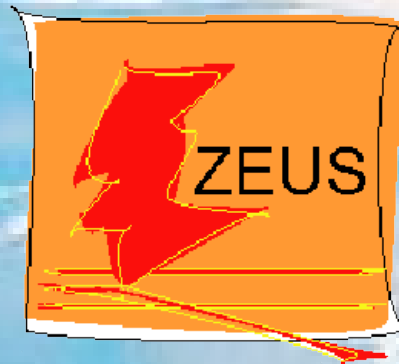


Beauty Production at HERA

Michel Sauter

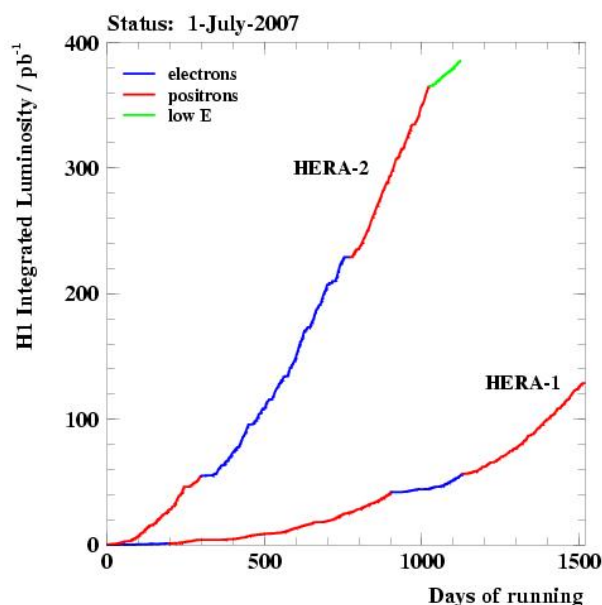
Ruprecht-Karls-Universität Heidelberg
for the H1 and ZEUS Collaborations

Low X Workshop, GREECE, June 23–27, 2010

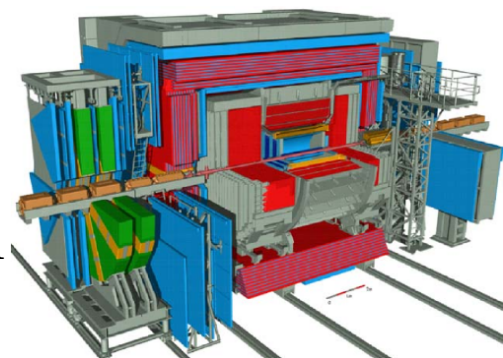
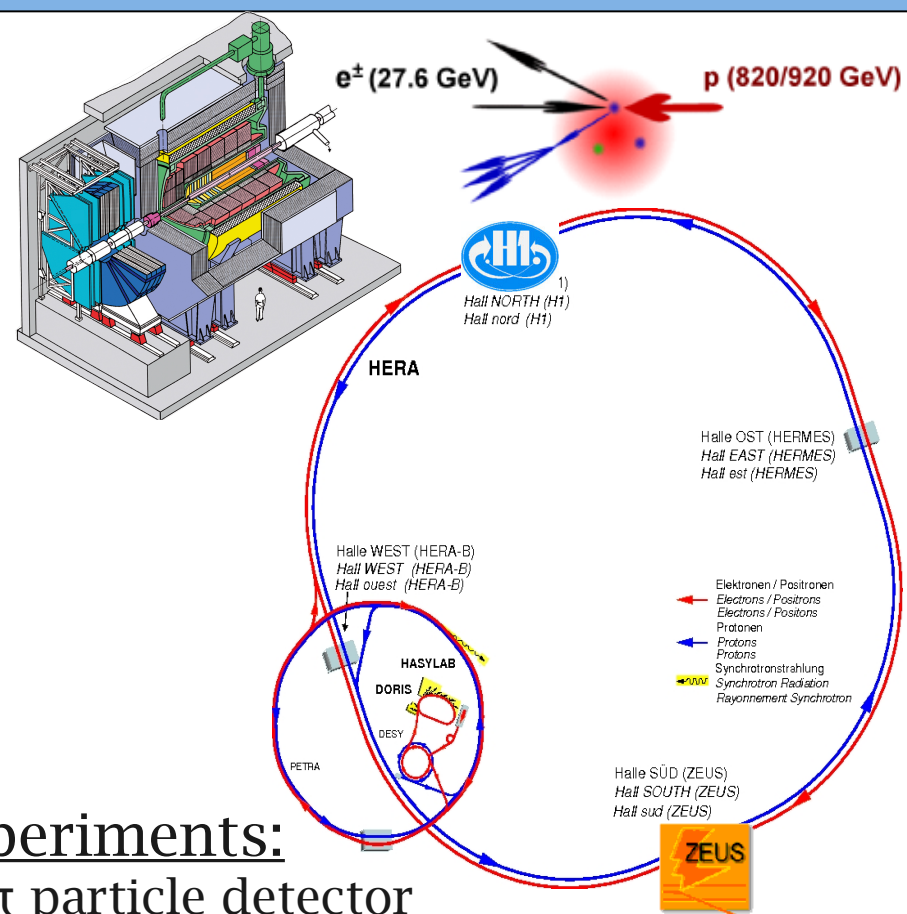


The H1 and ZEUS experiments at the HERA accelerator

- **HERA:** ep collider → 2 accelerators:
 - e^- (e^+) : 27.6 GeV
 - p: 920 GeV (820 GeV)
 - center of mass energy: 319 GeV
- Running periods:
 - HERAI 1992–2000
 - luminosity upgrade 2000–2002
 - HERA II 2002–2007 (end)
- Integrated luminosity on tape:
 - $\sim 0.5 \text{ fb}^{-1}$ (per experiment)

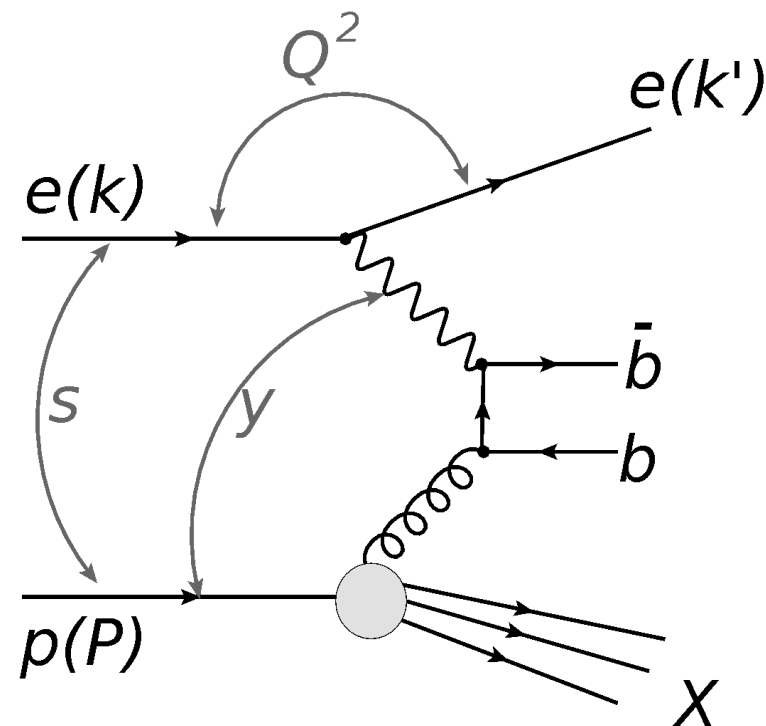


- **H1 & Zeus experiments:** Multi purpose 4π particle detector with an asymmetric design.
- Most relevant subdetectors:
 - Tracking system, silicon vertex detectors and gas chambers
 - Calorimeter: LAr (H1), Uranium (Zeus)
 - Muon chambers



Motivation to Measure Heavy Flavor Production

- Charm and Beauty quarks at HERA are mainly produced in Photon-Gluon-Fusion \rightarrow sensitive to gluon in proton.
- Hard scales for perturbative QCD:
 - $m_q \sim 5 \text{ GeV}$, p_T of quarks/jets, Q^2 .
 - multi-scale problem.
- Interpretation of Heavy Flavor measurements:
 - Trust the pQCD calculations and **constrain the gluon density of the proton.**
 - Take the gluon density from elsewhere and **determine the accuracy of the pQCD calculation.**



Leading order Feynman diagram for beauty production in ep at HERA.

$$\begin{aligned}s &= (k + P)^2 \\ x &= \frac{Q^2}{2 P \cdot q} \\ Q^2 &= -(k - k')^2\end{aligned}$$

$$\begin{aligned}Q^2 < 1 \text{ GeV}^2, & \quad \text{Photoproduction} \\ Q^2 > 1 \text{ GeV}^2, & \quad \text{DIS}\end{aligned}$$

- Number of theoretical approaches:
 - Massless and massive schemes.
 - General mass flavor number schemes (combination of massive/massless scheme).
- Monte Carlo Generators, $\text{LO}(\alpha_s) + \text{Parton Shower}$:
 - Collinear factorization, DGLAP evolution (PYTHIA for photoproduction and RAPGAP for DIS).
 - k_T factorization, CCFM evolution (CASCADE).
 - Used for data corrections and model comparisons.
- Calculations
 - Massive scheme, $\text{NLO}(\alpha_s^2)$:
 - FMNR: Photoproduction.
 - HVQDIS: DIS.
 - GM-VFNS used in latest global PDF fits (MSTW and CTEQ).
 - Used for comparisons of different models.

