

Ringberg Castle 8 October 2008

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

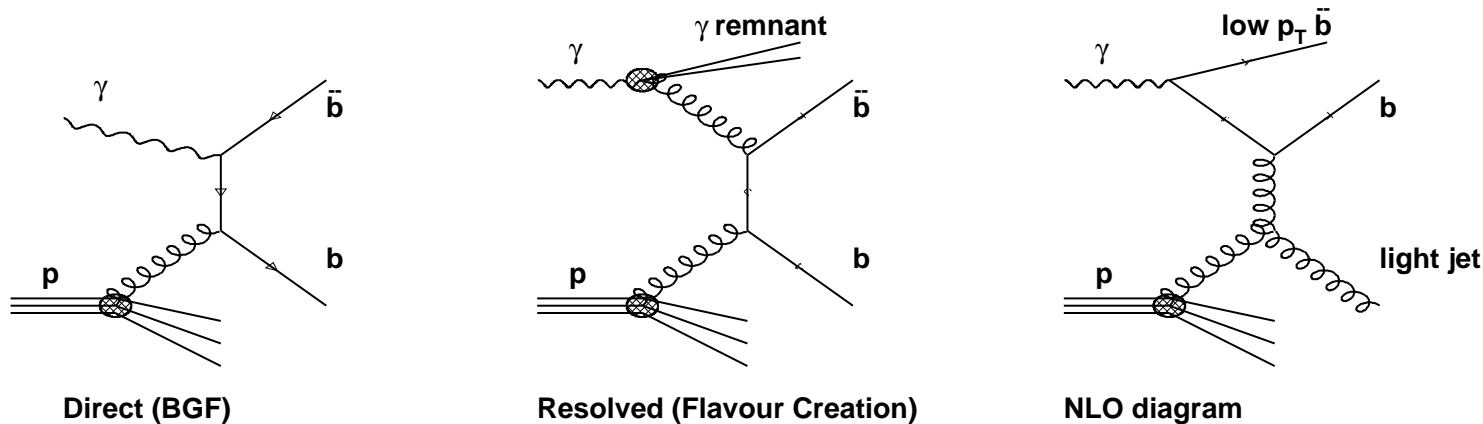
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INFN Bologna



Introduction

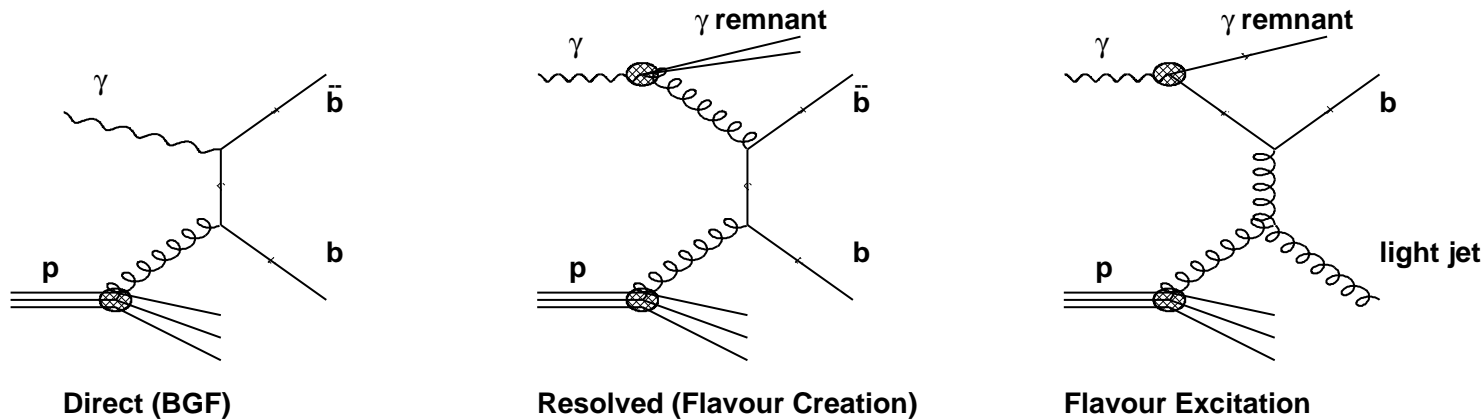
$$ep \rightarrow e' b \bar{b} X$$



- 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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Theoretical uncertainties (photoproduction)

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

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

mass probably known better

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

- 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)

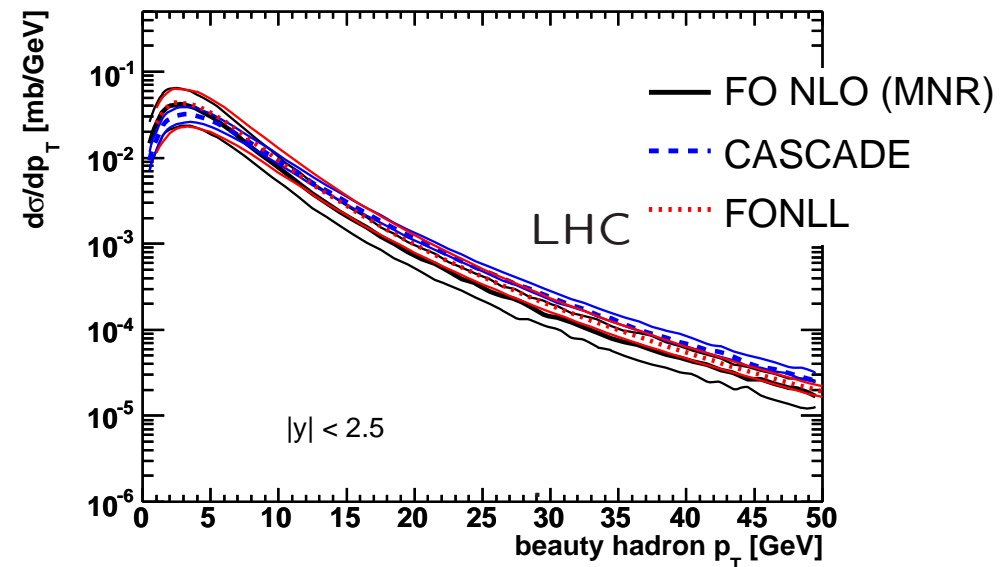
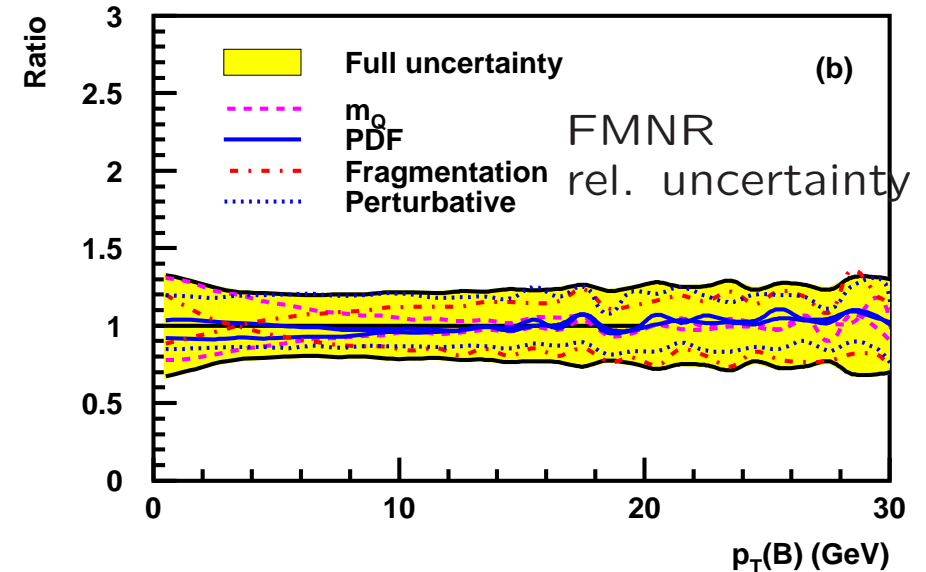
- FO, “resummed” and k_T -fact. agree
“resummed” have smaller unc. at large p_T



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

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

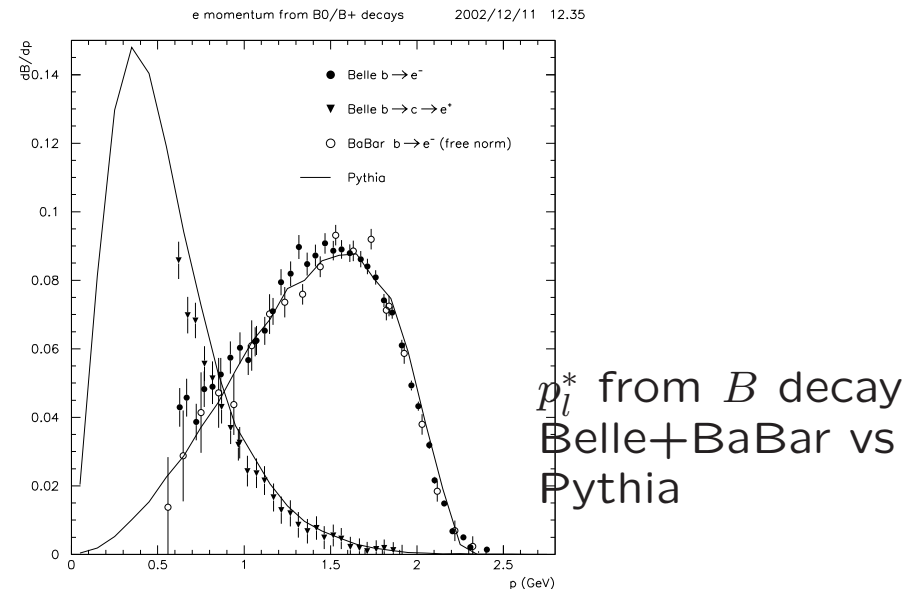
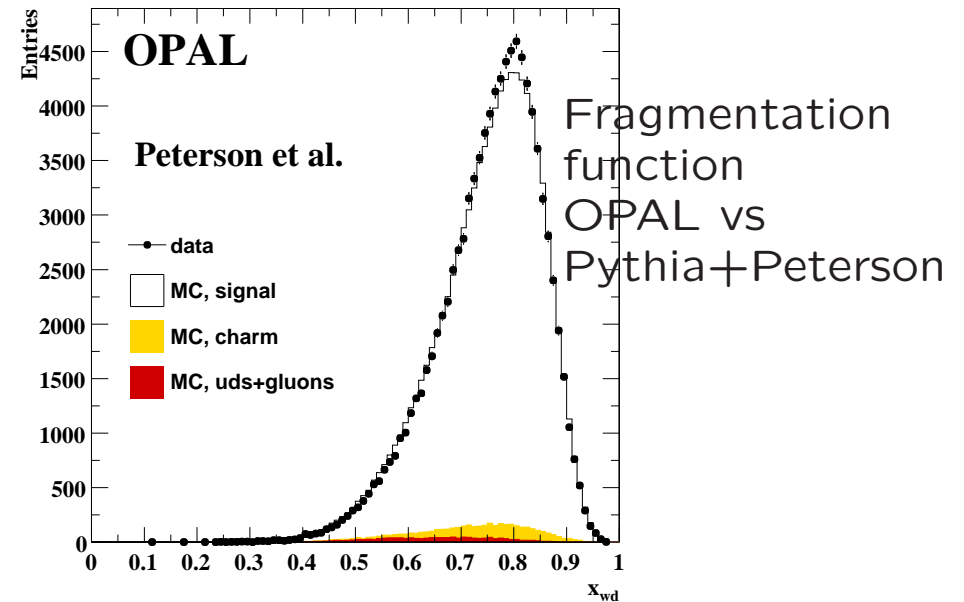
$$\Delta\Phi_{jj} \ll \pi$$



Non-perturbative uncertainties

- **fragmentation** ($b \rightarrow B$)
 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)

