Ringberg, June 2001

Ignacio Redondo

adrid

Open Charm Production

at HERA

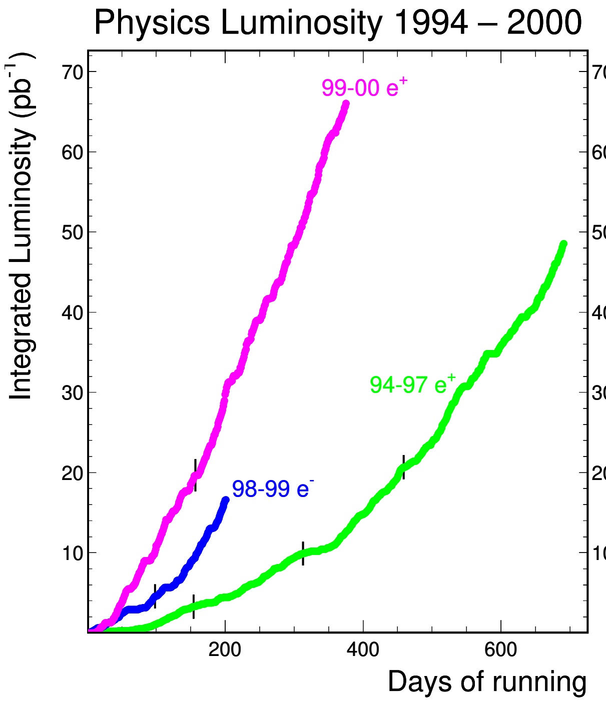
OUTLINE

- Introduction.
- Measurements of c-final state cross sections.
  - Photoproduction (D_s, D^* tagged and untagged)
  - DIS (D^*, $\bar{c} \rightarrow e^-$ decays, D^0)

$\rightarrow$ Comparison to NLO pQCD.

- $F_2^{c\bar{c}}$: extraction and discussion.
- Summary and personal outlook for HERA II.

Data Samples



- 94+97 ($\sqrt{s}$=300 GeV, e^+)

$\mathcal{L}_{\mathbf{ZEUS,H1}} \sim$ 48, 38 pb^{-1}

- 98+99e ($\sqrt{s}$=318 GeV, e^-)

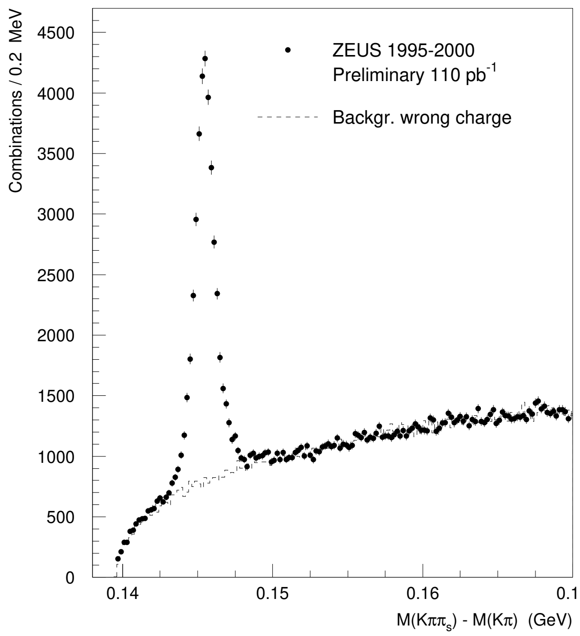
$\mathcal{L}_{\mathbf{ZEUS,H1}} \sim$ 17, 14 pb^{-1}

- 99p+00 ($\sqrt{s}$=318 GeV, e^+)

$\mathcal{L}_{\mathbf{ZEUS,H1}} \sim$ 66, 68 pb^{-1}

$\boxed{\gtrsim \text{ 100 pb}^{-1}\text{/experiment.}}$

$\Rightarrow$ **Big charm samples**



- $\sim$ 27000 reconstructed $D^{*\pm}$

$D^{*+} \rightarrow D^0 \pi_s^+$ +c.c.

$\quad \hookrightarrow K^- \pi^+$

BR=0.0262$\pm$0.0010

$\quad \hookrightarrow K^- \pi^+ \pi^+ \pi^-$

BR=0.051$\pm$0.003

- D_s, D^0
- e^- from semileptonic c decays,

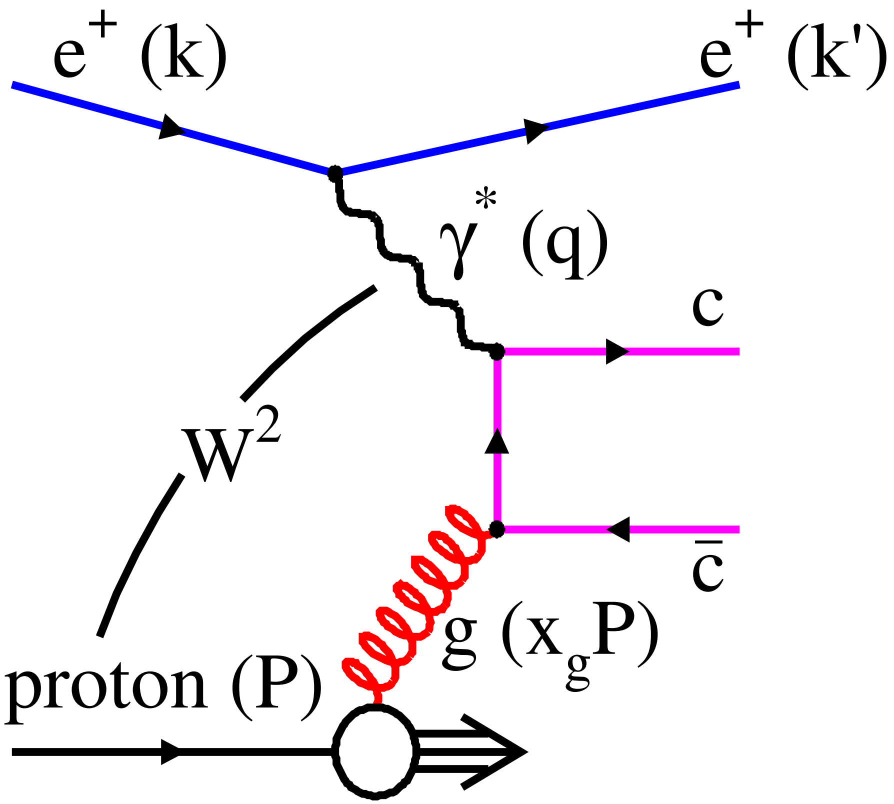
$f(\bar{c} \rightarrow e^-) = \mathbf{0.095 \pm 0.009}$

Spectroscopy of D mesons: "Production of P-Wave Charm Mesons at HERA" (Contributed Paper to ICHEP2000)

Kinematics

Charm tagging implies experimental cuts $\Rightarrow$

Measurements exclusive in c quark phase space



- $p_T, \eta = -log(tan(\theta/2))$
- rapidity $= \frac{1}{2} ln \frac{E+P_z}{E-P_z}$ (=η for massless particles.)
- $x(D^*) = \frac{2p^{\gamma^* p}(D^*)}{W}$ distinguish BGF and QPM. Not invariant.
- $z_D(D^*) = P \cdot p_{D^*} / P \cdot q = (E-P_z)^{D^*}/(E-P_z)^{\gamma^*}$.

QPM: $0 \approx M^2_{hard} = (x_q P + q)^2 = x_q^2 m_p^2 + 2x_q(q \cdot P) - Q^2 \Rightarrow x_q = x_{bj}$

if $M^2_{hard}, m_p^2 << Q^2, 2x_g(q \cdot P)$

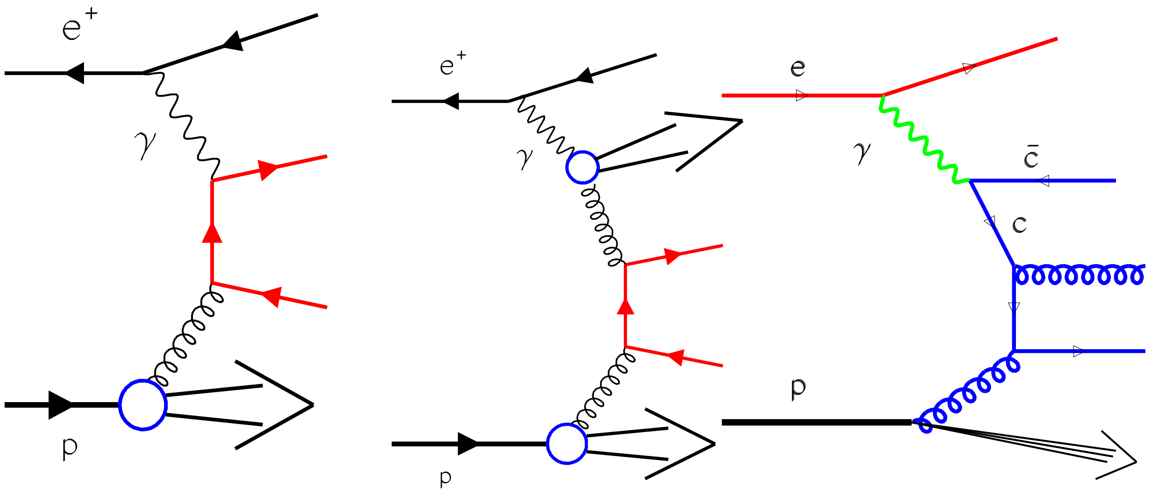
BGF: If M^2_{hard} is not negligible $x_g = x_{bj}(M^2_{hard} + Q^2)/Q^2 \Rightarrow x_g > x_{bj}$.

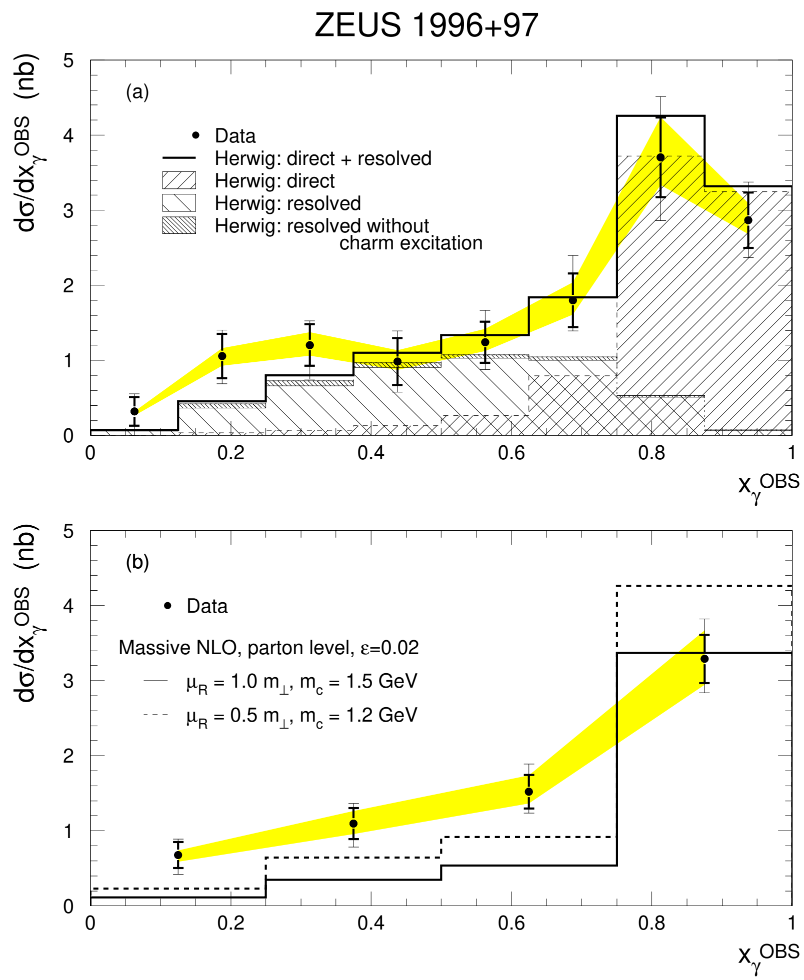
$$\sigma^{c\bar{c}}(x_{bj}, Q^2) \propto e_c^2 \alpha_s(\mu_r) \int_{x_g^{min}}^1 \frac{dx_g}{x_g} f_g(x_g, \mu_f) \hat{\sigma}(x_g, \mu_f, \mu_r);\; x_g^{min} = x_{bj} \frac{4m_c{}^2 + Q^2}{Q^2}$$

Sensitivity to the gluon in the proton

Open Charm Production in photoproduction

- γ-p interactions have a hadronic component (resolved). $\longrightarrow$ The photonic pdf's are required as input for NLO calculations.
- What is the production mechanism?
- BGF + charm in the photon $\longrightarrow$ sensitivity to the g.





