Heavy Flavour Production at HERA

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On behalf of the H1 and ZEUS Collaborations

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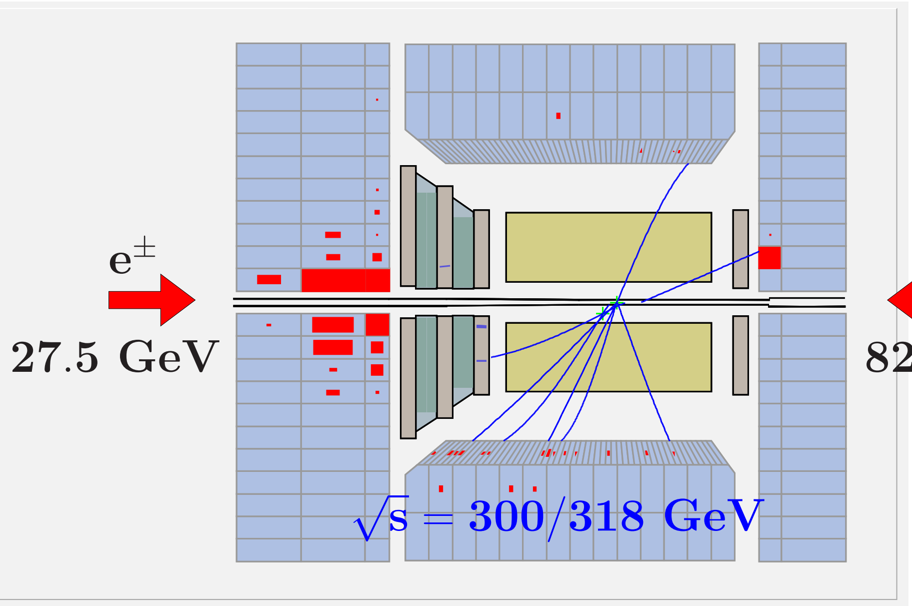
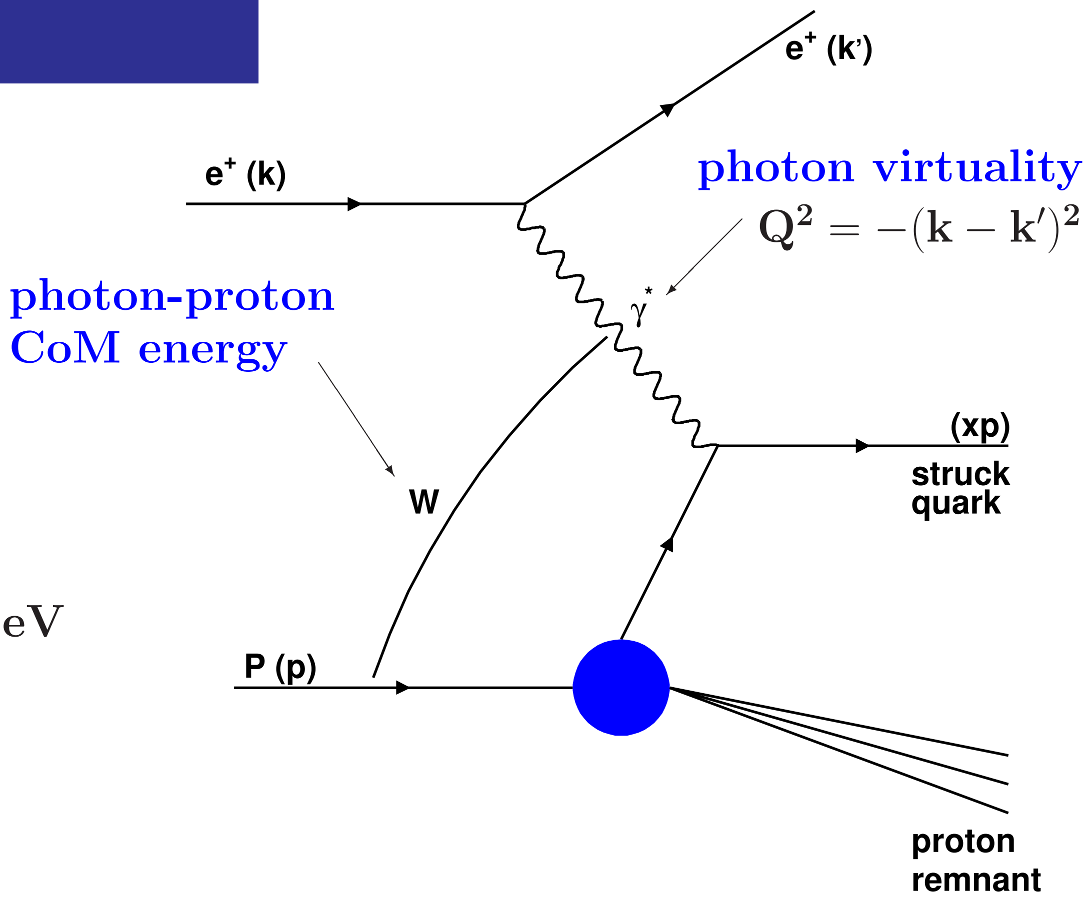
- ▷ **Motivation**
- ▷ **Beauty in photoproduction**
- ▷ **Charm in photoproduction**
- ▷ **Charm in deep inelastic scattering**
- ▷ **Charm fragmentation**

