Photoproduction of Open Charm at HERA

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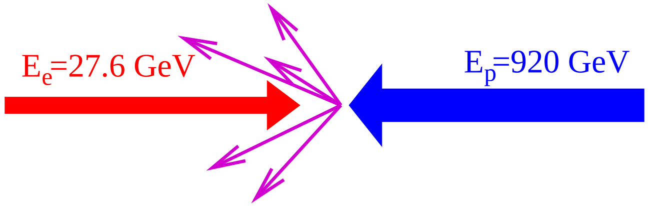
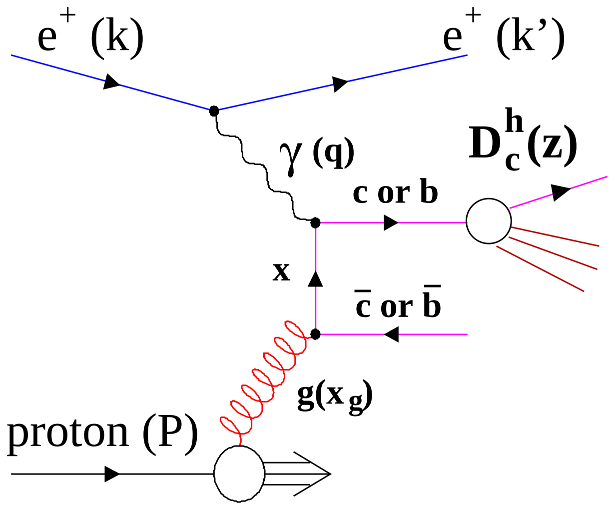
- Introduction, Theoretical Framework
- Hadronization of charm quarks
- Inclusive $D*$ meson production
- Dijet angular distribution of charm

Introduction - HERA Kinematics



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

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



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

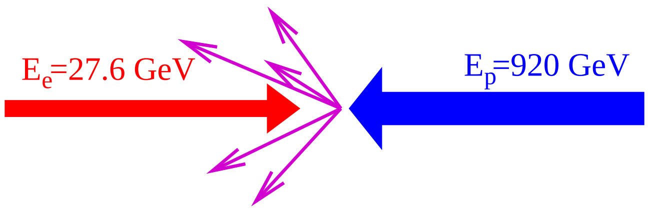
$$Q^2 = -q^2 = -(k - k')^2$$

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

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

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

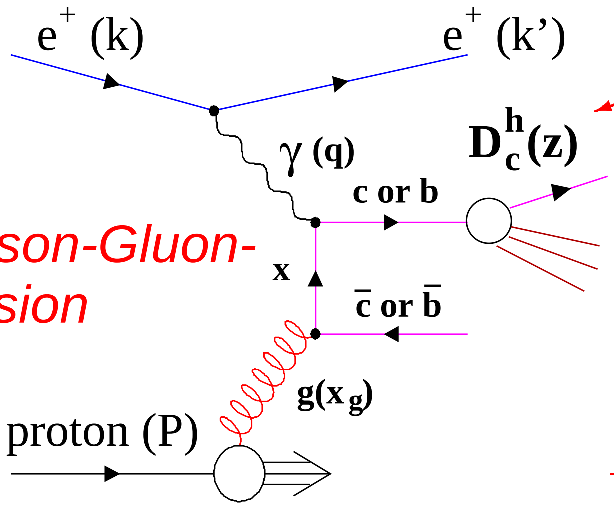
Introduction - Charm Production at HERA



LO picture

Direct contribution

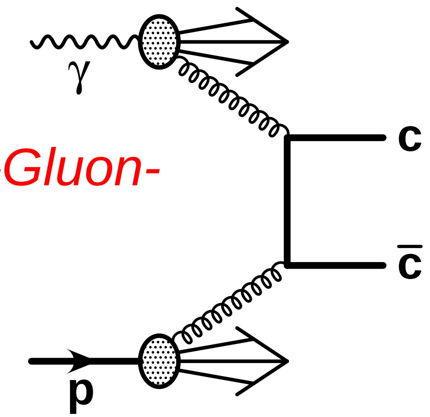
Boson-Gluon-Fusion



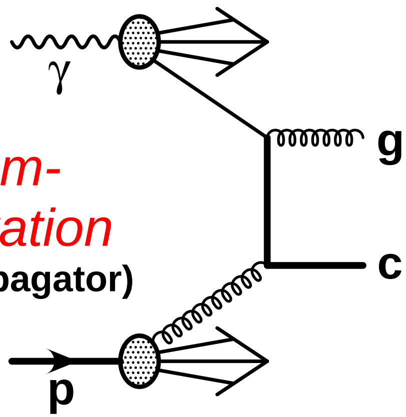
$Q^2 \simeq 0$ GeV^2 $\Rightarrow$ Photoproduction

Resolved contributions

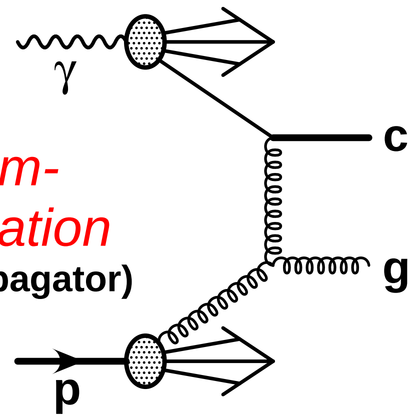
Gluon-Gluon-Fusion



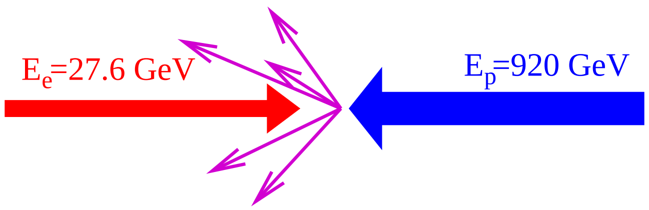
Charm-Excitation
(q-Propagator)



Charm-Excitation
(g-Propagator)

