Open Charm Production at HERA

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on behalf of the
H1 and ZEUS Collaborations

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Introduction

HERA ep **collider:** $e^{\pm} \Longrightarrow \Longleftarrow p$

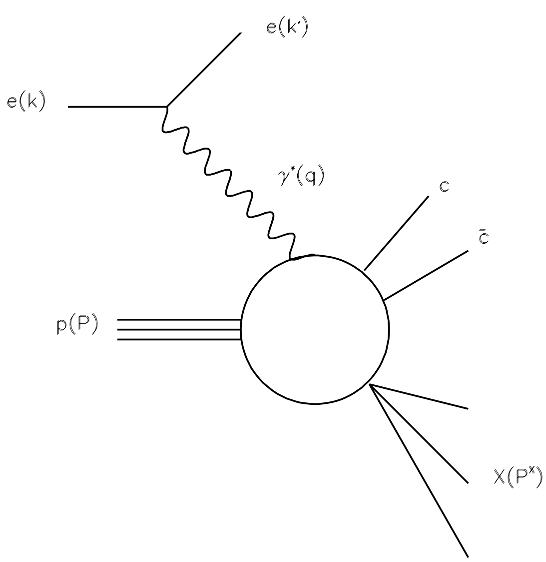
27.6 GeV **820 - 920 GeV**

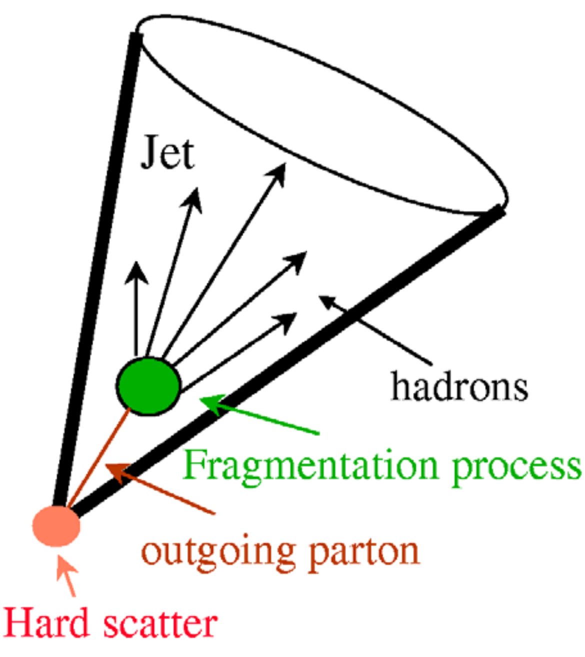
$$\sqrt{s} \approx 300 - 319\ GeV$$

2 Collider Experiments: H1, ZEUS

Open charm production at HERA:

- **Hard process**
  e.g. Boson-Gluon Fusion (BGF) $\gamma g \to c\bar{c}$
- **Parton shower development**
- **Final-state parton→ hadron transition**
  Hadronisation, Fragmentation





Two kinematic regimes:

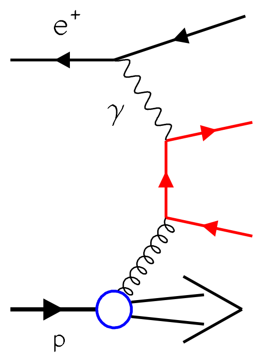
- **Deep Inelastic Scattering (DIS)** $Q^2 > 1GeV^2$
  Scattered e visible in main detector
- **Photoproduction (PHP)** $Q^2 < 1GeV^2$
  $< Q^2 > \approx 3 \cdot 10^{-4}$
  No scatter e in main detector $\Rightarrow$ **quasi-real** γ

Theoretical Framework

Hard scale $m_c >> \Lambda_{QCD}$
$\Rightarrow$ pQCD calculations - valid

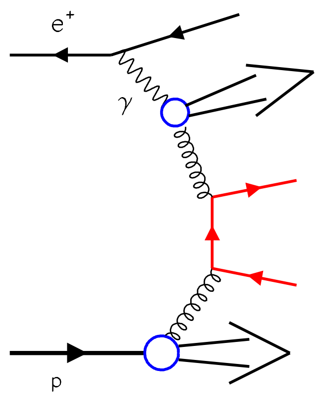
QCD LO contributions to open c production:

"Direct" BGF



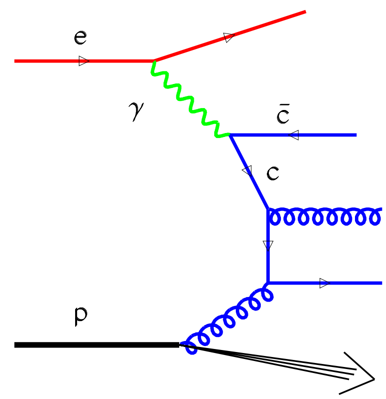
$\gamma g \rightarrow c\bar{c}$

"Resolved" photon



$gg \rightarrow c\bar{c}$

"Charm excitation"



$cg \rightarrow cg$

$\Rightarrow$ probe g in p **γ partonic structure**

Next-to-Leading order (NLO) calculations:

DGLAP evolution:	Frixione et al.	Kniehl et al.
	Fixed-order ("massive")	Resummed ("massless")
• p, γ active flavours:	u,d,s	u,d,s,c
• Scheme valid for:	Q^2,$p_\perp^2 \approx m_c^2$	Q^2,$p_\perp^2 >> m_c^2$

Matched ("FONLL") calculation: Cacciari et al.

Incorporate mass effects up to NLO
resummation of p_T logs up to NLL level

CASCADE MC based on CCFM evolution

At large x **CCFM$\longrightarrow$ DGLAP Q^2 evolution**
For $x \rightarrow 0$ **CCFM$\longrightarrow$ BFKL $1/x$ evolution**

