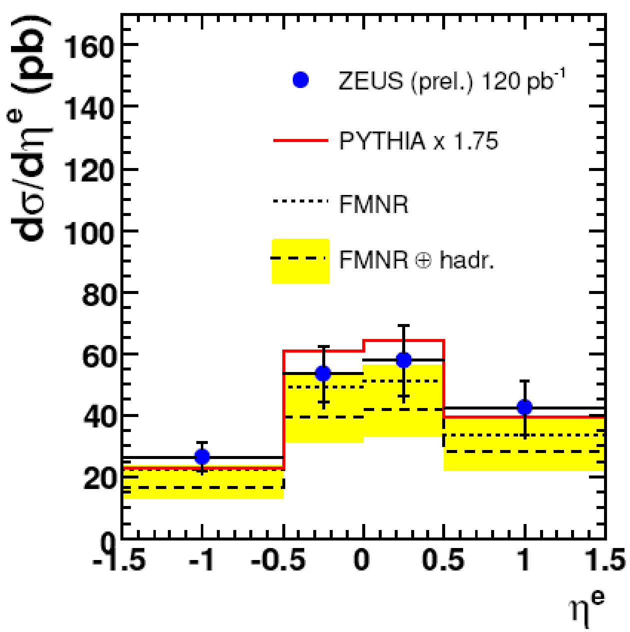
$$\text{Likelihood } \mathcal{L}_{i,j} = \alpha_i(p_T,\eta) \cdot \mathcal{P}(dE/dx) \cdot \mathcal{P}(E_{ECAL}/E_{tot}) \cdot \mathcal{P}(E^{cal}/p_{trk}) \cdot \alpha_j(p_T,\eta) \cdot \mathcal{P}(\sphericalangle(\not{p}_t,p_{trk})) \cdot \mathcal{P}(p_\perp^{rel})$$

Tagging Beauty with e+jets (II)



