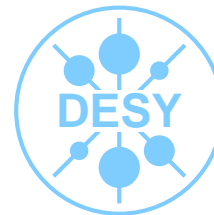
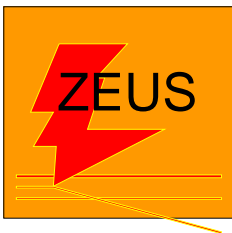


Workshop on low x physics  
Prague, September 17, 2004

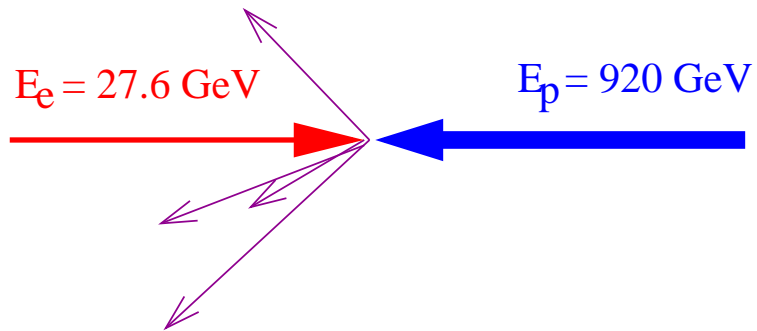
# New results on heavy flavour physics at HERA

Detlef Bartsch  
University of Bonn

- motivation
- charm
- beauty
- summary



# HERA and kinematics



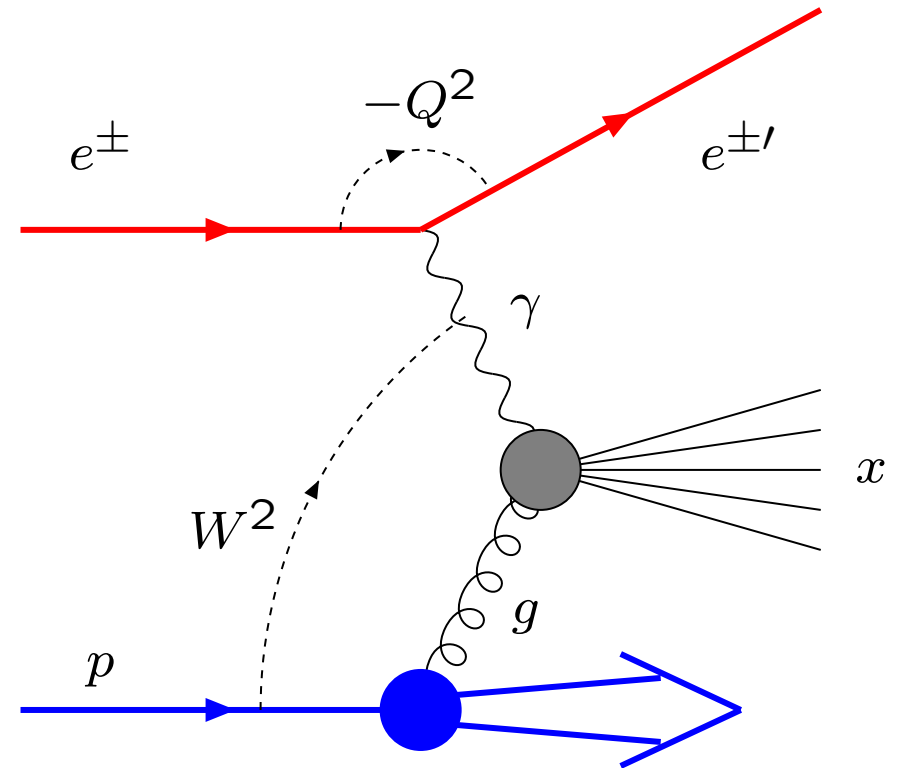
$$\sqrt{s} = 320(300) \text{ GeV}$$

$Q^2$ : 4-momentum transfer squared

$x$  : Bjorken  $x$

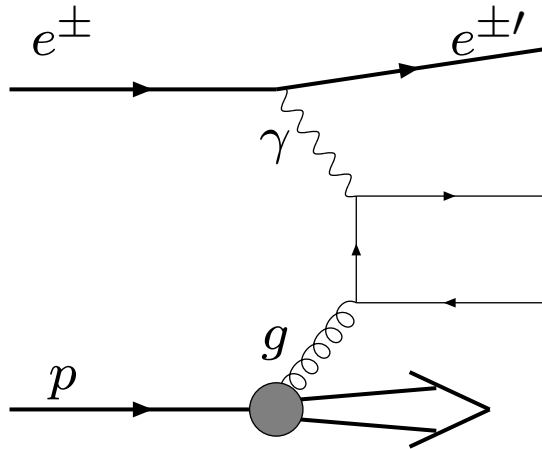
$y$  : Inelasticity

$W$  : Mass of the hadronic system



# heavy flavour production at HERA

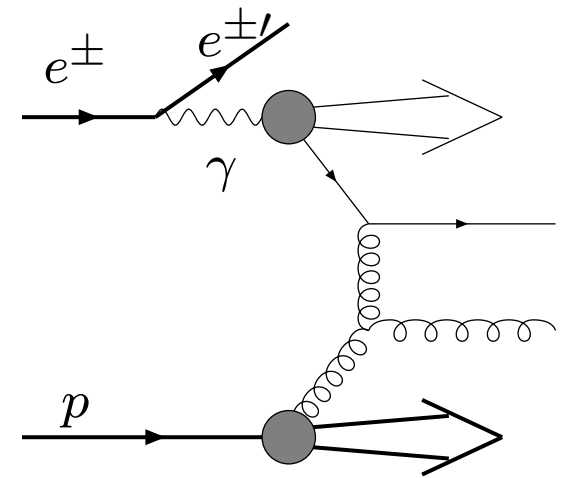
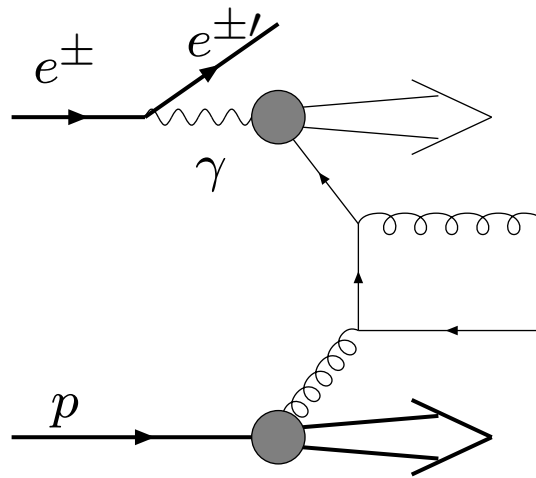
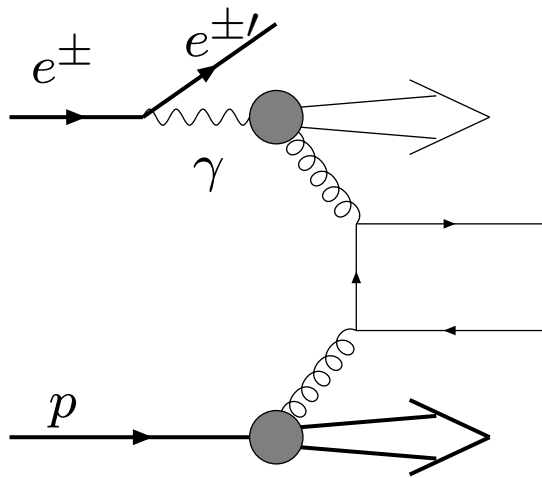
pointlike component



- Dominant process for HFL production at HERA: **boson gluon fusion (BGF)**

- Two kinematic regimes:  
 Deep Inelastic Scattering (DIS):  $Q^2 > 1 \text{ GeV}^2$   
 Photoproduction (PHP):  $Q^2 \approx 0 \text{ GeV}^2$

Important other source in PHP: **resolved component**



# QCD calculations and MC

- **Fixed order NLO calculations**  
(massive scheme)  
heavy quark produced dynamically  
 $p_t \sim m_q$ 
  - PhP: FMNR
  - DIS: HVQDIS
- **resummed NLL calculations**  
(massless scheme)  
heavy quark is active flavour of proton  
or photon  
 $p_t \gg m_q$ 
  - PhP: Cacciari et al., Kniel et al.
- **Matched scheme FONLL**  
(fixed order and NLL  $p_t$  resummation)
  - Cacciari et al.

MC generators

- **AROMA:**  
direct only,  
LO matrix elements +  
LL DGLAP evolution
- **PYTHIA, RAPGAP,  
HERWIG:**  
direct + resolved,  
LO DGLAP
- **CASCADE:**  
CCFM evolution  
 $k_t$  dependent gluon density

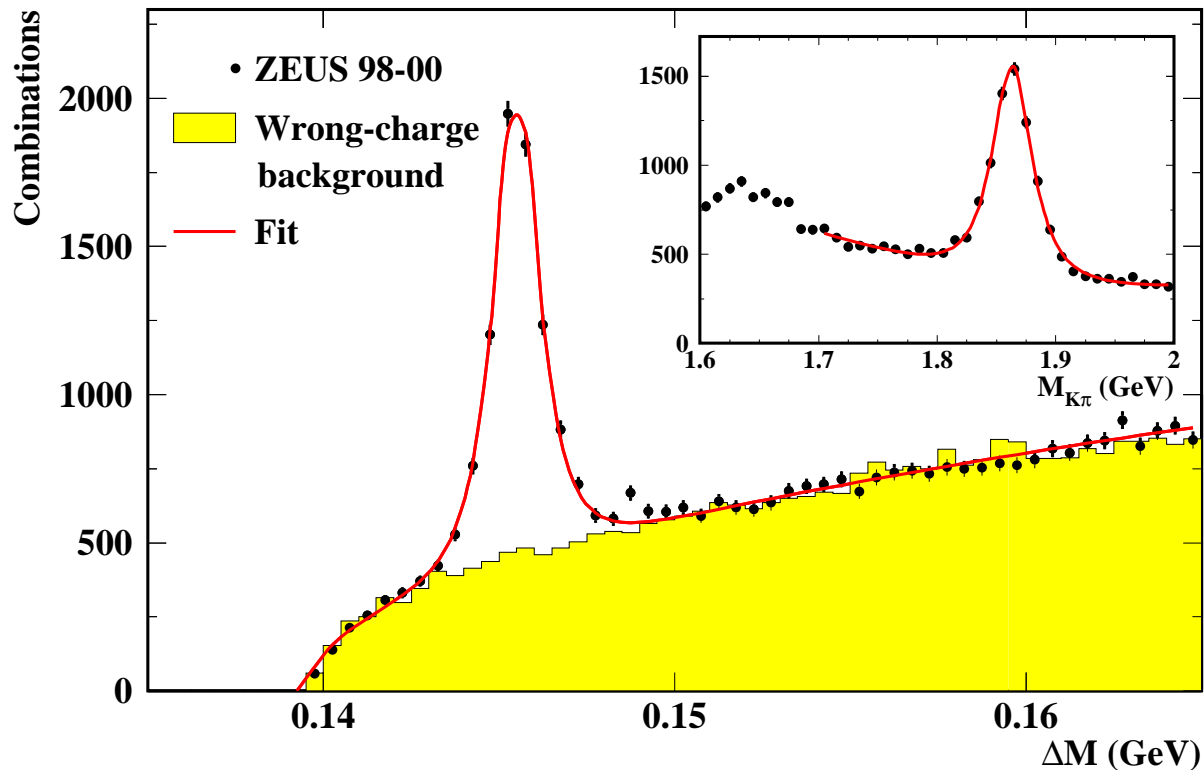
Fragmentation: non-perturbative models

# $D^*$ tagging

Charm is tagged at HERA most efficiently with the reconstruction of a  $D^*$  meson in the decay channel  $D^{*\pm} \rightarrow \bar{D}^0 \pi_s^\pm \rightarrow K^\mp \pi^\pm \pi_s^\pm$

Mass difference:  $\Delta M = M(K\pi\pi) - M(K\pi)$

## ZEUS



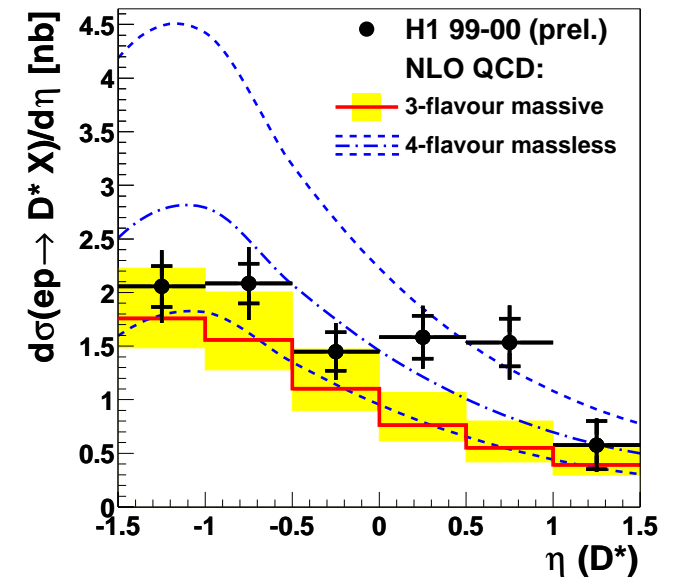
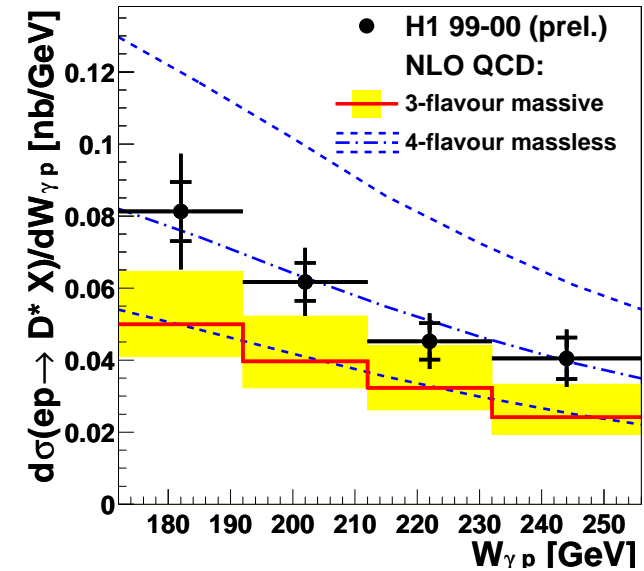
high signal/background ratio due to small phase space for the  $D^*$  decay (small combinatorical background)

