Beauty Production at HERA

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The HERA ep-Collider

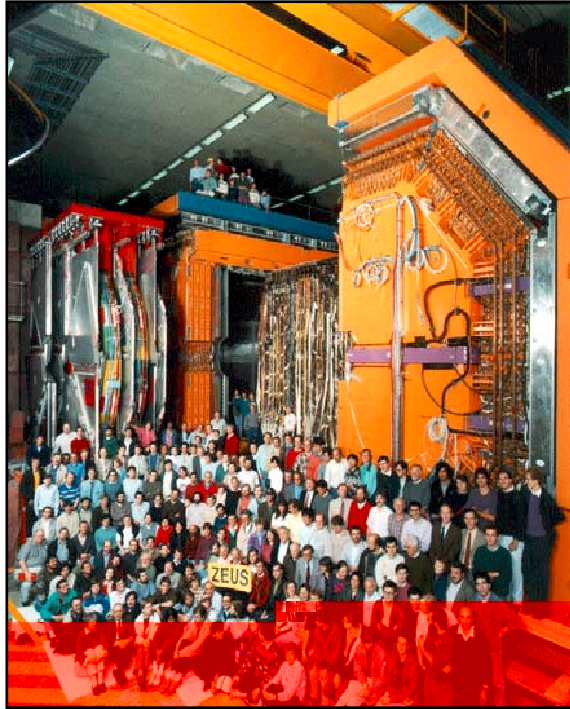## @ DESY/Hamburg

$\sqrt{s}$ = 320 GeV

[920 GeV]

[27.6 GeV]
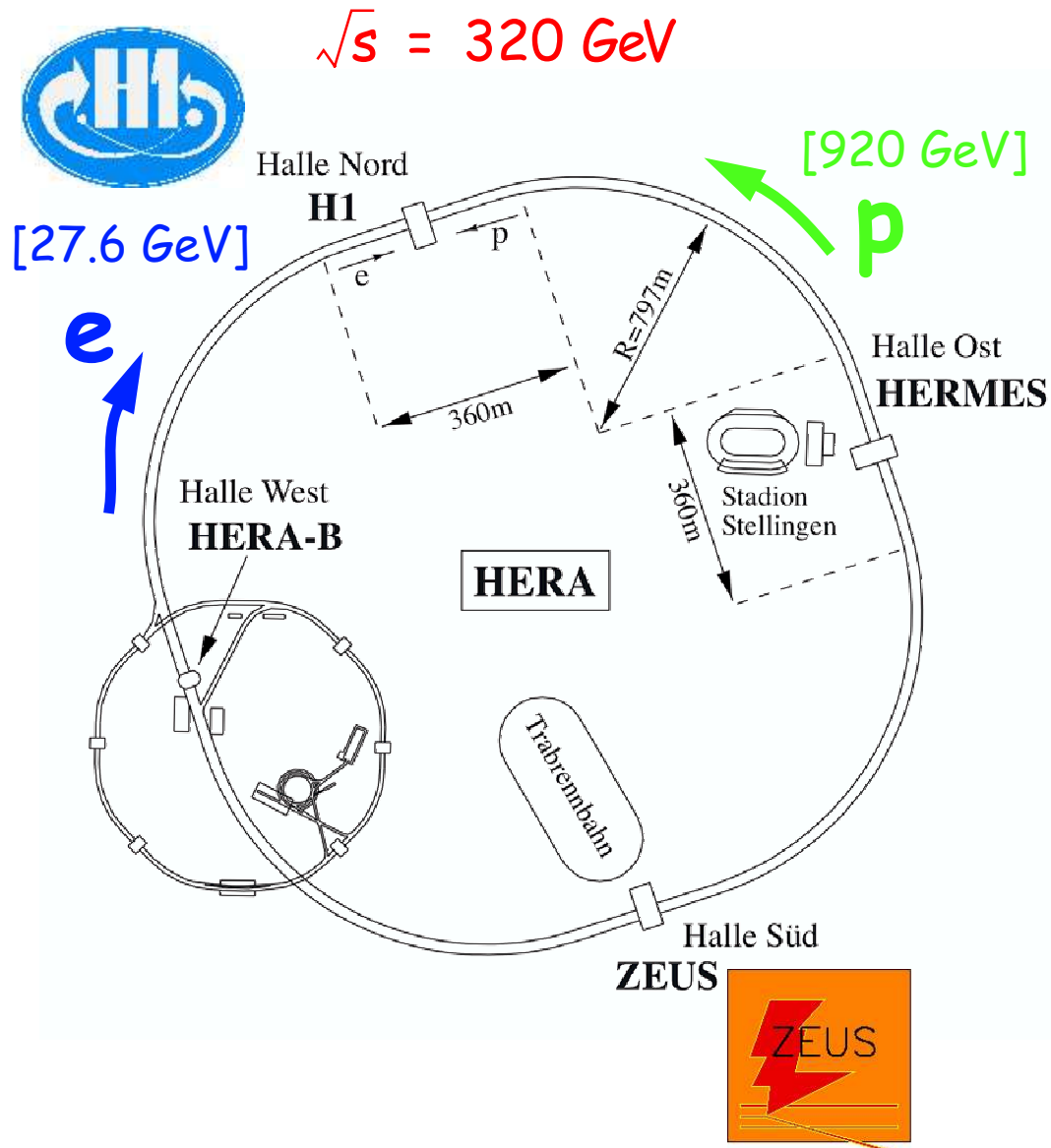
HERA I [1994 –2000]

e^+p Scattering: L ~ 100 pb^{-1}
e^-p Scattering: L ~ 15 pb^{-1}

HERA II [2003++]

Int. Luminosity: 1000 pb^{-1}
$e^{\pm}$-Polarisation ~50%

[+ low energy ep-data]

HERA Detectors

[ZEUS Collaboration]

ZEUS

Uranium Calorimeter
- $\sigma(E)/E = 18\%/\sqrt{E}$ for electrons
- $\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons

Central Tracker Resolution
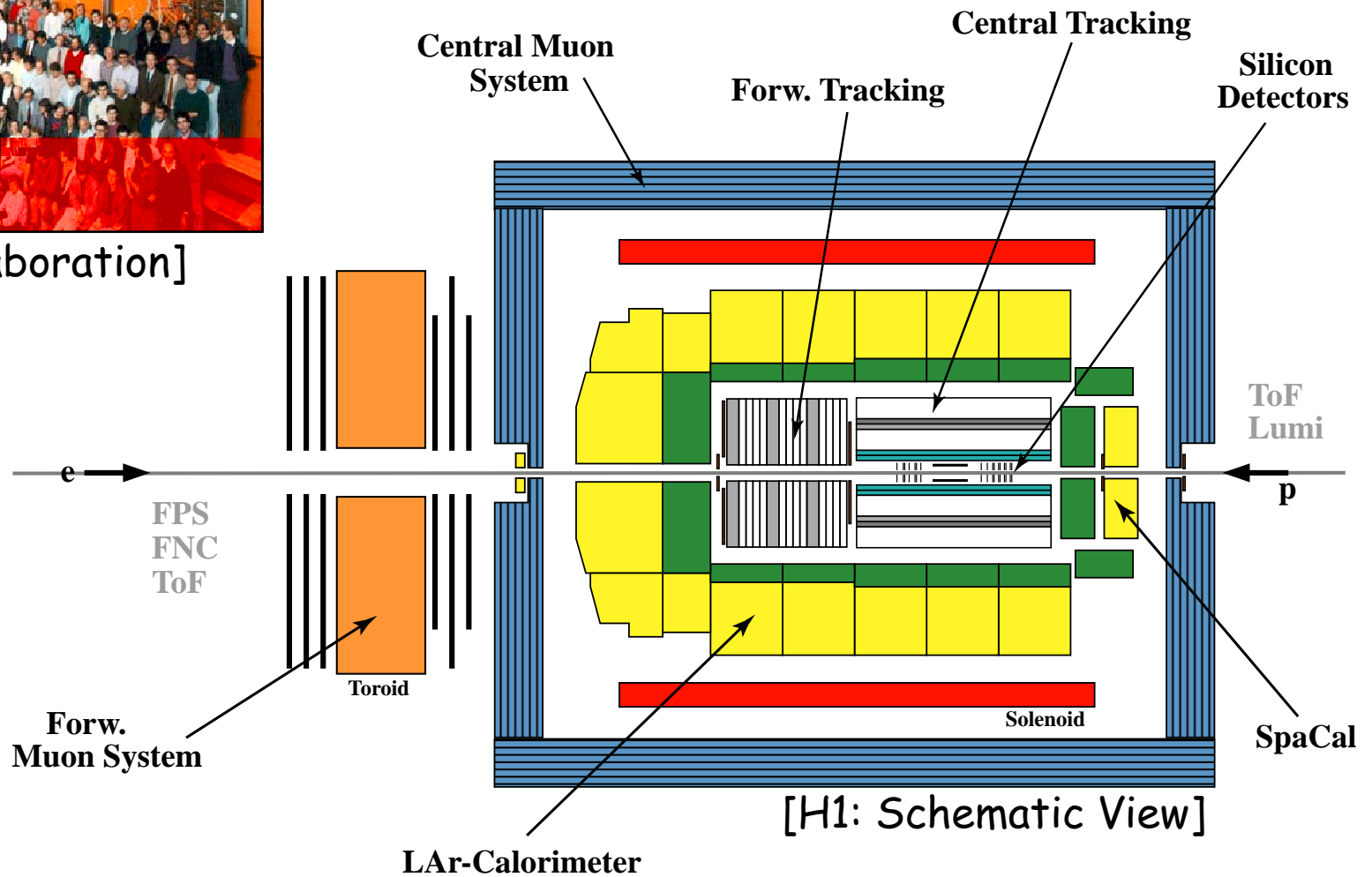- $\sigma(p_t)/p_t = 0.0058\ p_t/GeV \oplus 0.0065$

