Beauty Production at HERA

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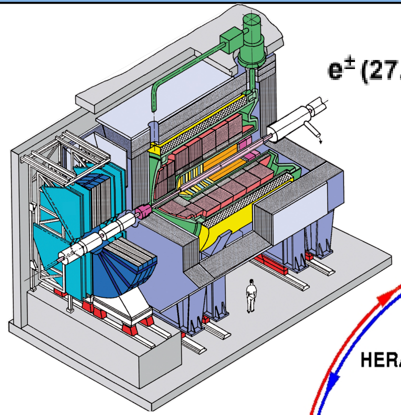
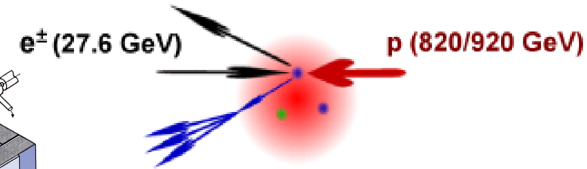
Low X Workshop, GREECE, June 23-27, 2010

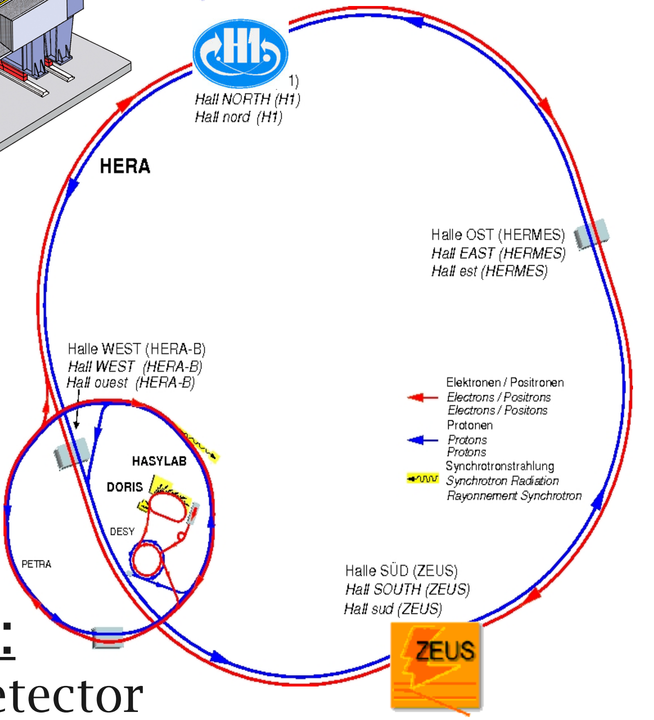
The H1 and ZEUS experiments at the HERA accelerator

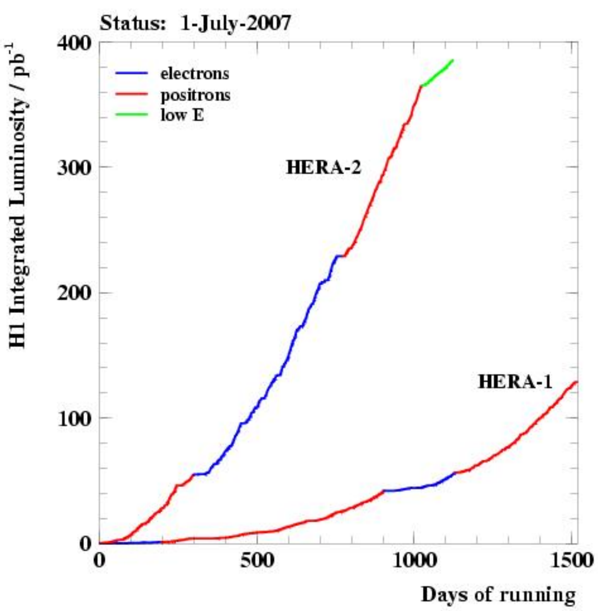
- <u>HERA:</u> ep collider → 2 accelerators:
  - e^- (e^+) : 27.6 GeV
  - p: 920 GeV (820 GeV)
  - center of mass energy: 319 GeV
- Running periods:
  - HERAI 1992–2000
  - luminosity upgrade 2000–2002
  - HERA II 2002–2007 (end)
- Integrated luminosity on tape:

  ~0.5 fb^{-1} (per experiment)

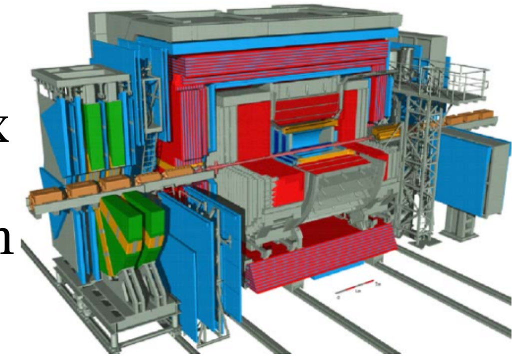






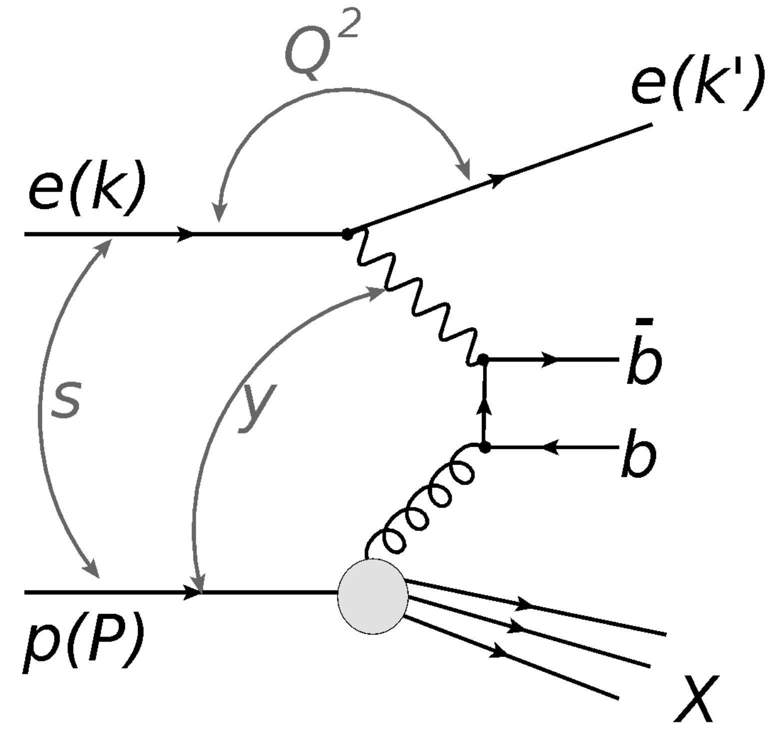


- <u>H1 & Zeus experiments:</u>
  Multi purpose 4π particle detector with an asymmetric design.
- Most relevant subdetectors:
  - Tracking system, silicon vertex detectors and gas chambers
  - Calorimeter: LAr (H1), Uranium (Zeus)
  - Muon chambers



Motivation to Measure Heavy Flavor Production

- Charm and Beauty quarks at HERA are mainly produced in Photon–Gluon–Fusion → sensitive to gluon in proton.
- Hard scales for perturbative QCD:
  - $m_q \sim 5$ 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.

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

$Q^2 < 1\,GeV^2$, *Photoproduction*
$Q^2 > 1\,GeV^2$, *DIS*

Beauty Production Models

- Number of theoretical approaches:
  - Massless and massive schemes.
  - General mass flavor number schemes (combination of massive/massless scheme).

- Monte Carlo Generators, LO(α_s) + 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, NLO(α_s^2):
    - FMNR: Photoproduction.
    - HVQDIS: DIS.
  - GM-VFNS used in latest global PDF fits (MSTW and CTEQ).
  - ➢ Used for comparisons of different models.