# photoproduction of $D^*$

- data compared with 'massive' NLO and 'massless' NLO
- shape of  $d\sigma/dW$  described well by both
- shape of  $d\sigma/d\eta(D^*)$  less well described
- large uncertainties in theory

$$Q^2 < 0.01 \text{ GeV}^2, \quad 171 < W < 256 \text{ GeV}$$

$$p_t(D^*) > 2.5 \text{ GeV}, \quad |\eta(D^*)| < 1.5$$



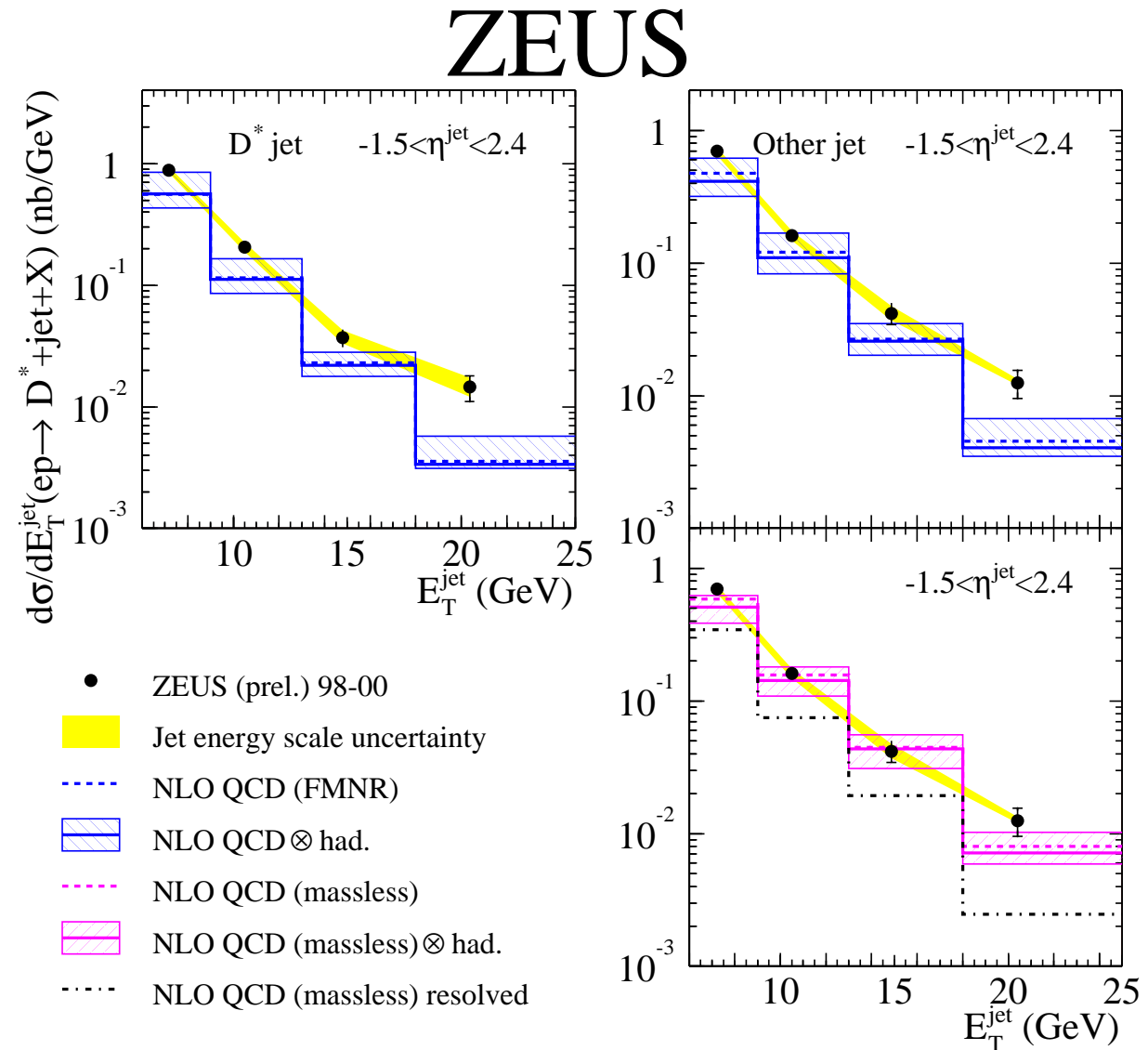
# PHP of $D^*$ , inclusive jet cross sections

- additional scale added  $E_T^{jet}$
- 'massive' NLO calculation below data at high  $E_T^{jet}$
- 'massless' NLO calculation in reasonable agreement with data
- theories have large uncertainties

$$Q^2 < 1 \text{ GeV}^2, \quad 130 < W < 280 \text{ GeV}$$

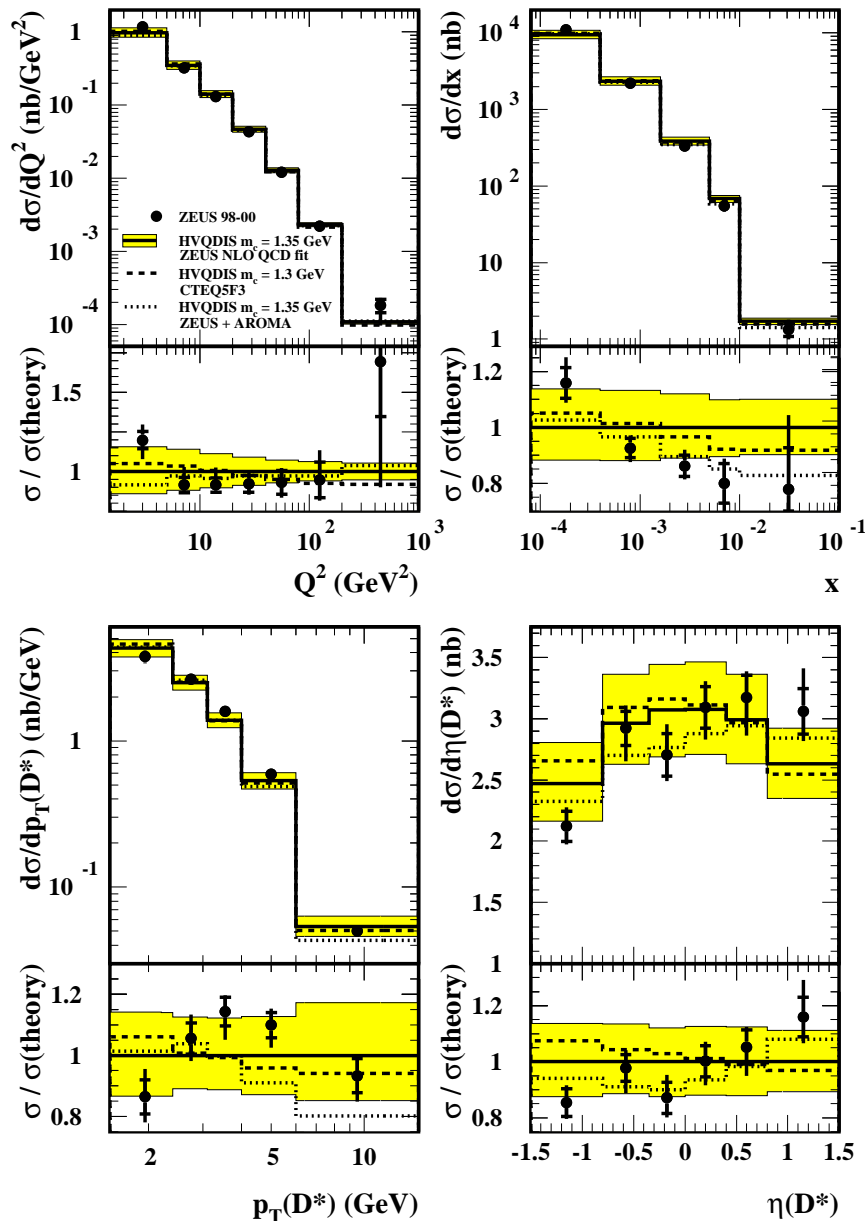
$$p_t(D^*) > 3 \text{ GeV}, \quad |\eta(D^*)| < 1.5$$

$$E_T^{jet} > 6 \text{ GeV}, \quad -1.5 < \eta^{jet} < 2.4$$



# $D^*$ production in DIS

ZEUS



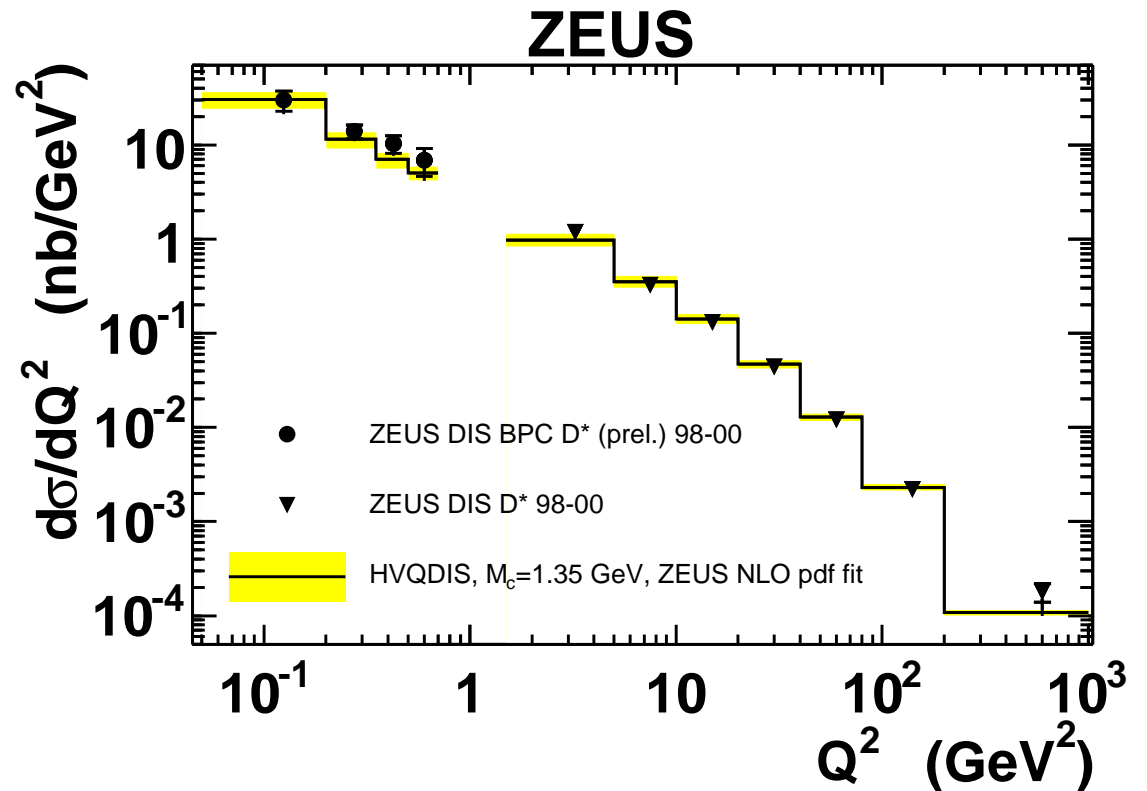
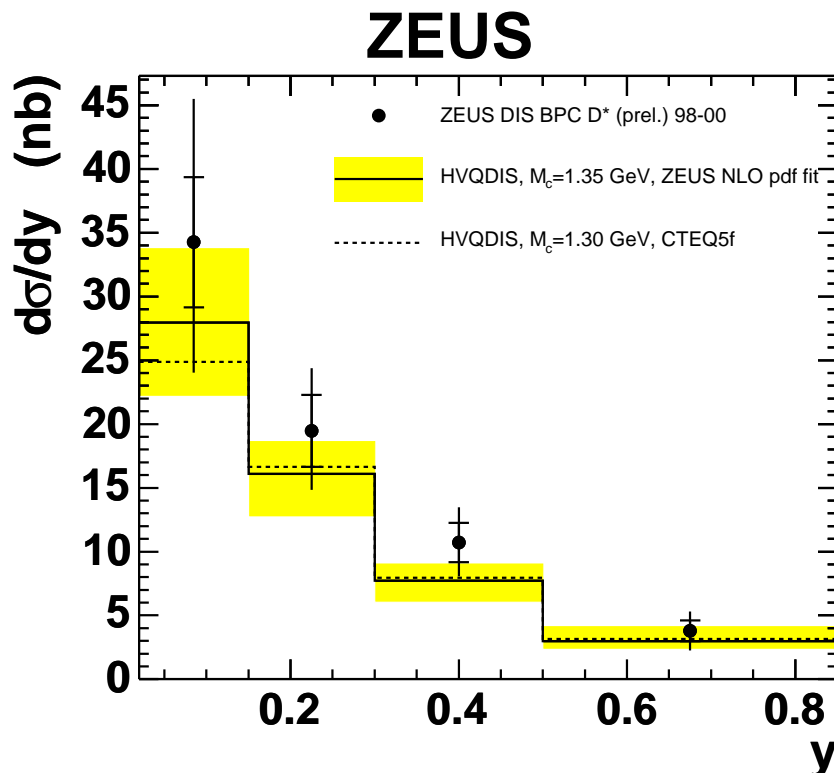
- NLO QCD in reasonable agreement with measurement
- sensitivity to choice of PDF found
- cross sections have potential to be used for PDF's

$1.5 < Q^2 < 1000 \text{ GeV}^2$ ,  $0.02 < y < 0.7$ ,  
 $1.5 < p_T(D^*) < 15 \text{ GeV}$ ,  $|\eta(D^*)| < 1.5$

# $D^*$ production in DIS at low $Q^2$

$0.05 < Q^2 < 0.7 \text{ GeV}^2$ ,  $0.02 < y < 0.85$ ,  $1.5 < p_t(D^*) < 9 \text{ GeV}$ ,  $|\eta(D^*)| < 1.5$

Test of NLO QCD calculation  
of BGF charm production  
in region of transition  
to PHP regime

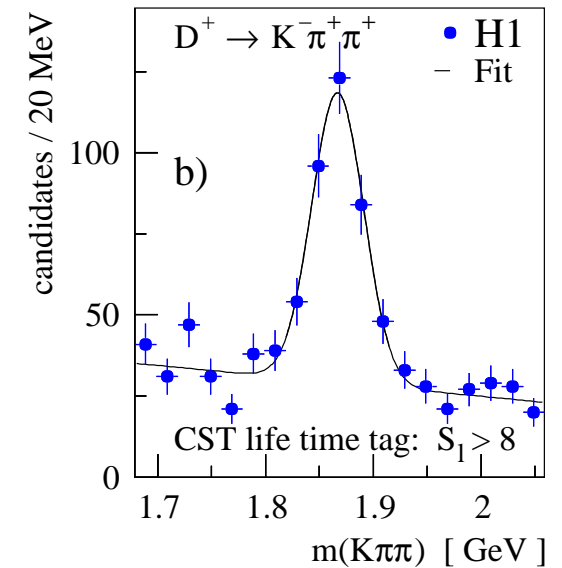
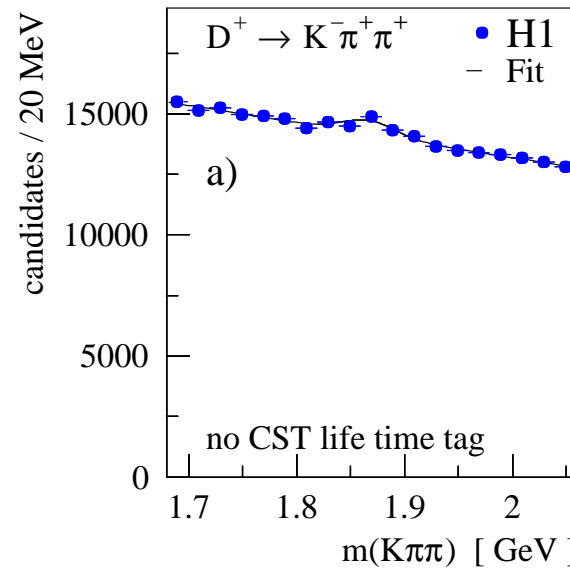
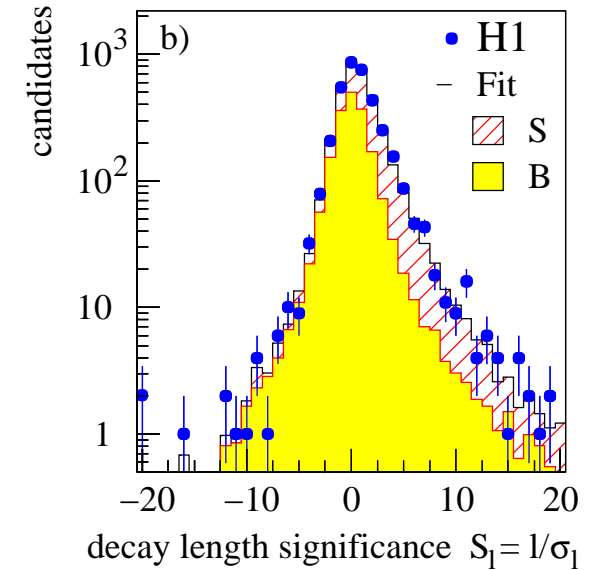
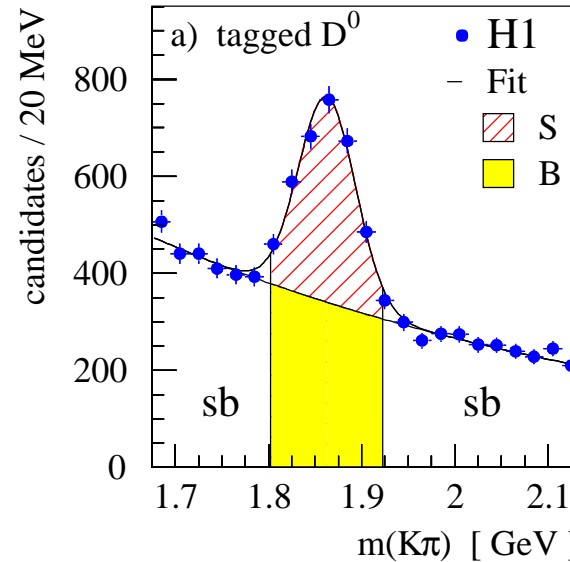
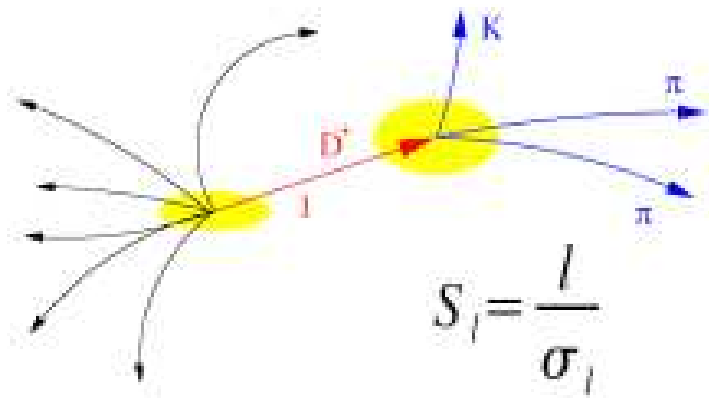