HERA kinematics

▷ HERA: world's only ep collider





▷ Bjorken scaling variable: $x = \frac{Q^2}{2p \cdot q}$

▷ $Q^2 = xys$

▷ "Photoproduction": $Q^2 < 1$ GeV^2

▷ Deep Inelastic Scattering: $Q^2 > 1$ GeV^2

Why study heavy flavour production at HERA ?

▷ **Heavy quark mass ⇒ hard scale**

- **stringent test of perturbative QCD**
- **Is charm mass large enough to be hard scale ?**

▷ **Q^2 and p_T can also provide a hard scale**

- **multi-scale problem**

▷ **Study non-perturbative aspects, eg. fragmentation**

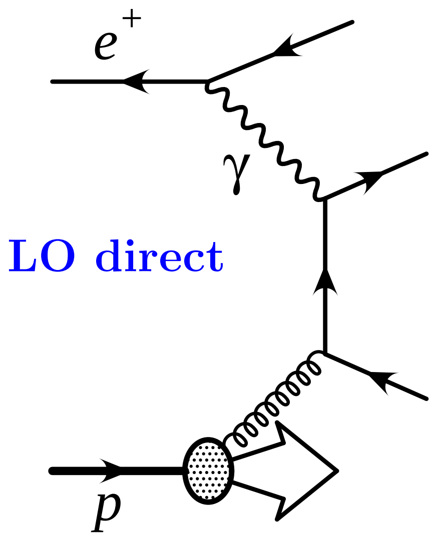
▷ **Direct processes: point-like photon**

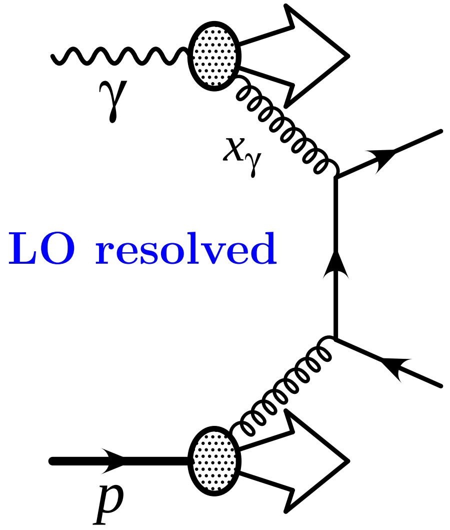
- **Access to proton parton densities**
  ⇒ Particular sensitivity to the gluon

▷ **Resolved processes:**

- **photon acts as source of partons**
  ⇒ sensitive to photon parton densities

▷ **Important to understand evolution of heavy flavours properly**





Perturbative QCD heavy flavour calculations

▹ **Fixed order NLO calculations (massive — heavy quark produced dynamically)**

- **Charm/Beauty: FMNR (Frixione et al.); HVQDIS (Harris & Smith)**
- **Three/four active flavours in proton and photon**
- **Not valid for $p_T >> m_Q$, $Q >> m_Q$**

▹ **Resummed NLL calculations (massless — charm as active flavour)**

- **Charm: Kniehl et al.**
- **Four active flavours in proton and photon**
- **Valid for $p_T >> m_Q$, $Q >> m_Q$**

