Ringberg Castle 8 October 2008

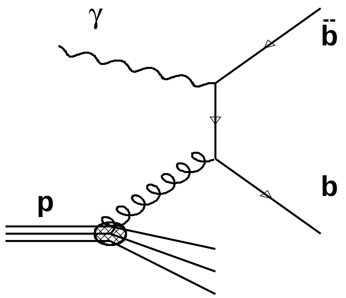
Beauty production and $F_2^{b\bar{b}}$

Massimo Corradi

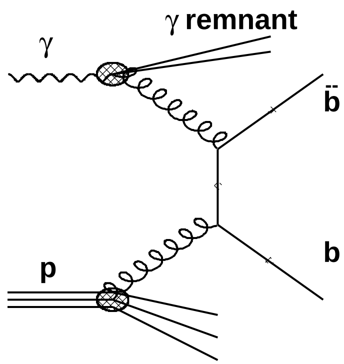
INFN Bologna

Introduction

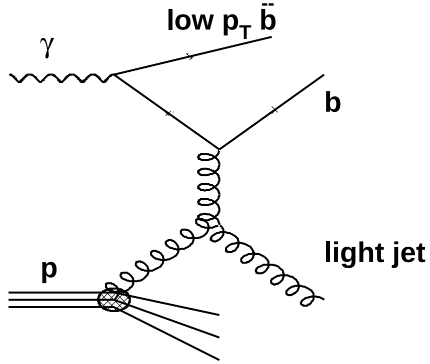
$$ep \longrightarrow e'b\bar{b}X$$



Direct (BGF)



Resolved (Flavour Creation)



NLO diagram

- leading order: boson-gluon fusion (BGF)
- photoproduction ($Q^2 \sim 0$): hadronic γ component
- NLO known from the '90
  (full final state codes: FMNR (γp), HVQDIS(DIS))
- some "large" correction beyond LO can be seen as a NLO diagram
  or as "flavour excitation" (b from photon PDF)

Introduction

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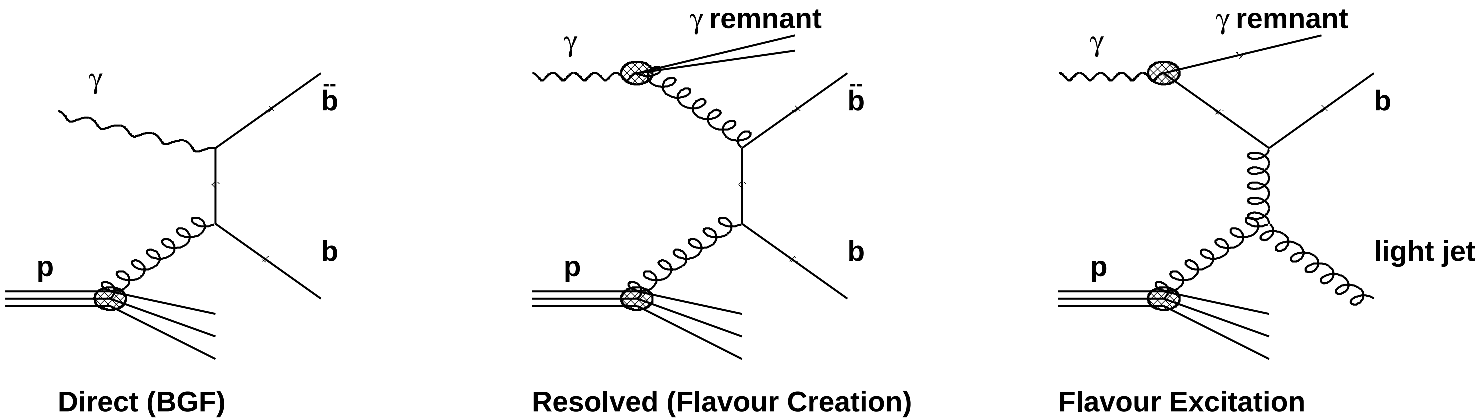

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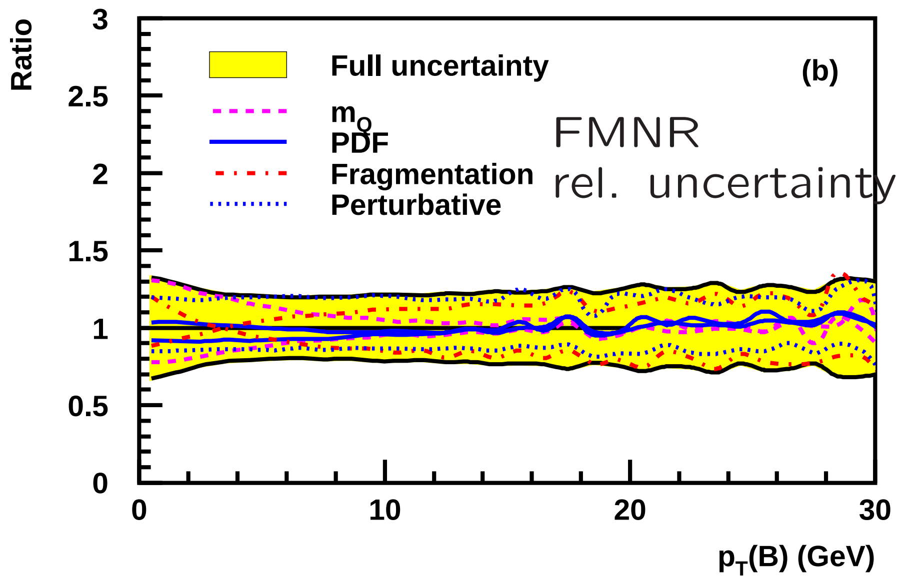
Theoretical uncertainties (photoproduction)

- uncertainty on total cross section (FMNR):
  - 30% from mass $4.5 < m_b < 5.0$ GeV
  - 20% from scale variation $\Longrightarrow$

  $\mu_r = \mu_f = 2^{0\pm1}\sqrt{m^2 + \langle p_t \rangle^2}$

  mass probably known better

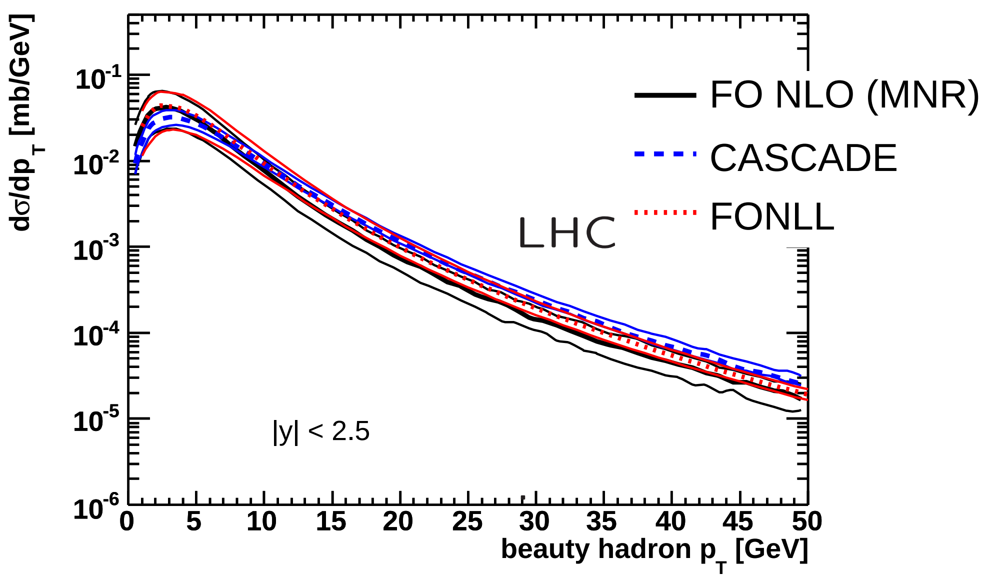
  $m_b^{\bar{M}S}(m_b) = 4.16 \pm 0.02$ (Kuehn et al. 07)



- for $p_T \gg m_b$ and near threshold, precision of fixed order (FO) limited, need resummation (FONLL, GMVFNS, MC@NLO)

- possible "low"-x effects beyond collinear QCD in K_T–factorization (LZ, Cascade)

- FO, "resummed" and k_T–fact. agree
  "resummed" have smaller unc. at large p_T
  $\Longrightarrow$



- in some 3-jet corner of the phase space NLO is effectively LO e.g.

  low-$x_\gamma^{\rm obs} = (E - P_z)_{2j}/(E - P_z)_{\rm all}$

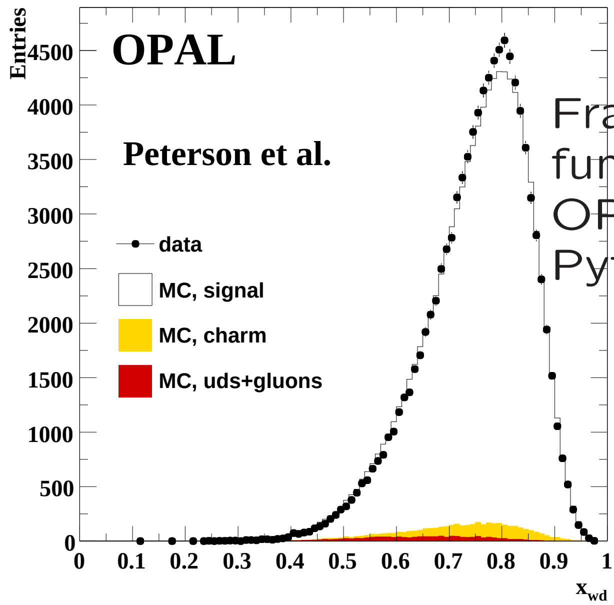
  $\Delta\Phi_{jj} << \pi$

Non-perturbative uncertainties

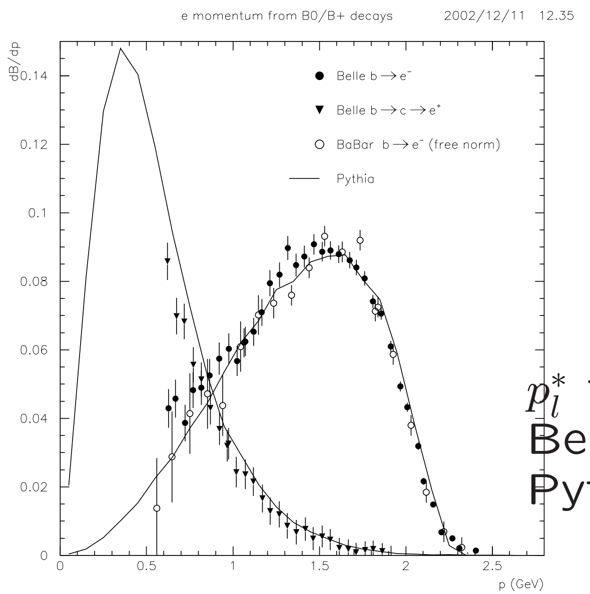
- **fragmentation** $(b \to B)$
  fragm. function (FF)
  - well measured at LEP, SLC
  - parton level convoluted with FF
  or interfaced to MC
  (MC@NLO, FMNR×Pythia)
  - Small effect for b (NOT for c!)
  (in general $\Delta p_t/p_t = \mathcal{O}(< \Lambda/m_b)$)

- **jet hadronisation**
  - jet observable need had. corrections
  - based on MC (Pythia/Herwig)
  - minimised by good hadron–level definition
  (K_T, massive recomb., B hadron included)
- **decay**
  - decay lepton spectrum needed for
  leptonic observables
  - well measured at B factories
- **PDF**
  - cross section $\propto$ gluon at
  $Q^2 \geq m_b^2$, $0.001 < x <\sim 0.05$
  - unc. $\sim 3-6\%$ (MRST2001E–CTEQ6.6)

Non–perturbative uncertainties are small ($\sim 5\%$)



