Charm Production with a Leading Baryon

Heavy Quark Physics
at the Upgraded HERA Collider

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The results of ZEUS Collaborations

O U T L I N E

- Diffractive charm production →
  - Introduction
  - DIS and $D^{*\pm}$ Selection
  - Diffractive Selection
  - Cross Sections & $F_2^{D(3),c\bar{c}}$
  - $D^{*\pm}$ in Photoproduction
  - Conclusions
- Charm photoproduction associated with an energetic neutron →
  - Introduction
  - Cross Sections & Ratios
  - Conclusions

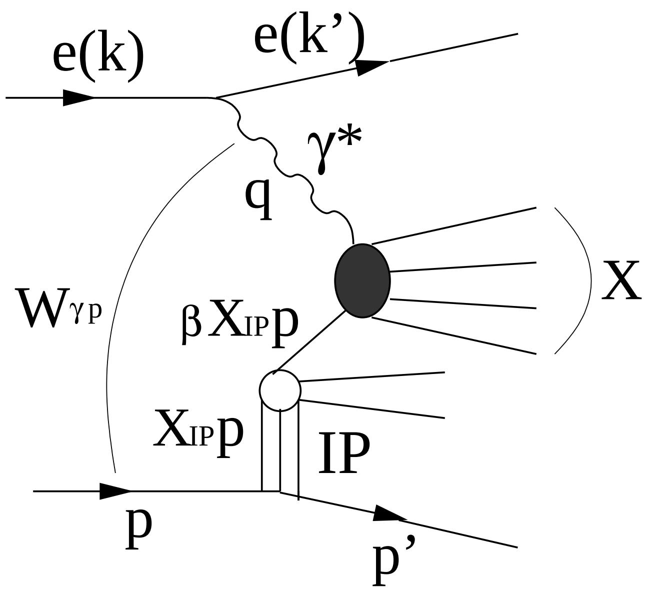
Motivation

- **To invesigate partonic structure of diffraction ;
charm is sensitive to role of gluons in diffractive exchange**
- **To test diffractive dynamics ;
variety of models for diffractive interactions
(resolved Pomeron, 2-gluon exchange)**
- **To test diffractive pdf's**
- **the new data w.r.t. the previous analyses:**
  - **large luminosity 82** pb^{-1}
  - **better detector: Forward Plug Calorimetr (FPC)**
  - **large** $x_{\mathbb{P}}$ **range** $x_{\mathbb{P}} < 0.035$
  - **proton dissociation admixture estimation**

New published ZEUS data :
DESY-03-094 (accepted by Nuclear Physics B)

Kinematic Variables

$ep \rightarrow eXp \rightarrow eD^{*}X'p$



$$Q^2 = -(k-k')^2 = -q^2$$

$$W^2 = (P+q)^2$$

$$x_{I\!P} = \frac{M_X^2+Q^2}{W^2+Q^2}$$

$$\beta = \frac{Q^2}{Q^2+M_X^2}$$

DIS Selection:

- **reconstruct a good positron:**
  $E_{EL} > 10$ **,**
  remove PhP background:
  $40 < \Sigma(E-Pz) < 65$
- **final DIS kinematic range:**
  $0.02 < y < 0.7$**,**
  $1.5 < Q^2 < 200$ ^{2}

$D^{*\pm}(2010)$ Reconstruction

Mass difference method

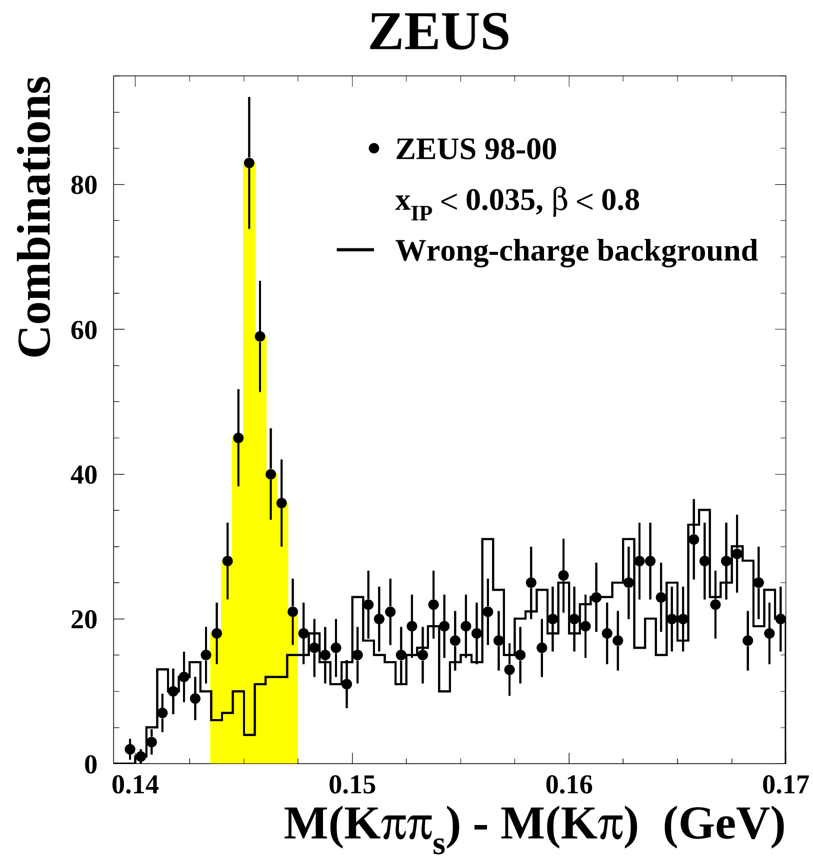
$$D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+ \quad (+c.c.)$$

($BR = 0.0257 \pm 0.0006$) **(PDG 2002)**

$$\Delta M = M(D^*) - M(D^0) \approx 0.14542 \textbf{ GeV}$$
$$0.143 < \Delta M < 0.148 \textbf{ GeV,}$$
$$1.81 < M(D^0) < 1.92 \textbf{ GeV}$$

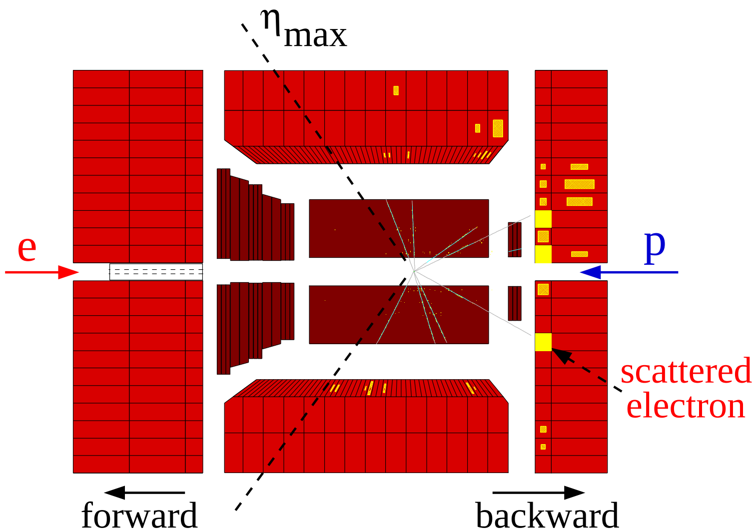
$$1.5 < p_\perp(D^{*\pm}) < 10 \textbf{ GeV}$$
$$-1.5 < \eta(D^{*\pm}) < 1.5$$
$$p_\perp(\pi_s) > 0.12 \textbf{ GeV}$$
$$p_\perp(K,\pi) > 0.5 \textbf{ GeV}$$

$x(D^{*\pm}) = \frac{2|\bar{P}^*(D^{*\pm})|}{W}$, **where** $\bar{P}^*(D^*)$ **is** D^* **momentum in** γP **system**

