Heavy flavour production at HERA

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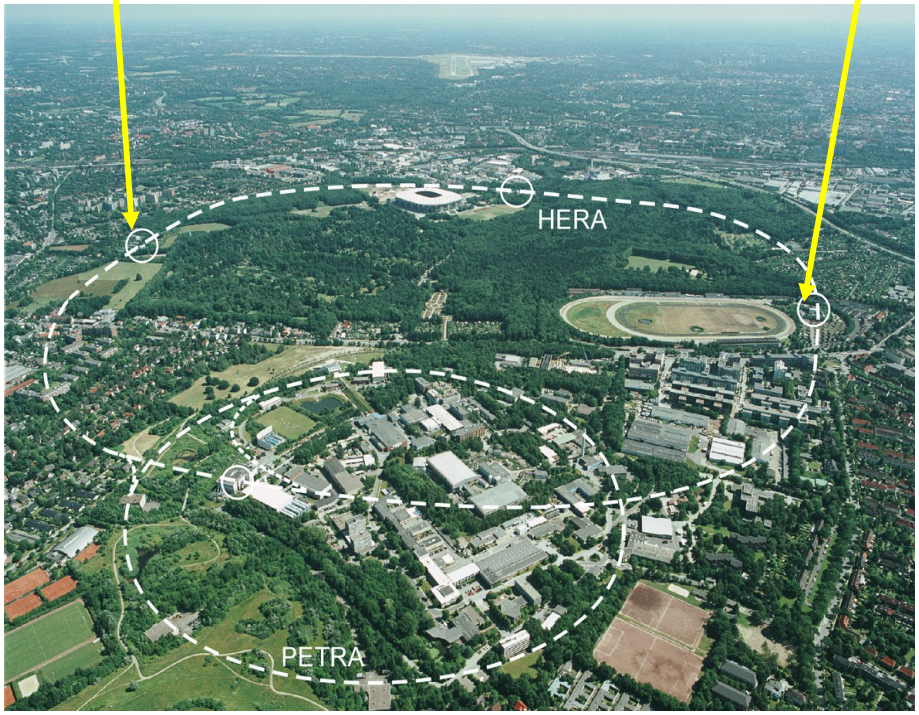
On behalf of the

H1 & ZEUS collaborations

Outline:

- Introduction
- Charm production
- Beauty production
- Conclusions

The HERA accelerator



The HERA ring: ~ 30 m below ground level

- Located near the DESY research center in Hamburg, Germany

e^+/e^- 27.5 GeV

p 920 GeV

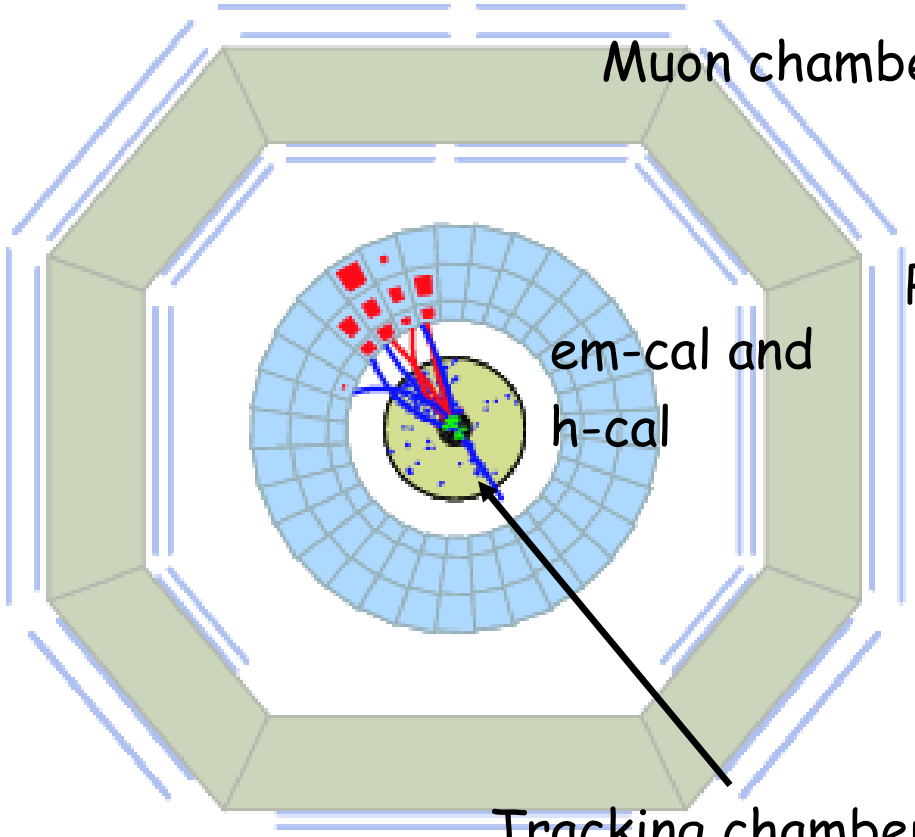
820 GeV (before 1998)

Maximum center of mass energy:
$\sqrt{s} = 318$ GeV

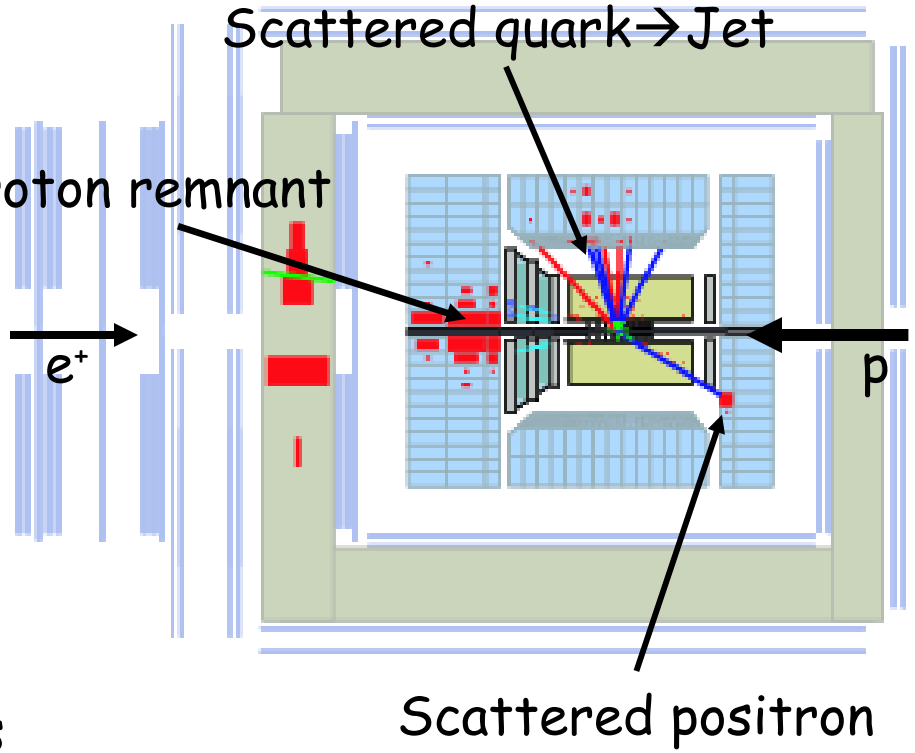
Instrumentation

ep event (ZEUS)

$E_p \gg E_e \rightarrow$ Asymmetric detector



xy view



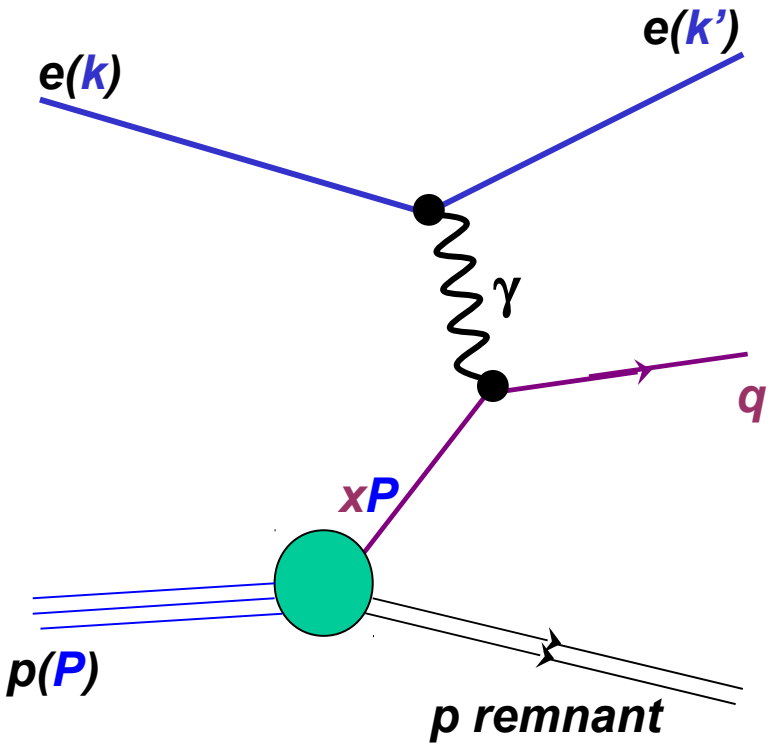
zr view

HERA-running

- HERA I 1992-2000
  - Largest part of the data taken from 1996-2000
  - Data sample per experiment:
    - $L \approx 100\ pb^{-1}\ e^{+}p$
    - $L \approx 15\ pb^{-1}\ e^{-}p$
- Heavy flavour measurements reported here are from HERA I sample

