24^{th} September 2002

Charm and Beauty Production at HERA

HADRON 02

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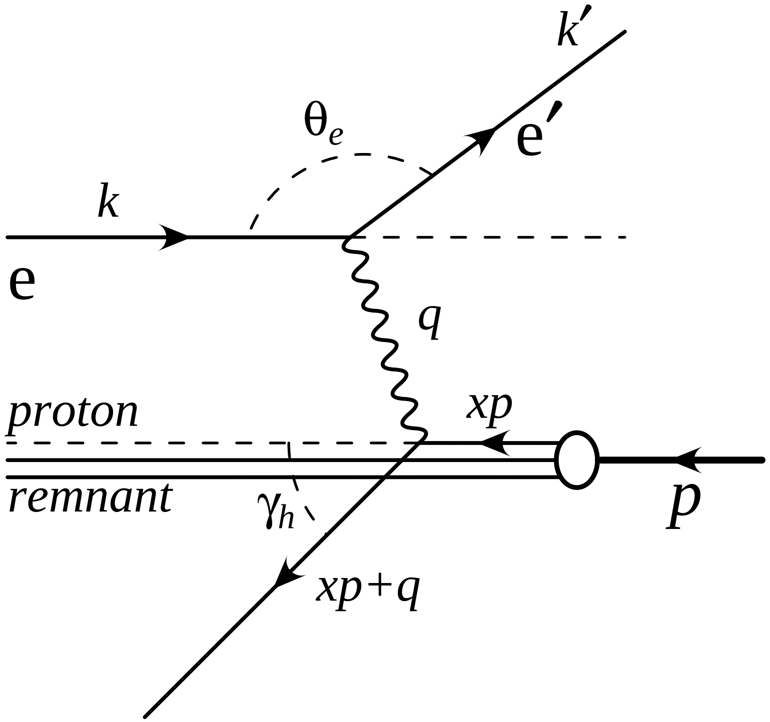
Introduction to HERA

▷ **HERA collides 27.5 GeV e$^{\pm}$ with 920 (820) GeV protons**

$$\rightarrow \sqrt{s} = 320\ (300)\ \mathrm{GeV}$$

Neutral Current Exchange: $\mathrm{e\,p} \rightarrow \mathrm{e}^{'}\mathrm{X}$



Q^2 photon virtuality

$$Q^2 \equiv -q^2 = -(k - k^{'})^2$$

x fraction of proton's momentum carried by struck parton

$$x \equiv \frac{Q^2}{2p.q}$$

W is $\gamma^{\star}$p centre of mass energy

Photoproduction:

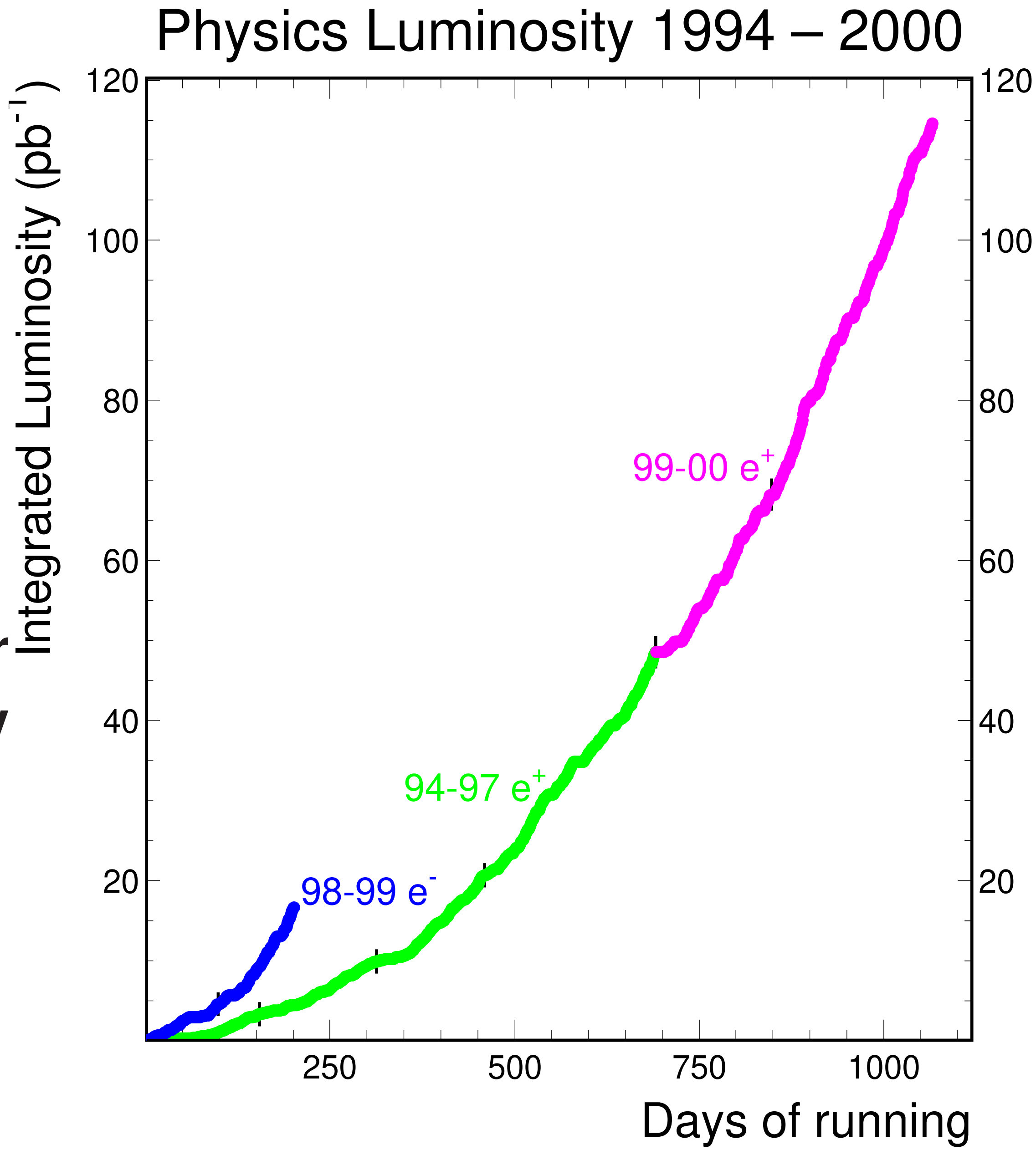
$Q^2 <$ **1 GeV^2**

Deep Inelastic Scattering:

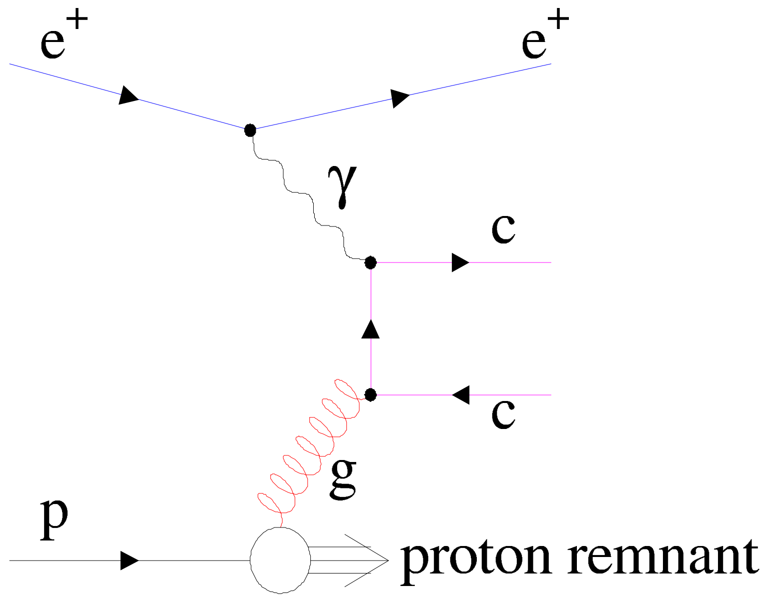
$Q^2 >$ **1 GeV^2**

Luminosity Collected at HERA I

- **Data collected at HERA I:**
  - ▷ $\sim$ **130 pb^{-1}**
  - ▷ **115 pb^{-1} e^{+}p**
  - ▷ **15 pb^{-1} e^{-}p**
- **Sufficient statistics for testing pQCD with heavy flavour physics at HERA**



Heavy Flavour Physics — Motivation



- **Study heavy flavour production mechanisms**
- **m$_c$ and m$_b$ give a hard scale to process**
  - ▷ **Good testing ground for pQCD**
- **Q^2 and E$_T^{jet}$ can also provide a hard scale**
  - ▷ **Multi-scale problem**
- **Access to parton densities in proton, photon, or the "pomeron"**
- **Study non-perturbative issues such as fragmentation**
- **Beauty production in $p\overline{p}$ and e$^+$e$^-$ above expectations**
  - ▷ **What about ep collisions?**

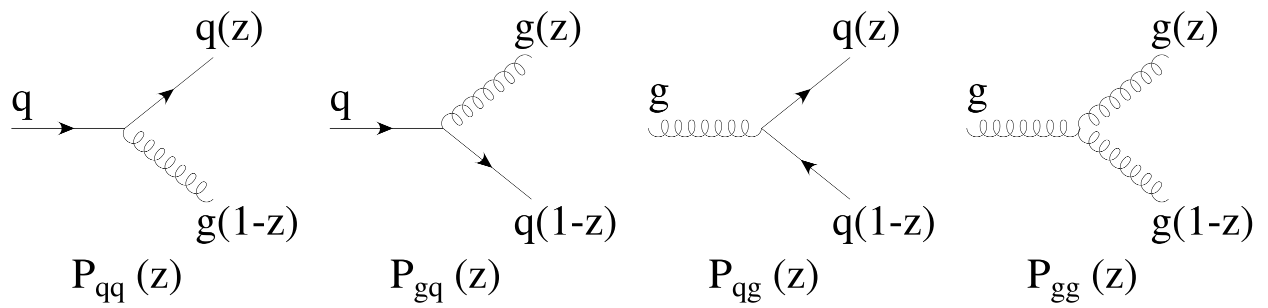
Heavy Flavour Physics is a major unresolved topic in QCD

Heavy Flavour Physics — pQCD Calculations

- **Fixed Order NLO Calculations (massive) — FMNR, HVQDIS**
  - ▷ **Charm - 3 active flavours in p and γ**
  - ▷ **Not valid only for p$_T >>$ m$_C$, Q $>>$ m$_C$ (Large logarithms $\frac{p_T}{m_c}, \frac{Q}{m_c}$)**
- **Resummed NLL Calculations (massless) — Caciarri et al, Kniehl et al**
  - ▷ **Charm - 4 active flavours in p and γ**
  - ▷ **Valid for p$_T >>$ m$_C$, Q $>>$ m$_C$**
- **Matched Calculations (FONLL)**
  - ▷ **NLO mass effects + NLL p$_T$ resummation**

Parton Evolution Schemes

Need a QCD description of parton evolution $\longrightarrow$ AP Splitting functions:

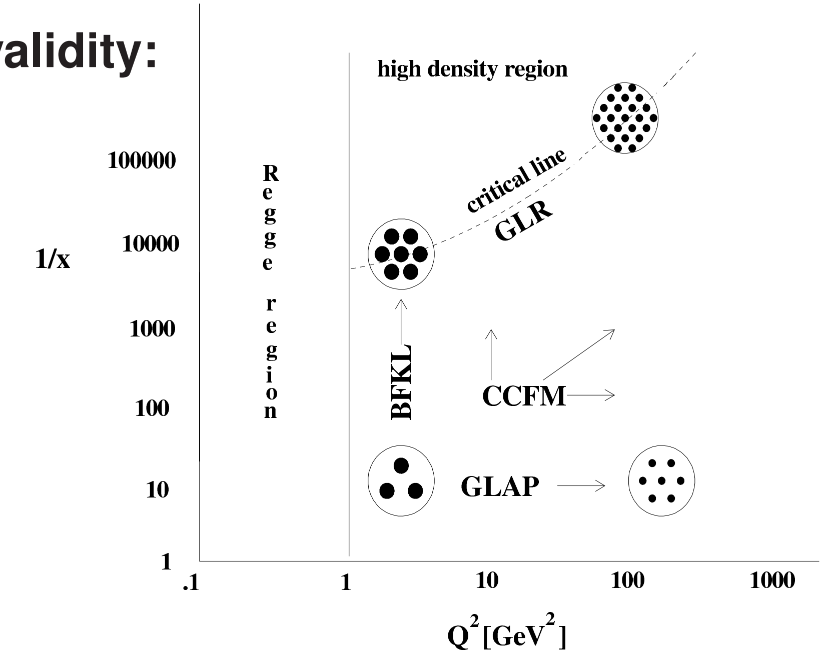


The approaches and their expected areas of validity:

DGLAP ▷ Evolution in Q^2

BFKL ▷ Evolution in $1/x$

CCFM ▷ Attempt to unify DGLAP and BFKL



LO ME + Parton Showers MC models:

PYTHIA, AROMA, RAPGAP $\longrightarrow$ DGLAP

CASCADE $\longrightarrow$ CCFM

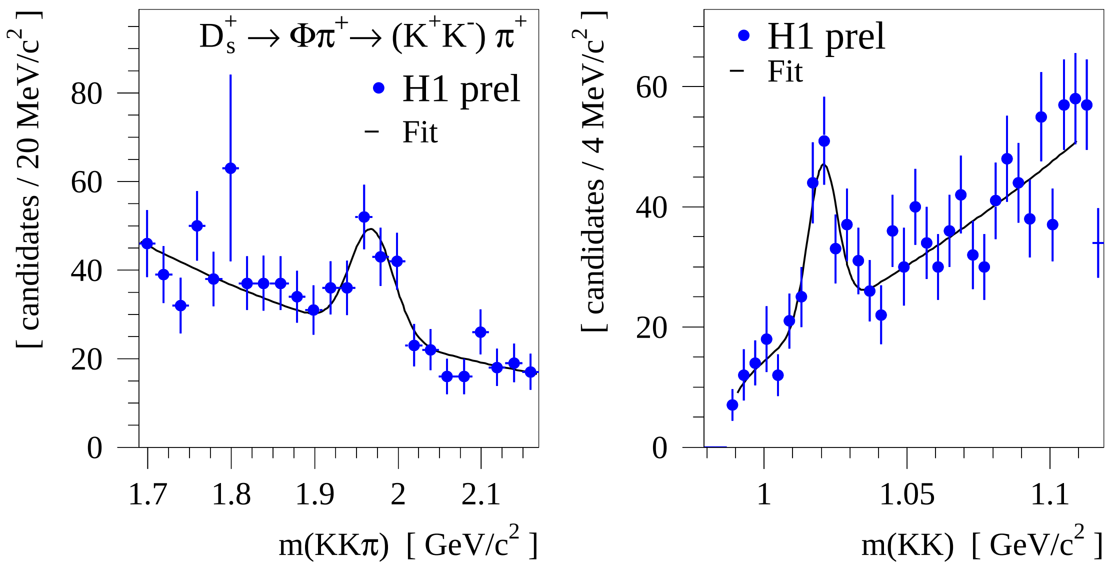
▷ Can we see evidence of these different evolution schemes in the data?

