Beauty Production in Deep Inelastic Scattering at HERA using Decays into Electrons

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-for the ZEUS Collaboration-

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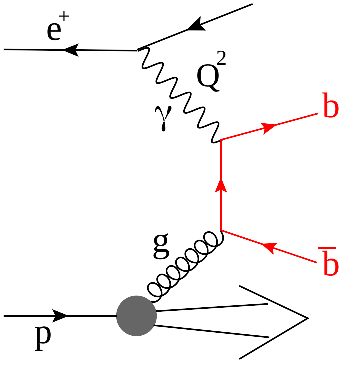
Outline

1. Introduction
2. Beauty production at HERA
    - Event selection
    - Signal extraction
    - Systematics
3. Results
    - Cross sections
    - Structure function ($F_2^{b\bar{b}}$)
4. Summary

Beauty Production in DIS

- Kinematics at HERA:
  - Photon virtuality: $Q^2 = -q^2$
  - Bjorken scaling: $x = \frac{Q^2}{2p \cdot q}$
  - Inelasticity: $y = \frac{p.q}{p.k}$
- Dominant production mechanism: Boson-Gluon fusion
- Quarks fragment/hadronise into hadrons and appear as jets in the detector
- The large mass of b quark and Q^2 provide hard scales
  $\rightarrow$ Perturbative theory (pQCD) is applicable
  $\rightarrow$ Measurement provides a powerful tool for testing p structure and pQCD



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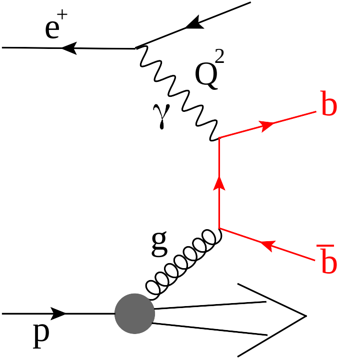
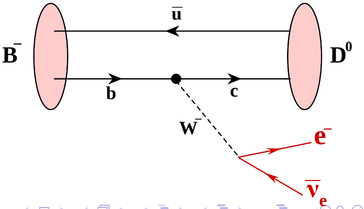


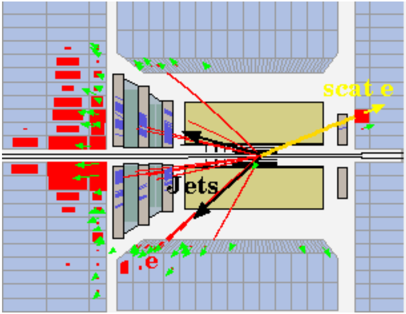
- b quark identification possible using semileptonic decays of B hadrons
- Used semileptonic $e^{\pm}$ channel
  $ep \rightarrow e'bX \rightarrow e'e_{sl}\nu_e X'$



Data and Event Selection

Data and MC:

- HERAII (04-07) data: ($\mathcal{L} \approx 363\,\mathrm{pb}^{-1}$)
- Inclusive beauty and charm (RAPGAP)
- Inclusive light flavor (DJANGOH)



Event selection:

- DIS events: $Q^2 \geq 10\,\mathrm{GeV}^2$, $0.05 < y < 0.7$
- Scattered electron (e') in the calorimeter: $E' > 10\,\mathrm{GeV}$
- At least one jet in the event: $p_T^{\mathrm{jet}} > 2.5\,\mathrm{GeV}$
- One candidate for semileptonic electron: $0.9 < p_T^e < 8\,\mathrm{GeV}$, $|\eta^e| < 1.5$

Signal Extraction: Approach

Signal

$e^{\pm}$ from semileptonic b decays (prompt and cascade):

- $b \to e, b \to c \to e$

Background sources

$\mathbf{e}^{\pm}$ background:

- $c \to e, \gamma \to e^+e^-, \pi^0 \to \gamma e^+e^-$ and mis-reconstructed e'

non-$\mathbf{e}^{\pm}$ background:

