

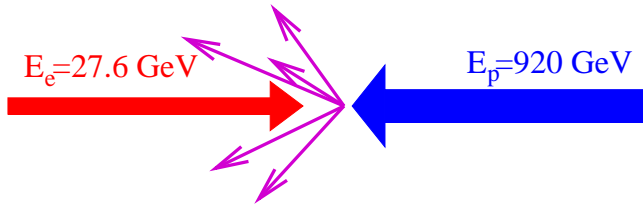
Photoproduction of Open Charm at HERA



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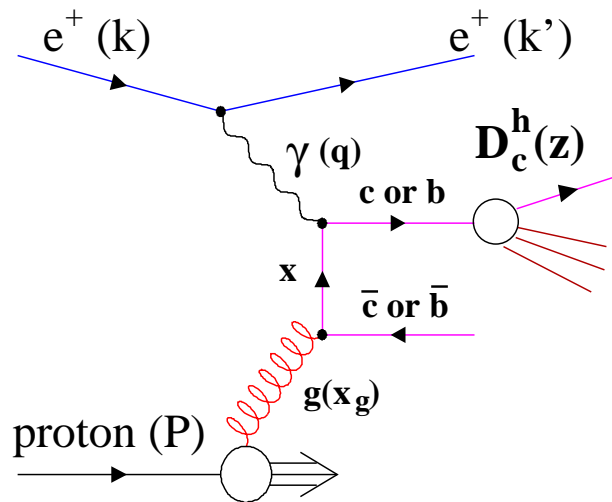
- Introduction, Theoretical Framework
- Hadronization of charm quarks
- Inclusive D^* meson production
- Dijet angular distribution of charm

Introduction - HERA Kinematics



1992-1997: $E_p = 820 \text{ GeV} \Rightarrow \sqrt{s} = 300 \text{ GeV}$

1998-2000: $E_p = 920 \text{ GeV} \Rightarrow \sqrt{s} = 318 \text{ GeV}$



ep Kinematics for $s = (P + k)^2$

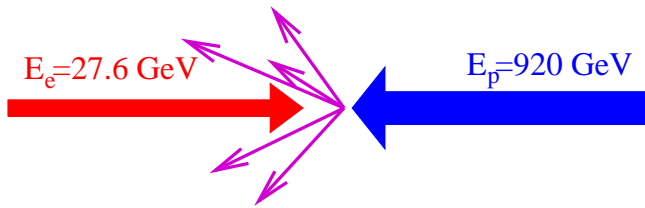
$$Q^2 = -q^2 = -(k - k')^2$$

$Q^2 \simeq 0 \text{ GeV}^2 \Rightarrow \text{Photoproduction}$

$$y = \frac{q \cdot P}{k \cdot P}$$

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

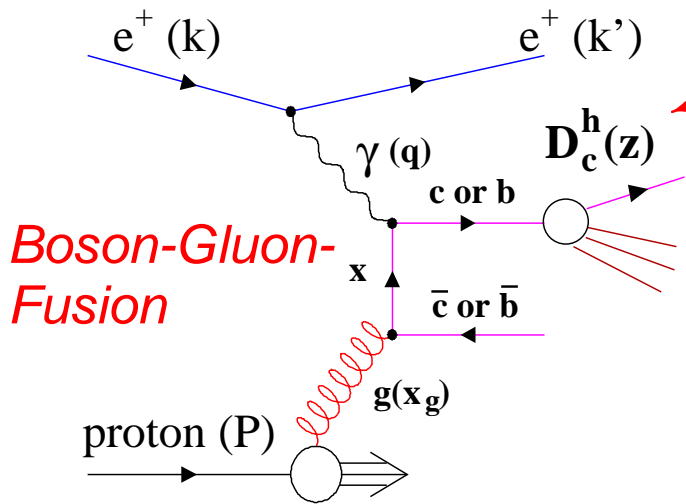
Introduction - Charm Production at HERA



LO picture

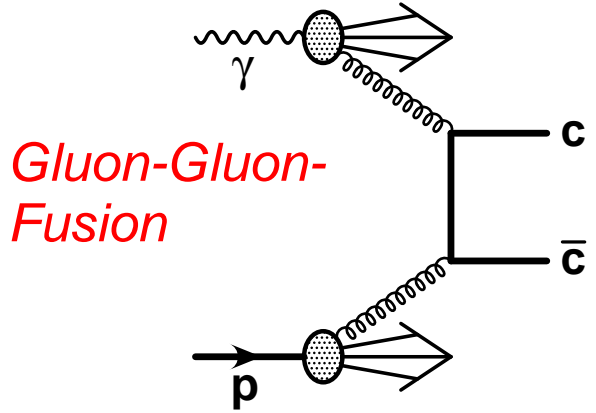
Direct contribution

$Q^2 \simeq 0 \text{ GeV}^2 \Rightarrow \text{Photoproduction}$

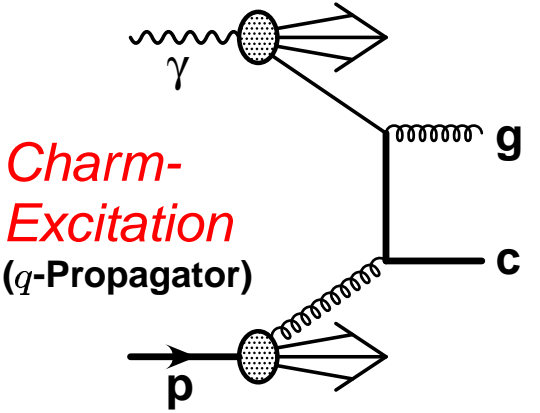


Boson-Gluon-Fusion

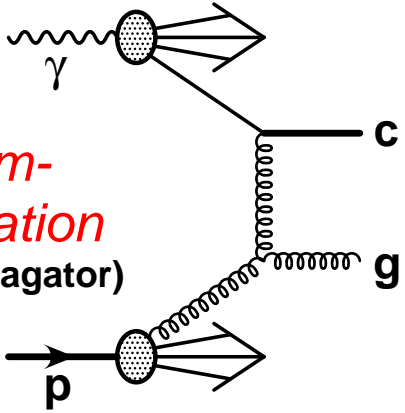
Resolved contributions



Gluon-Gluon-Fusion

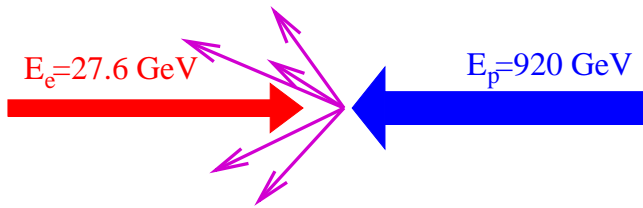


Charm-Excitation (q-Propagator)