Physics Topics Addressed in this Talk

- **Charm Production**
  - ▷ Charm Photoproduction
  - ▷ Charm + Dijets ▷ Production mechanisms
  - ▷ Charm Fragmentation
  - ▷ Charm in Deep Inelastic Scattering
  - ▷ Diffractive Charm in Deep Inelastic Scattering
- **Beauty Production**
  - ▷ In Photoproduction . . .
  - ▷ . . . and in Deep Inelastic Scattering
  - ▷ Double tagged events
- **Summary and Outlook**

Tagging Charm I

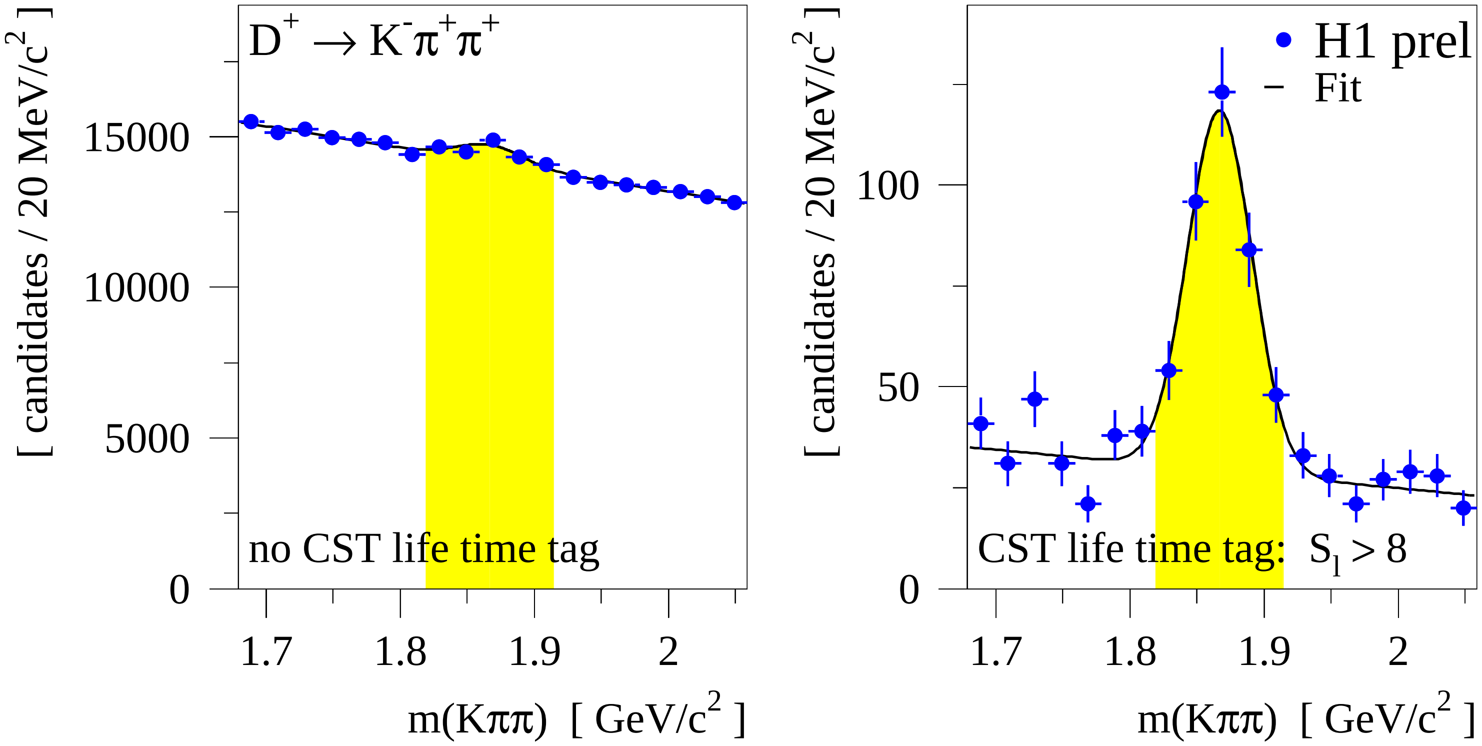
- **Charmed Meson reconstruction from charged decay products**
  - ▷ **No particle ID used**
- $D^\star$**(2010) mesons identified with** ΔM **method**
  - ▷ $D^{\star\pm} \rightarrow K^\mp \pi^\pm \pi_s^\pm$
  - ▷ ΔM **= M(**$K\pi\pi_s$**) - M(**$K\pi$**)**
- **Similarly for other charmed mesons, eg D**$_s^+$**:**



Tagging Charm II

- **Finite lifetimes of mesons lead to a separation of production and decay vertices**

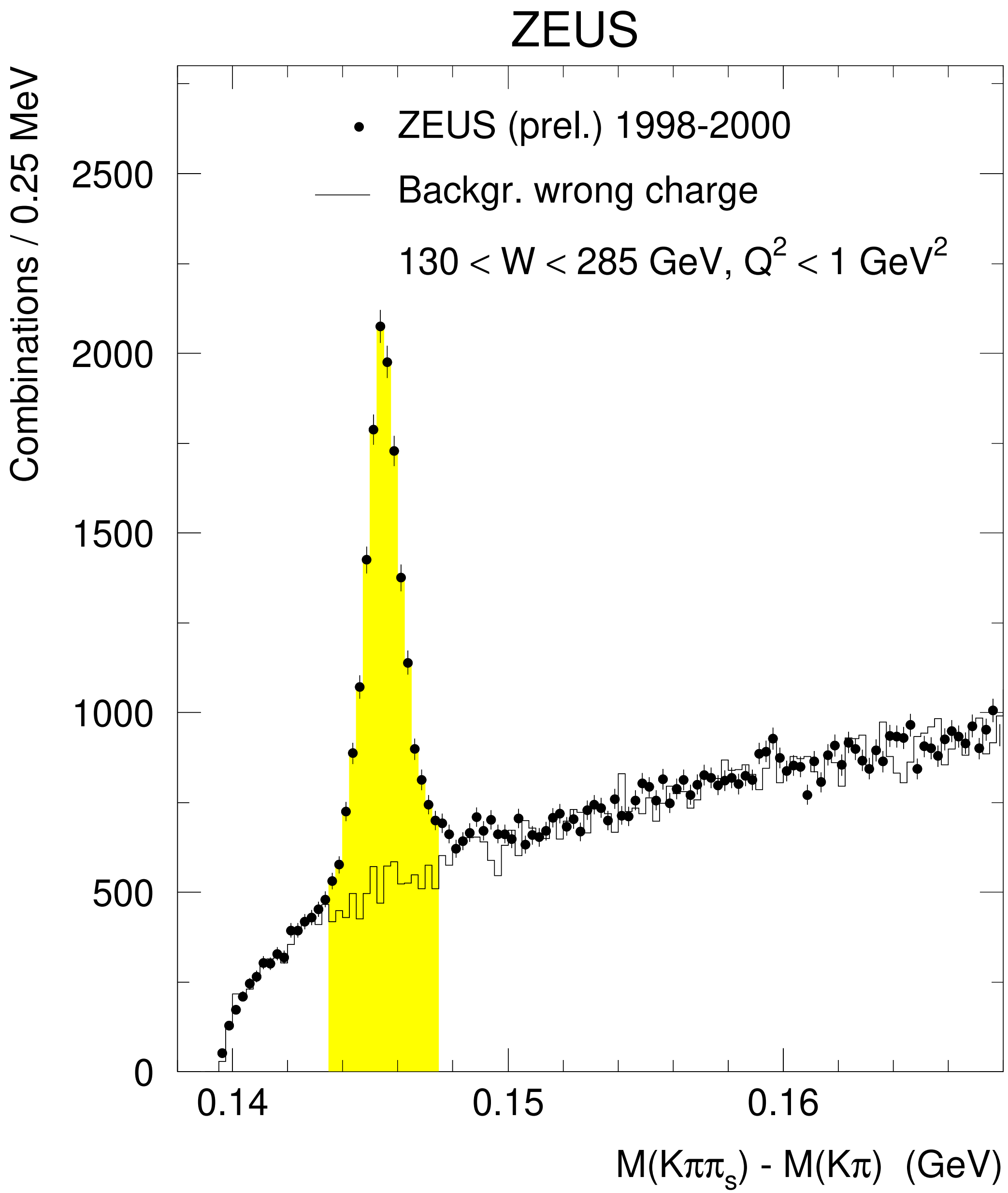
▷ **Look at closest approach of tracks to vertex** ▷ **Generate significance from this**



- **D^+ signal greatly enhanced by cutting on significance**
- **Also Semileptonic decays can be used to tag open charm**

Charm in Photoproduction

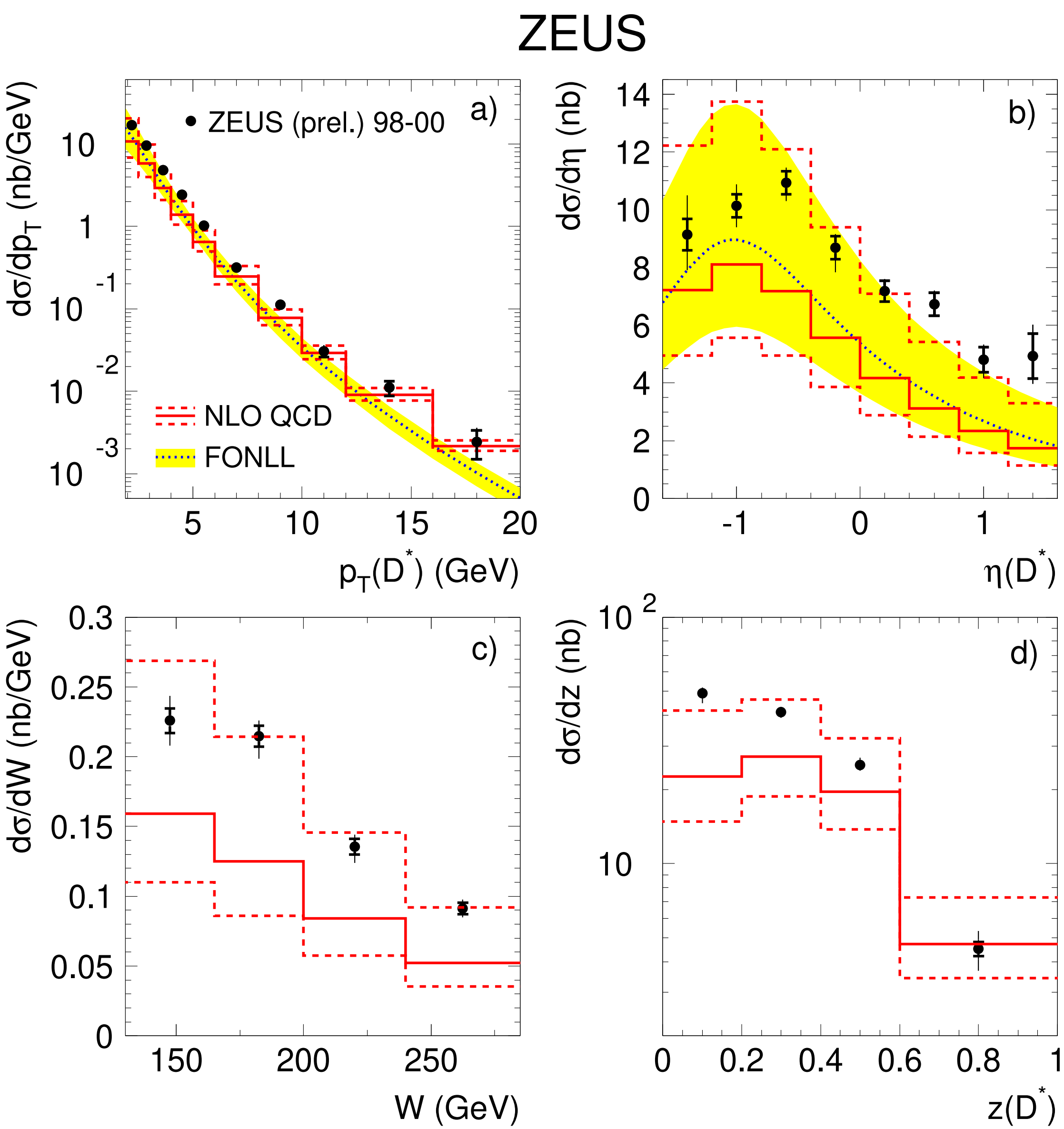
- $D^\star$ **Mesons in photoproduction**
- **10 350 $\pm$ 160 $D^\star$ candidates**
  - ▷ **Significant increase in statistics over previous results**
  - ▷ **Can measure double differential cross sections**
- **Precision tests of pQCD for charm production**
  - ▷ **Compare to NLO and NLL predictions**



Results on Charm in Photoproduction — Differential Cross Sections

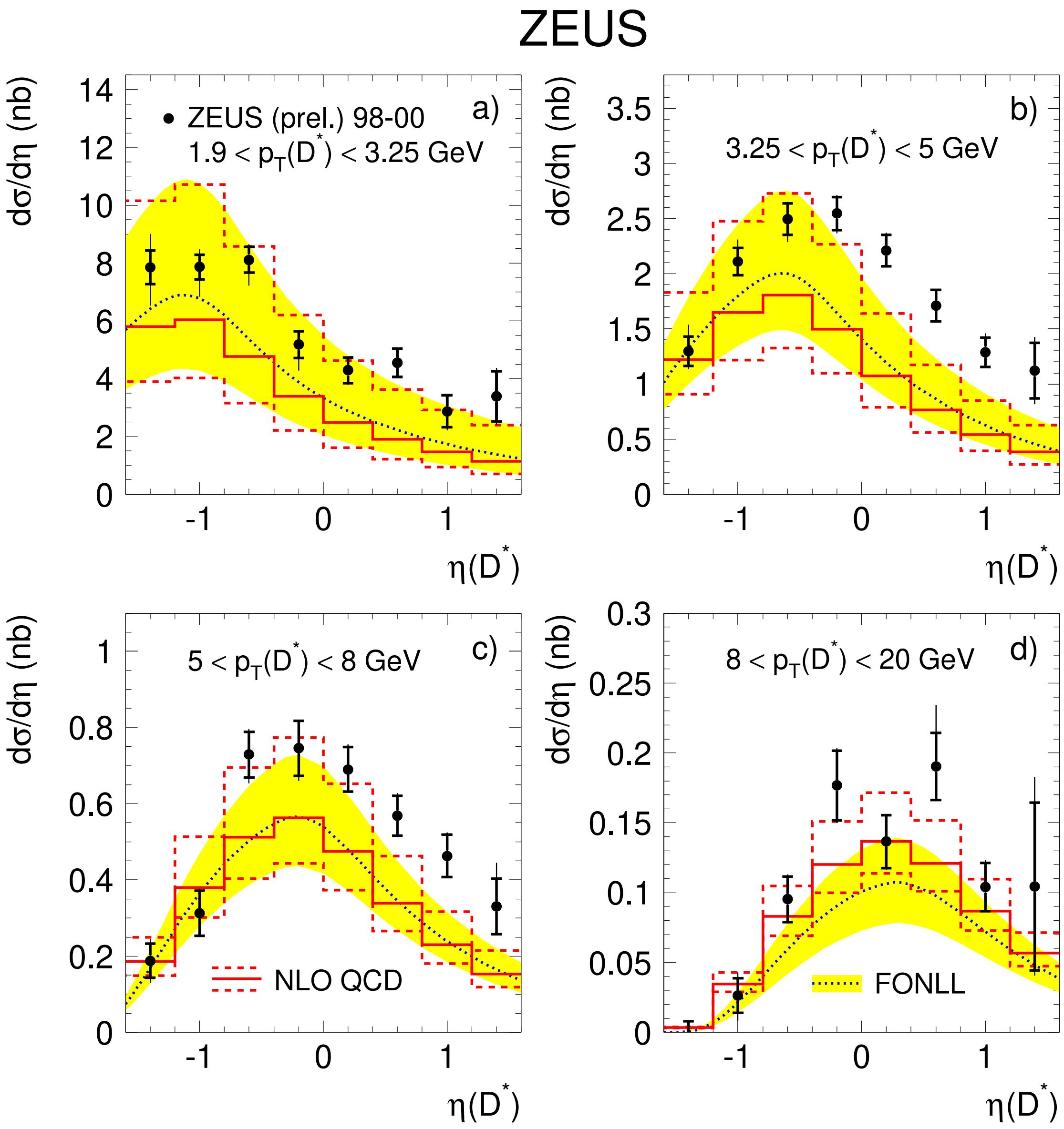
- $z(D^\star)$ is fraction of photon energy carried by $D^\star$ in proton rest frame
- Bands on theory show effect of varying renormalisation scale and charm mass
- NLO seems to describe data better than FONLL
- Data towards higher limit of NLO

▷ Medium $p_T(D^\star)$, forward $\eta(D^\star)$, low $z(D^\star)$ data in excess of NLO



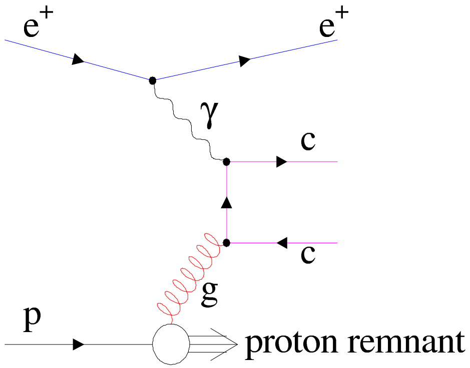
Charm in Photoproduction — Double Differential Cross Sections

- **Double Differential $D^\star$ cross sections shown here for $\eta(D^\star)$ in p$_T(D^\star)$ slices**
- **Again data tends towards upper band of NLO predictions**
- **NLO seems to better describe data than FONLL**
- **NLO undershoots data at forward $\eta(D^\star)$ especially for medium p$_T$**