Beauty Measurements discussed today:

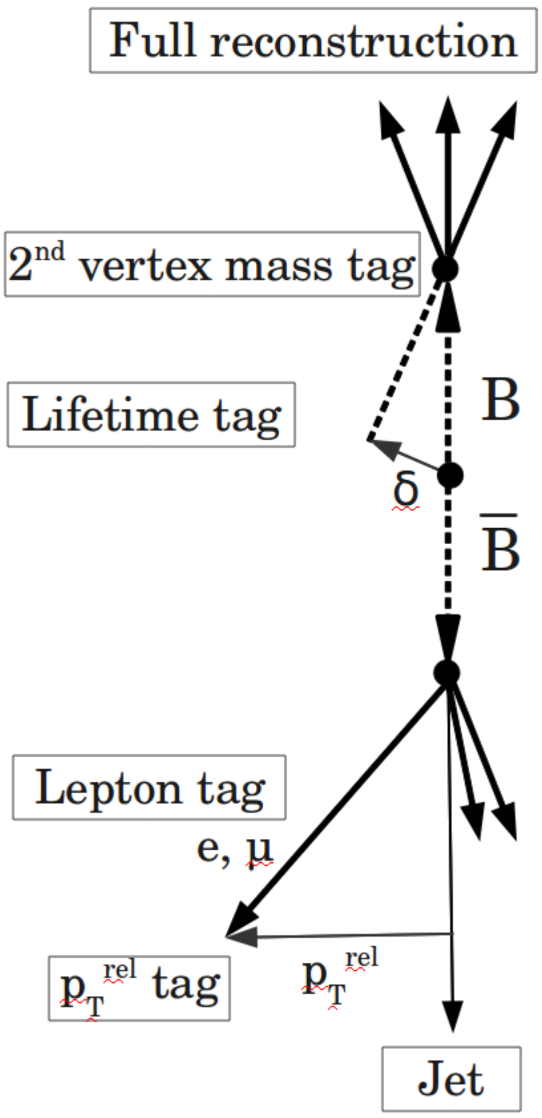
- Photoproduction:
  - "Measurement of Beauty Photoproduction from Inclusive Secondary Vertexing at HERA-II"
    ZEUS-prel-09-005, http://www-zeus.desy.de/public_results/publicsearch2.php
- Beauty in DIS:
  - "Measurement of Charm and Beauty Jets in Deep Inelastic Scattering at HERA"
    H1prelim-10-073, 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

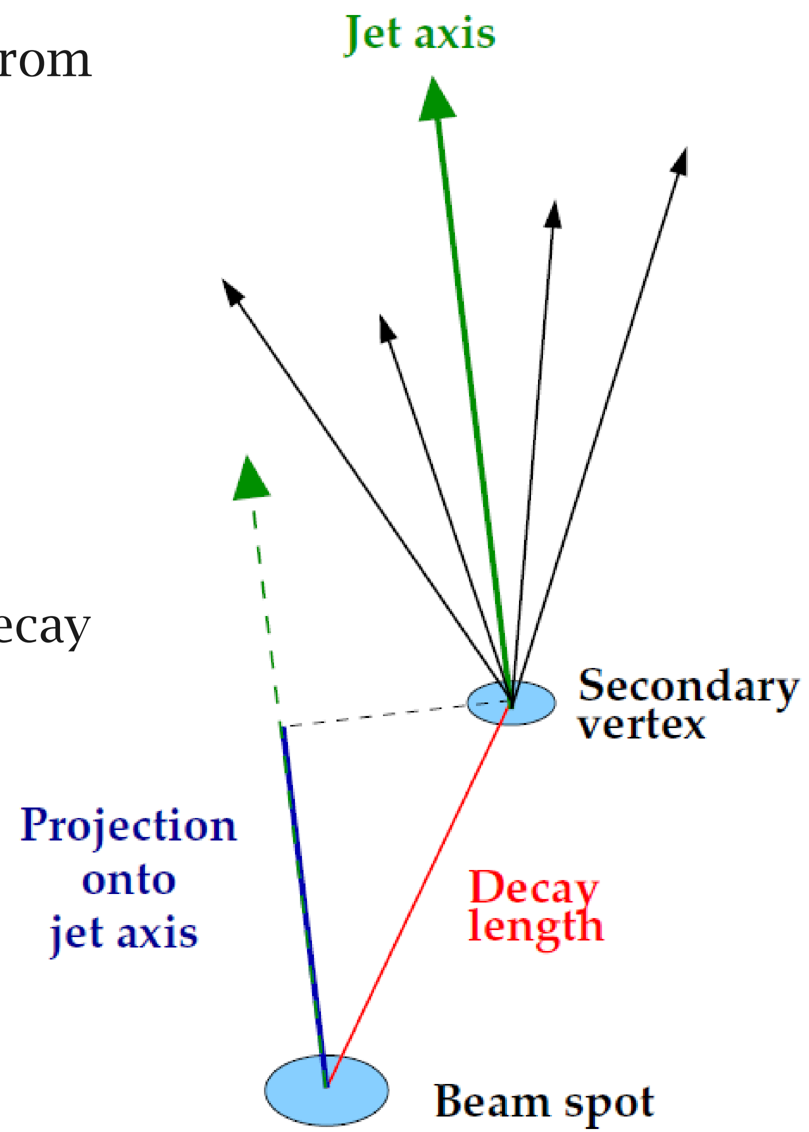
- At HERA beauty is only ~0.03% of the total γp cross section.
- Beauty enrichment is possible with:

1) Lepton tagging
   - Use semileptonic b/c decay channels:
     - look for μ or e , high BR(b→ lepton + 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*→Kππ, J/ψ→μμ , ee. No suitable beauty decay channels with high statistics.

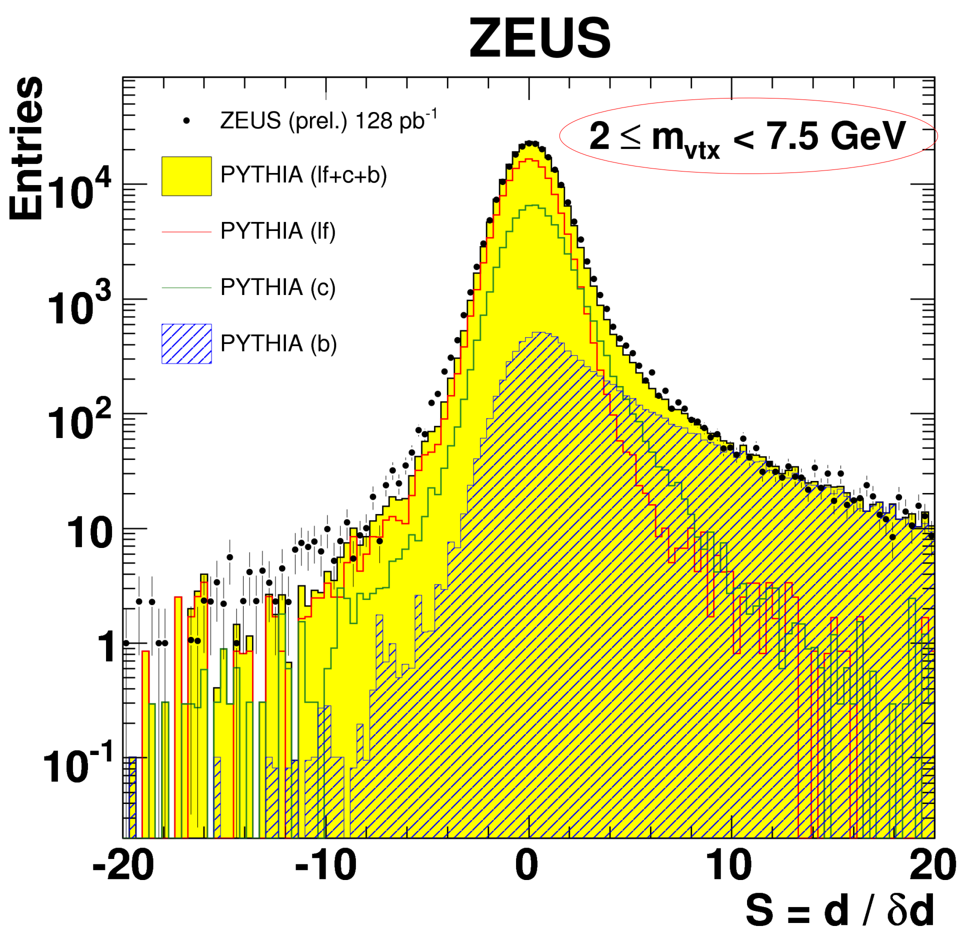
- Combination of different tagging methods.