Predictions are consistent  
with measured cross sections  
at low  $Q^2$

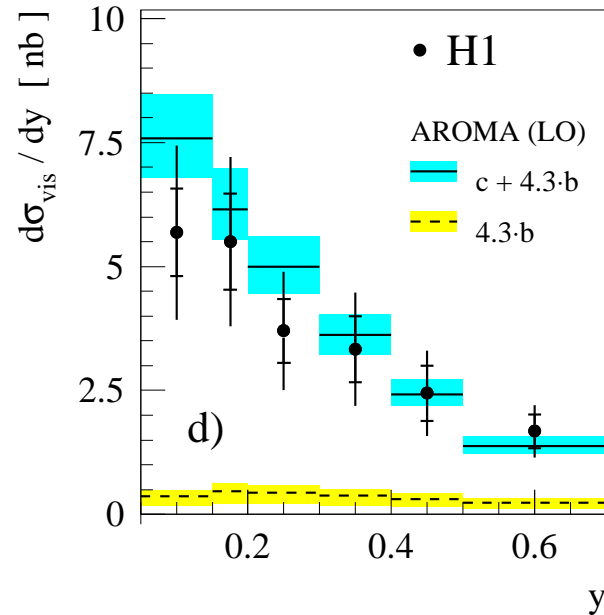
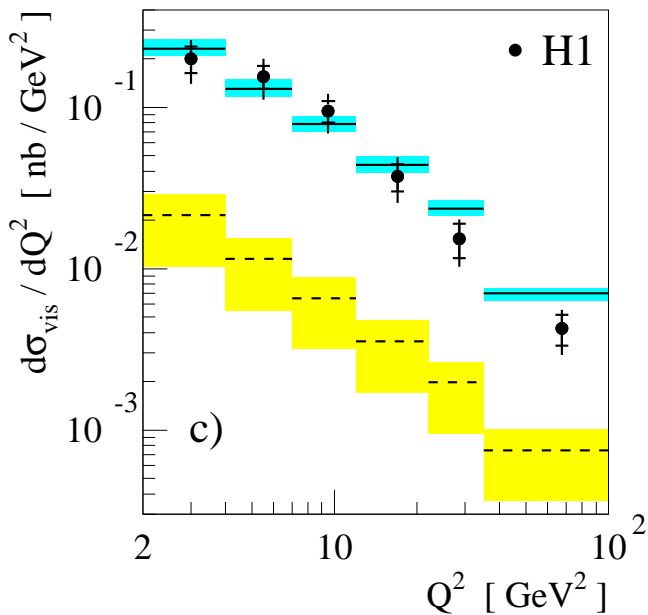
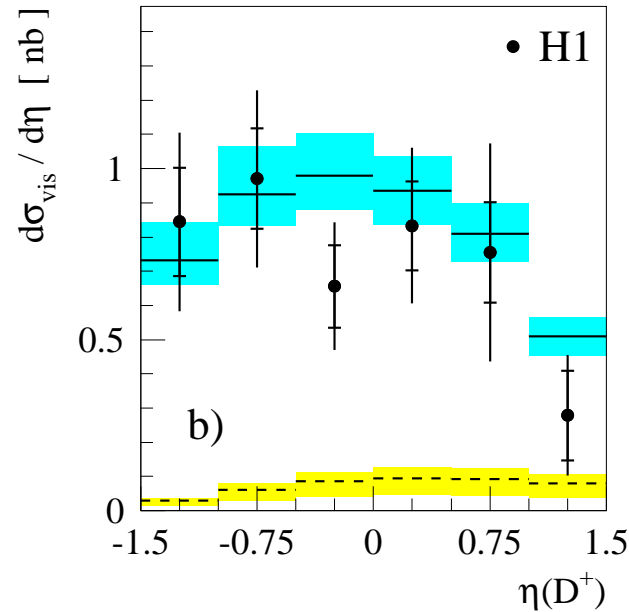
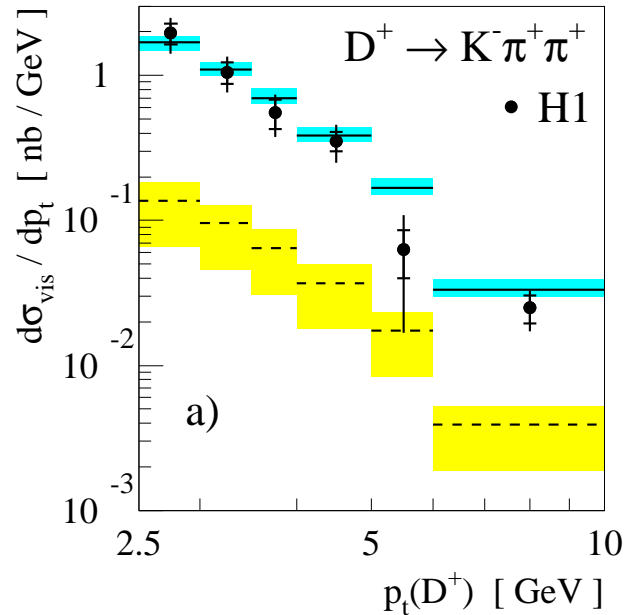
# charm tagging

secondary vertex identification  
with H1 central silicon tracker  
(CST)

background reduced with cut  
on decay length significance



# $D^+$ mesons



- large scale factor for beauty contribution
- visible cross section described well by AROMA
- shapes described reasonably

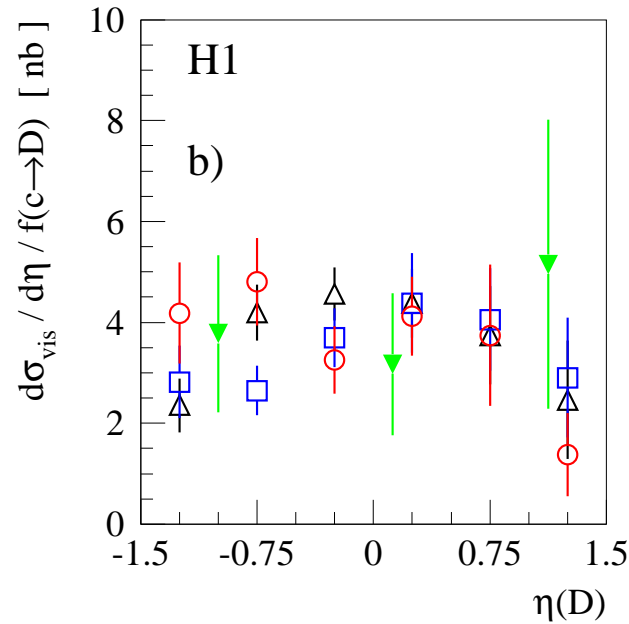
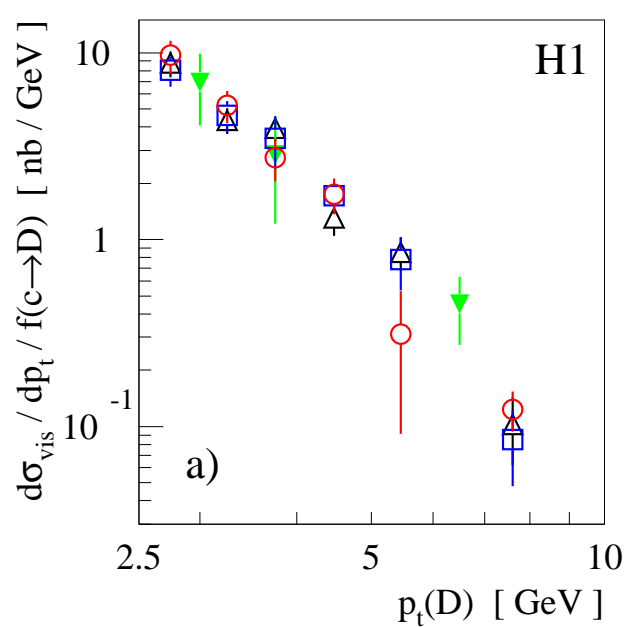
$$2 < Q^2 < 100 \text{ GeV}^2$$

$$0.05 < y < 0.7$$

$$p_t(D) > 2.5 \text{ GeV}$$

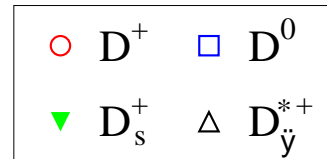
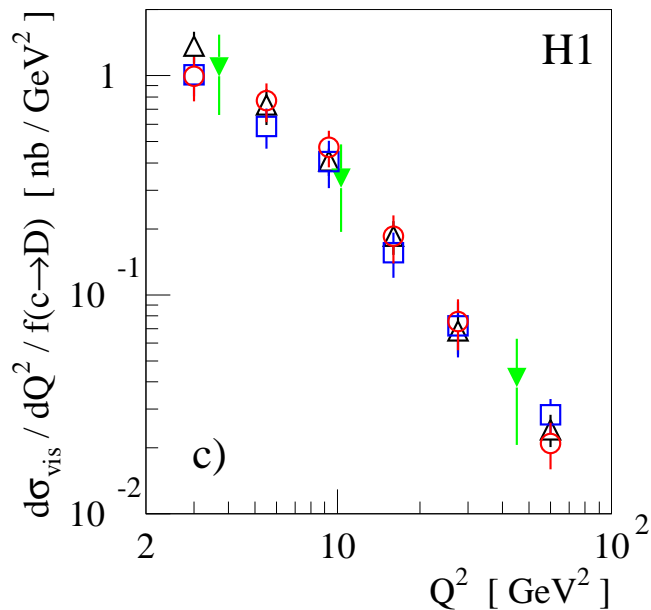
$$|\eta(D)| < 1.5$$

# fragmentation of charm quarks



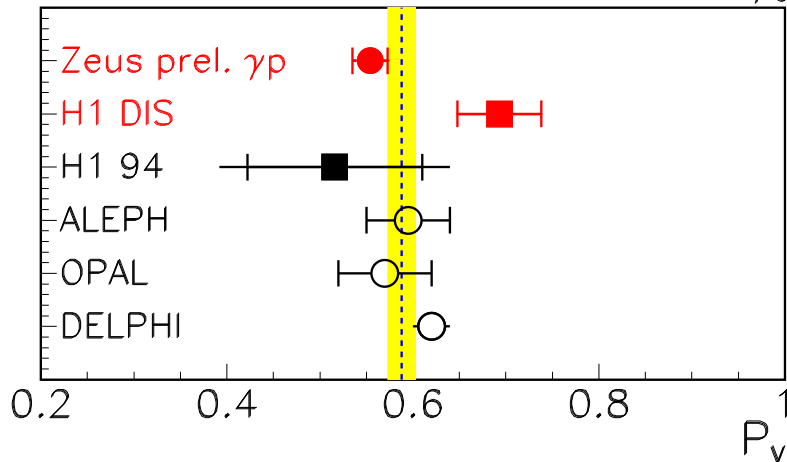
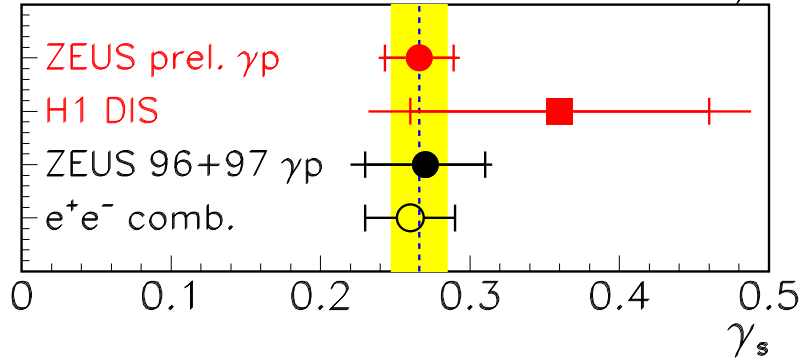
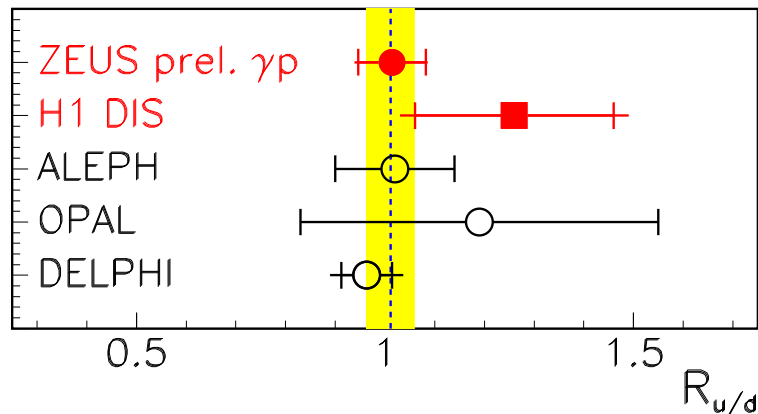
visible cross section /  
fragmentation factor

- similar shapes for different D mesons



universal fragmentation ansatz reasonable  
(independent of the hard scattering process  
and of the charm production scale)