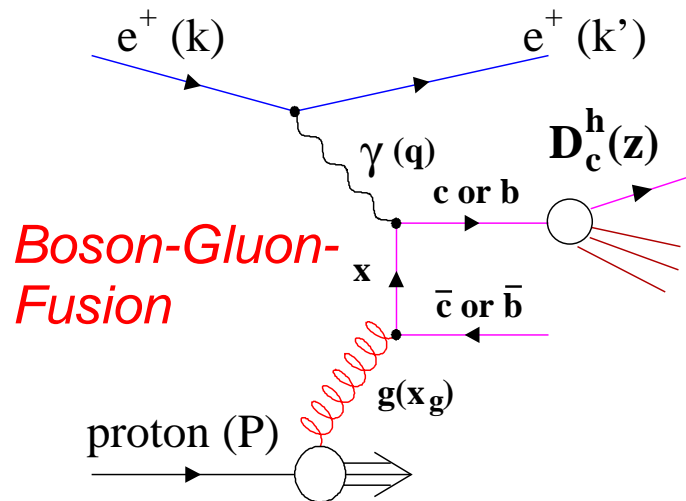


Charm-Excitation (g-Propagator)

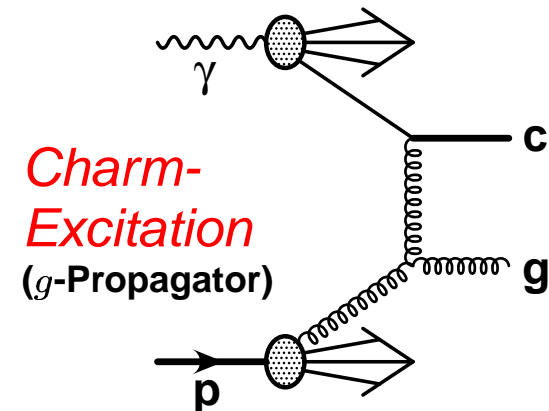
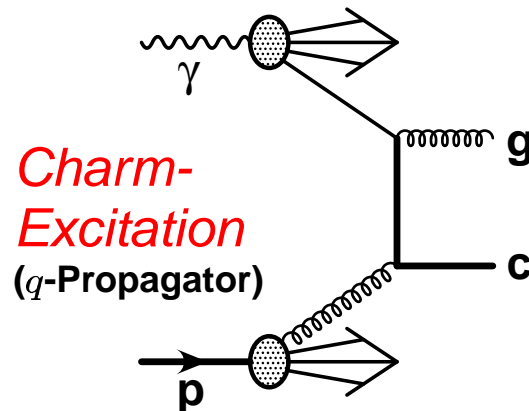
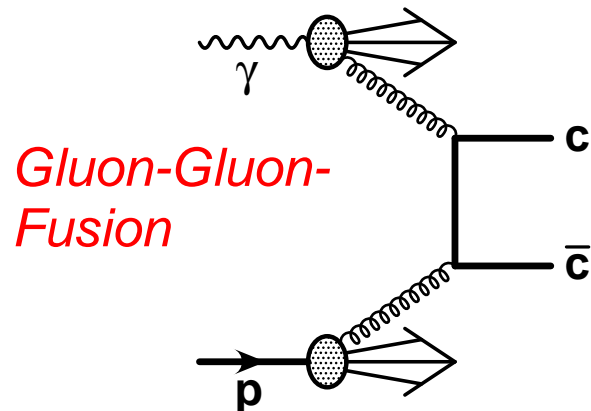
Introduction - Questions to Be Addressed



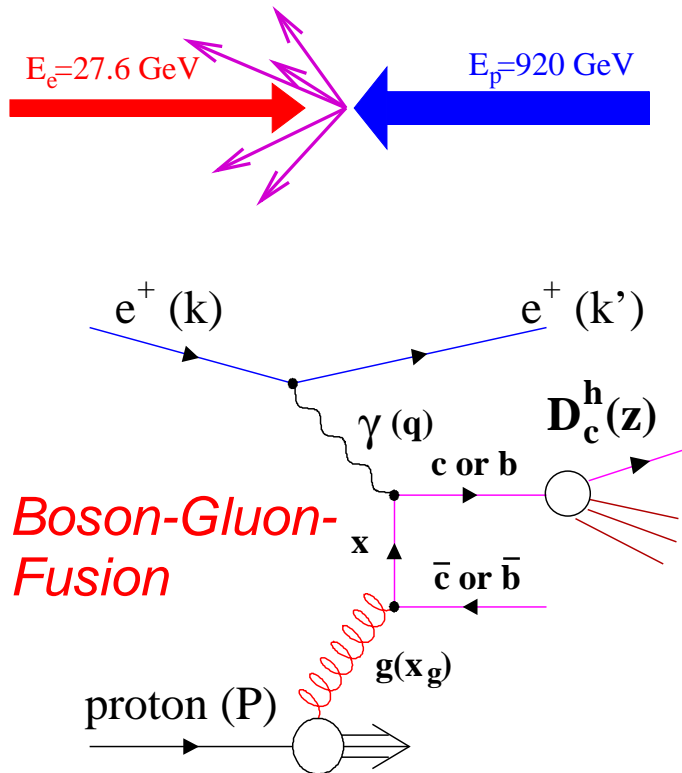
Good understanding of charm production crucial for QCD precision measurements at HERA



- How well do we understand charm production in ep scattering on the parton level in pQCD?
- Is the hadronization of charm in ep scattering the same as in e.g. e^+e^- ?



Introduction - Theoretical Schemes



Calculations using the DGLAP evolution

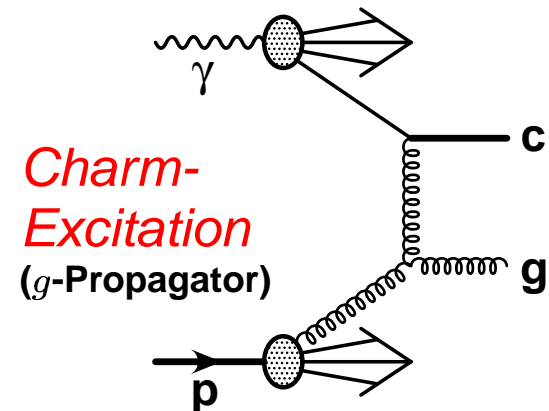
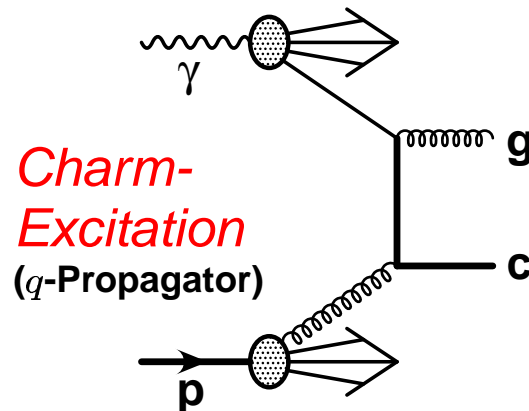
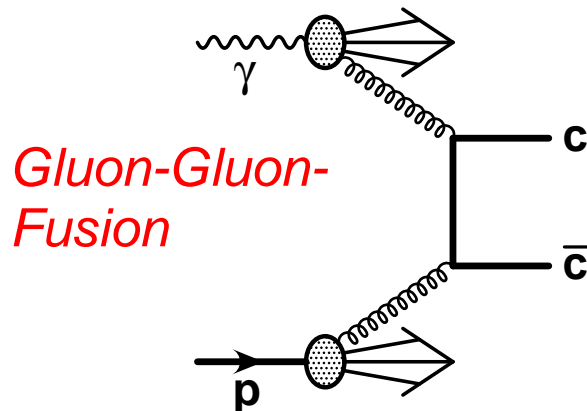
massive scheme, fixed order NLO: charm produced dynamically; valid for $p_t \lesssim m_q$ (Frixione et al.)

massless scheme resummed NLL : charm in γ or p ; $p_t \gg m_q$ (Kniehl et al.,...)