- 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:
    - $p_T^{\text{jet } 1(2)} > 7\ (6)$ 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:

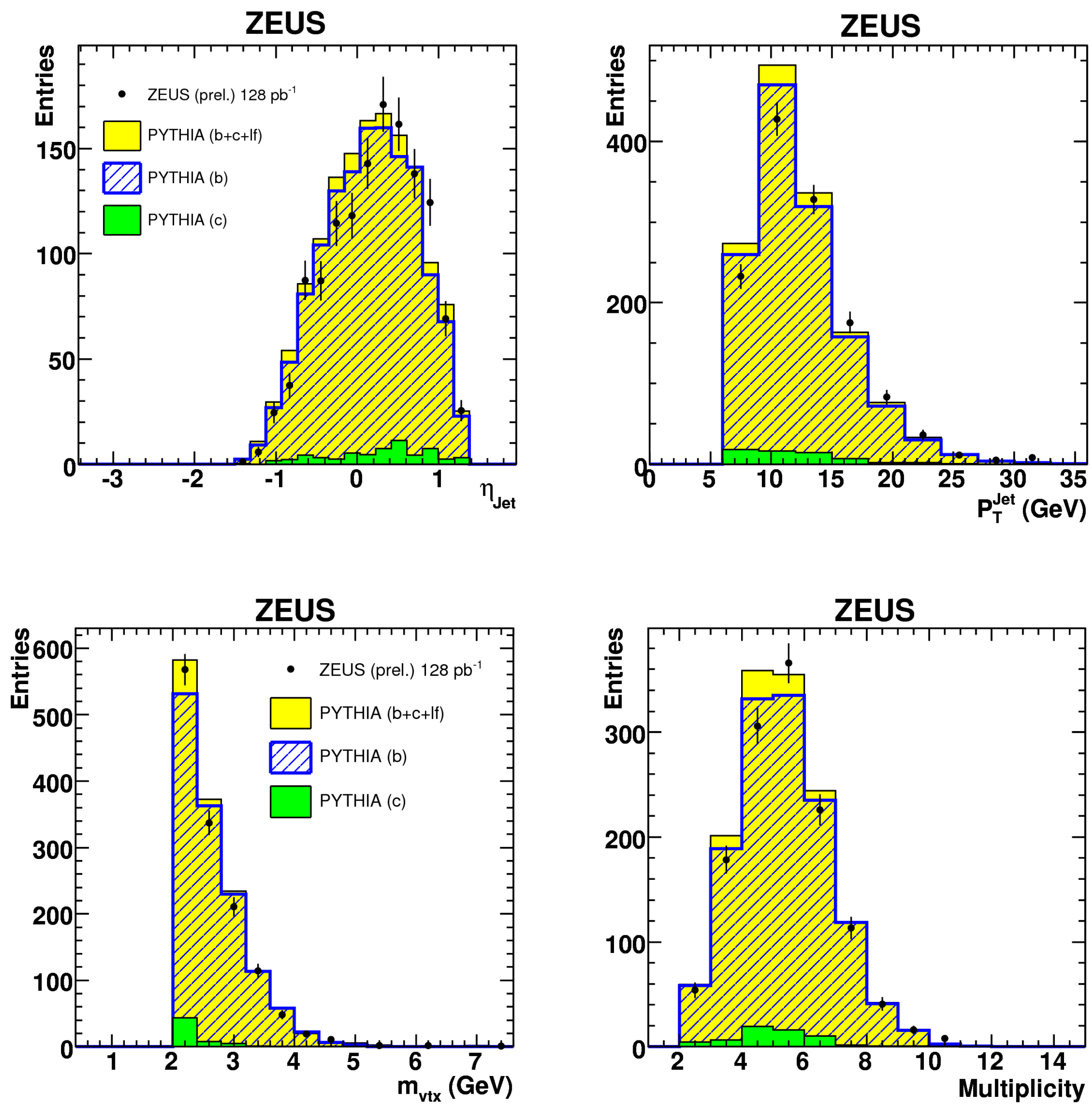


- Decay length significance : $S = DL / \sigma(DL)$
- Symmetric distribution for light flavors.
- At high secondary vertex masses m_{vtx} almost pure beauty contribution.

➢ Fit mirrored and subtracted decay length significance in 3 secondary vertex mass bins.

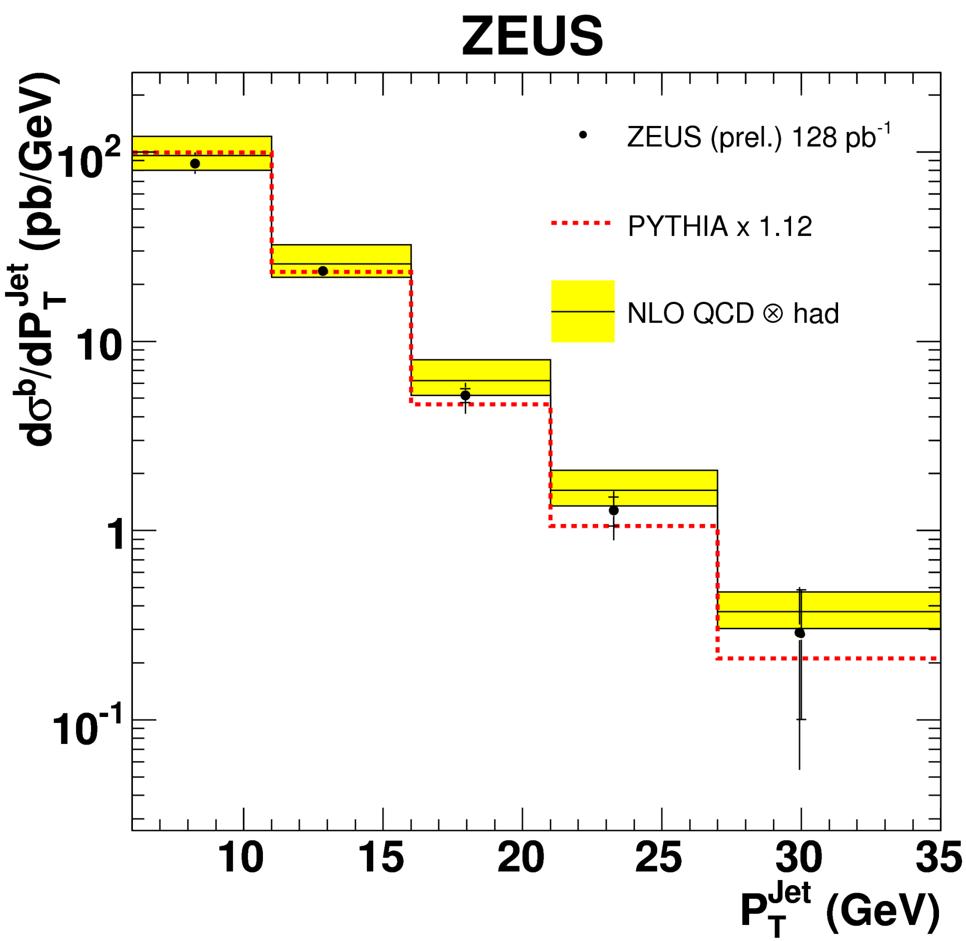
Beauty Photoproduction from Inclusive Secondary Vertexing

