

# Heavy flavour production with leptons and hadrons

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- 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

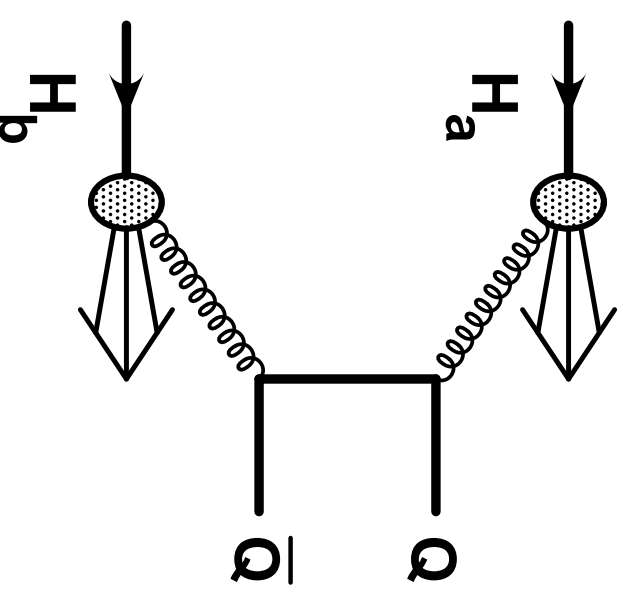
Make measurements of CP violation

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?

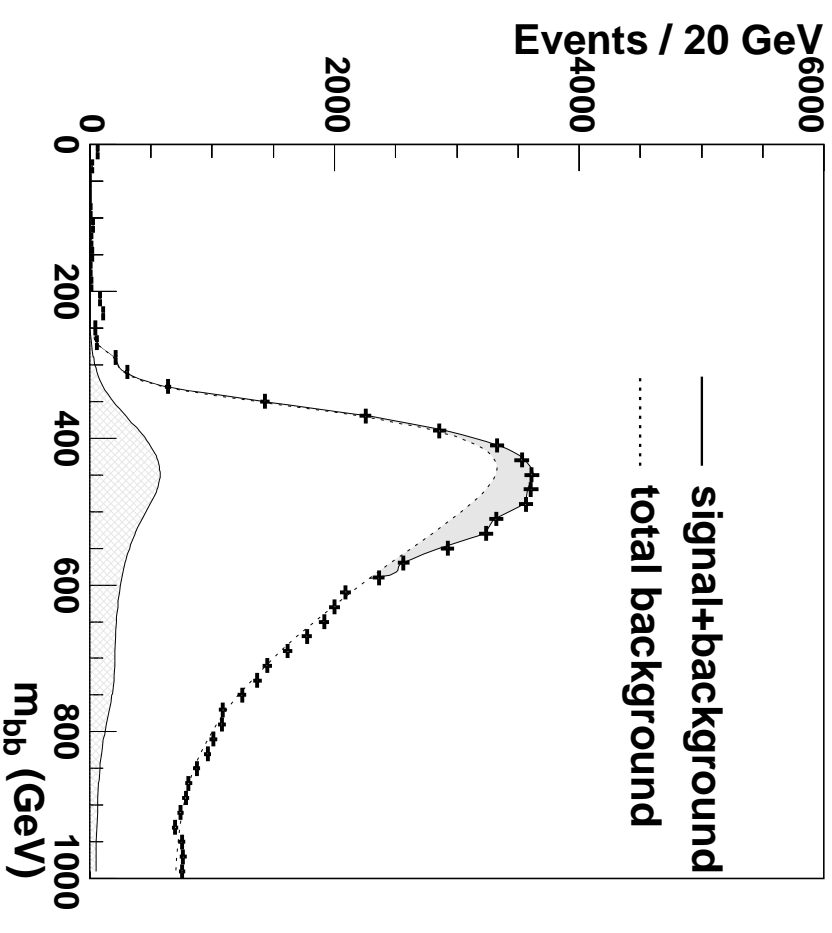
Example of why the heavy quark production rate needs to be understood (ATLAS TDR)