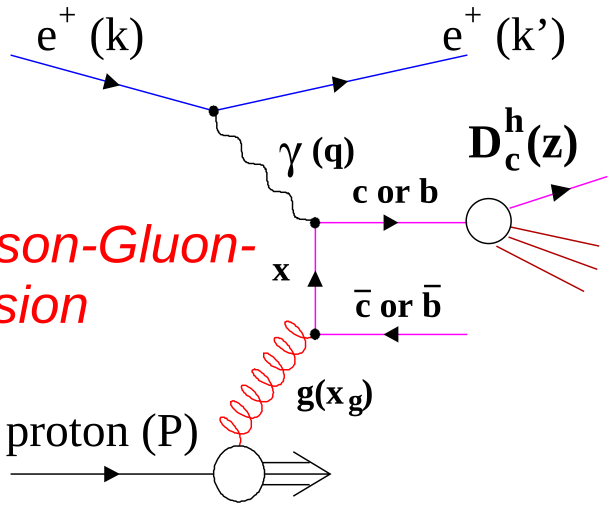


Introduction - Questions to Be Addressed



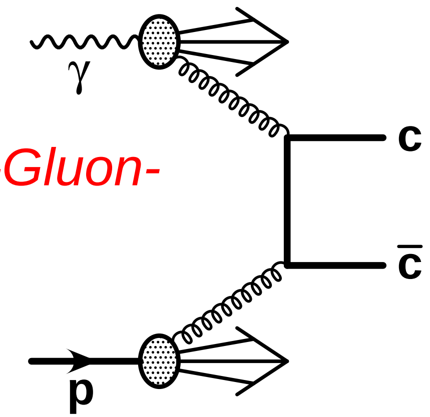
Good understanding of charm production crucial for QCD precision measurements at HERA

Boson-Gluon-Fusion



- 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^-?

Gluon-Gluon-Fusion



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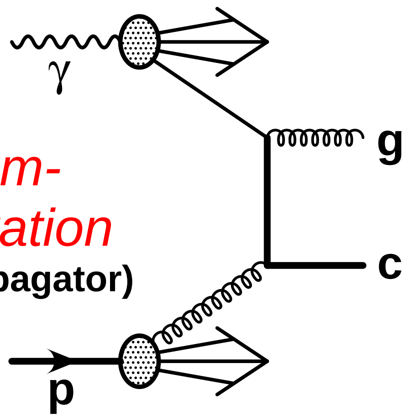

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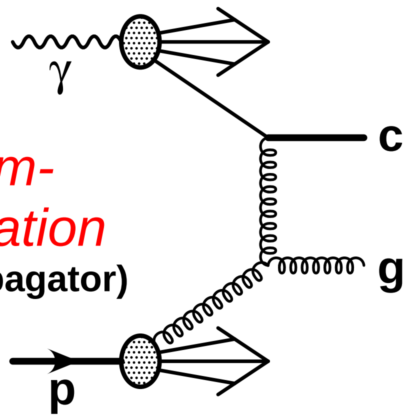
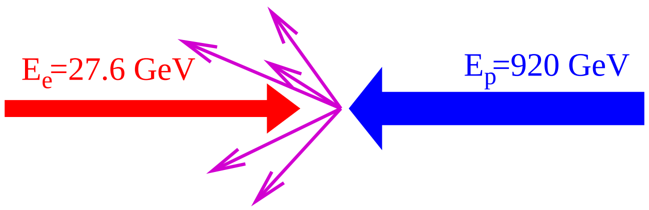


Introduction - Theoretical Schemes



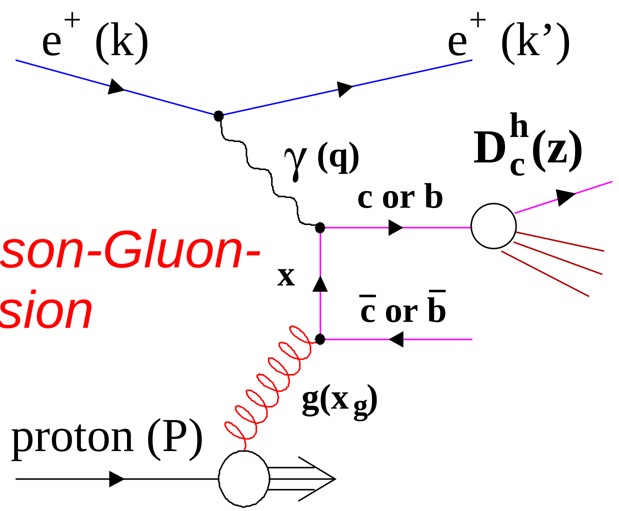
Calculations using the DGLAP evolution

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.)**

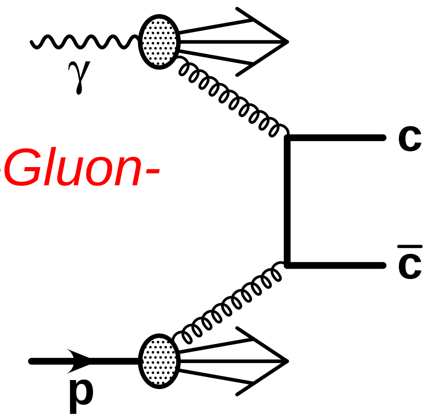
Boson-Gluon-Fusion



Calculation using the CCFM evolution

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

Gluon-Gluon-Fusion



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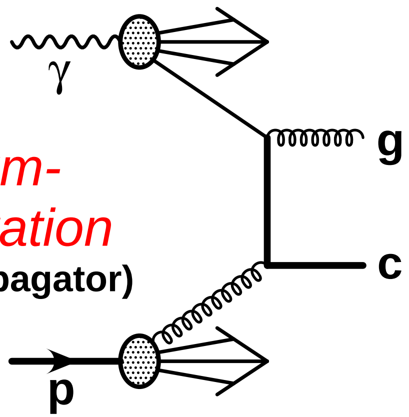

Charm-Excitation
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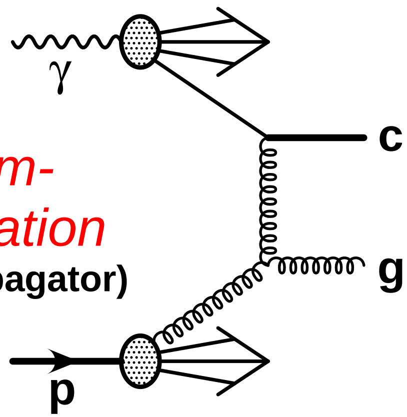


- What is the QCD vacuum felt by the charm quark during hadronization?