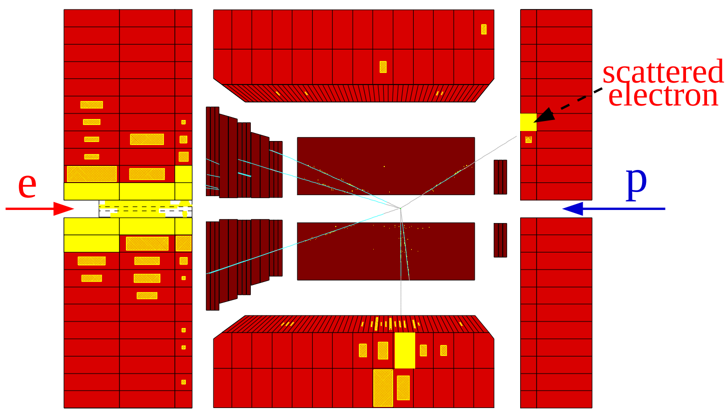


After wrong charge background subtraction $\boxed{253 \pm 21}$ **diffractive** $D^{*\pm}$ **events were found**

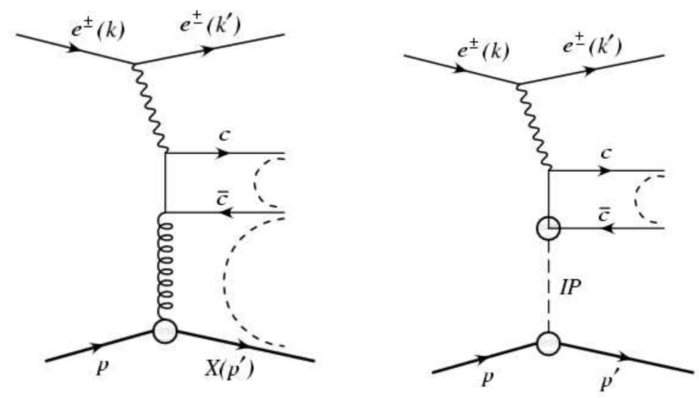
Diffractive Selection

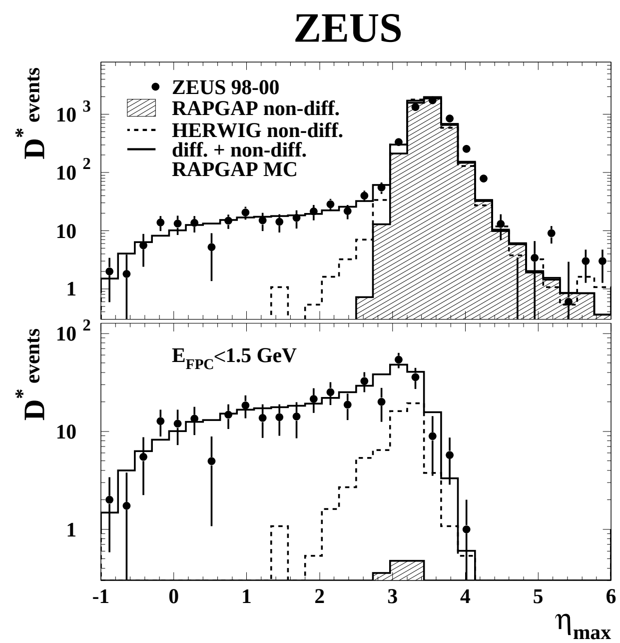


diffractive event



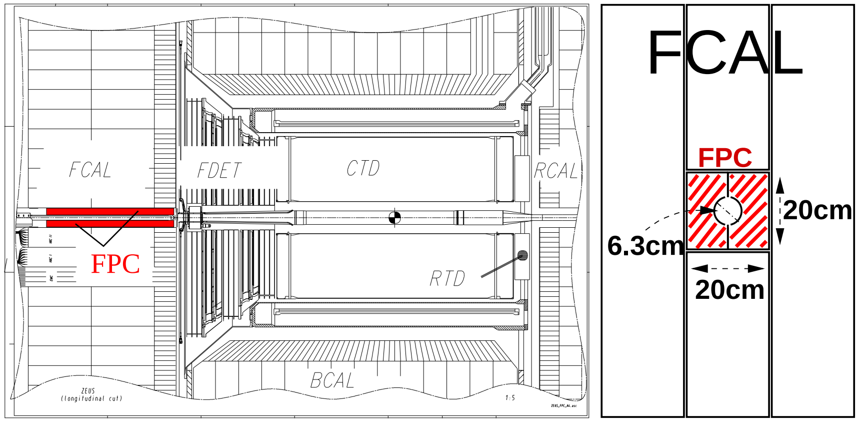
nondiffractive event

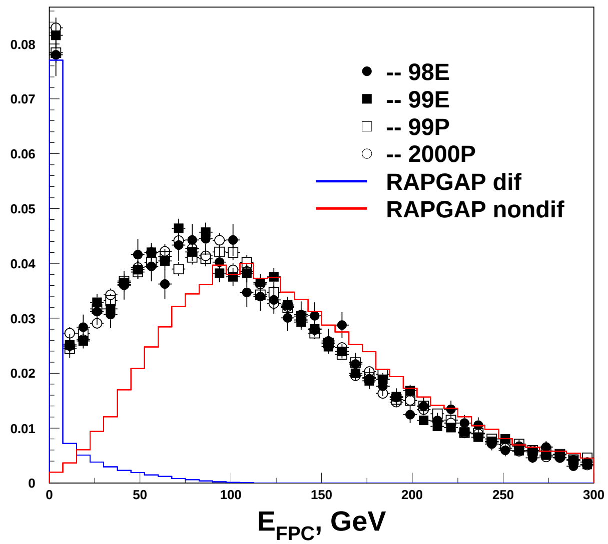


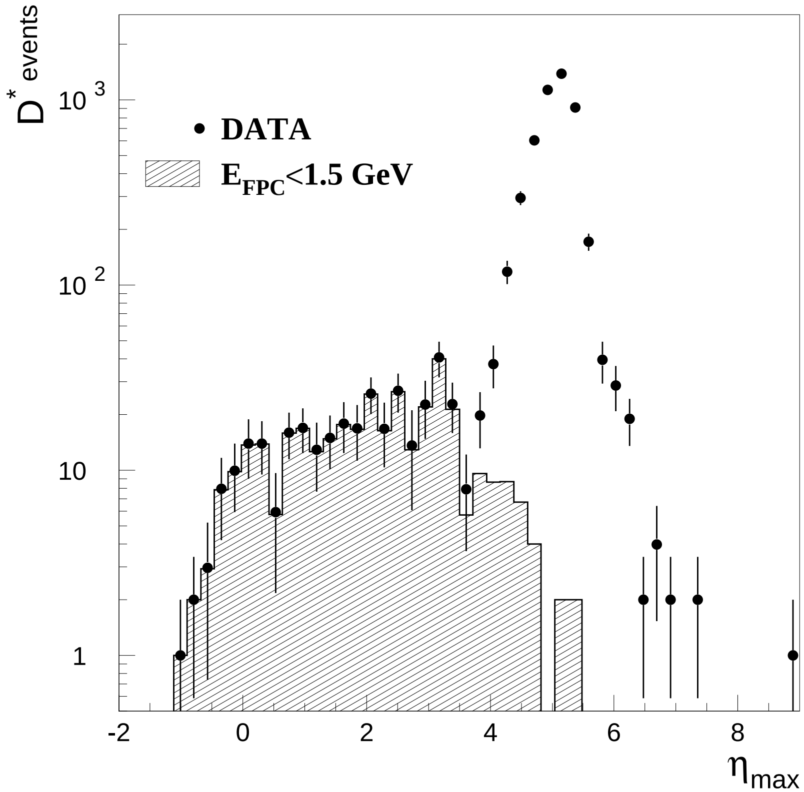


$\eta = -\ln(tg\frac{\theta}{2})$, $\eta_{\rm max}$ **: the largest** η **value in event**

