Heavy Flavour production at HERA

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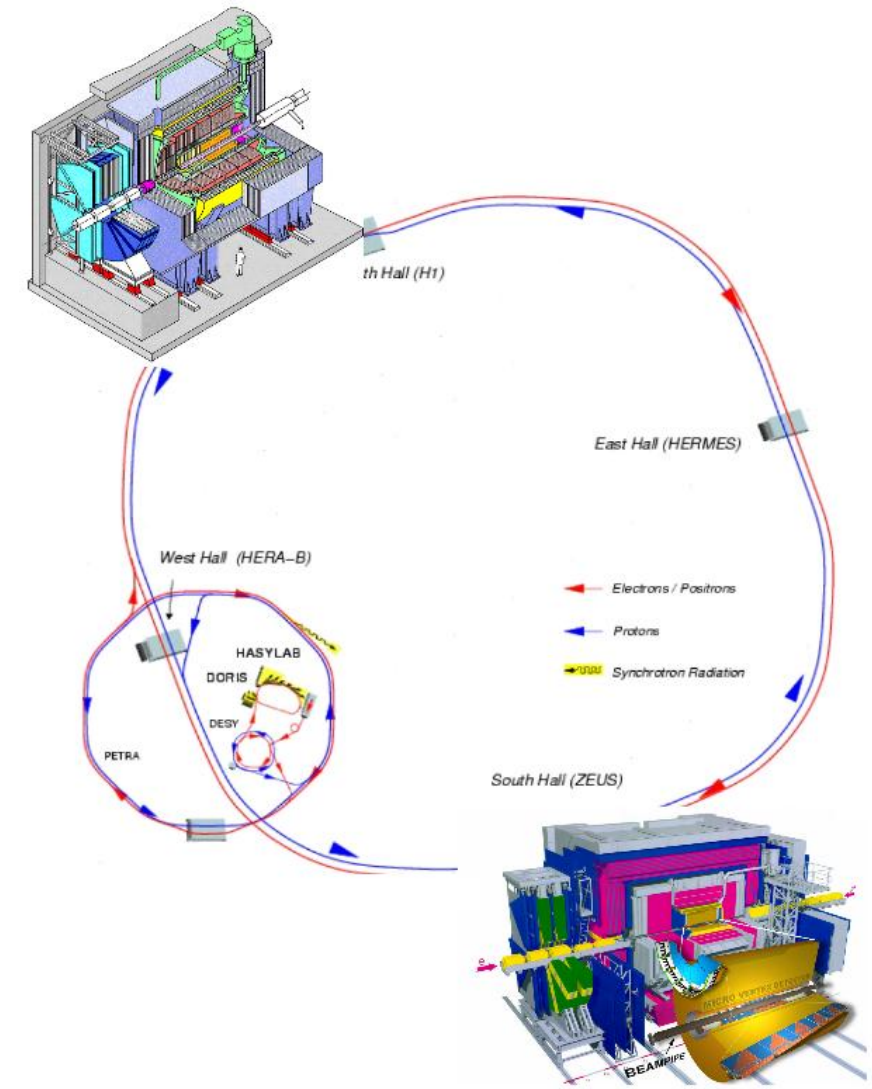
on behalf of the H1 and ZEUS collaborations

DESY

Rencontres de Moriond: QCD and Hadronic Interactions
17-24 March 2007

Outline

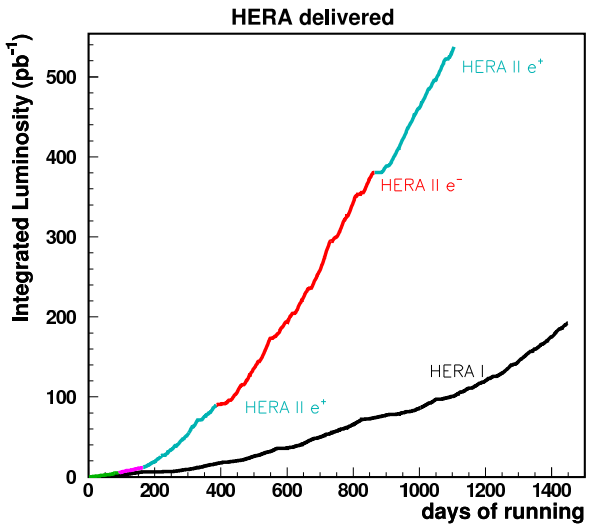
The HERA Collider



- E_p =920 GeV, E_e =27.6 GeV $\longrightarrow$ $\sqrt{s}$ = 320 GeV

Luminosity collected by H1/ZEUS

- 96/00(HERA I): $e^{\pm}p \sim 130 pb^{-1}$
- 03/07(HERA II): $e^{\pm}p \sim 380 pb^{-1}$

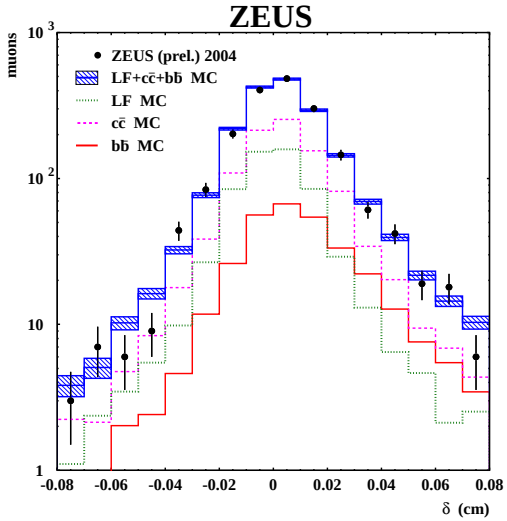


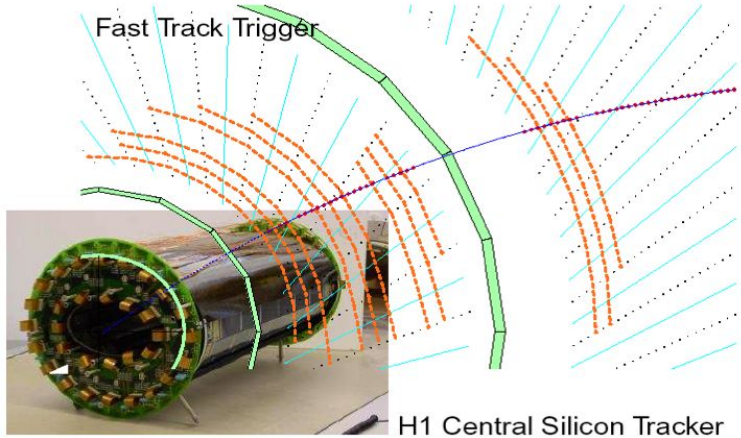
End of HERA program: June 2007

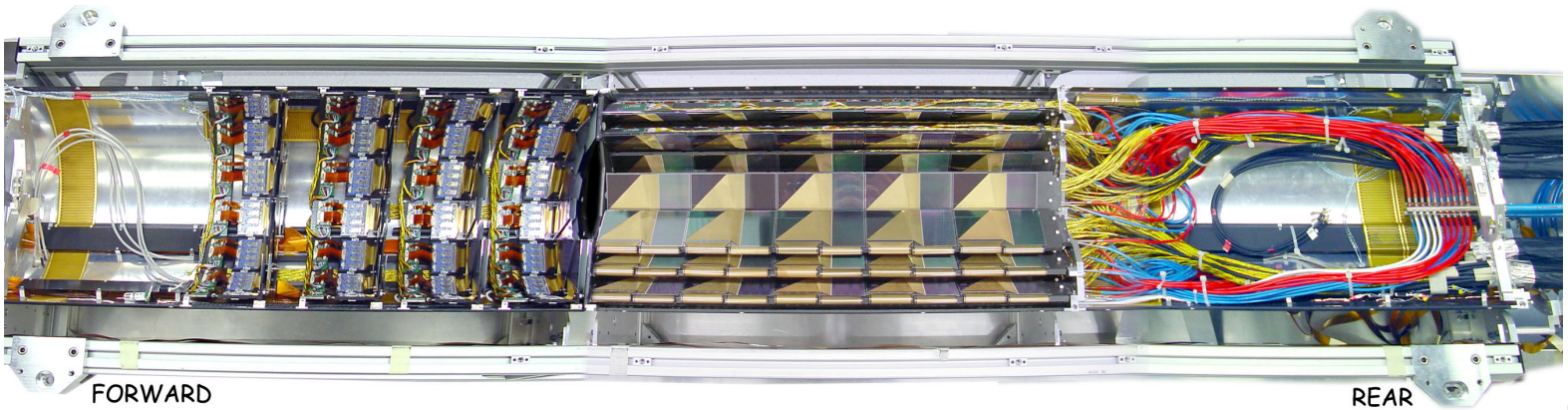
(last 3 months low energy running $\longrightarrow$ F_L)

Most relevant upgrades for HFL production:

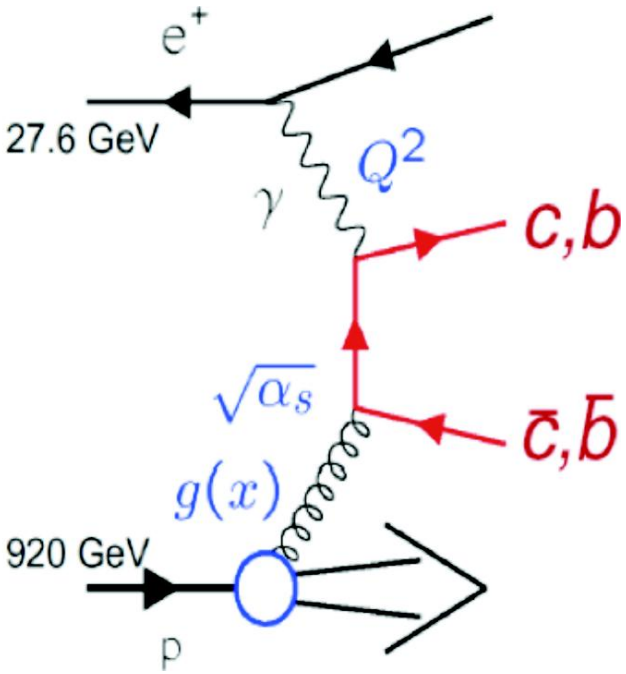
- H1 Fast Track Trigger
- ZEUS Micro Vertex Detector (MVD)