Test function $T_{i,j} = \frac{\mathcal{L}_{i,j}}{\sum_{k,l} \mathcal{L}_{k,l}}$

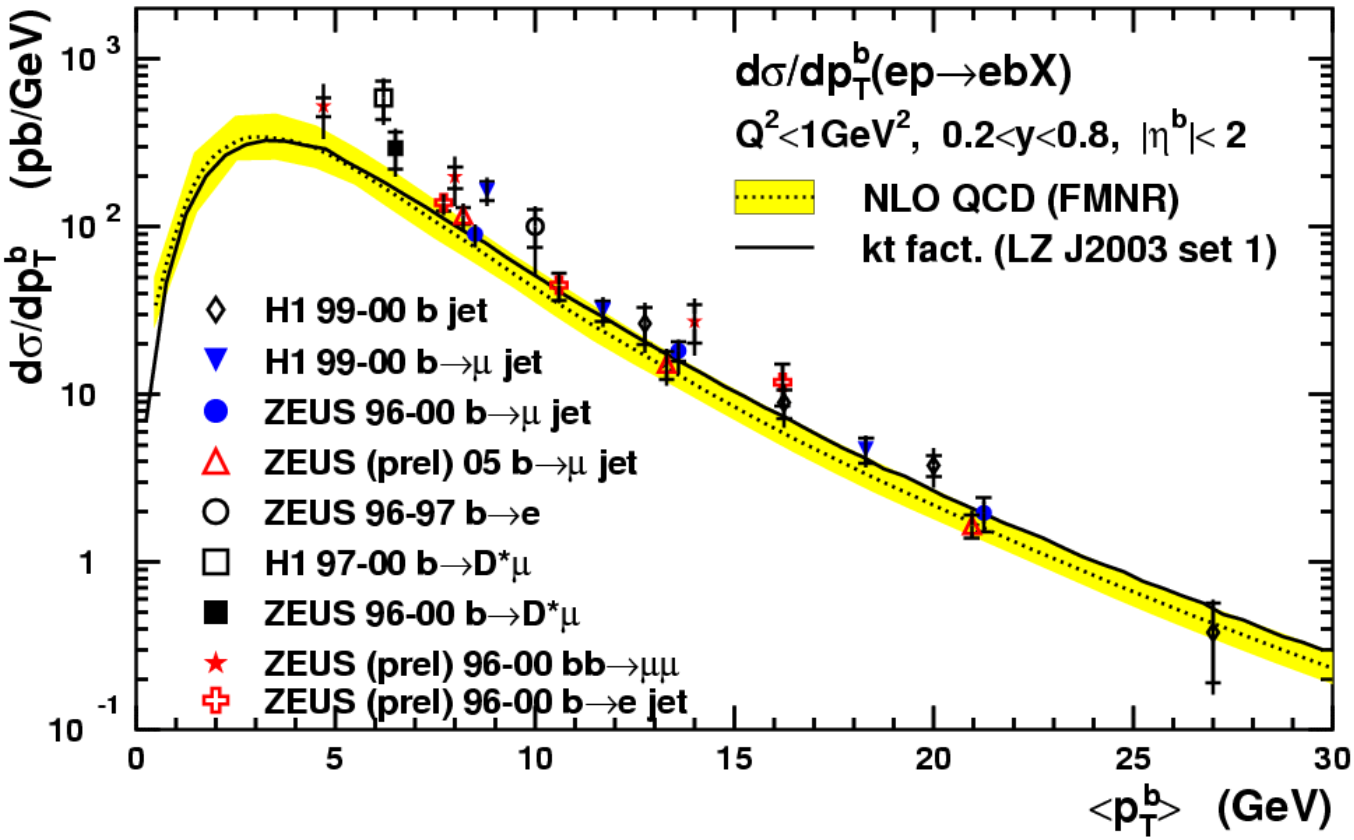




- Measurements in good agreement within errors with theoretical predictions

Summary of PHP measurements

HERA



Cross sections for b production extrapolated using NLO calculations

General good agreement with NLO QCD predictions

Measurement of F_2^{bb} with HERA-II by H1

- F_2^{bb} is related to double differential cross section:

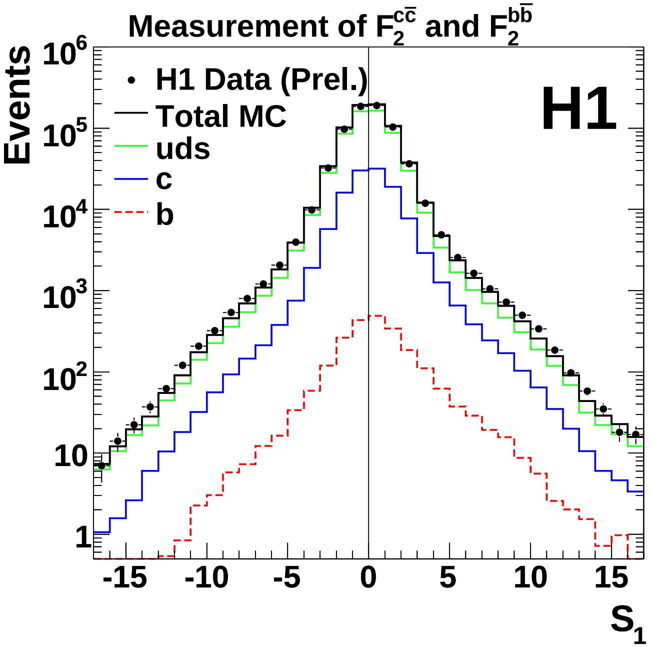
neglected (small y)

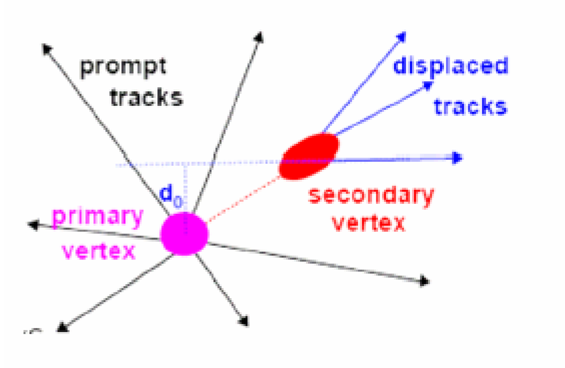
$$d^2\sigma^{bb}/(dx \cdot dQ^2)=(2\pi\alpha^2/Q^4x)\ \{[1+(1-y)^2]F_2^{bb}(x,Q^2)-y^2F_L^{bb}(x,Q^2)\}$$