- HERA II 2001-…
  - Luminosity upgrade
  - Aimed at $L \approx 1\ fb^{-1}$ in 2005.
  - Detector upgrades
  - Long start up phase
    - Background conditions were worse than expected
    - Modifications were necessary
  - Since October 2003
    - Luminosity running
    - Recorded up to now: ~30 pb^{-1} (ZEUS) ~40 pb^{-1} (H1)
  - HERA II program extended until 2007

ep kinematics



$Q^2 = -(\mathbf{k}-\mathbf{k}')^2$: photon virtuality

$x = Q^2/2\mathbf{P}\cdot\mathbf{q}$: fraction of proton four momentum of struck quark

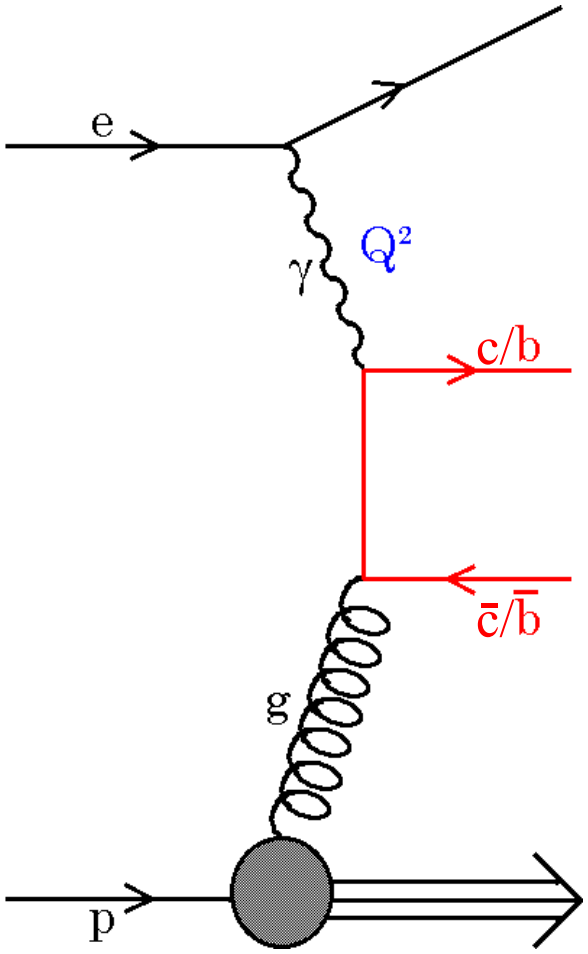
Two regimes used for heavy flavour production

Deep Inelastic Scattering (DIS): $Q^2 > 1$ GeV^2

Photoproduction (γp): $Q^2 \sim 0$ GeV^2 { Resolved and Direct photoproduction

Heavy quark production at HERA

→ Dominated by Boson-Gluon fusion (BGF)



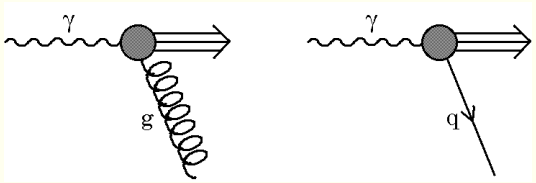
- Driven by gluon density in the proton
- Mass of heavy quark gives "hard scale" to the interaction

☛ perturbative QCD should work…

Prediction of the cross section

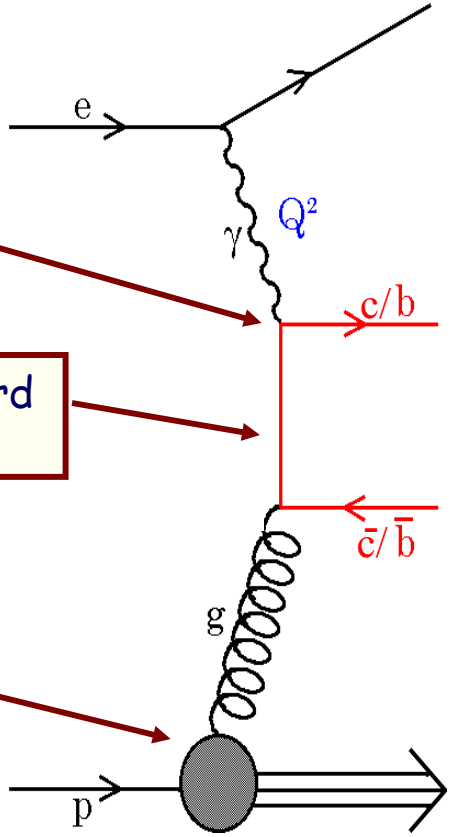
Factorization: Photon structure ⊗ Matrix element ⊗ Proton structure

Photon structure:



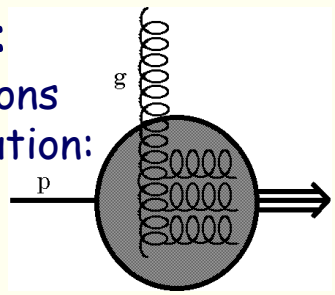
Resolved photons: gg-->cc̄, cg→cg and qq->cc̄

Hard ME



Proton structure:

Parton density functions (PDFs) and QCD evolution: DGLAP, BFKL, CCFM



QCD models compared to data:

- Monte Carlo:
  LO + parton shower:
  - Pythia (DGLAP)
  - RAPGAP (DGLAP)
  - Cascade (CCFM)
- NLO Calculations:
  - γP: FMNR
  - DIS: HVQDIS
- QCD schemes
  - Massive: Heavy quark is produced dynamically
  - Massless: Heavy quark active flavour in proton

Measured channels at HERA

- c/b quark fragments into hadrons and leptons

Decay		Measurement strategy
$c \rightarrow D^{*\pm} \rightarrow D^0 \pi^{\pm}$	*	Mass difference
$c \rightarrow e^-$		Particle identity
$c \rightarrow D^0, D^{\pm}, \ldots$		Tracks, secondary vertex
$b \rightarrow e^-, \mu^{\pm}$ and jet	*	p_t relative to jet axis, impact parameter of lepton
$b \rightarrow D^{*\pm}\ \mu^{\pm}$		"Double tags"
c,b → tracks in jet	*	Imp. Parameters

blue needs microvertex detector.

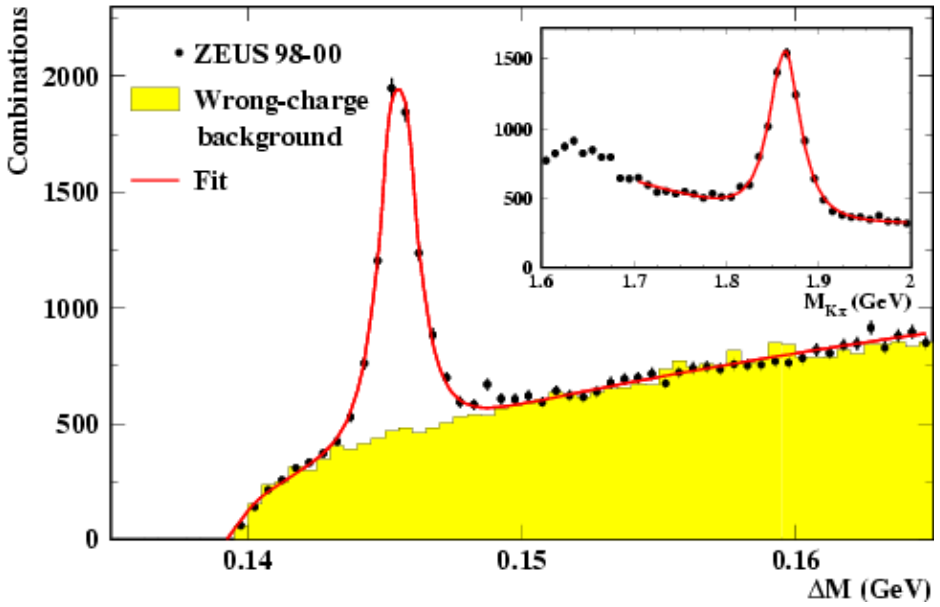
H1: CST (1997, HERA-I)

ZEUS: MVD (2001, HERA-II)

* Results are shown in this talk

c→D* in DIS

ZEUS 98-00



ΔM

- Reconstruction of $D^{*+}(2010) \rightarrow D^0\pi^+(slow)$, $D^0 \rightarrow K^-\pi^+$ (and c.c)
- Signal regions
  $1.80 < M(D^0) < 1.92$ GeV
  $0.143 < \Delta M < 0.148$ GeV
- Investigate cross section for data bins in x, Q^2, $p_t(D^*)$ and $\eta(D^*)$