FONLL, 'matched' scheme fixed order + NLL scheme, incorporate mass effects up to NLO, avoid double counting (Cacciari et al.)

Calculation using the CCFM evolution

CASCADE unintegrated gluon, off shell matrix element, full hadron level MC (Jung et al.)



Hadronization of Charm

- What is the QCD vacuum felt by the charm quark during hadronization?

$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} ? \quad \gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}} ?$$

- Vector (D^*) vs. pseudoscalar (D^0) mesons: Does spin counting hold for charmed hadrons?

$$P_V = \frac{V}{V+P} = 3/4 ?$$

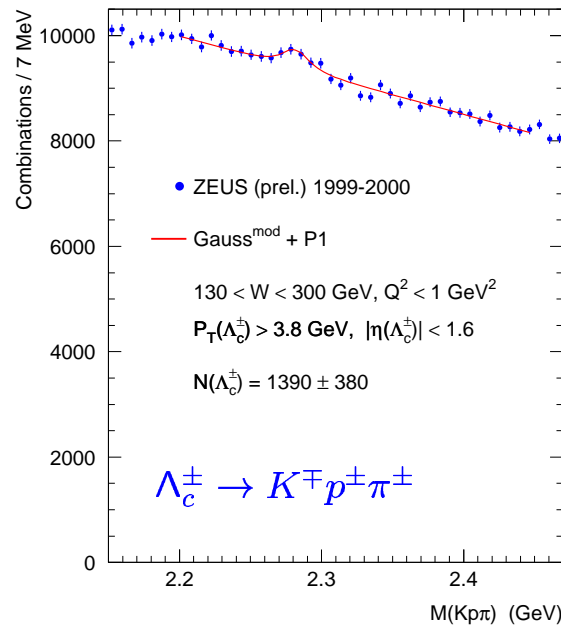
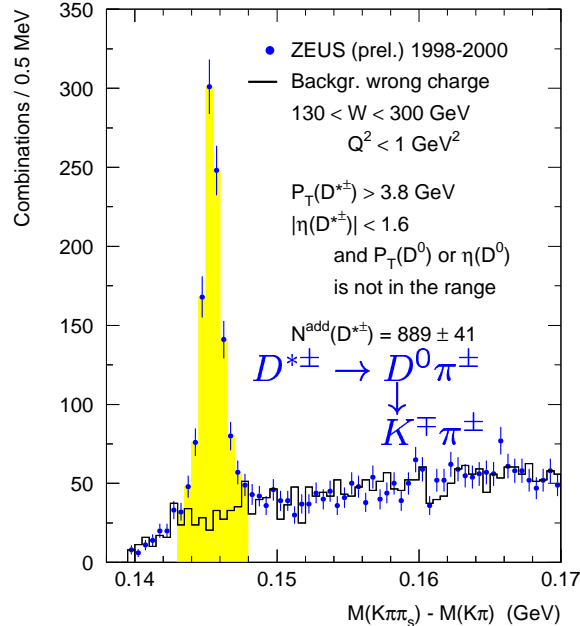
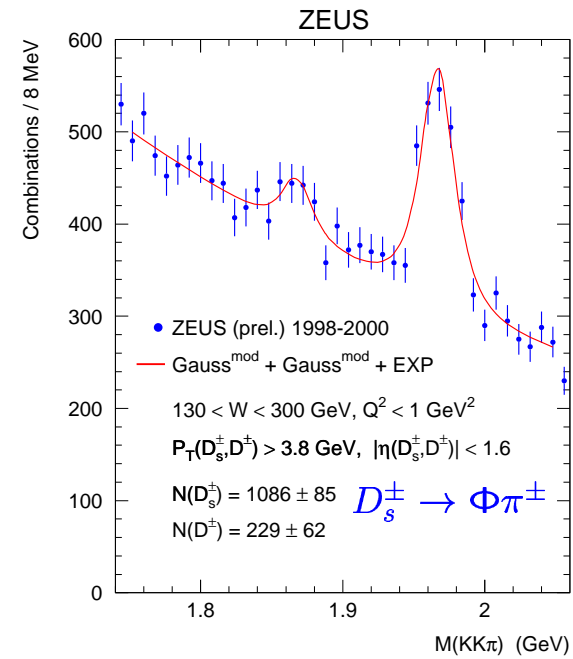
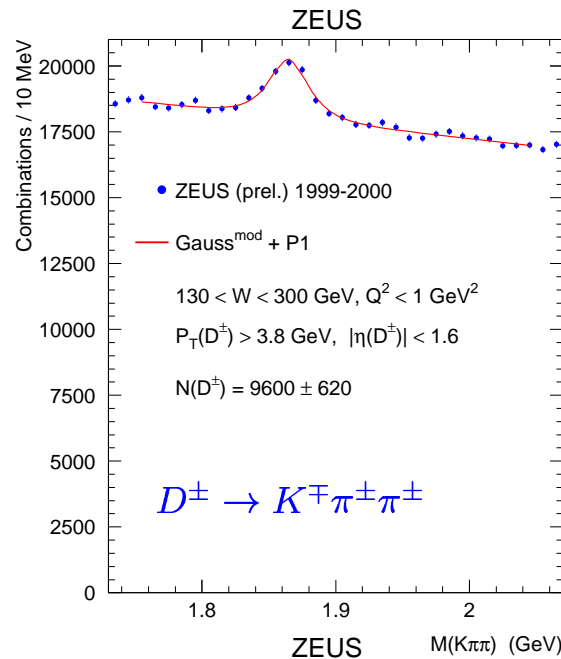
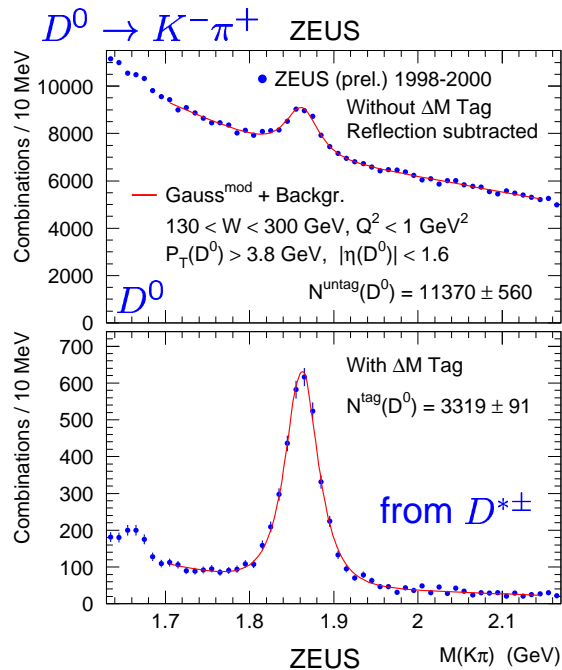
- What is the relative fragmentation fraction of charmed hadrons?

$$\text{e.g. } f(c \rightarrow D) = \frac{N(D)}{N(c)} = \frac{\sigma(D)}{\sum_{\text{all}} \sigma(D, \Lambda_c, \dots)} ?$$

Are these ratios and fractions universal?