Fragmentation function OPAL vs Pythia+Peterson



p_l^* from B decay Belle+BaBar vs Pythia

Experiment: leptonic tags

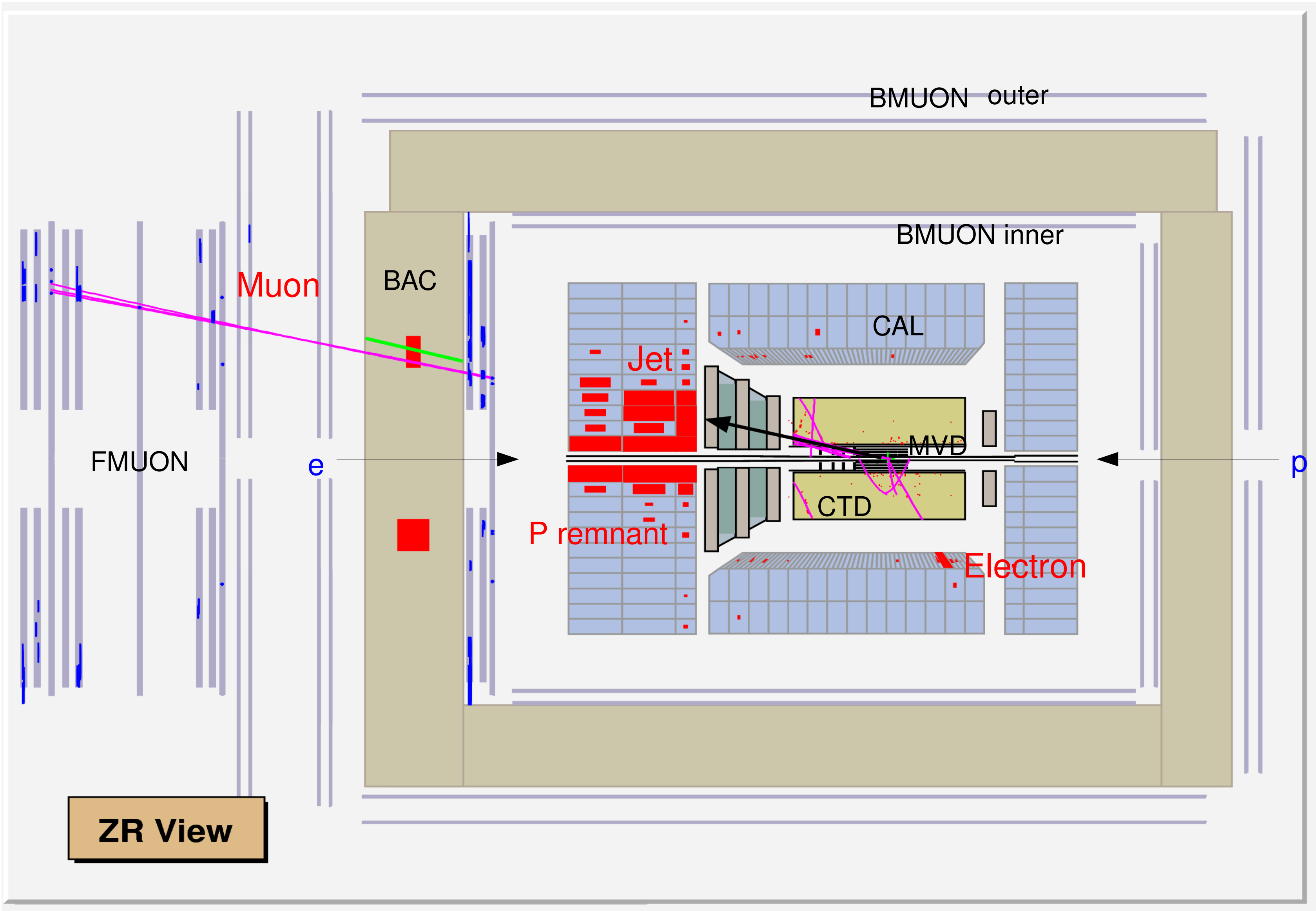
- beauty cross section at HERA is ~ 10 nb
  small fraction of the total:
  $r = \sigma_{b\bar{b}}/\sigma_{\text{tot}} \sim 0.1\%$ (cfr charm $\sigma_{c\bar{c}}/\sigma_{\text{tot}} \sim 5\%$)
  increases to $r \sim 6\%$ in High-E_T jets and $r \sim 1-4\%$ in DIS at large Q^2
  BGF limit $Q^2 >> m^2$, $x \ll 1$: $r = 1/11$

- requiring an high-p_T lepton increases the fraction to $r \sim 20\%(10\%)$ in dijets (DIS)
  $B(b- > lX) \sim 22\%$ including cascade decays $b \to c \to lX$

- μ channel,
  ID based on muon chambers
  backgrounds from c and "fake" muons (decays of K, π, punch–through)

- e channel,
  ID based on CAL shower shape and dE/dx
  backgrounds from c, photon conversions, $\pi \to e^+e^-\gamma$, wrongly identified hadrons

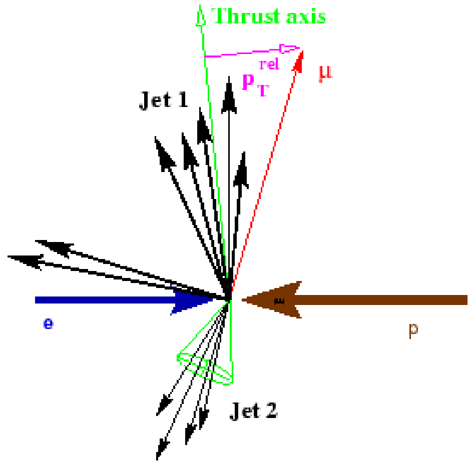
A DIS event with a muon in ZEUS

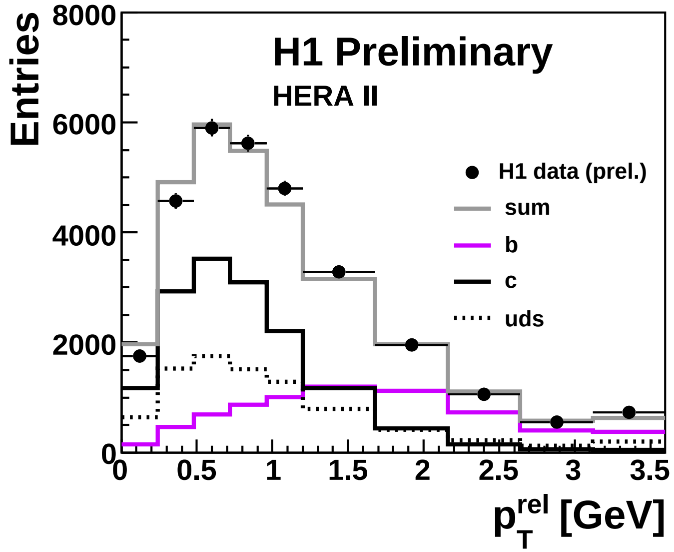


Extraction of b fraction

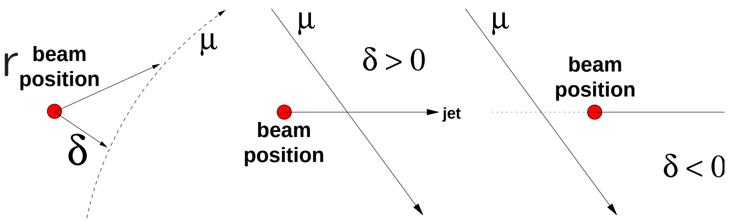
Beauty content extracted statistically from fits to discriminant variables, e.g.

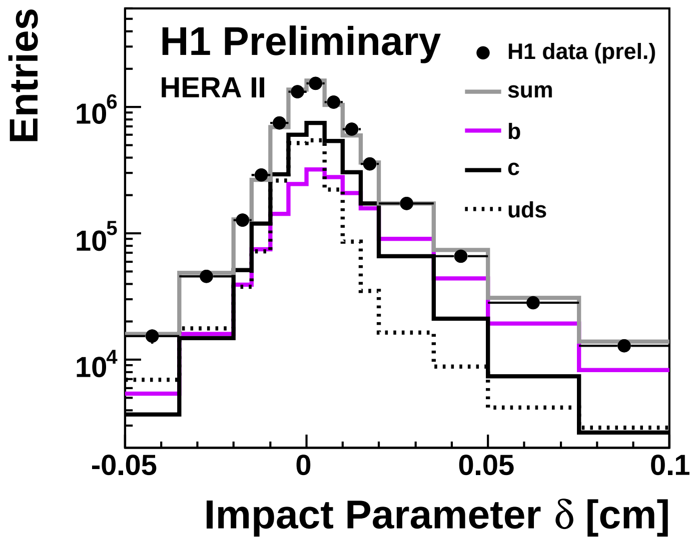
p_T^{rel}:
- transverse lepton momentum w.r.t. jet axis
- needs good MC templates
- can be obtained from inclusive data





δ:
- Signed impact parameter
- needs precise Si tracker (H1 CST, ZEUS MVD)

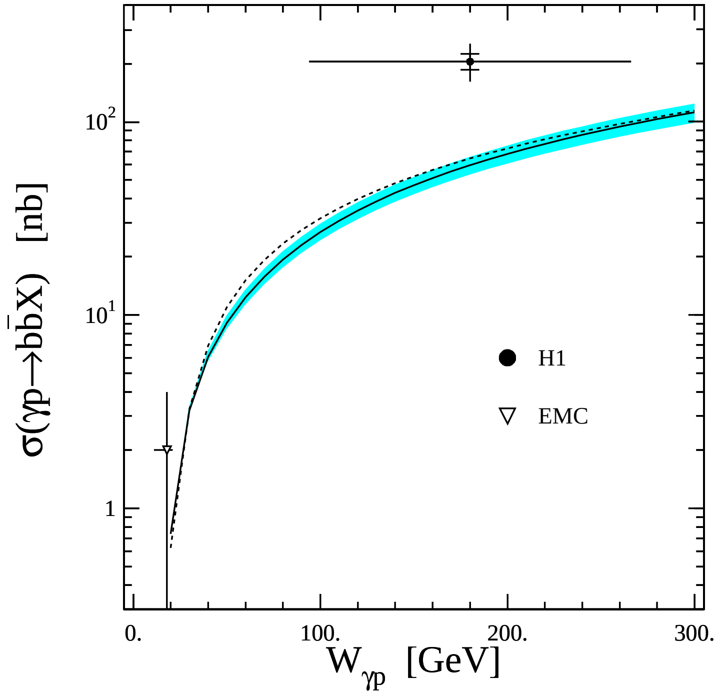


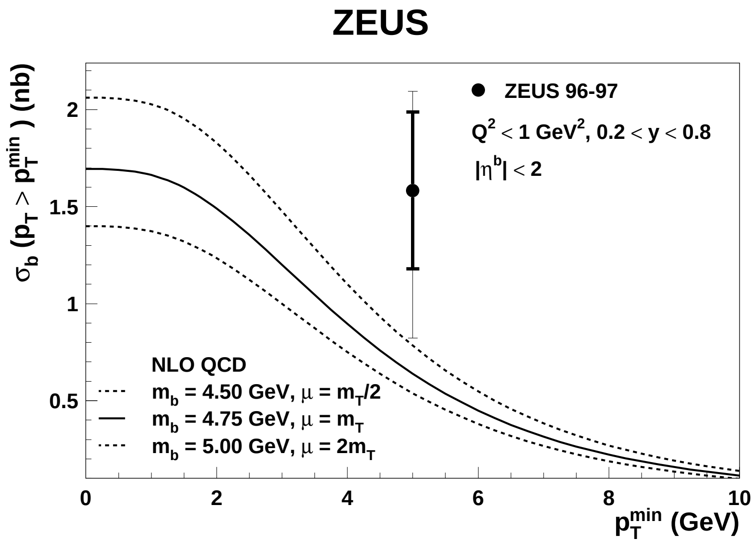


First HERA results (∼2000)

- H1, $ep \to b\bar{b}X \to \mu jjX'$
  - p_T^{rel}
  - factor 3 excess over NLO
  - PLB 467 (1999) 156, Erratum-ibid. B518 (2001) 331

- ZEUS electron plus 2 jets
  - p_T^{rel}
  - Large uncertainty, inconclusive
  - EPJC 18 (2001) 625



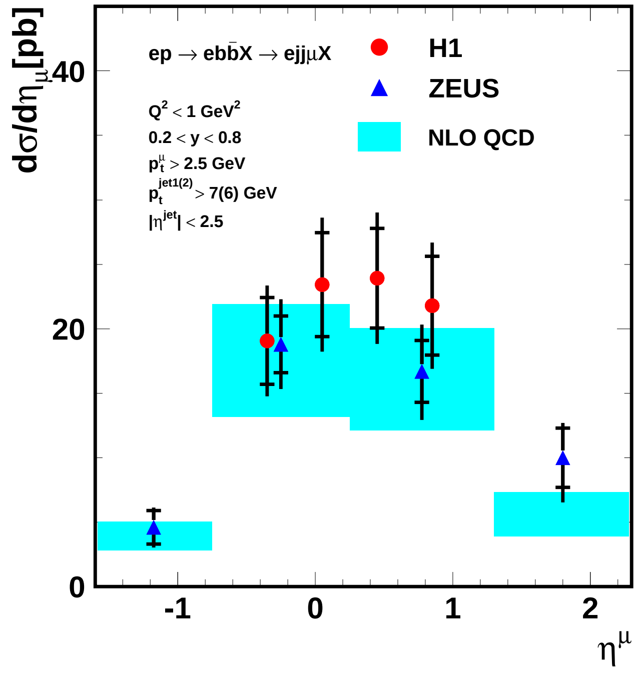


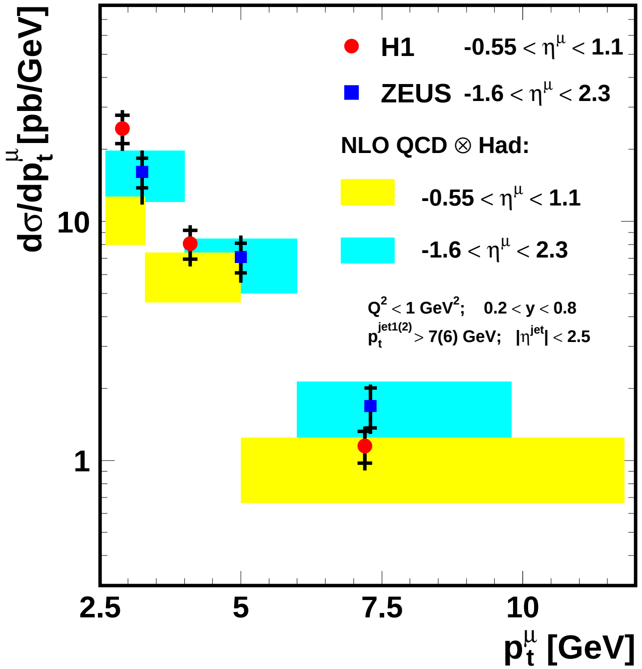
Second generation (∼2003-2004)

- ZEUS, $ep \to b\bar{b}X \to \mu jjX'$
  - $0.2 < y < 0.8$, $Q^2 < 1$ GeV^2
  $p_T^\mu > 2.5$ GeV, $-1.6 < \eta^\mu < 2.3$
  $p_T^{\text{jet}} > 7,6$ GeV
  - HERA I data
  - p_T^{rel}
  - Agreement with NLO
  - .ZEUS, PRD 70 (2004) 012008,
  .Erratum: ibid. D74 (2006) 059906(e)

- H1,$ep \to b\bar{b}X \to \mu jjX'$
  - similar kinematic region but
  $-0.55 < \eta^\mu < 1.1$ range
  - HERA I data
  - p_T^{rel}, δ
  - General in agreement with NLO
  excess at low p_T^μ ?
  - H1, EPJC 41 (2005) 453

- uncertainties 15% (for total), 20-30% (for diff.)





