Heavy flavour production with leptons and hadrons

Matthew Wing (Bristol University)

- **Introduction, motivation, theoretical and experimental techniques**

- **Latest measurements on open charm and beauty production**

- **Charm in diffraction**

- **Summary and outlook**

Introduction and motivation

Why study heavy quarks?

**New particles decay often decay to beauty (and charm) quarks**

Make measurements of CP violation

Precise measurements of electroweak parameters

To understand and probe QCD in as much detail as possible

Parton densities of proton and photon need to be precise. *cf* **future colliders,** pp**,** e^+e^- **and** $\gamma\gamma$**, ...**

QCD-production rate should be accurately understood which can be a significant background to "new" physics
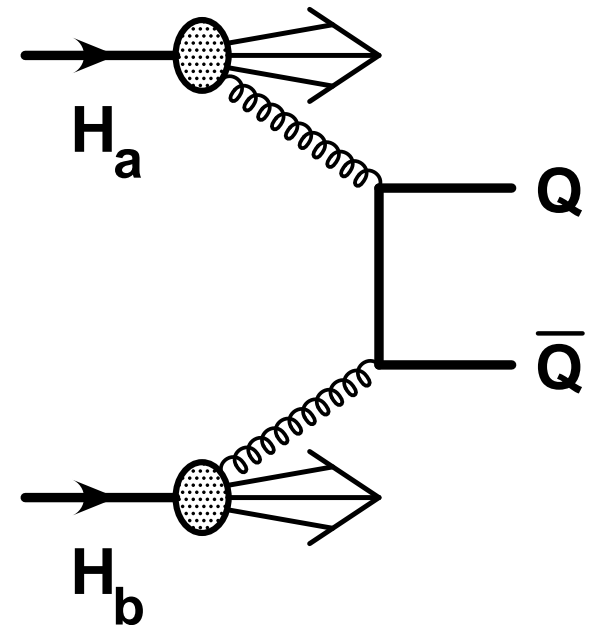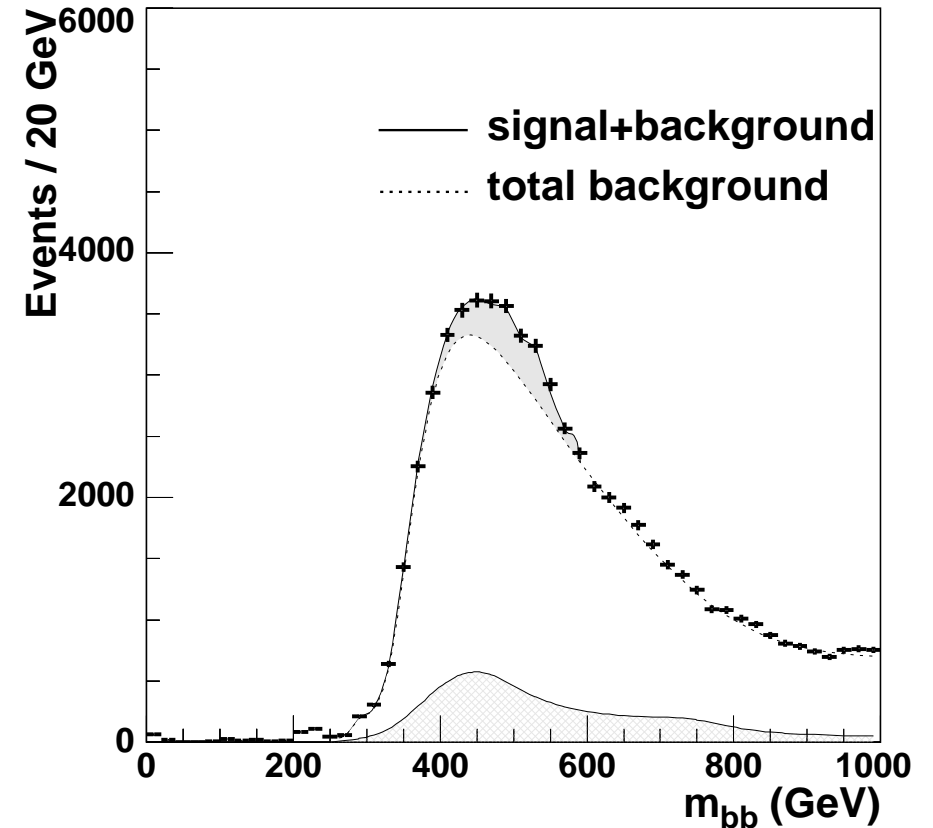
Why study heavy quark production?

Example of why the heavy quark production rate needs to be understood (ATLAS TDR)

Consider $b\bar{b}H/A$ **with** $H/A \to b\bar{b}$ **production at the LHC**

Even requiring four b **jets,** $S/B \sim$ **few %**

Background from gluon splitting to $b\bar{b}$ **and** $gg \to b\bar{b}$

5σ **discovery possible if QCD backgrounds known precisely**

$m_A = 500$ GeV

How well is the QCD background known?

Perturbative QCD formalism

For generic collision between two hadrons producing a heavy quark,

$$H_a + H_b \to Q\bar{Q} + X$$

Cross section can be written as;

$$\sigma(S) = \sum_{i,j} \int dx_1 \int dx_2 \ \hat{\sigma}_{ij}(x_1 x_2 S, m^2, \mu^2) f_i^{H_a}(x_1, \mu) f_j^{H_b}(x_2, \mu)$$

A convolution of the parton densities and short distance cross section

$$\hat{\sigma}_{ij}(s, m^2, \mu^2) = \frac{\alpha_s^2(\mu^2)}{m^2} \left[f_{ij}^{(0)}(\rho) + 4\pi\alpha_s(\mu^2) \left[f_{ij}^{(1)}(\rho) + \bar{f}_{ij}^{(1)}(\rho) \log(\mu^2/m^2) \right] + \mathcal{O}(\alpha_s^2) \right], \quad \rho = 4m^2/s$$

Perturbative expansion in mass of heavy quark, m

Larger $m \Rightarrow$ faster convergence

Mass needs to be "treated" consistently

"Massive" scheme - $p_T^2 < m^2$, no heavy quarks in hadron ($gg \to Q\bar{Q}$)

"Massless" scheme - $p_T^2 > m^2$, active heavy quarks in hadron (also $gQ \to gQ$)

Fragmentation of heavy quarks

Sprays of hadrons and leptons are measured in the detector

Tag B/D mesons ($D^* \to K\pi\pi_s$) and $Q \to \mu, e$

Calculation is in terms of final state partons

The two need to be "matched" to perform a comparison

Reliant on non-perturbative models, such as Lund, cluster, to describe the fragmentation

NLO QCD calculations usually add on a Peterson function

Jet

hadrons

Fragmentation process

outgoing parton

Hard scatter

Are the models and current parametrisations correct?

- **Measure the fragmentation function**

- **Make measurements where the effects are reduced; jets, high energy**
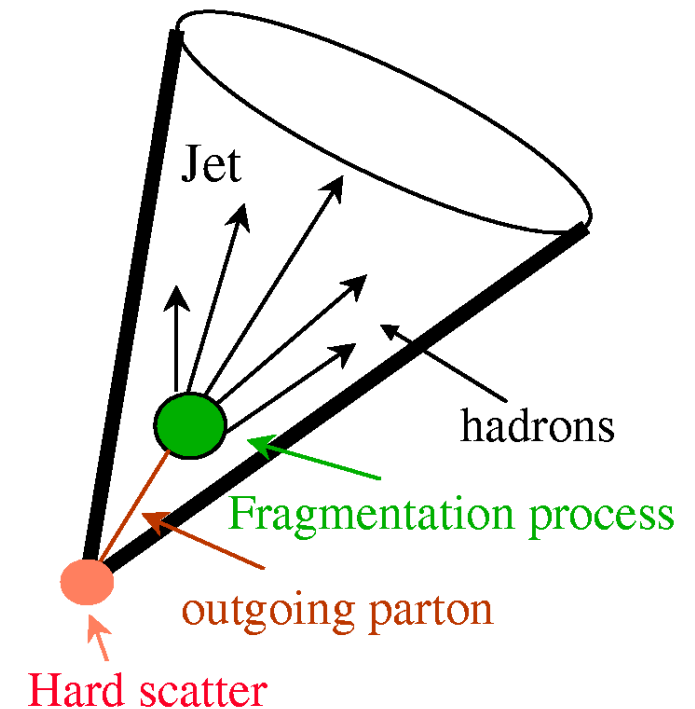
Where heavy quark production is measured

LEP	HERA	TeVatron

100 GeV $e^- \rightarrow \leftarrow e^+$ **100 GeV**   **27.5 GeV** $e \rightarrow \leftarrow p$ **920 GeV**   **980 GeV** $\bar{p} \rightarrow \leftarrow p$ **980 GeV**

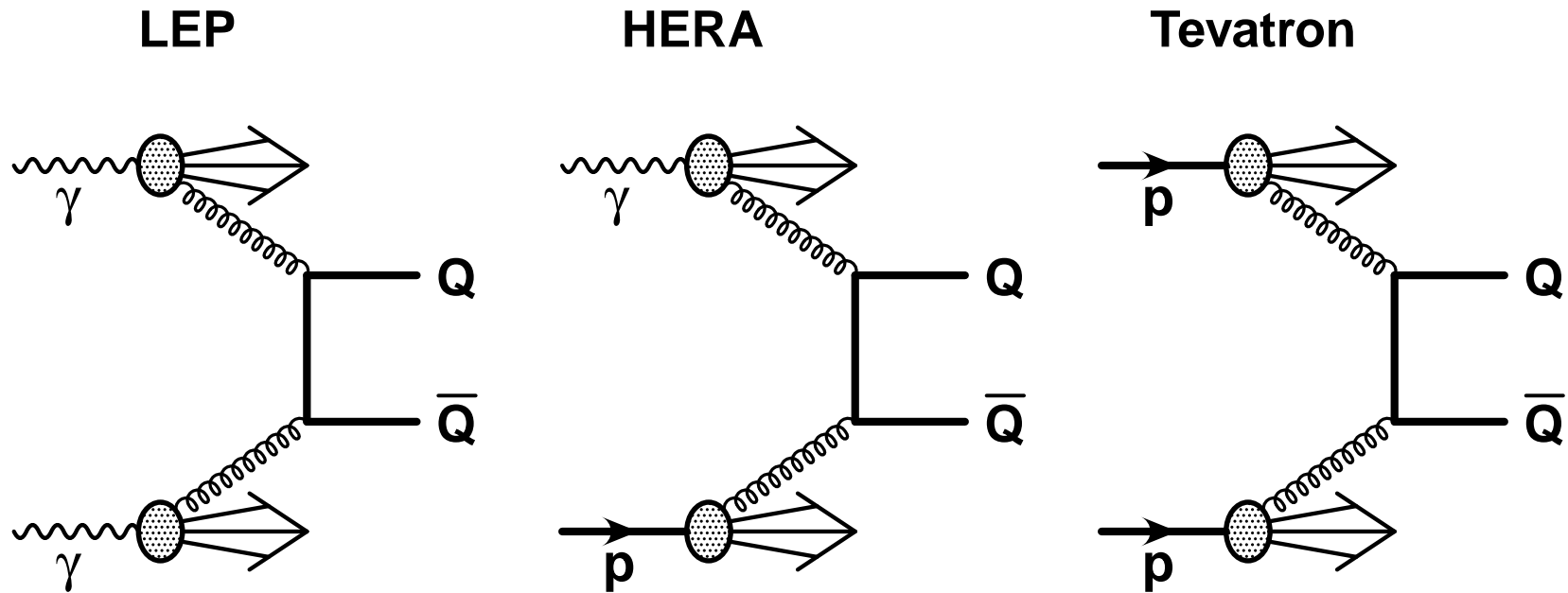$\sqrt{s}$ = 200 GeV $\sqrt{s}$ = 320 GeV $\sqrt{s}$ = 1.96 TeV

4 experiments   2 experiments   2 experiments

All use general purpose detectors

The physics of the experiments at each collider is different, but the production of heavy quarks is essentially the same...