- Photoproduction:
 - "Measurement of Beauty Photoproduction from Inclusive Secondary Vertexing at HERA-II"
[ZEUS-prel-09-005](#), http://www-zeus.desy.de/public_results/publicsearch2.php
- Beauty in DIS:
 - "Measurement of Charm and Beauty Jets in Deep Inelastic Scattering at HERA"
[H1prelim-10-073](#), http://www-h1.desy.de/publications/H1preliminary.short_list.html
 - "Differential Beauty Cross Sections using Inclusive Secondary Vertices"
[ZEUS-prel-09-005](#).
- Beauty Structure Functions:
 - "Measurement of the Charm and Beauty Structure Functions using the H1 Vertex Detector at HERA"
[Eur.Phys.J. C65 \(2010\) 89](#), [arXiv:0907.2643](#)
 - "Measurement of Beauty Production in DIS and F_2^{bb} Extraction at ZEUS"
to be published in [EPJ C](#), http://www-zeus.desy.de/zeus_papers/zeus_papers.html

Tagging Methods for Heavy Flavor Physics at HERA

- At HERA beauty is only $\sim 0.03\%$ of the total γp cross section.
- Beauty enrichment is possible with:

1) Lepton tagging

- Use semileptonic b/c decay channels:
 - look for μ or e , high $\text{BR}(b \rightarrow \text{lepton} + \text{anything})$

2) Lifetime tagging

- b/c quark have long lifetimes:
 - look for displaced vertices.
 - look for tracks with large impact parameters δ .

3) p_T^{rel} tagging

- Use high b quark mass
 - look for decay leptons with a high transverse momentum w.r.t the b quark flight direction.

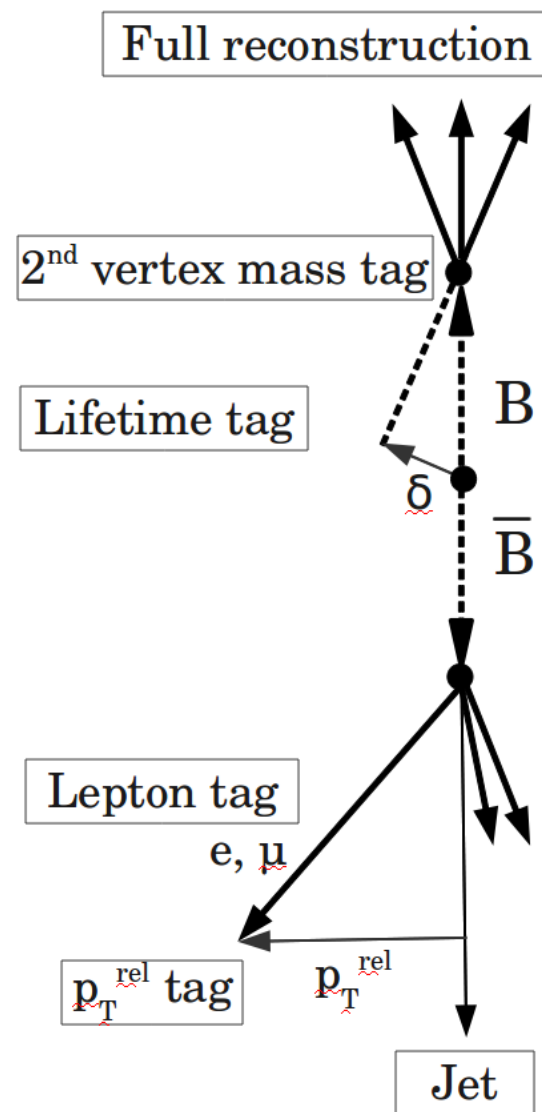
4) Secondary vertex mass tagging

- Use high b quark mass
 - look for high secondary vertex masses.

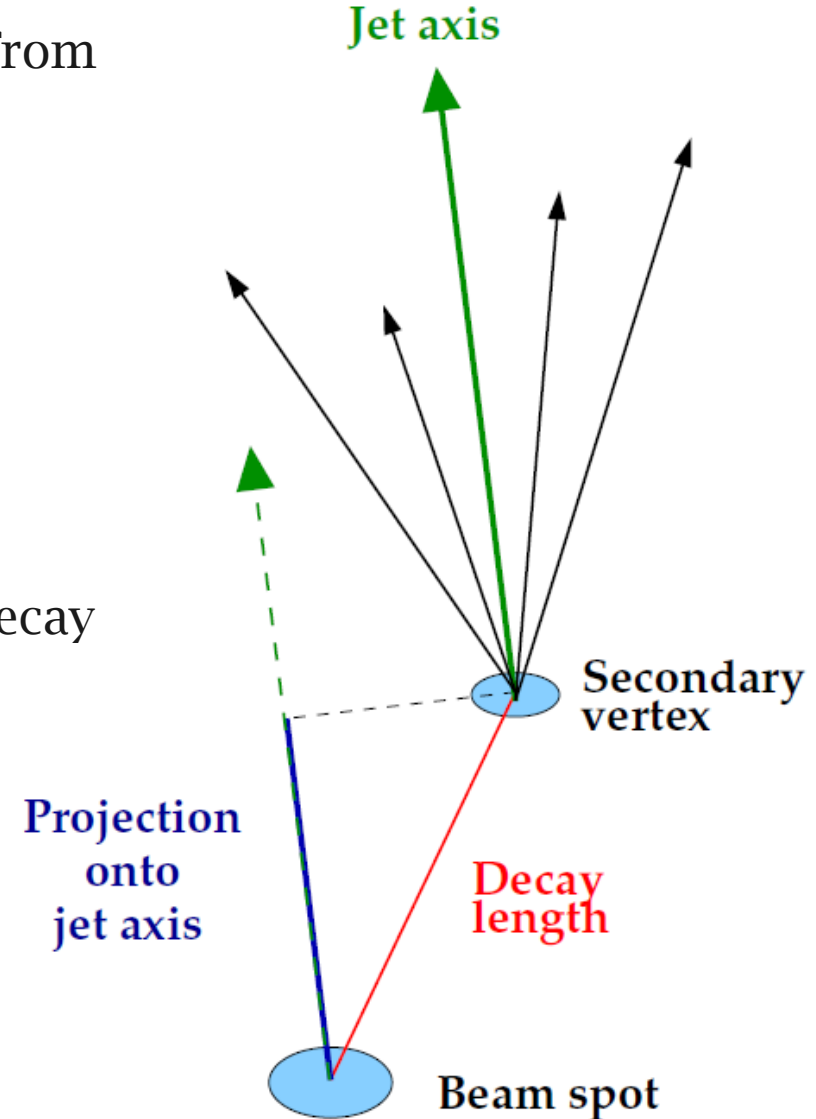
5) Full reconstruction of exclusive decay channel

- Only possible for charm at HERA, eg. $D^* \rightarrow K\pi\pi$, $J/\psi \rightarrow \mu\mu$, ee . No suitable beauty decay channels with high statistics.

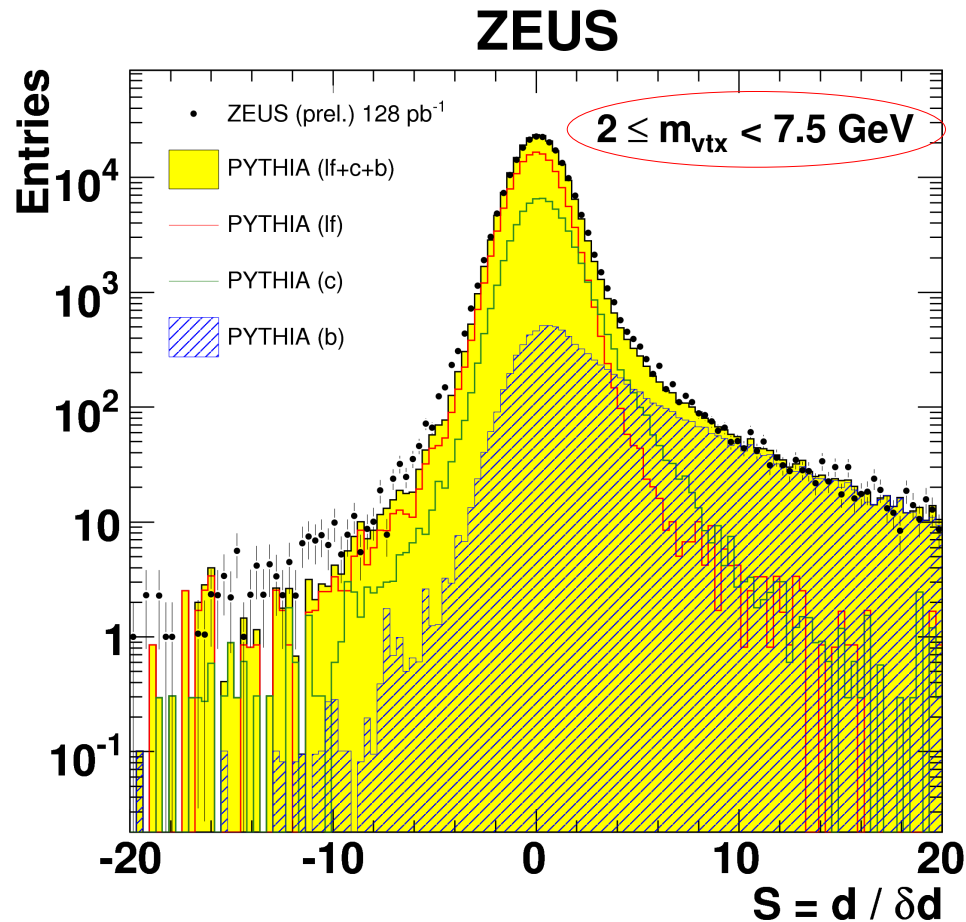
- Combination of different tagging methods.



