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Inclusive Charm Production in Photoproduction and DIS at HERA

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Physics Topics Addressed in this Talk

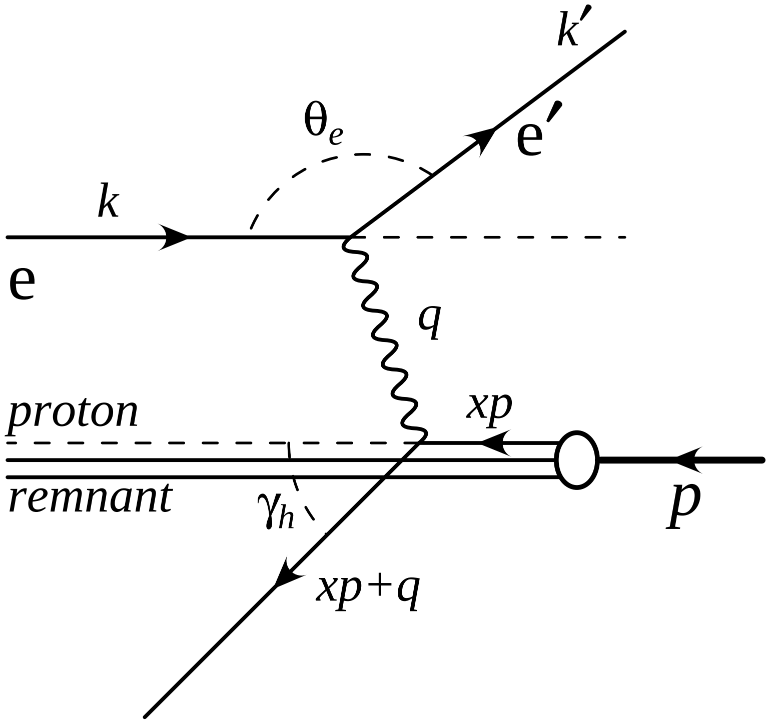
- Introduction
- Charm Production
  - ▷ Charm Photoproduction
  - ▷ Charm in Deep Inelastic Scattering
- Summary and Outlook

Introduction to HERA

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

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

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



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:

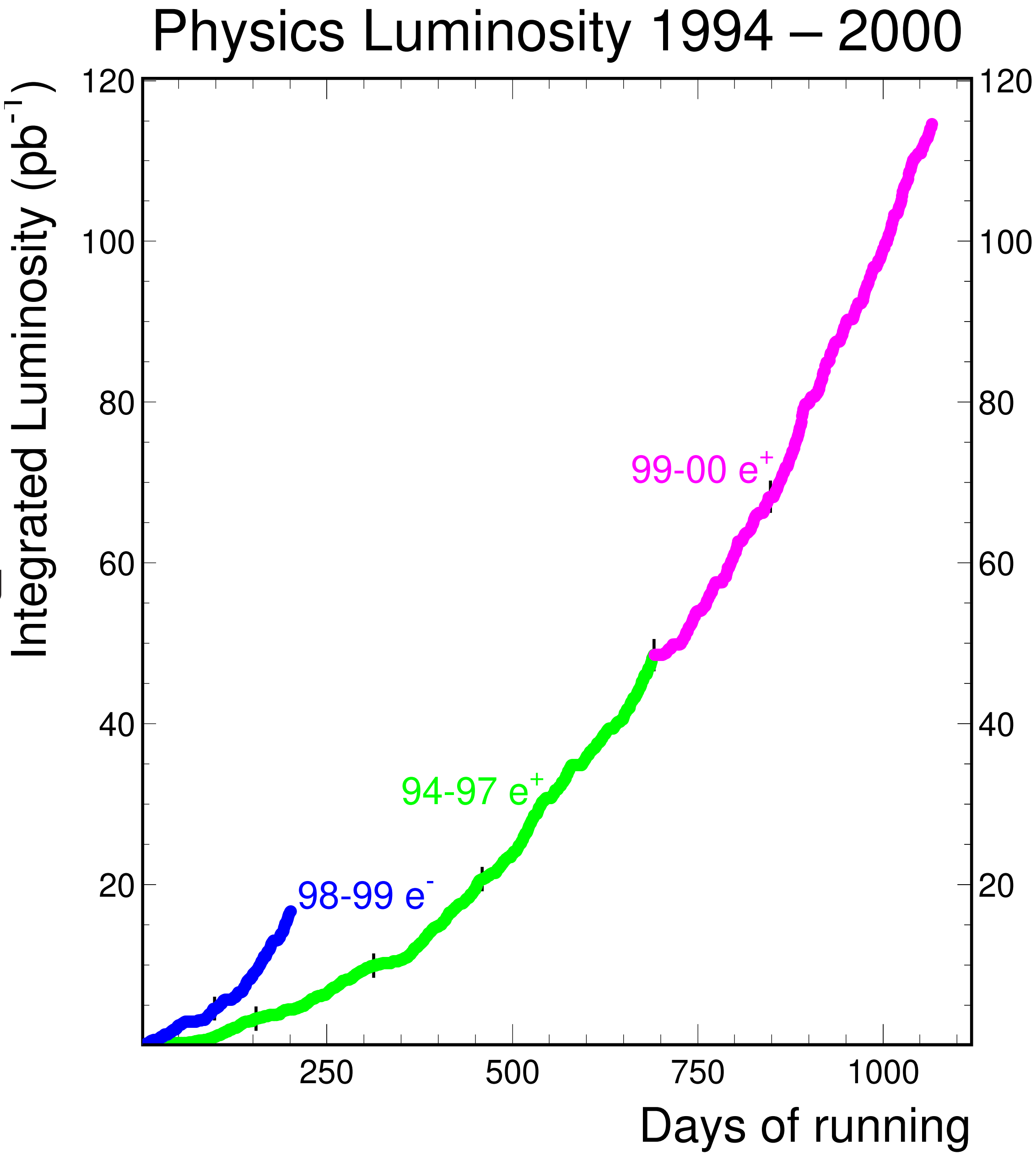
$$Q^2 < 1\ \text{GeV}^2$$

Deep Inelastic Scattering:

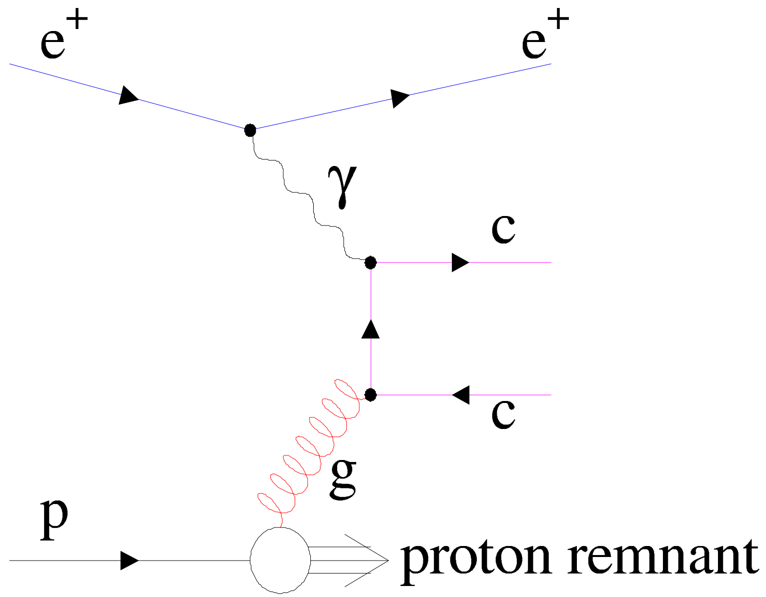
$$Q^2 > 1\ \text{GeV}^2$$

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

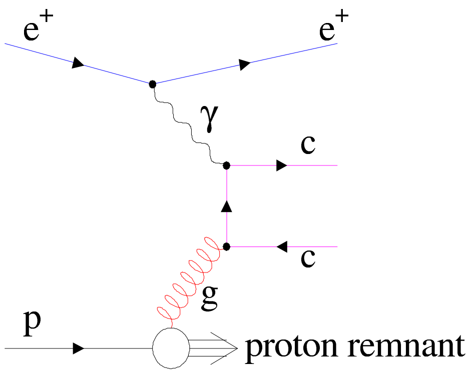


- Study heavy flavour production mechanisms
- m$_c$ (and m$_b$) gives a hard scale to process
  - ▷ Good testing ground for pQCD
  - ▷ Is m$_c$ hard enough?
- Q^2 and P$_T$ can also provide a hard scale
  - ▷ Multi-scale problem
  - ▷ Which scale is most appropriate?
- Also non-perturbative issues such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