- All misidentified $e^{\pm}$ candidates: $K^{\pm}, \pi^{\pm}, p/\bar{p}, \mu^{\pm}$

- Separate beauty signal from background using variables sensitive to electron identification as well as to semileptonic decay kinematics

Discriminating Observables

Electron identification

Variables used for electron identification:

- dE/dx: the energy loss per unit length
- E^{cal}/p_{trk}: the ratio of energy deposited in the calorimeter to the track momentum measured in the central tracking detector
- d_{cell}: the penetrating depth of the energy deposited in the calorimeter

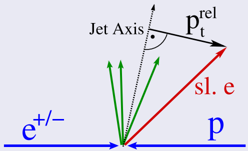
Decay identification

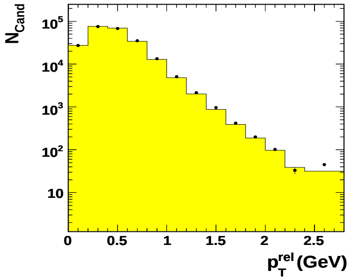
Variables used for decay identification:

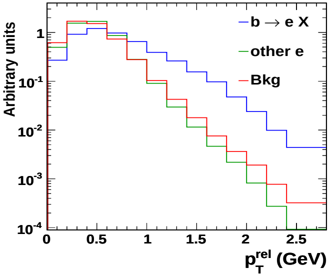
- $p_{\mathrm{T}}^{\mathrm{rel}}$: relative transverse mom. of the e to the corresponding jet
- $\Delta\phi$: the difference of azimuthal angles of e and $\nu_e(p_{\mathrm{T}}^{\mathrm{miss}})$
- $d/\delta d$: decay length of B hadron relative to vertex divided by its error

Discriminating Observables: Example

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







- Calculate probability density function for all variables
- Calculate particle and decay abundances
- Use likelihood function to combine the information of different variables in one discriminating variable

Hypothesis Test for Signal Extraction

Hypothesis test for particle of sort i (decay sort j)

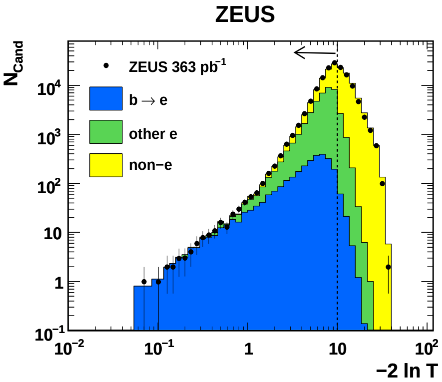
$$\begin{aligned}\text{Likelihood } \mathcal{L}_{(i,j)} \;=\; & \alpha_i(p_T,\eta) \cdot \mathcal{P}(dE/dx) \cdot \\ & \mathcal{P}(E^{cal}/p_{trk}) \cdot \mathcal{P}(d_{cell}) \cdot \\ & \hat{\alpha}_j(p_T,\eta) \cdot \mathcal{P}(d/\delta(d)) \cdot \\ & \mathcal{P}(p_T^{rel}) \cdot \mathcal{P}(\Delta\phi)\end{aligned}$$

$$\begin{aligned}\alpha_i &= \text{particle abundance} \\ i &\in \{\pi^\pm, K^\pm, p/\bar{p}, e^\pm, \mu^\pm\} \\ \hat{\alpha}_j &= \text{decay abundance} \\ j &\in e^\pm \text{ from sl. b decays, other } e^\pm\end{aligned}$$

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

Likelihood Fit

- Fit distribution of test function using $b \to e$ hypothesis
- Determine relative contributions of the three samples
- Use region below $-2 \ln T = 10$ for fit