FPC as a Diffraction Tagger







Diffractive event selection :

$$E_{FPC} < 1.5\ GeV \oplus \eta_{\max} < 3$$

$$x_{I\!P} < 0.035\ ,\quad \beta < 0.8$$

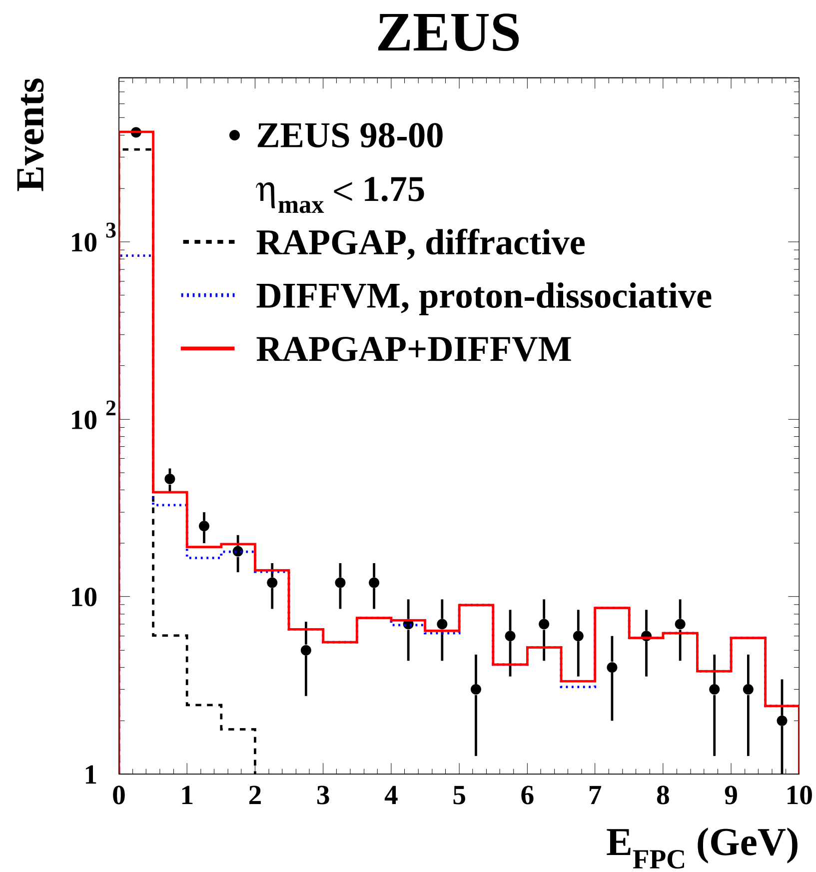
Proton Dissociation Estimation

Proton dissociation events : $ep \rightarrow e'XN$

Use E_{FPC} **distribution in the range :**
$\eta_{MAX} < 1.75$ **and** $E_{FPC} < 10$ **GeV**
to find proton dissociation relative contribution.

Systematic error :

- **Use** η_{MAX} **calculated on calorimeter w/o 1st FCAL RING and** $\eta_{MAX}(w/o\ 1st\ FR) < 1.25$ **:** **-2.7 %**
- **Use reweighting to new pomeron intercept** $\alpha_{IP}(0)$ **in DIFFVM MC** ± 0.4 **:** **+3.7 %** **-3.0 %**
- **Different p.diss. MCs :**
  PHOJET $\rightarrow$ **+0.9 %**
  RAPGAP $\rightarrow$ **-0.9 %**
  EPSOFT2 $\rightarrow$ **+1.6 %**



$$N^{admixture}_{E_{FPC}<1.5,\eta_{MAX}<3} = 16\ ^{+4}_{-4}\ \%$$

Integrated Cross Sections

For any ξ cross section :

$$\frac{d\sigma(ep \to eD^{*\pm}Xp)}{d\xi} = \frac{\mathcal{N}_{D^{*\pm}}(1 - f_{pdss})}{\mathcal{A}\cdot\mathcal{L}\cdot\mathcal{B}\cdot\Delta\xi}$$

— $\mathcal{L} \approx 82\,\mathbf{pb}^{-1}$ **(luminosity)**
— $\mathcal{B} = 0.0257 \pm 0.0006$ **(decay modes)**
— $\mathcal{A} = \frac{\mathcal{N}^{rec}_{D^{*\pm}}}{\mathcal{N}^{gen}_{D^{*\pm}}}$ **(acceptance);**

$\mathcal{N}^{rec}_{D^{*\pm}}$ **number of reconstructed** $D^{*\pm}$**;**

$\mathcal{N}^{gen}_{D^{*\pm}}$ **number of generated** $D^{*\pm}$

(integrated value $\mathcal{A} = 20.2$ **%)**

— $\mathcal{N}_{D^{*\pm}}$ **number of measured diff.** $D^{*\pm}$
— f_{pdss} **fraction of events due to the pr. diss. background.**

$$1.5 < p_\perp(D^{*\pm}) < 10 \textbf{ GeV}$$
$$-1.5 < \eta(D^{*\pm}) < 1.5$$
$$0.02 < y < 0.7$$
$$1.5 < Q^2 < 200 \textbf{ GeV}^2$$
$$x_{I\!P} < 0.035\ , \quad \beta < 0.8$$

Integrated cross section :

$\sigma = 521 \pm 43(stat)^{+34}_{-58}(syst)^{+25}_{-25}(p.dis.)$ **pb**

Integrated ratio :

$R_D = \frac{\sigma^{diff}}{\sigma^{inc}} = 6.4 \pm 0.5(stat)^{+0.3}_{-0.7}(syst)^{+0.3}_{-0.3}(p.dis.)$ **%**

Comparison :

ZEUS 98-2000: $\sigma^{x_{I\!P}<0.016}_{4<Q2<400} = 197 \pm 21(stat)$ **pb,**

ZEUS 95-97:
$\sigma^{x_{I\!P}<0.016}_{4<Q2<400} = 288 \pm 44(stat)^{+44}_{-46}(syst) \pm 62(p.dis.)$ **pb**

ZEUS 95-97 higher then ZEUS 98-00, but consistent.

ZEUS 98-2000: $\sigma^{x_{I\!P}<0.04}_{2<Q2<100} = 316 \pm 27(stat)$ **pb,**

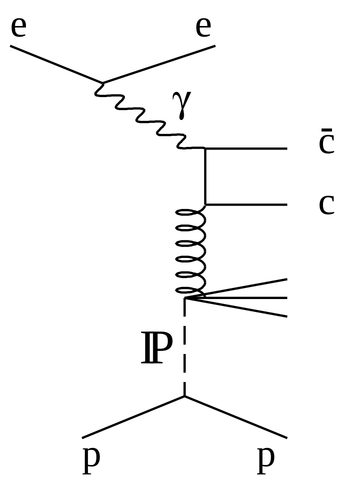
H1 95-97:
$\sigma^{x_{I\!P}<0.04}_{2<Q2<100} = 246 \pm 54(stat) \pm 56(syst)$ **pb**

H1 95-97 lower then ZEUS 98-00, but consistent.

Models of Diffractive Exchange

Resolved Pomeron model :

- **Based on Regge theory with Pomeron exchange**
- **Treat $I\!P$ as object with substructure**
- **Charm Production in diffractive DIS $\rightarrow$ probe gluon content of $I\!P$**



- **gluon-dominated $I\!P$**

Examples :

– H1 QCD fit ("h1 fit2") in LO RAPGAP

– NLO QCD code *DHVQDIS* with fit by Alvero, Collins, Terron and Whitmore (*ACTW*) to ZEUS and H1 data. Gluon–dominated fits "B", "D" and "SG"

Factorisation in Diffraction

The combination of:

- **QCD Hard Scattering Factorisation (Collins et al):**

$$\frac{d^2\sigma(x,Q^2,x_{I\!P},t)^{\gamma^* p\to p' X}}{dx_{I\!P}dt} = \sum_i \int_x^{x_{I\!P}} d\xi \hat{\sigma}^{\gamma^* i}(x,Q^2,\xi) p_i^D(\xi,Q^2,x_{I\!P},t)\ (+highertwist)$$

- $\hat{\sigma}^{\gamma^* i}$ **universal partonic cross sections, as in incl. DIS**
- p_i^D **diffractive parton distributions (conditional probabilities), obey NLO DGLAP**

and:

- **Regge Factorisation:** $x_{I\!P}$, t **dependance factorises out (Donnachie, Landshoff, Ingelman, Schlein)**

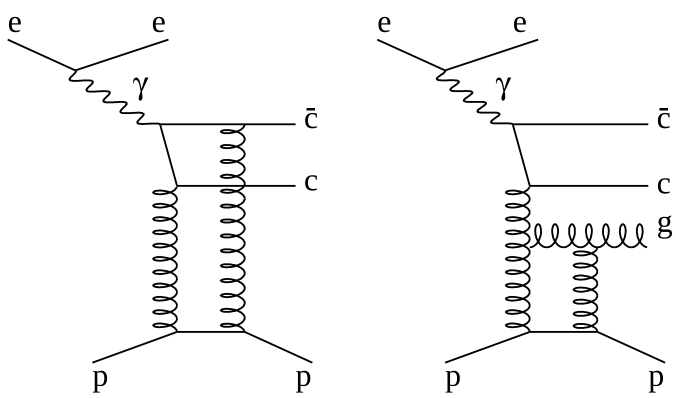
$$F_2^D(x_{I\!P},t,\beta,Q^2) = f_{I\!P/p}(x_{I\!P},t) F_2^{I\!P}(\beta,Q^2)$$