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

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

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

**$5\sigma$  discovery possible if QCD backgrounds known precisely**



**How well is the QCD background known?**

# Perturbative QCD formalism

For generic collision between two hadrons producing a heavy quark,

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

Cross section can be written as;

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

**A convolution of the parton densities and short distance cross section**

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

**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 ( $gg \rightarrow Q\bar{Q}$ )

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

# Fragmentation of heavy quarks

Sprays of hadrons and leptons are measured in the detector

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

Calculation is in terms of final state partons

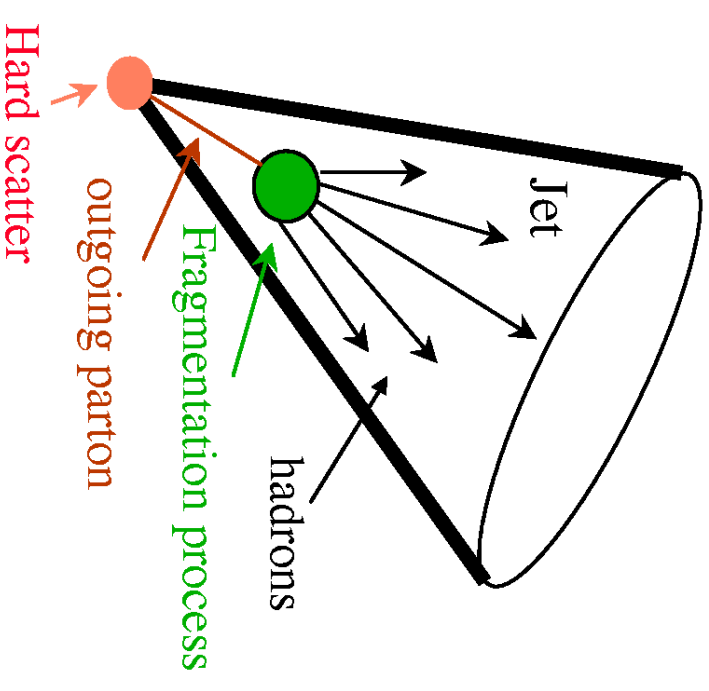
The two need to be “matched” to perform a comparison

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

NLO QCD calculations usually add on a Peterson function

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

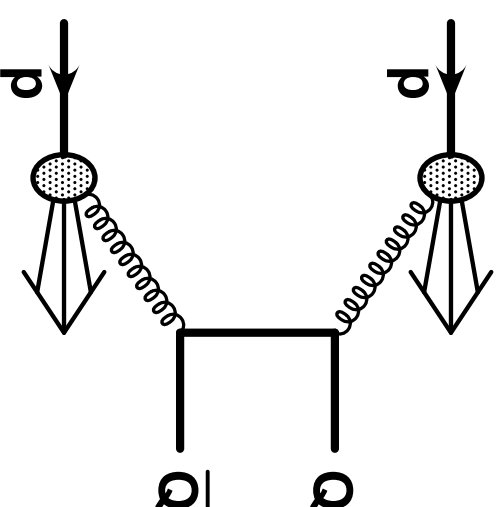
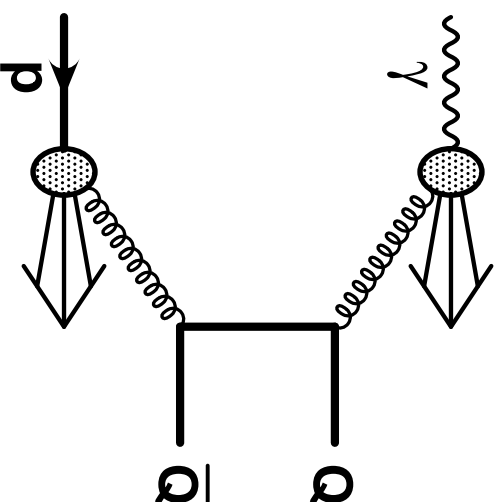
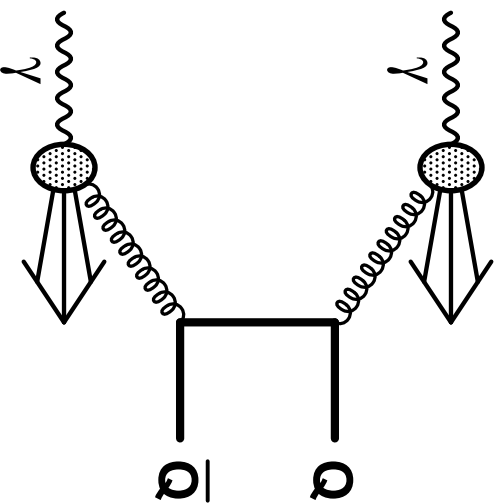
The physics of the experiments at each collider is different, but the production of heavy quarks is essentially the same...