H1

LAr Calorimeter
- $\sigma(E)/E = 12\%/\sqrt{E}$ for electrons
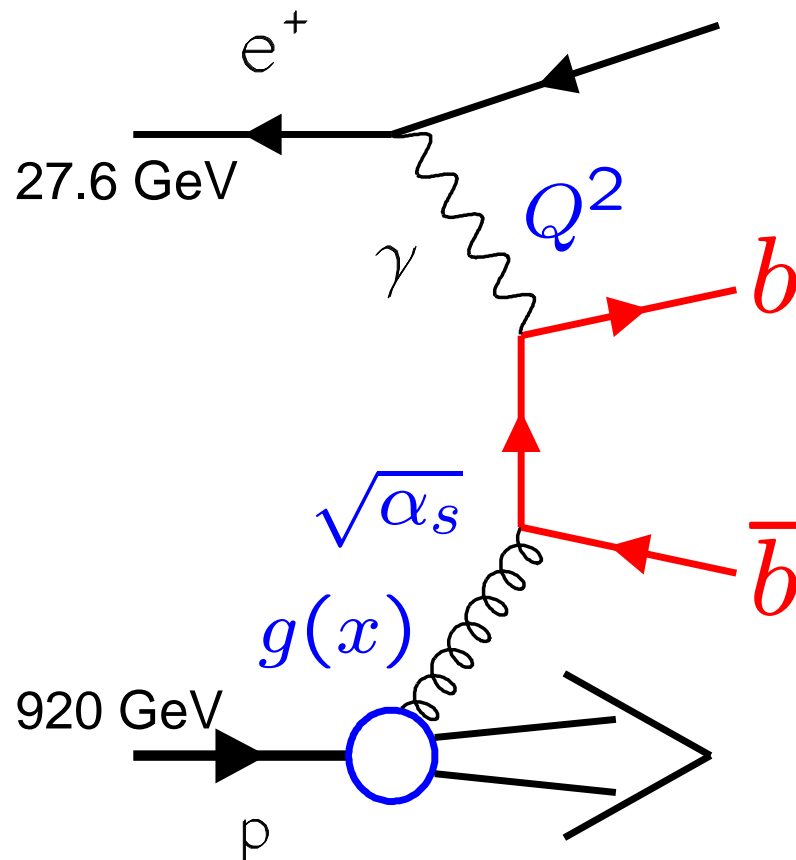- $\sigma(E)/E = 50\%/\sqrt{E}$ for hadrons

Central Tracker Resolution
- $\sigma(p_t)/p_t = 0.006\ p_t/GeV \oplus 0.02$

[H1: Schematic View]

Dominant production process in ep-collisions: Boson-Gluon-Fusion

- Driven by **gluons** in the proton

- Relevant scales:
$$m_b \qquad \sim 5 \text{ GeV}$$
$$Q^2 \qquad \lesssim 1 \text{ GeV}^2 \rightarrow \gamma p$$
$$\qquad \qquad > 2 \text{ GeV}^2 \rightarrow \text{DIS}$$
$$p_T^b$$

- **Various scales** available: pQCD should work

Heavy Quarks: Multiscale Problem in QCD

- **Factorisation:**

  $\otimes$ Photon Structure
  $\otimes$ Matrix Element
  $\otimes$ Proton Structure
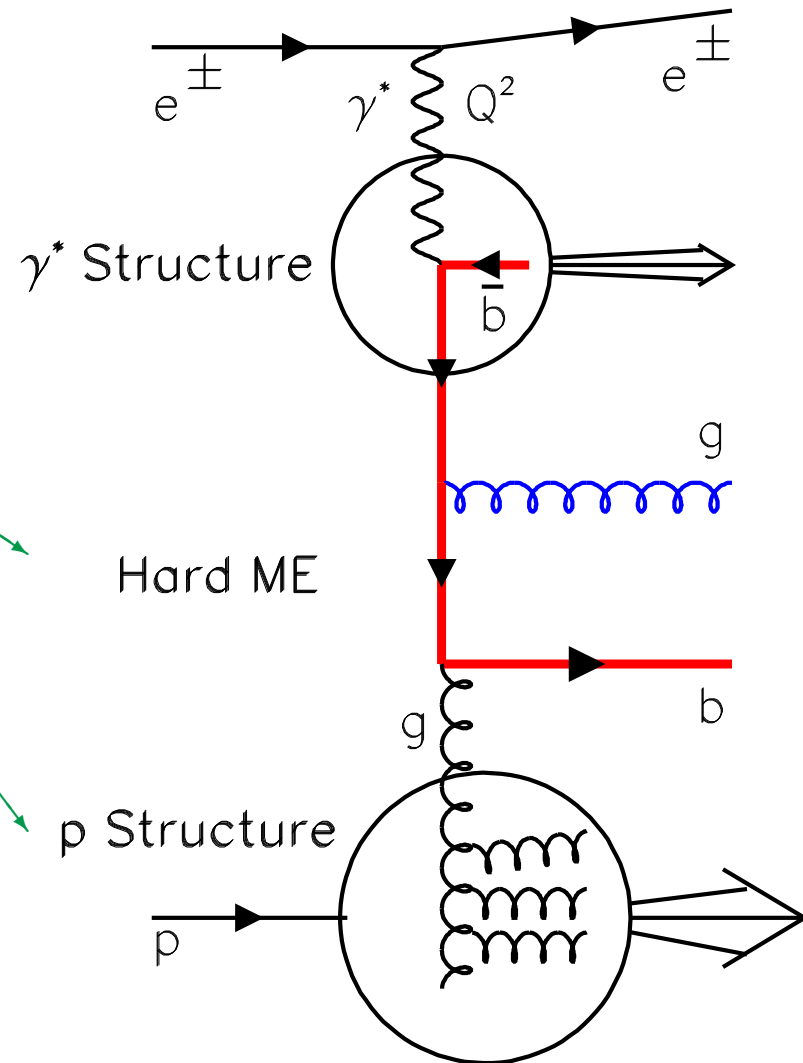
- **Factorisation:**

  $\otimes$ Photon Structure
  $\otimes$ Matrix Element
  $\otimes$ Proton Structure

- **Key Questions:**

  – Role of resolved photons
    for beauty production?

  – pQCD approximation
    of gluon radiations
    (DGLAP, CCFM, BFKL)
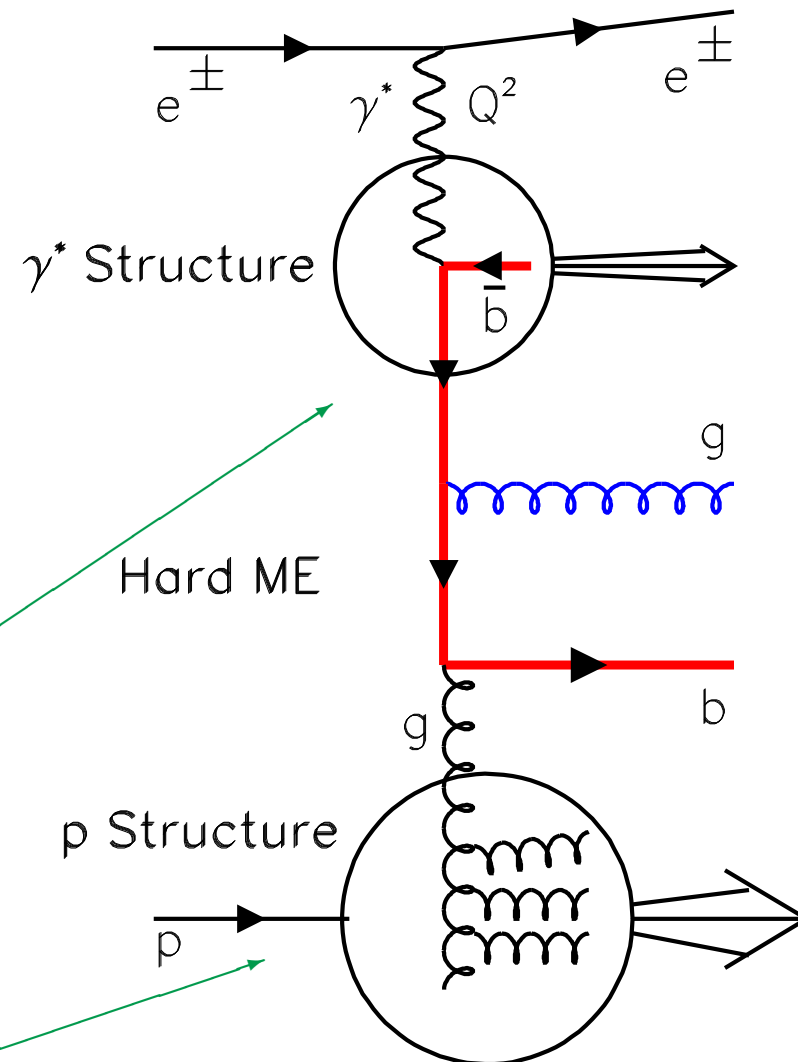
QCD models compared to data:

- NLO $\mathcal{O}(\alpha_s^2)$ calculations

  γp: FMNR

  Frixione, Mangano, Nason, Ridolfi

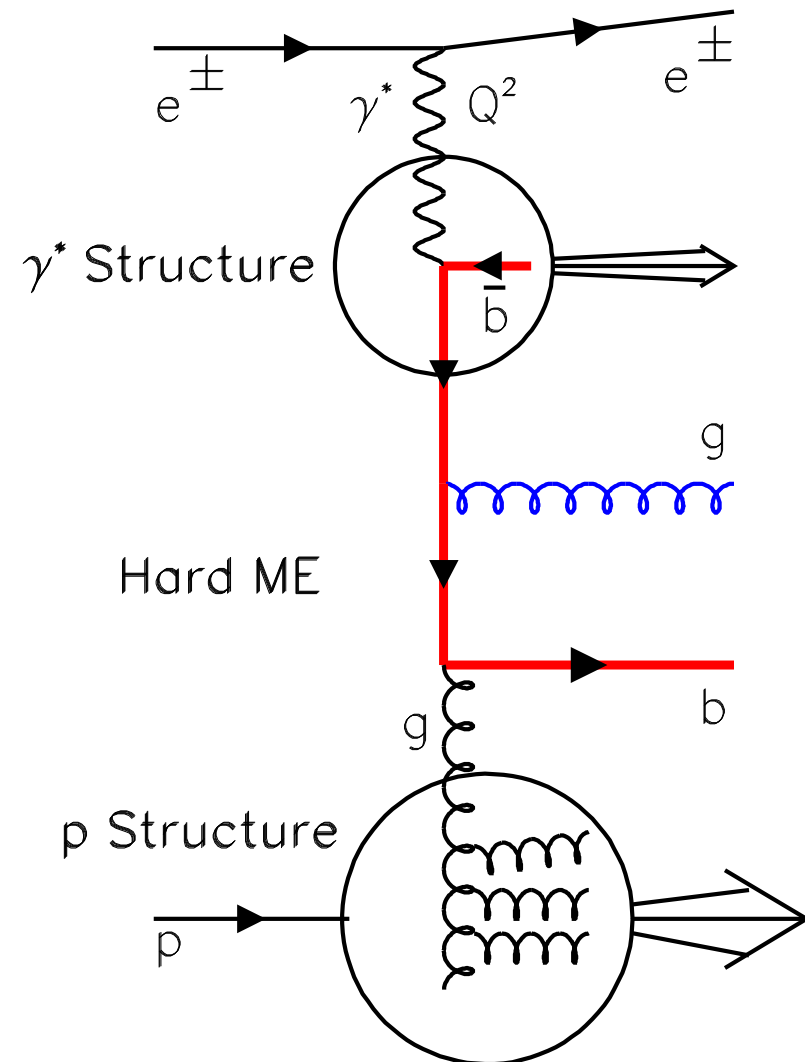 DIS: HQVDIS

  Harris, Smith

- LO $\mathcal{O}(\alpha_s)$ + Parton shower:

  Pythia MC (DGLAP)

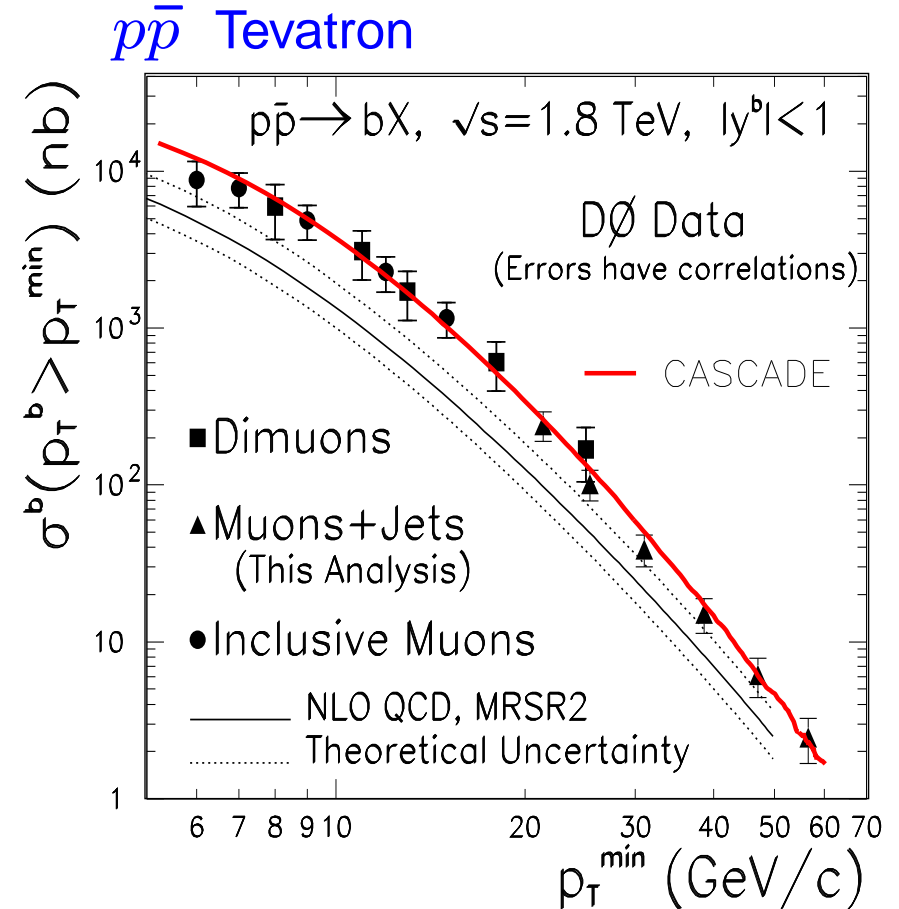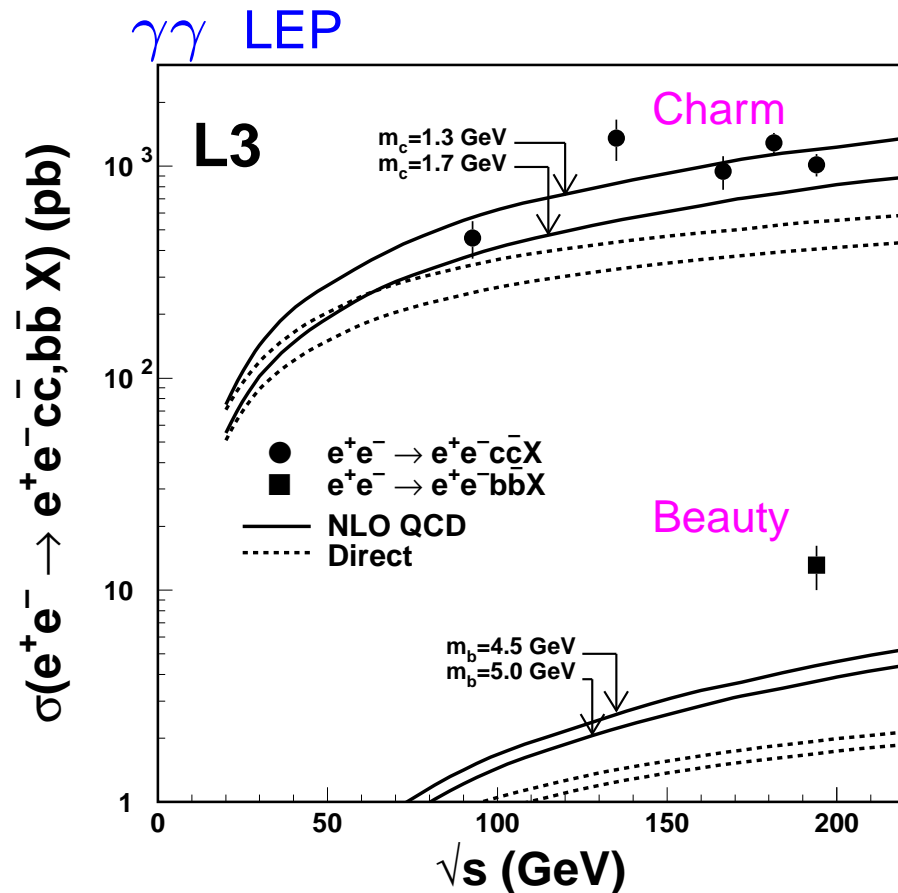 T.Sjöstrand

  Cascade MC (CCFM)