- Analysis:
 - "Measurement of beauty photoproduction from inclusive secondary vertexing at HERA-II", [ZEUS-prel-09-005](#).
- Phase Space
 - $Q^2 < 1\text{GeV}^2$, $0.2 < y < 0.8$
 - Events with least 2 jets with:
 - $p_T^{\text{jet } 1(2)} > 7 \text{ (6) GeV}$
 - $|\eta^{\text{jet } 1(2)}| < 2.5$ (one jet with central: $-1.6 < \eta^{\text{jet } 1(2)} < 1.3$)
 - inclusive selection, no requirements on b decay final state
- HERA II data
 - 2006 / 07, 128 pb^{-1}
- Beauty tagging
 - Reconstruction of secondary vertex:
 - Decay length
 - Mass of tracks associated with the secondary vertex, m_{vtx}



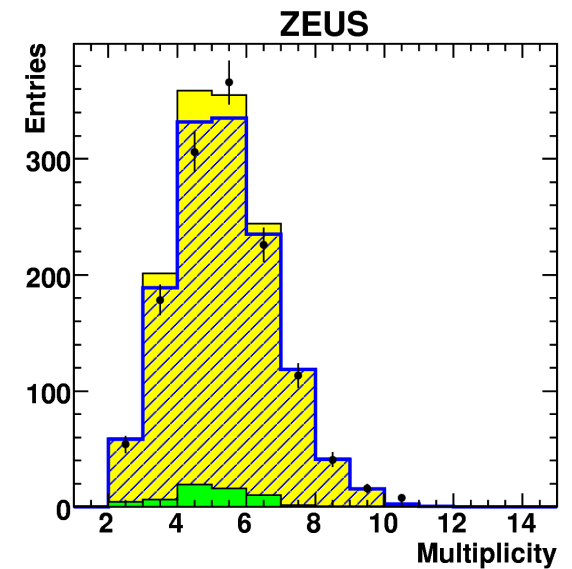
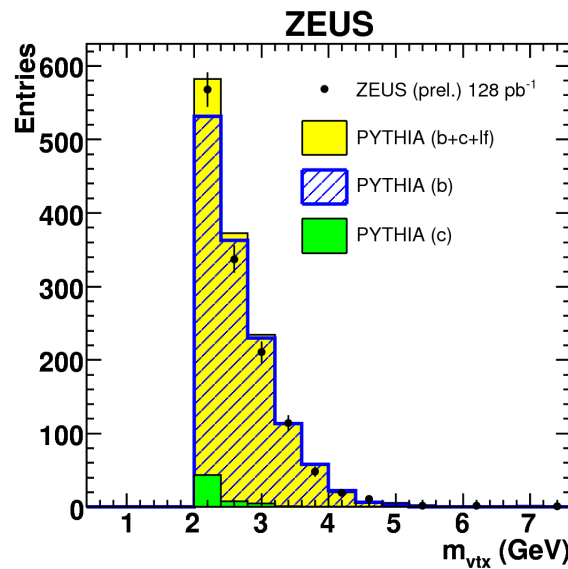
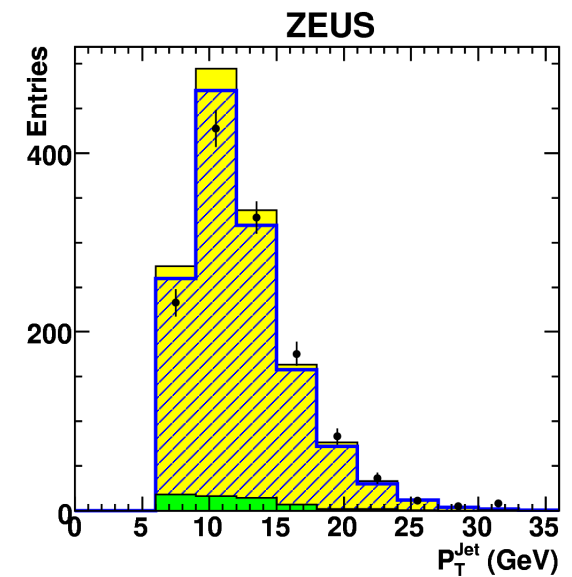
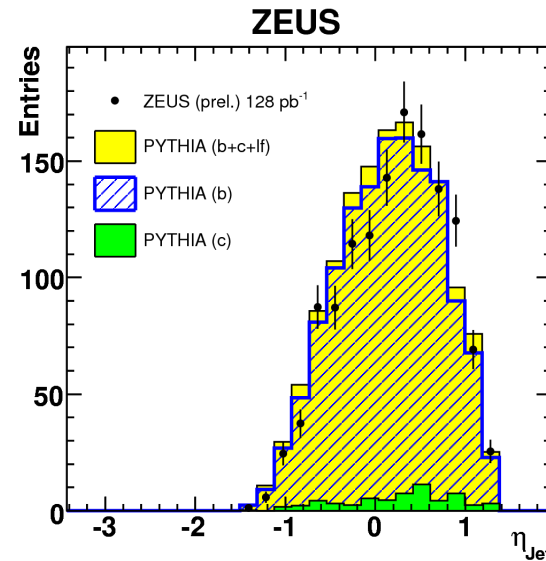
Flavor separation:



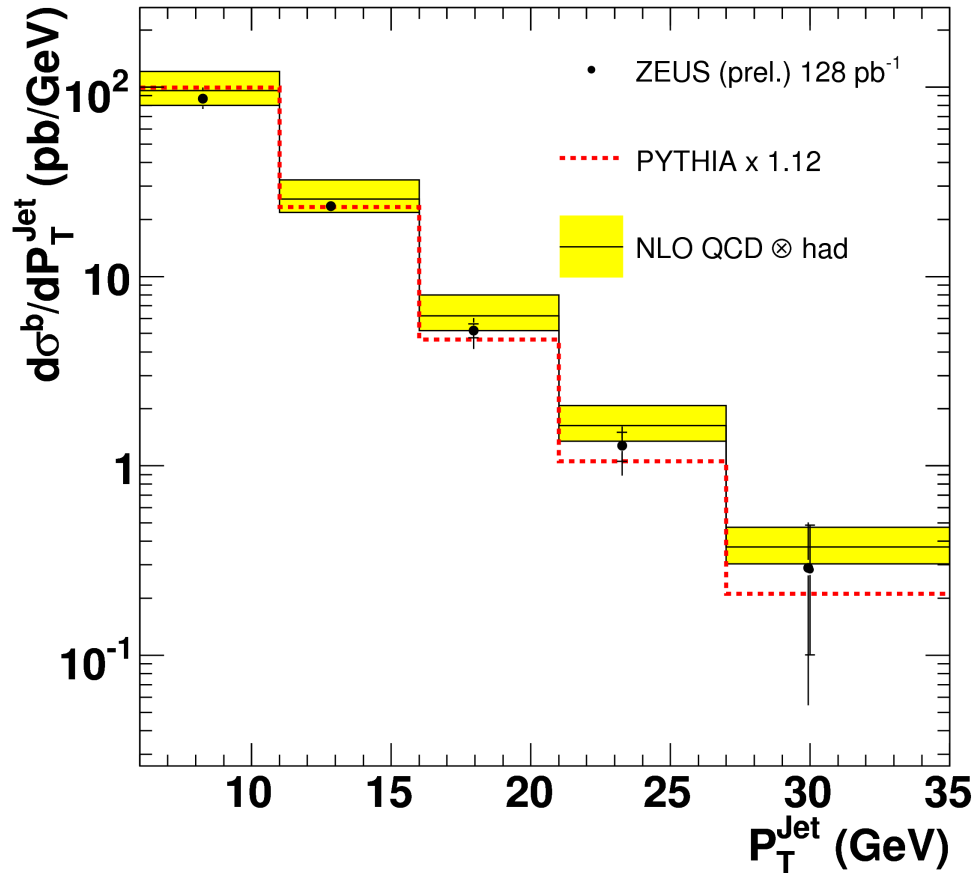
- Decay length significance :
 $S = DL / \sigma(DL)$
- Symmetric distribution for light flavors.
- At high secondary vertex masses m_{vtx} almost pure beauty contribution.
- Fit mirrored and subtracted decay length significance in 3 secondary vertex mass bins.