$p_t(D^*) > 1.5$ GeV,

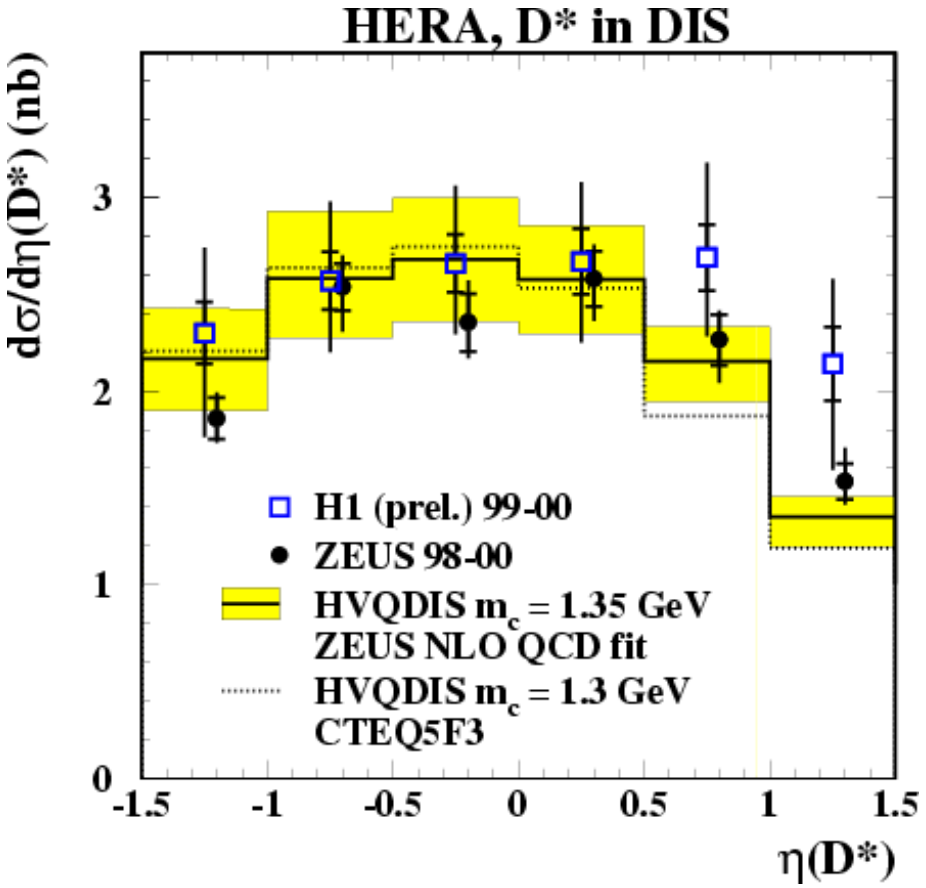
$|\eta(D^*)| < 1.5$, $1.5 < Q^2 < 1000$ GeV^2

$N(D^{*\pm})=5545\pm129$

c→D* in DIS

Differential DIS D* cross section in η

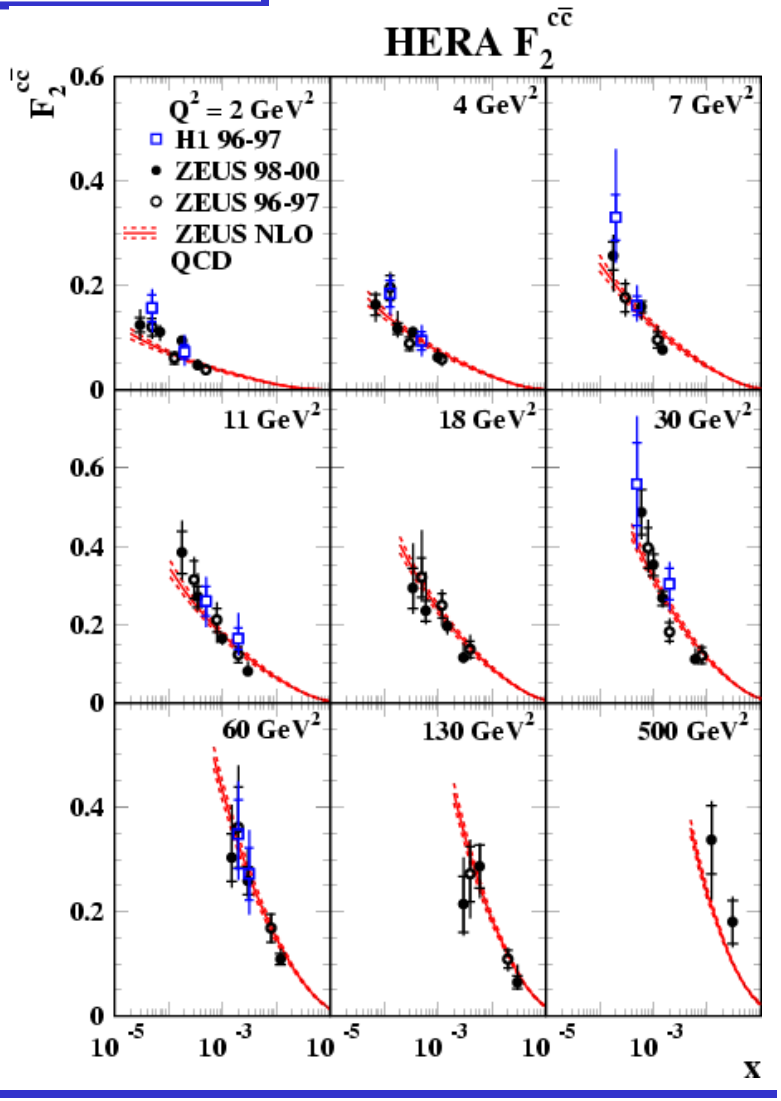
- Good agreement with the NLO QCD calculations
- Error band represents theoretical uncertainties:
  - Charm mass
  - Factorization and renormalization scale
  - Fragmentation parameters
- 2 sets of proton PDFs functions are shown



$$\eta = -\ln(\tan(\theta/2))$$

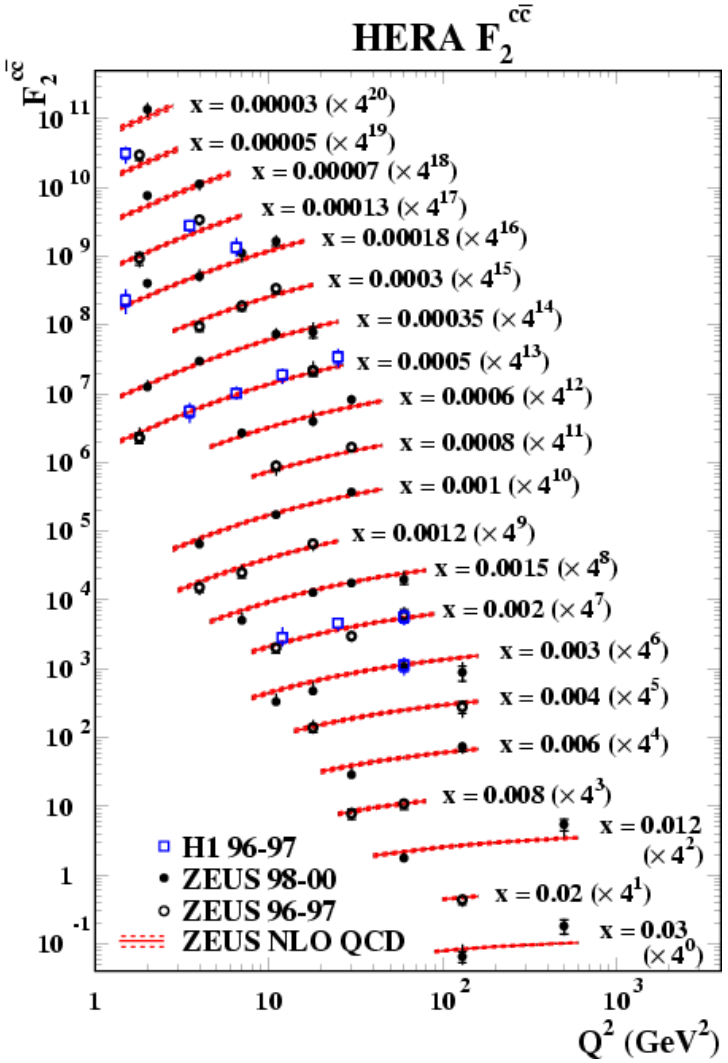
Charm contribution to the proton structure function F_2

- Extraction of $F_2(cc)$
  - Data shown for fixed Q^2
  - Agreement between ZEUS and H1
  - Agreement with predictions NLO QCD fit from inclusive measurements.
  - Rise of $F_2(cc)$ for higher Q^2.
    - Effected by the proton gluon density
  - Measurements verify the fitted gluon density from inclusive measurements.



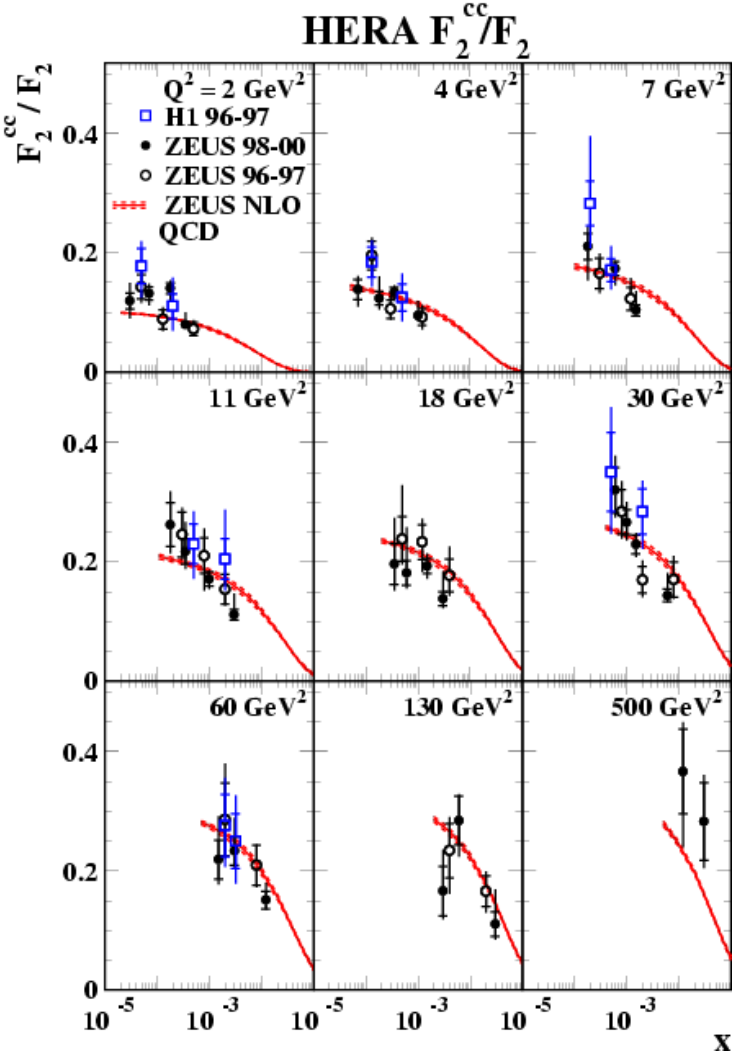
$F_2(cc)$ scaling violations

- $F_2(cc)$ for fixed x
  - Scaling violations → $F_2(cc)$ becomes steeper at lower x



$F_2(cc)$

- Ratio of $F_2(cc)$ and the proton structure function F_2



- Charm contribution to DIS cross section rises up to 35%

Beauty production

- b quark has larger mass, smaller charge
  - Cross section ~200 smaller than for charm
  - Theoretical predictions expected to be more reliable (larger mass)

HERA-I results for

b → μj in photoproduction

b → μj in DIS

b(and c)→tracks in high Q^2 DIS

Event selection

- Photoproduction

  $\gamma p \rightarrow bbX \rightarrow \mu jjX$

  - DIS rejection
  - At least 2 jets
    - $P_t > 7{,}6$ GeV
    - $|\eta| < 2.5$
  - At least one muon linked to one of the jets.