- D^* dijets $\qquad x_\gamma^{OBS} = \frac{\Sigma_{jets} E_T e^{-\eta}}{2yE_e}$
- $\sim$ 40% resolved $\sim$ 60% direct in HERWIG
- resolved contribution dominated by c excitation

Open Charm Production in Photoproduction II

- NLO Fixed order ("massive") calculations are available, FMNR[a] (differential in the final state partons) $\longrightarrow$
  charm is produced from u,d,s,g; no c is present in the pdf.

[a] Frixione et al., Nucl. Phys B454 (1995) 3

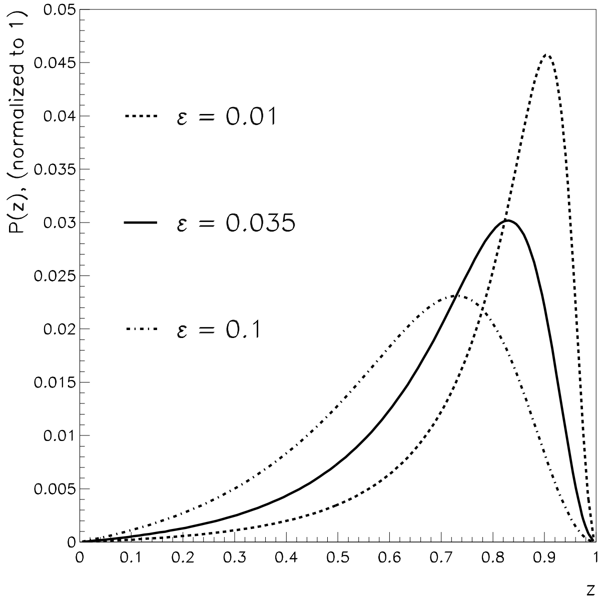
- NLO resummed ("massless") calculations, [a] (differential in the final state partons) $\longrightarrow$
  charm is present in the pdf's. Resum large p_T/m_c logs.

[a] Kniehl et al., Binnewies et al., Cacciari et al.

$$\boldsymbol{F_2},\ \boldsymbol{F_2^{\gamma}},\ldots\text{(data)} \xrightarrow{\text{DGLAPfit}} \boldsymbol{g, q, \bar{q}} \text{ in } \boldsymbol{p} \text{ and } \gamma \xrightarrow{\text{Model}} \boldsymbol{\sigma^{c\bar{c}}} \text{ (pred)} \Leftrightarrow \boldsymbol{\sigma^{c\bar{c}}} \text{ data}$$

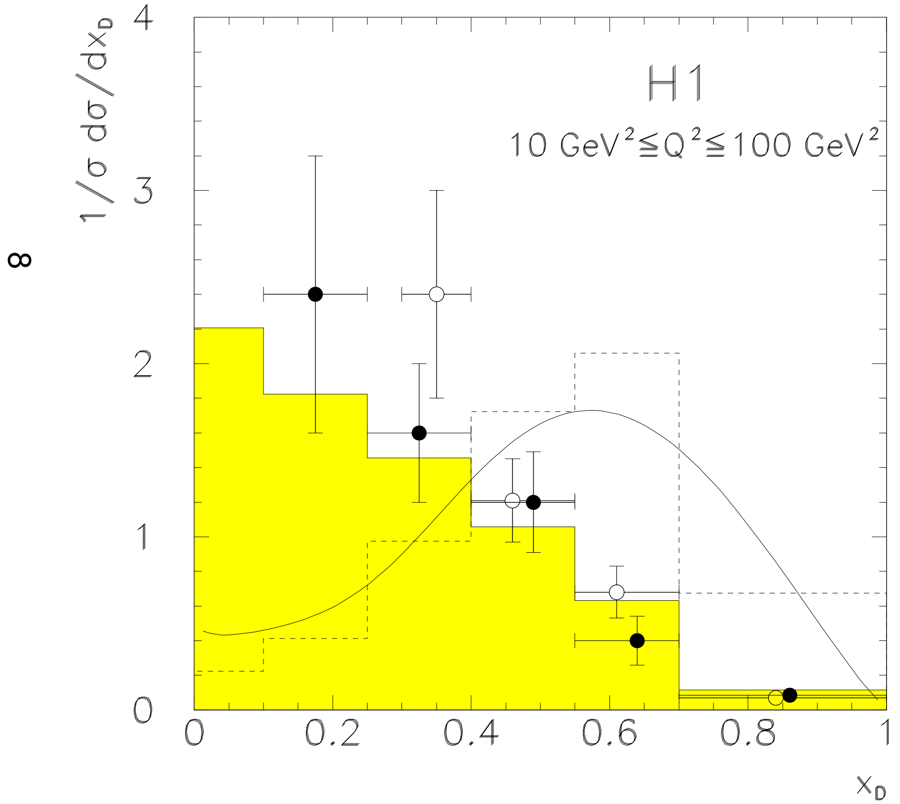
Test of QCD and of the universality of the pdf of the proton and the γ.

- New iteration on γ pdf badly needed. $\Leftrightarrow$ What is the production model?
- pQCD can not predict the fragmentation $c \longrightarrow$ hadron. $\Rightarrow$
  - Use the e^+e^- hadron fractions,
    f($c \longrightarrow D^{*+}$)=0.235$\pm$0.007$\pm$0.007 (hep-ex/9912064),
  - ... and fragmentation functions (Peterson):
    $$P(z) \propto z^{-1}[1 - 1/z - \epsilon/(1-z)]^{-2}$$
    ϵ=0.035, fit to e^+e^- hep-ph/9903541
    Note that P(z) is not lorentz invariant.



Open Charm Production in DIS

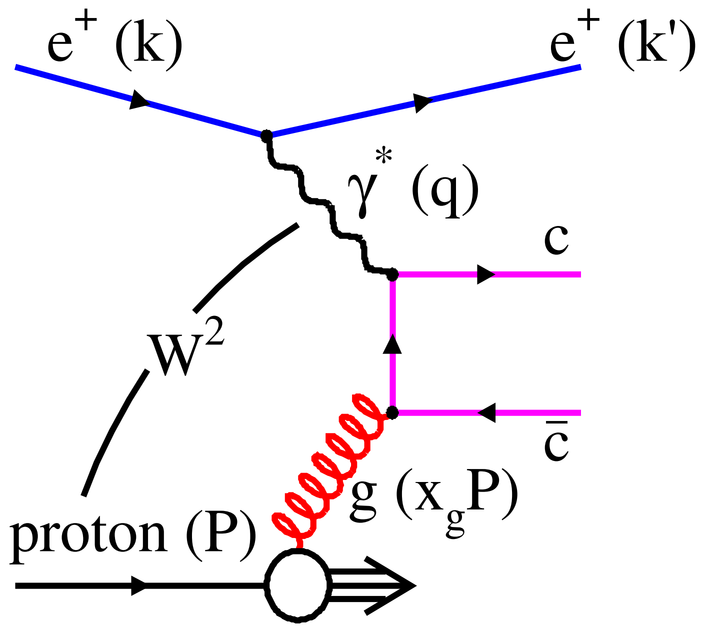
- HERA ($\sqrt{s} \sim 300$ GeV) and fixed target data ($\sqrt{s} \sim 30$ GeV) show that open charm electroproduction is dominated by BGF.



$$x_D = 2p^*_D/W$$

Sea Quark$< 5\%$ (95% C.L.)

- $\sigma^{c\bar{c}} \sim \alpha_s g\,;\, x_{bj} < x_g$

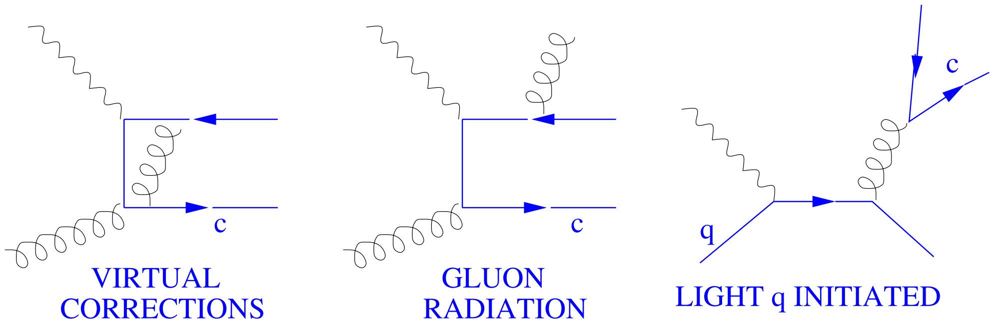


$$\frac{d^2\sigma^{c\bar{c}}}{dx_{bj}dQ^2} = \frac{2\pi\alpha^2}{x_{bj}Q^4}[1+(1-y)^2]F_2^{c\bar{c}}$$

- $F_2^{c\bar{c}}{}_{HERA} >> F_2^{c\bar{c}}{}_{\text{fixed tarjet}}$
- $F_2^{c\bar{c}}/F_2 \sim 25\%$ at HERA

Open Charm Production in DIS II

- The presence of high scales ($\sqrt{Q^2}$ and $m_c >> \Lambda_{QCD}$) allows to perform precise pQCD calculations.



NLO Three Flavour Number Scheme (TFNS) are available, HVQDIS[a] (differential in the final state partons) $\longrightarrow$
charm is produced from u,d,s,g; no c is present in the proton.

[a] B.W. Harris and J. Smith, Phys. Rev. D57, 2806 (1998)

$$\boxed{F_2\text{(data)} \xrightarrow{\text{DGLAPfit}} g, q, \bar{q} \xrightarrow{\text{HVQDIS}} \sigma^{c\bar{c}}\text{ (pred)} \Leftrightarrow \sigma^{c\bar{c}}\text{ data}}$$

Test of QCD and of the universality of the parton distributions of the proton.

Caveats:

- QCD cannot predict the fragmentation $c \longrightarrow$ hadron. $\Rightarrow$
  Use the e^+e^- hadron fractions and fragmentation functions (Peterson).

- Experiments can only measure $\sigma^{c\bar{c}}$ in restricted regions on the c-hadron variables $\Rightarrow$
  Theory input is needed to extrapolate to $F_2^{c\bar{c}}$.