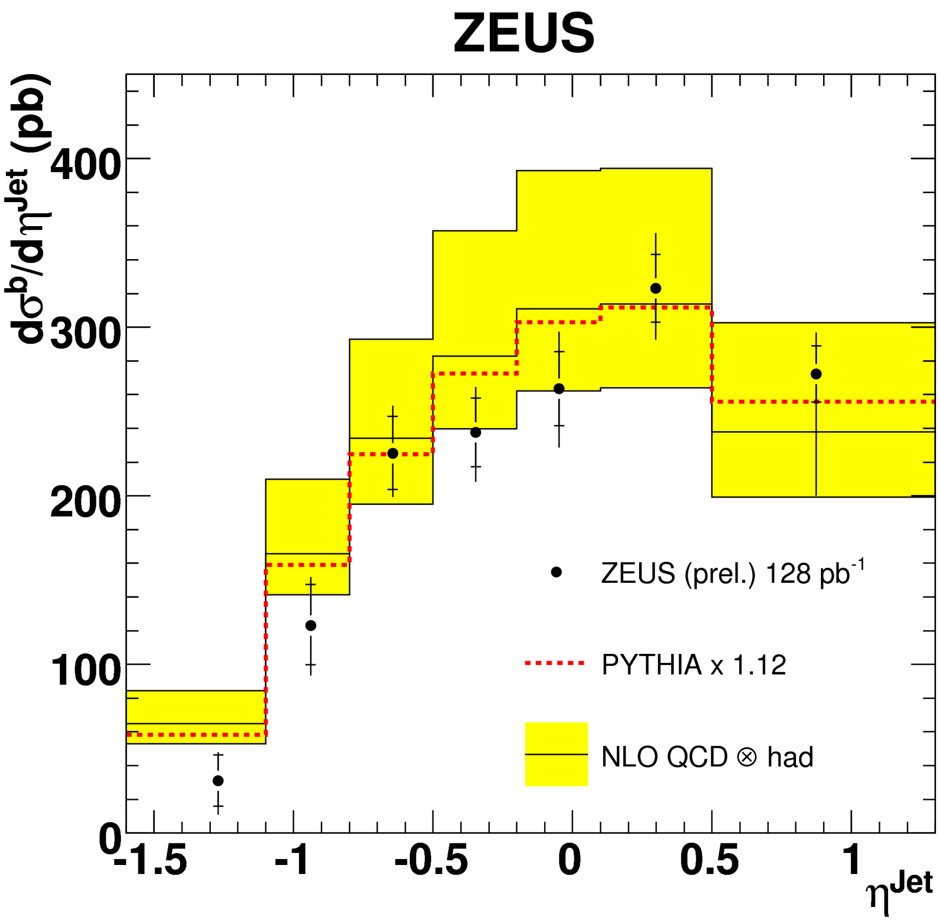
Beauty enriched control distributions



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

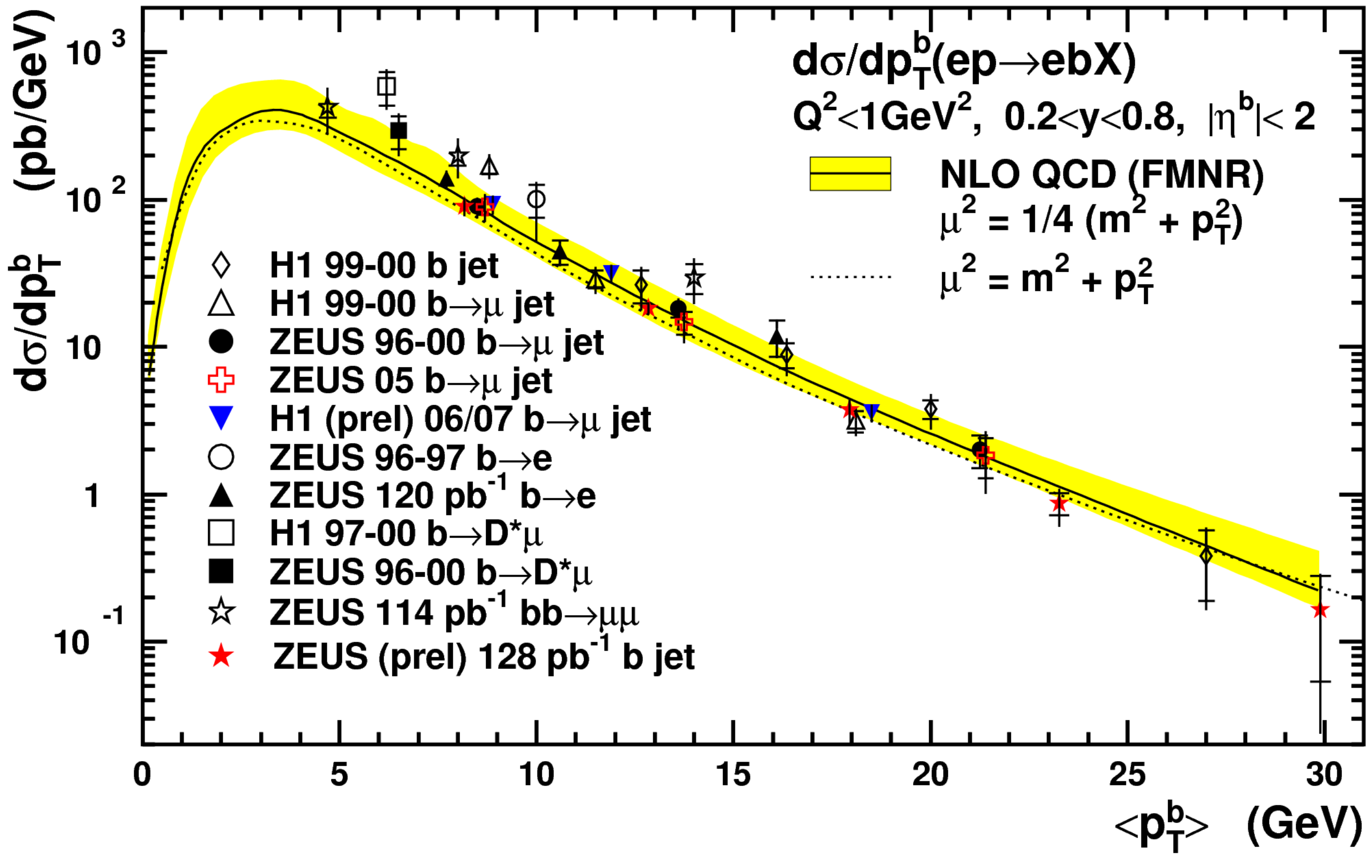
Beauty Photoproduction from Inclusive Secondary Vertexing





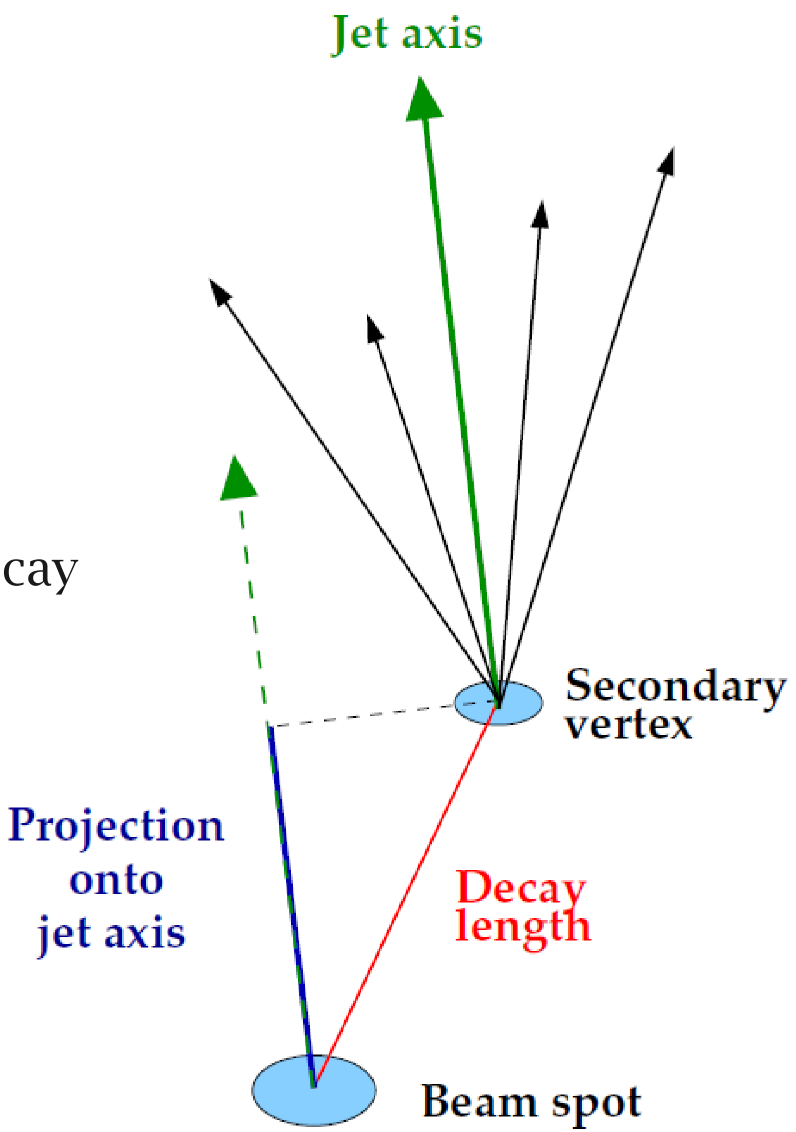
- Differential cross section in p_T^{jet} and η^{jet}.
- Good agreement with scaled LO MC (Pythia) and NLO QCD calculation (FMNR).

