Workshop on low x physics
Prague, September 17, 2004

New results on heavy flavour physics at HERA

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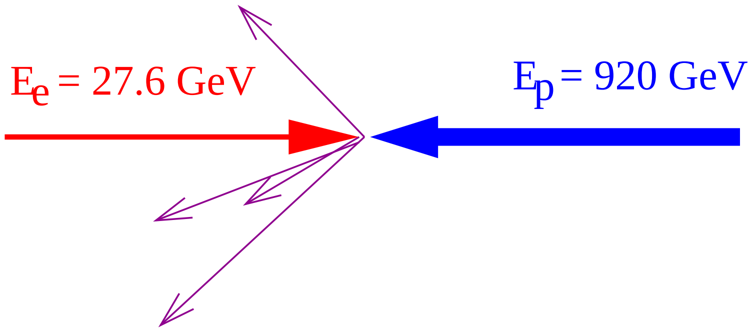
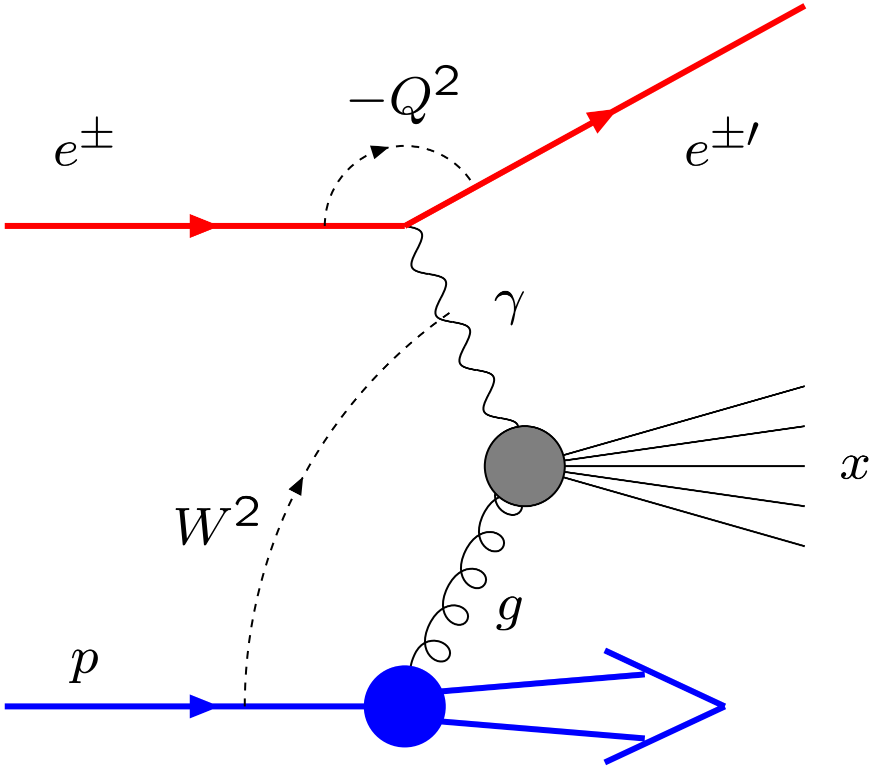
- motivation
- charm
- beauty
- summary

ZEUS DESY Uni Bonn Rheinische Friedrich-Wilhelms-Universität

HERA and kinematics





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

Q^2:4-momentum transfer squared

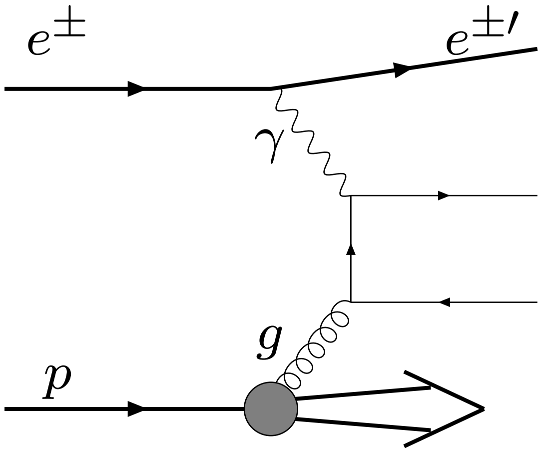
x :Bjorken x

y :Inelasticity

W :Mass of the hadronic system

heavy flavour production at HERA

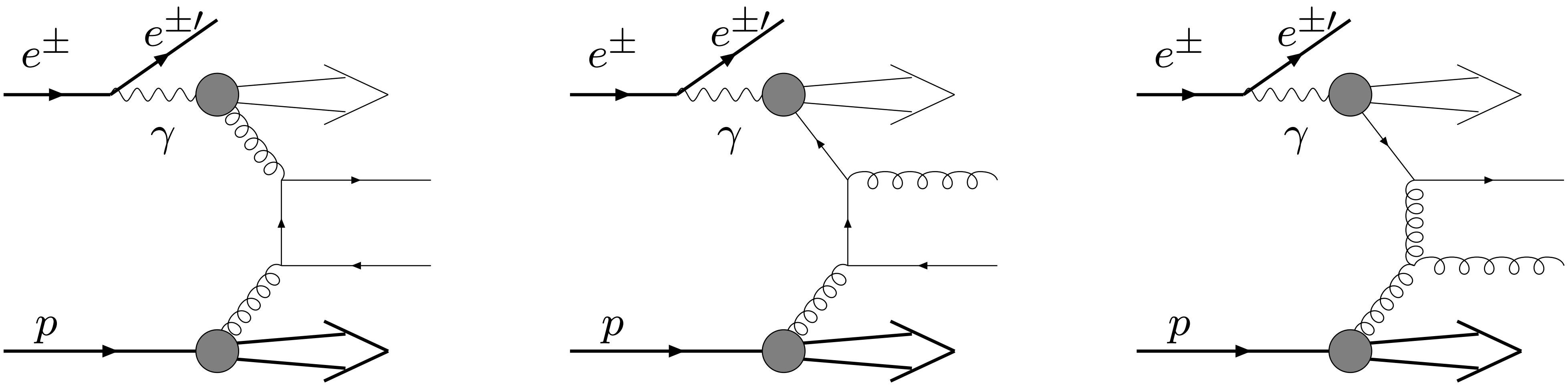
pointlike component



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

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

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
  $p_t >> m_q$
  - 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

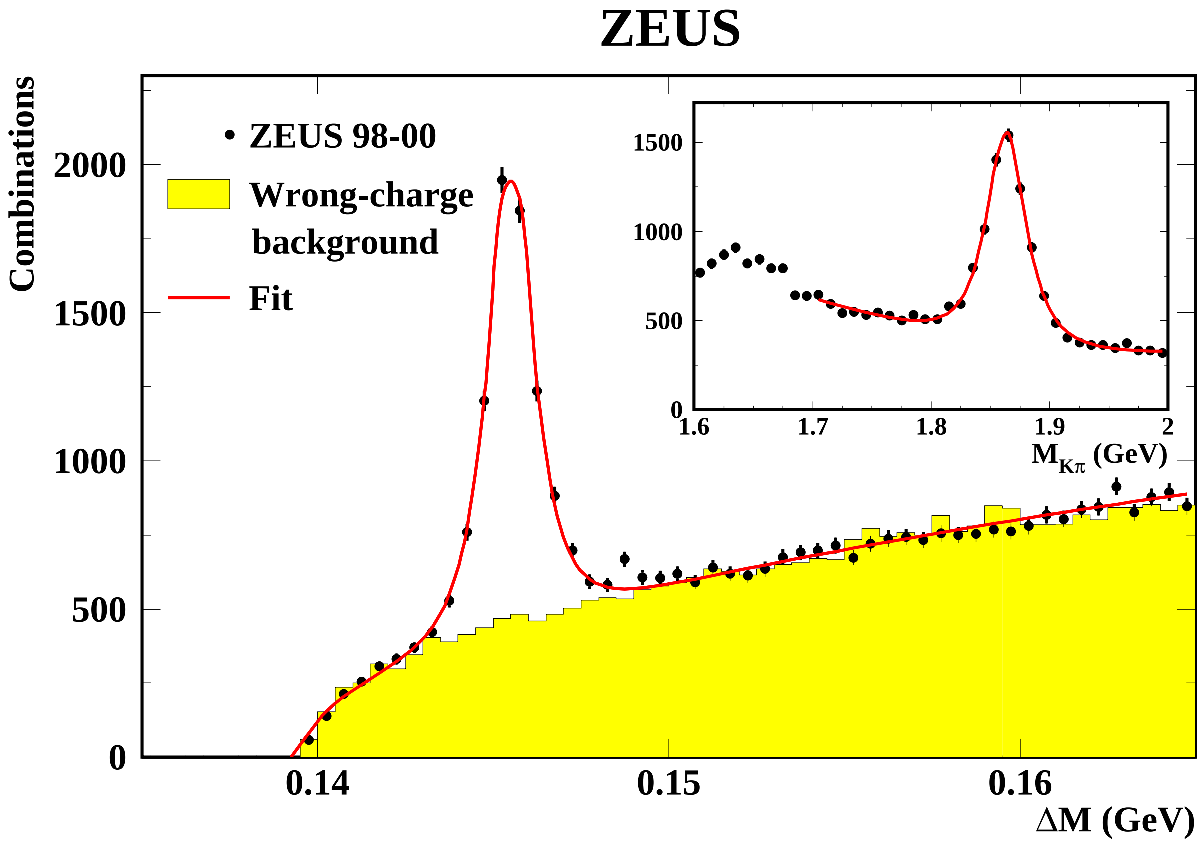
- CASCADE:
  CCFM evolution
  k_t dependent gluon density

Fragmentation: non-pertubative models

D^* tagging

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

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



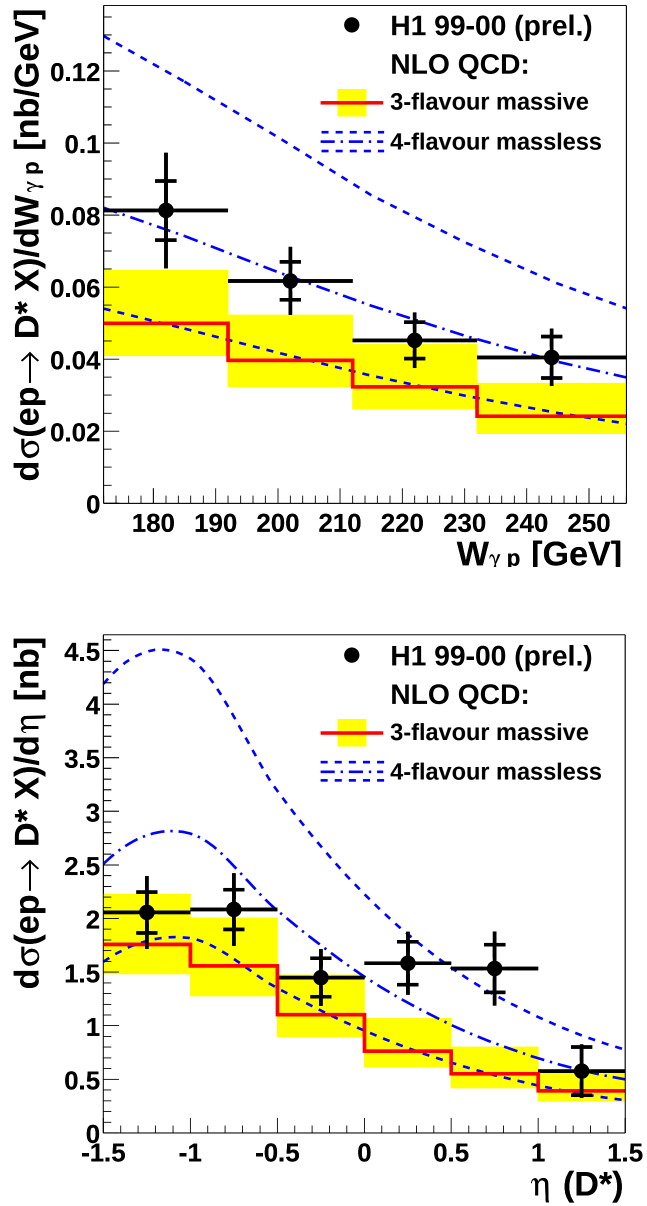
high signal/background ratio due to small phasespace for the D^* decay (small combinatorical background)

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

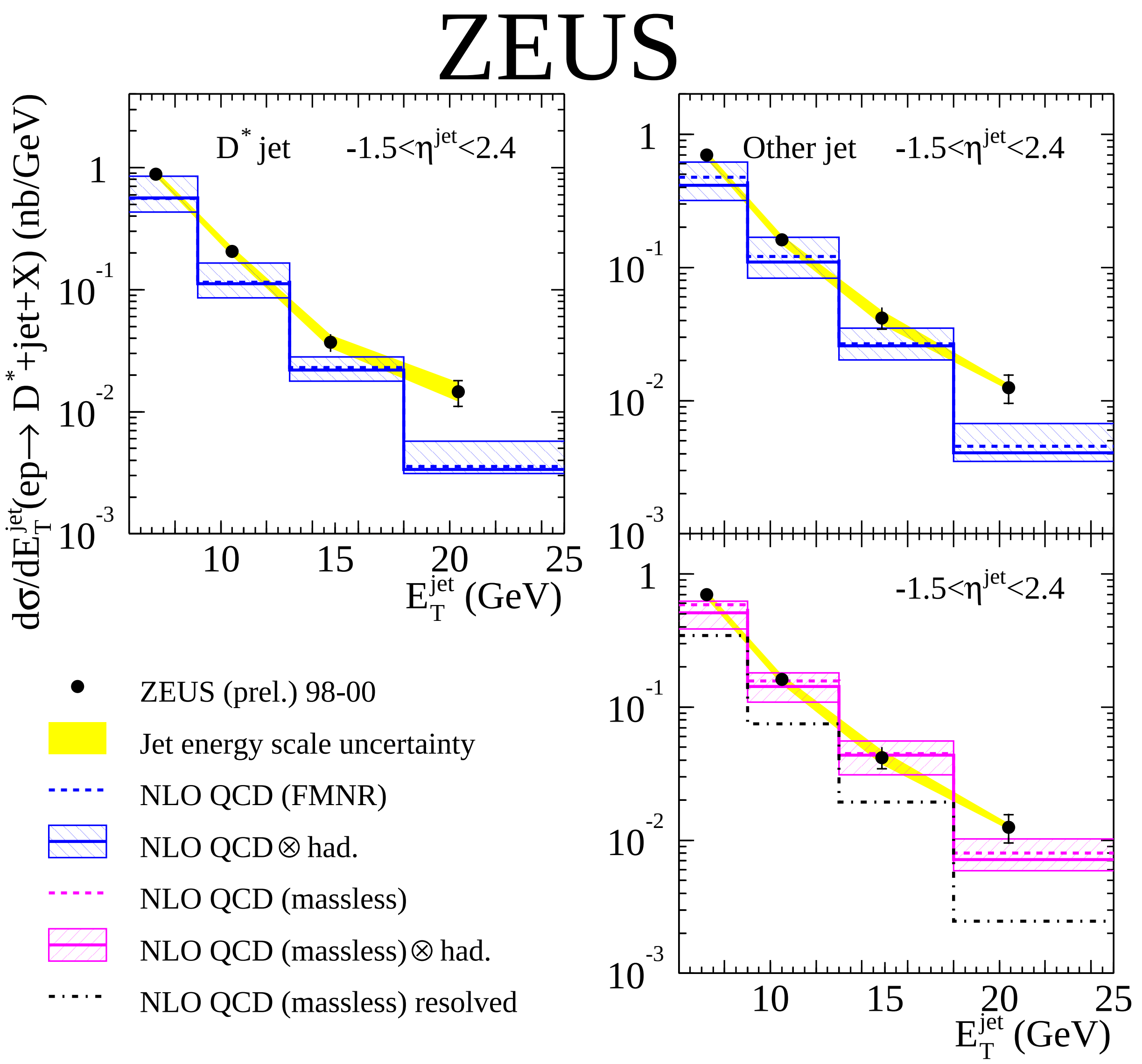
$Q^2 < 0.01\,\text{GeV}^2,\ 171 < W < 256\,\text{GeV}$

