Les Rencontres de Physique de la
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Heavy Flavour Physics at HERA

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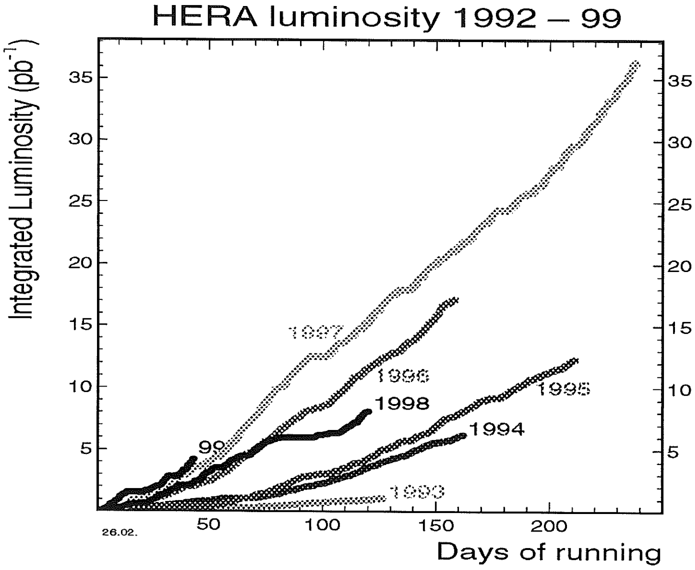
Outline:

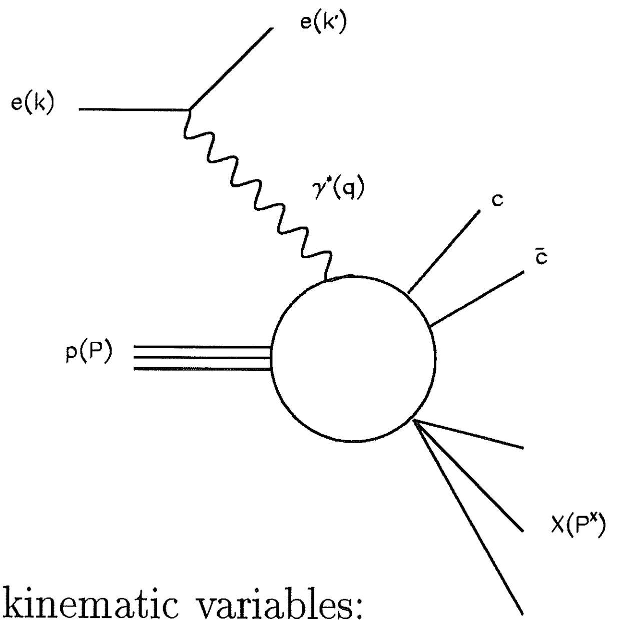
- introduction
- open heavy quark:
  - production channels at HERA
  - D^* in photoproduction and DIS regime
  - direct gluon density extraction
  - beauty photoproduction
- bound charm:
  - J/ψ production channels at HERA
  - inelastic J/ψ photoproduction
  - inclusive J/ψ in DIS
- summary and outlook

Introduction

$$e^{\pm} \Longrightarrow \Longleftarrow p$$

$$E^{e^{\pm}} = 27.5 \text{ GeV} \quad E^{p} = 820\ (920) \text{ GeV until 97 (after 98)}$$





kinematic variables:

$$Q^2 = -q^2 = -(k - k')^2 \qquad x = \frac{Q^2}{2\ P\cdot q}$$

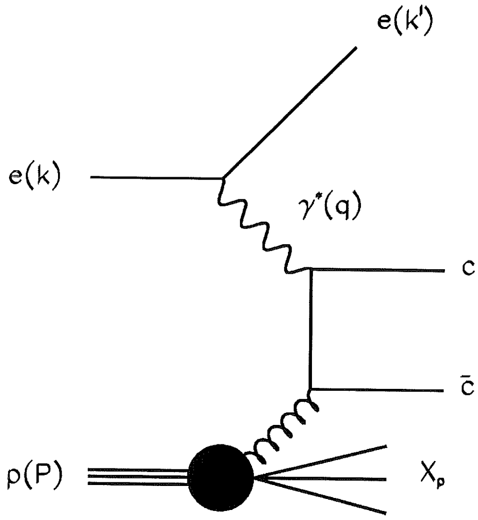
$$y = \frac{P \cdot q}{P \cdot k} \qquad W^2_{\gamma p} = (P + q)^2 \cong 4\ E_e\ E_p\ y$$

$$\eta = -\ln(\tan\frac{\theta}{2}) \qquad \hat{y} = -\frac{1}{2}\ln\frac{E-p_z}{E+p_z}$$

Open heavy quark: production channels at HERA

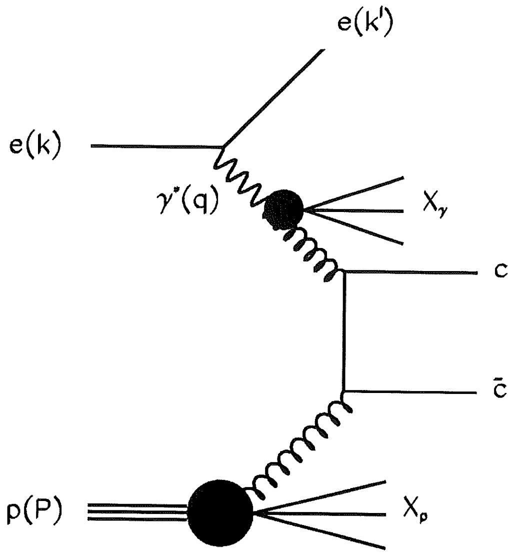
Motivations:

- a hard scale, m_Q, is available $\Rightarrow$ pQCD can be applied and tested
- study production channels
- study proton and photon parton (mainly gluon) densities



