$24^{th}$ April 2003

# Inclusive Charm Production in Photoproduction and DIS at HERA

## DIS'03, St. Petersburg

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ZEUS

# *Physics Topics Addressed in this Talk*

- **Introduction**
- **Charm Production**
  - ▷ **Charm Photoproduction**
  - ▷ **Charm in Deep Inelastic Scattering**
- **Summary and Outlook**

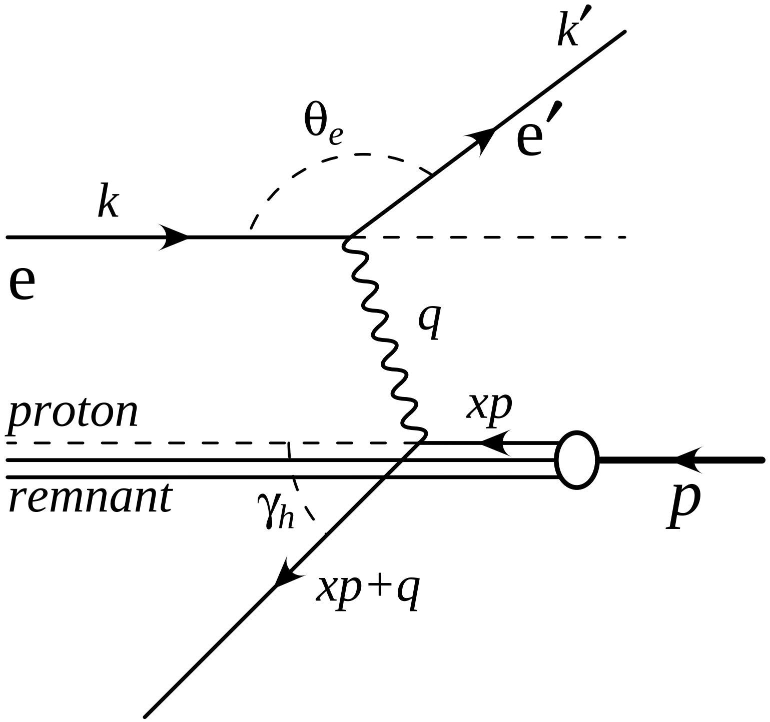
## *Introduction to HERA*

▷ **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:**

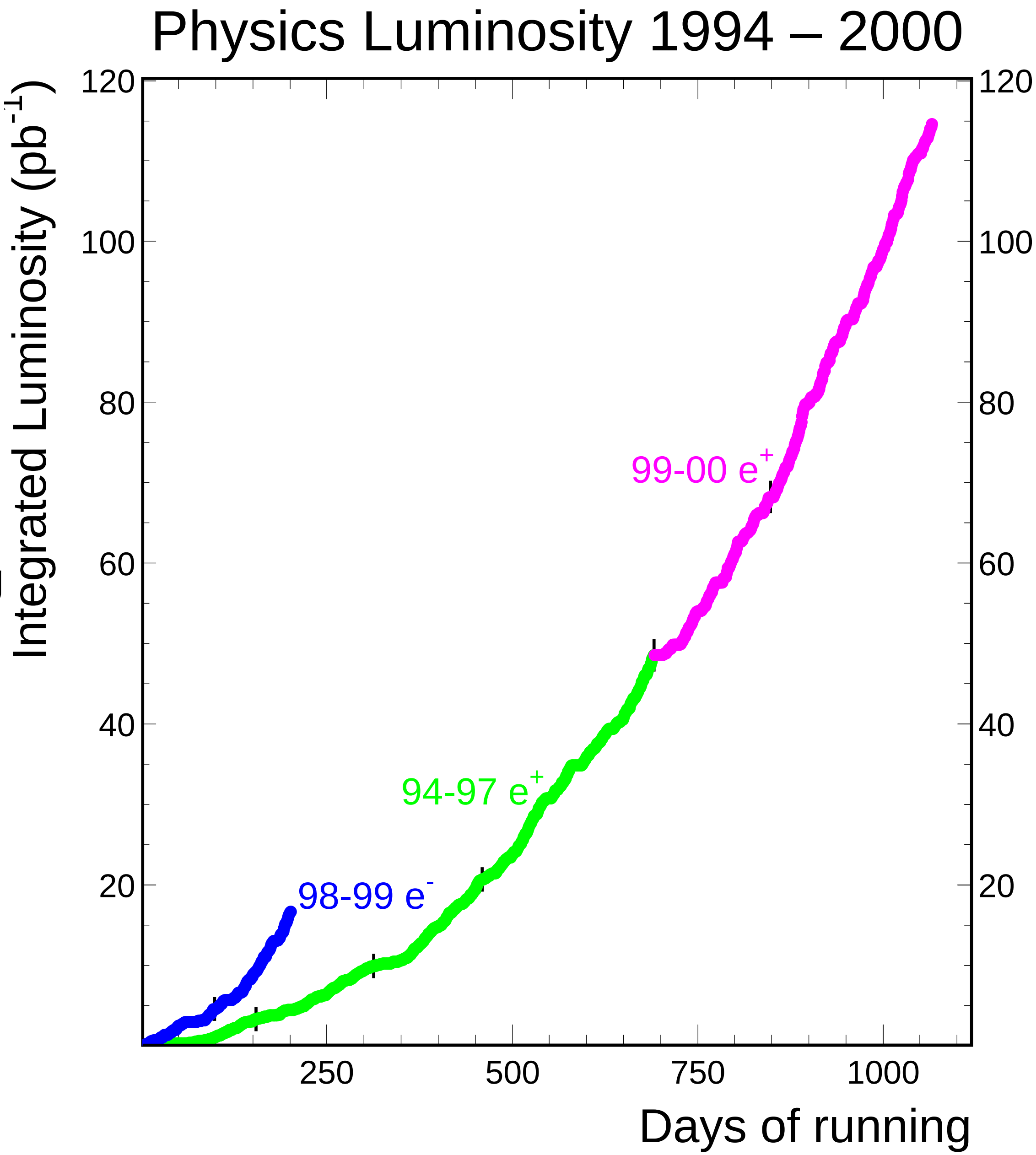
$Q^2 <$ **1 GeV$^2$**

**Deep Inelastic Scattering:**

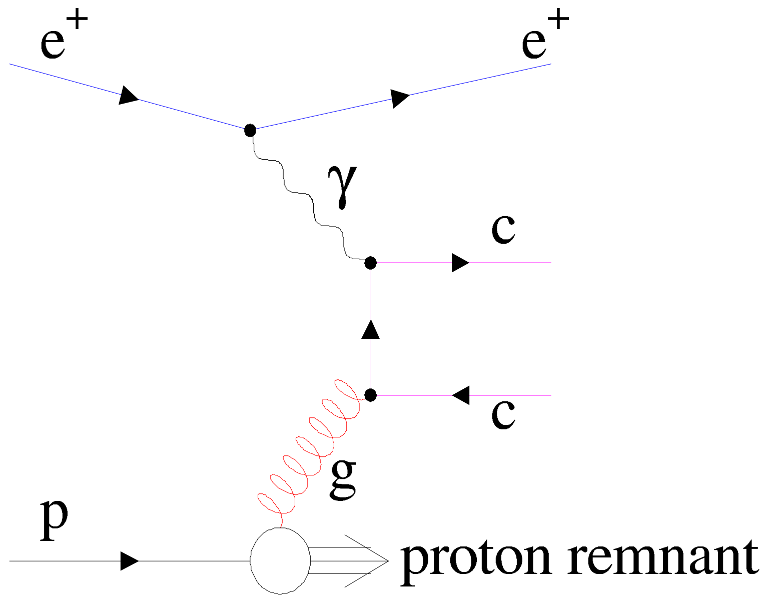
$Q^2 >$ **1 GeV$^2$**

# *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 charm at HERA**
- **1994-7: 820 GeV protons**
  - ▷ **1996-7 published (37 pb**$^{-1}$**)**
- **1998-2000: 920 GeV protons**
  - ▷ **Results here** $\sim$ **80 pb**$^{-1}$



# *Heavy Flavour Physics — Motivation*

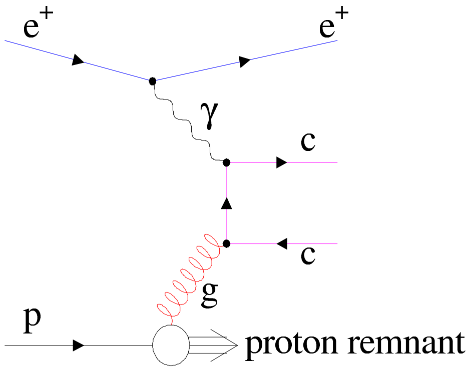



- **Study heavy flavour production mechanisms**
- **m$_c$ (and m$_b$) gives a hard scale to process**
  - ▷ **Good testing ground for pQCD**
  - ▷ **Is m$_c$ hard enough?**
- **Q$^2$ and P$_T$ can also provide a hard scale**
  - ▷ **Multi-scale problem**
  - ▷ **Which scale is most appropriate?**
- **Also non-perturbative issues such as fragmentation**
- **Access to parton densities in proton, photon, or the "pomeron"**
  - ▷ **Particular sensitivity to gluon**