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

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

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

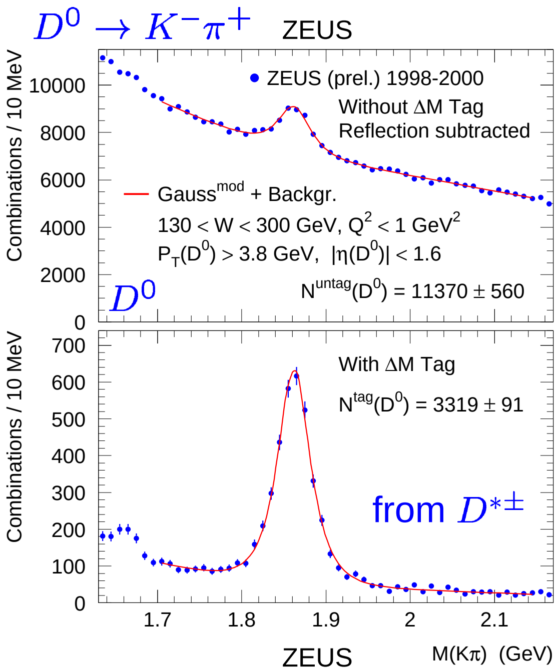
- What is the relative fragmentation fraction of charmed hadrons?

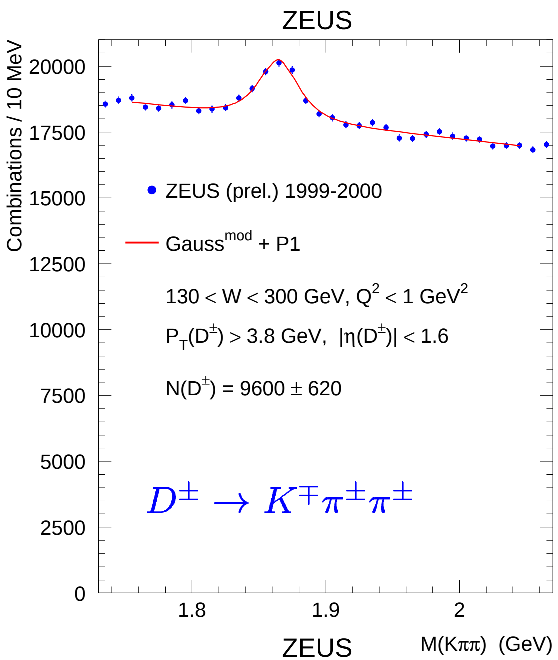
$$\text{e.g. } f(c \to D) = \frac{N(D)}{N(c)} = \frac{\sigma(D)}{\sum_{all} \sigma(D, \Lambda_c, \ldots)}\ ?$$

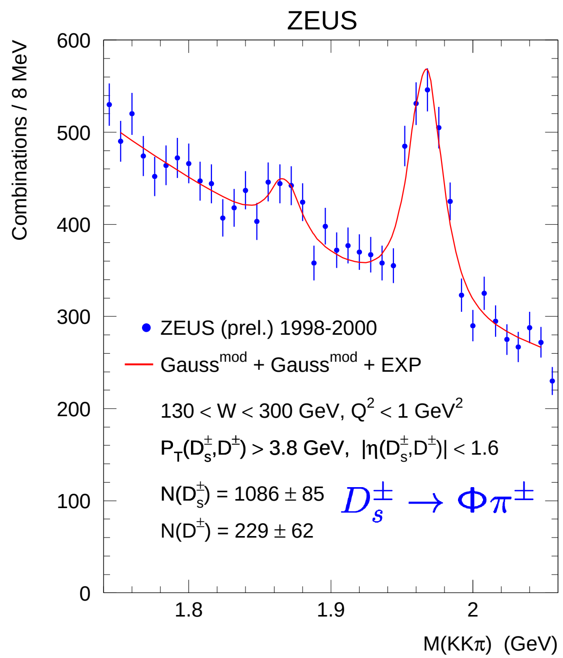
Are these ratios and fractions universal?

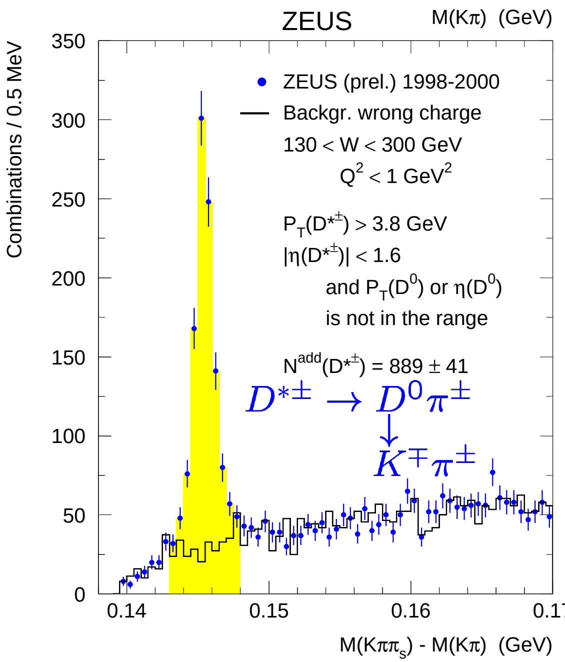
☛ Need to measure ground state hadrons, i.e. D^0, $D^\pm$, $D_s^\pm$, $\Lambda_c^\pm$, and $D^{*\pm}$

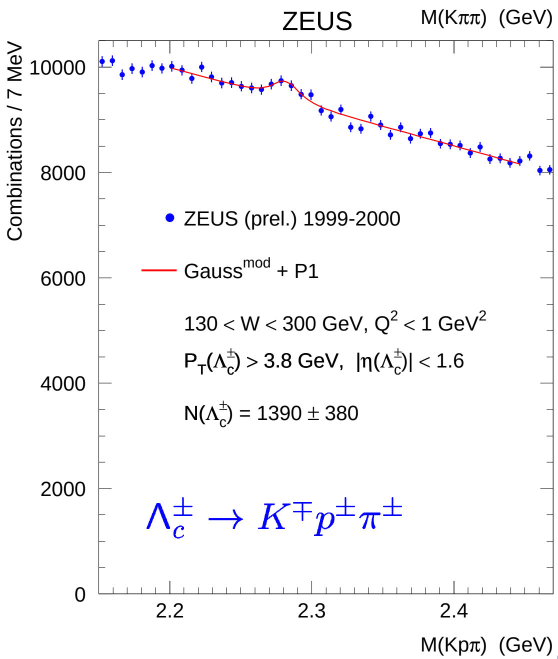
Signals of Charmed Hadrons











- Kinematic region:

  $130 < W < 300$ GeV, $Q^2 < 1$ GeV^2

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

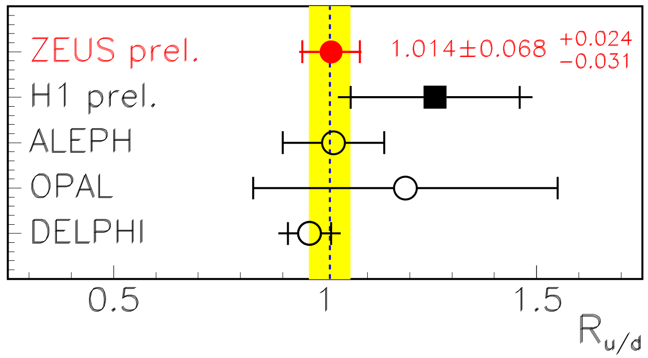
- Measured cross sections:

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

$R_{u/d}$, γ_s and P_V

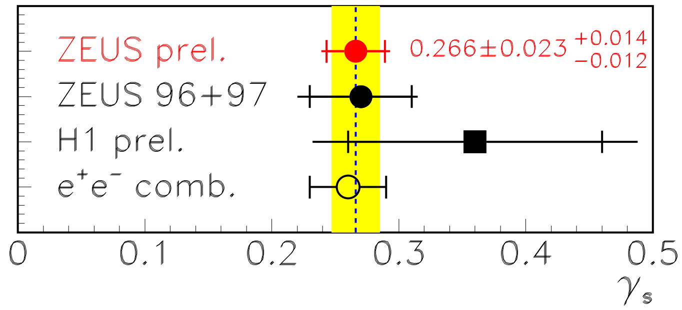
$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} = \frac{\sigma(D^{0,*0})}{\sigma(D^{\pm,*\pm})} = \frac{\sigma^{untag}(D^0)}{\sigma(D^{\pm}) + \sigma^{tag}(D^0)}$$

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



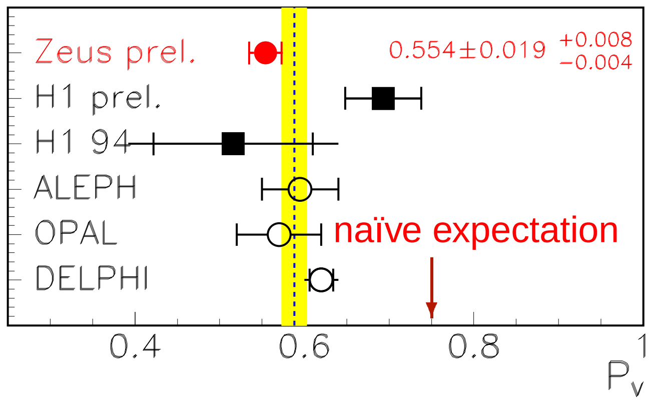
$$\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}} = \frac{2\sigma(D_s^{\pm})}{\sigma^{dir}(D^{\pm}) + \sigma^{dir}(D^0) + 2\sigma(D^{*\pm})}$$

s quarks are suppressed by a factor of 4



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

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, $D_s^{\pm}$, $\Lambda_c^{\pm}$ and $D^{*\pm}$ $\sim$ 66 or 79 pb^{-1}

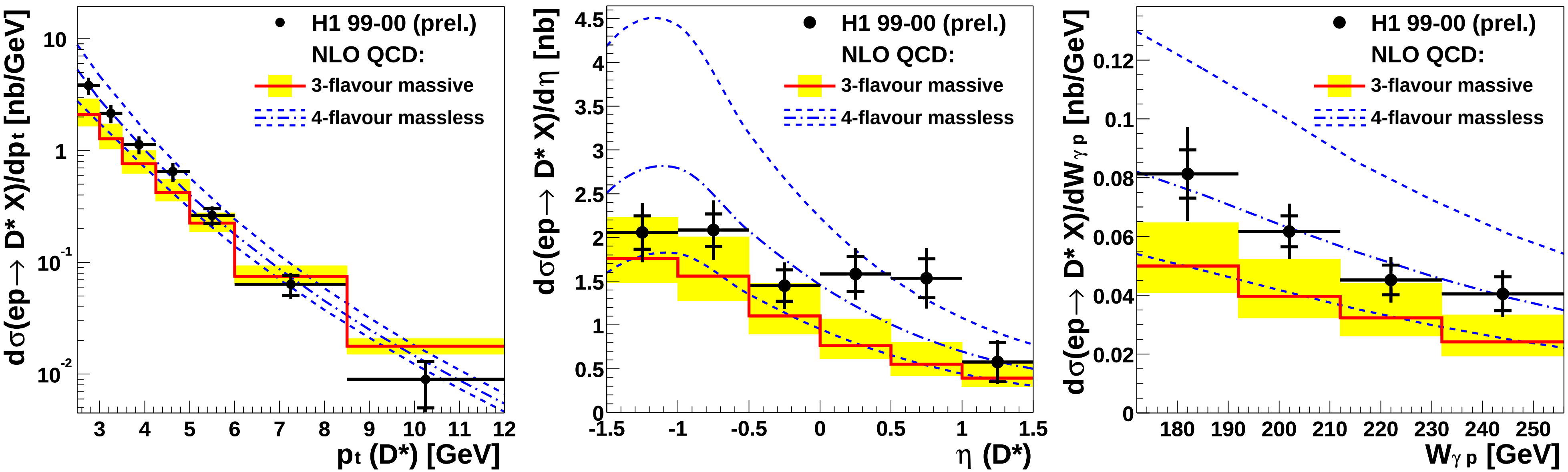
Determine from data:

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

charm fragmentation fractions are universal

Inclusive D^* Meson Production

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



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

H1 prel.