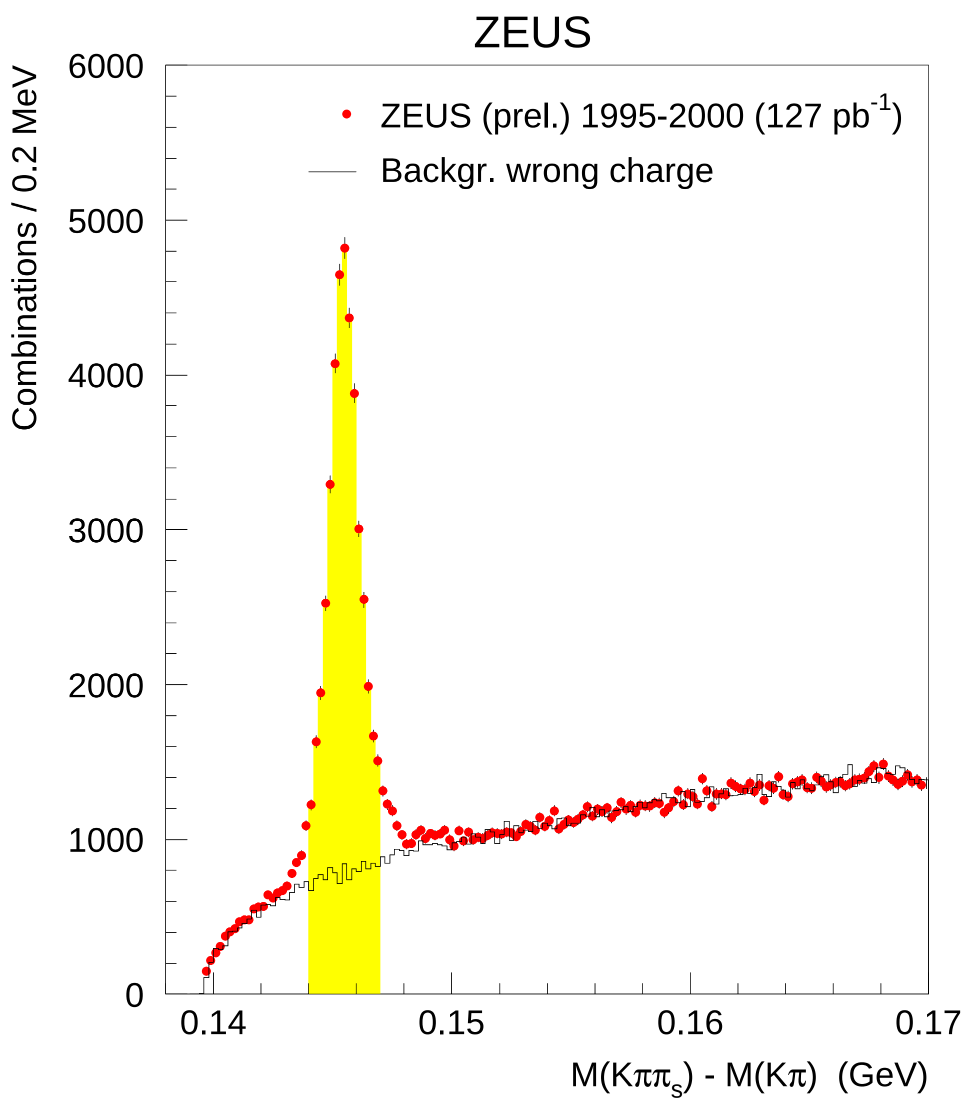
Charm Tagging Methods

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

$f(c \to D^{*+}) \approx 24\%$, $BR = 2.6\%$

$\Delta M = M(D^{*+}) - M(D^0) = 0.14542$ **GeV** $\sim m_\pi$

$P_\perp^{D^*} > 2$ **GeV and** $-1.5 < \eta^{D^*} < 1.5$



In the yellow band after background subtraction:

$N(D^{*\pm}) = 31350 \pm 240$ **from** $\mathbf{L = 127\ pb^{-1}}$

better than 1% **stat. precision**

Charm Tagging Methods

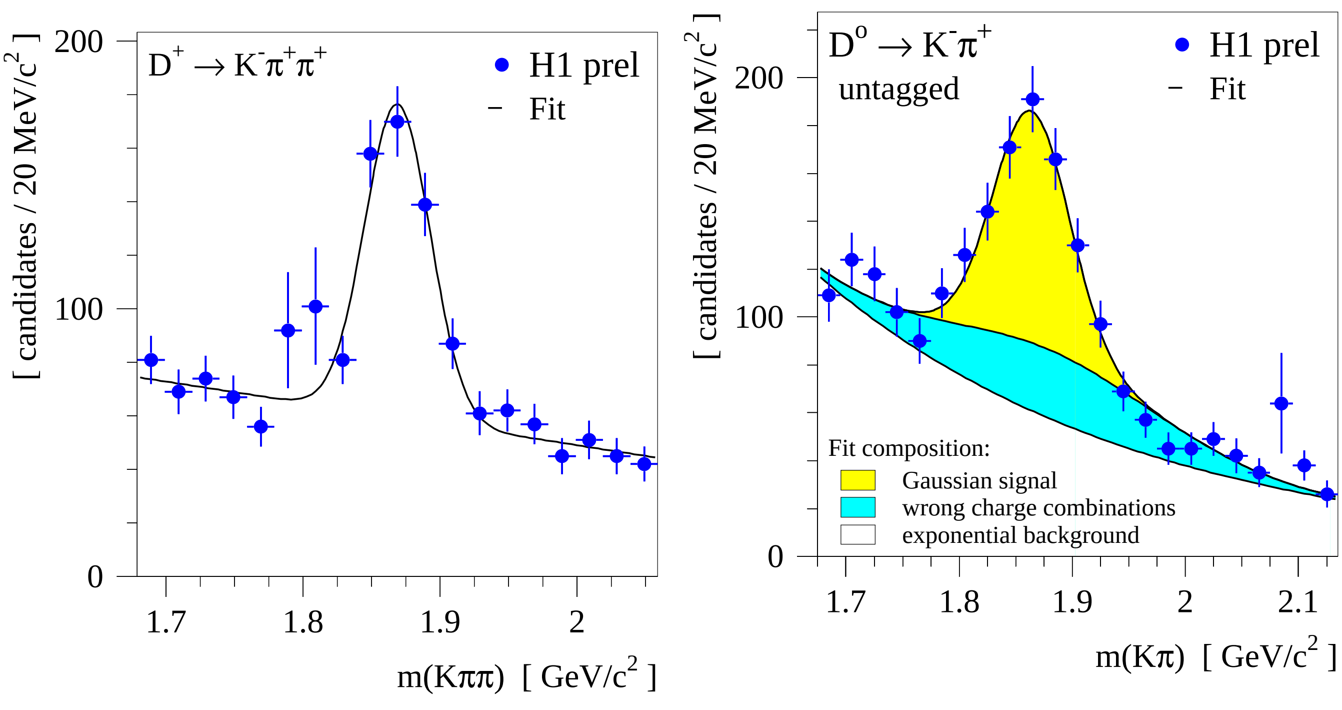
Other charm signals: $D^* \to D^0\pi_s \to (K^-\pi^+\pi^+\pi^-)\pi_s$
$D^0 \to K^-\pi^+$ **untagged**
$D^+ \to K^-\pi^+\pi^+$
$D_s \to \phi\pi \to (K^-K^+)\pi$
s-l electrons or muons

Charm tagging via decay length

Reconstruct charm hadrons via secondary vertex

H1 central silicon tracker (CST): Background reduced via decay length significance $S_l = l/\sigma_l$

D^+ **and untagged** D^0 **signals from** $K^-\pi^+\pi^+$ **and** $K^-\pi^+$ **mass distributions (DIS events 48 pb^{-1})**