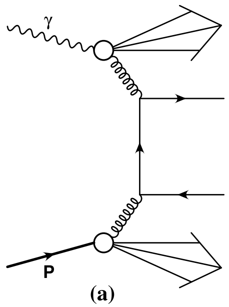
**Heavy Flavour Physics is a major unresolved topic in QCD**

# Heavy Flavour Production at HERA

- Resolved + direct processes contribute at leading order:




**Direct**




**Resolved**

- In resolved events, photon acts as a source of partons
- Resolved charm production $\rightarrow$ sensitive to $\gamma$ structure
- Definition is ambigious beyond LO

# *Heavy Flavour Physics — pQCD Calculations*

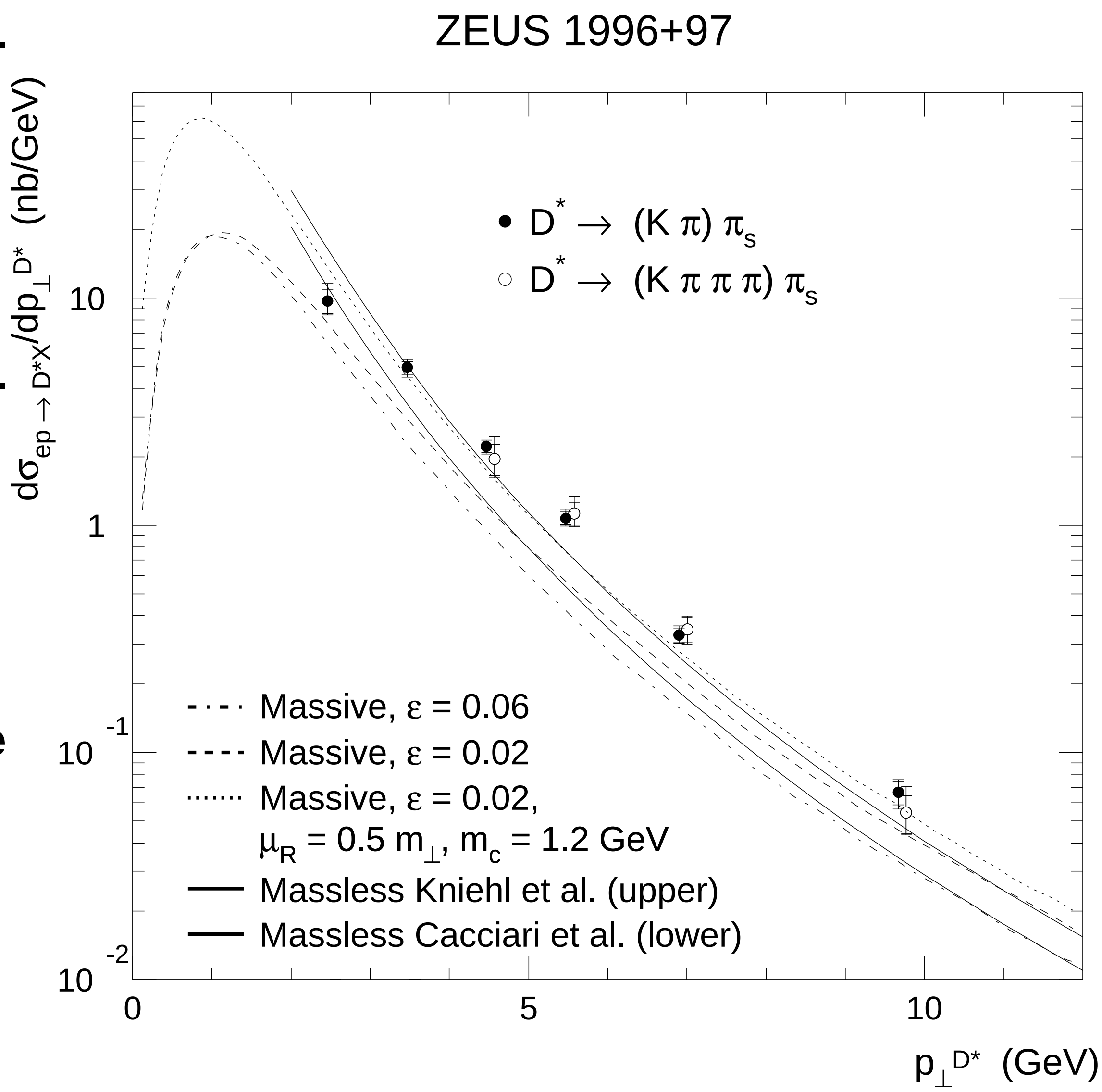
**Various approaches in pQCD $\longrightarrow$ How to treat charm?**

- **Fixed Order NLO Calculations (massive) — FMNR (PhP), HVQDIS (DIS)**
  - ▷ **Charm - 3 active flavours in p and $\gamma$**
  - ▷ **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) — Kniehl et al**
  - ▷ **Charm - 4 active flavours in p and $\gamma$**
  - ▷ **Valid for p$_T >>$ m$_C$, Q $>>$ m$_C$**
- **Matched Calculations (FONLL)**
  - ▷ **NLO mass effects + NLL p$_T$ resummation**

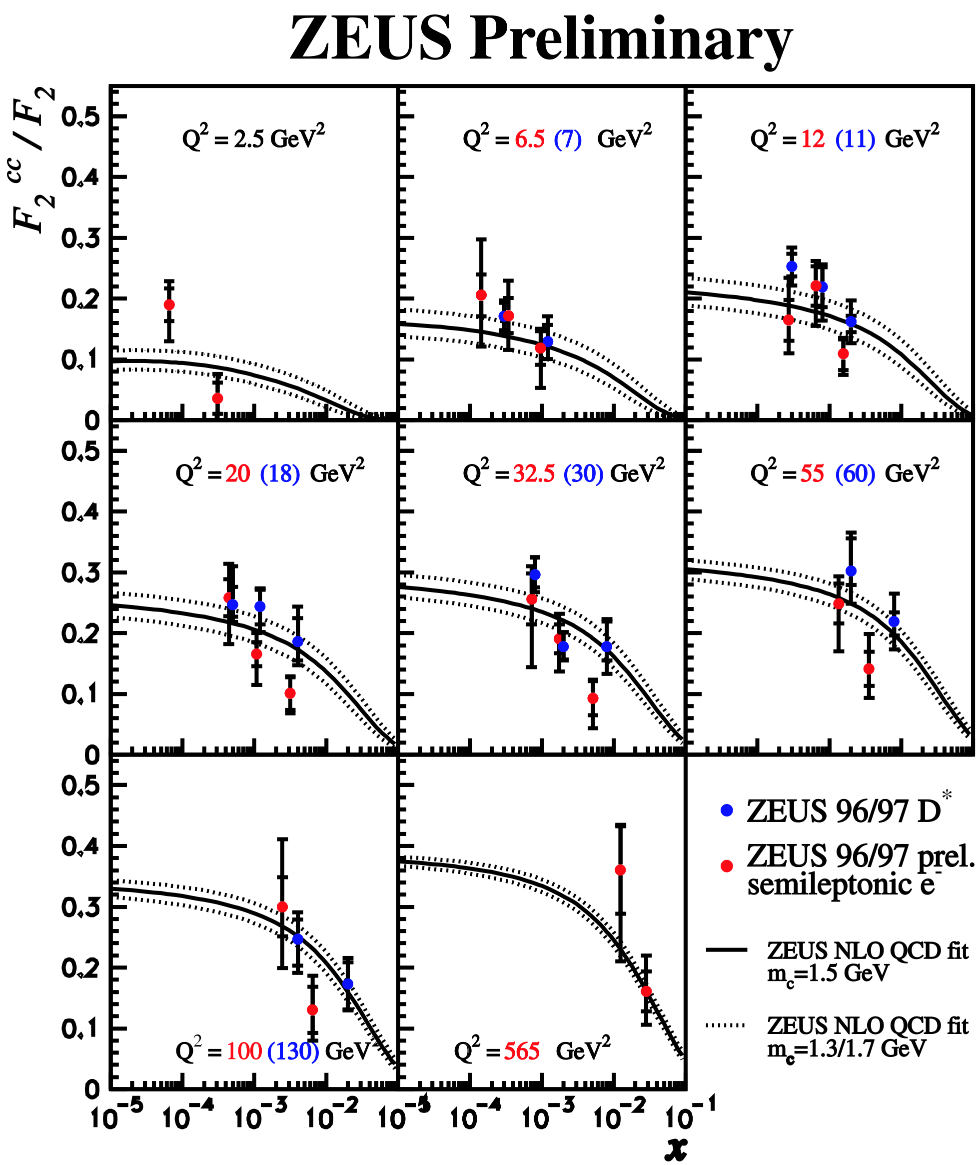
# *Charm in Photoproduction — Motivation*

- **Largest statistics charm measurement at HERA**
  - ▷ **Test pQCD predictions**
- **1996-7 Data already published:**

  *Eur. Phys. J. C6 (1999) 67*
- **Twice as much data available**
  - ▷ **Can now look at double differential cross sections**