Open Charm Photoproduction (Untagged), ZEUS $\mathcal{L} \sim 38$ pb^{-1}

Kinematic range (e not in the detector):

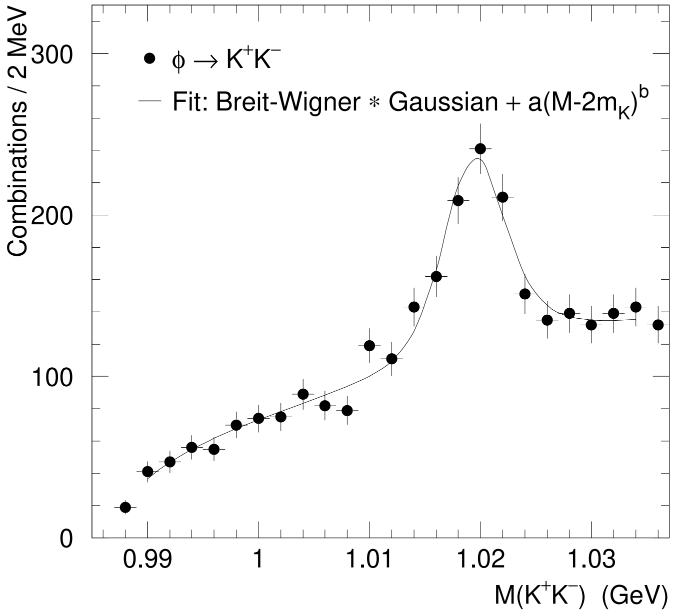
$$130 < W < 280\, GeV \quad Q^2 < 1\, GeV^2;\ (\mathrm{Q}^2_{\mathbf{median}} \approx 3 \cdot 10^{-4})$$

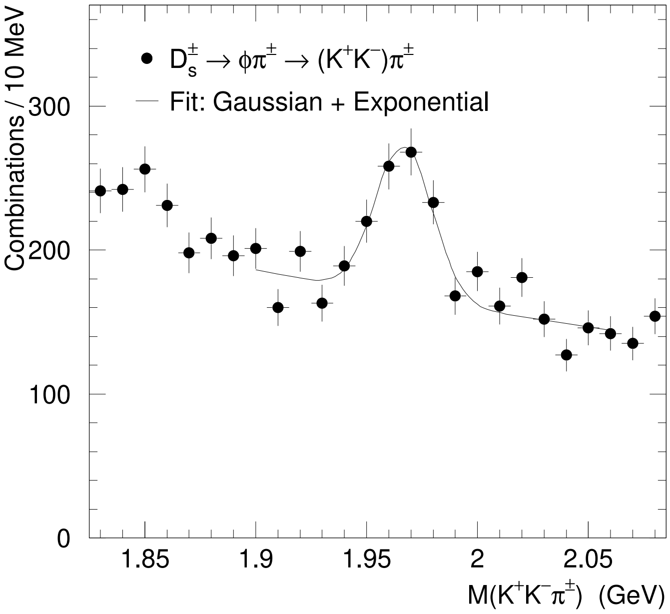
$D^* \rightarrow K\pi\pi$: (EPJ C6 (1999) 67-83)

$$2,3 < p_T(D^*) < 12\, GeV \qquad |\, \eta(D^*)\, | < 1.5$$

$$D_s^+ \rightarrow \phi\pi^+ \rightarrow (K^+K^-)\pi^+ (+c.c.)$$

$$3 < p_T(D_s) < 12\, GeV \qquad |\, \eta(D_s)\, | < 1.5$$





$339 \pm 48\ D_s$ mesons

$$\frac{\sigma(D_s)}{\sigma(D^*)} = 0.41 \pm 0.07(stat.)^{+0.03}_{-0.05}(syst.) \pm 0.10(br.)$$

$\Rightarrow \gamma_s$ (LUND model) $= 0.27 \pm 0.05 \pm 0.07(br.)$

..in agreement with e^+e^-.

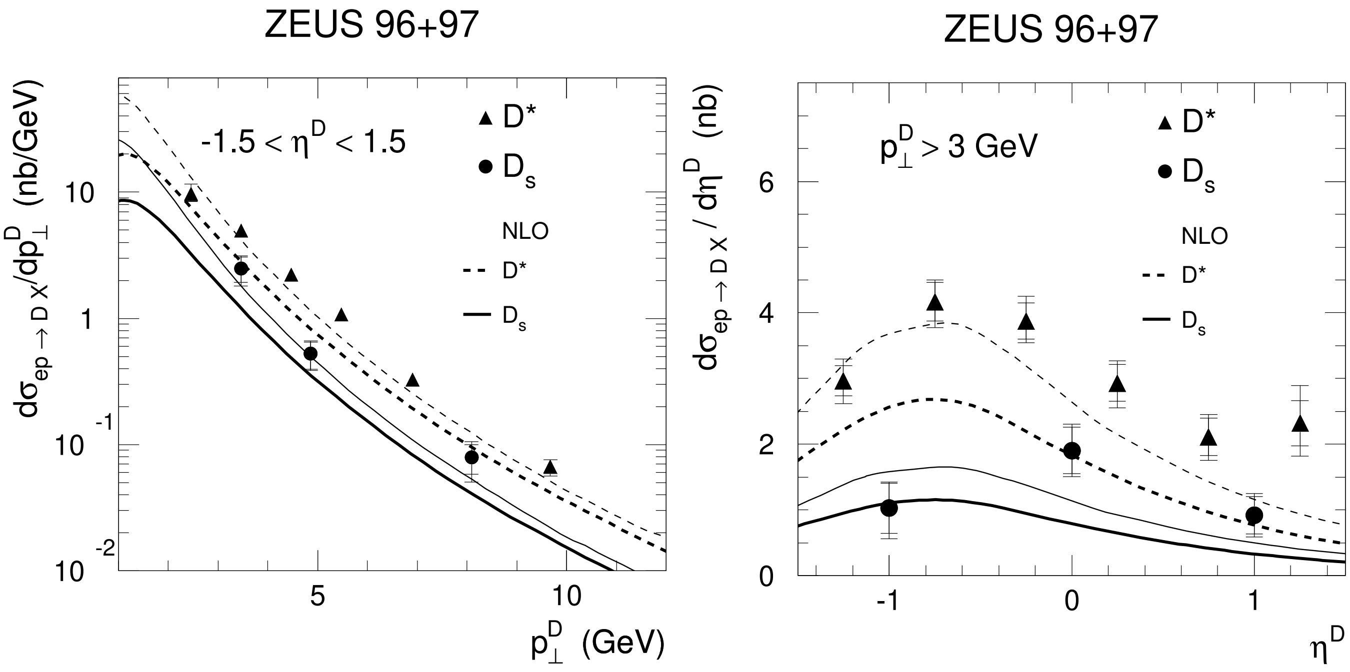
Supports universality of c fragmentation.

Open Charm Photoproduction, (Comparison with pQCD) ZEUS

NLO FMNR (3 flavour DGLAP) Peterson fragmentation ϵ=0.035

Normalization uncertainty: $\Delta(f(c \to D^*)) \sim$ 3%,
$\Delta(f(c \to D_s)) \sim$ 9%

pdf's: MRSG (p,$\alpha_s = 0.114$), GRV-G H0 (γ, $\alpha_s = 0.111$)



To ilustrate uncertainty:

Thin:

$$\mu_R = 0.5\sqrt{m_c^2 + p_T^2}\ ;\ m_c = 1.2\,GeV\ ;\ \mu_F = 4\mu_R$$

Bold: $\mu_R = \sqrt{m_c^2 + p_T^2}\ ;\ m_c = 1.5\,GeV\ ;\ \mu_F = 2\mu_R$

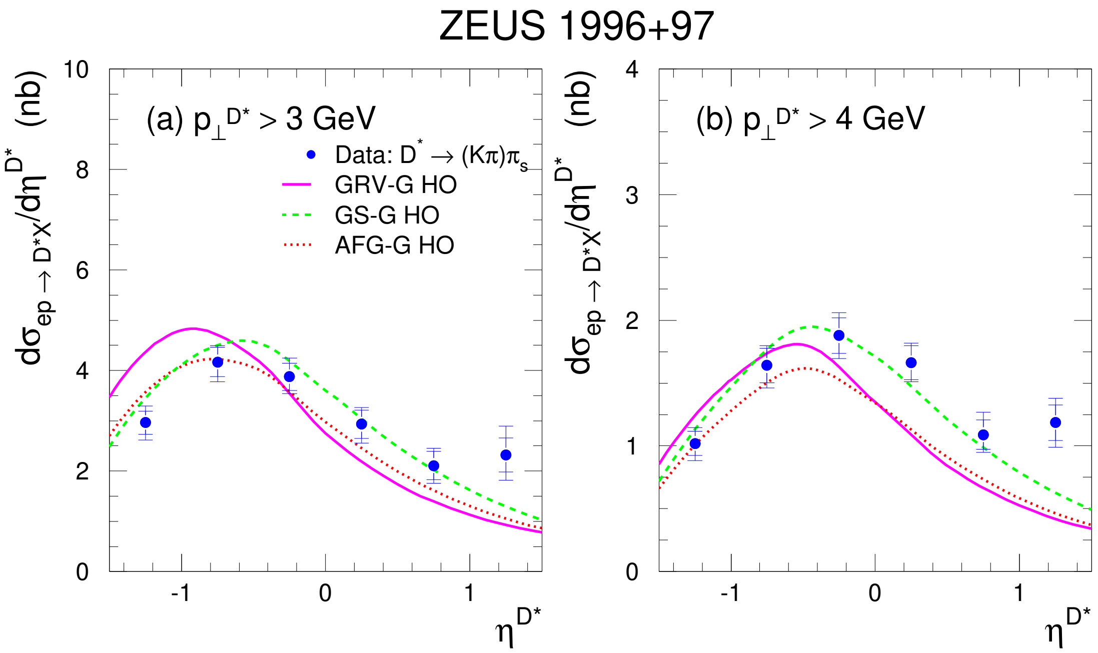
D_s supports the more accurate D^* conclusions. Namely:

- **Normalization of the theory is too low**
- **η distribution not well described**

Open Charm Photoproduction (Comparison with pQCD), ZEUS

"Massless" predictions: pdf CTEQ4M, $\alpha_s = 0.116$ (p) $\epsilon = 0.1$

$$\mu_R = \sqrt{m_c^2 + p_T^2}\ ;\ m_c = 1.5\,GeV\ ;\ \mu_F = 2\mu_R$$



Better agreement with massless prediction

Not expected. Frixione DIS01: Resummation small for $p_T(D^*) < 10$ GeV

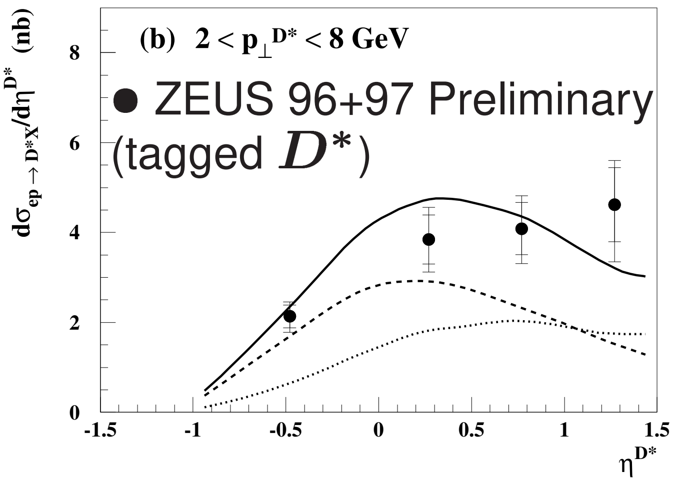
η is sensitive to the pdf (γ)

Predictions with GS-G HO (c=u) are closest to data.