- DIS

  $ep \rightarrow ebbX \rightarrow e\mu jX$

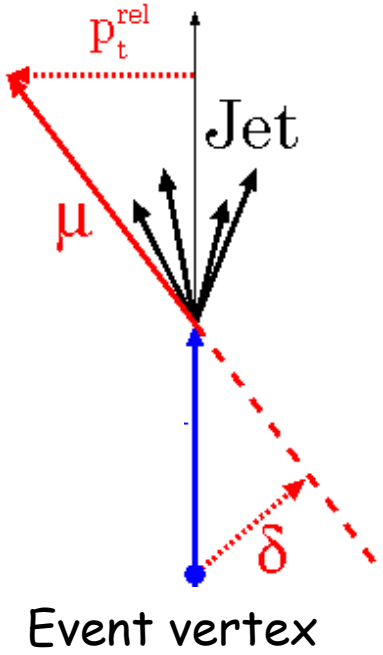
  - Scattered positron
  - At least 1 jet
    - $P_t^* > 6$ GeV
    - $|\eta| < 2.5$
  - At least one muon linked to the jet

- $P_{t,\mu} >\sim 2.5$ GeV
- $|\eta_\mu|$

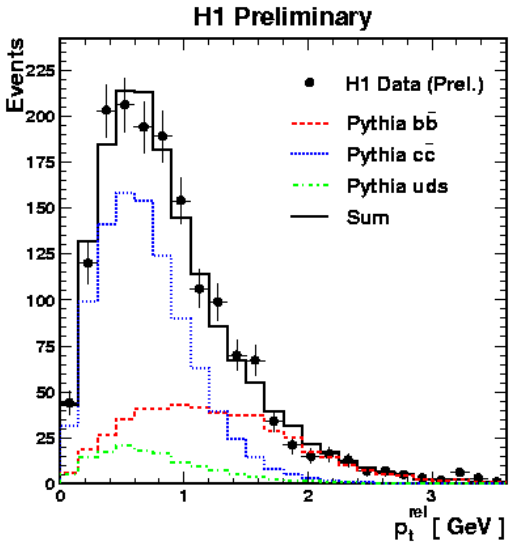
Are H1/ZEUS dependent

*Breit frame:
(γ–parton CM frame)

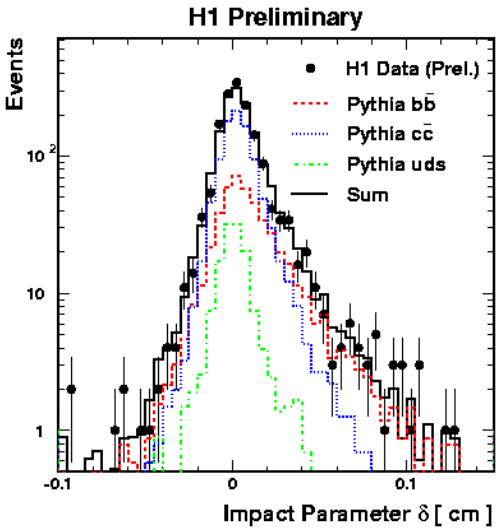
Fraction of b quarks



Fit light, c and b quark MC shapes to data



Large B mass:
→ p_T of μ relative to the closest jet is larger



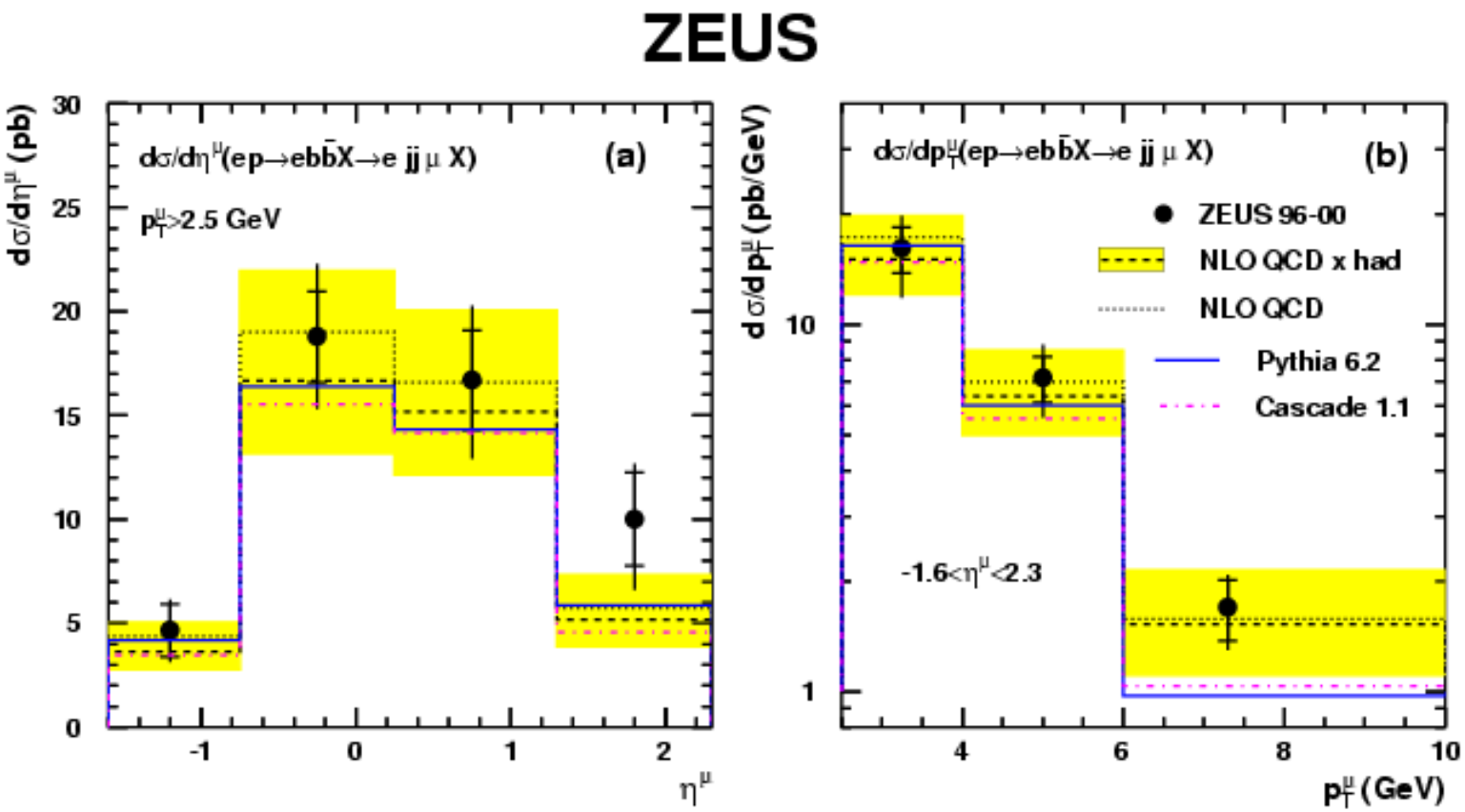
Large B lifetime:

→ μ impact parameter δ

H1 γP (prel.): Combined max Likelihood fit (δ, p_T^{rel}): f_b=30.7±2.5 %

b→μ in photoproduction

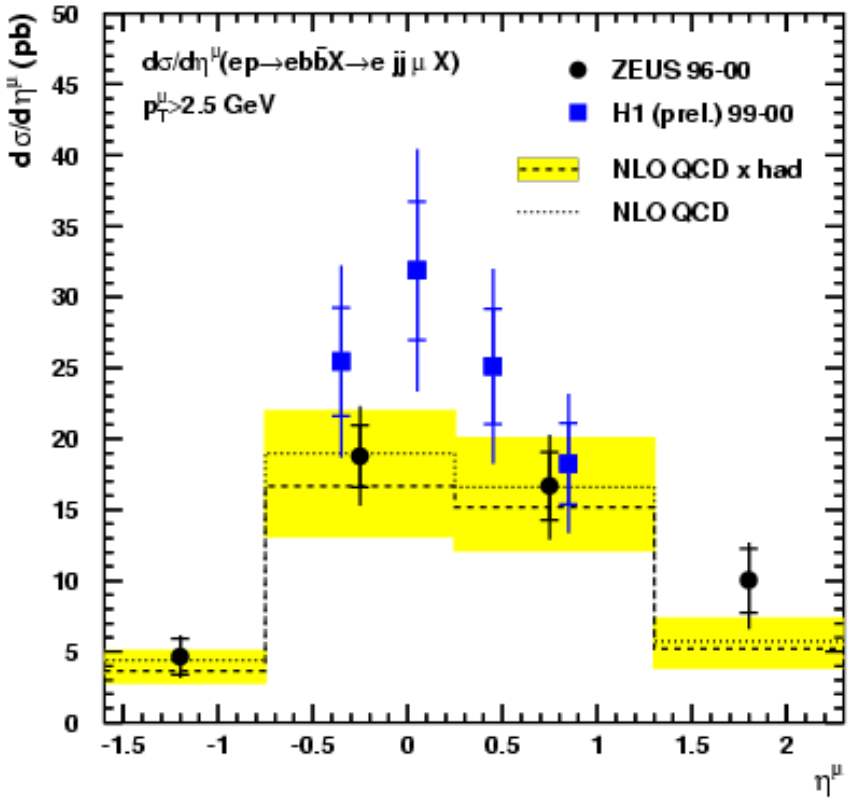
Comparisons in η_μ and $p_{t,\mu}$



Good agreement between data and NLO!