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



Direct sensitivity to the gluon content of the proton

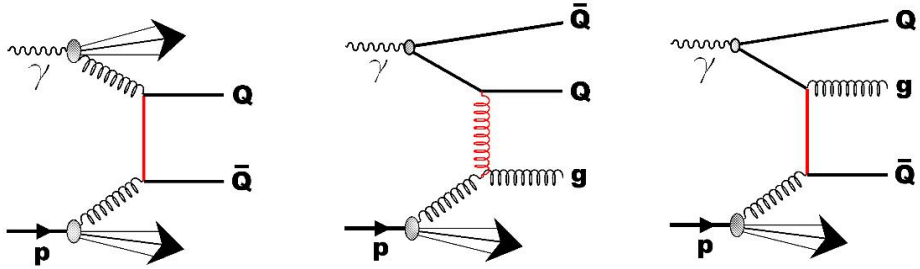
Kinematic variables:

- $Q^2 = -q^2$ photon virtuality, squared momentum transfer
- $x = \frac{Q^2}{2pq}$ Bjorken scaling variable

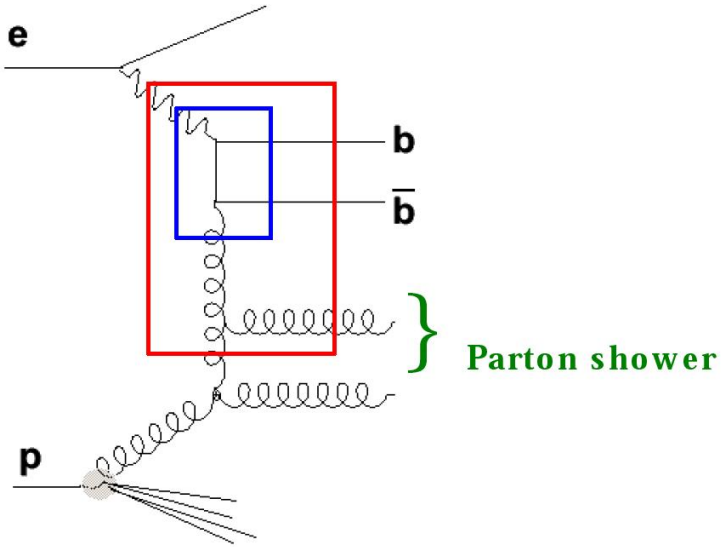
Multiple scales involved:

- $M_b \sim 5$ GeV, $M_c \sim 1.4$ GeV
- $Q^2 \sim 0$ GeV^2 (photoproduction - γp)
- $Q^2 >\sim 1$ GeV^2 (deep inelastic scattering - *DIS*)
- $P_t^{c,b}$ few GeV

Powerful tool for testing *p* structure and the applicability of *pQCD*



NLO and MC



Prediction:		Describes:
LO+PS: PYTHIA, HERWIG	(DGLAP)	γp
RAPGAP	(DGLAP)	DIS
CASCADE	(CCFM)	γp&DIS
NLO: FMNR		γp
HVQDIS		DIS

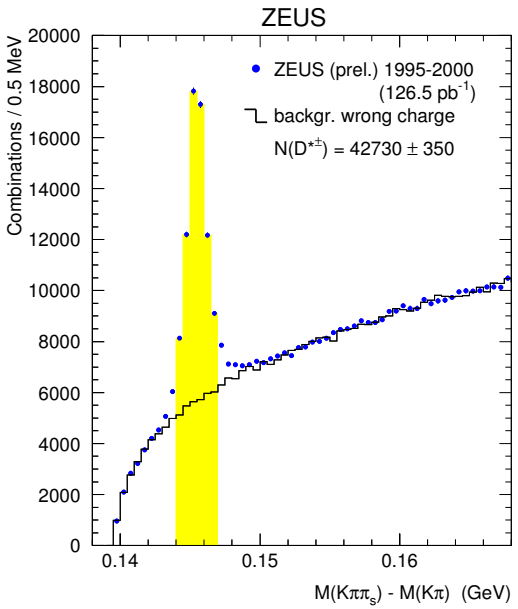
MONTE CARLO

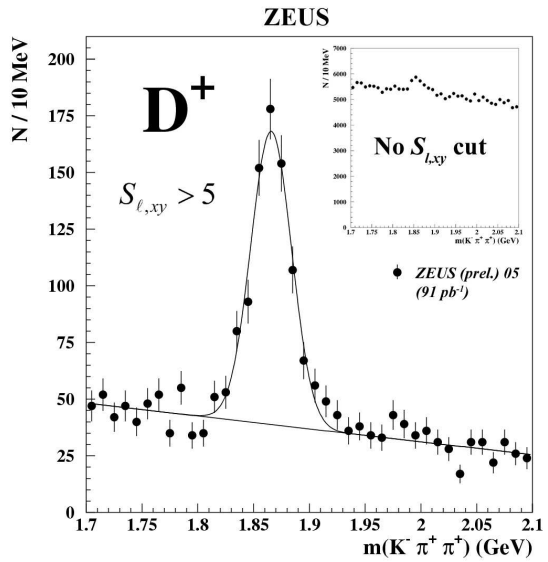
- leading order + parton shower models available, including flavour excitation, DGLAP evolution (PYTHIA, HERWIG)
- CCFM evolution with k_t factorisation (CASCADE)

THEORETICAL CALCULATIONS

- full NLO calculation (FMNR, HVQDIS) available
- massive scheme FFNS (heavy quark dynamically generated in the hard process)

Charm tagging

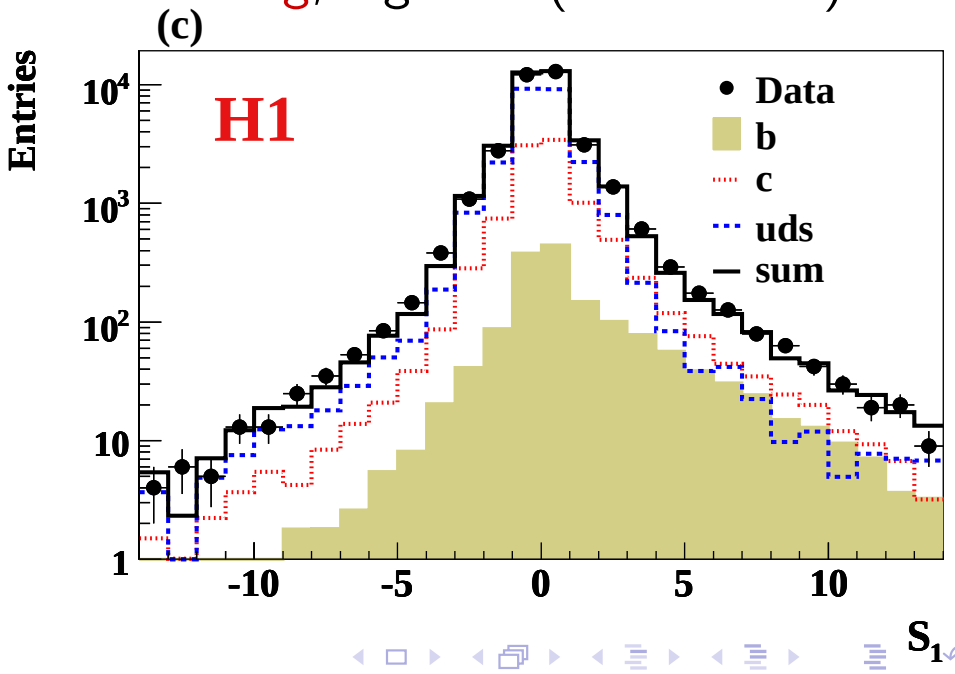




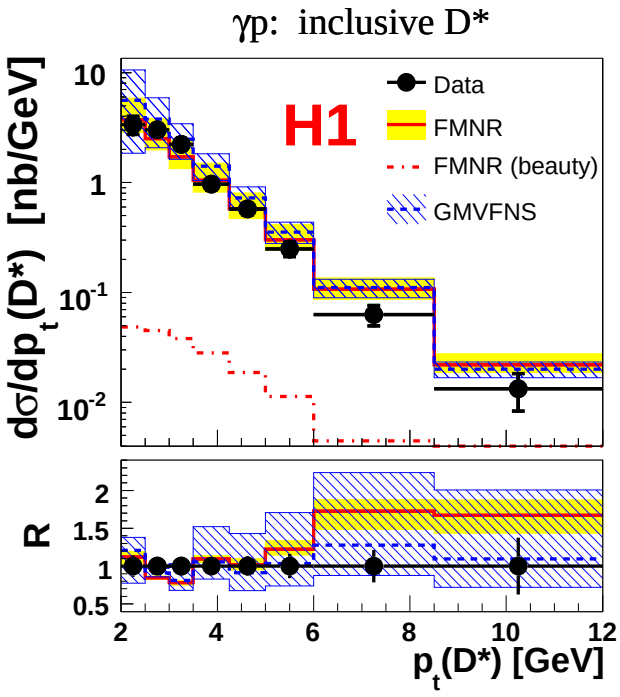
HERA is a charm factory!