direct–γ: γ–g fusion

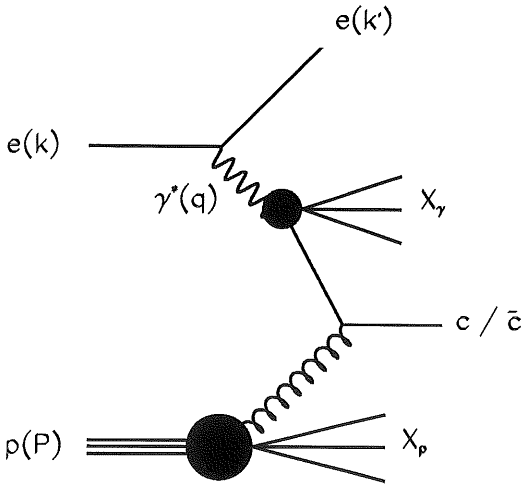
$\Rightarrow g^p(x, Q^2)$



resolved–γ: $g\ g \rightarrow c\ \bar{c}$

$\Rightarrow g^p(x, Q^2) \otimes g^\gamma(x, Q^2)$

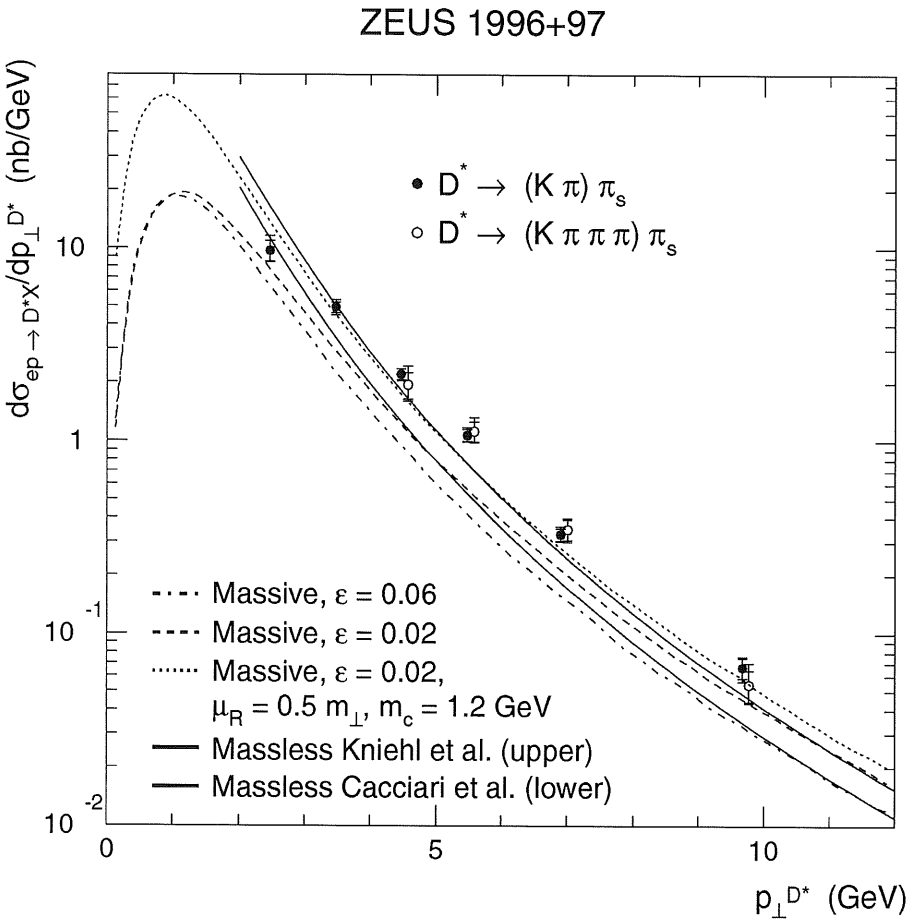
supressed with Q^2



resolved–γ: c excitation

Open heavy quark: D^* photoproduction

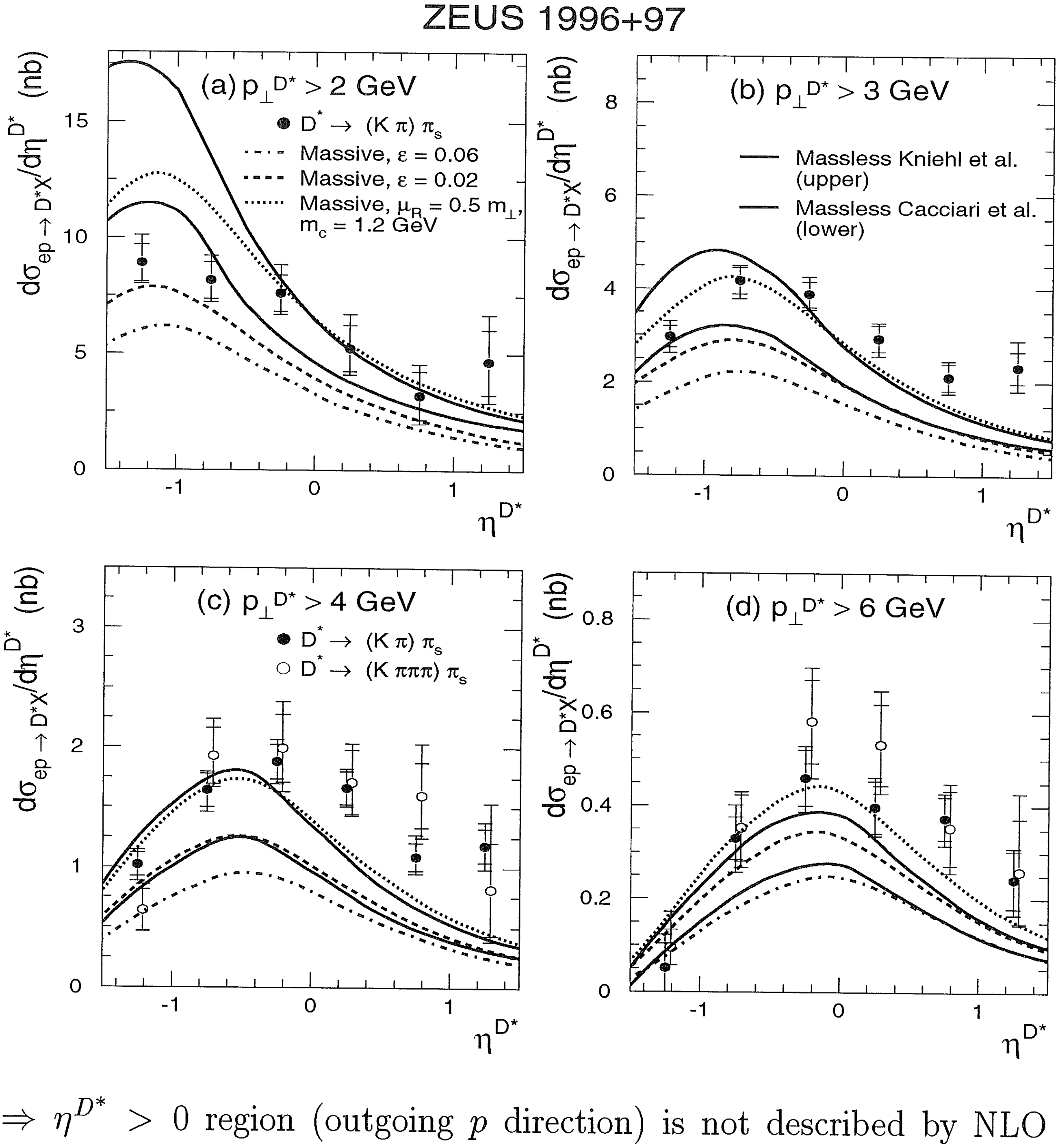
- $L = 36.9 \text{ pb}^{-1}$
- scattered e^+ not seen $\Leftrightarrow Q^2 < 1 \text{ GeV}^2 \Leftrightarrow$ photoproduction regime
- $130 < W_{\gamma p} < 280$ GeV $\quad p_\perp^{D^*} > 2\ (4)$ GeV $\quad |\eta^{D^*}| < 1.5$



- full NLO calculations
- massive approach: g and light q are the only active partons within p and γ, massless: c is an additional active flavour
- $f(c \to D^*) \sim 0.22$, $z = \frac{p^{D^*}}{p^c}$ $\quad \frac{dn}{dz} \propto f(z, \epsilon)$, $m_c = 1.5$ GeV, $\mu_R = m_\perp = \sqrt{m_c^2 + p_\perp^2}$, $\mu_F = 2\, m_\perp$, MRSG p and GRV–G HO γ parton density parametrizations