- **No proof in QCD; consistent with data at the present level of precision**

If QCD Factorisation works, the diffractive pdf's should predict cross sections for heavy quarks

Models of Diffractive Exchange

Perturbative QCD models:



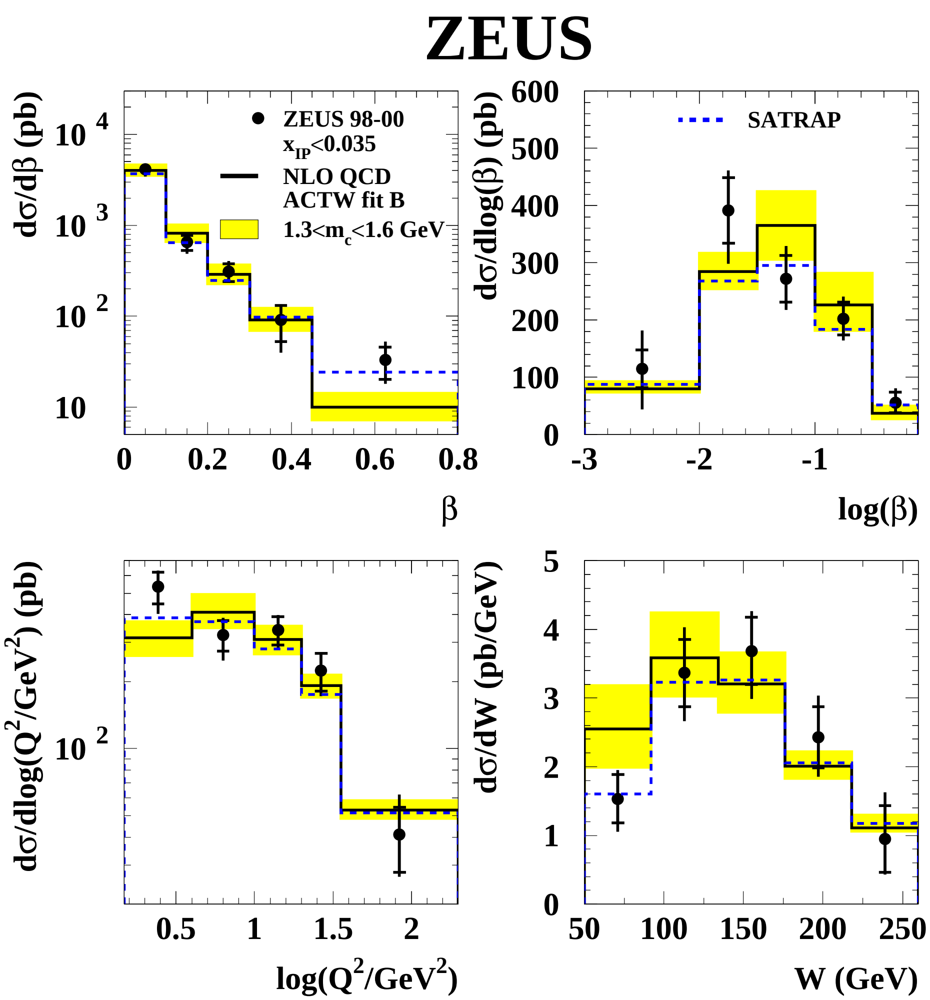
- t**-channel gluon exchange**
- $\sigma \propto$ (**gluon density**)^2
- **Higher order processes** $\gamma^* \to c\bar{c}g$ — **cancels suppression for large masses**

Examples :

– **two-gluon exchange model implemented in RAPGAP generator Bartels et al.** (*BJLW*)**;**
unordered k_T

– **two-gluon exchange "saturation" model implemented in** *SATRAP* **generator;**
strongly ordered k_T : $p_T^g \ll p_T^q$

Model Comparison with Diffractive DIS D^*



- **Published ZEUS data :**

  $Lumi = 82$ **pb**$^{-1}$ **(DESY-03-094)**
  $1.5 < Q^2 < 200\,$**GeV**^{2}**,** $0.02 < y < 0.7$**,**
  $x_{I\!P} < 0.035$**,** $\beta < 0.8$

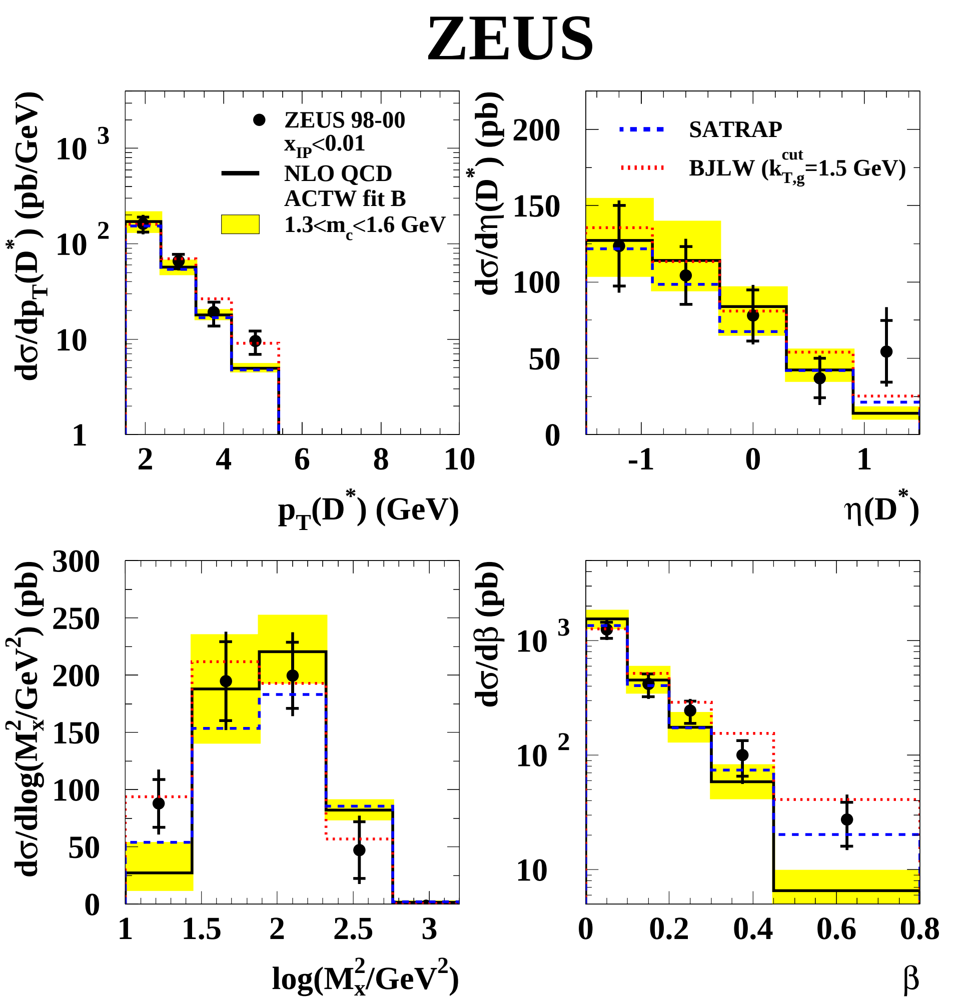
  $p_T(D^{*\pm}) > 1.5\,$**GeV and** $|\eta(D^{*\pm})| < 1.5$

- **ACTW NLO Calculations :**

  Gluon dominated pdf "fit B"
  $\mu_R = \mu_F = \sqrt{Q^2 + 4m_c^2}$
  The NLO error band : $1.3 < m_c < 1.6$ **GeV**
  Peterson fragmentation with $\epsilon = 0.035$
  The probability for charm to fragment into a $D^{*\pm}$ **meson was set to :**
  $f(c \to D^{*+}) = 0.235$