- F_2^{bb} can be calculated from the ratio of measured and theory cross sections:

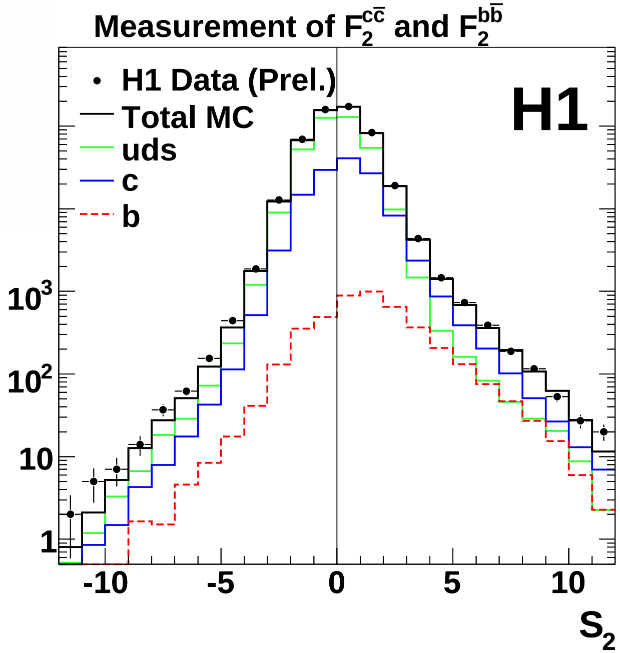
$$F_2^{bb}(x,Q^2)=[\sigma_{measured}/\sigma_{NLO}]\cdot F_2^{bb}{}_{NLO}(x,Q^2)$$

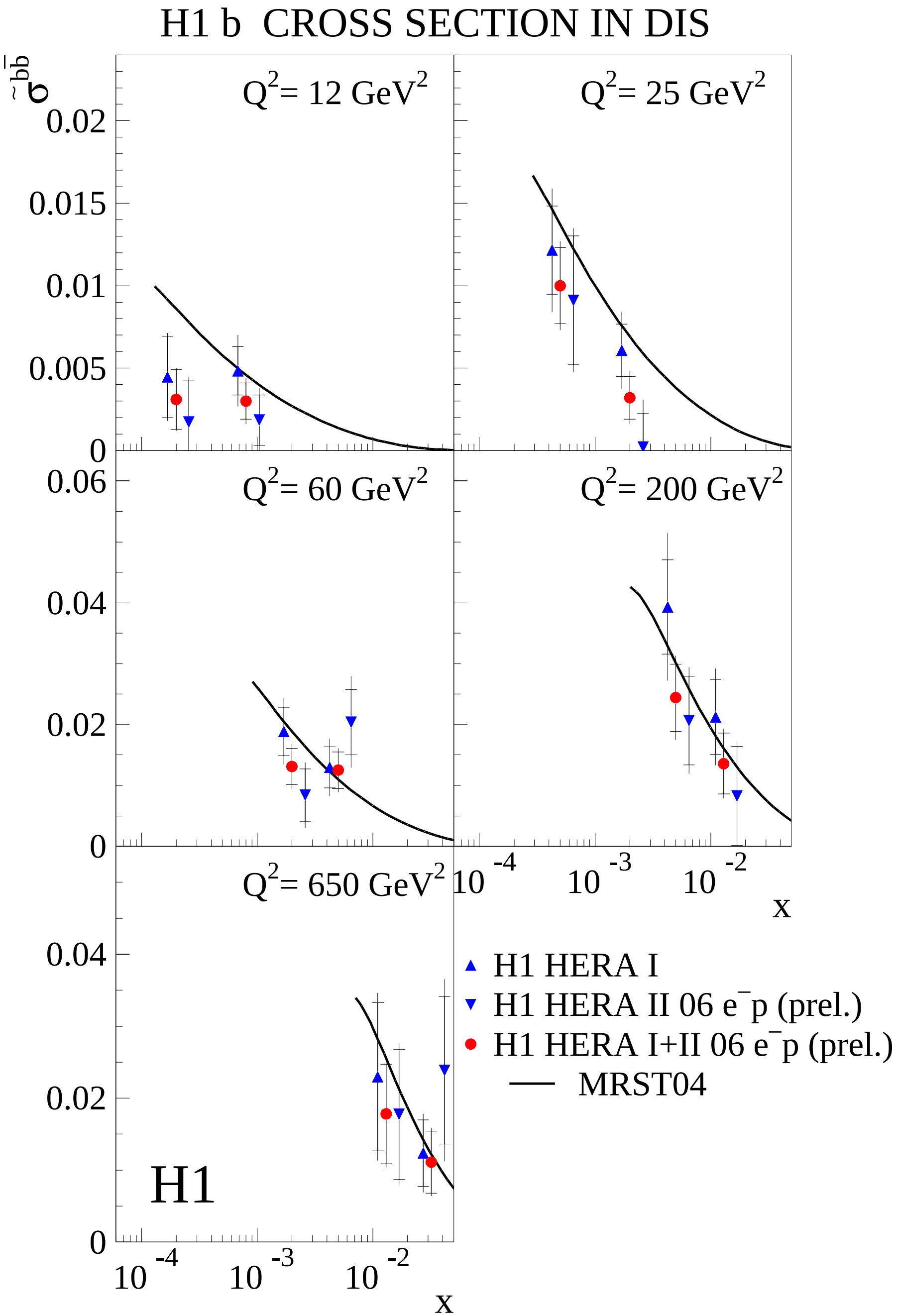
- H1: inclusive measurement. Method based on IP used to extract the signal