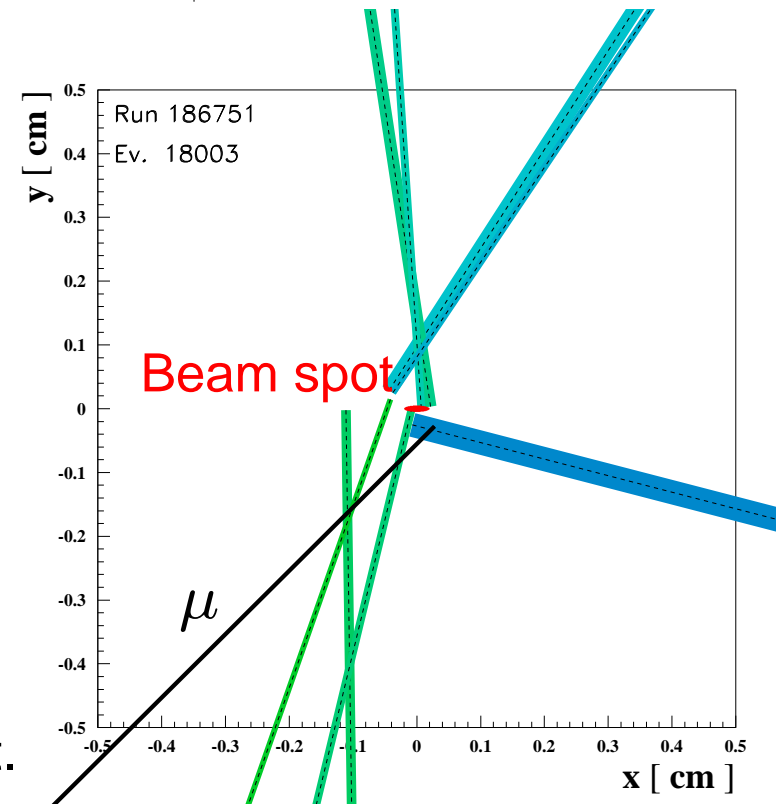 H.Jung

Beauty-Production at LEP and Tevatron

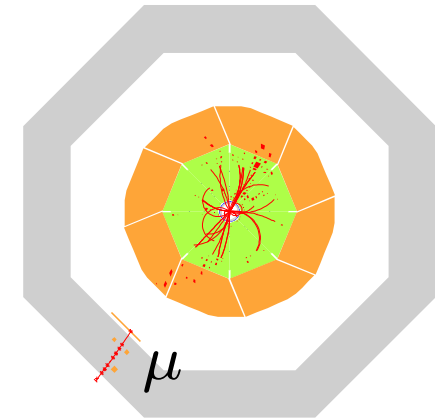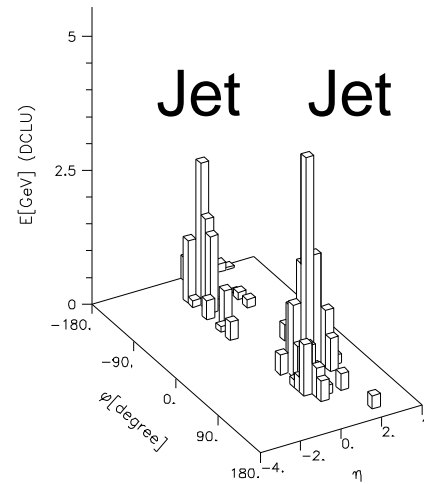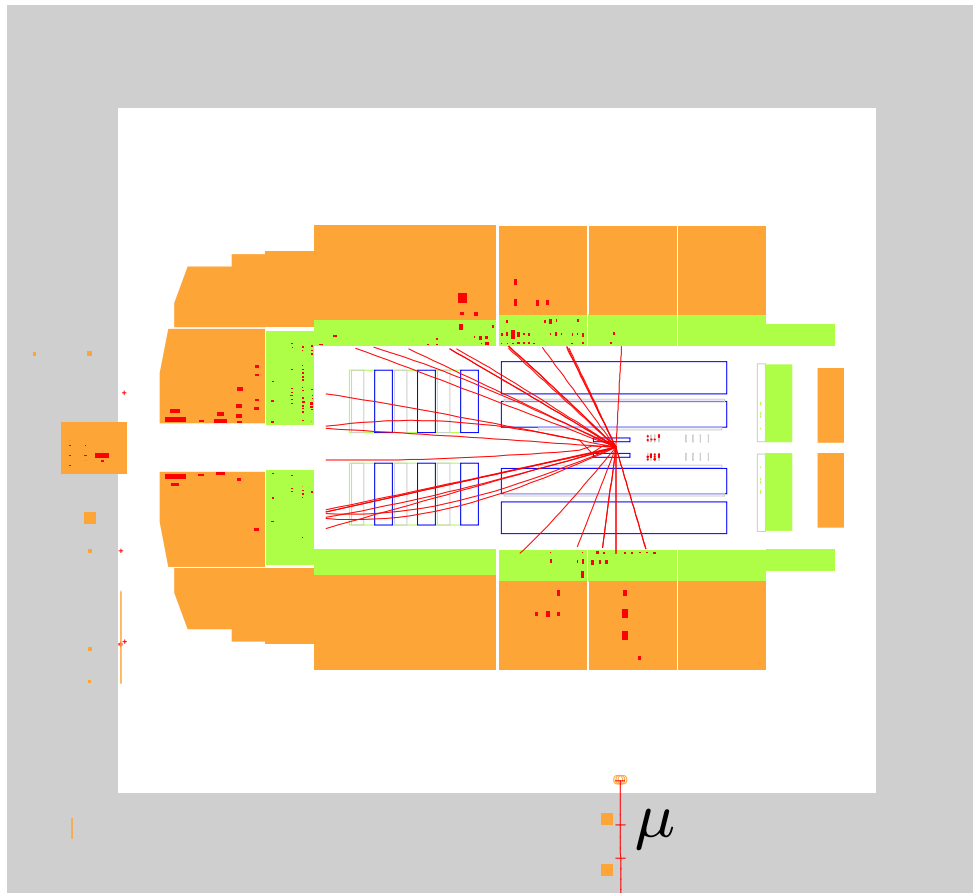- **Tevatron, LEP: NLO-expectations low compared to data**
- $p\bar{p}$: **Improved calculations are closer**

What about b at HERA?

Run 186751
Ev. 18003

Beam spot

μ
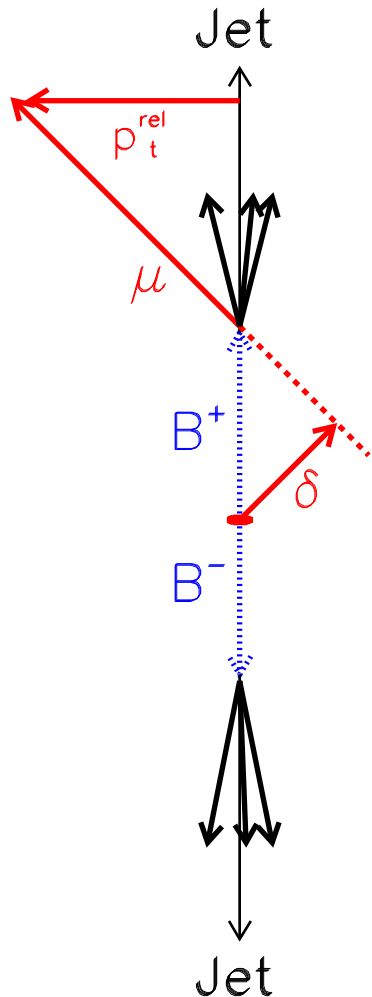
HERA-I data fully analysed

$\int \mathcal{L} dt \sim 100$ pb^{-1} (ZEUS)

$\sim ~~50$ pb^{-1} (H1), with Silicon Vertex Det.

Beauty Production at HERA
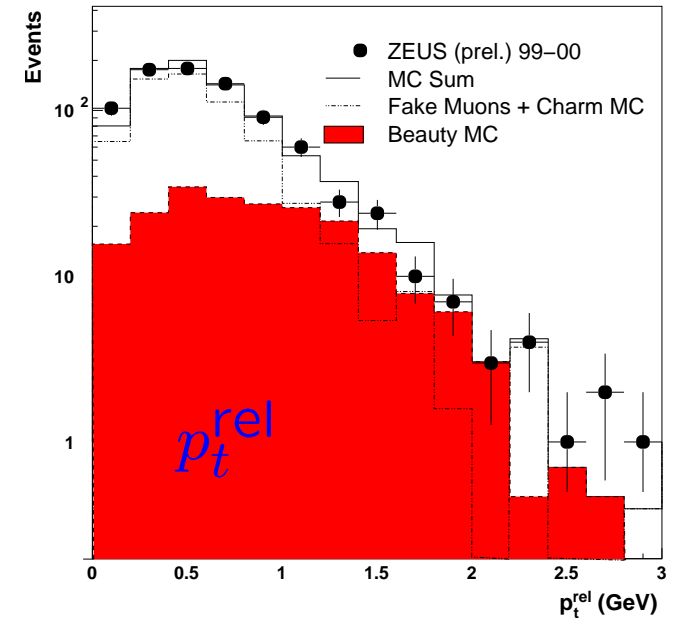
- Large B-Mass:

  p_t^{rel}: p_t of μ relative to jet axis

- Large B-Lifetime:

  μ Impact-Parameter δ

  MC for simulation of b, c, uds
  b-fraction from fit to p_t^{rel} and δ

$Q^2 \sim 0$ $\qquad\qquad b\bar{b} \to jj\mu X$

Beauty Production

Left plot:

$d\sigma/d\eta_\mu$ ($ep \to eb\bar{b}X \to ejj\mu X$)

$Q^2 < 1$ GeV^2
$0.2 < y < 0.8$
$p_t^\mu > 2.5$ GeV
$p_t^{jet} > 7(6)$ GeV
$|\eta^{jet}| < 2.5$

● H1 Data
▲ ZEUS Data
NLO QCD ⊗ Had

Right plot:

$ep \to eb\bar{b}X \to ejj\mu X$

● H1 (Prel.) $-0.55 < \eta^\mu < 1.1$
▲ ZEUS (Prel.) $-1.6 < \eta^\mu < 2.3$
NLO QCD ⊗ Had