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

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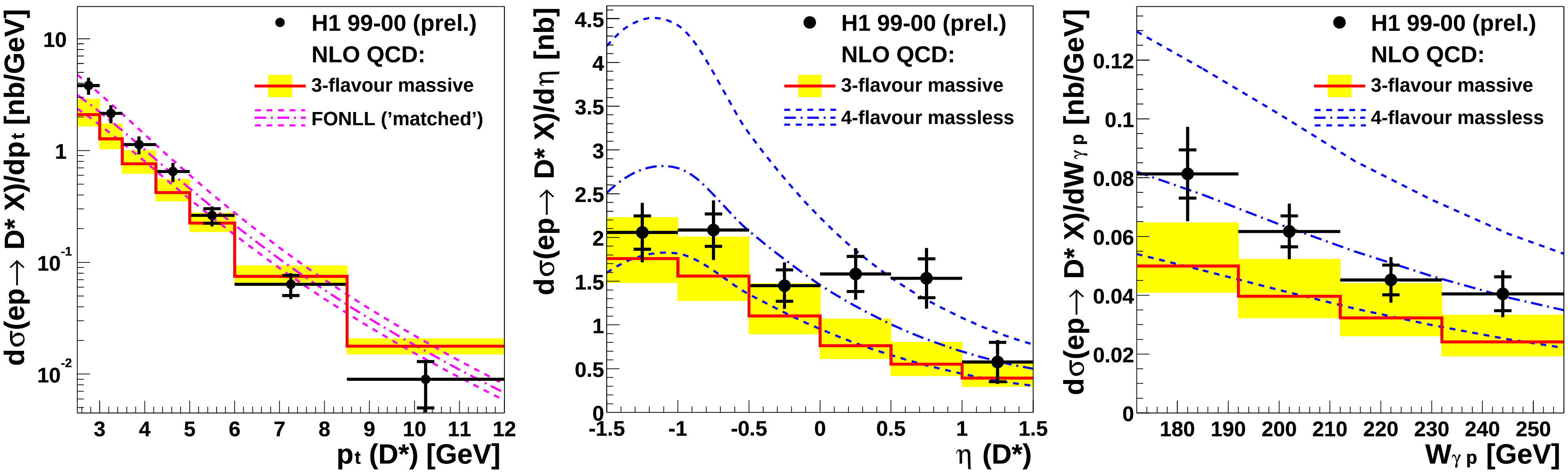
Electron tag $Q^2 < 0.01$ GeV^2, $171 < W_{\gamma p} < 256$ GeV, $p_T^{D^*} > 2.5$ GeV; $|\eta^{D^*}| < 1.5$ 49 pb^{-1}



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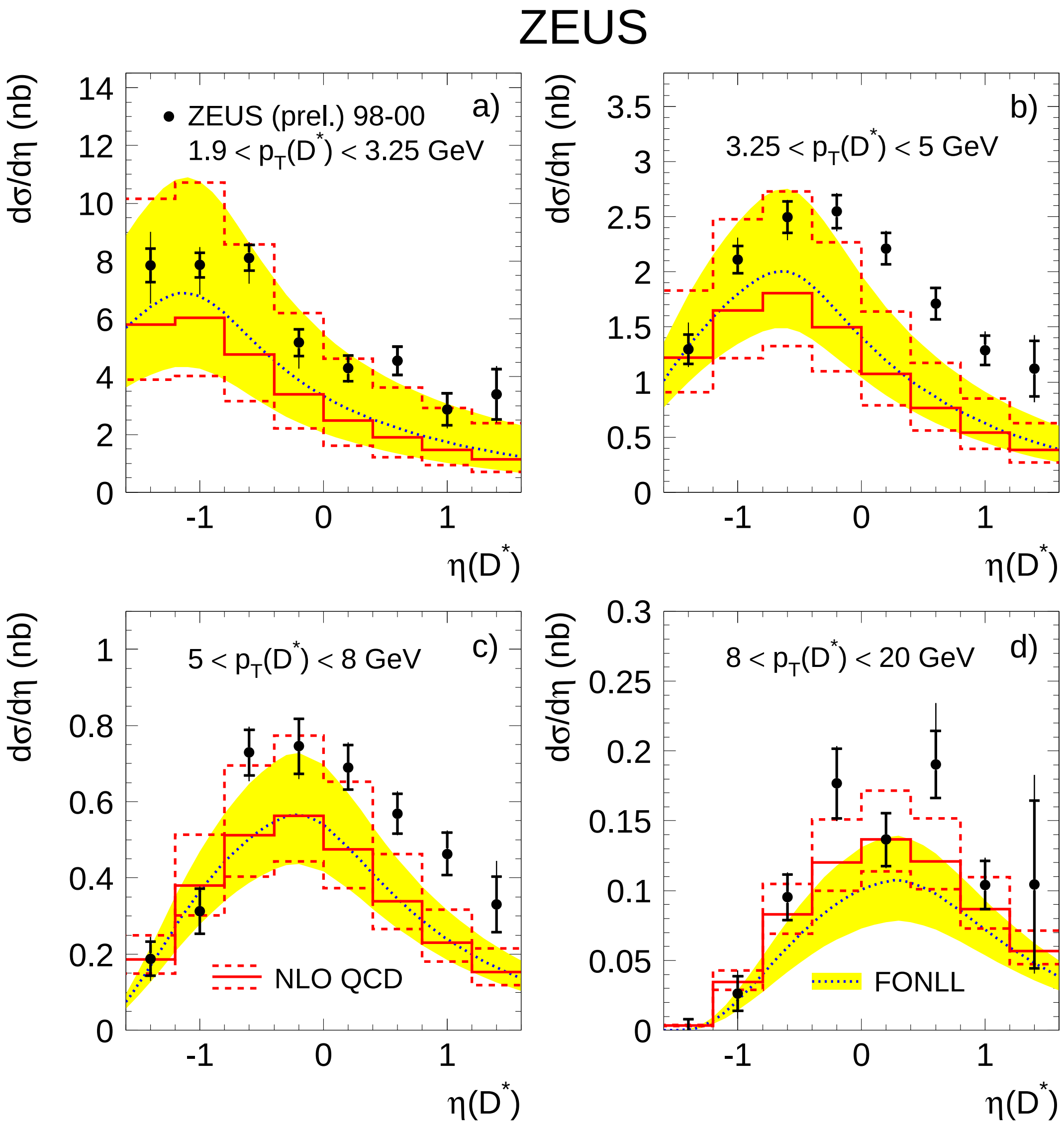
H1 prel.