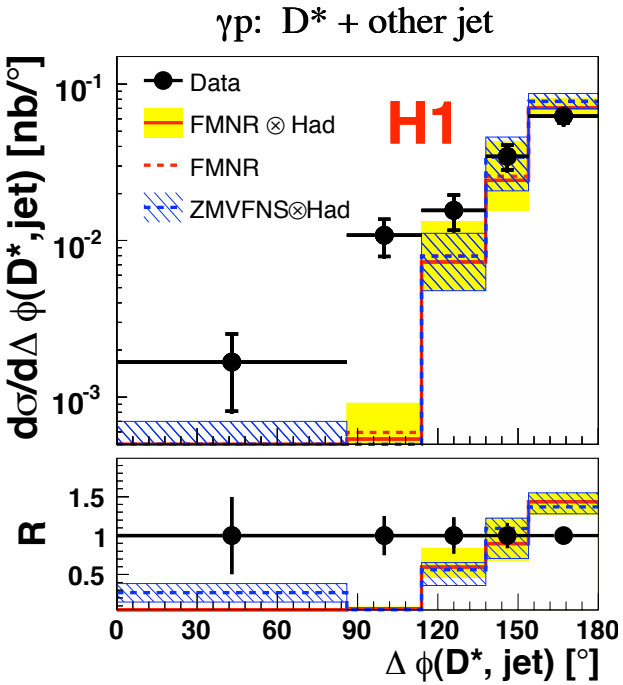
$$\sigma_{uds} : \sigma_{charm} : \sigma_{beauty} \sim 2000 : 200 : 1$$

- meson tag, e.g. D^* golden channel: $D^* \to K^-\pi^+\pi^+$
- lifetime tag, e.g. D^+ (or inclusive)



Charm in PHP





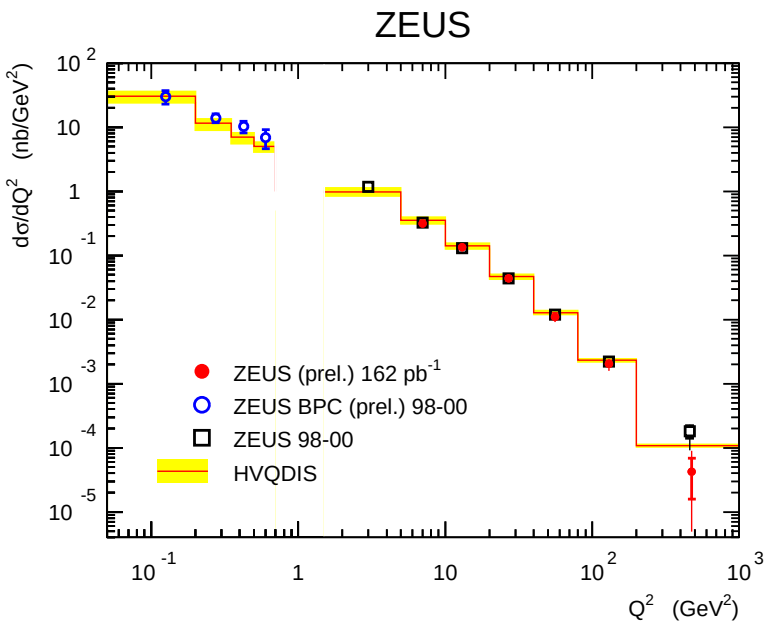
CTEQ6M and GRV-GHO used as proton and photon PDFs.

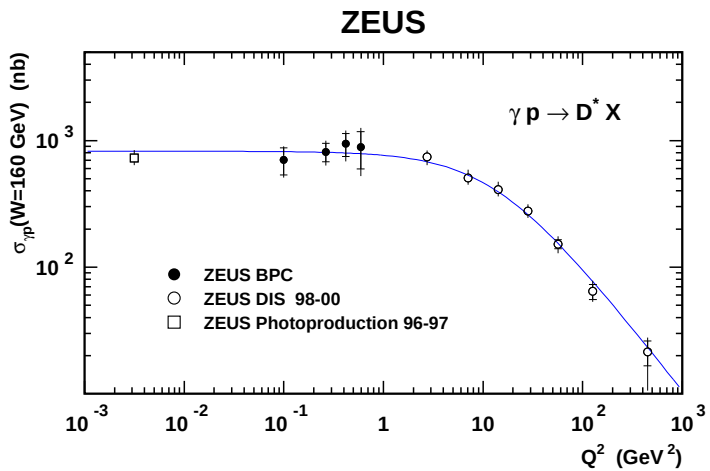
- H1 updated D^* PHP results: 5x statistics (51 pb^{-1})
- Explored region extended
  $\rightarrow$ P_T^{jet} lowered to 3 GeV
- Theoretical uncertainties of GMVFNS larger than data

- Available NLO underestimate significantly the xsec in $\Delta\phi(D^*, jet) < 120^\circ \rightarrow$ higher order contributions

GMVFNS (General-mass variable-flavour-number scheme), ZMVFNS (Zero-mass variable-flavour-number scheme).

Charm in DIS





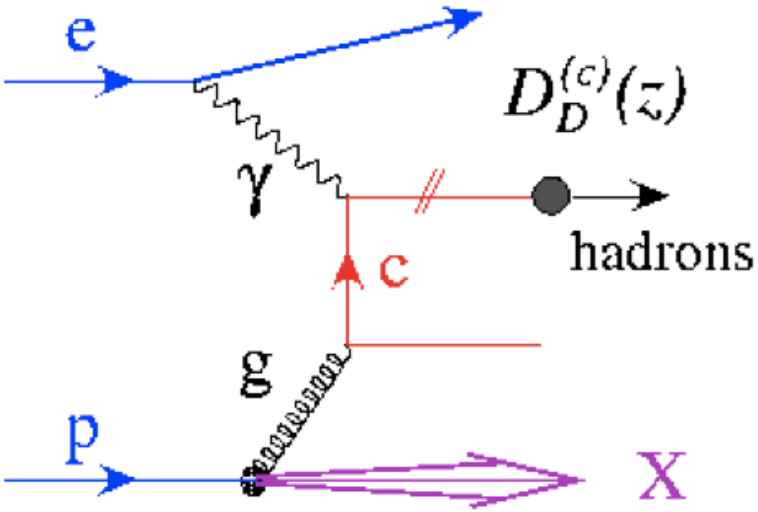
- Data described by NLO QCD over 5 order of magnitude.
- current HERA II results (162 pb^{-1}) comparable precision
- First measurement in transition region between PHP and DIS (DESY-07-012)
  Low Q^2 values reached by measuring the scattered electron in Beam Pipe Calorimeter.

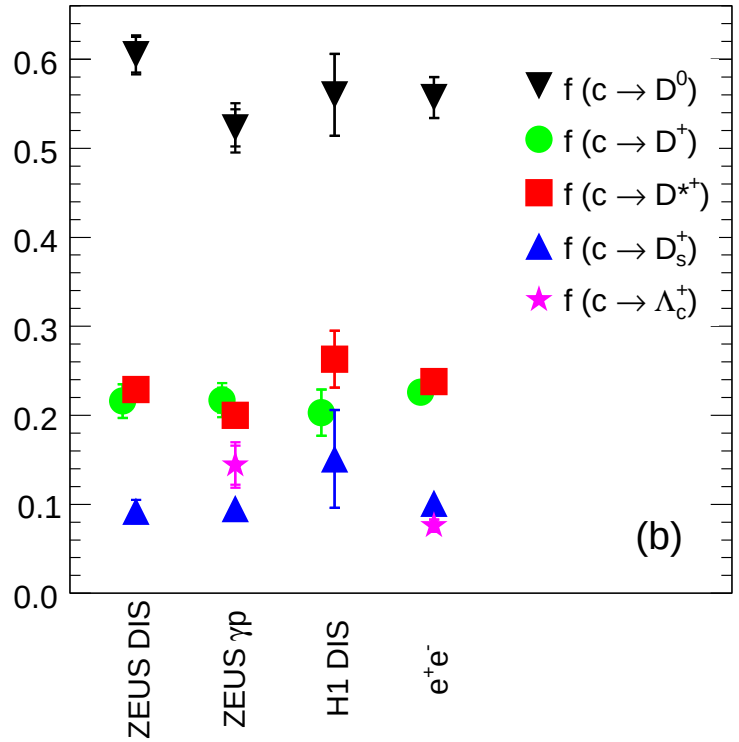
BPC results

- $0.05 < Q^2 < 0.7$ GeV^2
- fit $\sigma(Q^2) = SM^2/(Q^2 + M^2)$, $\rightarrow M^2 = 13 \pm 2$ GeV^2, ($M^2 \sim 4m_c^2$)

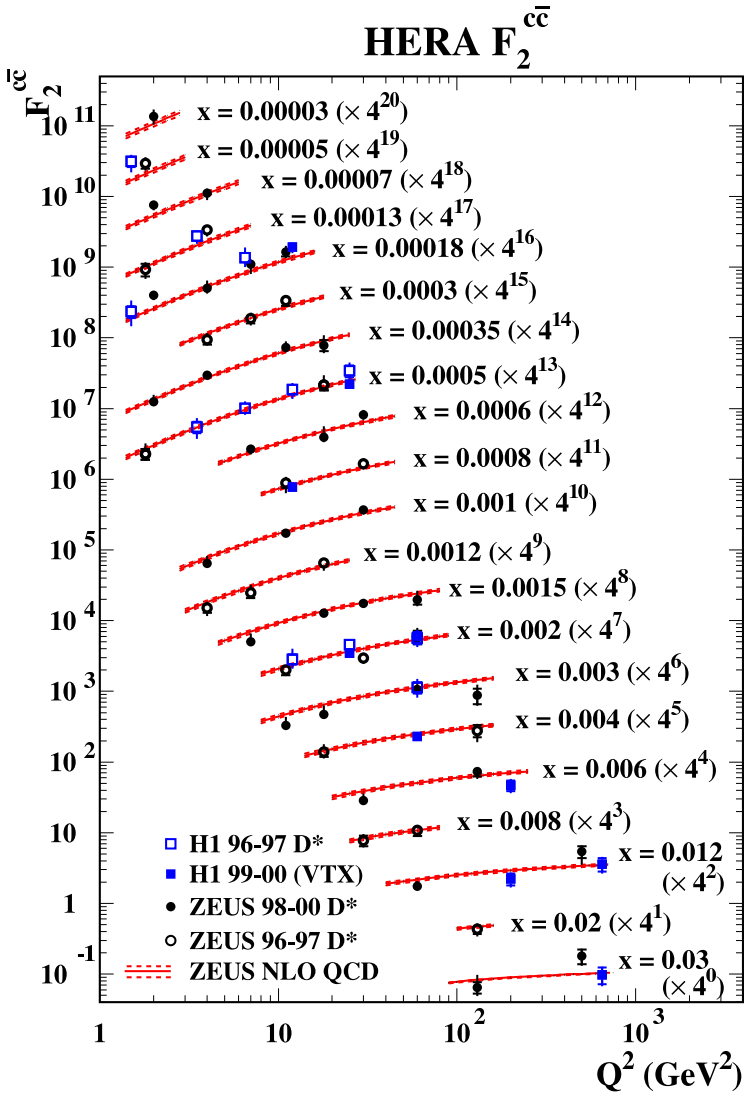
Fragmentation

The production cross section of each charmed meson can be measured and the fragmentation fractions of charm into each meson can be estimated