Generic nature of production

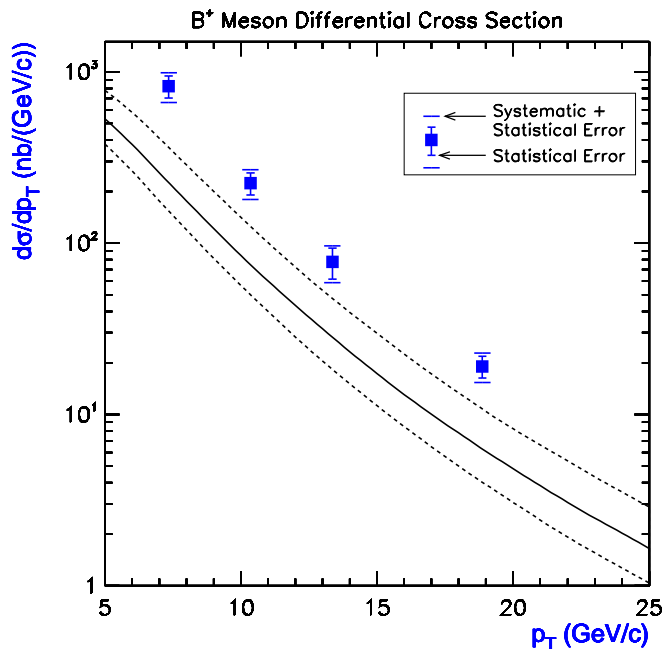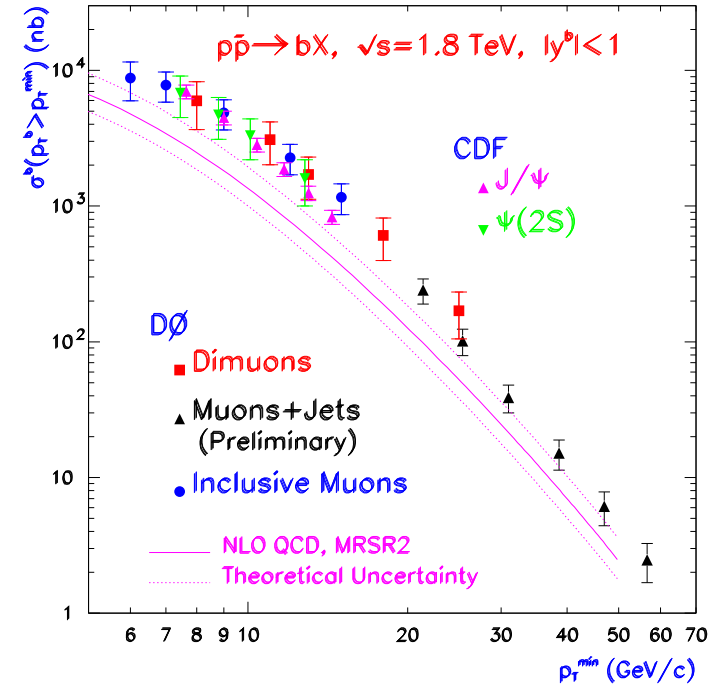| PDF →	Hard scatter →	Fragmentation
Structure functions of proton and photon	Dynamics of NLO QCD	Description of parton-hadron transition
Direct sensitivity to the gluon content	Implementation of diagrams and dynamics into programs	Non-perturbative, but essential.

Beauty production at the Tevatron Run I
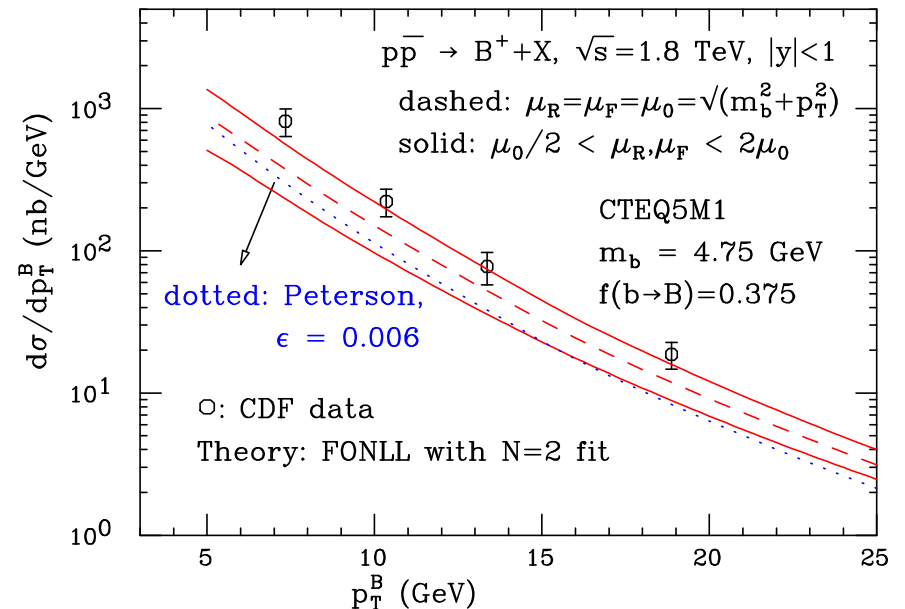
Significant disagreement with QCD

Extrapolation to the the b quark level $\rightarrow$

Measurement of B hadrons gives more reliable results

Led to improvement in theory

$p\bar{p} \rightarrow bX$, $\sqrt{s} = 1.8$ TeV, $|y^b| < 1$

$\sigma^b(p_T^b > p_T^{min})$ (nb)

CDF
J/ψ
$\psi(2S)$

D∅
Dimuons
Muons+Jets (Preliminary)
Inclusive Muons
NLO QCD, MRSR2
Theoretical Uncertainty

p_T^{min} (GeV/c)

Fragmentation
$\rightarrow$ in theory $\rightarrow$
tuned to data

B$^+$ Meson Differential Cross Section

$d\sigma/dp_T$ (nb/(GeV/c))

Systematic + Statistical Error
Statistical Error

p_T (GeV/c)

$p\bar{p} \rightarrow B^+ + X$, $\sqrt{s} = 1.8$ TeV, $|y| < 1$
dashed: $\mu_R = \mu_F = \mu_0 = \sqrt{(m_b^2 + p_T^2)}$
solid: $\mu_0/2 < \mu_R, \mu_F < 2\mu_0$

CTEQ5M1
$m_b = 4.75$ GeV
$f(b \rightarrow B) = 0.375$

dotted: Peterson, $\epsilon = 0.006$

O: CDF data
Theory: FONLL with N=2 fit

$d\sigma/dp_T^B$ (nb/GeV)

p_T^B (GeV)

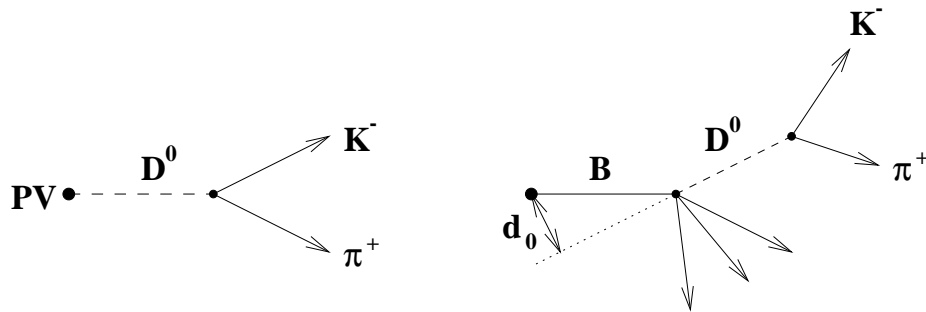# Experimental methods for tagging heavy quarks

Reconstruction of hadron mass resonances

Decay to lepton and its transverse momentum relative to the quark
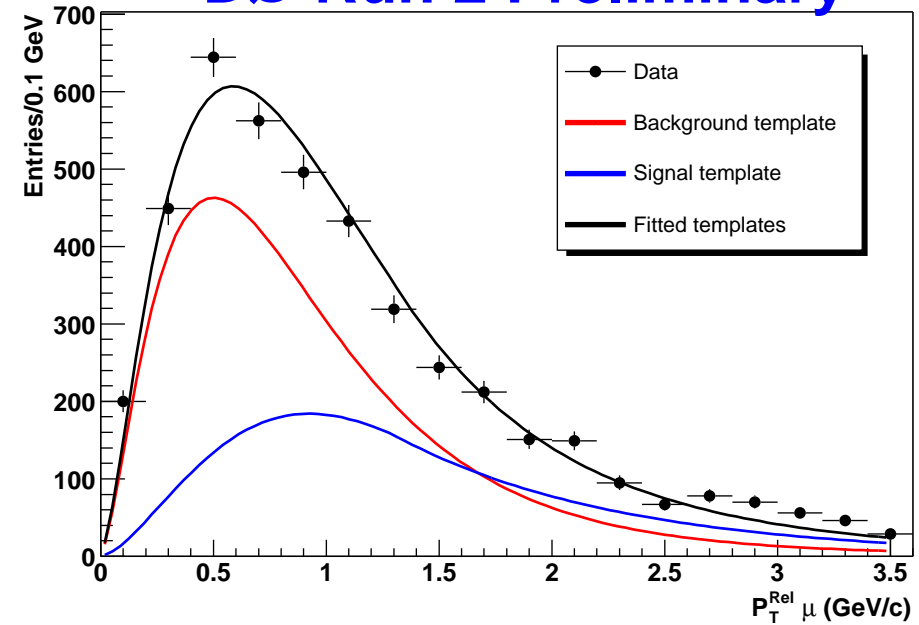
Use of a vertex detector - weak decays, long-lived

Direct Production
D points back to PV

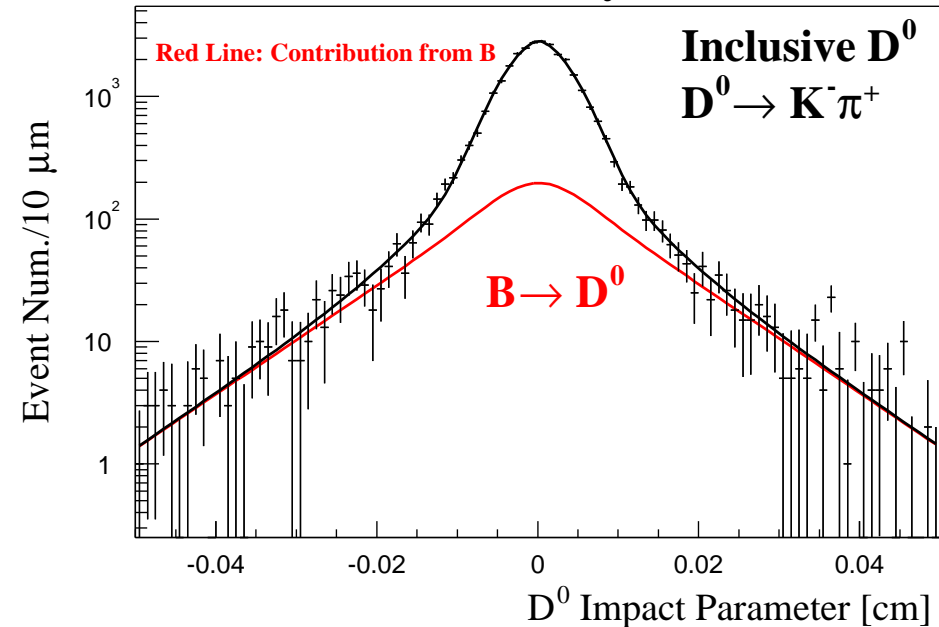**Secondary Production**
D has finite impact parameter

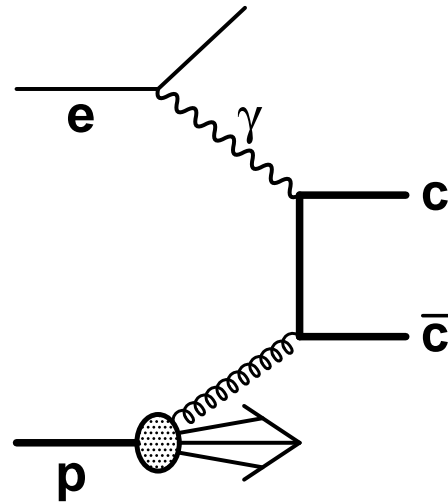**Experiments use different methods depending on their apparatus, but in general have the same techniques**
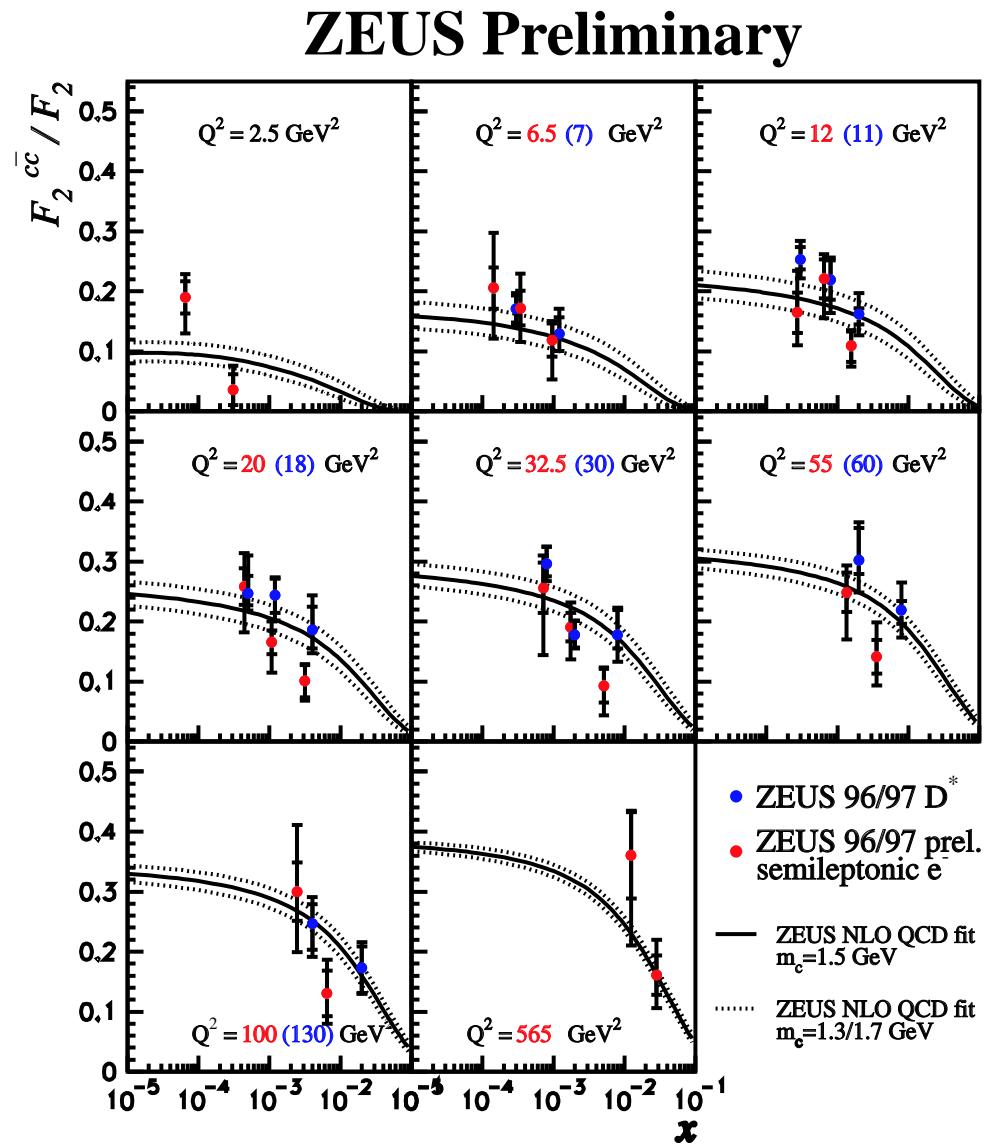
DØ Run 2 Preliminary