$\Rightarrow$ predicted cross sections are lower

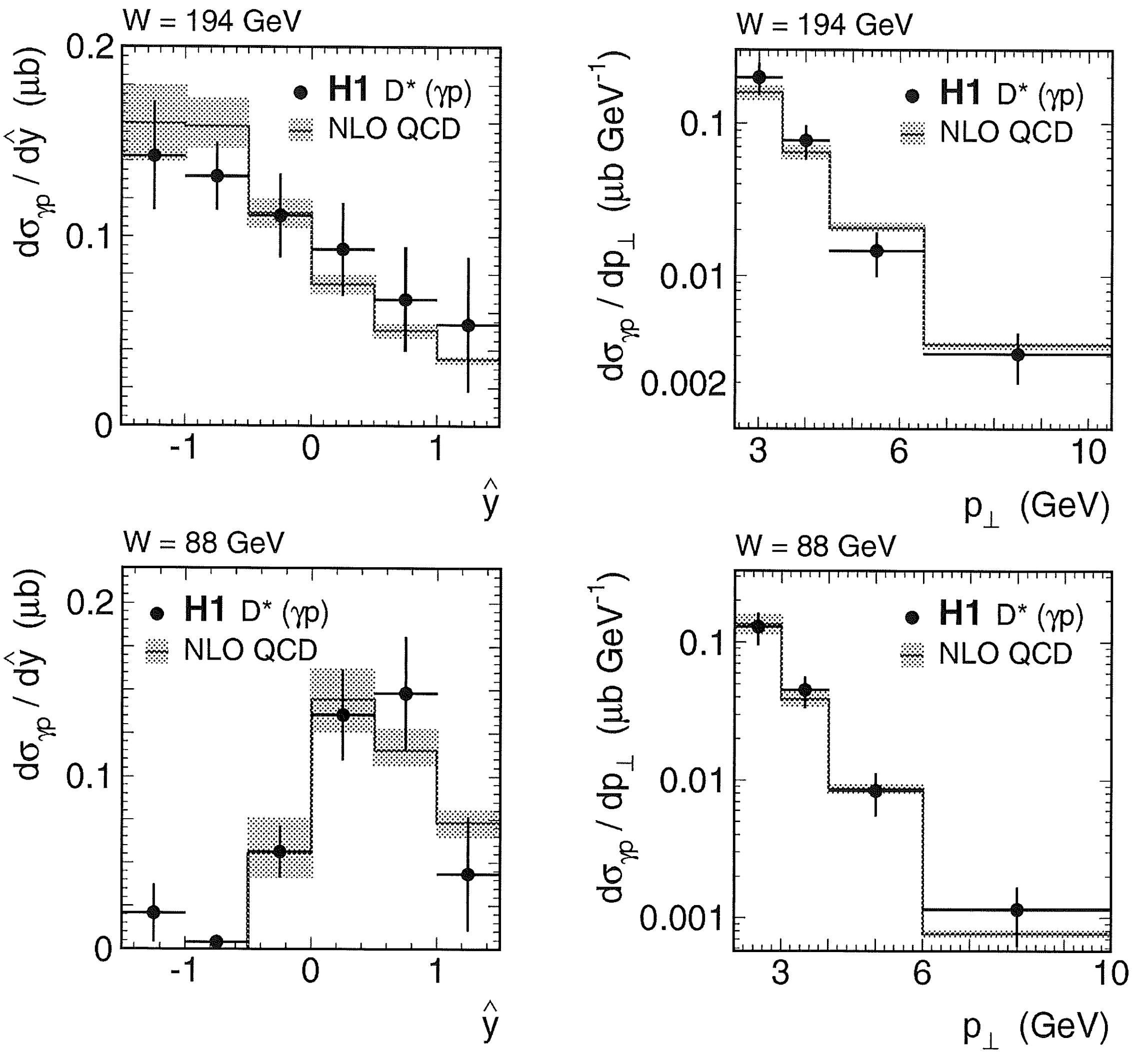
Open heavy quark: D^* photoproduction (cont.)



$\Rightarrow \eta^{D^*} > 0$ region (outgoing p direction) is not described by NLO predictions

Open heavy quark: D^* photoproduction (cont.)

- $L = 10.7\ (10.2)\ \mathrm{pb}^{-1}$
- e^+ seen in low angle e-taggers $\Leftrightarrow Q^2 < 0.01\ (0.009)\ \mathrm{GeV}^2$, $< W_{\gamma p} > = 194\ (88)$ GeV
- $D^* \to (K\ \pi)\ \pi_s \quad p_\perp^{D^*} > 2.5\ (2)$ GeV $\quad |\ \hat{y}^{D^*}| < 1.5$



- full NLO calculations
- massive approach
- $f(c \to D^*) \sim 0.27,\ \ \epsilon = 0.036,\ \ m_c = 1.5$ GeV, $\mu_F = \sqrt{4m_c^2 + 4p_\perp^2},\ \ \mu_R = \mu_F/2$, MRST1 p and GRV HO γ parton density parametrizations

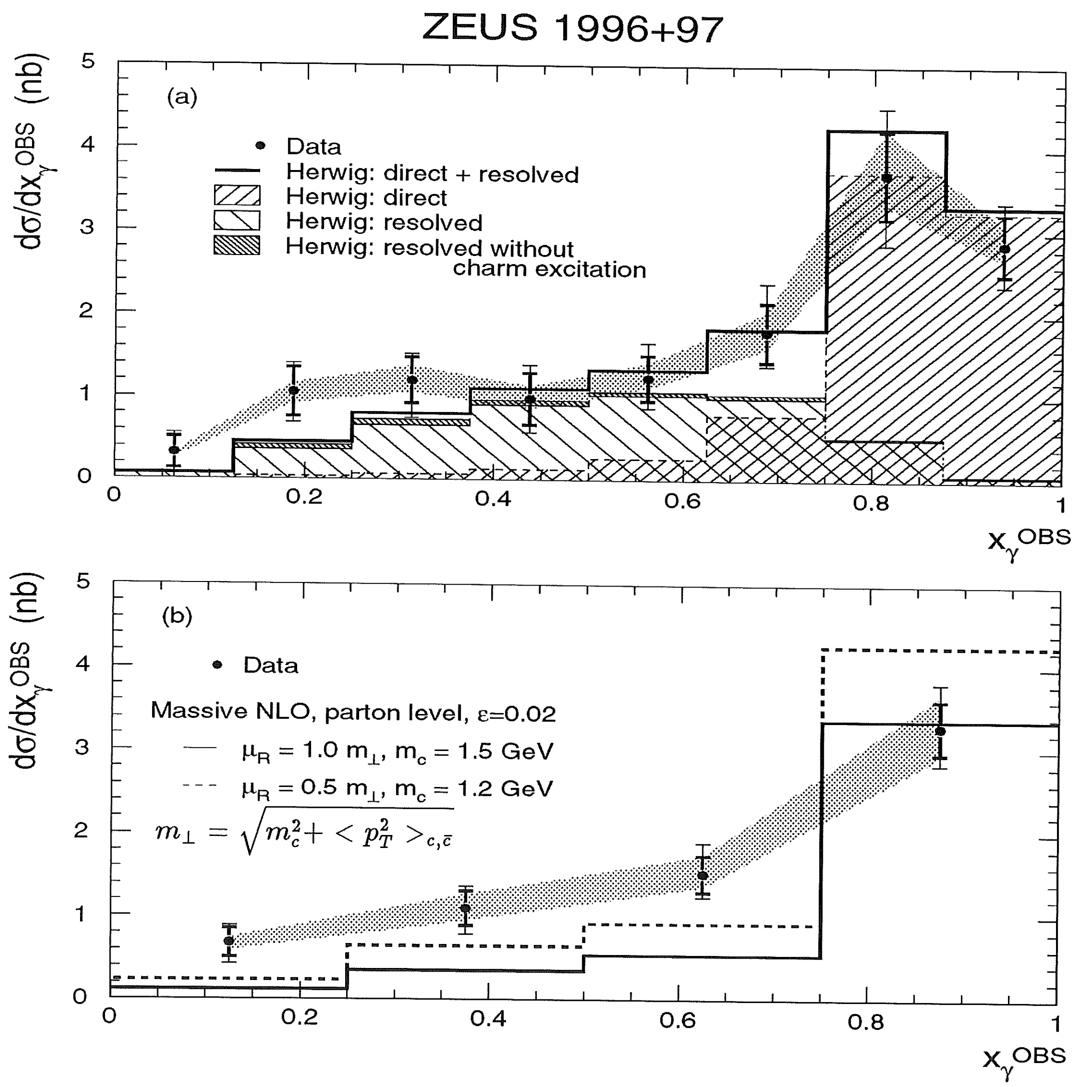
$\Rightarrow$ fair agreement between data and NLO computation