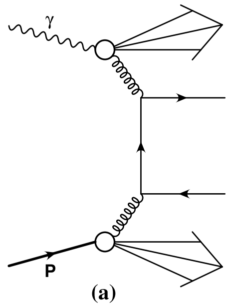
Charm with Jet Production

Now high enough statistics to look at charm + dijet production



Direct

High x_γ



Resolved

Low x_γ

This simple picture only holds at LO, but can define x_γ^{obs} at all orders ($\longrightarrow$)

- **In resolved events, photon acts as a source of partons**
- **Resolved charm production $\rightarrow$ sensitive to γ structure**
- **Charm with dijets give access to the production dynamics**
- **Charm Fragmentation can be studied**

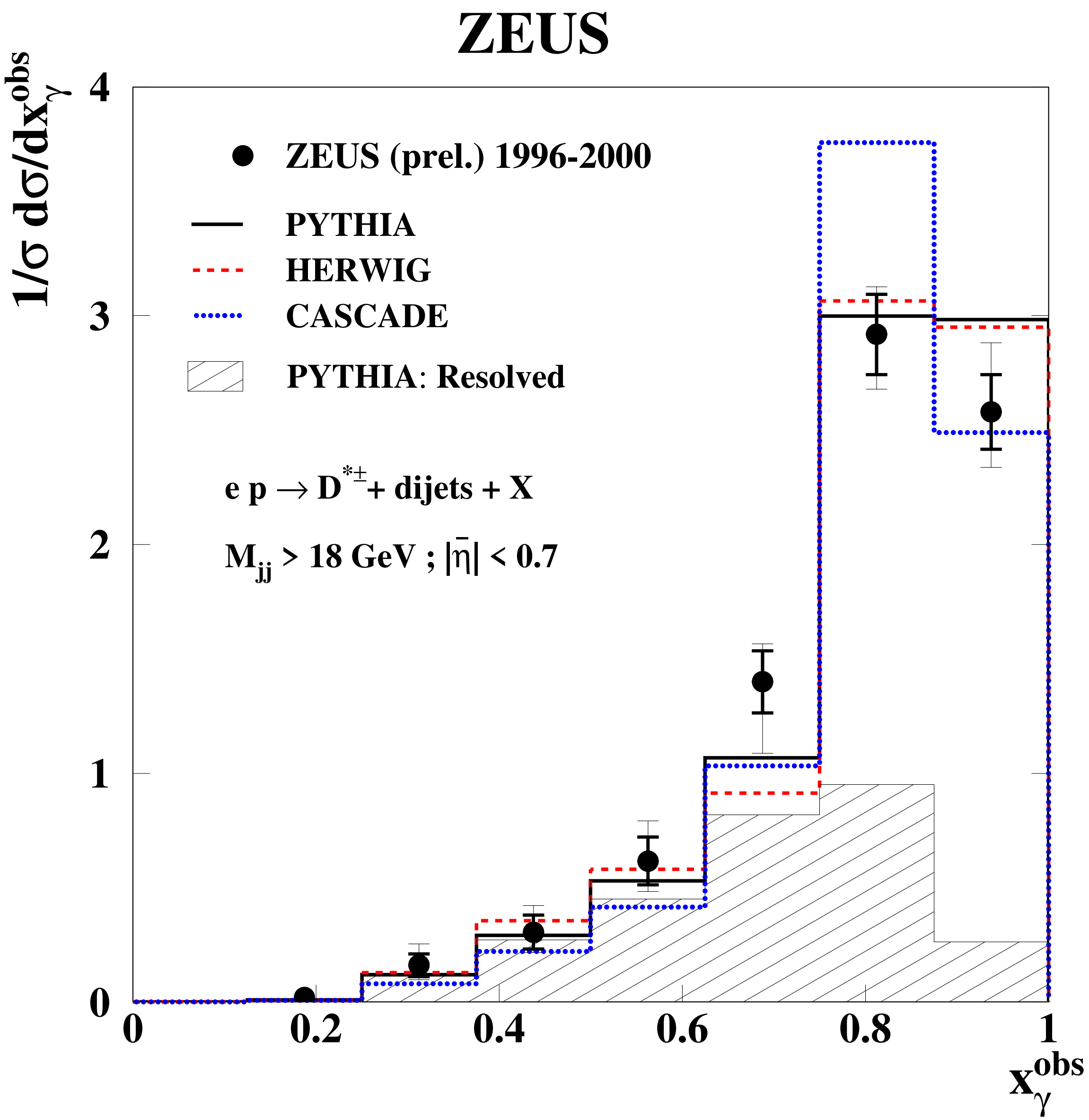
Charm and Jets — x_γ Distribution

$$x_\gamma^{obs} = \frac{\Sigma E_T^{jets} e^{-\eta^{jets}}}{2yE_e}$$

- Normalised x_γ cross section
- Compared to several LO MC models

▷ LO models describe data

- Previous results have shown that NLO predictions undershoot cross section at low x_γ^{obs}



Charm with Dijet Production

$\cos\theta^{\star}$: **Angle between the jet - jet axis and beam axis in the dijet rest frame**

$$\cos\theta^{\star} = \tanh\frac{\eta^{jet1} - \eta^{jet2}}{2}$$

- **Dependance of $\sigma(\cos\theta^{\star})$ on the propagator:**

▷ **q propagator:** $\sigma \propto$ **(1 -** $|\cos\theta^{\star}|)^{-1}$

▷ **g propagator:** $\sigma \propto$ **(1 -** $|\cos\theta^{\star}|)^{-2}$

- **Associate $D^{\star}$ with one of the jets**

▷ $\cos\theta^{\star} > 0$ **is the proton direction**

▷ $\cos\theta^{\star} < 0$ **is the photon direction**

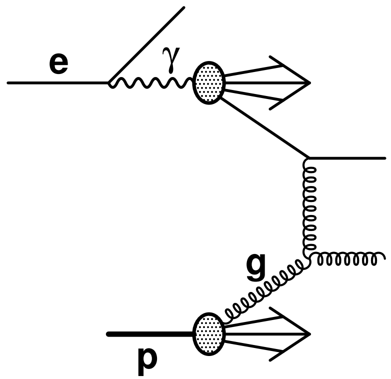
- **Using $\cos\theta^{\star}$ it is possible to determine the propagator for charm production**

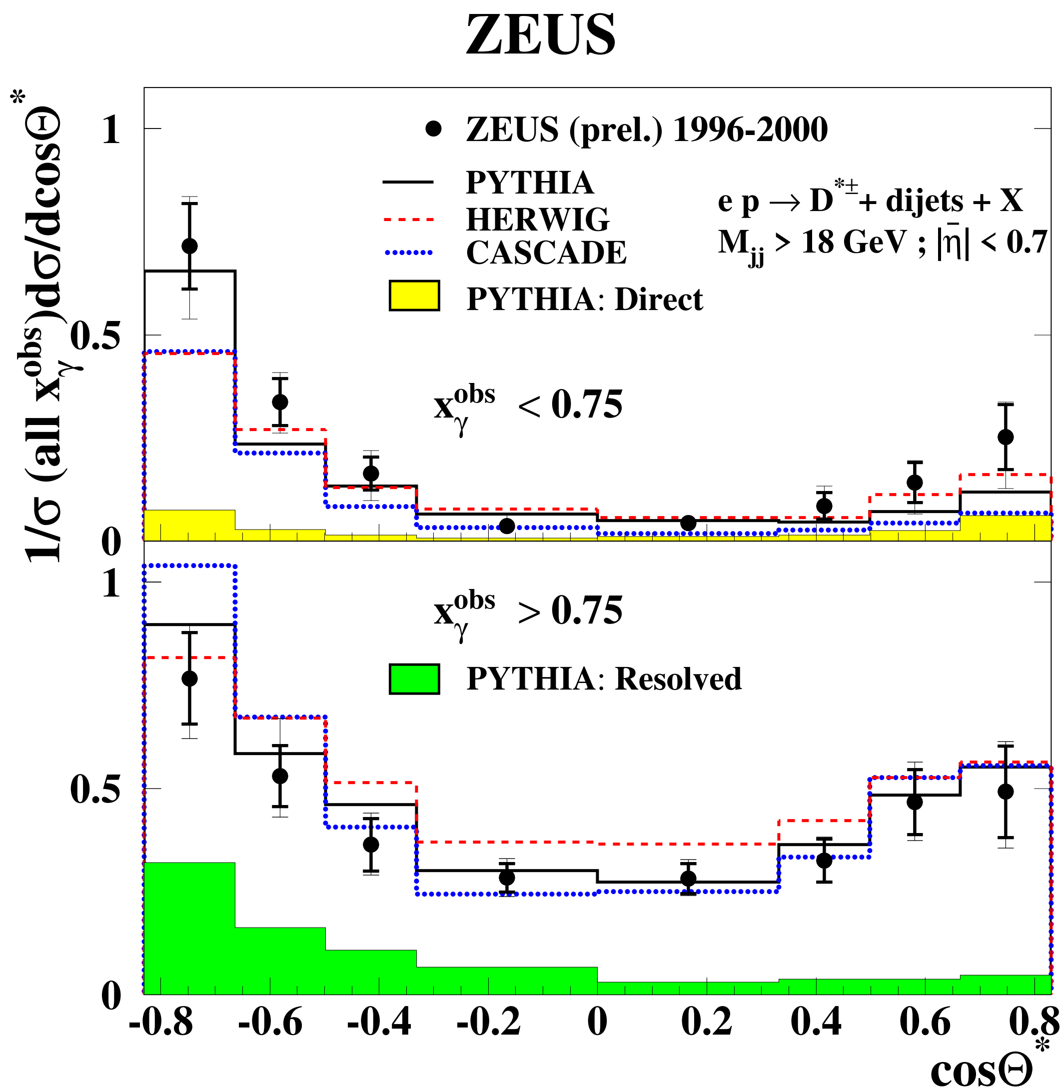
Charm and Jets

- Idea: Probe production mechanism
- Direct: Approx. Symmetric

▷ Boson Gluon Fusion

- Resolved: Strong assymetry in photon direction



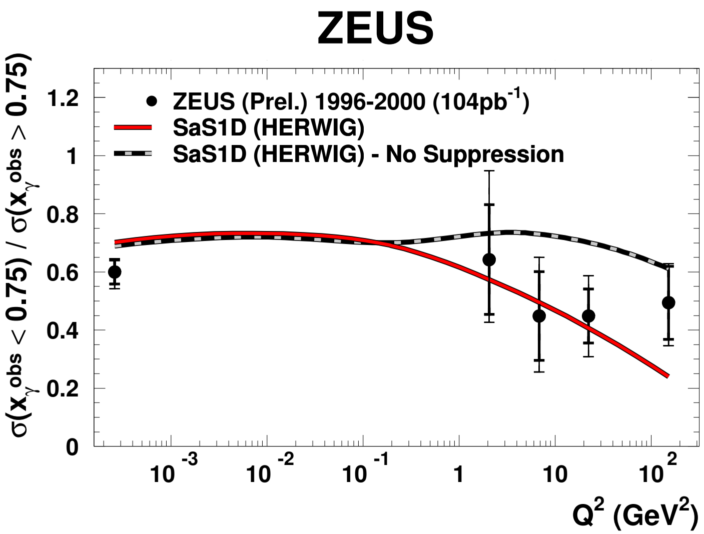


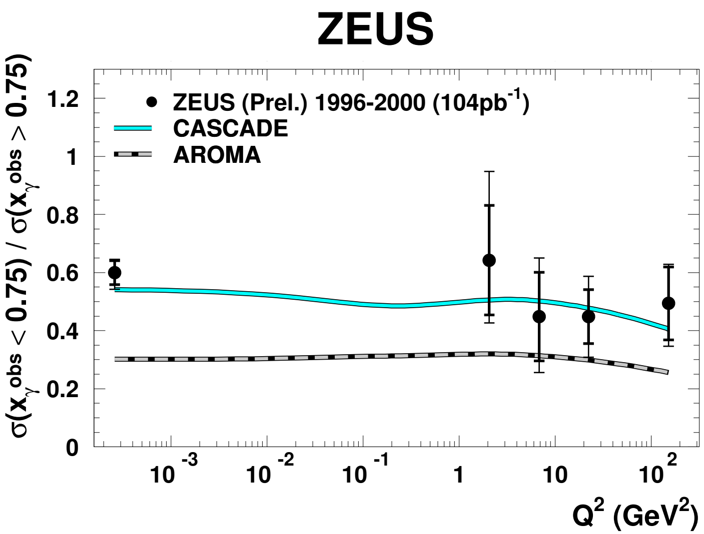
▷ Strong evidence for charm in the photon

The Virtual Photon and Charm

$$R = \frac{\sigma(x_\gamma^{\rm OBS} < 0.75)}{\sigma(x_\gamma^{\rm OBS} > 0.75)}$$

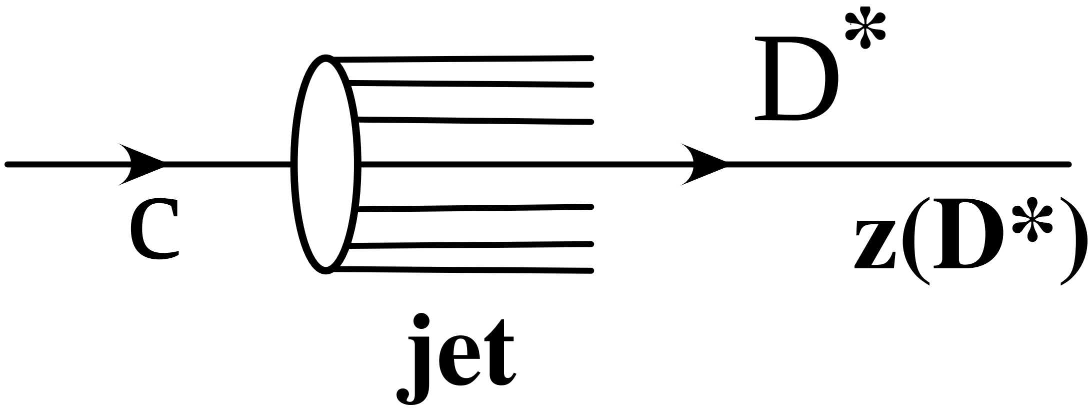
- **Evolution of R with Q^2**
  - ▷ **Resolved fraction with Q^2**
  - ▷ **Surprising that resolved component persists to high Q^2**
- **Model with photon structure describes data**
- **No photon structure**
  - ▷ **DGLAP models underestimates R**
  - ▷ **CCFM describes data**
- **Results can be described either:**
  - ▷ **DGLAP evolution with photon structure**
  - ▷ **Alternative evolution scheme**





Charm Fragmentation

- Fragmentation, c $\rightarrow$ $D^{\star}$, is usually taken from e^{+}e^{-}
- ▷ Is charm fragmentation universal?
- ▷ A major source of uncertainty for theoretical predictions of $D^{\star}$ cross sections
- Measure fragmentation: Charm $\rightarrow$ D* meson
- ▷ Energy fraction, z, carried by D*:



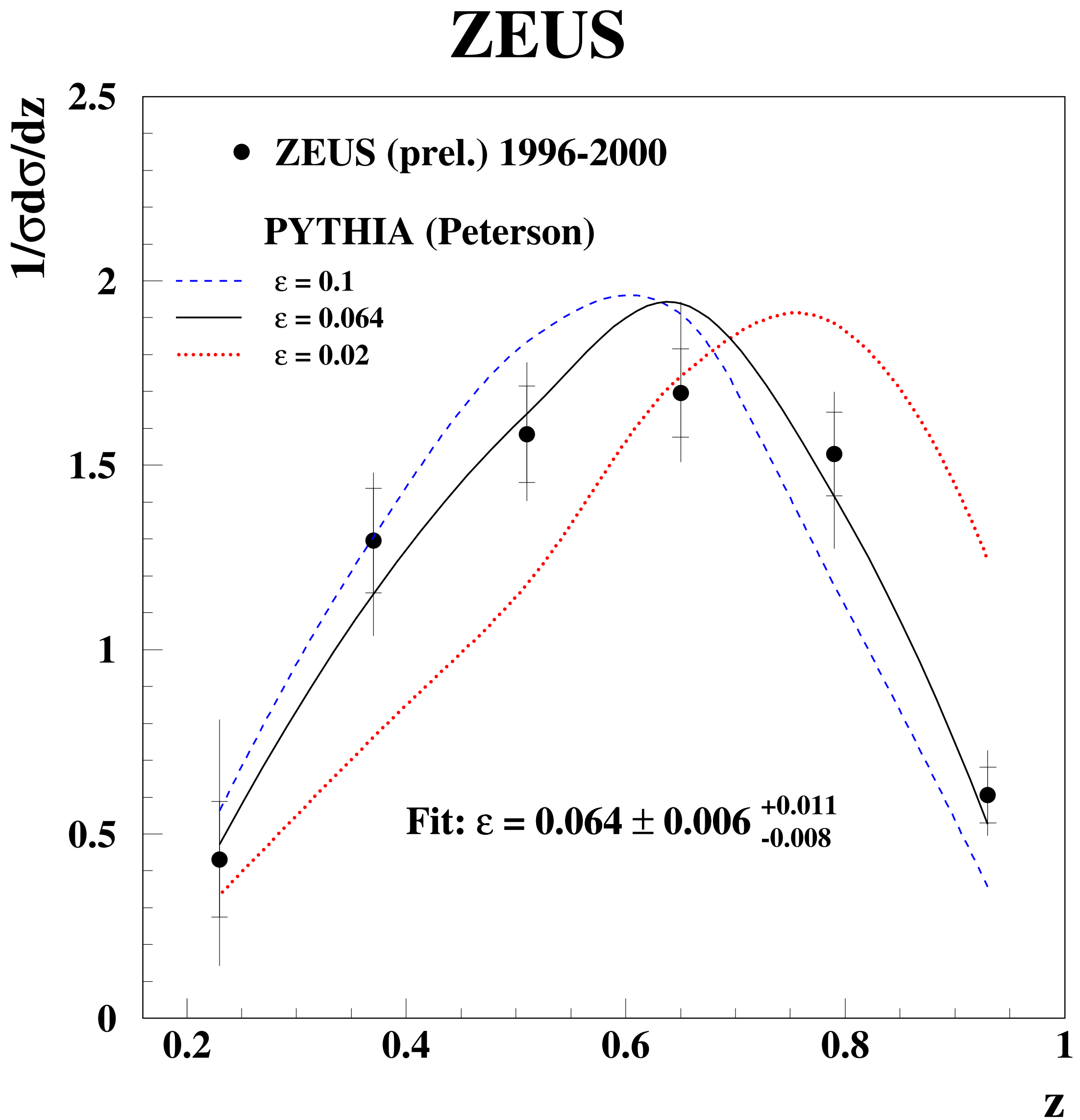
$$z = \frac{(E + p_{\|})^{D^{\star}}}{2E_{jet}}$$

Charm Fragmentation

- Normalised cross section in z
  - Compare to LO MC incorporating Peterson Fragmentation:

$$f(z) = \frac{1}{z(1 - 1/z - \epsilon/(1-z))^2}$$

- Compares well to ϵ from comparable fit to LEP data: ϵ = 0.053 (hep-ph/9903541)
- Strong sensitivity to ϵ value



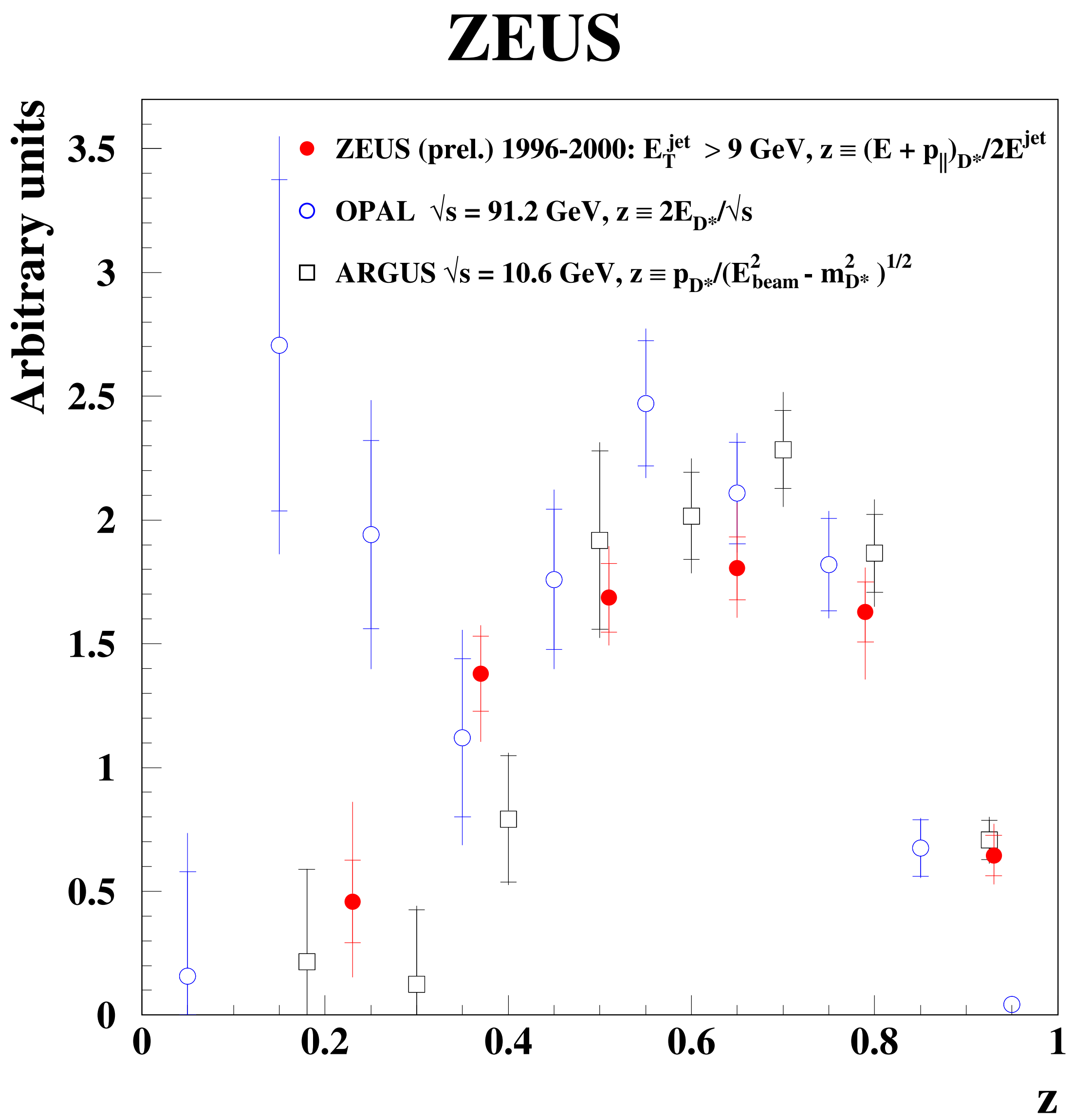
Charm Fragmentation

- **Compare z measured from ep to that from e^+e^-**

▷ *Caveat: z is not the same definition*

- **ep data similar to that from e^+e^-**
- **Very different production process for charm**

▷ **More quantative comparison requires a fit to the data**



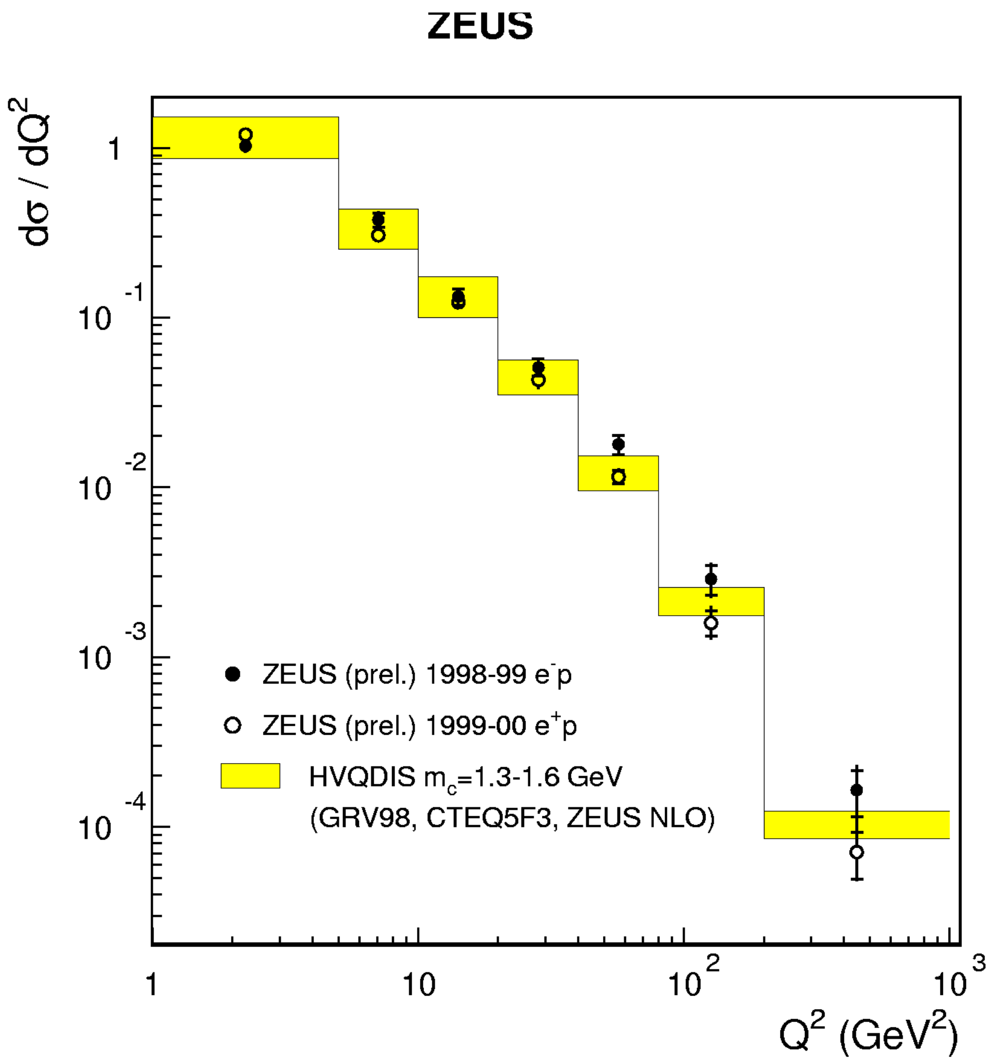
Precision competitive with LEP

Charm in Deep Inelastic Scattering

- Important for understanding charm in the proton
- Tag charm by $D^{\star}$ mesons
- Improvement in errors from previous results

▷ Precision data at high Q^2

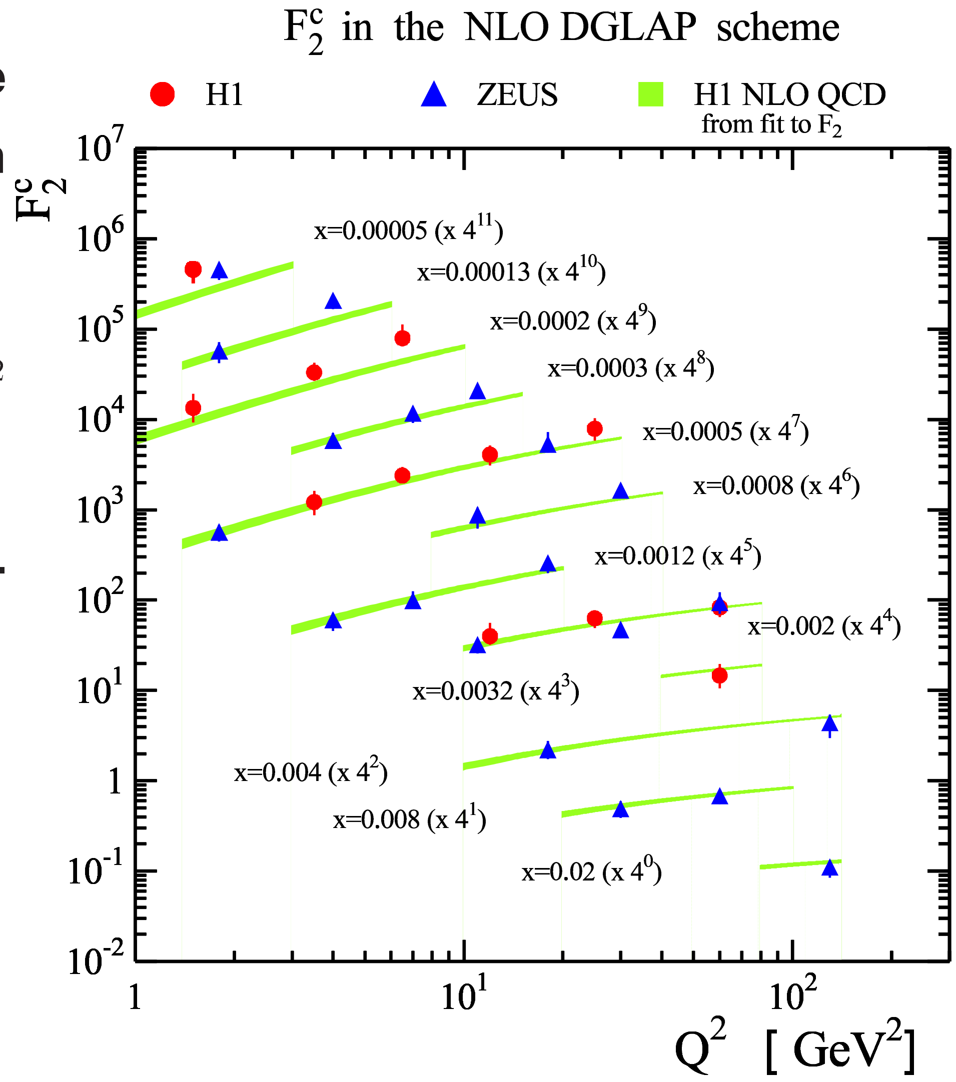
- First time $\sigma(e^-)$ measured at HERA
- $\sigma(e^+)$ and $\sigma(e^-)$ in agreement with pQCD