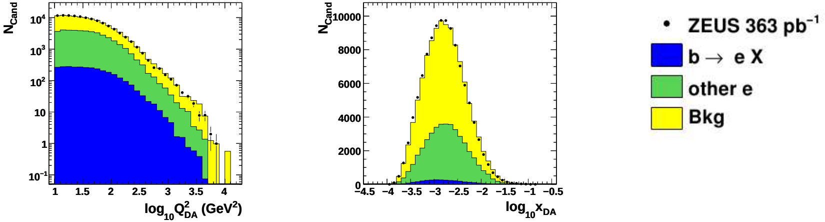
- $k-$factors indicate deviation of measured cross section to leading order cross section
- Use these factors to scale distributions and predicted cross sections

Fit results:

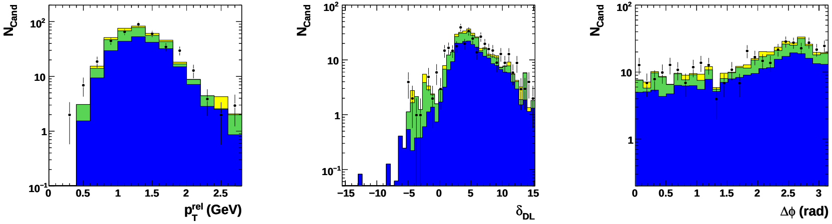
$$\begin{aligned} k_{\mathrm{b}} &= (1.32 \pm 0.11) \\ k_{\text{other e}} &= (1.12 \pm 0.03) \\ k_{\mathrm{Bkg}} &= (1.32 \pm 0.03) \end{aligned}$$

Control Plots

$T_{e,slb} < 10$



$T_{e,slb} < 1.5$

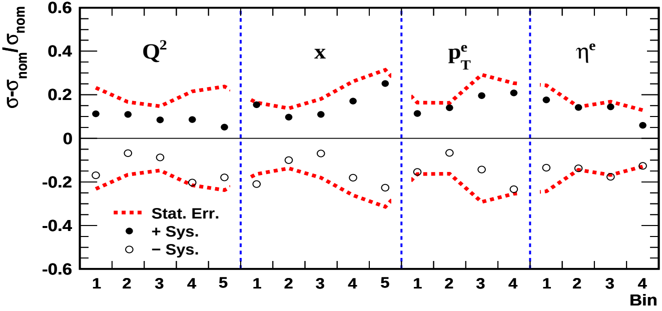


- MC contributions scaled by fit results

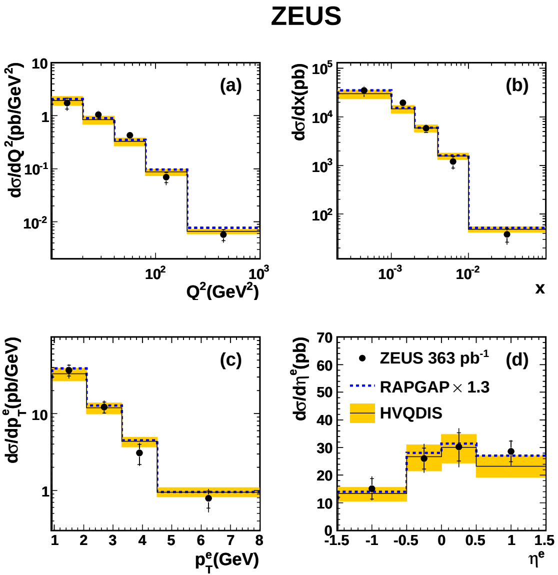
Systematic Checks

- **Selection criteria:**
  $\rightarrow$ Event and candidate selection
  $\rightarrow$ Jet energy scale
  $\rightarrow$ Global energy scale
  $\rightarrow$ Trigger correction
- **Likelihood distribution:**
  $\rightarrow$ Signal extraction procedure
  $\rightarrow$ Description of likelihood input variables
  $\rightarrow$ Variation of corrections
- **Background variation:**
  $\rightarrow$ Variation of relative contributions of $\gamma \rightarrow e^+e^-$, $\pi^0 \rightarrow \gamma e^+e^-$ and e' in e-bkg
  $\rightarrow$ Variation of charm contribution