Open heavy quark: D^* photoproduction (cont.)

$$x_\gamma^{OBS} \equiv \frac{\Sigma_{1,2}\, E_T^{jet}\, e^{-\eta^{jet}}}{2\, E_e\, y}$$

direct (resolved) photon process $\equiv x_\gamma^{OBS} \geq 0.75$ (< 0.75)
fine for measurements, MC simulations and higher order calculations

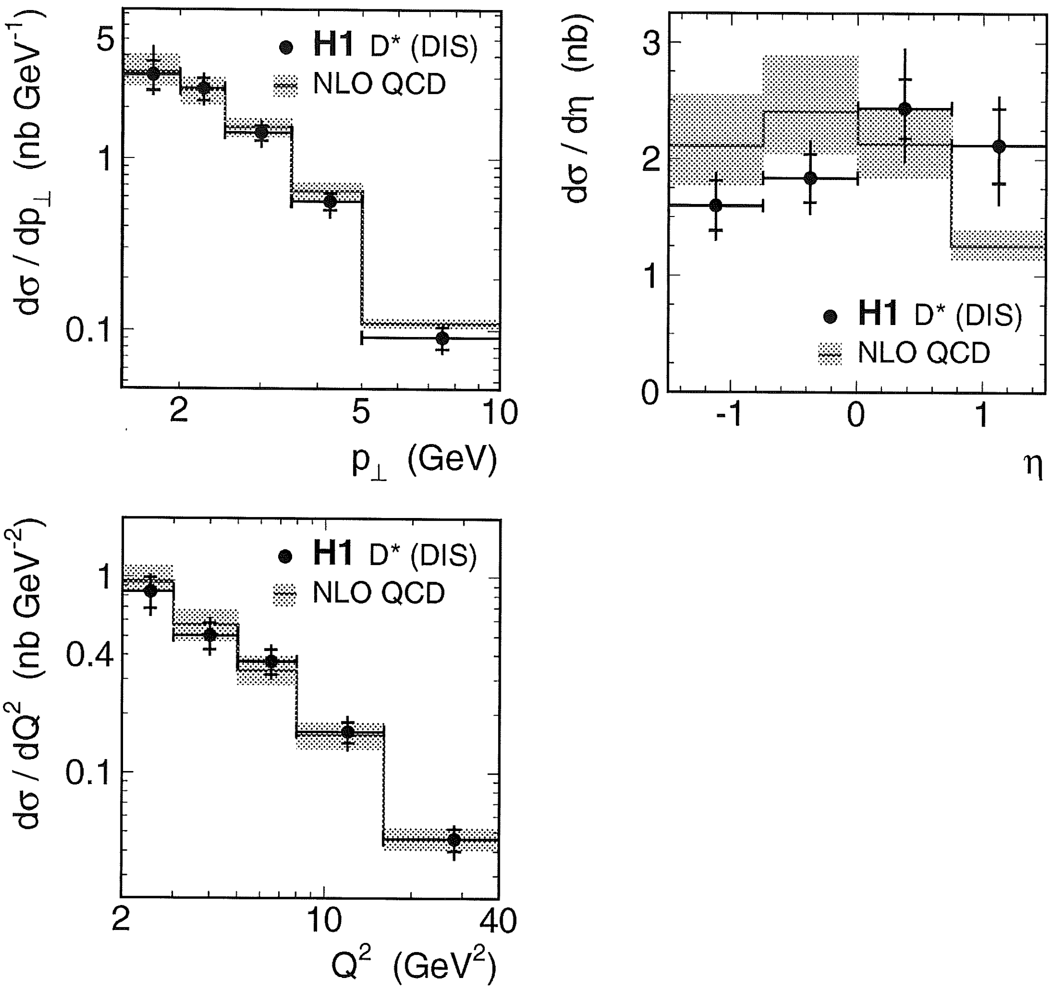
- $Q^2 < 1$ GeV^2 $\quad 130 < W_{\gamma p} < 280$ GeV
- $p_\perp^{D^*} > 3$ GeV $\quad |\,\eta^{D^*}| < 1.5$
- $|\,\eta^{jet}| < 2.4 \quad E_T^{jet1} > 7$ GeV $\quad E_T^{jet2} > 6$ GeV



⇒ LO resolved component required, mostly c excitation in the γ
⇒ massive NLO parton level calculation undershoot the low x_γ^{OBS} tail

Open heavy quark: D^* in DIS

- $L = 9.7\ \text{pb}^{-1}$
- scattered e^+ in the main detector $\Leftrightarrow 2 < Q^2 < 100\ \text{GeV}^2 \Leftrightarrow$ DIS regime
- $0.05 < y < 0.7 \quad p_\perp^{D^*} > 1.5\ \text{GeV} \quad |\eta^{D^*}| < 1.5$



- full NLO massive calculation
- $f(c \to D^*) \sim 0.27,\ \epsilon = 0.036,\ m_c = 1.5\ \text{GeV},$
  $\mu_F = \mu_R = \sqrt{4m_c^2 + Q^2},$
  CTEQ4F3 p parton density parametrization

$\Rightarrow$ NLO QCD agrees with data except for the $d\sigma/d\eta$ in the forward (outgoing p direction) and (to a smaller extend) backward region

Open heavy quark: direct gluon density extraction

at LO the kinematics of $\gamma\ g \to c\ \bar{c}$ is fixed measuring one incoming and one outgoing particle: incoming e^+ + scattered $e^+ \to \gamma$, $D^* \rightsquigarrow c$