- Massive NLO calculation below data
- Massless NLO calculculations 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)



No electron tag 79 pb^{-1}

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

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

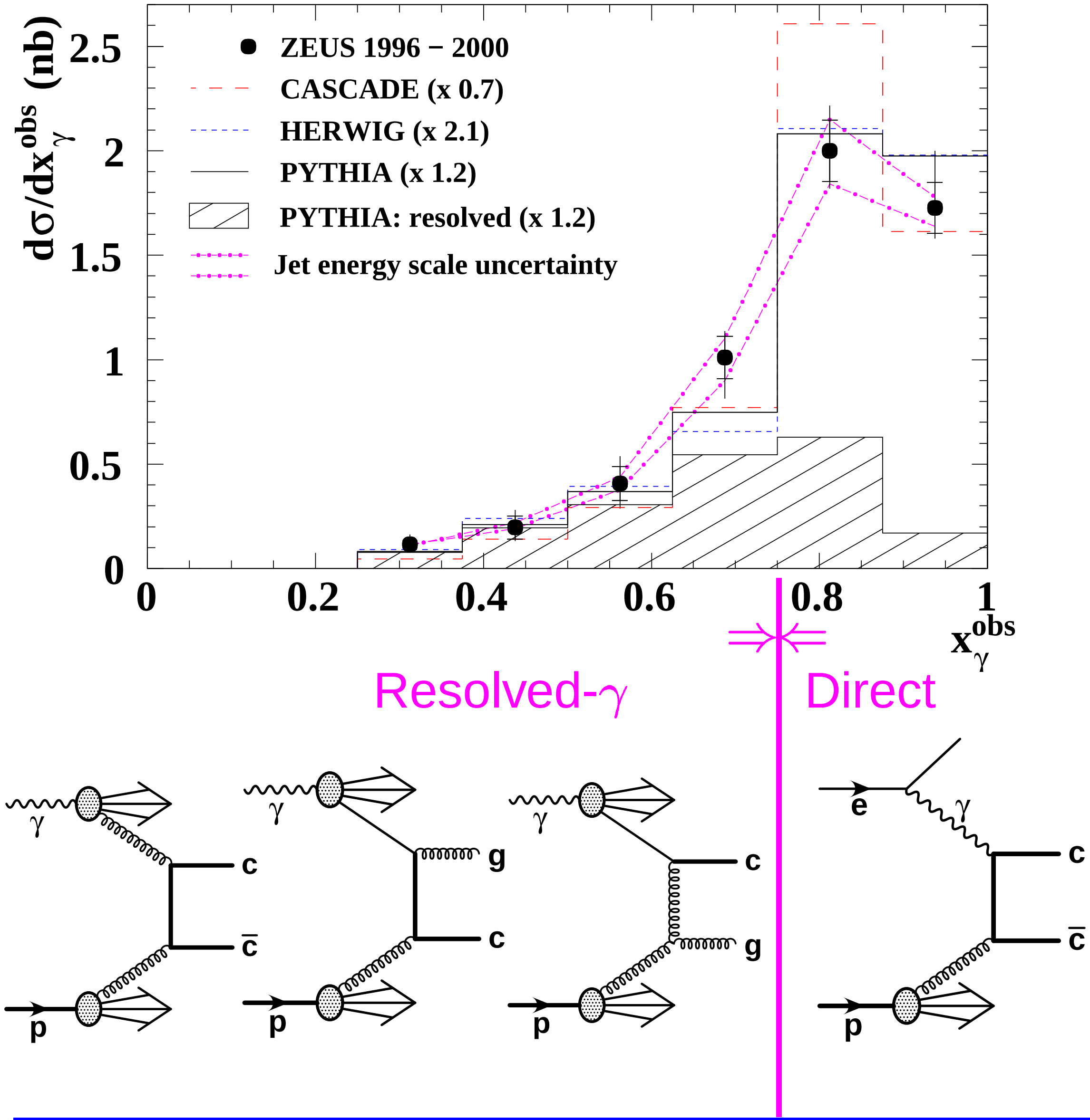
η distribution in $p_T^{D^*}$ bins

- 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: $\gamma p \to D^{*\pm} + jj + X$



$\sim 120\,\mathrm{pb}^{-1}$

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

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

$M_{jj} > 18$GeV

Momentum fraction of photon in jets:

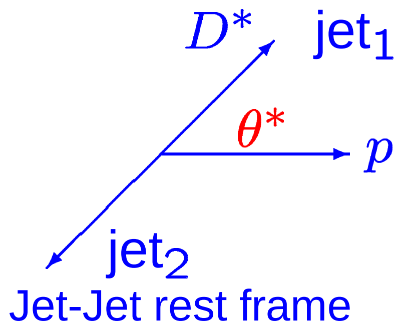
$$x_\gamma^{\text{obs}} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

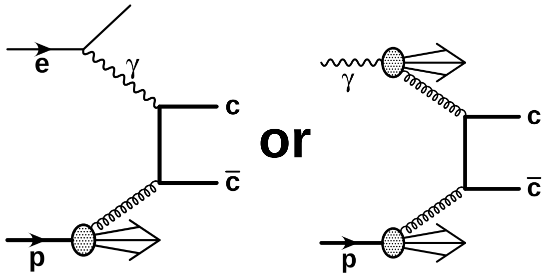
- **Significant resolved contribution ($\sim$ 40%) like in previous measurements**
- **MCs: good description of shape but off in normalization large charm content in the photon required**
- **CASCADE different at high x_γ^{obs} cross section too high**
- **NLO below data at low x_γ^{obs} (not shown)**

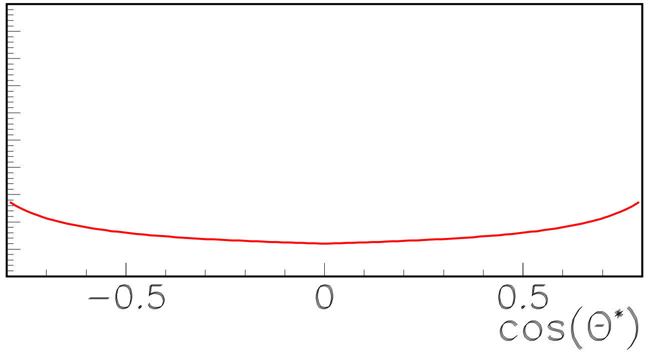
Charm: Dijet Angular Distributions (LO Picture)