- Need to measure ground state hadrons, i.e. D^0 , D^\pm , D_s^\pm , Λ_c^\pm , and $D^{*\pm}$

Signals of Charmed Hadrons



- Kinematic region:

$$130 < W < 300 \text{ GeV}, Q^2 < 1 \text{ GeV}^2$$

$$p_T(D, \Lambda_c) > 3.8 \text{ GeV}, |\eta(D, \Lambda_c)| < 1.6$$

- Measured cross sections:

$$\sigma^{\text{untag}}(D^0), \sigma^{\text{tag}}(D^0), \sigma(D^{*\pm})$$

$$\sigma(D^\pm), \sigma(D_s^\pm), \sigma(\Lambda_c^\pm)$$

$R_{u/d}$, γ_s and P_V

$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} = \frac{\sigma(D^{0,*0})}{\sigma(D^{\pm,*\pm})} = \frac{\sigma_{\text{untag}}(D^0)}{\sigma(D^{\pm}) + \sigma_{\text{tag}}(D^0)}$$

The vacuum as seen by the charm quark contains an equal number of u and d quarks

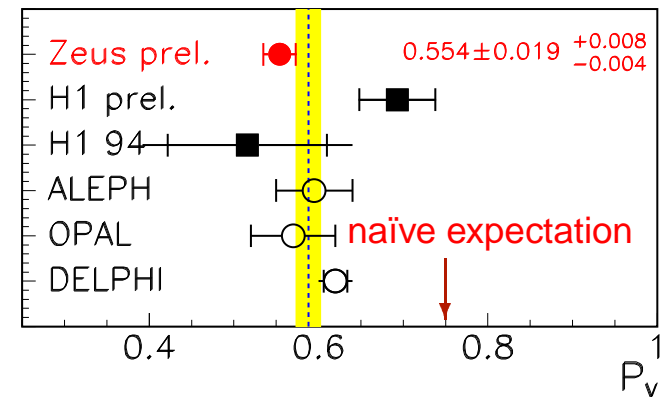
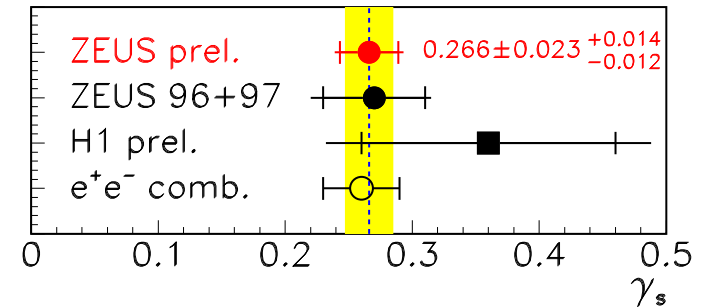
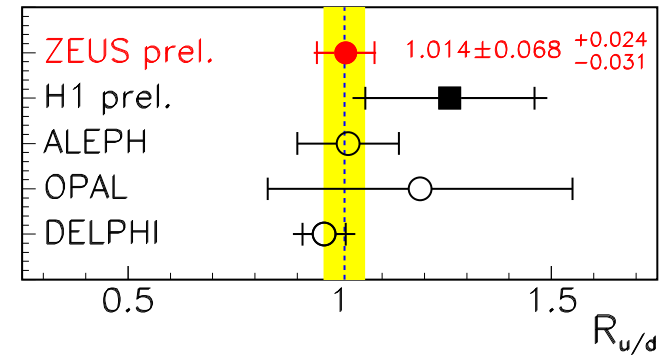
$$\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}} = \frac{2\sigma(D_s^{\pm})}{\sigma^{\text{dir}}(D^{\pm}) + \sigma^{\text{dir}}(D^0) + 2\sigma(D^{*\pm})}$$

s quarks are suppressed by a factor of 4

$$P_V = \frac{V}{V+P} = \frac{\sigma(D^*)}{\sigma(D^*) + \sigma^{\text{dir}}(D)} \neq 3/4$$

Naïve spin counting does not work for charm

QCD vacuum seen by charm quarks is independent of the hard physics



Charm Fragmentation Fractions

ZEUS: reconstruct all charm ground states, D^\pm , D^0 , D_s^\pm , Λ_c^\pm and $D^{*\pm}$ ~ 66 or 79 pb^{-1}

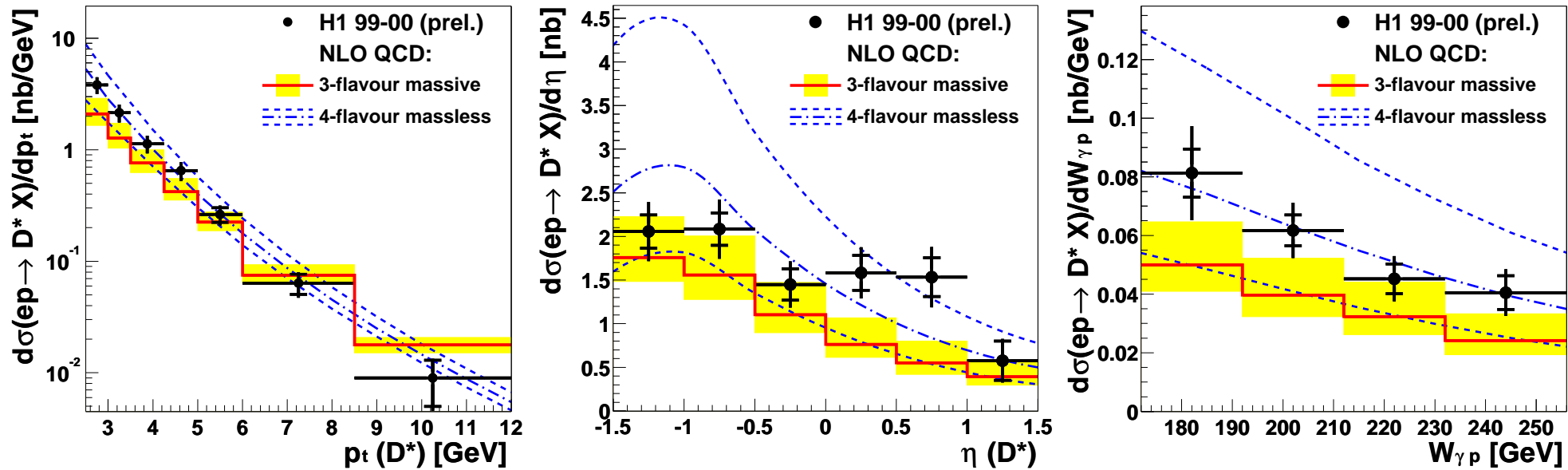
Determine from data:

ZEUS prel. (γp) $P_T(D, \Lambda_c) > 3.8 \text{ GeV}, \eta(D, \Lambda_c) < 1.6$	Combined e^+e^- data	H1 prel. (DIS)
$f(c \rightarrow D^+) = 0.249 \pm 0.014_{-0.008}^{+0.004}$	0.232 ± 0.010	$0.202 \pm 0.020_{-0.033}^{+0.045} \text{ }_{-0.021}^{+0.029}$
$f(c \rightarrow D^0) = 0.557 \pm 0.019_{-0.013}^{+0.005}$	0.549 ± 0.023	$0.658 \pm 0.054_{-0.148}^{+0.115} \text{ }_{-0.048}^{+0.086}$
$f(c \rightarrow D_s^+) = 0.107 \pm 0.009 \pm 0.005$	0.101 ± 0.009	$0.156 \pm 0.043_{-0.035}^{+0.036} \text{ }_{-0.046}^{+0.050}$
$f(c \rightarrow \Lambda_c^+) = 0.076 \pm 0.020_{-0.001}^{+0.017}$	0.076 ± 0.007	
$f(c \rightarrow D^{*+}) = 0.223 \pm 0.009_{-0.005}^{+0.003}$	0.235 ± 0.007	$0.263 \pm 0.019_{-0.042}^{+0.056} \text{ }_{-0.022}^{+0.031}$

charm fragmentation fractions are universal

Inclusive D^* Meson Production

Electron tag $Q^2 < 0.01 \text{ GeV}^2$, $171 < W_{\gamma p} < 256 \text{ GeV}$, $p_T^{D^*} > 2.5 \text{ GeV}$; $|\eta^{D^*}| < 1.5$ 49 pb^{-1}



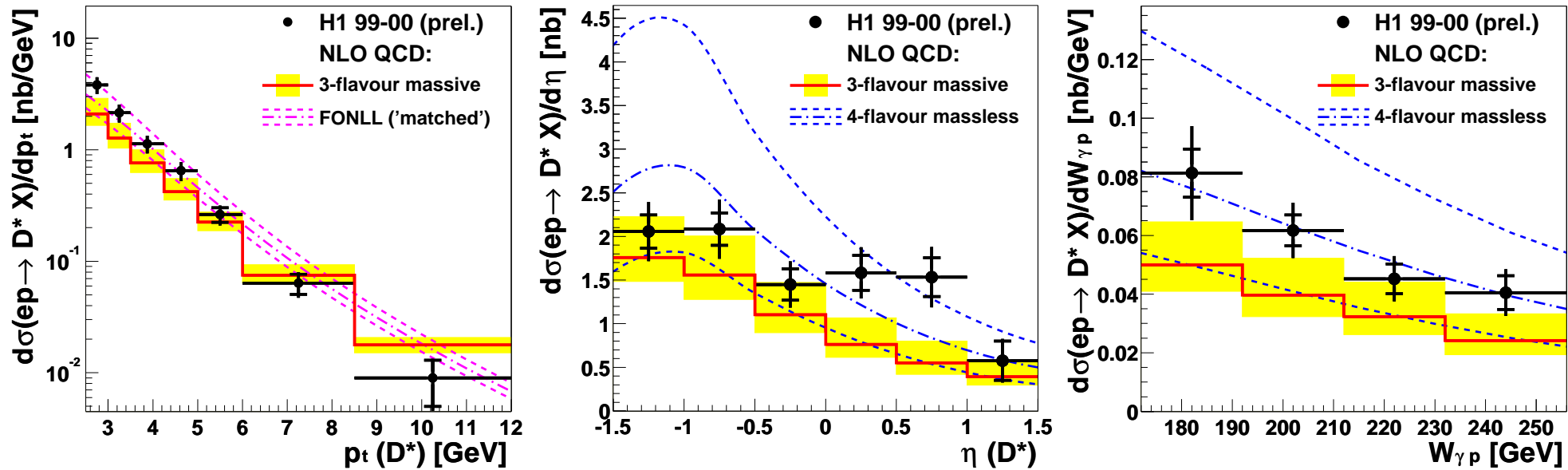
$$\sigma_{vis}(ep \rightarrow eD^{*\pm}X) = 4.74 \pm 0.32(stat.) \pm 0.64(syst.) \text{ nb}$$

H1 prel.

- **Massive** NLO calculations below data
- **Massless** NLO calculations in reasonable agreement with data

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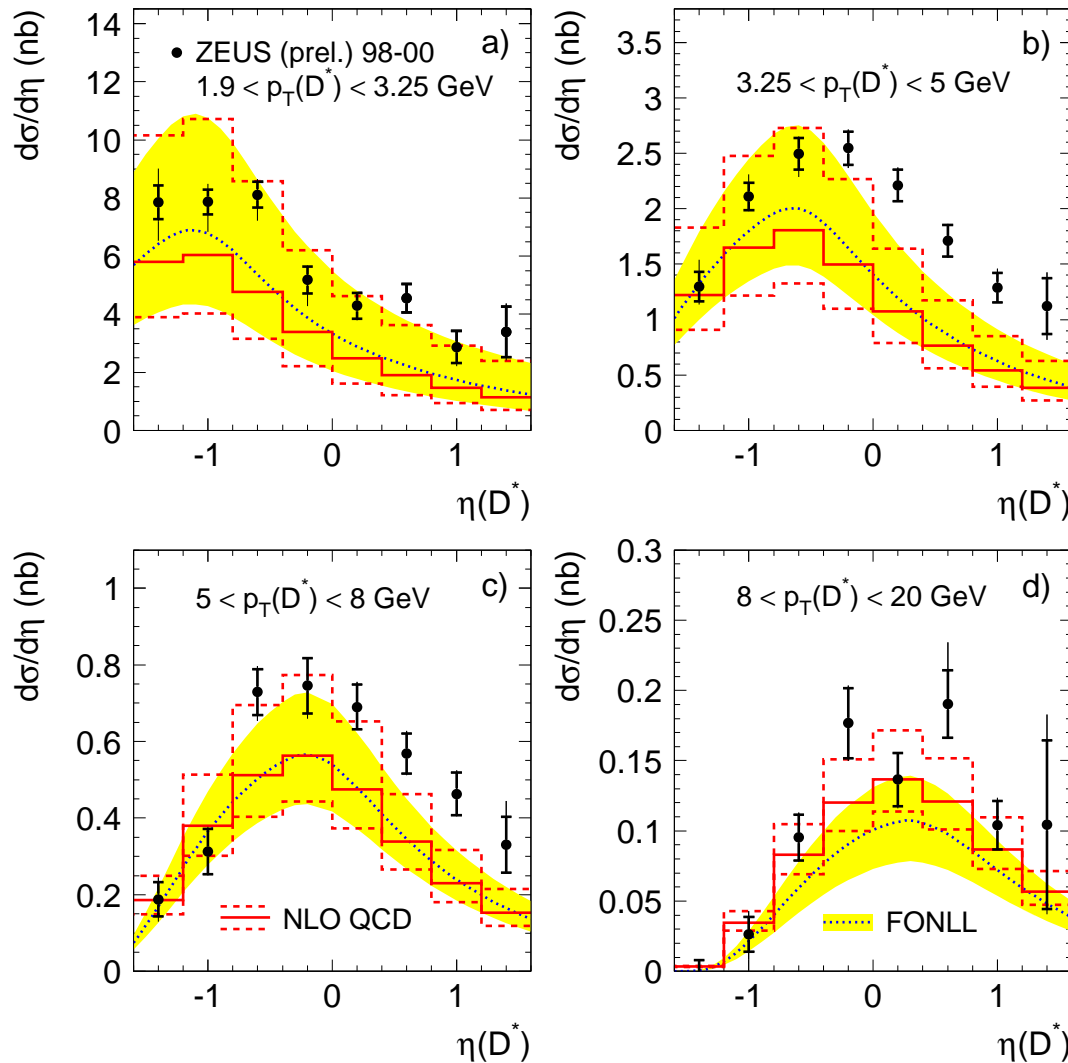
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H1 prel.