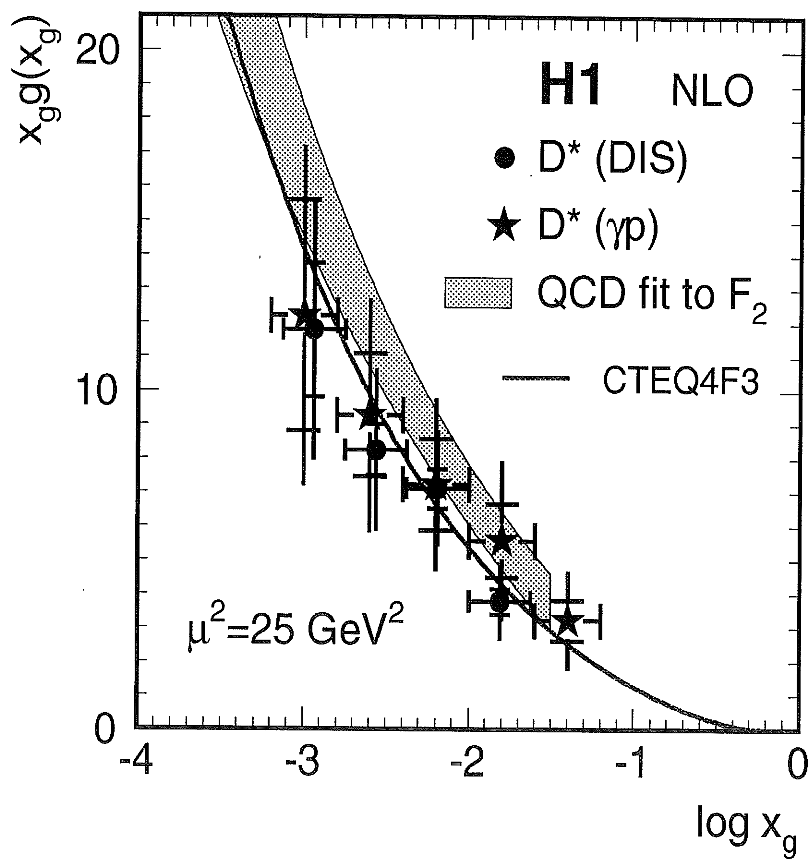
$$x_g = \frac{M^2 + Q^2}{4\ E_e\ E_p\ y} \qquad (g \text{ momentum fraction})$$

$$M^2 = \frac{p_{\perp c}^{*2} + m_c^2}{z(1-z)} \qquad z = \frac{(E - p_z)_c^{\rm lab}}{2\ y\ E_e}$$

$$p_{\perp c}^* \to 1.2\ p_{\perp D^*}^* \quad (E - p_z)_c^{\rm lab} \to (E - p_z)_{D^*}^{\rm lab}$$

$$\Rightarrow x_g \to x_g^{OBS}$$

$$\sigma(x_g^{OBS}) = \int\ dx_g\ [g(x_g, \mu^2)\ \hat{\sigma}(x_g, \mu^2)\ A(x_g^{OBS}, x_g, \mu^2)] + \sigma_{quark}(x_g^{OBS})$$

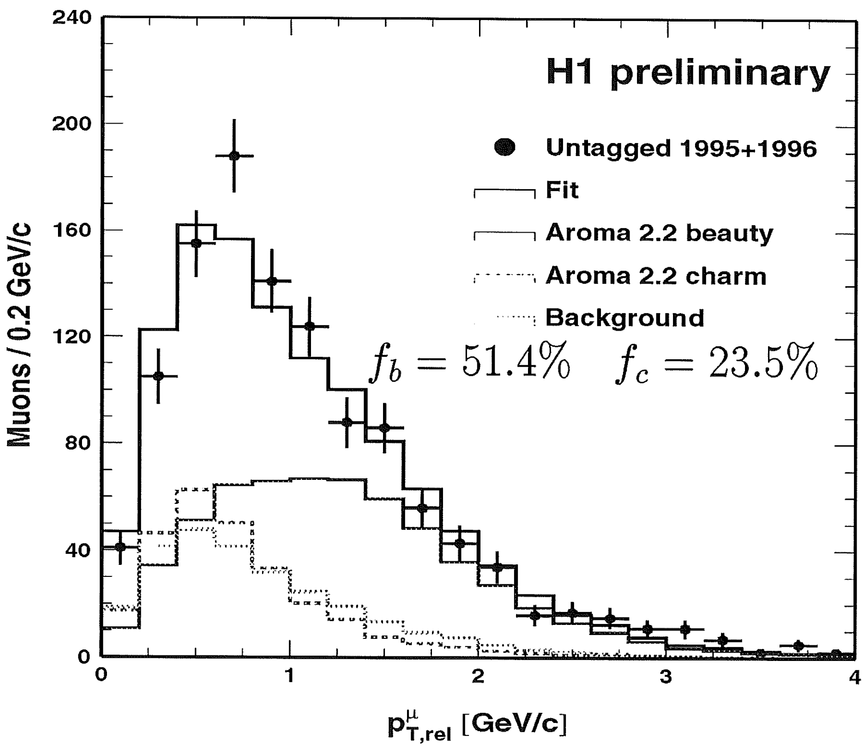


⇒ measurement is still dominated by the stat. error

⇒ within the errors, demonstration of the universality of $x_g g(x_g)$

Open heavy quark: beauty photoproduction

- $L = 8.3$ pb^{-1}
- scattered e^+ not seen $\Leftrightarrow Q^2 < 1$ GeV$^2 \Leftrightarrow$ photoproduction regime
- at least 2 jets ($E_T > 6$ GeV $|\eta| < 2.5$), at least 1 μ ($p_t^\mu > 2$ GeV $35^o < \theta^\mu < 130^o$), μ within one of the jets
- $p^\mu_{T,\mathrm{rel}} \equiv$ transverse momentum w.r.t. the thust axis of the asociated jet
- from the $P_h^\mu(p,\theta)$ (obtained from MC and cross cheked with $K_S^0 \to \pi^+\,\pi^-$) the fake μ bkg can be fixed: $f_{\mathrm{fake}} = 23.5\%$