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



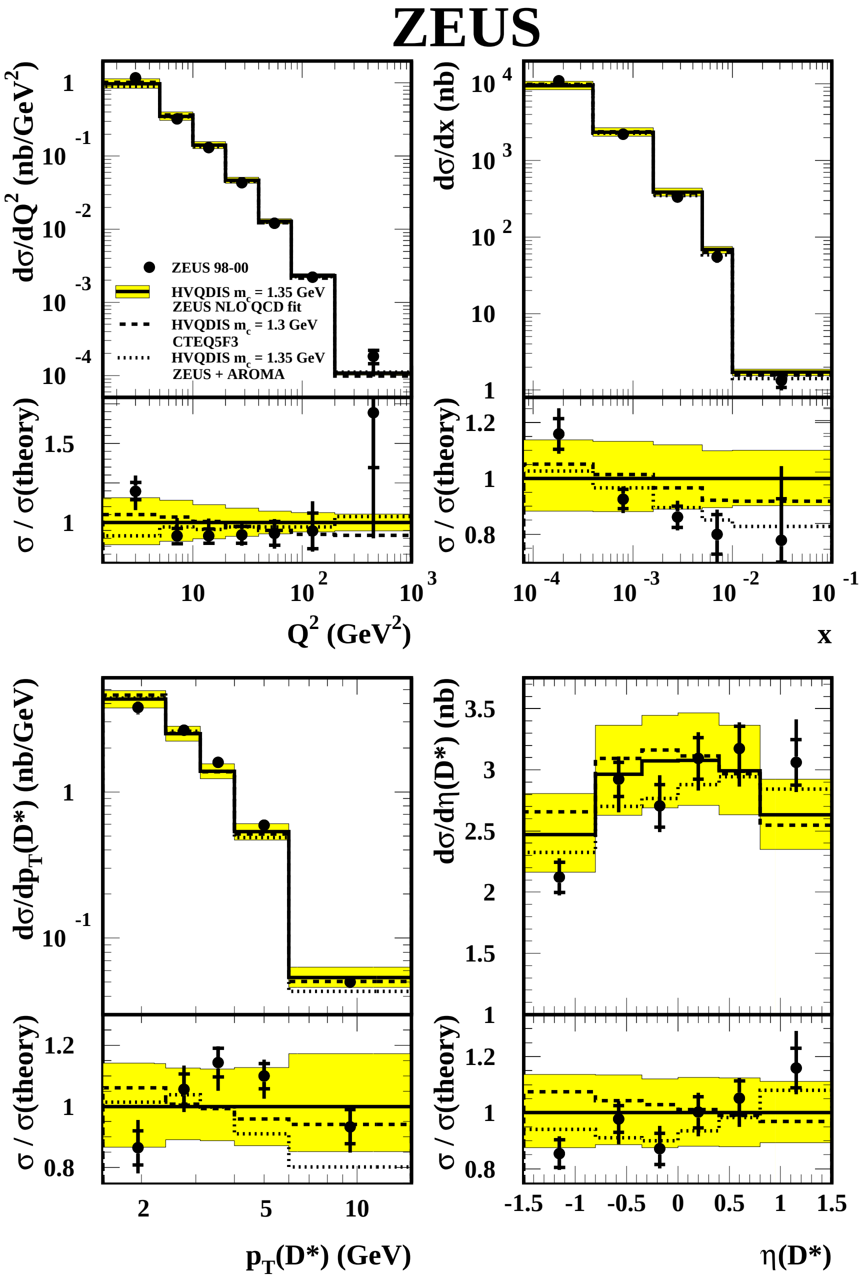
PHP of D^*, inclusive jet cross sections

- 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



$Q^2 < 1$ GeV^2, $130 < W < 280$ GeV
$p_t(D^*) > 3$ GeV, $|\eta(D^*)| < 1.5$
$E_T^{jet} > 6$ GeV, $-1.5 < \eta^{jet} < 2.4$

D^* production in DIS



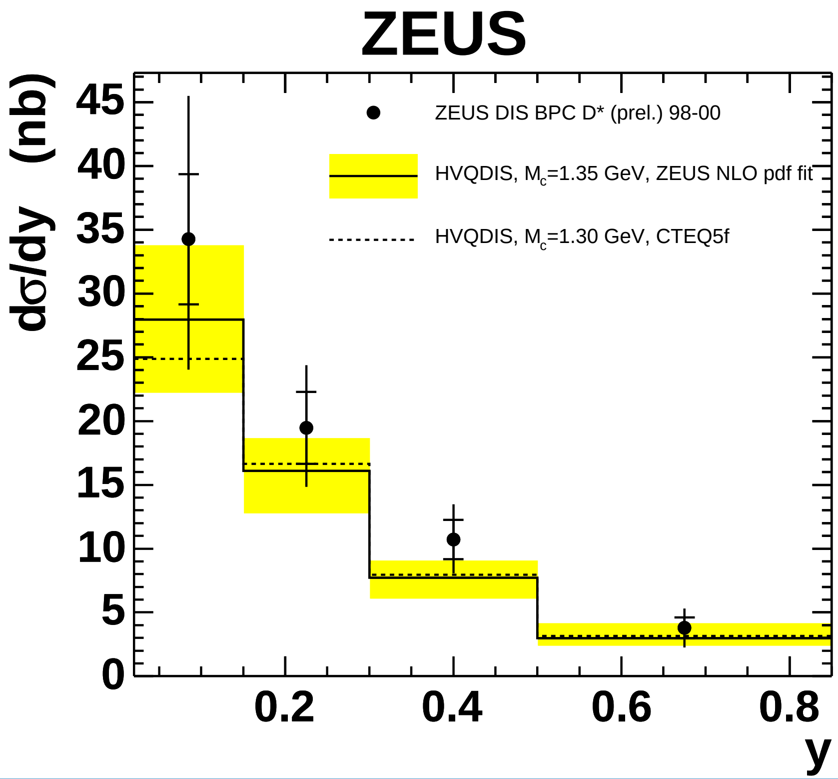
- NLO QCD in reasonable agreement with measurement
- sensitivity to choice of PDF found
- cross sections have potential to be used for PDF's

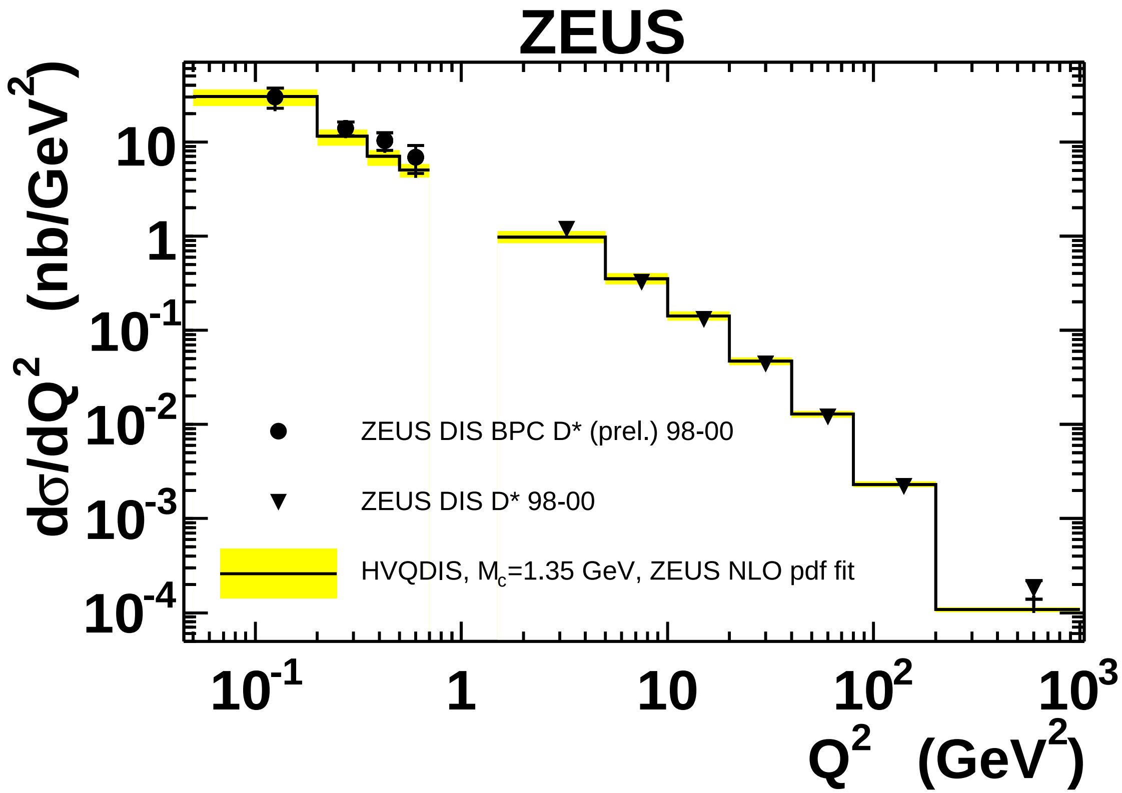
$1.5 < Q^2 < 1000\,\text{GeV}^2,\ 0.02 < y < 0.7,$
$1.5 < p_t(D^*) < 15\,\text{GeV},\ |\eta(D^*)| < 1.5$

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

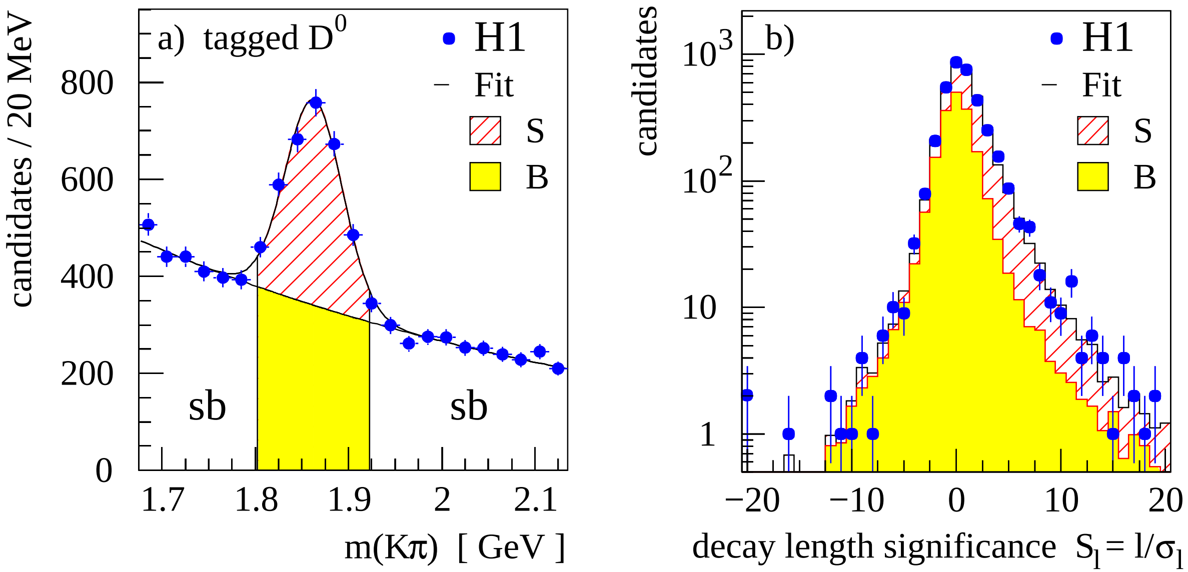


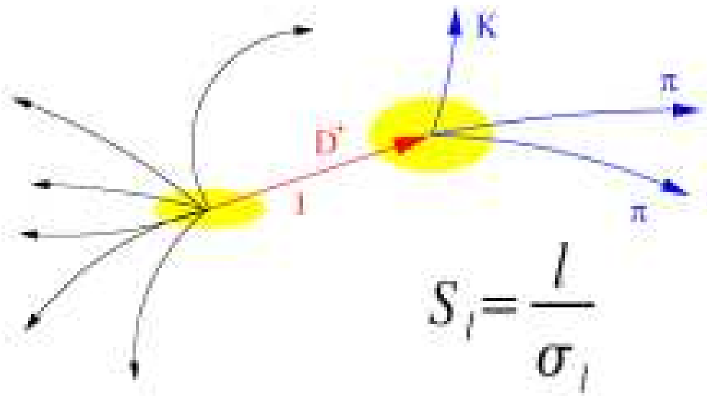


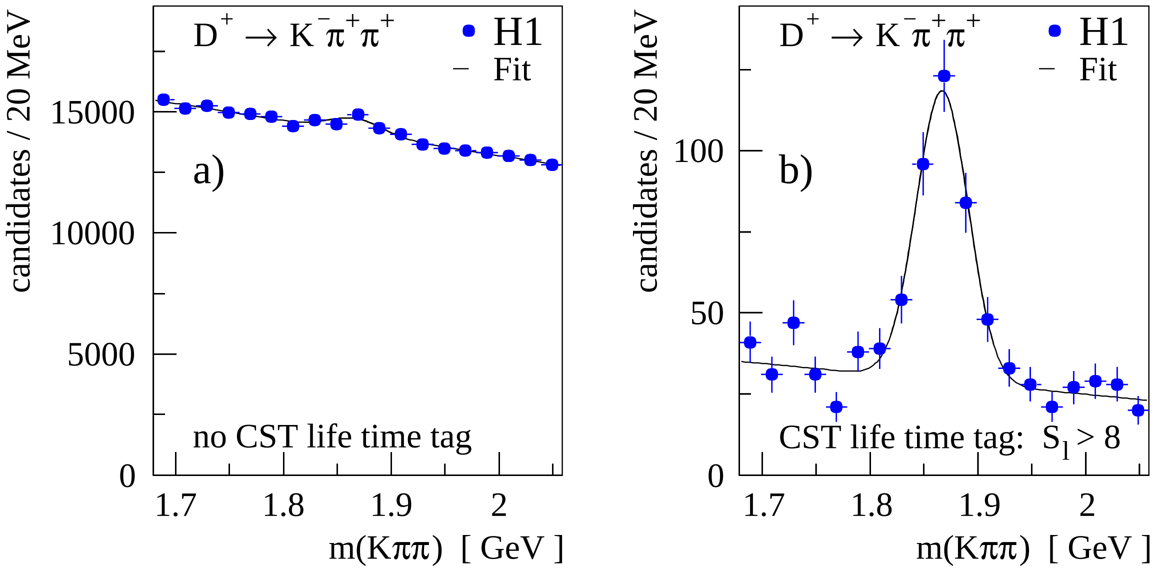
Predictions are consistent
with measured cross sections
at low Q^2

secondary vertex identification with H1 central silicon tracker (CST)