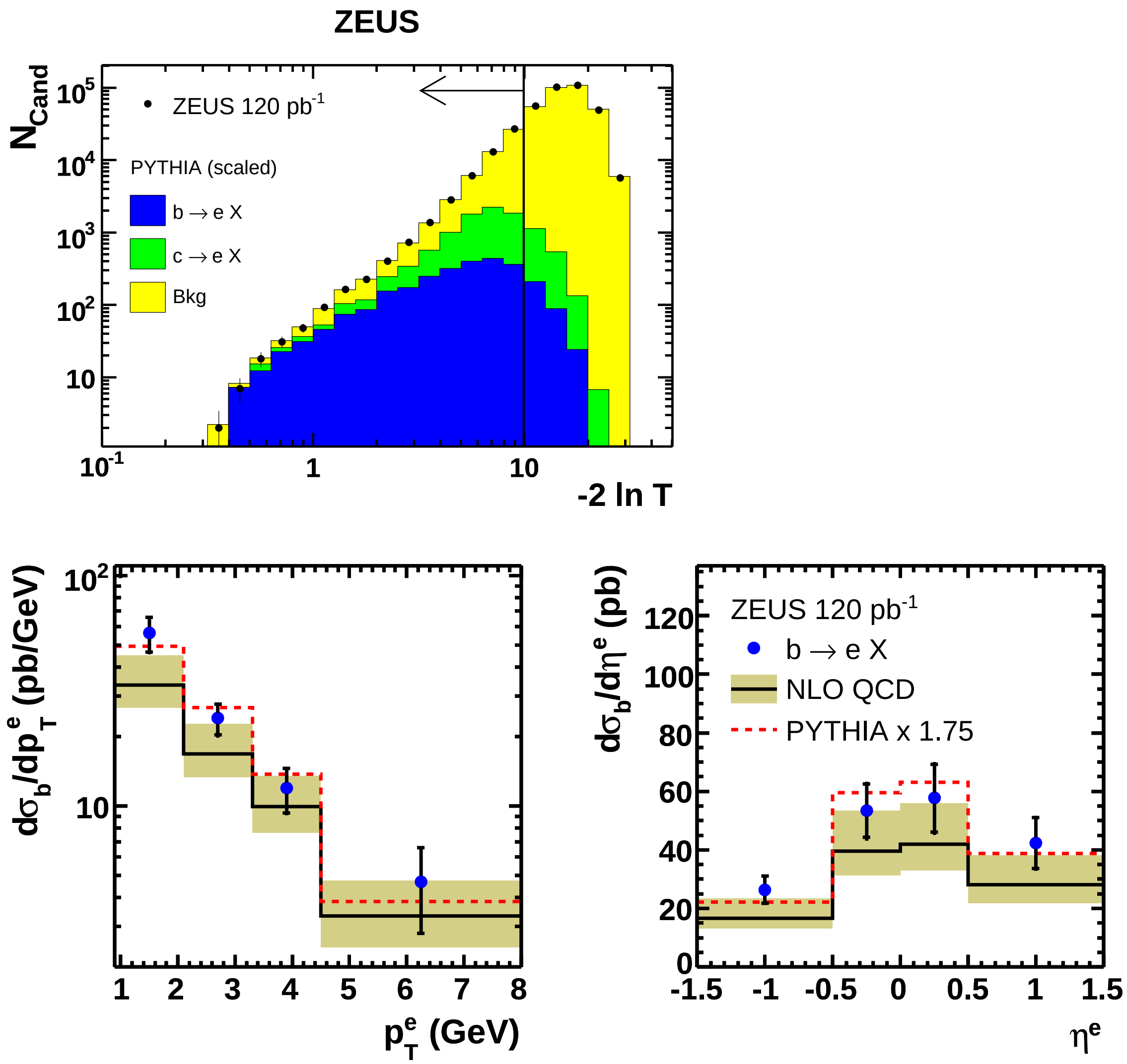
ZEUS results with electron tag

- ZEUS, $ep \to b\bar{b}X \to ejjX'$
  - similar kinematic region
  lower threshold: $p_T^e > 0.9$ GeV
  - HERA I data
  - $p_T^{\rm rel}$ for c/b separation
  - Likelihood method to distinguish semileptonic electrons

  - Agreement with NLO

  - DESY-08-056

- similar uncertainties to muon data

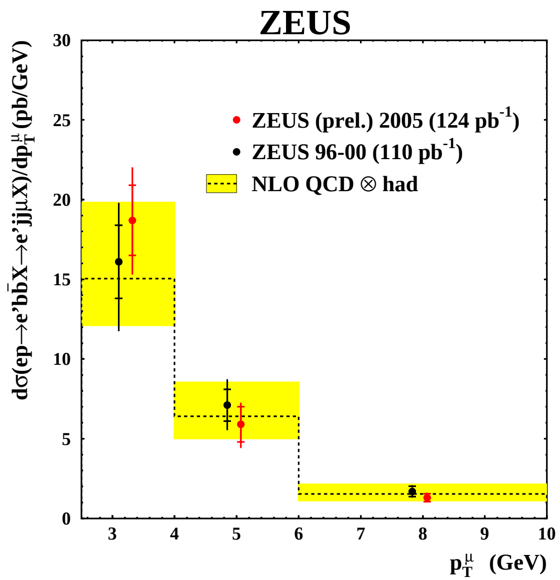


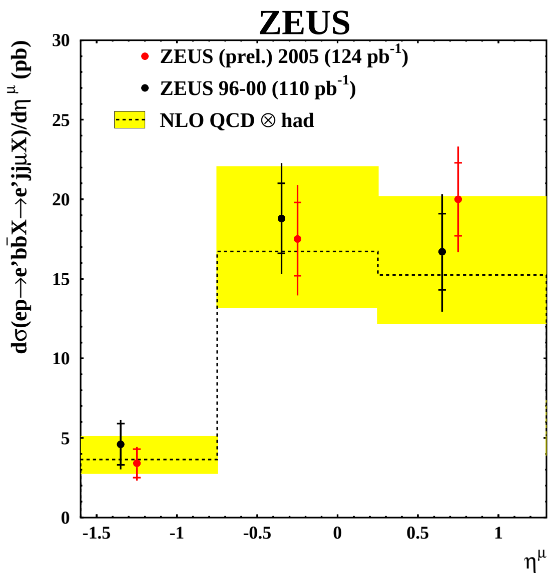
New HERA II muon tag results (2006-2008)

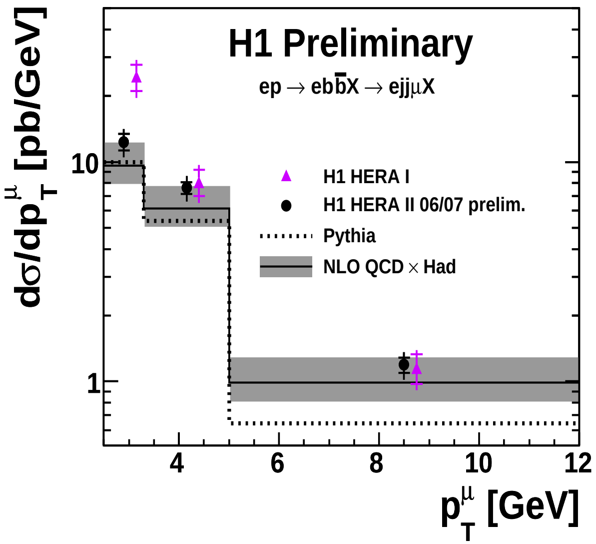
- ZEUS, $ep \to b\bar{b}X \to ejjX'$
  - same kinematic region
  - $p_T^{\rm rel}, \delta$
  - 125 pb^{-1}, HERA II (2005)
  - Agrees with previous results and NLO
  - ZEUS prel. for EPS05 (2004 data), EPS07 (2005 data)

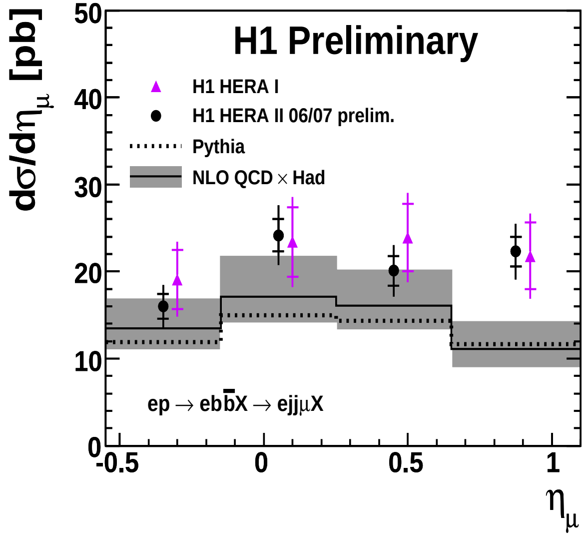
- H1 $ep \to b\bar{b}X \to ejjX'$
  - same kinematic region
  - $p_T^{\rm rel}, \delta$
  - HERA II (2006+2007) 170 pb^{-1}
  - Agrees with NLO, ZEUS, no more low-p_T^{μ} excess
  - H1 prel. for ICHEP 2008

- H1 uncertainties $\sim 13-20\%$ dominated by systematics



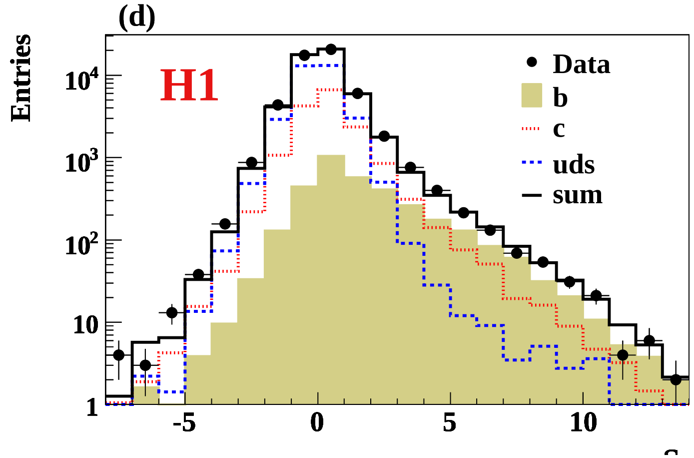


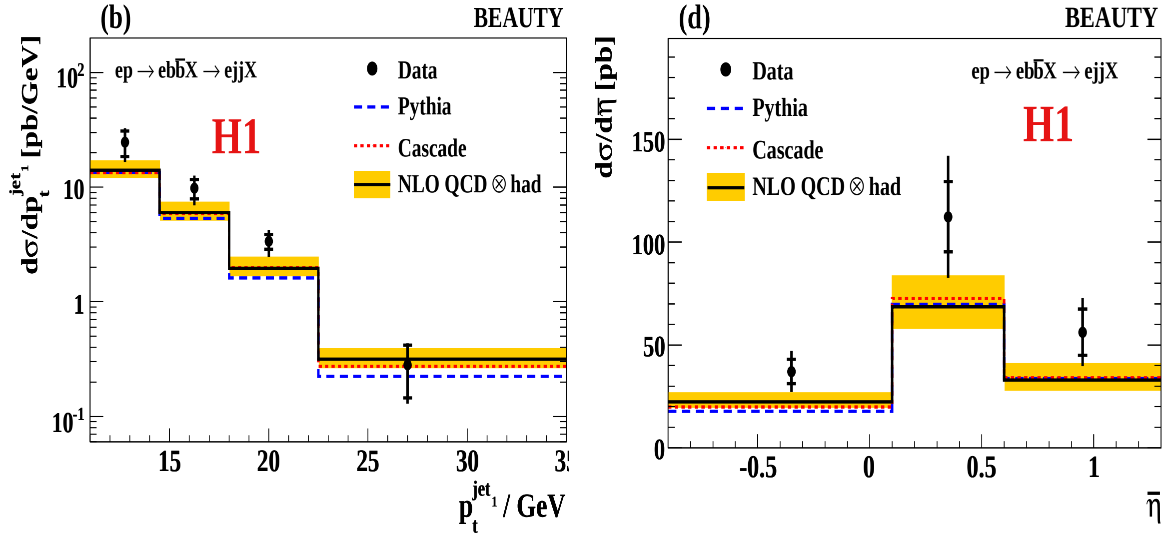




Inclusive lifetime tags, H1 dijet results

- H1 $ep \to b\bar{b}X \to jjX'$
  - $p_T^j > 11(8)$GeV, $-0.9 < \eta^j < 1.3$
    no lepton requests
  - HERA I data
  - fraction of c, b extracted from impact parameter significance $S = \delta/\sigma_\delta$ of inclusive tracks (2$^{\text{nd}}$–highest S most effective for b)
  - Good understanding of tracking needed!
  - EPJC 47 (2006) 597-610
  - Agreement with NLO
- uncertainties $\sim 20-30\%$





Double tag methods

- Double tag analyses (μD^*, $\mu\mu$) allow to access low p_T^b (no jets requirements)