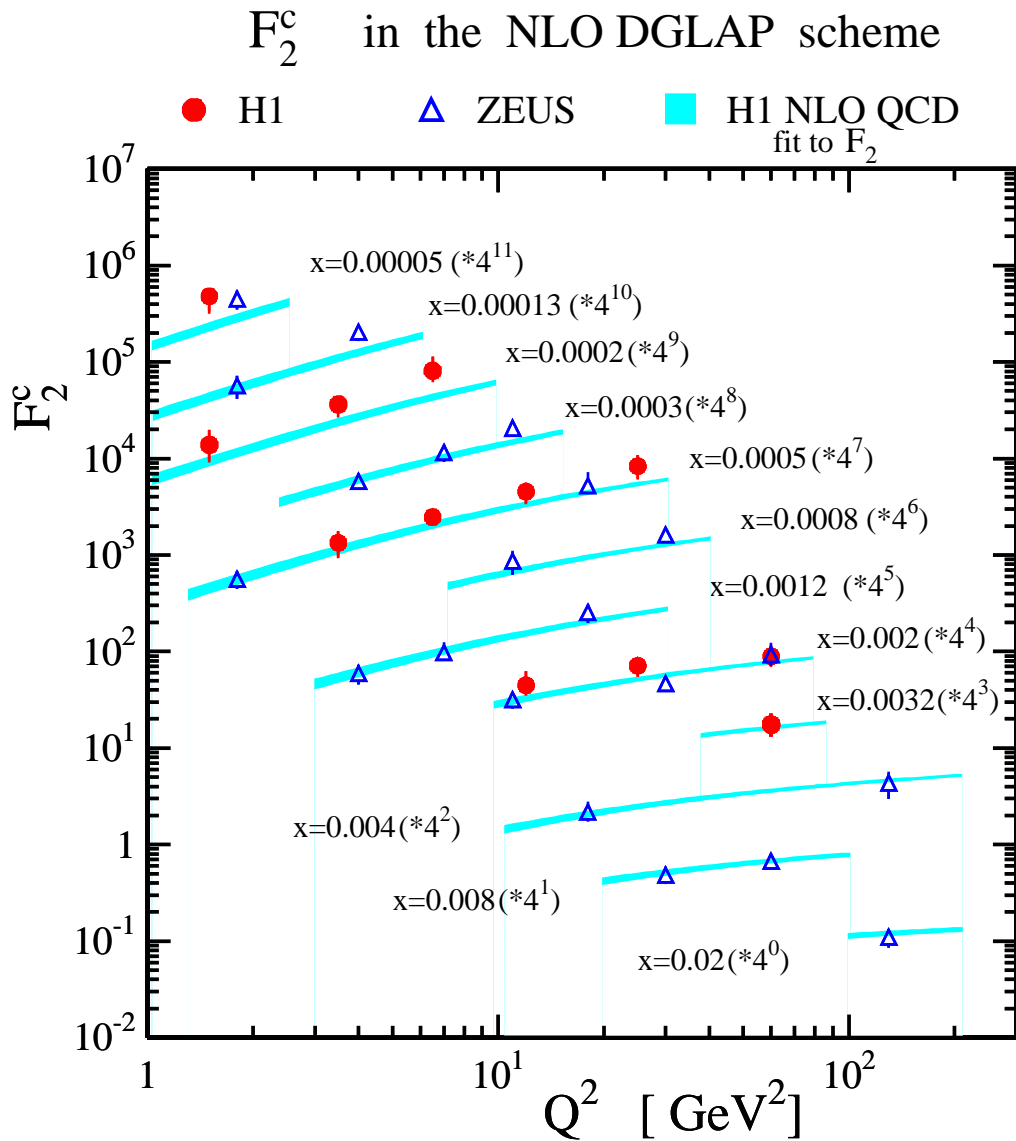**CDF RunII Preliminary**

Latest results - structure functions

# Charm contribution to the proton structure function

F_2^c in the NLO DGLAP scheme

● H1   △ ZEUS   ▮ H1 NLO QCD fit to F_2

x=0.00005 (*4^{11})
x=0.00013 (*4^{10})
x=0.0002 (*4^9)
x=0.0003 (*4^8)
x=0.0005 (*4^7)
x=0.0008 (*4^6)
x=0.0012 (*4^5)
x=0.002 (*4^4)
x=0.0032 (*4^3)
x=0.004 (*4^2)
x=0.008 (*4^1)
x=0.02 (*4^0)

F_2^c

Q^2 [GeV^2]

ZEUS Preliminary

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

$Q^2 = 2.5\ GeV^2$
$Q^2 = 6.5\ (7)\ GeV^2$
$Q^2 = 12\ (11)\ GeV^2$
$Q^2 = 20\ (18)\ GeV^2$
$Q^2 = 32.5\ (30)\ GeV^2$
$Q^2 = 55\ (60)\ GeV^2$
$Q^2 = 100\ (130)\ GeV^2$
$Q^2 = 565\ GeV^2$

● ZEUS 96/97 D*
● ZEUS 96/97 prel. semileptonic e$^-$
— ZEUS NLO QCD fit m_c=1.5 GeV
···· ZEUS NLO QCD fit m_c=1.3/1.7 GeV

x

Charm production represents a significant amount of the inclusive cross section

Charm contribution to the photon structure function
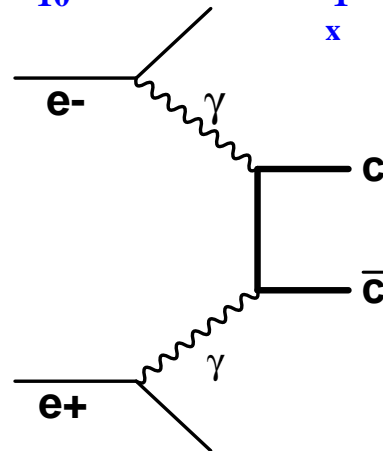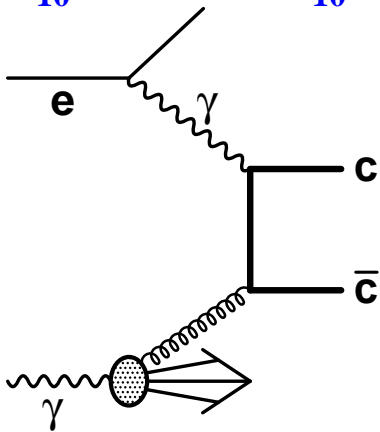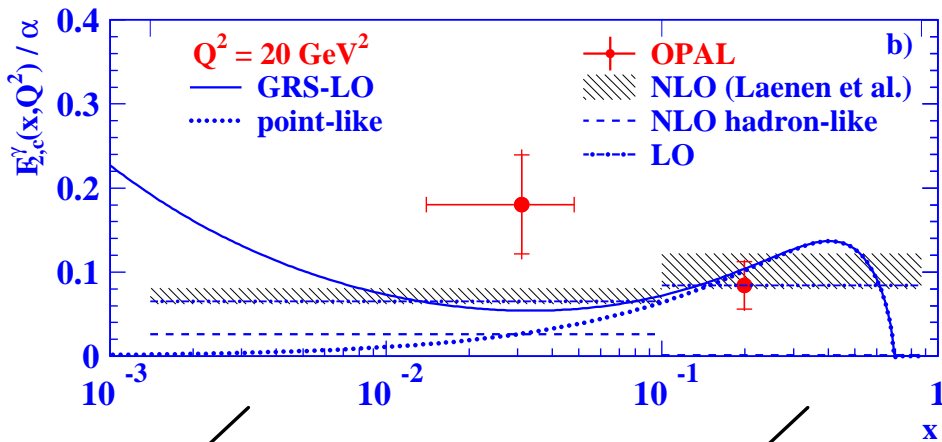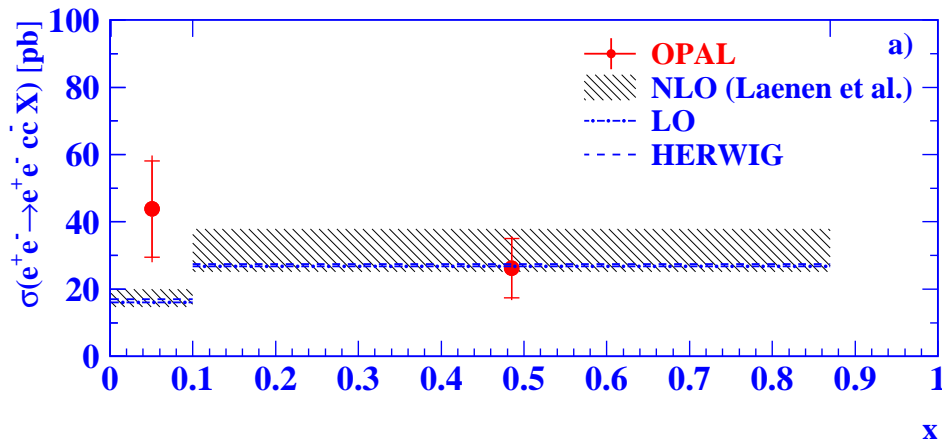
Charm production expected to proceed via EM coupling to photons