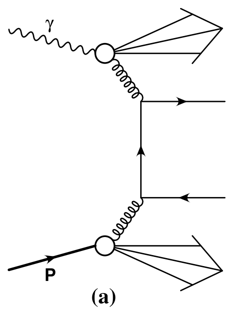
Heavy Flavour Physics is a major unresolved topic in QCD

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 γ structure
- Definition is ambigious beyond LO

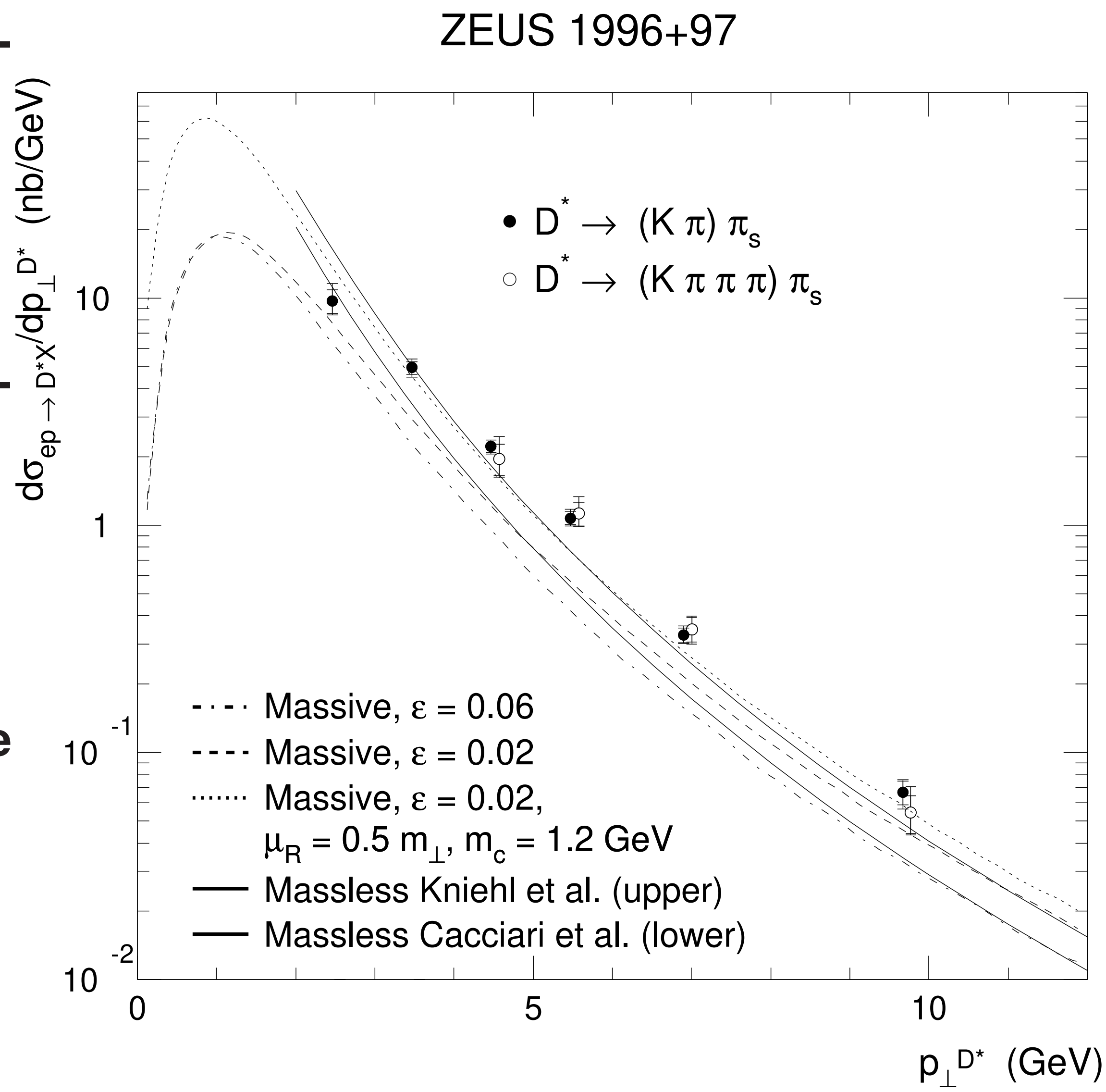
Heavy Flavour Physics — pQCD Calculations

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

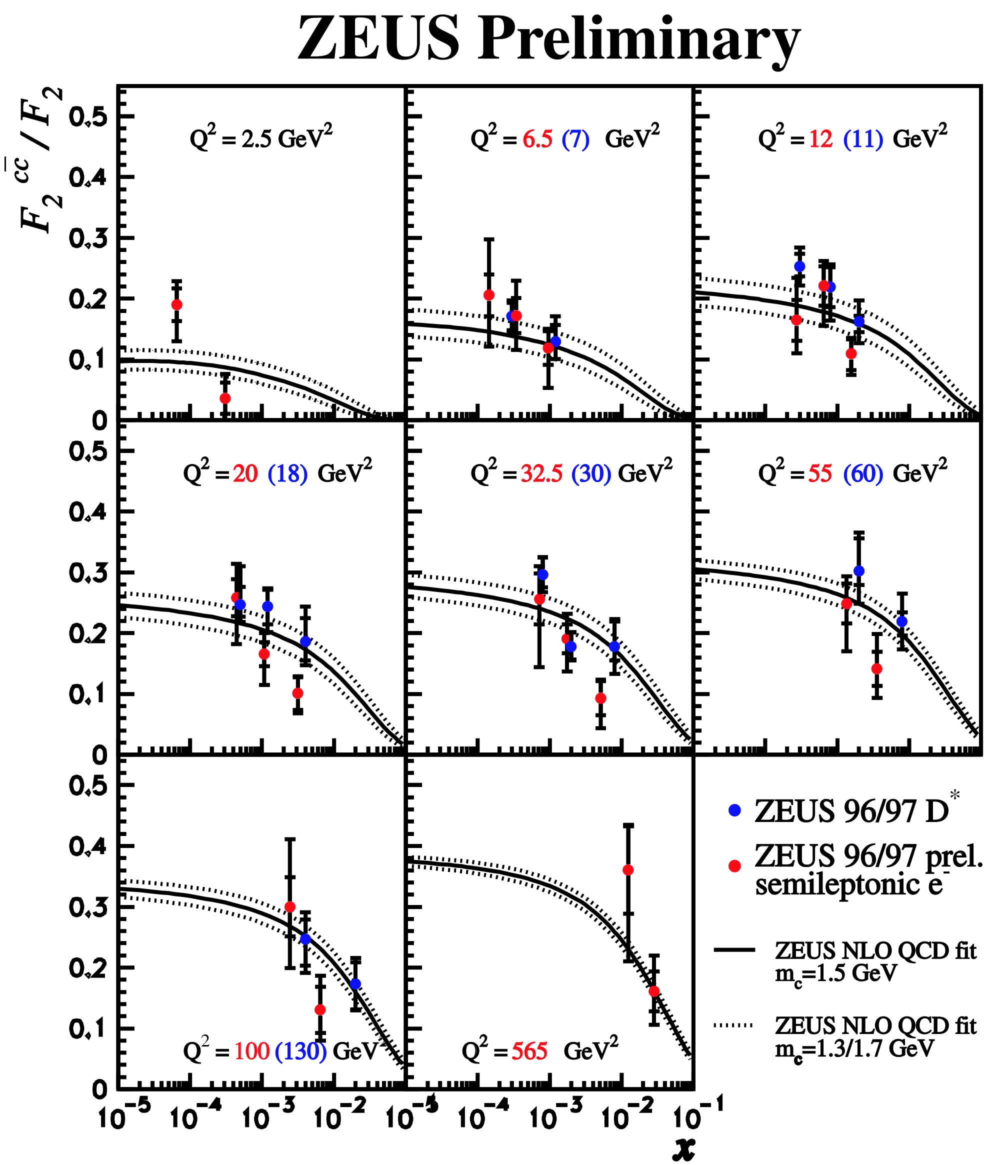
- **Fixed Order NLO Calculations (massive) — FMNR (PhP), HVQDIS (DIS)**
  - ▷ **Charm - 3 active flavours in p and γ**
  - ▷ **Not valid only for p$_T >>$ m$_C$, Q $>>$ m$_C$ (Large logarithms $\frac{p_T}{m_c}, \frac{Q}{m_c}$)**
- **Resummed NLL Calculations (massless) — Kniehl et al**
  - ▷ **Charm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