- **Massive** NLO calculation below data
- **Massless** NLO calculations in reasonable agreement with data
- **FONLL 'matched'** calculation reasonable in $p_T(D^*)$
- ➡ **Theories have large uncertainties**
- ➡ **Measurement are able to constrain theories significantly**

D^* Photoproduction (Double Differential Cross sections)

ZEUS



No electron tag

79 pb^{-1}

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

$p_T^{D^*} > 1.9 \text{ GeV}$; $|\eta^{D^*}| < 1.6$

η distribution in $p_T^{D^*}$ bins

- **NLO** below data at medium $p_T^{D^*}$ and high η

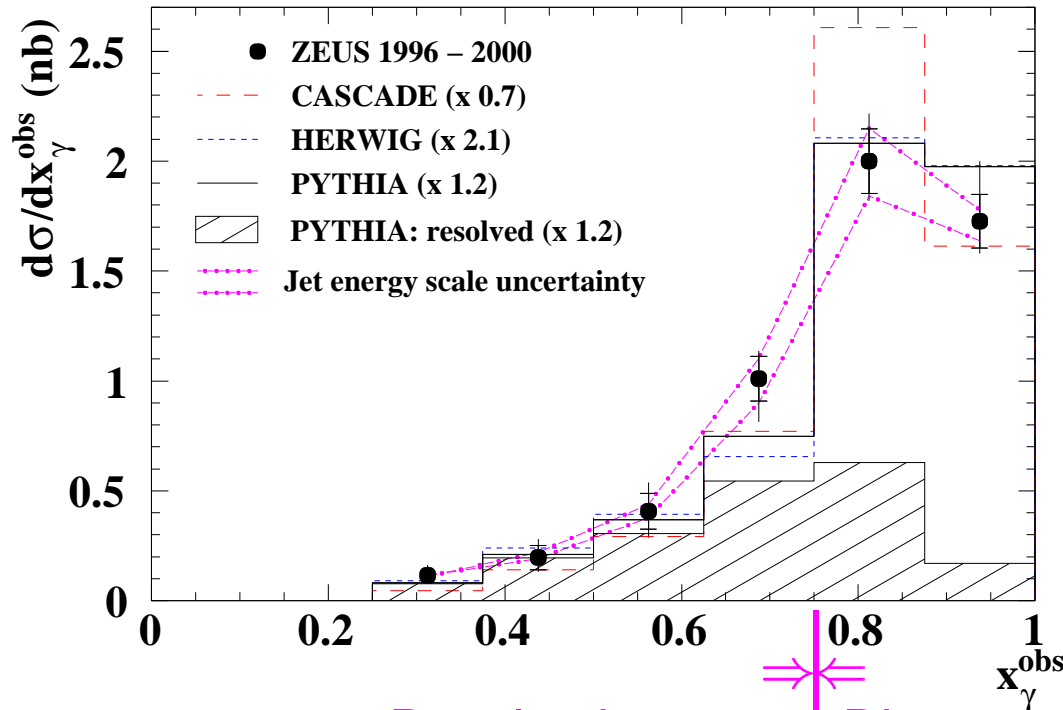
- **FONLL** close to data only at low $p_T^{D^*}$

☞ Theories are not able to describe all aspects observed in data

D^* + Dijet-Events

ZEUS: $\gamma p \rightarrow D^{*\pm} + jj + X$

$\sim 120 \text{ pb}^{-1}$



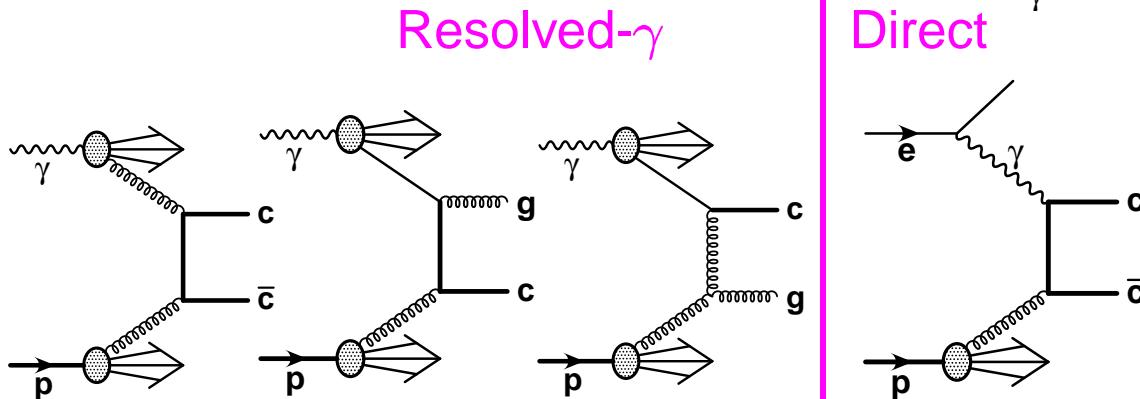
$$p_T^{D^*} > 3 \text{ GeV}$$

$$2 \text{ jets: } E_T^{jet} > 5 \text{ GeV, } |\eta^{jet}| < 2.4;$$

$$M_{jj} > 18 \text{ GeV}$$

Momentum fraction of photon in jets:

$$x_\gamma^{\text{obs}} = \frac{\sum_{j_1, j_2} (E_T^j e^{-\eta^j})}{2yE_e}$$

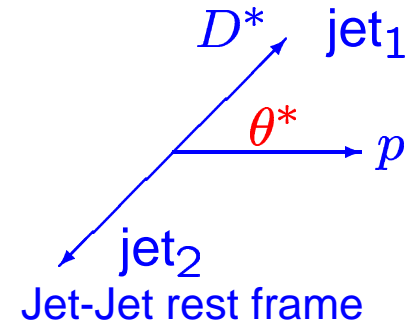


- **Significant resolved contribution ($\sim 40\%$)** like in previous measurements
- **MCs: good description of shape but off in normalization**
large charm content in the photon required
- **CASCADE different at high x_γ^{obs}**
cross section too high
- **NLO below data at low x_γ^{obs}**
(not shown)