# *Charm in Deep Inelastic Scattering — Motivation*




- $F_2^{\rm charm}$ / $F_2$ **large at low x, high $Q^2$**
  - ▷ **Above 30 % at highest $Q^2$**
  - ▷ **Need to understand charm production**
- **1996-7 Data already published**

  *Eur. Phys. J. C 12 (2000) 1, 35*
- **Extrapolate over unmeasured $P_T(D^\star)$, $\eta(D^\star)$ region**
  - ▷ **Model assumptions in $F_2^{\rm charm}$**
- **Rigourous comparisons should be made to differential cross sections**

## *Tagging Charm*

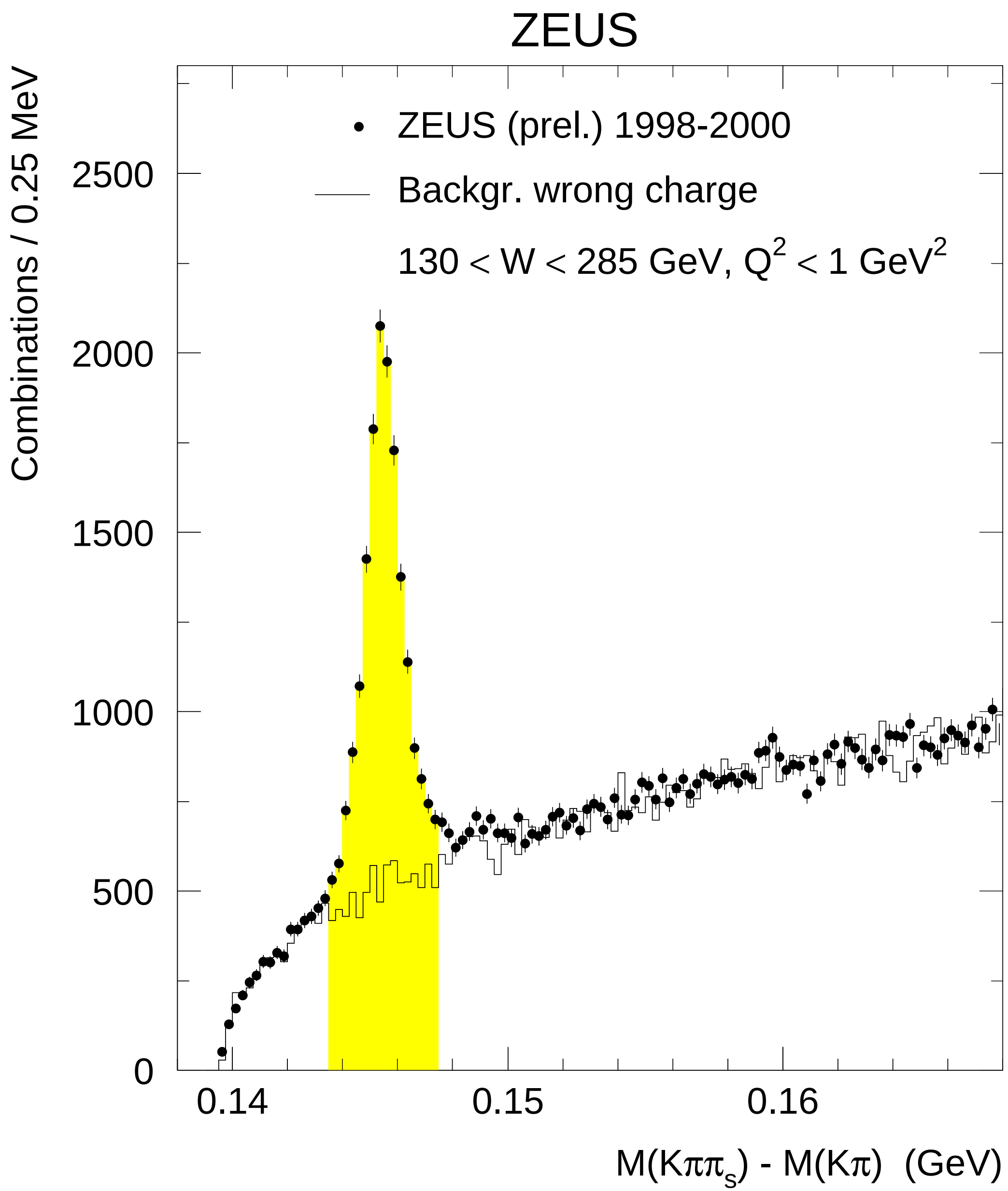
- **Charmed Meson reconstruction from charged decay products**
  - ▷ **No particle ID used**

- $D^{\star}$**(2010) mesons identified with** $\Delta M$ **method**
  - ▷ **Golden decay mode**
  - ▷ $D^{\star\pm} \rightarrow K^{\mp}\pi^{\pm}\pi_s^{\pm}$
  - ▷ $\Delta M$ **= M(**$K\pi\pi_s$**) - M(**$K\pi$**)**

- **Results from reconstructing other charmed mesons and from semileptonic decay modes not dealt with here**

# *Charm in Photoproduction*

- $D^\star$ **Mesons in photoproduction**
- **10 350 $\pm$ 160 $D^\star$ events**
  - ▷ **Significant increase in statistics over previous results (*cf 3700*)**
  - ▷ **Can measure double differential cross sections**
- **Precision tests of pQCD for charm production**
  - ▷ **Compare to NLO, NLL and FONLL predictions**