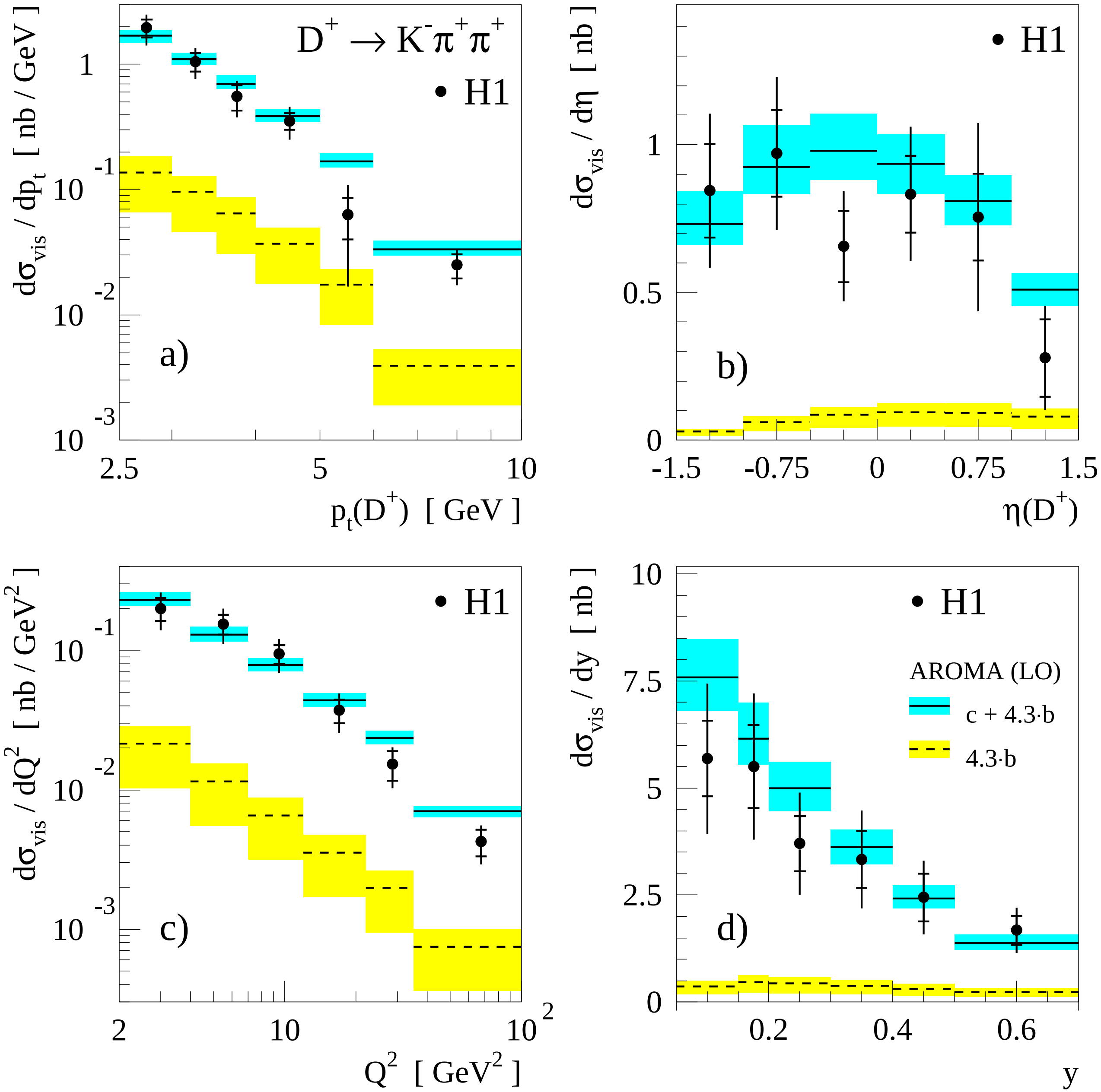
background reduced with cut on decay length significance







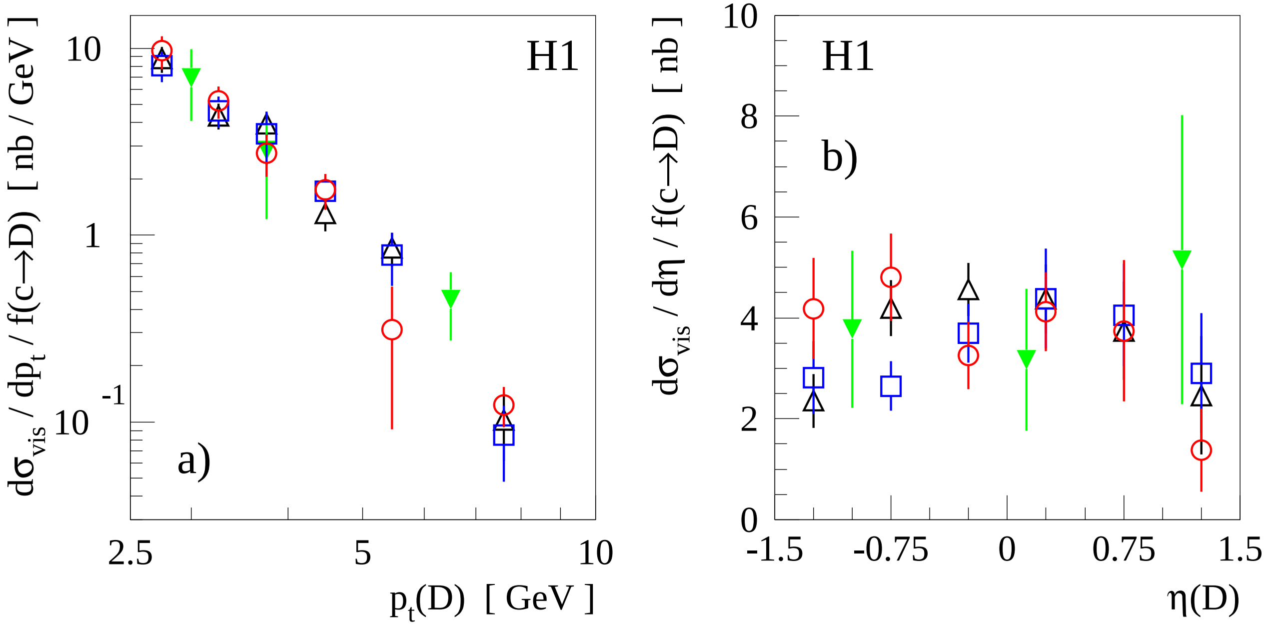
D^+ mesons



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

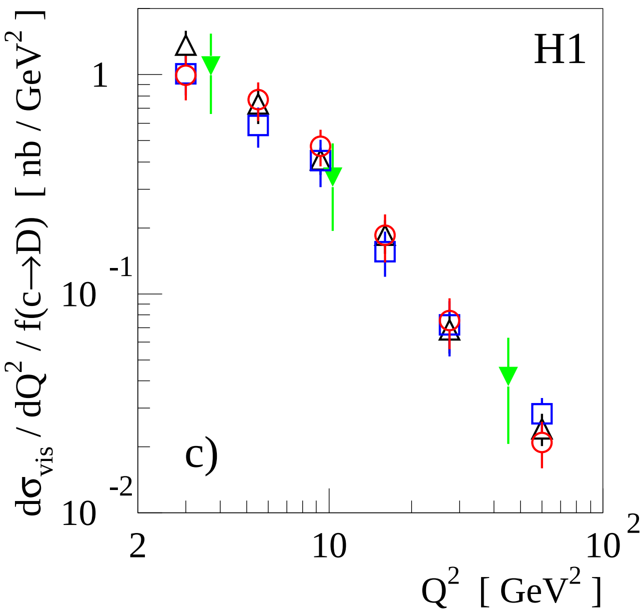
$2 < Q^2 < 100$ GeV^2
$0.05 < y < 0.7$
$p_t(D) > 2.5$ GeV
$|\eta(D)| < 1.5$