44 meter tagger, $\mathcal{L} \sim 38$ pb^{-1}

$80 < W < 120$ GeV,

$Q^2 < 0.015$ GeV^2



Same picture regarding massive-massless

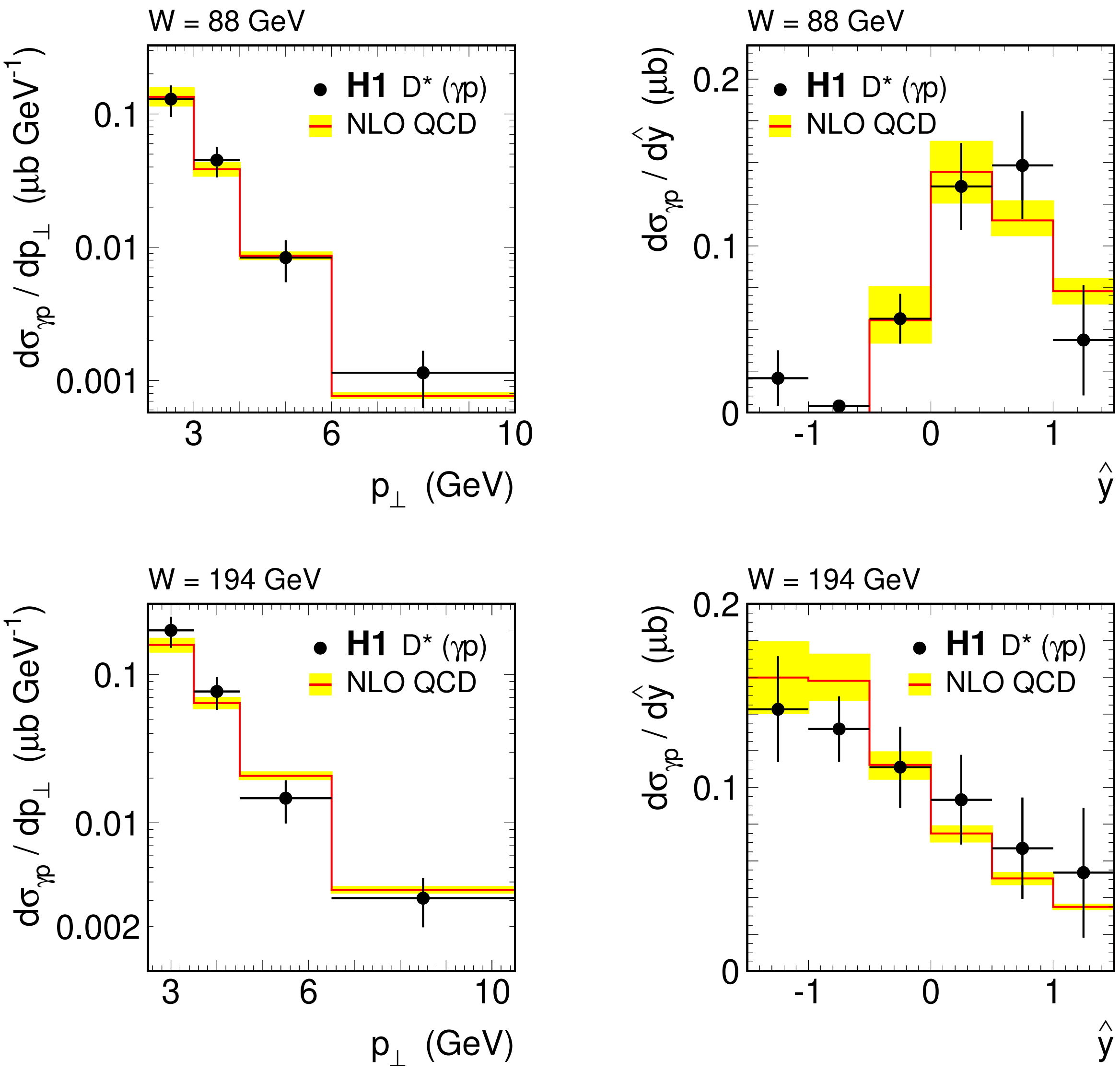
BKL (hep-ph/9905555) tree-level calculation fit the untagged ZEUS D^* data and reproduce the low W data.

Open charm Photoproduction, H1 (tagged), $\mathcal{L} \sim 10\ pb^{-1}$

PHP selected using the 44 (33) m taggers

$Q^2 < 0.009(0.01)GeV^2$; $< W >= 88(194)\ GeV$

$p_T(D^*) > 2(2.5)\ GeV$; $|\,\mathrm{rapidity}(D^*)\,|$ <1.5



NLO FMNR $\epsilon = 0.035$

$\mu_R = \sqrt{m_c^2 + p_T^2}$; $m_c = 1.3 - 1.7\,GeV$; $\mu_F = 2\mu_R$

↑ Old value of $f(c \to D^*)$, 15% too high

↑ pdf (p) MRST1, α_s=0.1175, (γ) GRV-HO

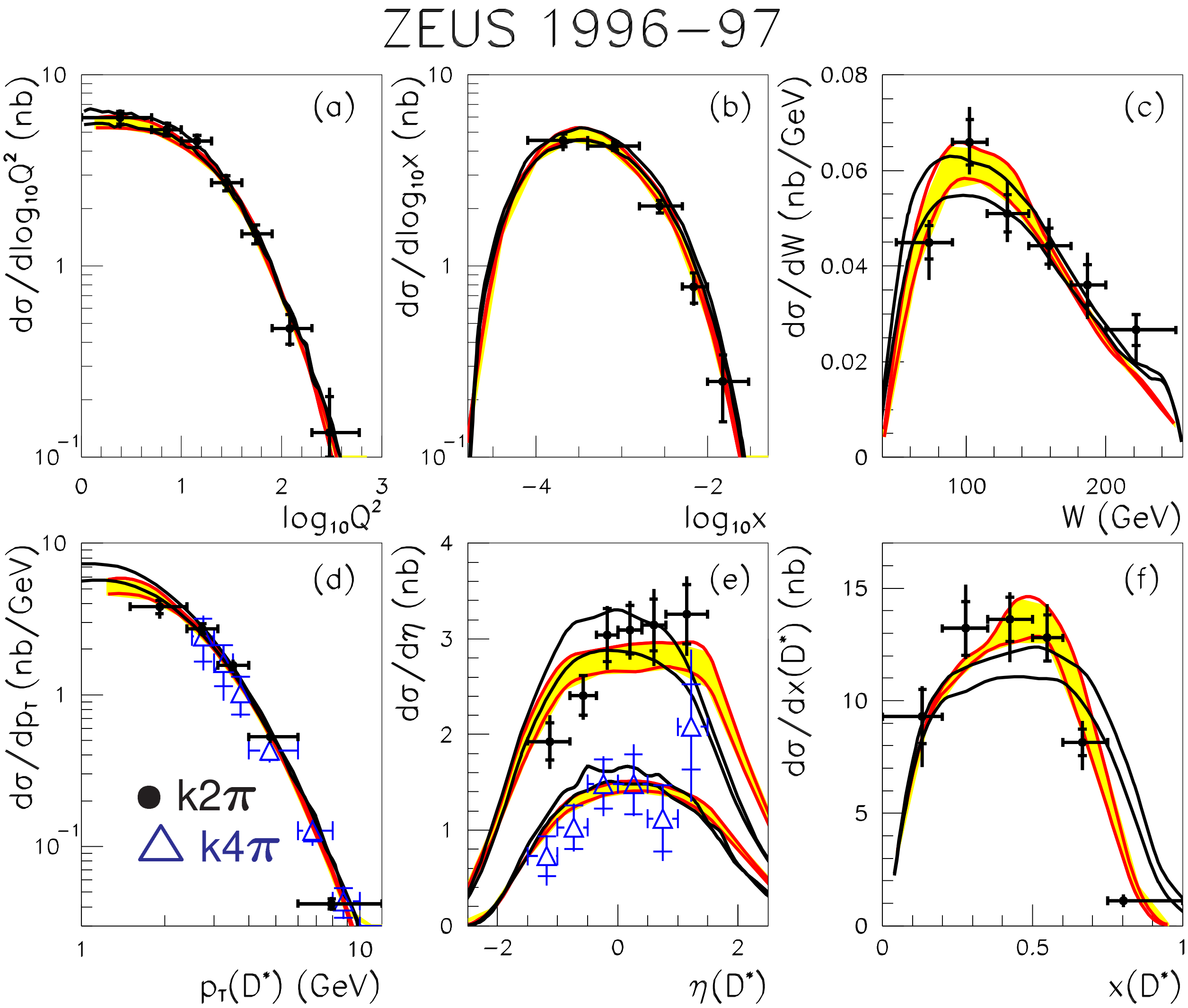
H1 finds reasonable agreement ⟶ Used to extract $x_g g(x_g)$

D^* in DIS, ZEUS $\mathcal{L} \sim 37pb^{-1}$

$$1 < Q^2 < 600\,GeV^2 \quad 0.02 < y < 0.7$$

$$1.5(2.5) < p_T(D^*) < 15\,GeV \quad |\,\eta(D^*)\,| < 1.5$$

Two decays, $D^* \rightarrow K2\pi(K4\pi)$, in agreement.



Open band is NLO HVQDIS , pdf ZEUS NLO fit, α_s=0.119,

$\downarrow$ Old $f(c \rightarrow D^{*+})$ 9 % too low, $\epsilon = 0.035$, lab

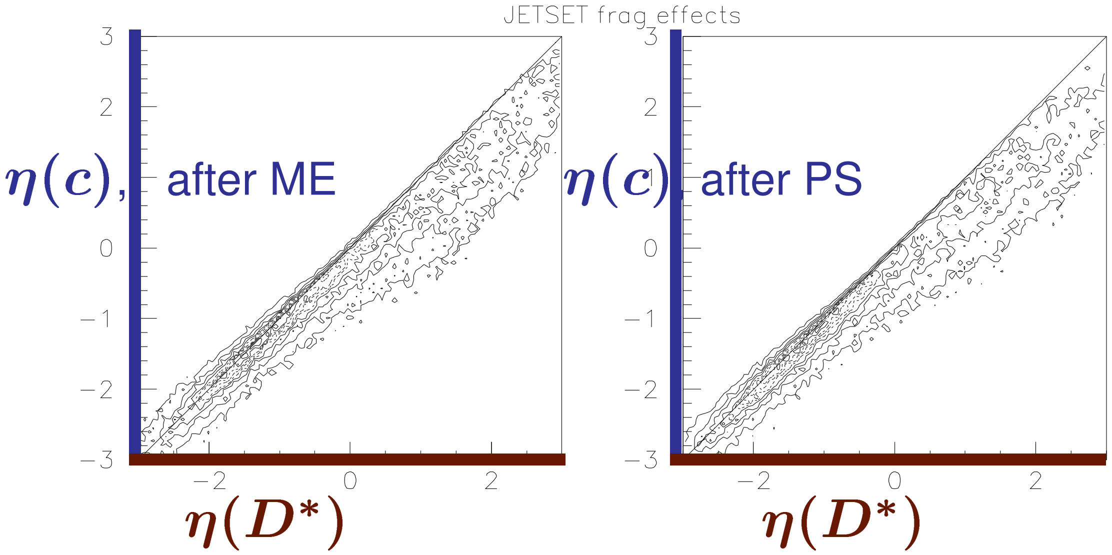
$$\mu_R = \mu_F = \sqrt{4m_c^2 + Q^2}\,;\ m_c = 1.3 - 1.5\,GeV$$

- Good agreement with HVQDIS in Q^2, x_{bj} and W.
- Shifted wrt the data in $\eta(D^*)$, $x(D^*)$.