# Generic nature of production

LEP

HERA

Tevatron



**PDF** →

**Hard scatter** →

**Fragmentation**

Structure functions of  
proton and photon

Dynamics of NLO QCD  
Implementation of

Description of parton-  
hadron transition

Direct sensitivity to the  
gluon content

diagrams and dynamics  
into programs

Non-perturbative, but  
essential.

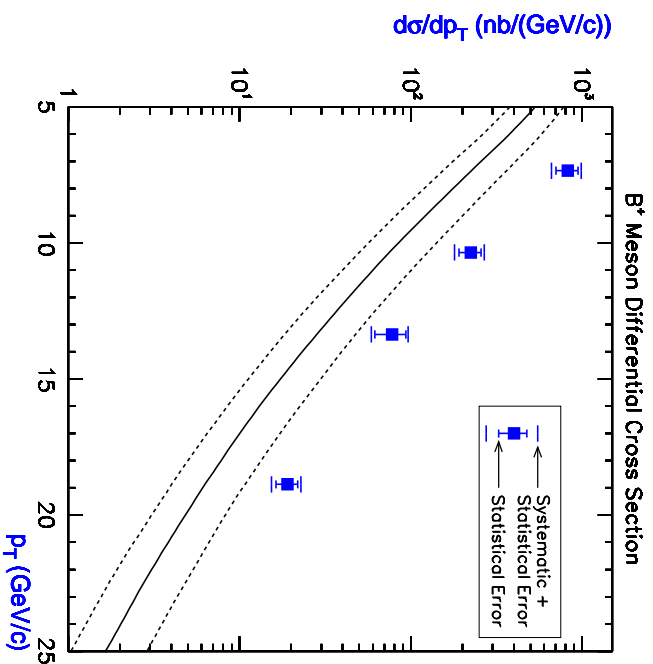
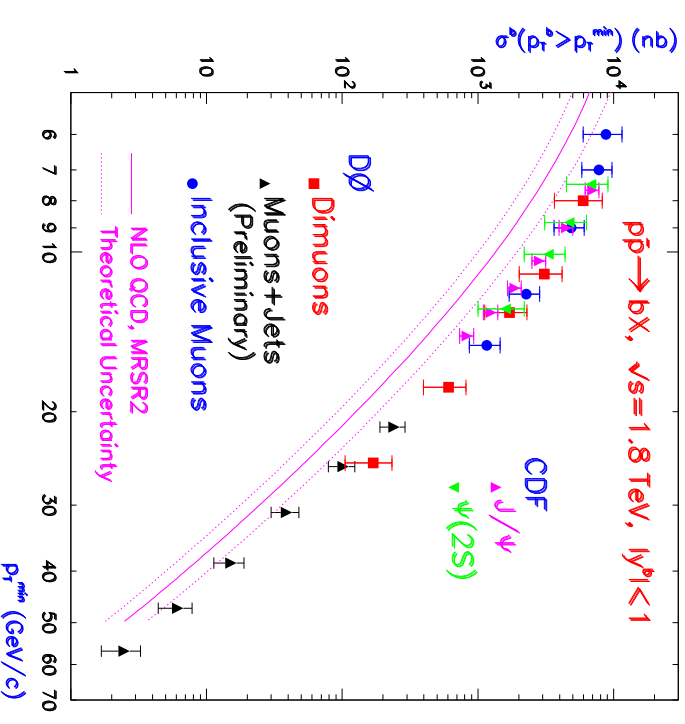
# Beauty production at the Tevatron Run I