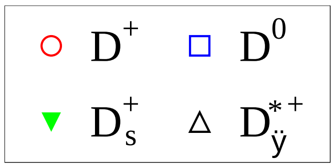
fragmentation of charm quarks



visible cross section / fragmentation factor

- similar shapes for different D mesons

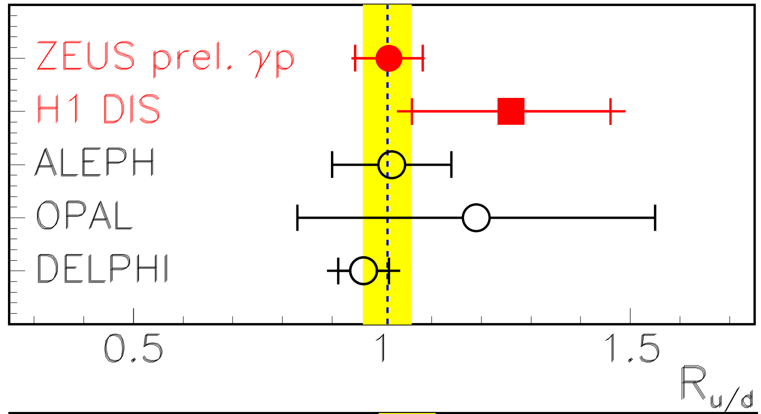




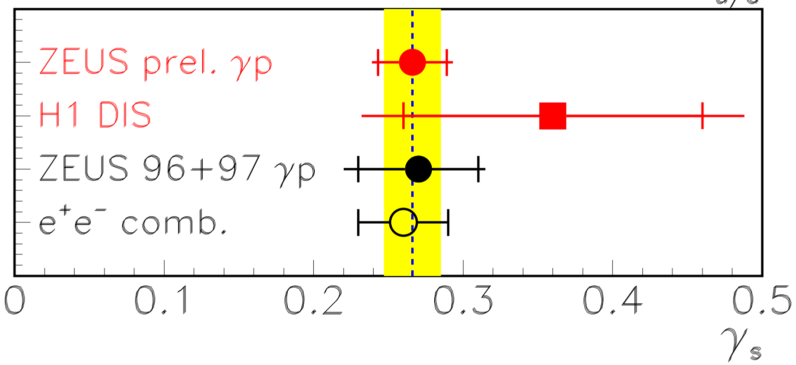
$\longrightarrow$

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

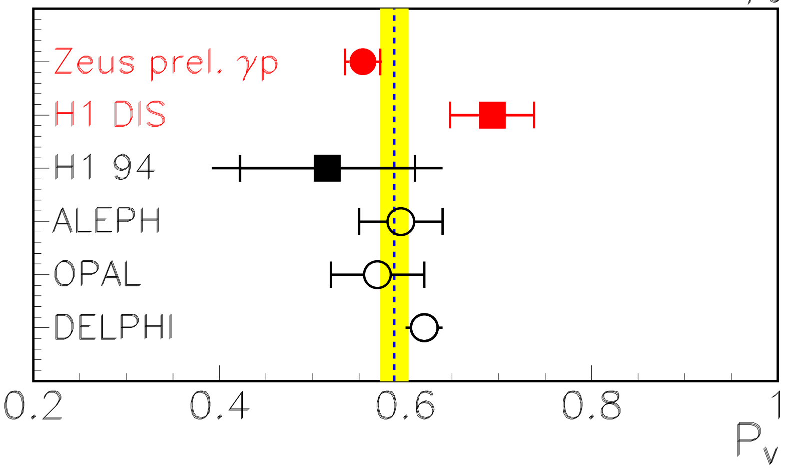
fragmentation ratios



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

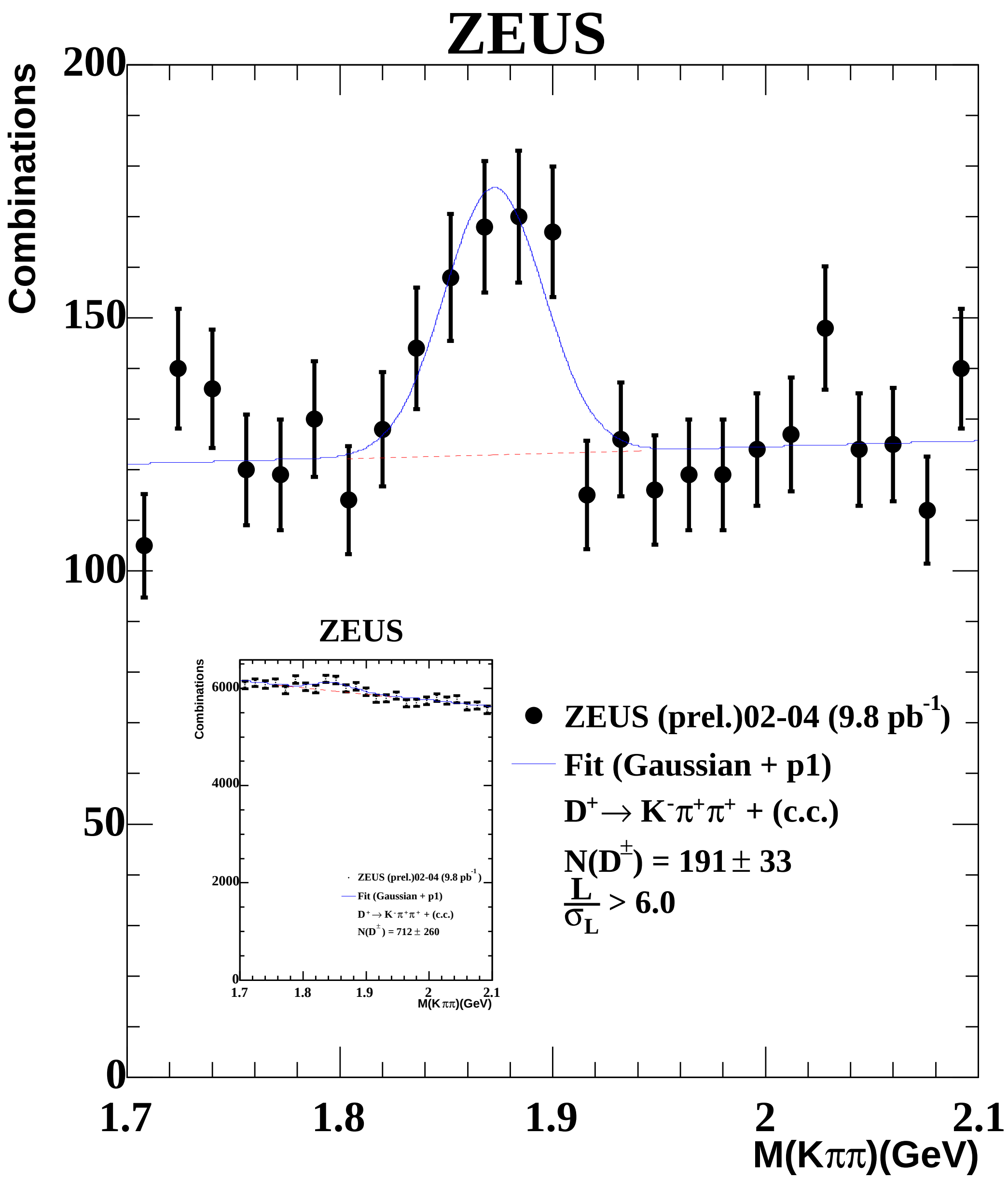


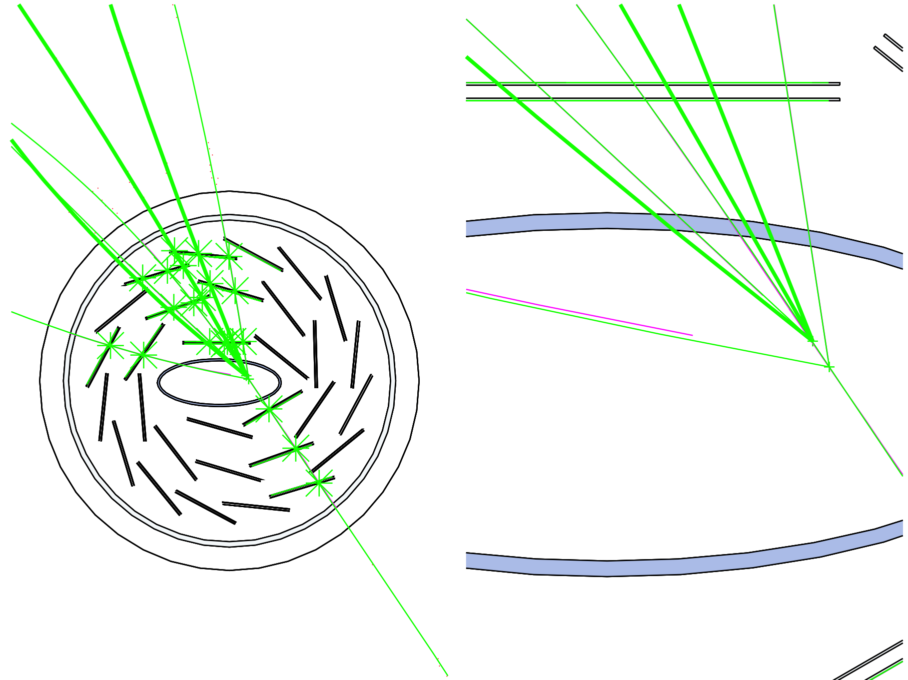
- $\gamma_s = 2c\bar{s}/(c\bar{u} + c\bar{d})$
  strangeness suppression factor



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

precision comparable with DELPHI



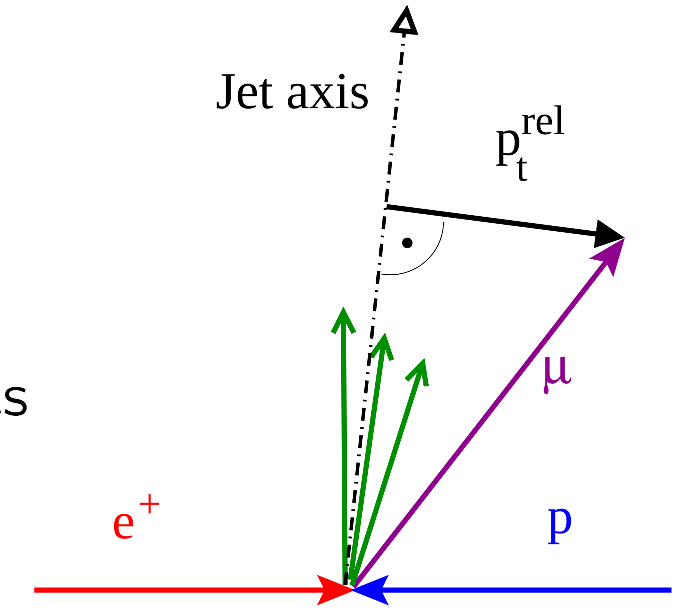


cleaner event selection possible

beauty tagging: p_t^{rel}

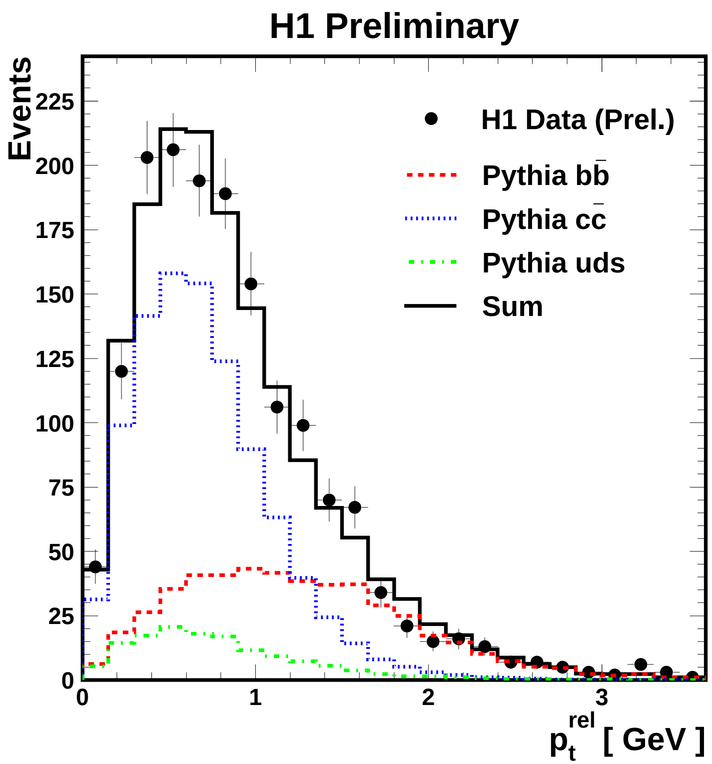
Why beauty?

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



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

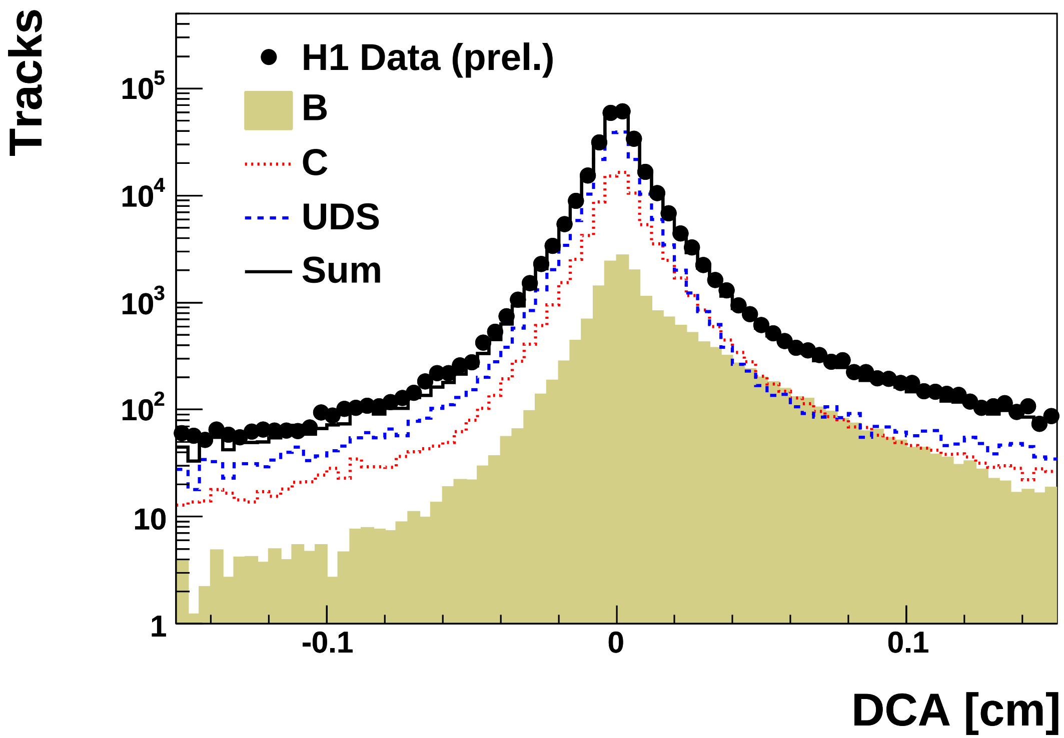
2 jet events (BGF) with tagged μ in one of the jets



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

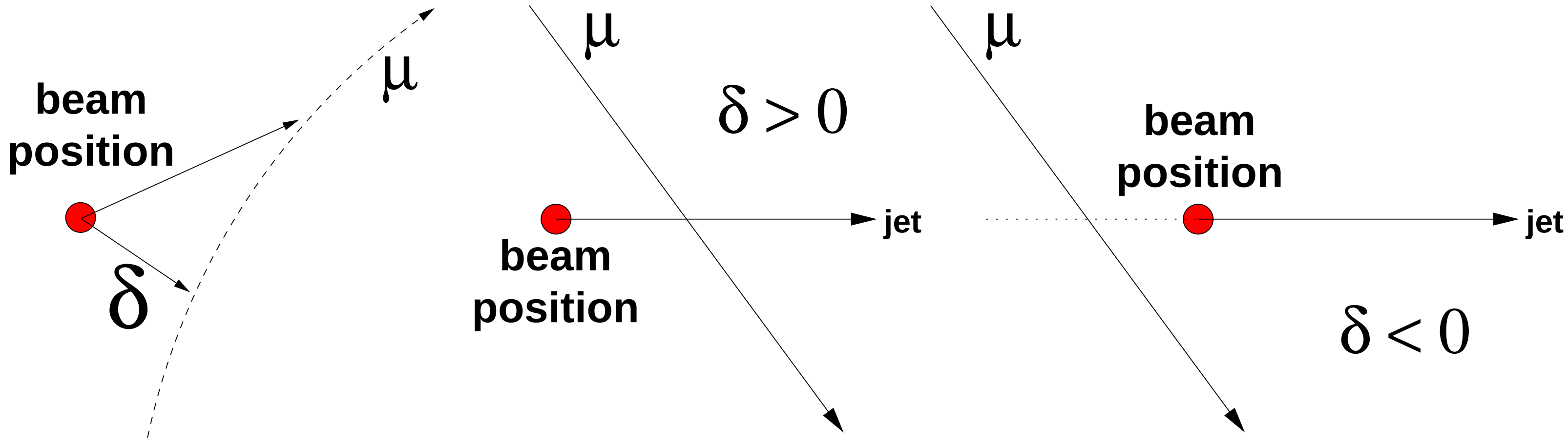
beauty tagging: lifetime

2 jet events (BGF)