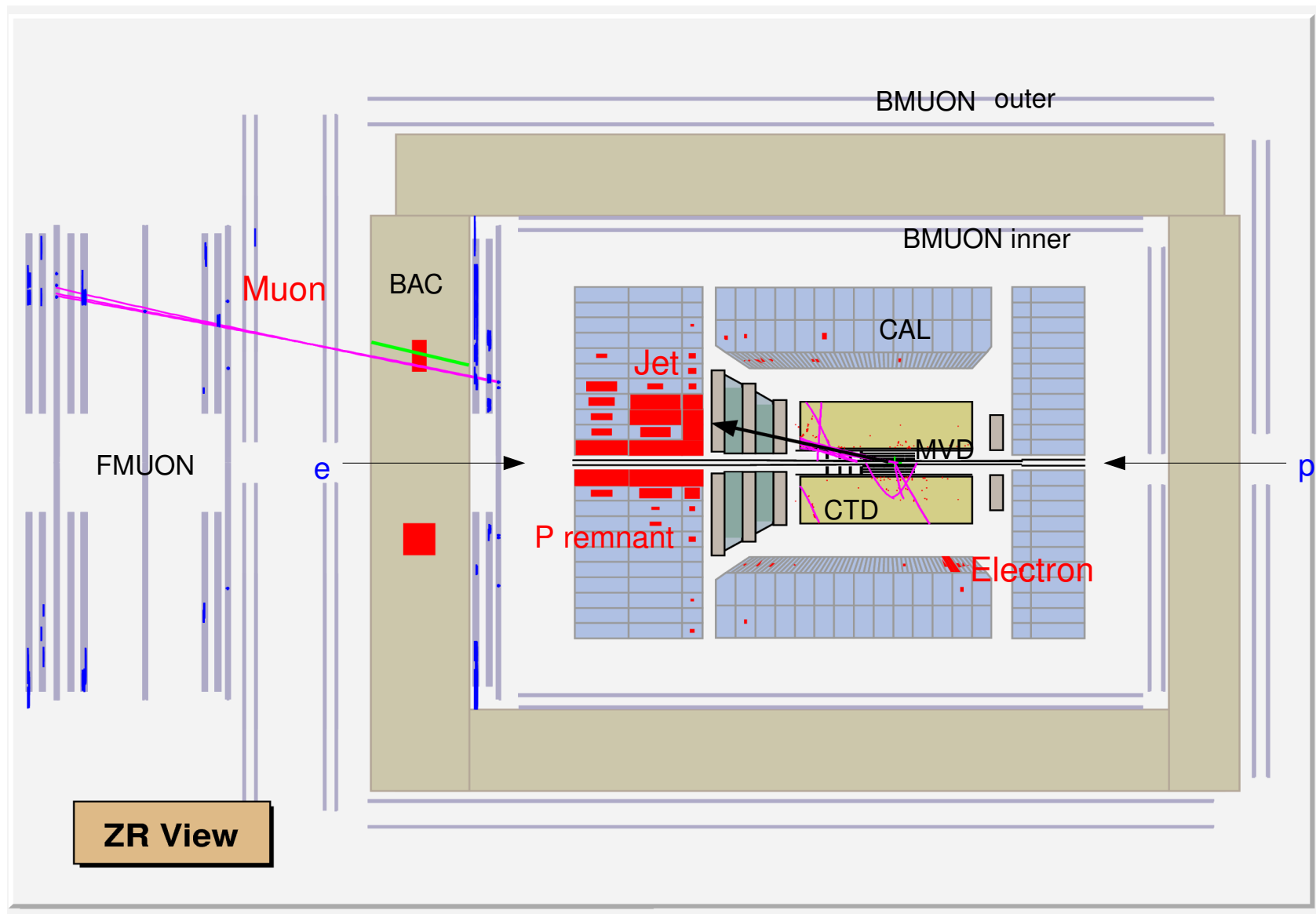
Non-perturbative uncertainties are small ($\sim 5\%$)



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 $Q^2 \gg m^2$, $x \ll 1$: $r = 1/11$
- requiring an high- p_T lepton increases the fraction to $r \sim 20\%(10\%)$ in dijets (DIS)
 $B(b \rightarrow lX) \sim 22\%$ including cascade decays $b \rightarrow c \rightarrow lX$
- 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, $\pi \rightarrow e^+e^-\gamma$, wrongly identified hadrons

A DIS event with a muon in ZEUS

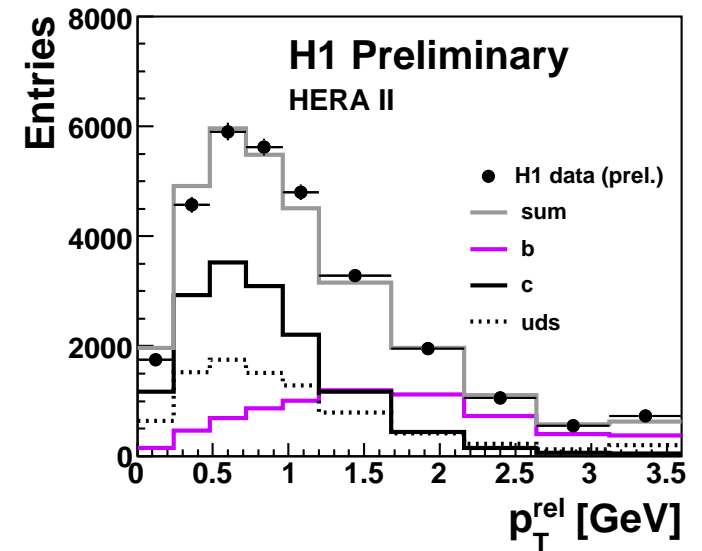
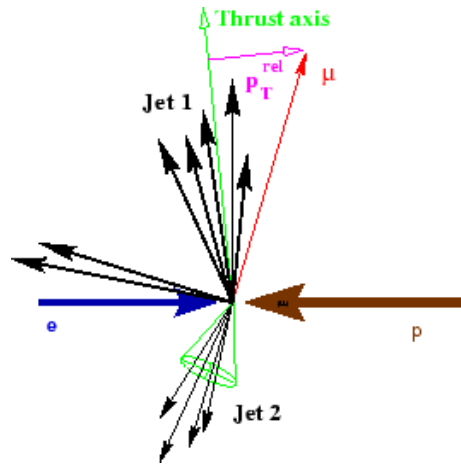


Extraction of b fraction

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

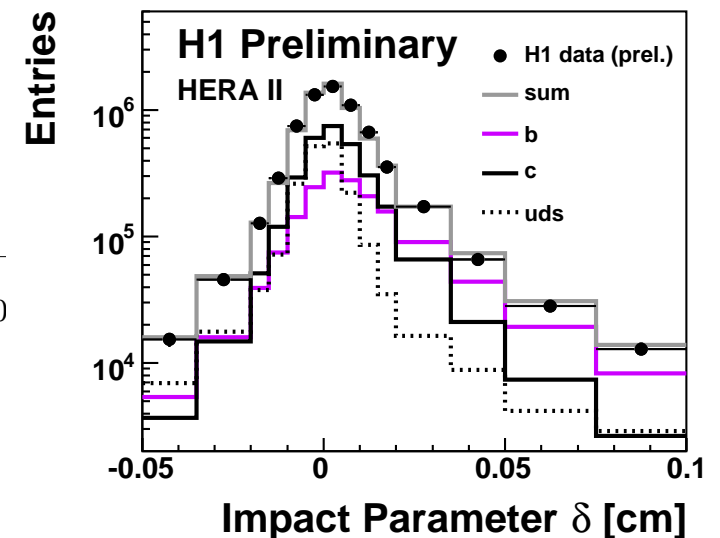
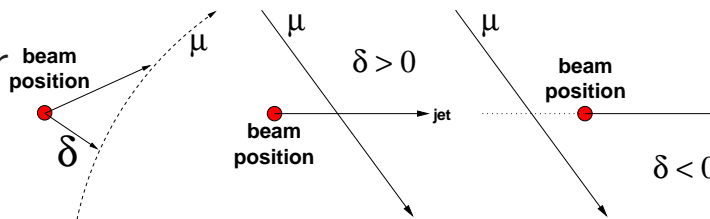
p_T^{rel} :

- transverse lepton momentum w.r.t. jet axis
- needs good MC templates
- can be obtained from inclusive data



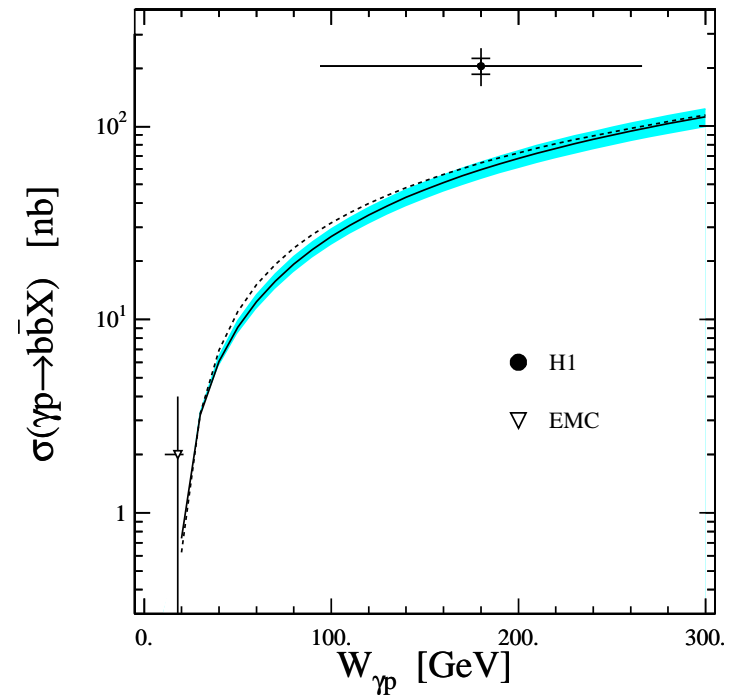
δ :

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

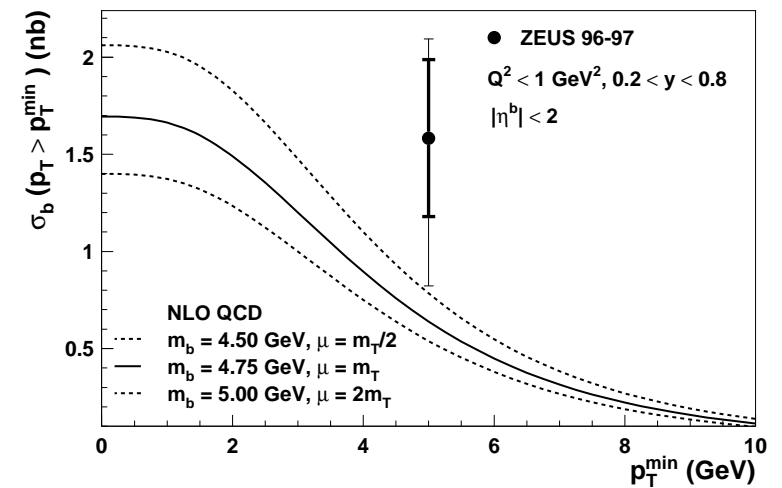


First HERA results (~ 2000)

- H1, $ep \rightarrow b\bar{b}X \rightarrow \mu jj X'$
 - 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

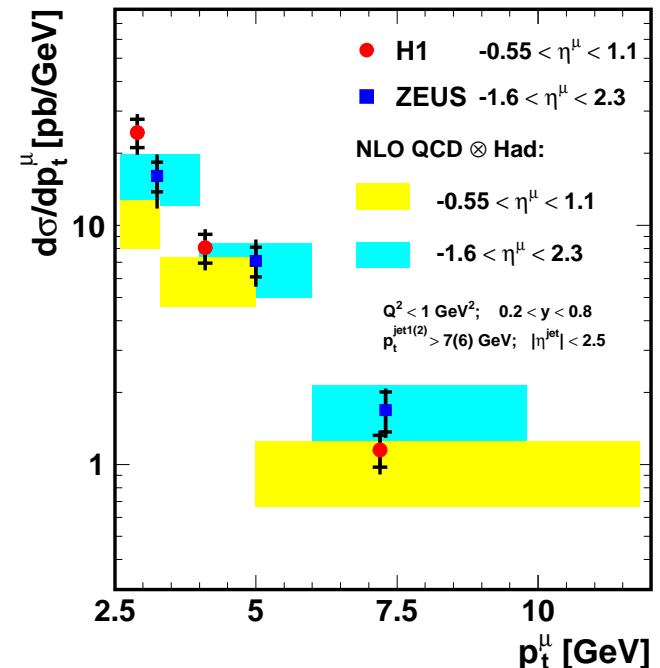
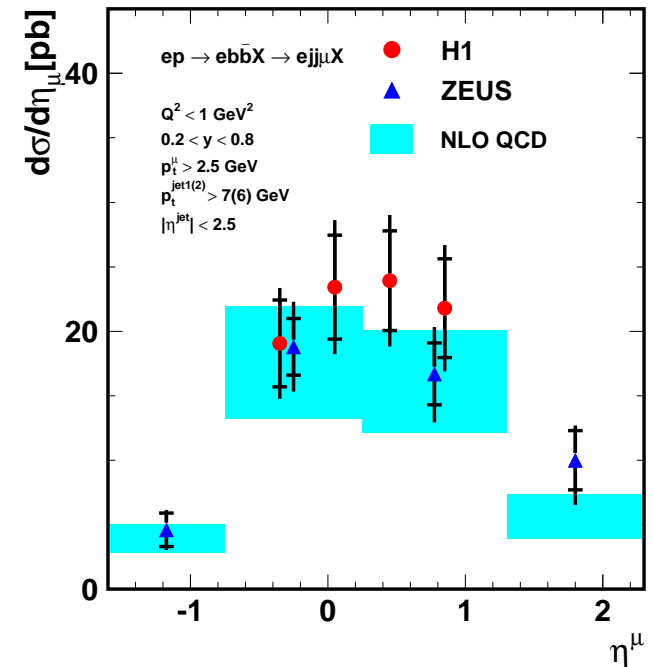