Yellow band is obtained folding jetset and NLO

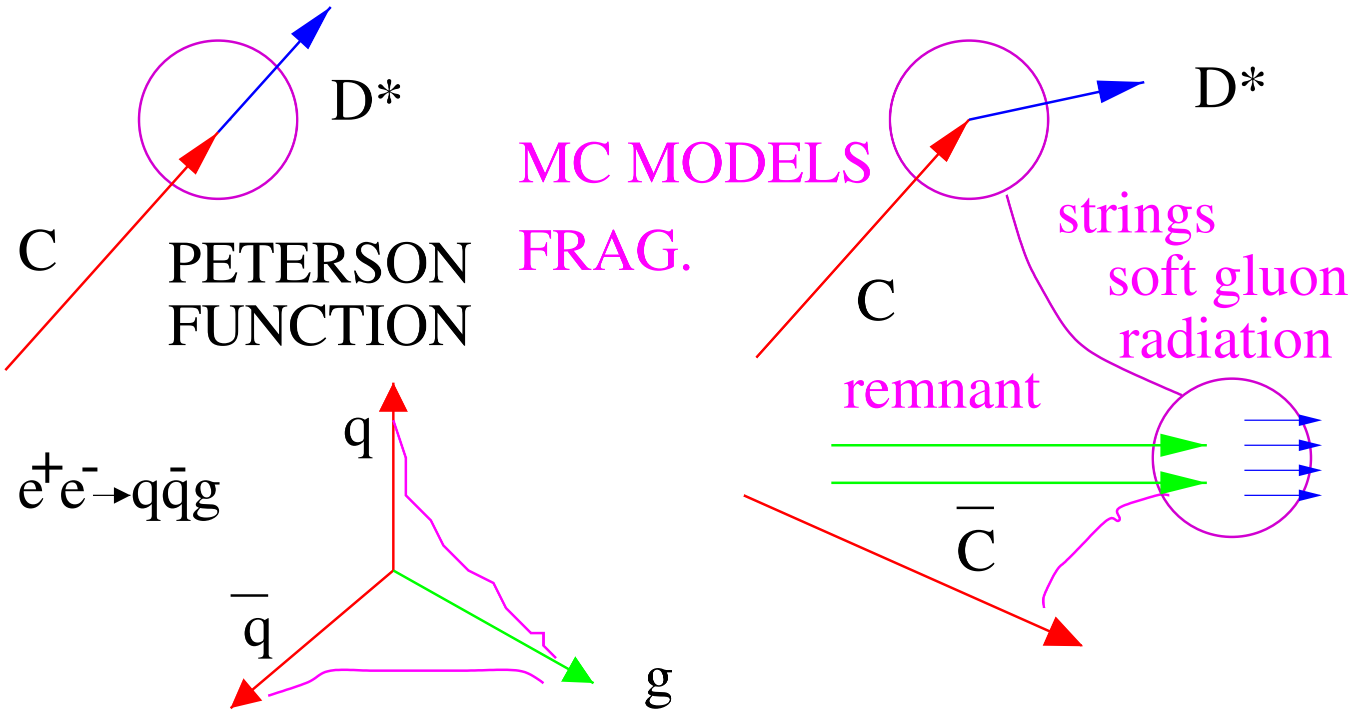
Fragmentation interlude, non perturbative effects

The NLO calculation is folded with JETSET by means of reweighting the $pt(c)$,$\eta(c)$ 2d distribution of a LO MC after ME and letting JETSET hadronize $\longrightarrow$ Yellow band.



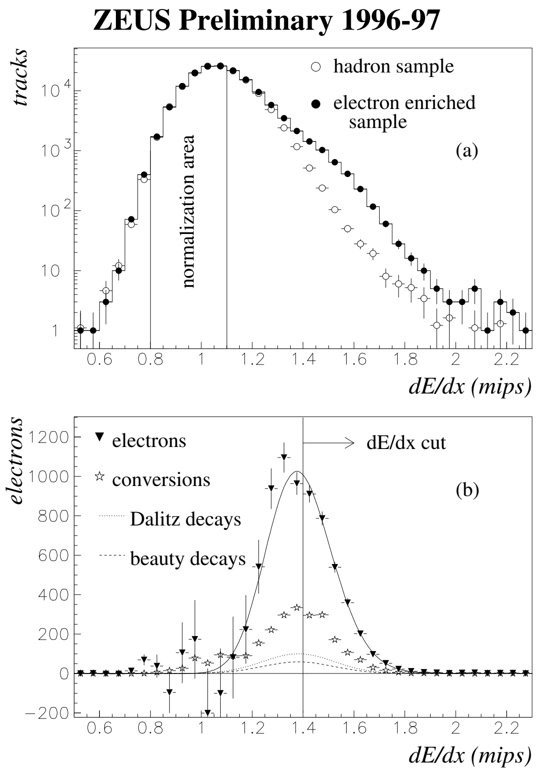
Similar picture with HERWIG or ARIADNE.

Shift into the forward direction due to the string model



The colour configuration is similar to $e^+e^- \longrightarrow q\bar{q}g$, string effect, the remnant acting as a colour octect.

Semileptonic charm in DIS, ZEUS $\mathcal{L} \sim 34$ pb^{-1}



Use dE/dx of the tracks in the CTD to separate the e^- signal from the hadron background.

$$1.2 < p_e < 5\, GeV$$

$$|\, \eta_e \,| < 1.1$$

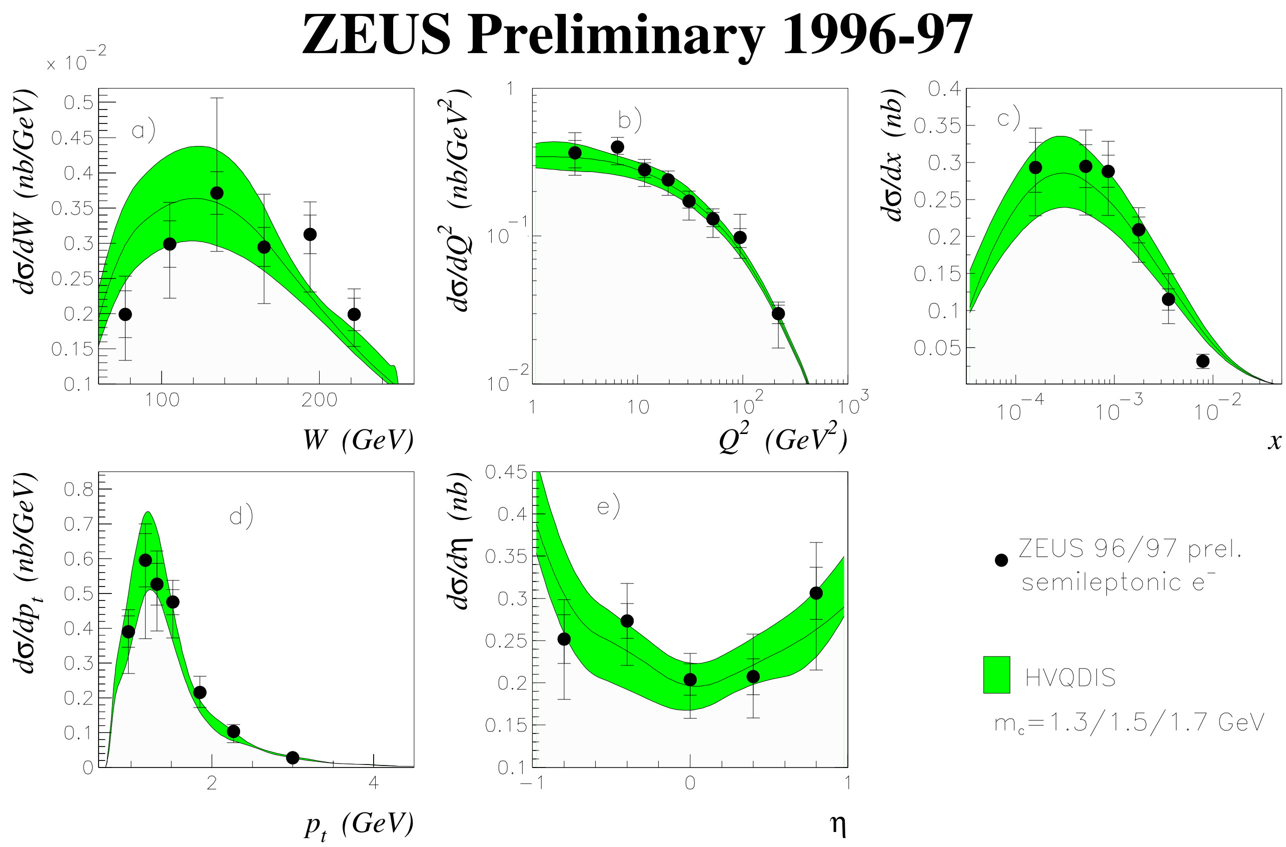
$$1 < Q^2 < 1000\, GeV^2$$

$$0.03 < y < 0.7$$

Complementarity with D^*analysis:

sl e^- probe harder $c \Rightarrow \uparrow p_T$ enriched

$\Rightarrow$ cover smaller phase space



In agreement with...

NLO HVQDIS pdf GRV94 H0, $\alpha_s = 0.111$, $\epsilon = 0.035$

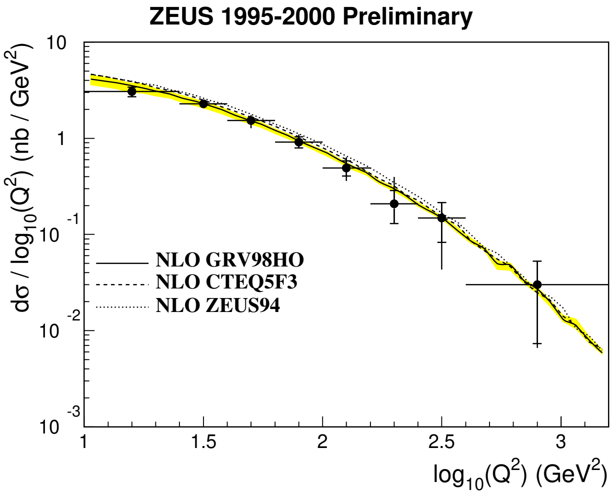
$$\mu_R = \mu_F = \sqrt{4m_c^2 + Q^2}\,;\; m_c = 1.3 - 1.7\, GeV$$

D^* in DIS at high Q^2, ZEUS $\mathcal{L} \sim 83\ pb^{-1}$ 38 at $\sqrt{s} = 318$

$$10 < Q^2 < 1000\ GeV^2\ ;\ 0.04 < y < 0.95$$

$$1.5 < p_T(D^*) < 15\ GeV\ ;\ \mid \eta(D^*) \mid < 1.5$$

$$\sigma(e^+ p \to e^+ D^{*\pm} X) = 2.33 \pm 0.12(\text{stat.})^{+0.11}_{-0.07}(\text{syst.})\ \text{nb}$$



pdf	Λ^4_{QCD} MeV	σ(nb) m_c 1.3-1.6
GRV98	257	2.71-2.27
CTEQF53	326	2.95-2.48
ZEUS NLO	404	3.2-2.63

Reasonable agreement with HVQDIS

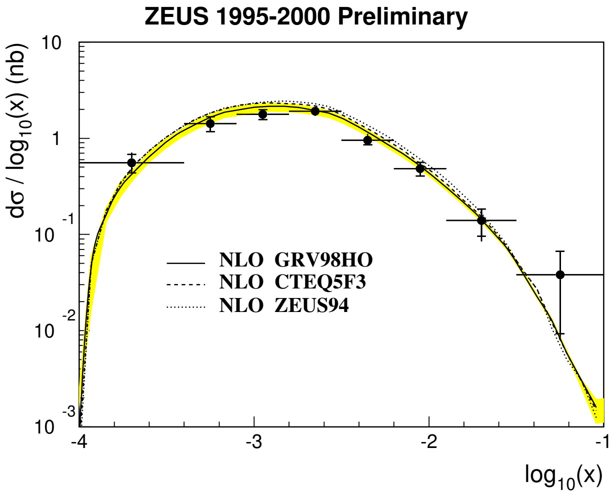
No sensitivity to IC, yet.