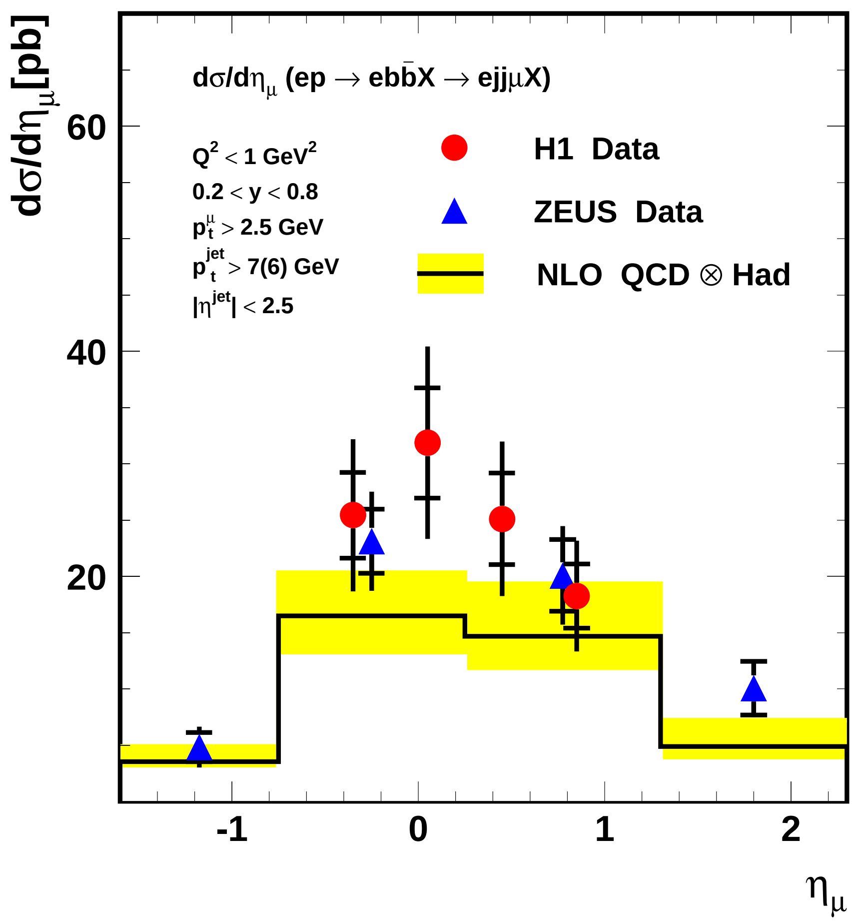


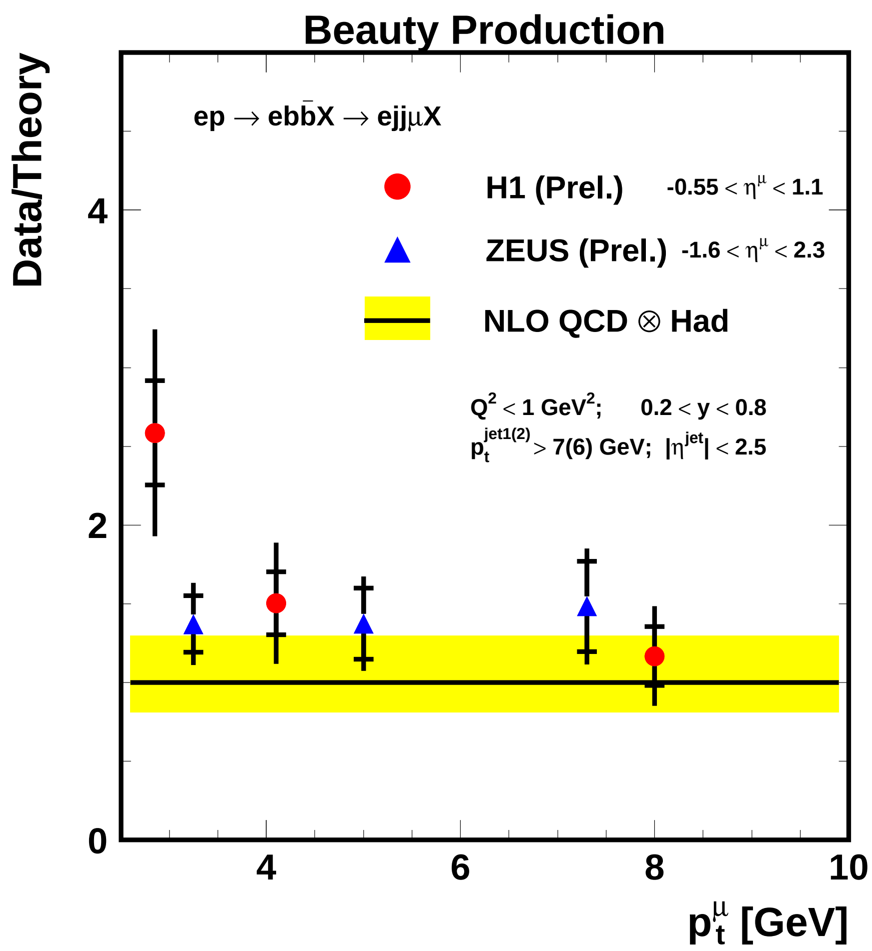
- Long lifetime of b causes large impact parameter δ of one (μ) track (H1, ZEUS with HERA II)

  Can be made with any track in the jet



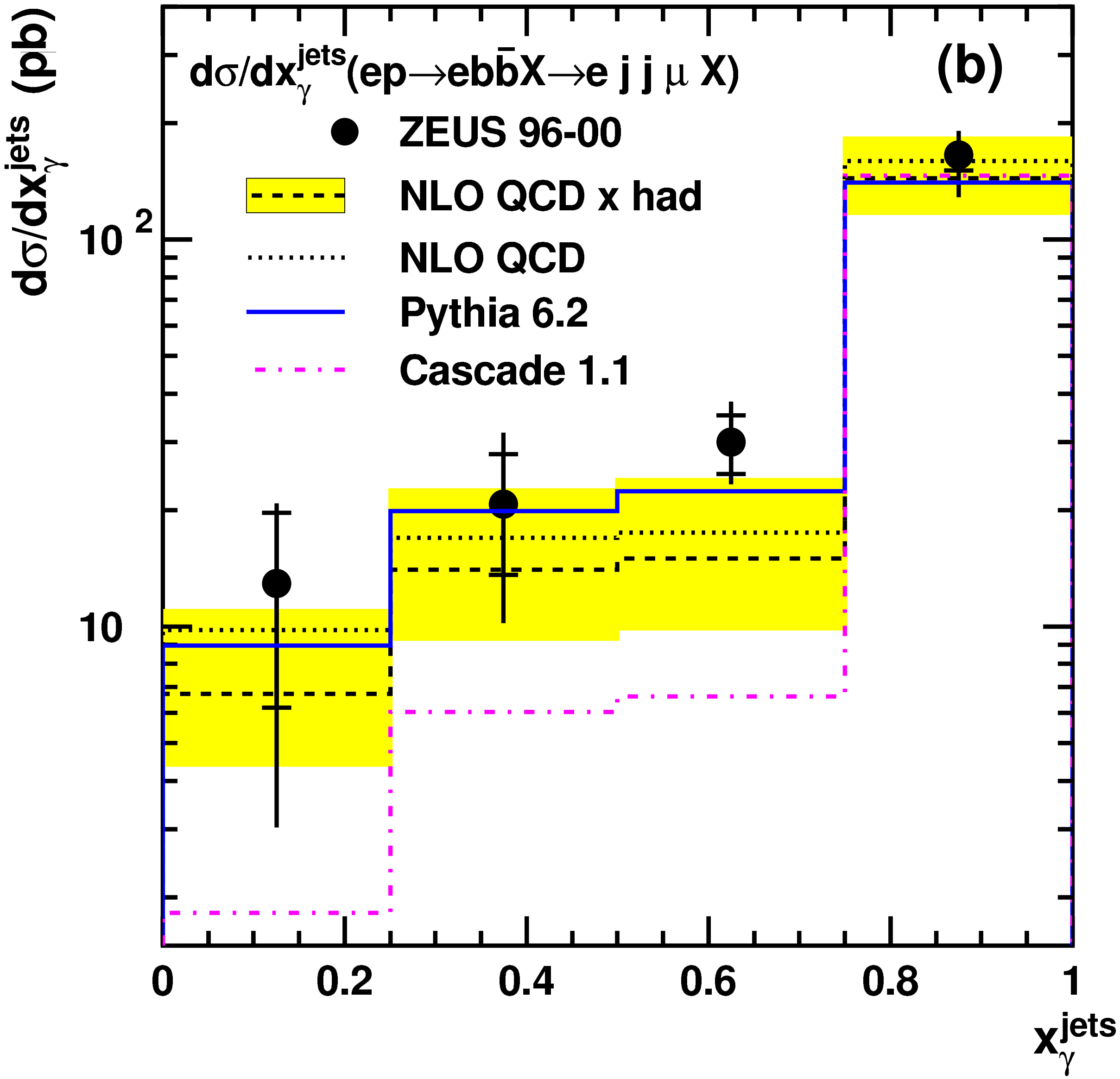
beauty in PHP





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

beauty in PHP: resolved photons

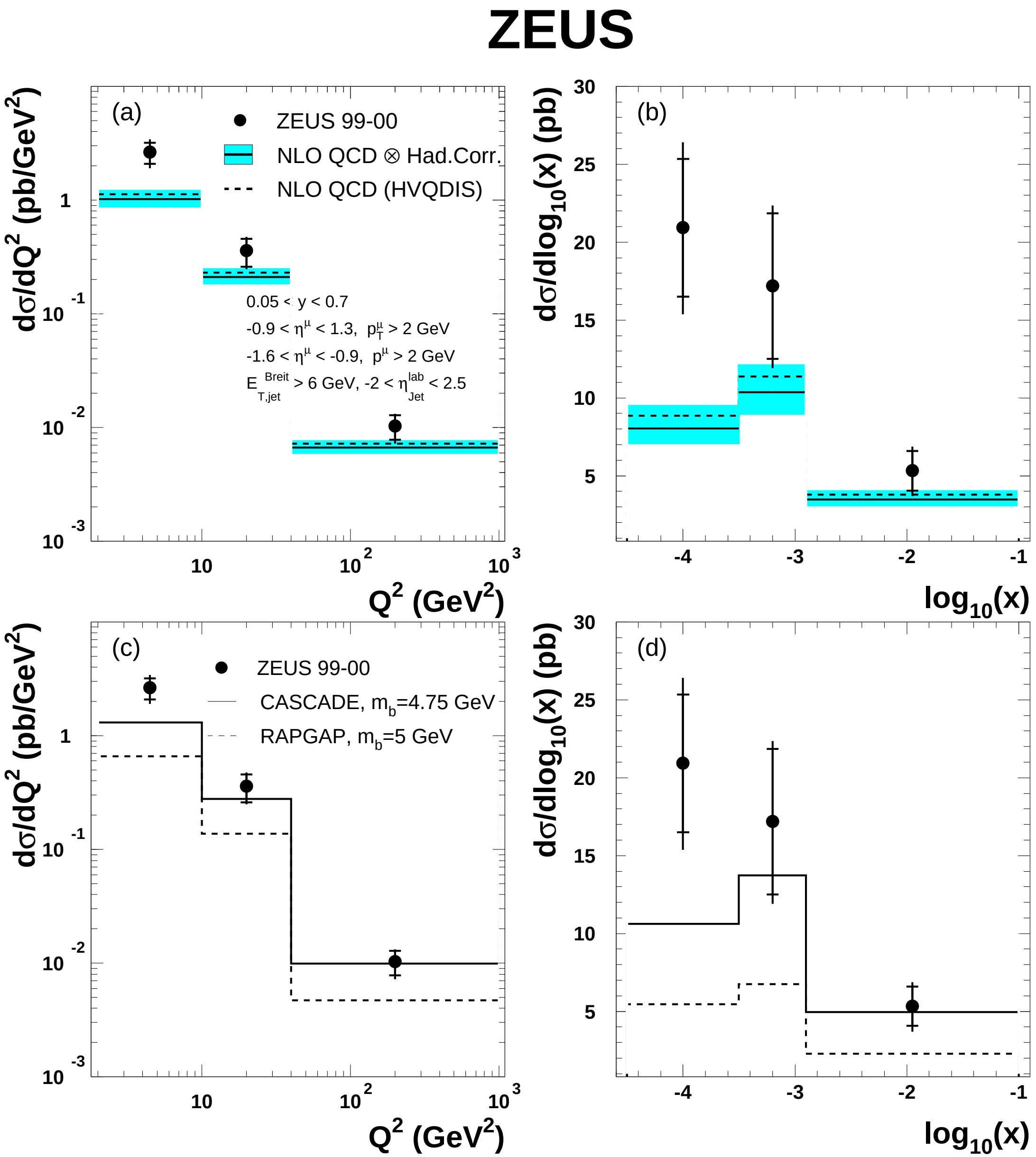


$$x_\gamma^{jets} = \frac{\sum_{j_1,j_2}(E_T^j e^{-\eta^j})}{2yE_e}$$

resolved photon enriched:
$x_\gamma^{jets} < 0.75$

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

$Q^2 < 1\ \text{GeV}^2,\ 0.2 < y < 0.8$
$p_t^{jet_1} > 7, p_t^{jet_2} > 6\ \text{GeV},\ \eta^{jet} < 2.5$

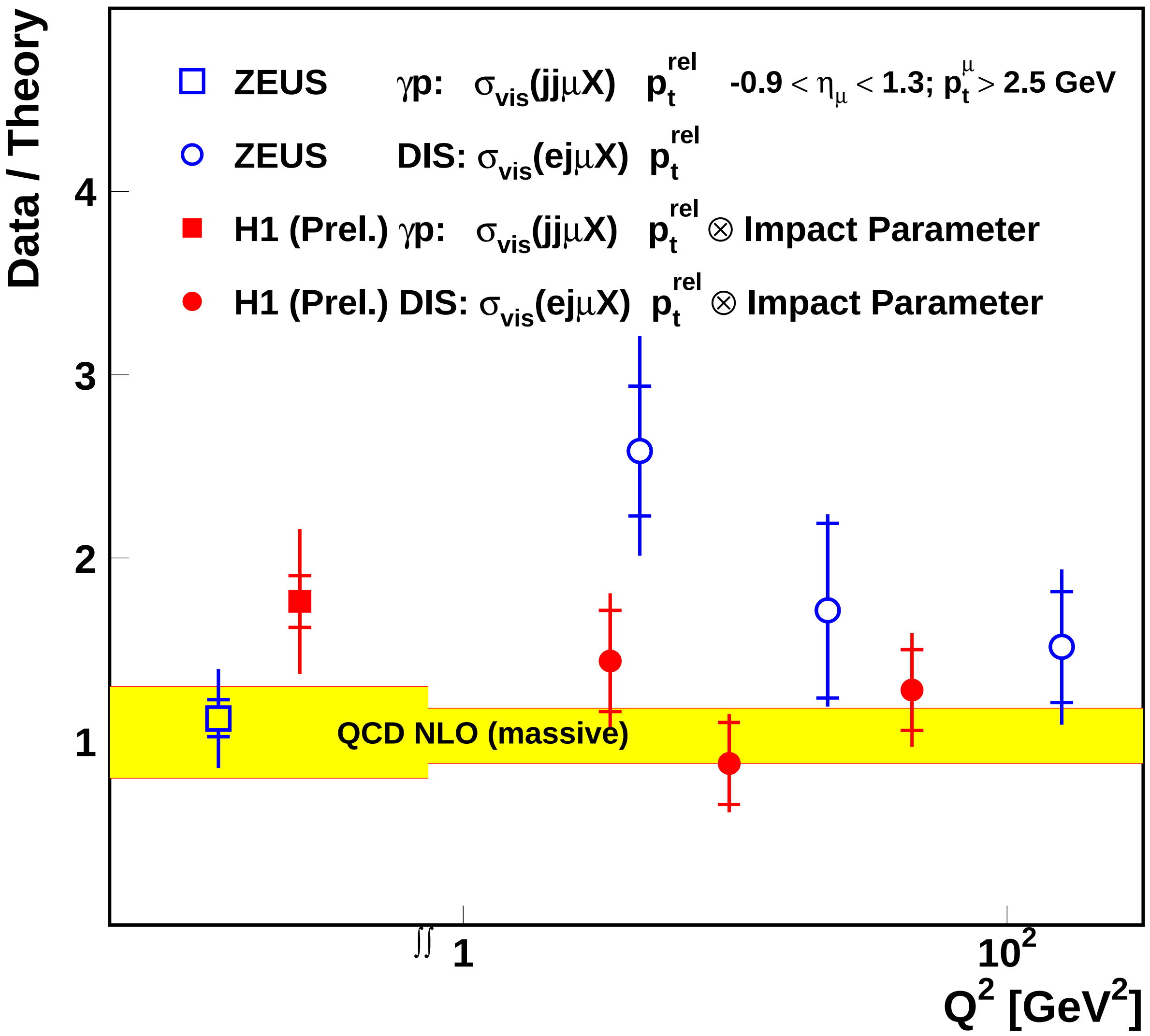


- Data higher than NLO, esp. at small Q^2 and x
- theoretical prediction up to $\sim 2.5\sigma$ below data