Evidence for production via hadronic structure of photon

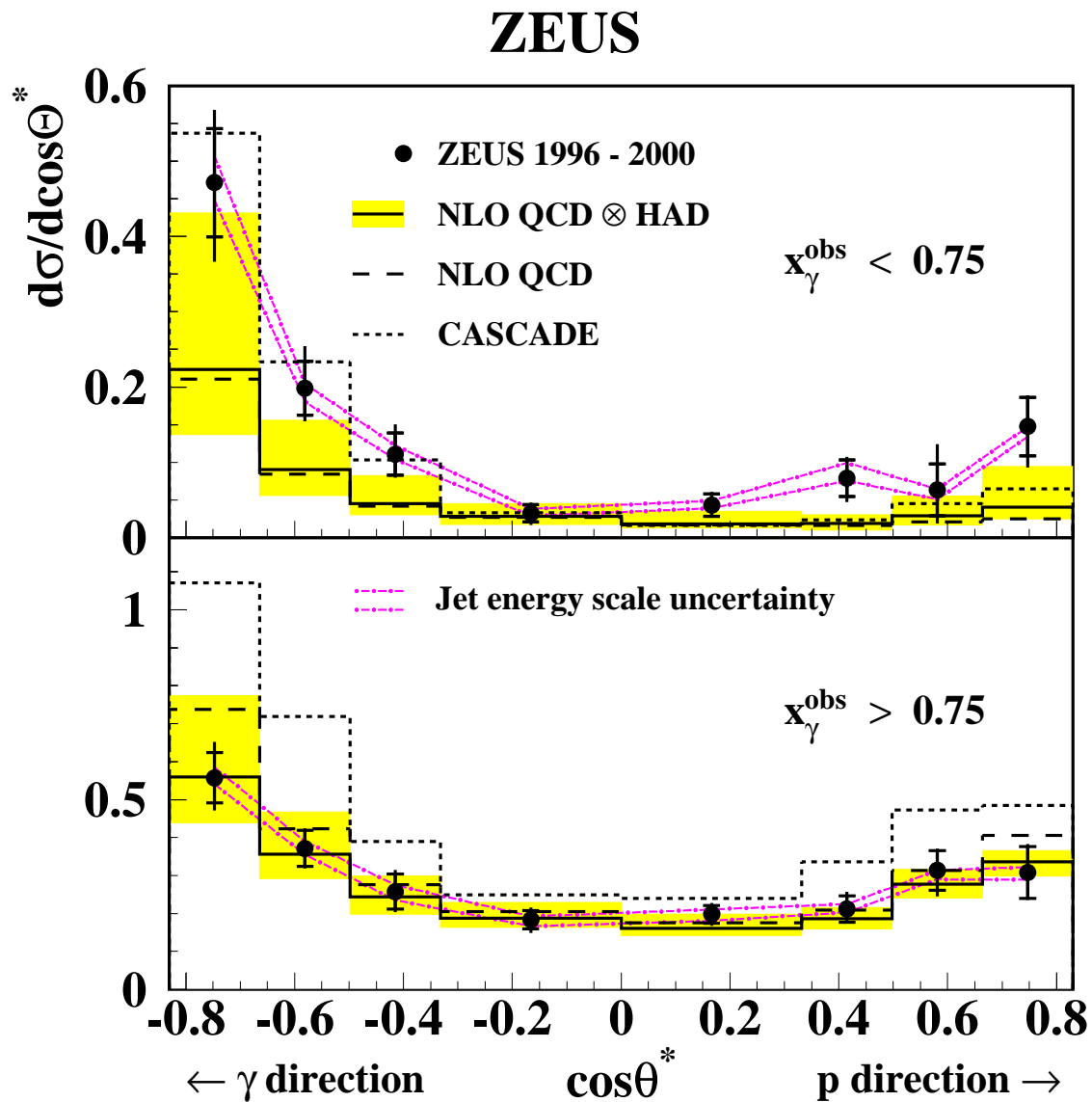**Note structure functions are not measured; there are extrapolations:**

- **detector has limited acceptance,** p_T, $\eta(= \ln \tan(\theta/2))$

- **total cross sections are "measured" using MCs**

$$(\sigma_{\text{tot}})_{\text{meas}} = \frac{(\sigma_{p_T,\eta})_{\text{meas}}}{(\sigma_{p_T,\eta})_{\text{MC}}} \cdot (\sigma_{\text{tot}})_{\text{MC}}$$
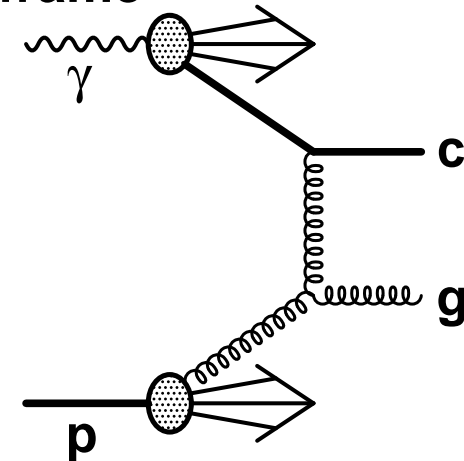
- **Extrapolation factors vary; up to $\sim$ 10-20**

But they are intuitive...
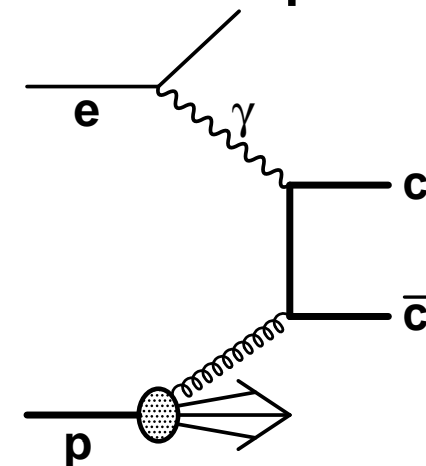
Charm from the photon

ZEUS

- ZEUS 1996 - 2000
- NLO QCD ⊗ HAD
- NLO QCD
- CASCADE

$x_\gamma^{obs} < 0.75$

$x_\gamma^{obs} > 0.75$

Jet energy scale uncertainty

$\leftarrow \gamma$ direction $\cos\theta^*$ p direction $\rightarrow$

Evidence for charm from the photon

Angular distribution in dijet centre-of-mass frame

γ

c

g

p

Similar to Rutherford scattering.
q **propagator** $\Rightarrow$ **shallow rise**
g **propagator** $\Rightarrow$ **steep rise**

e γ

c

$\bar{c}$

p

Charm cross section measurements

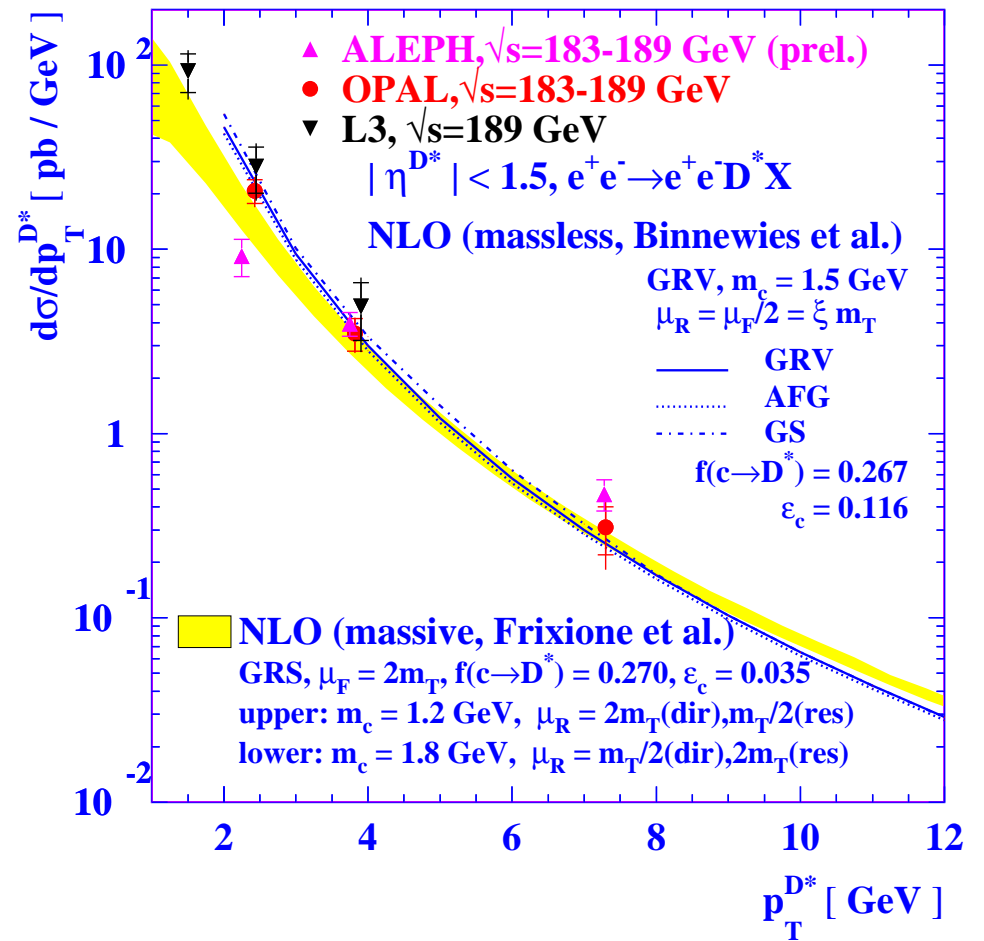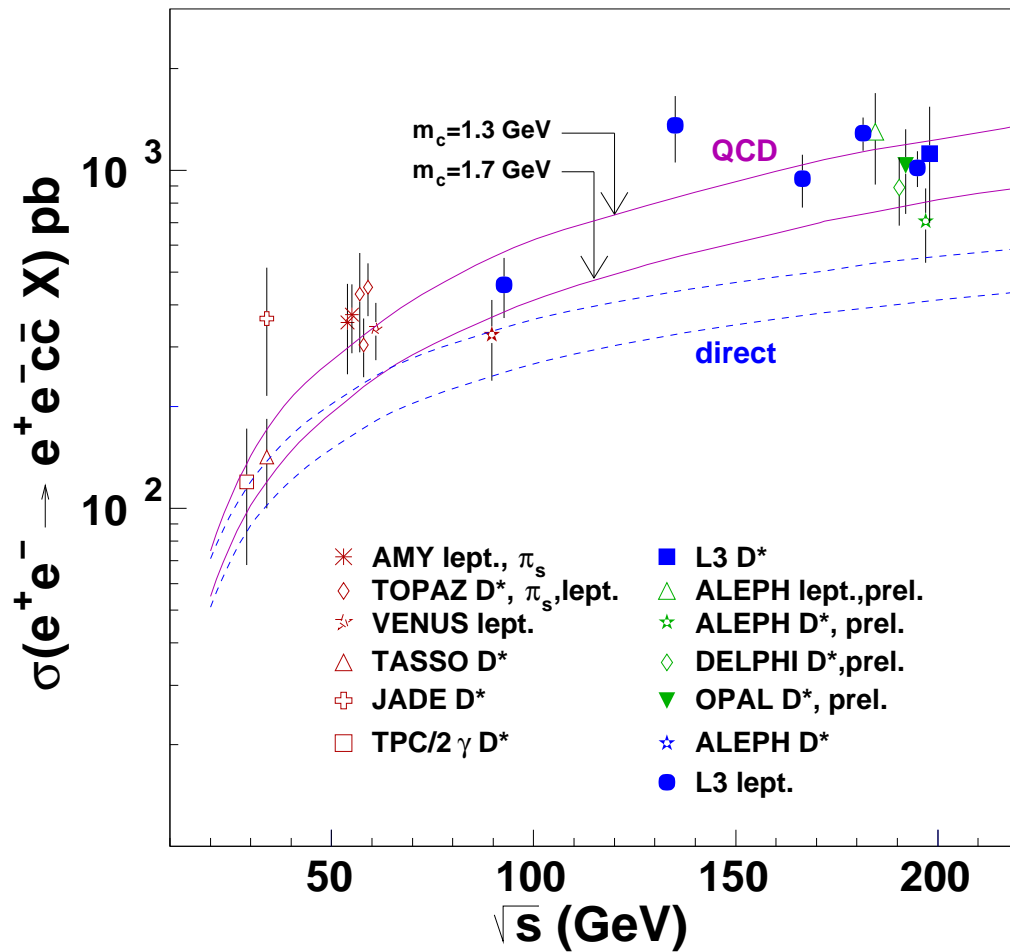# Charm in deep inelastic scattering at HERA
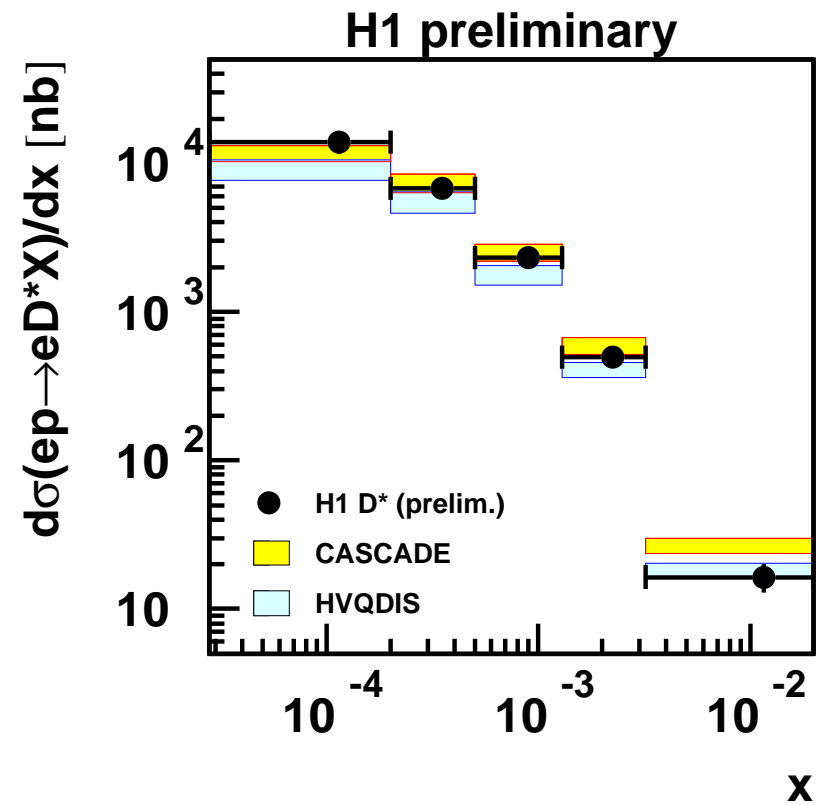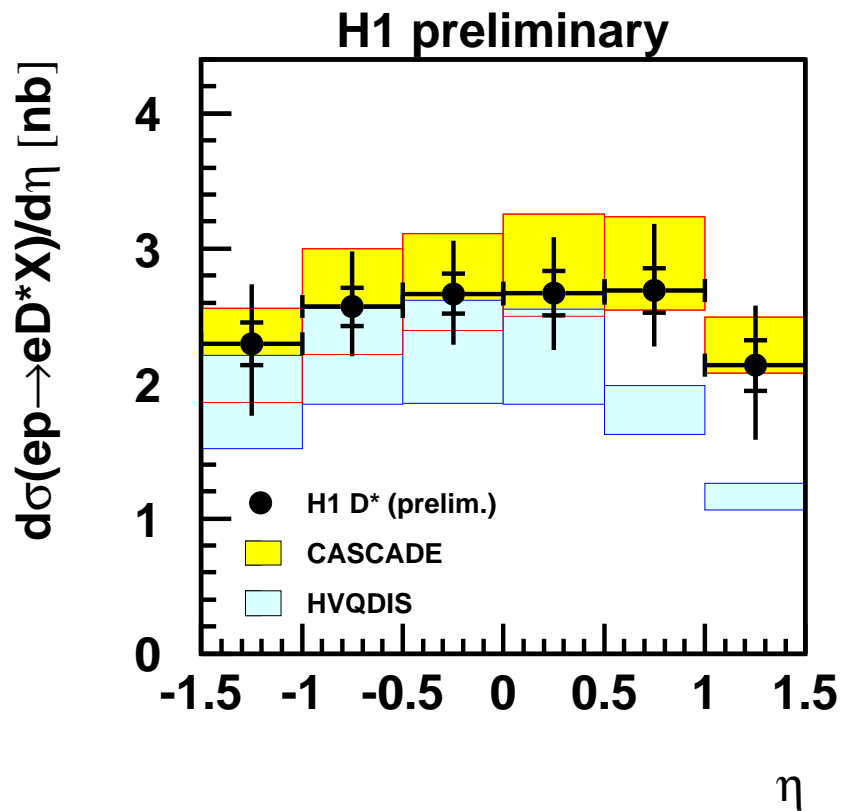
NLO (HVQDIS) prediction does not give complete description of the data