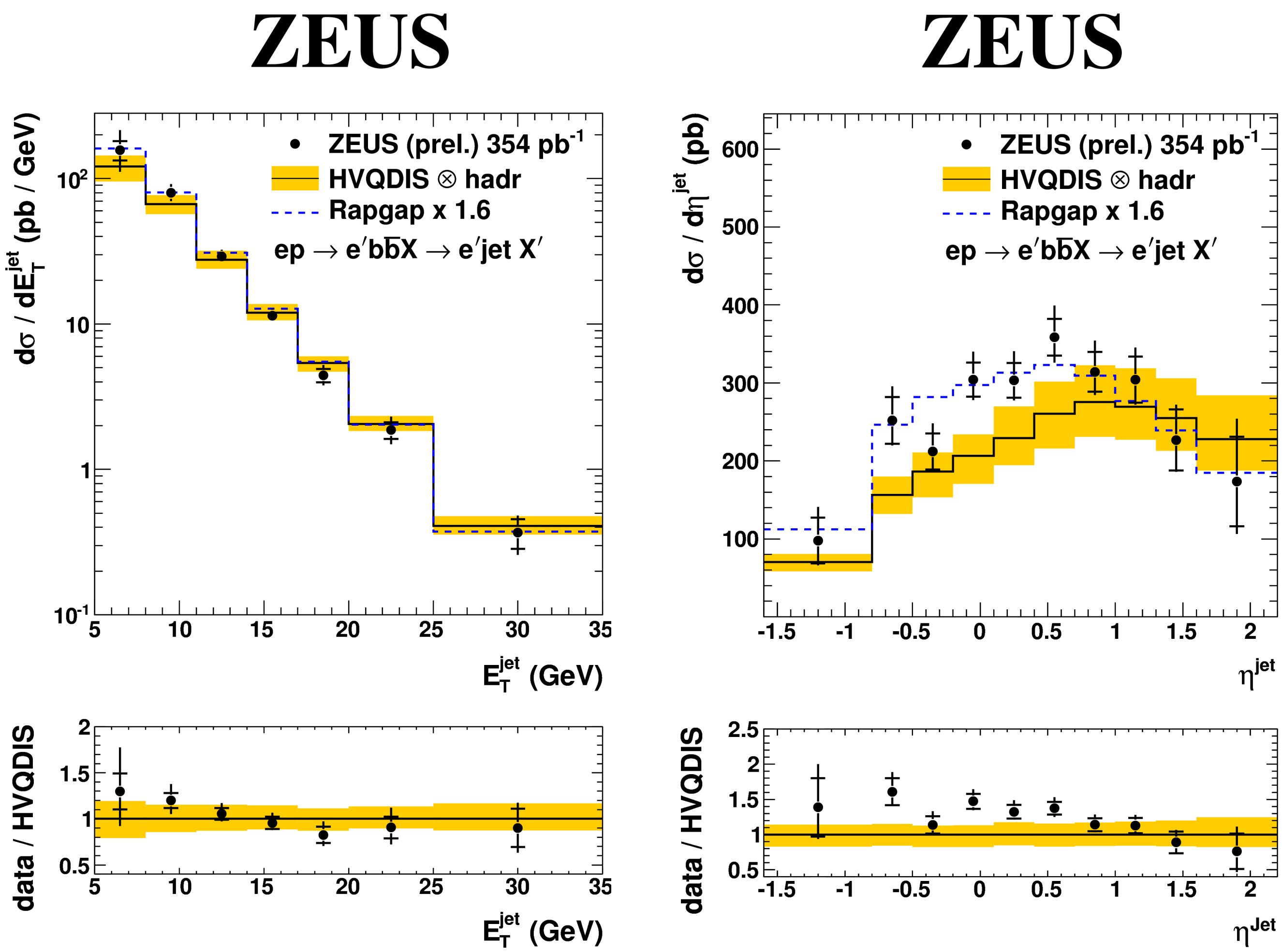
HERA



- 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
  - $5 < Q^2 < 1000 GeV^2$, $0.02 < y < 0.7$
  - Events with least 2 jets with:
    - $E_T^{jet} > 5$ GeV
    - $-1.6 < \eta^{jet} < 2.2$
  - 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.





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

Inclusive F_2^{cc}, F_2^{bb} and Charm–, Beauty–Jets in DIS

- 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}
    - $5 < Q^2 < 2000$ GeV^2
    - $0.0002 < x < 0.05$

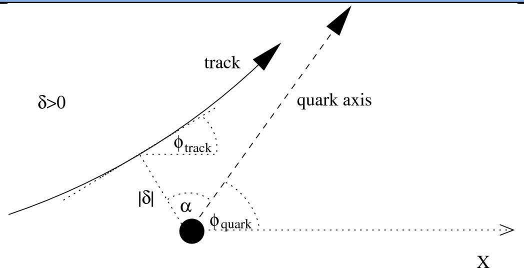
  - Charm–, Beauty–Jets analysis:
    - $6\text{GeV}^2 < Q^2$, $0.07 < y < 0.625$
    - Events with least on jets with: $E_T^{jet} > 6$ GeV, $-1 < \eta^{jet} < 1.5$

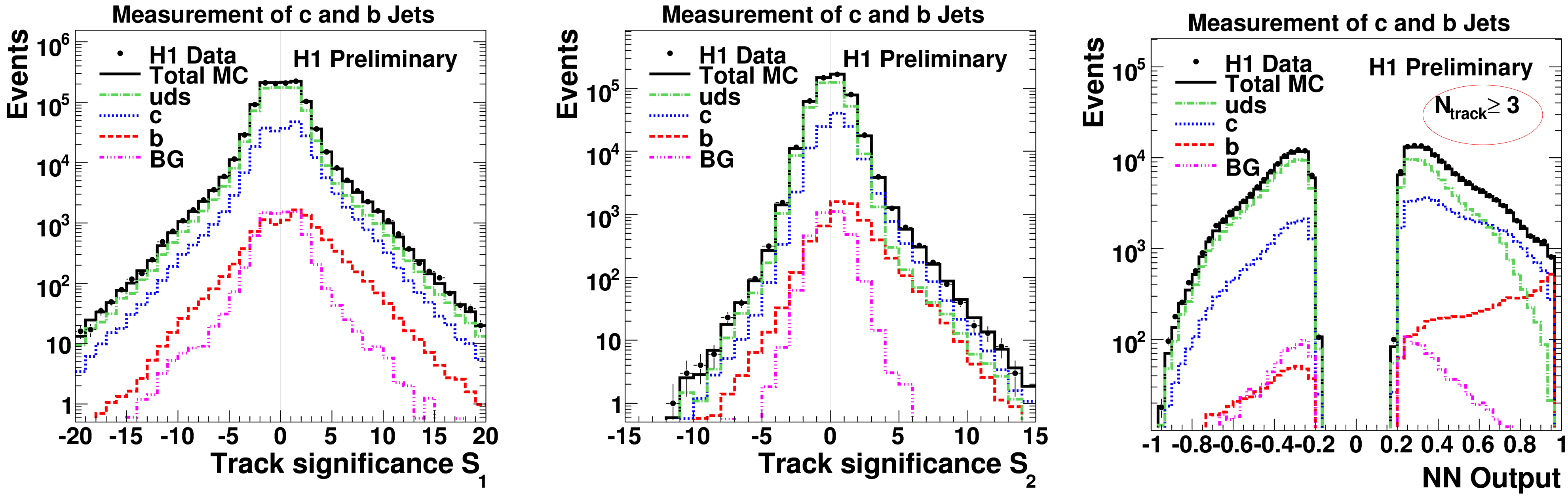
- HERA II data (both analyses)
  - 2006 / 07, 189 pb^{-1}

- 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 S1, S2 distributions due to lifetime.
- NN discriminates Beauty and Charm.