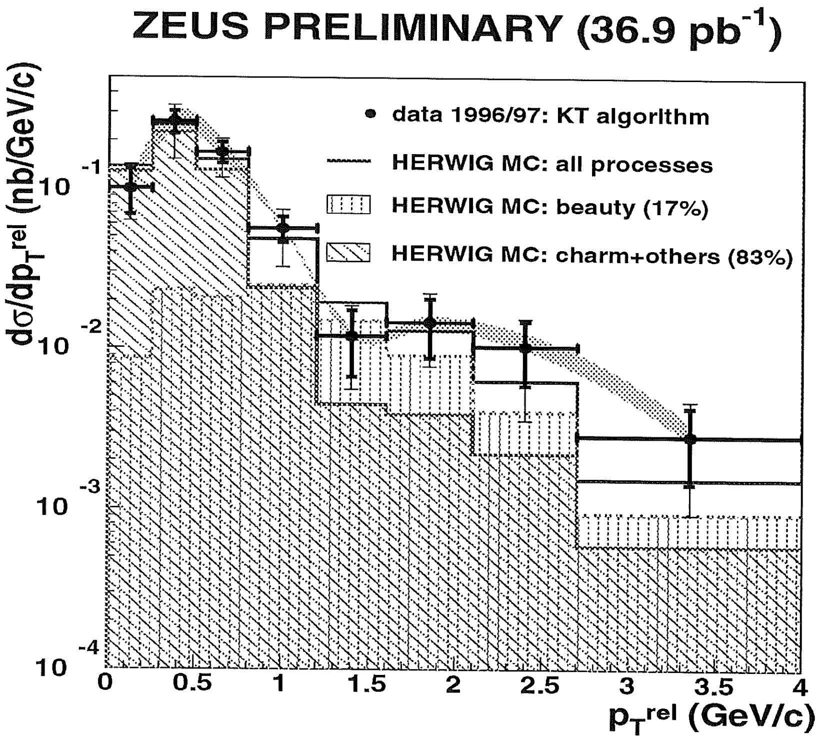
$$Q^2 < 1 \text{ GeV}^2 \quad 0.1 < y < 0.8 \quad p_t^\mu > 2 \text{ GeV} \quad 35^o < \theta^\mu < 130^o$$

$$\sigma(e\,p \to b\,\bar{b}\,X) = [0.93 \pm 0.08\ (\text{stat.})^{+0.21}_{-0.12}\ (\text{sys.})]\ \text{nb}$$

AROMA (LO) prediction in the visible range is 0.19 nb
AROMA prediction for open b production is 3.8 nb ($m_b = 4.75$ GeV, MRS(G) pdf) to be compared with 4.7 $\to$ 10 nb range from NLO QCD calculations

Open heavy quark: beauty photoproduction (cont.)

- $L = 36.9\ \mathrm{pb}^{-1}$
- scattered e^+ not seen $\Leftrightarrow Q^2 < 1\ \mathrm{GeV}^2 \Leftrightarrow$ photoproduction regime
- $0.2 < y < 0.8$
- at least 2 jets ($E_T^{jet1(2)} > 7(6)$ GeV $\quad |\eta^{jet}| < 2.4$), at least one e^- identified by CAL and dE/dx ($p_T^{e^-} > 1.6$ GeV $\quad |\eta^{e^-}| < 1.1$)
- stat. subtraction of the hadron bkg using the dE/dx distribution

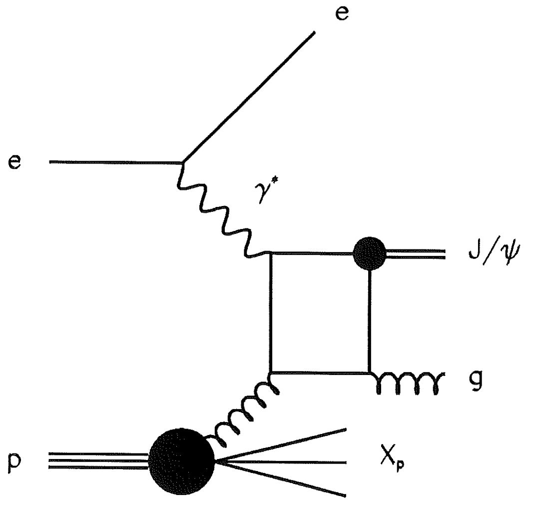


$$\sigma^{\mathrm{vis}}_{b\bar{b}}(e^+p \to e^- + \mathrm{dijet} + X) = [39 \pm 11\ (\mathrm{stat.})^{+23}_{-16}\ (\mathrm{sys.})]\ \mathrm{pb}$$

HERWIG (LO) prediction, using CTEQ4D p and GRV–LO γ parton densities, $m_c = 1.55$ GeV and $m_b = 4.95$ GeV
$\Rightarrow$ factor 3.7 below the data

Bound charm: J/ψ production channels at HERA

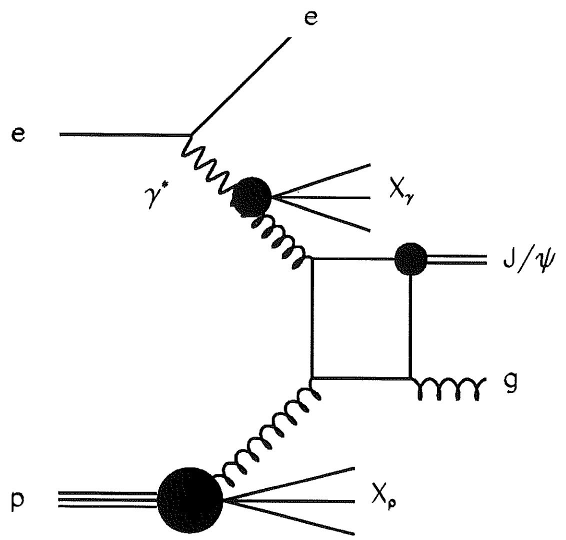
- $z \equiv \frac{P^p \cdot p^{J/\psi}}{P^p \cdot q^{\gamma^*}}$ (inelasticity), proton rest frame $z = \frac{E_{J/\psi}}{E_{\gamma^*}}$
- inelastic definiton $\equiv E_{\text{fwd}} >$ const GeV (ZEUS $\neq$ H1)



direct–γ

$\Rightarrow g^p(x, Q^2)$

dominant for $0.4 \lesssim z \lesssim 0.9$



resolved–γ

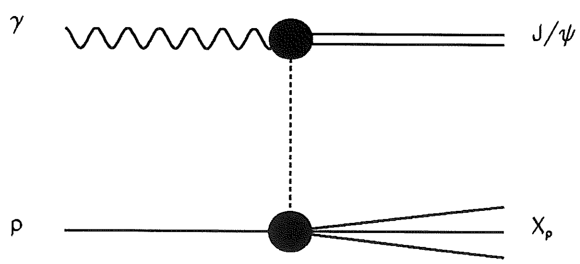
$\Rightarrow g^p(x, Q^2) \otimes g^\gamma(x, Q^2)$

dominant for $z \lesssim 0.4$

- in the CSM at the end of the hard subprocess a J/ψ state

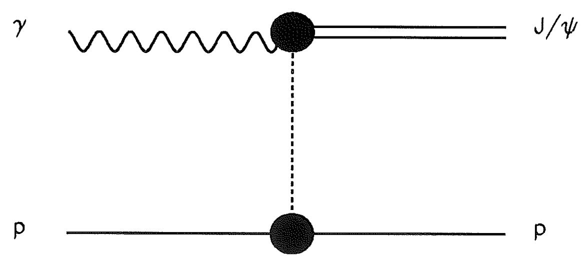
only 1 free param: CS ME fixed (at NLO) by $\Gamma_{J/\psi \to\ l^+l^-}$