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



- $\mathrm{F}_2^{\mathrm{charm}}$ / 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 $\mathrm{P}_T(\mathrm{D}^\star)$, $\eta(\mathrm{D}^\star)$ region
  - ▷ Model assumptions in $\mathrm{F}_2^{\mathrm{charm}}$
- Rigourous comparisons should be made to differential cross sections

Tagging Charm

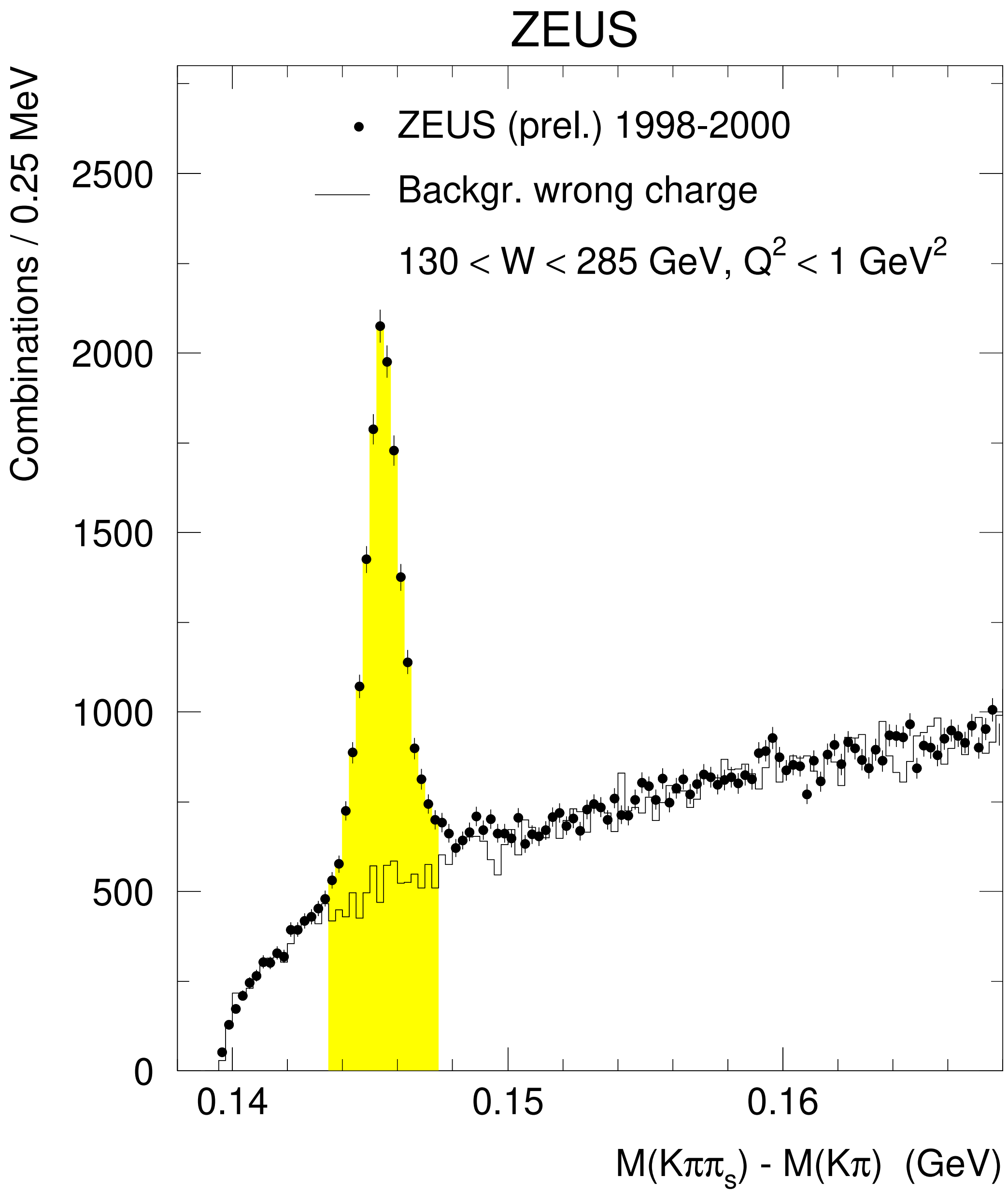
- **Charmed Meson reconstruction from charged decay products**
  - ▷ **No particle ID used**

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

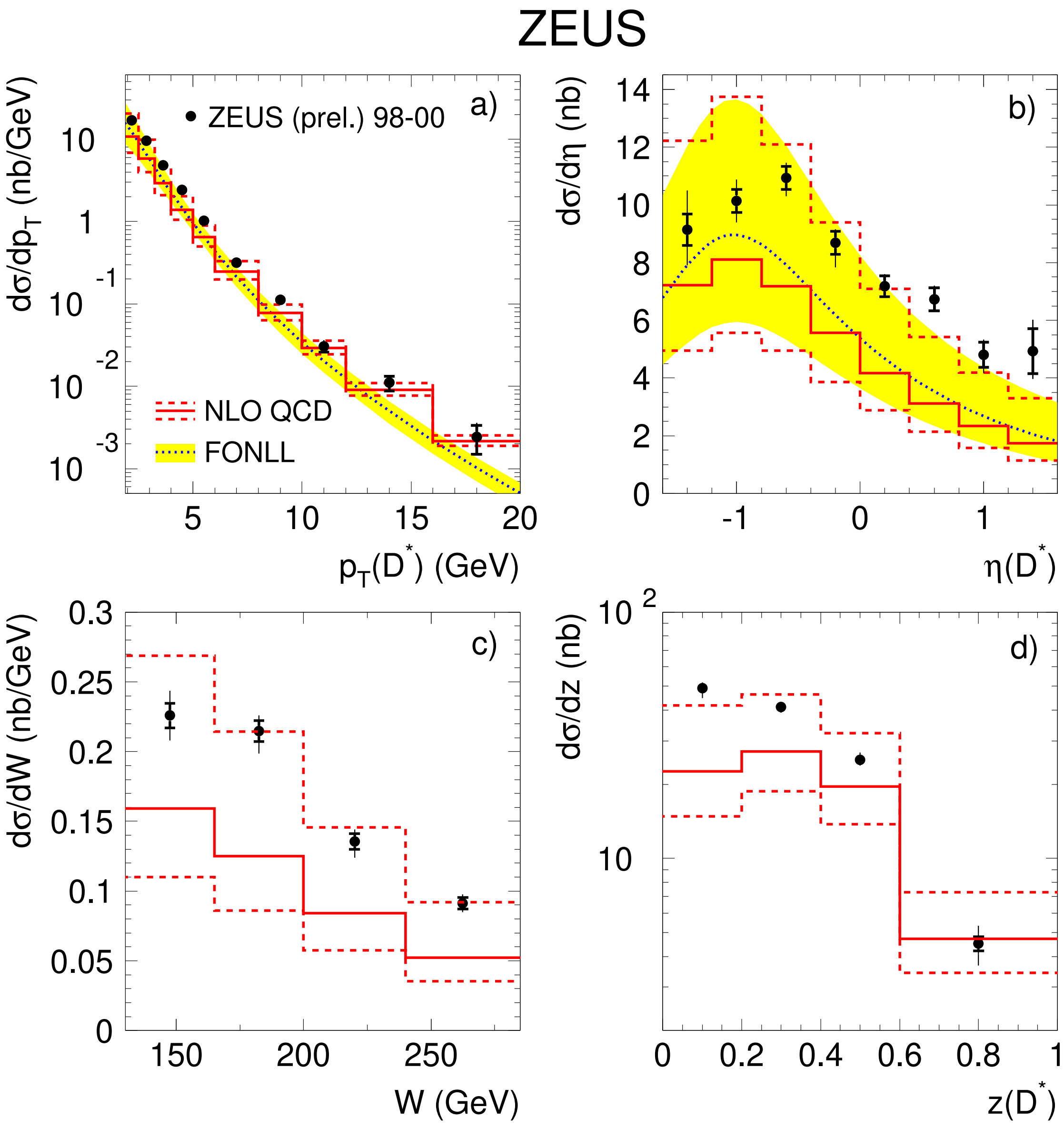
Kinematic region:

$Q^2 < 1$ GeV^2

$130 < W < 285$ GeV

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

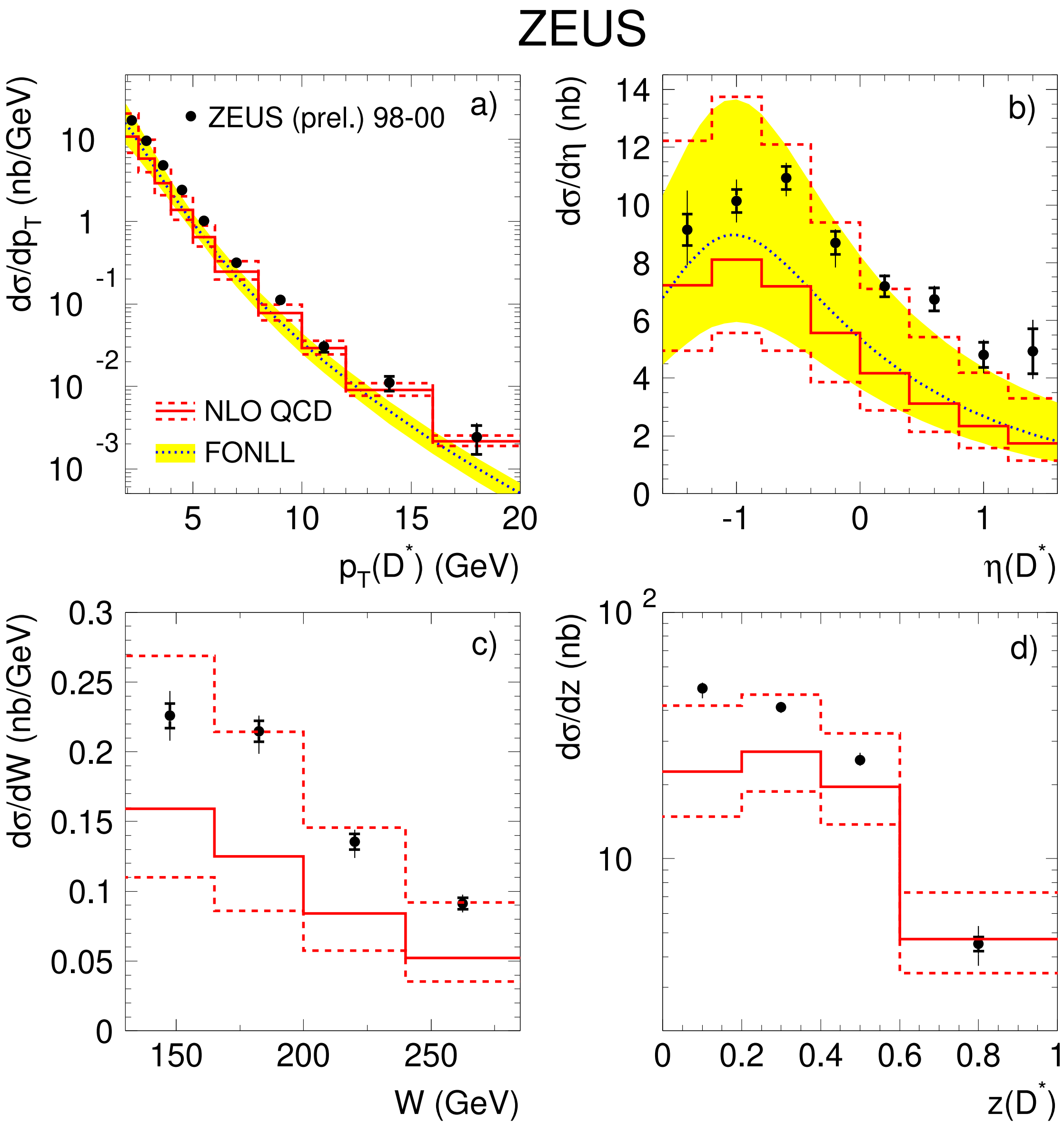
$-1.6 < \eta(D^\star) < 1.6$



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

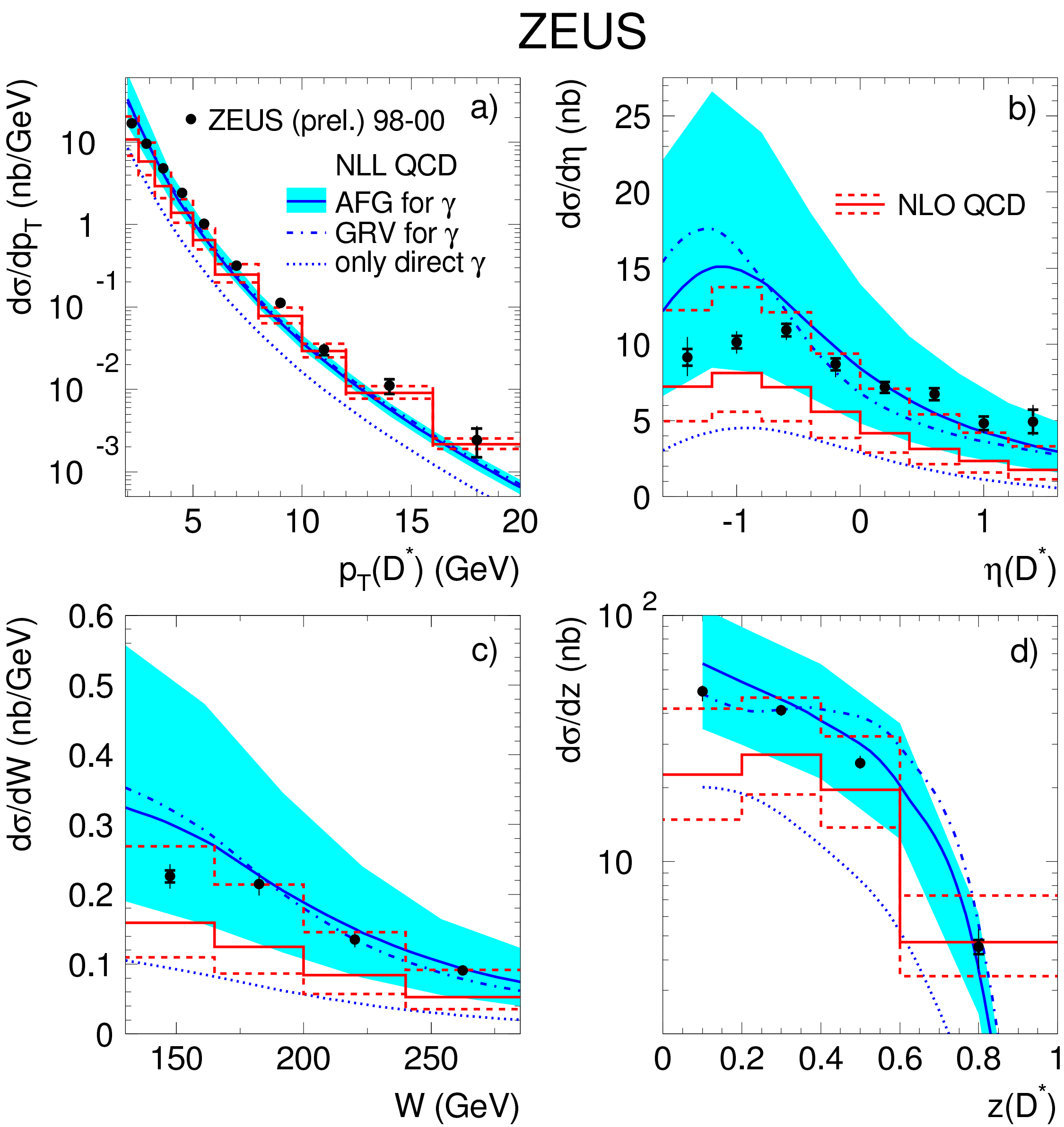
- **Bands on theory show effect of varying renormalisation scale and charm mass**
- **NLO seems to describe data better than FONLL**
- **Data towards higher limit of NLO**