Plot from thesis (R. Shehzadi)



- The quadratic sum of systematic uncertainties is of the same order as statistical uncertainty



- RAPGAP LO + PS Monte Carlo scaled with 1.3
- Good agreement with NLO QCD (HVQDIS)

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

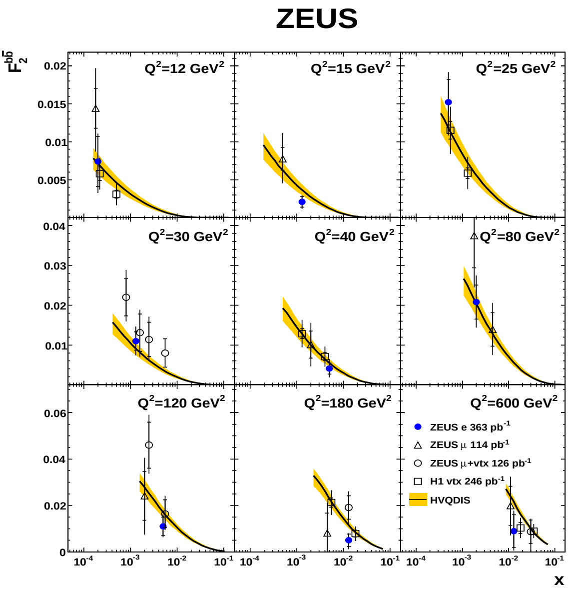
Beauty contribution to the proton structure function can be defined in terms of inclusive double differential cross sections as a function of x and Q^2:

$$\frac{d^2\sigma^{b\bar{b}}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(\left[1+(1-y)^2\right] F_2^{b\bar{b}}(x,Q^2) - y^2 F_L^{b\bar{b}}(x,Q^2)\right)$$

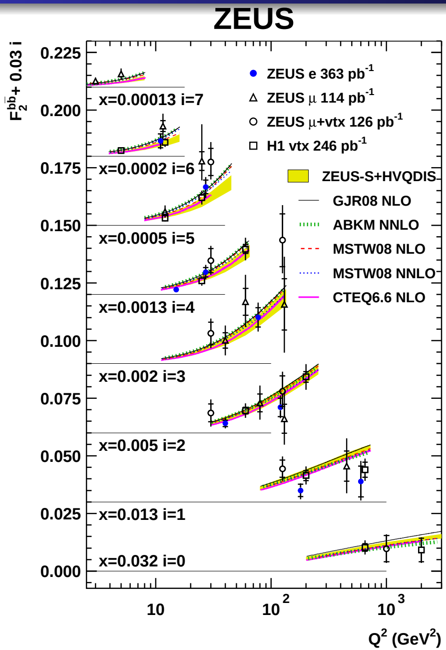
$F_2^{b\bar{b}}$ at a reference point in the x-Q^2 plane can be extracted from:

$$F_2^{b\bar{b}}(x_i,Q_i^2) = \frac{d^2\sigma_{b\to e}}{dx dQ^2} \cdot \frac{F_2^{b\bar{b},\mathrm{NLO}}(x_i,Q_i^2)}{d^2\sigma_{b\to e}^{\mathrm{NLO}}/dx dQ^2}$$

- For extrapolation from measured phase space for:
  $ep \to e'bX \to e'e_{sl}\nu_e X'$
  to full phase space, use NLO HVQDIS program



- Results from this measurement in blue
- Good agreement between different measurements
- NLO QCD calculations provide reasonable description of data



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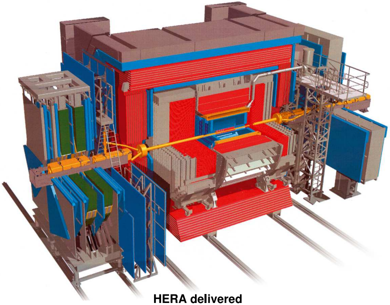
- Good agreement between different measurements
- NLO and approx. NNLO QCD calculations provide reasonable description of data