$Q^2 < 1$ GeV^2; $0.2 < y < 0.8$
$p_t^{jet1(2)} > 7(6)$ GeV; $|\eta^{jet}| < 2.5$
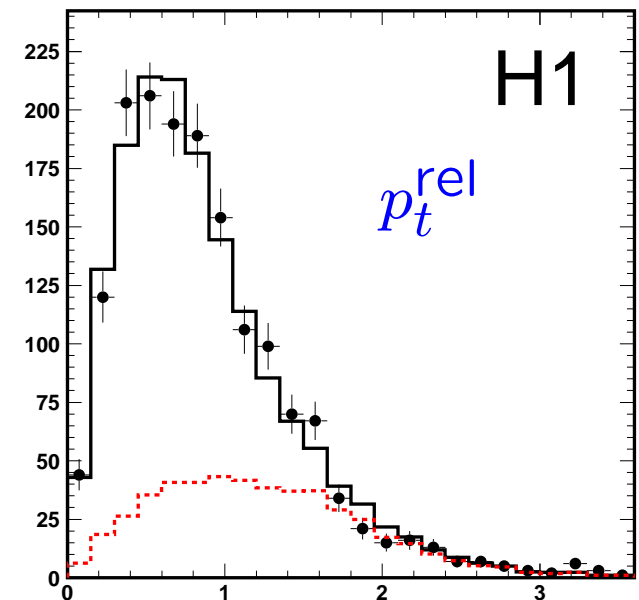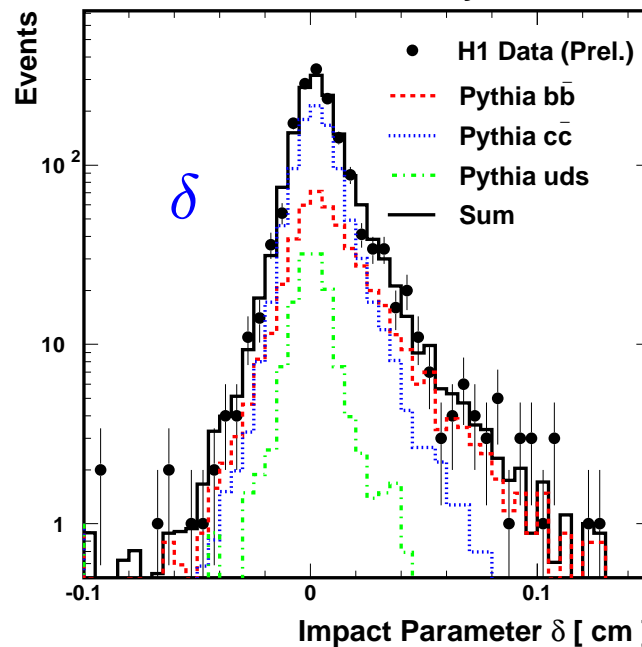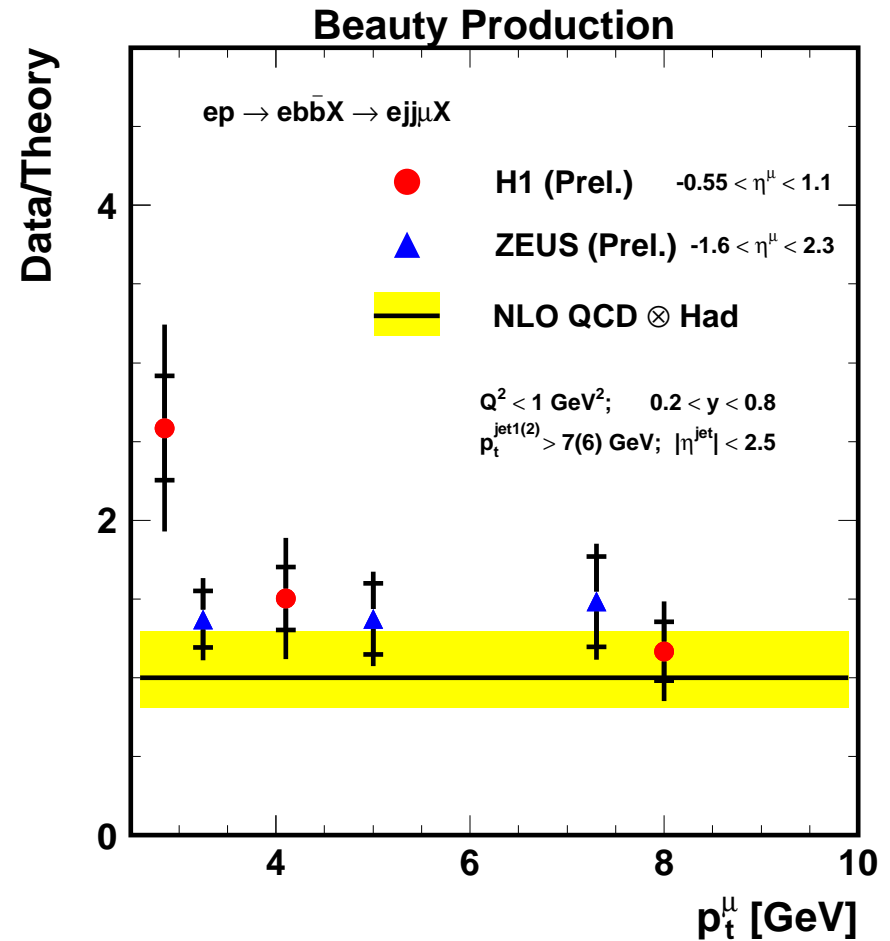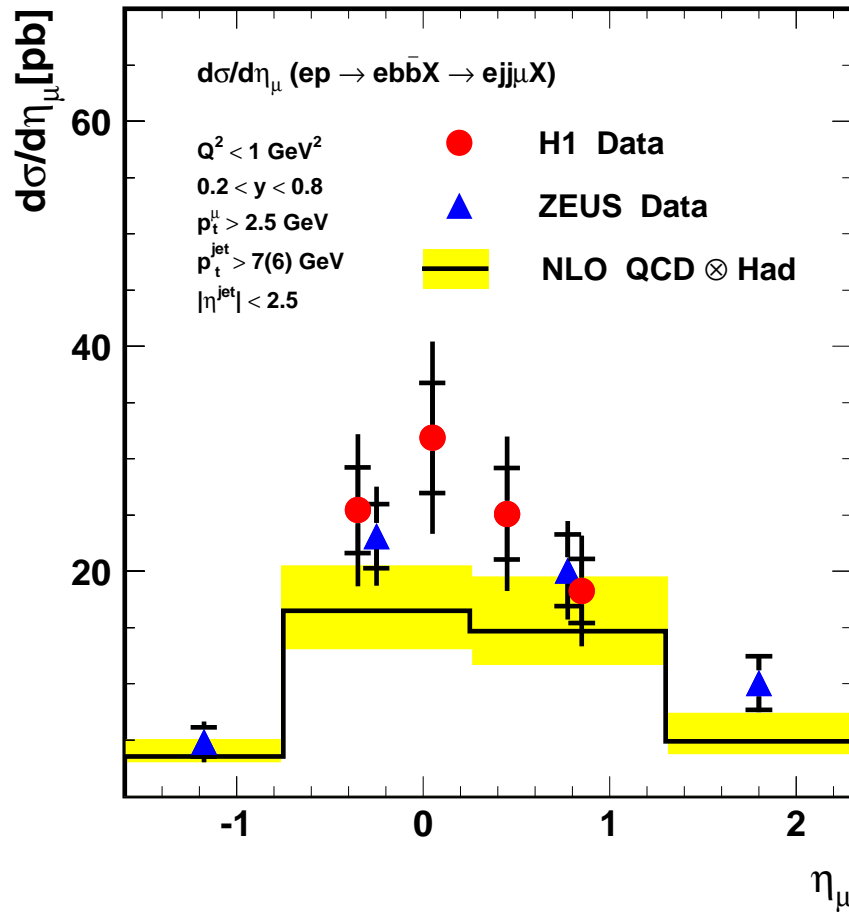
- ● Agreement between H1 and ZEUS
- ● All data points above NLO QCD
- ● Exp. and theory errors fairly large: Agreement within errors

$Q^2 \sim 0$ $b\bar{b} \to jj\mu X$

Left plot:

$d\sigma/dp_t^\mu(ep \to eb\bar{b}X \to ejj\mu X)$ **H1** Preliminary

- ● Data
- NLO QCD ⊗ Had
- ⋯⋯ NLO QCD

$Q^2 < 1$ GeV^2; $0.2 < y < 0.8$
$p_t^{jet} > 7(6)$ GeV; $|\eta^{jet}| < 2.5$
$-0.55 < \eta^\mu < 1.1$

p_t^μ [GeV]

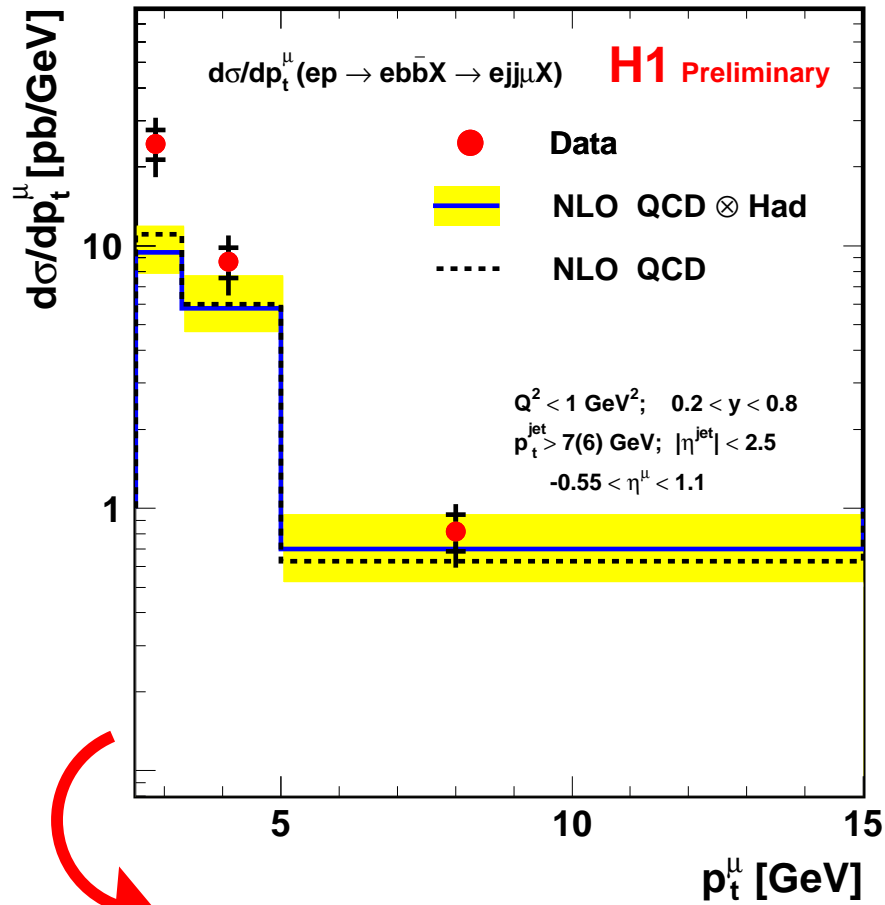NLO QCD: Too low at low p_T^μ

Right plot:

$d\sigma/dp_t^\mu(ep \to eb\bar{b}X \to ejj\mu X)$ **H1** Preliminary

- ● Data
- —— Pythia
- ⋯⋯ Pythia Res.
- - - - Cascade

$Q^2 < 1$ GeV^2; $0.2 < y < 0.8$
$p_t^{jet} > 7(6)$ GeV; $|\eta^{jet}| < 2.5$
$-0.55 < \eta^\mu < 1.1$

p_t^μ [GeV]
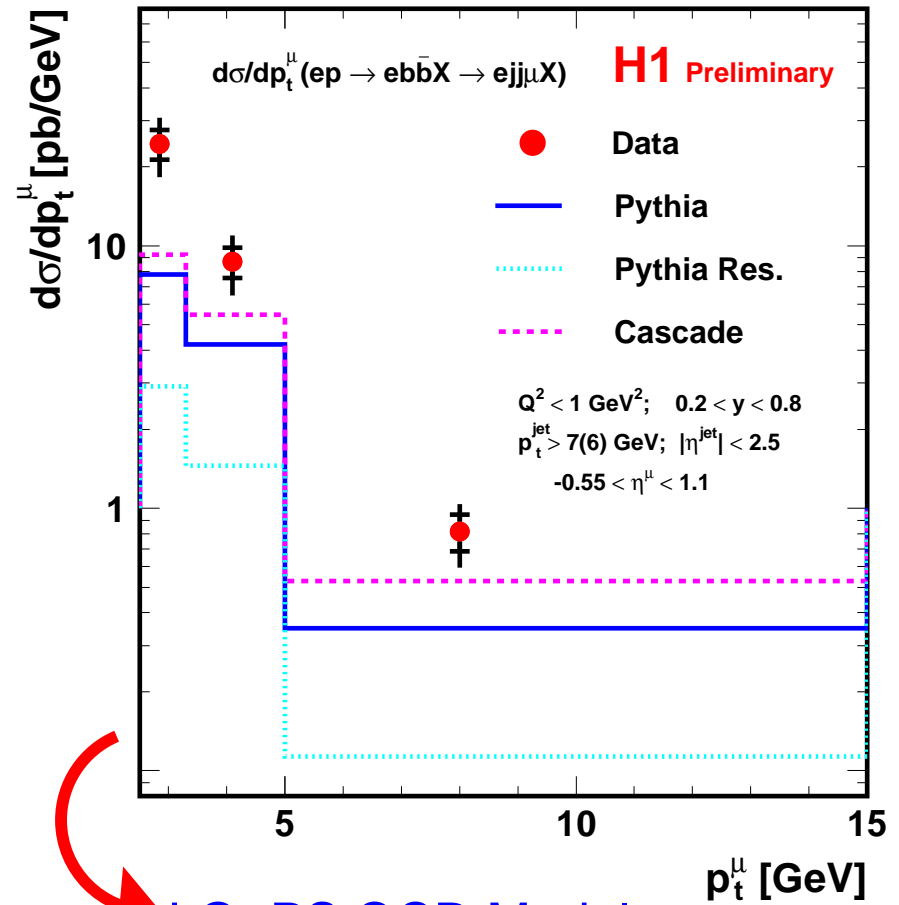
LO+PS QCD Models
Too low in normalization

Contributions from Resolved Photons

$Q^2 \sim 0$ **ZEUS** $b\bar{b} \to jjX$

$$\frac{d\sigma}{dx_\gamma}^{\text{meas}} (ep \to b\bar{b} \to e\, jj\, X)$$

$Q^2 < 1\ \text{GeV}^2$ $0.2 < y < 0.8$

$p_T^{j1,j2} > 7,6\ \text{GeV}$ $|\eta^j| < 2.5$

- **ZEUS (prel.) 96-00**
- NLO QCD x hadr.
- NLO QCD

x_γ
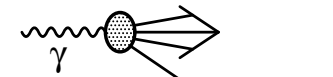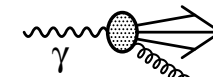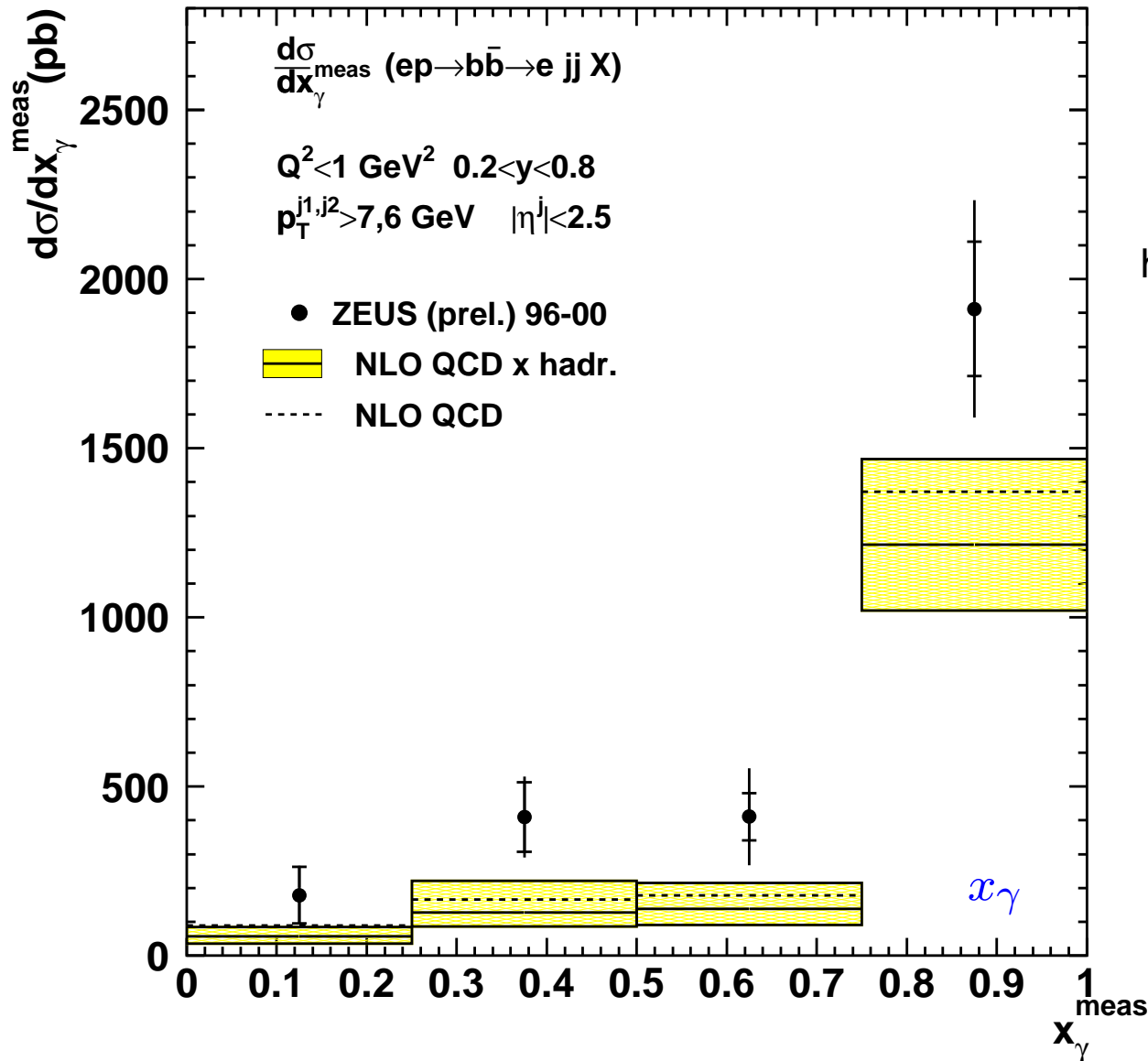
hadron-like: $gg \to b\bar{b}$ b-excitation: $bg \to gb$