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

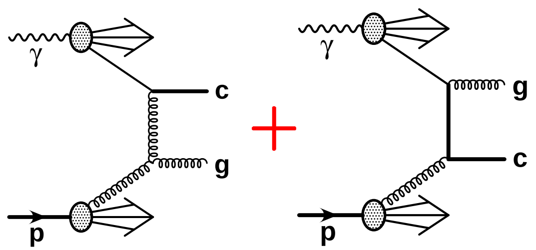
- go to the jet-jet rest frame
- define D^*-jet direction as positive z-axis
- look at the angle Θ^* of the proton w.r.t. the D^*-jet

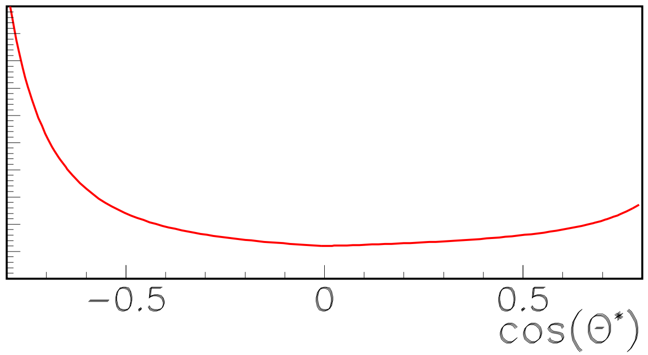






symmetric in $\cos\Theta^*$



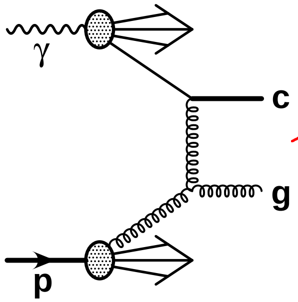


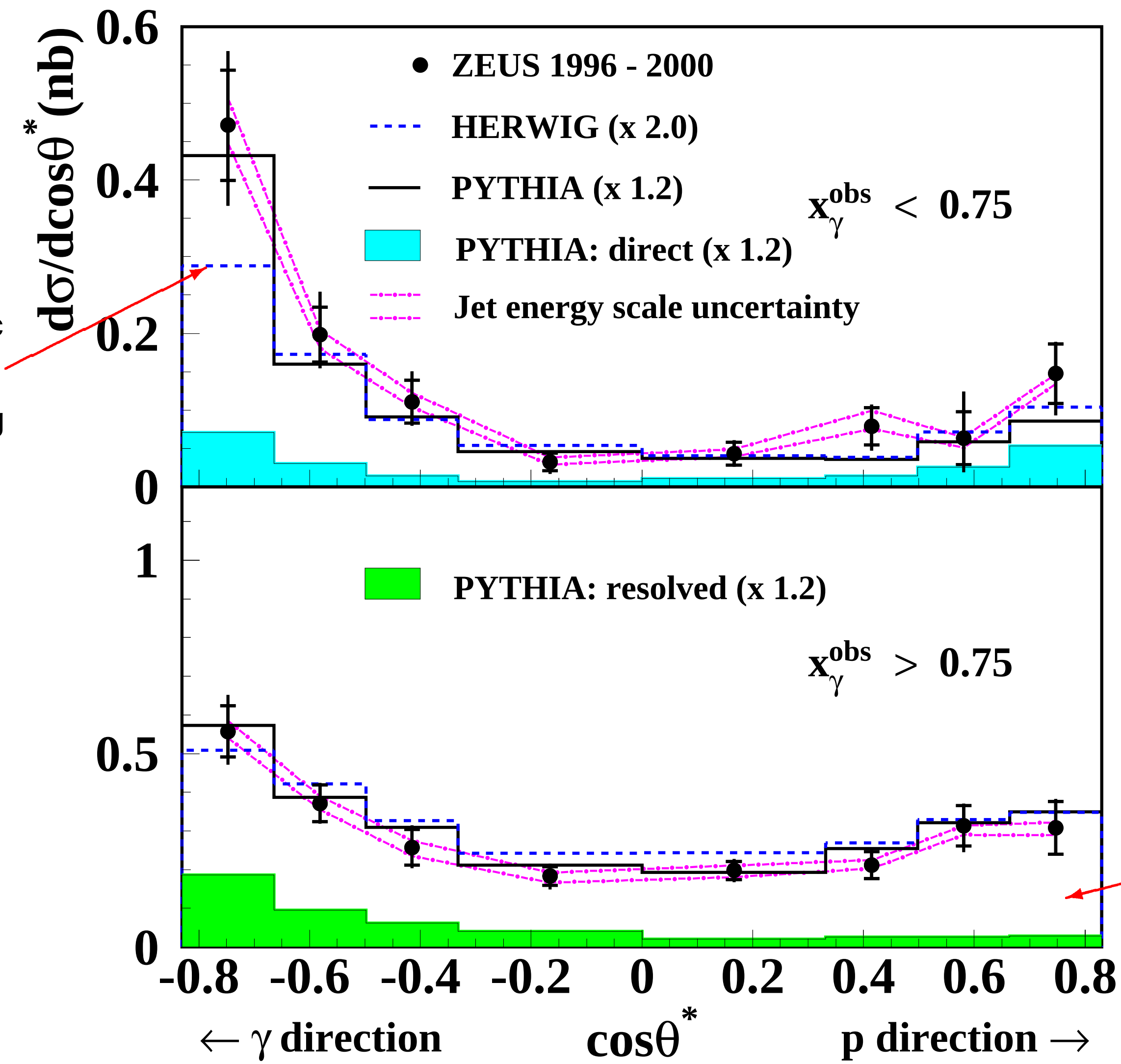
strongly backward peaking

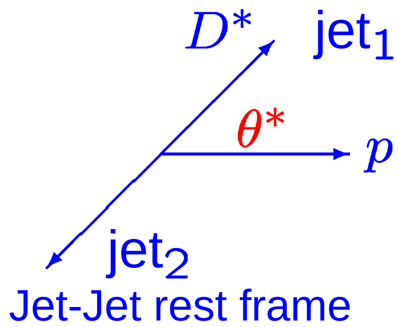
☛ Possible to prove that charm in the photon dominates the resolved process of charm production

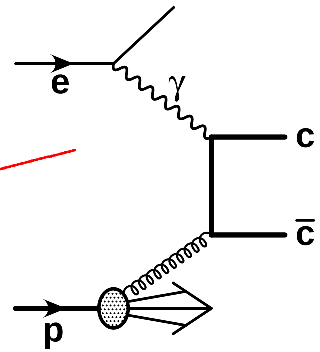
Dijet Angular Distributions (LO Picture)