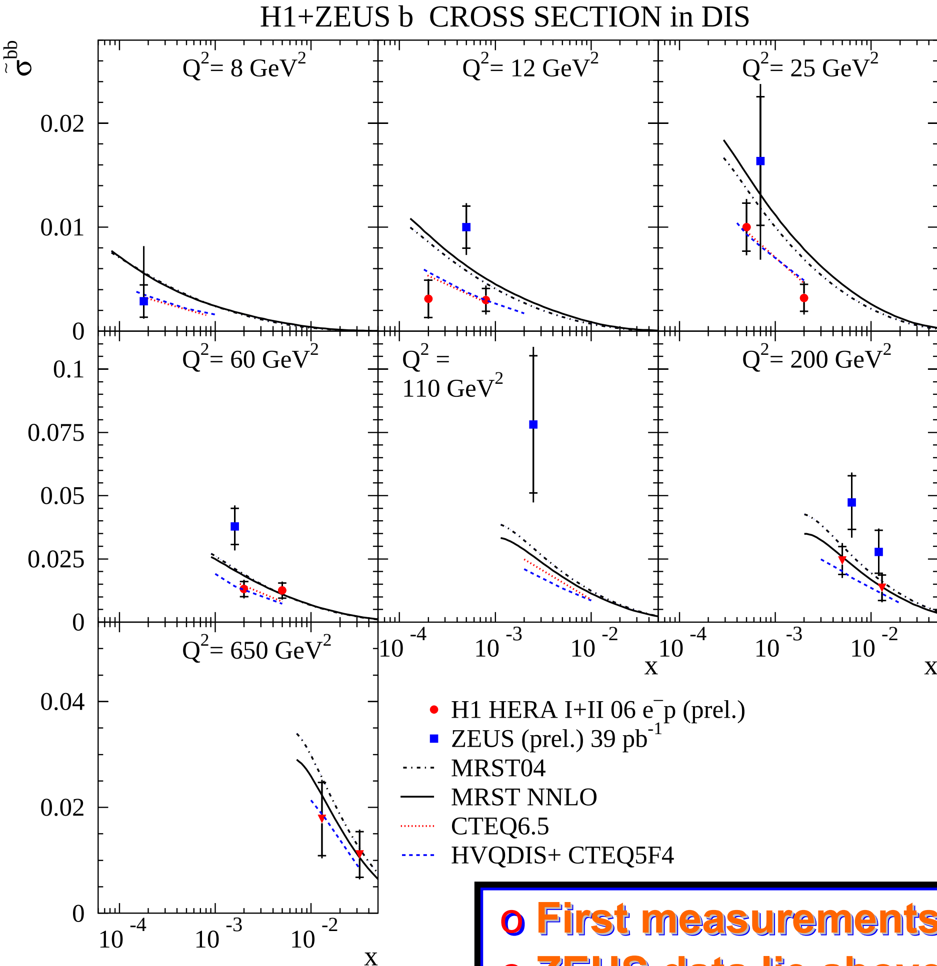
Data ~ 54 pb^{-1}

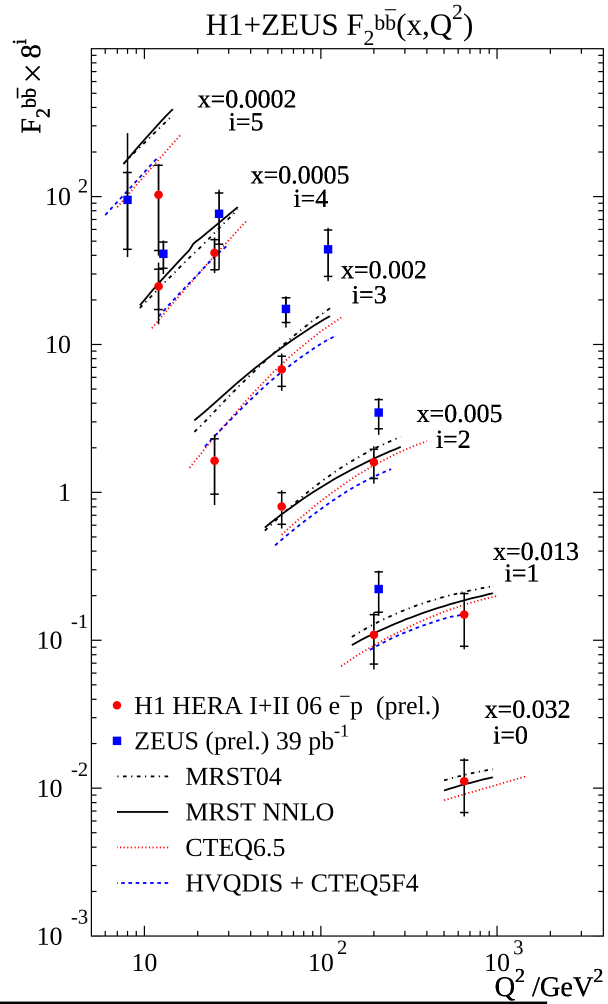




<u>Measured reduced cross section as a function of x in 5 bins of Q^2</u>

H1 + ZEUS

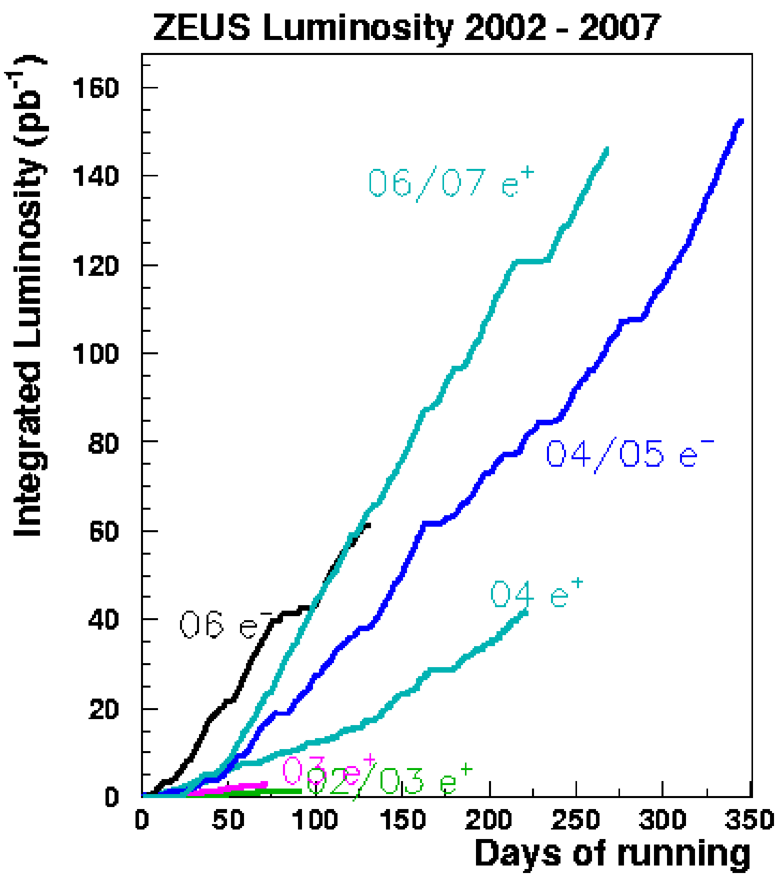




- o First measurements $F_2^{bb}(x,Q^2)$ at H1 with HERA-II data
- o ZEUS data lie above H1 data but compatible within errors
- o At high x and Q^2, still statistically limited
- o MRST04 and CTEQ6HQ differ up to factor two!
- o First NNLO calculations from Robert Thorne
- o Within current experimental errors, theoretical differences can not be yet resolved