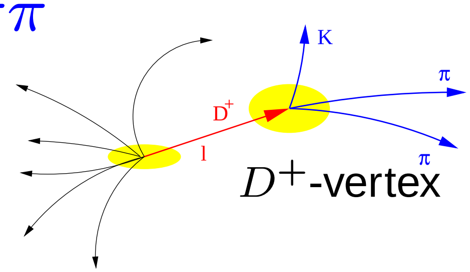


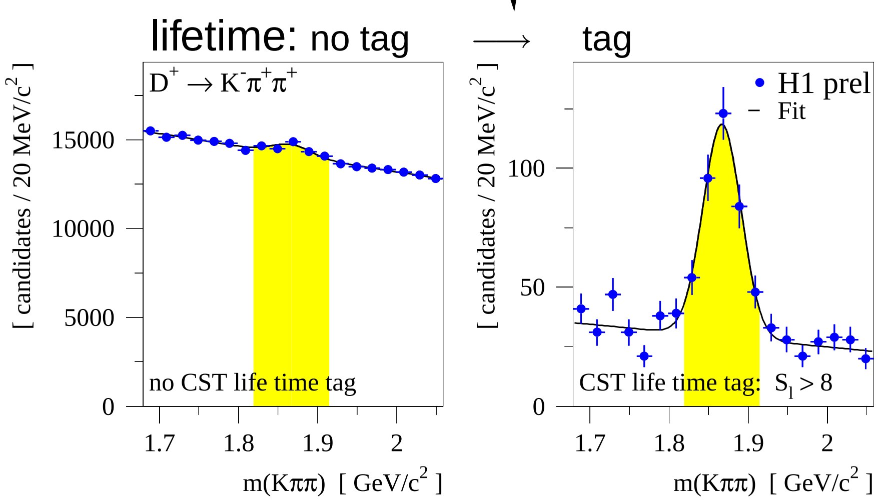
$S_l > 5$ $\qquad$ $S_l > 3$

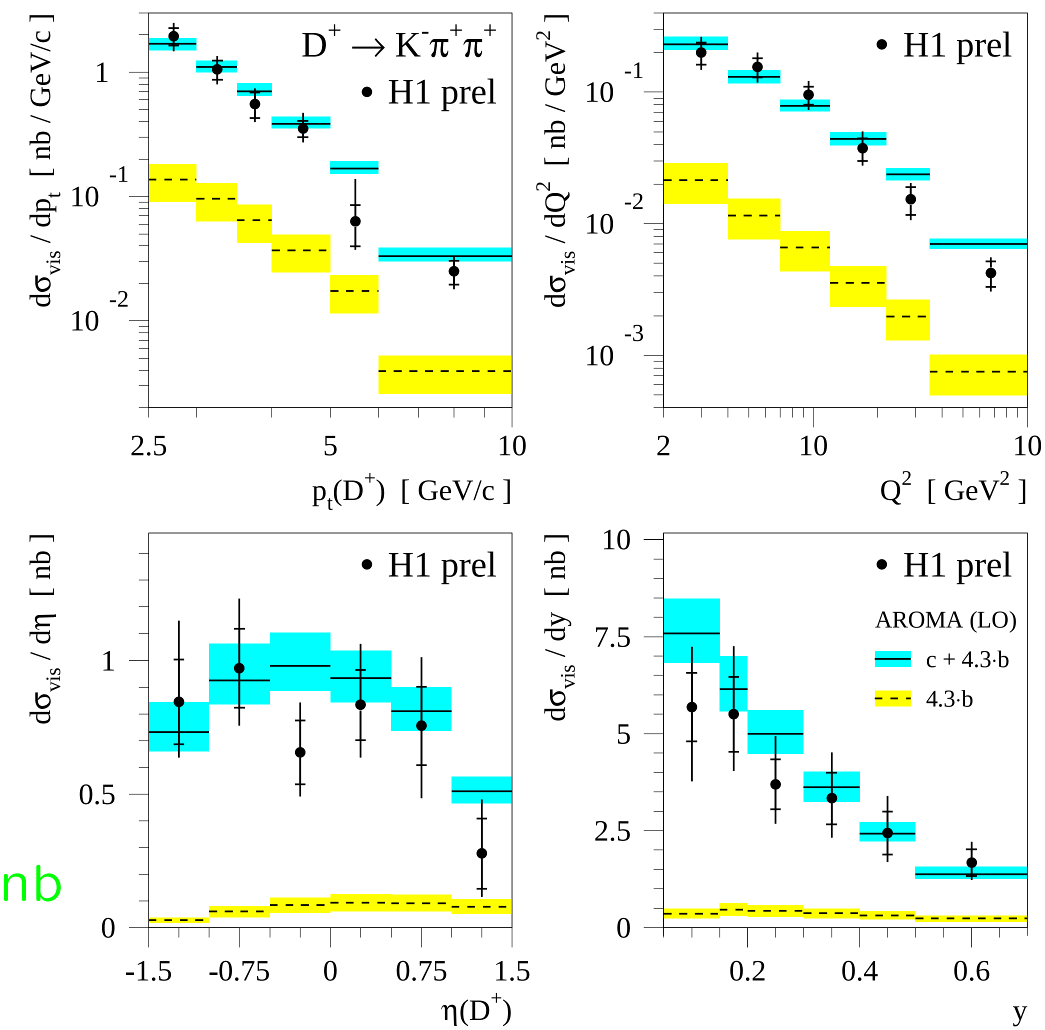
No particle identification applied

D-Meson Production in DIS

$D^+ \to K\pi\pi$







H1 Prelim.:

$$\sigma^{vis}_{ep\to eD^+X} = (2.16\pm0.19^{+0.46}_{-0.35})\text{nb}$$

$2 < Q^2 < 100$ GeV^2; $0.05 < y < 0.07$
$p_t^D > 2.5$ GeV; $|\eta_D| < 1.5$

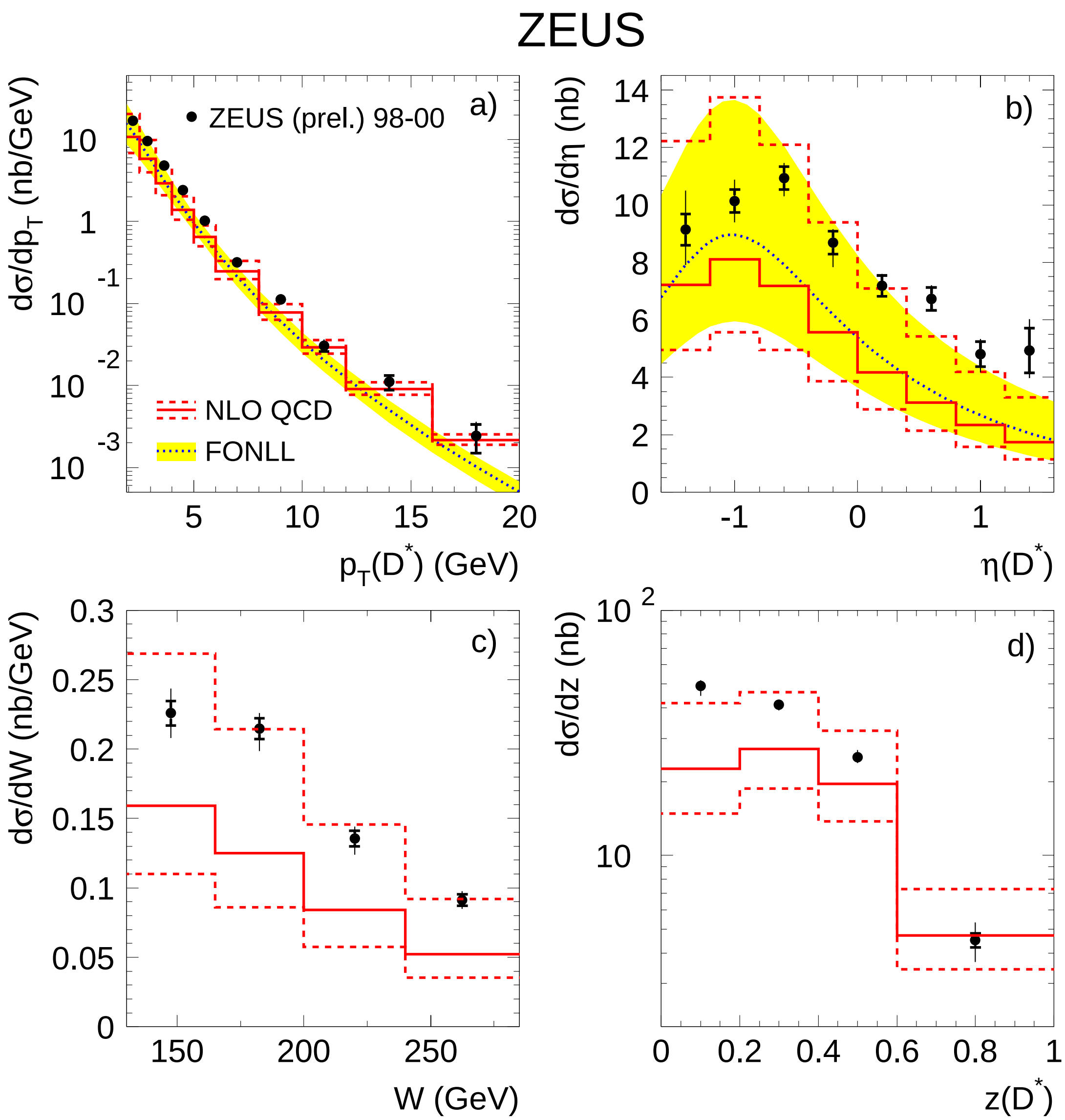
Norm and shapes well described by LO+PS models (AROMA)