▷ **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

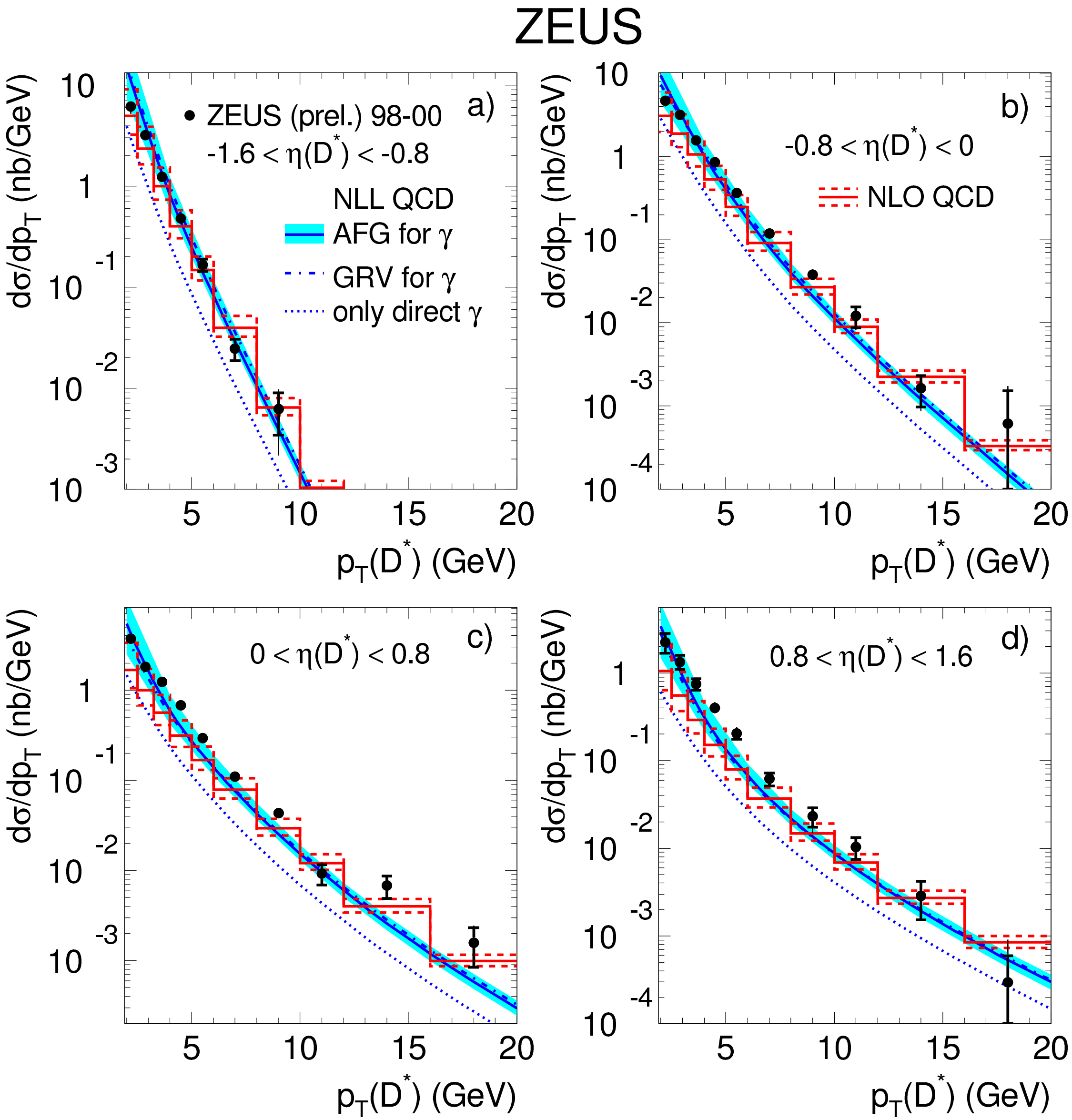
- **Bands on theory show effect of varying renormalisation scale and charm mass**
- **NLL uncertainties very large**
  - ▷ **Effect of changing photon structure function shown**
  - ▷ **Some sensitivity in NLL**
- **NLL seems to describe z($D^{\star}$) better than NLO**



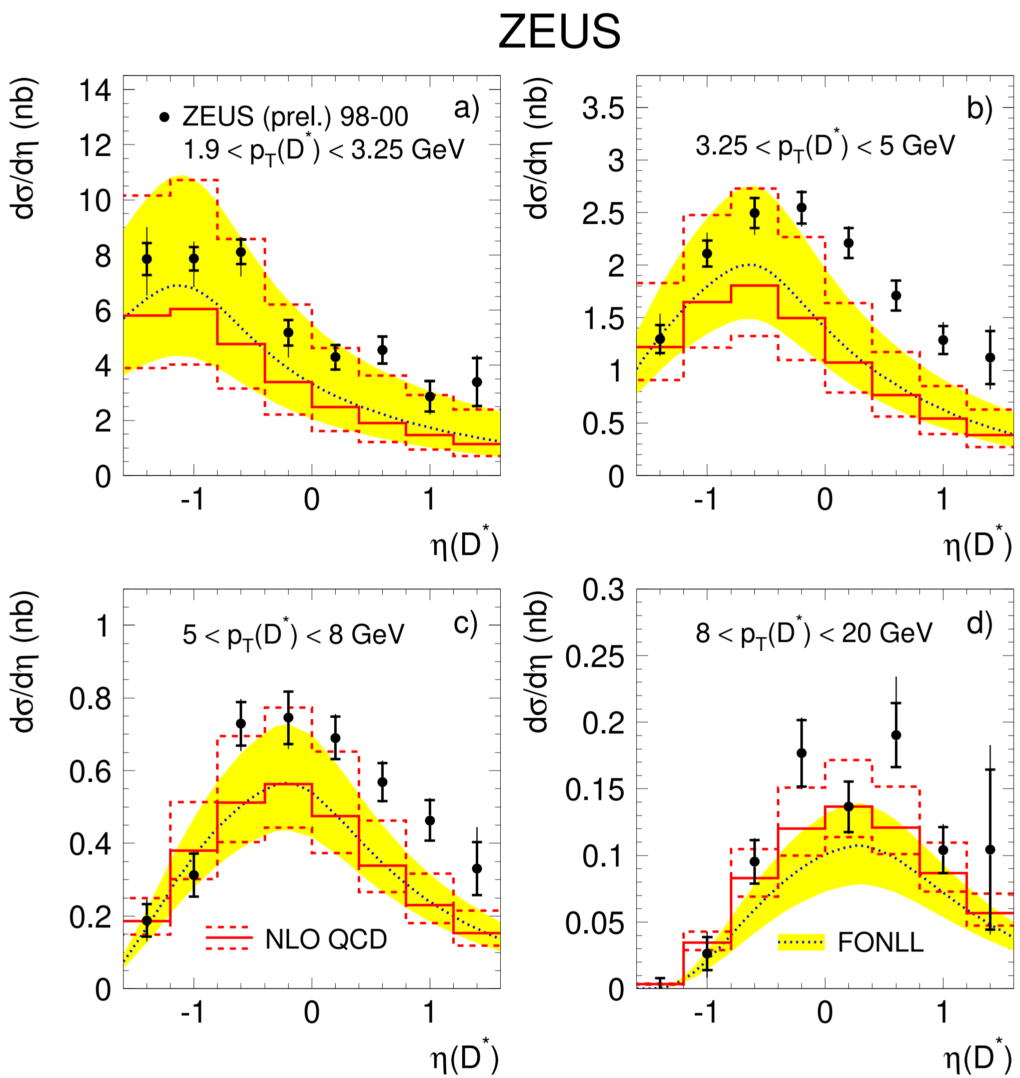
$D^\star$ Photoproduction — Double Differential Cross Sections