ZEUS



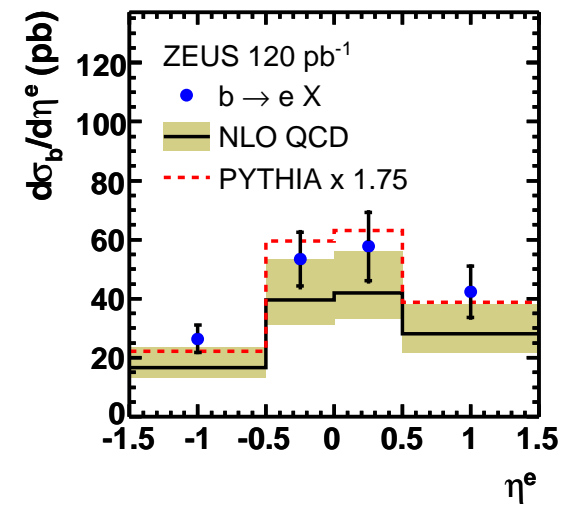
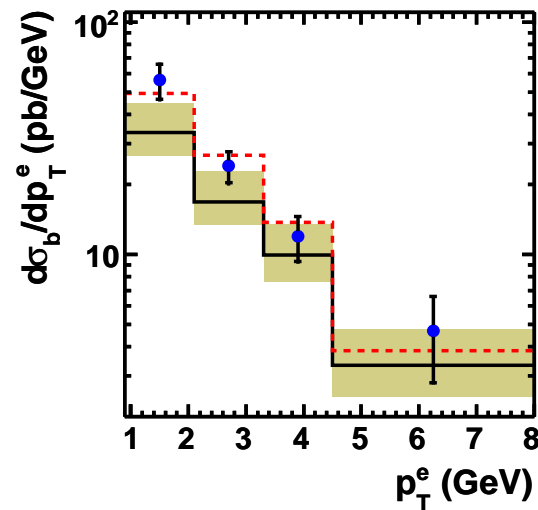
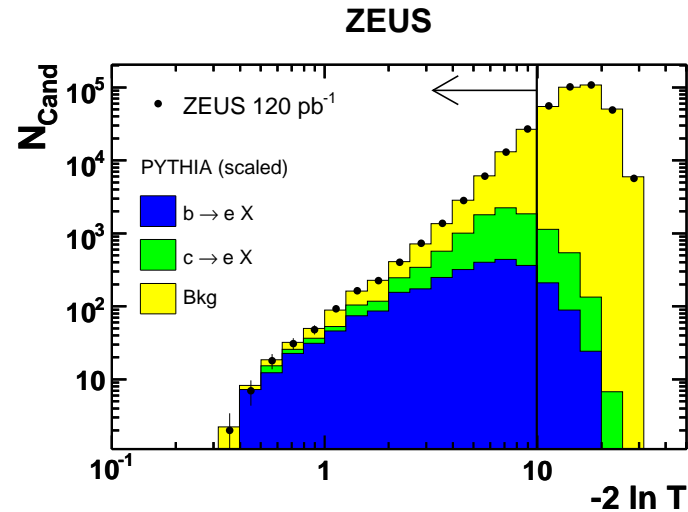
Second generation (~2003-2004)

- ZEUS, $ep \rightarrow b\bar{b}X \rightarrow \mu jjX'$
 - $0.2 < y < 0.8$, $Q^2 < 1 \text{ GeV}^2$
 - $p_T^\mu > 2.5 \text{ GeV}$, $-1.6 < \eta^\mu < 2.3$
 - $p_T^{\text{jet}} > 7, 6 \text{ GeV}$
 - HERA I data
 - p_T^{rel}
 - Agreement with NLO
 - .ZEUS, PRD 70 (2004) 012008,
 - .Erratum: ibid. D74 (2006) 059906(e)
- H1, $ep \rightarrow b\bar{b}X \rightarrow \mu jjX'$
 - 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.)



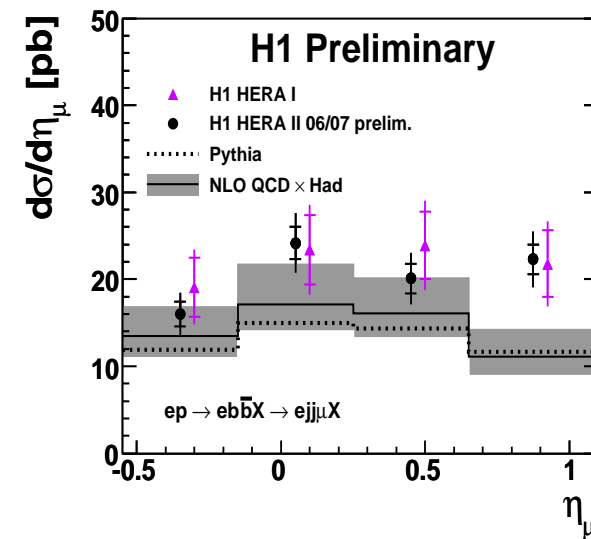
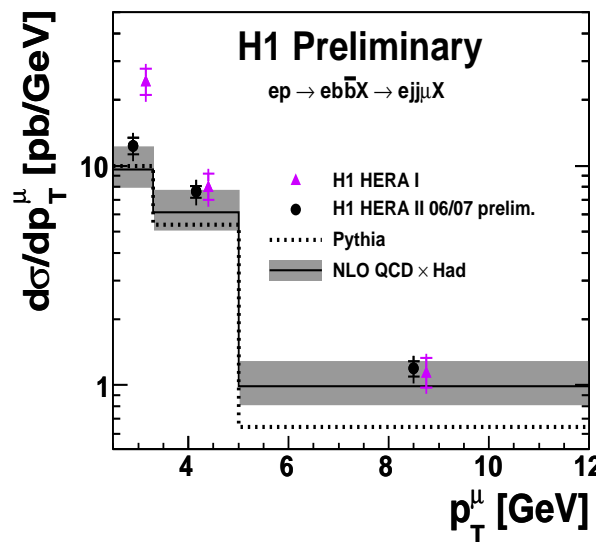
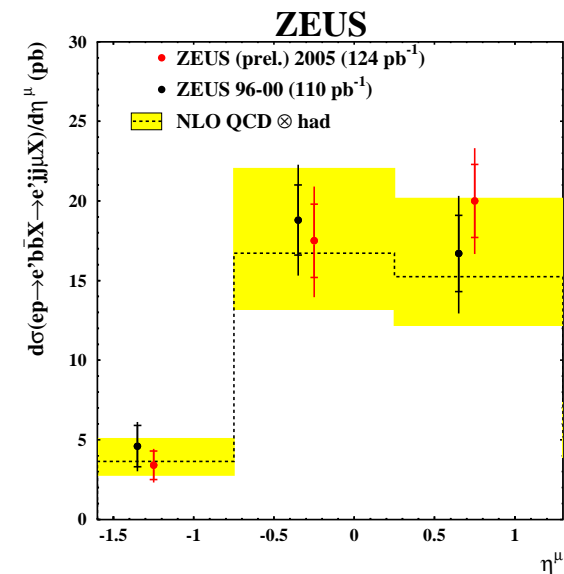
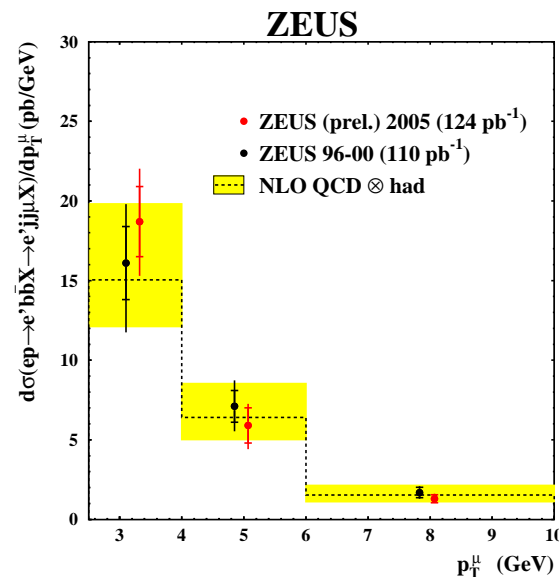
ZEUS results with electron tag

- ZEUS, $ep \rightarrow b\bar{b}X \rightarrow ejjX'$
 - similar kinematic region
 - lower threshold: $p_T^e > 0.9$ GeV
 - HERA I data
 - p_T^{rel} for c/b separation
 - Likelihood method to distinguish semileptonic electrons
- Agreement with NLO
- DESY-08-056
- similar uncertainties to muon data



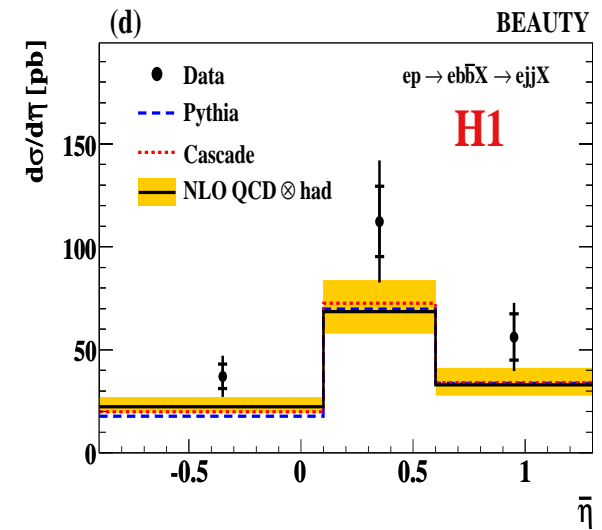
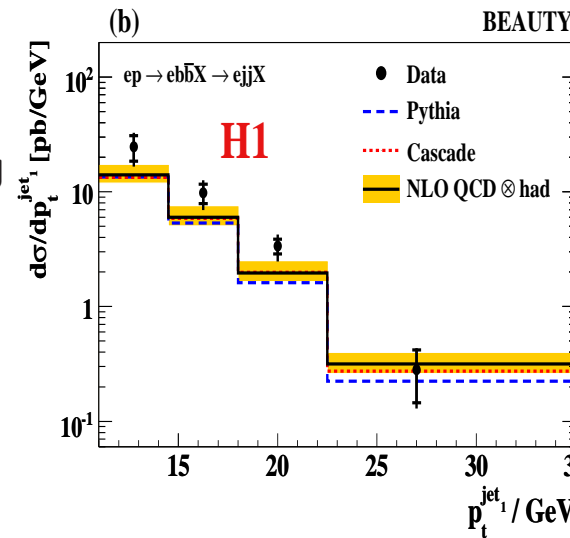
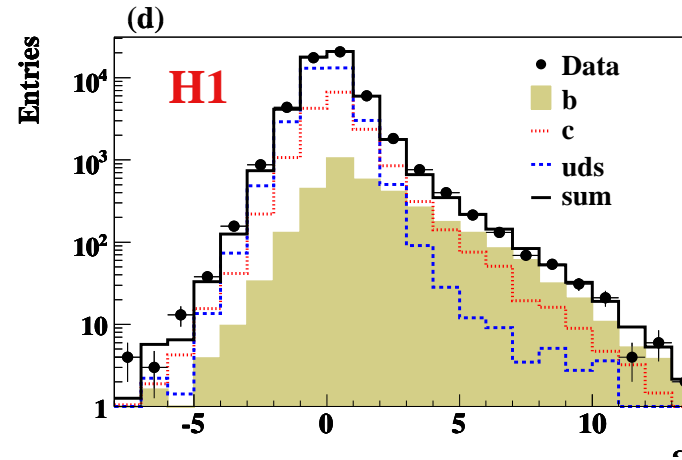
New HERA II muon tag results (2006-2008)

- ZEUS, $ep \rightarrow b\bar{b}X \rightarrow ejjX'$
 - same kinematic region
 - p_T^{rel}, δ
 - 125 pb^{-1} , HERA II (2005)
 - Agrees with previous results and NLO
 - ZEUS prel. for EPS05 (2004 data), EPS07 (2005 data)
- H1 $ep \rightarrow b\bar{b}X \rightarrow ejjX'$
 - same kinematic region
 - p_T^{rel}, δ
 - 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 $ep \rightarrow b\bar{b}X \rightarrow jjX'$
- $p_T^j > 11(8)\text{GeV}$, $-0.9 < \eta^j < 1.3$
no lepton requests
- HERA I data
- fraction of c, b extracted from impact parameter significance
 $S = \delta/\sigma_\delta$ of inclusive tracks
(2nd–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, $\mu\mu$