Significant disagreement with QCD

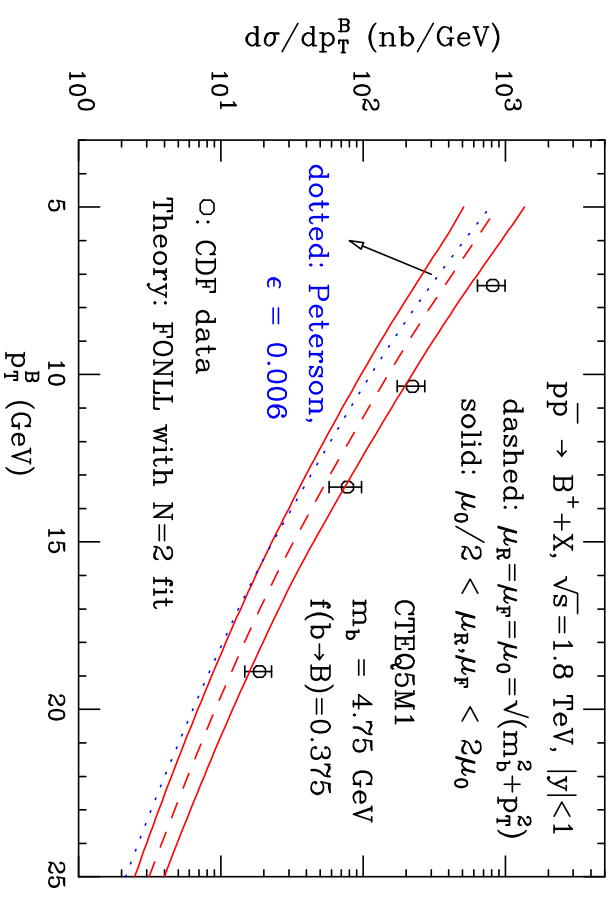
Extrapolation to the  $b$  quark level  $\rightarrow$

Measurement of  $B$  hadrons gives more reliable results

Led to improvement in theory



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



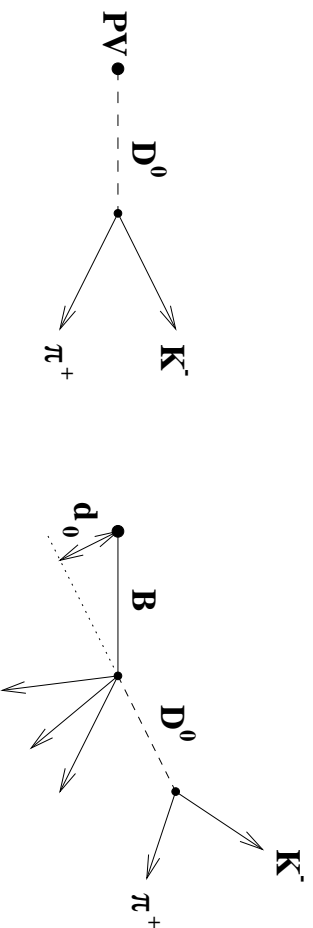
# Experimental methods for tagging heavy quarks