b→μ in photoproduction

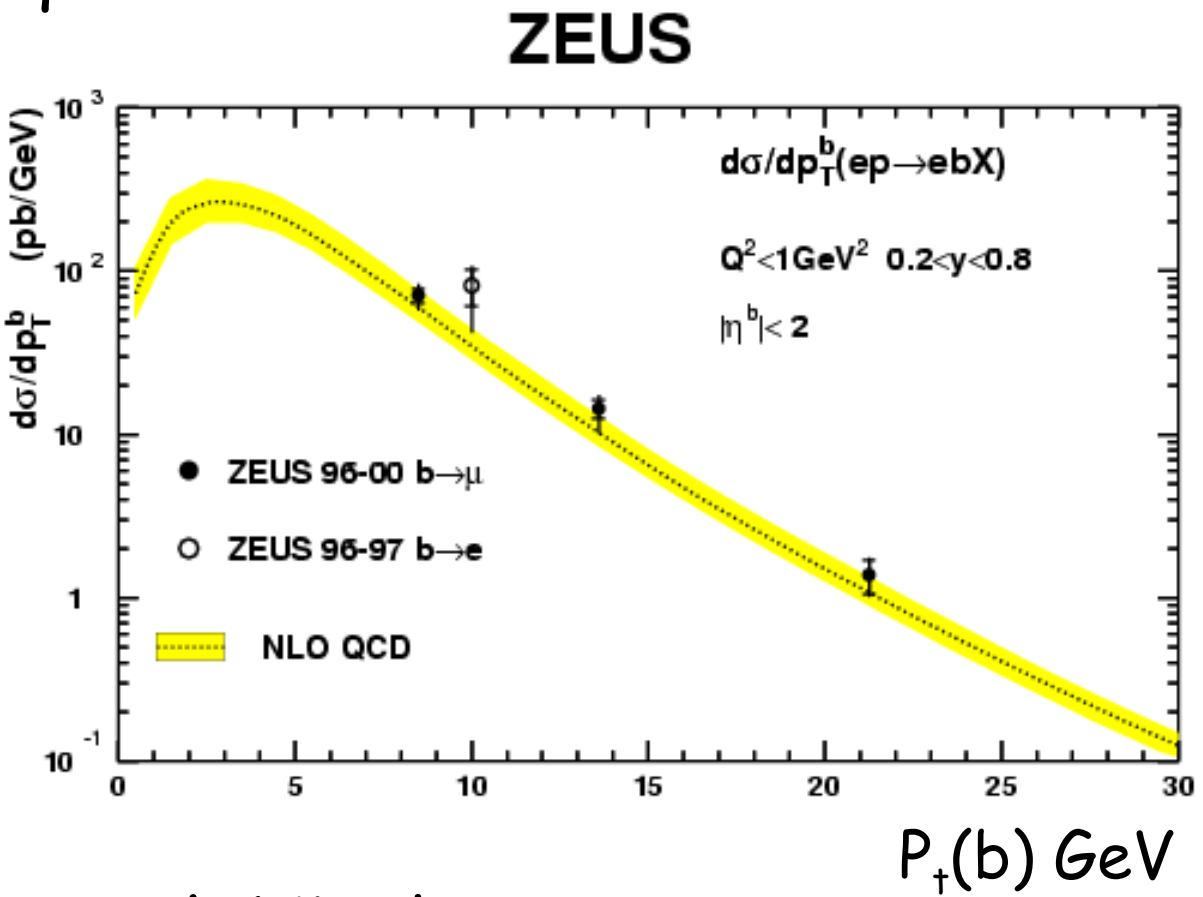
Comparison ZEUS and H1 in η_μ



- H1 and ZEUS in agreement

b→μ in photoproduction

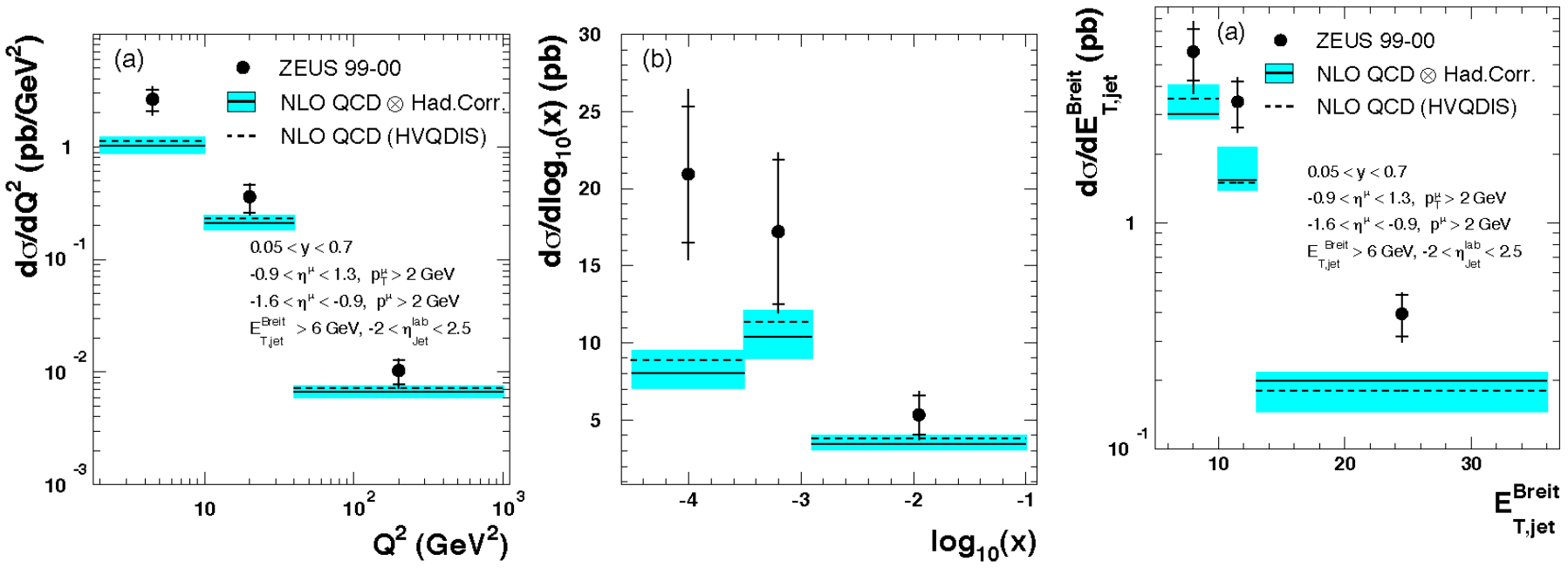
Extrapolation to quark level



Good agreement with NLO!

b→μ in DIS

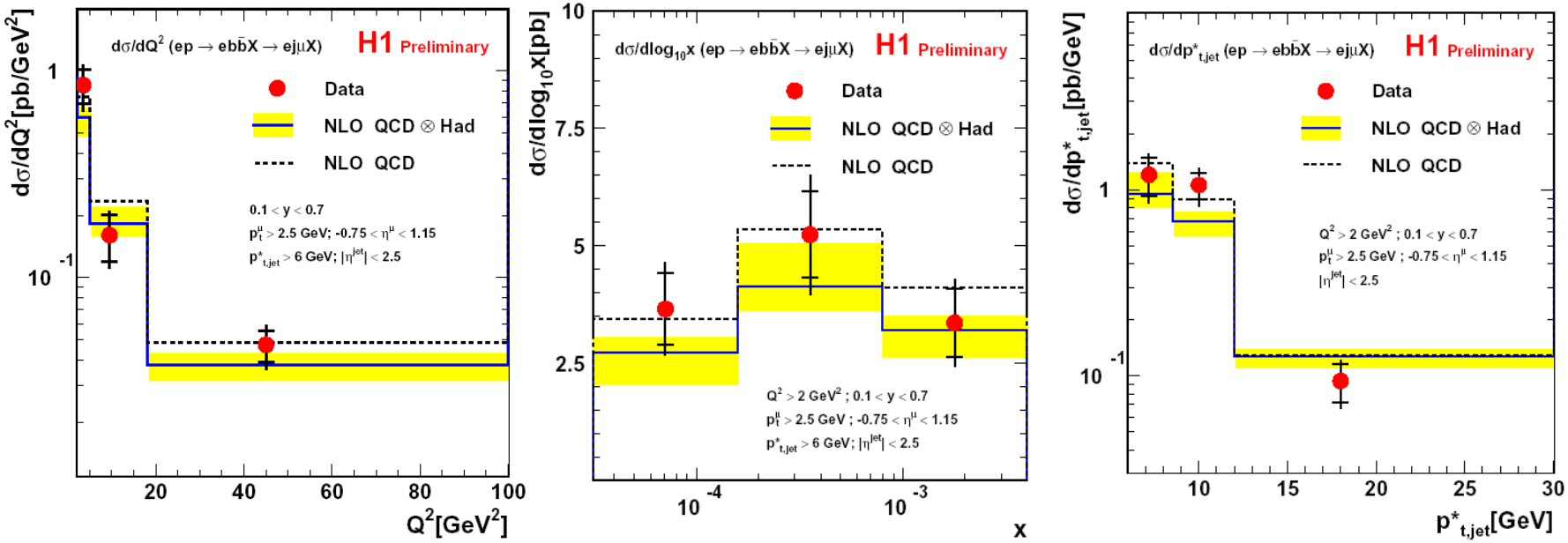
ZEUS cross sections in Q^2, x, E_t*jet



- ZEUS differential measurements generally consistent with NLO QCD calculations
- Largest deviations for low Q^2 , low x, high $E_{t,jet}$