VFNS $\longrightarrow$ see W.Tung talk

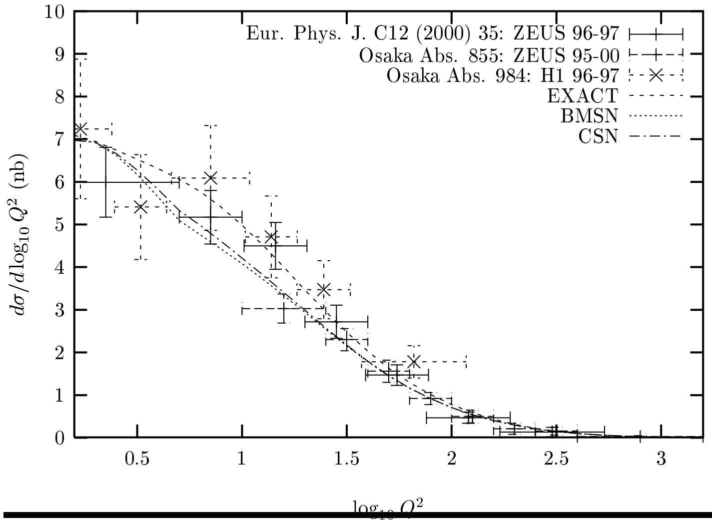
Chuvakin, Harris, Smith:

Can tell FFNS and VFNS's till

$x_{bj} > 0.1$ and high Q^2.



arXiv:hep-ph/0010350 v2 7 Nov 2000



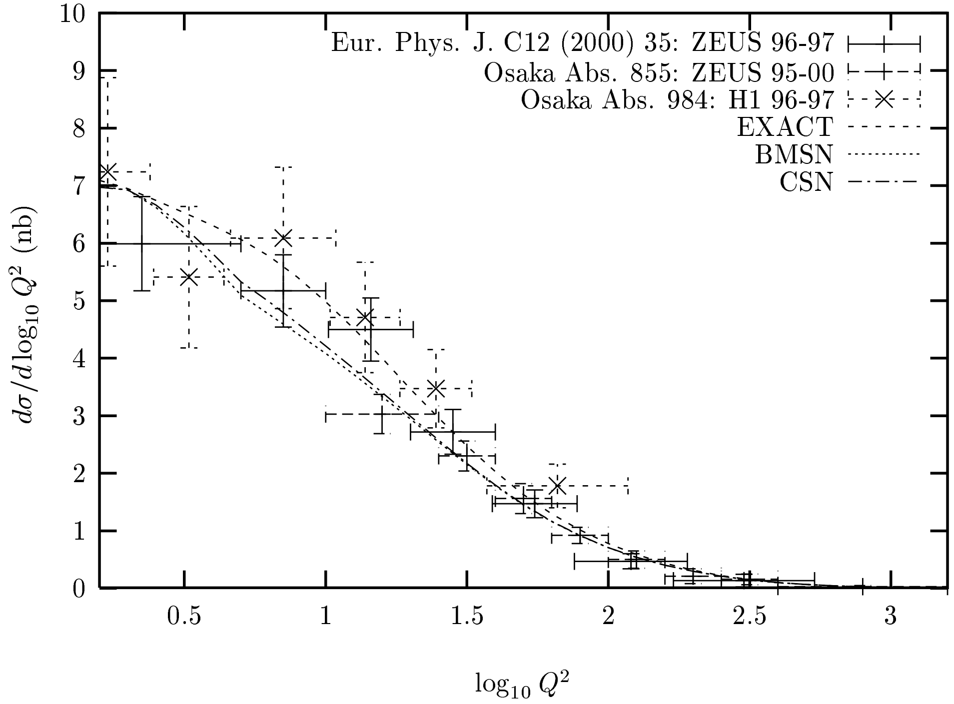
Fragmentation and/or mass uncertainties are of the same order as the $Q^2 \sim 10\ GeV^2$ difference.

D^* in DIS, H1 $\mathcal{L} \sim 18\ pb^{-1}$ (Comparison with ZEUS)

$$\sigma_{KIN}(e^+p \to e^+D^{*\pm}X) = 8.50 \pm 0.42(\text{stat.})^{+1.02}_{-0.76}(\text{syst.}) \pm 0.65(\text{mod.})\ \text{nb}$$

1<Q^2<100 GeV^2 ; 0.05<y<0.7

1.5 GeV<$p_T(D^*)$; $|\eta(D^*)|$<1.5



$$\sigma_{KIN}(e^+p \to e^+D^{*\pm}X) =$$
$$8.31 \pm 0.31(\text{stat.})^{+0.3}_{-0.5}(\text{syst.})\ \text{nb}$$

1<Q^2<600 GeV^2 ; 0.02<y<0.7

1.5 <$p_T(D^*)$<15 GeV ; $|\eta(D^*)|$<1.5

$$R_{KIN} = \frac{\sigma^{HVQDIS}_{ZEUSKIN}}{\sigma^{HVQDIS}_{H1KIN}} = 1.11 \Rightarrow$$

$$\frac{R^{DATA}_{KIN}}{R^{HVQDIS}_{KIN}} = 0.88^{+0.12}_{-0.15}$$, compatible with 1

H1 and ZEUS data agree within errors

D^* in DIS, H1 $\mathcal{L} \sim 18\ pb^{-1}$

$$\sigma_{KIN} = 8.50 \pm 0.42(\text{stat.})^{+1.02}_{-0.76}(\text{syst.}) \pm 0.65(\text{mod.})\ \text{nb}$$

1<Q^2<100 GeV^2 ; 0.05<y<0.7

1.5 GeV<$p_T(D^*)$; | $\eta(D^*)$ | <1.5

HVQDIS, GRV98 α_s=0.114, m_c=1.3-1.5 GeV, $< p_t^{\perp c} >$=350 MeV frag. in $\gamma^* p$ cms