- in the COM at the end of the hard subprocess a $[\underline{8}, {}^{2S+1}L_J]$ which later on evolve into a $J/\psi \Rightarrow$ additional free params: CO MEs



p–diffractive

$z \sim 1$



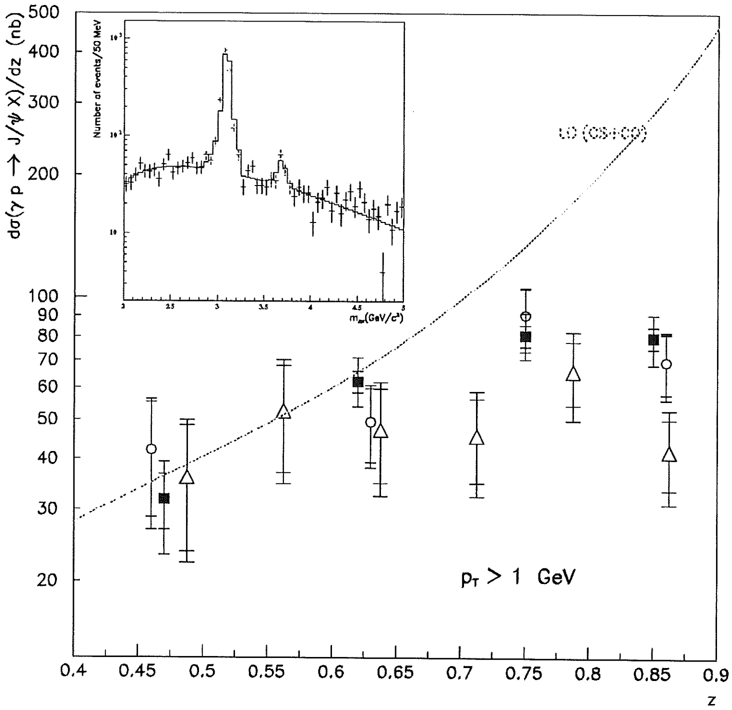
elastic

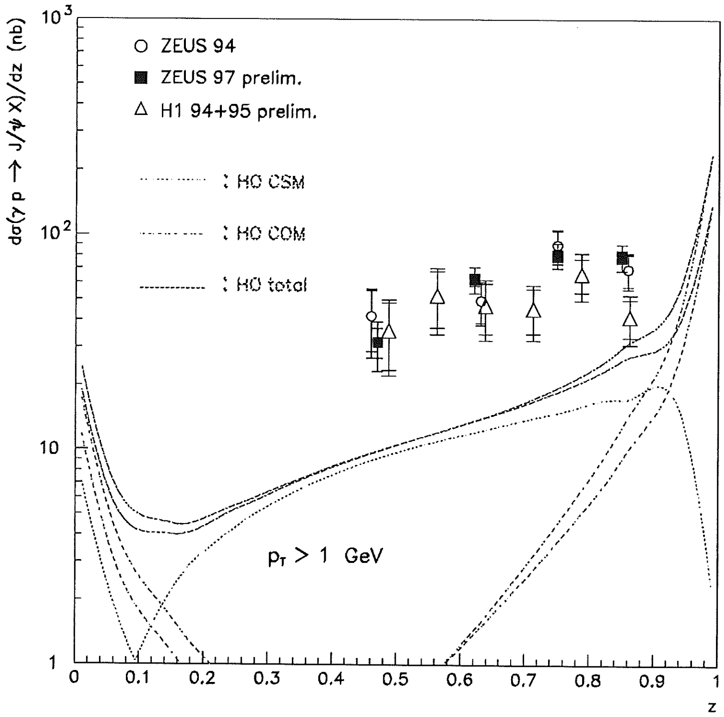
$z \equiv 1$

$E_{\text{fwd}} >$ const GeV removes it

Bound charm: inelastic J/ψ photoproduction

- $L = 26.0\ (6.6)\ \mathrm{pb}^{-1}$ ZEUS (H1)
- scattered e^+ not seen $\Leftrightarrow Q^2 < 1\ \mathrm{GeV}^2 \Leftrightarrow$ photoproduction regime
- $J/\psi \to \mu^+\mu^-$ $\quad 50\ (30) < W_{\gamma p} < 180\ (150)$ GeV $\quad p_t^{J/\psi} > 1$ GeV
- $\psi' \to J/\psi\ (\to \mu^+\mu^-)\ X$ are not subtracted $\Rightarrow \sim 15\ \%$ effect





$$\frac{d\sigma}{dp_T}(p\,\bar{p} \to J/\psi^{\mathrm{prompt}}\ X) = \Sigma_n\ \frac{d\sigma}{dp_T}(i\ j \to c\bar{c}[n]\ k) < O^{J/\psi}[n] >$$

$n = [\underline{1}, {}^3S_1]$ in the CSM or $n = [\underline{8}, {}^{2S+1}L_J]$ in the COM

- LO calculation of the p_T spectra $\Rightarrow$ overshoot at high z
- CTEQ4M p and GRV–HO γ parton densities

$\mu_F = \mu_R = \sqrt{4\ m_c^2 + p_T^2}$, $2\ m_c = m_{J/\psi}$, $\Lambda_{QCD} = 296$ MeV

CS ME fixed (at NLO) by $\Gamma_{J/\psi \to\ l^+l^-}$

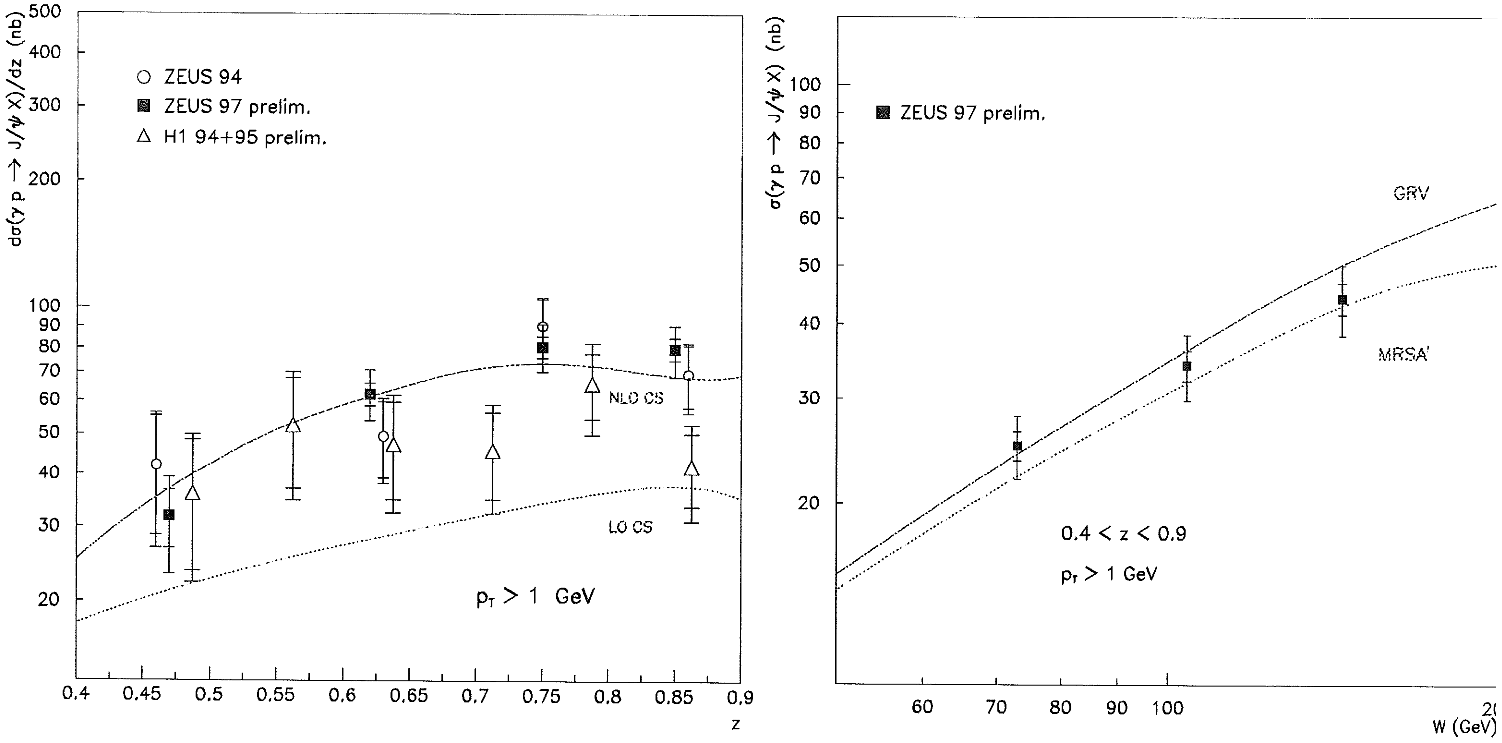
CO MEs are extracted from a QCD I/FSR corrected p_T spectra (by a MC technique)