Beauty enriched control distributions

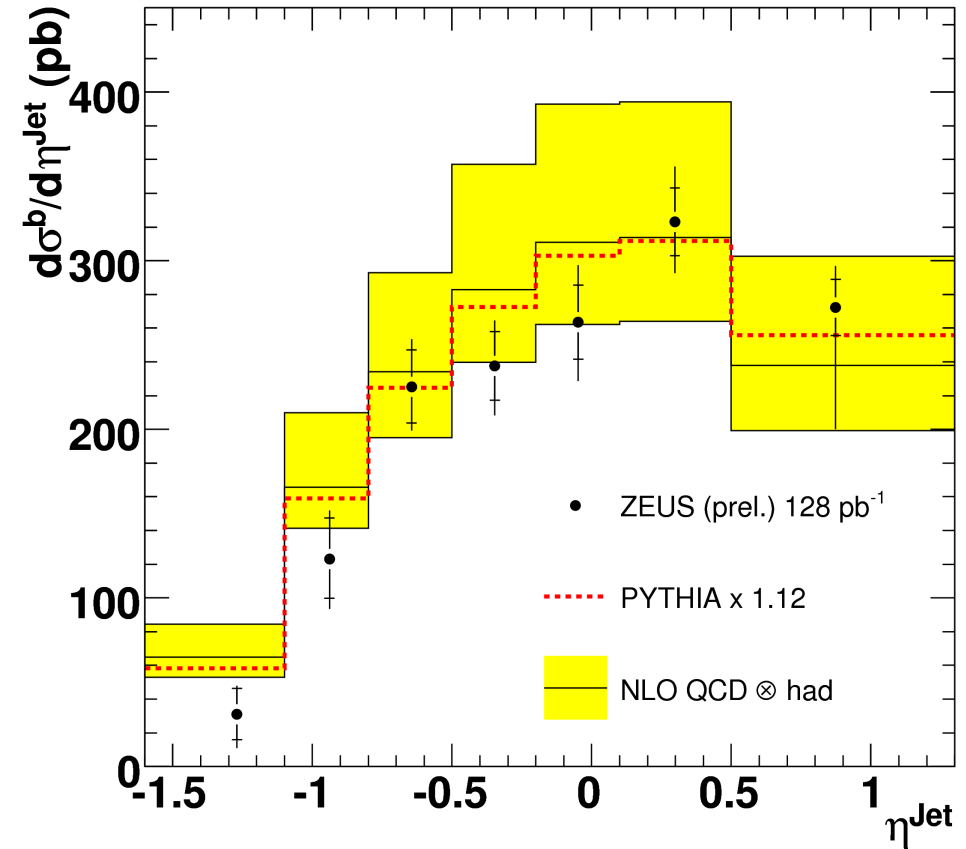
- Almost pure Beauty contribution.
- Good agreement between data and scaled LO-MCs.



ZEUS

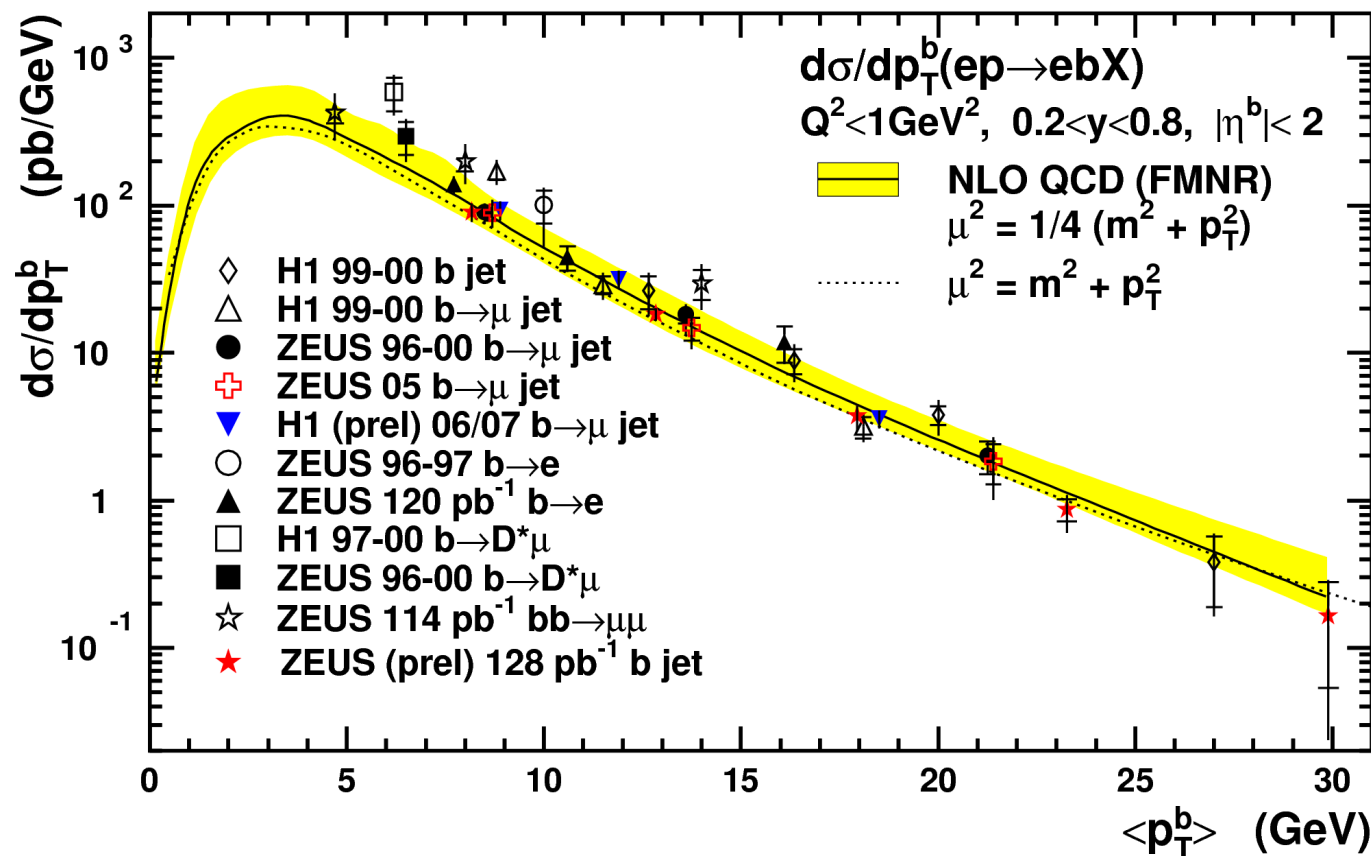


ZEUS



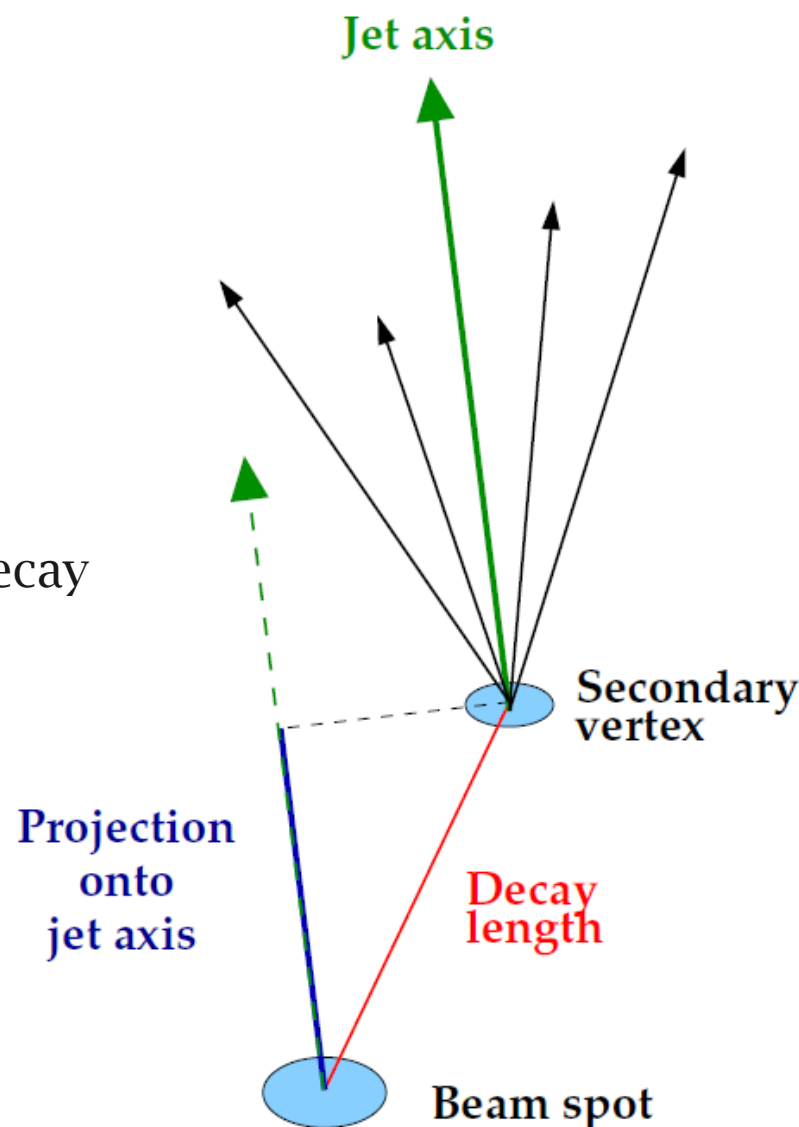
- Differential cross section in p_T^{jet} and η^{jet} .
- Good agreement with scaled LO MC (Pythia) and NLO QCD calculation (FMNR).