- Latest results: ZEUS, $\mu\mu$

- HERA I data
  DESY-08-129

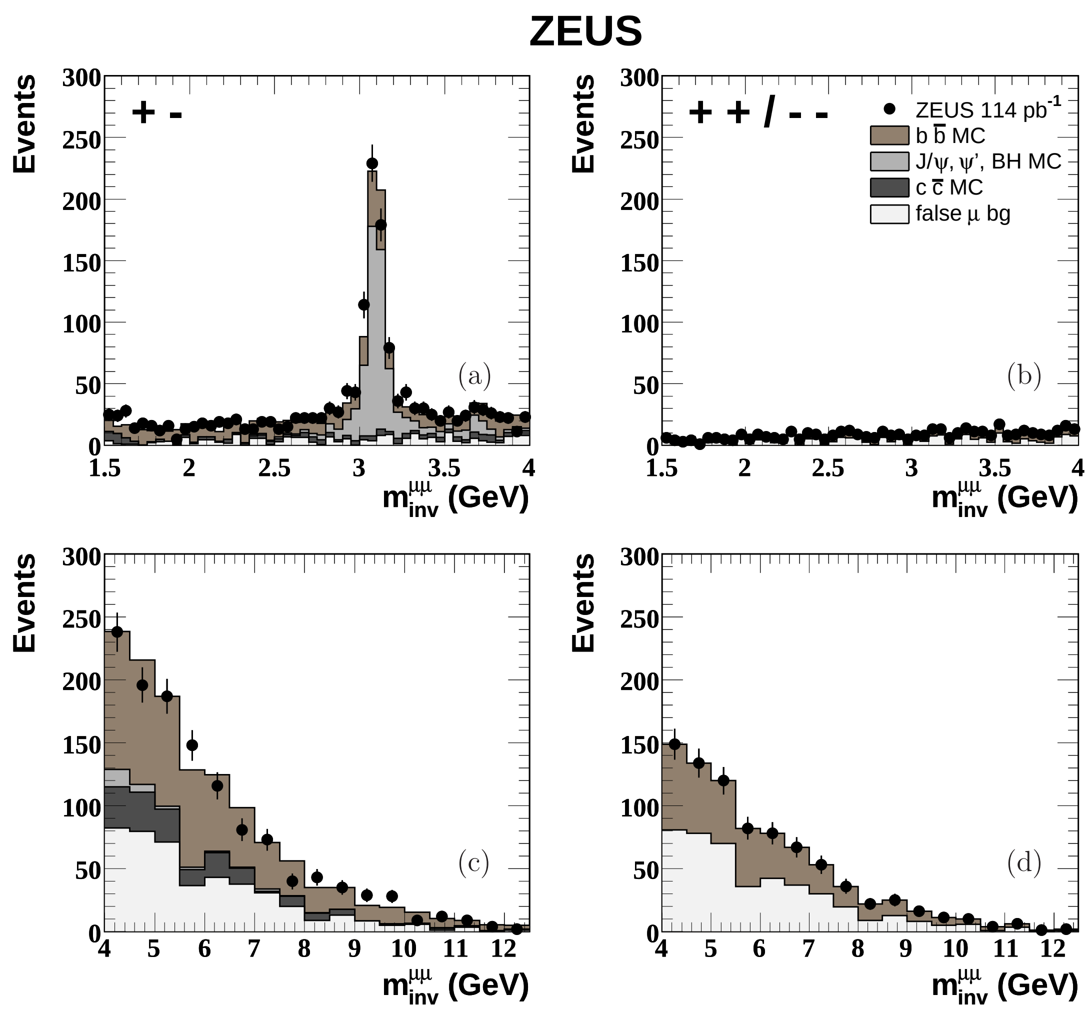
- High mass (> 4 GeV) non-isolated dimuon pairs:

$\mu^-\mu^-$,$\mu^+\mu^+$	$\mu^+\mu^-$
$b \to \mu^-, \bar{b} \to \bar{c} \to \mu^-$ fake μ	$b \to \mu^-, \bar{b} \to \mu^+$ charm, ψ, B.H. fake μ

- fake μ are symmetric
  $N(\mu^-\mu^-) = N(\mu^+\mu^-)$

- charm and other sources small and known

- $\Rightarrow$ extract beauty



Dimuons and $\sigma_{\mathrm{tot}}^{b\bar{b}}$

- diff. cross sections for $p_T^\mu > 1.5$ GeV $\eta^\mu < 2.5$
  -Agreement with (upper side of) NLO band

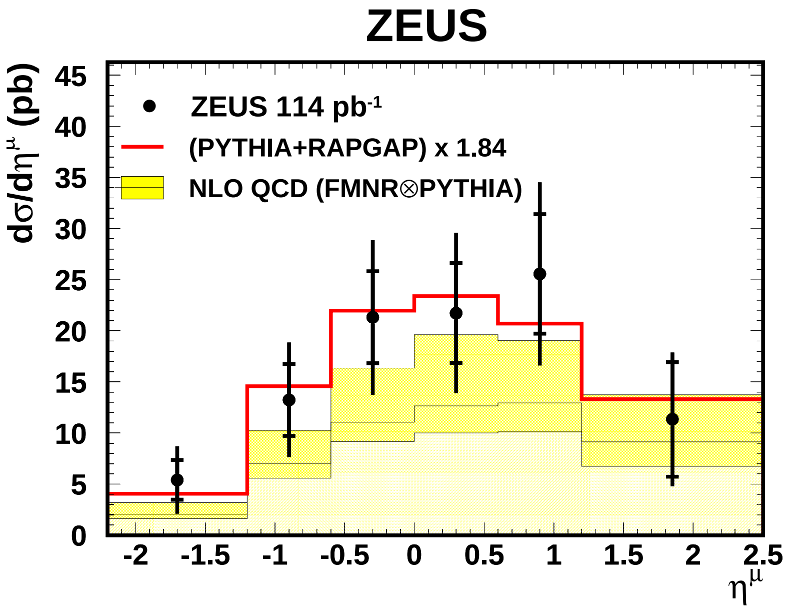
- Almost full b quark phase space coverage
  (except most forward 10%)
  allows a reliable extraction of σ_{tot}

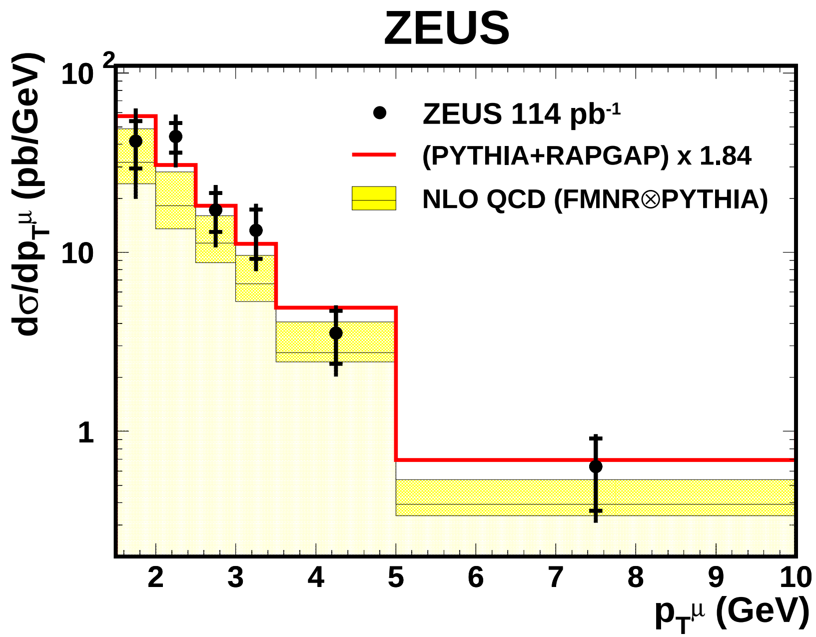
- uncertainty 30% for σ_{tot}

$$\sigma_{\mathrm{tot}}(ep \rightarrow b\bar{b}X) = 13.9 \pm 1.5(\mathrm{stat.})^{+4.0}_{-4.3}(\mathrm{syst.})\mathrm{nb}$$

To be compared with

$$\sigma_{\mathrm{tot}}^{\mathrm{NLO}}(ep \rightarrow b\bar{b}X) = 7.5^{+4.5}_{-2.1}\mathrm{nb}$$



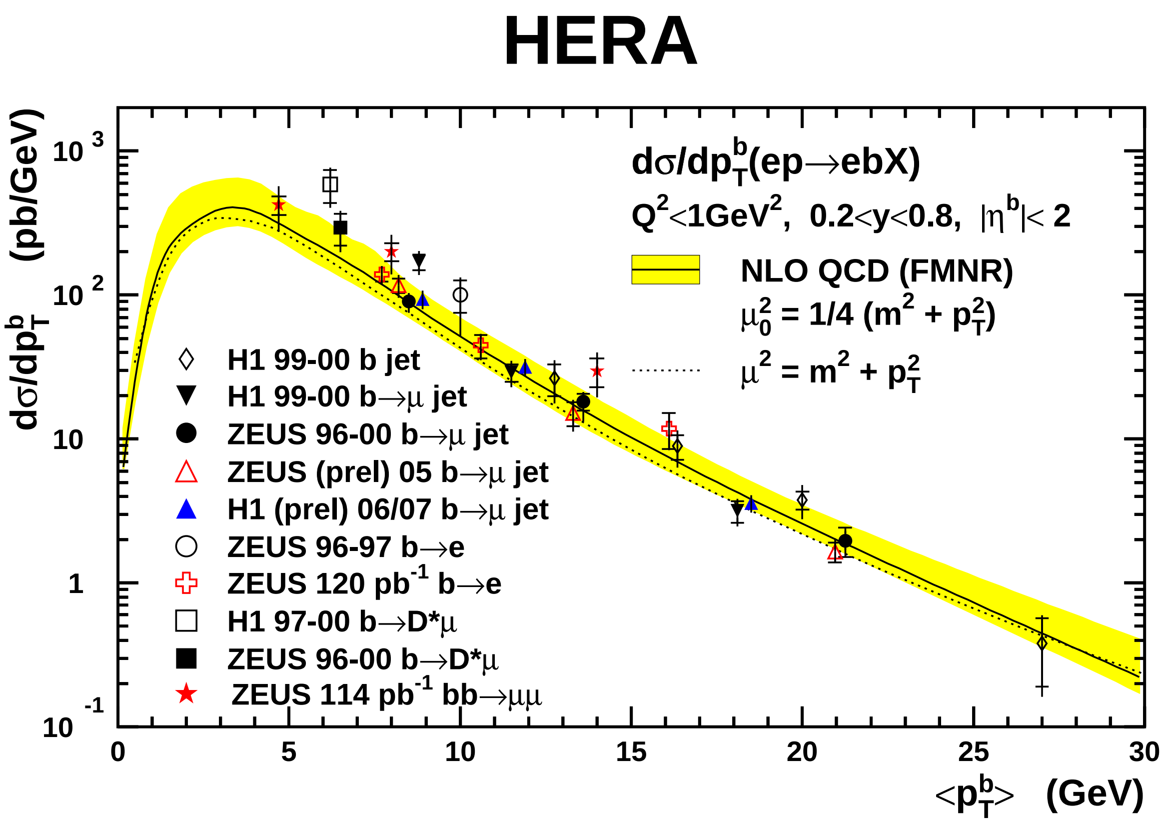


The "summary plot"

Each measurement in a visible kinematic range σ_{vis} translated in $d\sigma/dp_T^b$ at the average p_T^b of the reconstructed sample

$$\frac{d\sigma}{dp_T^b} = \sigma_{\text{vis}} \times \frac{d\sigma^{\text{NLO}}/dp_T^b}{\sigma_{\text{vis}}^{\text{NLO}}}$$

Results obtained with different methods and by different experiments in good agreement



Agreement with NLO with
$m_b = 4.75 \pm 0.25$ GeV
$\mu_R = \mu_b = \frac{1}{2}(2^{0\pm1})\sqrt{\langle p_T^b\rangle^2 + m_b^2}$,
(new scale choice, see A. Geiser DIS07)
Older central value
$\mu_r = \mu_f = \sqrt{\langle p_T^b\rangle^2 + m_b^2}$

Two choices ~ equivalent, all within perturbative uncertainties

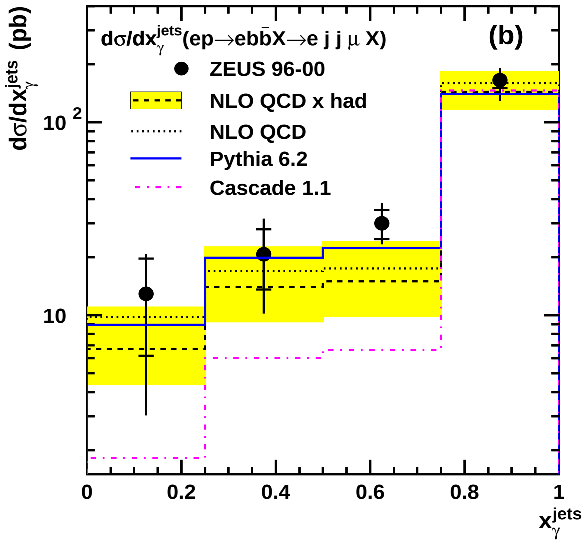
Need more precise theory now to get a real improvement

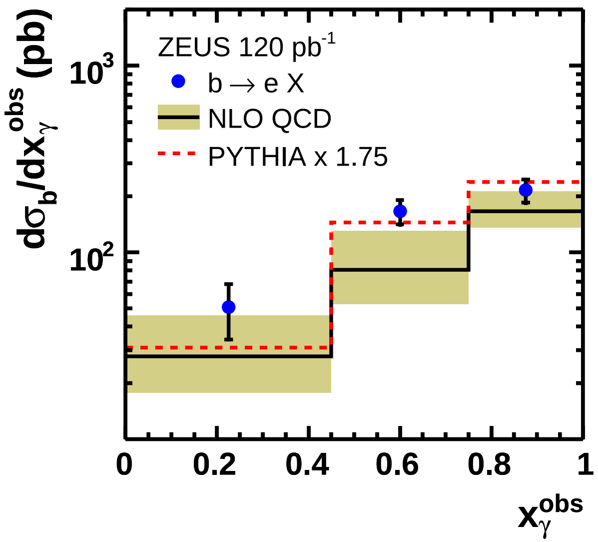
A closer look at x_γ^{obs}

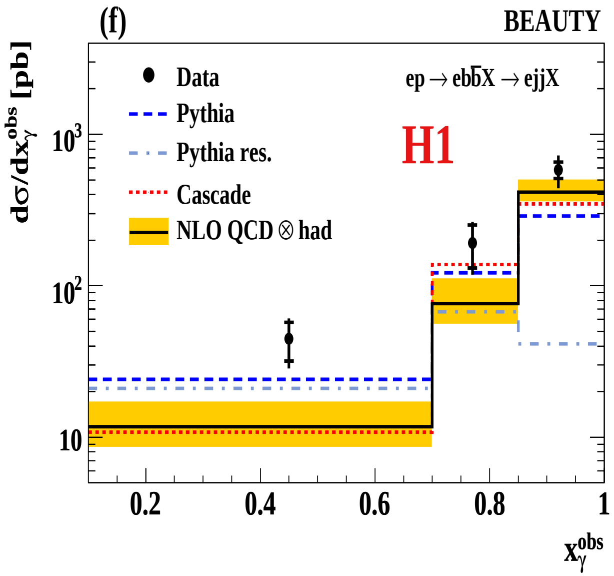
- what about resolved–photons and "flavour excitation" (i.e. low x_γ) ?