# fragmentation ratios



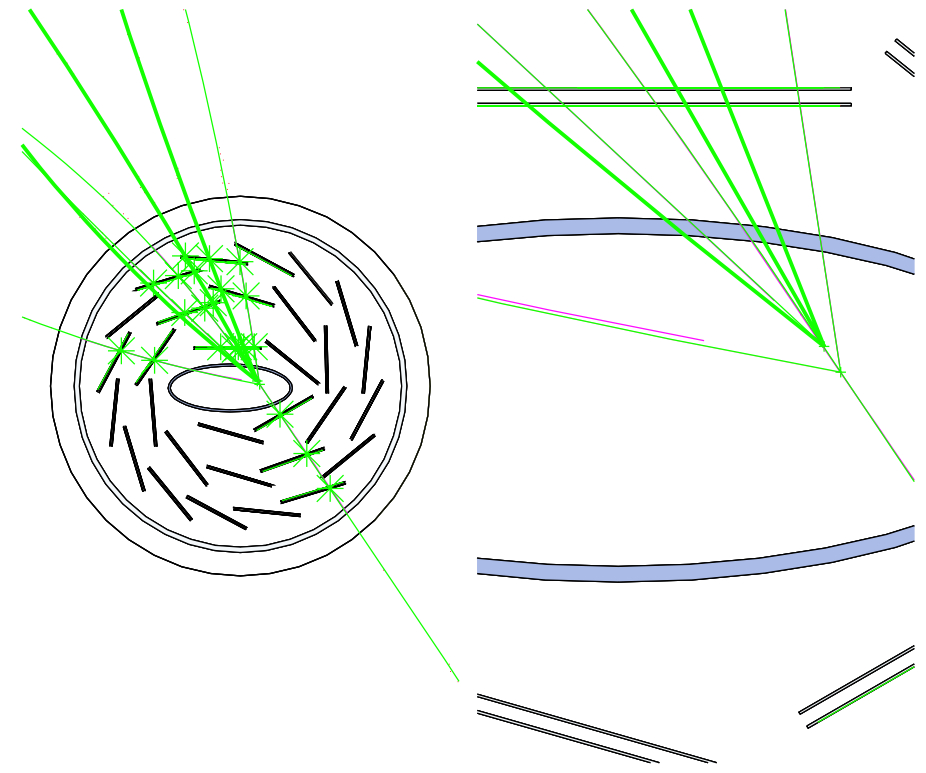
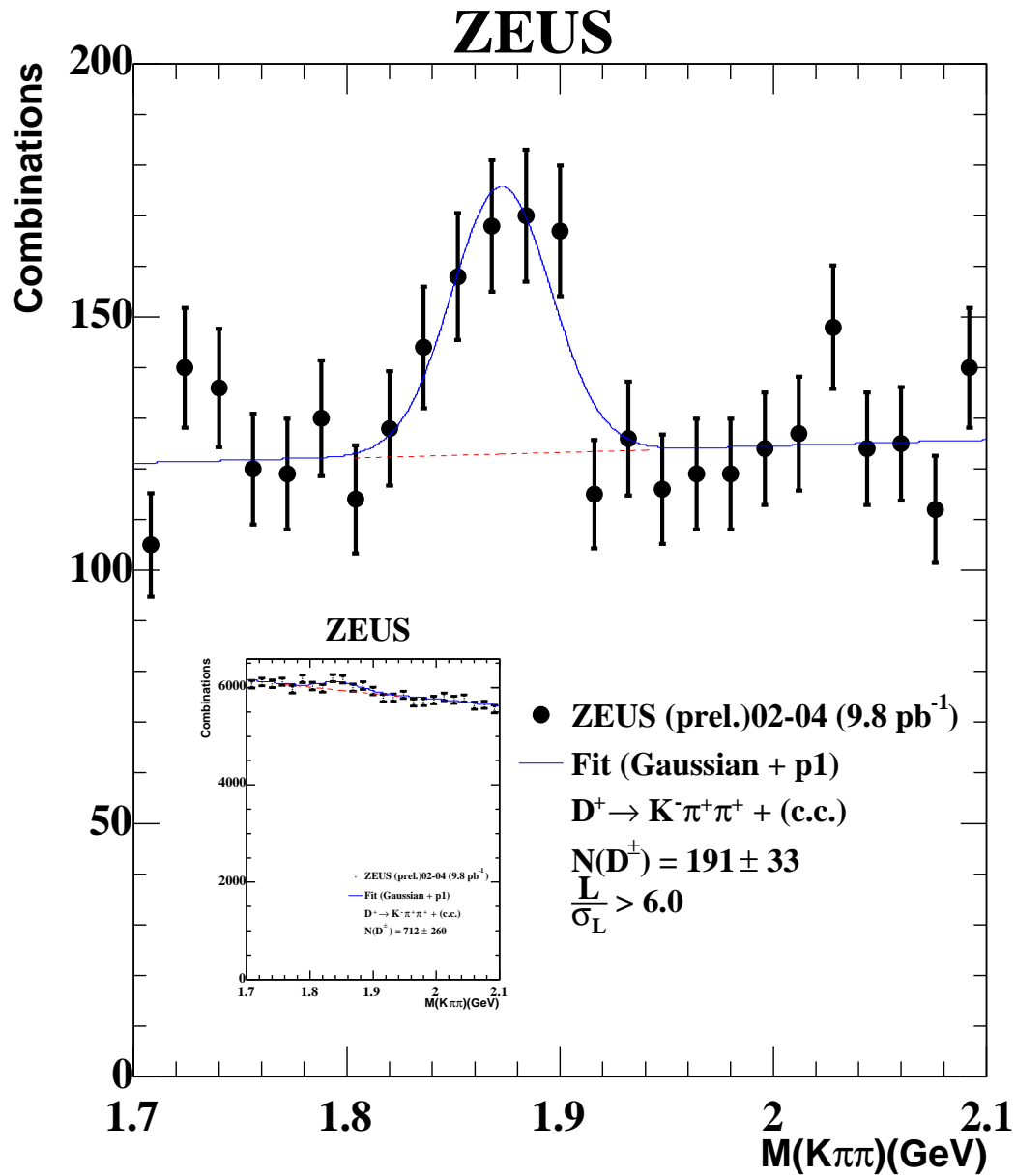
- $R_{u/d} = c\bar{u}/c\bar{d}$   
small  $u, d$  quark mass  $\rightarrow R_{u/d} \sim 1$

- $\gamma_s = 2c\bar{s}/(c\bar{u} + c\bar{d})$   
strangeness suppression factor

- $P_v = V/(V + PS)$   
from naive spin counting  
expected to be 3/4,  
 $\rightarrow$  spin counting does not work!

precision comparable with DELPHI

# D meson tagging with HERA II



cleaner event selection possible

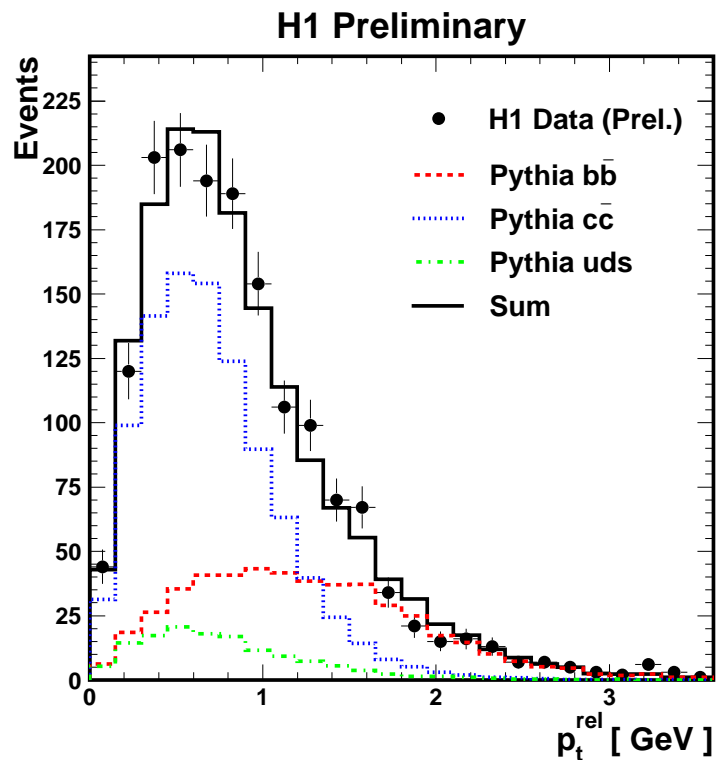
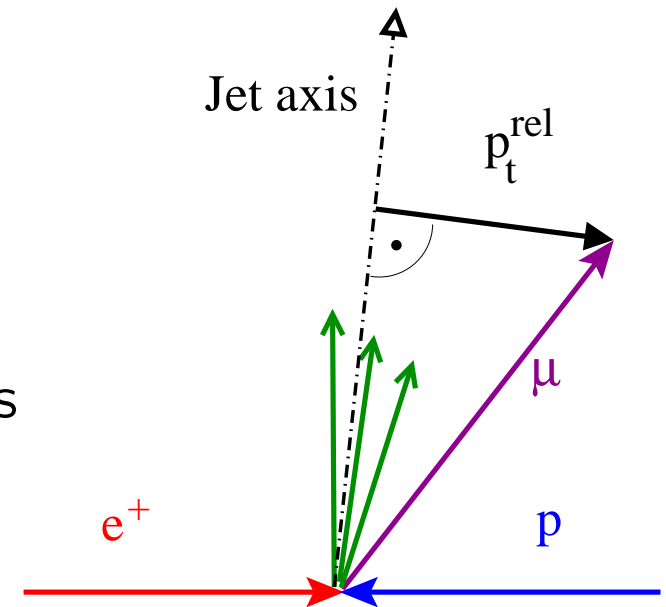
# beauty tagging: $p_t^{rel}$

Why beauty?

$\sigma_{b\bar{b}}/\sigma_{c\bar{c}} \sim 0.05 \Rightarrow$  hard to identify beauty, but  
 $m_b > m_c \Rightarrow$  pQCD should become more reliable

How to identify  $b \rightarrow l\bar{\nu}X$ ?

2 jet events (BGF) with tagged  $\mu$  in one of the jets



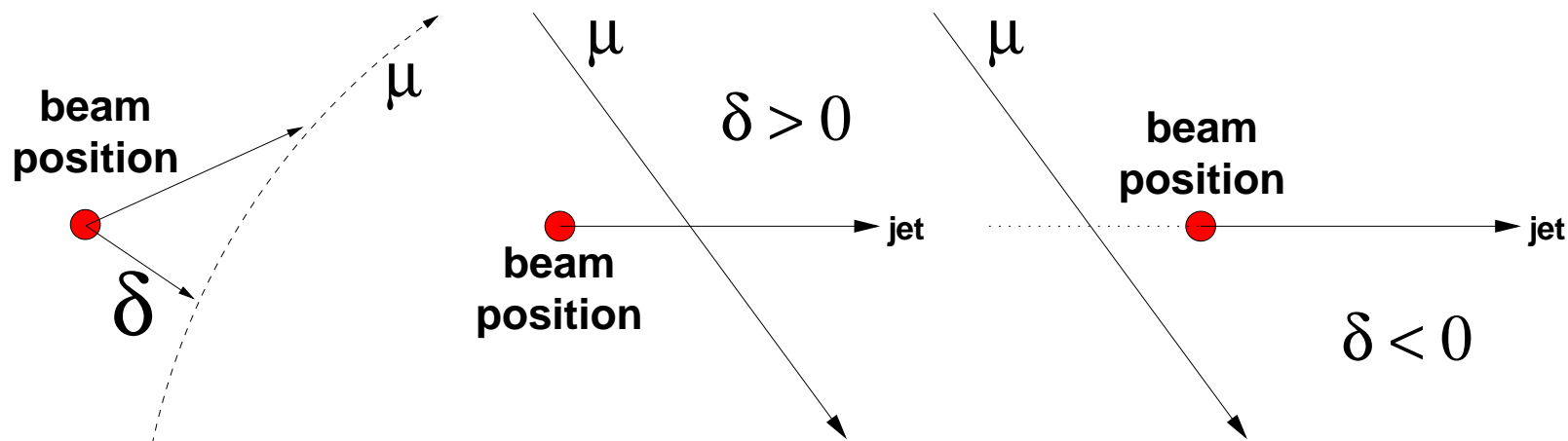
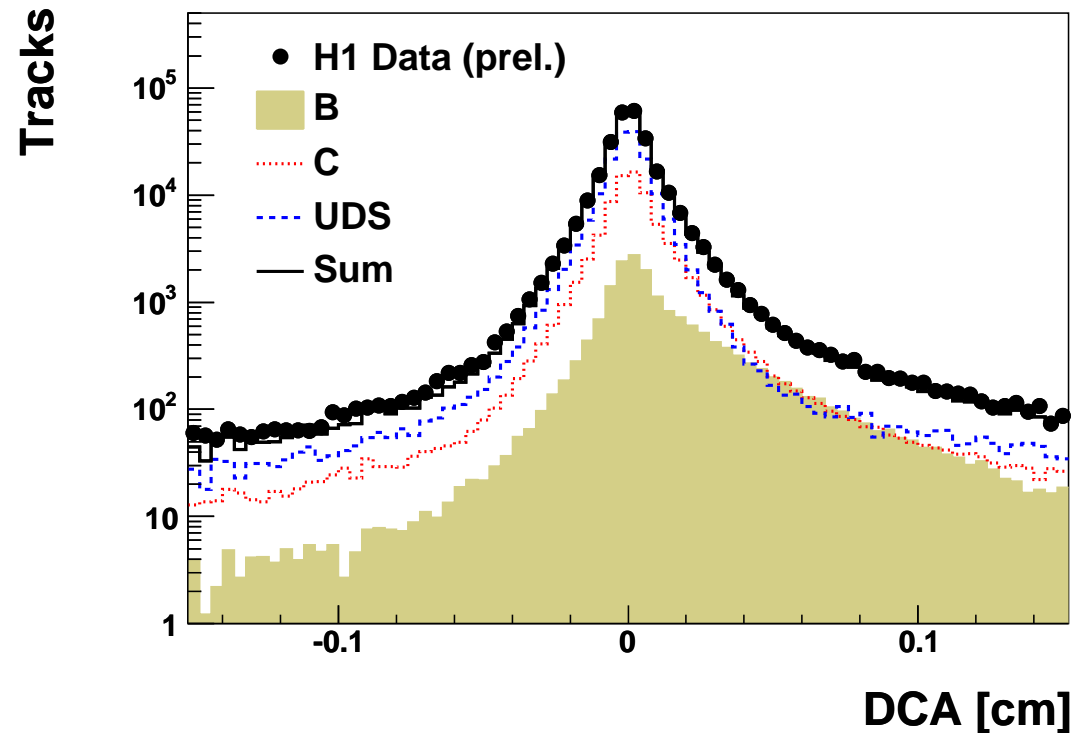
Large  $b$  mass causes high  $p_t$  of  $\mu$  relative to the jet ( $p_t^{rel}$ ) (H1 and ZEUS)