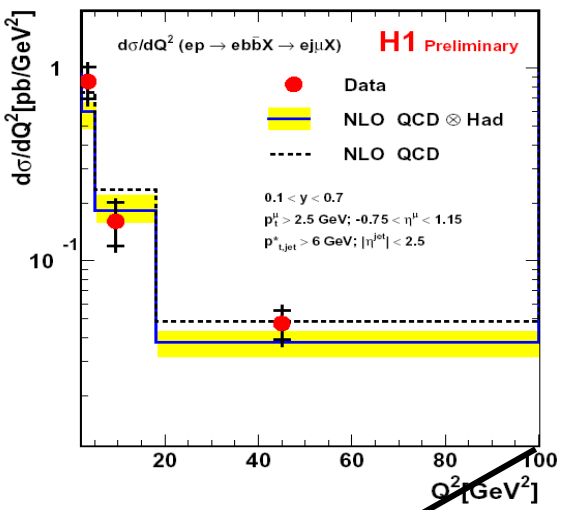
b→μ in DIS

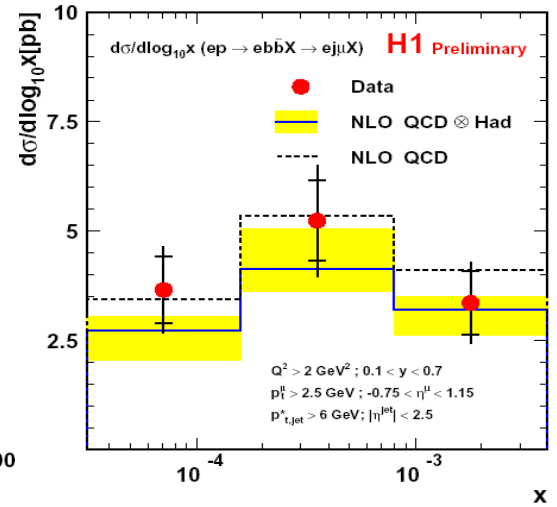
H1 cross sections in Q^2, x, P_t*jet

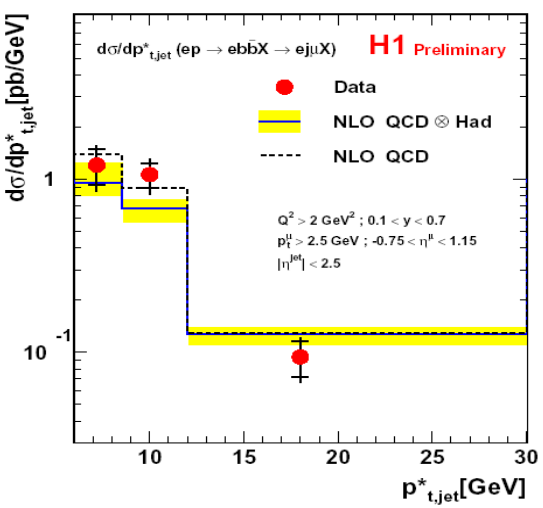


- experimental data in agreement with NLO QCD

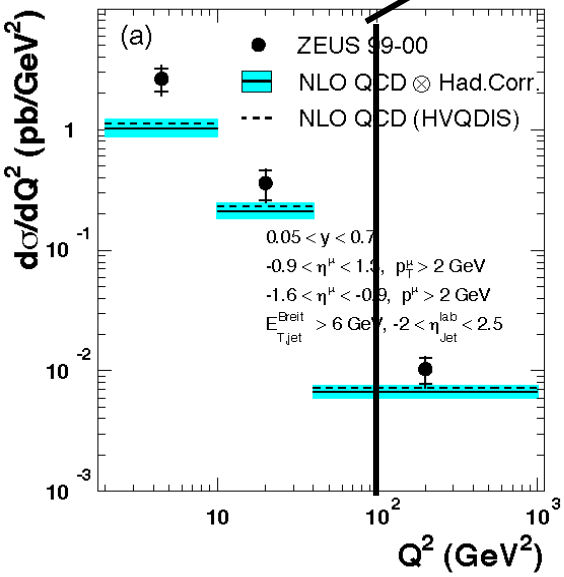
b→μ in DIS

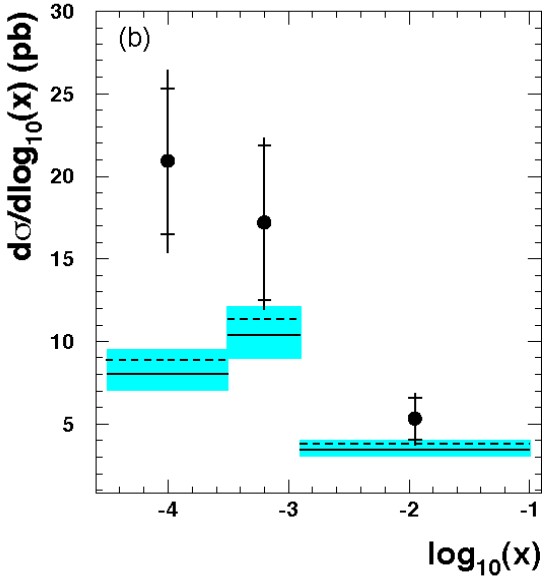


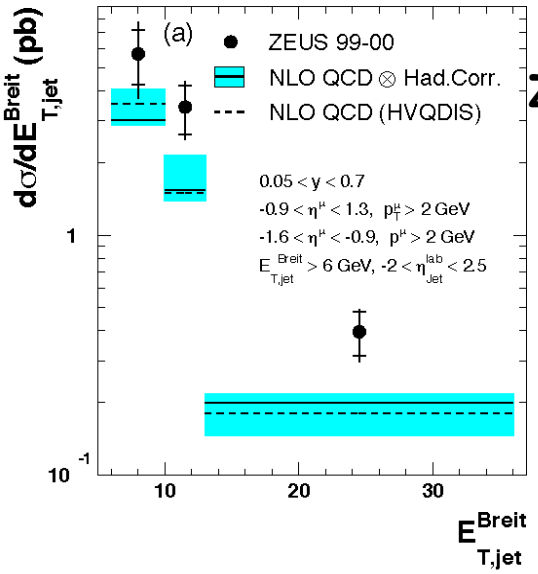




H1





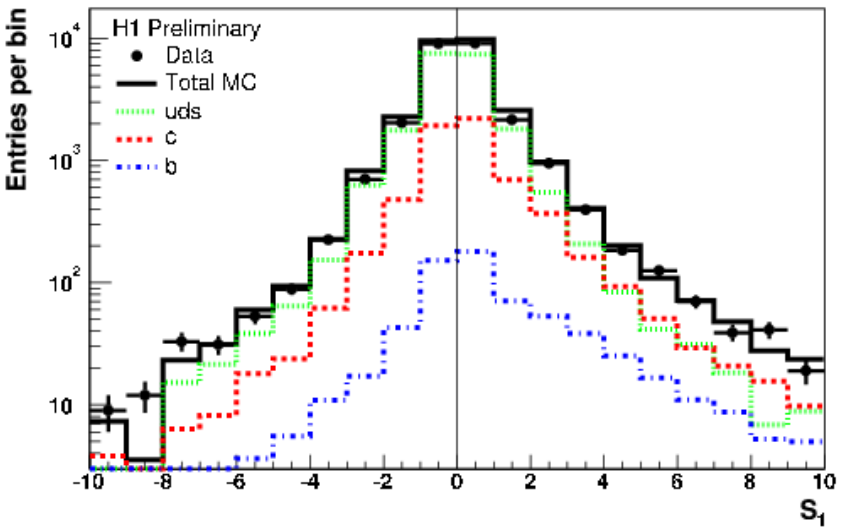


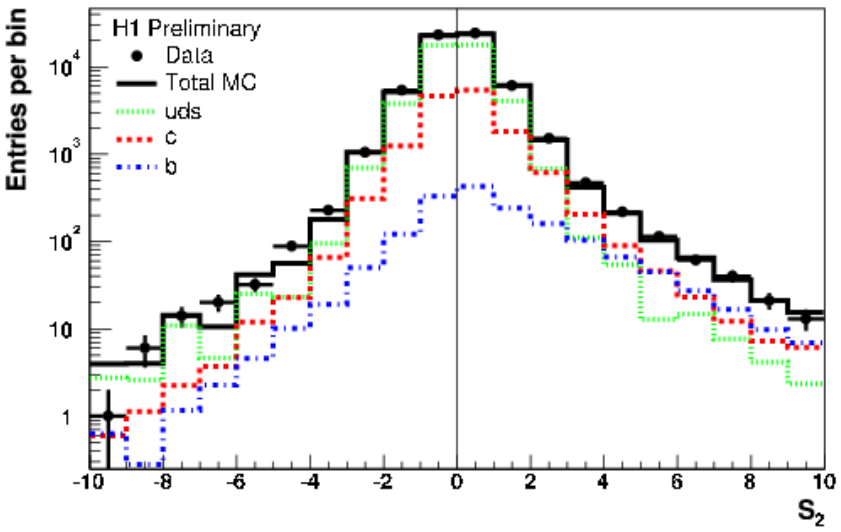
ZEUS

b,c→tracks in DIS

- New method used by H1
  - F_2(cc) and F_2(bb) for HERA I data by "Inclusive secondary vertexing"
  - Selection:
    - high Q^2 (>110 GeV) events. (3 bins in Q^2 and x defined.)
    - Well measured tracks (within jet) with extension to the silicon tracker
- Impact parameter significance: $S=d/s(d)$
  - Select the two highest significance tracks (S_1 and S_2)
- Light, charm and beauty fraction
  - Fit MC shapes for S_1 and S_2 for data in each bin.
  - Extract F_2(cc) and F_2(bb) from measured fractions and inclusive F_2 measurement