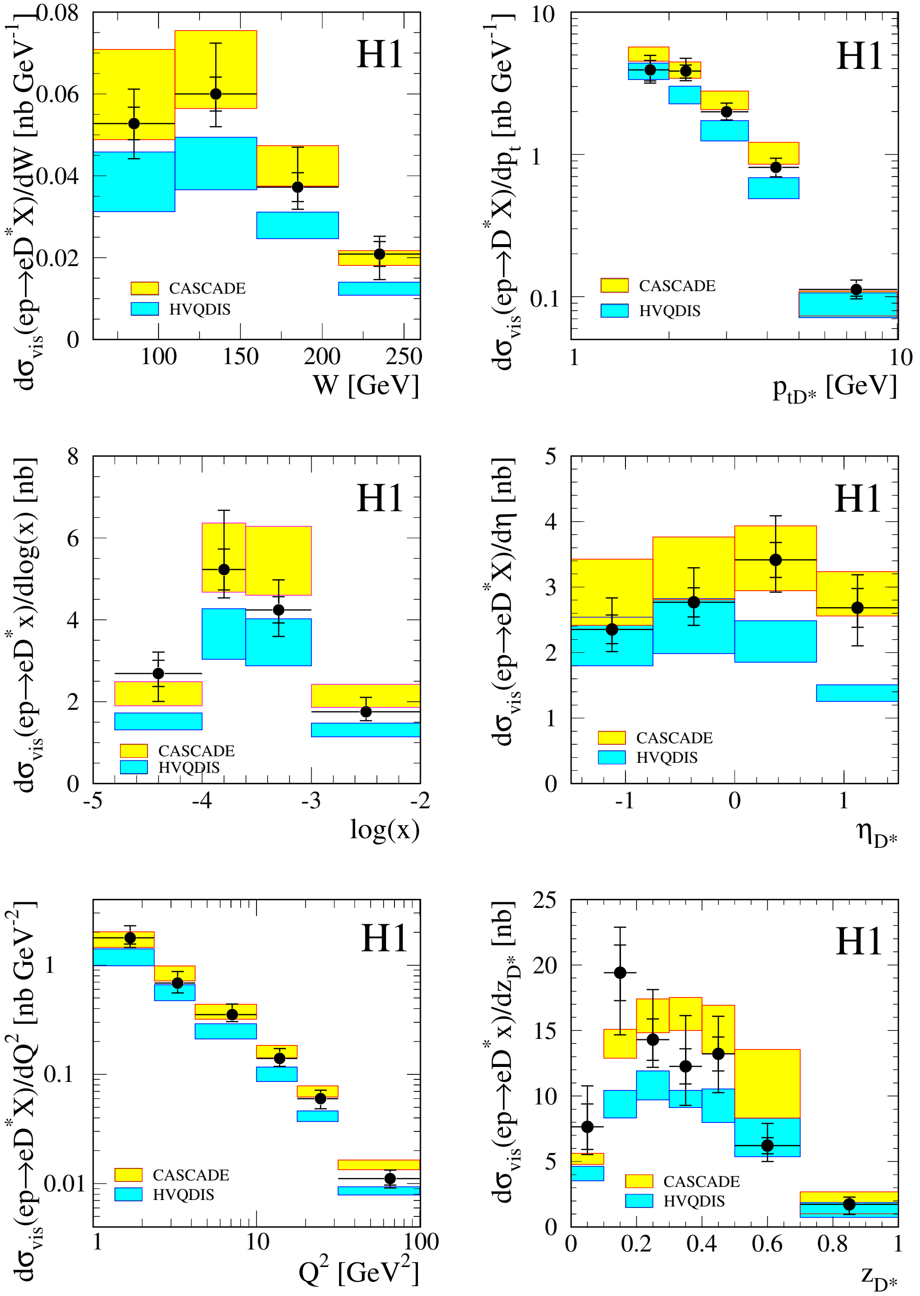
$7.02 - 5.17$ nb ϵ=0.035-0.1

CASCADE, unintegrated g fitted to H1 F_2, m_c=1.3-1.5 GeV

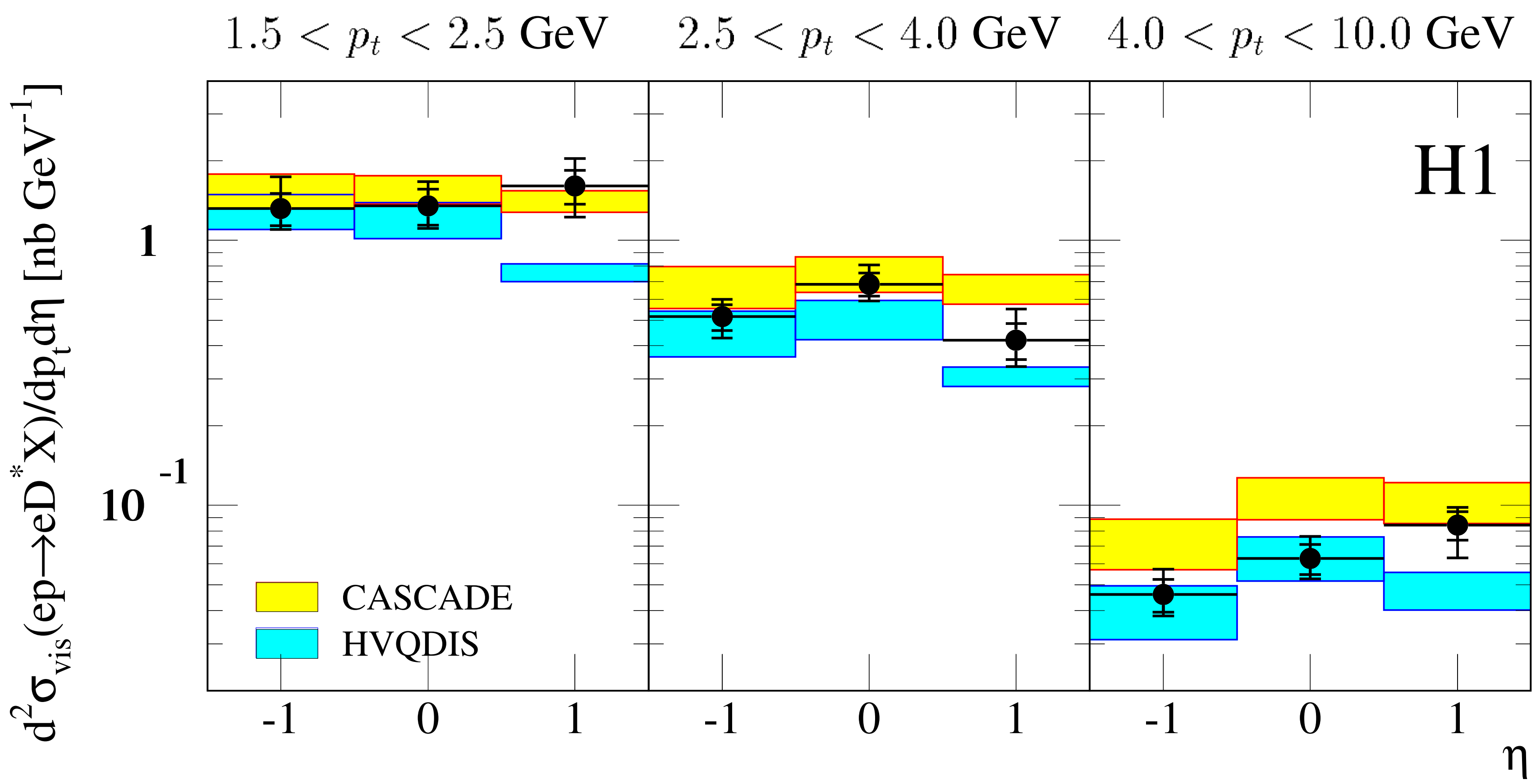
$10.77 - 8.04$ nb Jetset and ϵ=0.035-0.1

CASCADE show better agrement in norm.

HVQDIS too low at forward η, low z_D



Double differential D^* xsec, H1 $\mathcal{L} \sim 18$ pb^{-1}



- Disagreement with HVQDIS concentrated at low $p_T(D^*)$, forward $\eta(D^*)$(low z_D).
- Poor agreement with CASCADE at high $p_T(D^*)$.

Extraction of $F_2^{c\bar{c}}$

$$\frac{d^2\sigma^{c\bar{c}}(x,Q^2)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\{[1+(1-y)^2]F_2^{c\bar{c}}(x,Q^2) - y^2 F_L^{c\bar{c}}\}$$

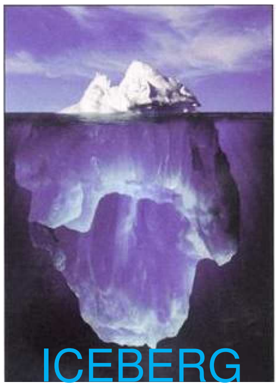
- **Assumptions:**

  $\longrightarrow$ neglect $F_L^{c\bar{c}} (< 1\%)$.

  $\longrightarrow$ neglect bound charm (<2.5-4.5 $\%$, Fleming).

  $\longrightarrow$ $f(c \rightarrow D^{*+})$ from e^+e^- is valid at HERA.

  $\longrightarrow$ $\frac{\sigma_{INT}}{\sigma_{KIN}}$ is well described.



- **Extrapolate outside the kinematical region (KIN) in p_T, η :**

$$F_2^{c\bar{c}}{}_{measu}(Q^2, x_{bj}) = F_2^{c\bar{c}}{}_{theo}(Q^2, x_{bj}) \times \frac{\sigma_{KIN}^{measu}(Q^2,y)}{\sigma_{KIN}^{theo}(Q^2,y)}$$

$\sigma_{INT}/\sigma_{KIN}$ $\leq$2 at high Q^2 to $\leq$4 at low Q^2 for D^* data.

$\leq$20 at low Q^2 for e^- data.

The extrapolation is not strongly affected by the fragmentation

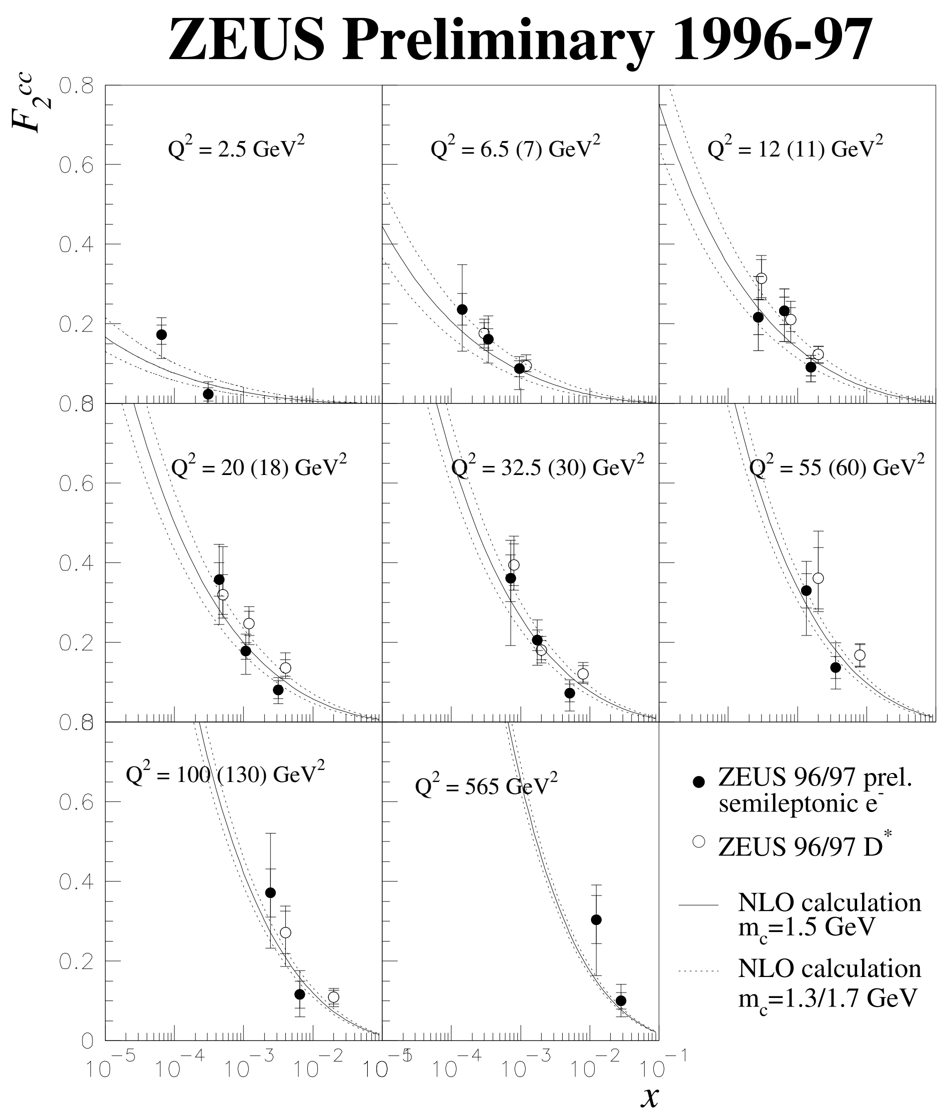
- **Interpretation of the $F_2^{c\bar{c}}$ plots:**

1. **Compare $F_2^{c\bar{c}}{}_{measu}$ with $theo$ used to extrapolate $\Rightarrow$**
   Read from the plot the agreement of the unextrapolated double differential $\sigma_{KIN}^{measu}(Q^2, y)$.

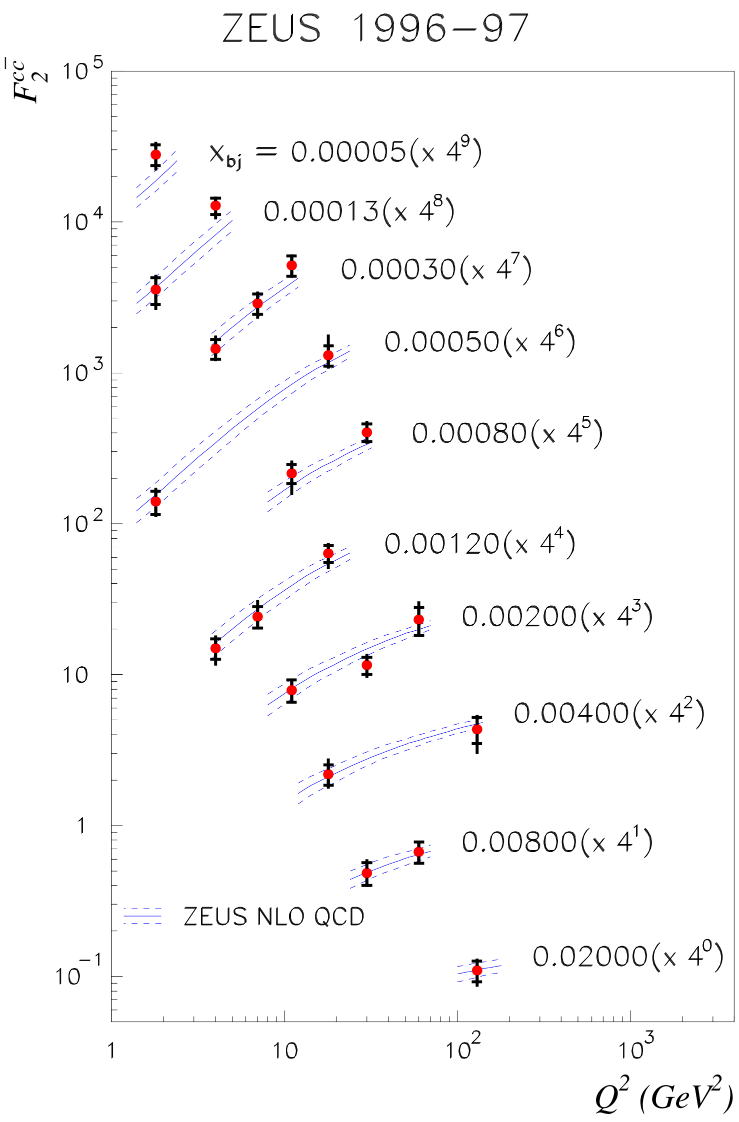
2. **Statements about the shape of $F_2^{c\bar{c}}{}_{measu}$ $\Rightarrow$**
   Dependent of the $theo$ used to extrapolate.

3. **Compare $F_2^{c\bar{c}}{}_{measu}$ with other $theo$ $\Rightarrow$**
   The comparison is between $theo$ and $theo$ in fact, rather than with the data.