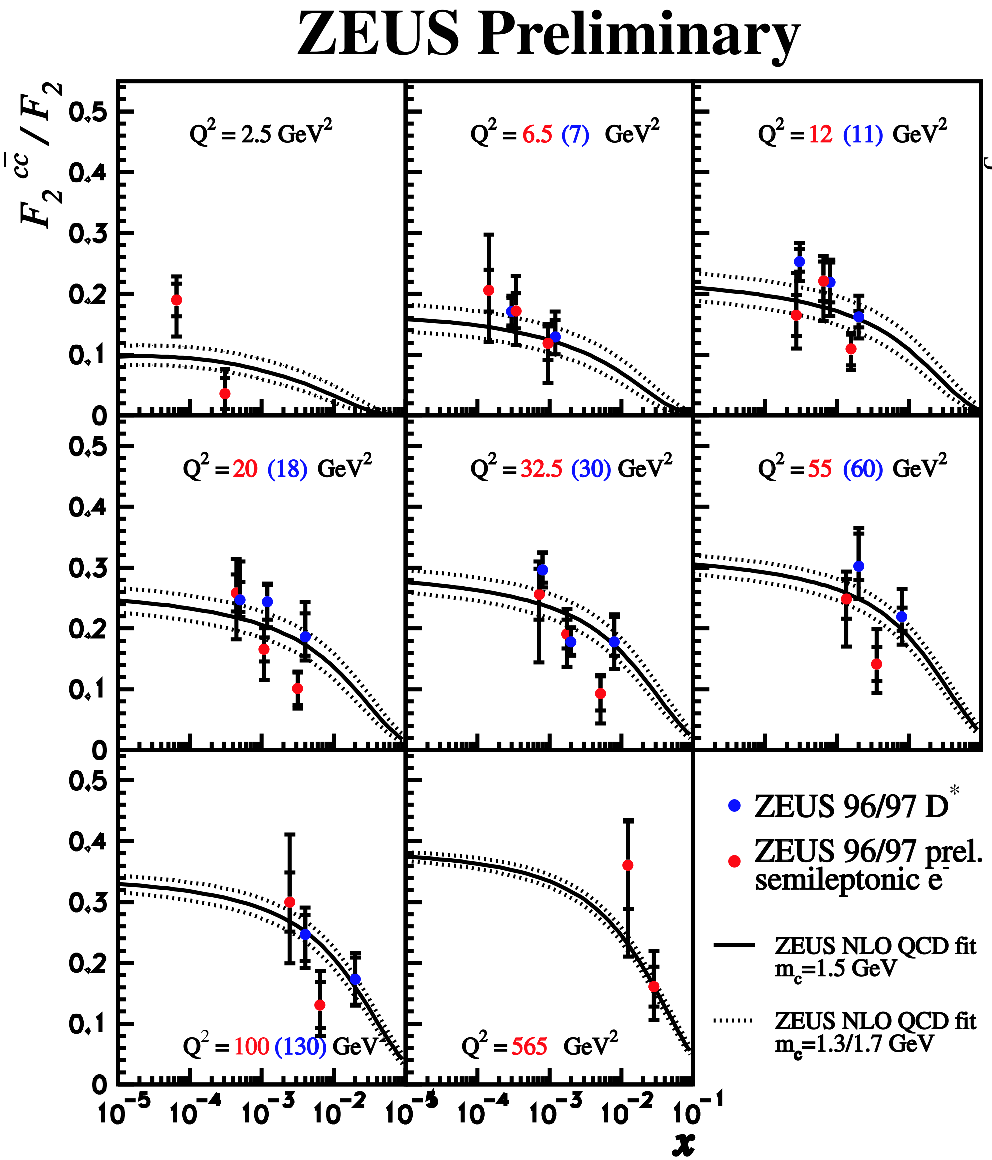
F_2^{charm}

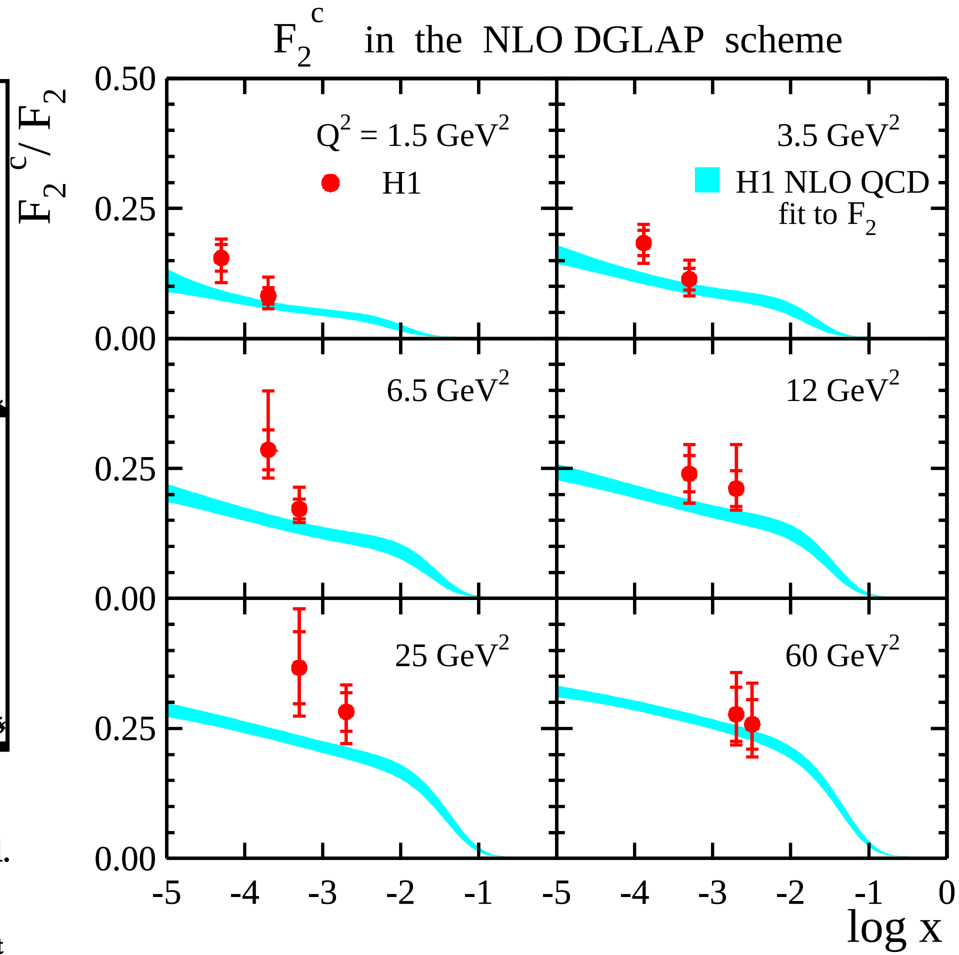
- **Use $D^\star$ cross sections to measure the charm structure function of the proton**

- **Significant scaling violations with Q^2 observed**
  - ▷ **Importance of gluons in charm production**
- **NLO QCD generally agrees with data**
  - ▷ **Slightly lower than data at low x**



Ratio $F_2^{\rm charm} / F_2$



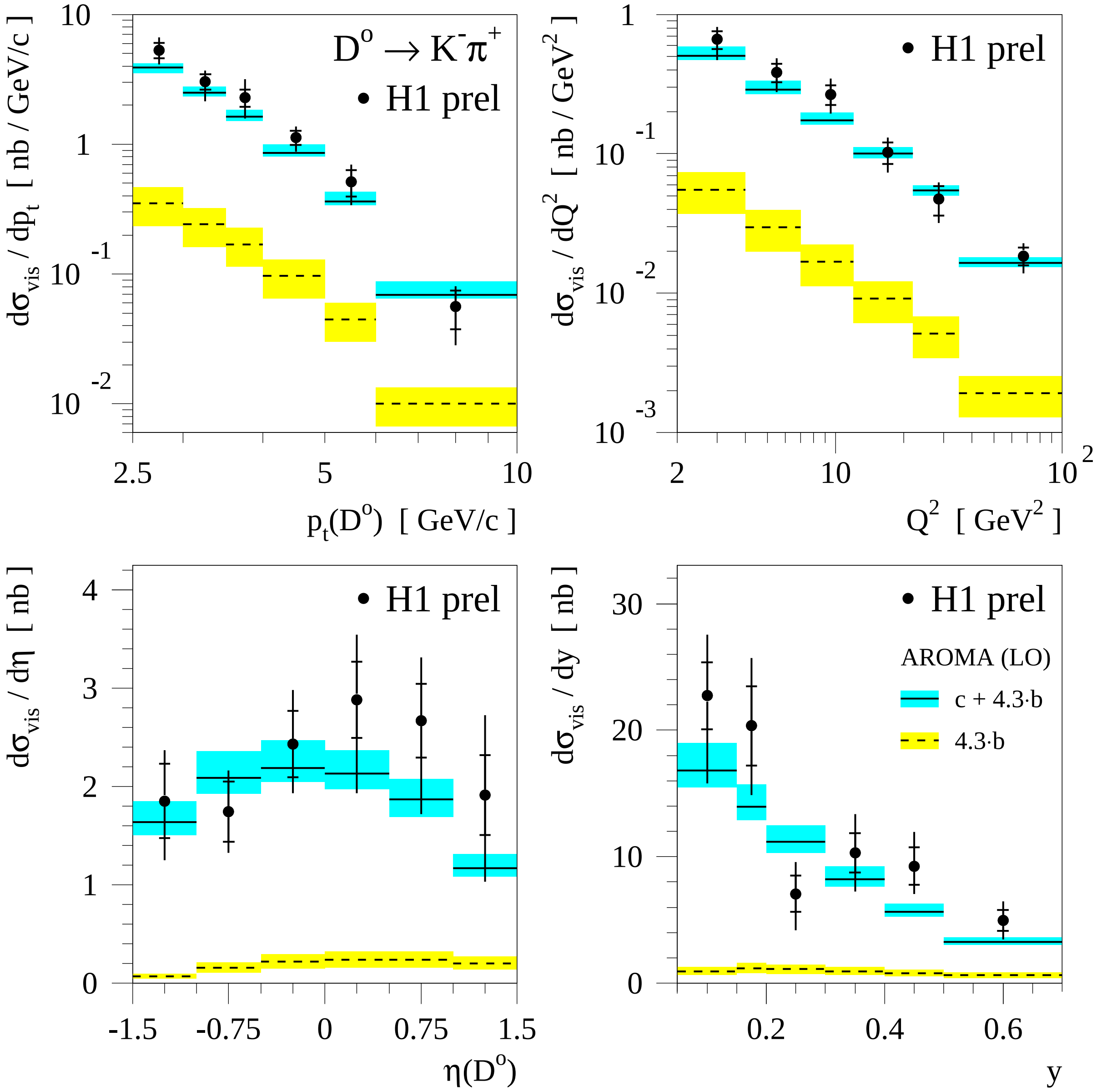


- What fraction of F_2 is charm?
- $F_2^{\rm charm} / F_2$ large at low x, high Q^2

▷ Above 30 % at highest Q^2

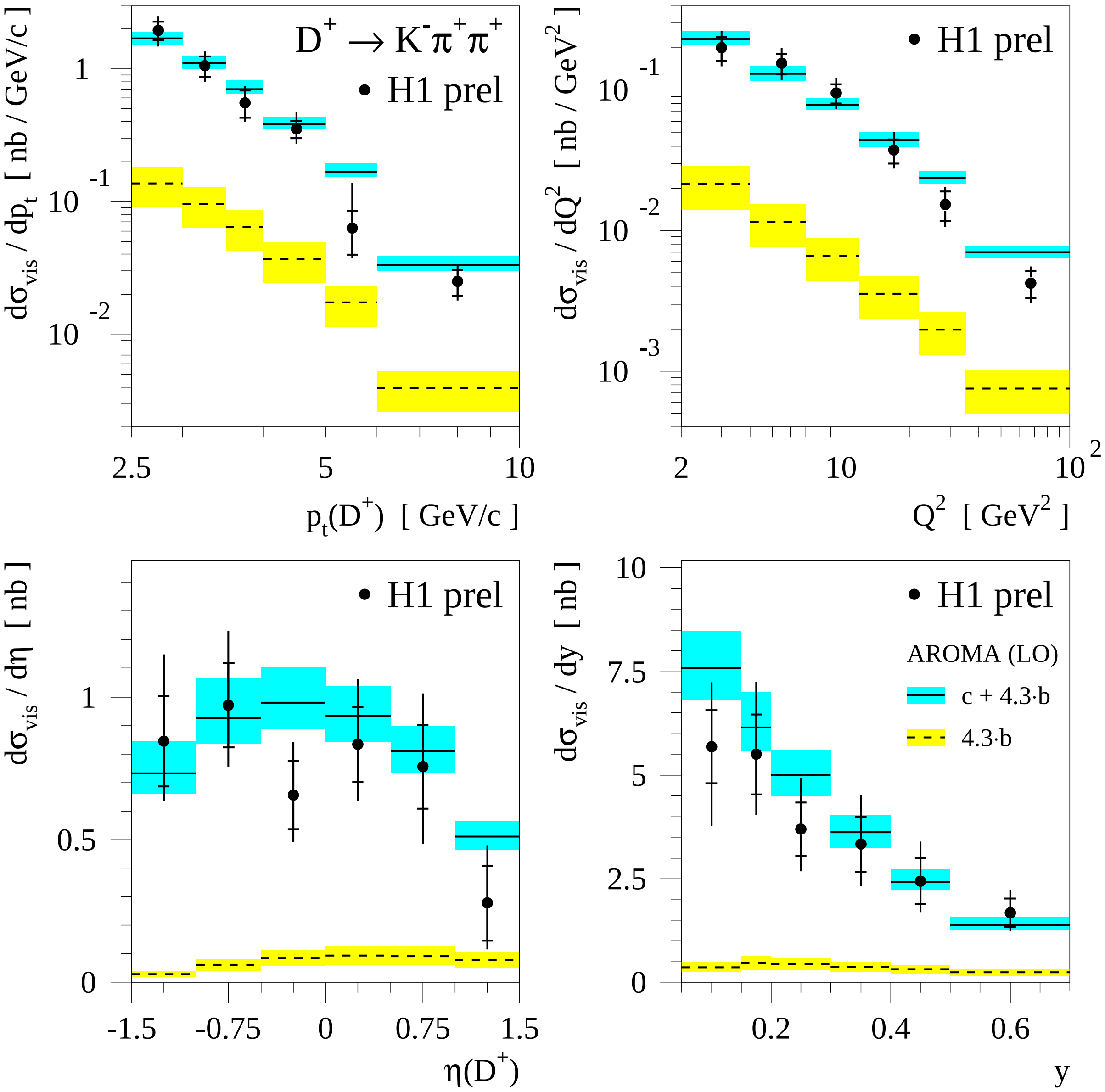
D Meson Production in Deep Inelastic Scattering

- $F_2^{c\overline{c}}$ is quite model dependent
  - ▷ Better to look at Meson production cross sections
- Look at the production cross section for various D mesons in deep inelastic scattering
  - ▷ Can then compare relative cross sections
- Differential cross sections for D^0 Meson production
  - ▷ LO MC model (AROMA) describes the data well



D Meson Production in Deep Inelastic Scattering

- Differential cross sections for D^+ production
  - ▷ First measurement at HERA
  - ▷ LO MC model (AROMA) describes the data well



D Meson Fragmentation Ratios

- From measured cross sections, calculate ratios of different quark / spin states

- P_V is fraction of vector mesons in fragmentation process
  - ▷ H1 (Prel): P_V = 0.693 $\pm$ 0.045 $\pm$ 0.010
  - ▷ ZEUS (Prel): P_V = 0.546 $\pm$ 0.045 $\pm$ 0.028
  - ▷ World average: 0.601 $\pm$ 0.032

$$P_V = \frac{VM}{VM + PS}$$

- γ_s is the strangeness suppression factor
  - ▷ H1 (prel): 0.36 $\pm$ 0.10 $\pm$ 0.08
  - ▷ ZEUS: 0.27 $\pm$ 0.05
  - ▷ World average: 0.26 $\pm$ 0.07

HERA results agree within errors with world averages

▷ Supports the idea of Charm Universality

- $R_{u/d}$ is the ratio of u - d quark differences
  - ▷ H1 (prel): 1.28 $\pm$ 0.19 $\pm$ 0.12
  - ▷ World average: 1.00 $\pm$ 0.09

HERA results compare favourably to world averages

Diffraction at HERA

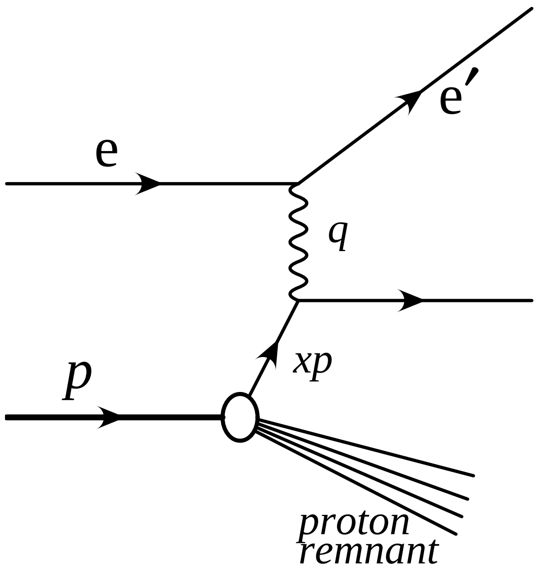
About 10$\%$ of events at HERA have little or no activity in the forward direction

▷ Termed Diffractive events

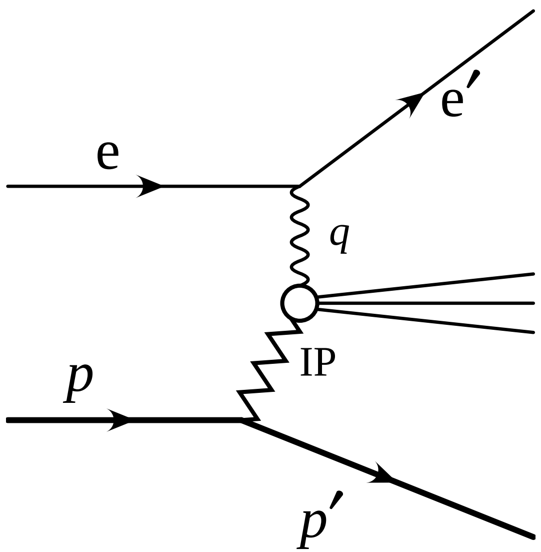
▷ Should be suppressed due to parton radiation into the colour field between struck quark and proton remnant

▷ Often described in terms of exchange of a colourless object - the pomeron ($I\!P$)

"Standard" DIS



"Diffractive" DIS

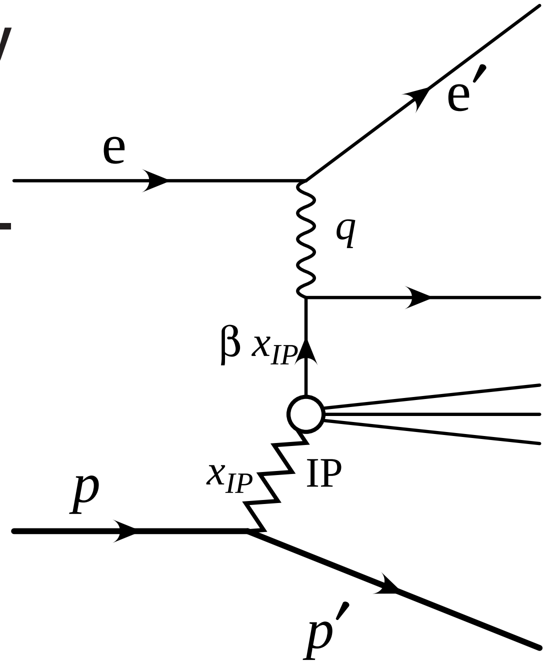


▷ What is the diffractive exchange?