Neural Network input includes S1, S2, S3, 2nd vertex decay length significance.

- 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).

Inclusive F_2^{cc}, F_2^{bb}

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

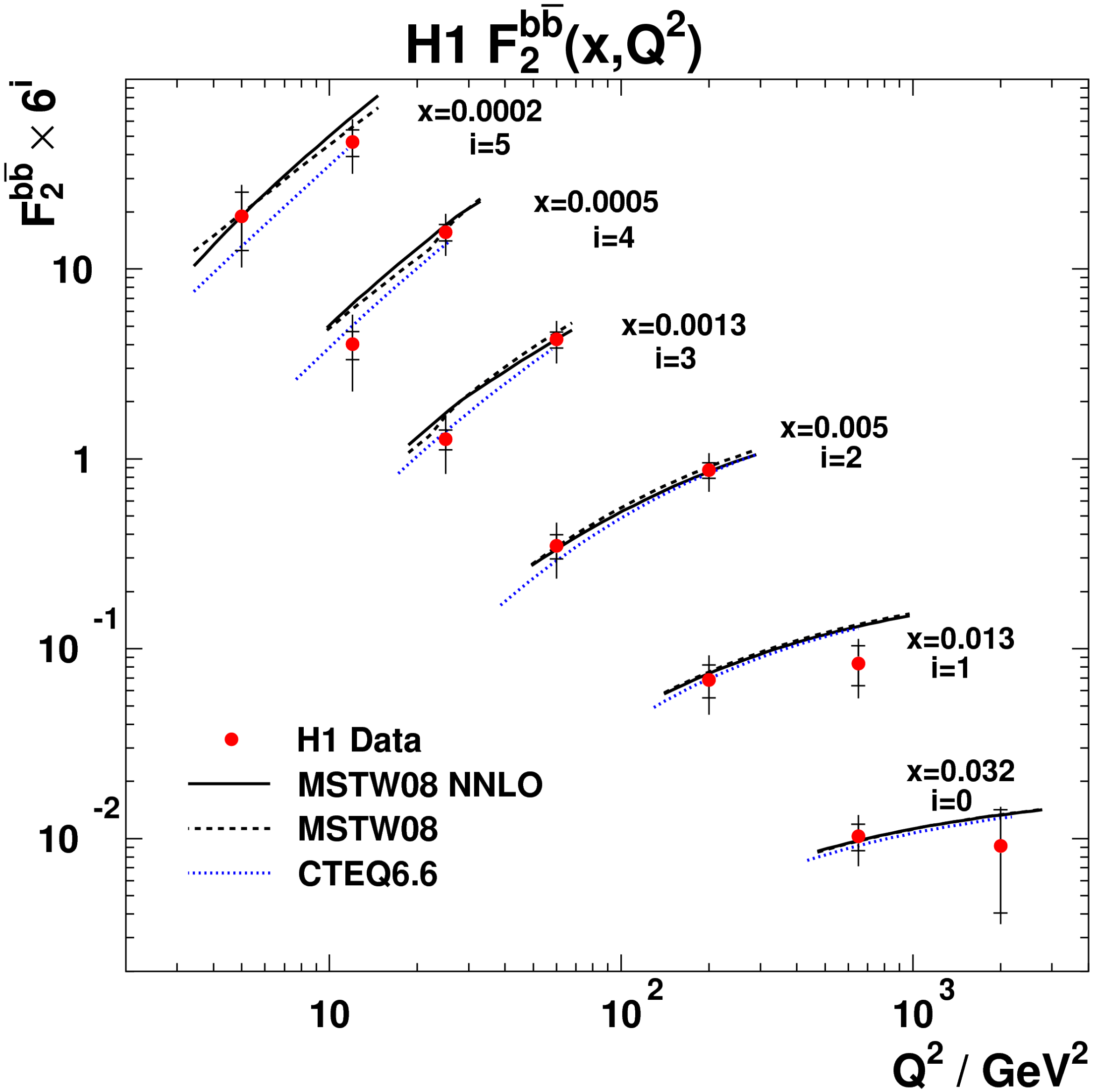
$$\tilde{\sigma}^{b\bar{b}}(x, Q^2) = \frac{d^2\sigma^{b\bar{b}}}{dx\, dQ^2} \frac{x Q^4}{2\pi\alpha^2(1+(1-y)^2)}$$

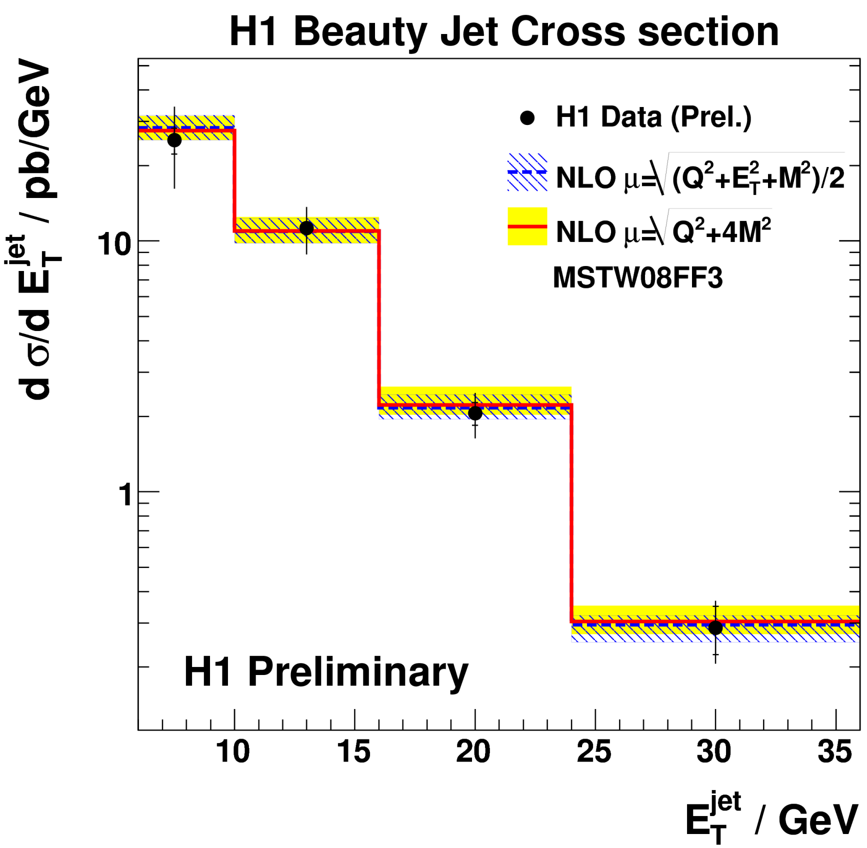
- The structure function F_2^{bb} is evaluated from the 'reduced cross section':