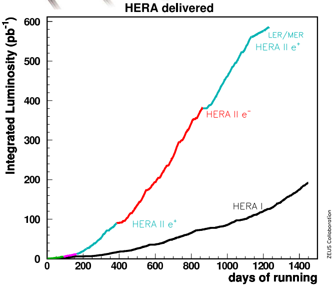
Summary

- Measurement of beauty production in DIS using full HERA II sample
  - Variables selected for particle and decay identification
  - Likelihood hypothesis used to extract beauty signal
  - Systematic uncertainties evaluated
- Cross sections extracted in bins of different variables
  - LO + PS MC is able to describe differential cross sections in shape
  - Results are consistent with NLO prediction
- $F_2^{b\bar{b}}$ extracted from double differential cross sections
  - Consistent picture of $F_2^{b\bar{b}}$ using different analyses in DIS
  - NLO and approx. NNLO QCD calculations give a reasonable description of data
- Results from this measurement published in EPJ C in Feburary 2011
- Will serve as an important input for H1 and ZEUS combined $F_2^{b\bar{b}}$

Backup

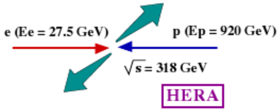
HERA and ZEUS

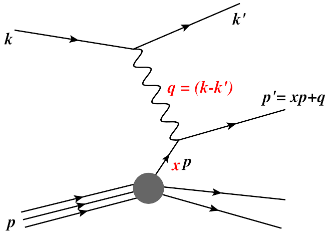




- 27.5 GeV$e^{\pm}$
  920 GeV$p \rightarrow \sqrt{s} = 318$ GeV
- HERAI: 1992-2000
- HERAII: 2003-2007
  $\rightarrow \sim 0.5\,\text{fb}^{-1}$ per experiment
- Relevant components:
  tracking detectors, calorimeter

Kinematics at HERA





Kinematic regimes:

1. Photoproduction (PHP): $Q^2 \approx 0\,\mathrm{GeV}^2$
2. Deep inelastic scattering (DIS): $Q^2 \geq 0\,\mathrm{GeV}^2$

Kinematics:

- Probing power of the lepton:

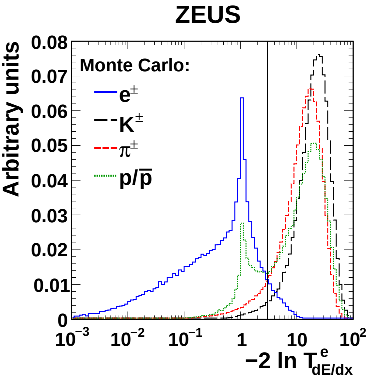
  $Q^2 = -q^2 = (k - k')^2$
- Bjorken scaling variable, the fraction of the proton's momentum carried by the struck quark (QPM):

  $x = \frac{Q^2}{2p \cdot q}$
- Inelasticity, the energy fraction transferred from the lepton in the proton's rest frame:

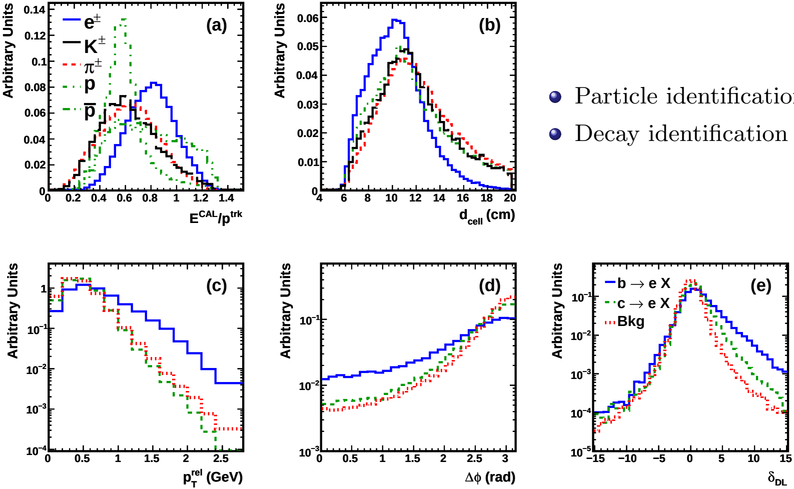
  $y = \frac{p.q}{p.k}$

- Used dE/dx likelihood information
- Likelihood for particle hypothesis

  trk_CTDdEdxLikelihood(dedx_ntracks)
- Electrons well separated from non-electrons

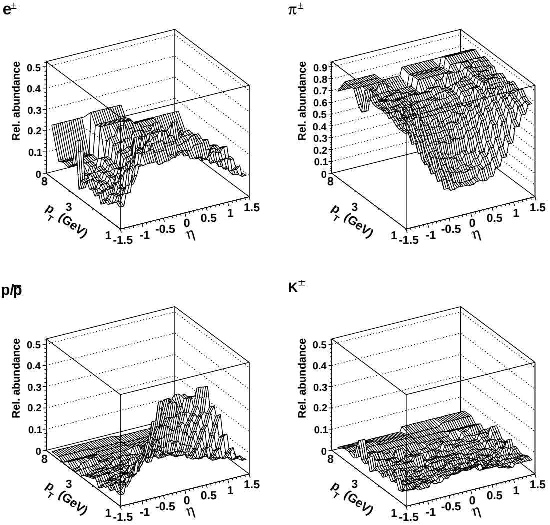


PDFs



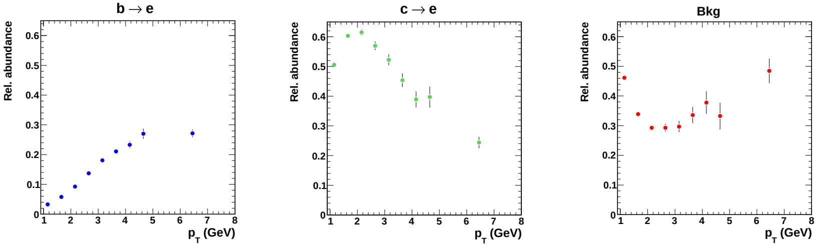
- Particle identification
- Decay identification

Plot from thesis (R. Shehzadi)



Decay abundances

Plot from thesis (R. Shehzadi)



Systematic Checks I

1. DIS & candidate selection $(E_{e'}, y_{jb}, E - p_z)$	$^{+1.7\%}_{-1.5\%}$
2. Trigger correction (-5% FLT30 in MC)	$+1.2\%$
3. dE/dx simulation (1σ mean and width)	$^{+0.4\%}_{-0.4\%}$
4. Decay length smearing ($\pm 50\%$)	$^{+2.6\%}_{-2.0\%}$
5. p_T^{rel} shape correction variation $(-100/+50\%)$	$^{-1.5\%}_{-2.4\%}$
6. Electron background variation($\pm 25\%$)	$^{+2.3\%}_{-2.1\%}$
7. Charm contribution ($\mp 25\%$)	$^{+0.9\%}_{-1.1\%}$
8. Charm spectrum reweighting ($\mp 50\%$ of CLEO corr.)	$^{+3.4\%}_{-2.9\%}$

Systematic Checks II

10 Energy scale ($\mp 2\%$)	$^{+1.2\%}_{-1.0\%}$
11 Jet energy scale ($\pm 3\%$)	$^{+0.7\%}_{+1.7\%}$
12 Tracking efficiency (2% of tracks removed)	-3.4%
13 Q^2 reweighting ($\pm 50\%$)	$^{+2.0\%}_{-1.9\%}$
14 Eta reweighting ($\pm 100\%$)	$^{+4.0\%}_{-3.7\%}$
15 Luminosity measurement	$^{+2.0\%}_{-2.0\%}$
Total uncertainty:	$^{+7.6\%}_{-8.1\%}$