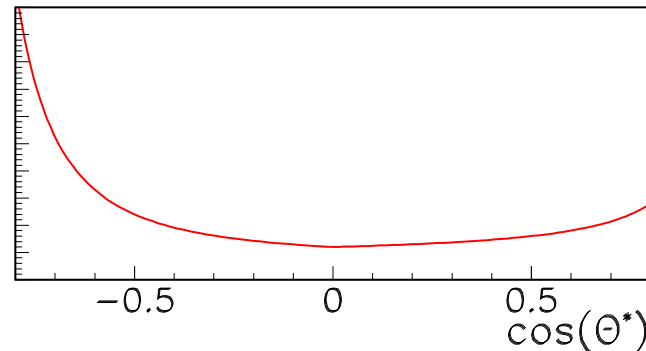
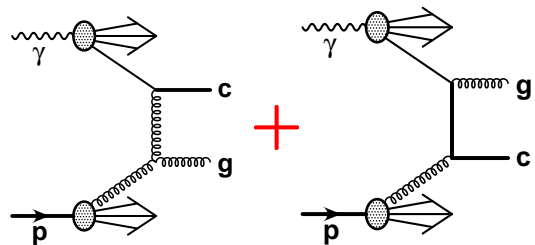
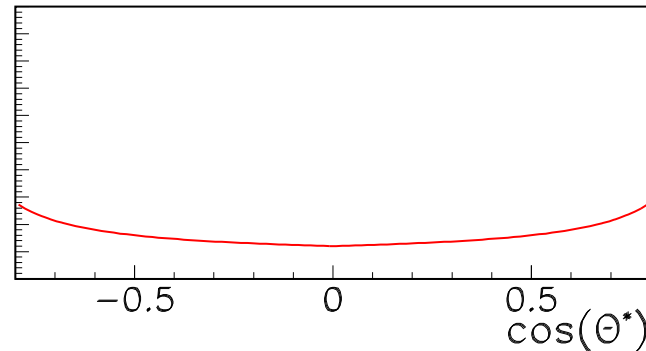
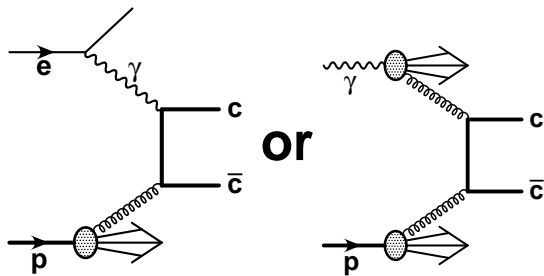
Charm: Dijet Angular Distributions (LO Picture)

- go to the jet-jet rest frame
- define D^* -jet direction as positive z -axis
- look at the angle Θ^* of the proton w.r.t. the D^* -jet