- **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

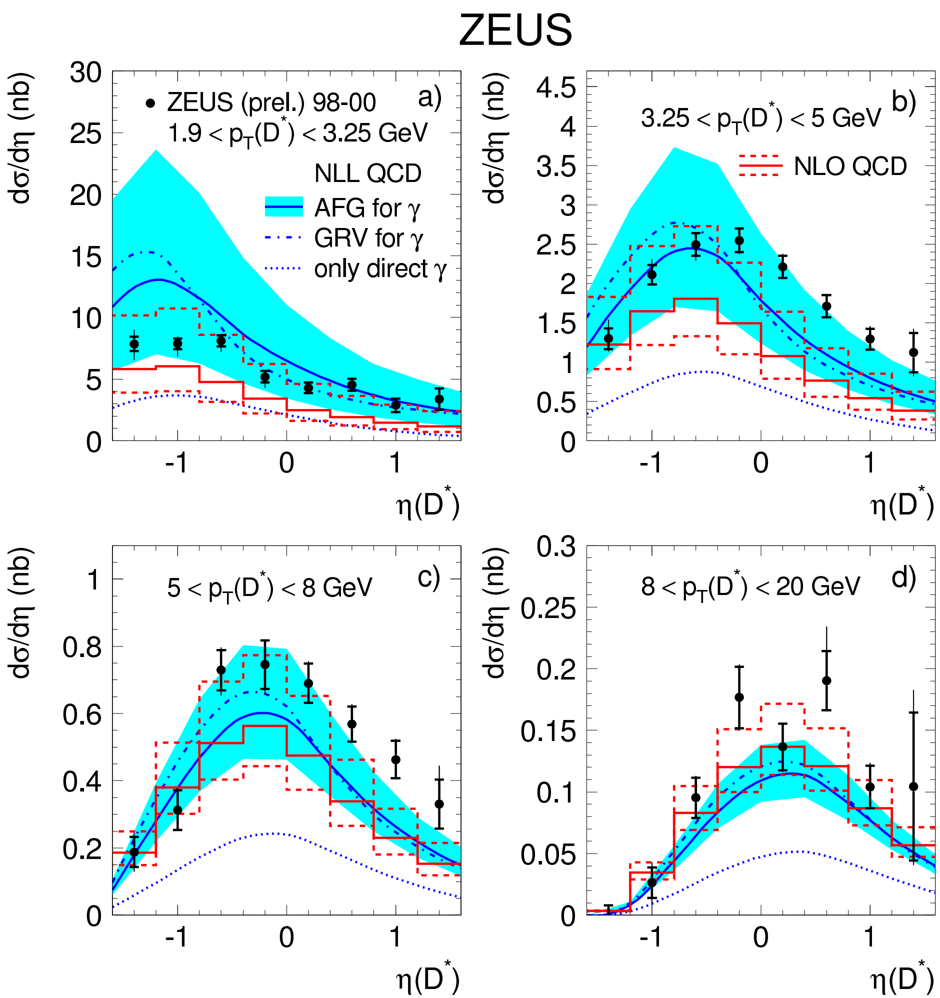


- **Double differential $D^\star$ cross sections shown here for $\eta(D^\star)$ in $p_T(D^\star)$ slices**
- **For double differential cross sections as well, NLO seems to do a better job than FONLL**
- **Again, excess in data over pQCD at forward $\eta(D^\star)$ and medium $p_T(D^\star)$ seem to be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

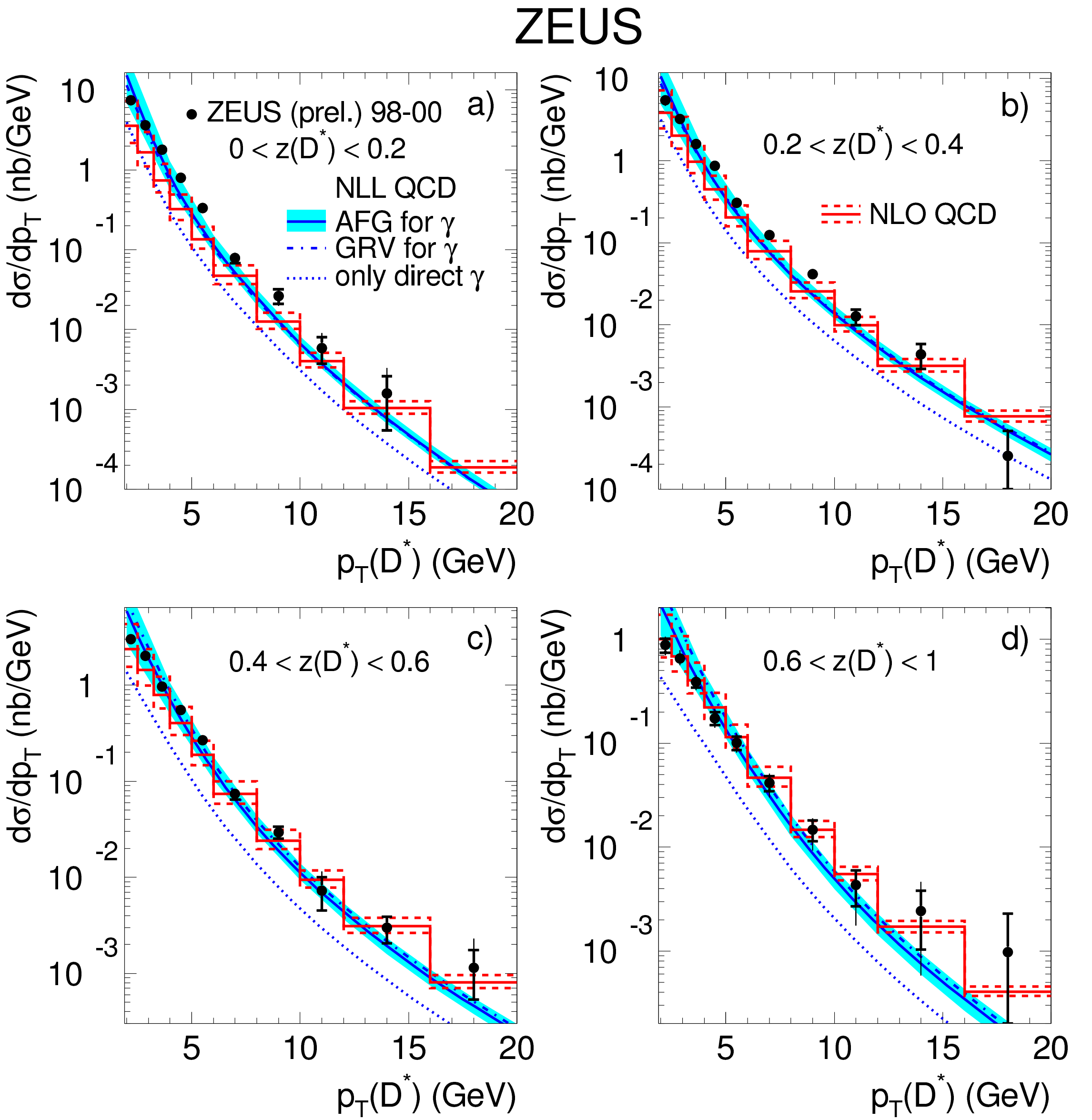
- **NLL seems also not to describe $\eta(D^\star)$ shape at medium p$_T$($D^\star$)**



$D^{\star}$ Photoproduction — Double Differential Cross Sections

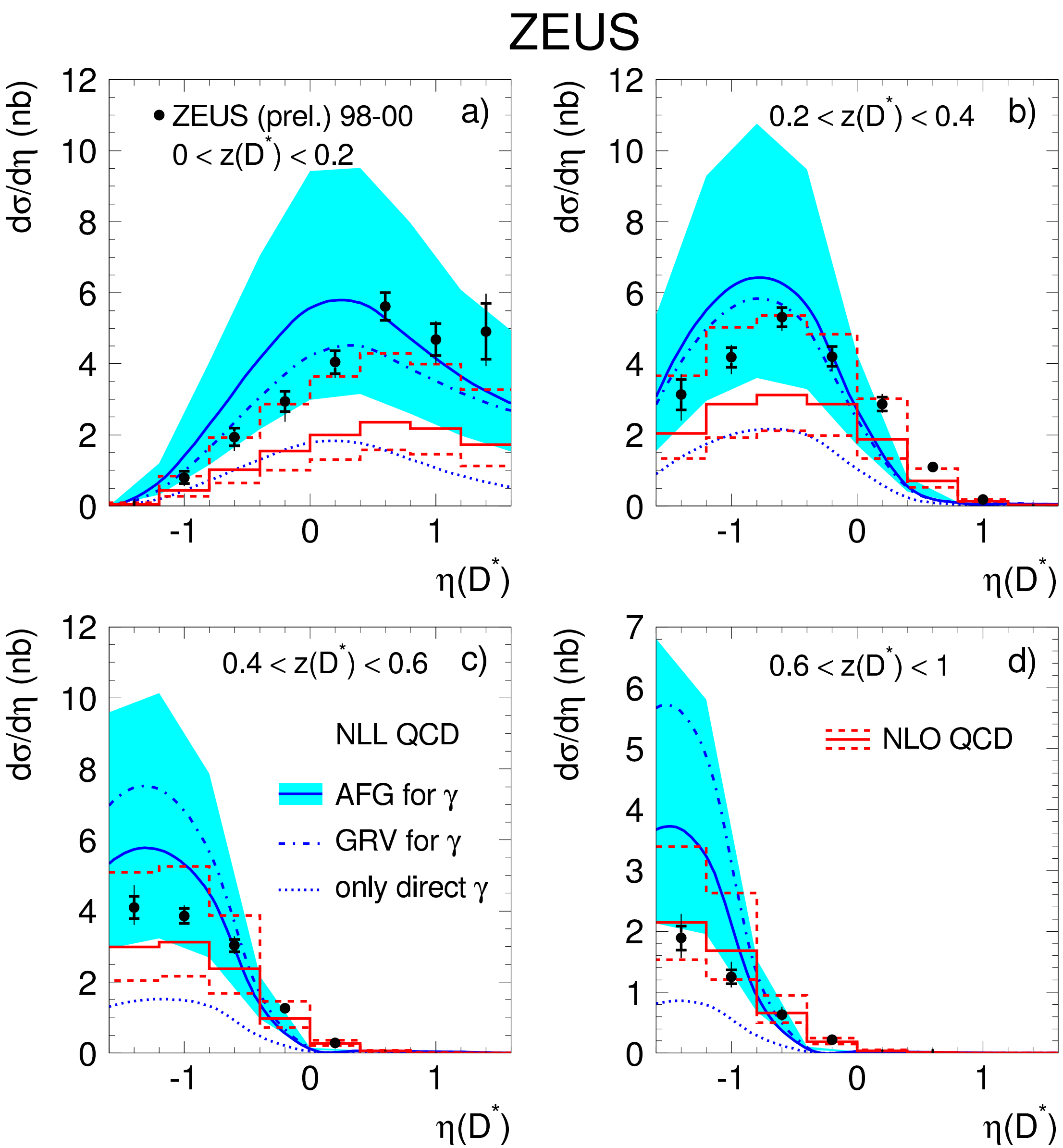
- **Double differential $D^{\star}$ cross sections shown here for $p_T(D^{\star})$ in $z(D^{\star})$ slices**