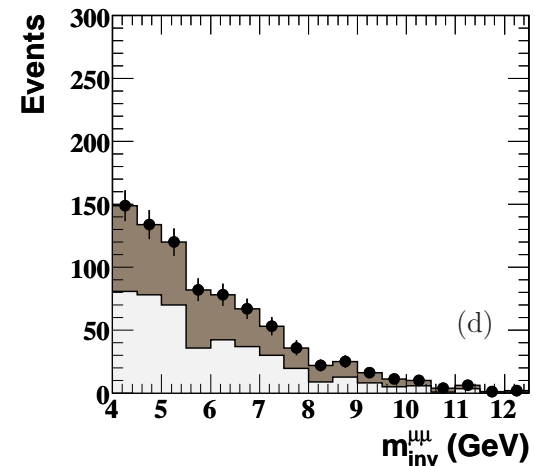
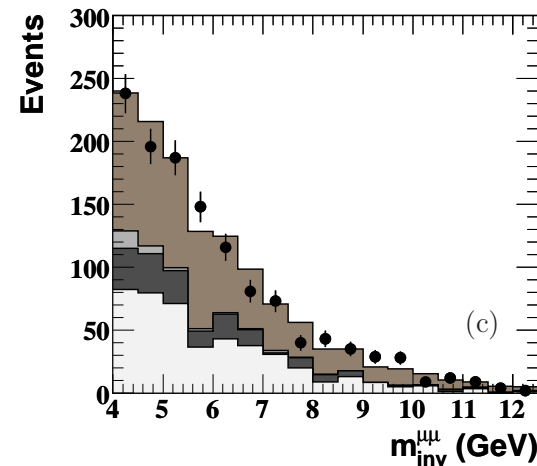
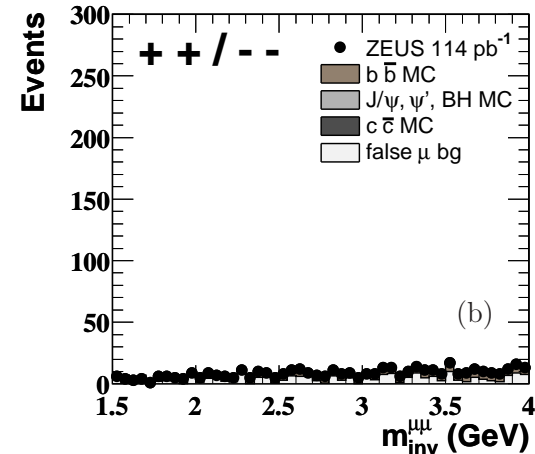
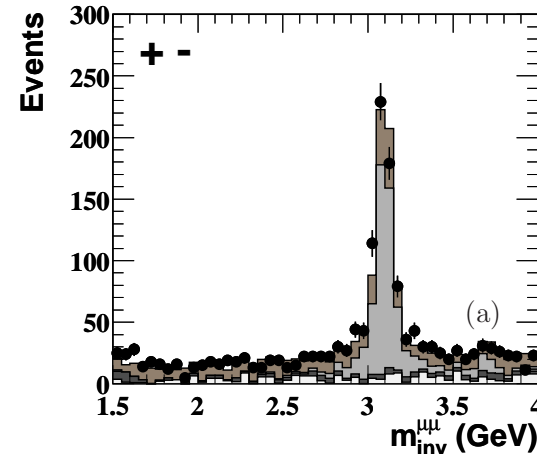
- HERA I data
DESY-08-129

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

$\mu^-\mu^-, \mu^+\mu^+$	$\mu^+\mu^-$
$b \rightarrow \mu^-, \bar{b} \rightarrow \bar{c} \rightarrow \mu^-$ fake μ	$b \rightarrow \mu^-, \bar{b} \rightarrow \mu^+$ 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

ZEUS



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

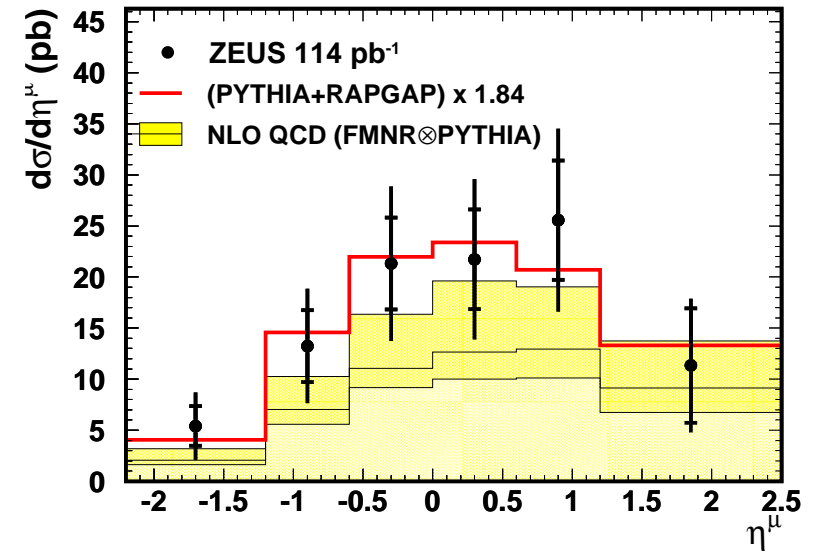
- diff. cross sections for $p_T^\mu > 1.5 \text{ GeV}$ $\eta^\mu < 2.5$
-Agreement with (upper side of) NLO band
- Almost full b quark phase space coverage
(except most forward 10%)
allows a reliable extraction of σ_{tot}
- uncertainty 30% for σ_{tot}

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

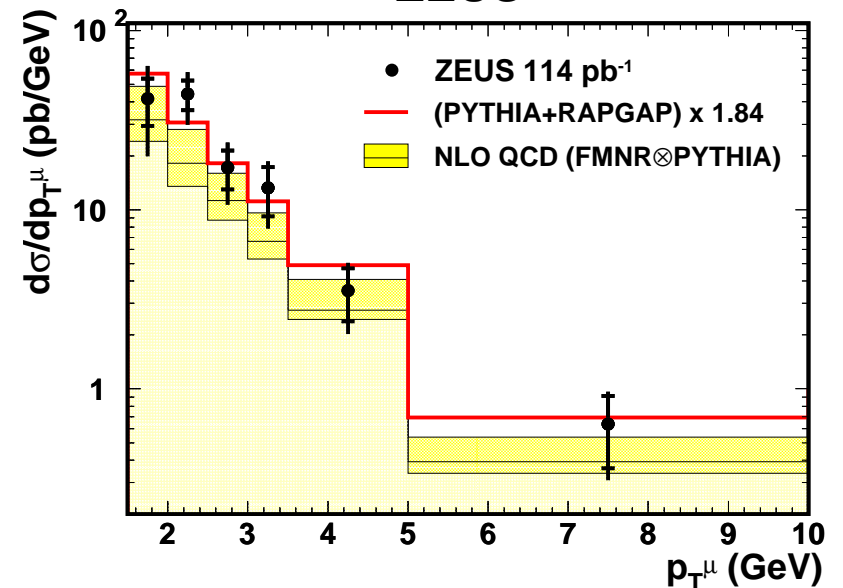
To be compared with

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

ZEUS



ZEUS



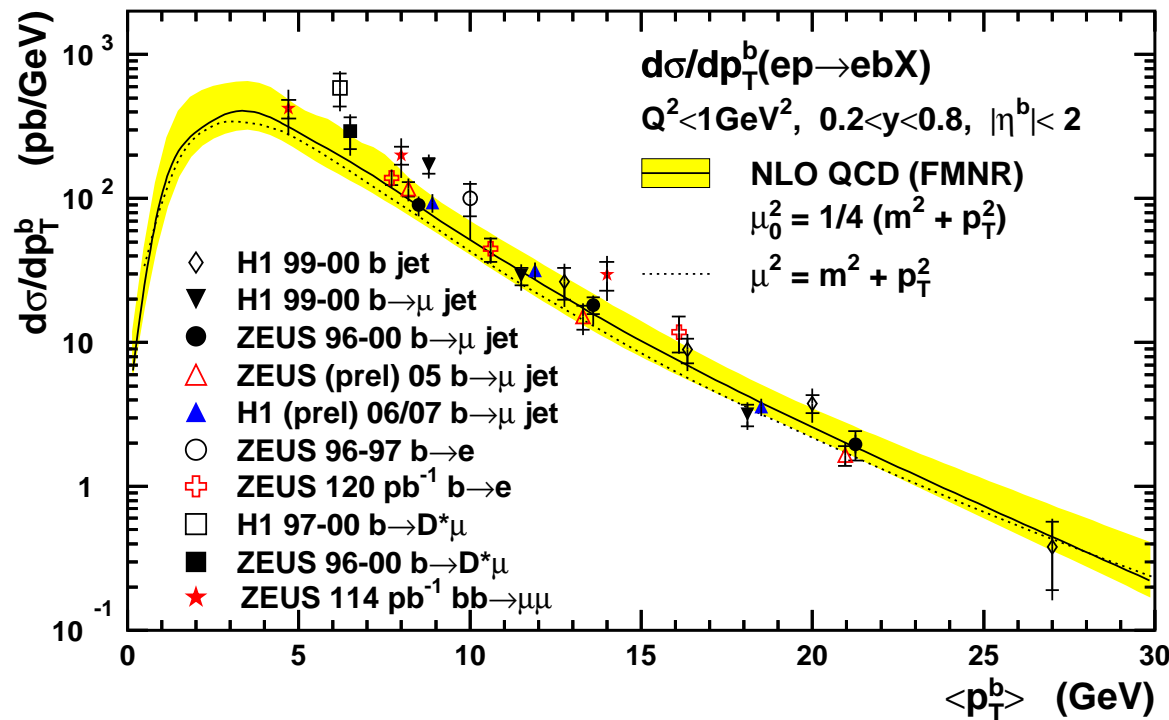
The “summary plot”

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

HERA



Agreement with NLO with

$$m_b = 4.75 \pm 0.25 \text{ GeV}$$

$$\mu_R = \mu_b = \frac{1}{2}(2^{0 \pm 1}) \sqrt{\langle p_T^b \rangle^2 + m_b^2},$$

(new scale choice,
see A. Geiser DIS07)