# Results on $D^\star$ Photoproduction — Differential Cross Sections

**$z(D^\star)$ is fraction of photon energy carried by $D^\star$ in proton rest frame:**

$$z(D^\star) = \frac{(E-p_z)^{D^\star}}{(E-p_z)}$$

- **Data has very small uncertainties over a wide kinematic region**

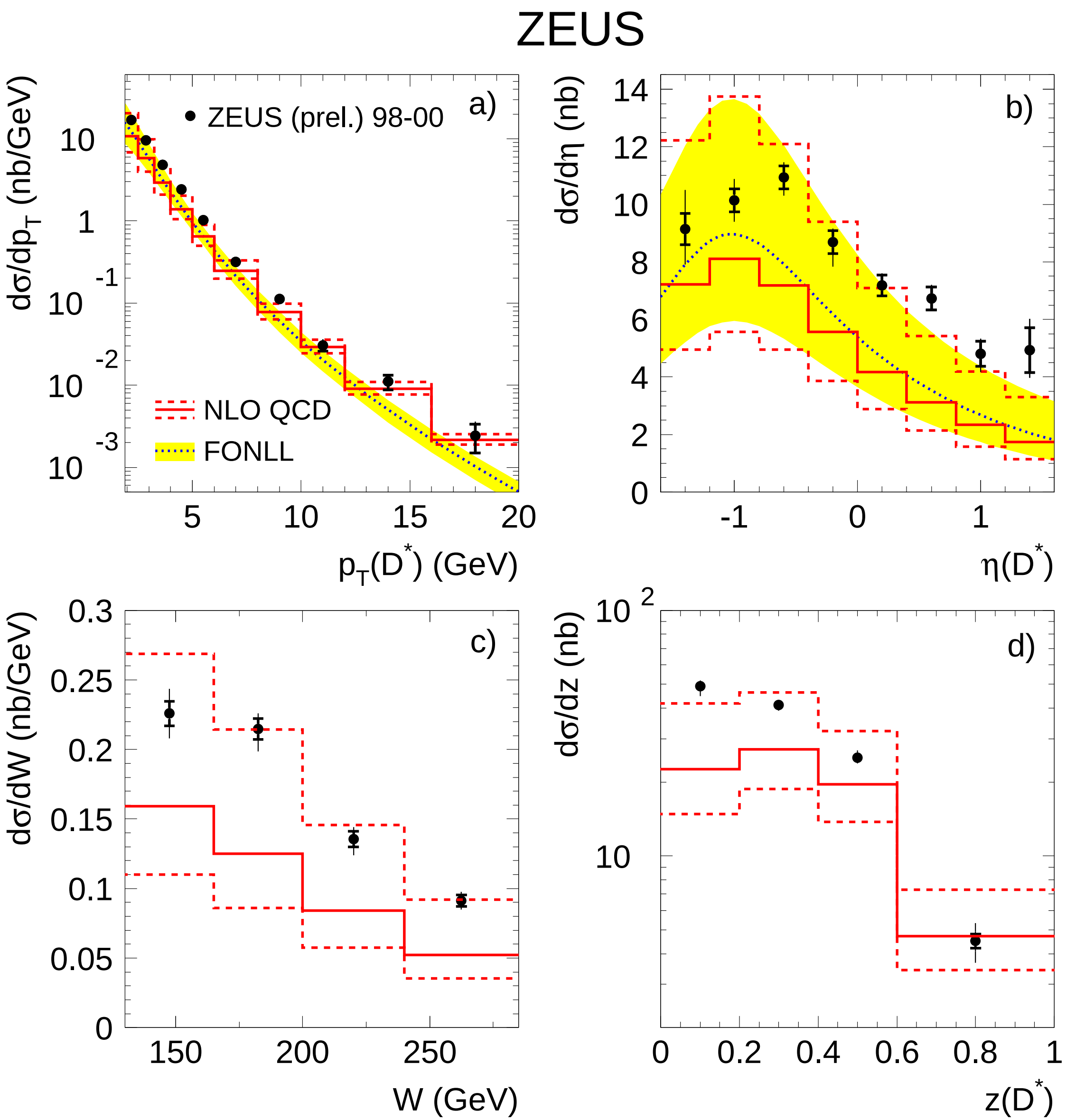
**Kinematic region:**

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

**$130 < W < 285$ GeV**

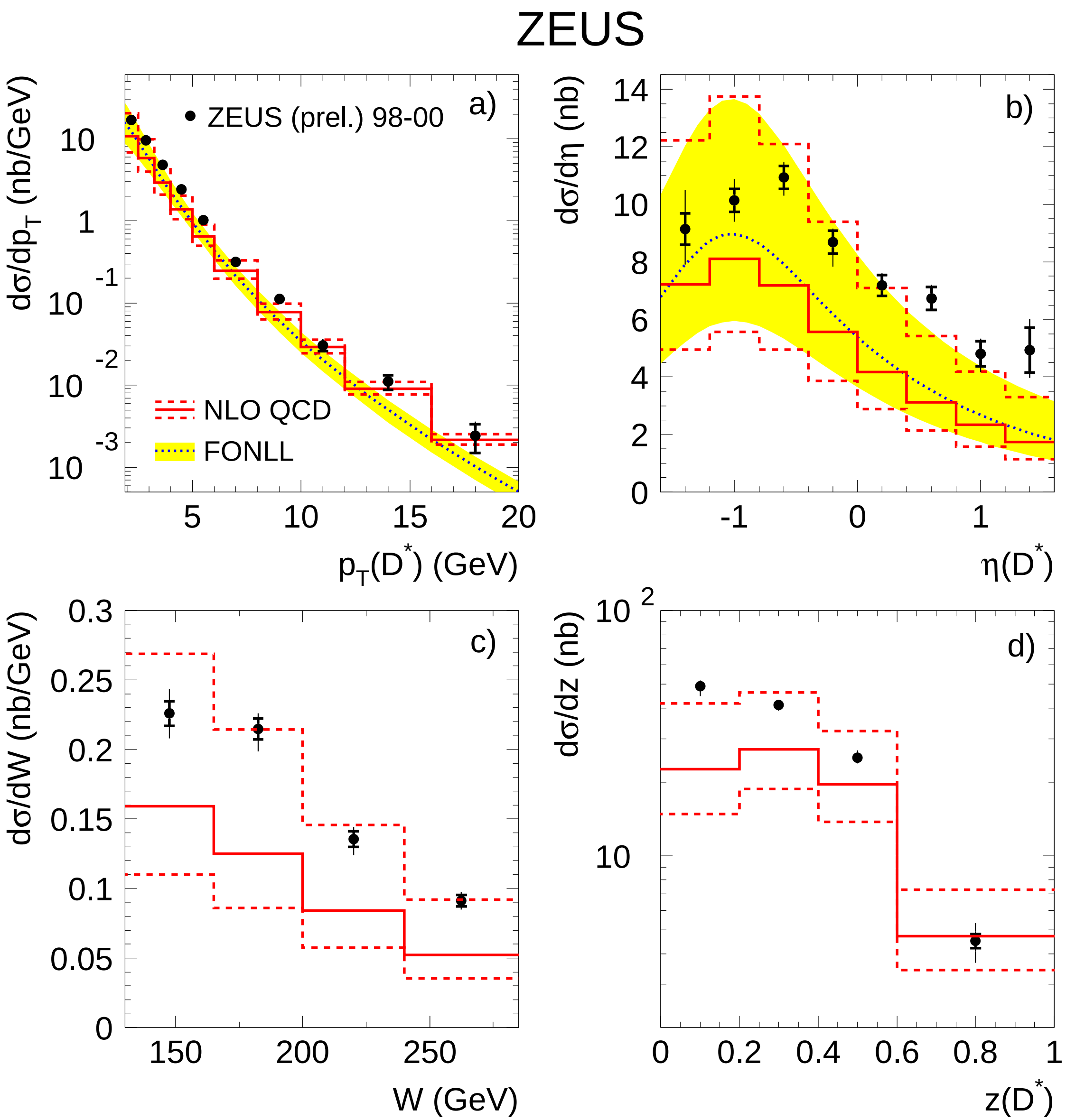
**$1.9 < P_T(D^\star) < 20$ GeV**

**$-1.6 < \eta(D^\star) < 1.6$**



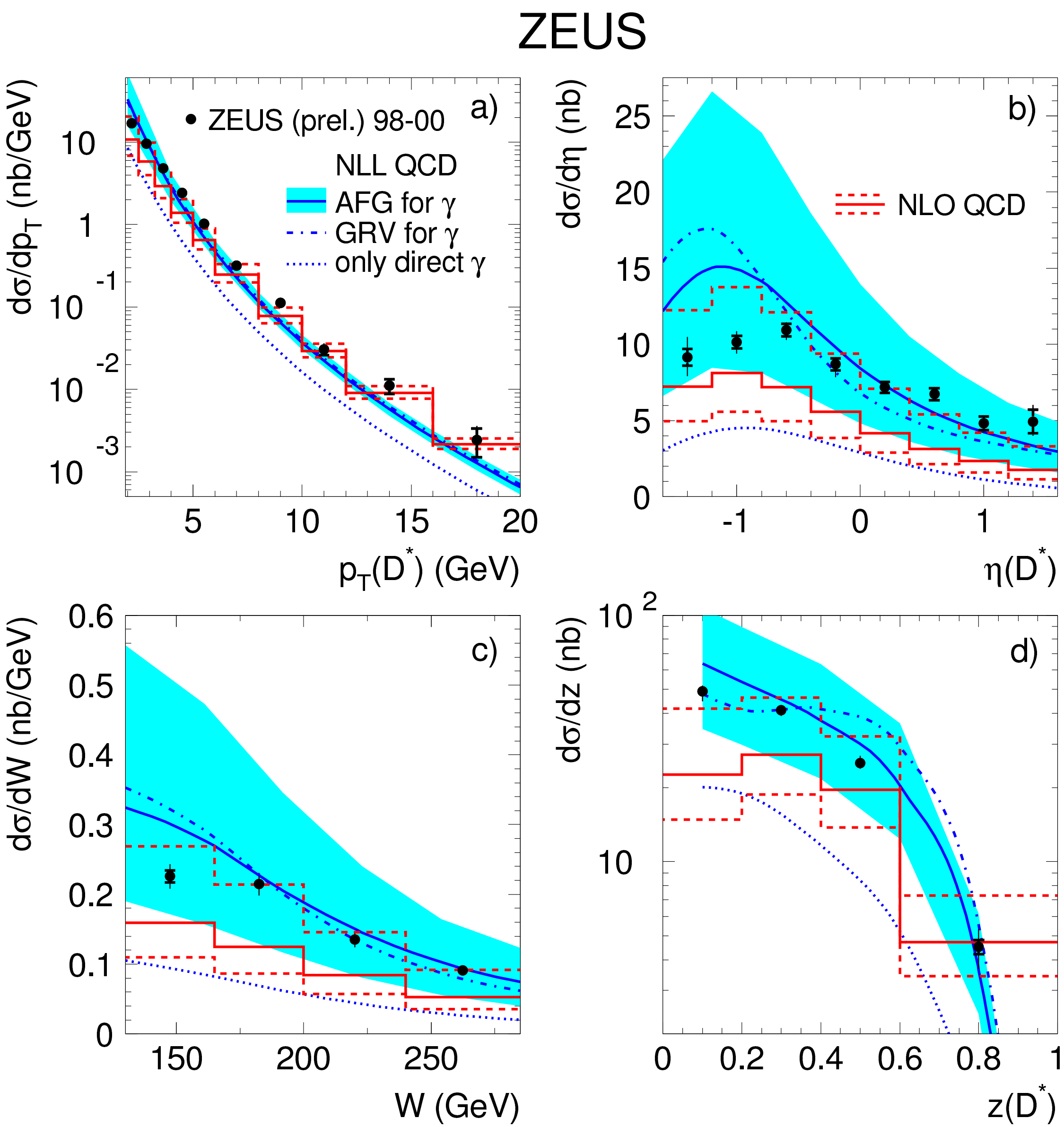
# *Results on $D^\star$ Photoproduction — Differential Cross Sections*

- **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**
- ▷ **Forward $\eta$(D$^\star$), low z(D$^\star$), medium p$_T$(D$^\star$) data in excess of NLO**