- *SATRAP* **describes well the region** $x_{I\!P} < 0.035$

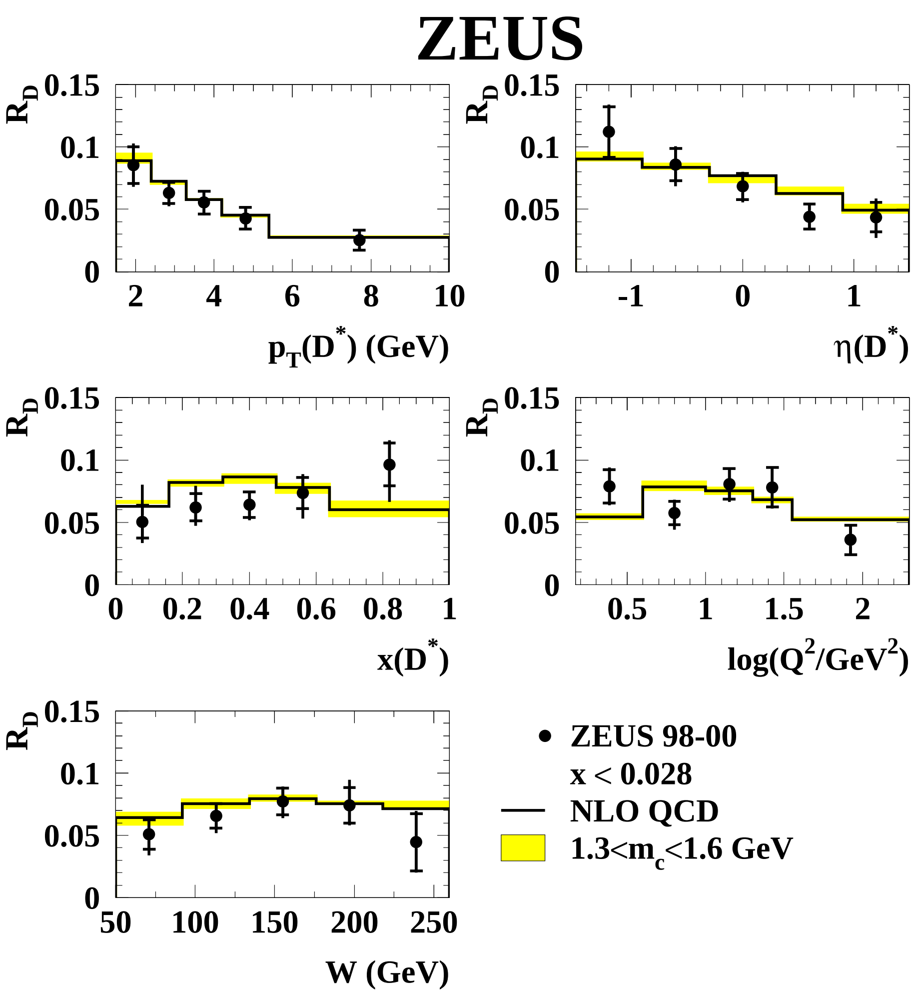
Model Comparison with Diffractive DIS D^*



- D^* for $x_{I\!P} < 0.01$
- <u>Two-gluon exchange models</u> :

  SATRAP and BJLW using MC RAPGAP proton PDF GRV94HO,
  $f(c \to D^{*+}) = 0.235$, $m_c = 1.45$ **GeV**
  $\mu_R = \mu_F = \sqrt{p_{c,T}^2 + 4m_c^2}$ $k_{T,g}^{\rm cut} = 1.5$ **GeV**
- Good agreement with *ACTW* NLO predictions with diffractive pdf “fit B”
- Good agreement with *BJLW* predictions and *saturation model*

Ratio of Diffractive to Inclusive $D^{*\pm}$ Production



- **Diffractive relative contribution at small $p_\perp(D^*)$ and negative $\eta(D^*)$ is large**
- **R_D has no significant dependance on $x(D^*)$, Q^2 or W**

Open-Charm Contribution to $F_2^{D(3)}$

The open-charm contribution to the diffractive structure function of the proton can be related to the cross section, measured in the full D^* kinematic region, by

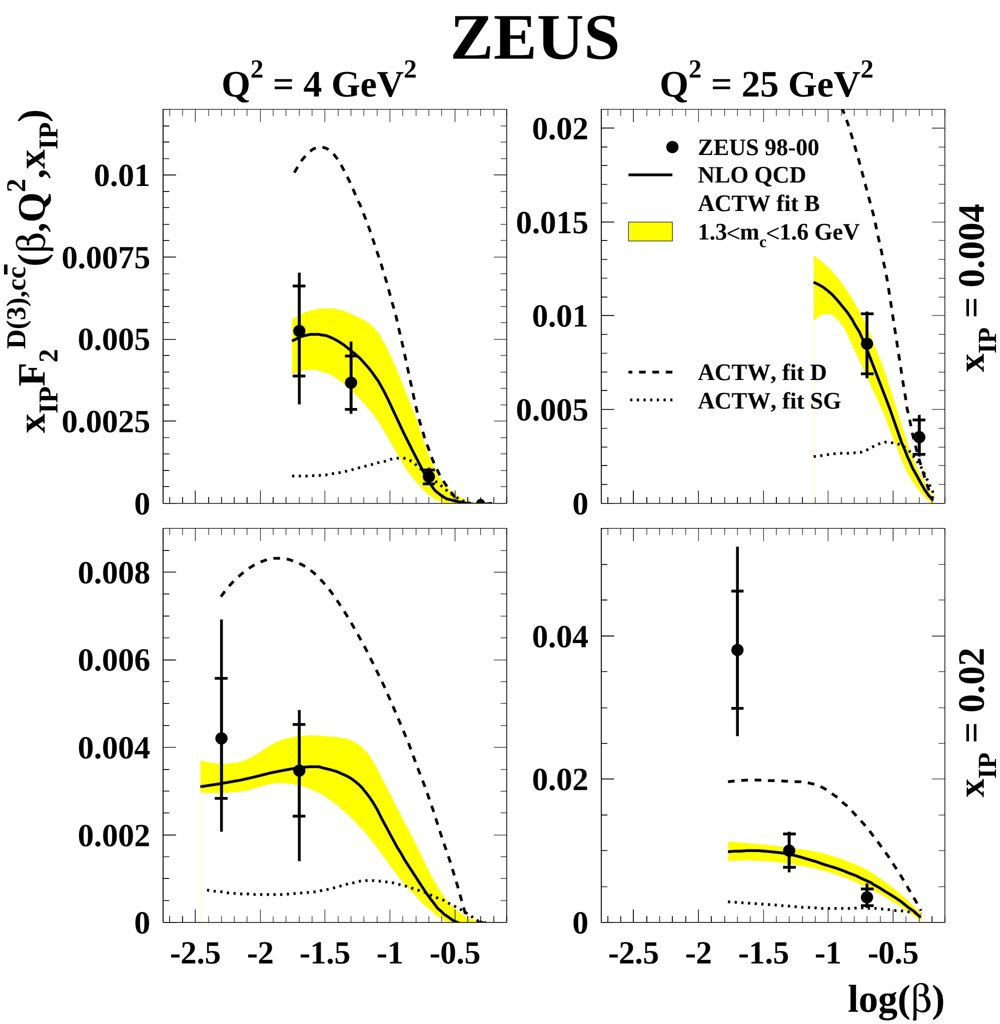
$$\frac{1}{2f(c \rightarrow D^{*+})} \frac{\mathrm{d}^3\sigma_{ep \rightarrow eD^{*\pm}X'p}}{\mathrm{d}x_{\mathbb{P}}\mathrm{d}\beta\mathrm{d}Q^2} = \frac{4\pi\alpha_{em}^2}{Q^4\beta}(1 - y + \frac{y^2}{2})F_2^{D(3),c\bar{c}}(\beta, Q^2, x_{\mathbb{P}})$$