$Q^2 > 2\,\text{GeV}^2$

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

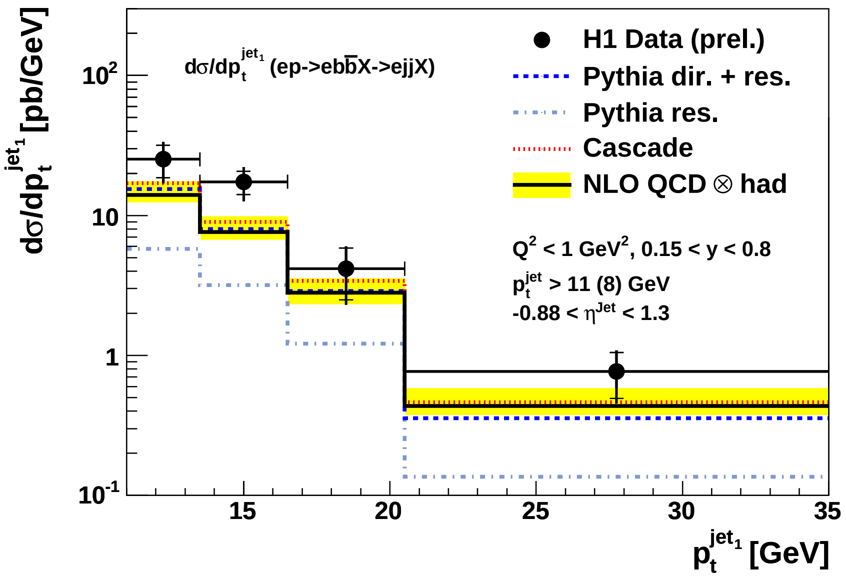
Data/Theory as a function of Q^2

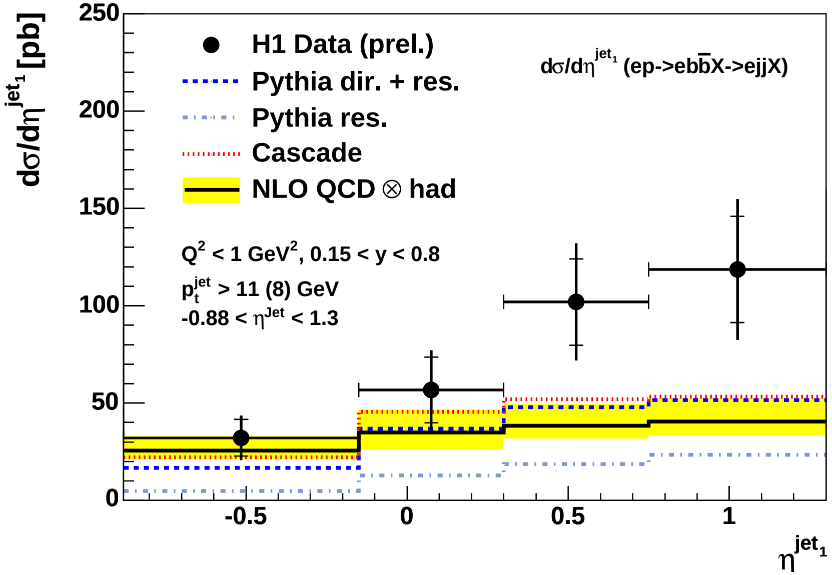


Data in agreement with (massive) NLO predictions,

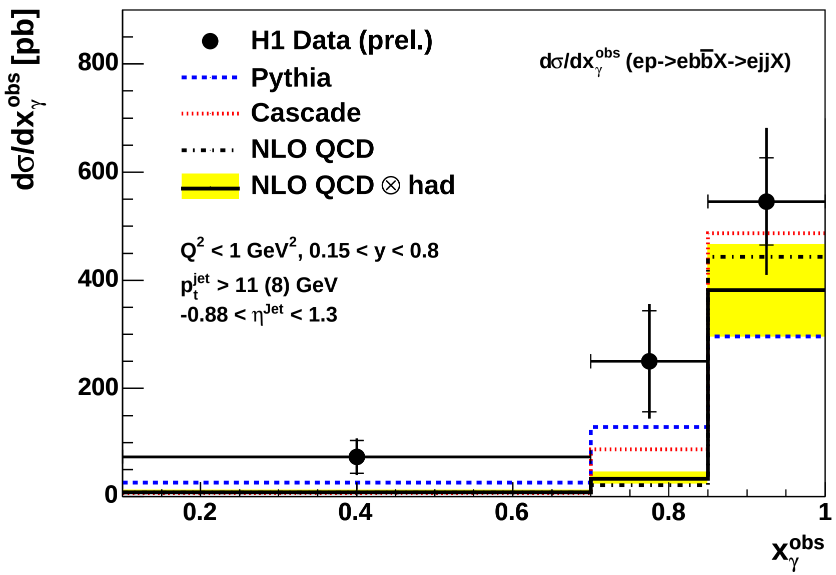
slightly higher in DIS for low Q^2

beauty in PHP with inclusive lifetime tag





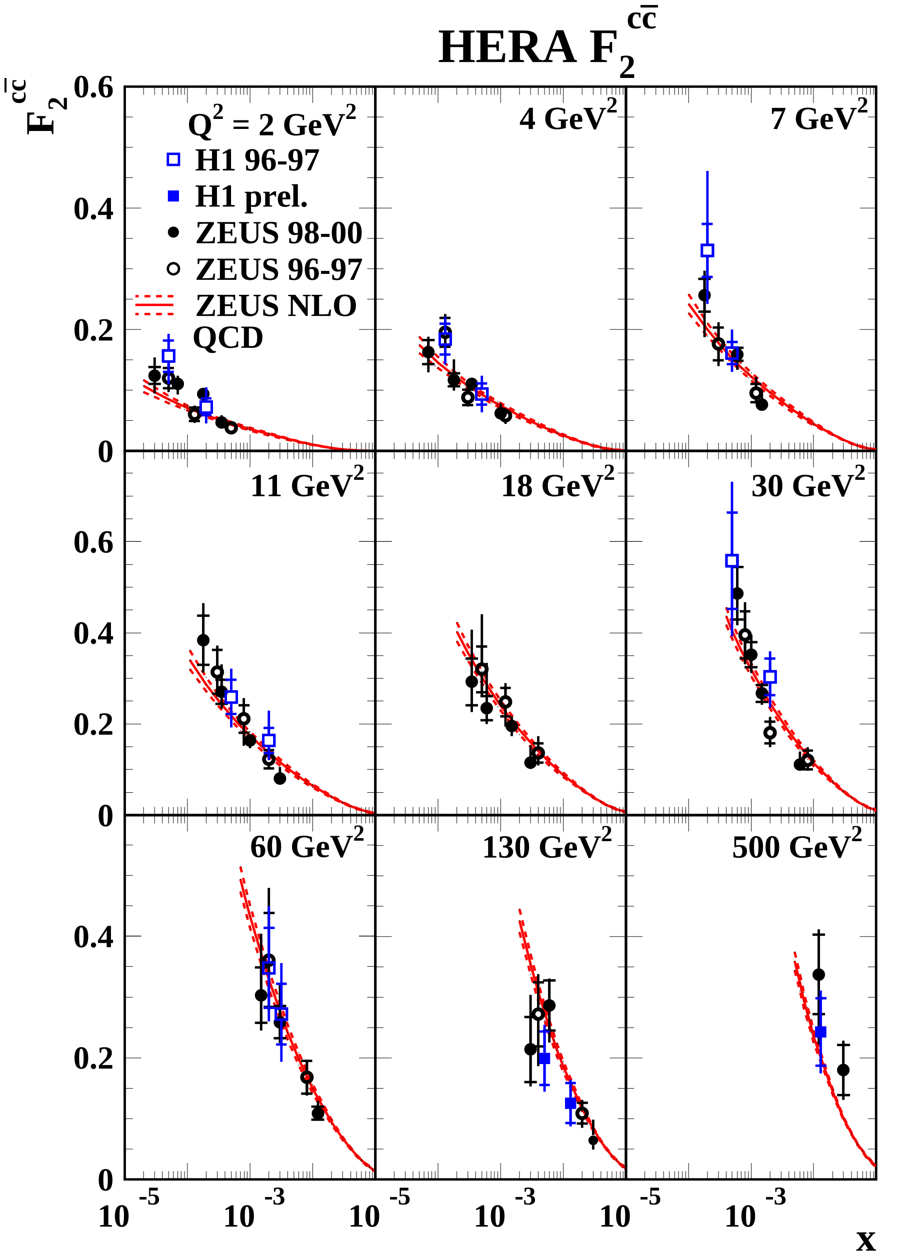
- MC falls below data by a factor of about 2
- shapes of $p_t^{jet_1}$ described well
- main difference in η^{jet_1} for forward jets and at small x_γ^{obs}



charm contribution to F_2

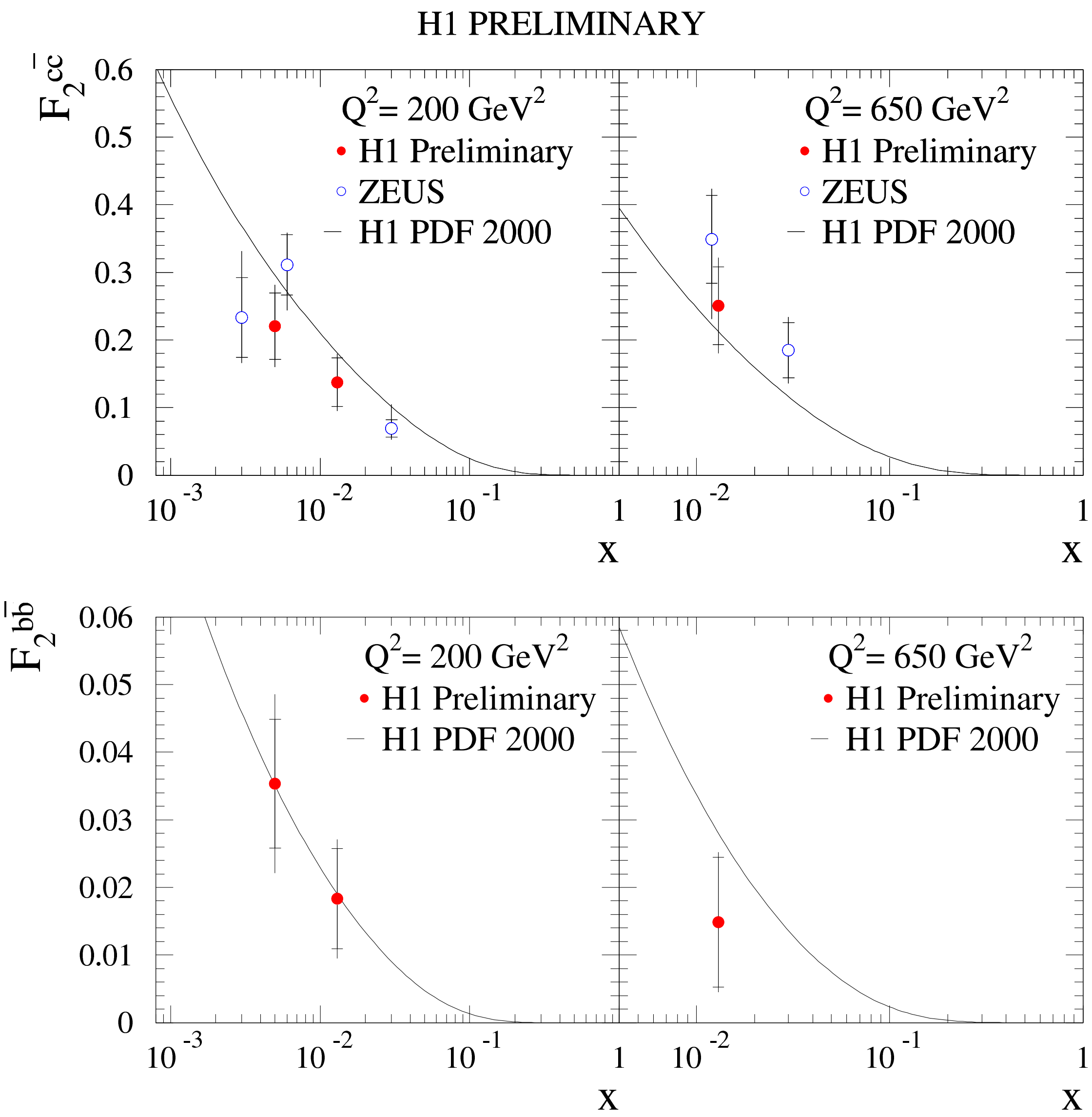
F_2: proton structure function

- 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^*)



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

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

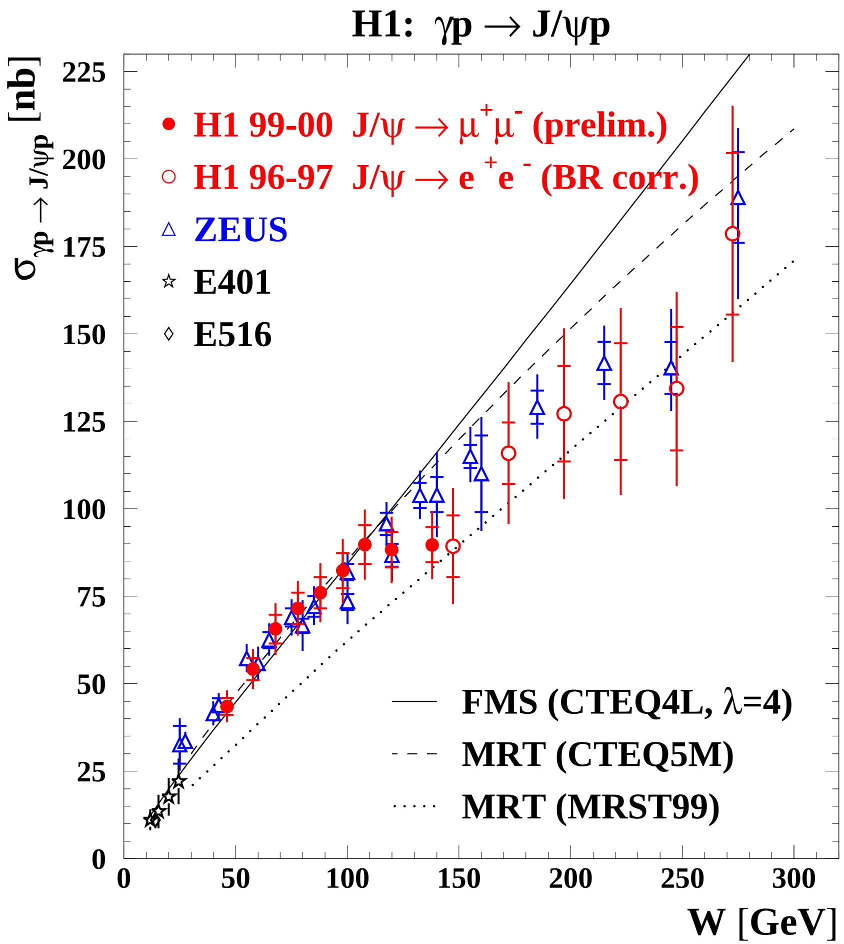
- new differential b cross section measurements in PHP and DIS
- measurements in agreement with massive NLO QCD predictions
- first determination of $F_2^{b\bar{b}}$ at $Q^2 > 150\,\text{GeV}^2$