# beauty tagging: lifetime

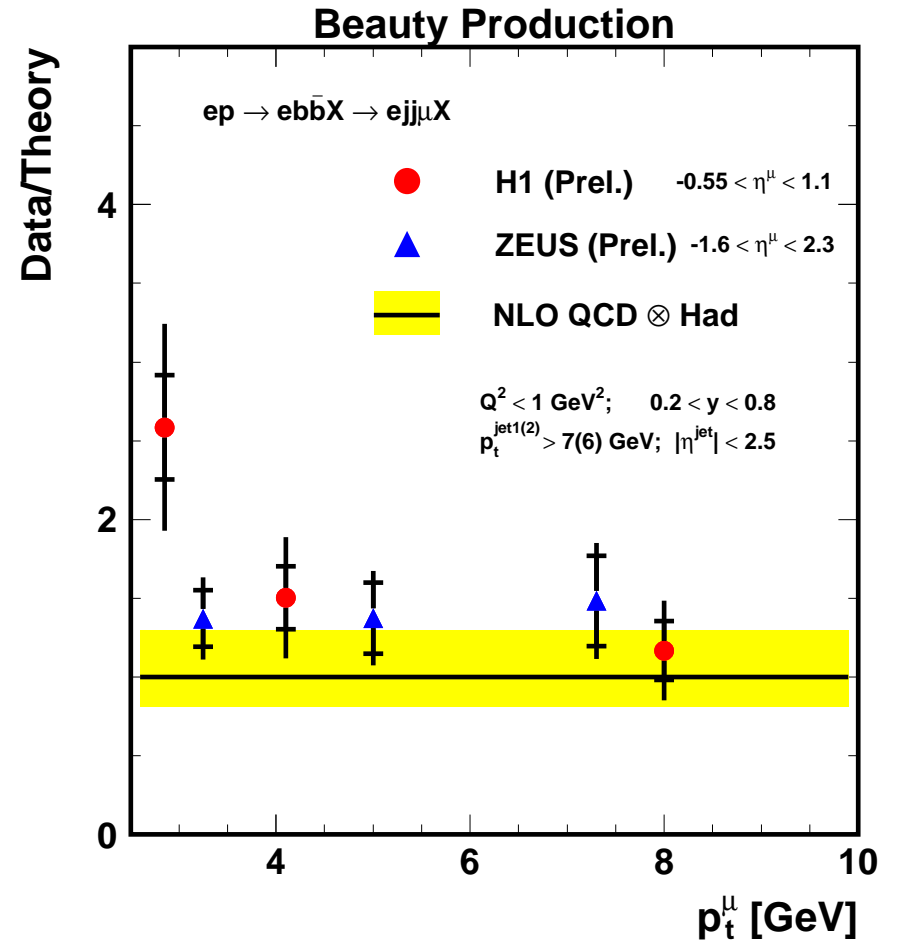
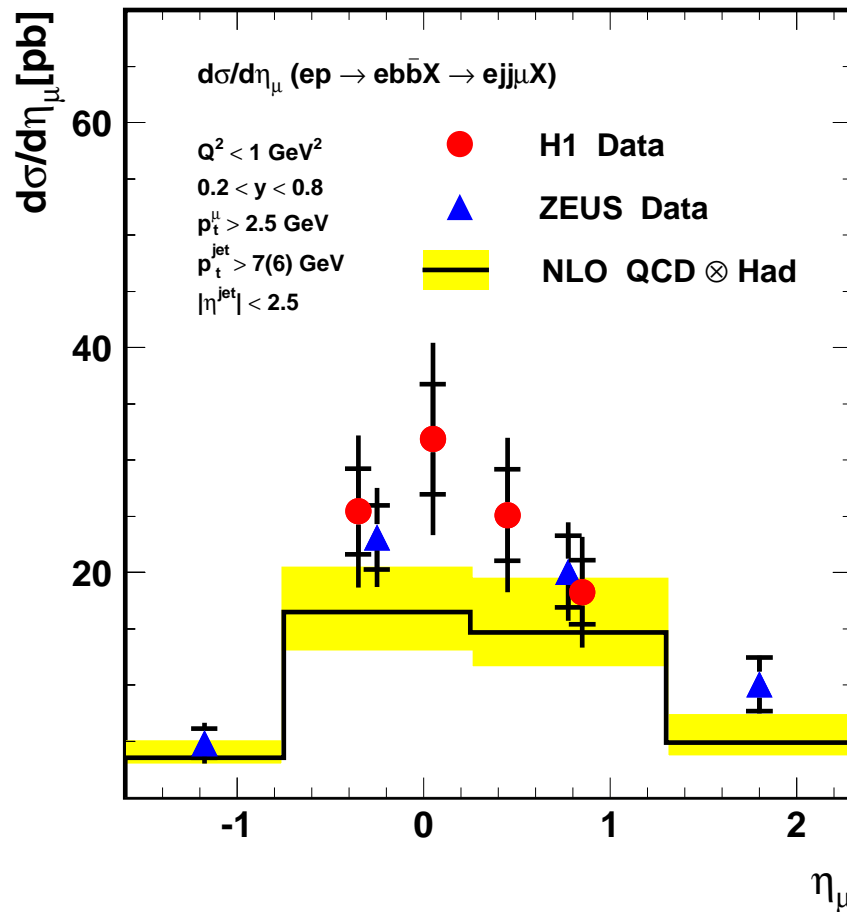
2 jet events (BGF)

- Long lifetime of  $b$  causes large impact parameter  $\delta$  of one ( $\mu$ ) track (H1, ZEUS with HERA II)

Can be made with any track in the jet

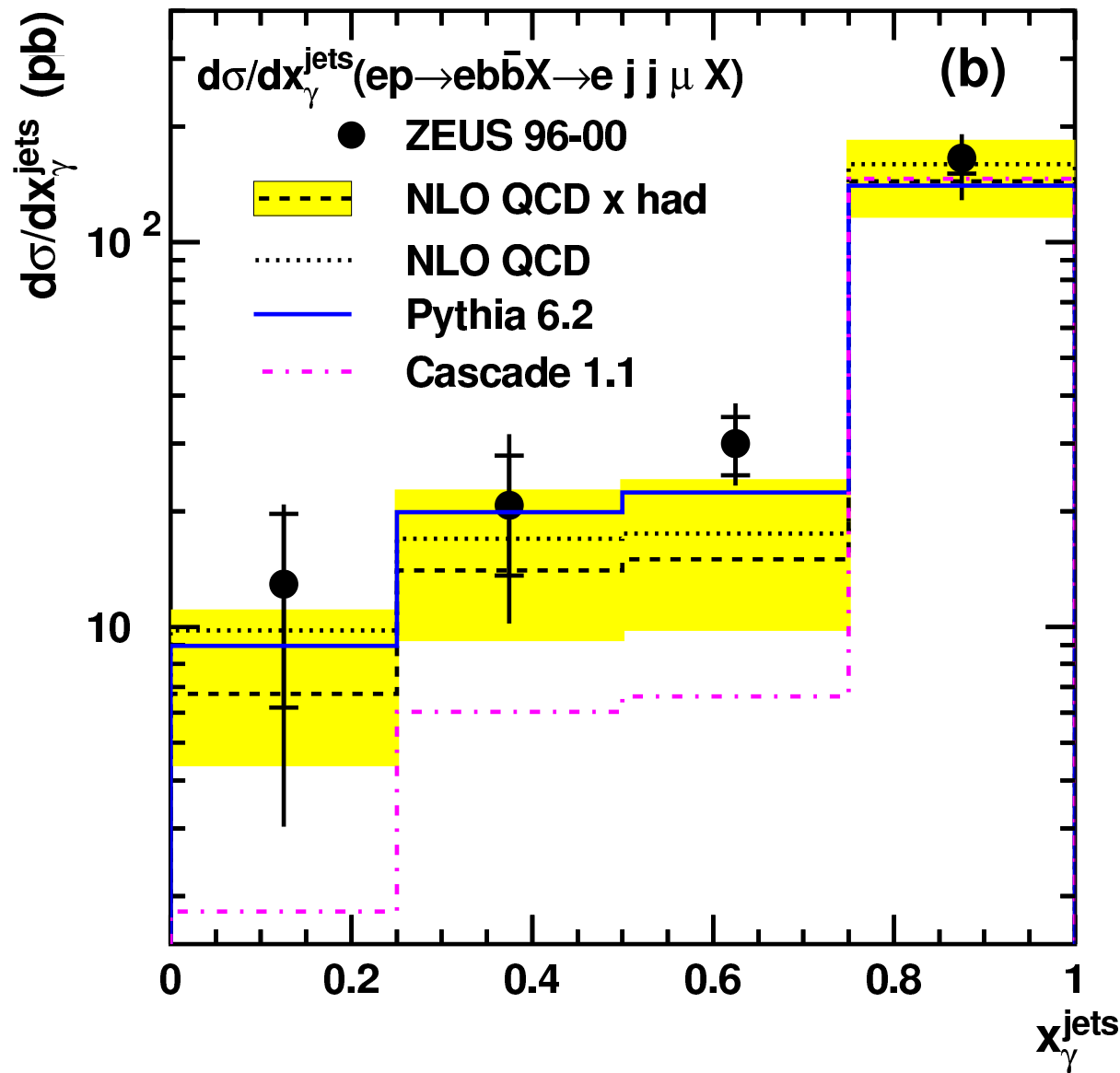


# beauty in PHP



- General agreement between H1 and ZEUS
- NLO undershoots data at low  $p_t^\mu$
- Still agreement within errors with massive NLO QCD (FMNR)

# beauty in PHP: resolved photons



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

resolved photon enriched:

$$x_\gamma^{jets} < 0.75$$

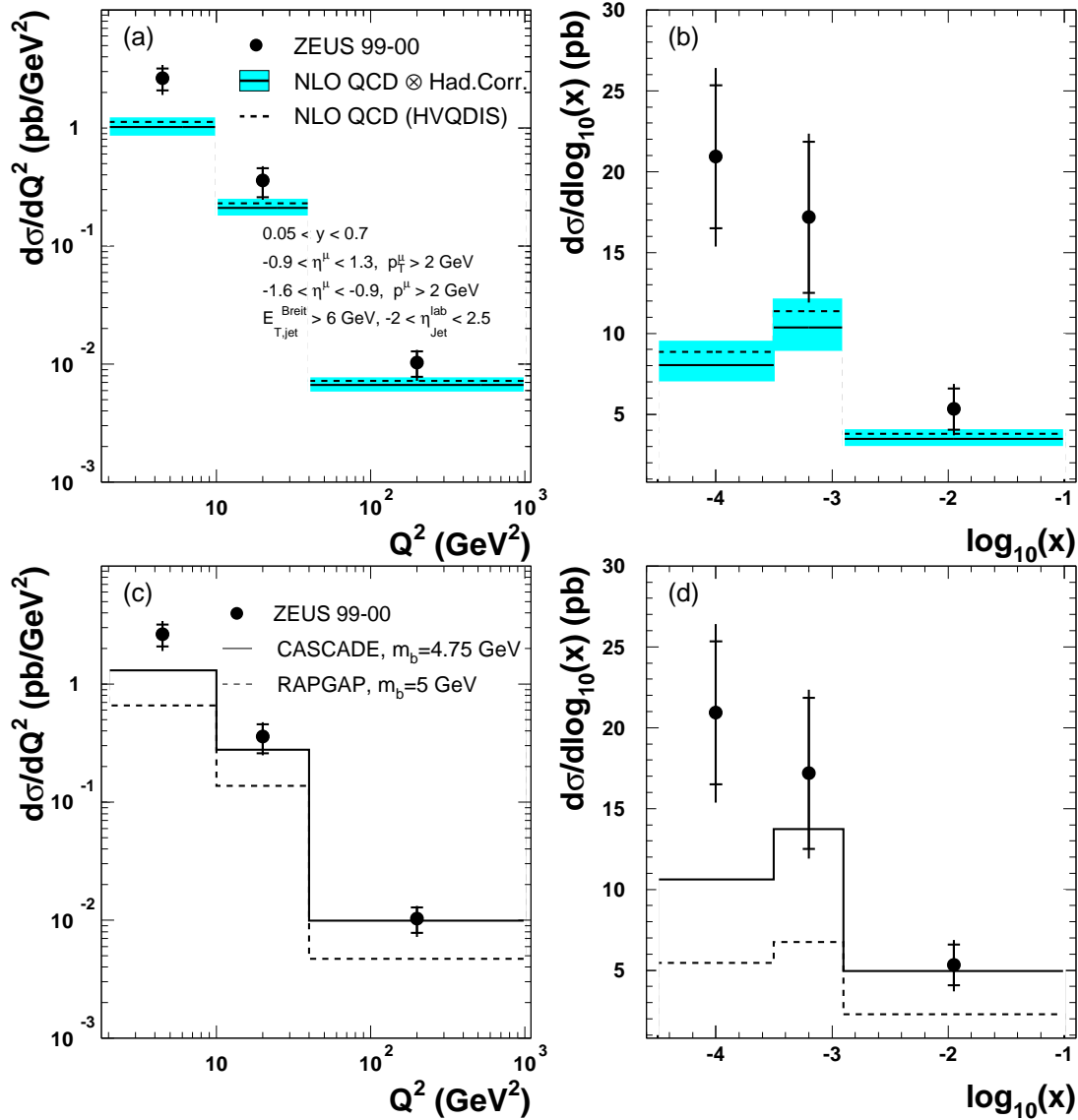
- significant fraction from resolved process
- good agreement with NLO QCD

$$Q^2 < 1 \text{ GeV}^2, \quad 0.2 < y < 0.8$$

$$p_t^{jet_1} > 7, p_t^{jet_2} > 6 \text{ GeV}, \quad \eta^{jet} < 2.5$$

# beauty in DIS

## ZEUS

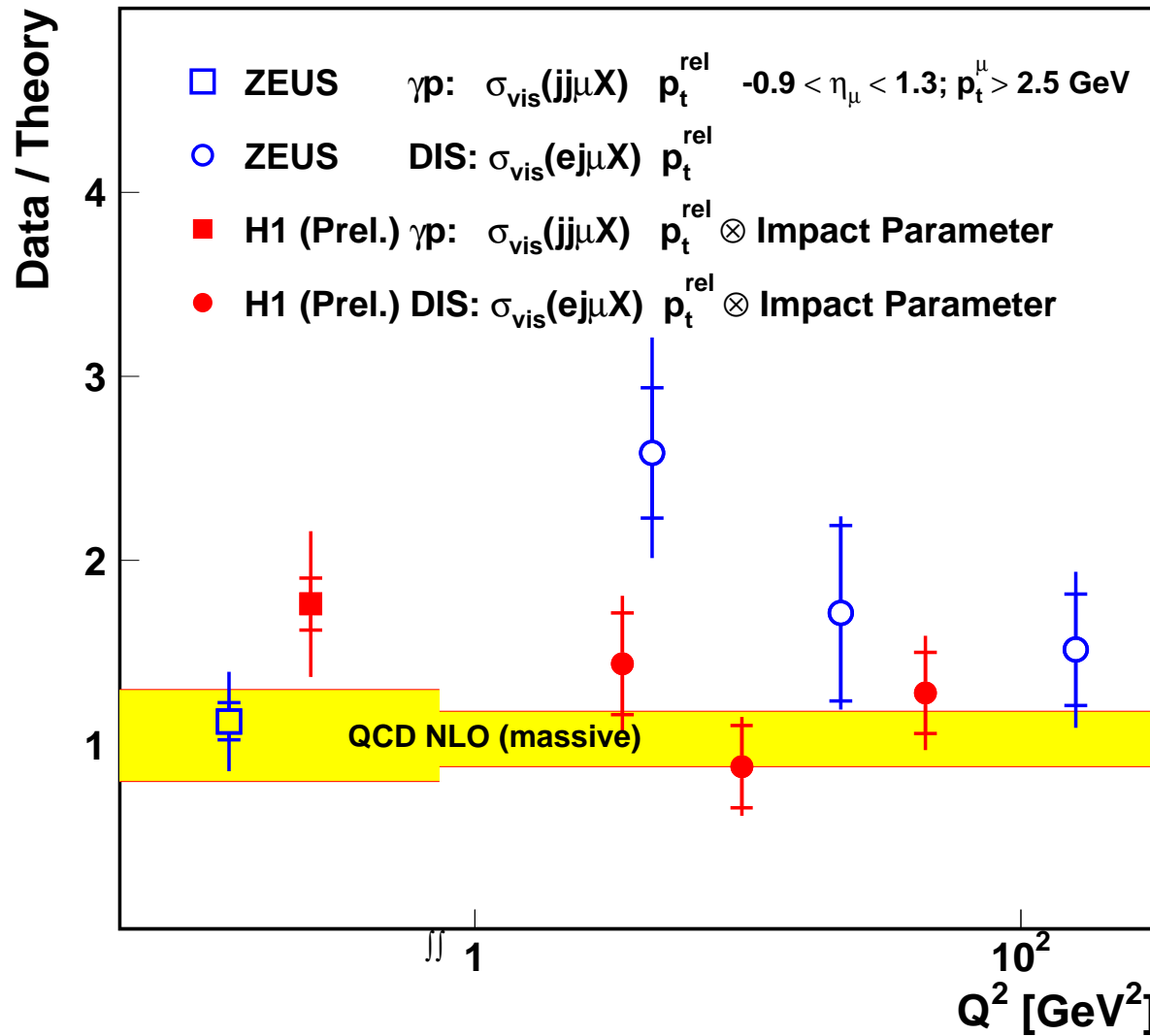


- Data higher than NLO, esp. at small  $Q^2$  and  $x$
- theoretical prediction up to  $\sim 2.5\sigma$  below data