Measurements at HERA agree with e^+e^-: charm fragmentation fractions do not depend on the hard subprocess (universality)



$F_2^{c\bar{c}}$ related to double differential cross section:

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

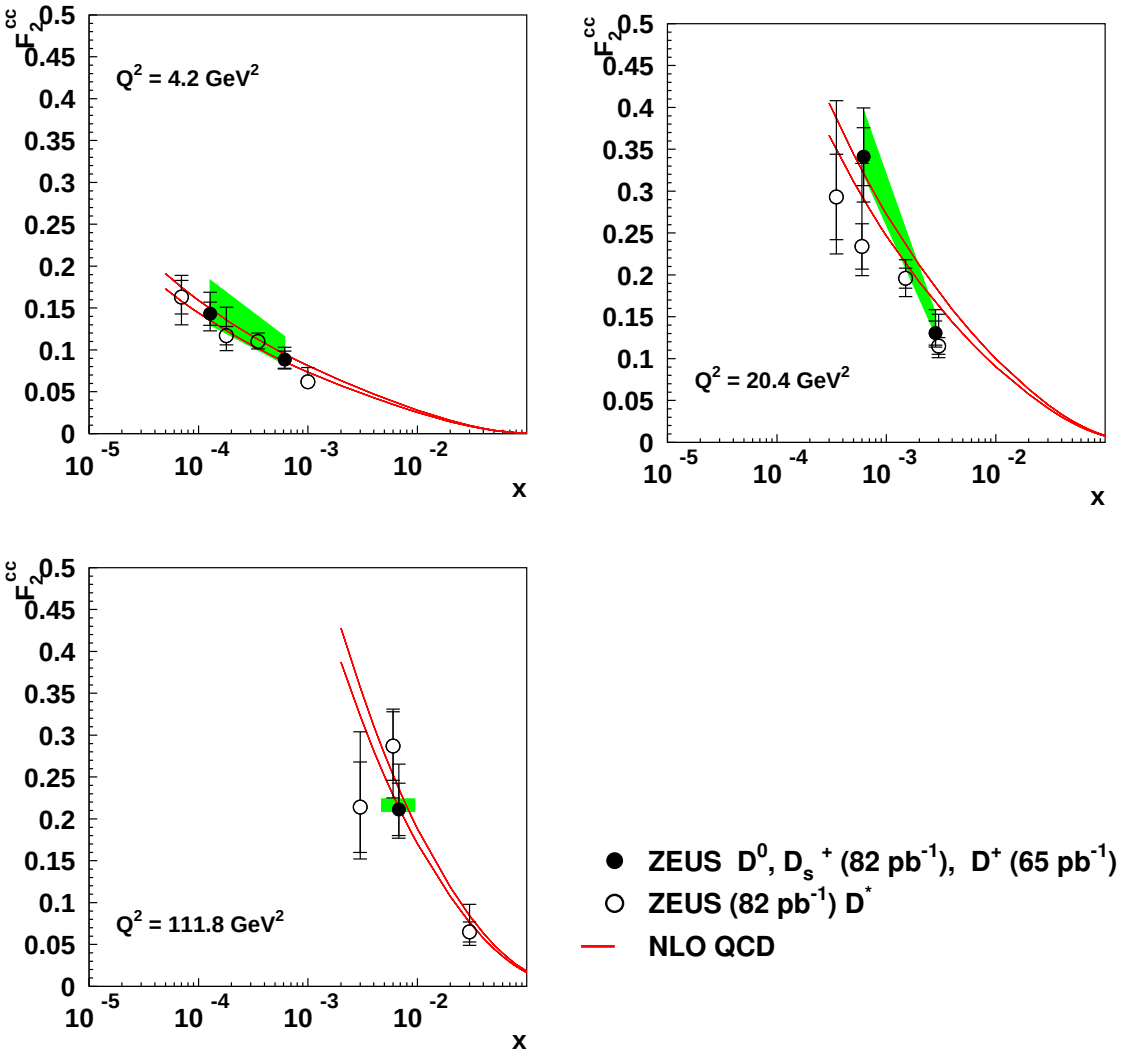
- $F_L^{c\bar{c}}$ neglected (y small)
- the measured $F_2^{c\bar{c}}$ unfolded using a ratio of measured and theory cross sections to $F_2^{c\bar{c}}$ thus:

$$F_{2,meas}^{c\bar{c}}(x_i,Q_i^2) = \frac{\sigma_{i,meas}(ep\to D^*X)}{\sigma_{i,theo}(ep\to D^*X)}F_{2,theo}^{c\bar{c}}$$

- Recent H1 measurement performed via lifetime tagging
- Scaling violation visible in $F_2^{c\bar{c}}$ evolution

$F_2^{c\bar{c}}$ cont'd

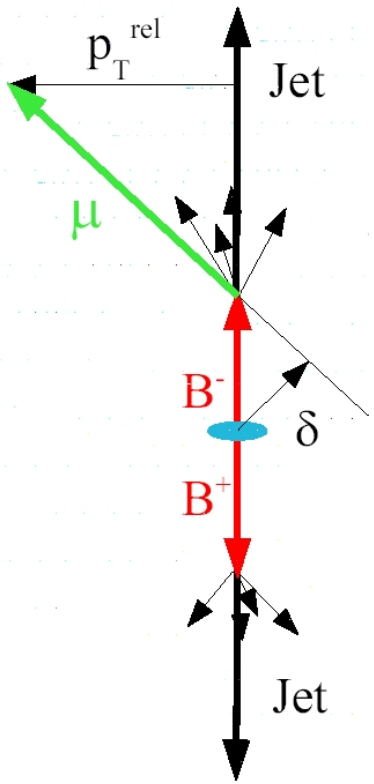
ZEUS

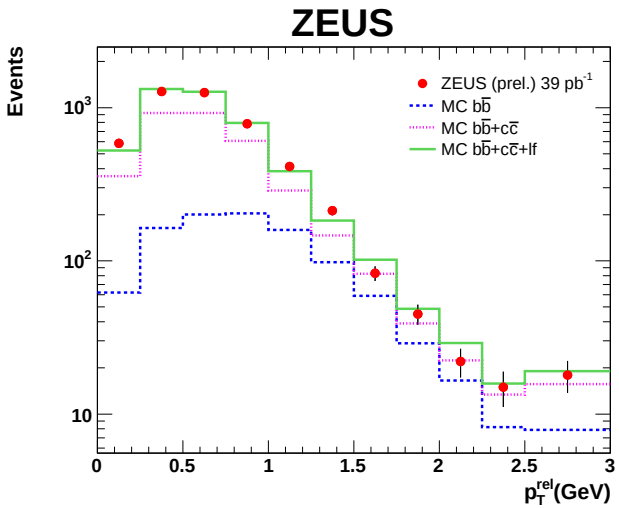


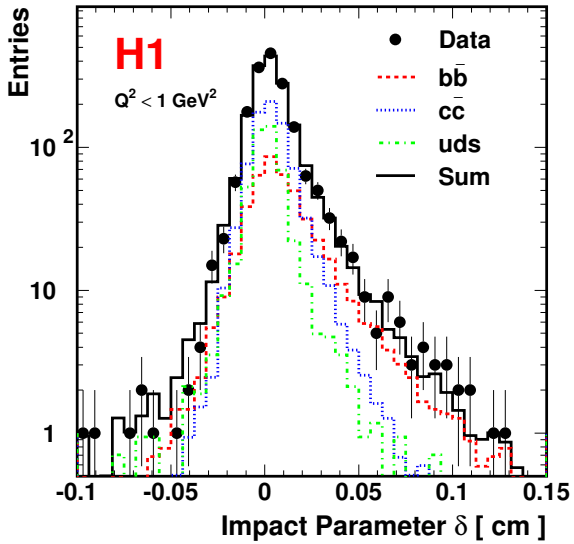
- $F_2^{c\bar{c}}$ measurement using D^0, D^+ and D_s comparable with those using D^*
- Predictions describe data well for all Q^2 and x

Beauty tagging

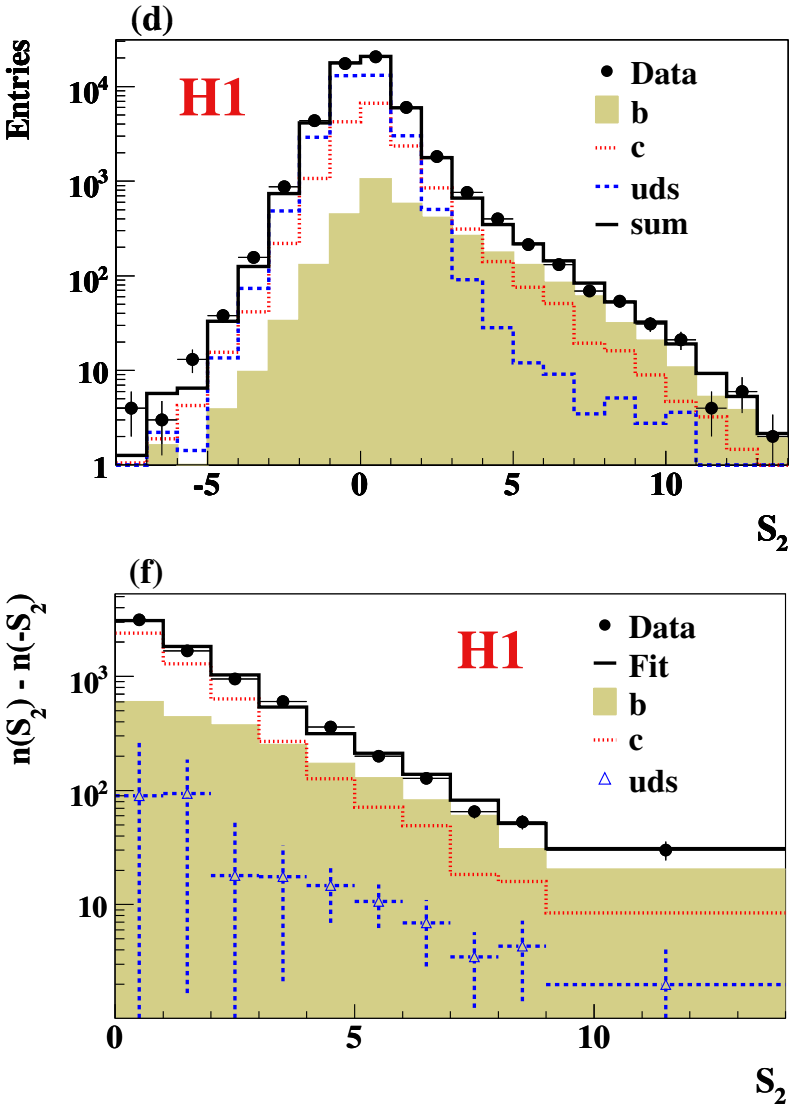
- Large B mass: P_t of muon relative to the jet axis (P_T^{rel})
- Long B lifetime: muon impact parameter (δ)