HERA

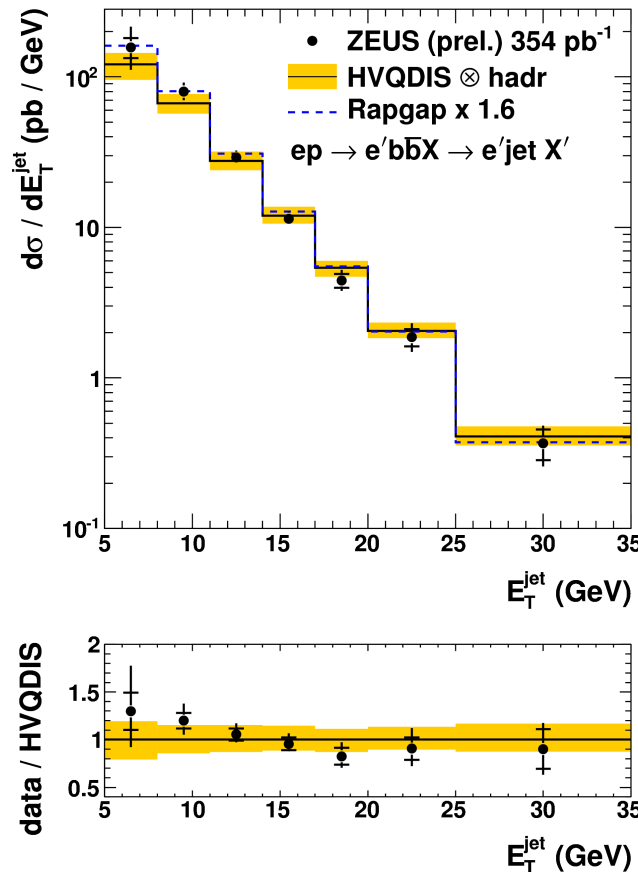


- Several measurements with different methods and systematics confirming each other and covering different $p_T(b)$ ranges.
- General good agreement observed for jet measurements, whereas lepton- and D^* -double-tagging measurements tend to lie above the NLO QCD calculation.

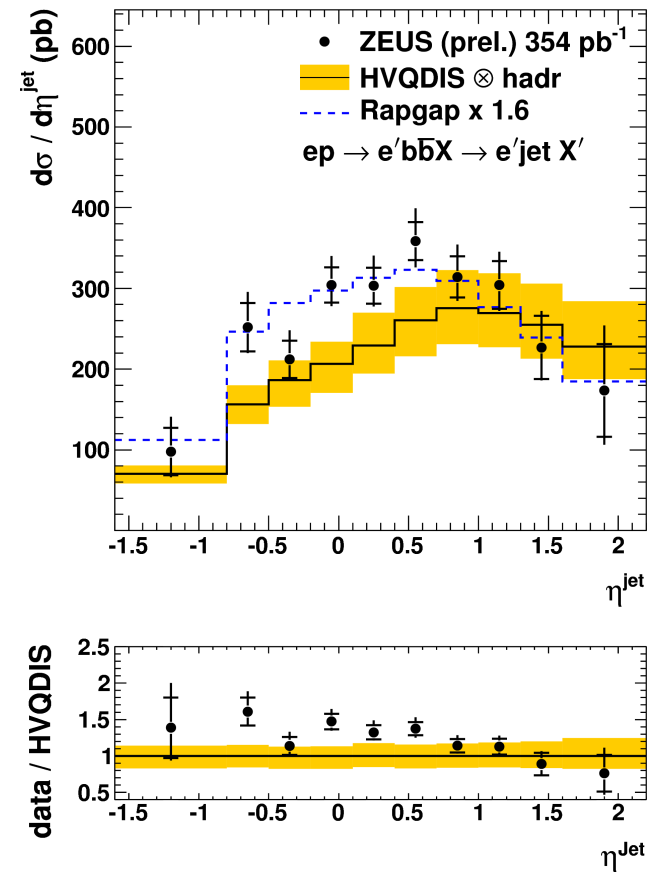
- Analysis:
 - "Differential Beauty Cross Sections using Inclusive Secondary Vertices"
[ZEUS-prel-09-004](#).
- Phase Space
 - $5 < Q^2 < 1000 \text{ GeV}^2$, $0.02 < y < 0.7$
 - Events with least 2 jets with:
 - $E_T^{\text{jet}} > 5 \text{ GeV}$
 - $-1.6 < \eta^{\text{jet}} < 2.2$
 - inclusive selection, no requirements on b decay final state
- Full HERA II data set
 - 2004-07, 354 pb^{-1}
- Beauty tagging
 - Reconstruction of secondary vertex:
 - Decay length
 - Mass of tracks associated with the secondary vertex, m_{vtx}
 - Same method as for Photoproduction analysis.



ZEUS



ZEUS



- Differential cross section in E_T^{jet} and η^{jet} .
- Good agreement with scaled LO MC (Rapgap) and NLO QCD calculation (HVQDIS).

- Analysis

- "Measurement of the Charm and Beauty Structure Functions using the H1 Vertex Detector at HERA", [Eur.Phys.J. C65 \(2010\) 89](#).
- "Measurement of Charm and Beauty Jets in Deep Inelastic Scattering at HERA", [H1prelim-10-073](#).

- Phase Space

- Inclusive F_2^{cc} , F_2^{bb}
 - $5 < Q^2 < 2000 \text{ GeV}^2$
 - $0.0002 < x < 0.05$

- Charm-, Beauty-Jets analysis:
 - $6\text{GeV}^2 < Q^2$, $0.07 < y < 0.625$
 - Events with least on jets with:
 $E_T^{\text{jet}} > 6 \text{ GeV}$, $-1 < \eta^{\text{jet}} < 1.5$

- HERA II data (both analyses)

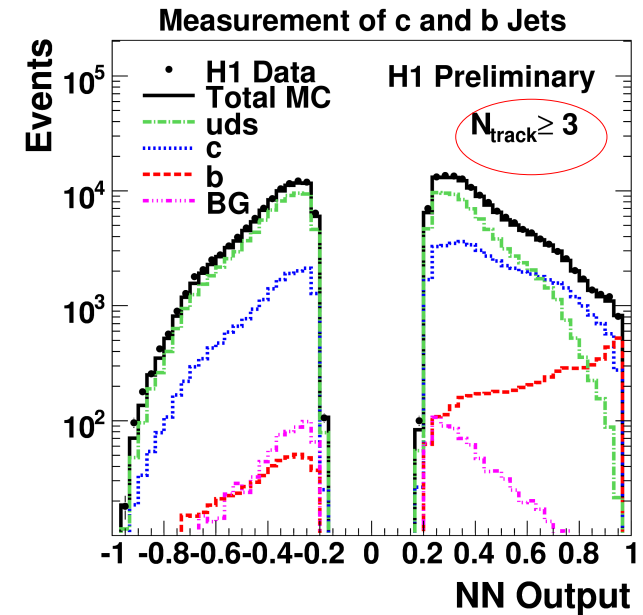
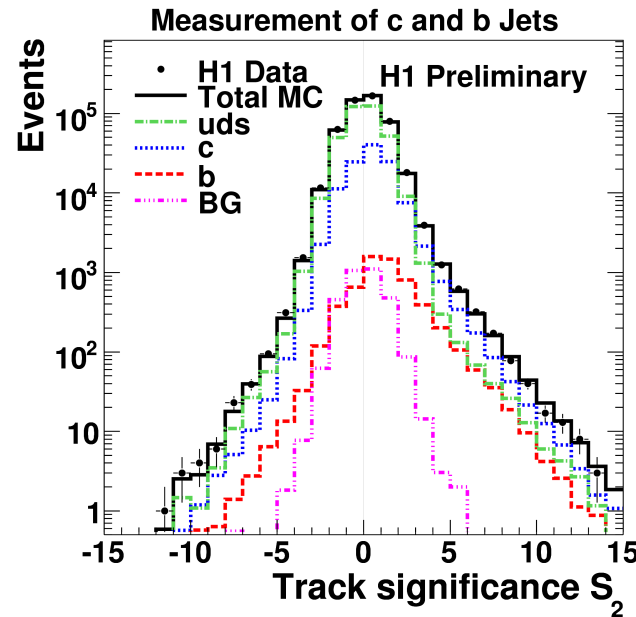
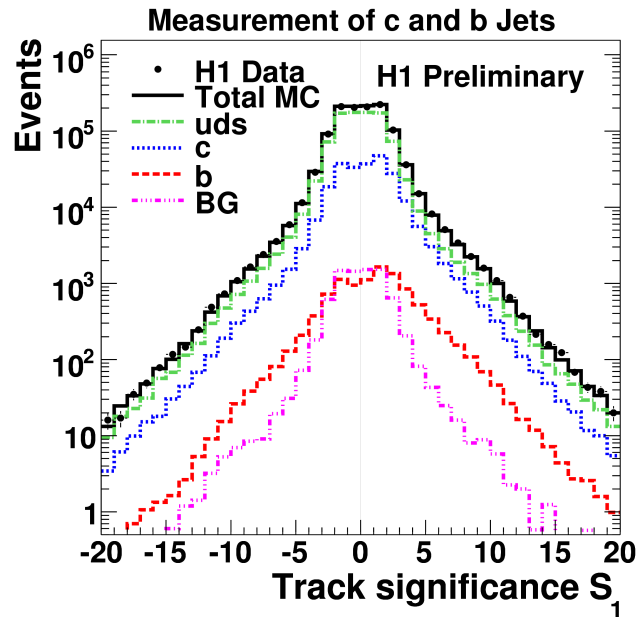
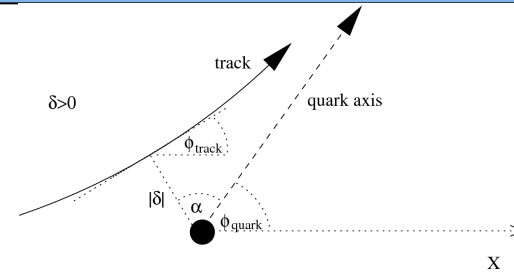
- 2006 / 07, 189 pb^{-1}