Older central value

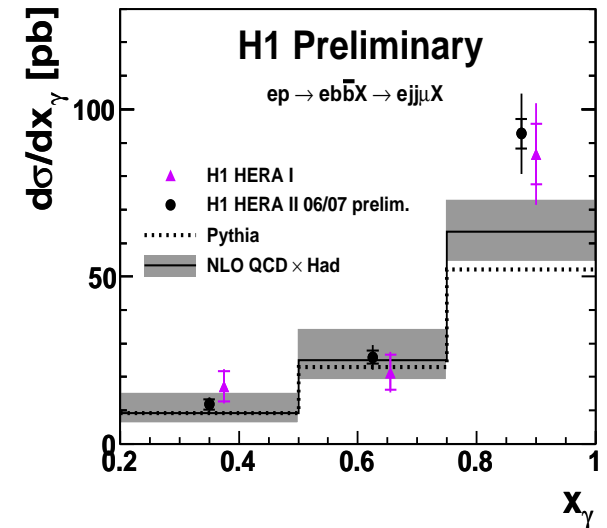
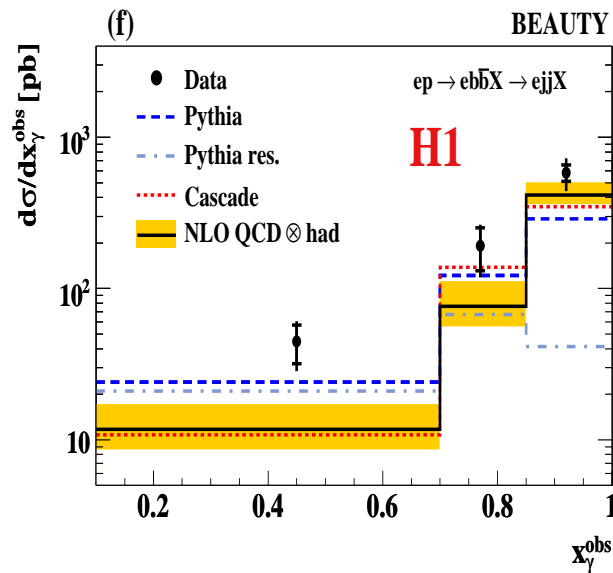
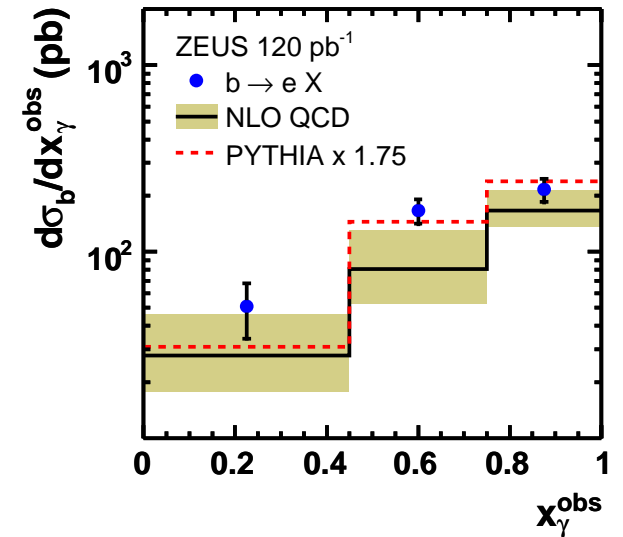
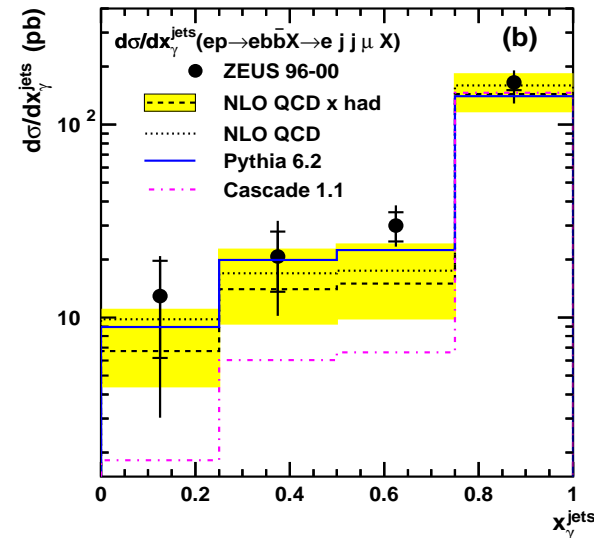
$$\mu_r = \mu_f = \sqrt{\langle p_T^b \rangle^2 + m_b^2}$$

Two choices \sim 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



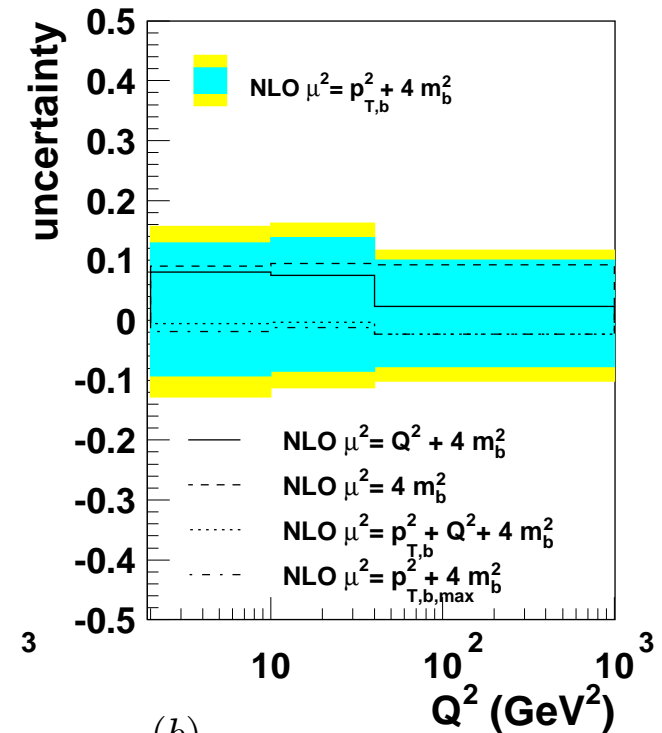
Beauty in DIS

- 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 $Q^2 > 20 \text{ GeV}^2$

- 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)

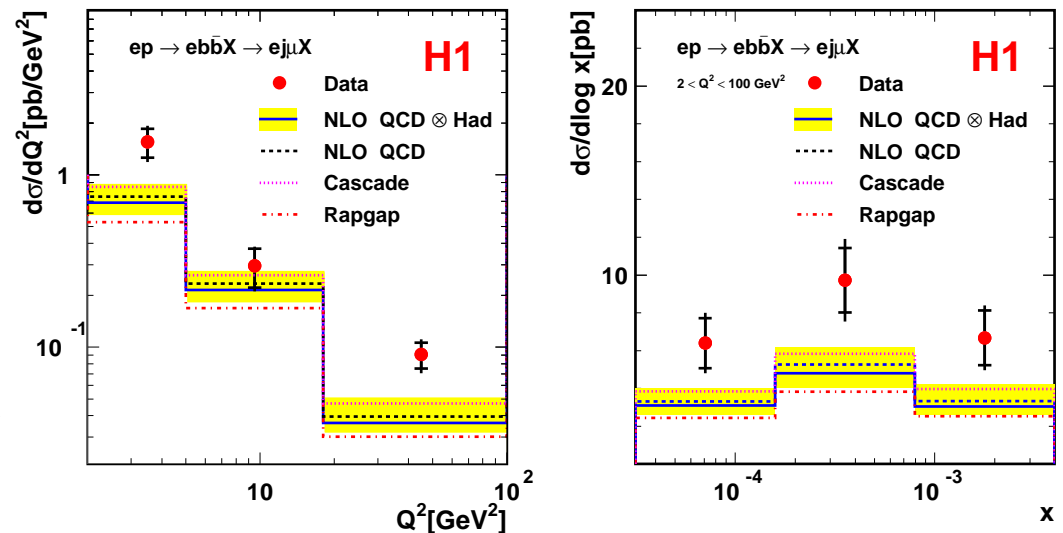
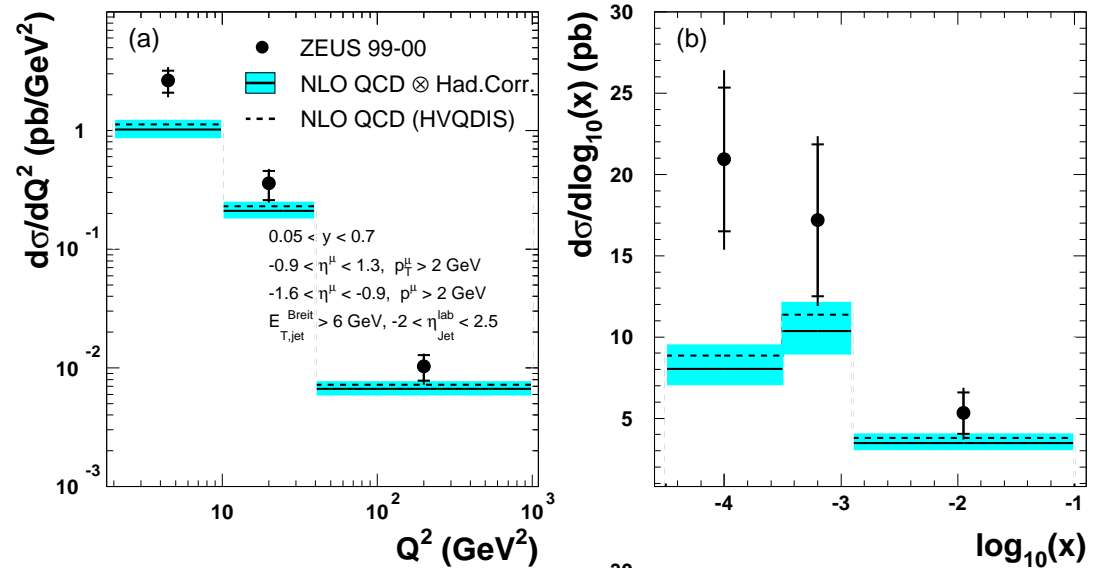


inner band: scale var. by 2
outer band: + mass var.

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

- Initial strategy: require a jet in the Breit Frame to enhance the fraction of BGF-like events
- ZEUS $e \rightarrow e' b \bar{b} X \rightarrow e' \mu j X'$
 - $p_T^\mu > 2 \text{ GeV}$, $E_{T,\text{Breit}}^j > 6 \text{ GeV}$
 - p_T^{rel}
 - HERA-I data
 - PLB 599 (2005) 173
- H1 $e \rightarrow e' b \bar{b} X \rightarrow e' \mu j X'$
 - almost same kin. region
 - HERA-I data
 - p_T^{rel}, δ
 - H1, EPJC 41 (2005) 453
- Both above theory at low Q^2 but large errors
- is the theoretical uncertainty underestimated ?
need for resolved photons at $Q^2 < m_b^2$?

ZEUS



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

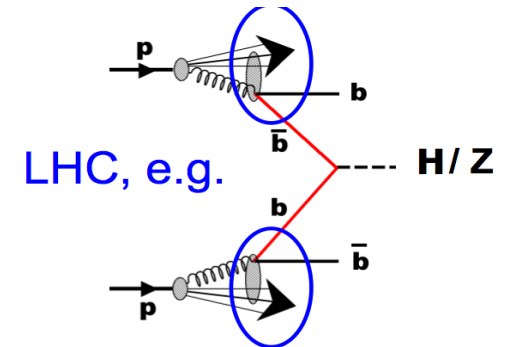
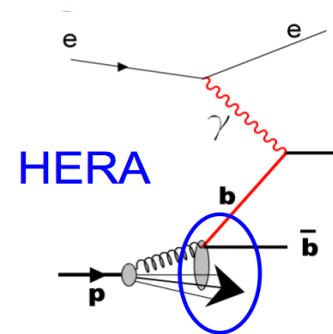
$$\frac{d^2\sigma^{b\bar{b}}}{dx dQ^2} = \mathcal{K} \tilde{\sigma}^{b\bar{b}}(x, Q^2, s) = \mathcal{K} \left[F_2^{b\bar{b}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{b\bar{b}}(x, Q^2) \right]$$

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

- 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 ?

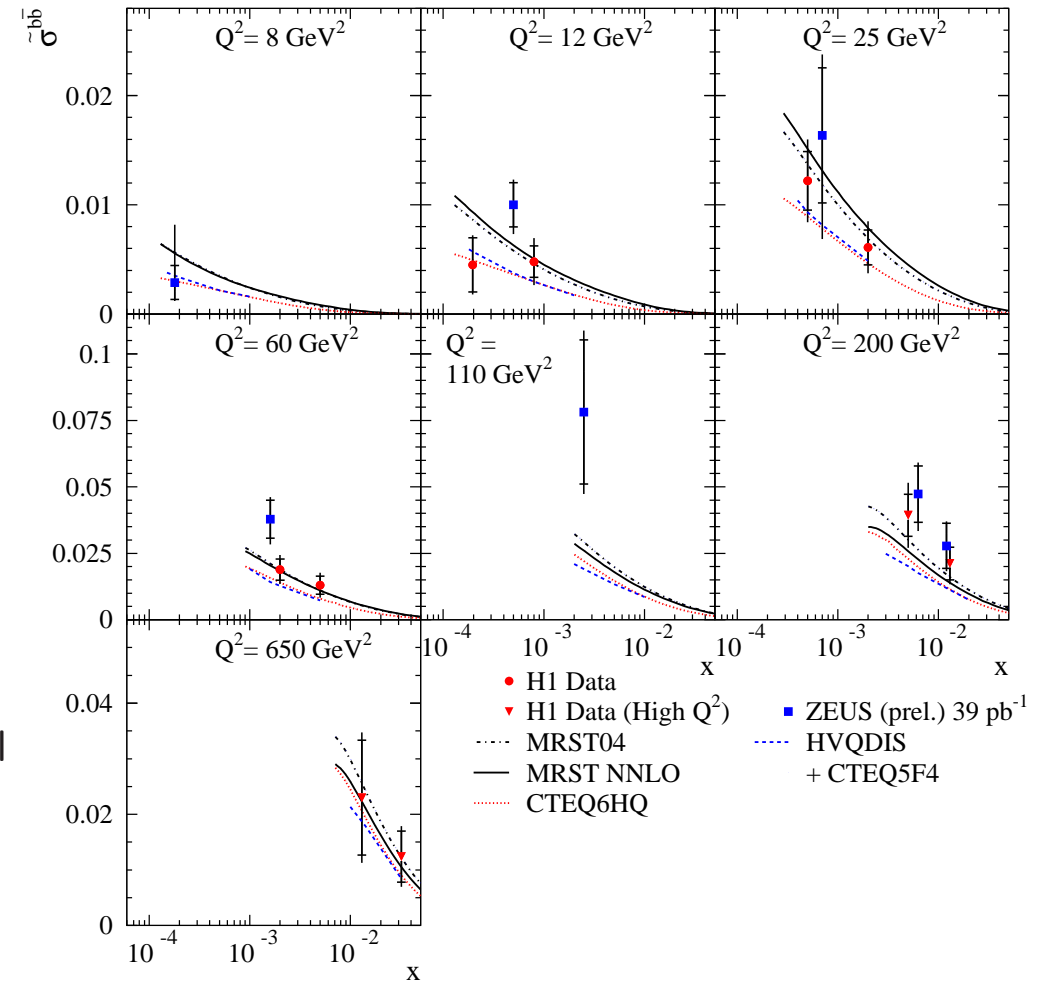
$F_2^{b\bar{b}}$ and b PDF

- 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: $b\bar{b} \rightarrow H$ simpler than FFNS equivalent $gg \rightarrow b\bar{b}H$
- $F_2^{b\bar{b}}$ 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