Variables sensitive to the gluon density in proton and hadronisation $c \to D^*$

ZEUS collaboration gets better agreement...

Charm in $\gamma\gamma$ collisions

Left panel axes: $\sigma(e^+e^- \to e^+e^-c\bar{c}\,X)$ pb versus $\sqrt{s}$ (GeV)

Left panel labels: $m_c=1.3$ GeV, $m_c=1.7$ GeV, QCD, direct

Left panel legend:
- AMY lept., π_s
- TOPAZ D*, π_s, lept.
- VENUS lept.
- TASSO D*
- JADE D*
- TPC/2γ D*
- L3 D*
- ALEPH lept., prel.
- ALEPH D*, prel.
- DELPHI D*, prel.
- OPAL D*, prel.
- ALEPH D*
- L3 lept.

Right panel axes: $d\sigma/dp_T^{D^*}$ [pb / GeV] versus $p_T^{D^*}$ [GeV]

Right panel legend and labels:
- ALEPH, $\sqrt{s}$=183-189 GeV (prel.)
- OPAL, $\sqrt{s}$=183-189 GeV
- L3, $\sqrt{s}$=189 GeV
- $|\eta^{D^*}| < 1.5$, $e^+e^- \to e^+e^-D^*X$
- NLO (massless, Binnewies et al.)
- GRV, $m_c = 1.5$ GeV
- $\mu_R = \mu_F/2 = \xi\, m_T$
- ——— GRV
- ········ AFG
- —·—· GS
- $f(c \to D^*) = 0.267$
- $\varepsilon_c = 0.116$
- NLO (massive, Frixione et al.)
- GRS, $\mu_F = 2m_T$, $f(c \to D^*) = 0.270$, $\varepsilon_c = 0.035$
- upper: $m_c = 1.2$ GeV, $\mu_R = 2m_T$(dir),$m_T/2$(res)
- lower: $m_c = 1.8$ GeV, $\mu_R = m_T/2$(dir),$2m_T$(res)

"Dangerous" total cross sections

Easy comparison over many experiments

Rigorous comparison possible with cooperation
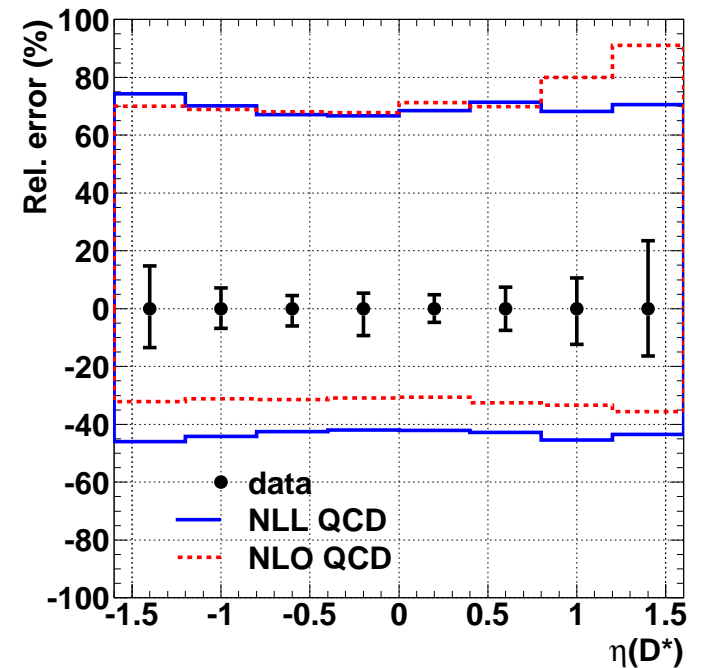
Charm in photoproduction at HERA

ZEUS
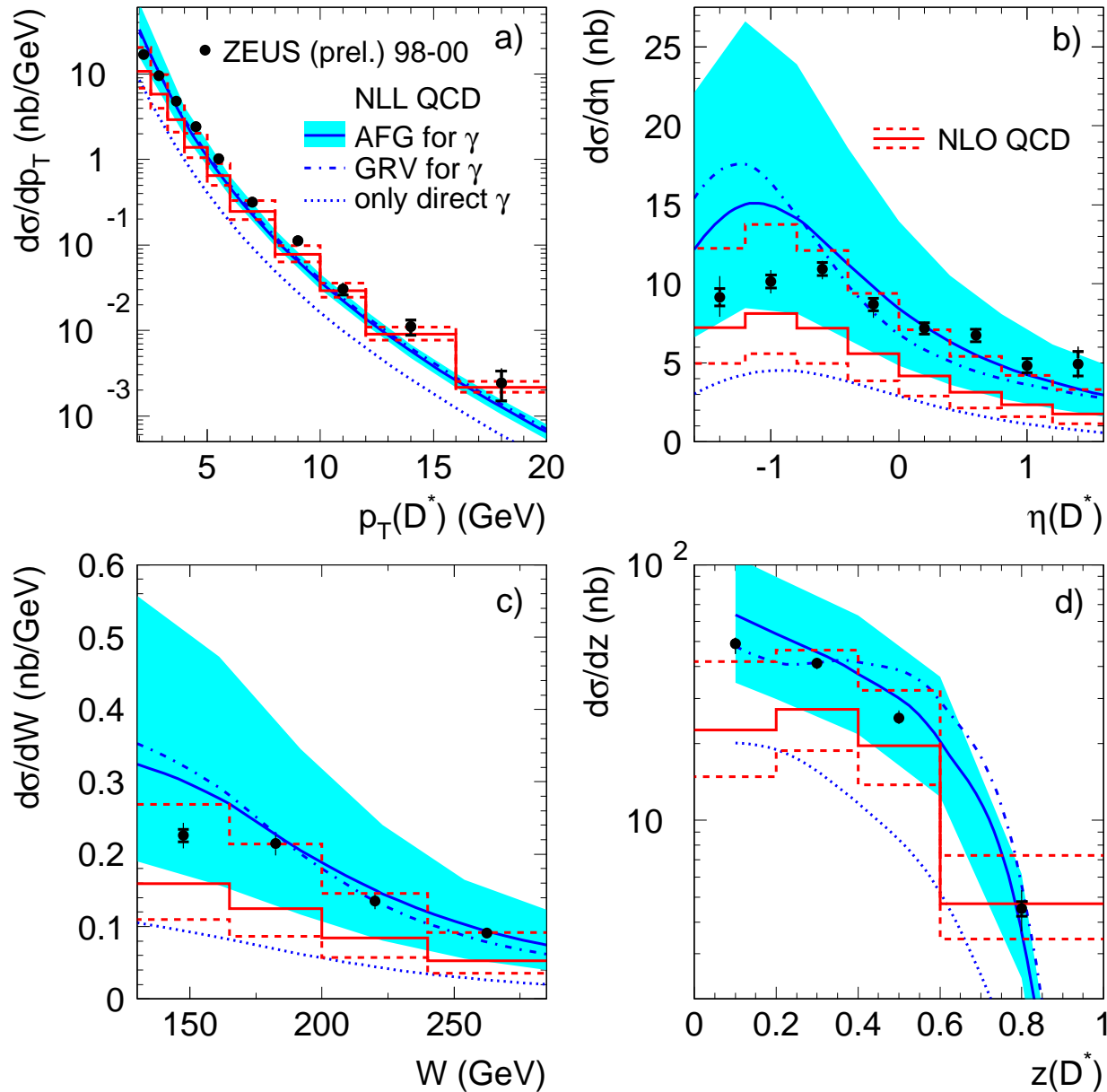
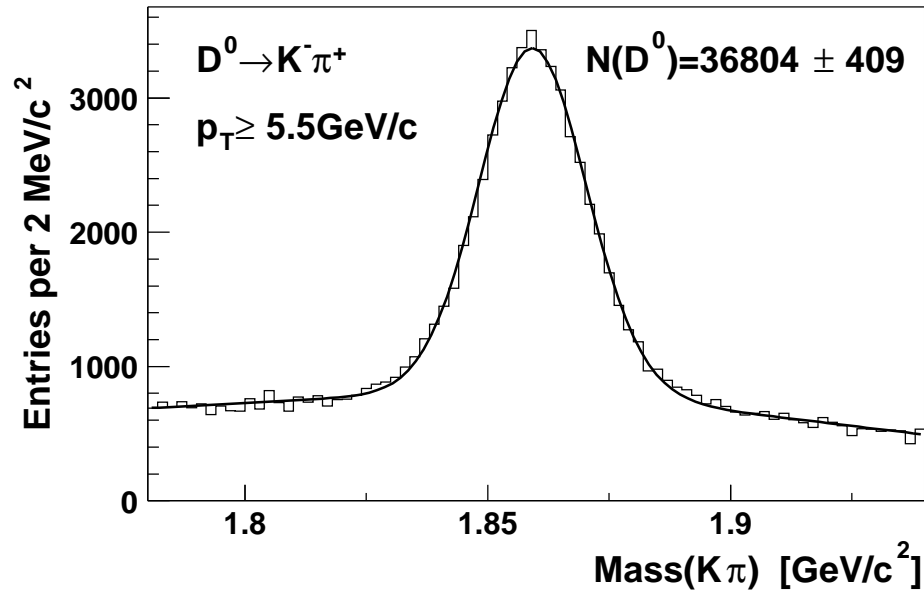**Description by NLO/NLL QCD not perfect.**