- **The 3d differential cross section was measured & $log(\beta)$ for different Q^2 and $x_{\mathbb{P}}$ regions**
- **Extrapolation factors of the measured cross sections to the full $p_T(D^{*\pm})$ and $\eta(D^{*\pm})$ phase space were estimated using the ACTW NLO "fit B" predictions (~ 3.5)**
- **In each bin $F_2^{D(3),c\bar{c}}$ was determined using the formula**

$$F_{2\ \mathrm{meas}}^{D(3),c\bar{c}}(\beta_i, Q_i^2, x_{\mathbb{P},i}) = \frac{\sigma_{ep \rightarrow eD^{*\pm}X'p}^{i,\mathrm{meas}}}{\sigma_{ep \rightarrow eD^{*\pm}X'p}^{i,\mathrm{ACTW}}} F_{2\ \mathrm{ACTW}}^{D(3),c\bar{c}}(\beta_i, Q_i^2, x_{\mathbb{P},i}),$$

where the cross sections σ^i in bin i are those for $p_T(D^{*\pm}) > 1.5$ GeV and $|\eta(D^{*\pm})| < 1.5$

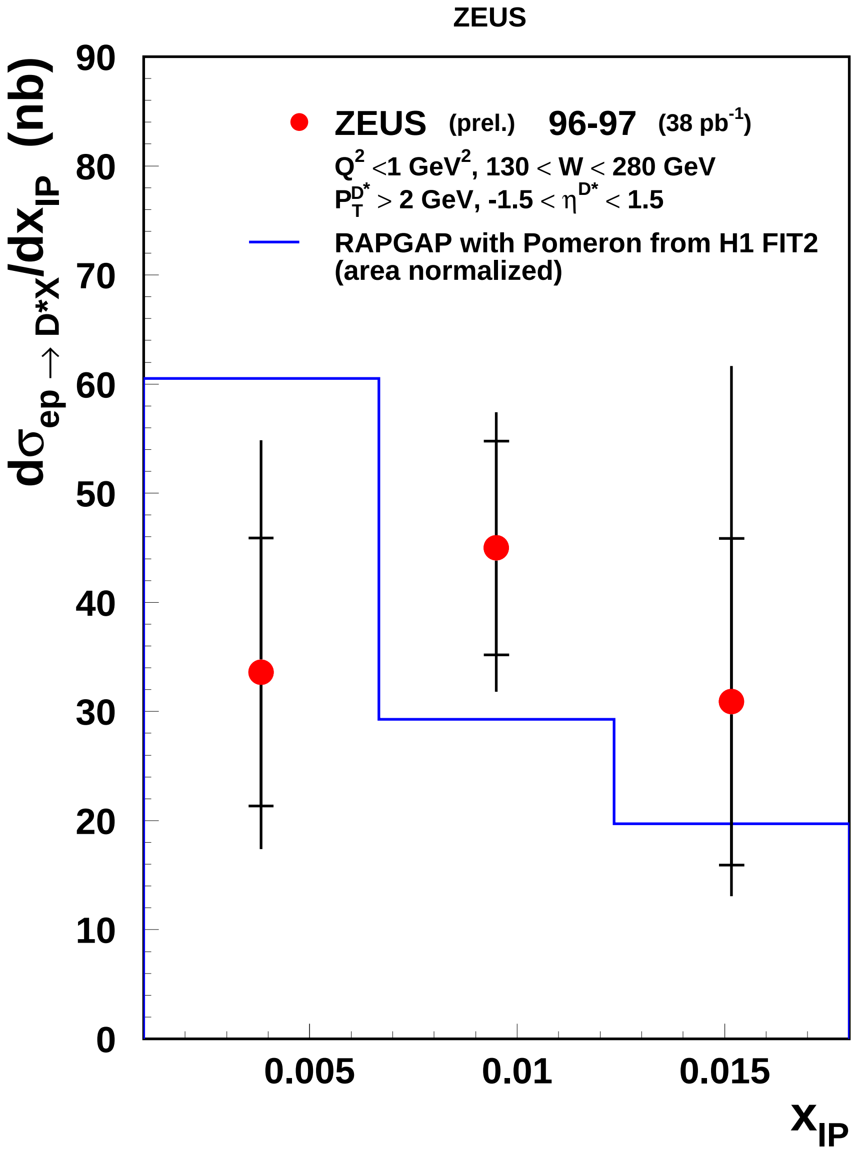
Open-Charm Contribution to $F_2^{D(3)}$



- For all values of Q^2 and $x_{I\!P}$, $F_2^{D(3),c\bar{c}}$ rises as $\beta \to 0$
- The data exclude fits D and SG and concistent with B.

Strong sensitivity to the diffractive parton densities

$D^{*\pm}$ Diffractive Cross Sections in Photoproduction



- **Preliminary ZEUS 96-97 data :**

  $Q^2 < 1$ **GeV**^{2}, $130 < W < 280$ **GeV,**
  $x_{I\!P} < 0.018$
  $p_T(D^{*\pm}) > 2\,$**GeV,** $|\eta(D^{*\pm})| < 1.5$

- $\sigma = 0.74 \pm 0.21(stat)^{+0.27}_{-0.18}(syst) \pm 0.16(p.d$ **nb**

- **Good agreement with Resolved Pomeron model in shapes of measured cross sections** $d\sigma/dp_T^{D^*}$, $d\sigma/d\eta^{D^*}$, $d\sigma/dM_X$ **(not show and** $d\sigma/dx_{I\!P}$

Summary

1. **Total diffractive cross section of DIS $D^{*\pm}$ production in the kinematic range**

$$1.5 < p_\perp(D^{*\pm}) < 10 \textbf{ GeV}$$
$$-1.5 < \eta(D^{*\pm}) < 1.5$$
$$0.02 < y < 0.7$$
$$1.5 < Q^2 < 200 \textbf{ GeV}^2$$
$$x_{I\!P} < 0.035 \text{ ,} \quad \beta < 0.8$$

is : $521 \pm 43(stat)^{+34}_{-58}(syst)^{+25}_{-25}(p.dis.)$ **pb**

2. **Relative contribution of diffractive mechanism to inclusive D^* in DIS production is :** $R_D = 6.4 \pm 0.5\ (stat)^{+0.3}_{-0.7}\ (syst)^{+0.3}_{-0.3}\ (p.diss.)\ \%$

3. **Diffractive relative contribution is large at small $p_\perp(D^*)$ and negative $\eta(D^*)$. R_D has no significant dependance on $x(D^*)$, Q^2 or W.**

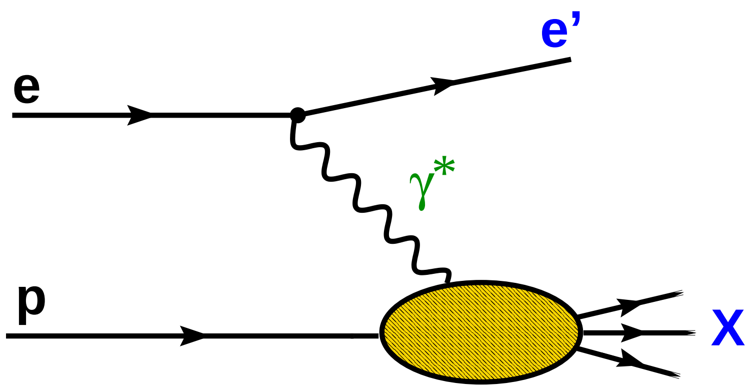
Summary II

4. **The diffractive open charm contribution, $F_2^{D(3),c\bar{c}}$, to the proton structure function rises as $\beta \to 0$. for all values of Q^2 and $x_{I\!P}$.**

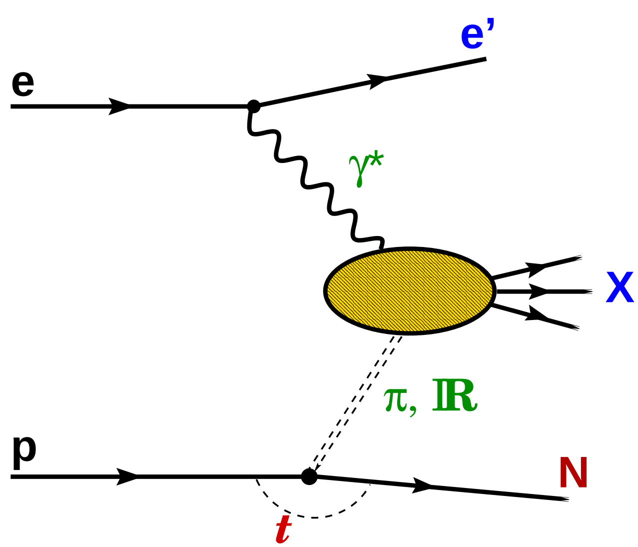
5. **No significant difference in predictions of different models was observed. The both models with resolved pomeron and based on pQCD correctly describe the main features of diffractive dynamic.**