# *Results on $D^\star$ Photoproduction — Differential Cross Sections*

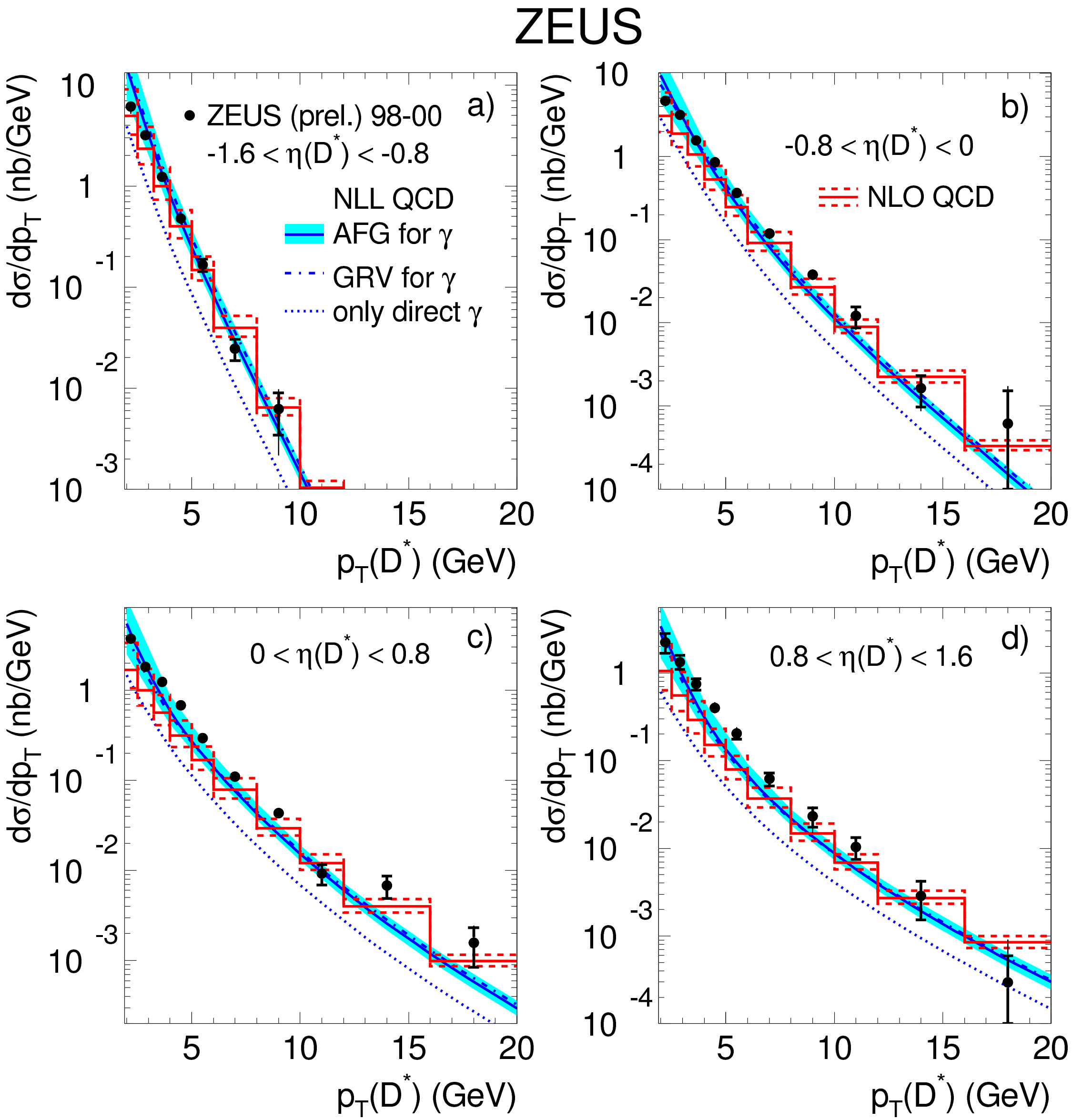
- **Bands on theory show effect of varying renormalisation scale and charm mass**
- **NLL uncertainties very large**
  - ▷ **Effect of changing photon structure function shown**
  - ▷ **Some sensitivity in NLL**
- **NLL seems to describe z($D^\star$) better than NLO**



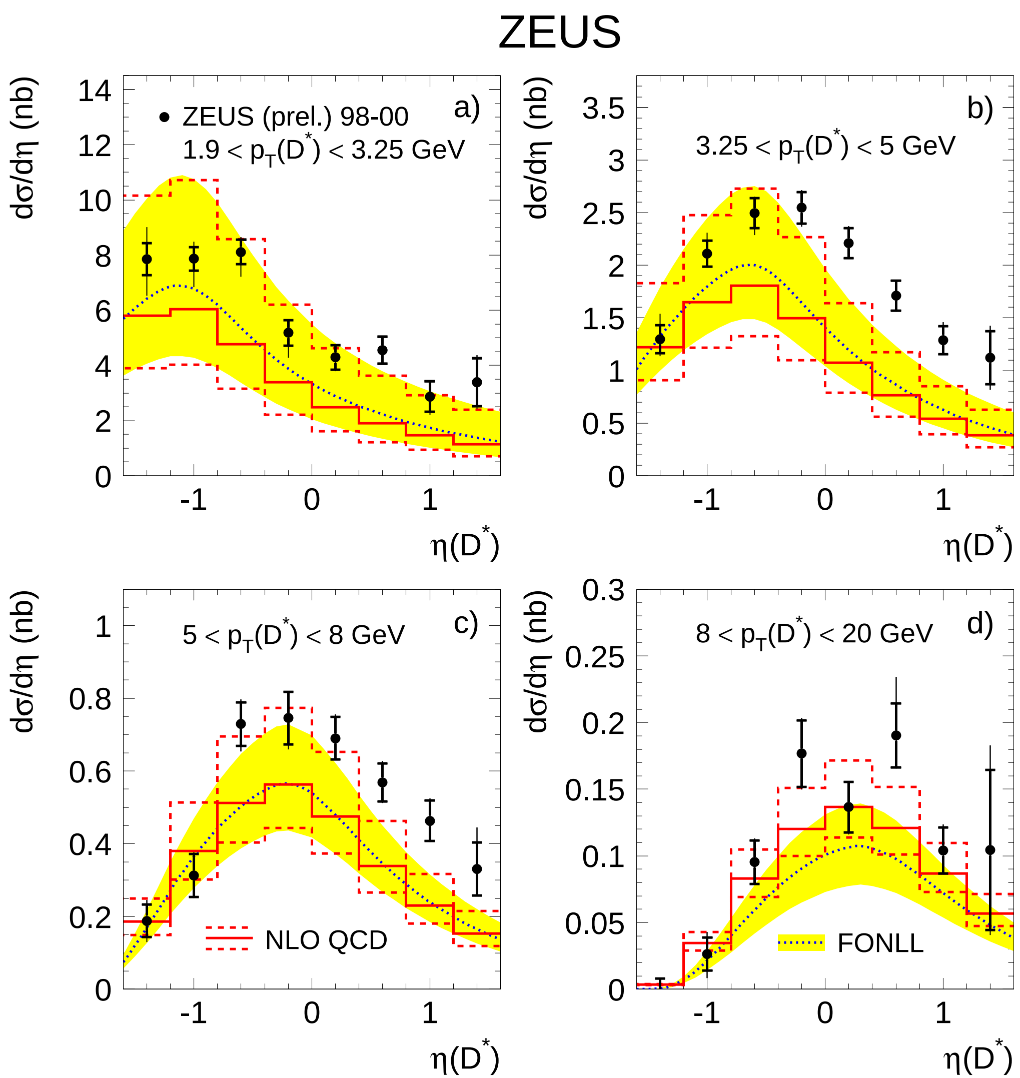
# $D^\star$ Photoproduction — Double Differential Cross Sections

- **Double differential $D^\star$ cross sections shown here for $p_T(D^\star)$ in $\eta(D^\star)$ slices**

- **Medium $p_T(D^\star)$ excess of data over pQCD is concentrated at forward $\eta(D^\star)$**