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





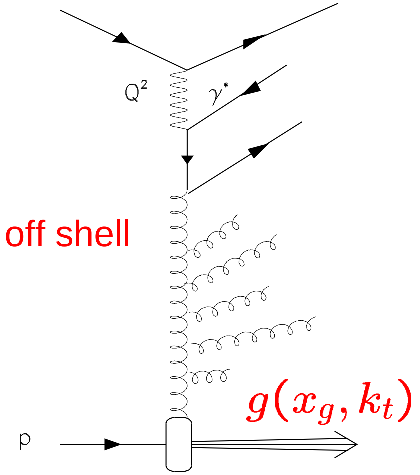


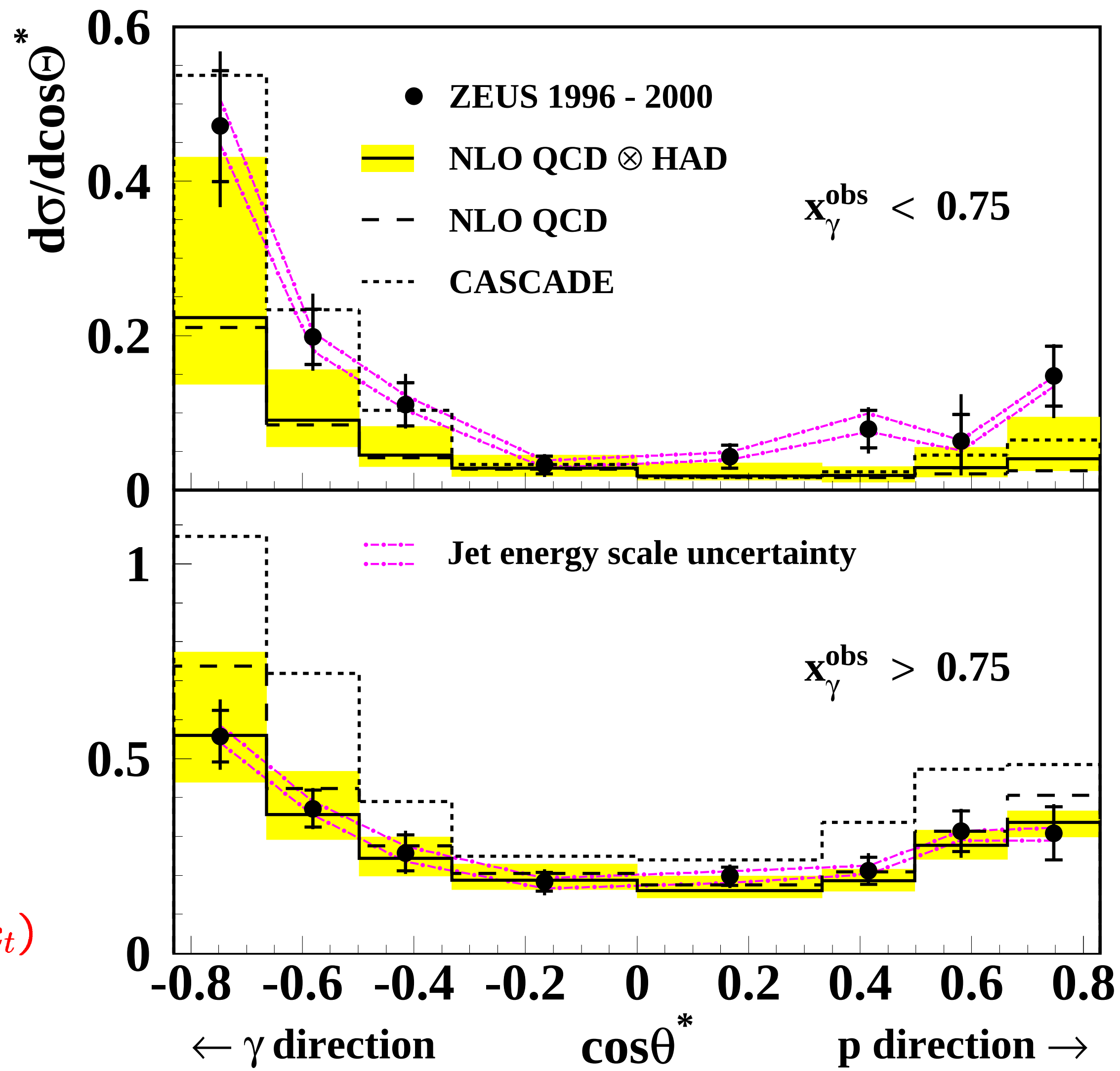


LO Picture:
- Strong rise in $d\sigma/d\cos\theta^*$ towards γ direction for $x_\gamma^{\mathrm{obs}} < 0.75$
- Clear evidence for charm as an active flavour in the photon

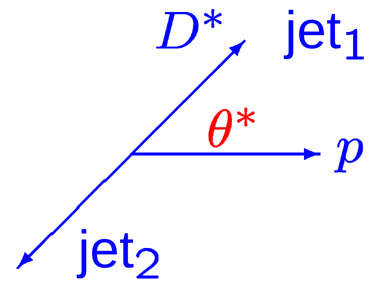
Charm: Dijet Angular Distributions (Evolution Scheme)

CCFM
(angular ordering)



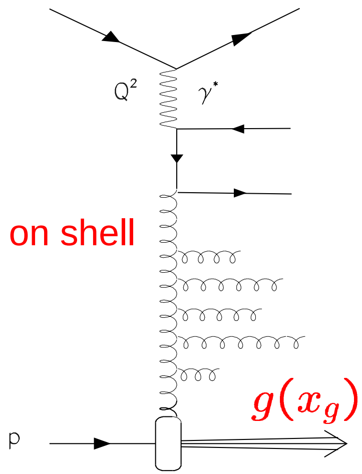


$\theta^* = \measuredangle(p, D^*\text{-Jet})$



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*

* Sevaral 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	$2 \cdot \mu$	$(1/2 \ldots 2) \cdot 2 \cdot \mu$	μ
μ_r	$(1/4 \ldots 1) \cdot \mu_f$	$(1/2 \ldots 2) \cdot 2 \cdot \mu$	$(1/2 \ldots 2) \cdot \mu_f$

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