HEAVY FLAVOUR PHYSICS AT HERA

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for the ZEUS and H1 Collaborations

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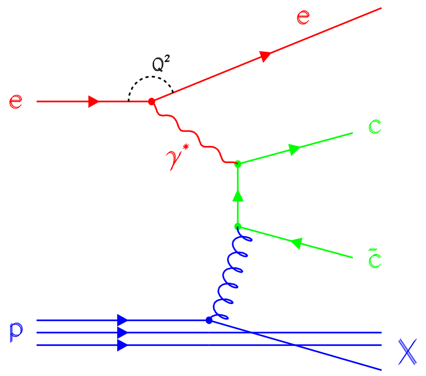
Outline

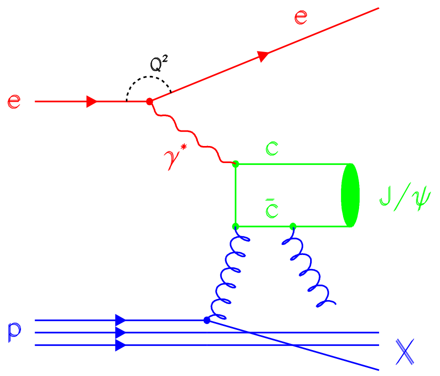
- **Introduction**
- **Measurement of F_2^{charm}**
- **Gluon Density $x\, g(x, \mu)$**
- **b production**
- **Inelastic Production of Charmonium**
- **Conclusions**

Introduction

At HERA 27.5 GeV $e^{\pm}$ collide with 820 GeV protons,
$\sqrt{s} = 300$ GeV

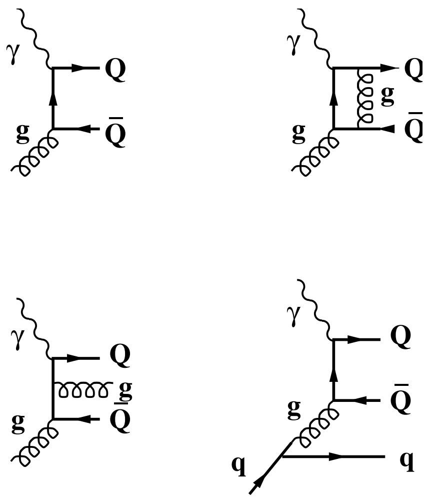
Heavy flavours mainly produced in pairs by photon gluon fusion (in LO QCD)





Other contributions: ”Resolved” Processes, Charm excitation...????

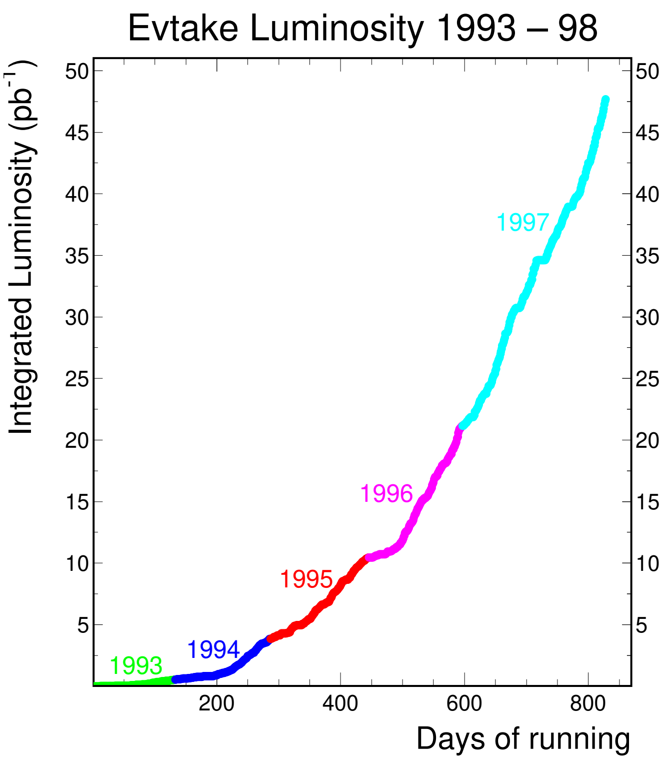
In general NLO QCD calculations available



- Tests of QCD and non perturbative questions (factorisation,..)
- Determination of gluon density in proton

Introduction

Luminosity increase from first collisions in 1993:



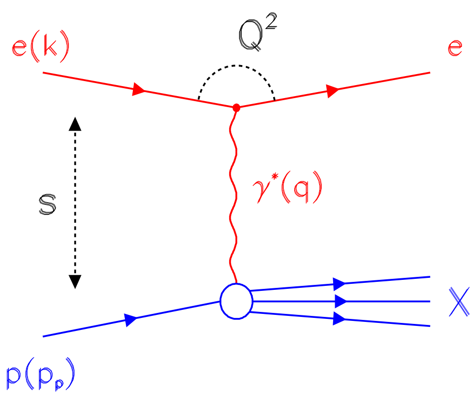
Data used in analyses

0.5 pb^{-1}	in 1993
3.0 pb^{-1}	in 1994
6.0 pb^{-1}	in 1995 $\longleftarrow$
10 pb^{-1}	in 1996 $\longleftarrow$
26 pb^{-1}	in 1997 $\longleftarrow$

useful for data analysis

this talk will cover analyses of data from the 1995 to 1997 data taking periods

Kinematic Variables

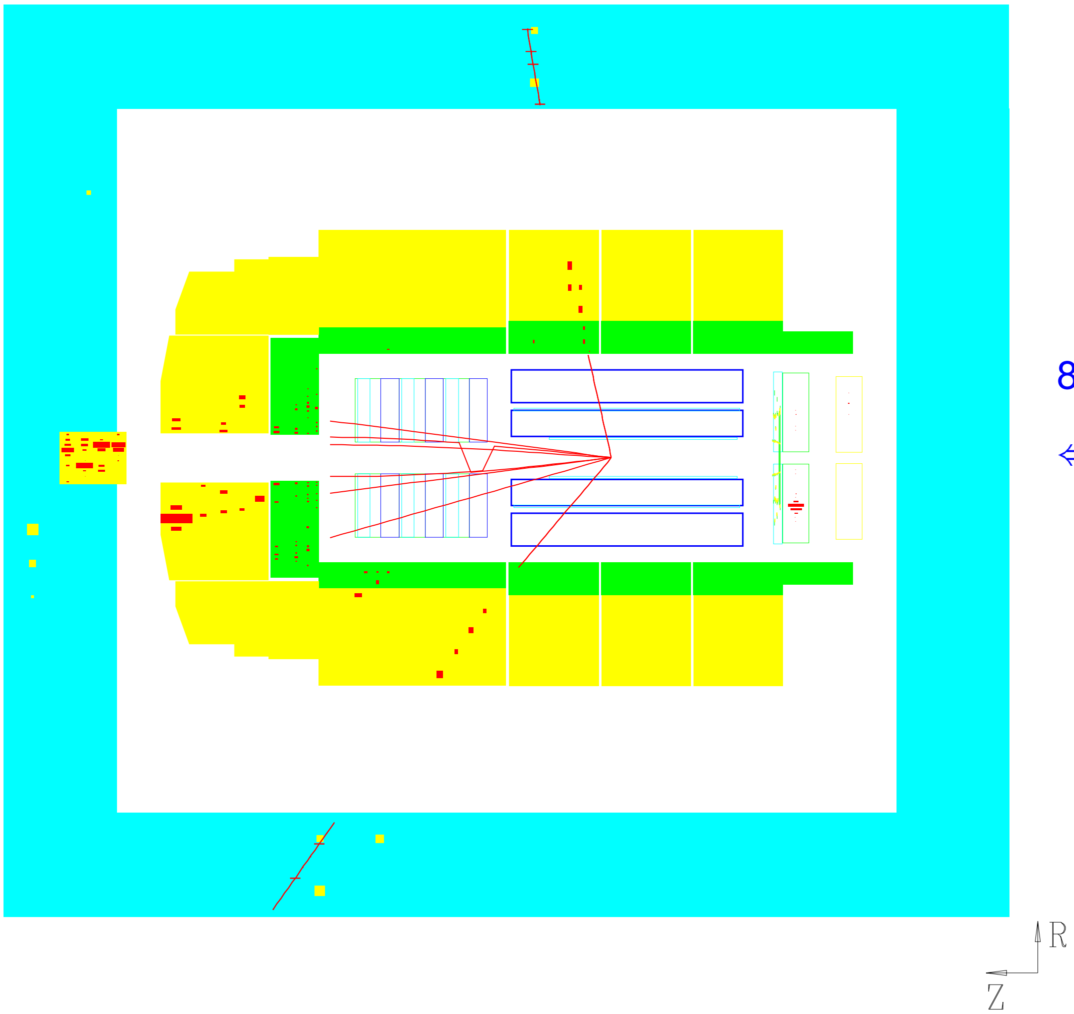


$$
\begin{aligned}
s &= (k+P)^2 \sim 2kP \\
Q^2 &= -q^2 = -(k-k')^2 \\
x &= \frac{Q^2}{2P\cdot q} \\
y &= \frac{q\cdot P}{k\cdot P} \\
W^2_{\gamma p} &= (q+P)^2 = sy - Q^2 \\
&= Q^2\,(1-\frac{1}{x})
\end{aligned}
$$

Introduction

27.5 GeV

$e^{\pm} \Longrightarrow$



820 GeV

$\Longleftarrow p$

Electron taggers at 33 m and 44 m $\Longrightarrow$

No Analysis with Si-Vertex Detectors yet, only preview...