Models of Diffraction

Resolved $I\!P$ approach $\longrightarrow$ partonic $I\!P$

- $x_{I\!P}$ is fraction of the proton's momenta carried by pomeron
- β - fraction of pomeron momenta that struck parton carries



The cross section factorises (Collins, 1997):

$$F_2^D \sim f^D \otimes \hat{\sigma}$$

$\longrightarrow$ Diffractive Parton Densities

Alternative approaches include 2 gluon exchange model

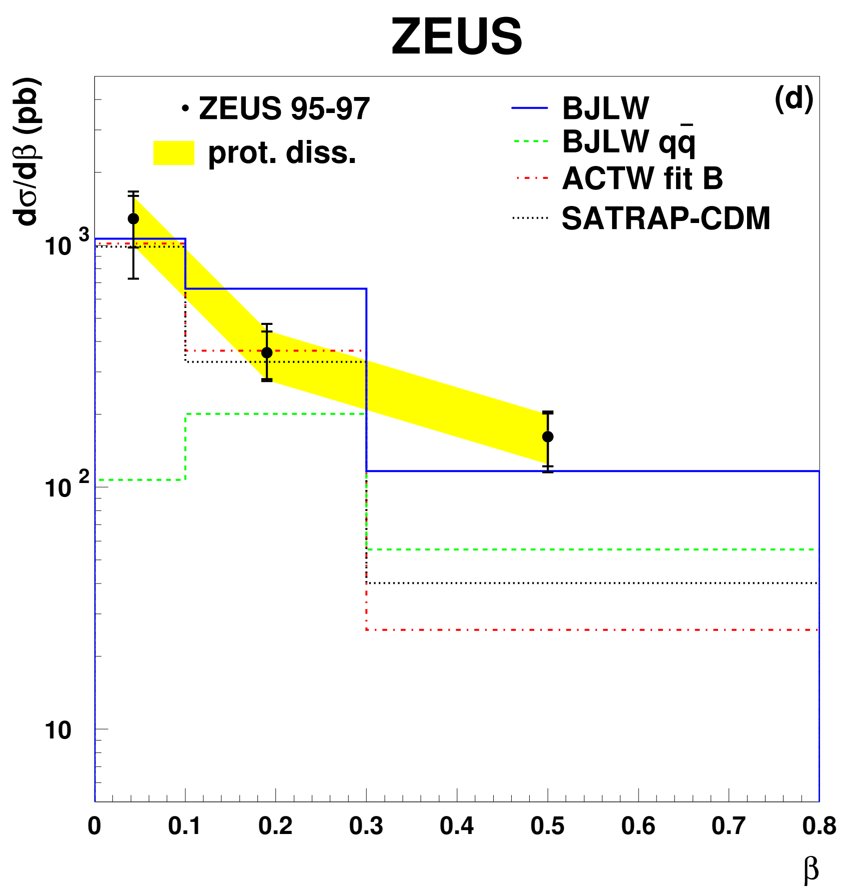
▷ Charm accesses gluonic part of exchange

▷ $m_c \longrightarrow$ pQCD should be valid

Investigate Pomeron Structure in the same way as for proton and photon ($\longrightarrow$)

Diffractive Charm Production in Deep Inelastic Scattering

- **Charm is sensitive to gluons**
  - ▷ **Gluonic content of pomeron**
- **Differential cross section shown vs β**
- **Models with 2 gluon exchange seem to be able to describe results better**

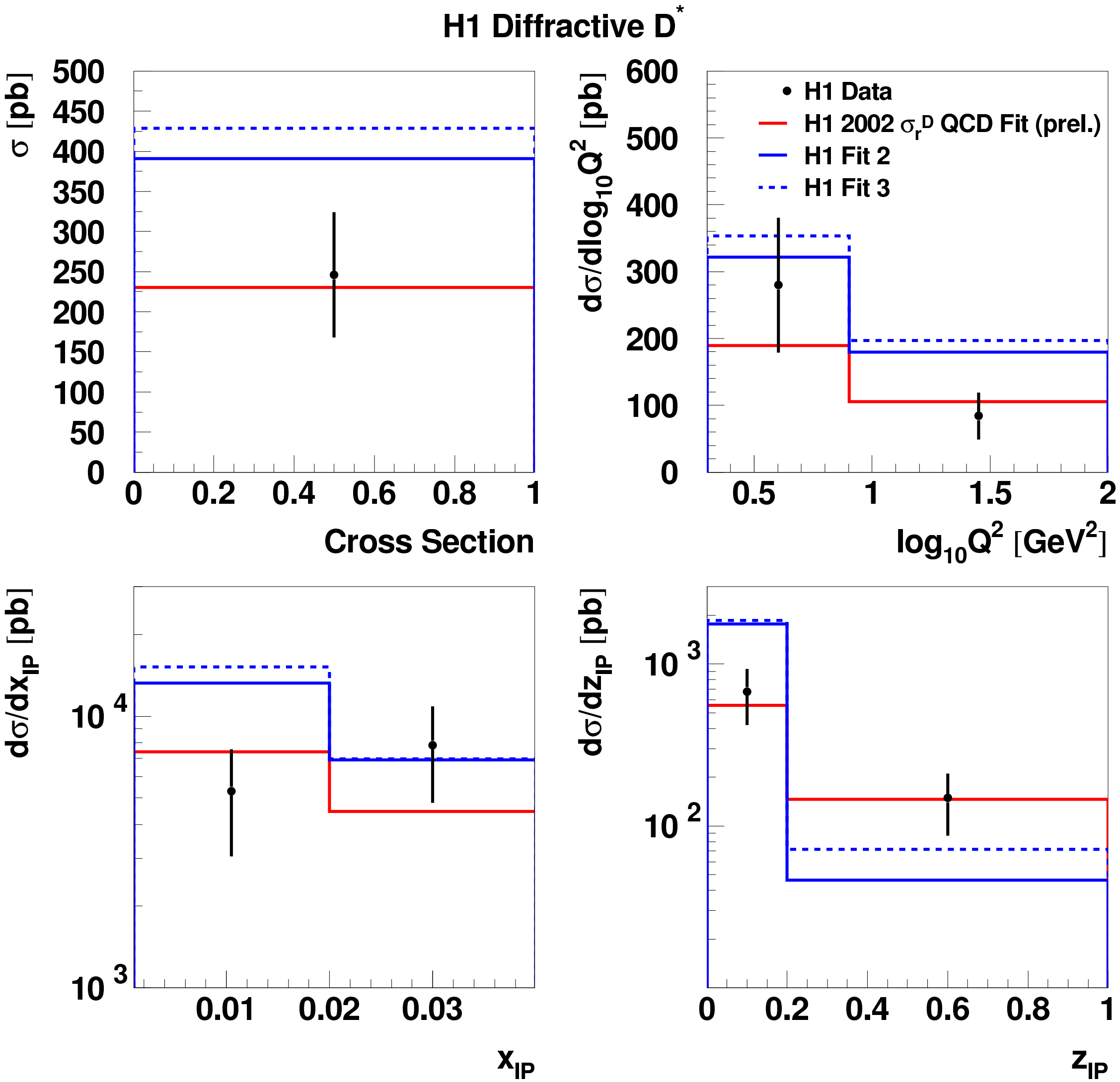


ACTW — Resolved Pomeron Model

BJLW — 2 gluon exchange model

Diffractive Charm Production in Deep Inelastic Scattering

- H1 measure larger range in $x_{I\!P}$
- Measured $x_{I\!P}$ is flat within errors
- What is the effect of varying the parton densities in the $I\!P$?
- Compare predictions from new H1 QCD fit to diffractive data
- Effect of new pdf's in resolved pomeron model significant
- ▷ New fit appears to describe the charm data better
- Charm in diffraction can help constrain $I\!P$ pdf's

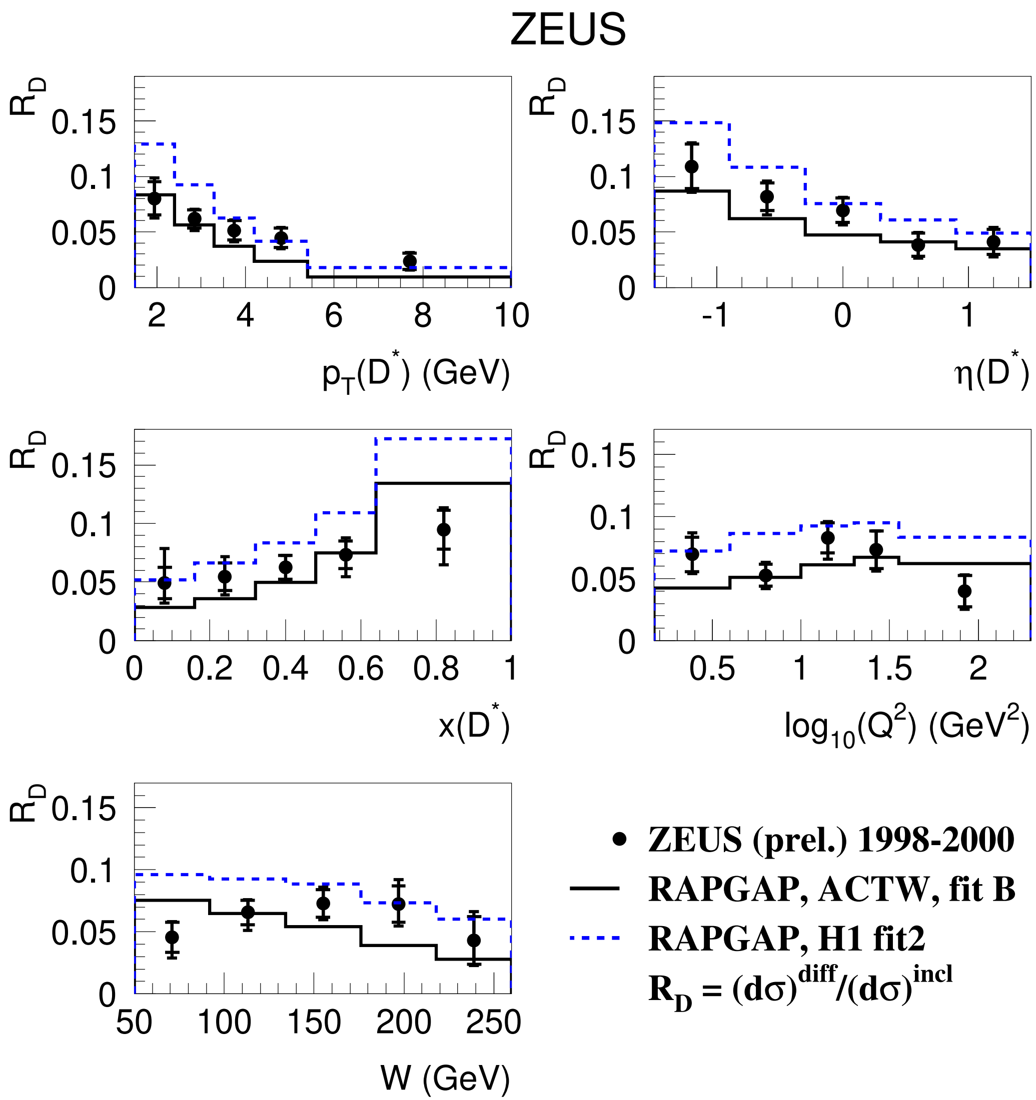


Diffractive Charm Production in Deep Inelastic Scattering

- Look at ratio of diffractive to inclusive $D^\star$ production

▷ About 6% of $D^\star$ production is diffractive in nature

- Diffractive $D^\star$ production appears to be harder in P_T and softer in x($D^\star$) than predicted
- ACTW and H1 Fit 2 are diffractive parton densities
- Sensitivity to diffractive pdf's
- Ratio looks powerful in terms of discriminating between different theoretical models



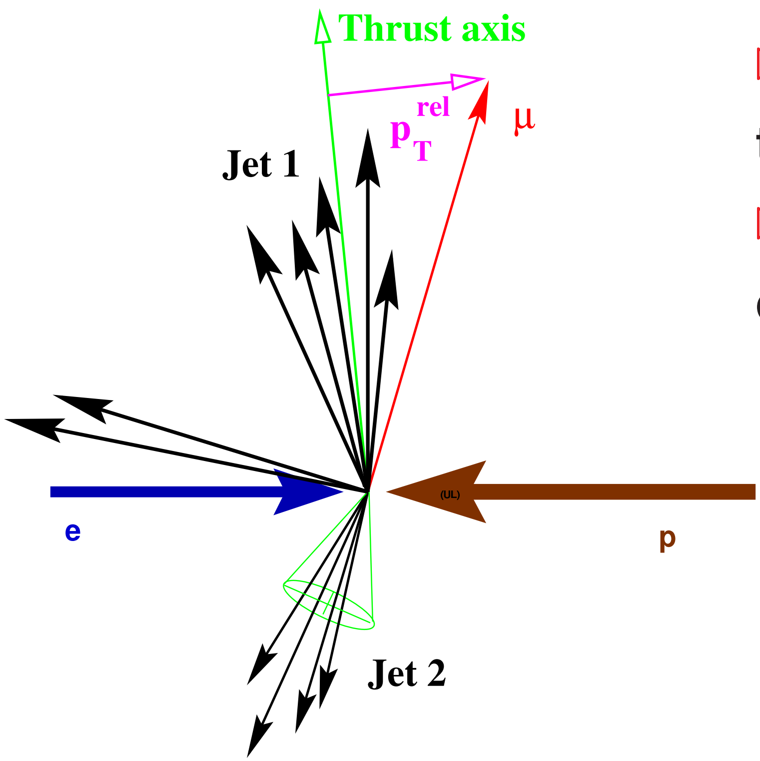
x($D^\star$) — fractional momentum of $D^\star$ in $\gamma^\star p$ system

Tagging Beauty at HERA

- At HERA, $\sigma(b) \sim 1\% \, \sigma(c)$

▷ Good background rejection needed

- Semileptonic decays have relatively low background and high branching fraction



▷ Large fraction of background is charm semileptonic decays

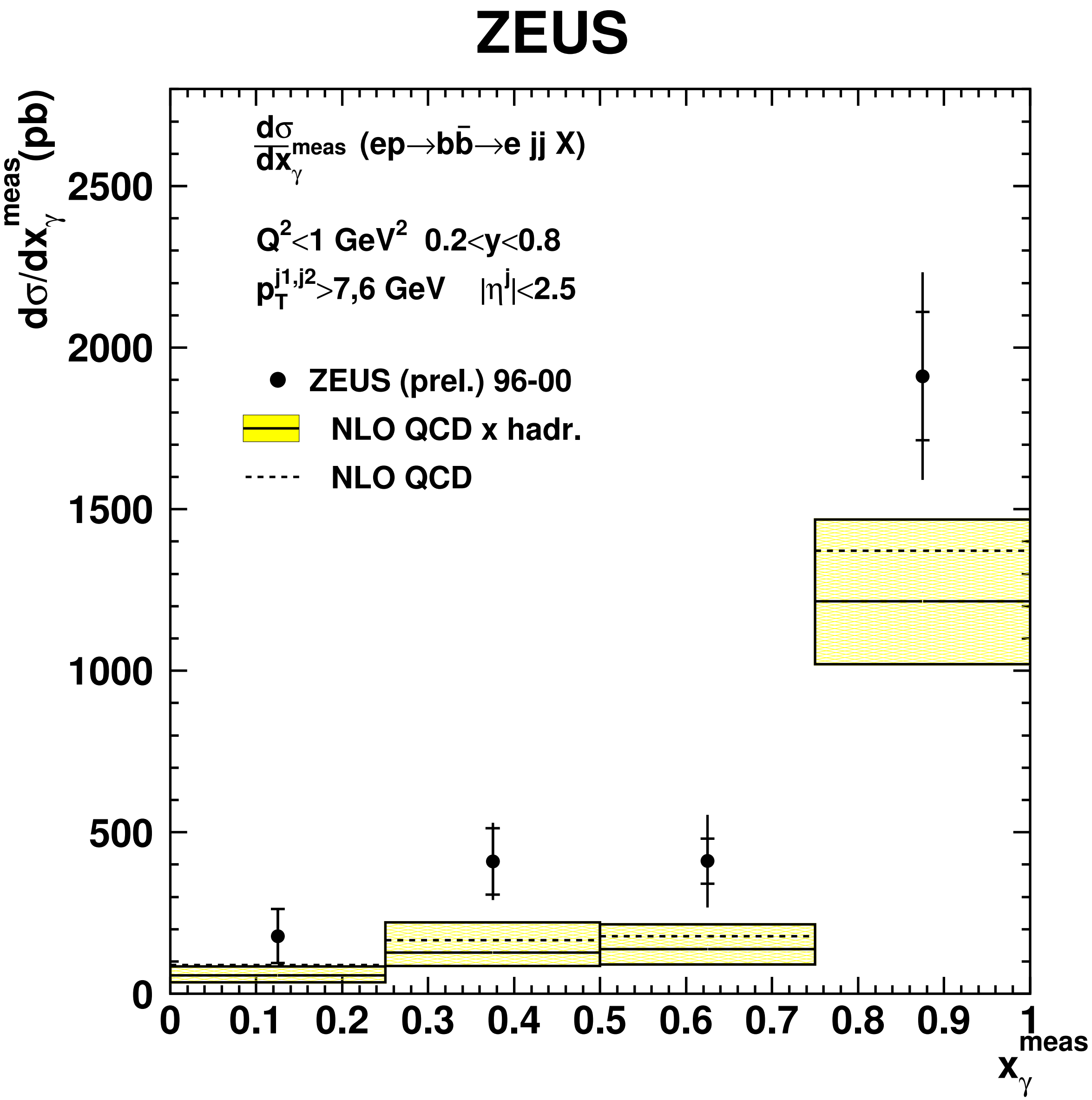
▷ P_T^{rel} can seperate beauty from charm (and light quark) decays