▹ **Matched calculations (FONLL) (Cacciari et al.)**

- **NLO mass effects + NLL p_T resummation**

▹ **Leading order Monte Carlo**

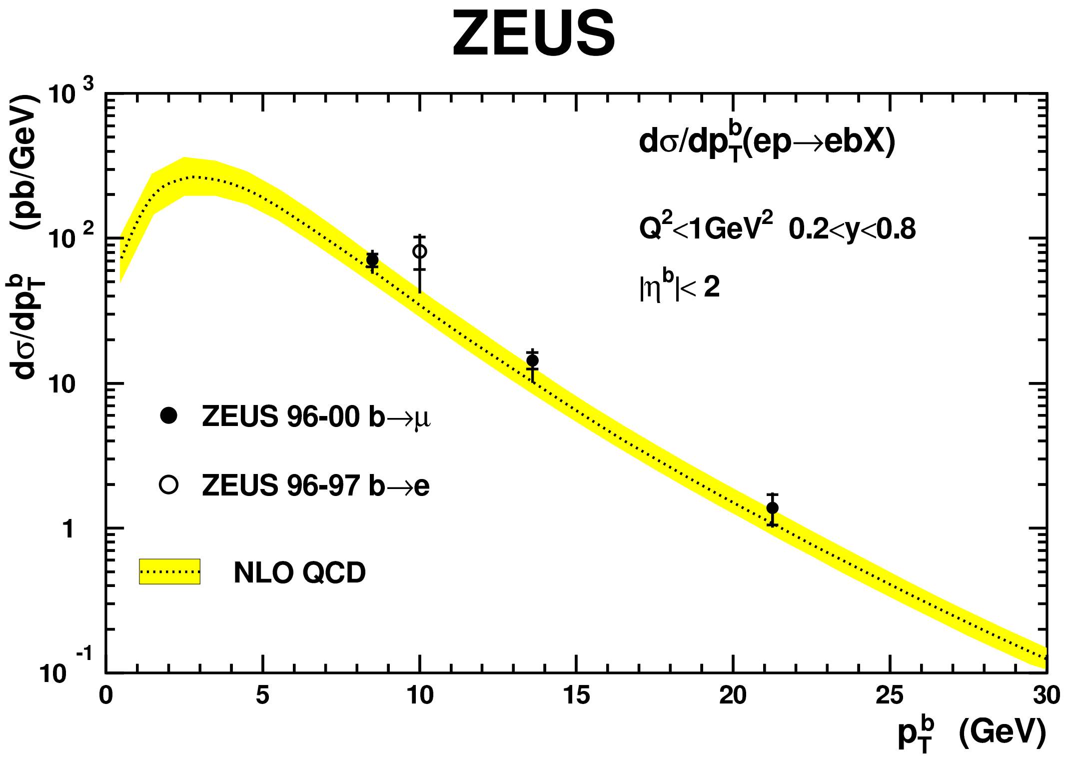
- **RAPGAP: DGLAP evolution; direct & resolved processes**
- **CASCADE: CCFM evolution; direct only, but resolved component effectively produced by lack of k_t ordering**

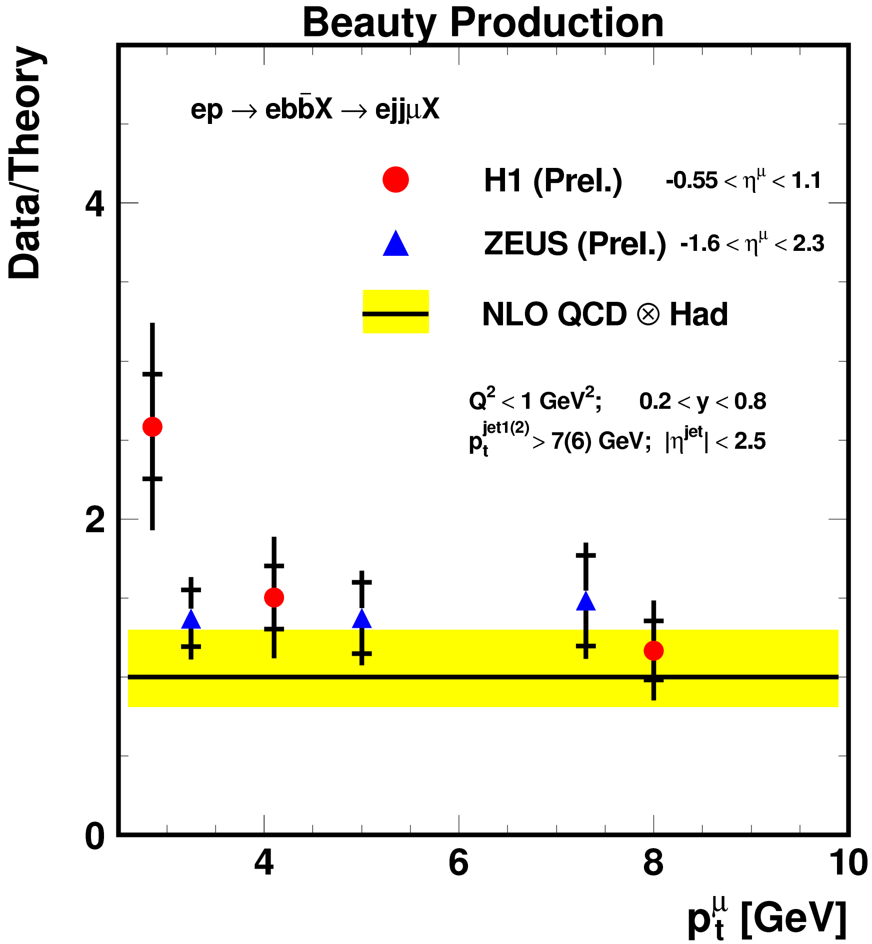
Beauty in photoproduction

▷ $ep \to eb\bar{b}X \to e$ jet jet $\mu X'$

▷ NLO QCD ("massive"):