The scattered lepton

- identified in main detector *(Electroproduction, DIS, $Q^2 > 1\,\mathrm{GeV}^2$)*
- lost in the beampipe or detected at small angles w.r.t. the lepton beam *(photoproduction, $Q^2 \sim 0$)*

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

Inclusive cross section for production of charm $ep \to e\, c\bar{c}\, X$ can be written as:

$$\frac{d^2\sigma^{ep\to e\, c\bar{c}\, X}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(1+(1-y)^2)\cdot F_2^{c\bar{c}}(x,Q^2)$$

F_L gives only % contribution and is neglected.

- Analysis in restricted region of Q^2, y, p_t, η
- correct for detector effects with MC: HERWIG, AROMA, RAPGAP...
- Extrapolate differential cross sections to full kinematic range using NLO QCD calculations (B.W. Harris, J. Smith; Laenen, Riemersma, Smith, van Neerven)

Important parameters:

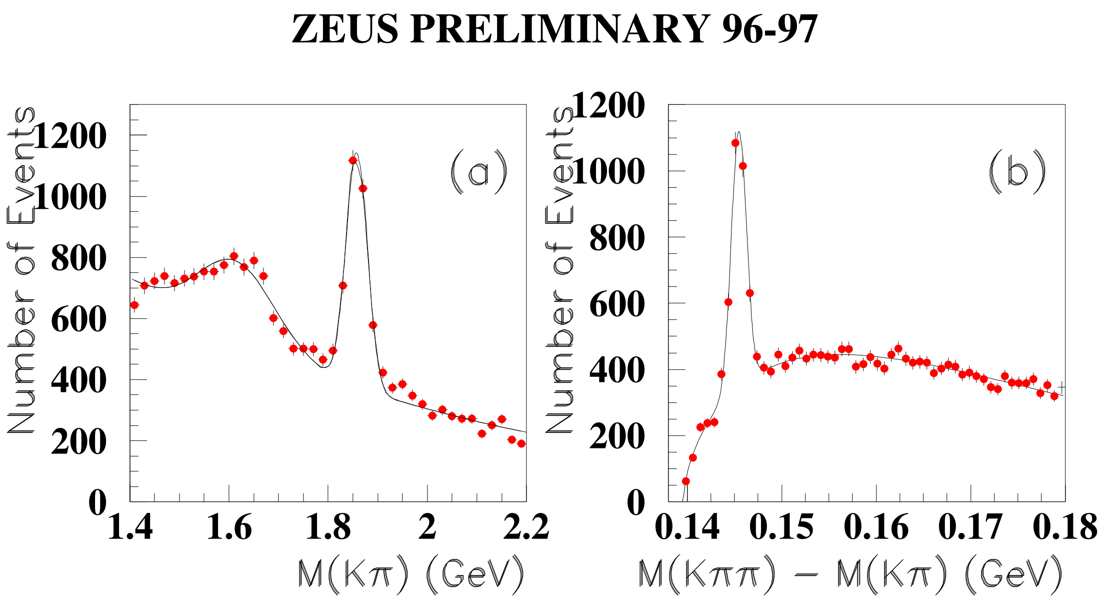
- QCD scalesμ for renormalisation and factorisation,
  $\mu_R = \sqrt{Q^2 + 4\, m_c^2}$: $\mu_F = \mu_R$ in DIS
  $\mu_R = \sqrt{p_t^2 + m_c^2}$: $\mu_F = 2\mu_R$ in photoproduction
- quark massesm_c, m_b
- Λ_{QCD}
- fragmentation, e.g. Peterson ϵ_c (in general from e^+e^-)

Charm Tagging

Charm is tagged through the detection of $D^{*\pm}$ mesons

$$D^{*+} \longrightarrow D^0\pi_s^+ \longrightarrow K^-\pi^+\pi_s^+ \quad \text{H1,ZEUS}$$
$$\longrightarrow K^-\pi^+\pi^-\pi^+\pi_s^+ \quad \text{ZEUS photoproduction}$$