- Impact parameters can also be used to clean up the sample

- Double Tagged Events represent a clean way to tag beauty events

Beauty Production — x_γ Distribution

- **Beauty + Dijets**
- **Beauty component identified here with muons and a fit to the P_T^{rel} distribution**
- **x_γ Distribution measured**
  - ▷ **Significant resolved component also in beauty production**
  - ▷ **NLO underestimate both resolved and direct beauty production**



Beauty Production — Double Tagged Events

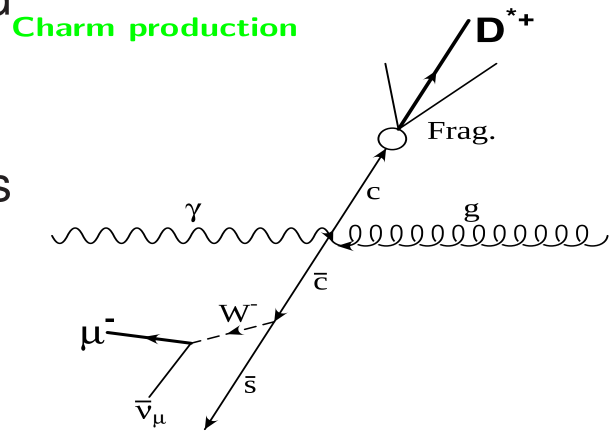
- Double tagged events possible from both charm and beauty:
- Identify $D^\star$ Meson from decay of one of the heavy quarks
- Identify μ from decay of another heavy quark

▷ Charm: Q(μ) $\neq$ Q($D^\star$)

▷ Beauty: Muons can come from either charm or beauty decays

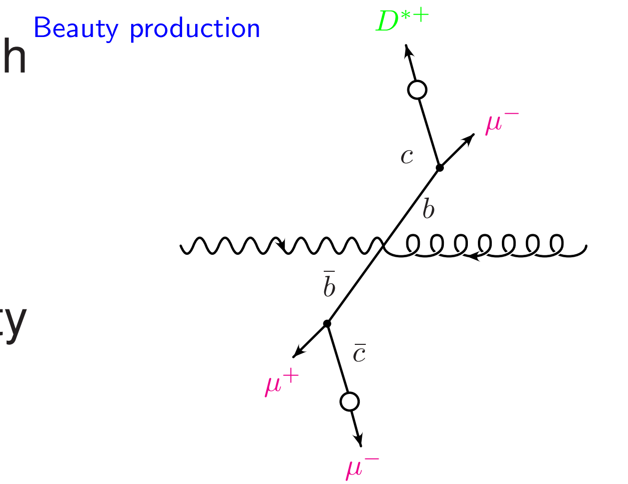
- Angular and charge correlations can be used to distinguish charm from beauty
- Double tagged events are a clean way to extract a beauty signal

Correlations in the γg-CMS (I)

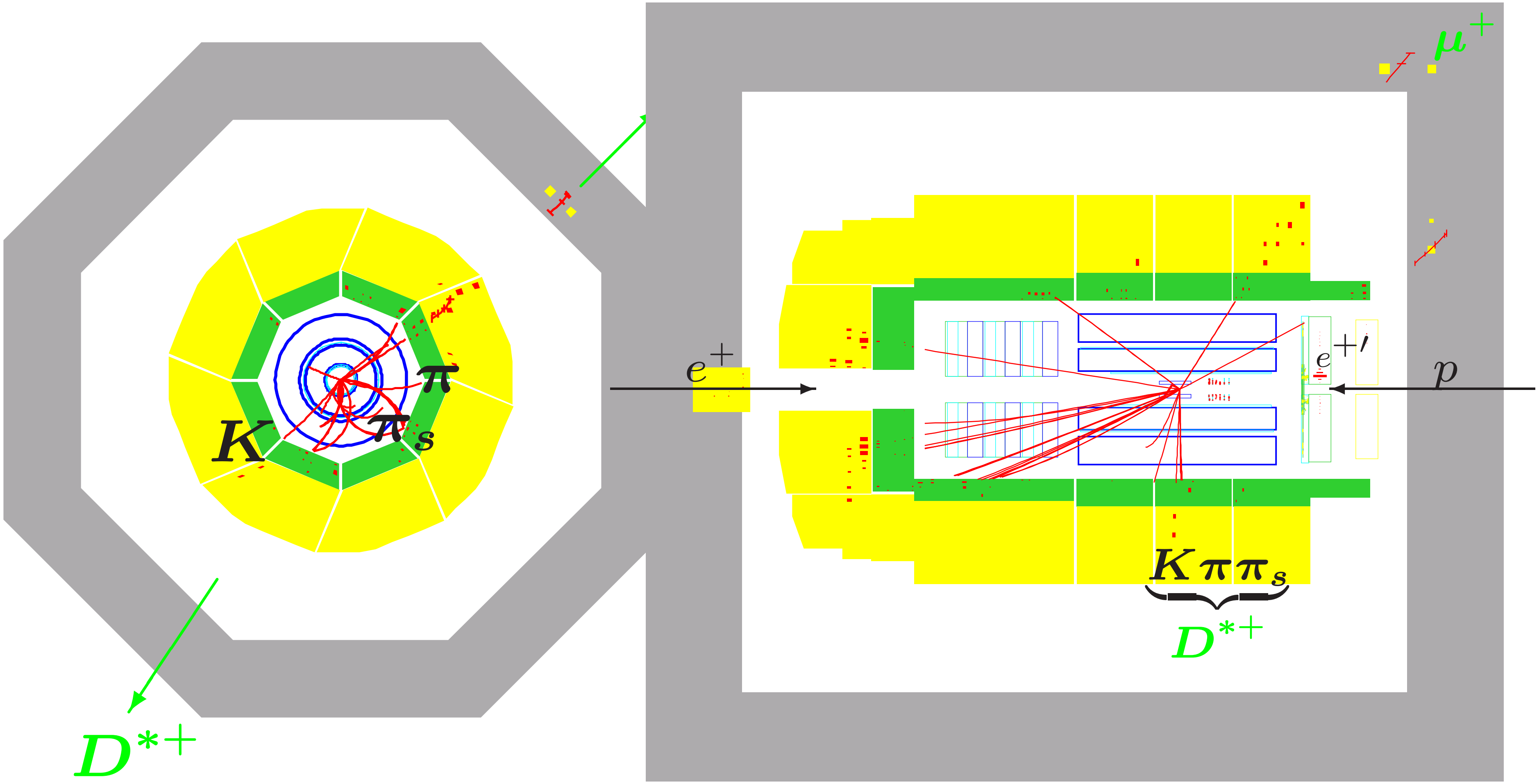


$\Delta\Phi \approx 180°$
$Q(D^*) \neq Q(\mu)$

Correlations in the γg-CMS (II)

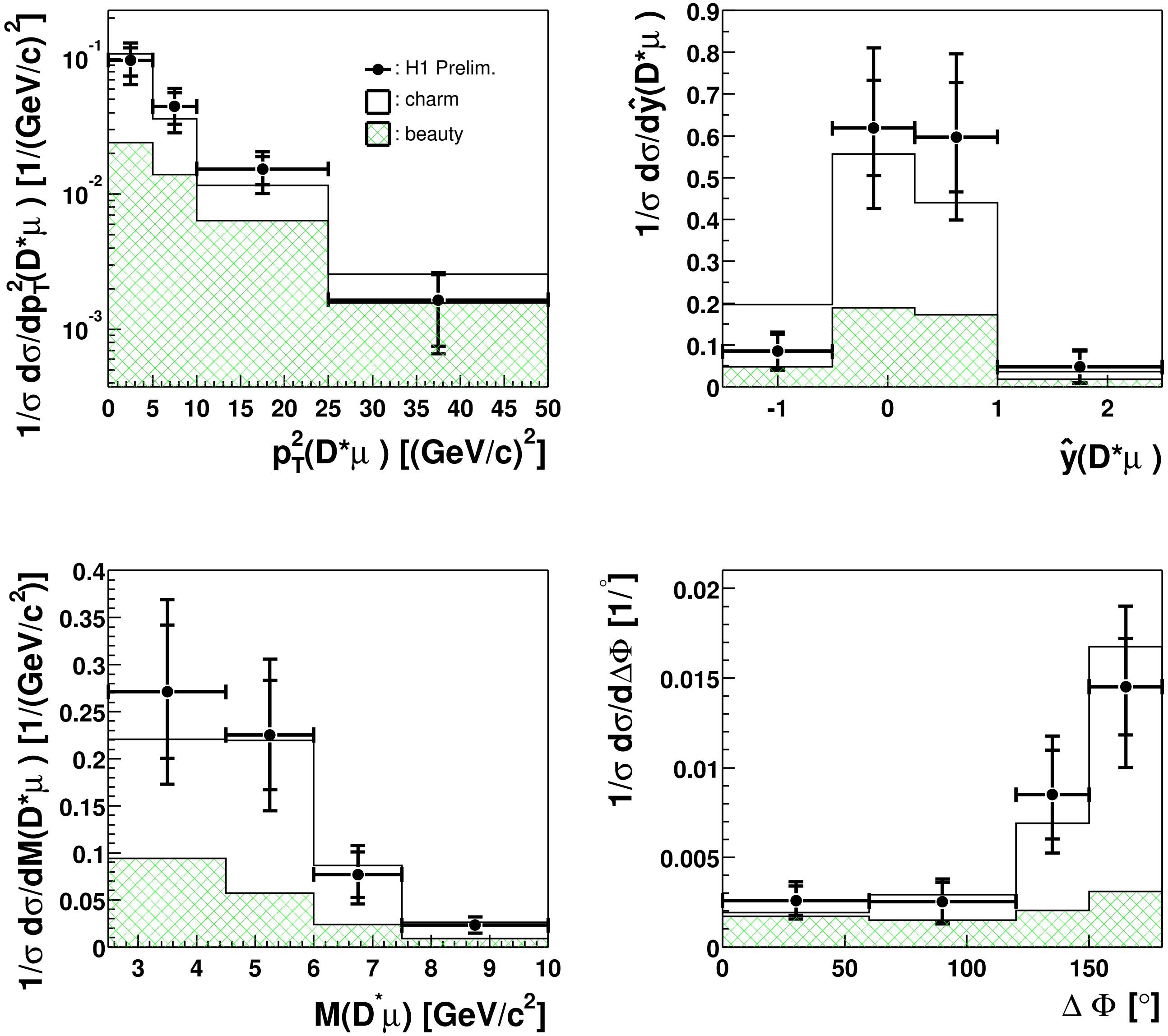


Beauty Production — Double Tagged Events



Charm + Beauty Production — Double Tagged Events

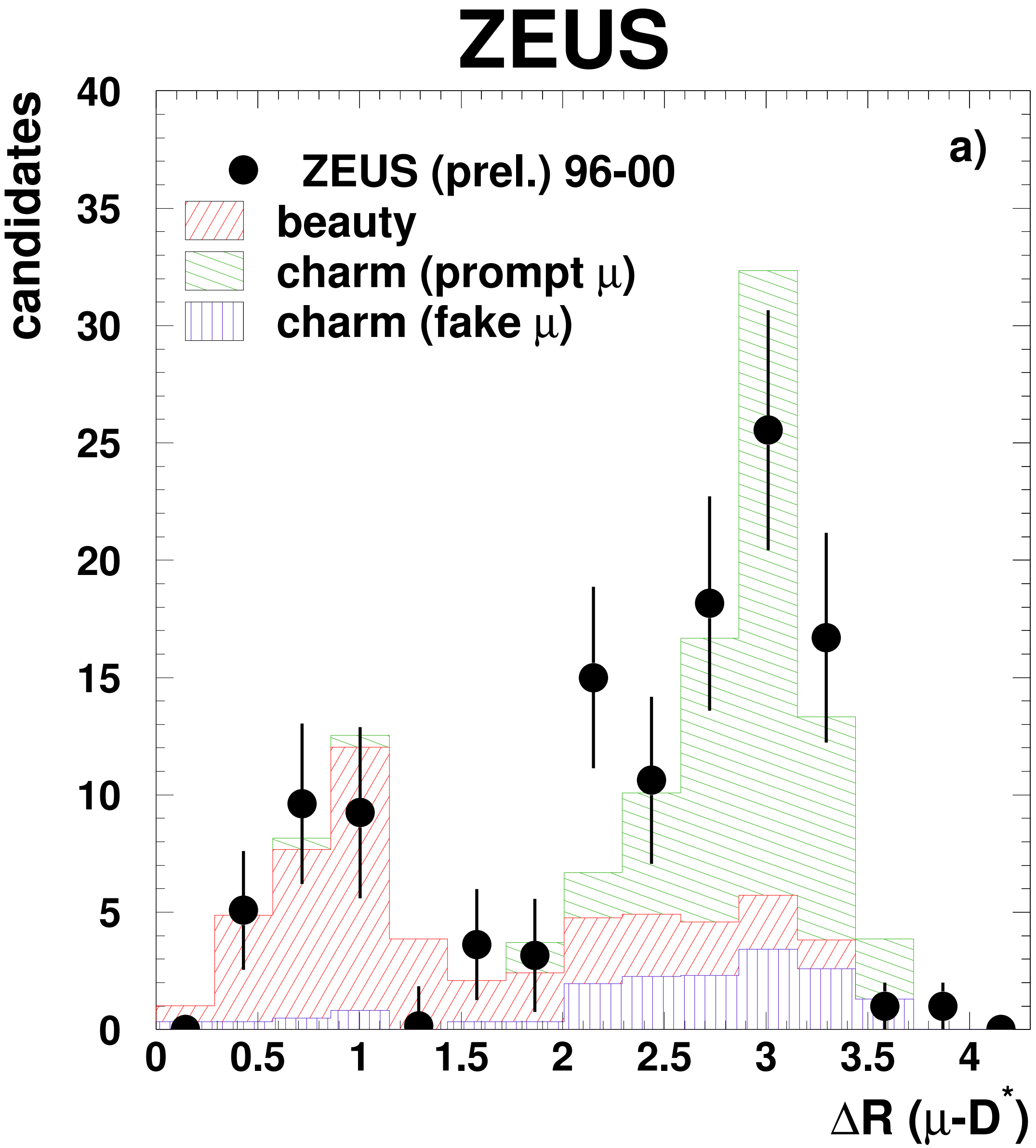
- Cross sections of charm + beauty production
  - ▷ P_T, rapidity, mass and separation of the $D^{\star}\mu$ pair
  - ▷ Compare to LO MC AROMA
  - ▷ Charm × 1.8
  - ▷ Beauty × 3.6
- Shape agrees between MC and Data
- These can be used to look at pQCD and non-pQCD effects in heavy quark production



Beauty Production — Double Tagged Events

- **Use ΔR to distinguish beauty from charm**
  - ▷ **ΔR is the separation of the μ and $D^\star$ in η-ϕ space**
- **Measured cross section:**
  - ▷ **$\sigma = 214 \pm 52^{+196}_{-84}$ pb (ZEUS prel.)**