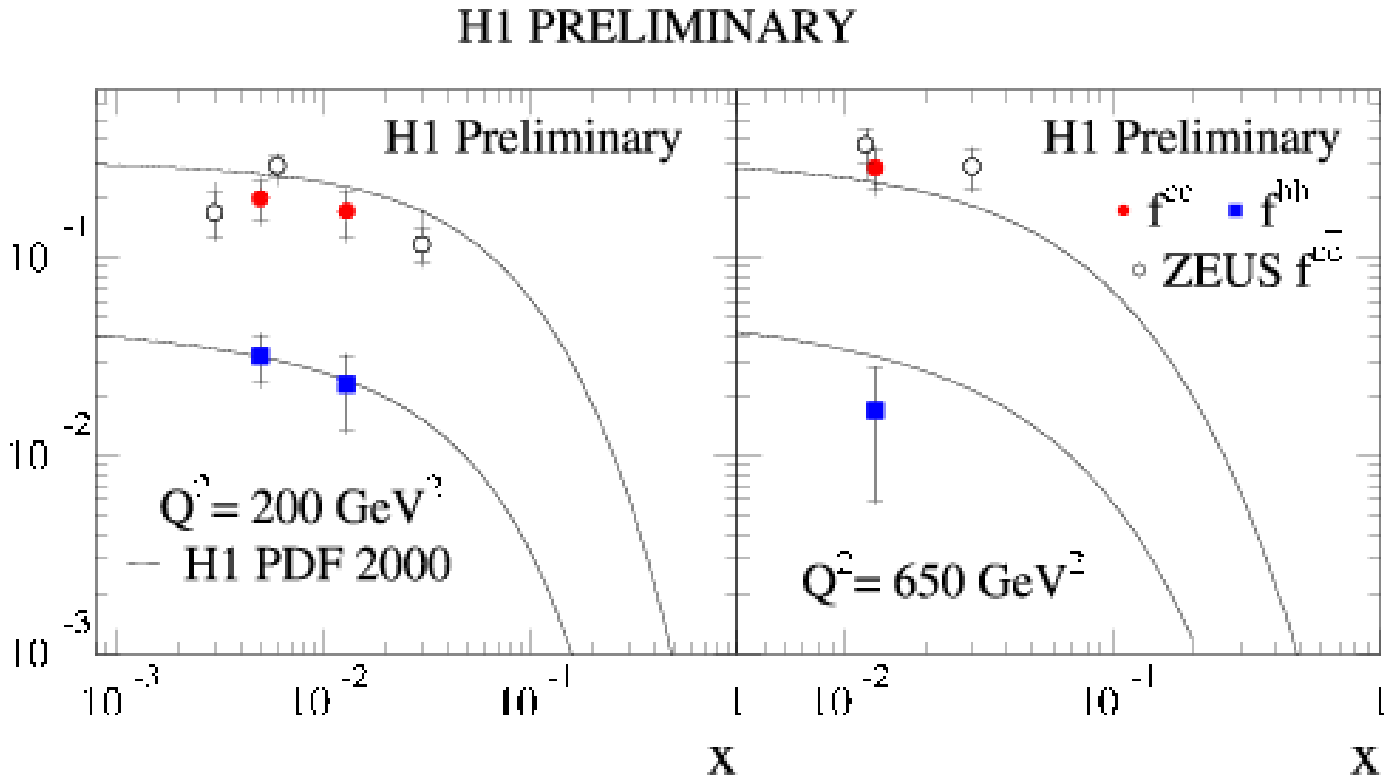
S_1 and S_2 distributions





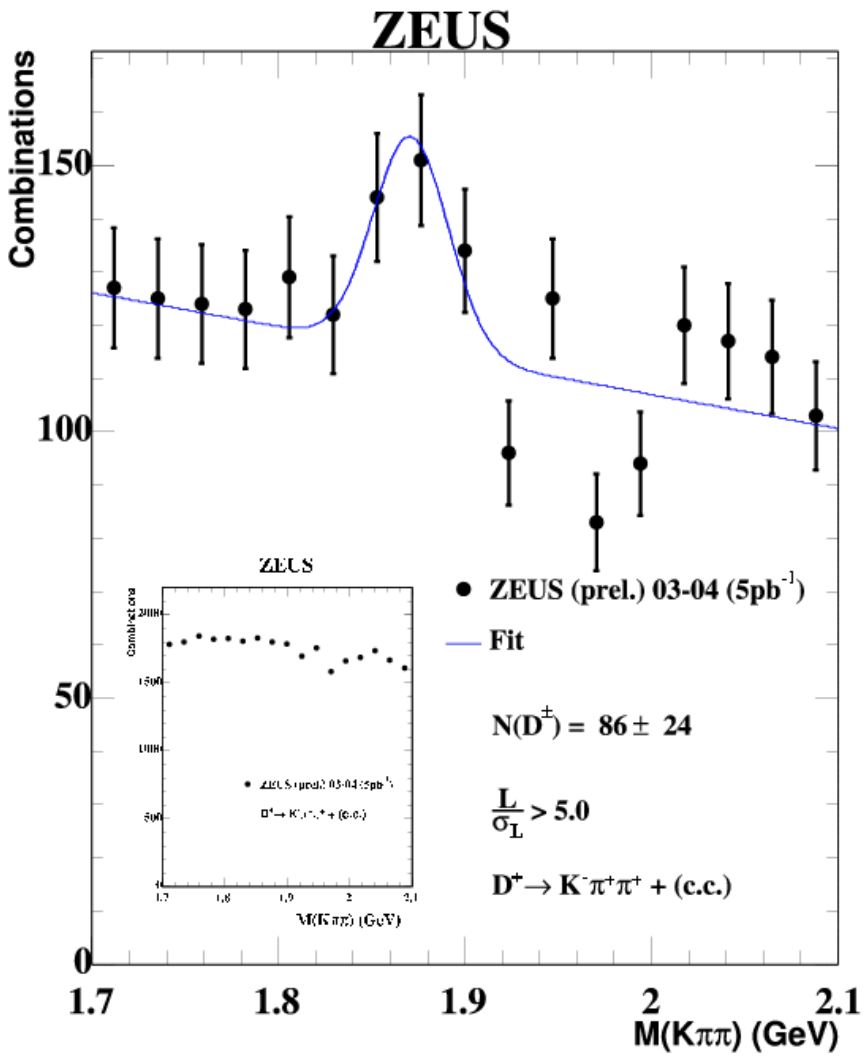
Measurement of $F_2(cc)$ and $F_2(bb)$

- $F_2(cc)/F_2$ and $F_2(bb)/F_2$



Agree with the ZEUS D* measurements and prediction from PDFs

First look to new ZEUS Data



- $D^+ \rightarrow K^-\pi^+\pi^+$
- D^+ invariant mass signal measured with MVD (microvertex detector) fitted tracks
- Apply decay length significance cut > 5