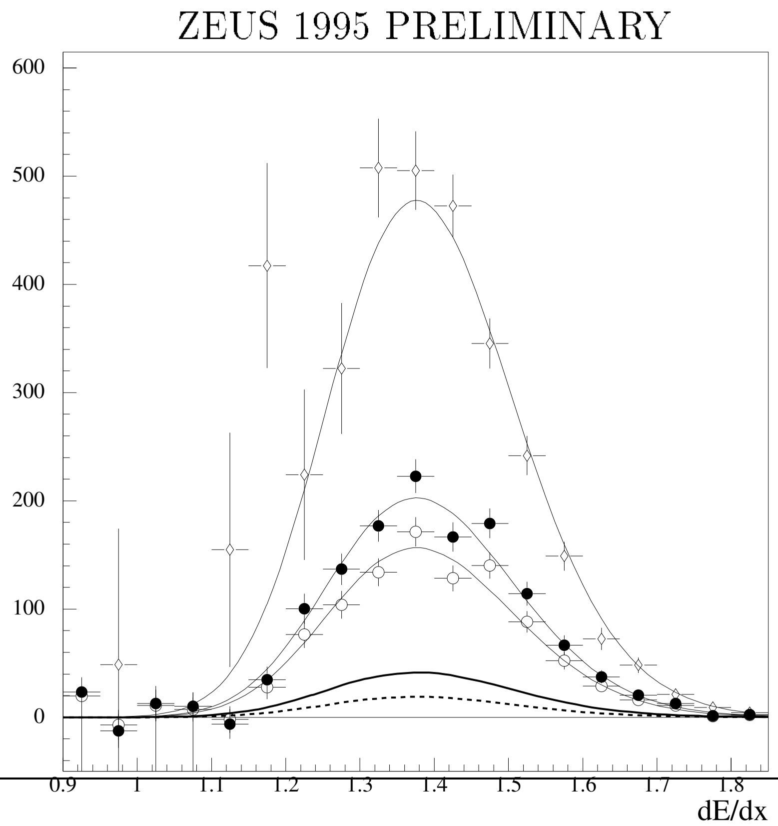
and charge conjugate



And semileptonic decay

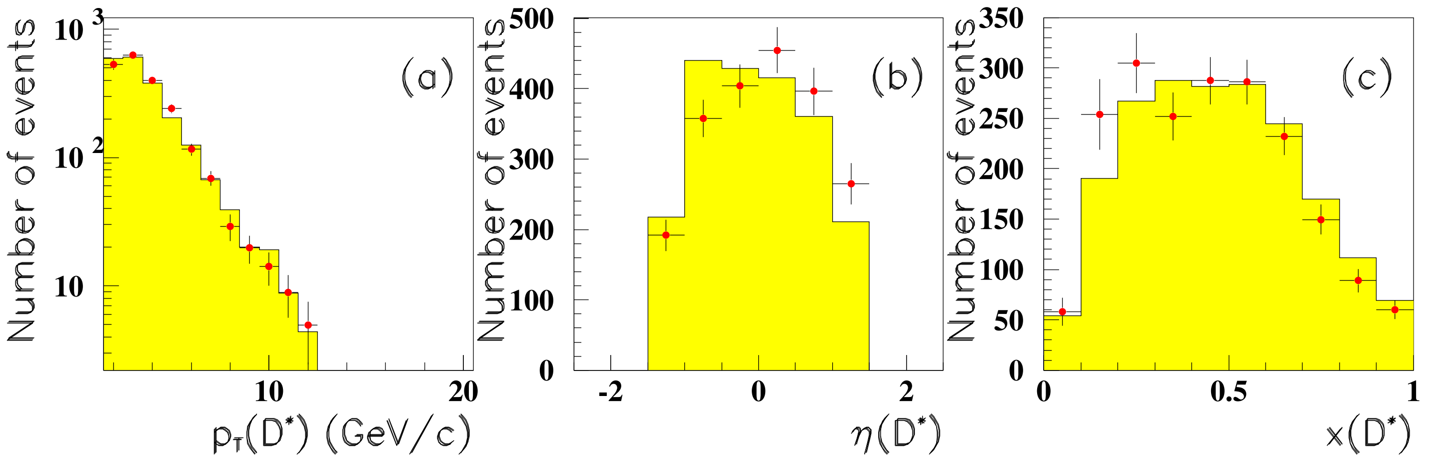
$c \to e^{\pm} + ...$

Electron identified
in el.mag. calorimeter
and by dE/dx
in tracking chamber

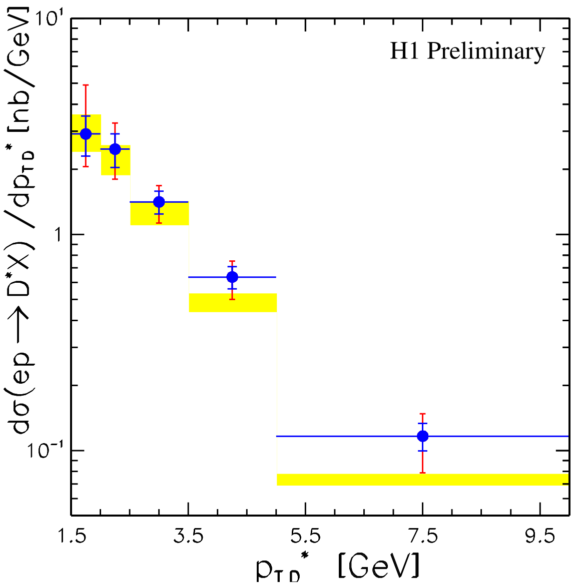


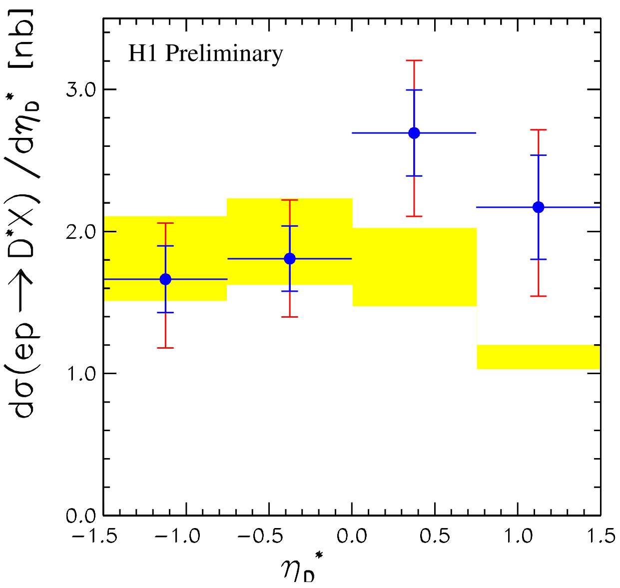
D^* production **DIS**

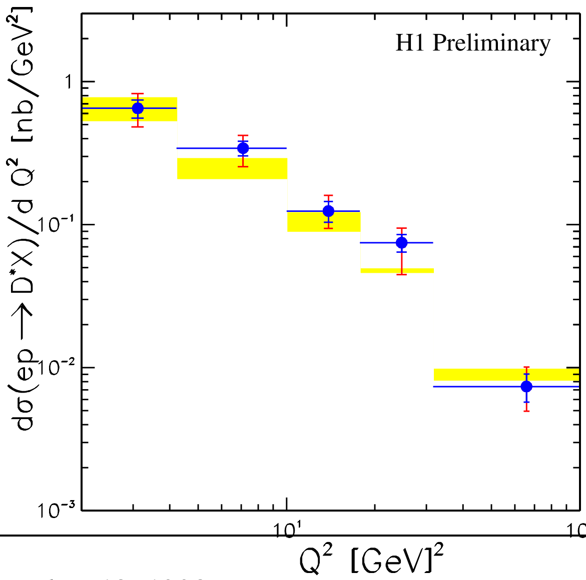
ZEUS: Data ($36\,\mathrm{pb}^{-1}$, 1996+97) vs Monte Carlo RAPGAP (detector level)



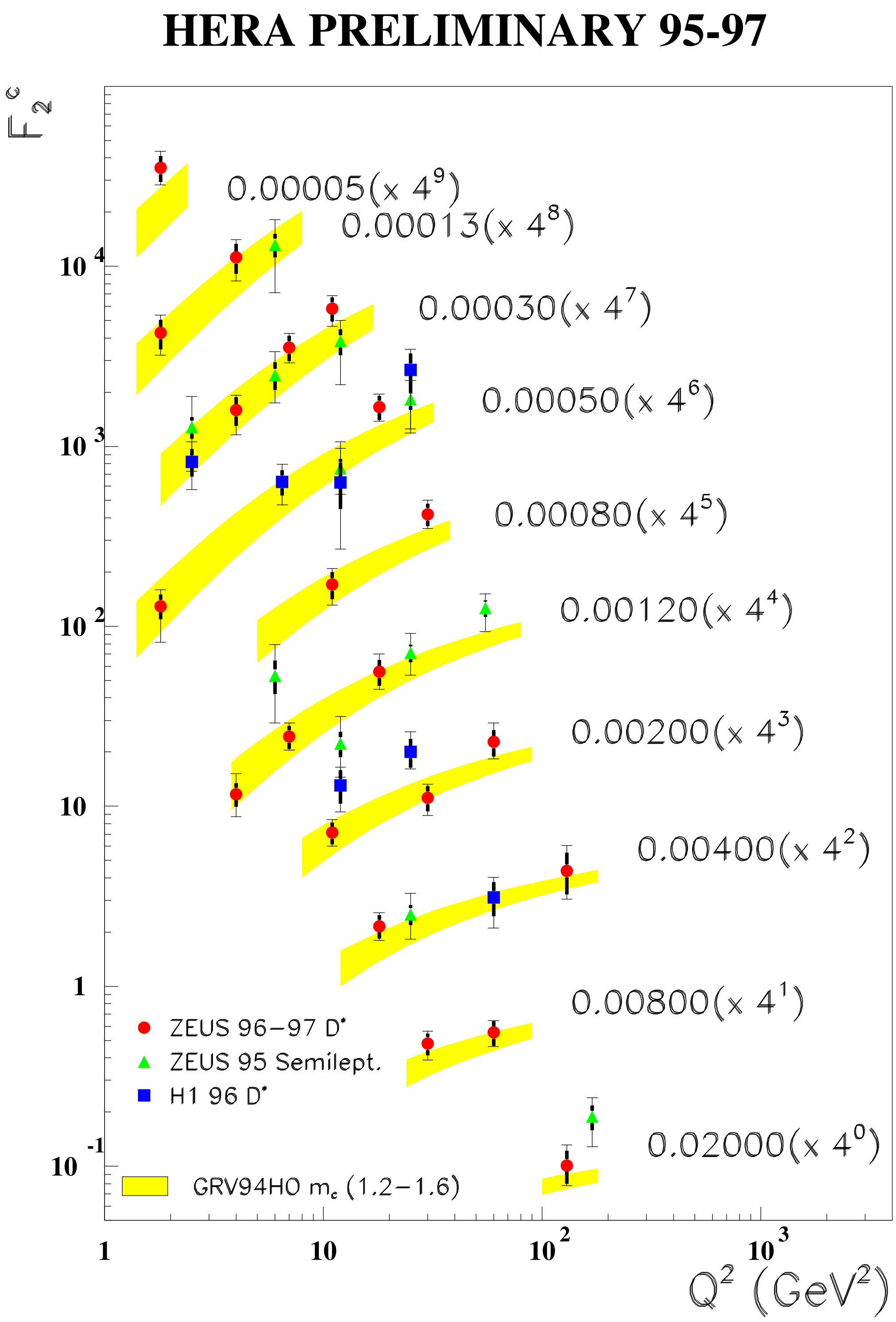
H1: Corrected Data ($7\,\mathrm{pb}^{-1}$, 1996) vs NLO calculations (HVQDIS,(Harris and Smith)