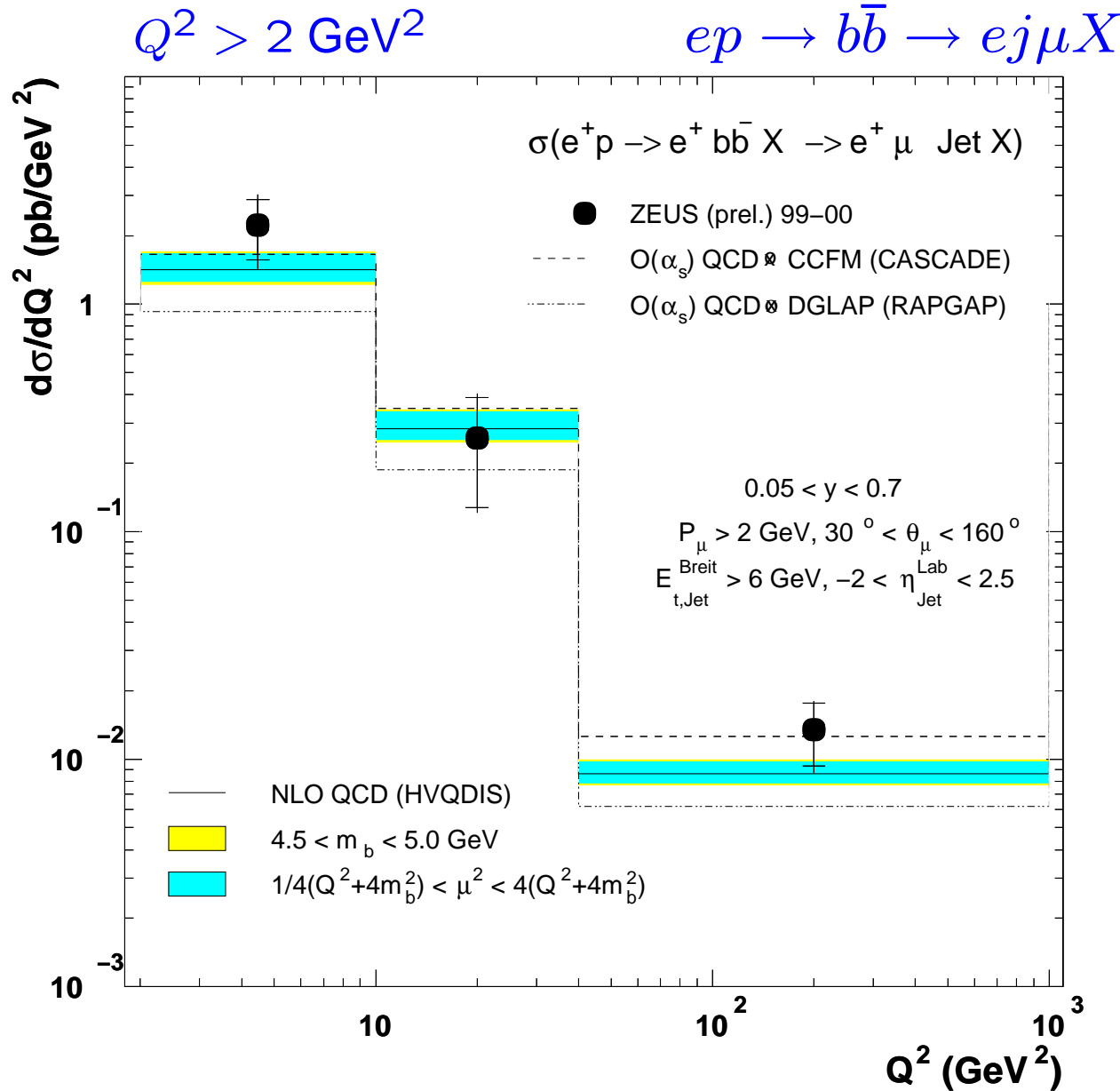$$x_\gamma^{\text{meas}} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

- Resolved Photon: $(x_\gamma \lesssim 0.75)$
  - $\to$ significant contribution

- NLO QCD:
  - $\to$ lower than data
  - $\to$ large uncertainties

ZEUS: $\sigma^{\text{vis}} = (733 \pm 61 \pm 104)$ pb
NLO (Frixione et al): $\sigma^{\text{vis}} = (381^{+117}_{-78})$ pb

$Q^2 > 2$ GeV^2 $ep \rightarrow b\bar{b} \rightarrow ej\mu X$

$\sigma(e^+p \rightarrow e^+ b\bar{b} X \rightarrow e^+ \mu$ Jet X$)$

● ZEUS (prel.) 99–00

- - - $O(\alpha_s)$ QCD ⊗ CCFM (CASCADE)

–·–·– $O(\alpha_s)$ QCD ⊗ DGLAP (RAPGAP)

$0.05 < y < 0.7$

$P_\mu > 2$ GeV, $30^{\,o} < \theta_\mu < 160^{\,o}$

$E_{t,Jet}^{Breit} > 6$ GeV, $-2 < \eta_{Jet}^{Lab} < 2.5$

NLO QCD (HVQDIS)

$4.5 < m_b < 5.0$ GeV

$1/4(Q^2+4m_b^2) < \mu^2 < 4(Q^2+4m_b^2)$
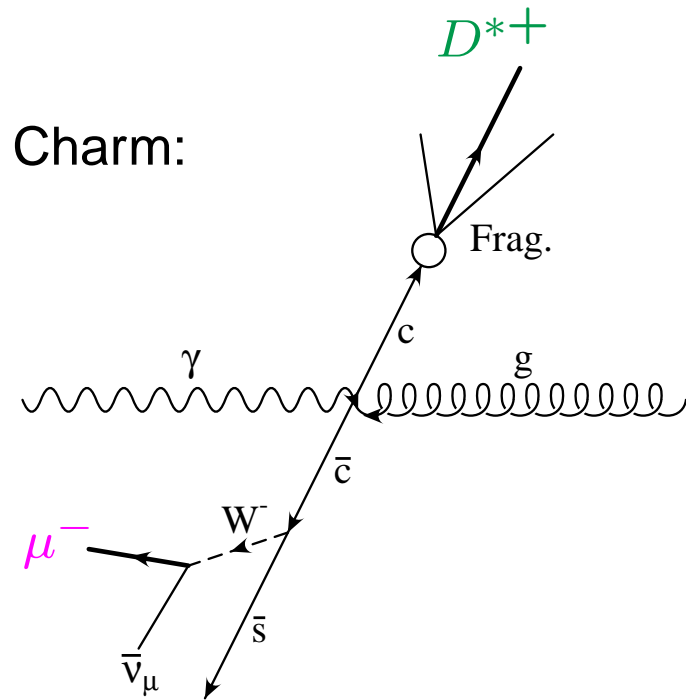
$\sigma^{vis} = (38.7 \pm 7.7^{+6.1}_{-5.0})$ pb

● **DGLAP (NLO):**

– ok within errors

NLO (Harris et al): $\sigma^{vis} = (28^{+5.3}_{-3.5})$pb

● **CCFM:**

– Good description

CASCADE-MC: $\sigma^{vis} \approx 35$pb

● **DGLAP (LO+PS):**

– too low

γg-Center of Mass System:

Charm:

$$\Delta\Phi \approx 180°$$

$$Q(D^*) \neq Q(\mu)$$
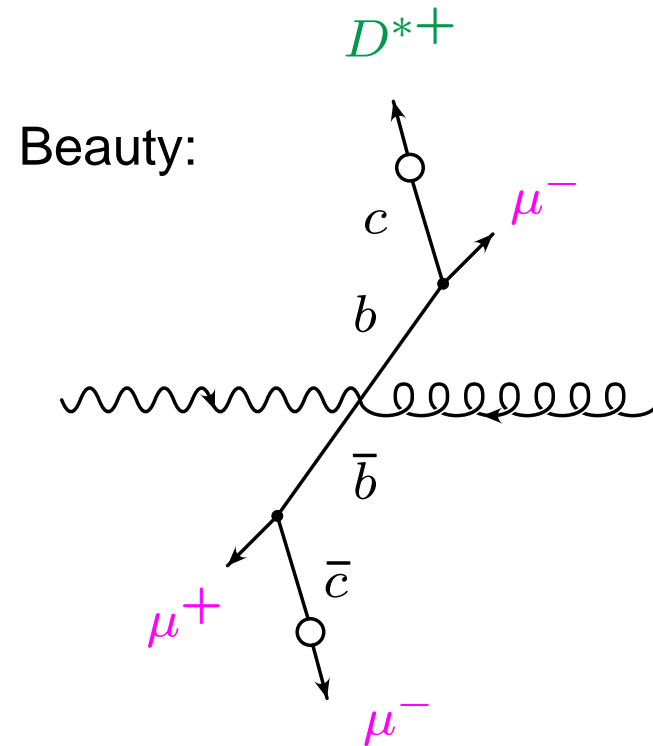
Beauty:

$$\Delta\Phi \approx 0° \quad ; Q(D^*) \neq Q(\mu)$$
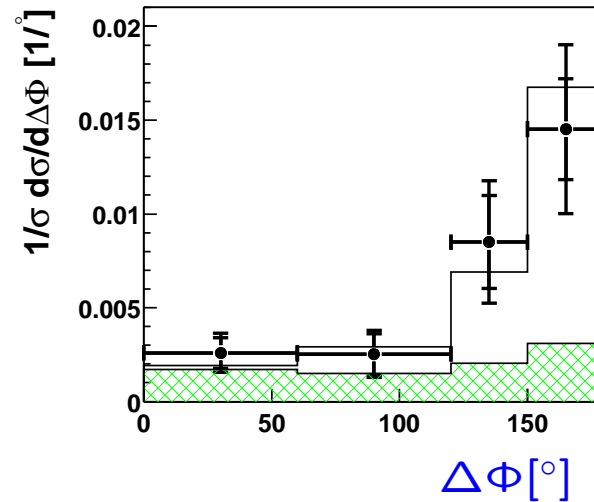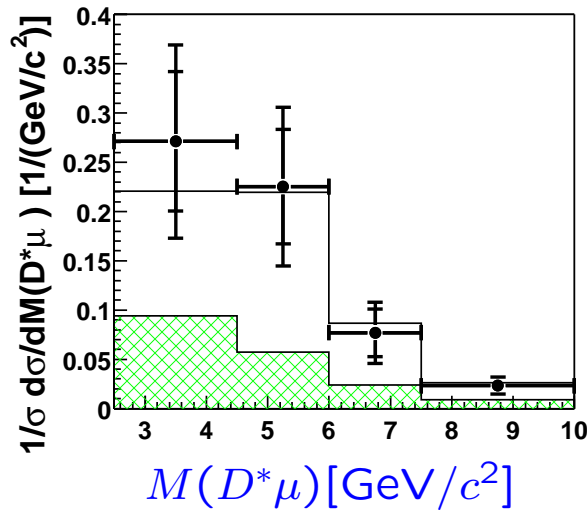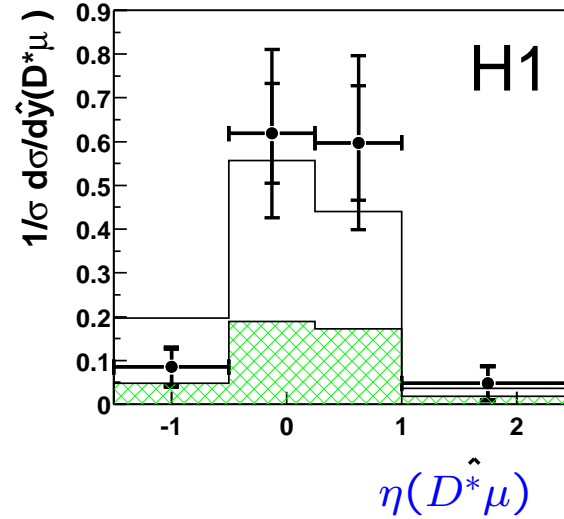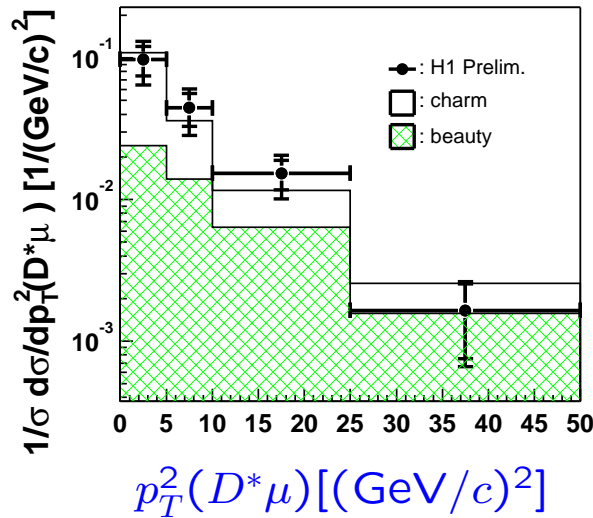
$$\Delta\Phi \approx 180°; Q(D^*) \neq Q(\mu)$$

$$\Delta\Phi \approx 180°; Q(D^*) = Q(\mu)$$

Separation of c and b via charge and angular correlations

Figures: LO Monte Carlo, Cross Sections normalized
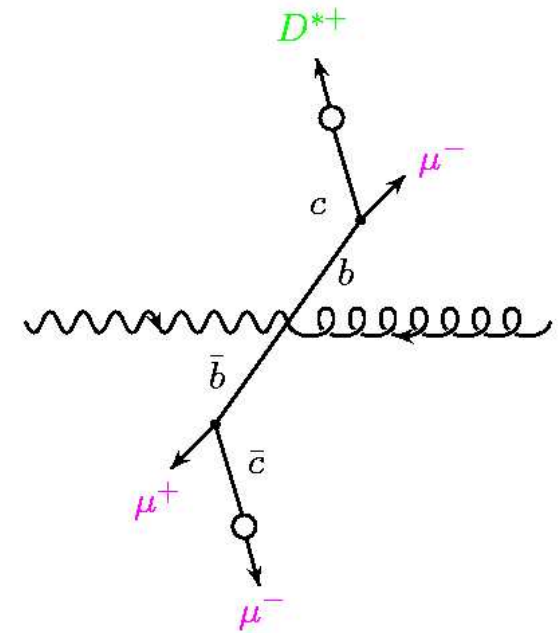
- Both Quarks measured:

$\rightarrow$ Full reconstruction of event

$\rightarrow$ Look for NLO effects

Beauty Cross Section from $D^*\mu$ Events
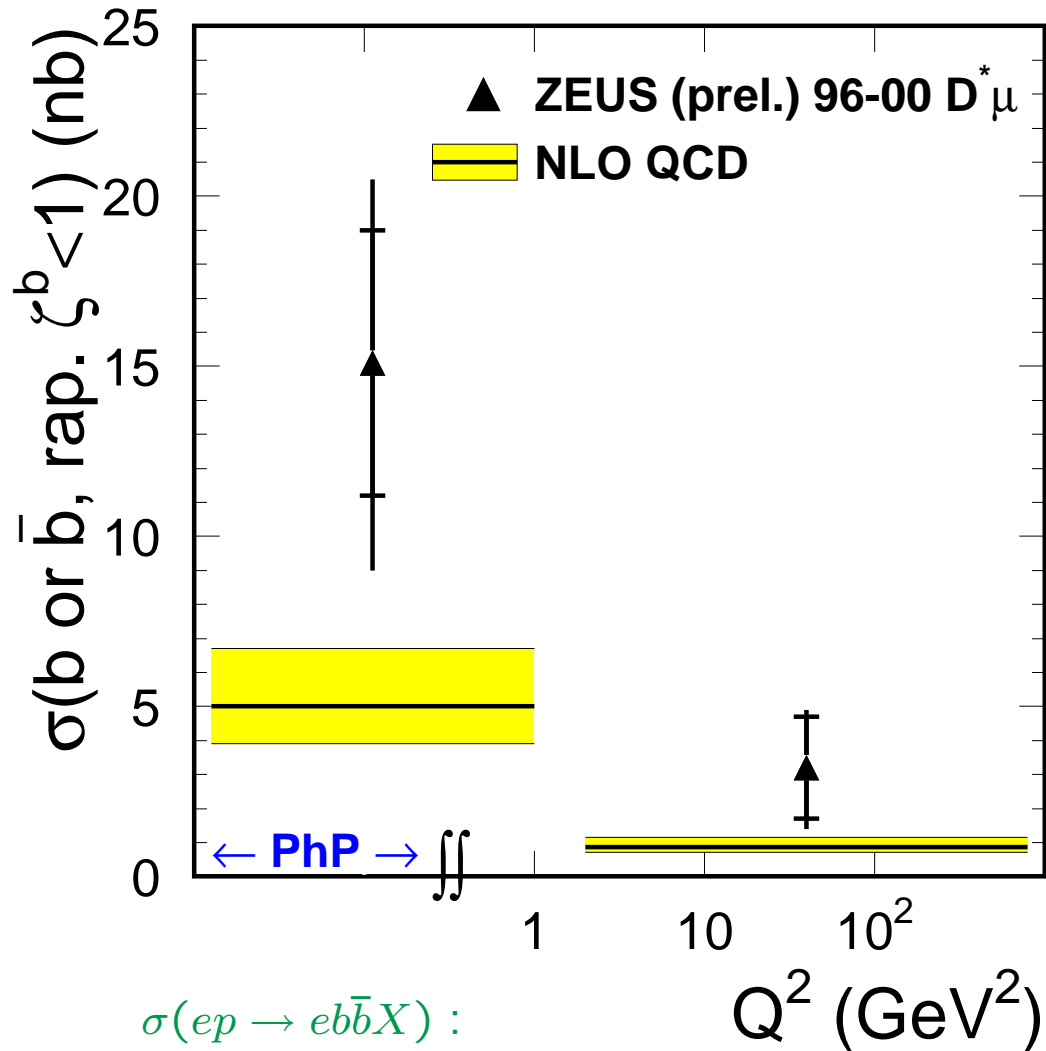
$\sigma(ep \to e b\bar{b}X)$:
ZEUS: $15.1 \pm 3.9^{+3.8}_{-4.7}$ pb
NLO (Frixione et al): $5.7^{+1.7}_{-1.1}$ pb
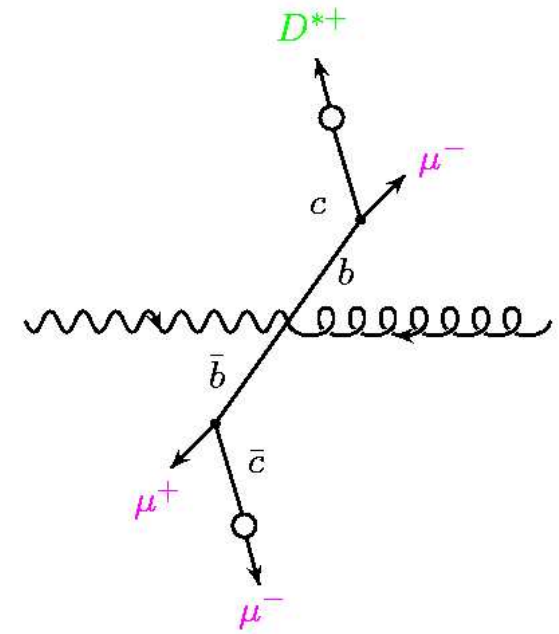
- Factor ~ 3 above NLO-expectation
  - $\to$ statistical uncertainty still large
  - $\to$ same trend as previous b-results

Conclusions

Summary: Beauty at HERA I

- New precise differential b-cross-section measurements using full HERA-I dataset
- H1 and ZEUS measurements agree
- Measurements are mostly above NLO QCD predictions (within ≤ 1.5 s.d.)
- Better description towards large Q^2, p_T^μ (?)

Outlook: Beauty at HERA II

- Go for precision answers to open questions
    - Factor of 10 in Luminosity
    - Improved Detectors
        (z.B. Trigger, Tracking / Vertexing, Angular Coverage)

ZEUS Microvertex-Detector

BOTTOM MICRO VERTEX DETECTOR

b Cross Sections at HERA