General description with caveats - double differential cross sections highlight differences
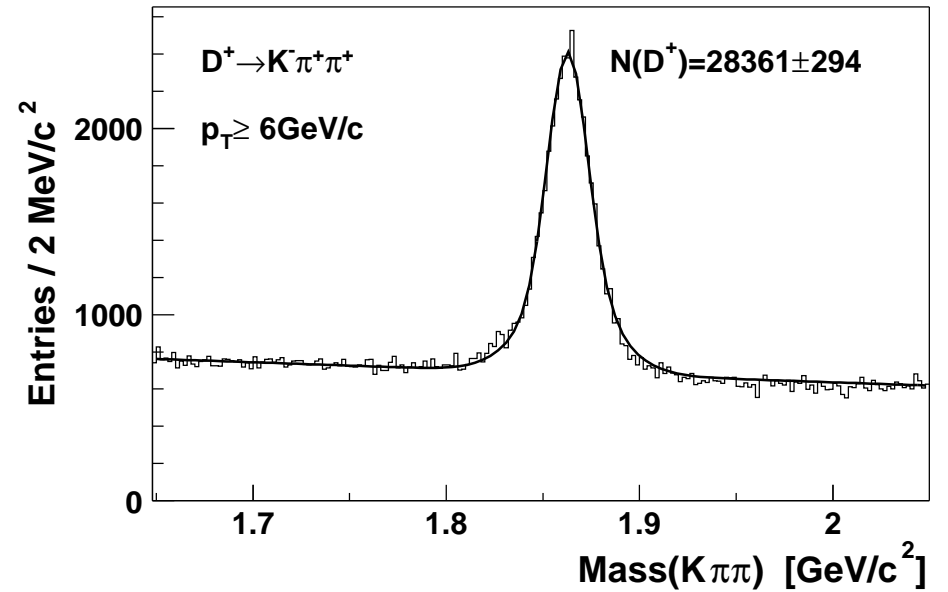
Is QCD really predictive?
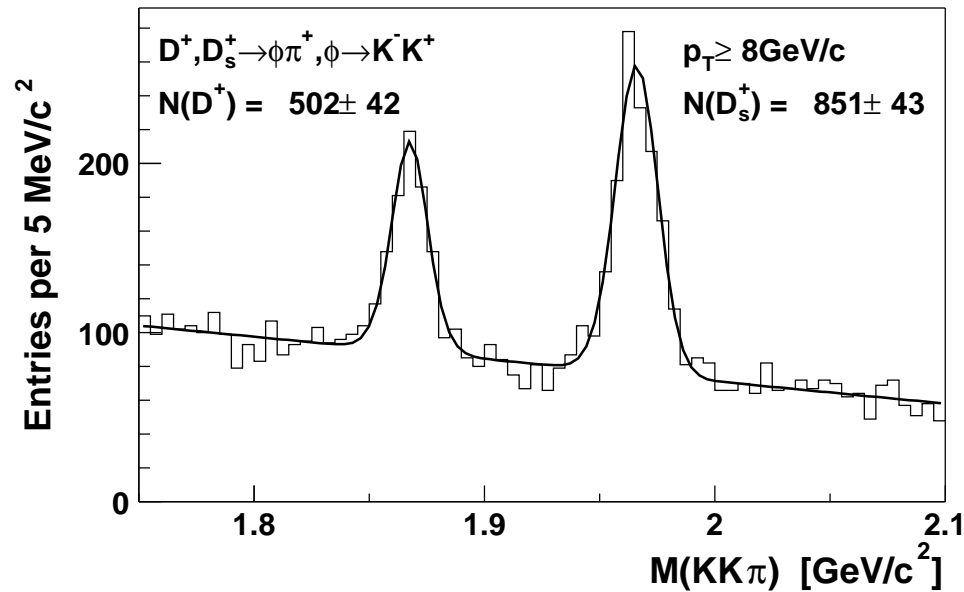
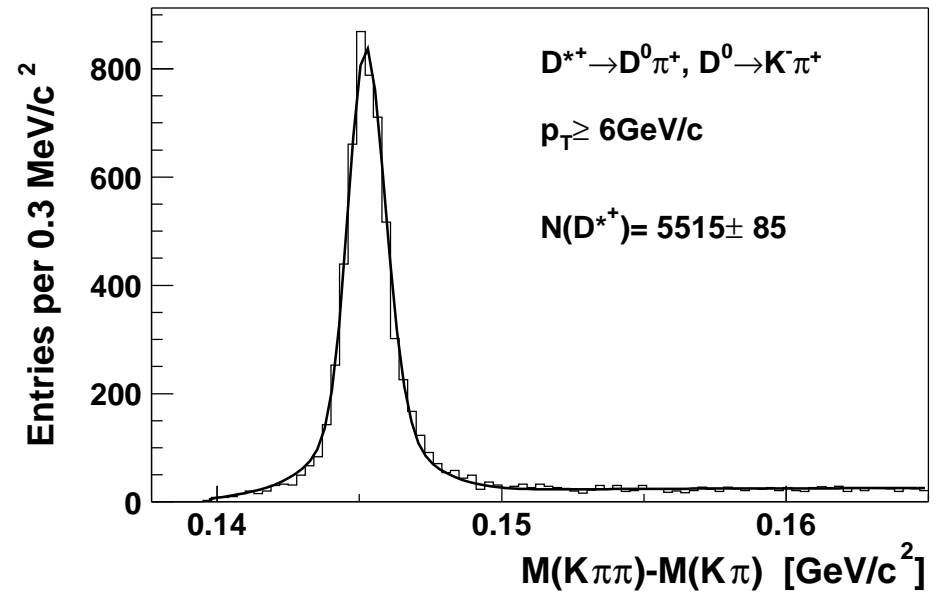# CDF's impressive charm signals

CDF Run II preliminary 5.8pb^{-1}

$D^0 \rightarrow K^- \pi^+$

$p_T \geq 5.5$GeV/c

$N(D^0) = 36804 \pm 409$

Entries per 2 MeV/c^2

Mass($K\pi$) [GeV/c^2]

CDF Run II Preliminary 5.8 pb^{-1}

$D^+ \rightarrow K^- \pi^+ \pi^+$

$p_T \geq 6$GeV/c

$N(D^+) = 28361 \pm 294$

Entries / 2 MeV/c^2

Mass($K\pi\pi$) [GeV/c^2]

CDF Run II Preliminary 5.8 pb^{-1}

$D^+, D_s^+ \rightarrow \phi\pi^+, \phi \rightarrow K^- K^+$

$N(D^+) = 502 \pm 42$

$p_T \geq 8$GeV/c

$N(D_s^+) = 851 \pm 43$

Entries per 5 MeV/c^2

M($KK\pi$) [GeV/c^2]

CDF Run II Preliminary 5.8 pb^{-1}

$D^{*+} \rightarrow D^0 \pi^+, D^0 \rightarrow K^- \pi^+$

$p_T \geq 6$GeV/c

$N(D^{*+}) = 5515 \pm 85$

Entries per 0.3 MeV/c^2

M($K\pi\pi$)-M($K\pi$) [GeV/c^2]

CDF charm cross sections

Comparison with FONLL QCD (Cacciari and Nason)

Inputs: CTEQ6M, $m_c = 1.5$ GeV,
$$\mu = \sqrt{m_c^2 + p_T^2}$$

Uncertainties in scale (m_c, PDF and fragmentation)

CDF charm cross sections
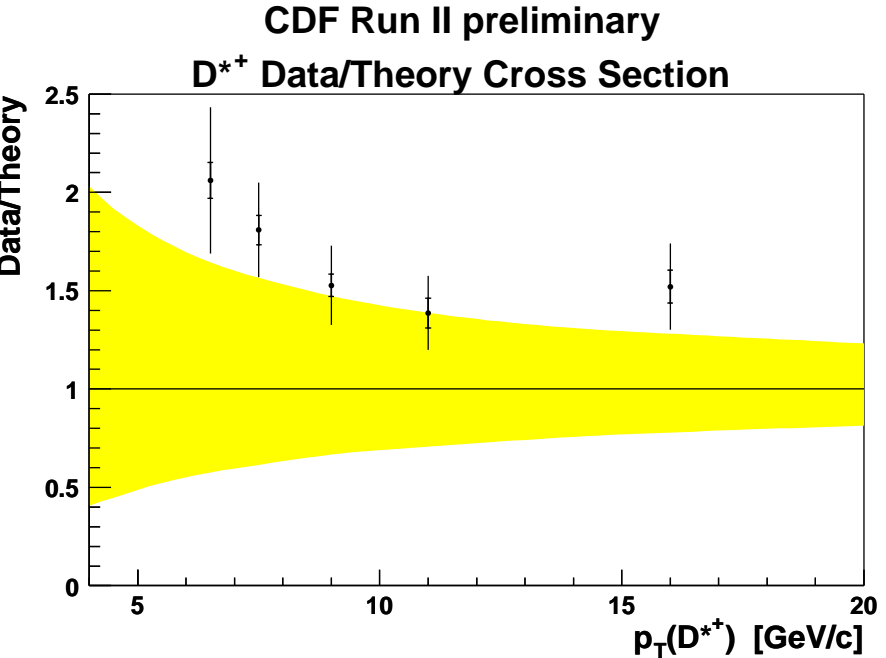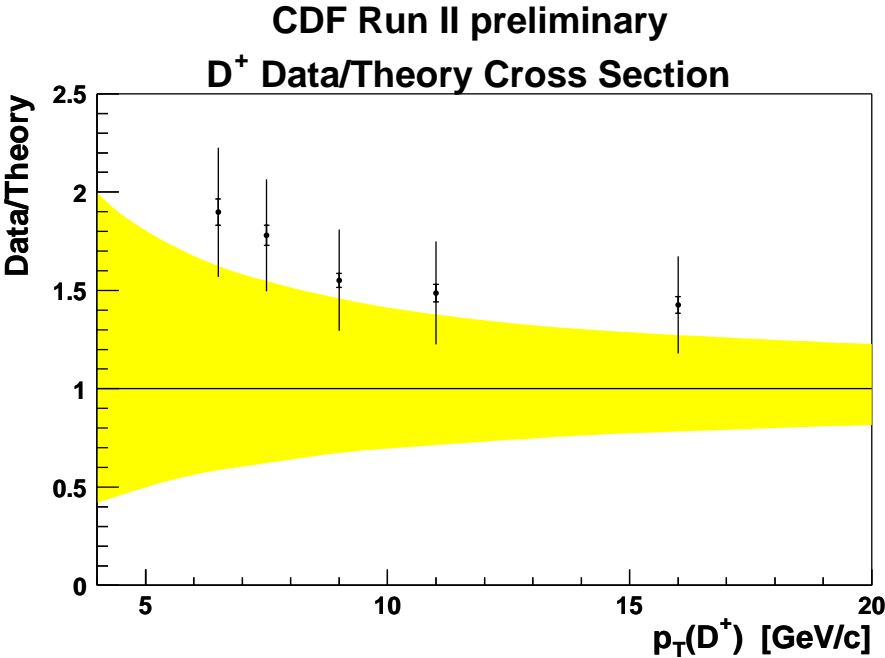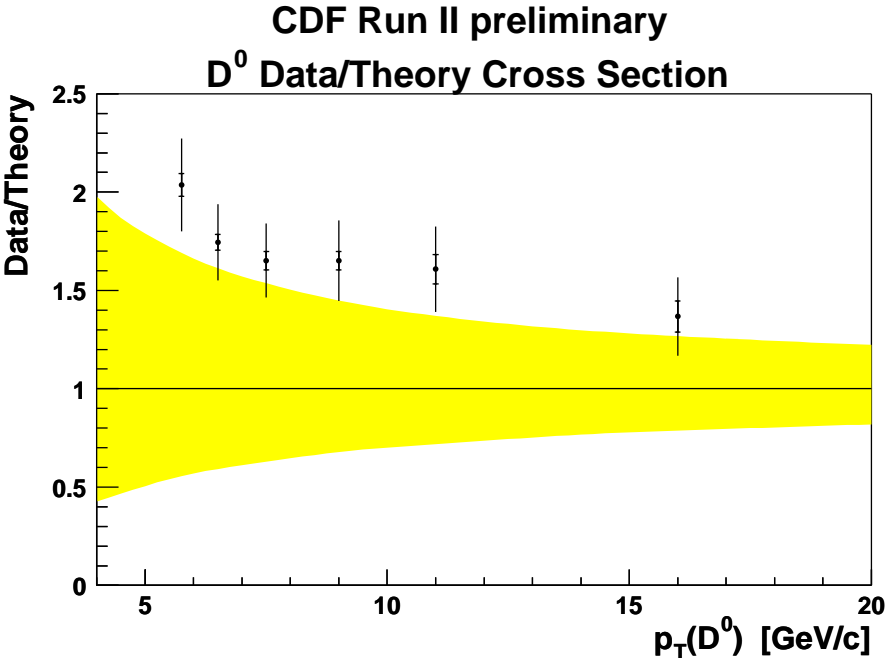

CDF Run II preliminary
D^0 Data/Theory Cross Section

CDF Run II preliminary
D^+ Data/Theory Cross Section

CDF Run II preliminary
D^{*+} Data/Theory Cross Section

Predictions are below the data.

General shape agreement.

Uncertainties are large for firmer conclusions.