$Q^2 > 2$  GeV<sup>2</sup>

# overview $j(j)\mu$ beauty cross sections

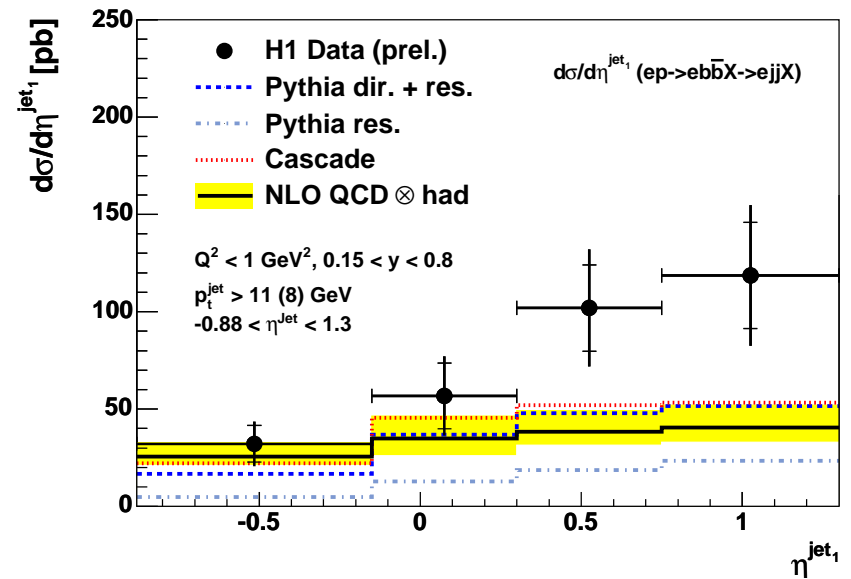
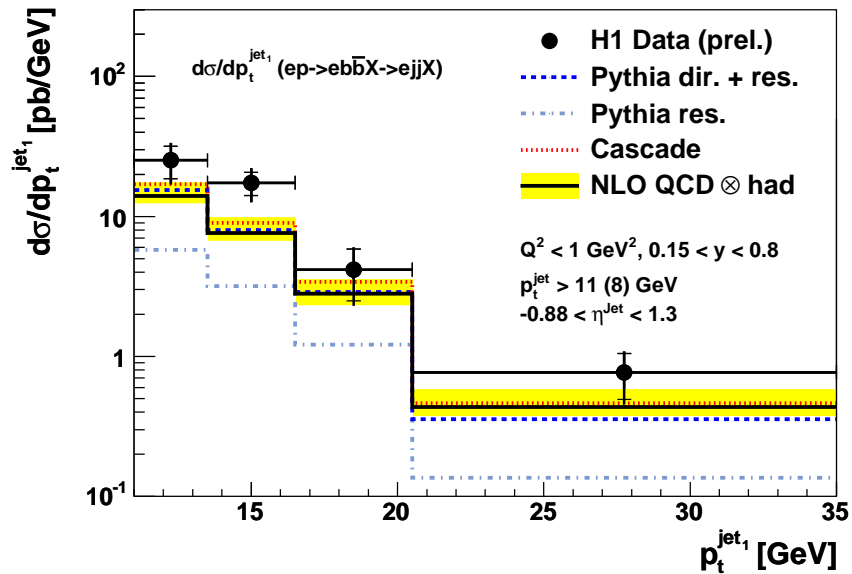
Data/Theory as a function of  $Q^2$



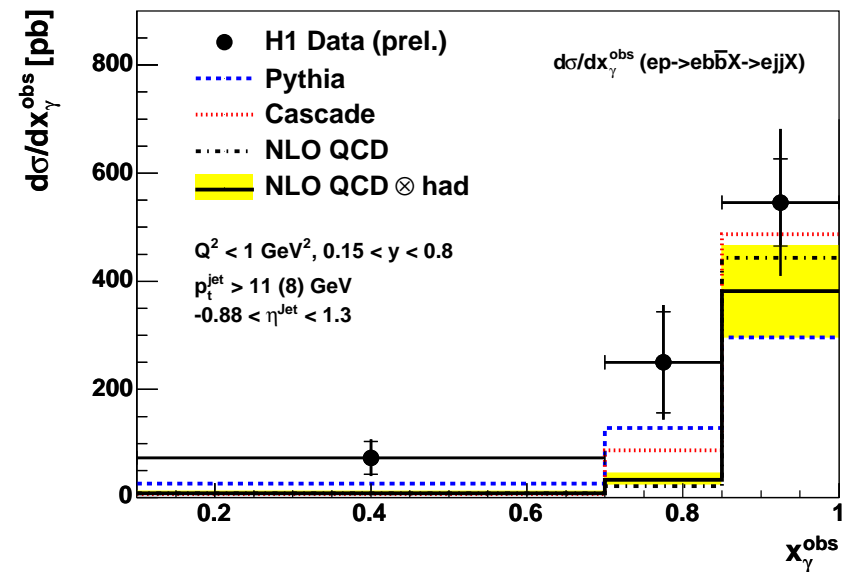
Data in agreement with  
(massive) NLO  
predictions,

slightly higher in DIS  
for low  $Q^2$

# beauty in PHP with inclusive lifetime tag



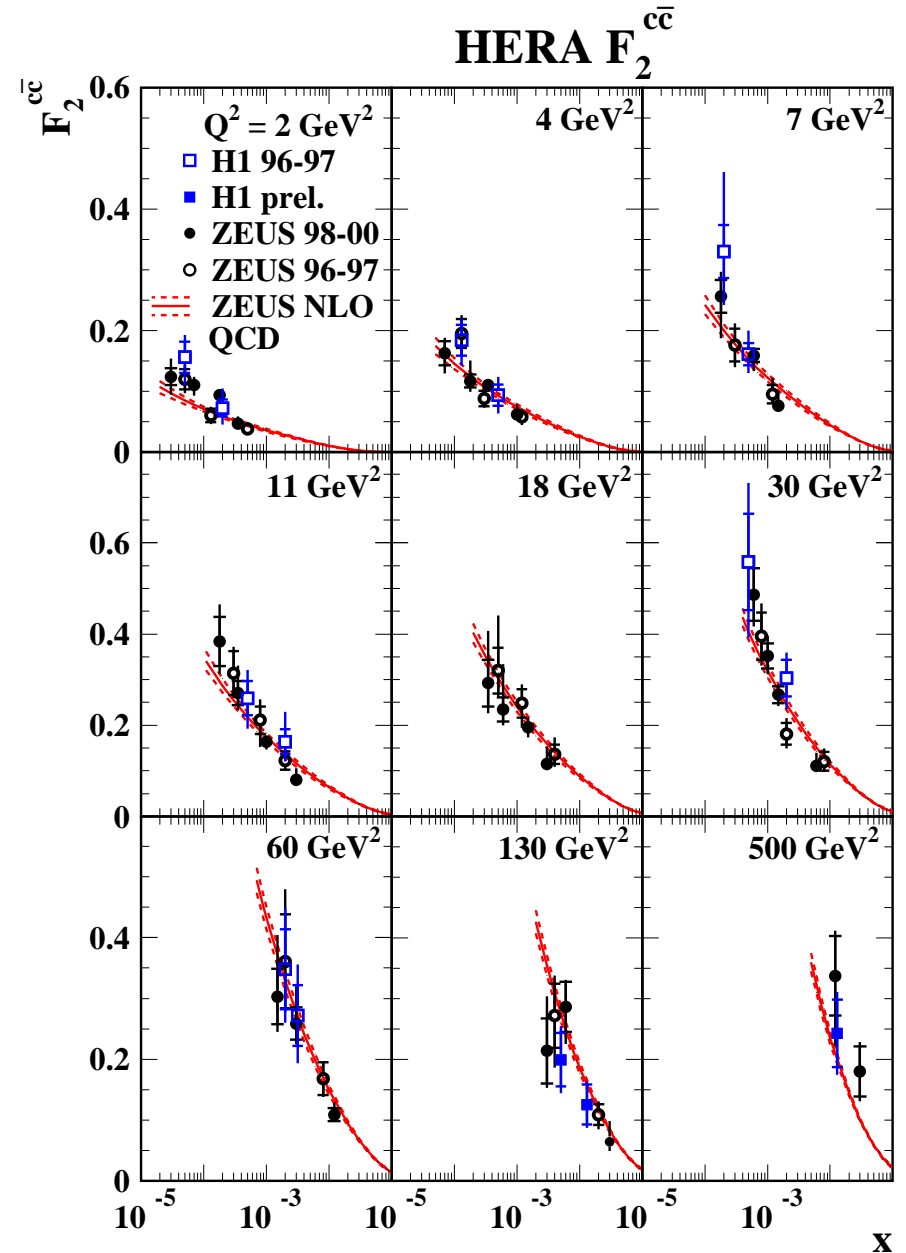
- MC falls below data by a factor of about 2
- shapes of  $p_t^{jet_1}$  described well
- main difference in  $\eta^{jet_1}$  for forward jets and at small  $x_\gamma^{obs}$



# charm contribution to $F_2$

$F_2$ : proton structure function

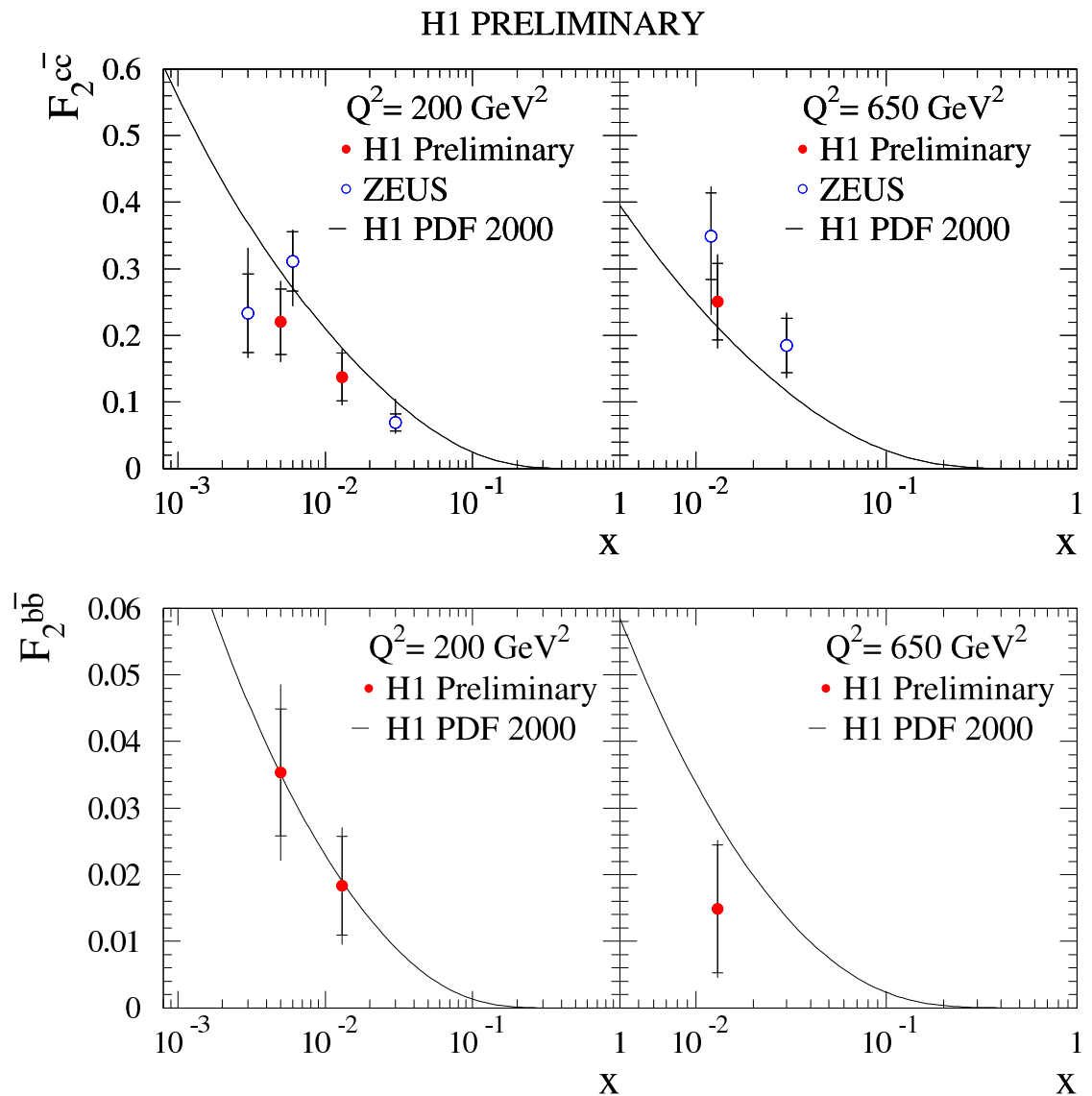
- extraction of  $F_2^{c\bar{c}}$
- ratio  $F_2^{c\bar{c}}/F_2$  rises from 10% to 30% with increasing  $Q^2$  and decreasing  $x$
- at low  $Q^2$  errors comparable with those from PDF fit



# measurement of $F_2^{b\bar{b}}$ and $F_2^{c\bar{c}}$

- extract **fully inclusive** cross sections (structure functions) in  $x$  and  $Q^2$
- model extrapolation small (10%)
- data consistent with NLO massless QCD and with ZEUS (from  $D^*$ )

$$Q^2 > 150 \text{ GeV}^2, \quad 0.1 < y < 0.7$$



# summary

## charm

- charm cross sections generally well described by pQCD
- many new measurements: low  $Q^2$ , jets, ...  
in this regime large theoretical uncertainties
- evidence for separation ansatz between hard process and fragmentation
- evidence for universal charm fragmentation in  $e^+e^-$  and  $ep$