Reconstruction of hadron mass resonances

Decay to lepton and its transverse momentum relative to the quark

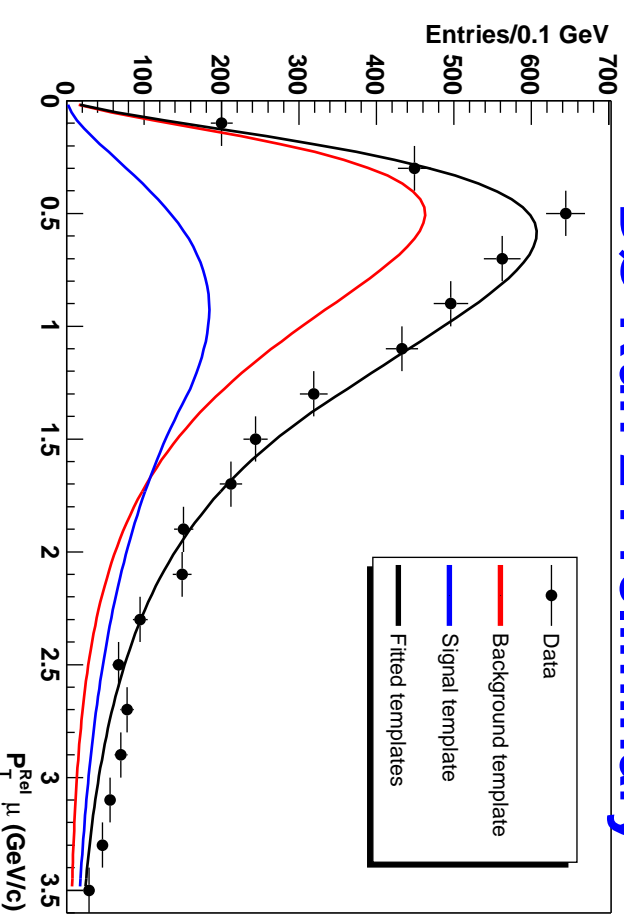
Use of a vertex detector - weak decays, long-lived

Direct Production      Secondary Production  
 D points back to PV      D has finite impact parameter

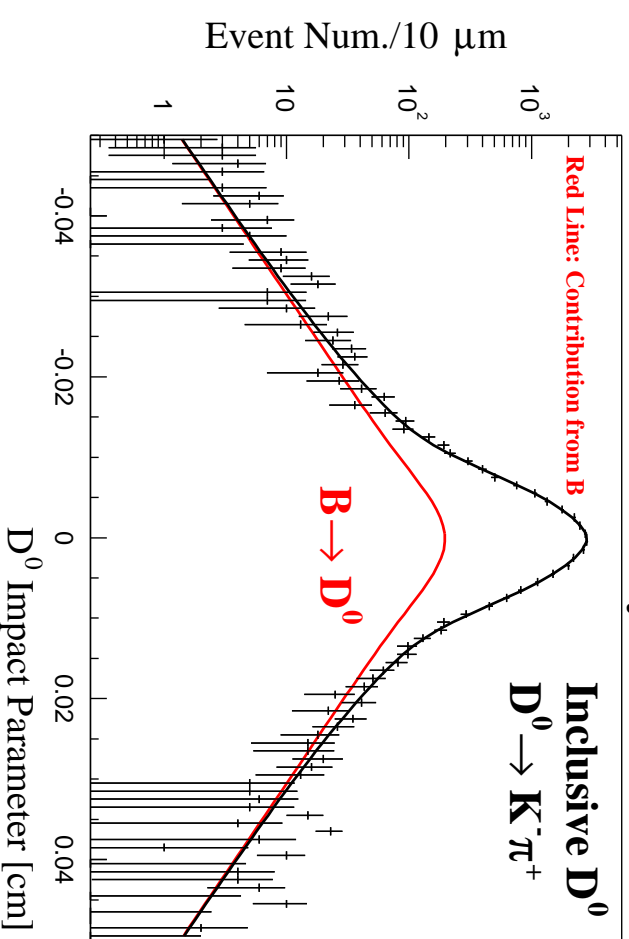


Experiments use different methods depending on their apparatus, but in general have the same techniques