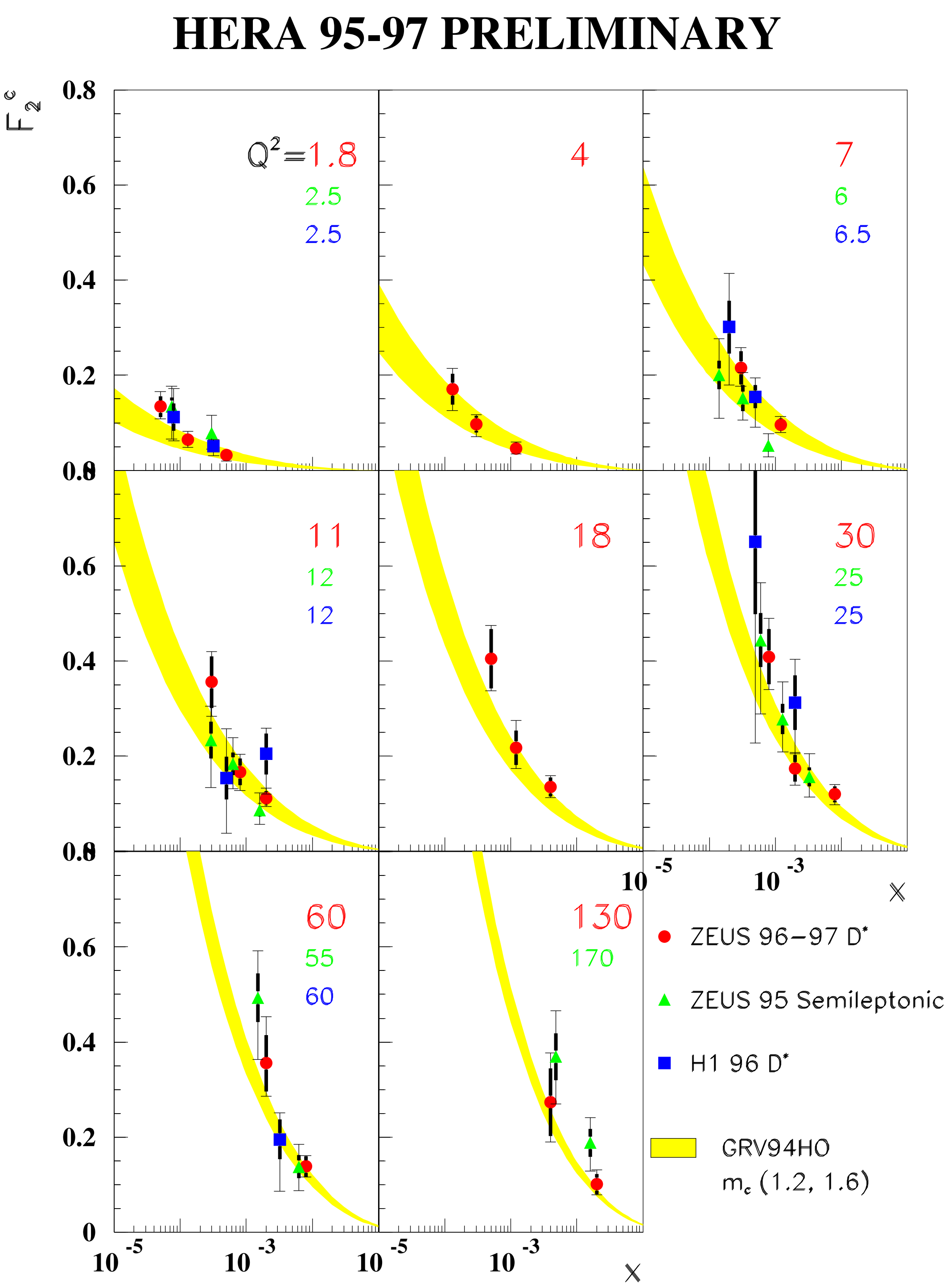




$F_2^{c\bar{c}}$ from H1 and ZEUS



Strong scaling violations
Good agreement between data and NLO calculations

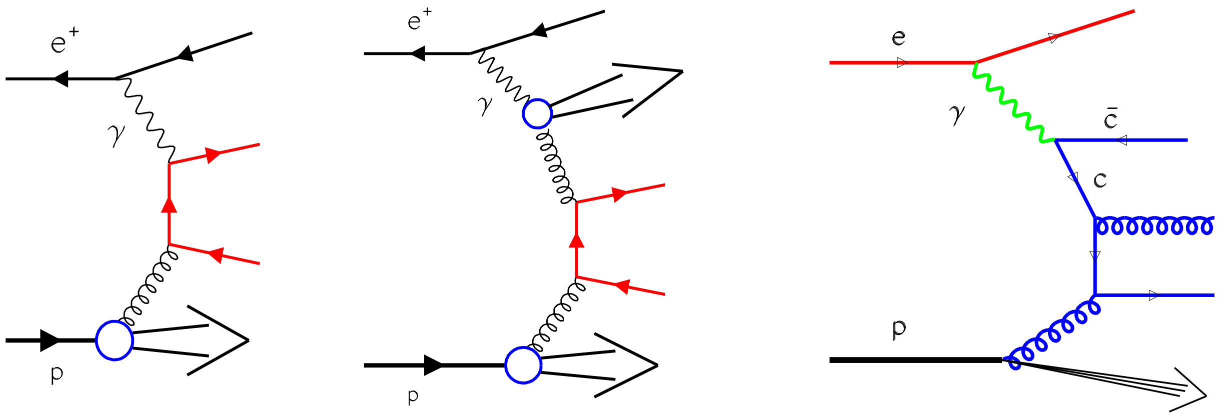


Strong rise of $F_2^{c\bar{c}}$ towards low x

Ratio $F_2^{c\bar{c}}/F_2$ about $10-30\%$ depending on Q^2 and x

D^* Photoproduction

Photon almost real, $Q^2 \to 0$
Additional contribution by resolved processes, LO diagrams:



In NLO only sum of contributions well defined

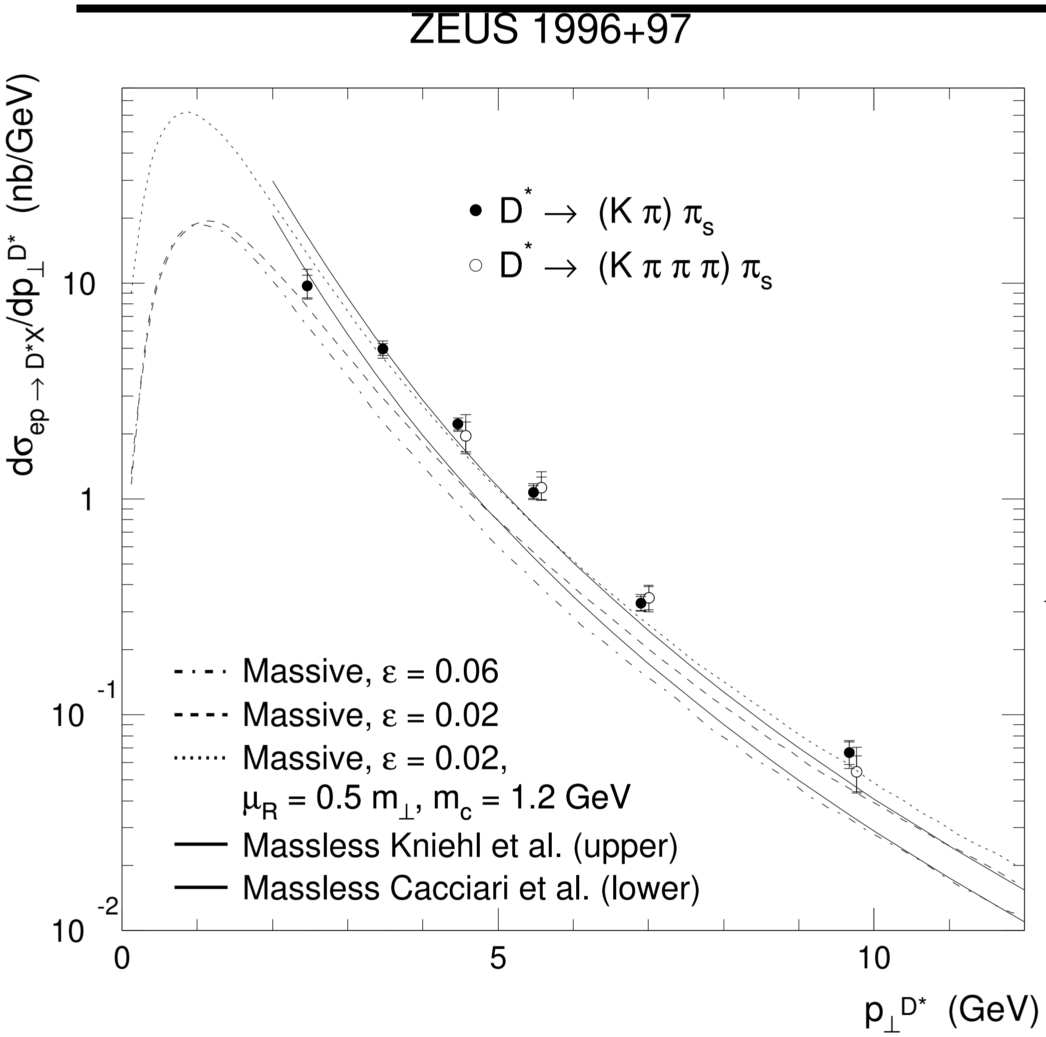
- Two different approaches for NLO pQCD calculation
  - ▷ massive charm calculation (S. Frixione et al., Nucl. Phys. B454 (1995) 3)

    (u, d, s) only are active flavours in the proton and in the photon, $m_c \gg \Lambda_{QCD}$
  - ▷ massless charm approach

    (M. Cacciari et al., DESY 96–146 and 97—029, B. Kniehl et al., DESY 96–210, 97–012,97–241)

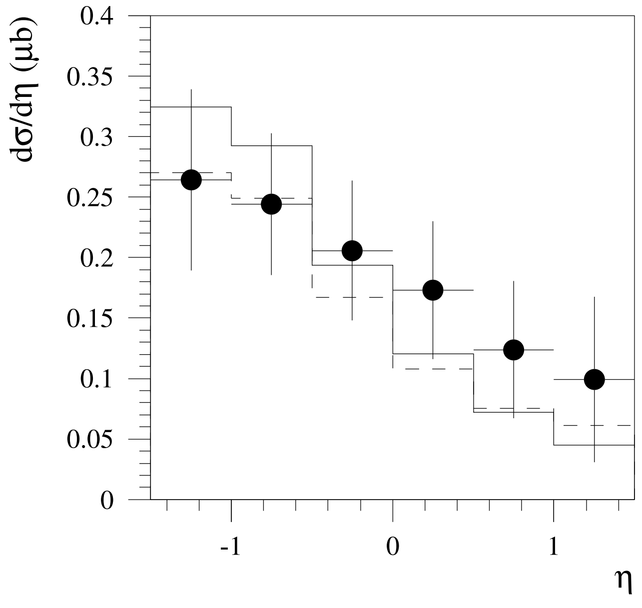
    (u, d, s) and charm are active flavours inside the proton and the photon; expected to be valid at $p_t \gg m_c$