1. HVQDIS(GRV 94) describe the ZEUS sl e^-



1. HVQDIS(ZEUS NLO fit) agree with ZEUS D^*

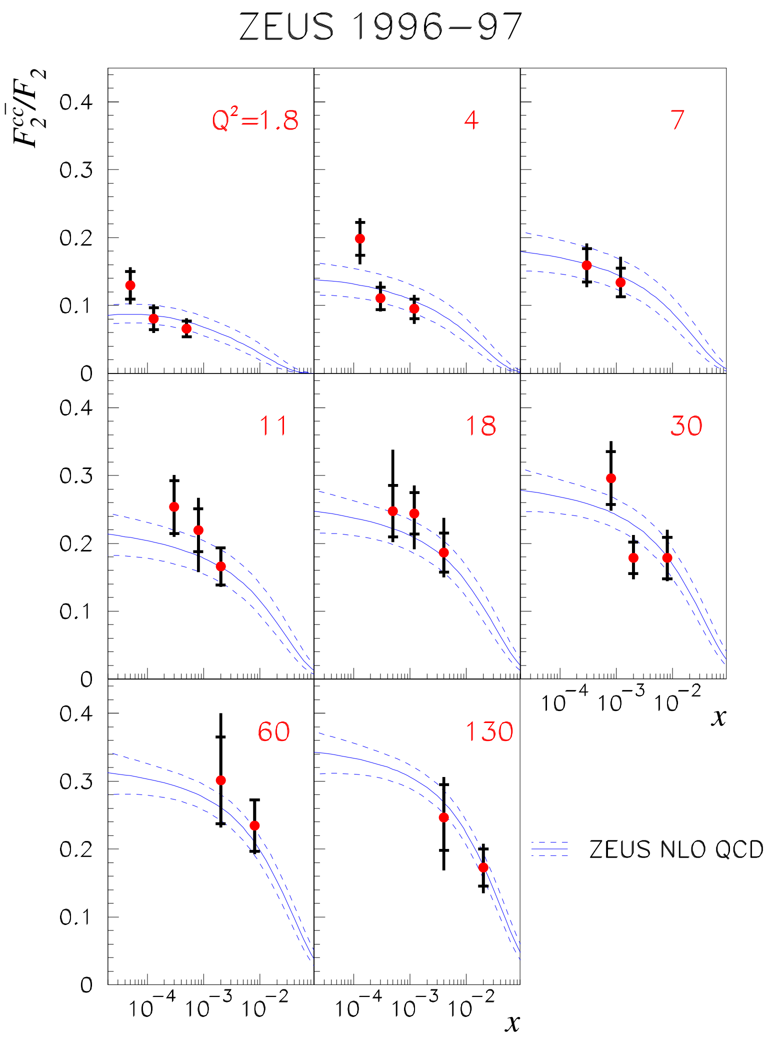


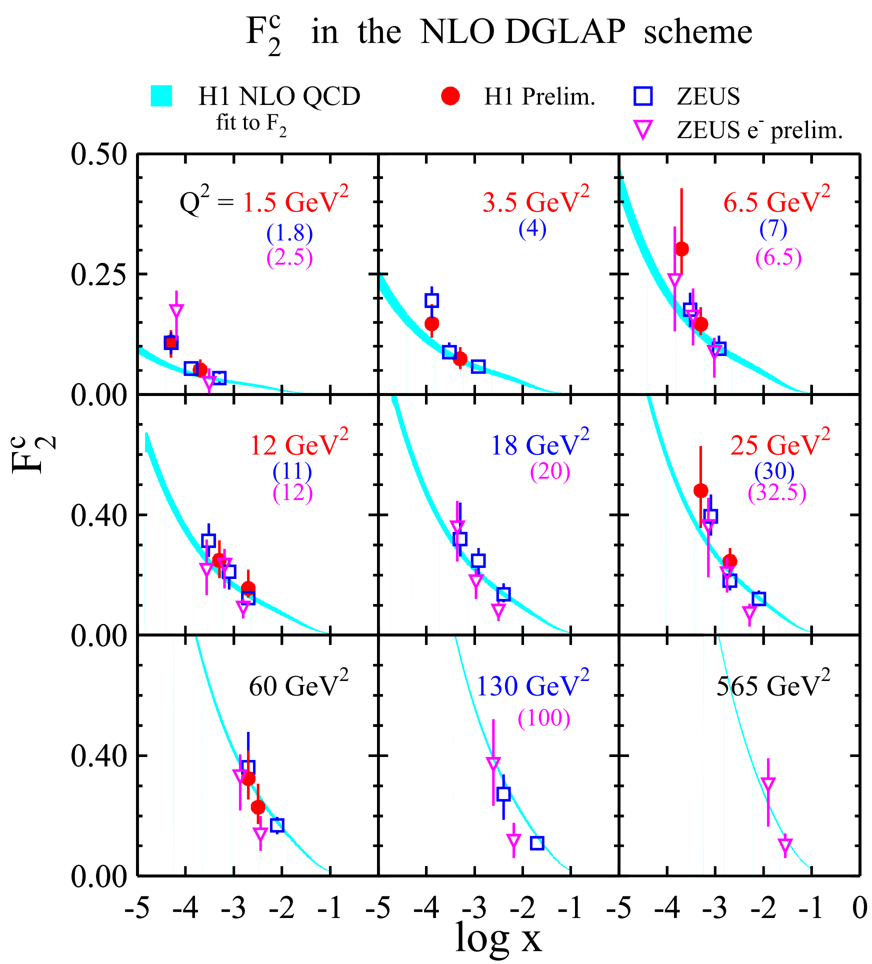
2. $F_2^{c\bar{c}}$ rises steeply as x_{bj} decreases $\Rightarrow$

It follows the rise of the gluon.

2. $F_2^{c\bar{c}}$ does not scale in the measured region$\Longrightarrow$

Consistent with BGF dominance





2. $\sim 25-30\%$ of F_2 for $Q^2 > 11$ GeV^2,low x_{bj}

2. flat at low x_{bj}: $F_2^{c\bar{c}}/F_2 \sim 4/11 \sim 0.36$

2. Rise at high x_{bj} due to the valence $\downarrow$ in F_2

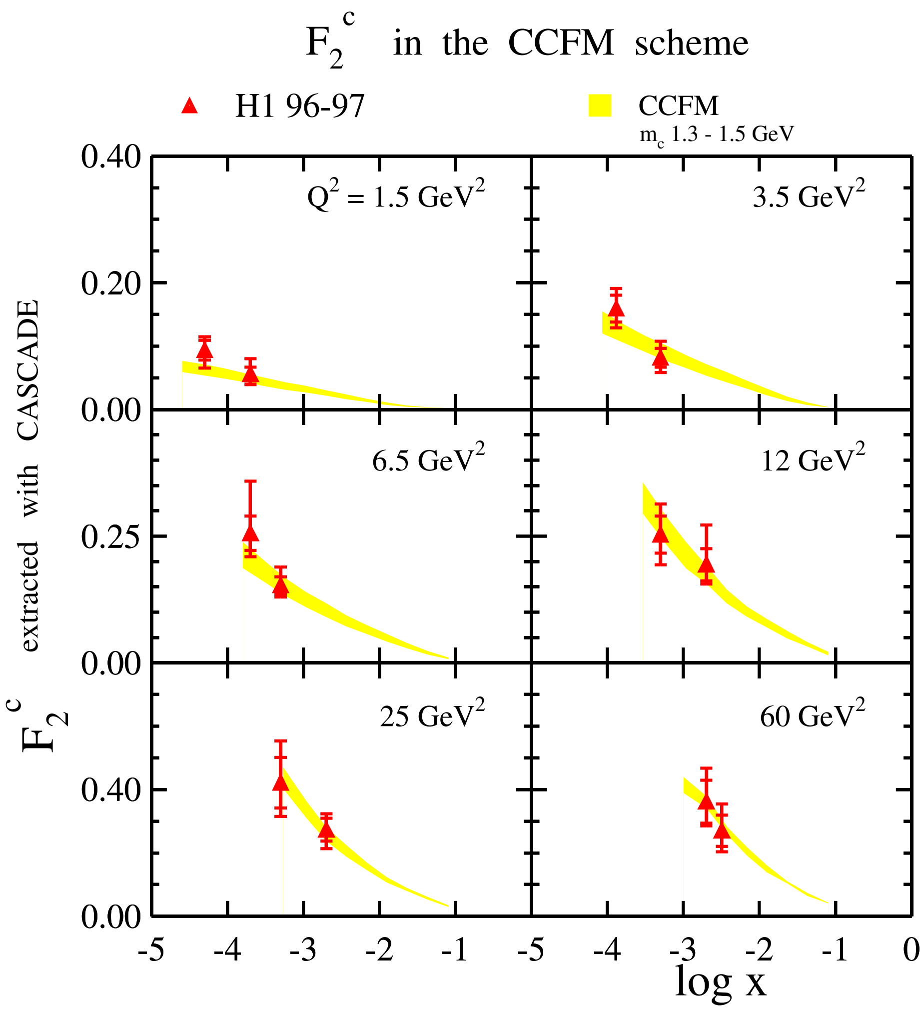
3. $F_{2\ measu}^{c\bar{c}}$ extracted with HVQDIS(GRV 98,GRV 94,ZEUS NLO) seem to be compatible.

3. H1 fit agrees reasonable well with the shape of HVQDIS(GRV 98,GRV 94,ZEUS NLO)

$$F_2\text{(data)} \xrightarrow{\text{DGLAPfit}} g, q, \bar{q} \xrightarrow{\text{HVQDIS}} \sigma^{c\bar{c}}\text{ (pred)} \Leftrightarrow \sigma^{c\bar{c}}\text{ data}$$

Test of QCD and of the universality of the parton distributions of the proton.

The agreement within theoretical uncertainties of NLO TFNS HVQDIS predictions using pdf extracted from DGLAP fits to the inclusive F_2 scaling violations with the H1 and ZEUS D^* production xsec and the ZEUS semileptonic xsec provides support for the universality of the parton distributions of the proton and the validity of factorization in charm electroproduction.



However...

1. Good Agreement between the H1 D^*xsec and the CCFM evolution as implemented in CASCADE

Summary

NLO pQCD (FO) confronted to the data:

Collab.	Photoproduction	DIS
ZEUS	$\ddot{\frown}$ "*The NLO calculations* [FMNR] *are generally below the data, in particular in the forward direction*" EPJ C6 (1999) 67-83 $\Longrightarrow$ massless calculations, BKL, fragmentation, NNLO	$\ddot{\smile}$ "*Good Agreement* [with HVQDIS] *is obtained after a more appropiate* $c \longrightarrow D^*$ *fragmentation such as that in JETSET is obtained*" EPJ C 12 (2000) 1, 35-52 $\Longrightarrow$ fragmentation
H1	$\ddot{\smile}$ "*The overall description of the differential cross sections by the theoretical calculations [*FMNR*] has been found to be adequate" (Nucl. Phys. B545 (1999) 21-44)*	$\ddot{\frown}$ "*The predictions of the CCFM based CASCADE program are in better agreement with the data than those from HVQDIS*" (ICHEP2000 Abstract: 984) $\Longrightarrow$ CCFM evolution

...but the data agree.

Outlook

- H1 silicon vertex detector results just starting to appear ($\longrightarrow$ Sefkow talk), ZEUS has installed a silicon vertex detector and has upgraded the forward tracking.

- Expand the coverage of the phase space, specially the forward region.
  $\Rightarrow$ Understand charm PHP.
  $\Rightarrow$ Search for IC in DIS.
  $\Rightarrow$ Deviation from FFNS in DIS.
  $\Rightarrow$ Minimize extrapolation to $F_2^{c\bar{c}}$. Standard D^* channels cannot go lower in $p_T(c)$ (D^*-π_s correlation). $\Rightarrow$ Other channels.

- 1 fb—$\mathbf{1}$ (27000 $D^*$with 10%)
  - $\nearrow$ Precise diffraction measurements.
  - $\rightarrow$ Spectroscopy of c-mesons.
  - $\searrow$ Double tagged final states.

Wish: Improved fragmentation treatment. NLO + frag. model(JETSET)?

Wish: Smoking gun for CCFM?

Wish: Include charm xsec data in global fits?