lifetime tag

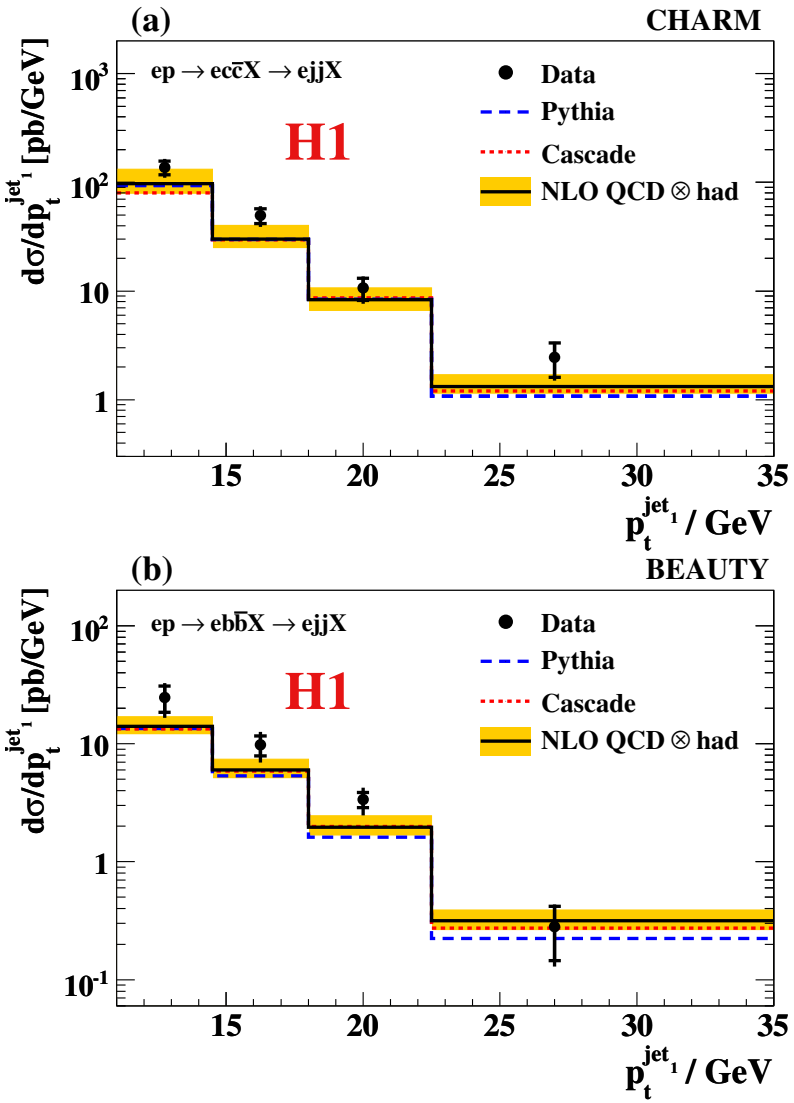


- Inclusive PHP sample (all tracks with $P_t > 500$ MeV)
- Significance of signed impact parameter: $S = \frac{\delta}{\sigma(\delta)}$

  $S1$ (1 track associated to jet) significance of the track

  $S2$ ($\geq$ 2 tracks associated to jet) second highest significance $\longrightarrow$ enhanced sensitivity to b
- extract b anc c fraction from fit to subtracted significance distributions

ADVANTAGE: higher statistics w.r.t. D^* or lepton analysis



First simultaneous measurement of Charm and Beauty in PHP.
Jet transverse momentum extended to larger values w.r.t. previous measurements.

- PYTHIA and CASCADE (LO+PS) : good shape description but generally data higher in normalisation.
- pQCD NLO prediction consistent both in shape and normalization

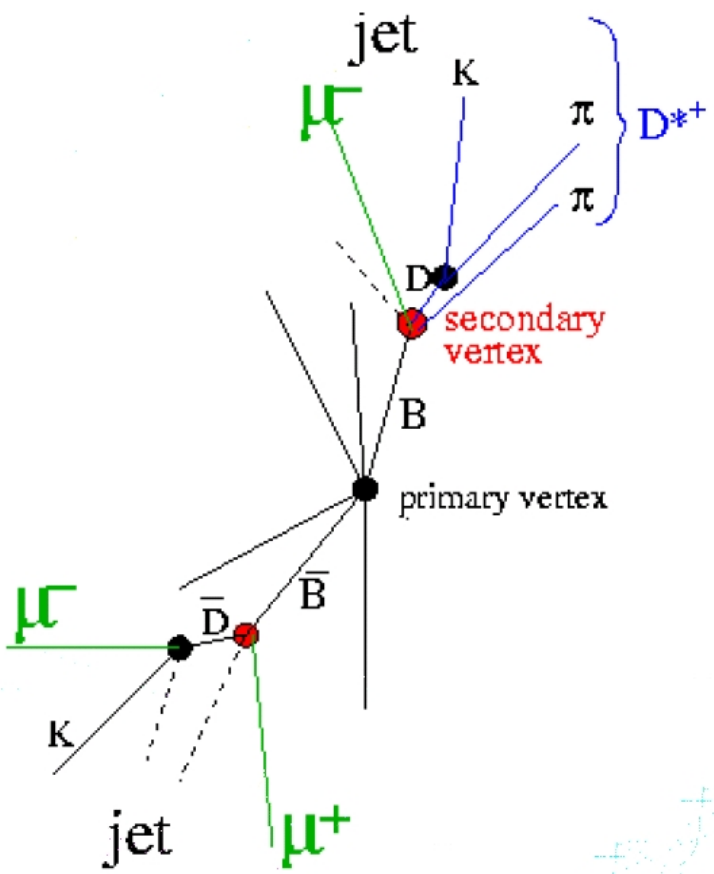
FMNR: CTEQ5F3 proton PDF , GRV-G HO photon PDF

double tagging

b double tag :

$ep \to b\bar{b}X \to \mu\mu X'$

$ep \to b\bar{b}X \to D^*\mu X'$



Low background

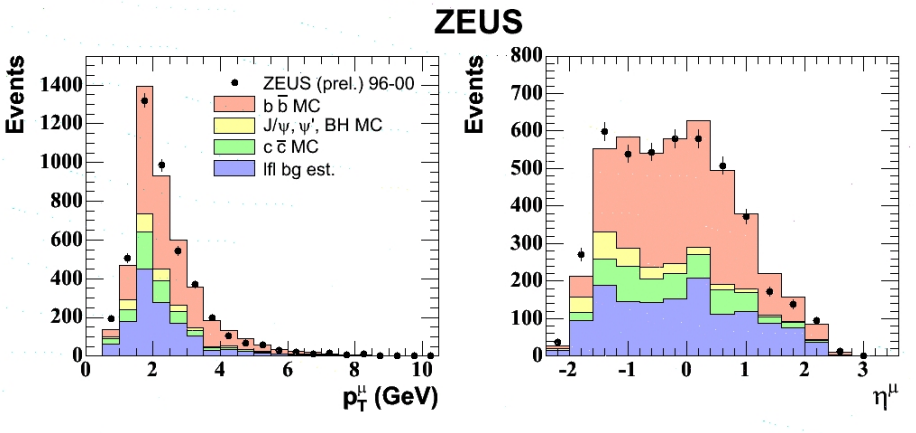
- di-mu and D^*-mu selection in final state
- separation of the sample in high-low mass, isolated and non-isolated, like and unlike sign muon pairs

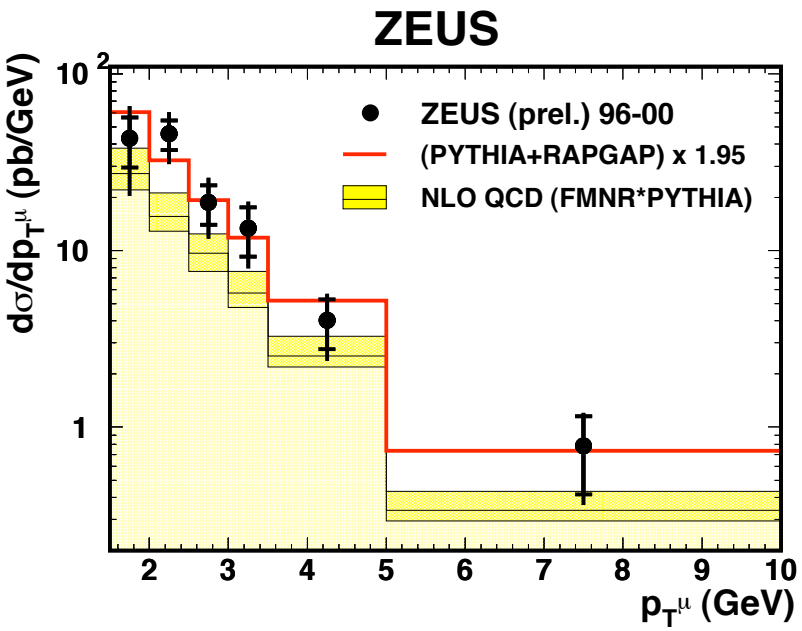
Full phase space for production

- low P_t threshold for muon identification
- large rapidity coverage of ZEUS muon system