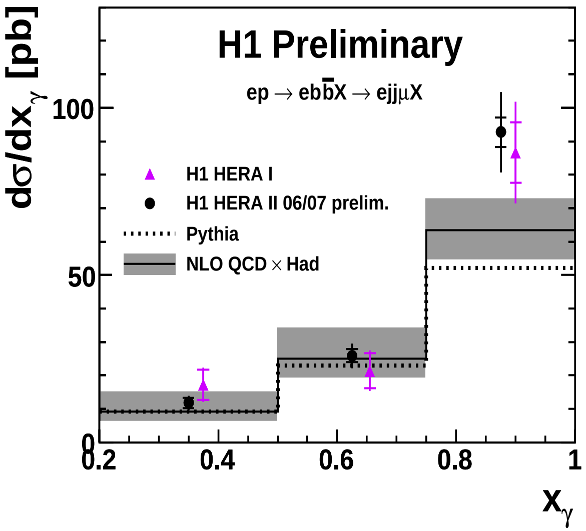
- x_γ^{obs} has been measured by most of the dijet analyses

- No serious discrepancy within the present data/theo. precision







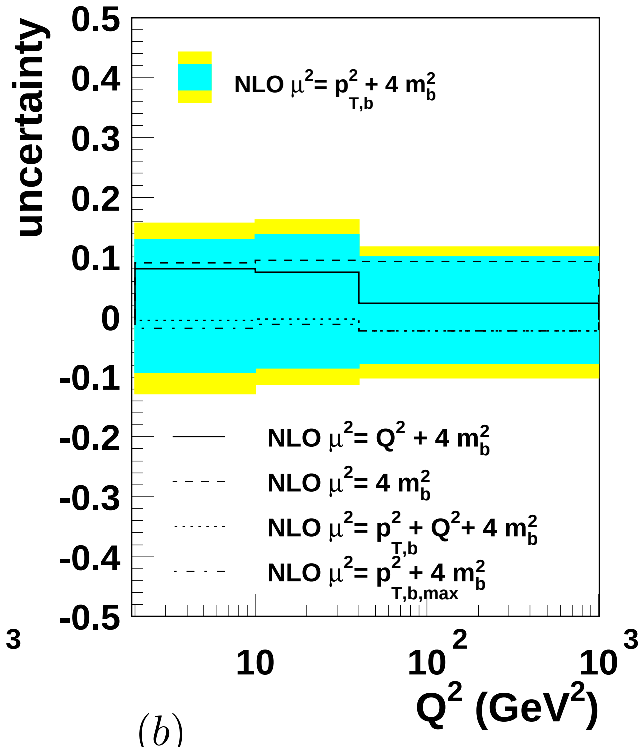


Beauty in DIS

- b fraction in DIS smaller than in high$-E_T$ jets more difficult measurement
- HVQDIS: NLO theoretical tool for "visible" cross sections with "final state" cuts
- theoretical uncertainties smaller than for photoproduction:

  for $Q^2 > 20$ GeV^2
  - 15% mass variation $4.5 - 5.0$ GeV
  - 10% scale μ_r varied by factor 2
  - 3-6% from PDFs
  (mass unc. can be reduced)

- measuring b in DIS with enough precision would provide a test/constraint of the gluon PDFs (if the (small) scale uncertainty is realistic)



(b)

inner band: scale var. by 2
outer band: + mass var.

First generation: $\mu + j$ results (2005)

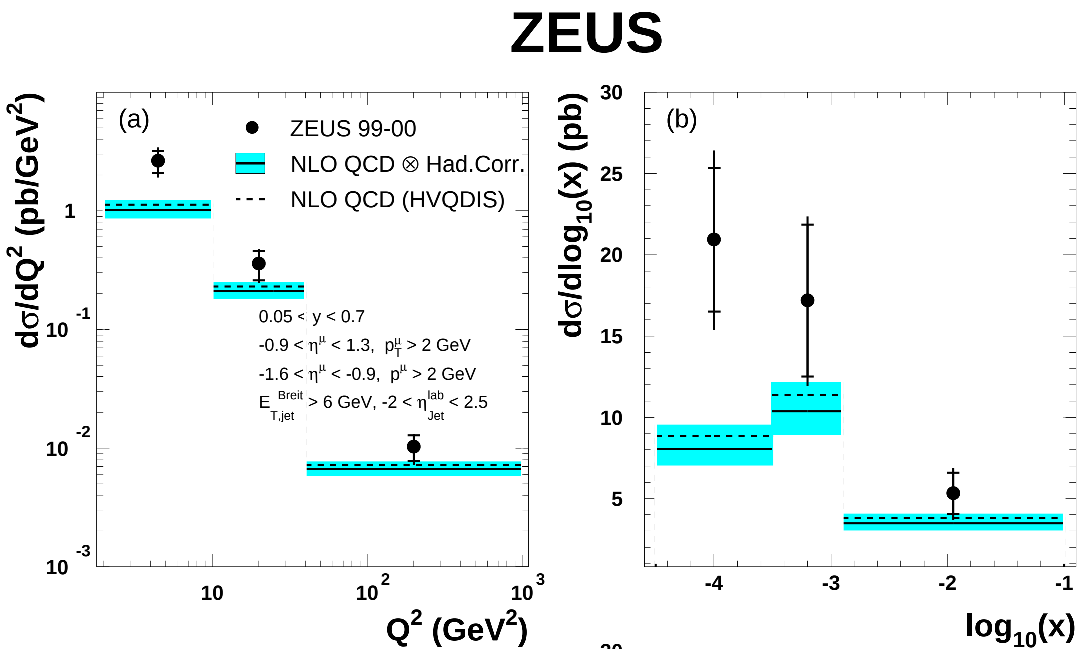
- Initial strategy: require a jet in the Breit Frame to enhance the fraction of BGF–like events

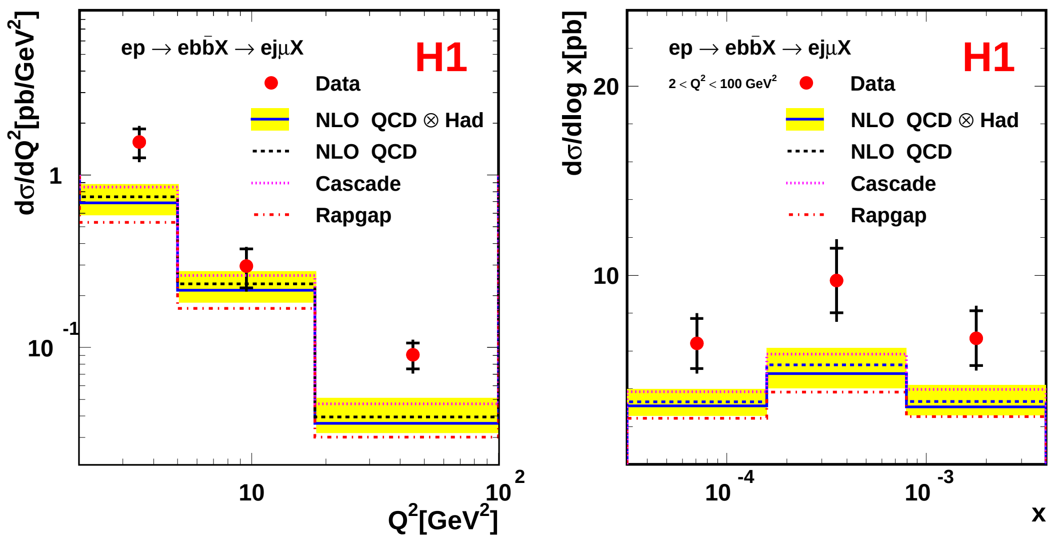
- ZEUS $e \to e'b\bar{b}X \to e'\mu jX'$
  - $p_T^\mu > 2$GeV, $E^j_{T,\mathrm{Breit}} > 6$GeV
  - p_T^{rel}
  - HERA-I data
  - PLB 599 (2005) 173

- H1 $e \to e'b\bar{b}X \to e'\mu jX'$
  - almost same kin. region
  - HERA-I data
  - $p_T^{\mathrm{rel}}, \delta$
  - H1, EPJC 41 (2005) 453

- Both above theory at low Q^2 but large errors

- is the theoretical uncertainty under-estimated ?
  need for resolved photons at $Q^2 < m_b^2$?





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

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

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

- Shift of focus from differential cross sections in a visible kinematic range to the beauty structure function $F_2^{b\bar{b}}(x,Q^2)$
  - \+ it is more fundamental (i.e. simpler to calculate): no need for fragmentation, decays, jet hadronisation, final state cuts
  - \+ many theoretical predictions for $F_2^{b\bar{b}}$ beyond simple NLO: e.g. GMVFNS, effective resummation at large Q^2
  - \+ allows a direct comparison of various measurements with different observables
  - – introduces a theoretical uncertainty due to the extrapolation beyond the observed phase space
  - – is $F_2^{b\bar{b}}(x,Q^2)$ an IR safe quantity ?

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

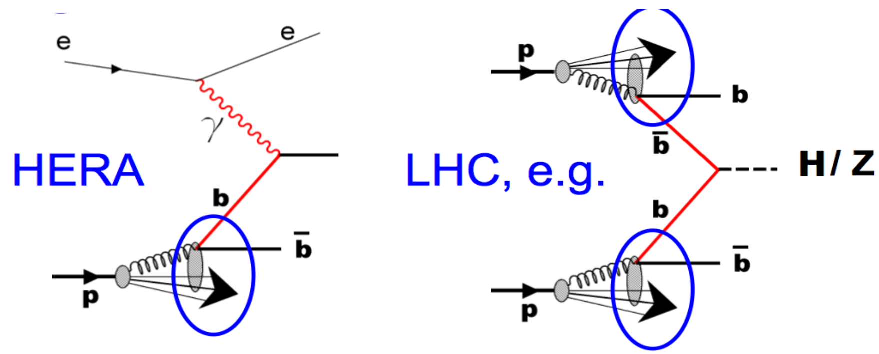
- b PDF not strictly needed as light quark PDFs
  we can live with $n_f = 3$ in the PDFs and the heavy quarks generated dynamically (see e.g. GRV PDFs)
  (fixed flavour number scheme FFNS)
  approach used in FMNR, HVQDIS

- possible intrinsic heavy quark component (Brodsky)
  no evidence for c; b should be even smaller

- b PDF can be anyway generated radiatively at $Q^2 > m_b^2$ (VFNS), useful under two aspects:

  1. resums effectively large logs of Q^2/m_b^2
     VFNS more precise than FFNS
     at $Q^2 \gg m_b^2$

  2. useful to calculate b–initiated processes at pp colliders:
     $b\bar{b} \to H$ simpler than
     FFNS equivalent $gg \to b\bar{b}H$



- $F_2^{b\bar{b}}$ is close to a the beauty PDF
  LO ZM-VFNS: $F_2^{b\bar{b}} = \frac{4}{9} b(x, Q^2)$
  $F_2^{b\bar{b}}$ is a direct handle on the b PDF