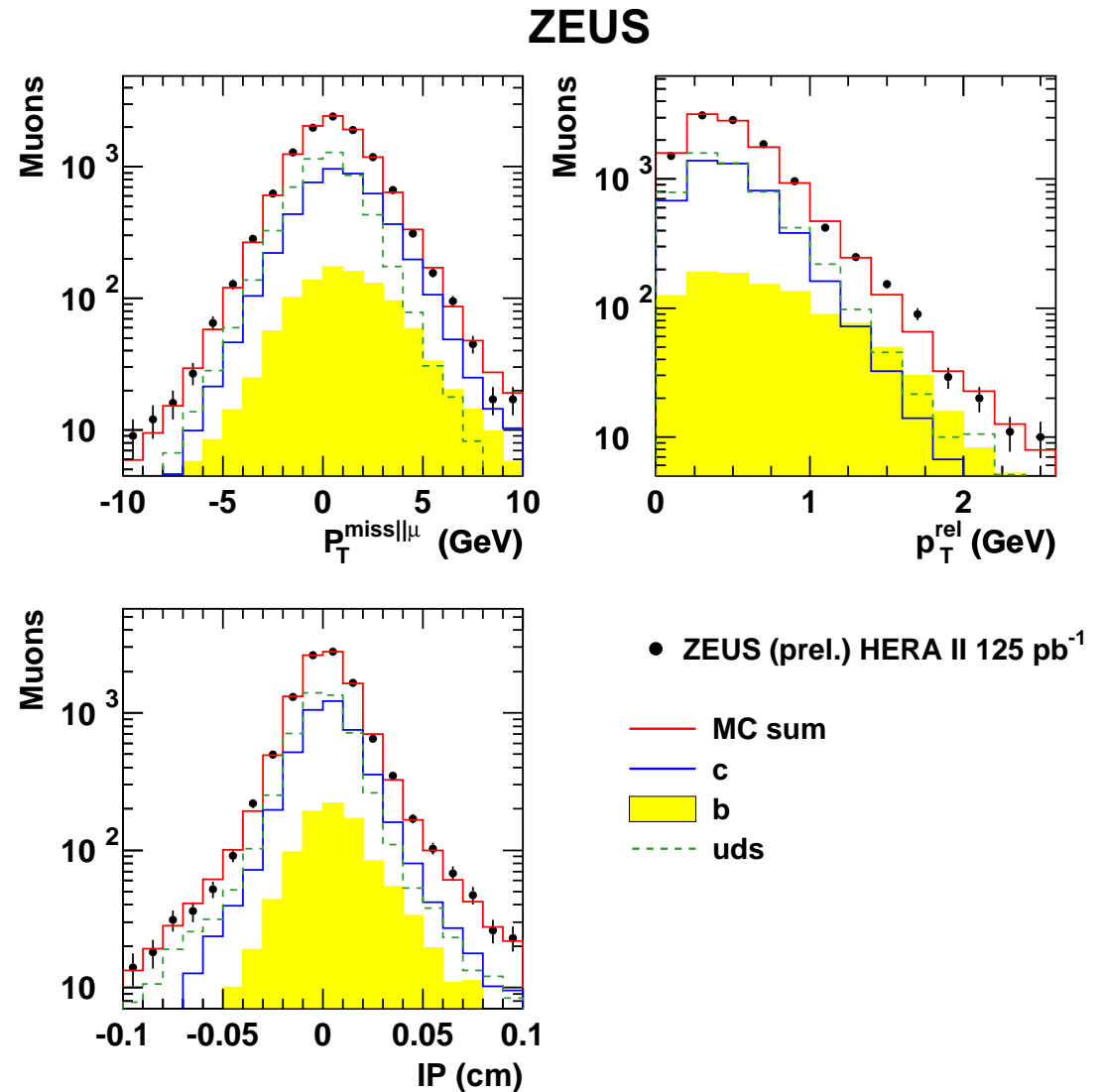
Status of $F_2^{b\bar{b}}$ last year

- 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

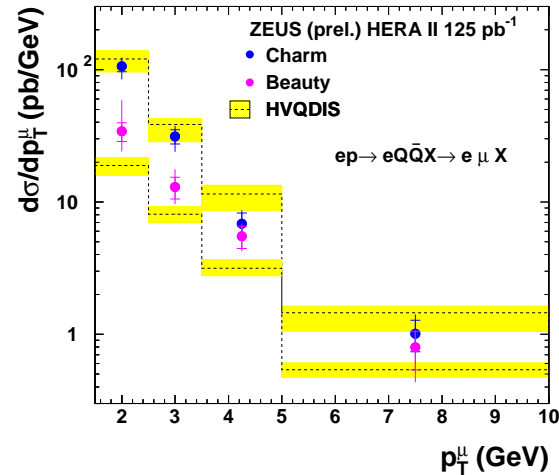
- ZEUS, muons in DIS
 - $Q^2 > 20 \text{ GeV}^2$, $0.01 < y < 0.7$,
 $p_T^\mu > 1.5 \text{ GeV}$, $-1.6 < \eta^\mu < 2.3$
 - 2005 data (125 pb^{-1})
 - fit to p_T^{rel} , δ and $p_T^{\text{miss}||\mu}$,
 missing momentum parallel to μ
 (tags neutrinos from SL decays)
 needs good p_T^{miss} measurement