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



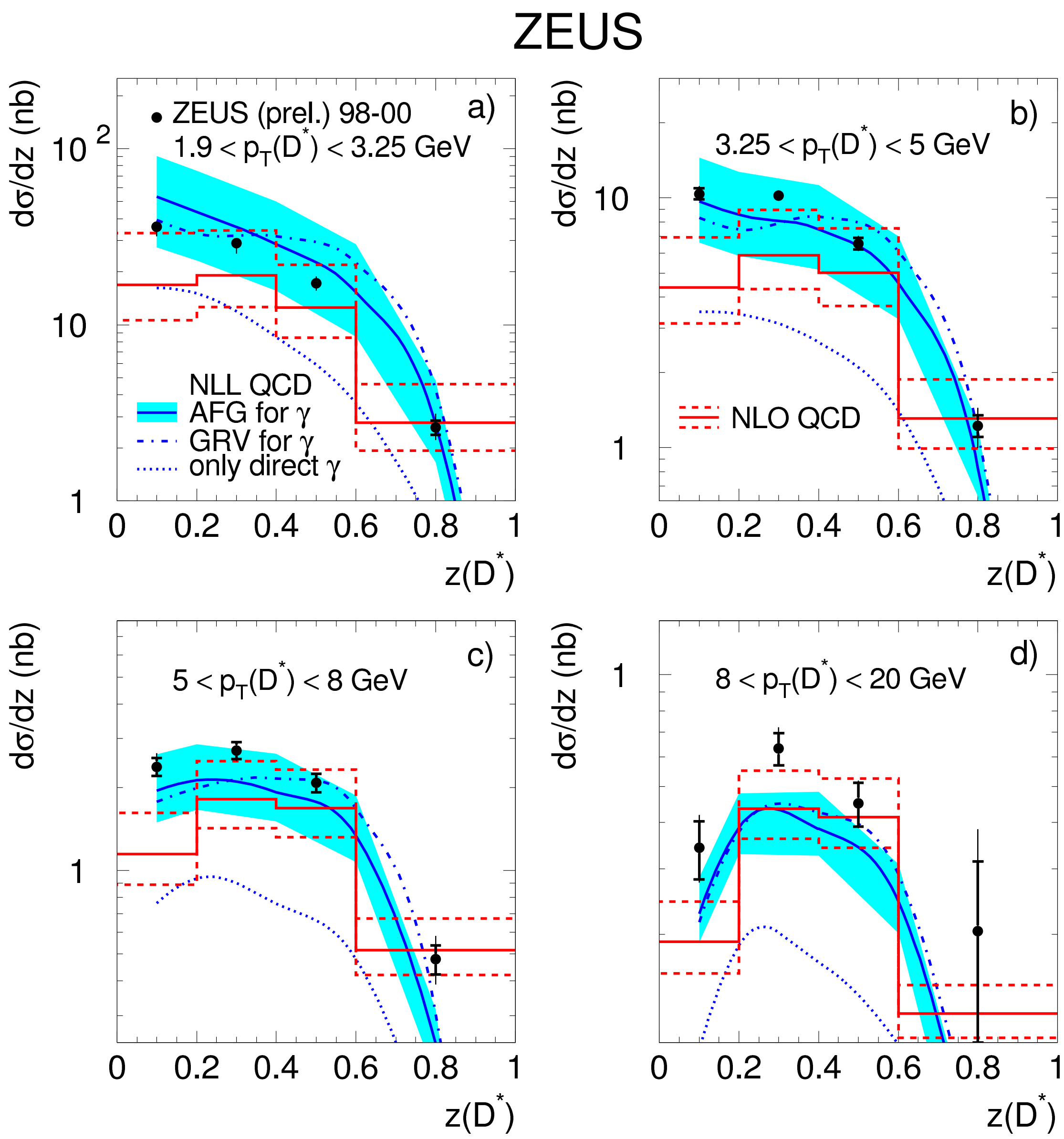
$D^\star$ Photoproduction — Double Differential Cross Sections

- **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**



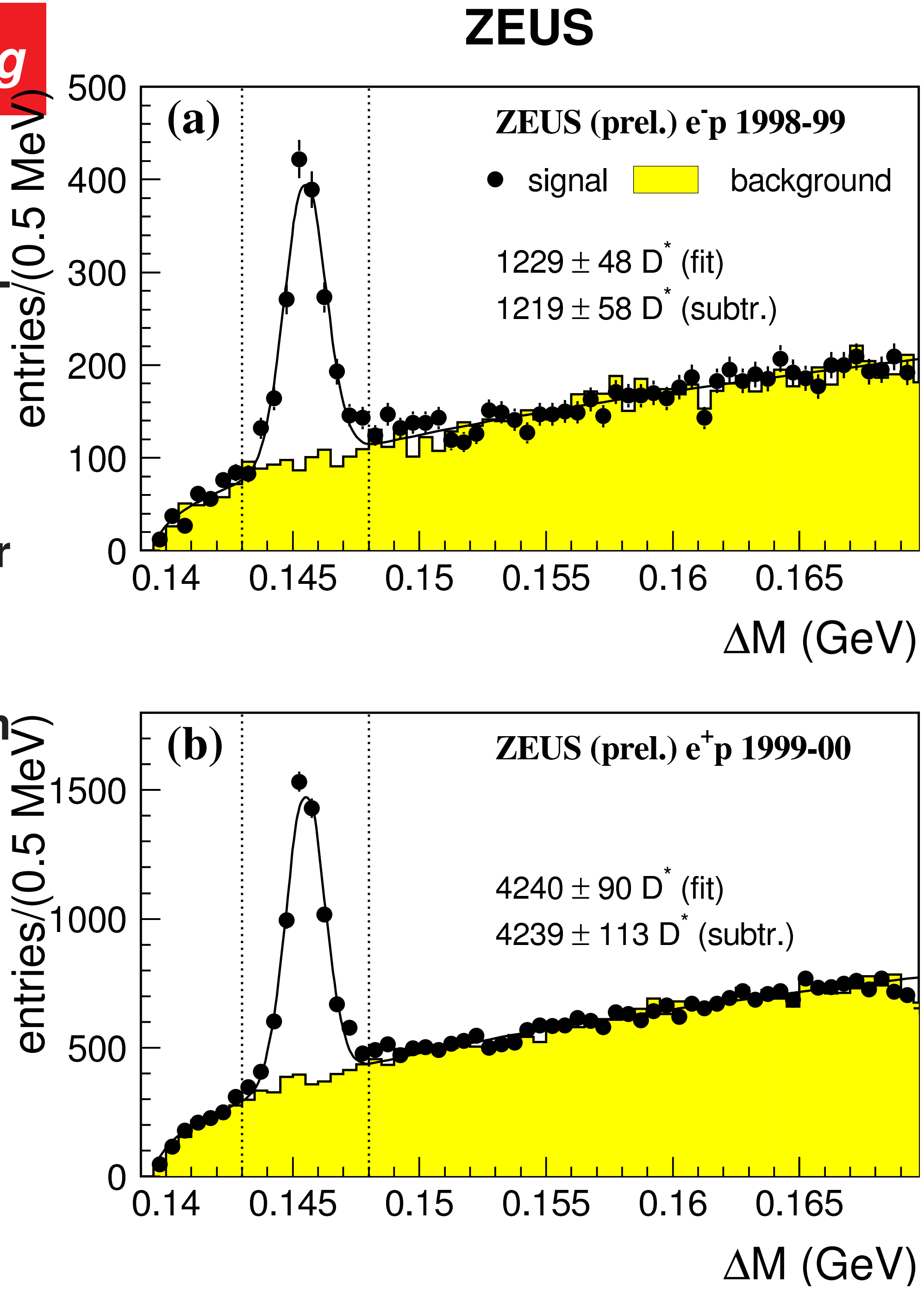
$D^\star$ Photoproduction — Double Differential Cross Sections