NLO Predictions (HVQDIS)

Central values:

- $m_b = 4.75\,\mathrm{GeV}$
- $\mu_F = \mu_R = \sqrt{Q^2 + 4m^2}$
- $\epsilon_b = 0.0035$
- ZEUS-S-FF NLO
- $\mathcal{B}(b \to e) = 0.217$

Variation:

- m_b : [4.5 - 5.0] GeV
- $\mu_{F,R}$: [0.5 - 2.0]
  (μ_F & μ_R varied separately)
- ϵ_b: [0.0015 - 0.0055]
- PDF varied by total experimental uncertainty

Total Visible Cross Section

Kinematic region:

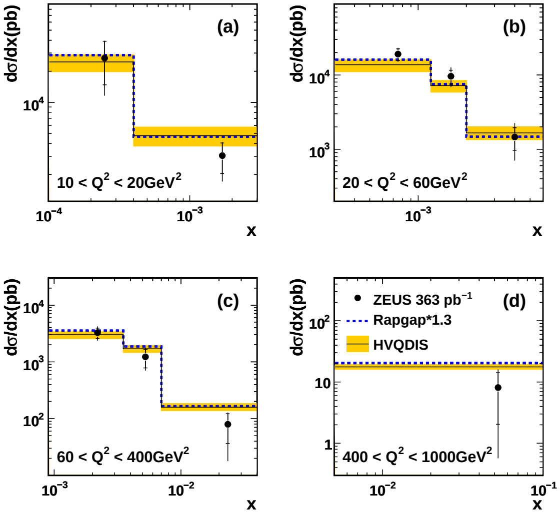
- $Q^2 > 10\,\mathrm{GeV}^2$
- $0.9 < p_T^e < 8\,\mathrm{GeV}$
- $0.05 < y < 0.7$
- $-1.5 < \eta^e < 1.5$

Visible cross section for $(ep \rightarrow e^{'} bX \rightarrow e^{'} e_{sl} \nu_e X^{'})$:

- $\sigma_{b\rightarrow e}^{\mathrm{vis}} = 71.8 \pm 5.5(\mathrm{stat.})^{+5.4}_{-5.8}(\mathrm{syst.})\,\mathrm{pb}$
- $\sigma_{b\rightarrow e}^{\mathrm{NLO}} = 67^{+10}_{-11}\,\mathrm{pb}$

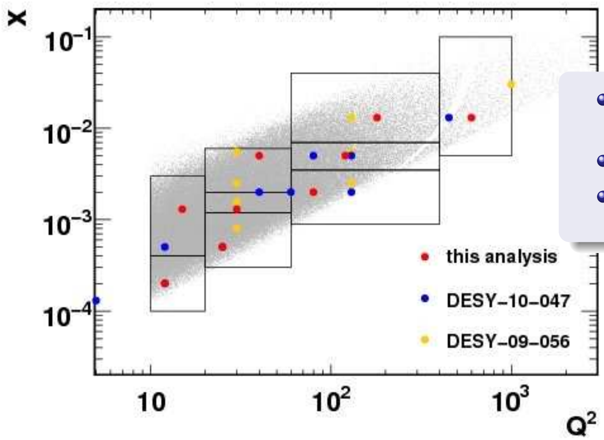
- Result is consistent with NLO QCD calculation
- Dominant uncertainty for HVQDIS prediction comes from mass and μ_R variation
- Determine cross sections in bins of Q^2, x, p_T^e, and η^e

Differential Cross Sections ($d\sigma/dx$ in bins of Q^2)



- Fitted bin-by-bin
- RAPGAP LO MC scaled with 1.3
- Good agreement with NLO QCD

Kinematic Plane



- Boxes define ranges of double differential cross sections
- This analysis: Red dots
- Previous ZEUS analyses: blue and yellow dots

- Define nine reference points in Q^2 and x to extract F_2^b