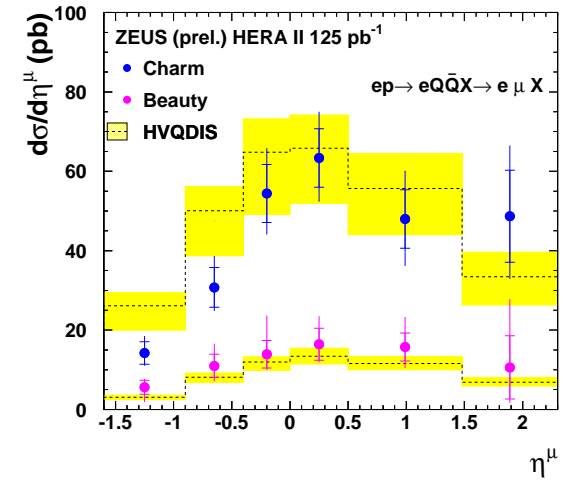
Results

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

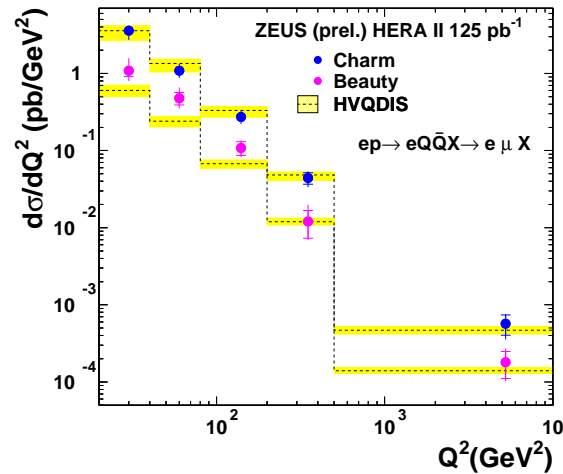
ZEUS



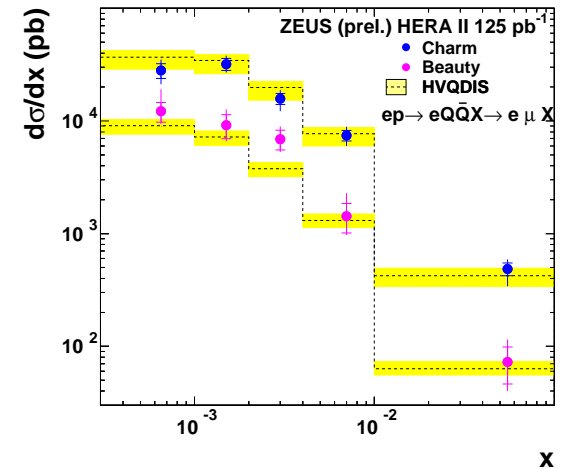
ZEUS



ZEUS

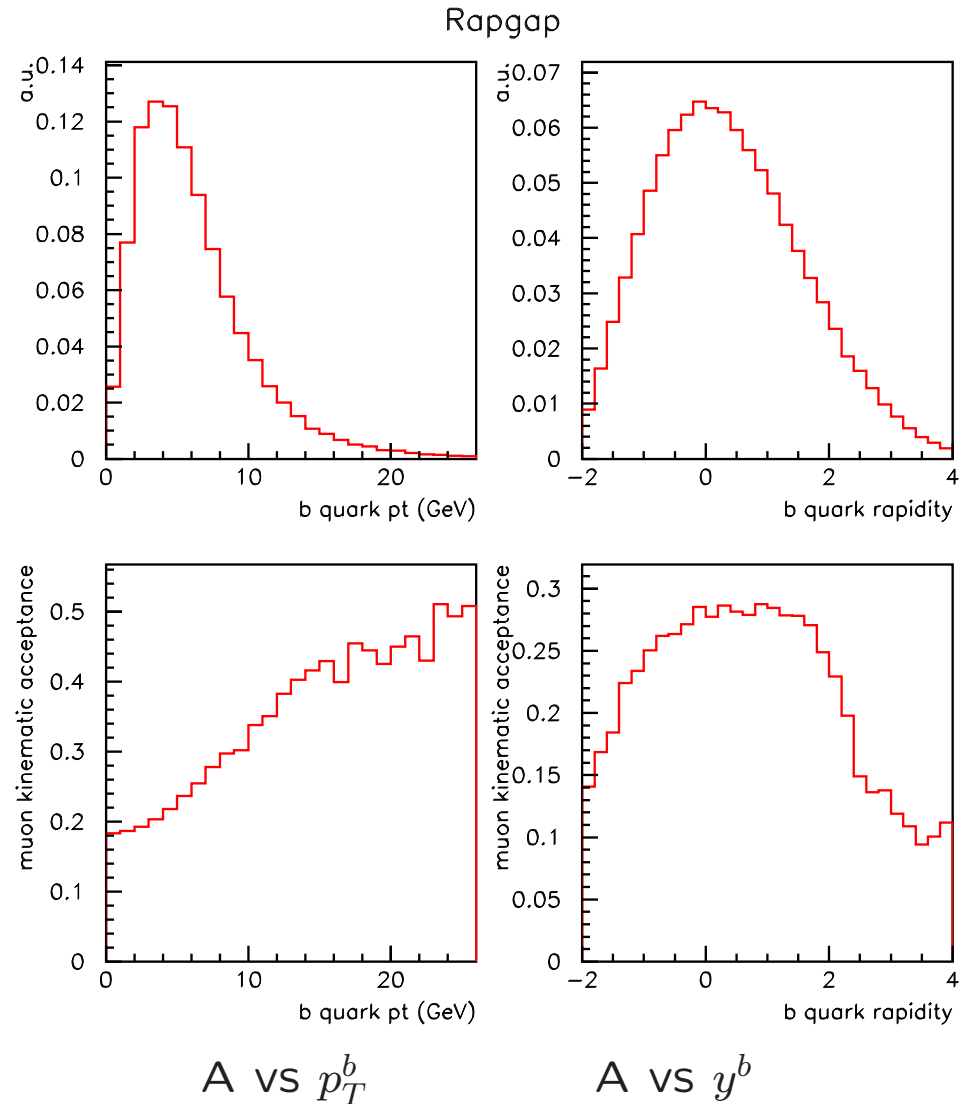


ZEUS



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

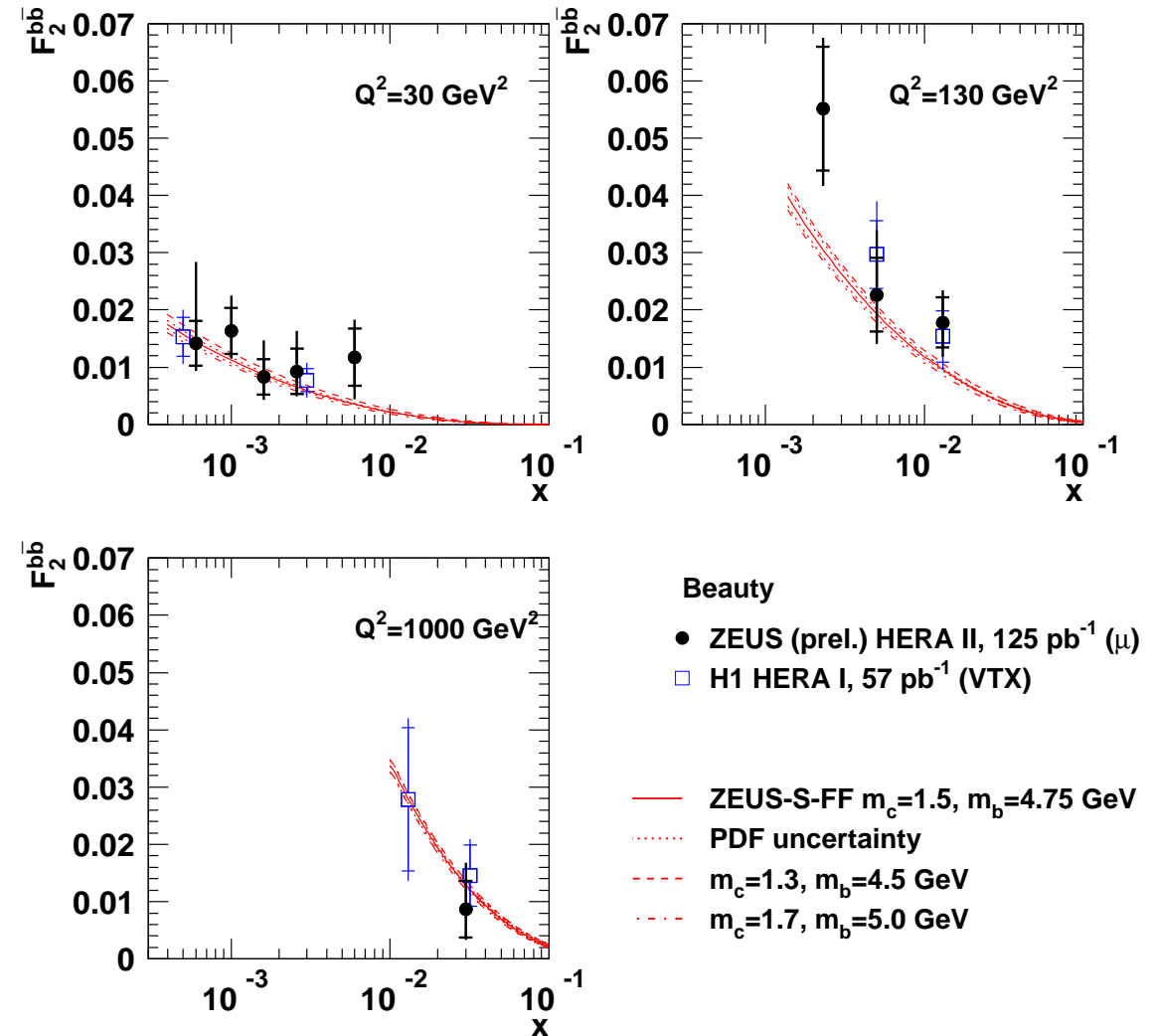
- $F_2^{b\bar{b}}$ extracted from visible cross section in x, Q^2 bins using HVQDIS
- kinematic acceptance of the muon cuts
 $p_T > 1.5 \text{ GeV}, -1.6 < \eta < 2.3$
wrt to the full muon phase space
 $A = N^\mu(vis)/N^\mu(all) = 25\% - 45\%$
from $Q^2 = 30$ to $Q^2 = 1000 \text{ GeV}^2$
- small dependence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



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

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

ZEUS

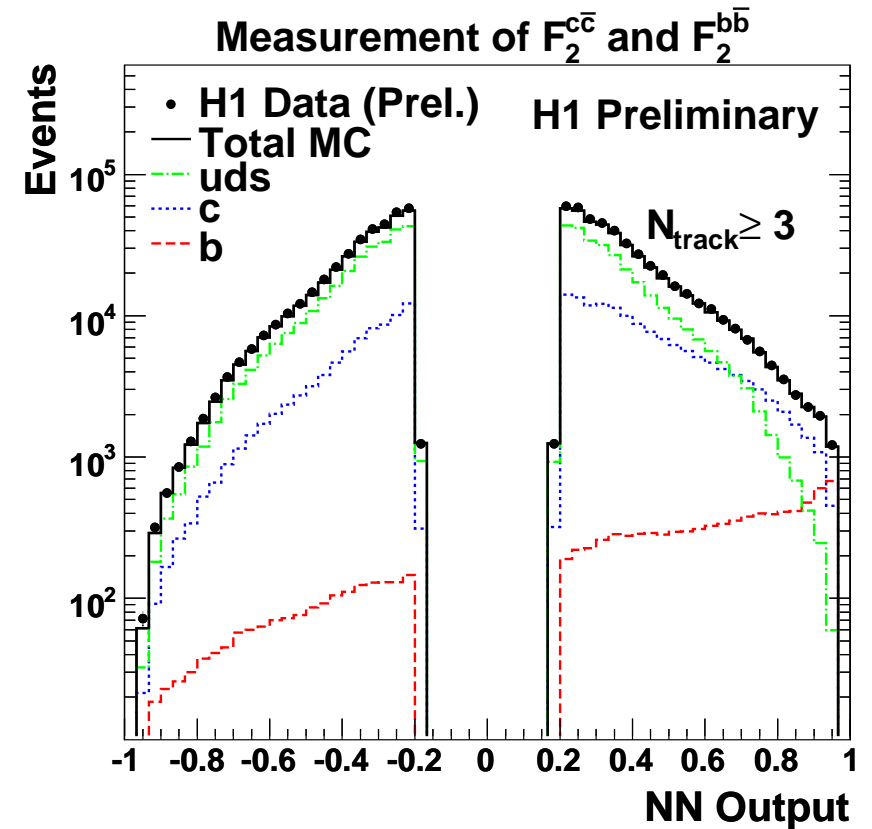


New HERA II result from H1

- 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)

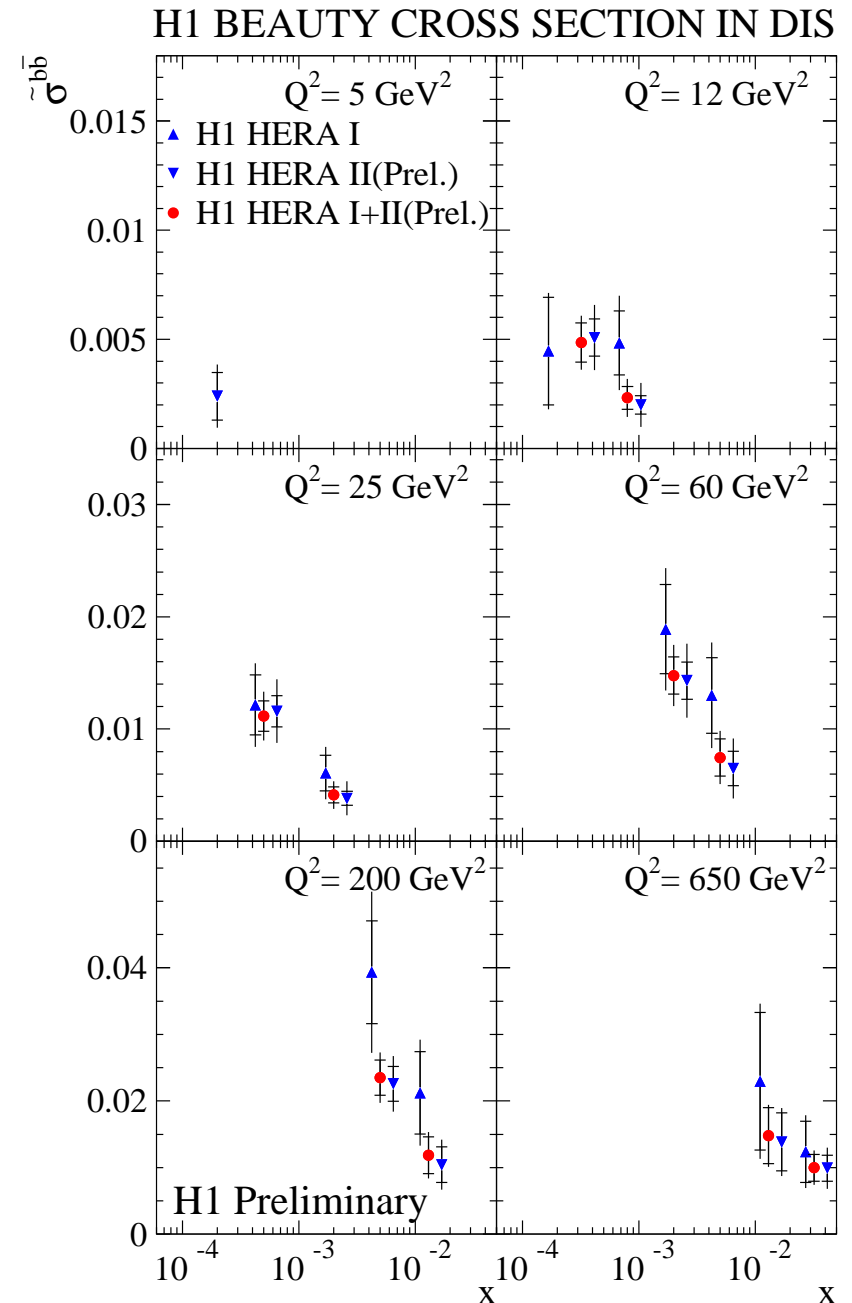
for events with ≥ 3 good CST tracks
use neural network with input:
 S_1 , S_2 , sec. vertex S_L ,
 p_T of first two tracks, multiplicity of prim.
and sec. vertex
sign assigned to NN output according to S_1

- - extract fraction of c , b



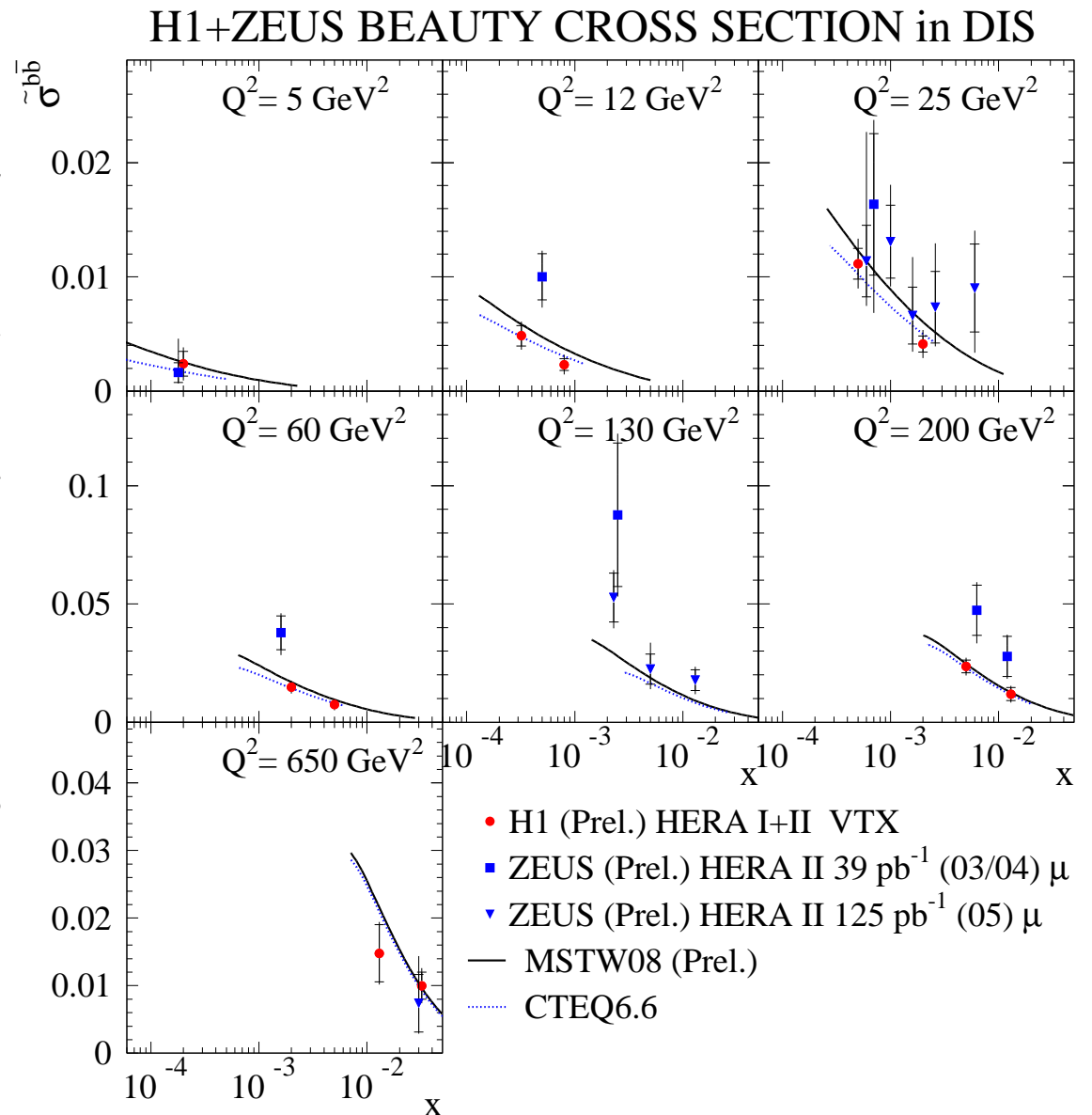
New HERA II result (H1)