Status of $F_2^{b\bar{b}}$ last year

- H1, inclusive lifetime tag

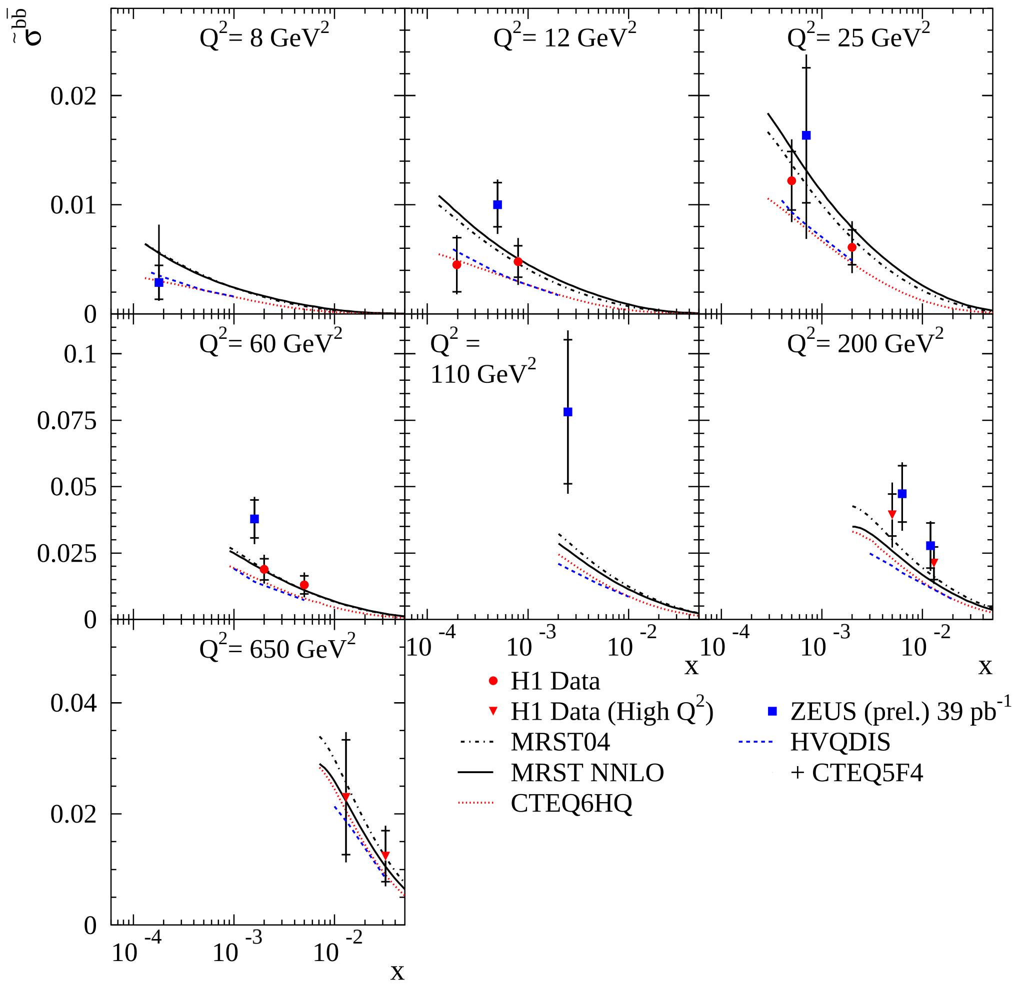
  - inc. track i.p. significance S
  - fit fraction of c and b
  - HERA I data
  - EPJC 40 (2005) 349, EPJC 45 (2006) 23

- ZEUS muons
  $p_T^{\mu} > 1.5$ GeV, jet $p_T > 4$ GeV
  first 39pb^{-1} of HERA II
  p_T^{rel}
  - prel. for DIS07

- uncertainties 30-50%

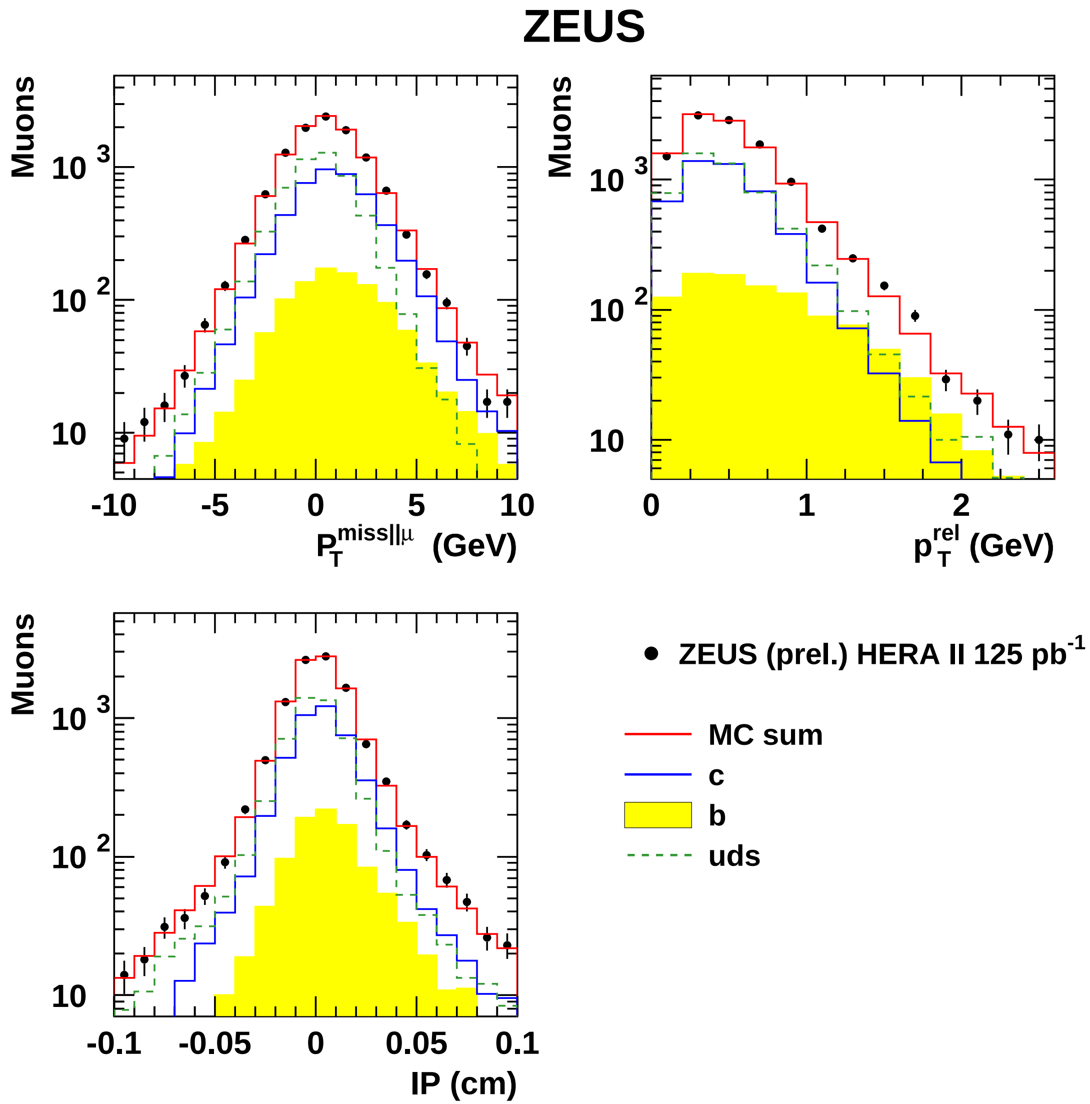
- ZEUS somewhat higher than H1, but still compatible

- large spread of prediction
  different treatment of mass threshold



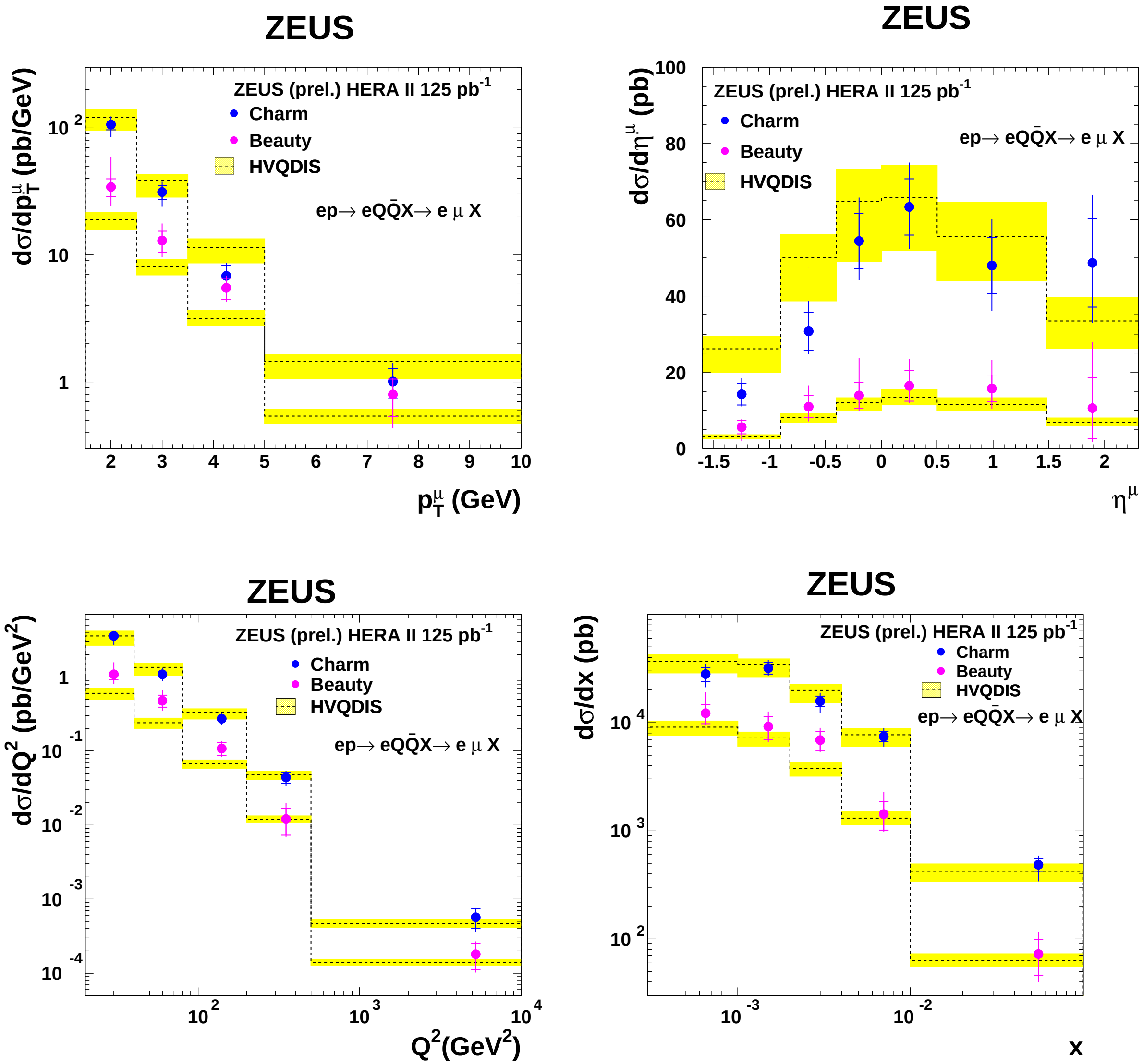
New ZEUS HERA II measurement

- ZEUS, muons in DIS
- $Q^2 > 20$ GeV^2, $0.01 < y < 0.7$, $p_T^\mu > 1.5$ GeV, $-1.6 < \eta^\mu < 2.3$
- 2005 data (125 pb^{-1})
- fit to p_T^{rel}, δ and $p_T^{\text{miss}||\mu}$, missing momentum parallel to μ (tags neutrinos from SL decays) needs good p_T^{miss} measurement



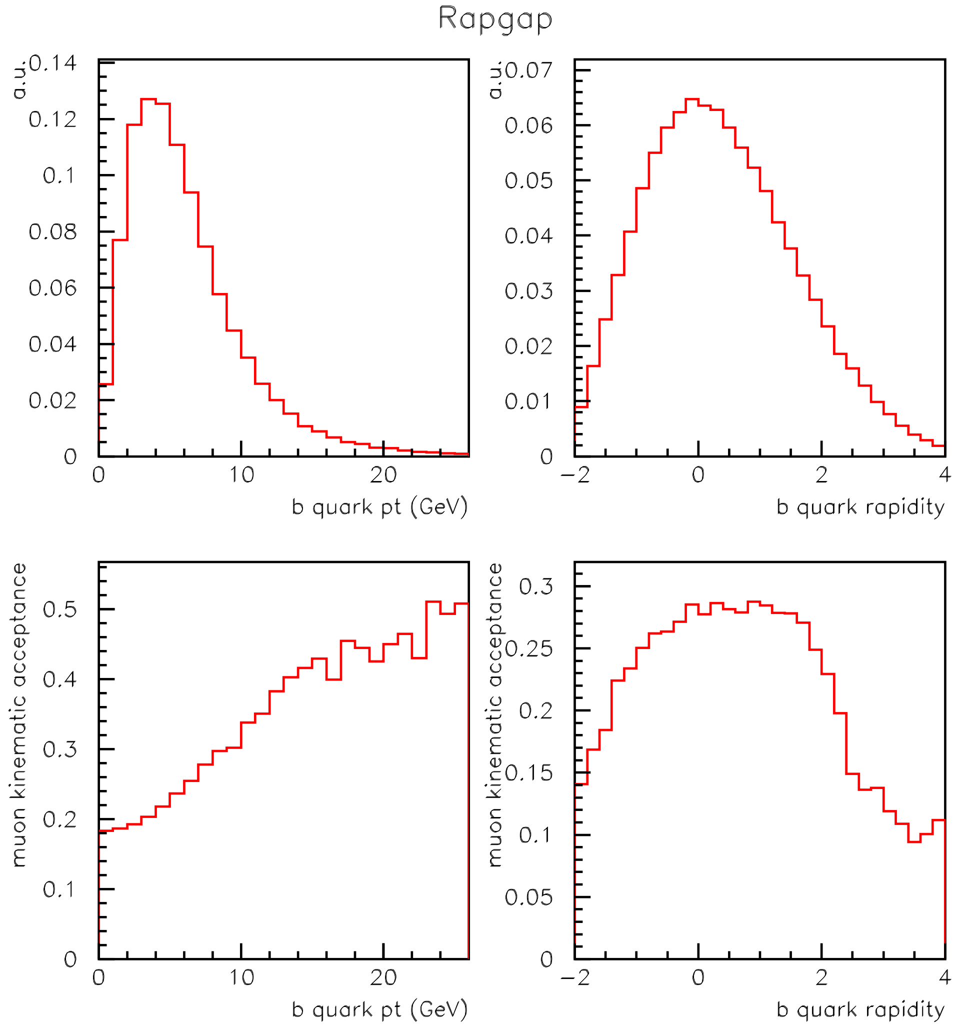
Results

- visible cross sections compared to HVQDIS with
  - ZEUS-S-FF PDF
  - $m_b = 4.75 \pm 0.25$ GeV
  - $\mu_r = \mu_f = \sqrt{Q^2 + 4m_b^2}$
  - μ_r varied by two
- beauty somehow higher than NLO at low-Q^2
- uncertainties for beauty are large (30–60%)