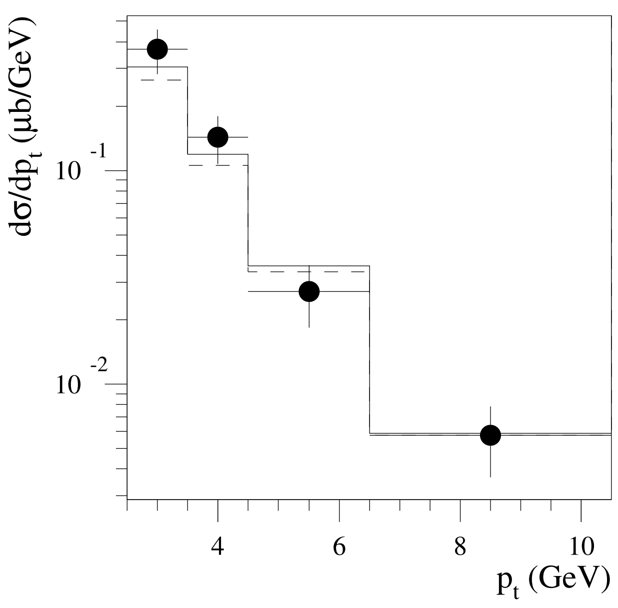
D^* Differential Cross Sections

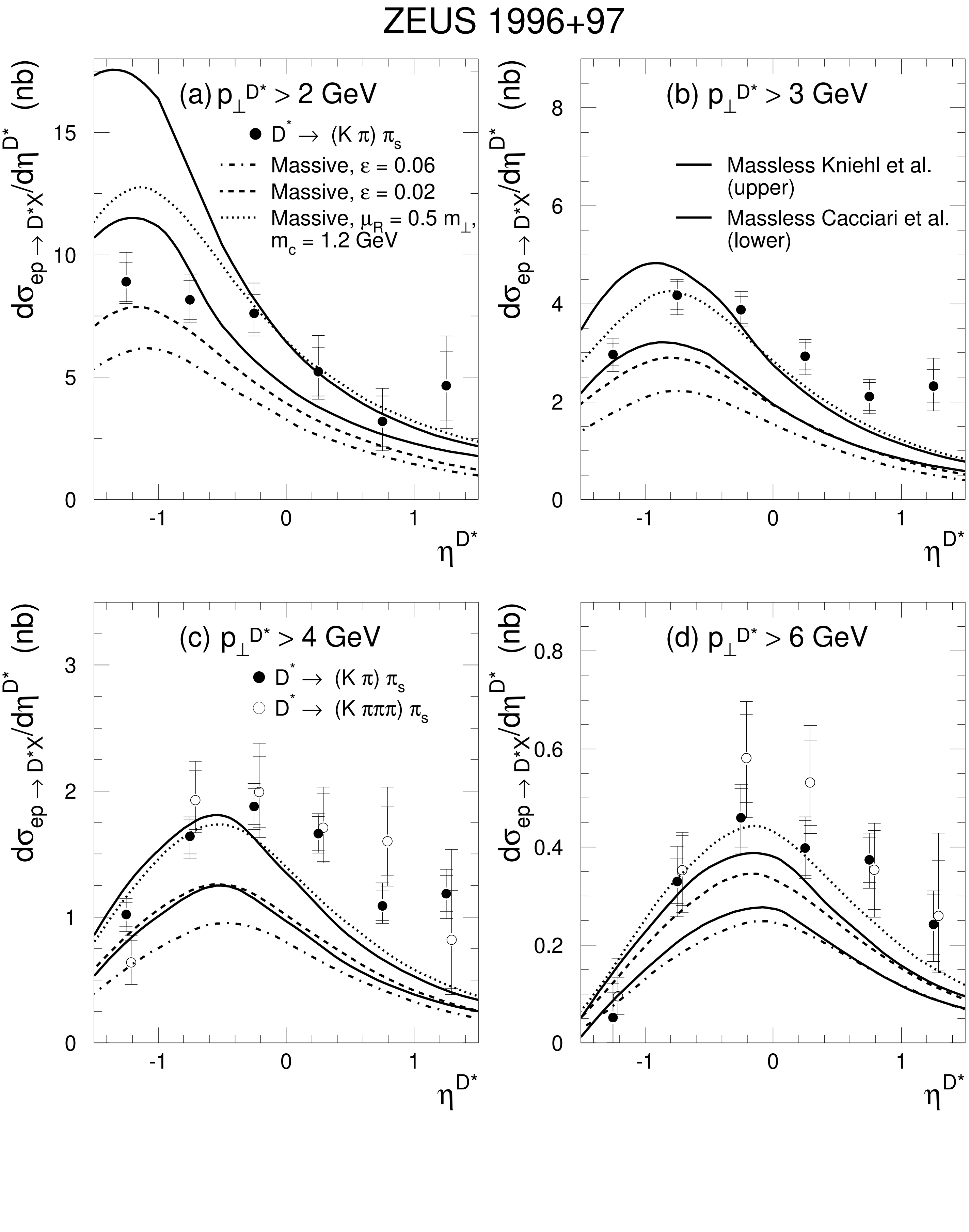


$Q^2 < 1\mathrm{GeV}^2$
$130 < W_{\gamma p} < 280$ GeV
$p_t^{D^*} > 2$ GeV
$|\eta^{D^*}| < 1.5$

H1 1995+96, $W_{\gamma p} \sim 194$ GeV, $p_t^{D^*} > 2.5$ GeV, $|\eta^{D^*}| < 1.5$





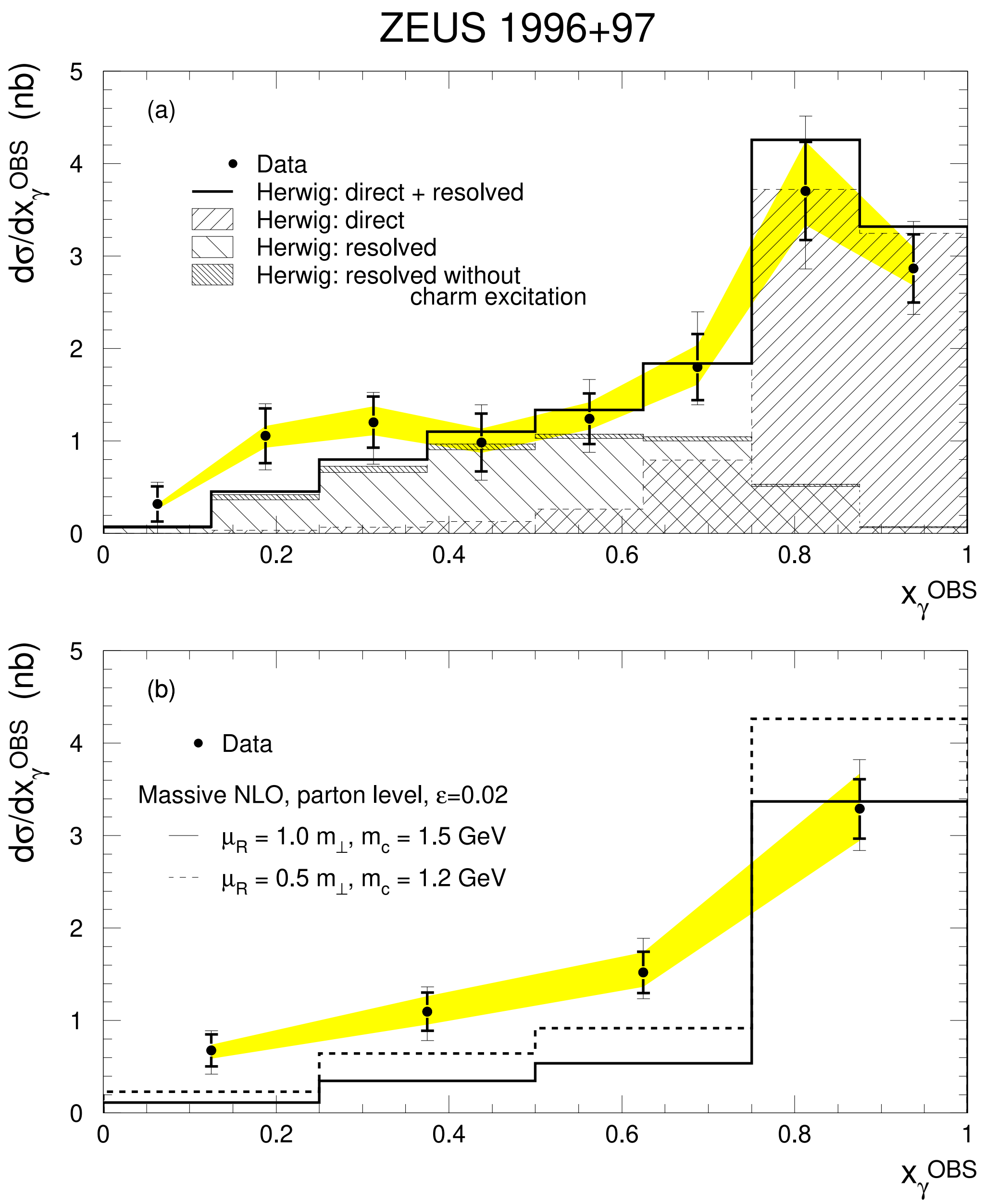


ZEUS 1996+97
(a) $p_\perp^{D^*} > 2$ GeV
(b) $p_\perp^{D^*} > 3$ GeV
(c) $p_\perp^{D^*} > 4$ GeV
(d) $p_\perp^{D^*} > 6$ GeV
$D^* \to (K\pi)\pi_s$
$D^* \to (K\pi\pi\pi)\pi_s$
Massive, $\varepsilon = 0.06$
Massive, $\varepsilon = 0.02$
Massive, $\mu_R = 0.5\ m_\perp$, $m_c = 1.2$ GeV
Massless Kniehl et al. (upper)
Massless Cacciari et al. (lower)
$d\sigma_{ep \to D^*X}/d\eta^{D^*}$ (nb)
η^{D^*}

Charm in Photon?

Analyse events with a D^* and 2 Jets ($E_t > 6$ and 7 GeV)
Reconstruct relative momentum of interacting parton out of photon x_γ

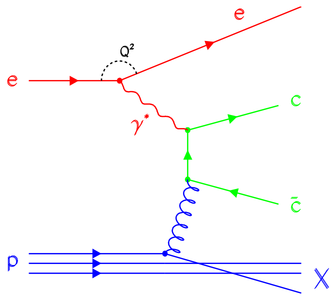
$$x_\gamma = \frac{\sum_{\text{jets}} E_T \cdot e^{-\eta}}{2 \cdot E_e \cdot y}$$



Observe large tail towards low x_γ
Contribution of charm excitation from photon required (LO MC HERWIG)

Gluon Density from D^* (H1)