Conclusions

- ✓ **Heavy Flavour production in ep collisions is:**
  - good testing ground for perturbative QCD
  - better understanding of multi-scale problem
- ✓ **Good description achieved with NLO calculations in all measurements**
- ✓ **First measurement of F_2^{bb} at H1 with HERA-II data**
  - good agreement between both experiments and with theory (NLO, NNLO)
- ✓ **Most of HERA-II data not analyzed yet:**
  - expect improved results soon!
  - new analyses possible



BACKUP SLIDES

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

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

Beauty Contribution to F_2

The Structure of the Proton

Effect of parity violation

Cross section:

Long. structure function

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

Dominant term to cross section

Significant at high y

Significant at high Q^2

- In the QPM, F^2 can be expressed as:

$$F^2 = F_2^{em} + [Q^2/(Q^2+M_z^2)]\, F_2^{\gamma/Z} + [Q^2/(Q^2+M_z^2)]^2\, F_2^{Z}$$

is dominated by F_2^{em} contribution at low Q2

Theoretical Calculations I

- **Fixed Order (FO):**

- heavy quarks produced at perturbative level
- reliable for $p_T \sim m_Q$

  - Frixione et.al. (FMNR) used for charm and beauty in photoproduction
  - Harris and Smith (HVQDIS) used for charm and beauty in deep inelastic scattering

Theoretical Calculations II

- **Next-to-leading log (NLL):**

-„massless" heavy quarks: active constituents of p and **g**

- masses only used for final state kinematics

- reliable for $p_T \gg m_Q$

  - Cacciari et. Al. and Kniehl et al. used for charm and beauty in photoproduction (only inclusive production, can not do e.g. dijets)
  - No program for DIS

- **Combined (FONLL):**

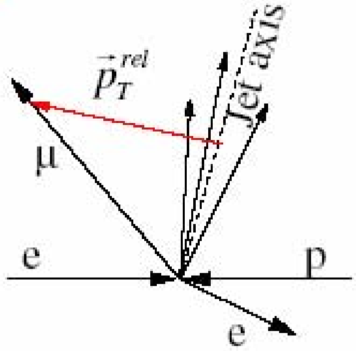
- matched calculations of both schemes

- FO at low p_T, NLL at large p^T

Beauty identification

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

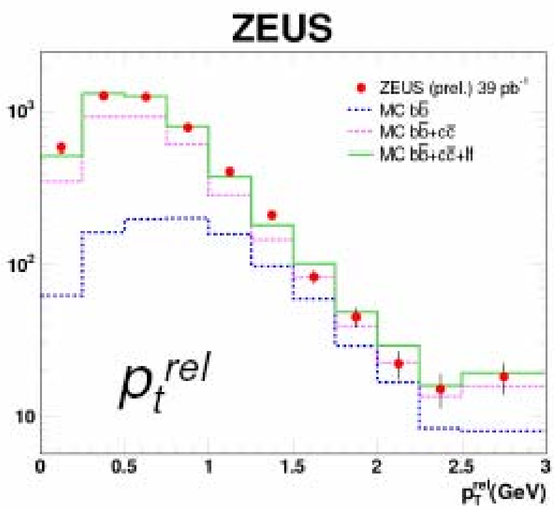
p_t^{rel} method:



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

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:

$$\tilde{\sigma}^{b\bar{b}}_{data}(x, Q^2) = \tilde{\sigma}^{b\bar{b}}_{NLO}(x, Q^2)\left(\frac{d^2\sigma^{b\bar{b}\to\mu}_{data}}{dx\,dQ^2} \Big/ \frac{d^2\sigma^{b\bar{b}\to\mu}_{NLO}}{dx\,dQ^2}\right)$$

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