Charm discussion

In general, NLO QCD is below the measurements of charm production but compatability within uncertainties
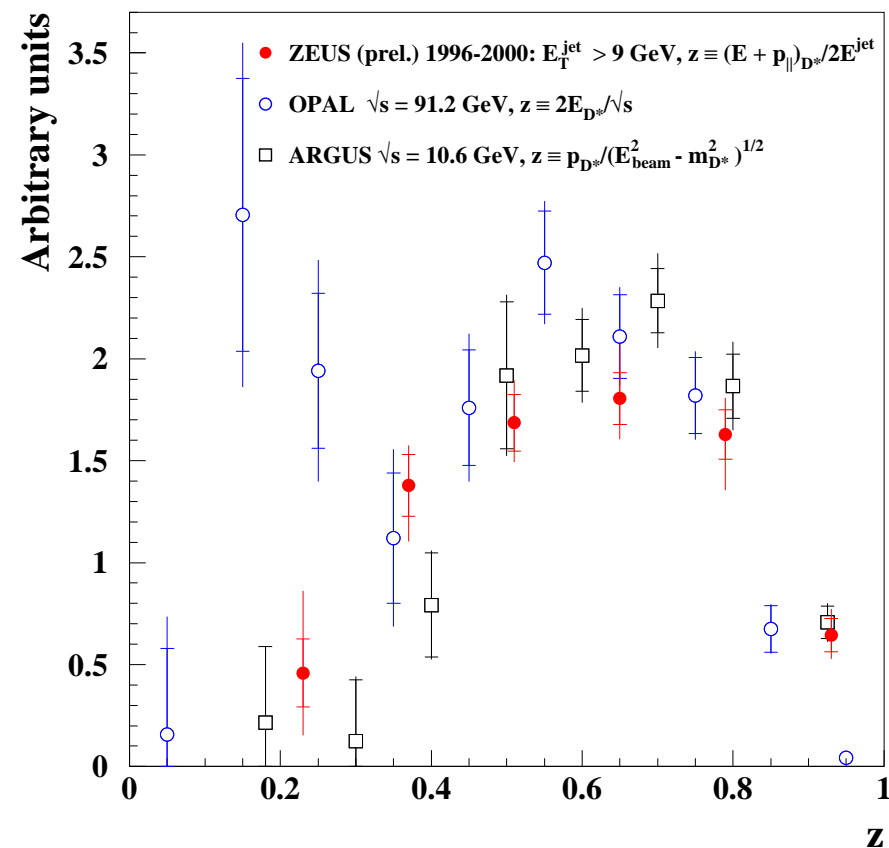
Still complicated convolution (PDF $\times$ Hard scatter $\times$ fragmentation)

Uncertainties are often large, but for data they are decreasing rapidly

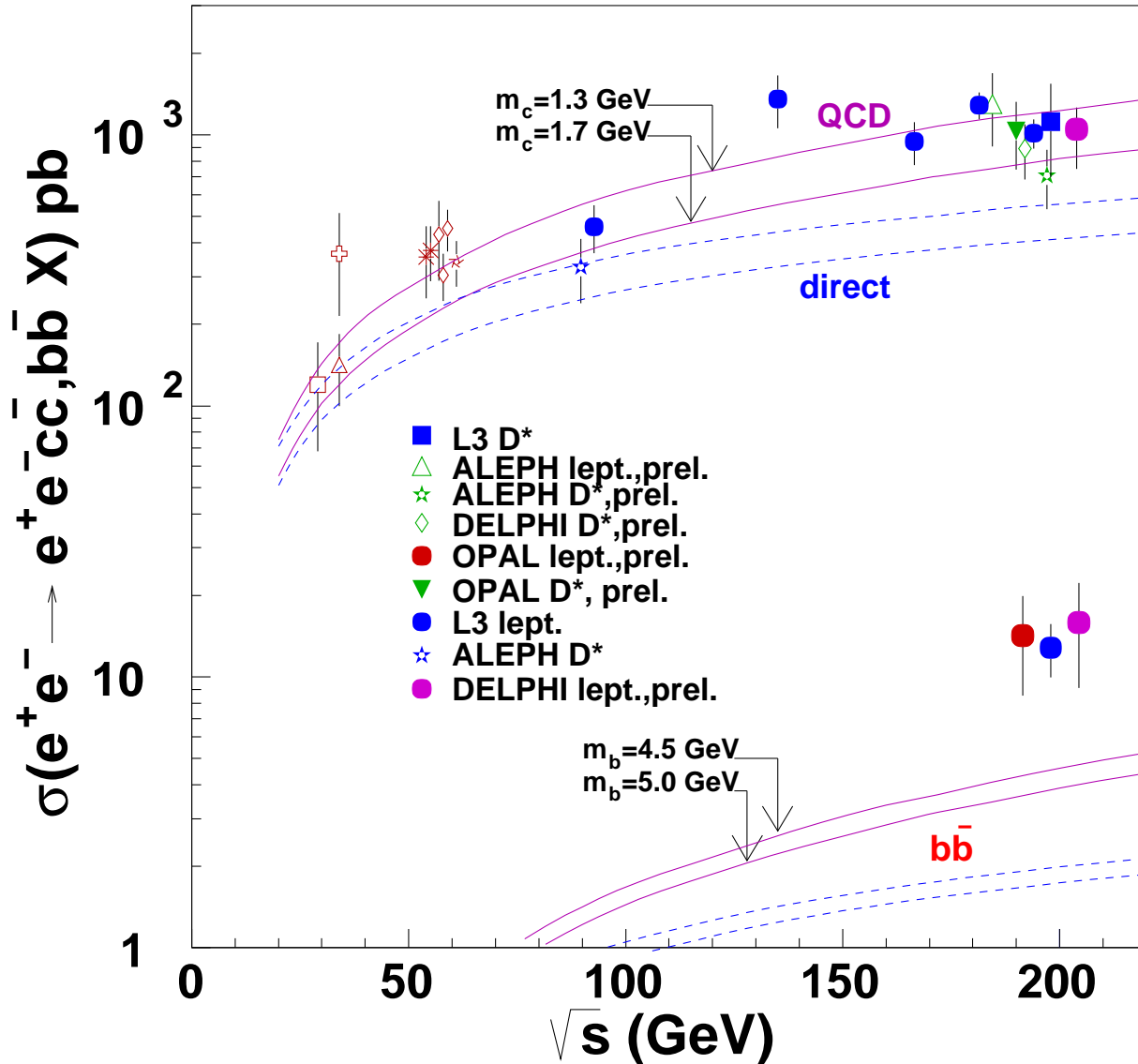**Independent ways of measuring fragmentation**

Measurements insensitive to fragmentation (e.g. jets)

Open beauty measurements
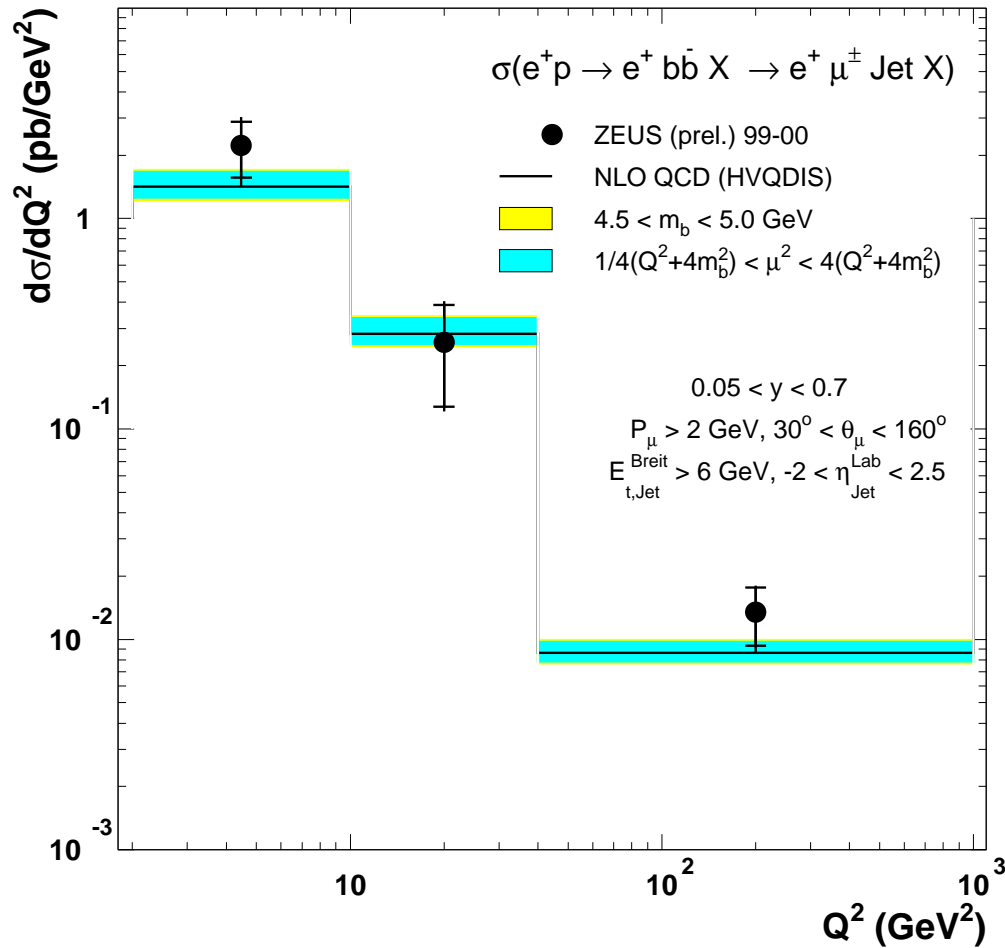
Beauty in $\gamma\gamma$ collisions

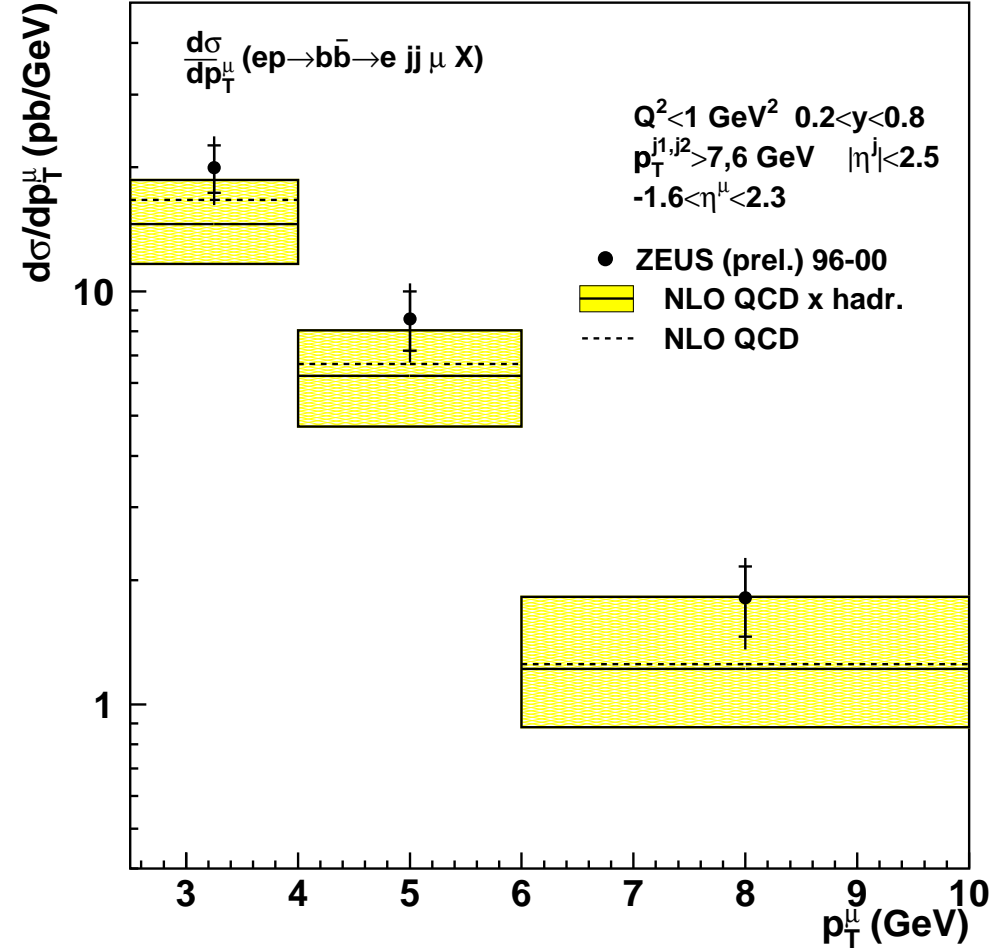NLO significantly below the data

Data undergone large extrapolation

Similar to old results from TeVatron Run I

Open beauty measurements at HERA

ZEUS

$\sigma(e^+p \rightarrow e^+ b\bar{b} X \rightarrow e^+ \mu^\pm \text{Jet } X)$

- ● ZEUS (prel.) 99-00
- — NLO QCD (HVQDIS)
- ▮ $4.5 < m_b < 5.0$ GeV
- ▮ $1/4(Q^2+4m_b^2) < \mu^2 < 4(Q^2+4m_b^2)$

$0.05 < y < 0.7$

$P_\mu > 2$ GeV, $30^o < \theta_\mu < 160^o$

$E_{t,Jet}^{Breit} > 6$ GeV, $-2 < \eta_{Jet}^{Lab} < 2.5$

ZEUS

$\frac{d\sigma}{dp_T^\mu} (ep \rightarrow b\bar{b} \rightarrow e \, jj \, \mu \, X)$

$Q^2 < 1$ GeV^2 $0.2 < y < 0.8$

$p_T^{j1,j2} > 7,6$ GeV $|\eta^j| < 2.5$

$-1.6 < \eta^\mu < 2.3$

- ● ZEUS (prel.) 96-00
- ▮ NLO QCD x hadr.
- ---- NLO QCD

Measurements in acceptance of detector

NLO QCD describes the data reasonably well...