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



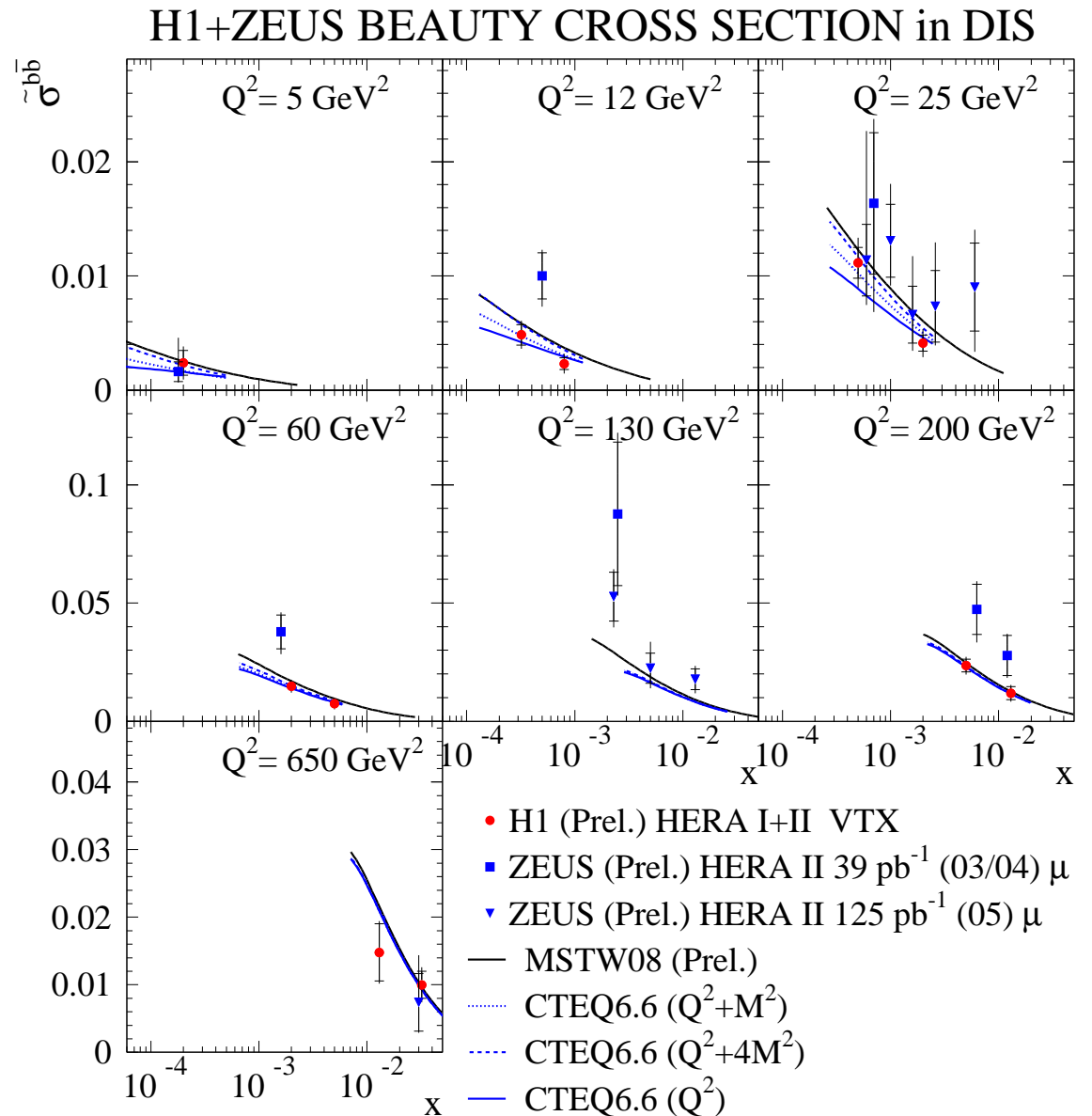
Summary of $F_2^{b\bar{b}}$

- 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 ?

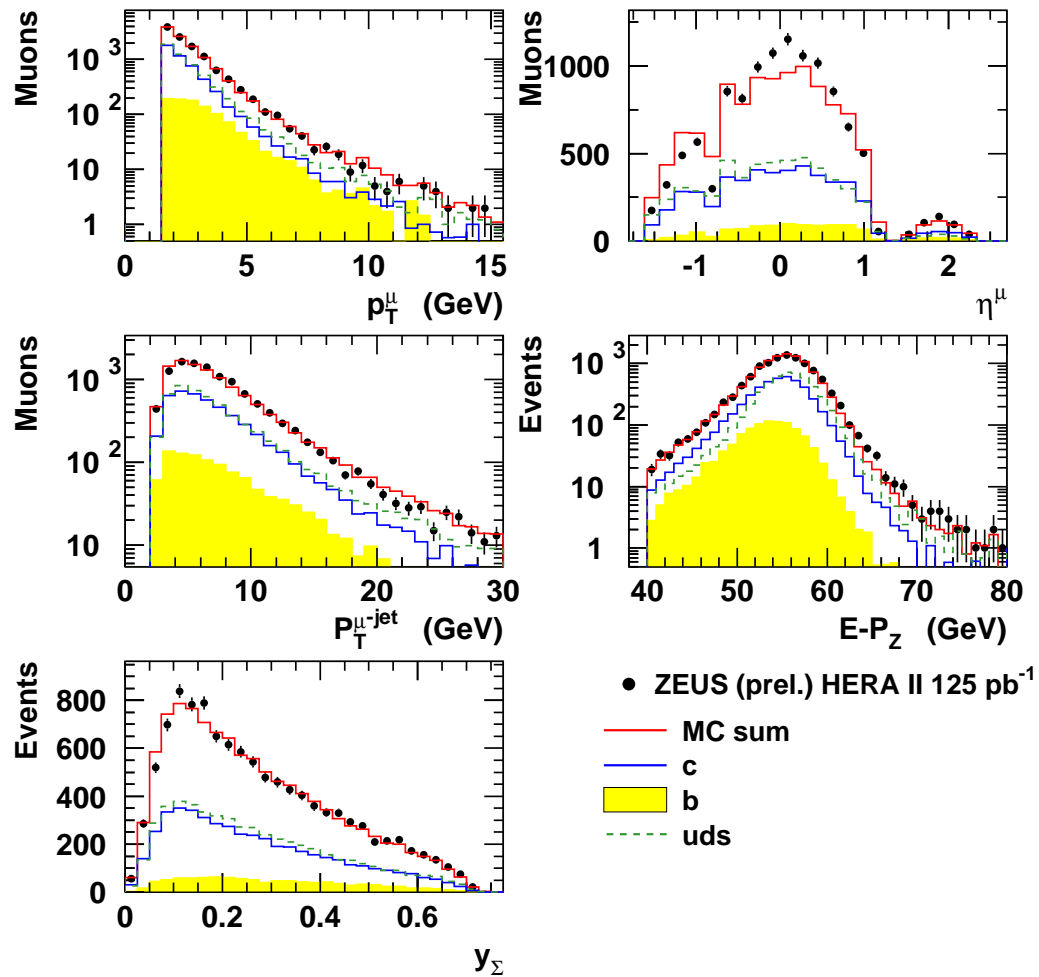
- **DIS**

- 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

backup

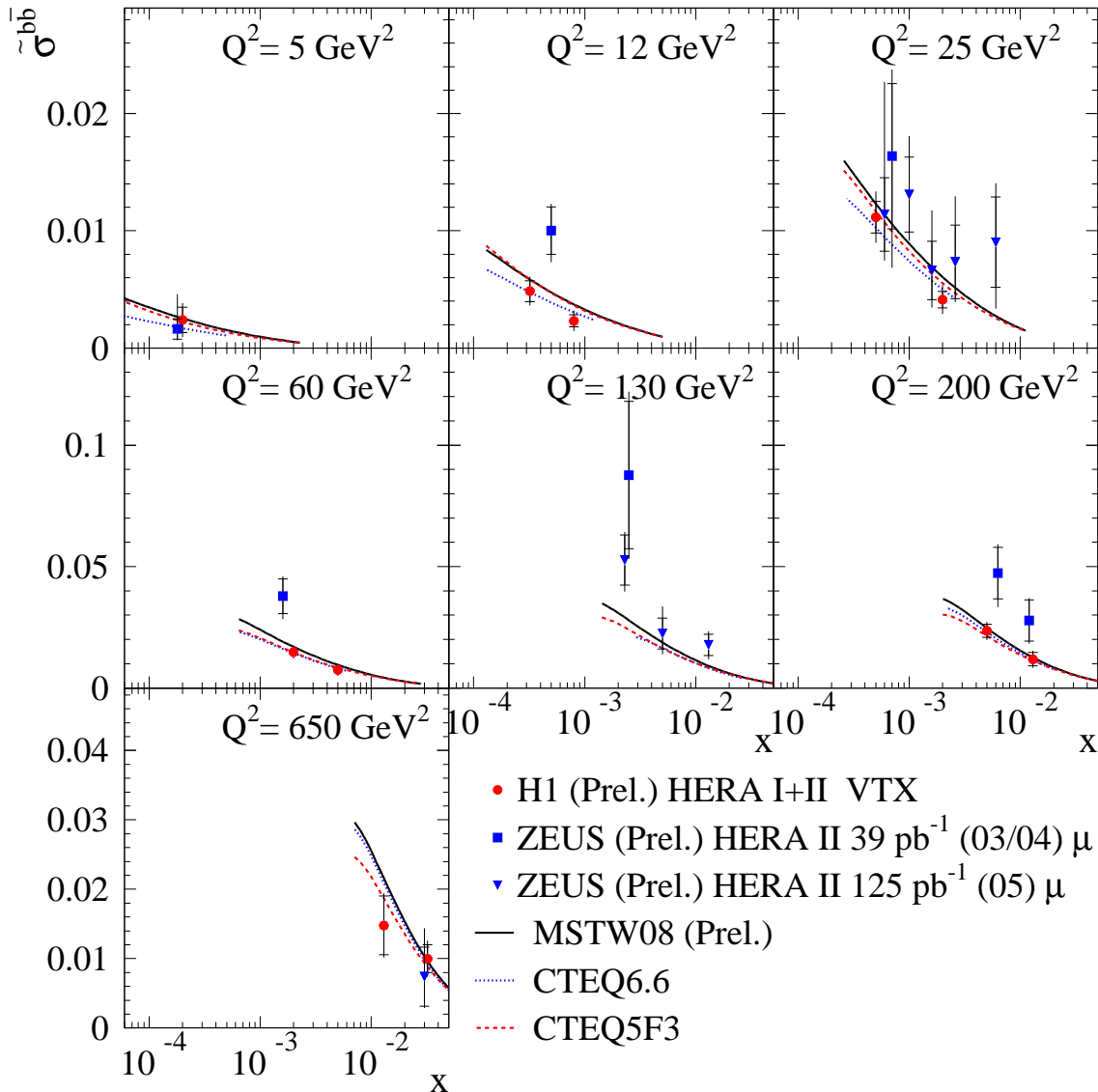
control plots of new ZEUS F_2^b

ZEUS



comparison to CTEQ5F

H1+ZEUS BEAUTY CROSS SECTION in DIS



backup

3 jets at CDF