## beauty

- new differential b cross section measurements in PHP and DIS
- measurements in agreement with massive NLO QCD predictions
- first determination of  $F_2^{b\bar{b}}$  at  $Q^2 > 150 \text{ GeV}^2$

improved analysis methods and higher statistics with HERA II data

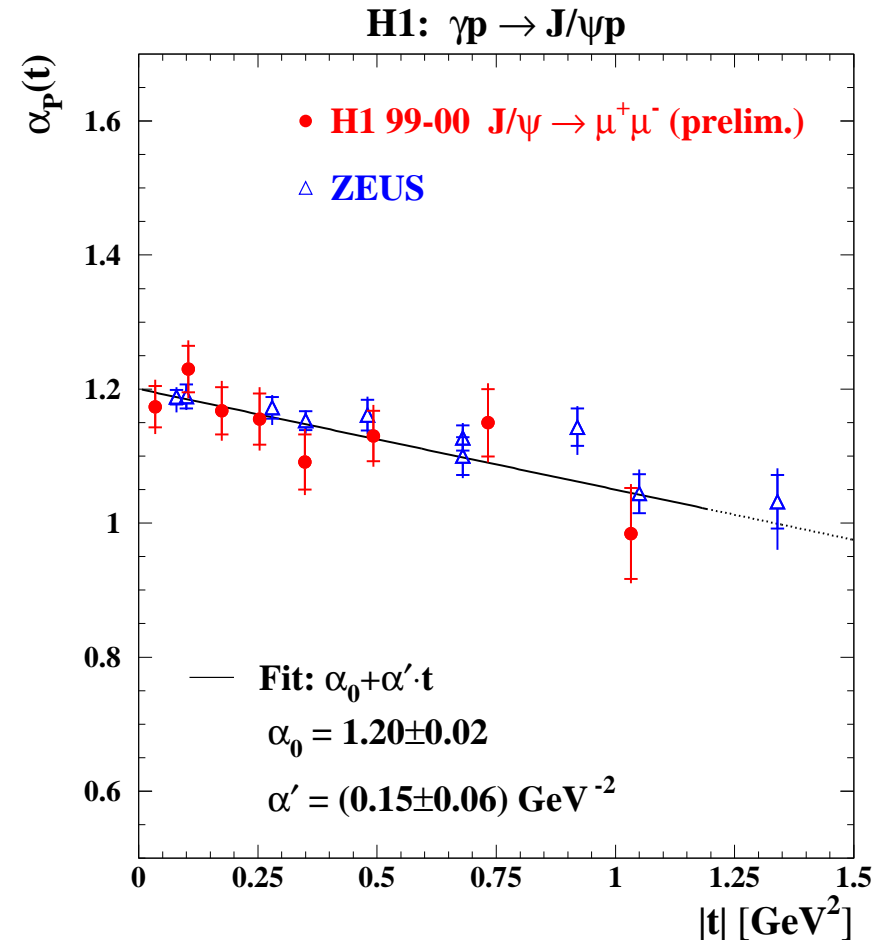
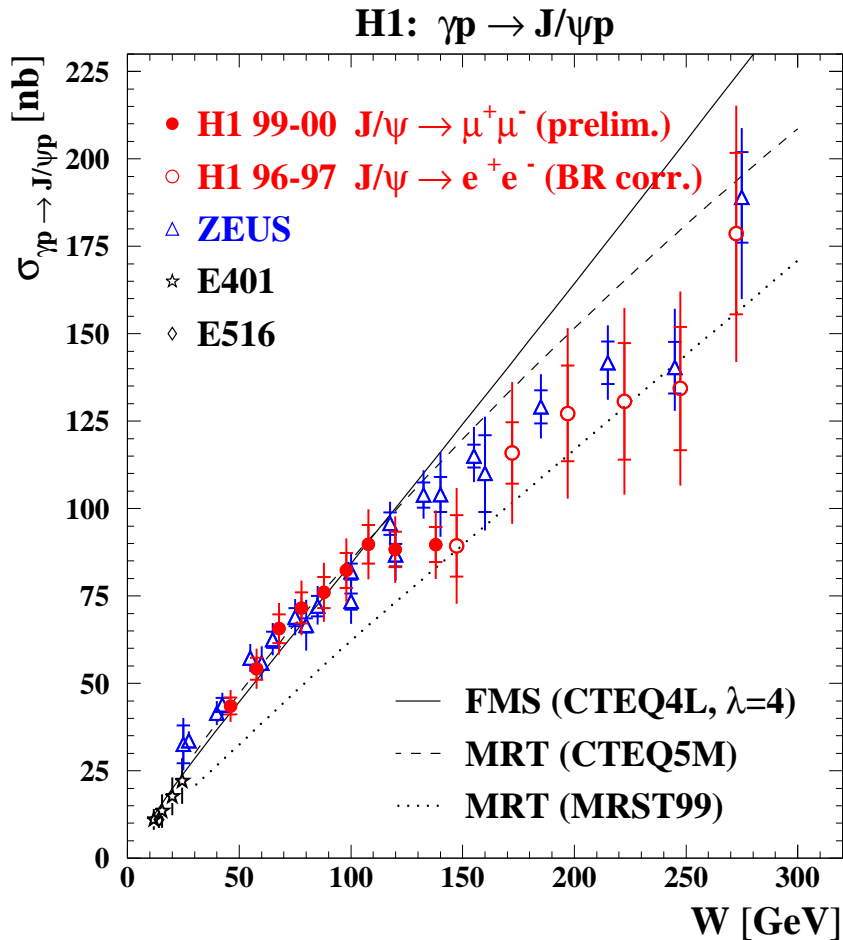
**backup slides**

# $J/\psi$ production in PHP

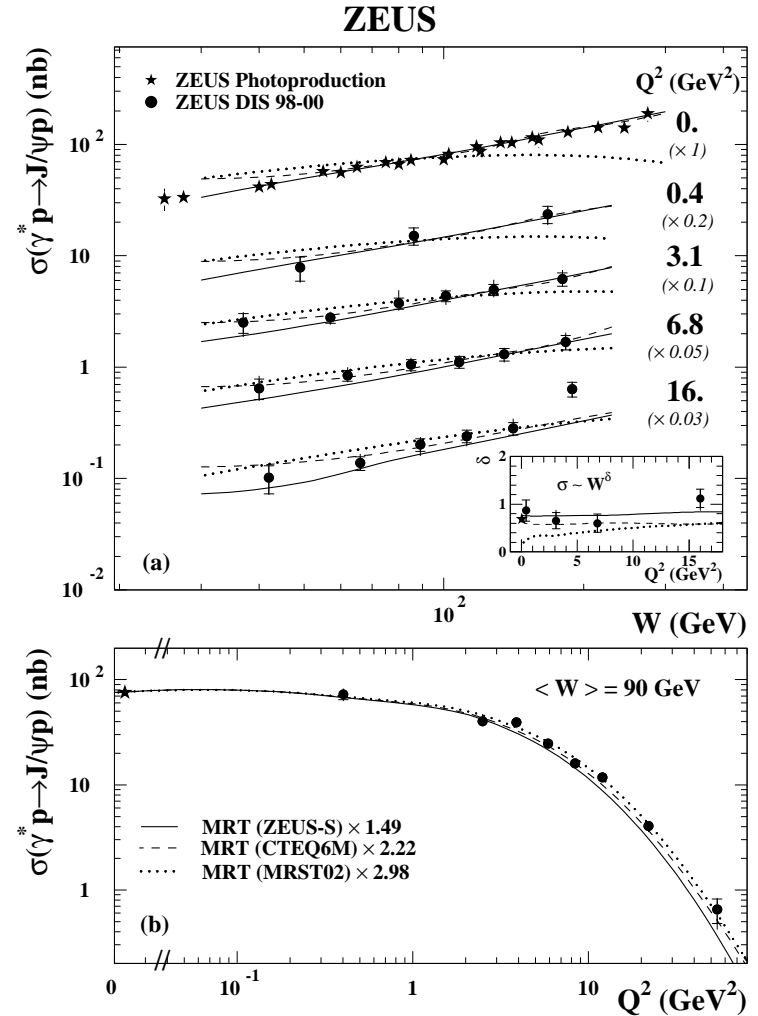
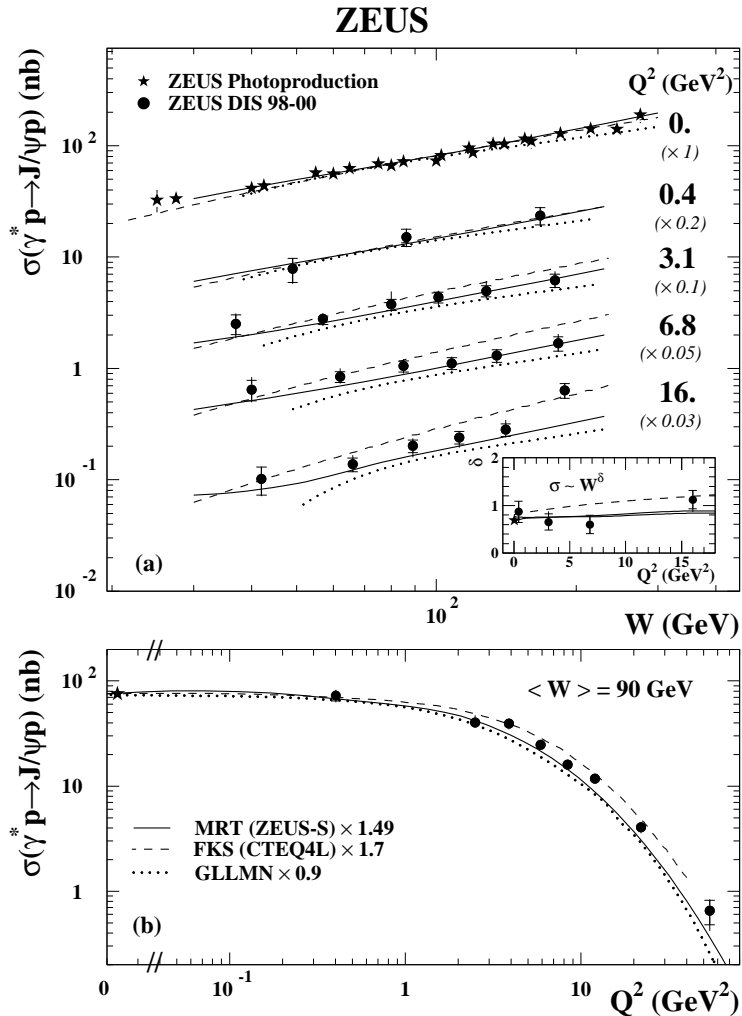
$J/\psi \rightarrow \mu\bar{\mu}$  in the kinematic range

$Q^2 < 1 \text{ GeV}^2$ ,  $40 \text{ GeV} < W_{\gamma p} < 150 \text{ GeV}$ ,  $|t| < 1.2 \text{ GeV}^2$

Agreement with previous measurements and MRT calculations



# exclusive $J/\psi$ -production in DIS



## comparison with QCD models

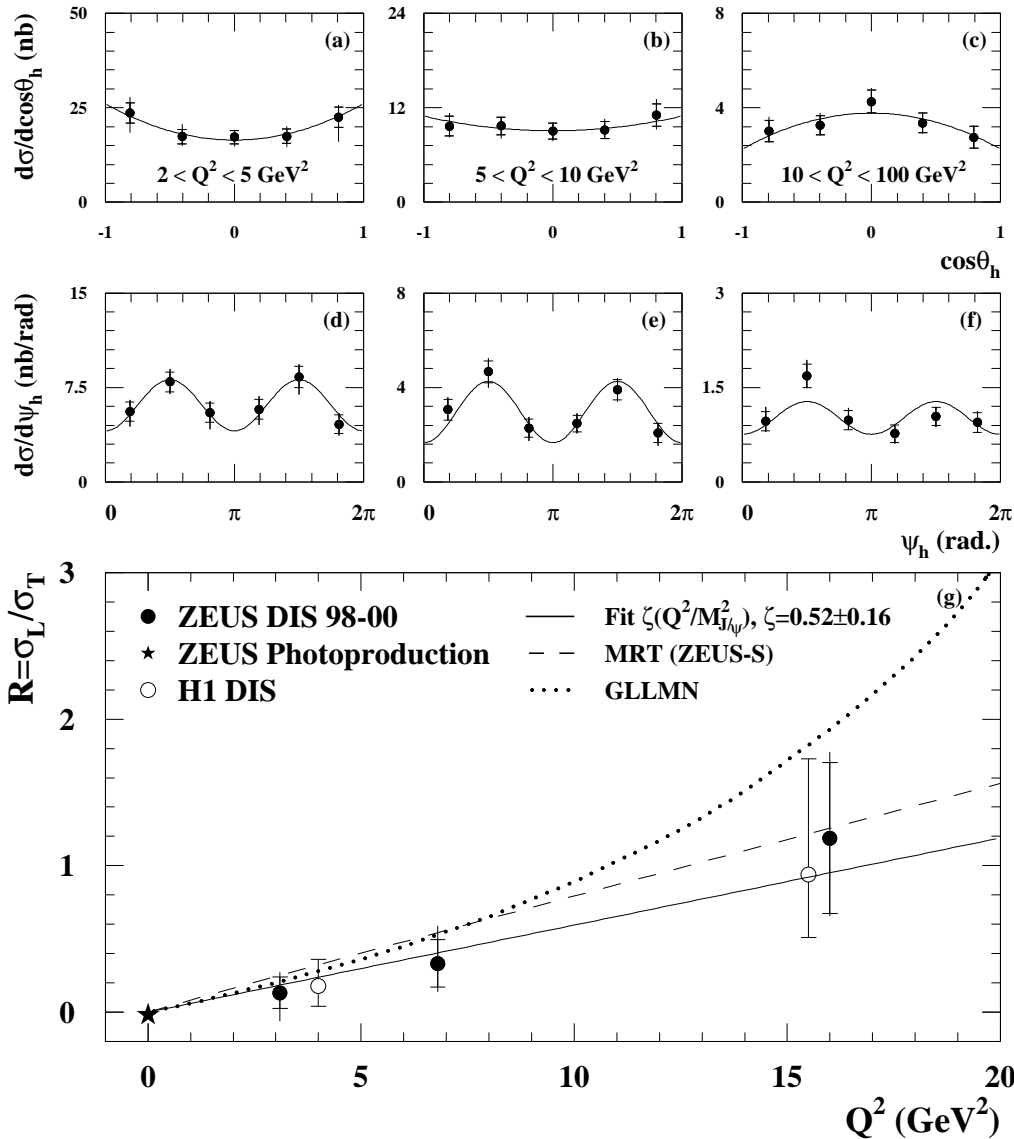
- models describe the data
- large uncertainty in normalization

## comparison for different PDF's

- CTEQ6M, ZEUS-S describe data
- MRST02 has wrong shape in  $W$

# exclusive $J/\psi$ -production in DIS

## ZEUS



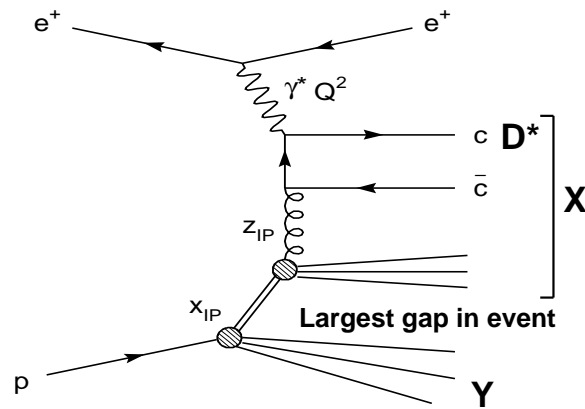
Under assumption of s-channel helicity conservation (SCHC):

Extraction of  $R = \sigma_L / \sigma_T$  from angular distributions

$$\begin{aligned} \frac{1}{N} \frac{dN}{d\cos\theta_h} &= \frac{3}{8} [1 + r_{00}^{04} + (1 - 3r_{00}^{04}) \cos^2\theta_h] \\ \frac{1}{N} \frac{dN}{d\psi_h} &= \frac{1}{2\pi} [1 - \epsilon r_{1-1}^1 \cos 2\psi_h] \\ R &= \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}, \quad \epsilon \approx 0.99 \end{aligned}$$