New TeVatron beauty measurement

DØ Run 2 Preliminary
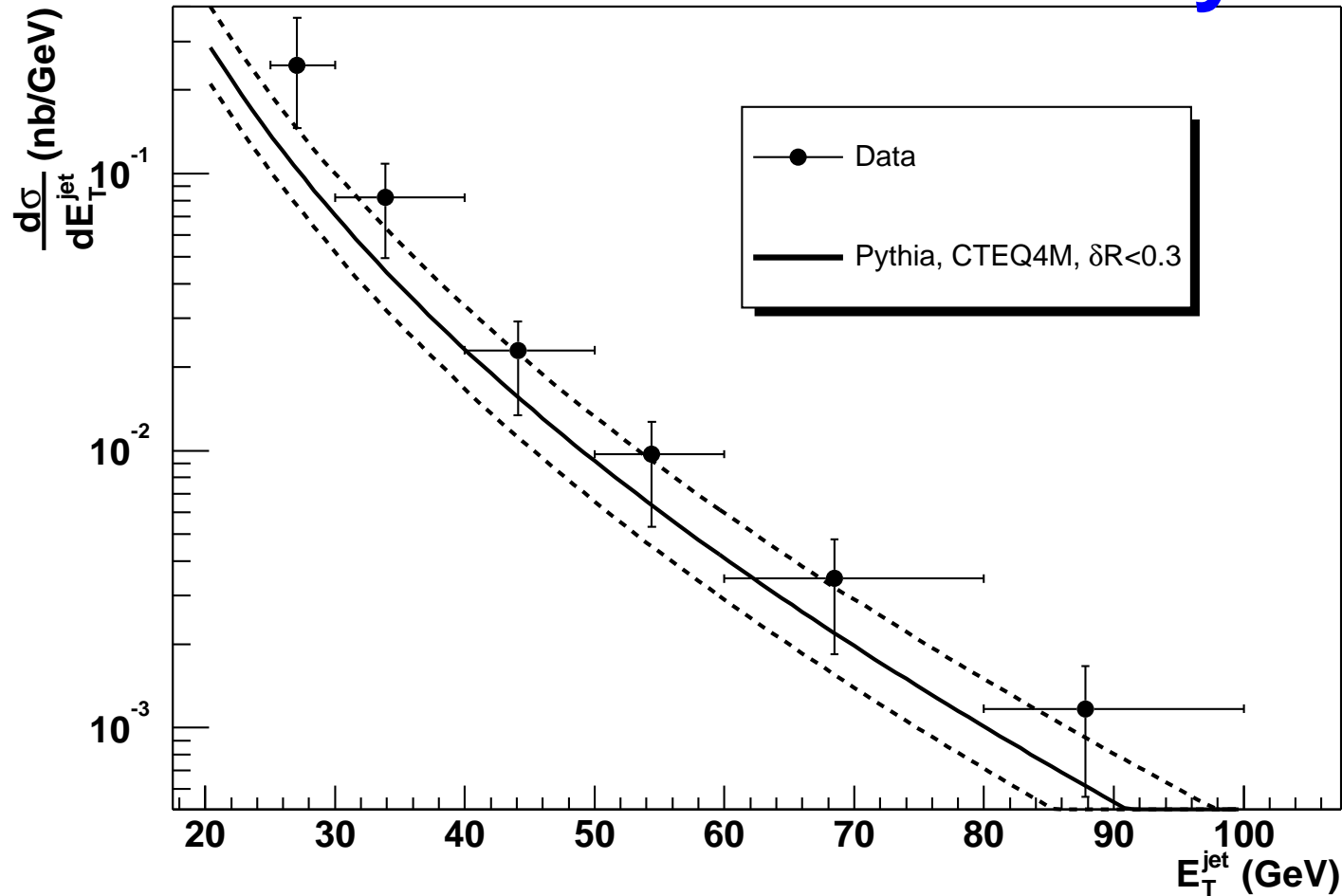
Measurement of jet cross section

Consistent with Run I results - better agreement with theory
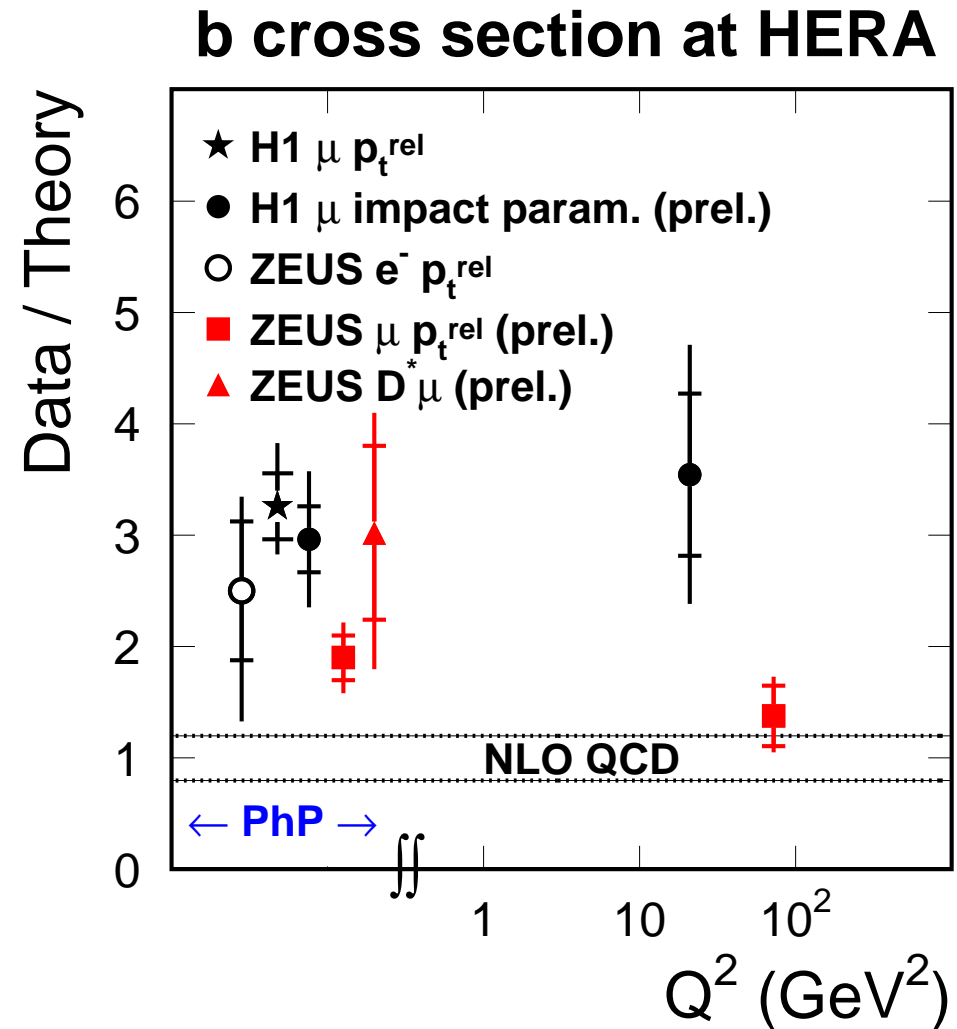
Beauty discussion

Situation not as clear as a few years ago

Many different kinematic regions measured and assumptions made

Significant work on fragmentation issues

Data still generally higher than NLO QCD, but some less than others...

b cross section at HERA

More data is needed and is coming...

Diffractive open-charm production

Diffractive processes contribute $\sim 10\%$ to the total DIS cross section

Events have clear experimental signature - large rapidity gap

QCD factorisation has been proven (Collins) for these class of events $\Rightarrow$ can measure "diffractive parton distributions"

Evolution with Q^2 according to DGLAP equations

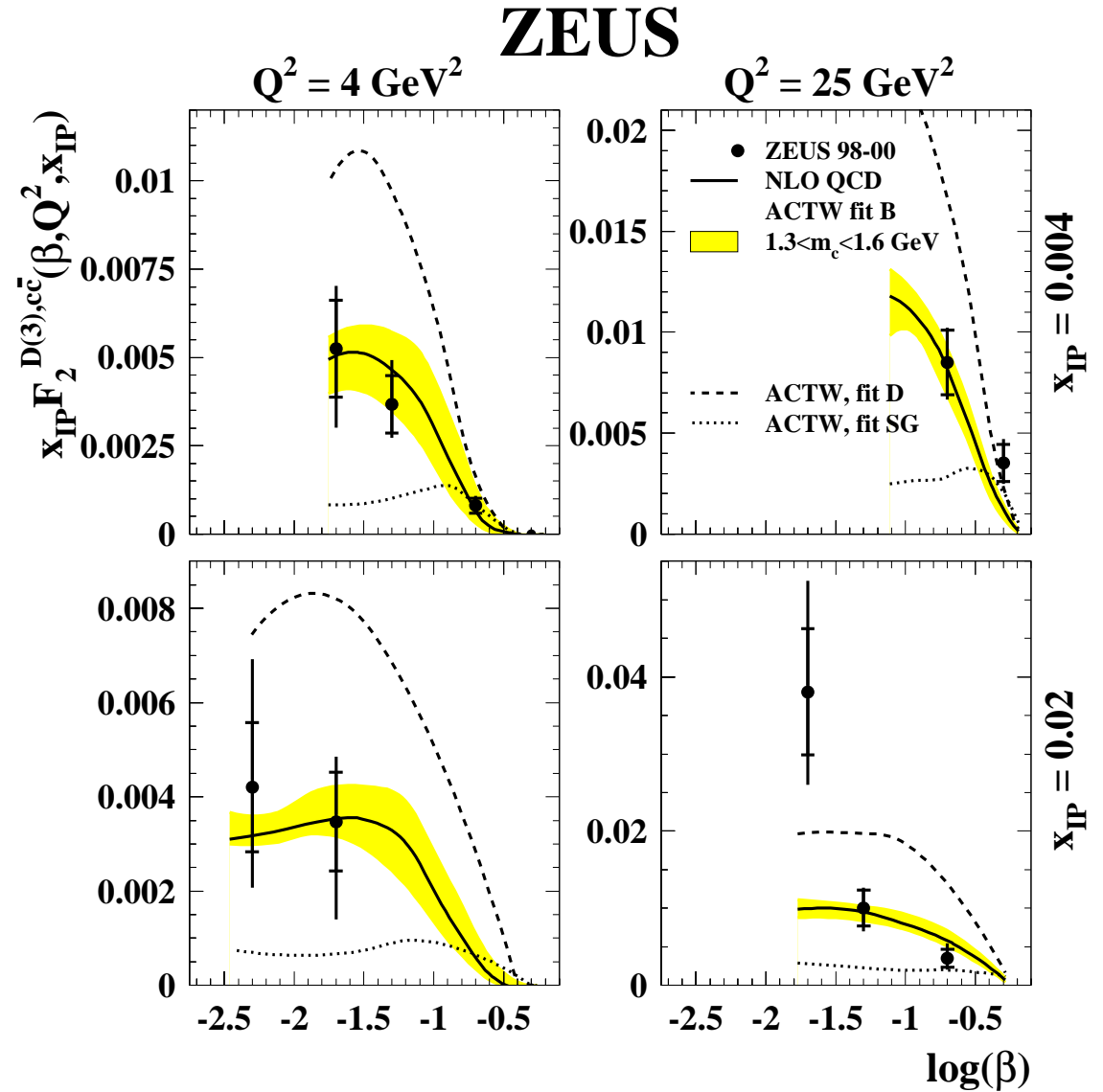**Extract parton densities and predict charm production**
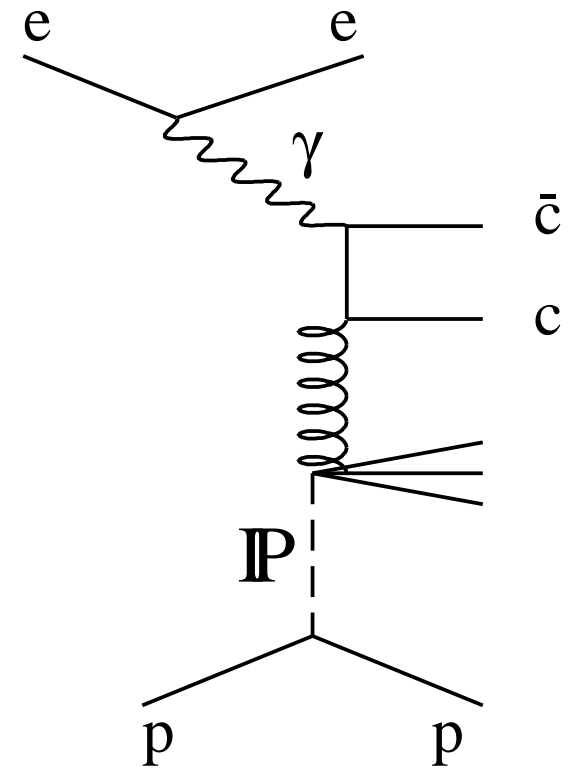
Charm contribution to diffractive structure function

Data show sensitivity to the parton density parametrisations

Some parametrisations are ruled out

One parametrisation consistent with data

Factorisation approach works

Summary

Increasing number of high precision measurements of heavy quark production

Complicated mix of experimental, phenomenological and theoretical issues

Hard to summarise. The theory does not adequately describe the data

Many more measurements to come from HERA and the TeVatron

Sort out before turning on the LHC?