$p_T^{D^\star} > 1.9$ GeV, $-1.5 < \eta(D^\star) < 1.5$
$p_T^{\mu} > 1.4$ GeV, $-1.3 < \eta(\mu) < 1.75$



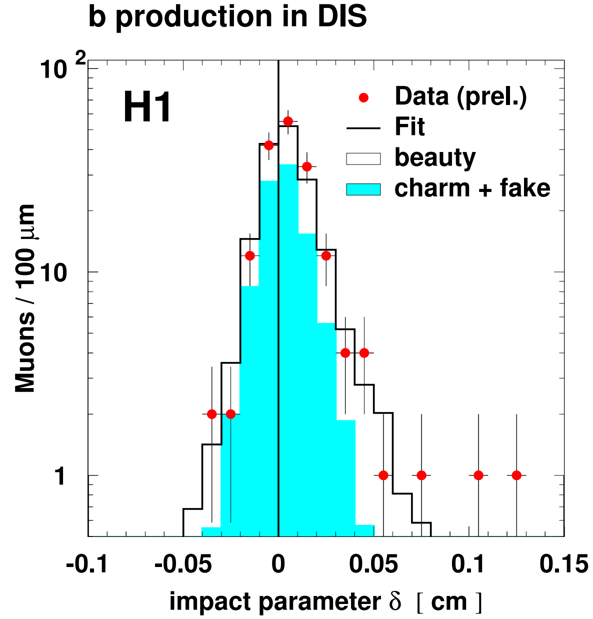
Beauty Production in Deep Inelastic Scattering

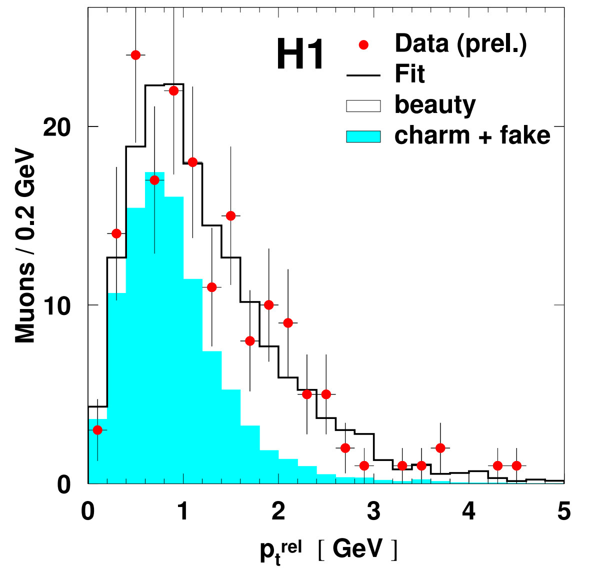
- H1 use impact parameter and P_T^{rel} to select a clean signal
  - ▷ Simultaneous fit to both distributions to extract beauty fraction
- Beauty fraction, $f_b = 43 \pm 8\%$
- Kinematic Region

  $2 < Q^2 < 100$ GeV^2, $0.05 < y < 0.7$

  $p_T^\mu > 2$ GeV, $35^\circ < \theta^\mu < 130^\circ$

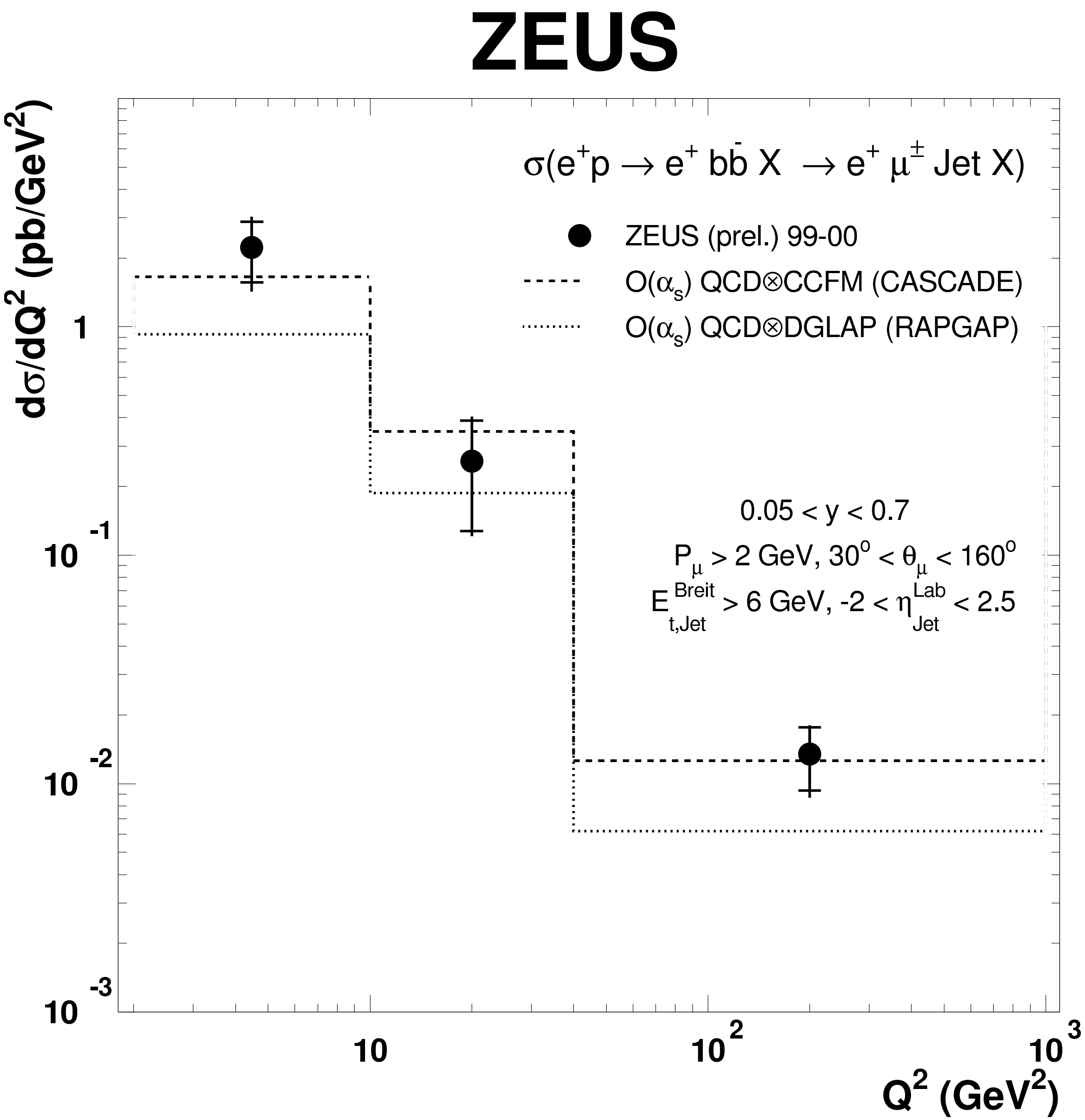
- $\sigma = 39 \pm 8 \pm 10$ pb
- NLO prediction 11 ± 2 pb
- AROMA (with DGLAP evolution) prediction 9 pb
- CASCADE (with CCFM evolution) prediction 15 pb
- Data significantly above NLO pQCD predictions
- LO MC models also underestimate the data





Beauty Production in Deep Inelastic Scattering

- Measure beauty from muon + jet in Breit frame
  - ▷ Extract beauty fraction from P_T^{rel} fit
- Differential Beauty Cross Section vs Q^2
  - ▷ Compared to prediction from LO MC models
  - ▷ CASCADE (with CCFM evolution) provides a good description of the data
  - ▷ RAPGAP (with DGLAP evolution) underestimates cross section at low and high Q^2

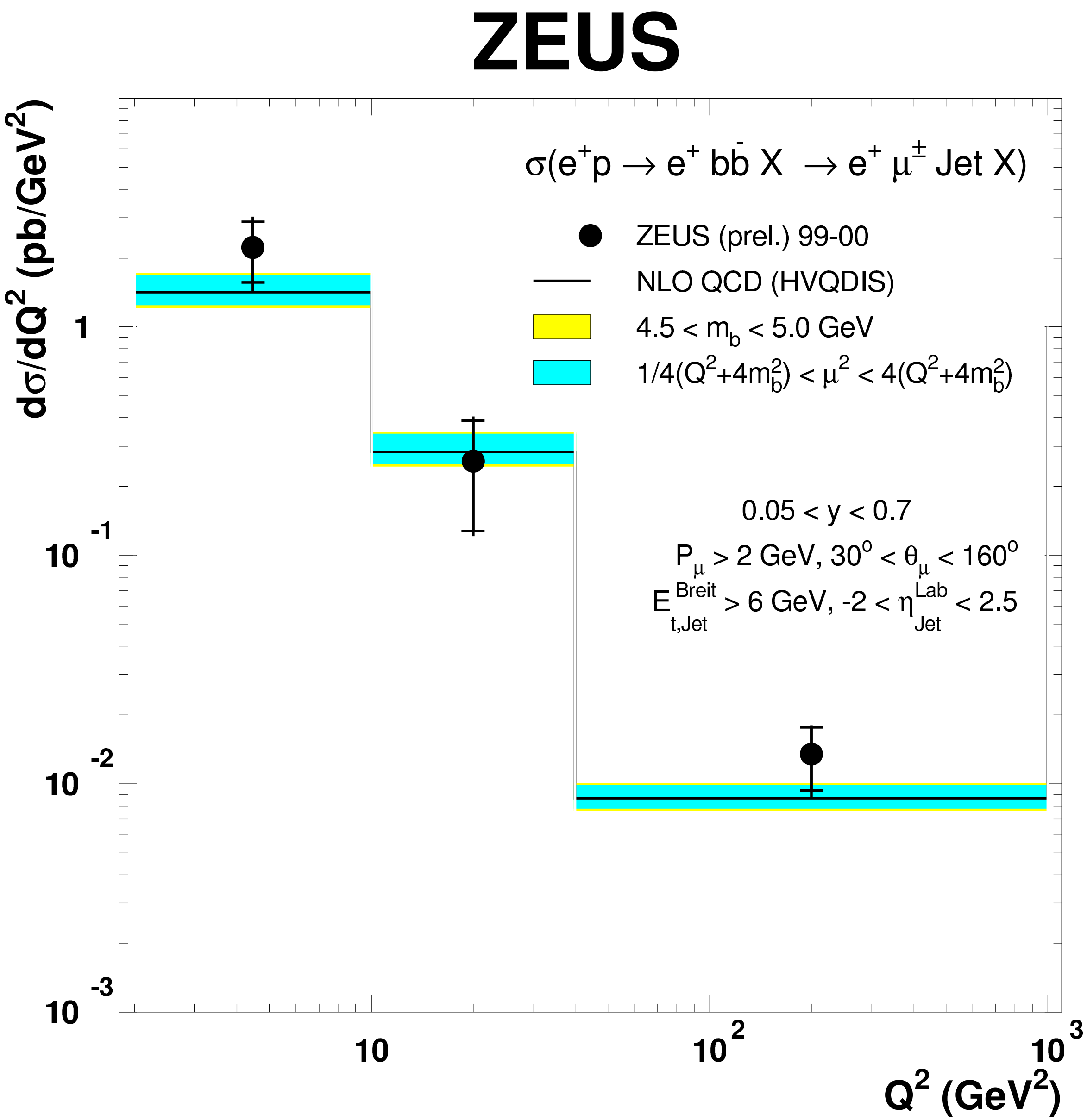


Beauty Production in Deep Inelastic Scattering

- Differential cross section of beauty production against Q^2

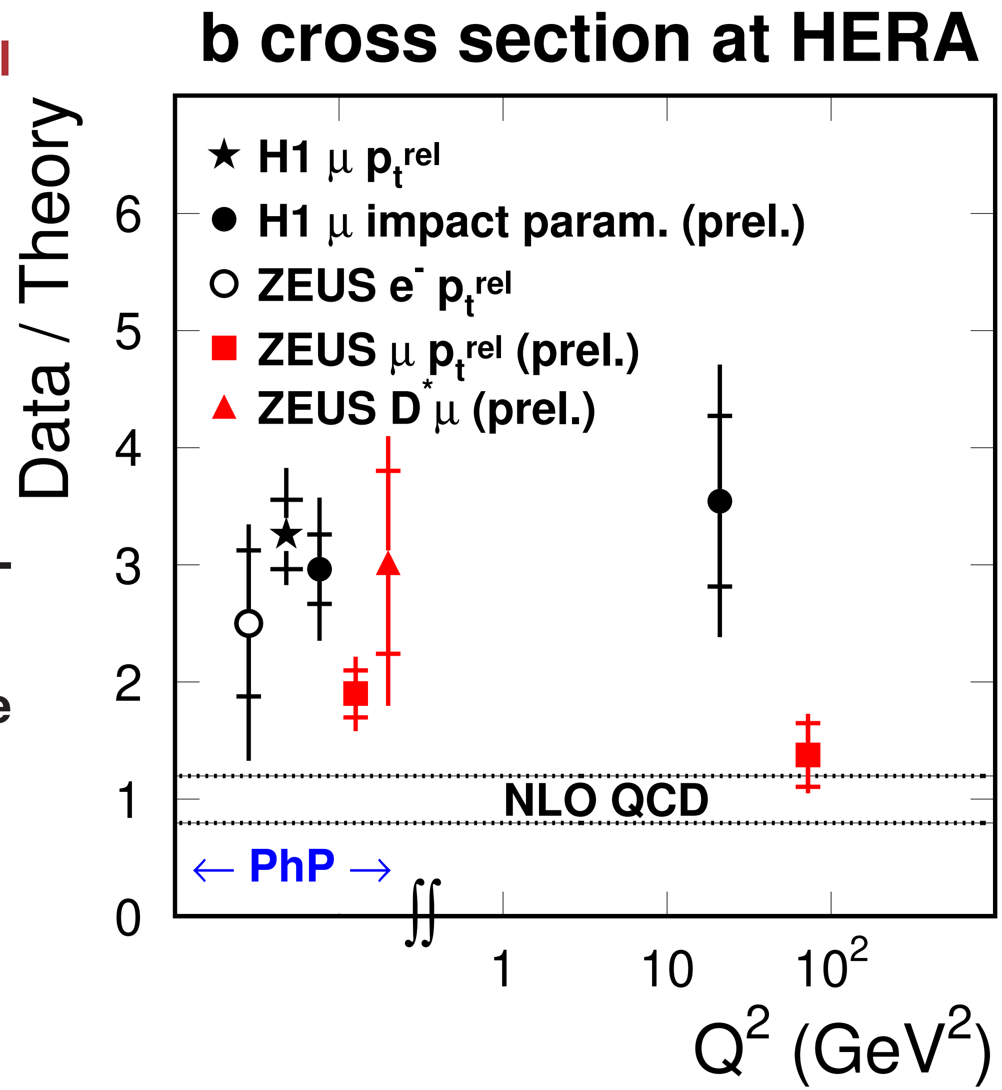
- NLO QCD prediction shown from HVQDIS

▷ Data lies above NLO prediction, but agrees within experimental uncertainties



Beauty Production at HERA - Summary of Results

- **HERA results on beauty in general above NLO pQCD predictions**
  - ▷ **Particularly in photoproduction**
  - ▷ **DIS results — situation unclear**
  - ▷ **Measurements represent very different kinematic regions**
  - ▷ **Different model assumptions made in NLO predictions**
  - ▷ **Statistical uncertainty still large**



HERA II data will be decisive for beauty production

Summary

- In general charm results can be described by NLO predictions
  - ▷ However in certain kinematic regions, data well above the predictions
  - ▷ Uncertainty on the predictions from theory is greater that the uncertainty on the experimental results
  - ▷ NNLO would be welcome!
- Charm with dijet production gives access to the production mechanisms
  - ▷ Evidence for charm in the photon
  - ▷ Resolved component persists to high Q^2
- Results on Fragmentation parameters (P$_v$, R$_{u/d}$, γ_s and z)
  - ▷ Results from HERA competitive with world average
- Beauty Results seem to be in general above pQCD predictions
  - ▷ Need to pin down in which kinematic regions disagreements concentrated
  - ▷ HERA II data will be decisive

Outlook — HERA II

- Since end 2000 HERA has been undergoing a luminosity upgrade

▷ H1 and ZEUS have had detector upgrades

- Recommisioning now ongoing

▷ **Recommissioning: L_{spec} = 1.4$\cdot\ 10^{30} cm^{-2} s^{-1} mA^{-2}$** (design 1.8$\cdot\ 10^{30}$)

HERA II data will be vital for understanding heavy quark physics