- Beauty tagging (both analyses)

- Reconstruction of secondary vertex.
- Displaced tracks.

Flavor separation

based on Track significance: $S = \delta / \sigma(\delta)$



- Symmetric distributions for light flavors.
- Beauty and Charm have asymmetric S_1 , S_2 distributions due to lifetime.
- NN discriminates Beauty and Charm.
- Fit mirrored and subtracted distributions to determine b, c and uds fractions in each bin (x and Q^2 for structure function analysis, E_T^{jet} and jet for η^{jet} analysis).

Neural Network input includes S_1 , S_2 , S_3 , 2nd vertex decay length significance.

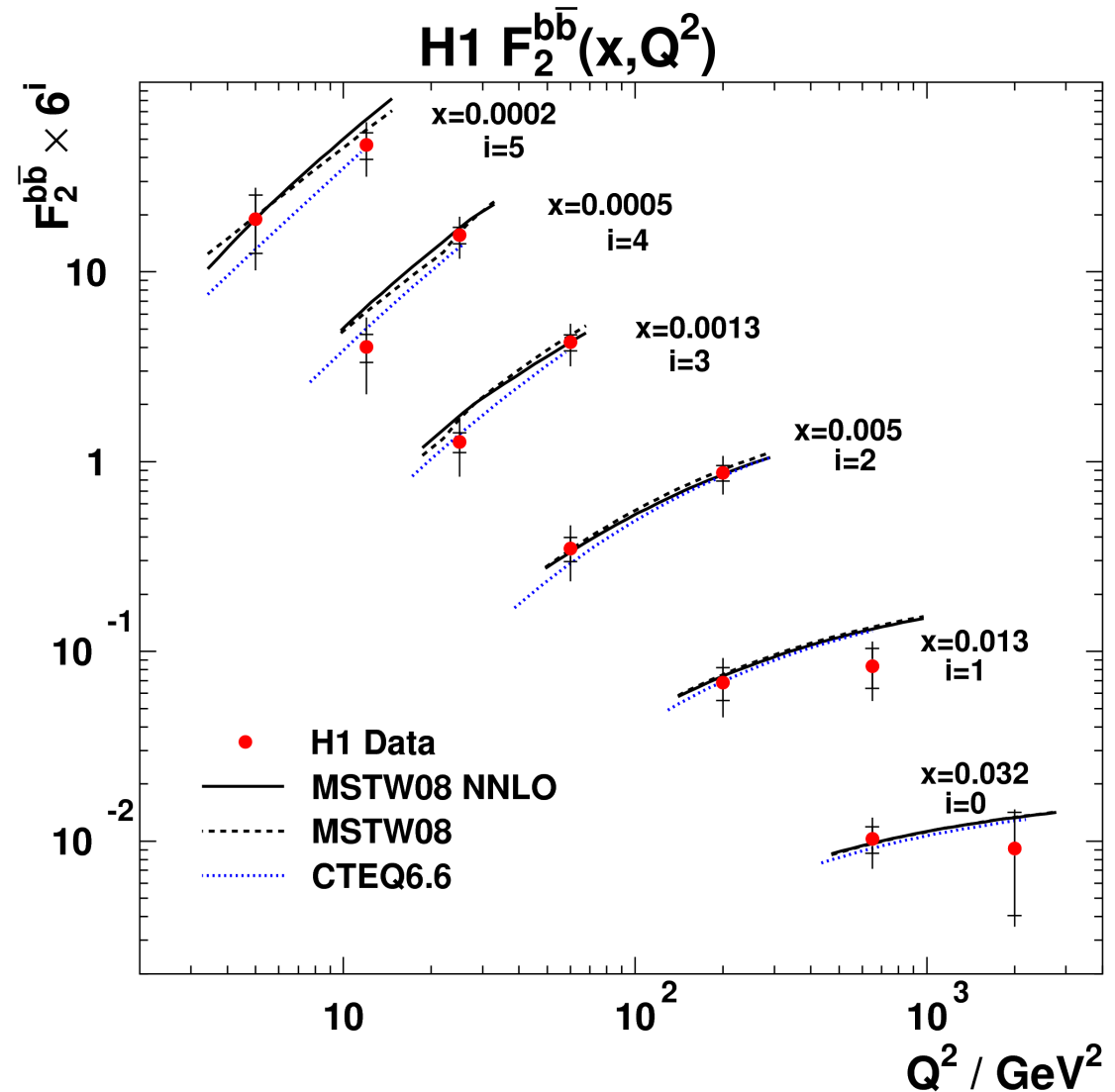
- Result of the fit converted to a measurement of the 'reduced b cross section':

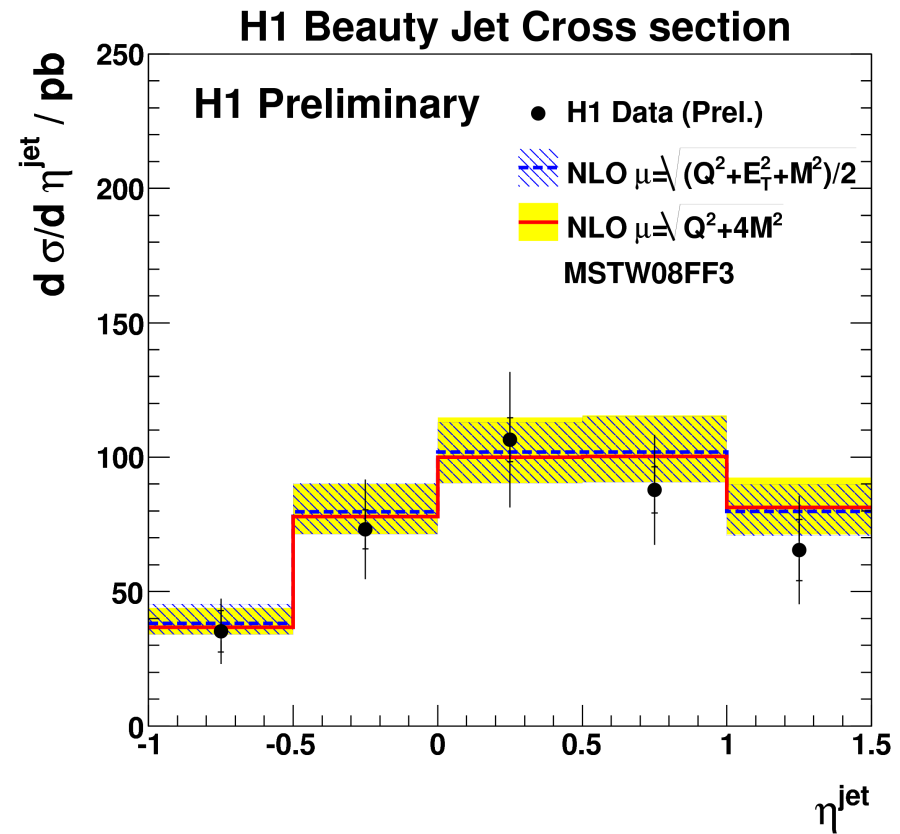
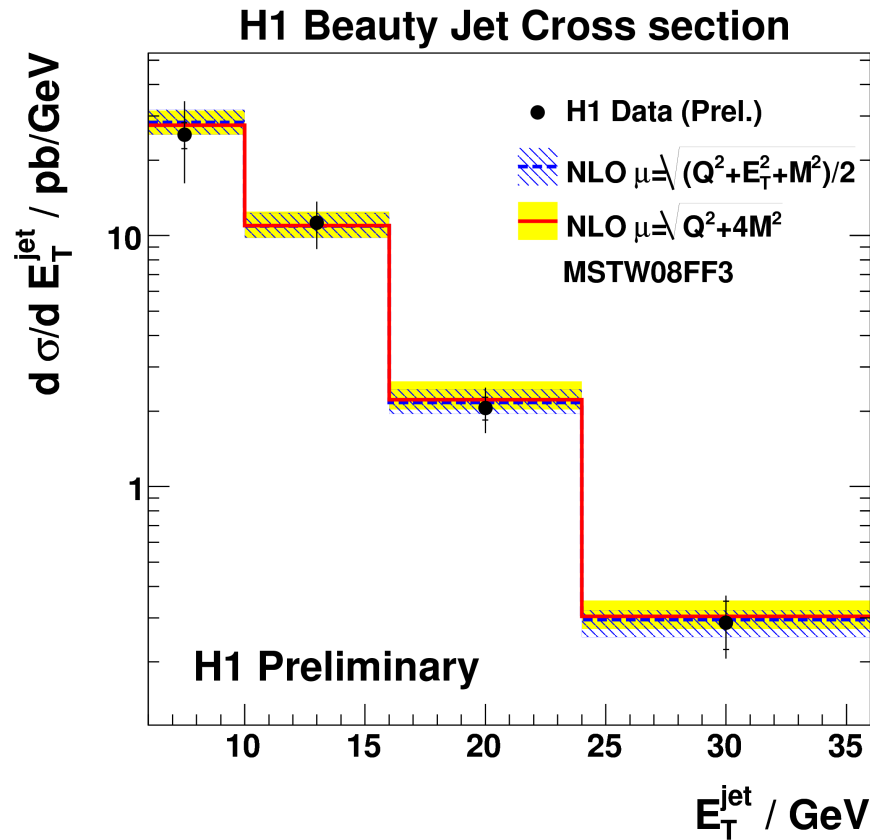
$$\tilde{\sigma}^{b\bar{b}}(x, Q^2) = \frac{d^2 \sigma^{b\bar{b}}}{dx dQ^2} \frac{x Q^4}{2\pi \alpha^2 (1 + (1-y)^2)}$$