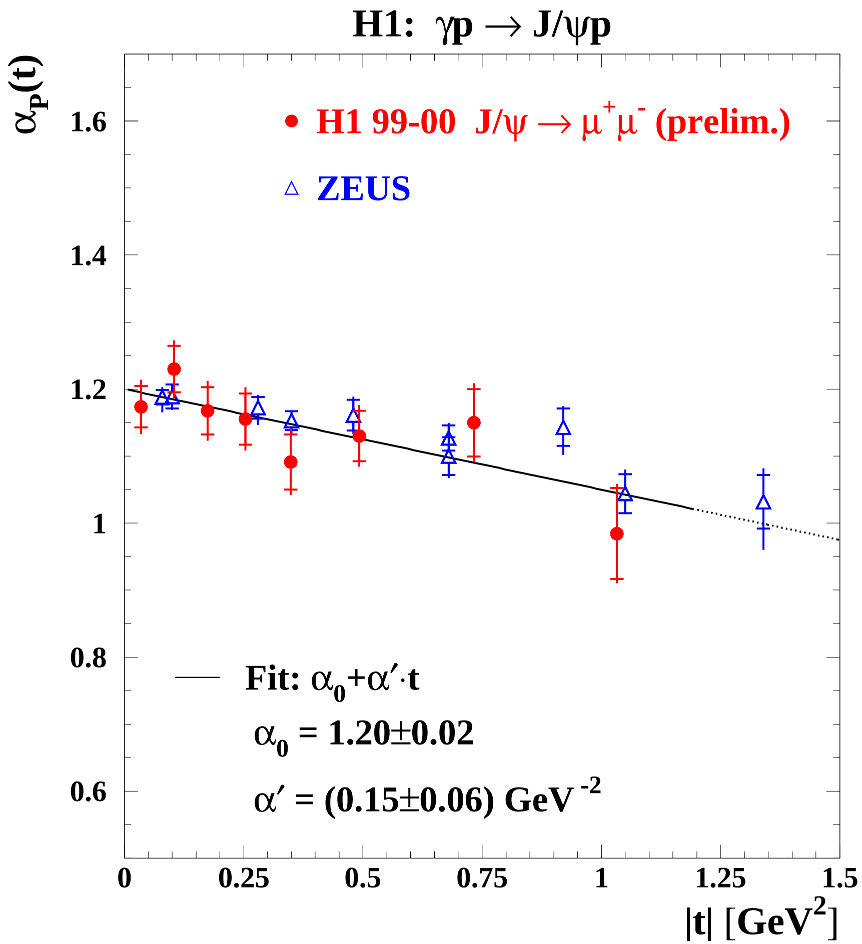
improved analysis methods and higher statistics with HERA II data

backup slides

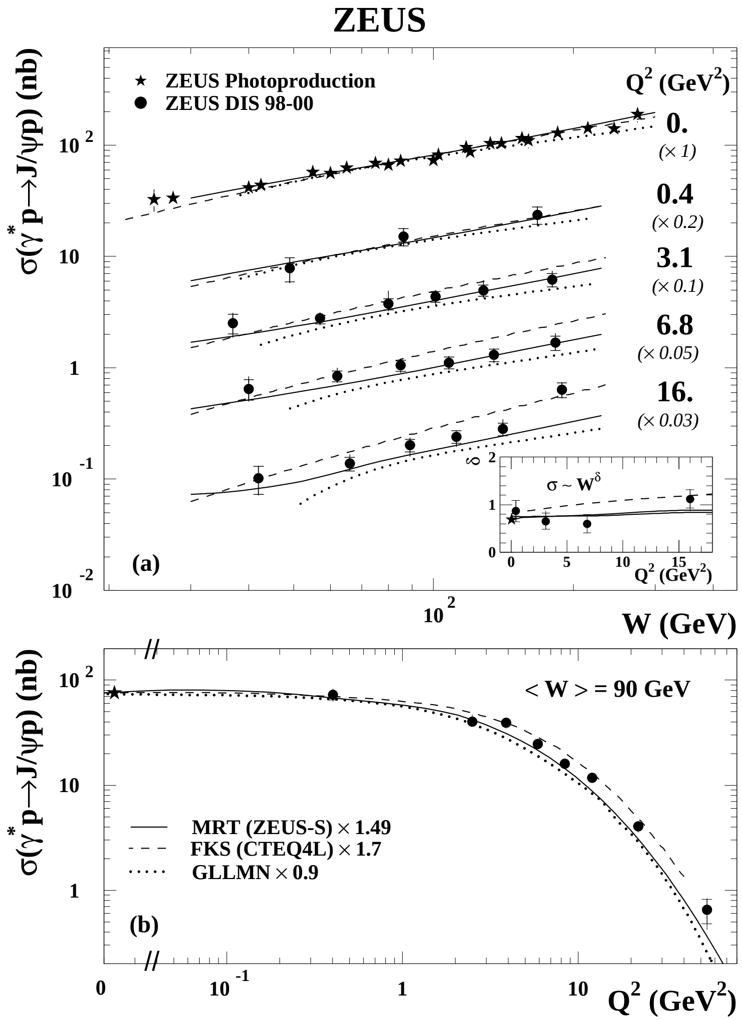
J/ψ production in PHP

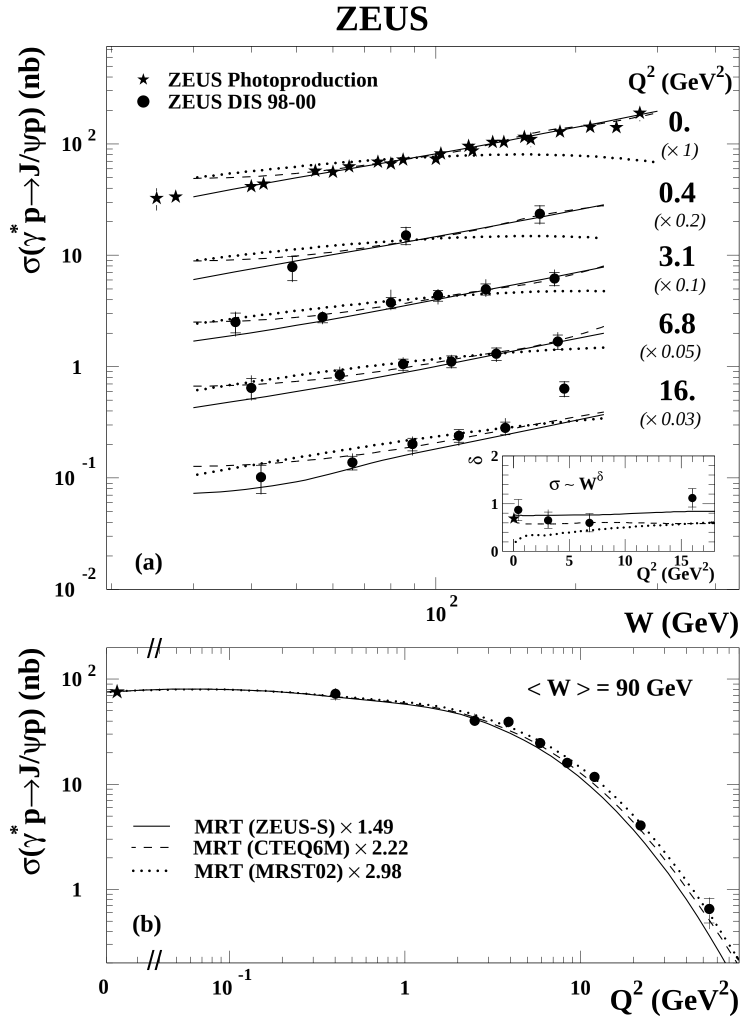
$J/\psi \to \mu\bar{\mu}$ in the kinematic range
$Q^2 < 1\,\text{GeV}^2$, $40\,\text{GeV} < W_{\gamma p} < 150\,\text{GeV}$, $|t| < 1.2\,\text{GeV}^2$
Agreement with previous measurements and MRT calculations





exclusive J/ψ-production in DIS





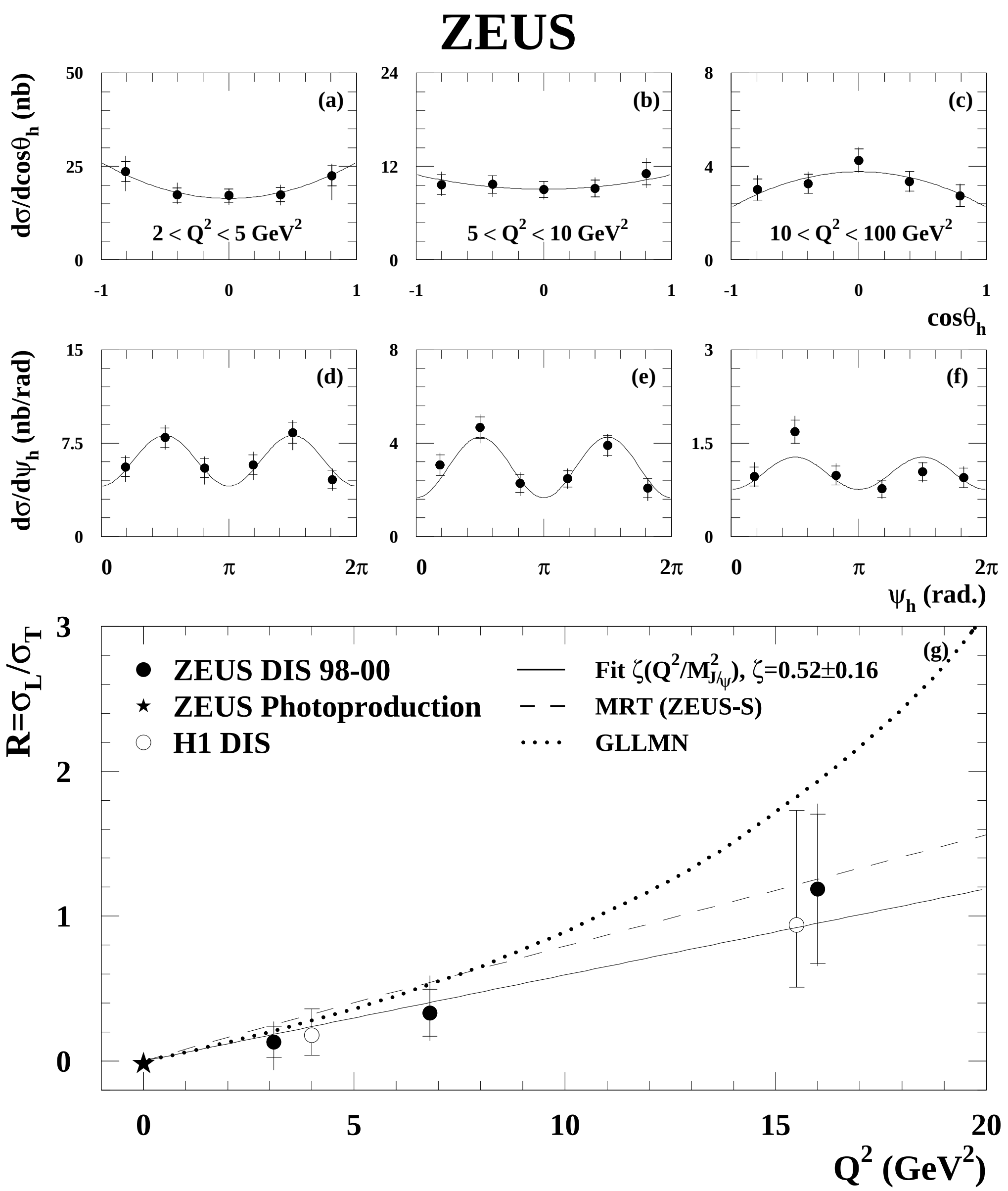
comparison with QCD models

- 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/ψ-production in DIS



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

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

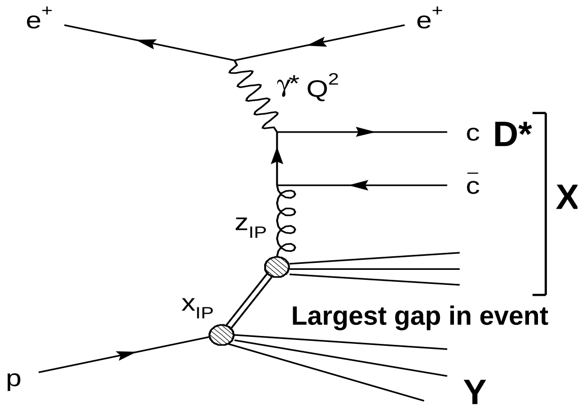
$$\frac{1}{N}\frac{dN}{d\cos\theta_h} = \frac{3}{8}[1 + r^{04}_{00} + (1 - 3r^{04}_{00})\cos^2\theta_h]$$

$$\frac{1}{N}\frac{dN}{d\psi_h} = \frac{1}{2\pi}[1 - \epsilon r^{1}_{1-1}\cos 2\psi_h]$$

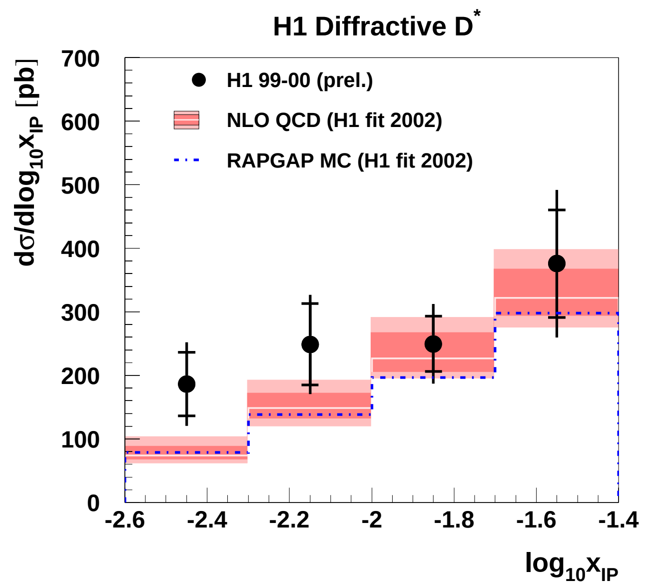
$$R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-r^{04}_{00}}, \qquad \epsilon \approx 0.99$$