Direct measure of total $b\bar{b}$ cross section w/o any cuts

- muons from same b: unlike sign, same hemisphere, mass below B hadron mass
- muons from different b: both like and unlike sign, different hemisphere





background sources

- open c production (high mass, unlike sign)
- hidden c ($J\Psi$, Ψ') (low mass, unlike sign)
- $\gamma\gamma$ processes (high mass, unlike sign)
- fake μ (light flavour bkg) (like and unlike sign)

background subtraction

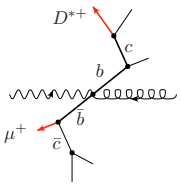
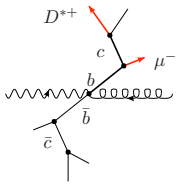
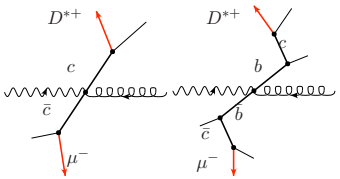
- charm pair production (unlike sample only) estimated from $D^* + \mu$ analysis
- fake μ bkg removed using difference sing-unlike sing samples (lfl cancels)

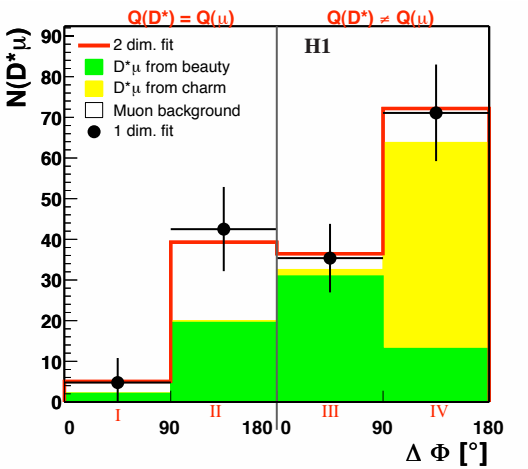
what is left is only b contribution

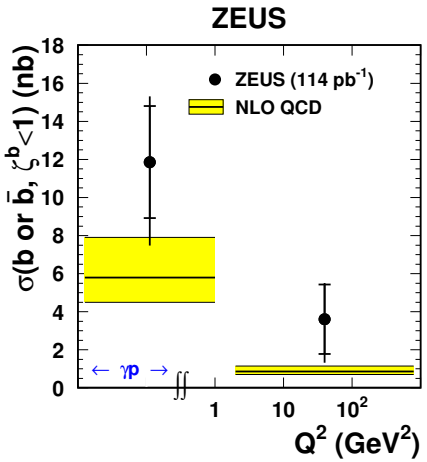
$(ep \rightarrow b\bar{b} \rightarrow \mu\mu X)$

- σ^{vis}: $63 \pm 7(stat.)^{+20}_{-18}(syst.)$ pb
- NLO: $30^{+9}_{-6}(NLO)^{+5}_{-3}(frag + br)$ pb

FMNR: p PDF CTEQ5M, γ PDF GRV-G-HO

	$\Delta\Phi < 90°$	$\Delta\Phi > 90°$
$Q(D^*) = Q(\mu)$	I	II 
	charm (%) 0.1 beauty (%) 3.8	0.1 20.4
$Q(D^*) \neq Q(\mu)$	III 	IV 
	charm (%) 6.0 beauty (%) 50.0	93.8 25.9





- This measure extends to significantly lower centre-of-mass energies of $b\bar{b}$ system than previous HERA xsections
- Simultaneously detection of D^* and $\mu \longrightarrow$ test high order QCD effects
- $D^*\mu$ sensitive to possible transverse momentum k_t of the gluons entering the quark pair production process

$\sigma_b^{vis}(ep \longrightarrow eD^*\mu X)$

- H1: $206 \pm 53 \pm 35$ pb (NLO: 53^{+14}_{-9} pb)
- ZEUS: $115 \pm 29^{21}_{-27}$ pb (NLO: 54^{+15}_{-10} pb)(DESY-06-166)

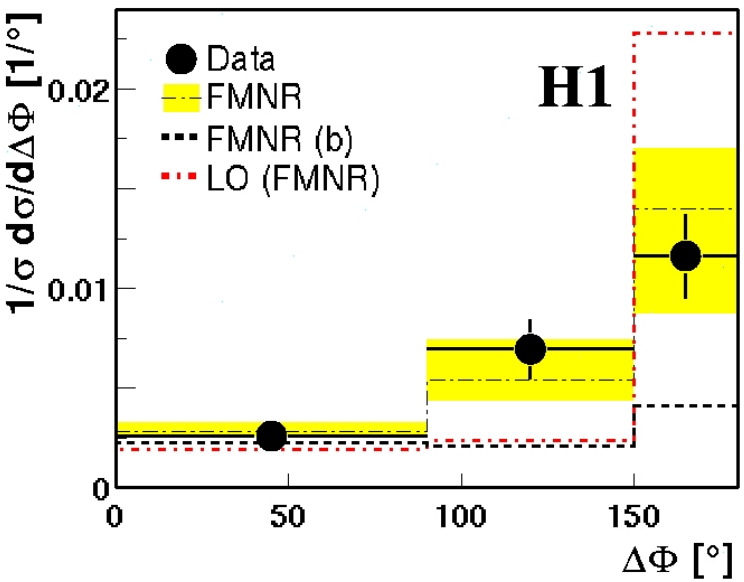
$\sigma_c^{vis}(ep \longrightarrow eD^*\mu X)$

- H1: $250 \pm 57 \pm 40$ pb (NLO: 286^{+159}_{-59} pb)

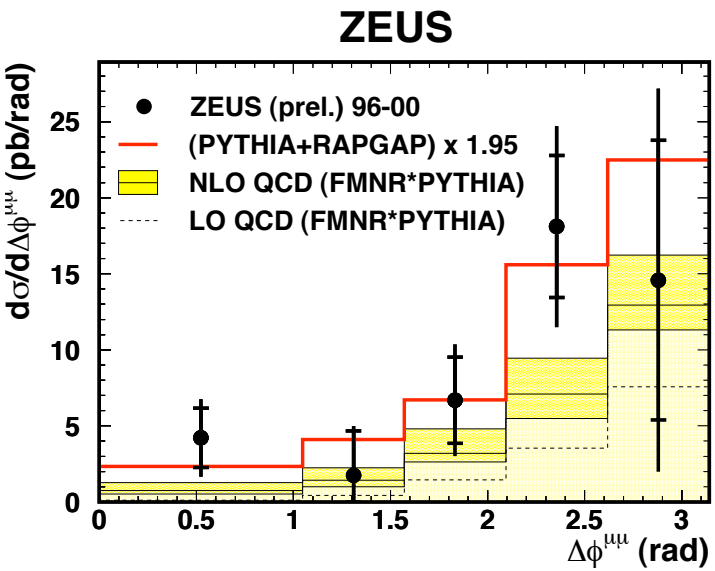
FMNR: p PDF CTEQ5M, γ PDF GRV-G-HO

Azimuthal correlations for:

$D^* - \mu$

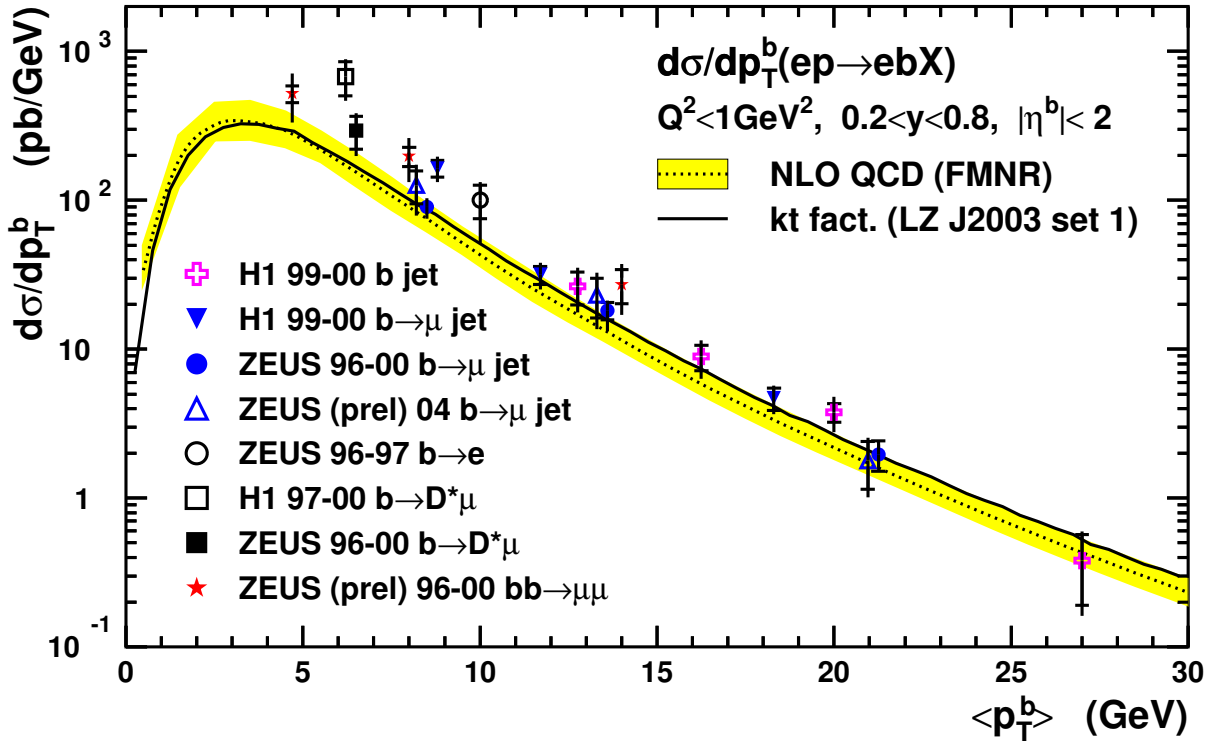


$\mu - \mu$

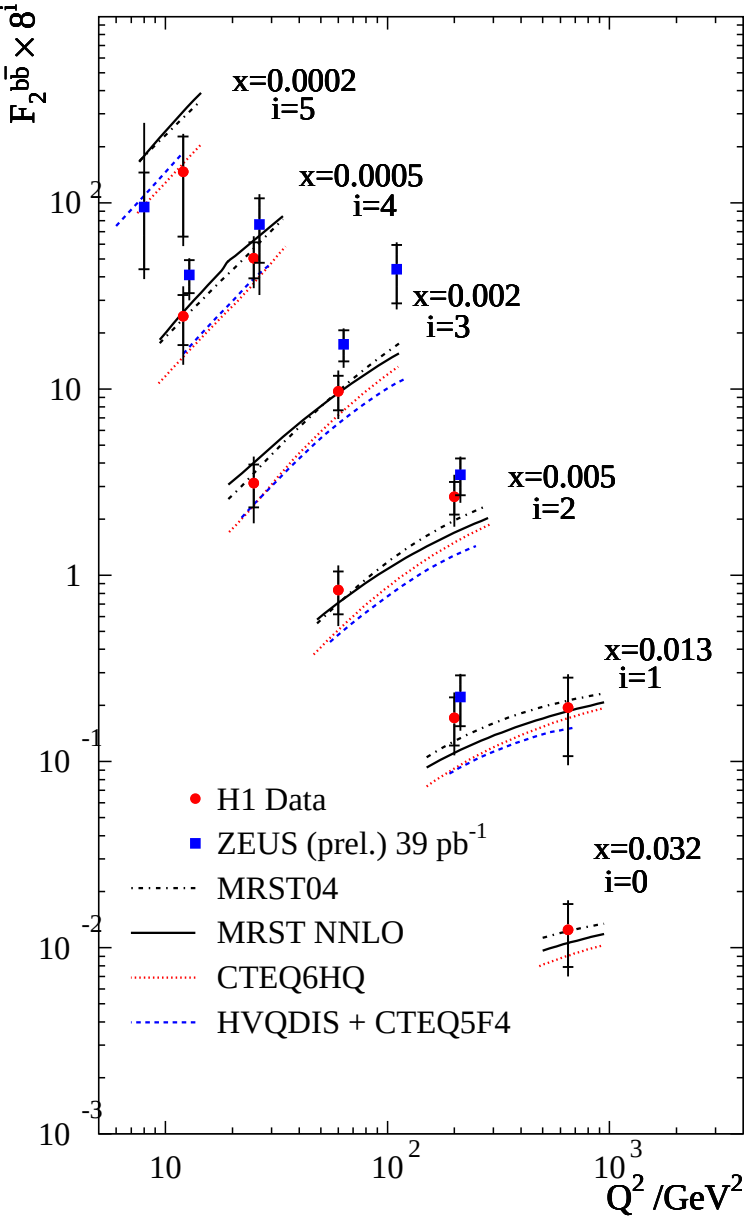


- deviations from LO $\rightarrow$ high order effects, good agreement with NLO

HERA



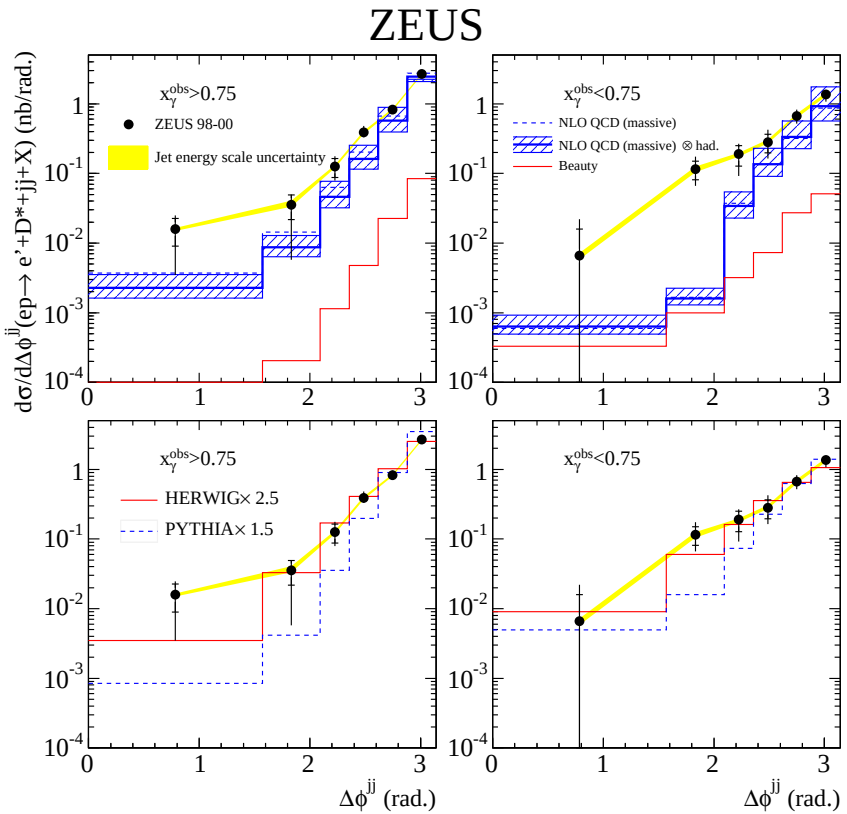
- at low p_T values data slightly above NLO QCD calculations
- HERA II data needed to improve cross section determination, especially in the low-p_T^b (double tag measurements) and high-p_T^b (lifetime mesurements) regions



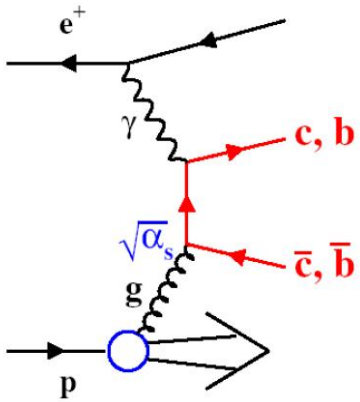
- First measurements of $F_2^{b\bar{b}}$
- First NNLO calculations available
- Large spread in theoretical predictions
- Measurements from the two experiments compatible within the errors and in agreement with theory

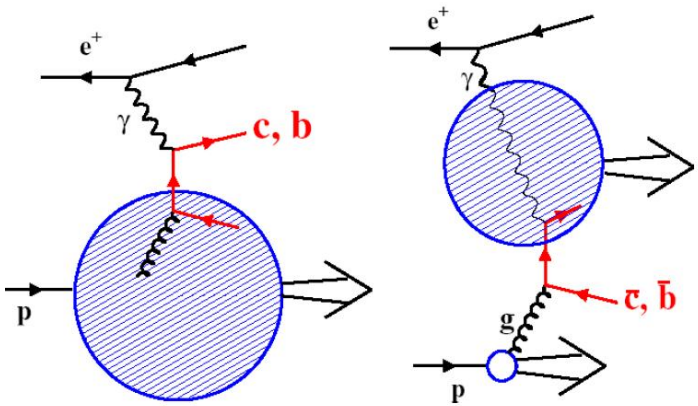
Summary

- pQCD tested with HFL production
- Charm production
  - NLO describe data well in a large range of Q^2 (including transition region between PHP and DIS)
  - Fragmentation universality confirmed
  - Charm data in PHP more precise than theory
- Beauty production
  - Data agree with NLO at high P_t, at lower P_t tendency of data to be above the central NLO predictions.
  - First measurements of $F_2^{b\bar{b}}$ structure function
- HERA II data are being analysed. More precise and interesting measurements to come...



- ZEUS PHP dijets correlations





massive scheme

- c, b massive
- neglects terms $(\alpha_s \ln(Q^2/m^2_{c,b,}))^n$
- scales m_b, m_c

$\longrightarrow$c, b produce perturbatively (not part of the photon or proton)

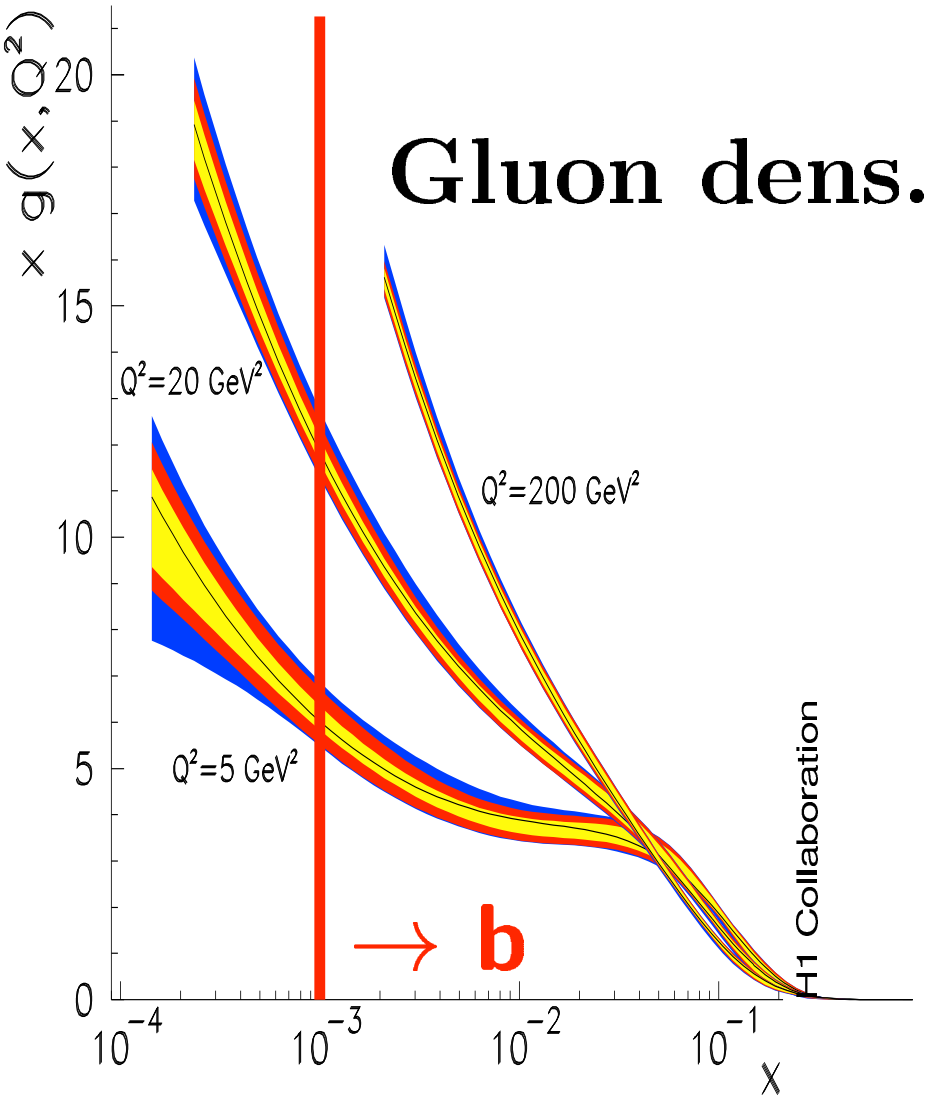
massless scheme

- c, b massless
- resums terms $(\alpha_s \ln(Q^2/m^2_{c,b,}))^n$
- scales Q^2, p_t