# $D^\star$ Photoproduction — Double Differential Cross Sections

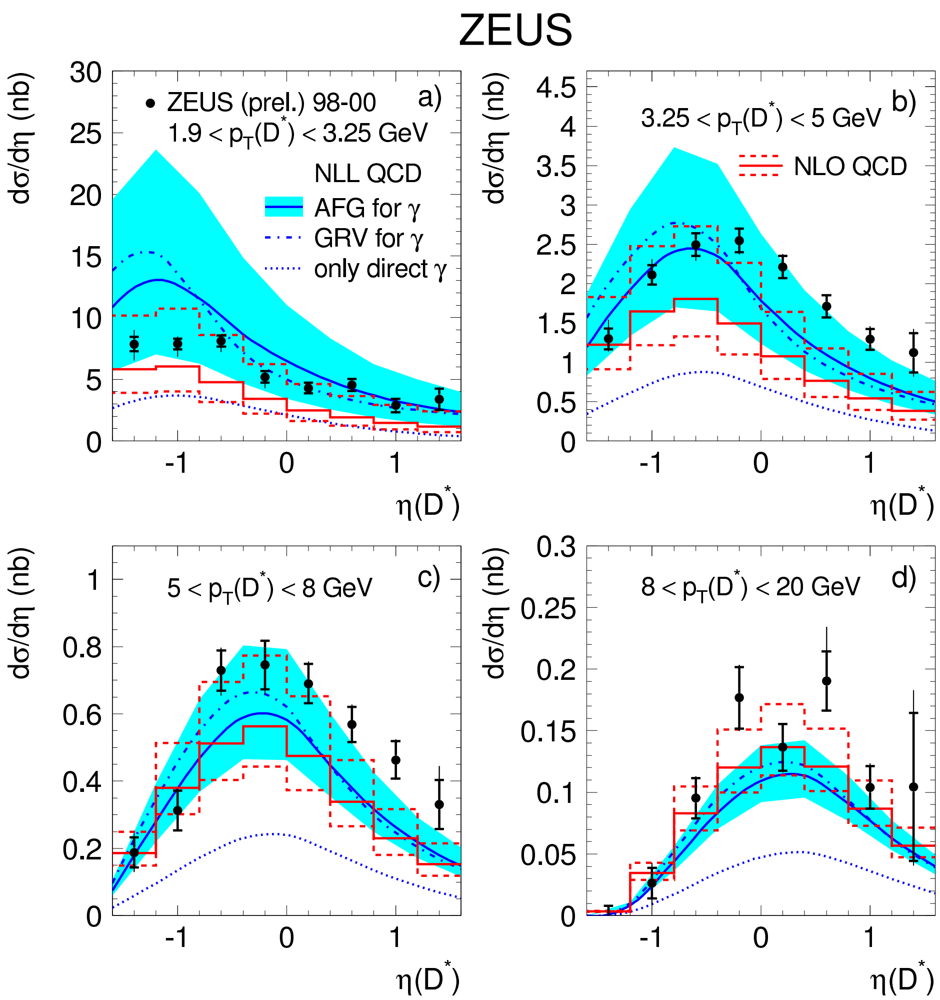



- **Double differential $D^\star$ cross sections shown here for $\eta(D^\star)$ in $p_T(D^\star)$ slices**
- **For double differential cross sections as well, NLO seems to do a better job than FONLL**
- **Again, excess in data over pQCD at forward $\eta(D^\star)$ and medium $p_T(D^\star)$ seem to be correlated**

# $D^\star$ Photoproduction — Double Differential Cross Sections

- **Double differential $D^\star$ cross sections shown here for $\eta(D^\star)$ in p$_T(D^\star)$ slices**

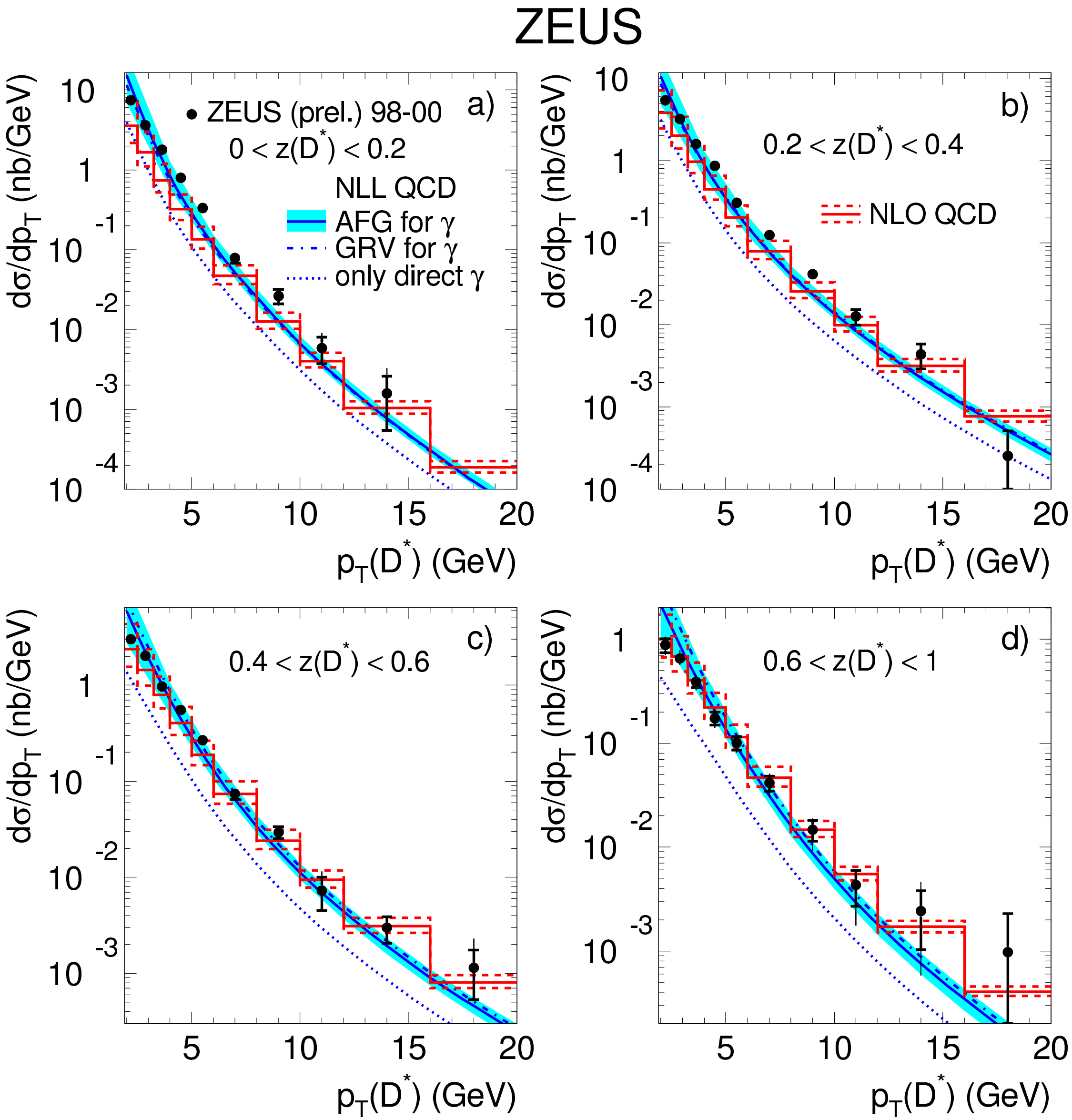
- **NLL seems also not to describe $\eta(D^\star)$ shape at medium p$_T(D^\star)$**



# *$D^\star$ Photoproduction — Double Differential Cross Sections*

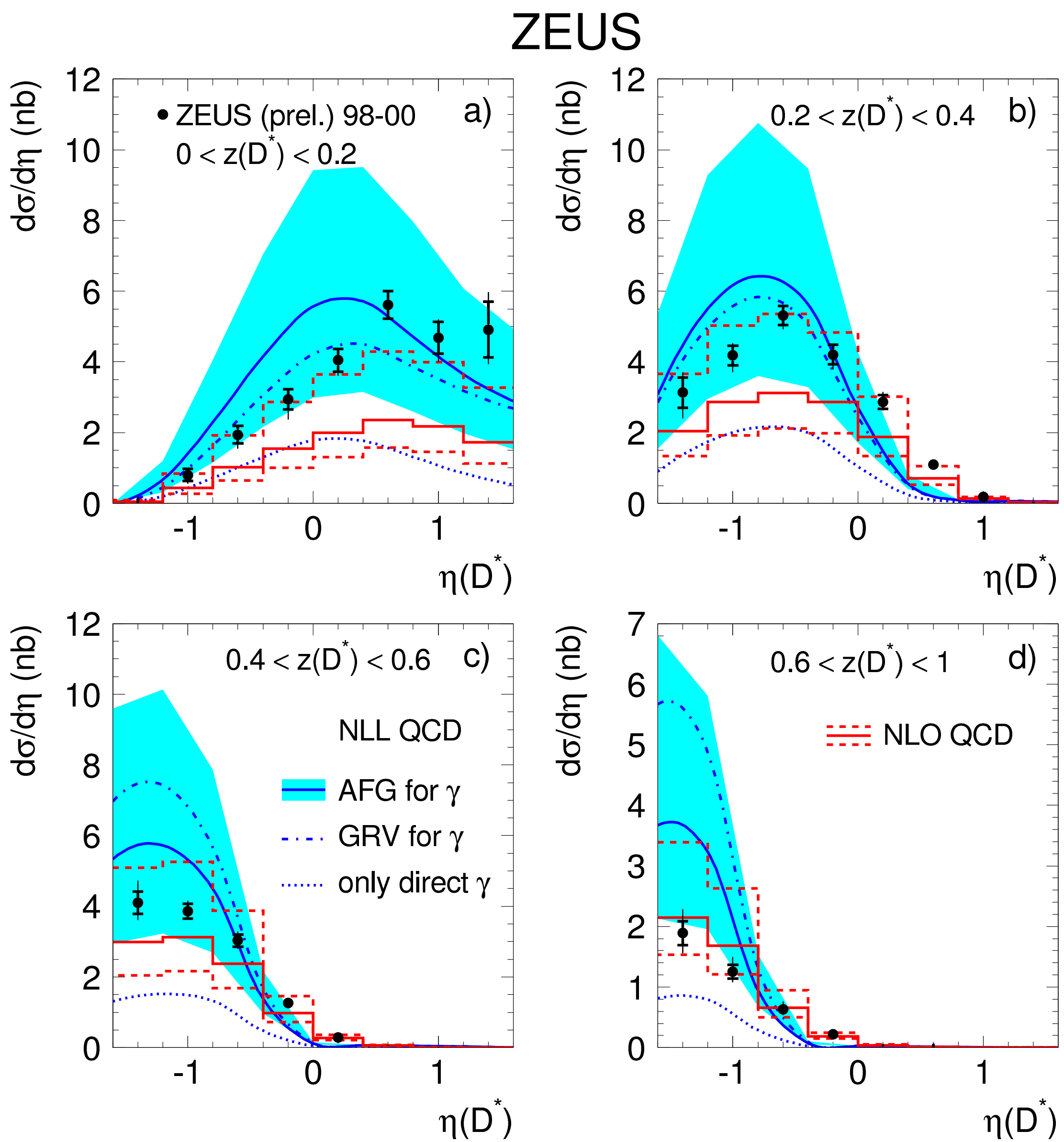
- **Double differential $D^\star$ cross sections shown here for $p_T(D^\star)$ in $z(D^\star)$ slices**