- good agreement with ZEUS data
- agreement with H1 data at higher p_T^μ

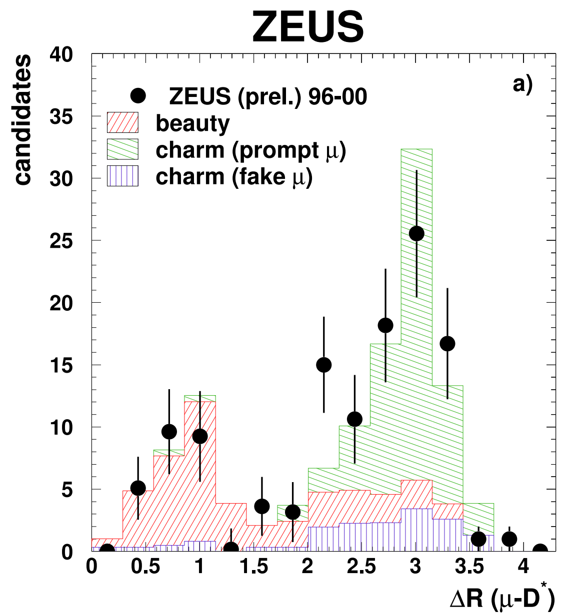




▷ Extrapolation to $ep \to ebX$

- good agreement with NLO QCD

Open beauty production: $D^* + \mu$ tag



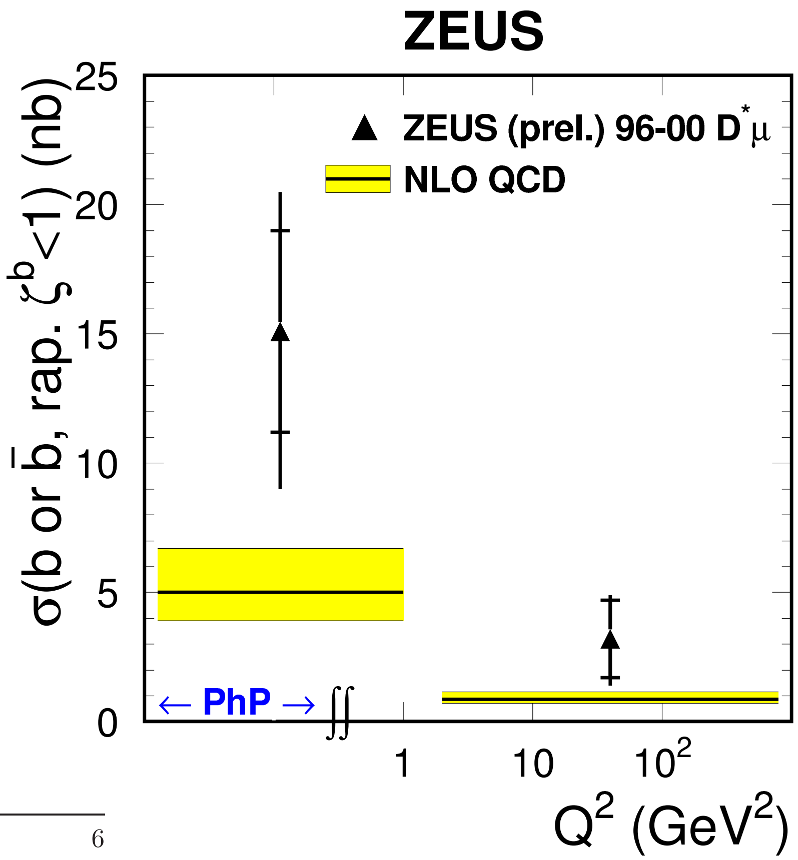
- ▷ Determine from $D^{*\pm} + \mu^{\mp}$ sample
  - beauty and charm decays
- ▷ Crosscheck with $D^{*\pm} + \mu^{\pm}$ sample
  - Beauty decays only
- ▷ Distinguish beauty fraction using

  $$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- ▷ Strong background suppression

  $\Rightarrow$ reach low p_T

- ▷ Determine $\sigma(\gamma^* p \rightarrow bX)$
  - no p_T^b requirement
- ▷ Small tendency for NLO QCD to underestimate the cross sections