- The structure function F_2^{bb} is evaluated from the 'reduced cross section':

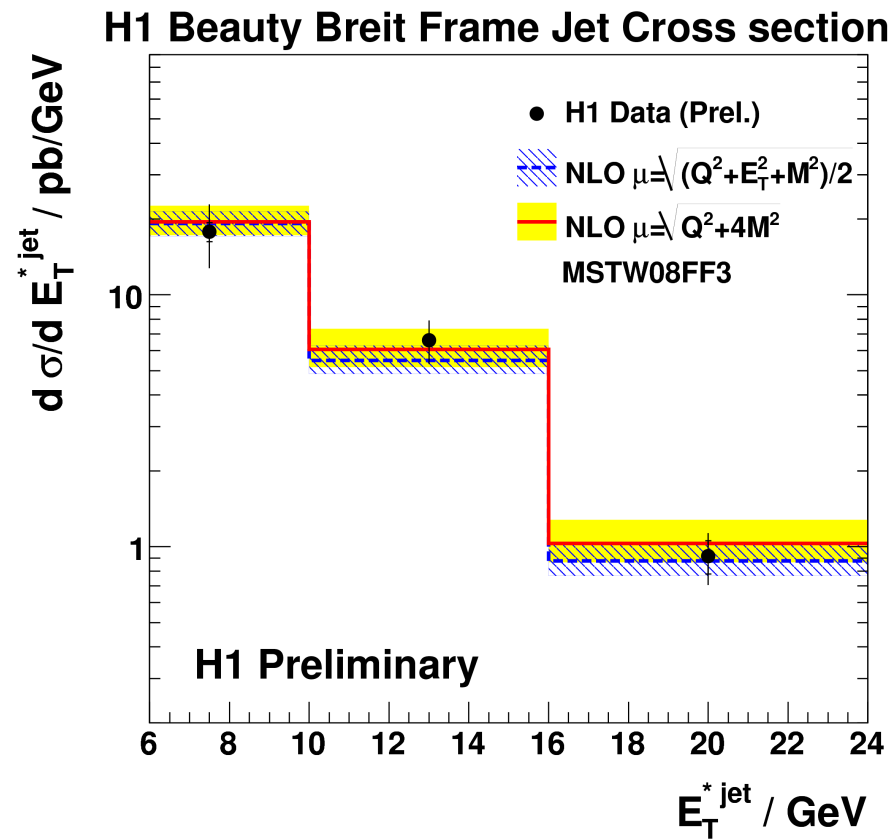
$$\tilde{\sigma}^{b\bar{b}} = F_2^{b\bar{b}} - \frac{y^2}{1 + (1-y)^2} F_L^{b\bar{b}}$$

- F_L^{bb} estimated from NLO QCD calculation.
- Data well described by all predictions.
- Small differences between CTEQ NLO and MSTW at low Q^2 .





- NLO QCD calculation (HVQDIS) gives good data description for both scale choices.



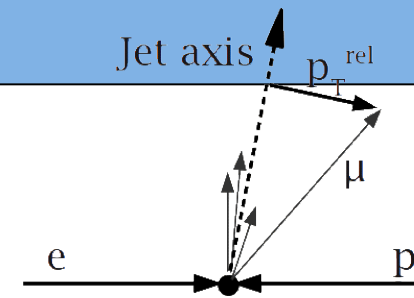
- Analysis extended to Breit frame. (Theoretically favorable and used in previous HF analyses).
- NLO QCD calculation (HVQDIS) gives good data description for both scale choices.

- Analysis
 - "Measurement of beauty production in DIS and F_2^{bb} extraction at ZEUS", to be published in [EPJ C](#).
- Phase Space
 - $2 \text{ GeV}^2 < Q^2$, $0.05 < y < 0.7$
 - Events with least 1 jets and an associated muon:
 - $E_T^{\text{jet}} > 5 \text{ GeV}$, $-2 < \eta^{\text{jet}} < 2.5$
 - $p_T^\mu > 1.5 \text{ GeV}$, $-1.6 < \eta^\mu \lesssim 2.5$
 - $\Delta R = \sqrt{(\Delta\Phi_{\mu, \text{jet}}^2 + \Delta\eta_{\mu, \text{jet}}^2)} < 0.7$
- HERA I data
 - 1996–2000, 114 pb^{-1}
- Beauty tagging
 - Muons with high transverse momentum relative to jet axis, p_T^{rel} .

Flavor separation

p_T of muon w.r.t. jet:

$$p_T^{rel} = \frac{|\vec{p}^\mu \times \vec{p}^{jet}|}{|\vec{p}^{jet}|}$$



- p_T^{rel} distribution contains at high values a Beauty dominated tail due to the high Beauty mass.

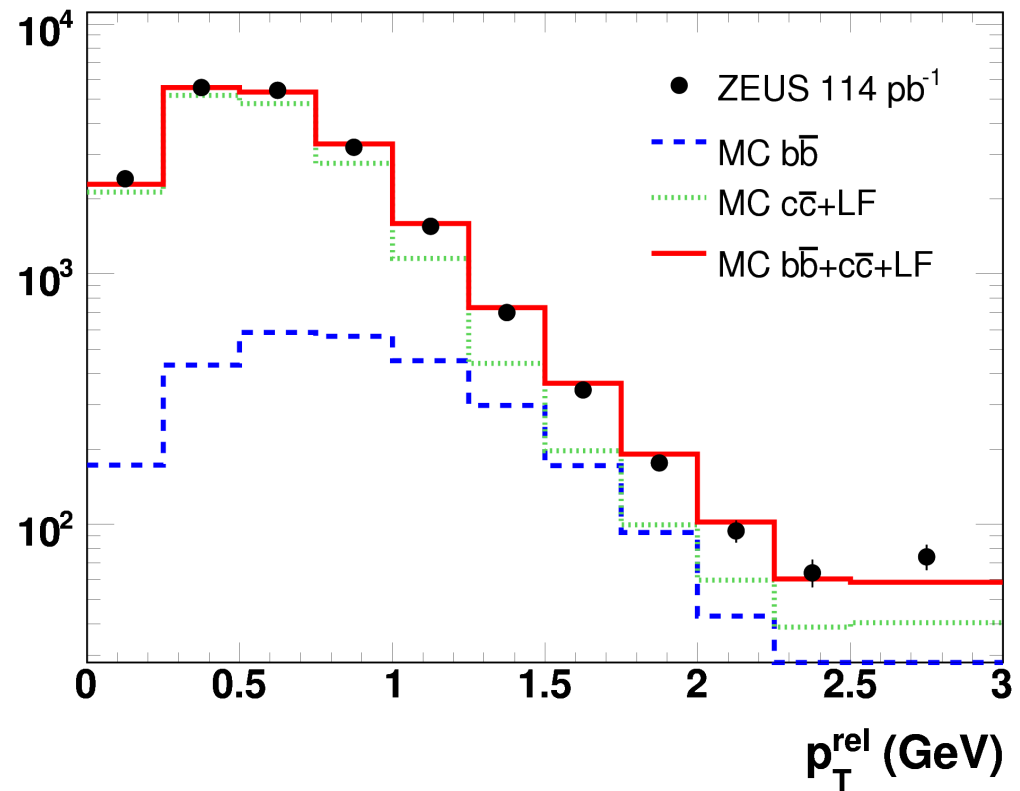
- Fit measured p_T^{rel} distribution d_μ with a two-component fit to determine f_{bb} fraction.

$$d_\mu = f_{b\bar{b}} \cdot d_\mu^{b\bar{b}} + f_{bkg} \cdot d_\mu^{bkg}$$

Beauty template distribution determined from MC

Background (charm and light flavors, LF) template distribution determined from MC and data. Charm-LF fraction fixed.