Charm Photoproduction Associated with an Energetic Neutron

Standard Fragmentation :

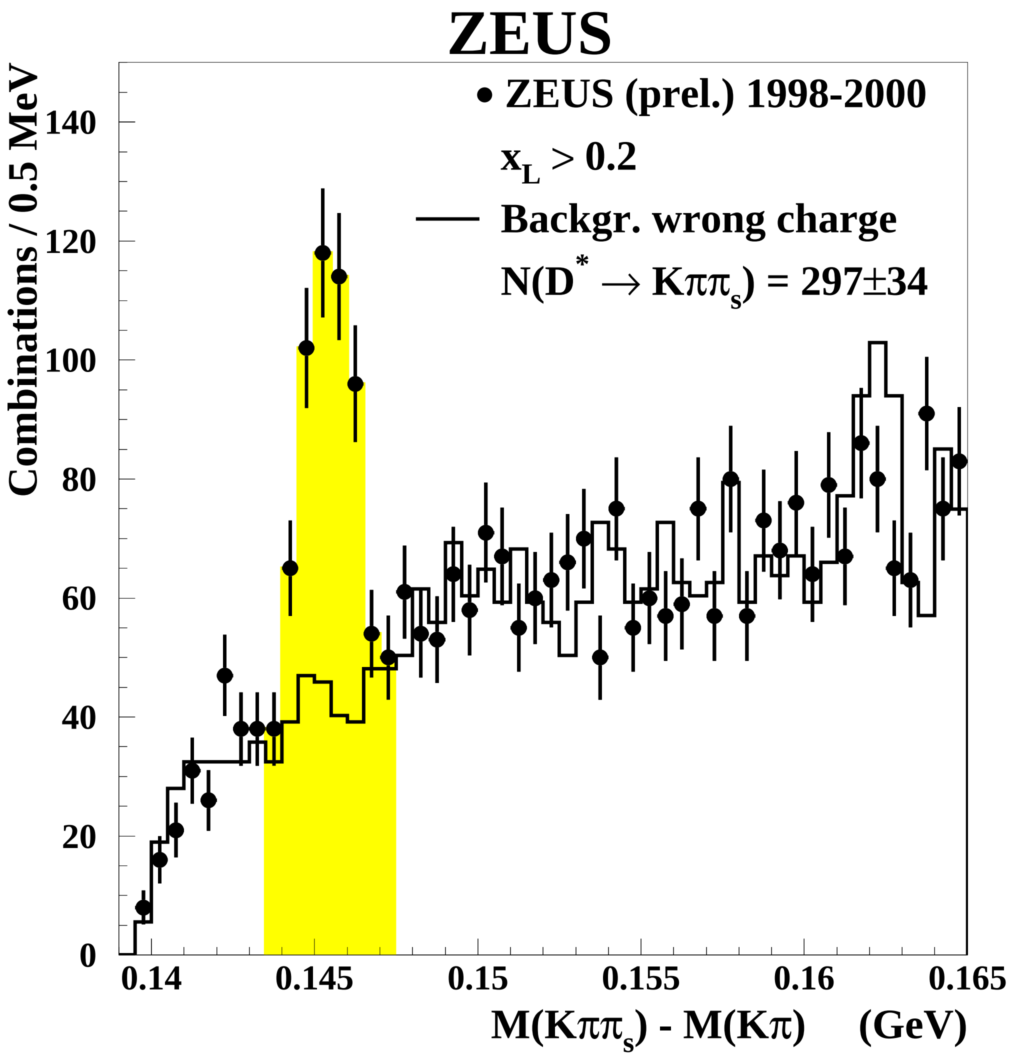


Particle Exchange :



- Significant part of ep scattering at HERA contains a baryon in final state $0.2 < x_L < 1$, $\quad x_L = E_{LB}/E_P$
- Production mechanism is not completely understood; Exchange models are usually applied to describe data
- Boson-gluon fusion mechanism dominates for charm production
  $\rightarrow$ sensitivity to gluon content of the exchanged particle

Results on Neutron Tagged D^* PHP



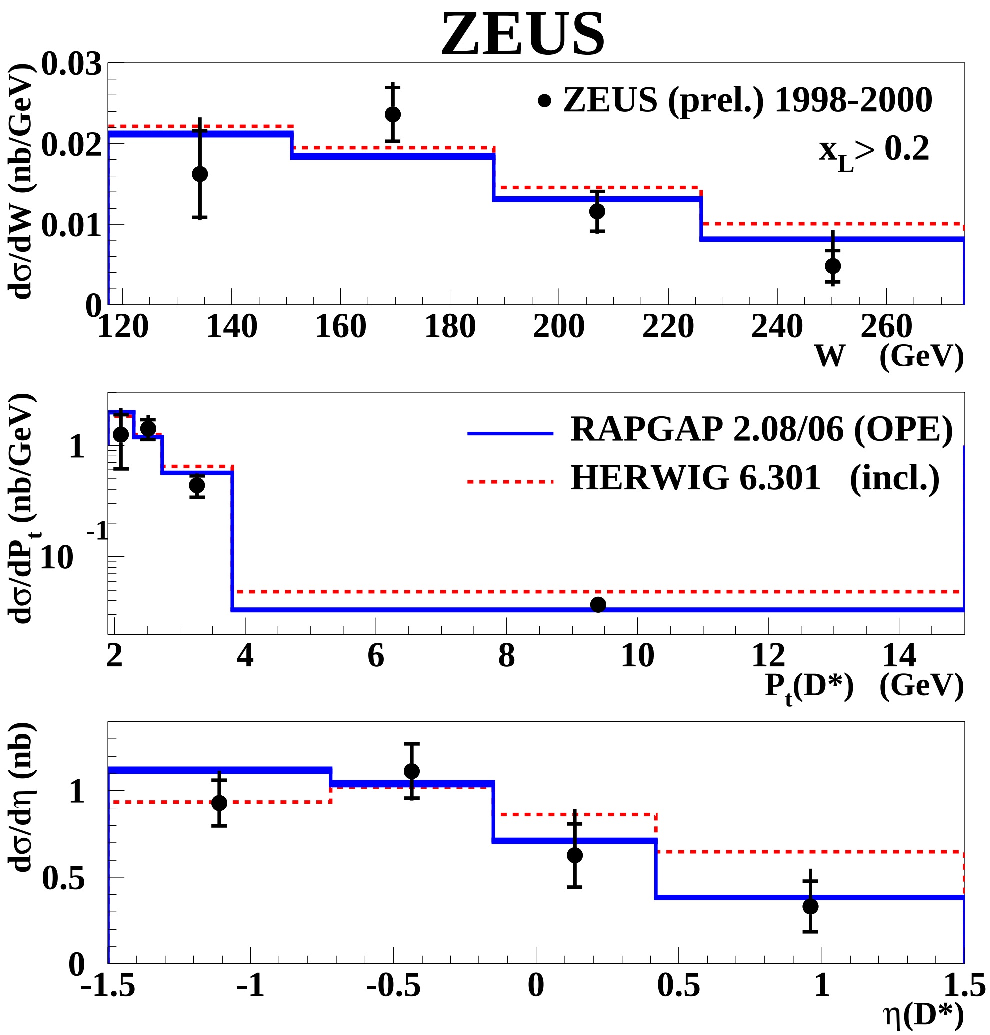
- **Preliminary ZEUS 98-2000 data :**

$Q^2 < 1$ **GeV**^{2}, $117.3 < W < 274.3$ **GeV**

Neutron detected in ZEUS
Forward Neutron Calorimeter
$0.2 < x_L < 1$, $\theta_n < 0.8\ mrad$