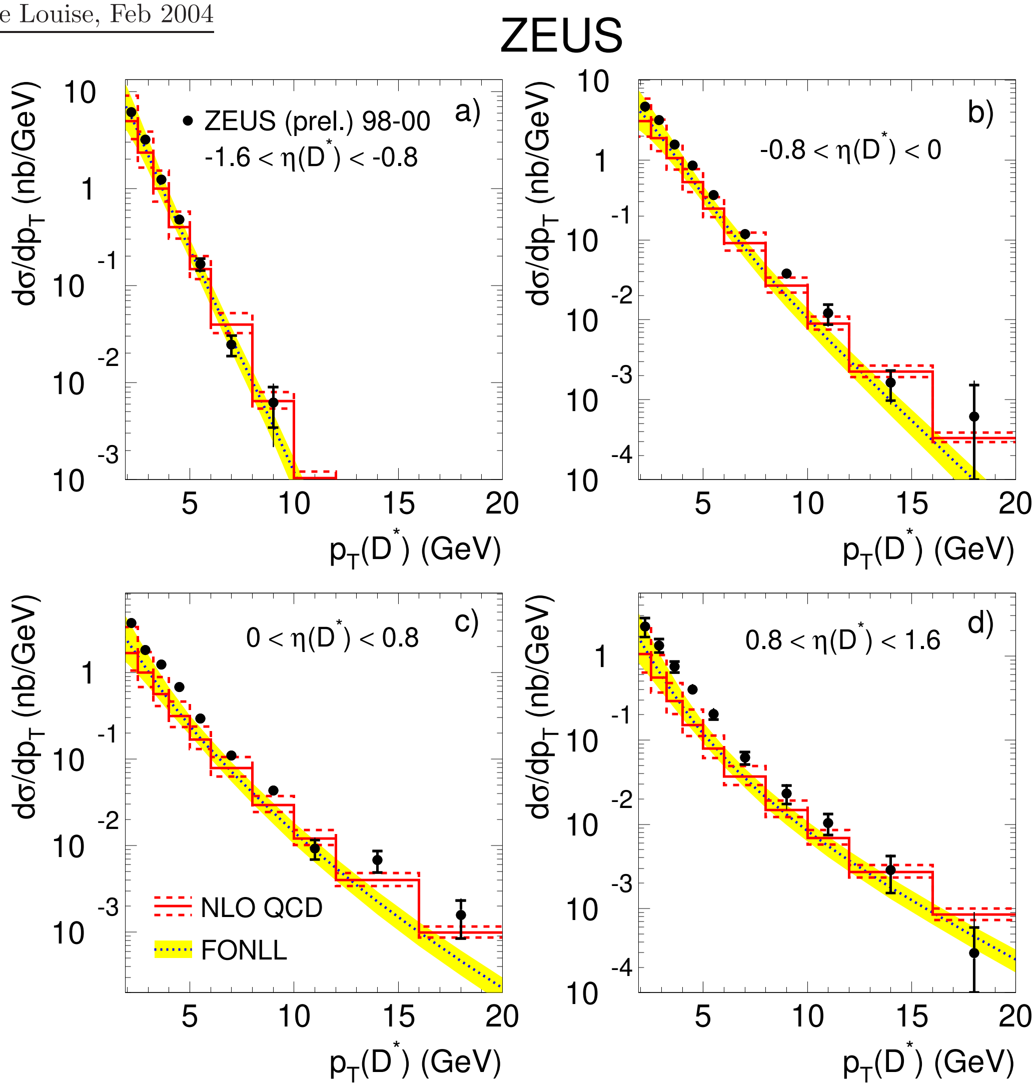


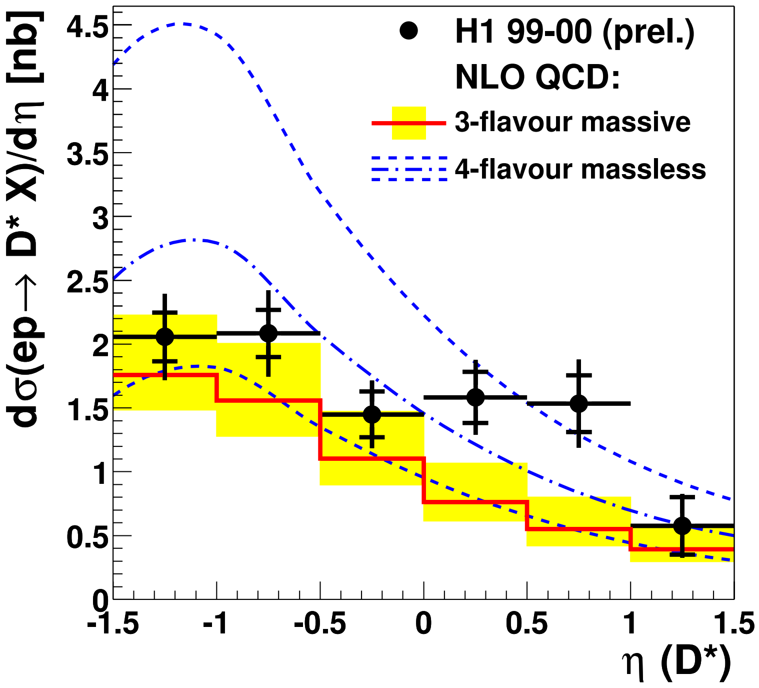
Charm in Photoproduction

▷ Identify charm via $D^{*\pm}(2010)$ production

▷ High statistics

- Precision test of perturbative QCD
- Help to constrain theoretical predictions





▷ NLO QCD underestimates data

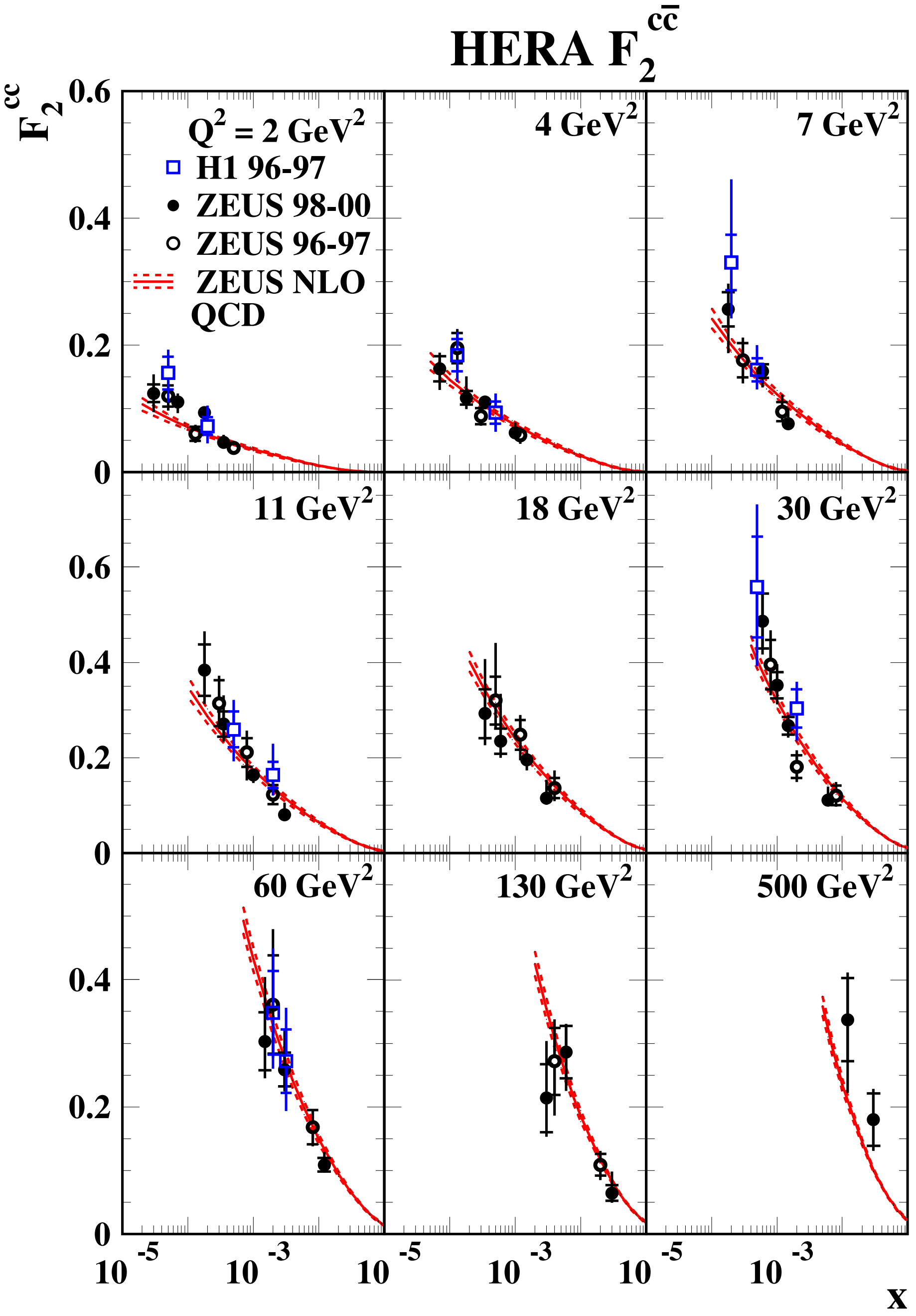
- most significant at medium p_T, positive η

▷ FONLL generally underestimates data

- OK at low p_T

Charm in Deep Inelastic Scattering

- ▷ Charm production accounts for up to 40 % of $F_2(x, Q^2)$
- ▷ Important to understand it properly
- ▷ Extract $F_2^{c\bar{c}}$ from differential cross sections
  - model dependent extraction
  - Good agreement between H1 and ZEUS results
- ▷ $F_2^{c\bar{c}}$ rises sharply with decreasing x
  - As expected from NLO QCD
- ▷ Use differential cross sections to constrain gluon density in future NLO QCD fits



Inclusive $D^{*\pm}$ and associated dijet production in DIS

▷ Three-scale problem: Q^2, m_c & E_T

▷ Compare to NLO QCD:

- Excess at low p_T, positive η

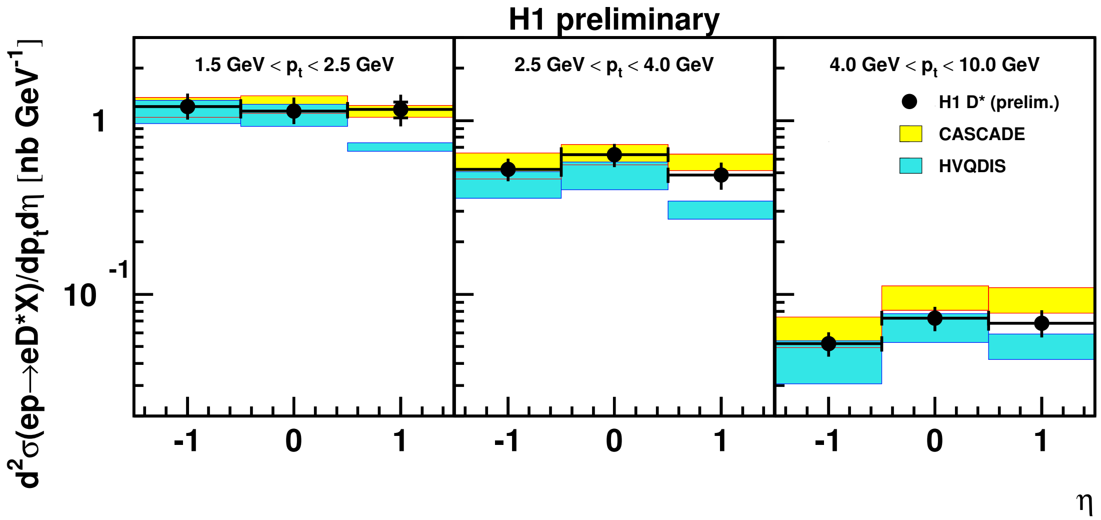
▷ Compare to CASCADE LO MC

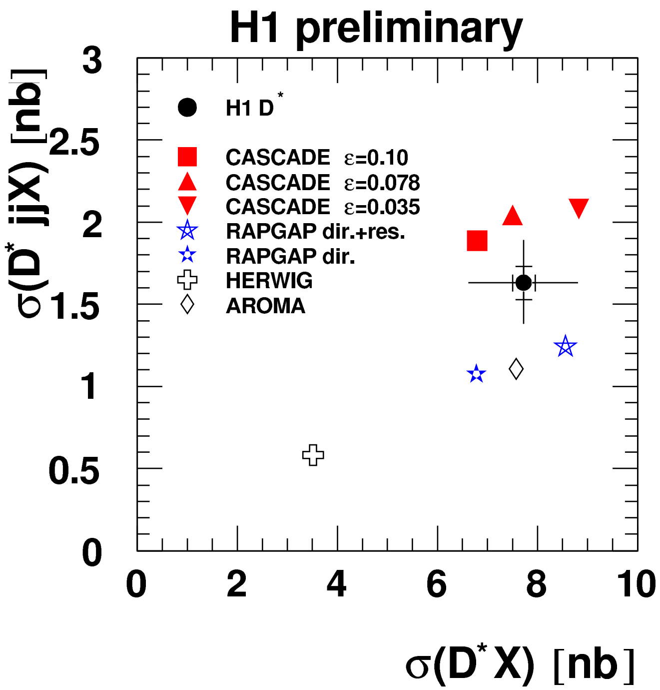
- Assumes CCFM evolution
- Describes inclusive D^* results well