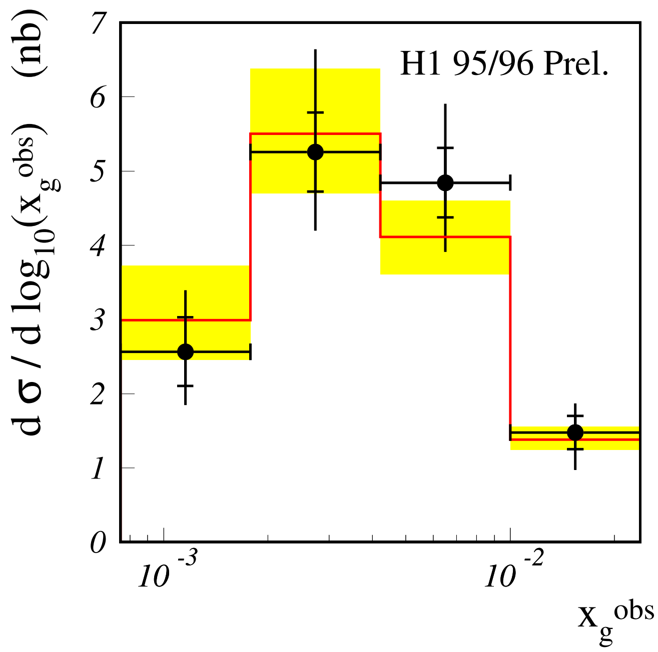
H1 Analysis, photoproduction and DIS, $10\,\mathrm{pb}^{-1}$,
Kinematic range:

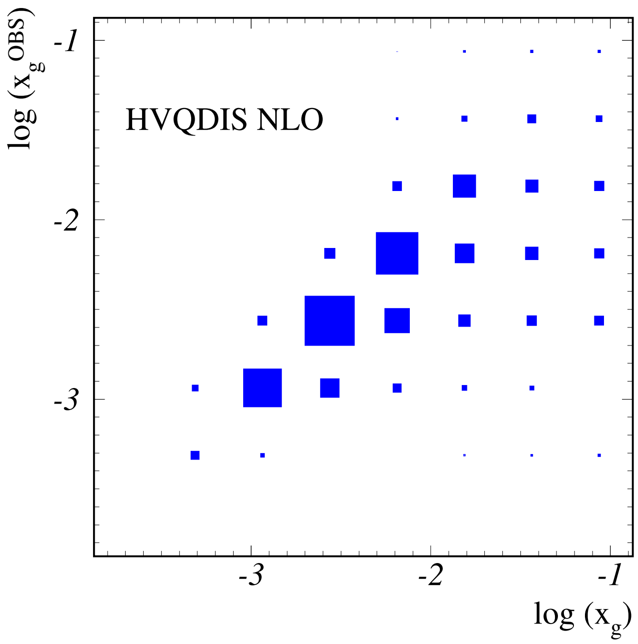


photoprod.	$0.02 < y < 0.32, \quad Q^2 \sim 0$
	$0.29 < y < 0.62,$
DIS	$0.05 < y < 0.7, \quad 2 < Q^2 < 100\,\mathrm{GeV}^2$

- From kinematics reconstruct momentum fraction of gluon x_g^{obs}
- Determine cross section $d\sigma/dx_g^{obs}$
- Unfold to TRUE x_g using NLO QCD program (with fragmentation)
- Assume only photon gluon fusion (additional cuts in photoproduction)

DIS

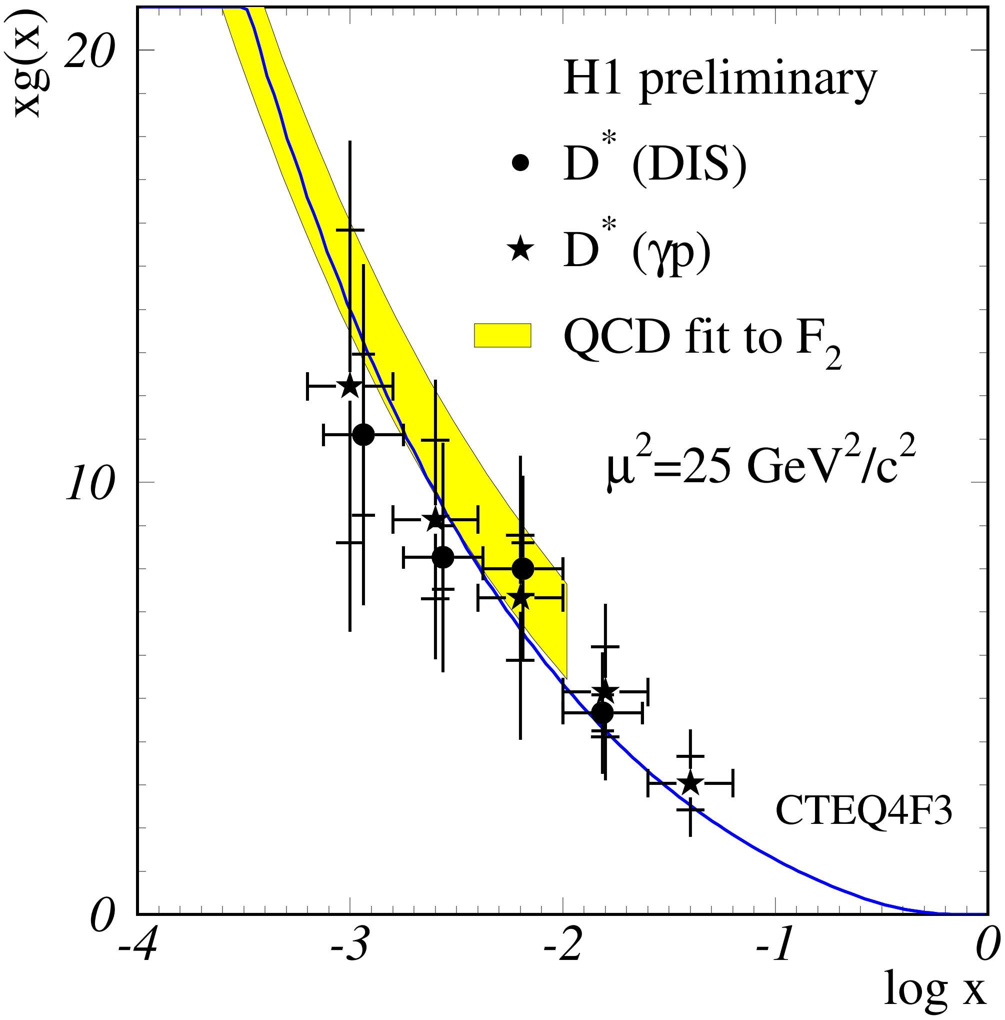




Gluon Density from D^*

The gluon density is obtained from the cross section measurement by

$$g(x_{g,i},\mu^2)^{exp} = g(x_{g,i},\mu^2)^{th} \cdot \frac{\sigma(x_{g,i})^{exp}}{\sigma(x_{g,i})^{th}} \qquad \mu^2 = \text{QCD scale}$$



Error dominated by statistics and fragmentation uncertainties

Observation of $b\bar{b}$ Production

Cross Section predicted to be LOW: $\sigma_{c\bar{c}} : \sigma_{b\bar{b}} \approx 200 : 1$

BUT: Theoretical uncertainties smaller due to larger mass of b quark ($\rightarrow$ QCD scale)

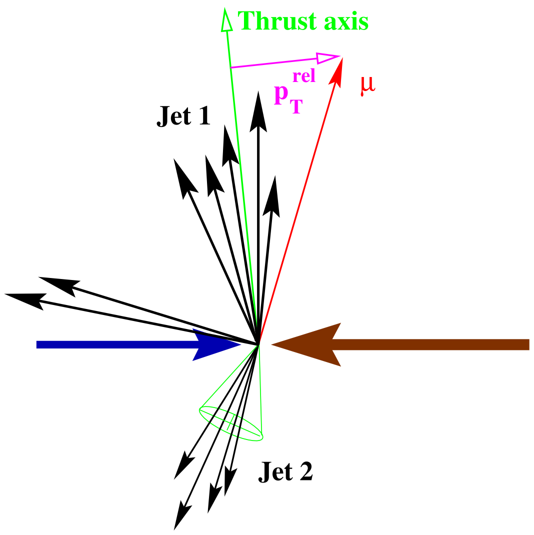
THE METHOD:

events with two jets — cone algorithm, $R = \sqrt{\Delta\Phi^2 + \Delta\eta^2} < 1$; $E_T^{jet} > 6$ GeV