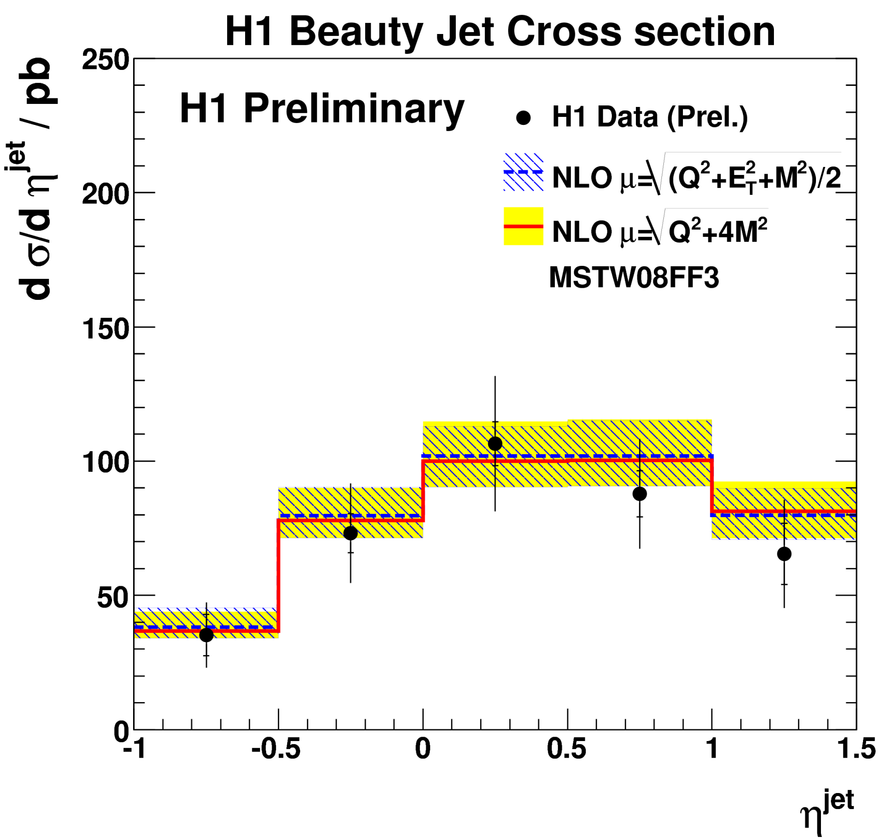
$$\tilde{\sigma}^{b\bar{b}} = F_2^{b\bar{b}} - \frac{y^2}{1+(1-y)^2} F_L^{b\bar{b}}$$

- F_L^{bb} estimated from NLO QCD calculation.

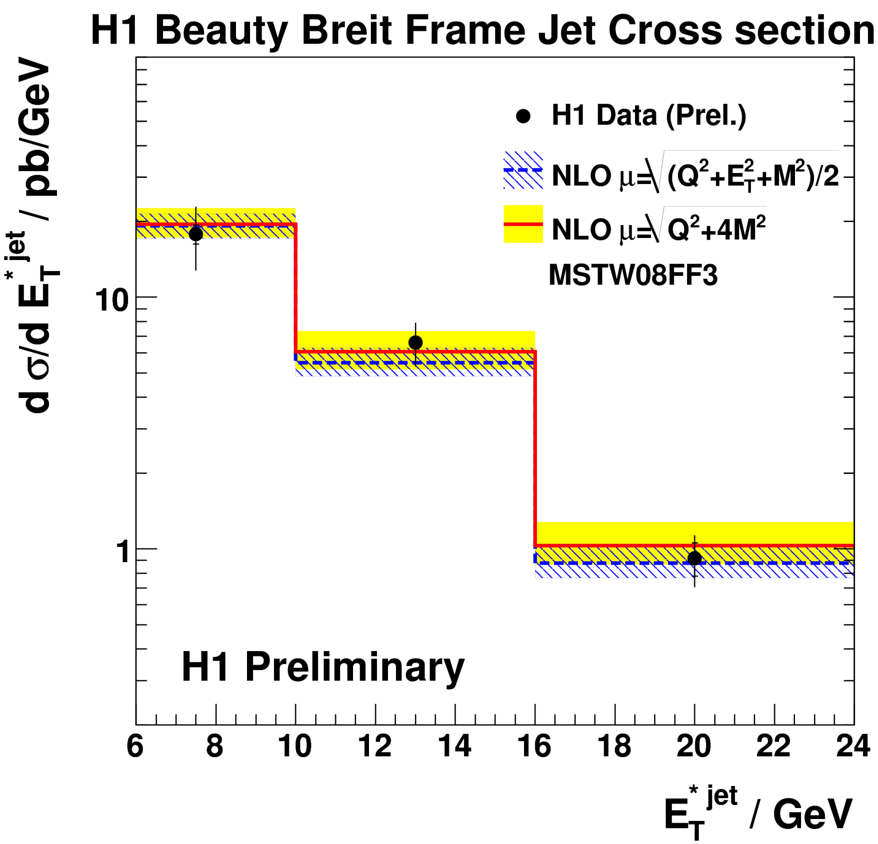
- Data well described by all predictions.
- Small differences between CTEQ NLO and MSTW at low Q^2.







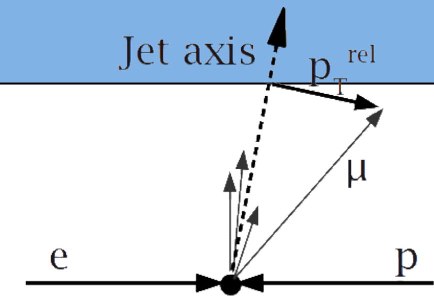
- NLO QCD calculation (HVQDIS) gives good data description for both scale choices.



- 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.

Beauty in DIS from Decays into Muons

- Analysis
  - "Measurement of beauty production in DIS and F_2^{bb} extraction at ZEUS", to be published in EPJ C.
- Phase Space
  - $2\ \mathrm{GeV}^2 < Q^2$, $0.05 < y < 0.7$
  - Events with least 1 jets and an associated muon:
    - $E_T^{jet} > 5$ GeV, $-2 < \eta^{jet} < 2.5$
    - $p_T^{\mu} > 1.5$ GeV, $-1.6 < \eta^{\mu} \lesssim 2.5$
    - $\Delta R = \sqrt{(\Delta\Phi^2_{\mu,\,jet} + \Delta\eta^2_{\mu,\,jet})} < 0.7$
- 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:

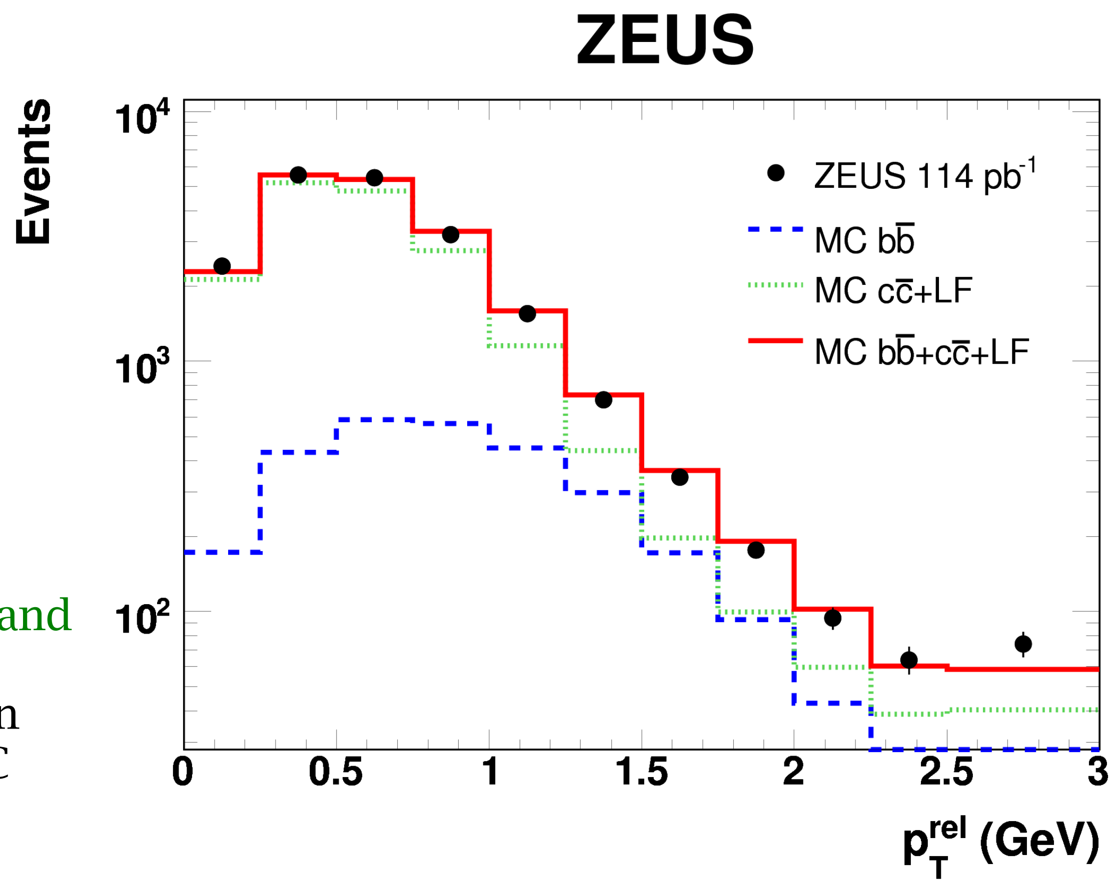
$$p_T^{rel} = \frac{|\vec{p}^{\,\mu} x\, \vec{p}^{\,jet}|}{|\vec{p}^{\,jet}|}$$