▷ Compare to RAPGAP LO MC

- Assumes DGLAP evolution
- Best description when resolved component included

▷ In general, $D^{*\pm}$ dijet cross sections not so well described

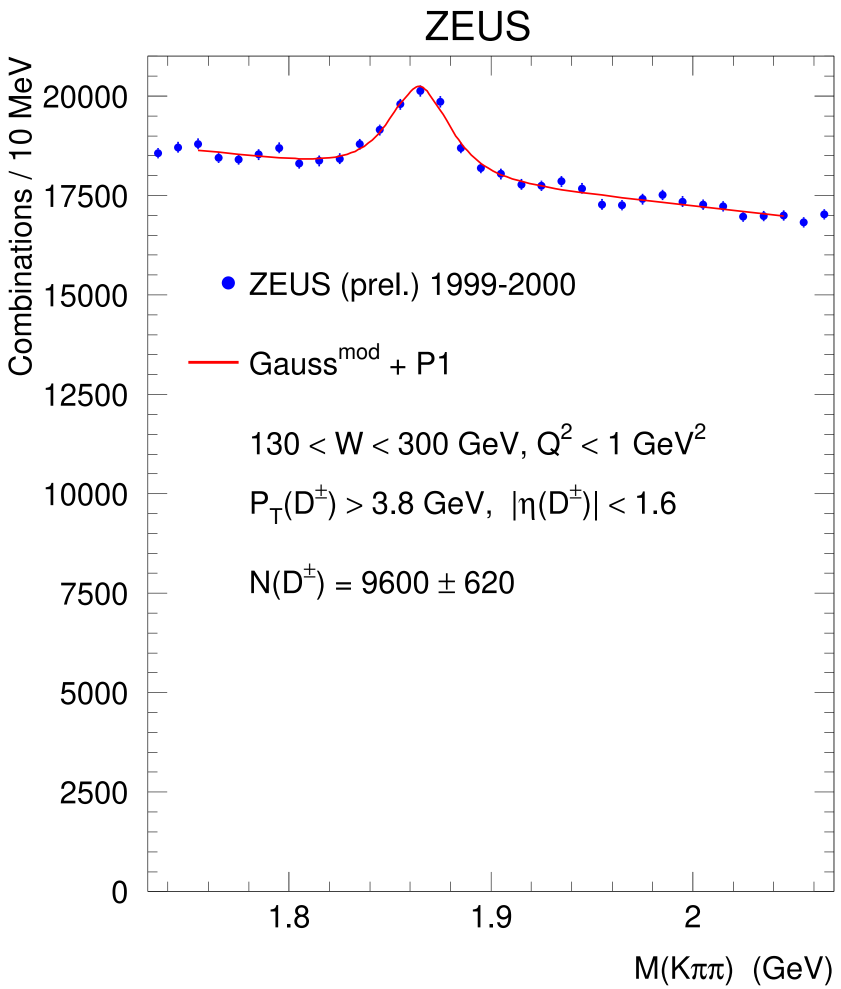




Charm fragmentation in photoproduction

▷ **Identify $D^{*\pm}$, D^0, $D^{\pm}$, $D_s^{\pm}$ & $\Lambda_c^{\pm}$ hadrons and measure:**

- $R_{u/d}$: ratio of neutral and charged D meson production rates
- γ_s: strangeness suppression factor
- P_v: fraction of D mesons produced in a vector state
- P_v^d: fraction of charged D mesons produced in a vector state
- $f(c \to D, \Lambda_c)$: fragmentation fractions



▷ **ZEUS results: calculated for $p_T(D, \Lambda_c) > 3.8$ GeV, $|\eta(D, \Lambda_c)| < 1.6$**

▷ **H1 results: extrapolated to full phase space (additional error quoted)**

- Extrapolation factor generally small

Charm fragmentation in photoproduction (II)

	ZEUS prel. (γp) results	H1 prel. (DIS) results	e^+e^- results
$R_{u/d}$	$1.014 \pm 0.068^{+0.024}_{-0.031}$	$1.26 \pm 0.20 \pm 0.11 \pm 0.04$	$0.963 \pm 0.051 \pm 0.054$ 1.02 ± 0.12 1.19 ± 0.36
γ_s	$0.266 \pm 0.023^{+0.014}_{-0.012}$	$0.36 \pm 0.10 \pm 0.01 \pm 0.08$	0.26 ± 0.03
P^d_v	$0.557 \pm 0.023^{+0.009}_{-0.006}$	$0.693 \pm 0.045 \pm 0.004 \pm 0.009$	0.595 ± 0.045
P_v	$0.554 \pm 0.019^{+0.008}_{-0.004}$	$0.613 \pm 0.061 \pm 0.033 \pm 0.008$	$0.620 \pm 0.014 \pm 0.014$ 0.57 ± 0.05
$f(c \to D^+)$	$0.249 \pm 0.014^{+0.004}_{-0.008}$	$0.202 \pm 0.020^{+0.045+0.029}_{-0.033-0.021}$	0.232 ± 0.010
$f(c \to D^0)$	$0.557 \pm 0.019^{+0.005}_{-0.013}$	$0.658 \pm 0.054^{+0.117+0.086}_{-0.142-0.048}$	0.549 ± 0.023
$f(c \to D^+_s)$	$0.107 \pm 0.009 \pm 0.005$	$0.156 \pm 0.043^{+0.036+0.050}_{-0.035-0.046}$	0.101 ± 0.009
$f(c \to \Lambda^+_c)$	$0.076 \pm 0.020^{+0.017}_{-0.001}$		0.076 ± 0.007
$f(c \to D^{*+})$	$0.223 \pm 0.009^{+0.003}_{-0.005}$	$0.263 \pm 0.019^{+0.056+0.031}_{-0.042-0.022}$	0.235 ± 0.007

▷ **Results from ep and e^+e^- in good agreement**

▷ **HERA results competitive with e^+e^- results**

Conclusions

- **Photoproduction beauty results now in good agreement with NLO QCD predictions**

- **Double-tag $D^*\mu$ open beauty measurements allow low p_T to be accessed**
  - **Need higher statistics**

- **Photoproduction $D^{*\pm}$ results now very precise**
  - **Should be possible to constrain NLO QCD predictions**

- **DIS $D^{*\pm}$ results also precise**
  - **Results can help to constrain the gluon density of the proton in future**
  - **Theory needed to describe $D^{*\pm}$ dijet results**

- **Precision results in charm fragmentation**
  - **HERA results now competitive with those from e^+e^- experiments**

- **Looking forward to new results from HERA II data**
  - **Addition/extension of silicon vertex detectors**
  - **Improved forward tracking & track triggering**