- **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

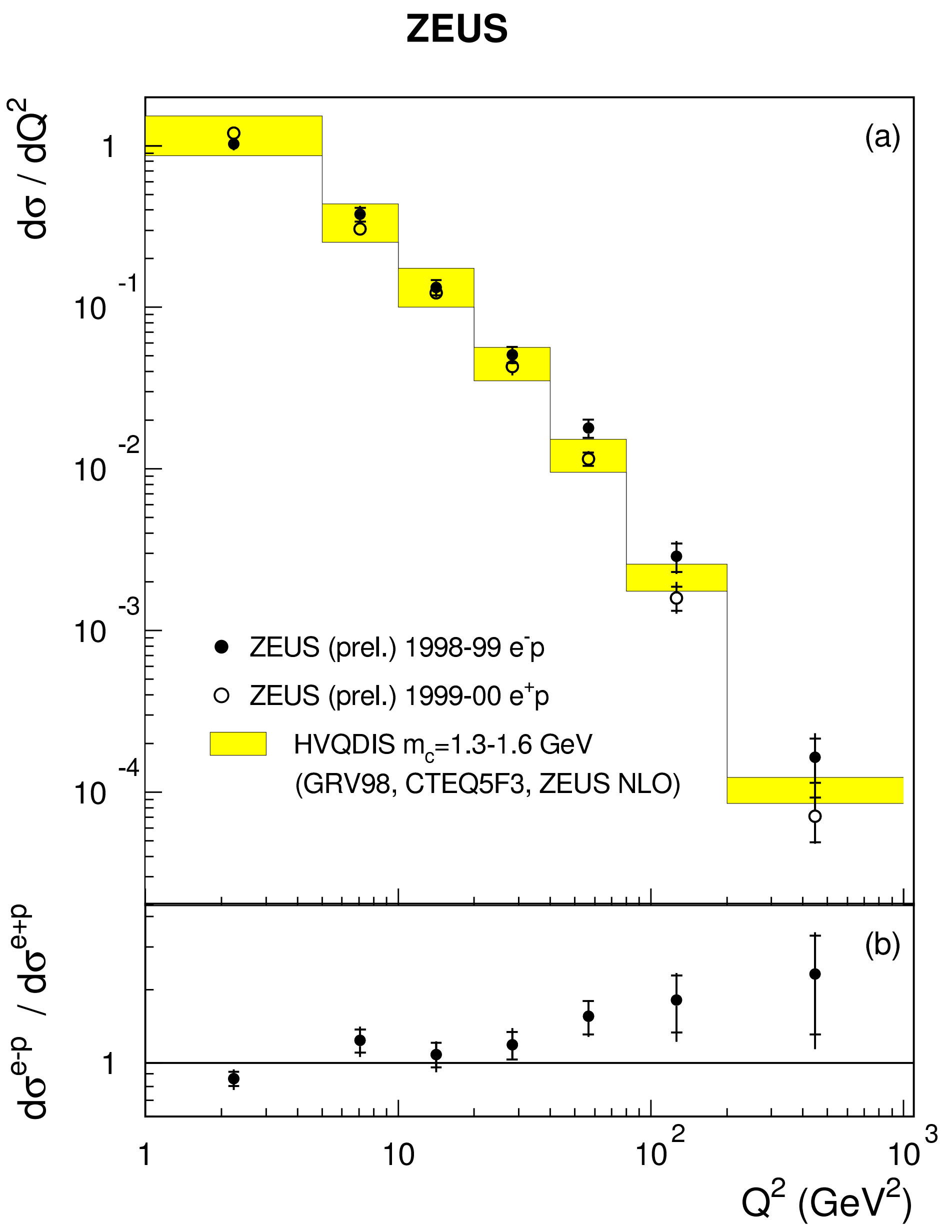
Kinematic region:

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

0.02 $<$ y $<$ 0.8

1.5 $<$ P$_T$(D*) $<$ 15 GeV

-1.5 $<$ η(D*) $<$ 1.5

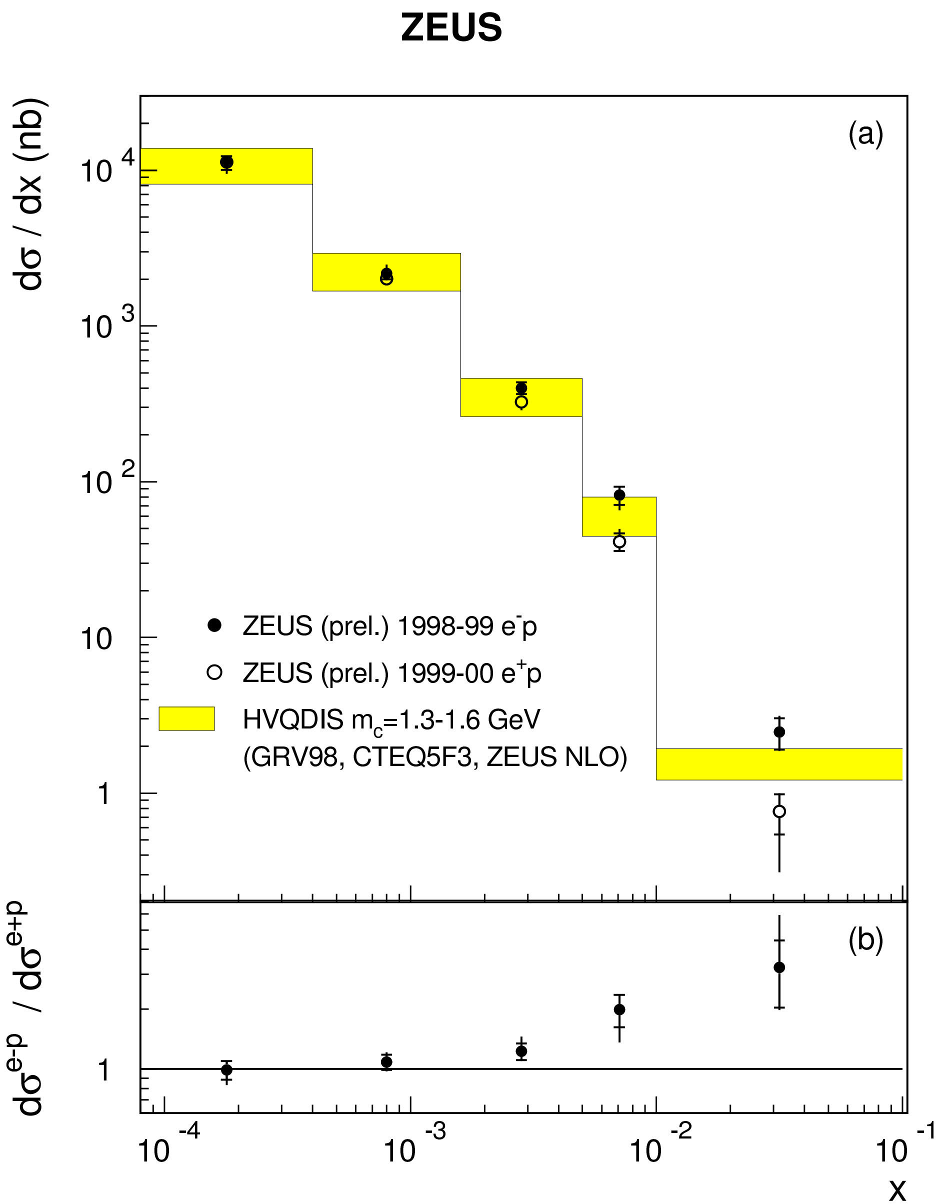


$D^\star$ Production in Deep Inelastic Scattering

- **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? (⟶)