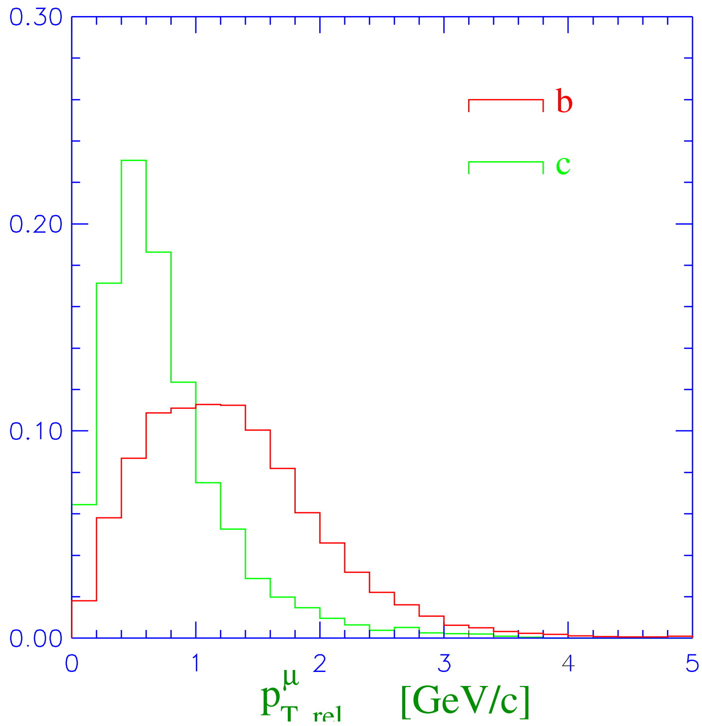
and

one muon — $p_T > 2$ GeV, $35° < \theta^\mu < 130°$

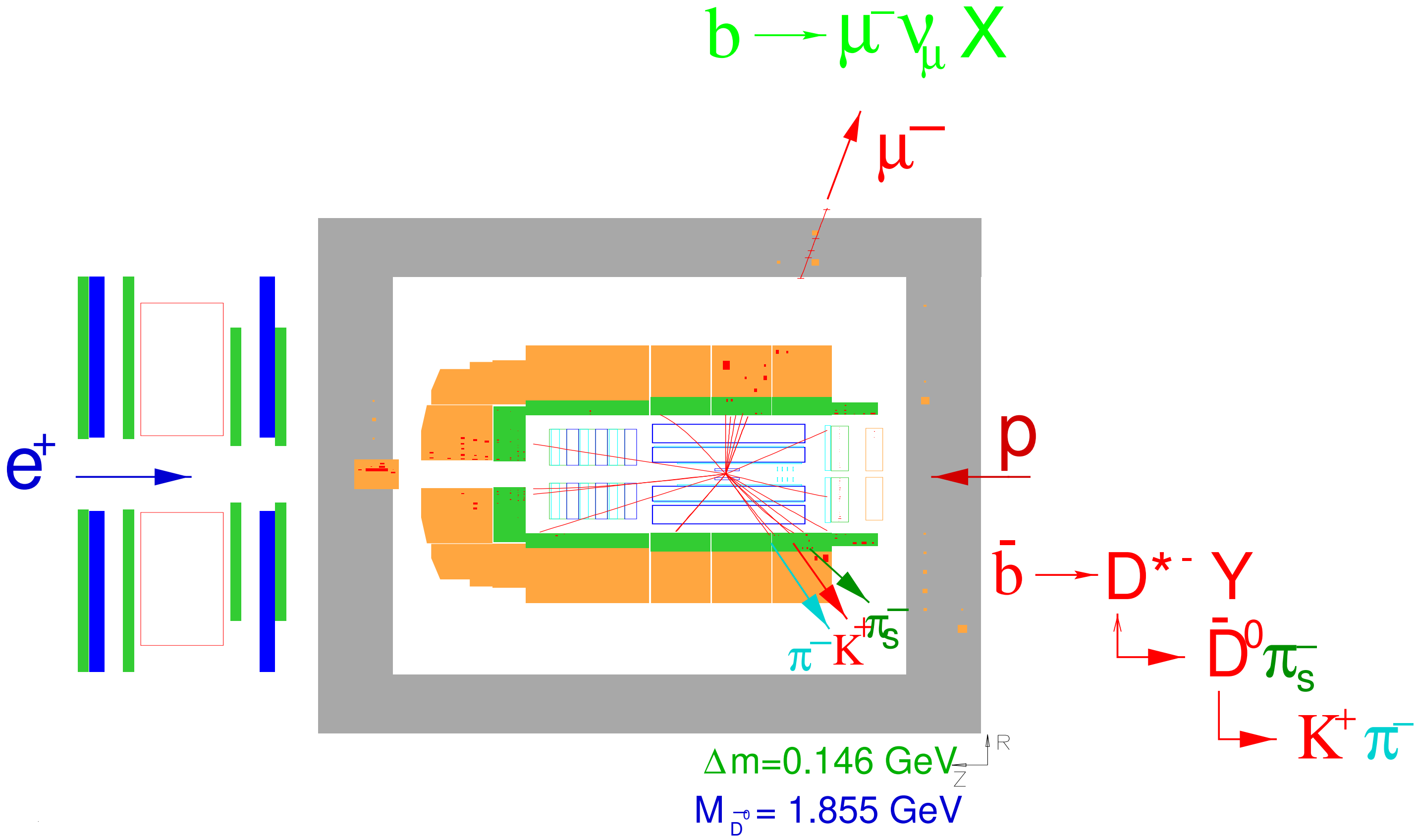
use transverse momentum of muon with respect to the jet axis (THRUST) as discriminating variable.



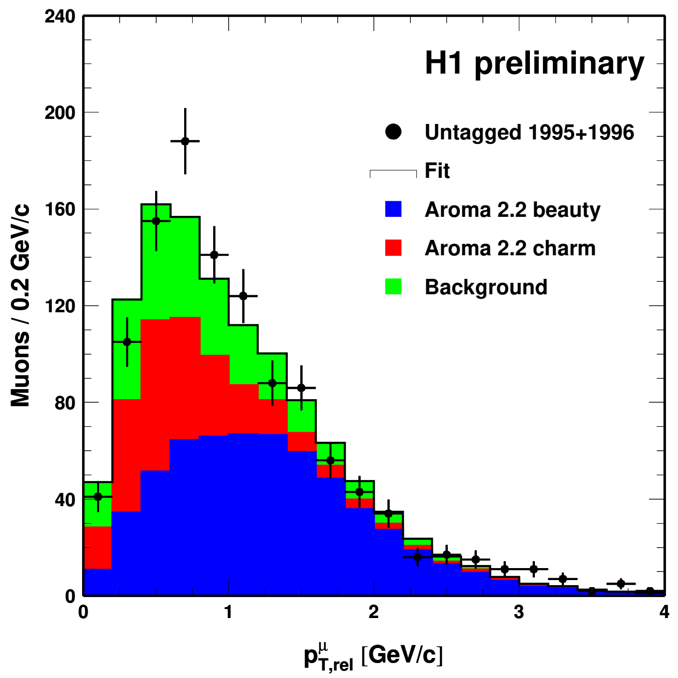
Thrust T = max $\frac{\sum |p_i^L|}{\sum |p_i|}$



Observation of $b\bar{b}$ Production



Observed $b\bar{b}$ cross-section



Fit contributions:

$b\bar{b}$	$51.4 \pm 4.4\%$
$c\bar{c}$	$23.5 \pm 4.3\%$
background from data and MC	$23.5\%\ (fixed)$

- Data: $\mathcal{L} = 8.3$ pb^{-1}
- Visible range:

$$Q^2 < 1\,\mathrm{GeV}^2 \quad ; \quad p_{T,lab} > 2.0\ \mathbf{GeV}$$
$$95 \lesssim W_{\gamma p} \lesssim 270\ \mathbf{GeV} \quad ; \quad 35^\circ < \theta^\mu < 130^\circ$$

- Visible b production cross section

$$\sigma(ep \to b\bar{b} + X)^{vis} = 0.93 \pm 0.08^{+0.17}_{-0.07}\ \text{nb}$$

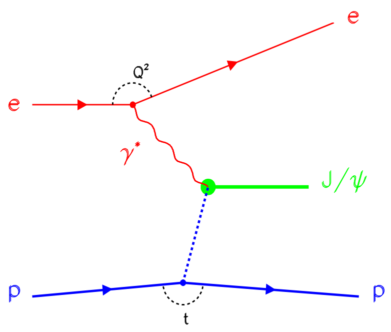
- AROMA 2.2: (direct, LO, MRSG, $m_b = 4.75$ GeV) predicts:

$$\sigma^{vis}_{b\bar{b}} = 0.19\ \text{nb}$$

- $\sigma_{c\bar{c}}$ consistent with previous D^* measurements $\sim 1\,\mu b$

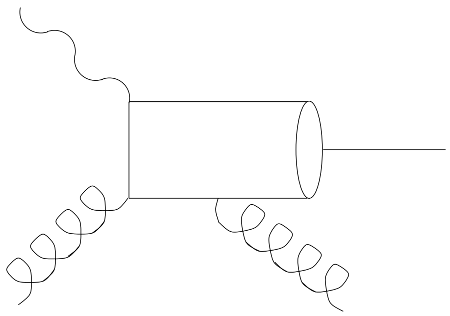
J/ψ Production

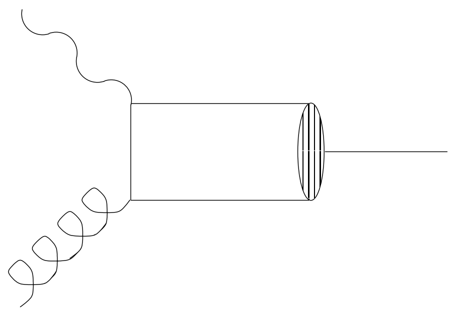
New data from ZEUS and H1 on J/ψ, ψ', Υ in inelastic and diffractive processes
concentrate on inelastic production of J/ψ in photoproduction (ZEUS) and DIS (H1)



Diffractive production of J/ψ, ψ', Υ
characteristic $t,\ W_{\gamma p},\ \theta$ dependence

Inelastic J/ψ Production calculated in pQCD:



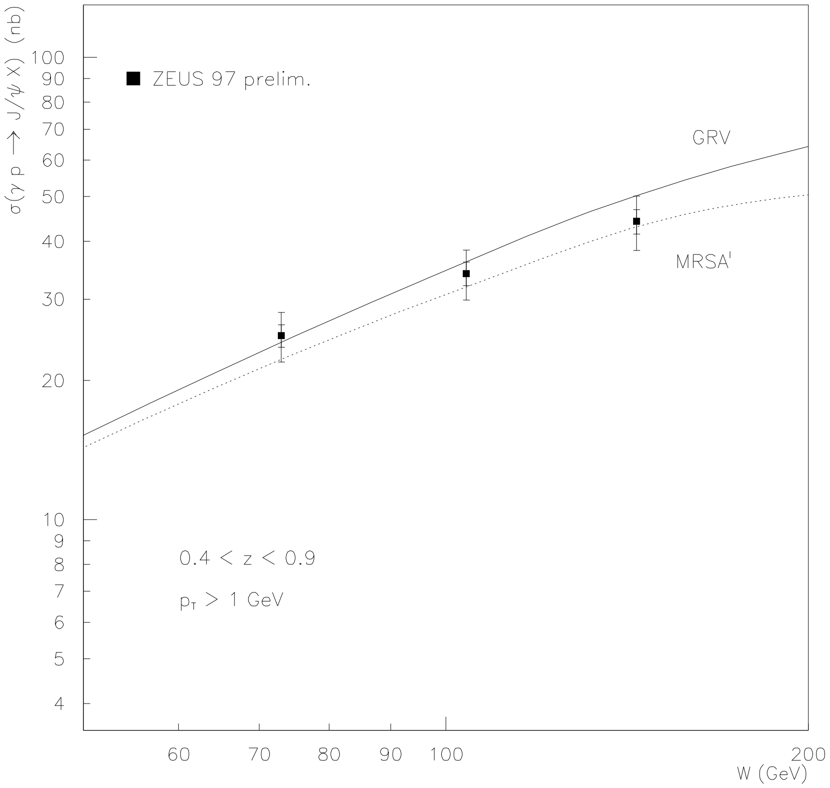


Colour Singlet **NRQCD: Colour Octet Production**

- Factorization approach/NRQCD: sum all $c\bar{c}$ states

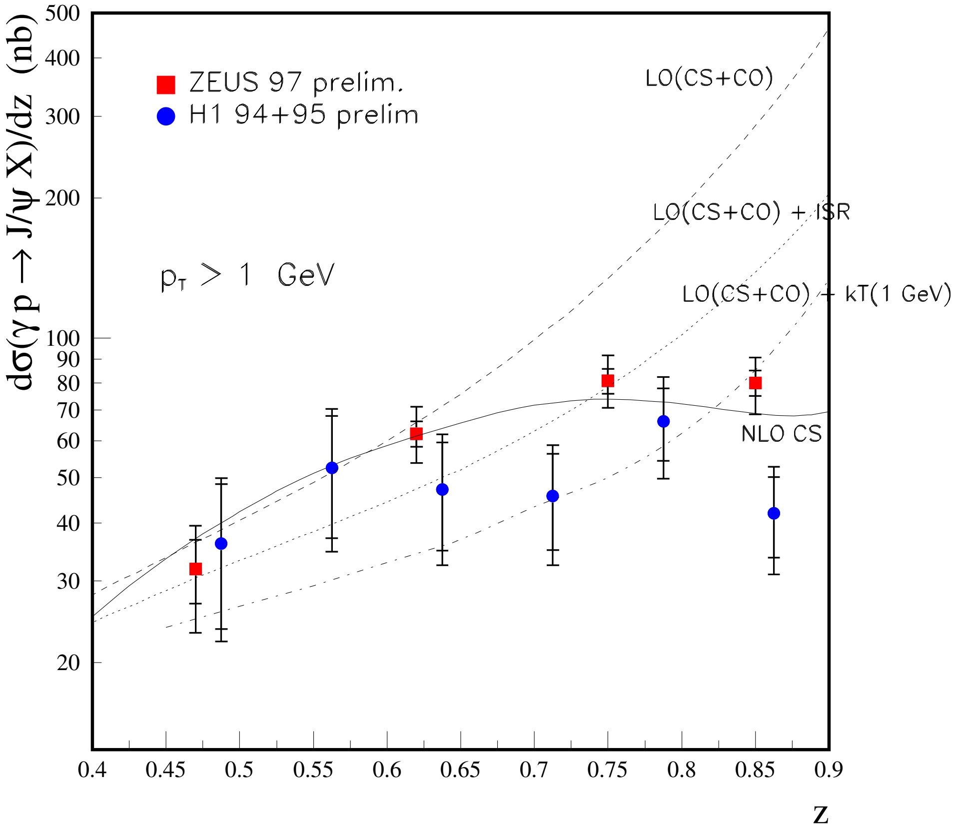
$$\sigma(A+B \to J/\psi + X) = \sum_n \hat{\sigma}_n(A+B \to c\bar{c}[n] + X)\langle 0|\mathcal{O}_n^{J/\psi}|0\rangle$$

J/ψ Cross Sections Photoproduction: $Q^2 < 1\,\mathrm{GeV}^2$



ZEUS: $Q^2 < 1$ GeV, $26\,$pb^{-1}
$50 < W_{\gamma p} < 180$ GeV
$p_t^\psi > 1$ GeV, $0.4 < z < 0.9$

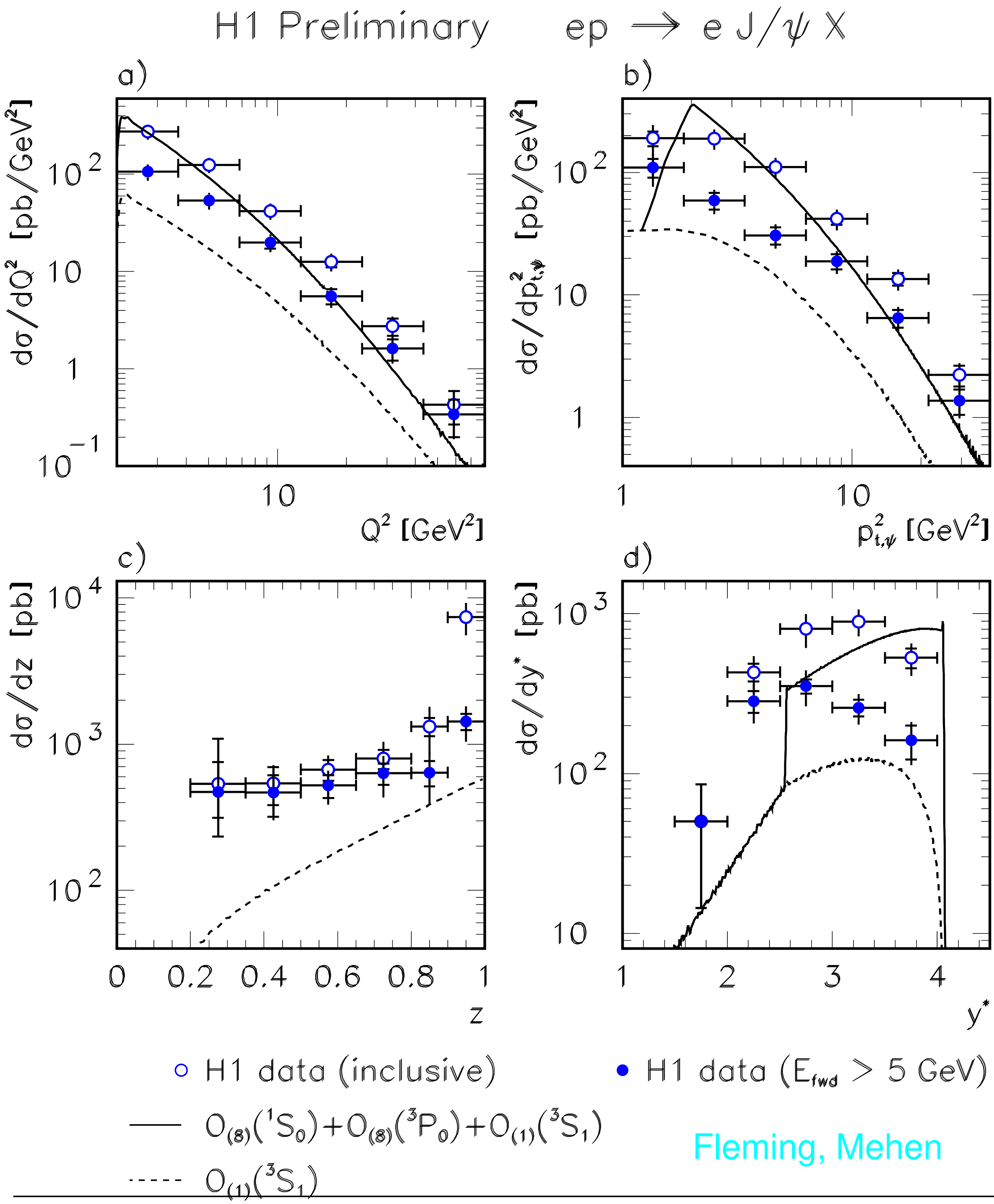
theory: Colour Singlet Model, NLO (M. Krämer et al.)
parameters: $\Lambda_{QCD} = 300\,$MeV, scale $\mu^2 = 2\,m_c^2$, $m_c = 1.4$ GeV



$$z = \frac{p_\psi \cdot q}{p_\psi \cdot P}$$

J/ψ Cross Sections Electroproduction: $Q^2 > 2\,\mathrm{GeV}^2$

$21\,\mathrm{pb}^{-1},\ 2 < Q^2 < 80\ \mathrm{GeV}^2,\ 40 < W_{\gamma p} < 180\ \mathrm{GeV}$



Summary

- Statistics of heavy flavour analyses considerably improved
- $F_2^{c\bar{c}}$ measured in the range $2 \lesssim Q^2 \lesssim 150\,\mathrm{GeV}^2$, down to $x_{Bj} \sim 10^{-4}$
  scaling violations at fixed x, steep rise of $F_2^{c\bar{c}}$ towards low x at fixed Q^2
  NLO pQCD calculations give good description of data.
- Photoproduction: Detailed comparisons to massive and massless NLO calculations possible; in some regions of phase space problems are revealed
- Determination of gluon density in DIS and photoproduction.
  Good agreement with indirect extraction from scaling violations in inclusive scattering
- b production measured in photoproduction:
  cross section in experimental kinematic region larger than expected from LO direct prediction
- Inelastic J/ψ production measured with increased statistics in photoproduction and DIS. No obvious need for colour octet contributions in photoproduction.
  In DIS better calculations needed.
- Future: Luminosity (and detector) upgrade in 2000
  Si Vertex Detectors (H1 now, ZEUS in 2000)