D^*-Meson Production in PHP

Sample: **PHP events 79 pb^{-1}**

Inclusive D^* with $p_T^{D^*} > 1.9\ GeV$, $|\eta^{D^*}| < 1.6$

Kinematic region: $Q^2 < 1\text{GeV}^2$,
$130 < W_{\gamma p} < 280\ GeV$



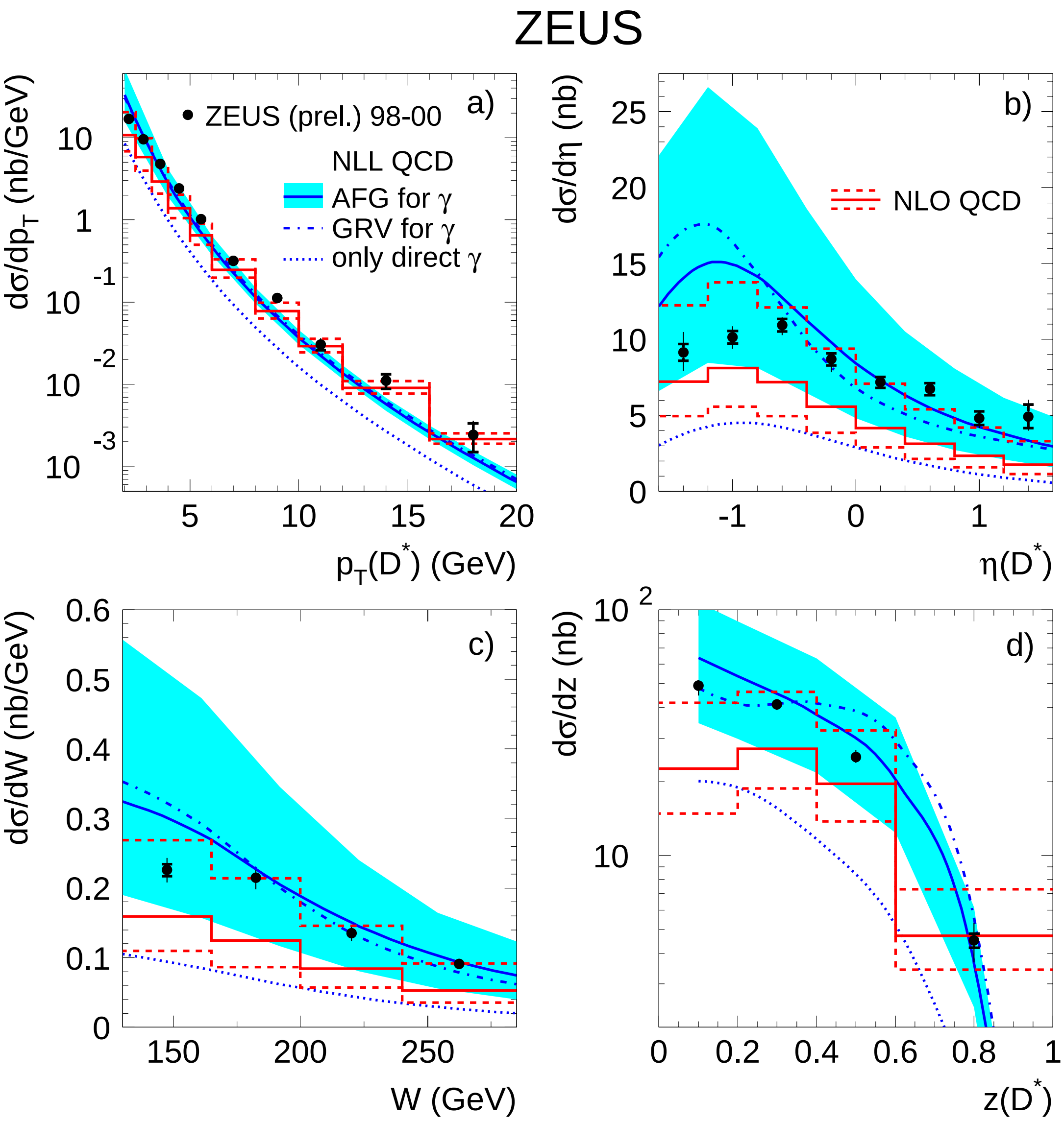
$z(D^*)$: **Photon energy fraction carried by D^* in p rest frame**

Theory bands: vary renormalisation scale, charm mass

Central FO predictions below data mainly for $\eta^{D^*} > 0$, **low** $z(D^*)$; **FONLL not better than FO**

High z region OK; $d\sigma/dW$ **below data, shape OK**

D^*-Meson Production in PHP



NLL vs. FO:

NLL uncertainties very large

Significant resolved photon contribution in NLL

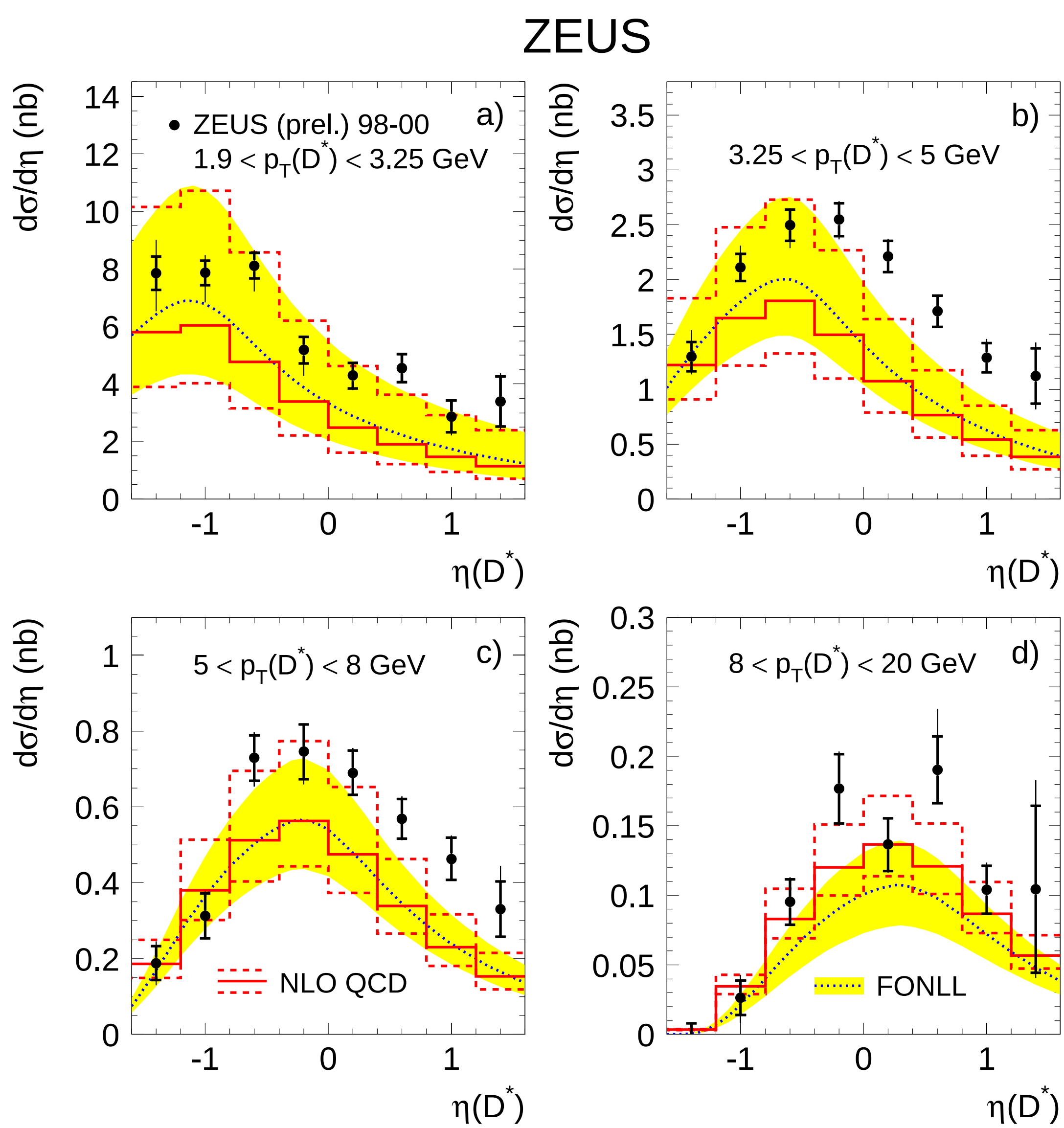
Central NLL predictions closer to data

NLL better than FO for $d\sigma/dz$ and $\eta(D^*) > 0$

Some sensitivity to γ s.f. parametrisation in NLL

D^*-Meson Production in PHP

Precise data enable measurements of double differential cross sections



Data: Close to upper band of predictions
Significantly above FO, FONLL at medium $p_T^{D^*}$, forward η^{D^*}
(Even upper bounds below data!)

For low $p_T^{D^*}$ FONLL predictions close to FO

For large $p_T^{D^*}$ FONLL predictions below FO

Challenge for theory. Need for NNLO?

Charm Dijet Photoproduction

D^* **dijet events** enable study of the **photon structure**, in particular it's **charm content**

120 pb^{-1} ; $Q^2 < 1\text{GeV}^2$; $130 < W_{\gamma p} < 280\ GeV$

Require D^* **with** $p_T^{D^*} > 3.0\ GeV$, $|\eta^{D^*}| < 1.5$

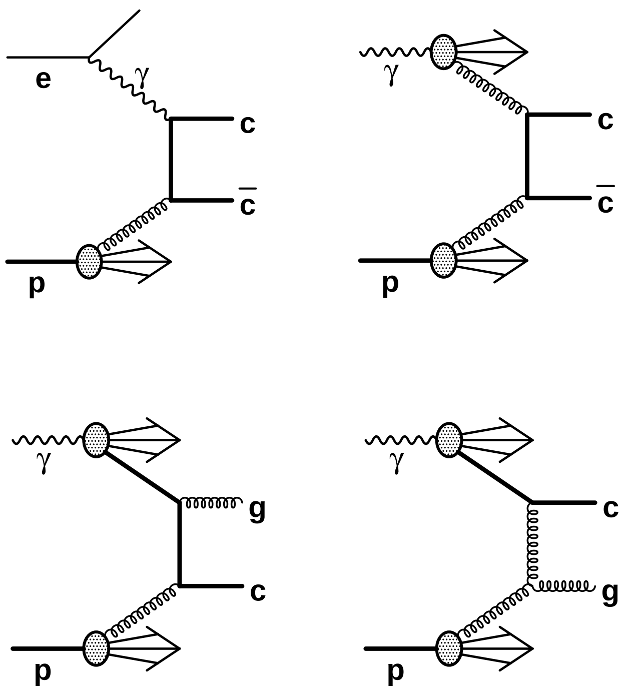
2 jets with $E_T^{\text{jet}} > 5\ GeV$, $|\eta^{\text{jet}}| < 2.4$,
$M_{jj} > 18\ GeV$, $|\bar{\eta}| < 0.7$

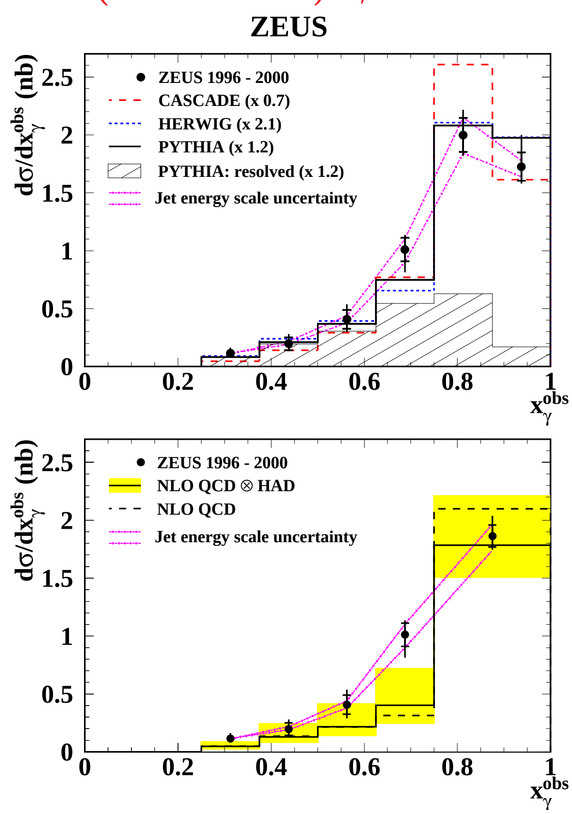
Fraction of photon momentum producing the dijet:

$$x_\gamma^{\text{OBS}} = \frac{\Sigma_{\text{jets}} E_T e^{-\eta}}{2yE_e}$$

x_γ^{OBS} **=1: direct** γ $x_\gamma^{\text{OBS}} < 1$: **resolved** γ

$x_\gamma^{\text{OBS}} > (<) 0.75$: **Enriched direct- (resolved-)** γ



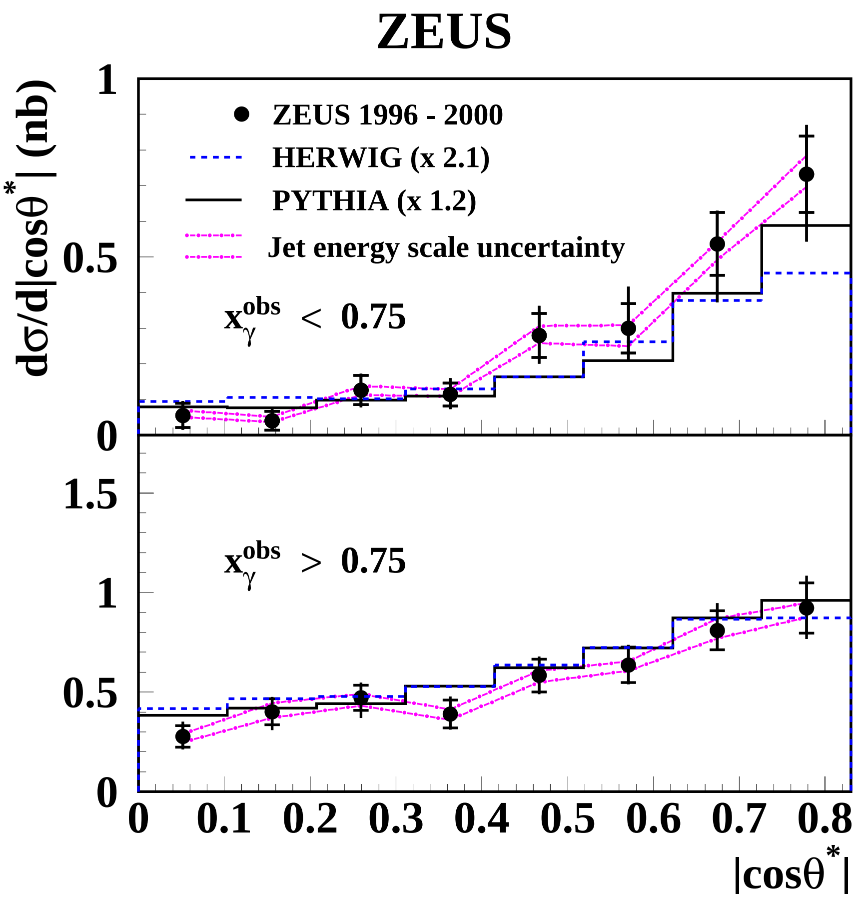


- **Significant contribution** $\approx 40\%$ **from resolved photons**
- **Good agreement in shape between data and LO MC's (CASCADE too high for high** x_γ^{OBS} **)**
- **Data compared to fixed-order NLO DGLAP calculation** $+$ **hadronisation correction**
- **Low** x_γ^{OBS} **tail of NLO cross section below data**

Charm Dijet Angular Distributions in PHP

Dijet scattering angle: $\cos\theta^* = \tanh\frac{\eta^{jet1}-\eta^{jet2}}{2}$

θ^*: **angle between jet-jet axis and beam axis in the dijet rest frame**



"q **exchange**" $\propto (1-|\cos\theta^*|)^{-1}$

"g **exchange**" $\propto (1-|\cos\theta^*|)^{-2}$

Resolved sample rises strongly with $|\cos\theta^*|$

→ Signature of g**-exchange**

Direct sample consistent with q **exchange**

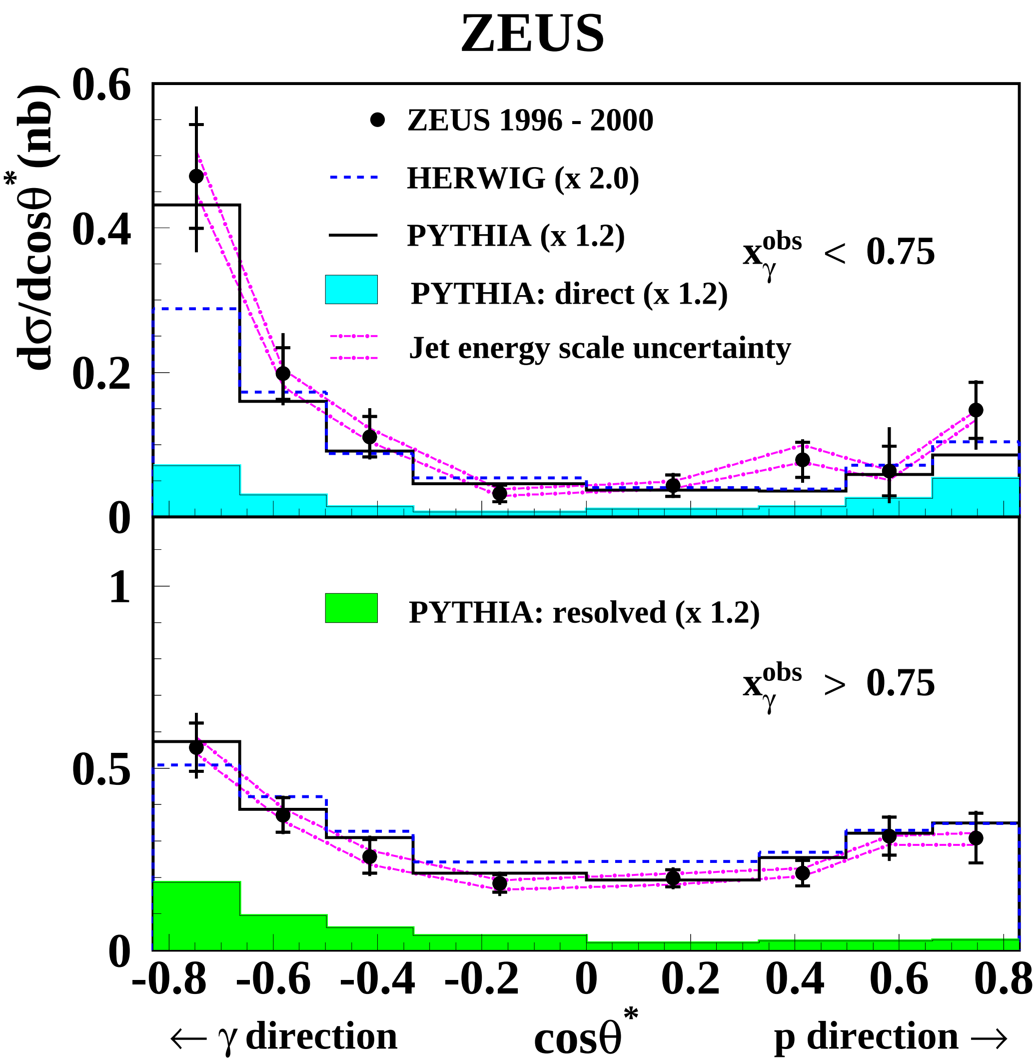
Evidence for resolved photon charm excitation

LO MC describe data shapes of both $x_\gamma^{\mathrm{OBS}} > 0.75$ **and** $x_\gamma^{\mathrm{OBS}} < 0.75$