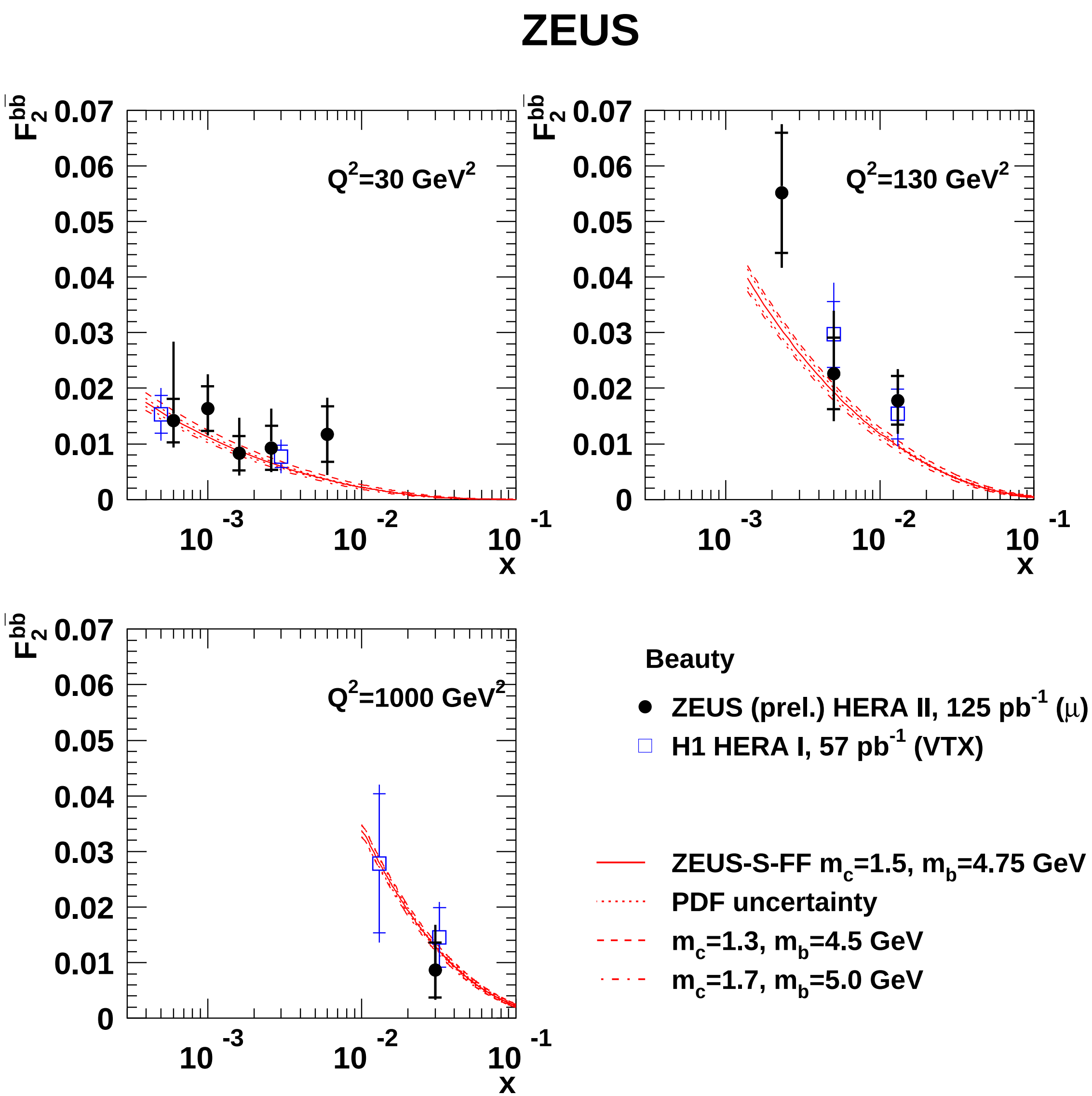
Extraction to $F_2^{b\bar{b}}$

- $F_2^{b\bar{b}}$ extracted from visible cross section in x, Q^2 bins using HVQDIS
- kinematic acceptance of the muon cuts
  $p_T > 1.5$ GeV, $-1.6 < \eta < 2.3$
  wrt to the full muon phase space
  $A = N^\mu(vis)/N^\mu(all) = 25\% - -45\%$
  from $Q^2 = 30$ to $Q^2 = 1000$ GeV^2
- small dependence on the b quark rapidity and $p_T \Longrightarrow$
- extraction to $F_2^{b\bar{b}}$ has small uncertainty ($\sim$ 5%) dominated by fragmentation
  (larger for charm)



A vs p_T^b A vs y^b

New ZEUS (prel.) $F_2^{b\bar{b}}$



- $F_2^{b\bar{b}}$ in agreement with FFNS (ZEUS-S)
- uncertainties $\sim 30-50\%$

New HERA II result from H1

- H1 Inclusive lifetime tag

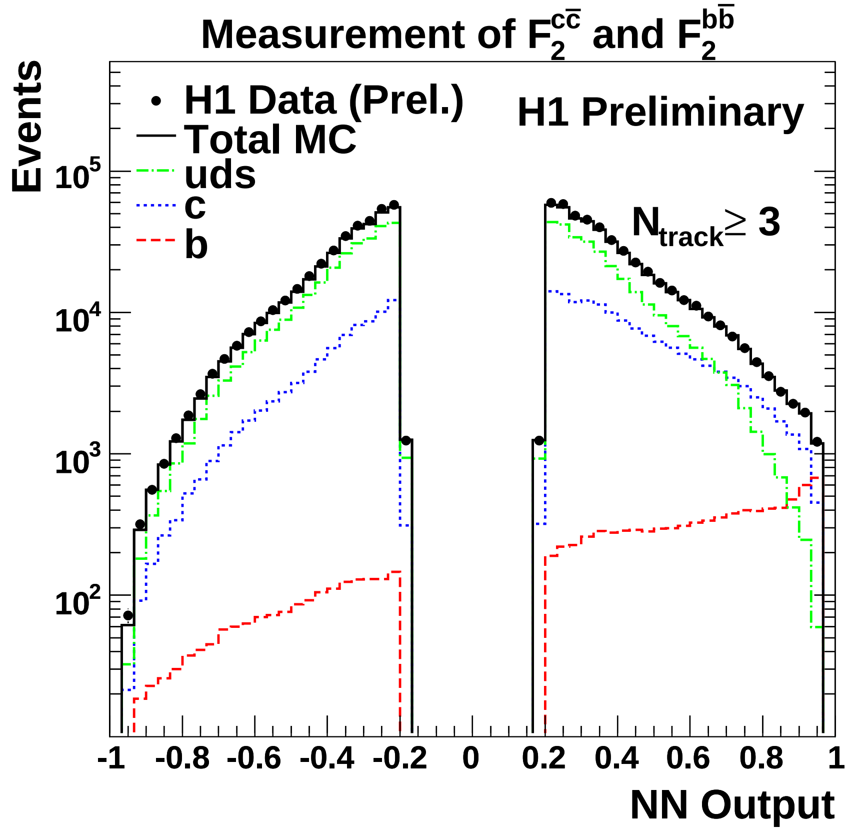
- 2006-2007 data: 189 pb^{-1}

- prel. for ICHEP08

- improved tracking precision and analysis method

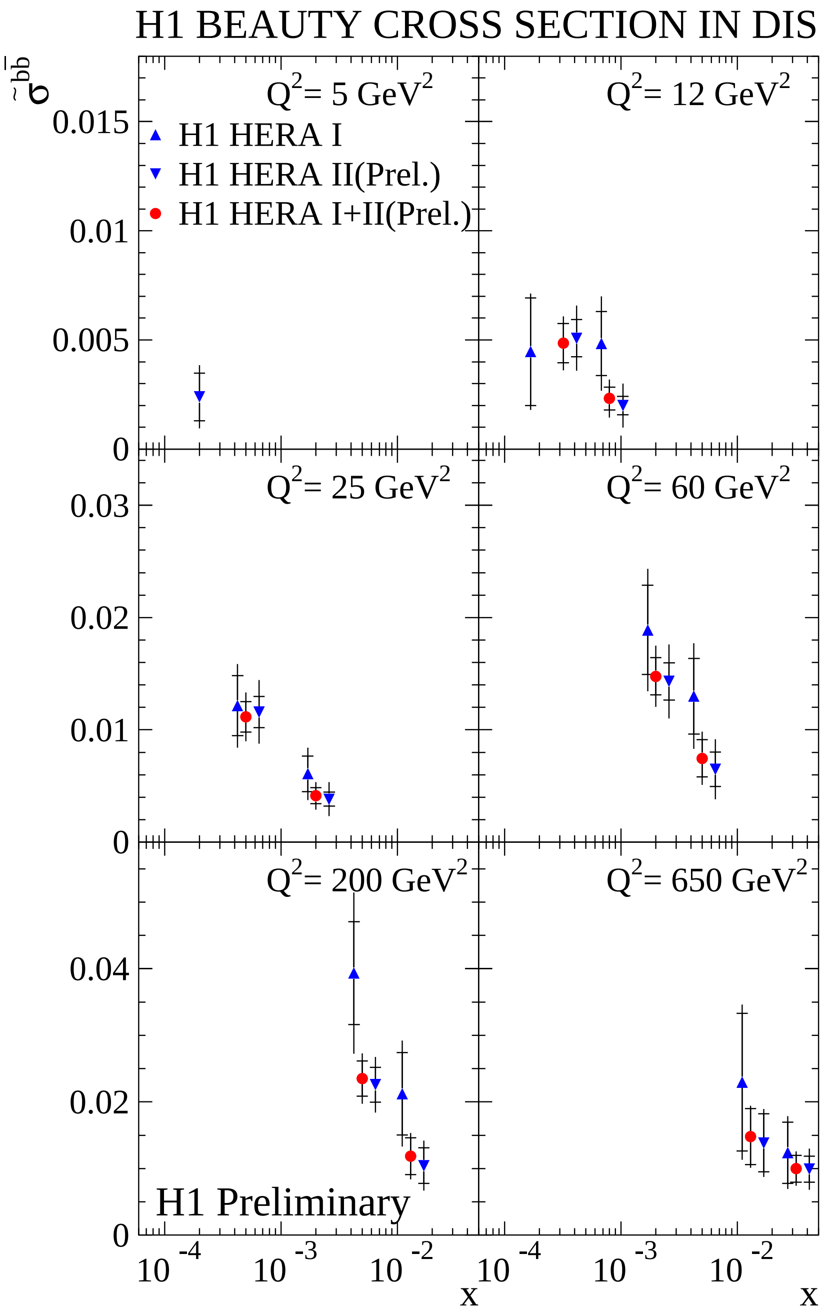
- for events with 1 (2) good CST tracks use impact parameter significance S_1 (S_2)

  for events with ≥ 3 good CST tracks use neural network with input: S_1, S_2, sec. vertex S_L, p_T of first two tracks, multiplicity of prim. and sec. vertex sign assigned to NN output according to S_1



- - extract fraction of c, b

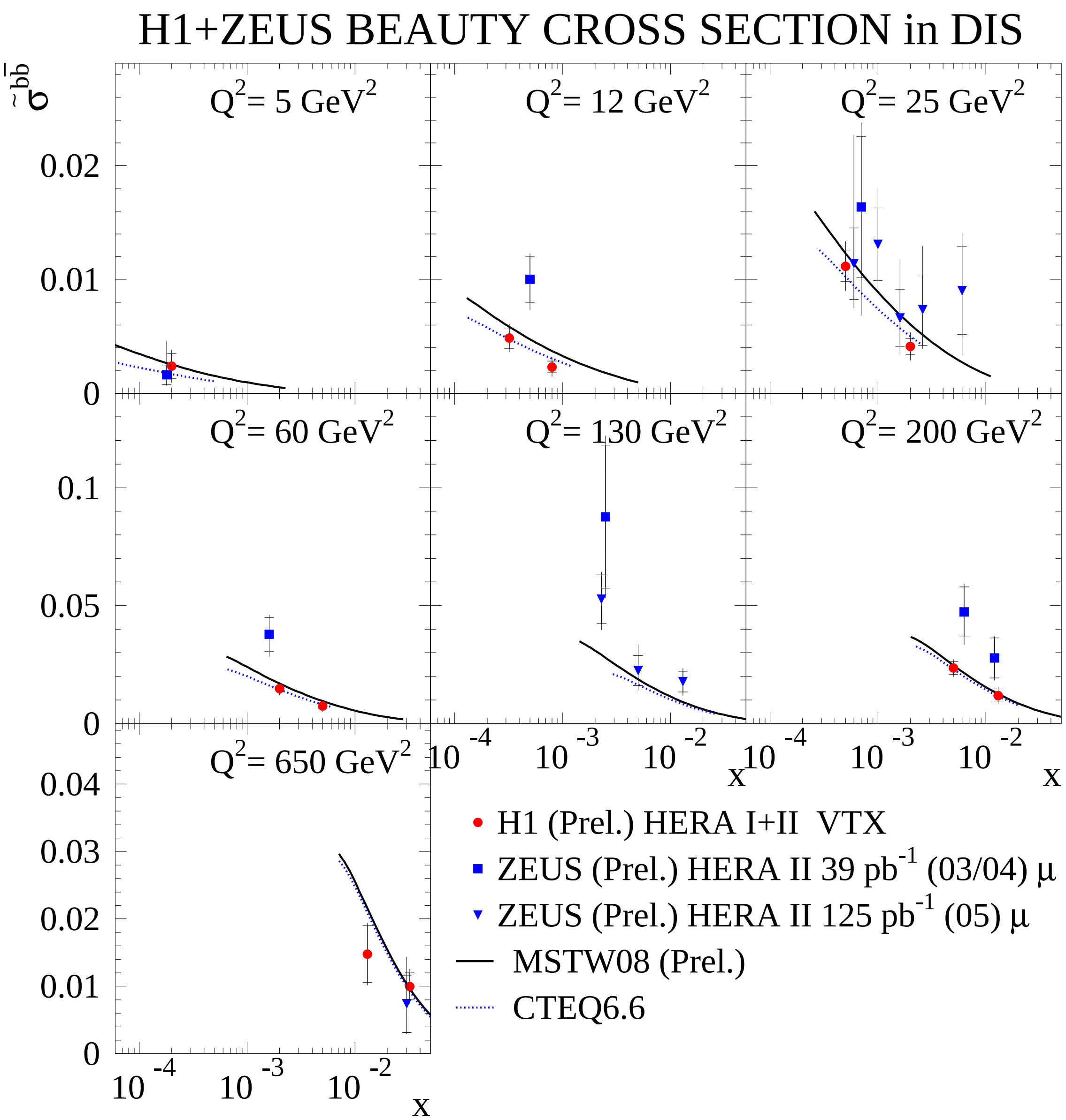
New HERA II result (H1)