- 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

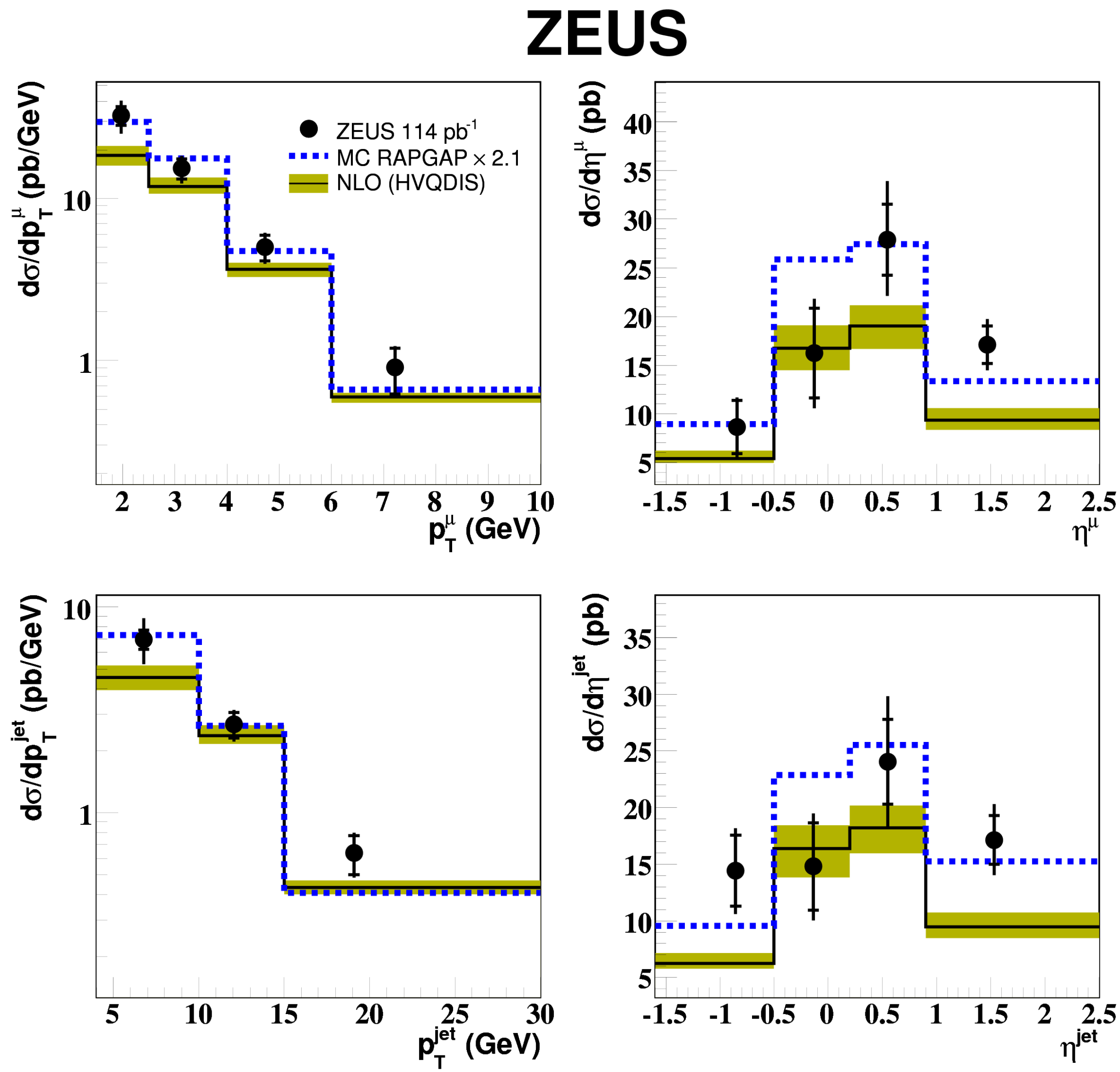
Background (charm and light flavors, LF) template distribution determined from MC and data. Charm–LF fraction fixed.



Beauty in DIS from Decays into Muons

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.

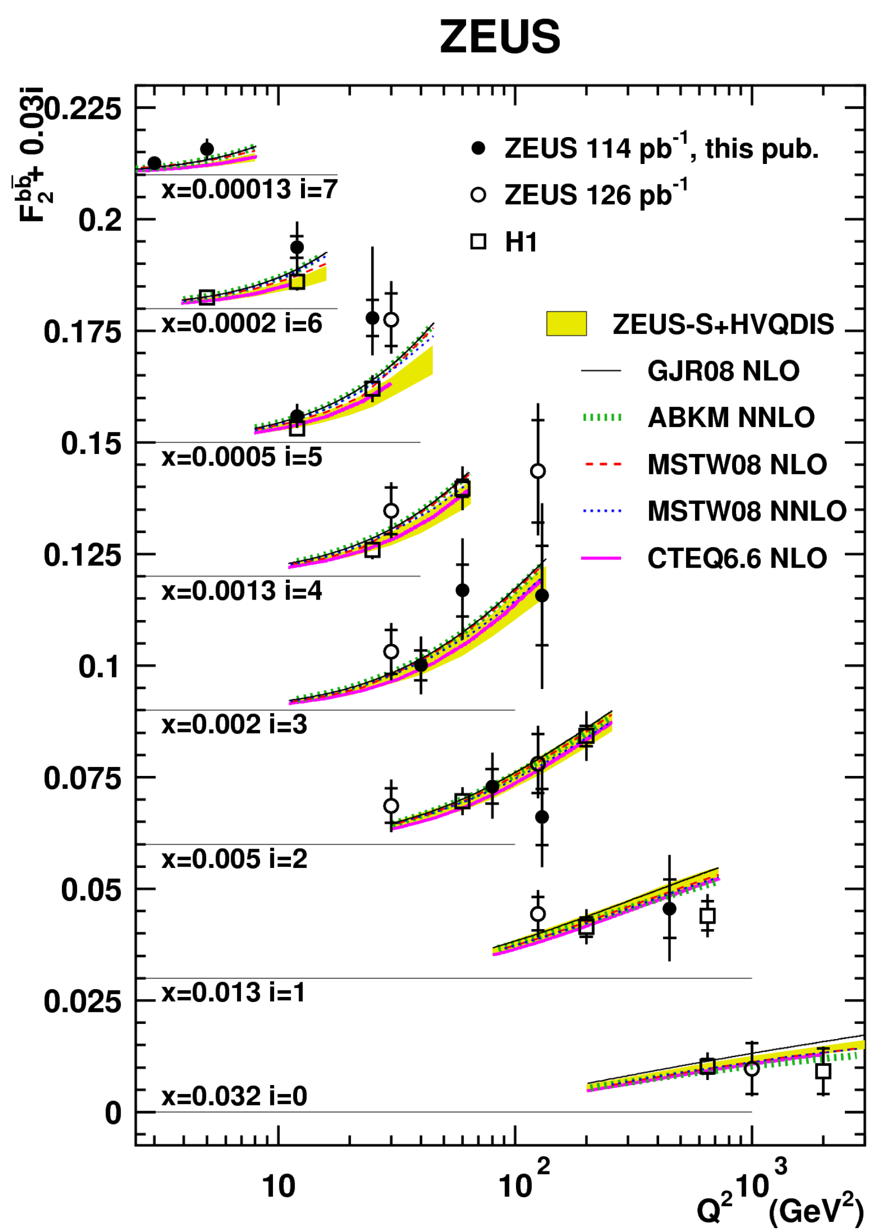


Beauty in DIS from Decays into Muons

- 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.



Summary and Conclusions

- 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.