the hard subprocesses are still computed at LO ($\to$ HO and not NLO)

$\Rightarrow$ room is left for a substantial K factor

$\Rightarrow$ direct–γ CSM dominant except for $z \lesssim 0.15$ and $z \gtrsim 0.85$

Bound charm: inelastic J/ψ photoproduction (cont.)

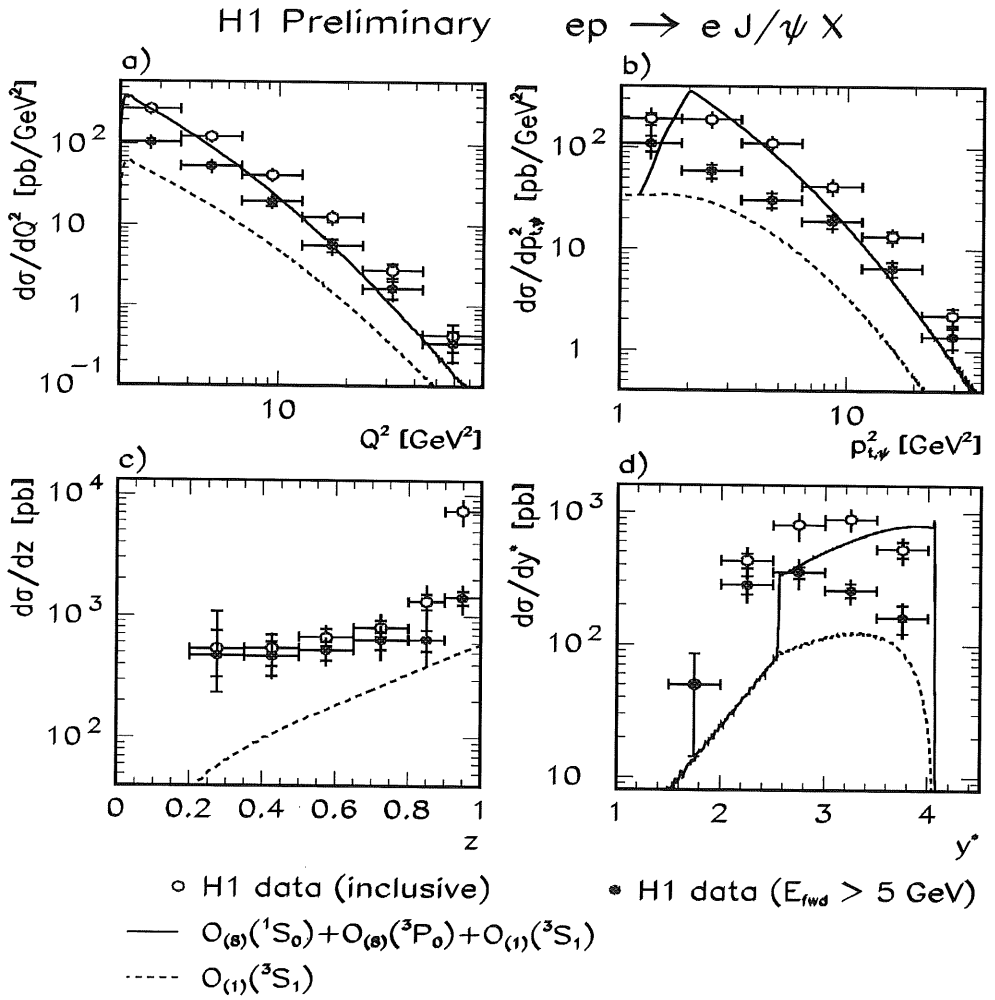


- full NLO calculation of the direct–γ component in the CSM approach
- $\mu_F^2 = \mu_R^2 = 2\ m_c^2$, $m_c = 1.4$ GeV, $\Lambda_{QCD} = 300$ MeV
- GRV p parton density parametrization
- $\sigma \propto \alpha_s^2/m_c^3 \longrightarrow$ normalization uncertainties
  $2\ m_c = m_{J/\psi}$ GeV, $\Lambda_{QCD} = 215$ MeV $\longrightarrow$ factor 3

$\Rightarrow$ currently accessible phase space region at HERA is well suited to study the direct–γ process as implemented in the CSM

Bound charm: inclusive J/ψ in DIS

- $L = 21$ pb^{-1}
- scattered e^+ in the main detector $\Leftrightarrow$ $2 < Q^2 < 80$ GeV^2 $\Leftrightarrow$ DIS regime
- $J/\psi \rightarrow\ l^+l^- \quad l = e,\ \mu \quad 40 < W < 180$ GeV
- inclusive $\equiv$ $E_{\rm fwd} > 5$ GeV cut is not applied ($E_{\rm fwd} > 5$ GeV leave 6 % of the starting p-diffractive event sample)



- CS ME fixed (at NLO) by $\Gamma_{J/\psi \rightarrow\ l^+l^-}$
- CO MEs used are consistent with the CDF measurements
- the computed LO CO contributions overshoot LO CS one

$\Rightarrow$ LO CS undershoots data by large factors
$\Rightarrow$ including CO better normalization but different shapes
$\Rightarrow$ adding the inelastic definition does not seem to help CO

Summary and outlook

- open charm:
  - NLO predictions work reasonably for c production at HERA
  - sensitivity to non–perturbative input parameters ($c \to D^*$, ϵ, m_c ...)
  - first studies on charm excitation in the photon
  - direct gluon density extraction already performed
- open beauty: first measurements of open b production indicate a cross section higher than expected
- J/ψ:
  - in photoproduction at HERA the effect of CO MEs seems to be modest
  - in DIS at HERA the CO picture is not in good agreement with data
- luminosity upgrade: $>$ 2000 HERA will run at 150 pb^{-1}/year (the largest data sample used in the talk was $<$ 40 pb^{-1} !)
  $\Rightarrow \sim$ 1 fb^{-1} by 2005
- detector upgrade: H1 already installed a Si–MVD and ZEUS will be ready by 2000