Charm Dijet Angular Distributions in PHP

Match the jet with a D^* in $(\eta - \phi)$ space

Define: **Jet (1) = D^* jet**
Jet (2) = Other jet



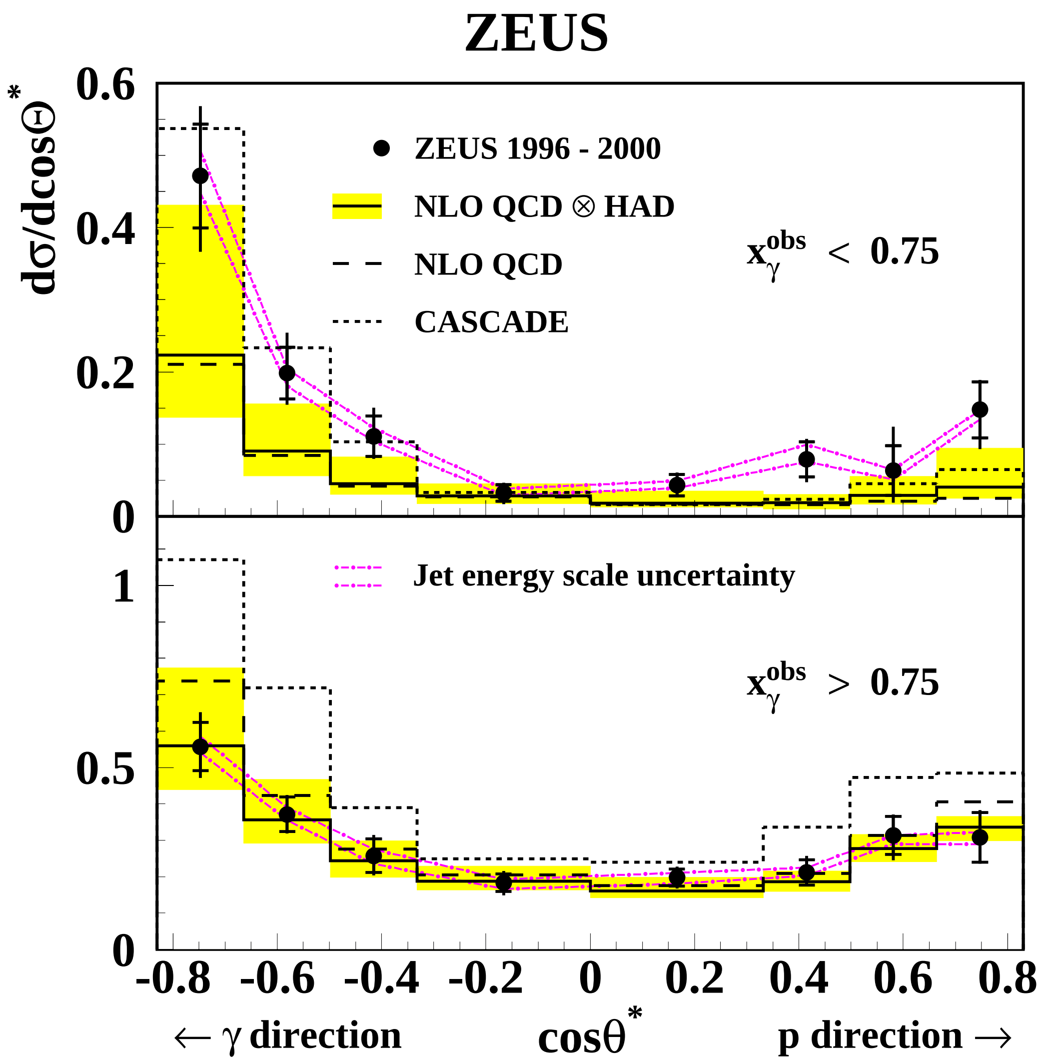
Contribution of LO resolved to $x_\gamma^{\rm OBS} > 0.75$ explains the asymmetric distribution in $\cos\theta^*$

Strong rise in $d\sigma/d\cos\theta^*$ towards γ direction for $x_\gamma^{\rm OBS} < 0.75$

Clear evidence for charm from the photon

Charm Dijet Angular Distributions in PHP

Comparison with fixed-order NLO and with CASCADE



For $x_\gamma^{\rm OBS} > 0.75$ NLO describe data well

For $x_\gamma^{\rm OBS} < 0.75$ NLO lower than data in both proton and photon directions. Shape OK

CASCADE exceed data by $\approx 30\%$, mostly in $x_\gamma^{\rm OBS} > 0.75$

Shape described reasonably well

Charm Fragmentation

c quark $\rightarrow$ c meson fragmentation: non-perturbative QCD $\Rightarrow$ described by phenomenological models

Important to study charm fragmentation to find:

- Are u and d quarks produced equally ?
  $R_{u/d} = \frac{cu}{cd}$ (=1 if isospin conserved)
- Are vector (D^*) and pseudoscalar (D) mesons produced as predicted by spin counting?
  $P_V = \frac{V}{V+PS}(= 0.75?)$
- What is the s-quark production suppression ?
  $\gamma_s = \frac{2cs}{cd+cu}$
- What are the relative production fractions of the various D-mesons?
  $f(c \rightarrow D) = \frac{N(D)}{N(c)} = \frac{\sigma(D)}{\Sigma_{all}\sigma(D)}$
- Are these fractions universal? Compare HERA with e^+e^- results

Fragmentation functions

- Few forms for energy transfer quark $\rightarrow$ meson
- Tunable parameters fixed from e^+e^- fits
- First ep measurement compared with e^+e^-

$\Rightarrow$ test of universality of charm fragmentation

Charm Fragmentation Function

Taken from e^+e^- when HERA data compared to QCD

Major source of theoretical uncertainty

Kinematic region: $Q^2 < 1\text{GeV}^2$ **(PHP)**

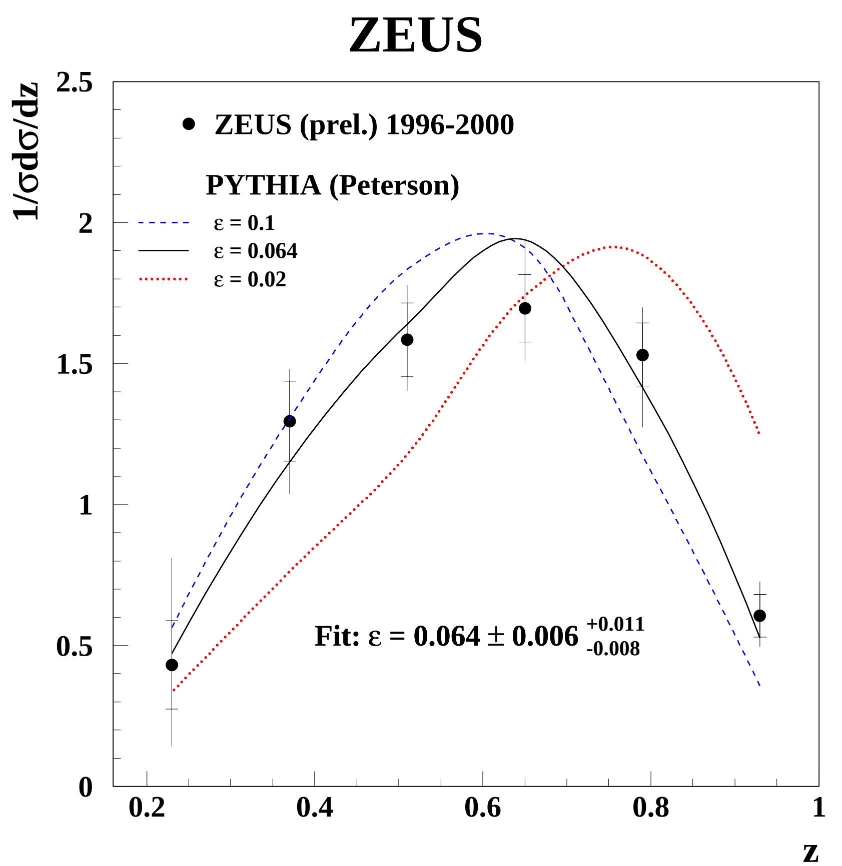
$130 < W_{\gamma p} < 280\ GeV$

At least one jet with $E_T^{\text{jet}} > 9\ GeV$, $|\eta^{\text{jet}}| < 2.4$

D^* with $p_T^{D^*} > 2.0\ GeV$, $|\eta^{D^*}| < 1.5$
associated with a jet

Fraction of jet energy carried by D^*: $z = \dfrac{(E+p_{\|})_{D^*}}{2E_{jet}}$

Normalised cross section in z:



Compare to LO MC via Peterson function:

$f(z) \propto [z(1 - 1/z - \epsilon/(1-z))^2]^{-1}$ ϵ **free parameter**

Strong sensitivity to ϵ value

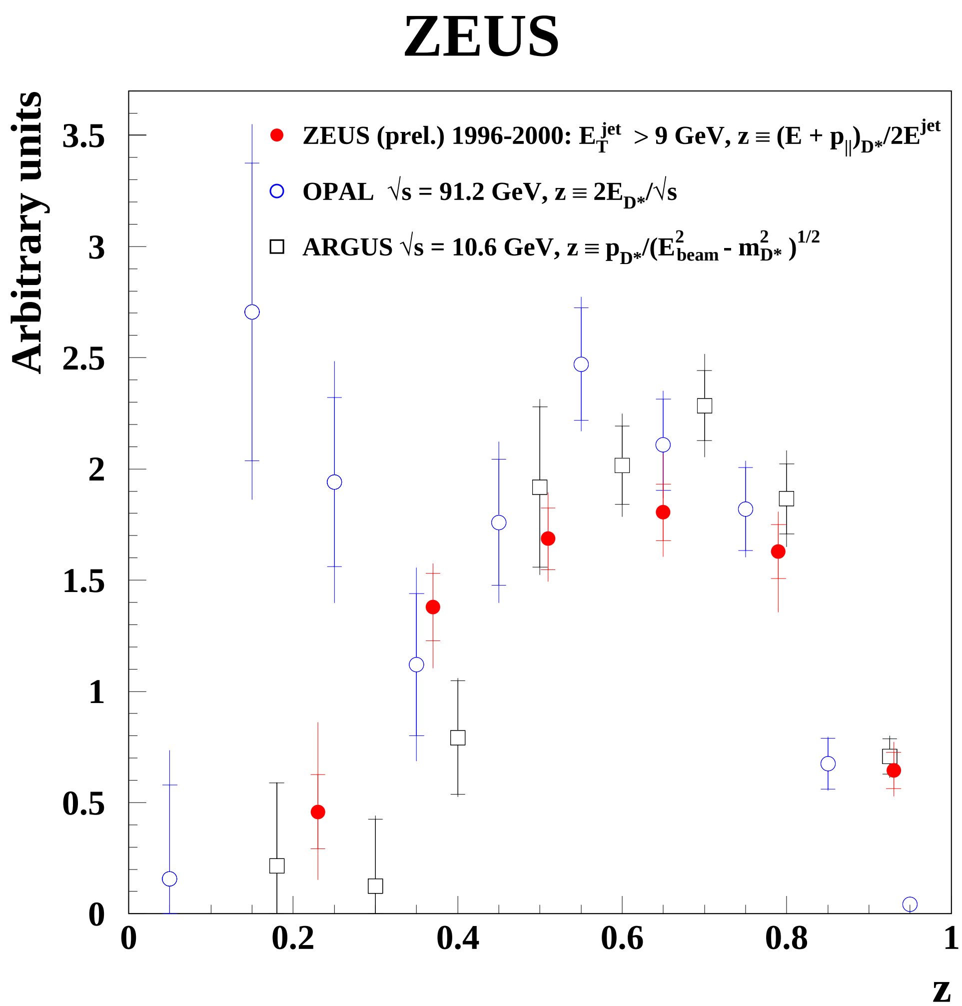
Fit of LO MC with Peterson function:

$\epsilon = 0.064 \pm 0.006^{+0.011}_{-0.008}$ **(= 0.053 from fits to LEP data)**

Charm Fragmentation Function

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

- **z defined differently in both cases**
  For e^+e^-: $z = E_{D^*}/E_{beam}$
- **Different charm production mechanisms**



LEP low-z peak due to $g \to c\bar{c}$ splitting

$z(ep)$: Similar shape for $z > 0.3$ as $z(e^+e^-)$ of ARGUS/OPAL analysed by Nason et al.

Precision competitive with LEP

Results support universal charm fragmentation

Charm Fragmentation Fractions/Ratios

From H1 measured $D^{*\pm}$, D^0, $D^\pm$, D_s cross sections, deduce fragmentation fractions (prel.)

	e^+e^- **world average**
$f(c \to D^+) = 0.20 \pm 0.02^{+0.04+0.03}_{-0.03-0.02}$	0.23 ± 0.02
$f(c \to D^0) = 0.66 \pm 0.05^{+0.12+0.09}_{-0.14-0.05}$	0.55 ± 0.03
$f(c \to D_s^+) = 0.16 \pm 0.04^{+0.04+0.05}_{-0.04-0.05}$	0.10 ± 0.03
$f(c \to D^{*+}) = 0.26 \pm 0.02^{+0.06+0.03}_{-0.04-0.02}$	0.24 ± 0.01

Uncertainty : stat. syst. theory

Calculate ratios of different quark/spin states

- **Ratio or u to d quarks** $R_{u/d} = \frac{cu}{cd} = \frac{\sigma^{dir}(D^0)+\sigma(D^{*0})}{\sigma^{dir}(D^\pm)+\sigma(D^{*\pm})}$

  $R_{u/d} = 1.26 \pm 0.20 \pm 0.12$ **H1 prel.**

  1.00 ± 0.09 e^+e^- **world average**

- **Fraction of vector mesons** $P_V = \frac{V}{V+PS} = \frac{D^*}{D^*+D}$

  $P_V = 0.69 \pm 0.04 \pm 0.01$ **from** cd **H1 prel.**

  $0.61 \pm 0.06 \pm 0.03$ **from** cd,cu **H1 prel.**

  $0.55 \pm 0.04 \pm 0.03$ D^{*+},D^0 **ZEUS prel.**

  0.60 ± 0.03 e^+e^- **world average**

- **Strangeness suppression factor** $\gamma_s = \frac{2f(c\to D_s^+)}{f(c\to D^+)+f(c\to D^0)}$

  $\gamma_s = 0.36 \pm 0.10 \pm 0.08$ **H1 prel.**

  $0.27 \pm 0.04 \pm 0.03$ **ZEUS**

  0.26 ± 0.03 e^+e^- **world average**

Good agreement with e^+e^-

$\Longrightarrow$ Charm fragmentation universal

Summary and Outlook

- **Large samples of charm events collected. Experimental errors typically below the large theoretical uncertainties**
- **Charm DIS cross sections are in reasonable agreement with pQCD calculations**
- **Charm PHP cross sections are above fixed-order NLO and FONLL calculations**
- **Resummed NLO (NLL) calculations for charm PHP are closer to data**
- **Strong evidence for charm from the photon**
- **Evidence that charm fragmentation is universal in e^+e^- and ep from $f(c \to D)$, $R_{u/d}$, P_V, γ_s**

OUTLOOK

- **Complete HERA I data analysis (1994-2000)**
- **Need better theoretical input (NLO MC's, improved matched NLO, NNLO calculations)**
- **HERA II(2003-2007): $\approx$ factor 4 increase in luminosity ($L_{int} \approx 1 fb^{-1}$)**
- **Detector upgrades: Si microvertex detector Forward tracking**

$\Rightarrow$ big improvement in c tagging efficiency

Expect a lot of more interesting Charm Physics from HERA II