- **Excess in data over pQCD at medium $p_T(D^\star)$ and low $z(D^\star)$ seem to be correlated**



# $D^\star$ Photoproduction — Double Differential Cross Sections

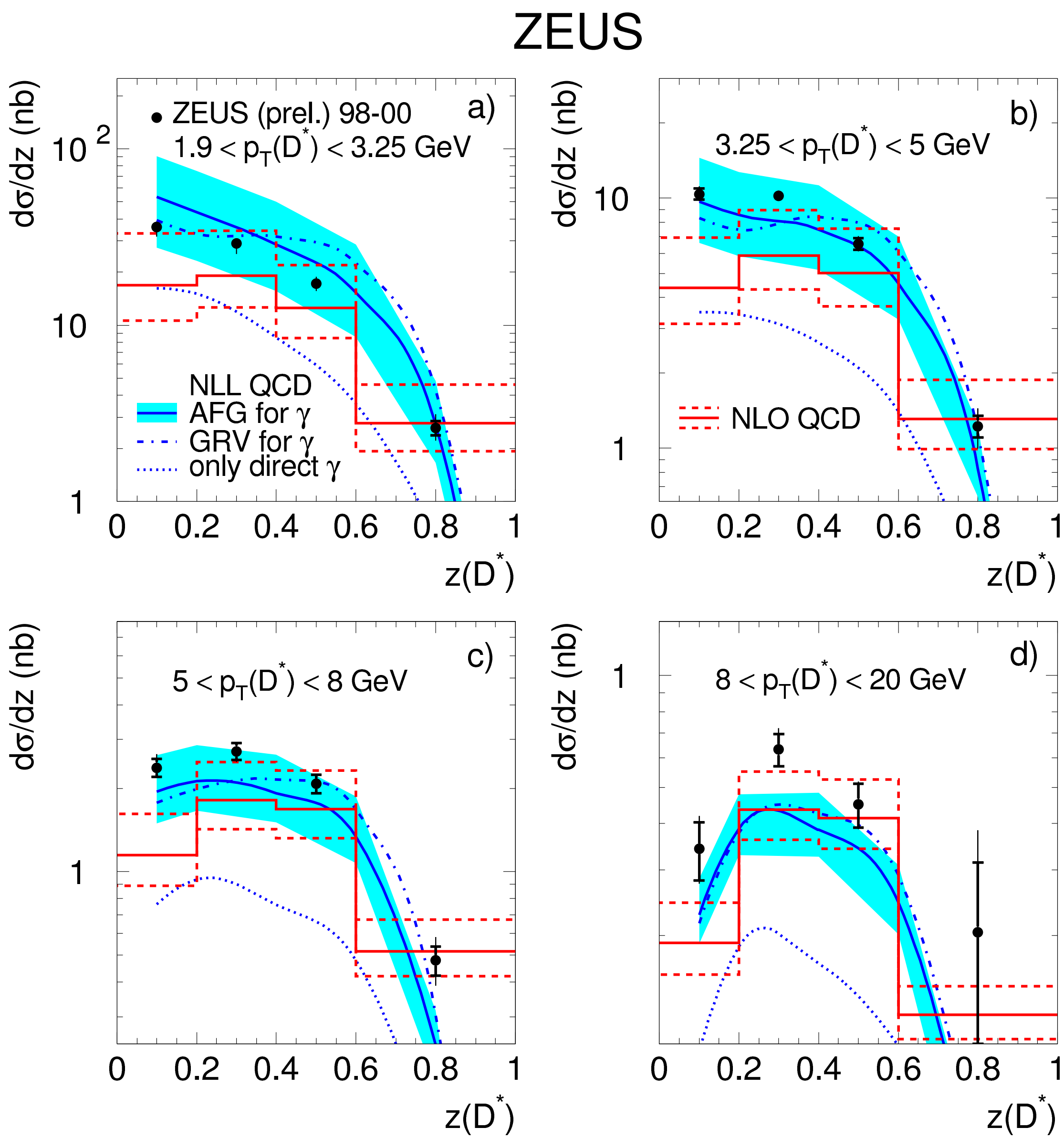
- **Double differential $D^\star$ cross sections shown here for $\eta(D^\star)$ in z($D^\star$) slices**
- **Data favours higher limit of NLO predictions at low z($D^\star$), and lower limit at high z($D^\star$)**
- **Shape in $\eta(D^\star)$ at low z($D^\star$) not well described by NLL**



# $D^\star$ Photoproduction — Double Differential Cross Sections

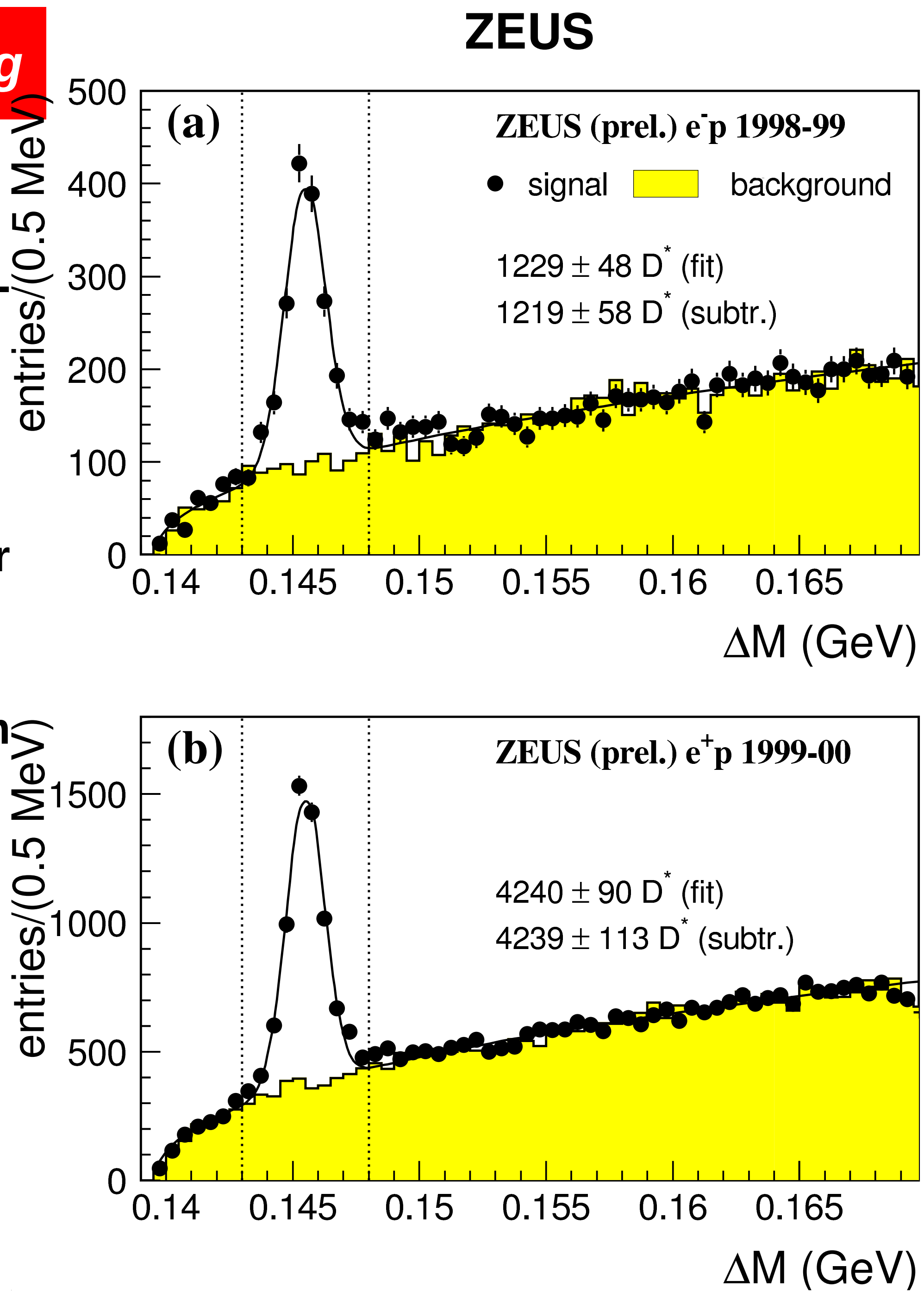
- **Double differential $D^\star$ cross sections shown here for z($D^\star$) in p$_T$($D^\star$) slices**