$\sigma_L$  expected to rise more rapidly with  $Q^2$  than  $\sigma_T$

# Diffractive $D^*$ production in DIS



$$x_{IP} = \frac{q \cdot (P - p_Y)}{q \cdot P}$$

$$\beta = \frac{x}{x_{IP}}$$

$$z_{IP} = \beta \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)$$

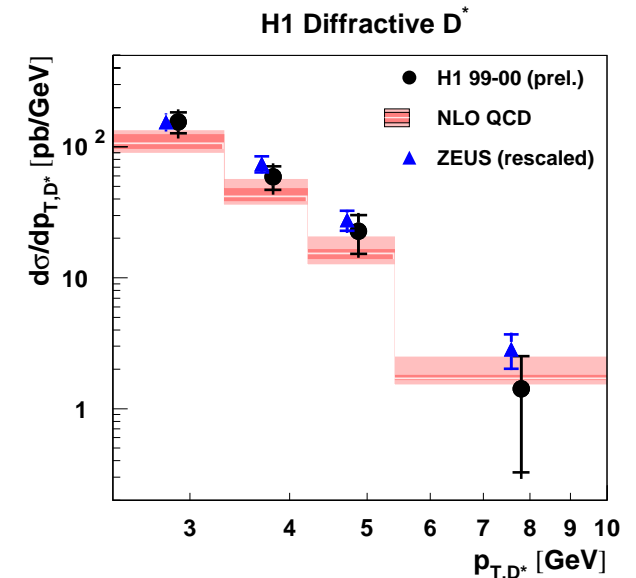
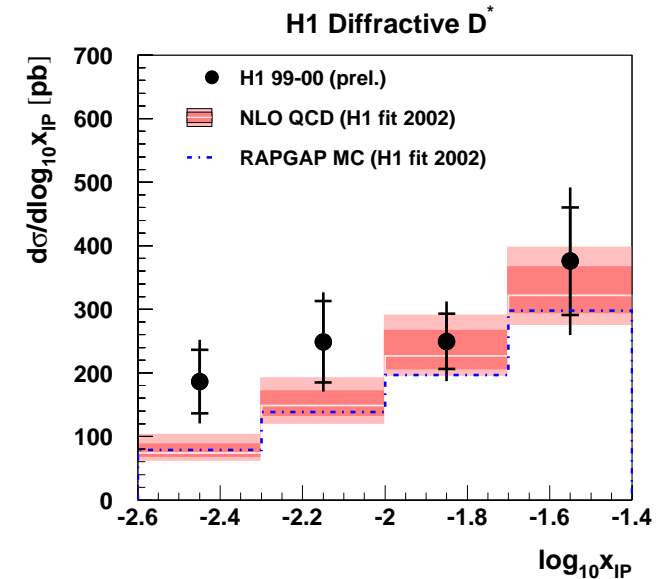
Measurements are in agreement with previous measurements of H1 and ZEUS

Agreement within error bars with theoretical prediction (HVQDIS with NLO diffractive parton distributions)

$$2 < Q^2 < 100 \text{ GeV}^2, \quad 0.05 < y < 0.7$$

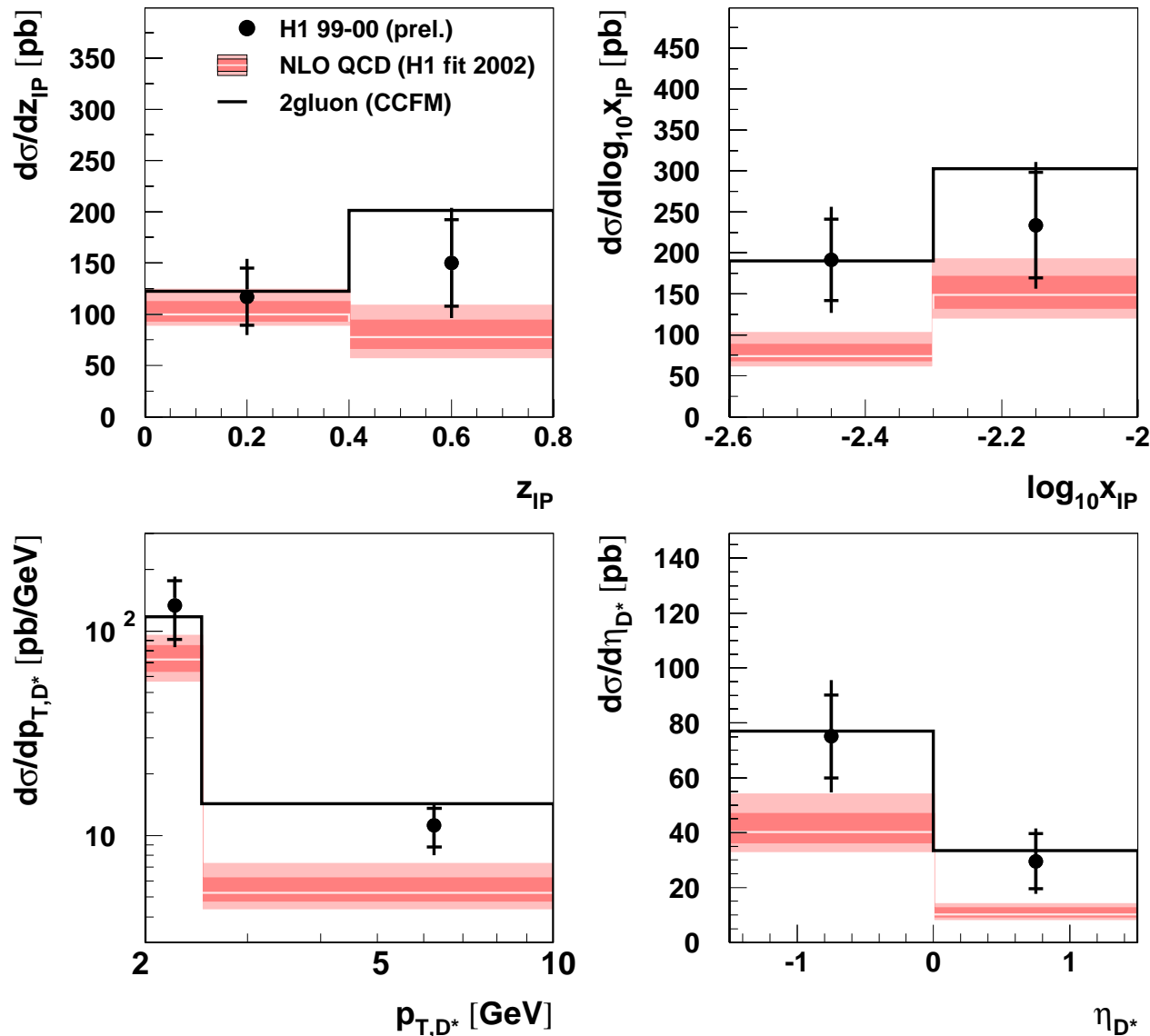
$$x_{IP} < 0.04, \quad M_Y < 1.6 \text{ GeV}, \quad |t| < 1 \text{ GeV}^2$$

$$p_{t,D^*} > 2 \text{ GeV}, \quad |\eta_{D^*}| < 1.5$$



# Diffractional $D^*$ production in DIS, cont.

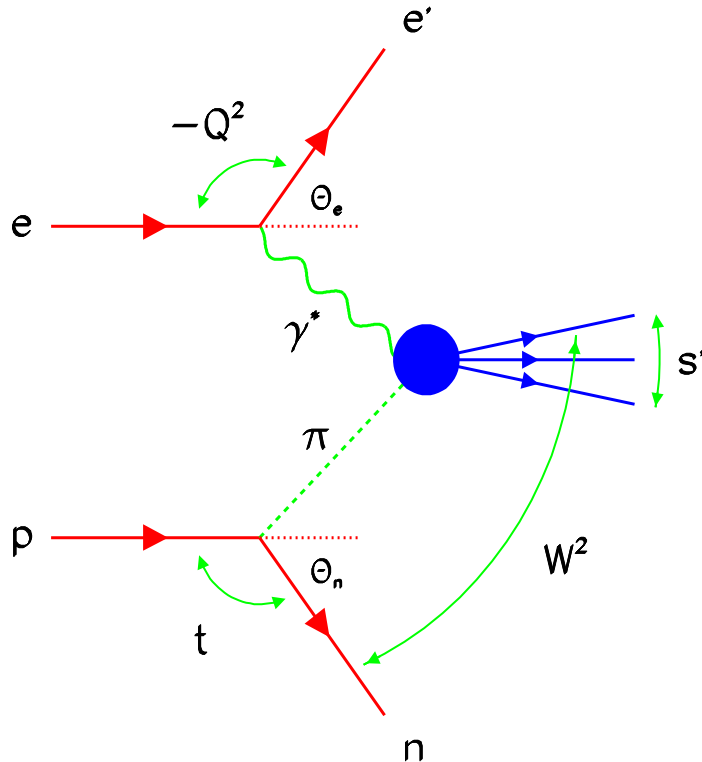
## H1 Diffractive $D^*$ , $x_{IP} < 0.01$



Prediction of perturbative 2-gluon approach with un-integrated gluon density also in good agreement with measurement.

# $D^*$ production with leading neutron

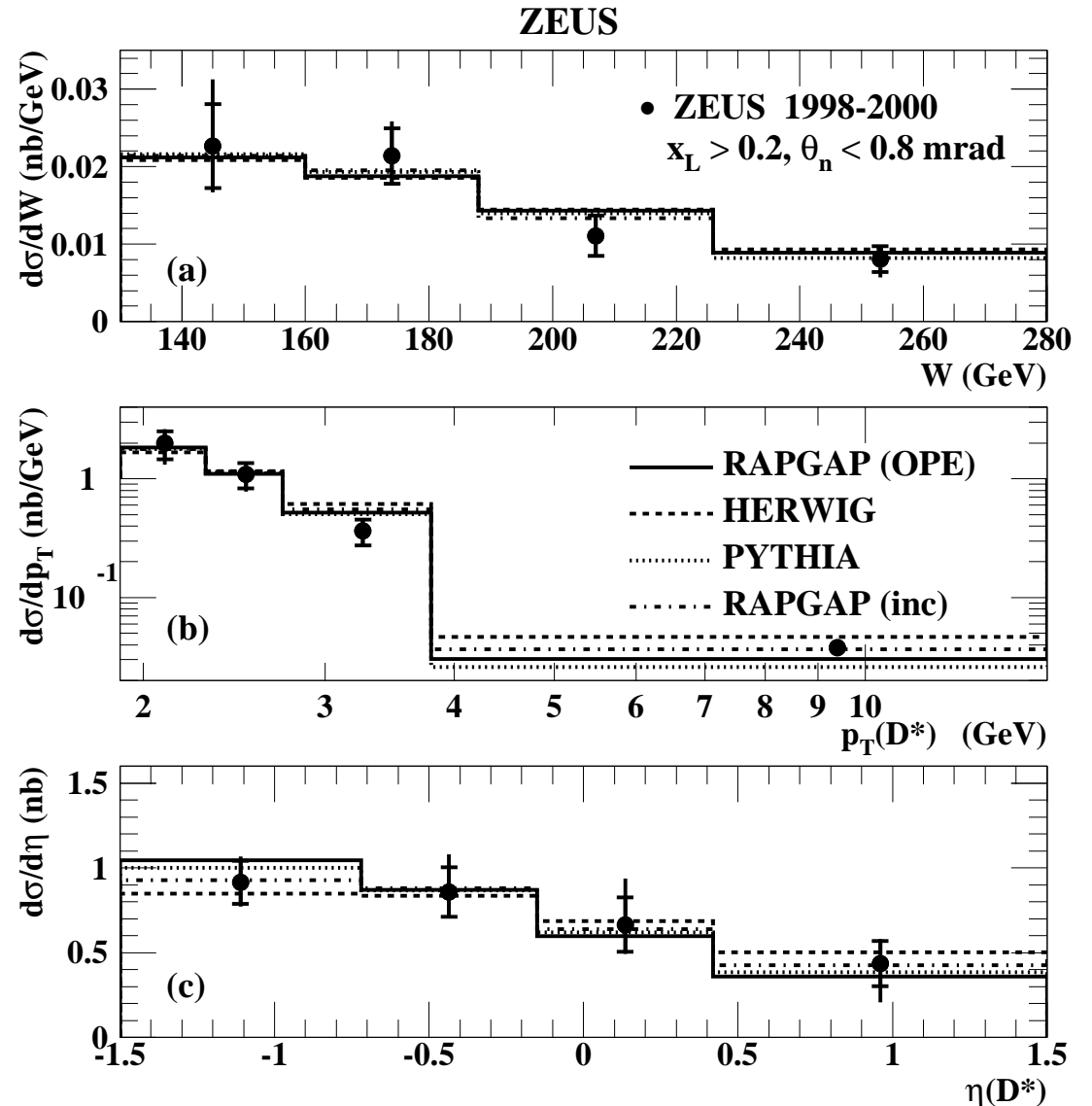
Exchange models applied to describe data:



$$Q^2 < 1 \text{ GeV}^2, \quad 130 < W < 280 \text{ GeV}$$

$$p_t(D^*) > 1.9 \text{ GeV}, \quad |\eta(D^*)| < 1.5$$

$$x_L > 0.2, \quad \theta_n < 0.8 \text{ mrad}$$



Good agreement with all MC models

# $D^*$ production with leading neutron, $x_L$ -dependence

$$x_L = E_{LB}/E_P$$

Cross section can be written as:

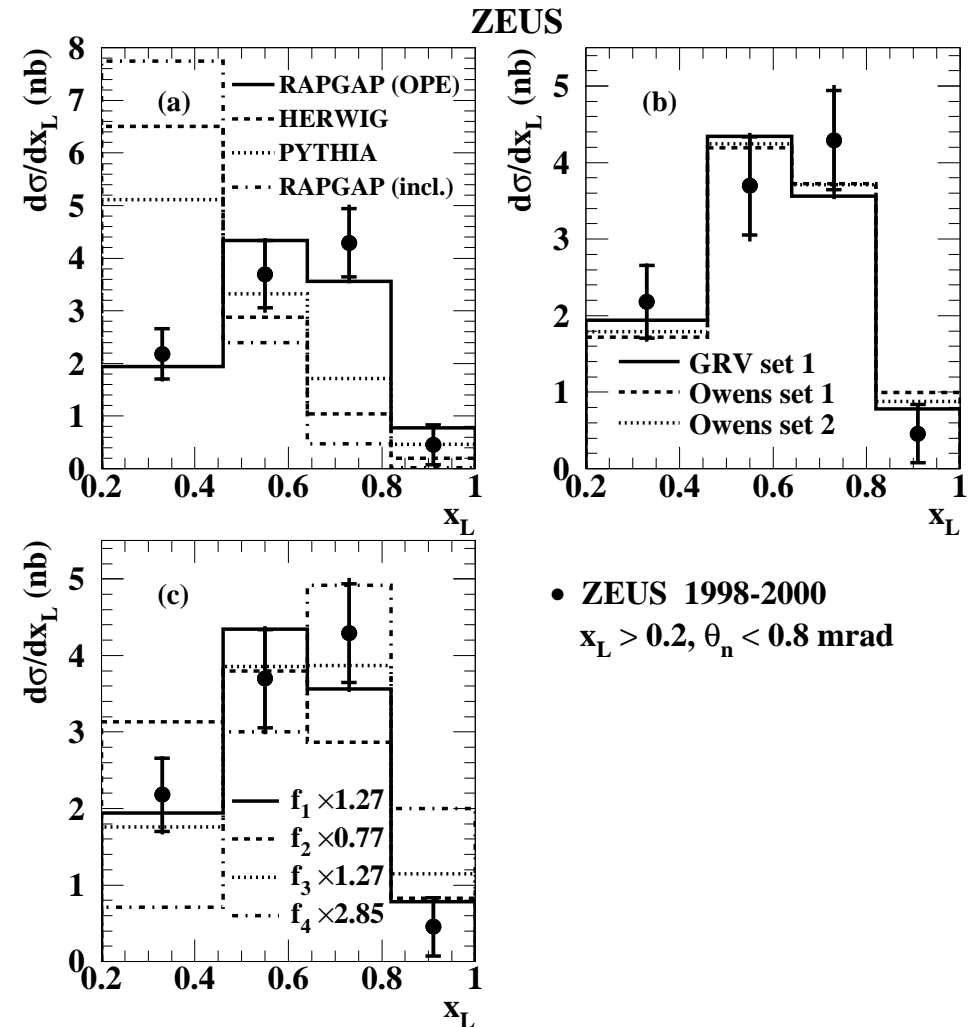
$$\frac{d\sigma_{ep \rightarrow e'nX}}{dx_L dt} = f_{\pi/p}(x_L, t) \sigma^{e\pi}(s')$$

$$s' = s(1 - x_L)$$

$$f_{\pi/p}(x_L, t) \approx (1 - x_L)^{1-2\alpha(t)} [F(x_L, t)]^2$$

Different flux factor parametrisations

$F(x_L, t)$  used.



Only one pion exchange model (OPE) describes the data.