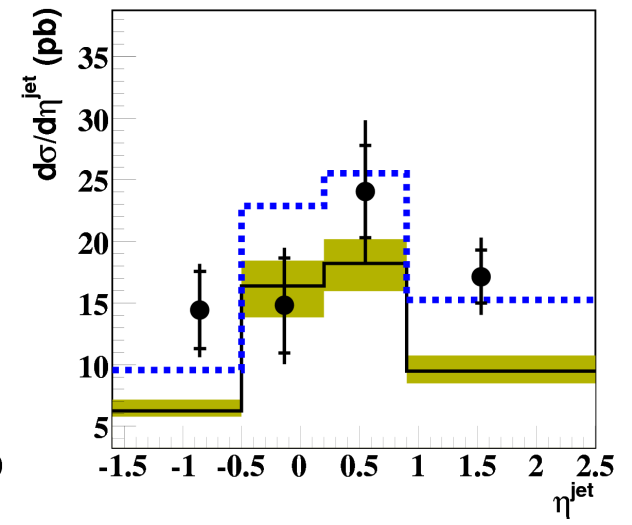
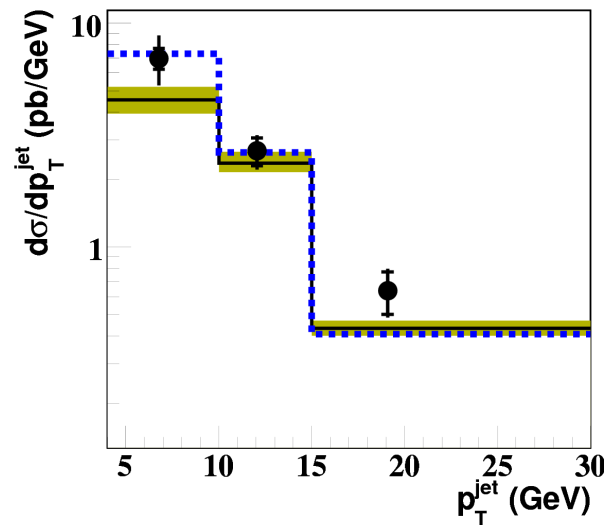
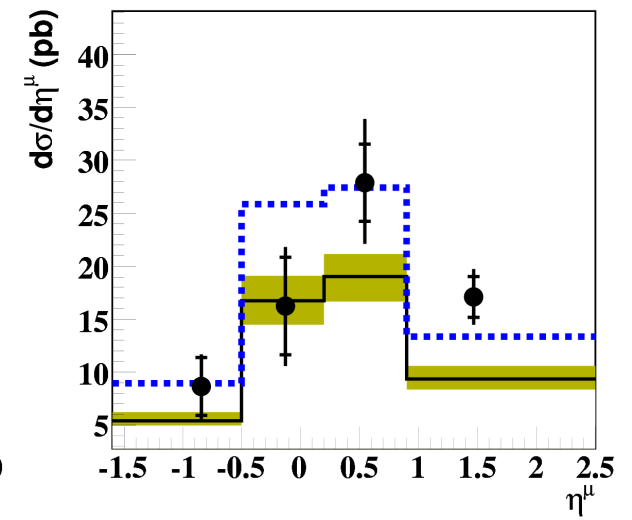
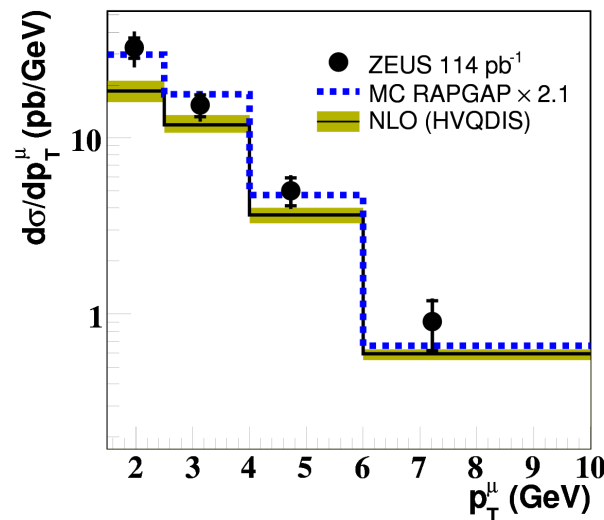
ZEUS



Differential Beauty cross sections as function of p_T^μ , η^μ , p_T^{jet} and η^{jet} .

- Compared to NLO QCD calculation (HVQDIS) and scaled LO MC (Rapgap).
- Shape reasonable described.
- Data seems to overshoot predictions at low p_T 's.

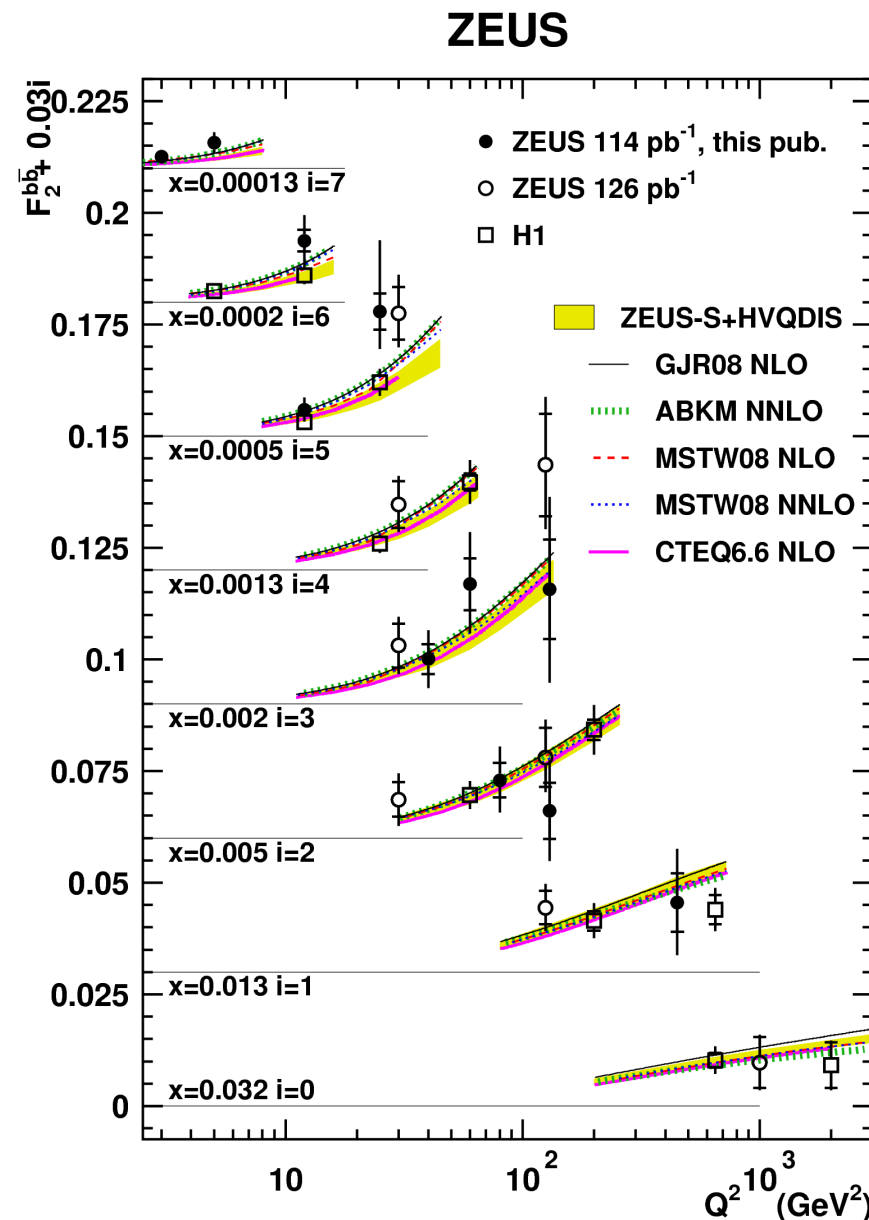
ZEUS



- Result of the fit converted to a measurement of the 'reduced b cross section':

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

- Data compared with H1 and previous ZEUS measurement and various NLO calculations:
 - Data are compatible within uncertainties, however ZEUS data has a tendency to be above the H1 data.
 - NLO calculations in general agree with data; HVQDIS underestimates ZEUS data at low Q^2 and x .



- Selection of recent HERA beauty production measurements presented:
 - Beauty from Inclusive Secondary Vertexing (Photoproduction and DIS)
 - Beauty Jets in DIS
 - Beauty structure function F_2^{bb} (2 measurements: impact parameter method, decay into muons)
- In general a good agreement with NLO pQCD predictions for the inclusive jet analyses.