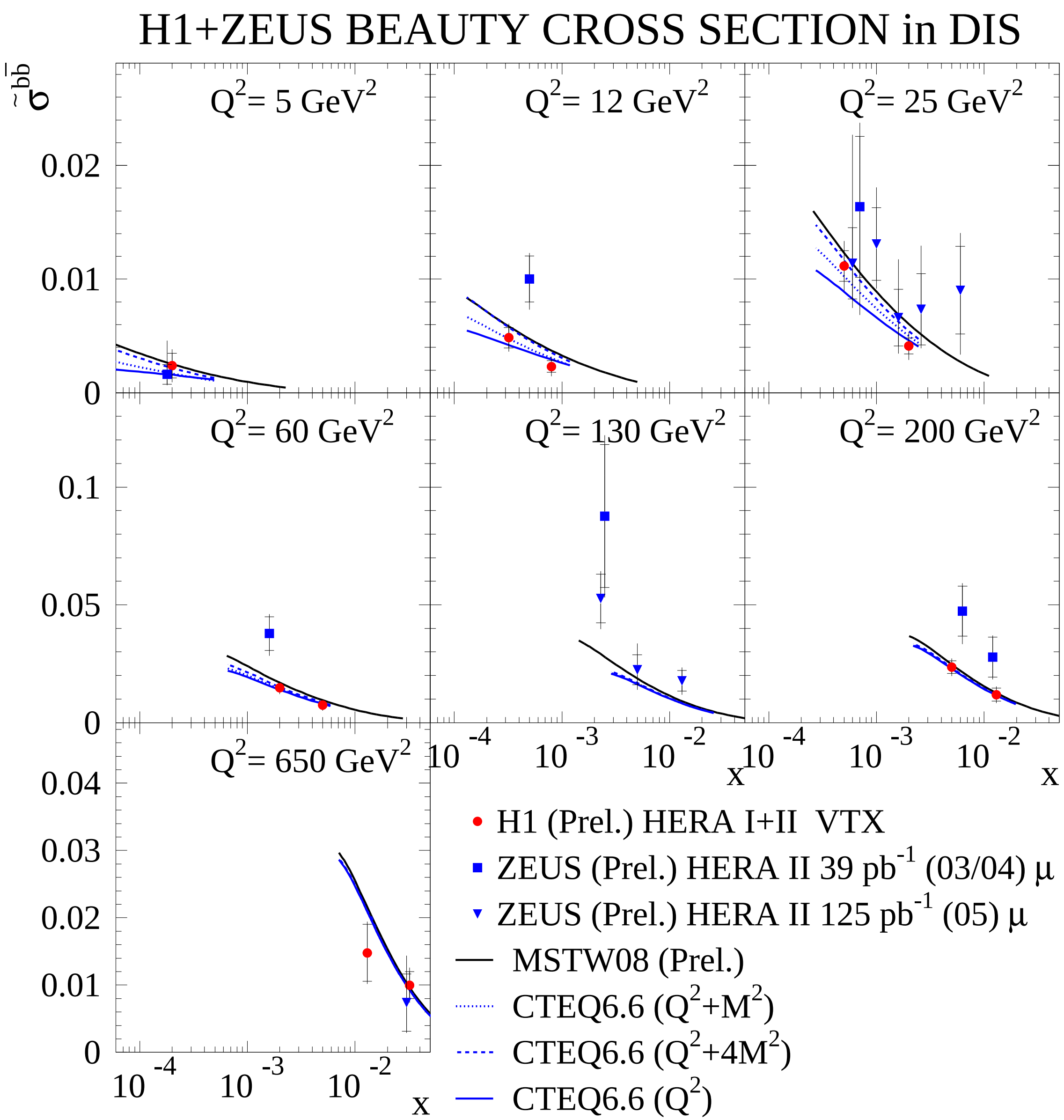
- somewhat lower but compatible with H1 HERA I result
- precision around 25%
- combined HERA I+II (236 pb^{-1}) result, even smaller uncertainties

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

- New combined H1 data are very precise
- New ZEUS data less precise but in agreement
- previous ZEUS prel. somewhat higher
- MRST08(prel.) and CTEQ6.6 GMVFNS calculation agree with data
- spread between two predictions larger than the FFNS band (previous page)



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



- (part of) the difference between CTEQ6.6 and MSTW08 due to CTEQ GMVFNS being LO FFNS at low Q^2 rather than NLO FFNS large scale uncertainty at $Q^2 \leq m_b^2$

Conclusions

- **photoproduction**
  - many beauty dijet measurement
    recent ones in good agreement among them and with NLO QCD
  - experimental precision comparable or better than theory
  - total b cross section measured by ZEUS from $\mu\mu$ correlations
    agrees with NLO within (large) errors
  - is a more precise measurement of σ_{tot} possible ?
- **DIS**
  - new DIS results on b in DIS
    ZEUS (prel.) μ data similar in precision to H1 HERA I inclusive data
    new H1 (prel.) inclusive data have smaller uncertainties $\sim$ 25%
  - agreement with theory, possible to distinguish among curves
  - theoretical uncertainty in DIS still $>$ 2 times smaller than experimental
    improvement would be highly welcome
  - waiting for ZEUS result with inclusive lifetime tagging, use of full HERA-II data, and combination of experiments and methods

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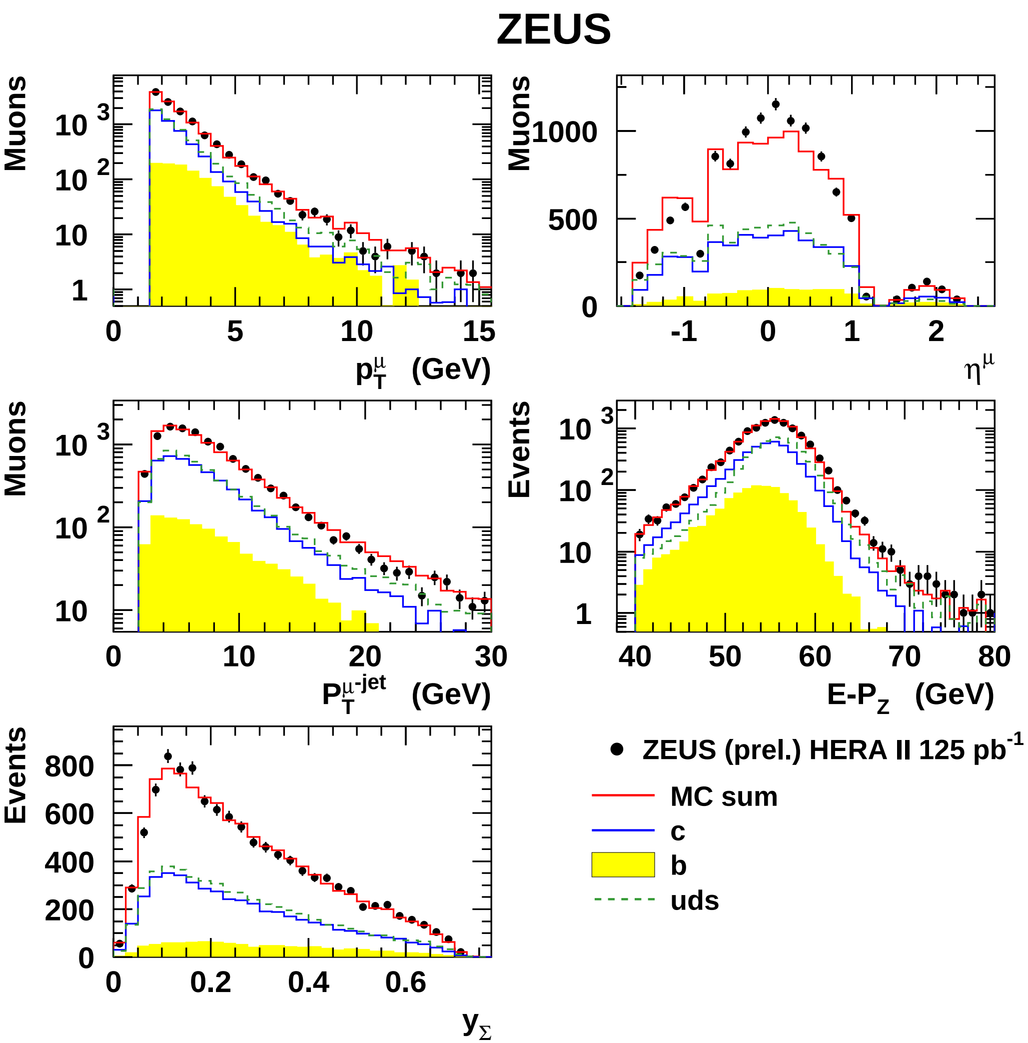
control plots of new ZEUS F_2^b



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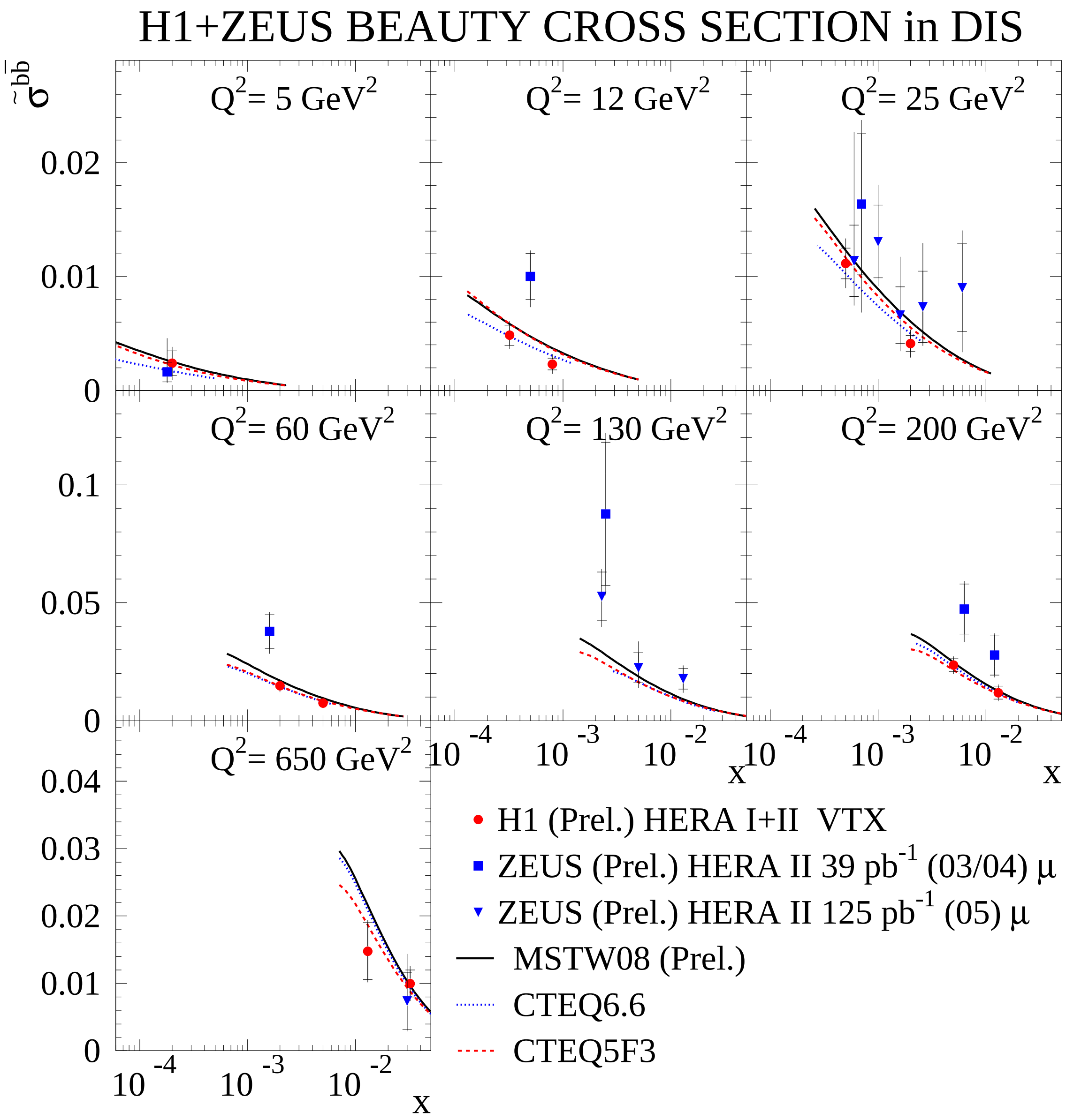
comparison to CTEQ5F



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ɔ jets at CDF