$$\theta^* = \angle(p, D^*\text{-Jet})$$



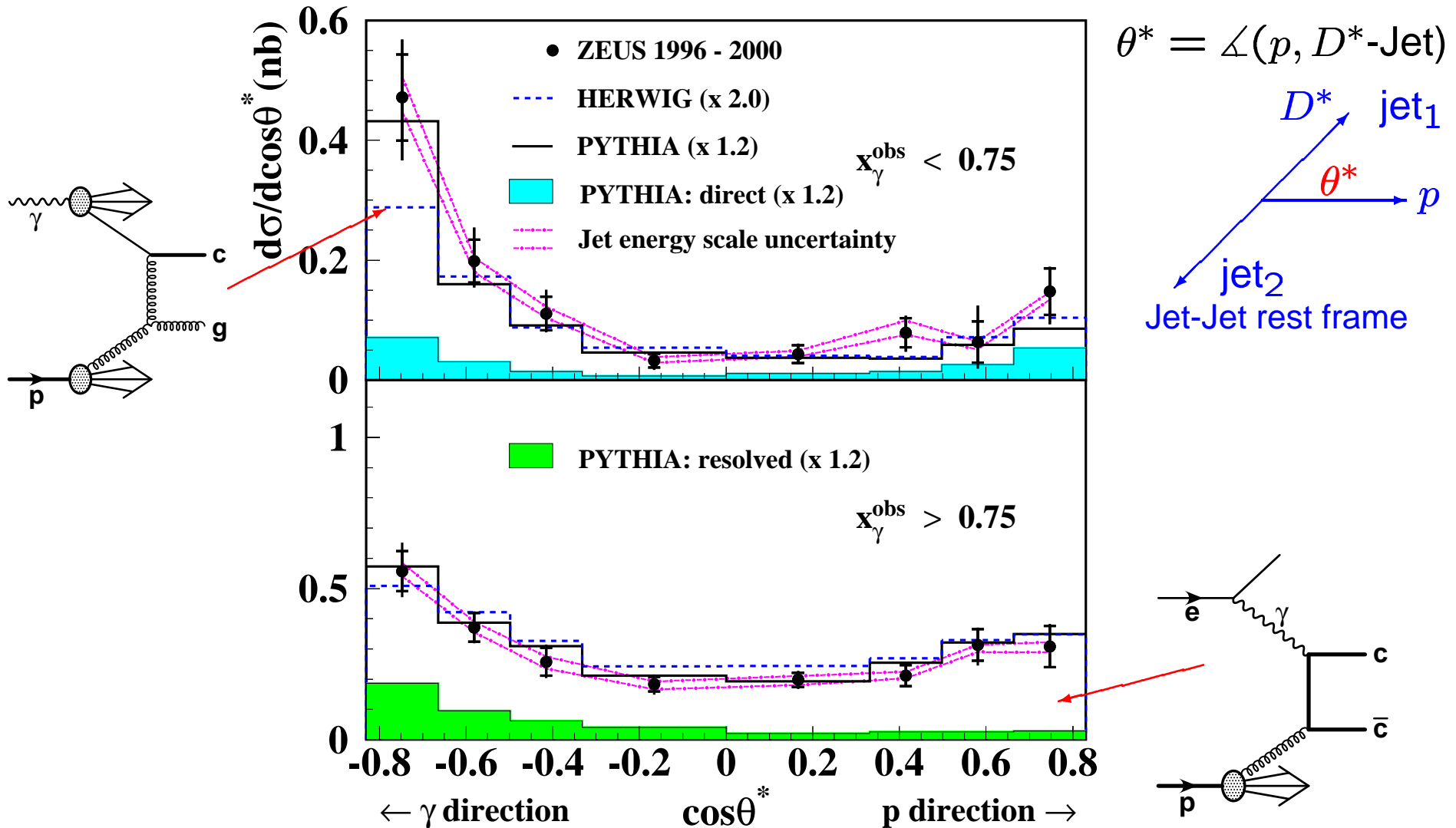
symmetric in $\cos \Theta^*$



strongly backward peaking

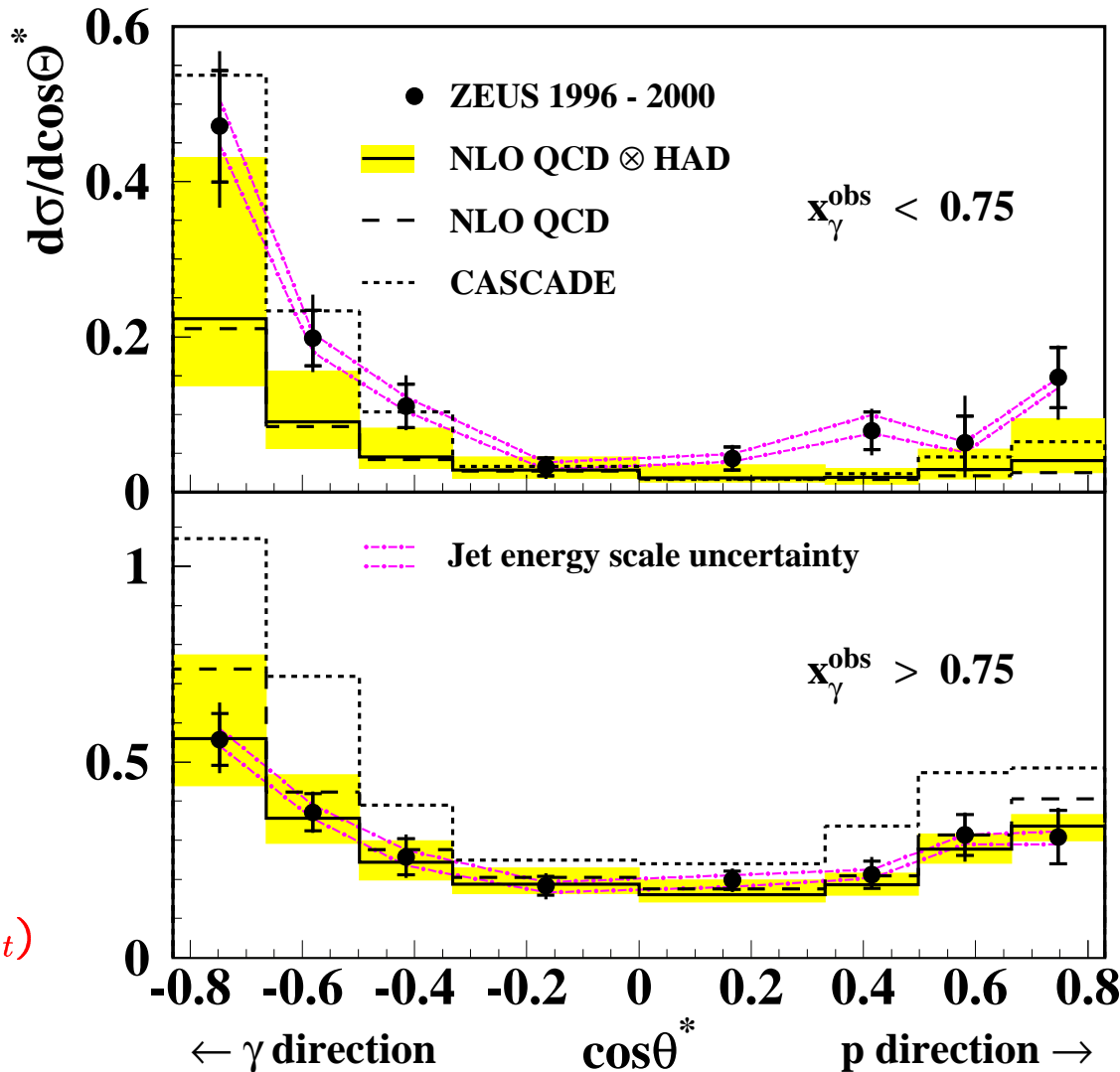
➡ Possible to prove that charm in the photon dominates the resolved process of charm production

Dijet Angular Distributions (LO Picture)



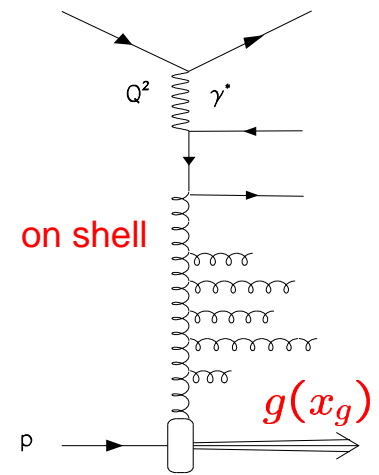
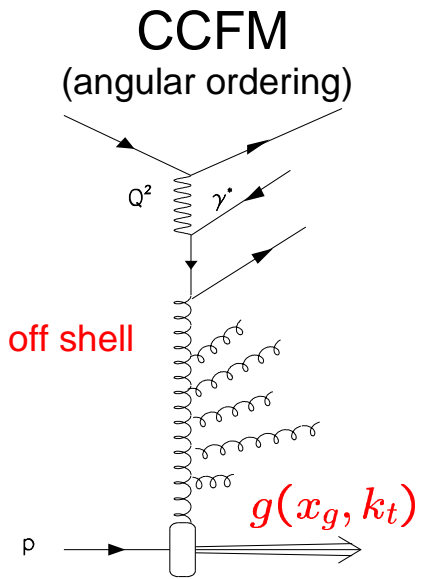
- LO Picture:
- Strong rise in $d\sigma/d\cos\theta^*$ towards γ direction for $x_\gamma^{\text{obs}} < 0.75$
 - Clear evidence for charm as an active flavour in the photon

Charm: Dijet Angular Distributions (Evolution Scheme)



$$\theta^* = \angle(p, D^*\text{-Jet})$$

D^* jet₁
 θ^*
 p
 jet₂
 Jet-Jet rest frame
 DGLAP NLO



QCD

- Schemes:
- NLO DGLAP ok for $x_\gamma^{\text{obs}} > 0.75$, but too low for $x_\gamma^{\text{obs}} < 0.75$
 - CCFM (Cascade) ok in shape, but too high in cross section

Conclusions

- Hadronization ratios and fragmentation probabilities:

➡ **Hadronization of charm is independent of the hard physics**

- Inclusive D^* -meson production:
 - Data are more precise than theoretical calculations
 - Theoretical predictions have large uncertainties
 - NLO calculations do not describe all aspects of data

➡ **More theoretical effort needed to get a better understanding**

- D^* plus dijet angular distribution:

➡ **Confirms large charm content in the photon in the LO+PS picture**

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- D^* plus dijet angular distribution:

➡ **Confirms large charm content in the photon in the LO+PS picture**

➡ **May also be a footprint of the relevance of k_T in the parton evolution***

* Several observations at HERA are better described in this scheme

Parameter on Theoretical Calculations

Parameter	Massive	Massless	FONLL
γ -Structure	GRV-G HO	AFG	GRV
p - Structure	CTEQ 5D	CTEQ 6M	CTEQ 5M1
Fragmentation	Peterson $\epsilon = 0.035$	BKK-O(1998)	Kartvelishvili
m_c [GeV]	1.5	1.5	1.5
μ_f	$2 \cdot \mu$	$(1/2 \dots 2) \cdot 2 \cdot \mu$	μ
μ_r	$(1/4 \dots 1) \cdot \mu_f$	$(1/2 \dots 2) \cdot 2 \cdot \mu$	$(1/2 \dots 2) \cdot \mu_f$

$$\mu = \sqrt{m_c^2 + p_t(c)^2}$$