$\longrightarrow$c, b also in proton and photon

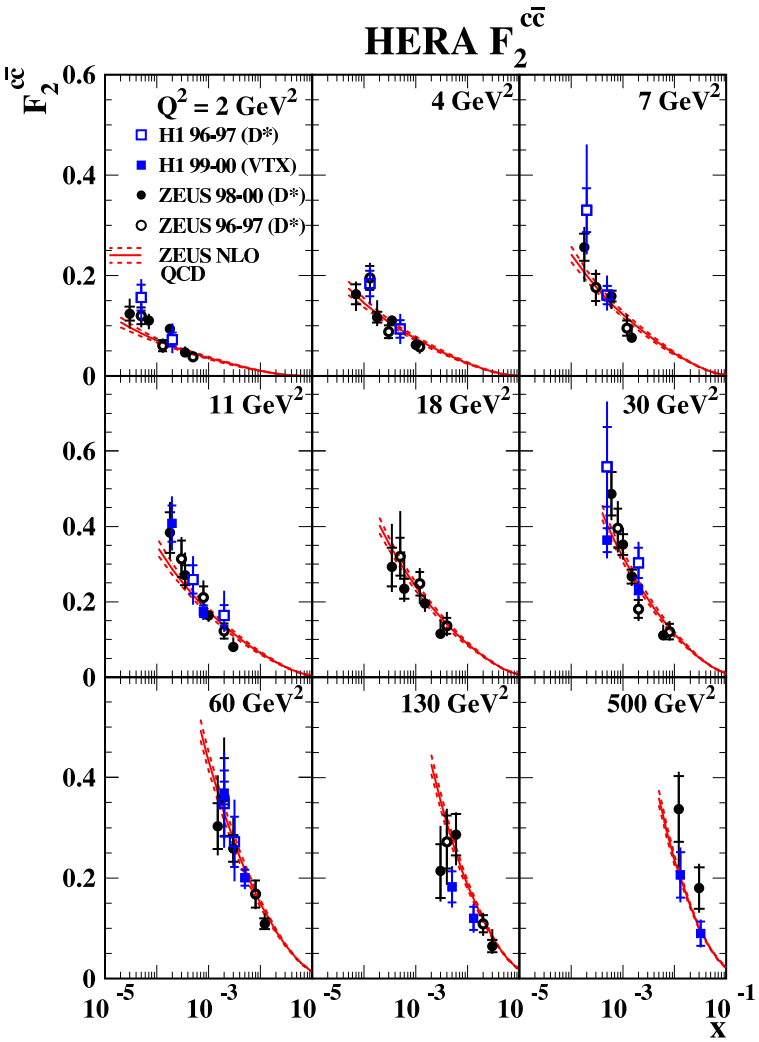
variable flavour number scheme

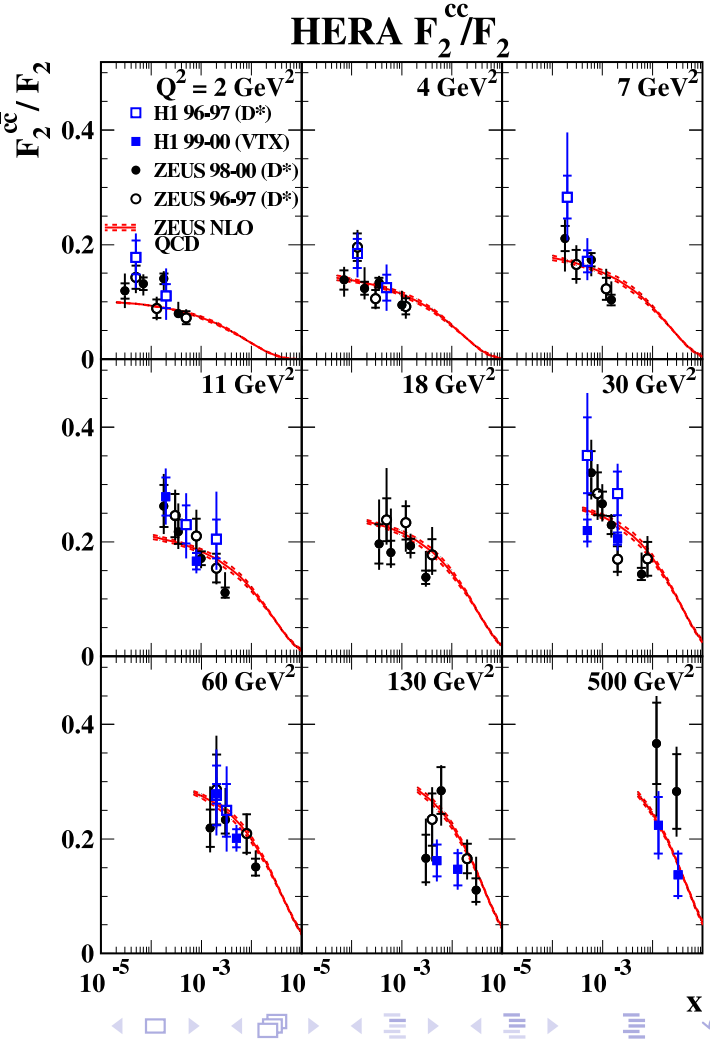
- massive at small Q^2
- massless at large Q^2

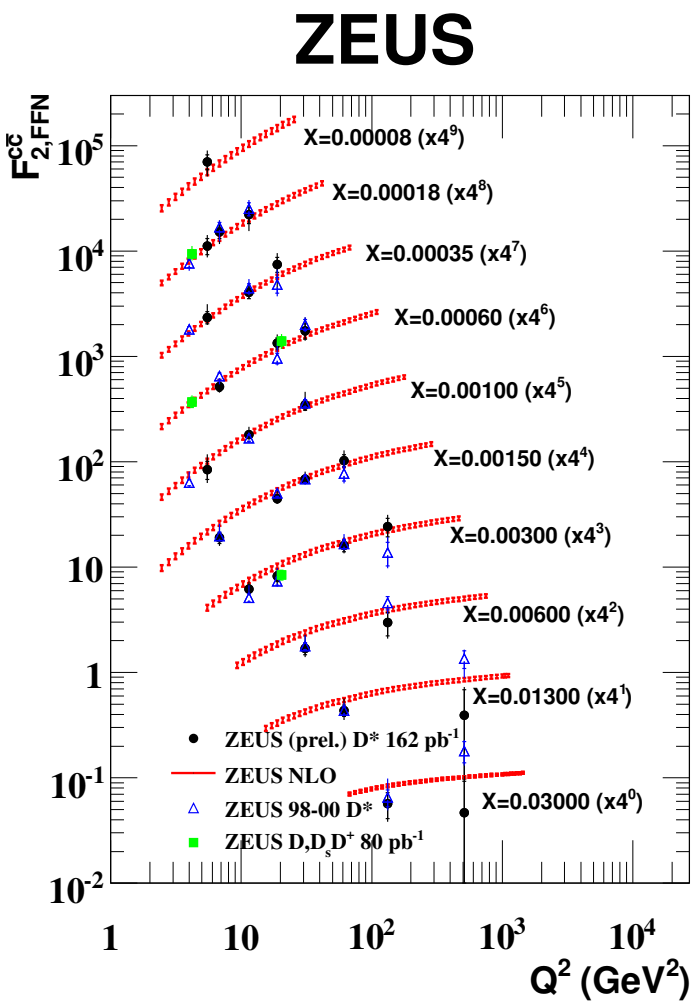


main reason for beauty suppression: phase-space factor

- kinematic threshold for b production due to its mass
- $x_g \geq \frac{m_Q^2}{E_\gamma \times 920\ GeV}$ (x_g fraction of four-momentum of the proton carried by the gluon participating in the hard interaction)
- for charm $x_g \geq 10^{-4}$, for beauty $x_g \geq 10^{-3}$


HERA $F_2^{c\bar{c}}$
$F_2^{c\bar{c}}$
Q^2 = 2 GeV^2
H1 96-97 (D*)
H1 99-00 (VTX)
ZEUS 98-00 (D*)
ZEUS 96-97 (D*)
ZEUS NLO QCD
4 GeV^2
7 GeV^2
11 GeV^2
18 GeV^2
30 GeV^2
60 GeV^2
130 GeV^2
500 GeV^2
x


HERA $F_2^{c\bar{c}}/F_2$
$F_2^{c\bar{c}}/F_2$
Q^2 = 2 GeV^2
H1 96-97 (D*)
H1 99-00 (VTX)
ZEUS 98-00 (D*)
ZEUS 96-97 (D*)
ZEUS NLO QCD
4 GeV^2
7 GeV^2
11 GeV^2
18 GeV^2
30 GeV^2
60 GeV^2
130 GeV^2
500 GeV^2
x


ZEUS
$F_{2,FFN}^{c\bar{c}}$
X=0.00008 (x4^9)
X=0.00018 (x4^8)
X=0.00035 (x4^7)
X=0.00060 (x4^6)
X=0.00100 (x4^5)
X=0.00150 (x4^4)
X=0.00300 (x4^3)
X=0.00600 (x4^2)
X=0.01300 (x4^1)
X=0.03000 (x4^0)
ZEUS (prel.) D* 162 pb^-1
ZEUS NLO
ZEUS 98-00 D*
ZEUS D,D_sD+ 80 pb^-1
Q^2 (GeV^2)