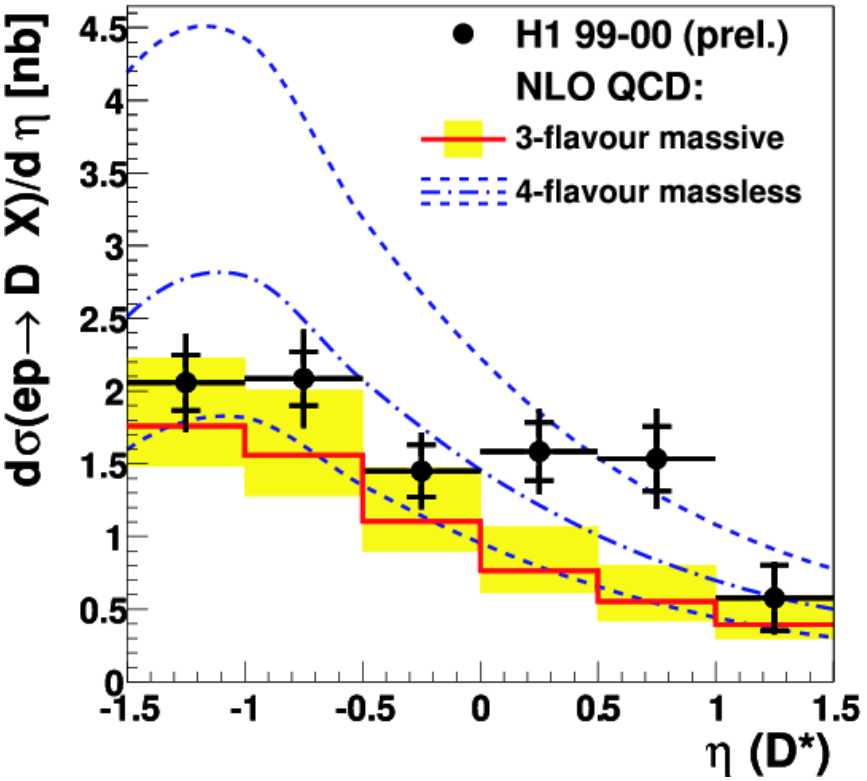
Conclusions and outlook

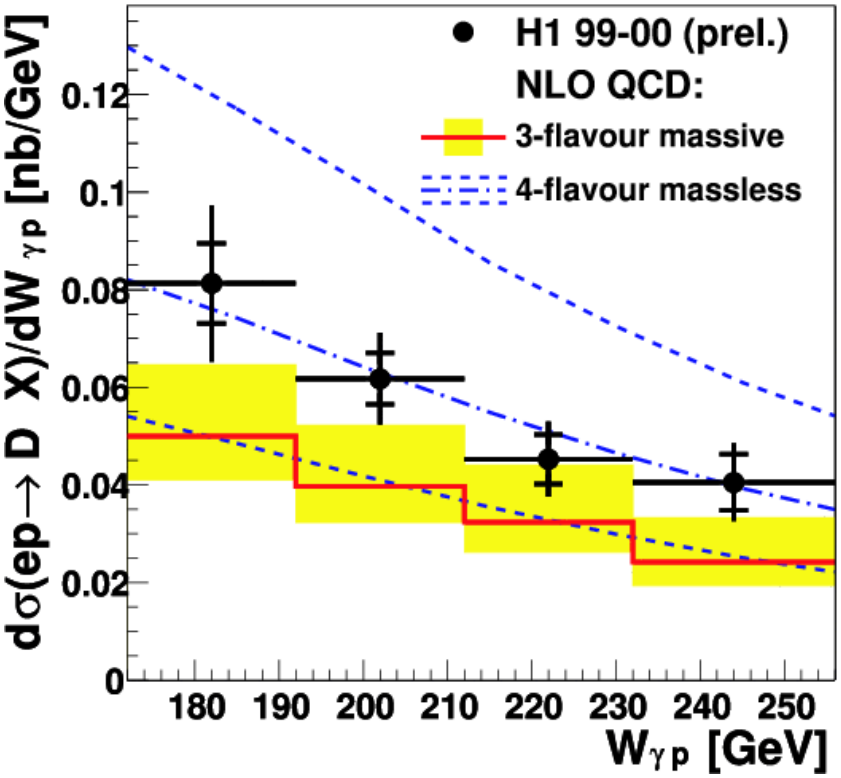
- HERA I has made substantial contributions to
  - Understand the production of charm and beauty
  - Improve our knowledge about the structure of the proton and the photon
- Uncertainties of the measurements and theoretical calculations are still large
  - More precise calculations are welcome and needed
  - HERA-II and the improved H1 and ZEUS detector will allow even deeper insight into these important topics of QCD.
- More interesting heavy flavour physics from HERA coming in the future.
  - HERA-II has really started since October 2003!

Heavy quarks as a tool

- The HERA experiments use charm and bottom signatures as a tool to study:
  - structure of resolved photons
  - Hard QCD scatter
  - Structure of the proton
  - Fragmentation

D* photoproduction



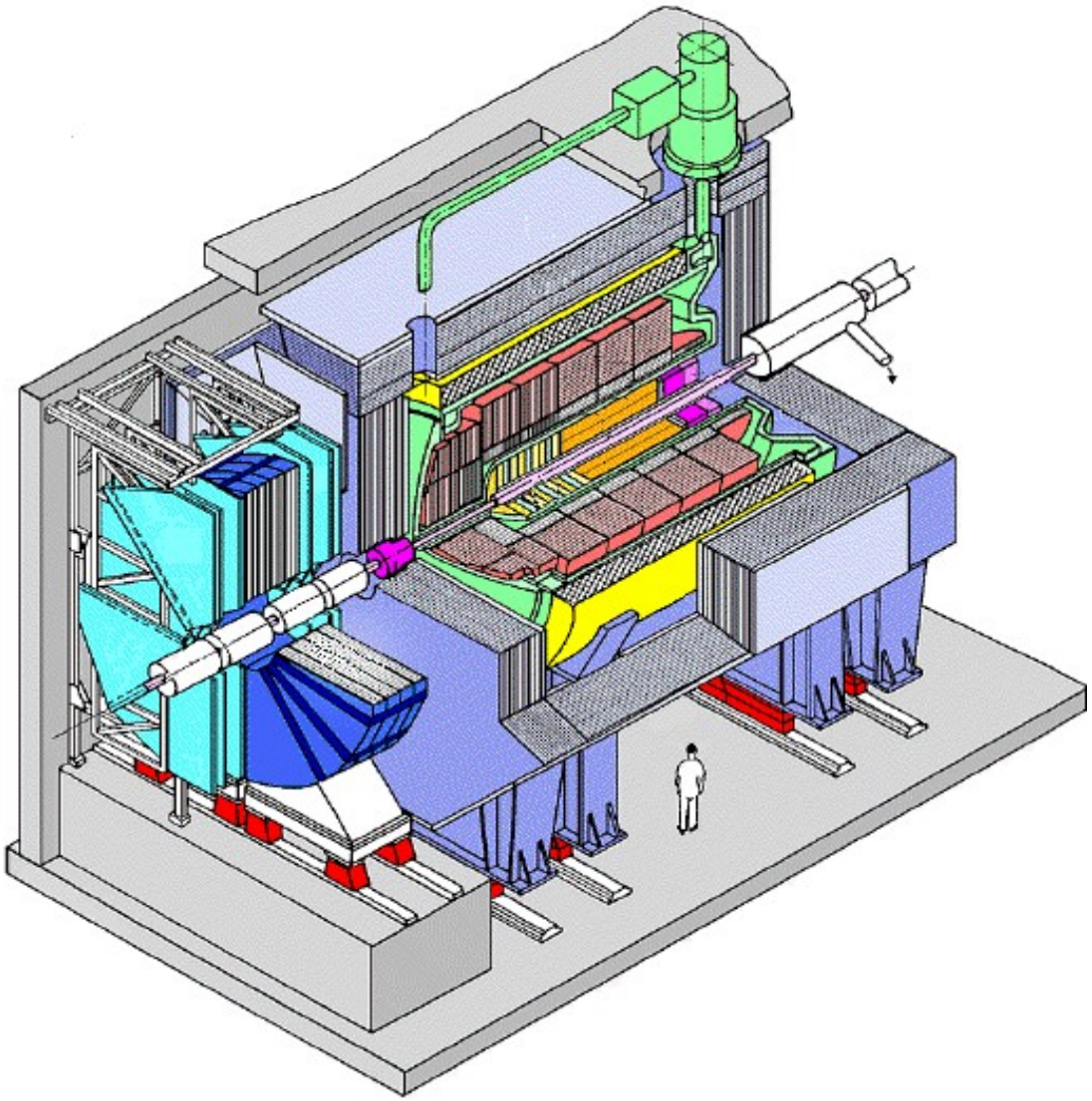


NLO Calculations: large theoretical uncertainties

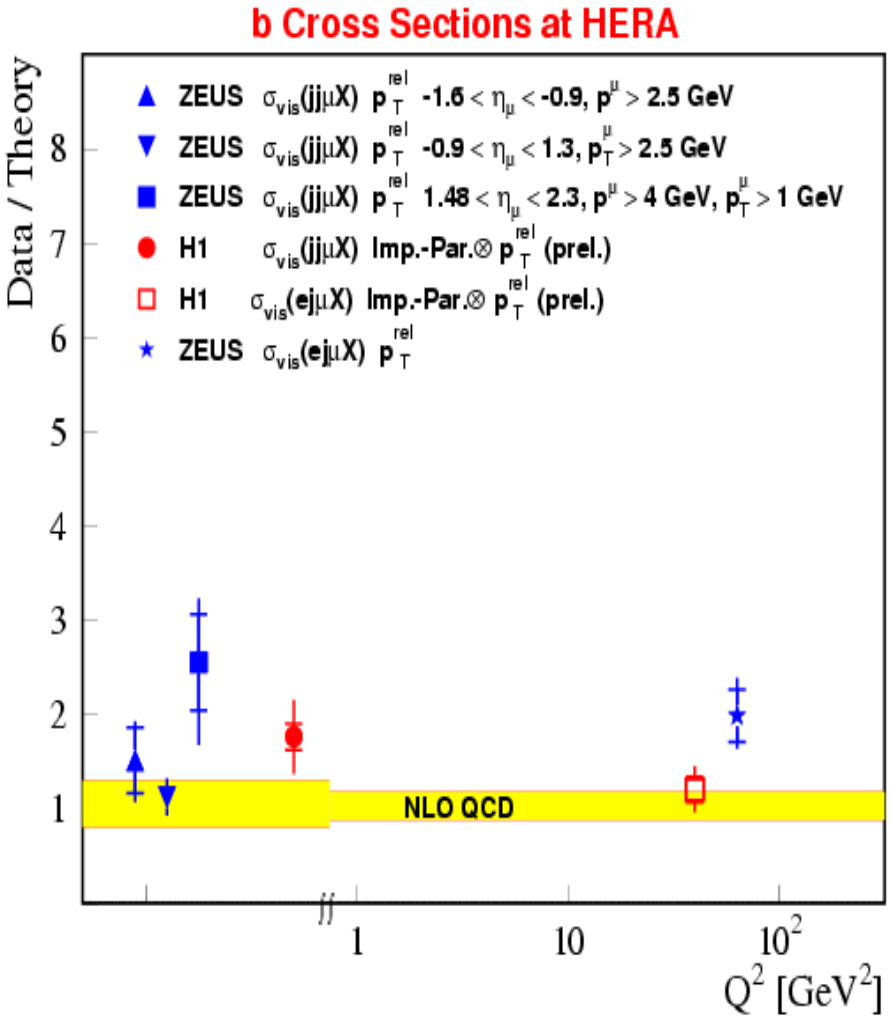
$W_{\gamma p} = (\mathbf{p}+\mathbf{q})^2$

➔ Not yet possible to distinguish between different charm treatments

The H1 Detector



Visible b cross sections at HERA



Note: Comparison of measurements in different phase space

D^+ candidate in DIS