σ_L expected to rise more rapidly with Q^2 than σ_T

Diffractive D^* production in DIS

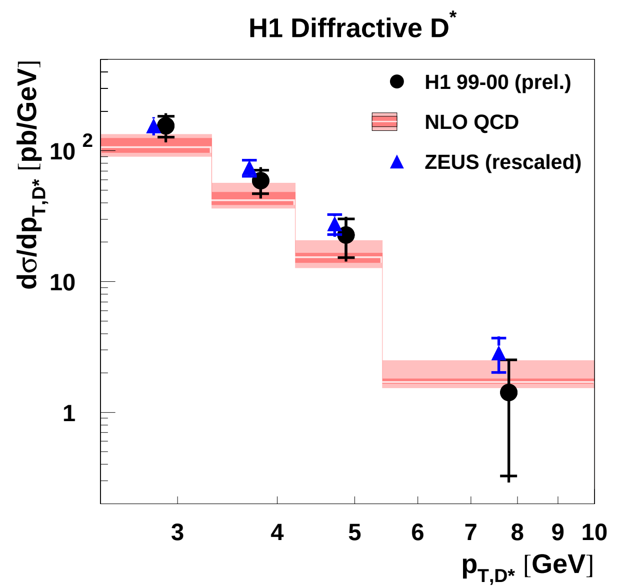


$$x_{IP} = \frac{q \cdot (P - p_Y)}{q \cdot P}$$
$$\beta = \frac{x}{x_{IP}}$$
$$z_{IP} = \beta \cdot (1 + \frac{\hat{s}}{Q^2})$$



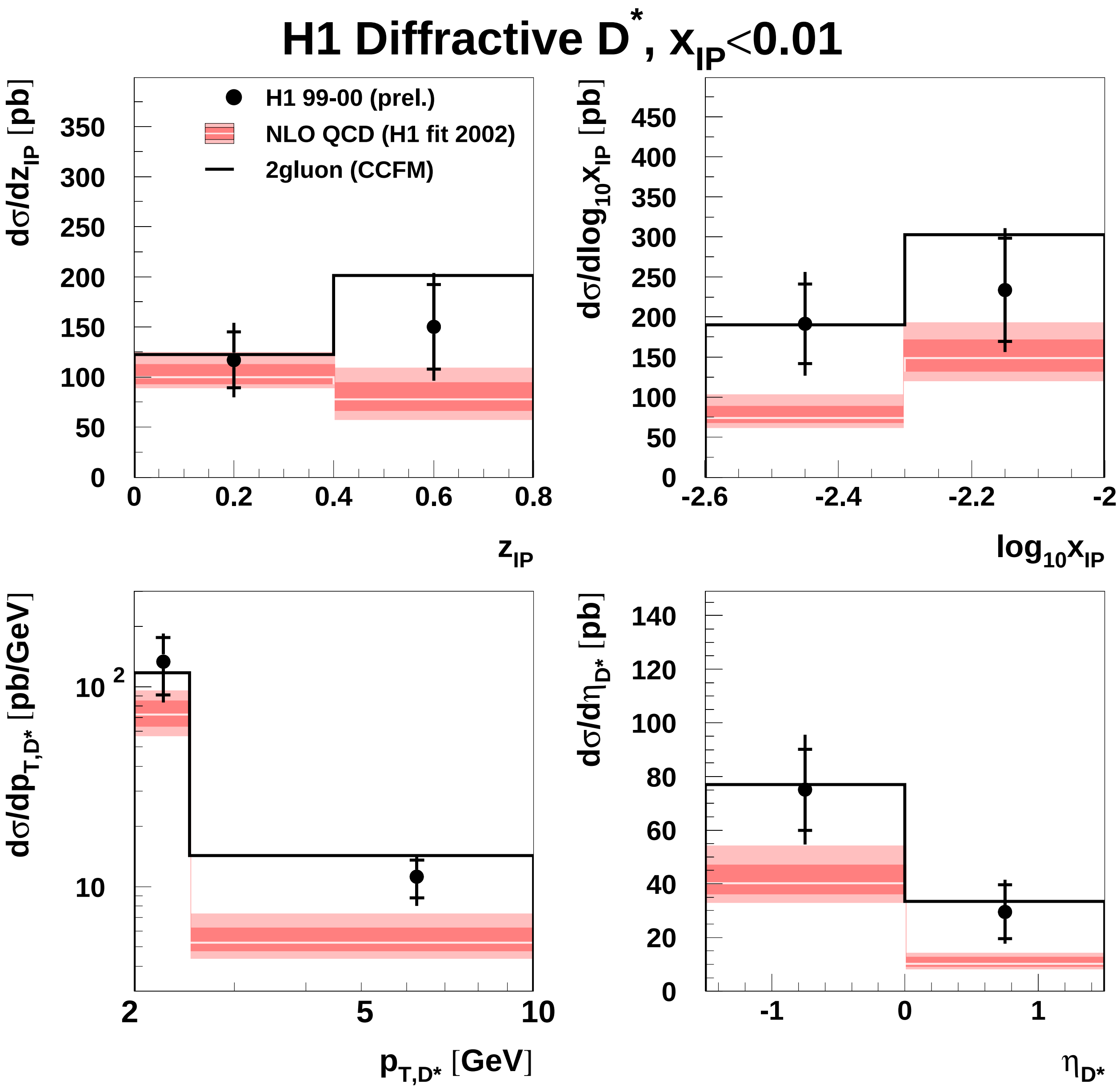
Measurements are in agreement with previous measurements of H1 and ZEUS

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



$2 < Q^2 < 100\,\mathrm{GeV}^2,\ 0.05 < y < 0.7$
$x_{IP} < 0.04,\ M_Y < 1.6\,\mathrm{GeV},\ |t| < 1\,\mathrm{GeV}^2$
$p_{t,D^*} > 2\,\mathrm{GeV},\ |\eta_{D^*}| < 1.5$

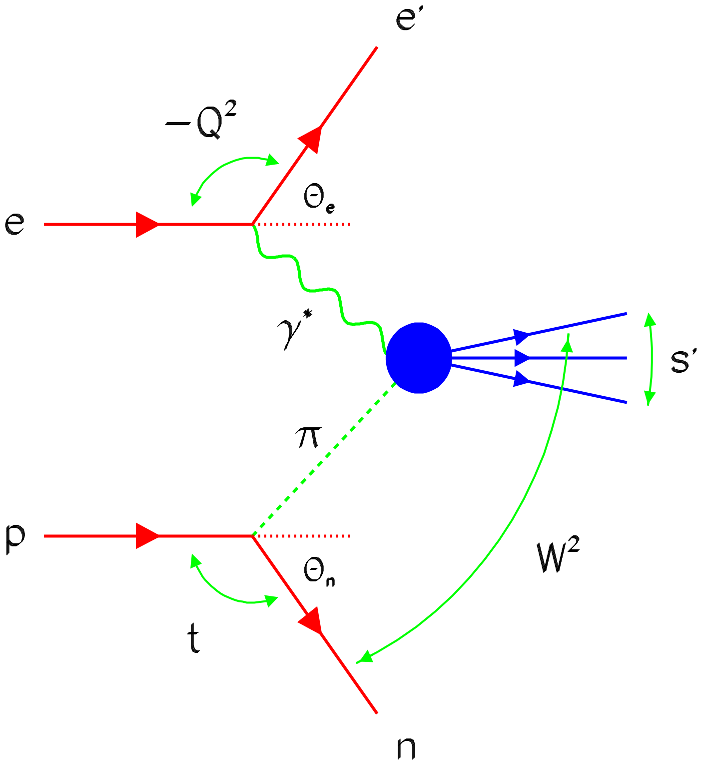
Diffractive D^* production in DIS, cont.



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

D^* production with leading neutron

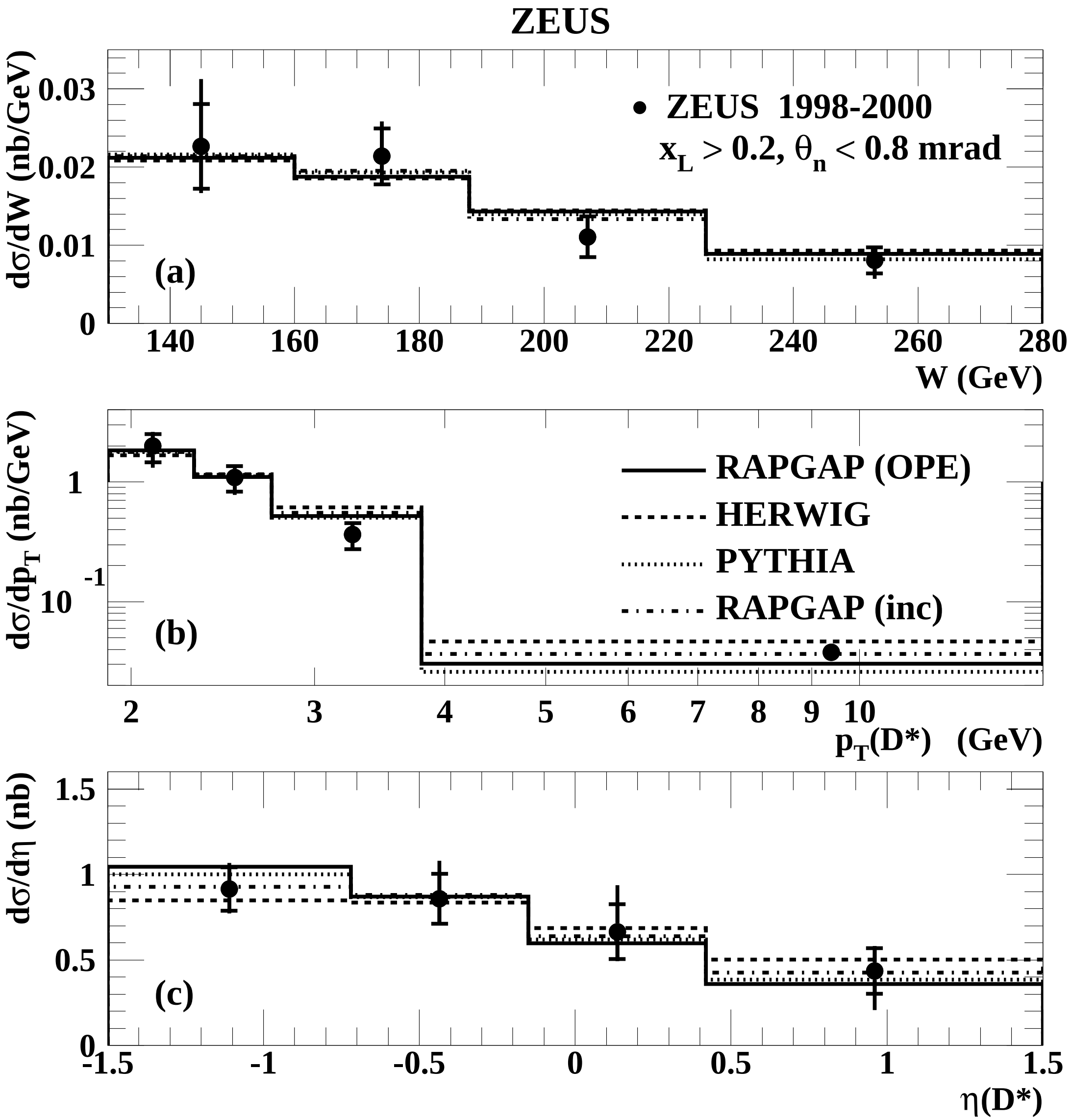
Exchange models applied to describe data:



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

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

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



Good agreement with all MC models

D^* production with leading neutron, x_L-dependence

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

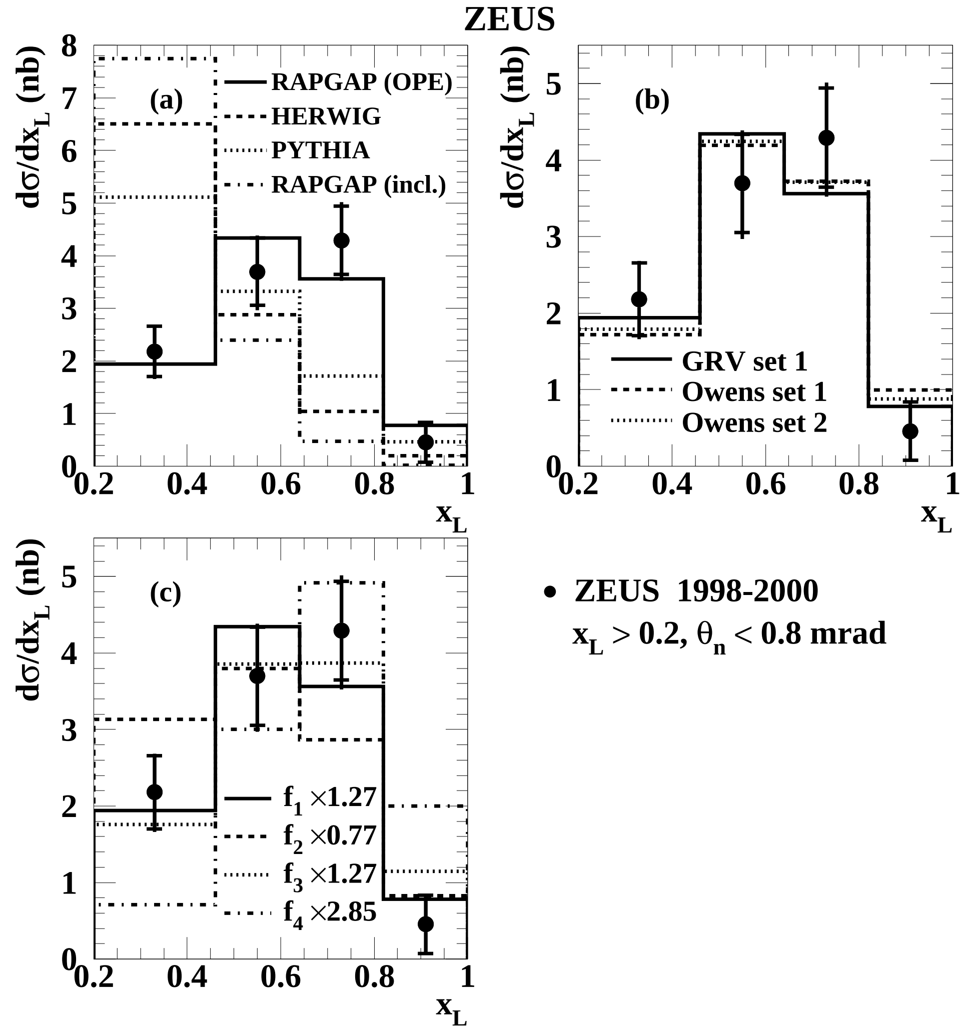
Cross section can be written as:

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

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

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

Different flux factor parametrisations $F(x_L, t)$ used.



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