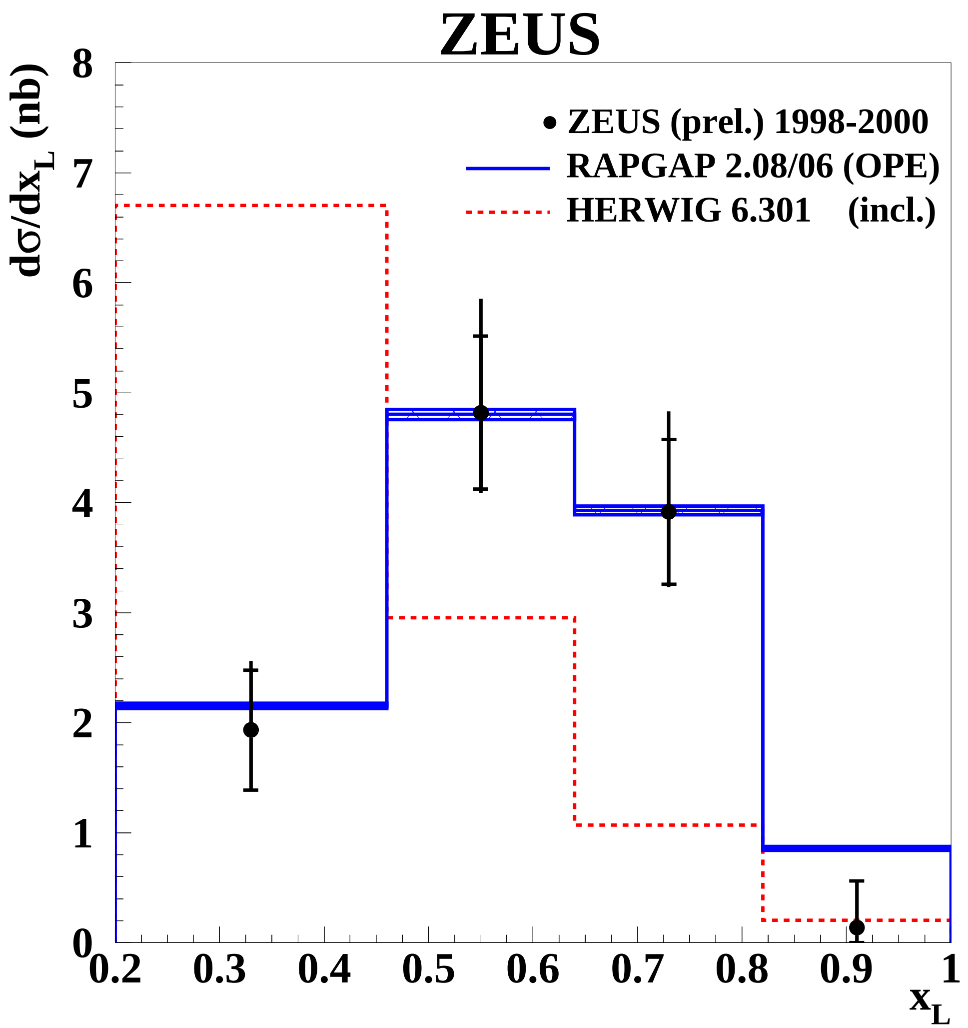
- $ep \rightarrow eD^{*\pm}nX$
  $p_T(D^{*\pm}) > 1.9$ **GeV**, $|\eta(D^{*\pm})| < 1.5$

Results on Neutron Tagged D^* PHP



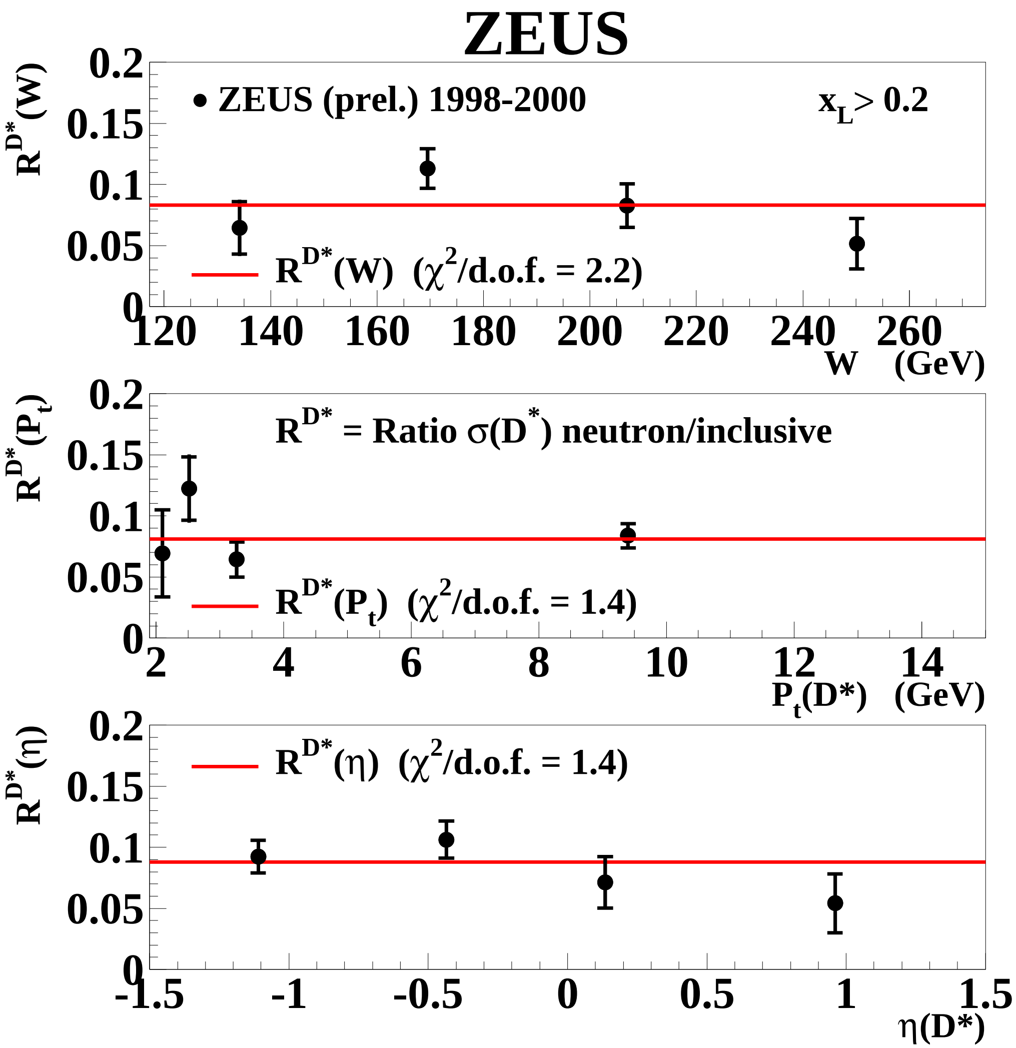
- Cross sections →
- *RAPGAP* →
  One Pion Exchange model
  HERWIG →
  Standard fragmentation
- **Area normalised distributions; comparison of shapes**
- **For W, $\eta(D^*)$ and $P_t(D^*)$ both models describe the data**

Results on Neutron Tagged D^* PHP



- Cross sections for $x_L \rightarrow$
- One Pion Exchange model (RAPGAP) describes data
- Standard fragmentation (HERWIG) does not describes data

Results on Neutron Tagged D^* PHP



- Ratios of neutron tagged D^* to inclusive D^* photoproduction $\rightarrow$
- Fits $R^{D^*} = constant$
- **Ratios are compatible with flat**
- Over whole kinematic range : $R^{D^*}(x_L > 0.2) = 8.2 \pm 0.9(stat) \pm 0.3(sys)$

Conclusions

1. **Ratios of neutron tagged D^* to inclusive D^* photoproduction in the kinematic range**

$$Q^2 < 1 \ \textbf{GeV}^2$$
$$117.3 < W < 274.3 \ \textbf{GeV}$$
$$0.2 < x_L < 1$$
$$p_\perp(D^{*\pm}) < 1.9 \ \textbf{GeV}$$
$$-1.5 < \eta(D^{*\pm}) < 1.5$$

is : $8.2 \pm 0.9(stat) \pm 0.3(sys)$ %

2. **Good agreement with particle exchange model;**
One pion exchange model describes x_L shape well

Research Tasks with ZEUS at HERA II

1. **Accurate measurements of total and differential cross sections of diffractive D^* meson production with higher statistics and smaller systematics in wider kinematic range**
   (*With new ZEUS components MVD, STT. Without FPC though ...*)

2. **Measurement of contribution of open charm production to diffractive structure function $F_2^{D(3)}$ with higher accuracy**

3. **Comparisons between data and various diffractive models trying to add to better understanding of diffractive nature**