- **NLL predictions seem to provide a better description of the data here**



## *Charm in Deep Inelastic Scattering*

- ▷ **What can this tell us about the structure function of the proton?**
- ● **5450 $D^{\star}$ events**
- ▷ **Significant increase in statistics over previous results (*cf 2060*)**
- ● **Precision tests of pQCD for charm production**
- ▷ **Compare to NLO predictions**



# $D^\star$ Production in Deep Inelastic Scattering

- **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**

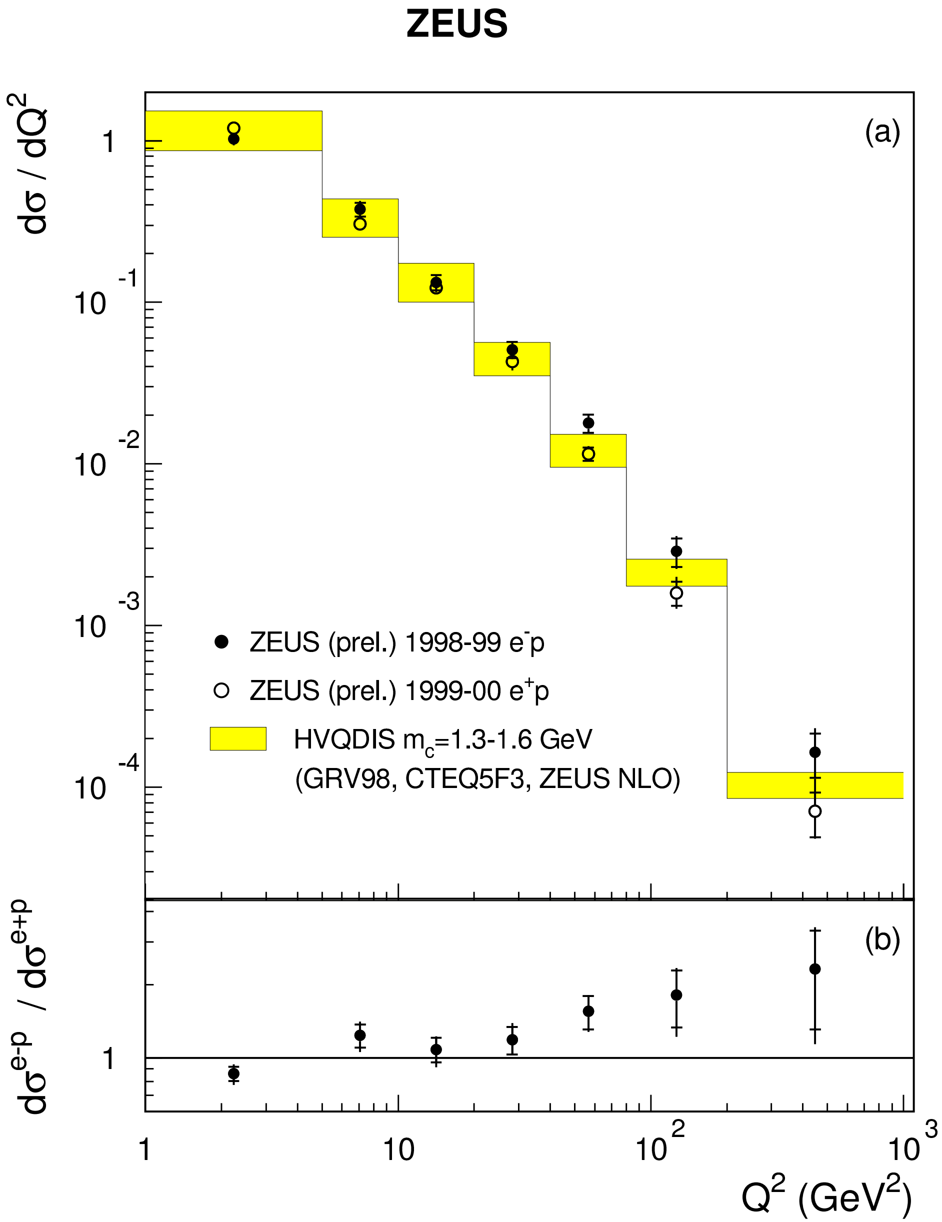
**Kinematic region:**

**1 $<$ Q$^2$ $<$ 1000 GeV$^2$**

**0.02 $<$ y $<$ 0.8**

**1.5 $<$ P$_T$(D$^\star$) $<$ 15 GeV**

**-1.5 $<$ $\eta$(D$^\star$) $<$ 1.5**



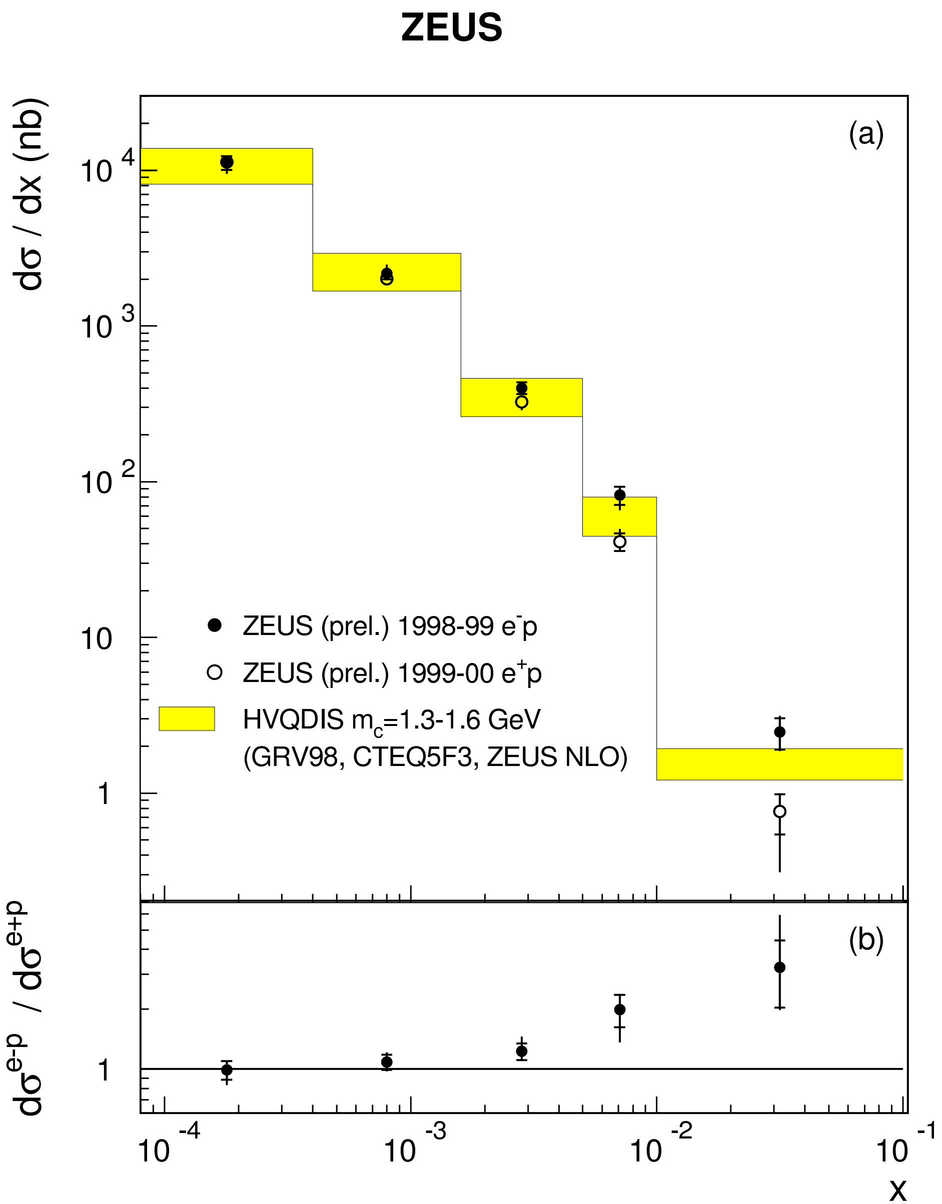
# *$D^\star$ Production in Deep Inelastic Scattering*

- **Differential cross section in $x$**

- **Improvement in errors from previous results**

▷ **Should be able to improve precision and understanding of $F_2^{c\bar{c}}$**

- **Apparent difference between $\sigma(e^+)$ and $\sigma(e^-)$ probably statistical fluctuation**



# *Summary*

- **Very precise data available over a wide kinematic region**
  - ▷ **Data presents a challenge to the precision of the theory**
- **In general charm results can be described by pQCD predictions**
- **However in certain kinematic regions, data well above the predictions**
  - ▷ **FONLL seems to do a worse job than NLO**
  - ▷ **Uncertainty on the predictions from theory is greater that the uncertainty on the experimental results**
  - ▷ **NNLO would be welcome!**
- **One possible explanation for b results? (⟶)**

**b cross section at HERA**