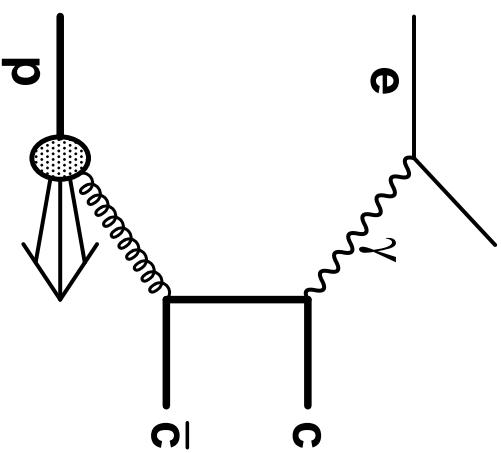
## DØ Run 2 Preliminary



## CDF RunII Preliminary

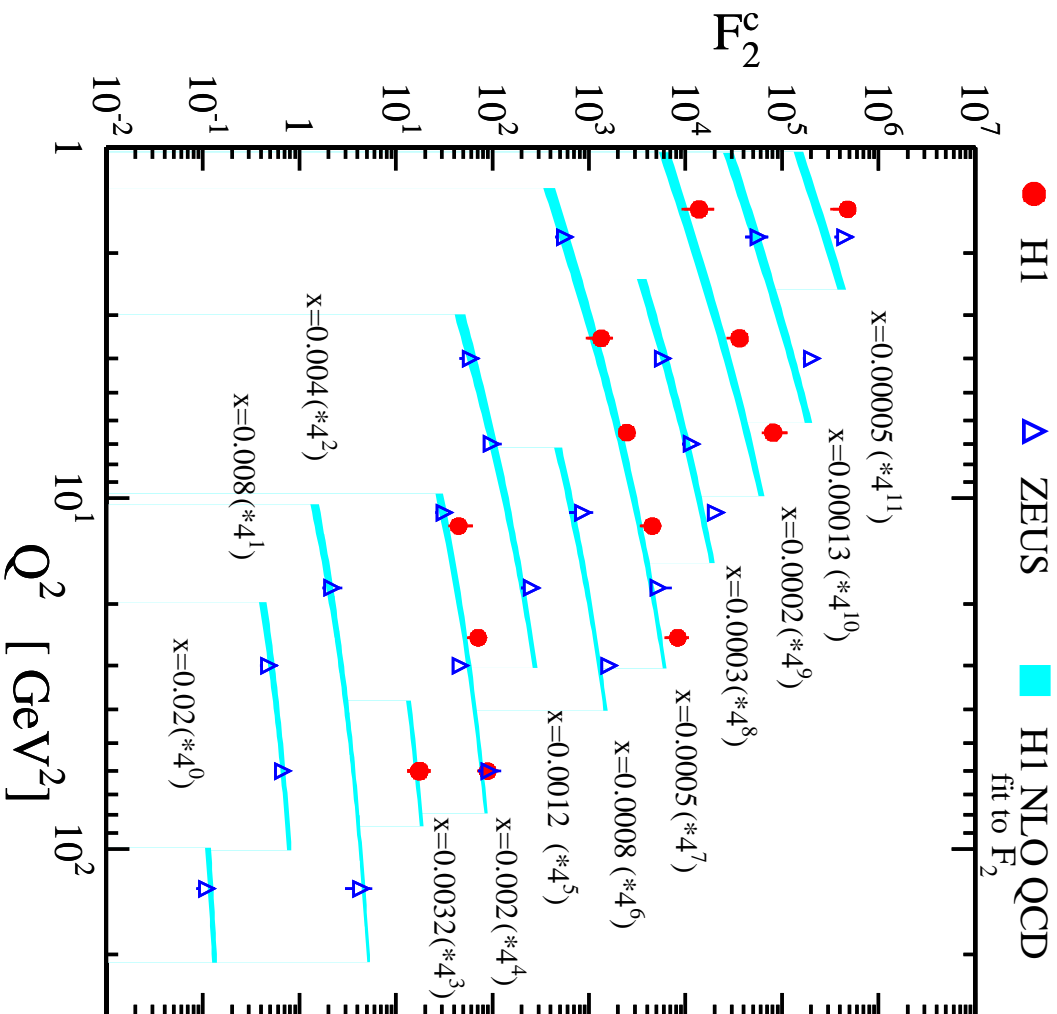


# Latest results - structure functions

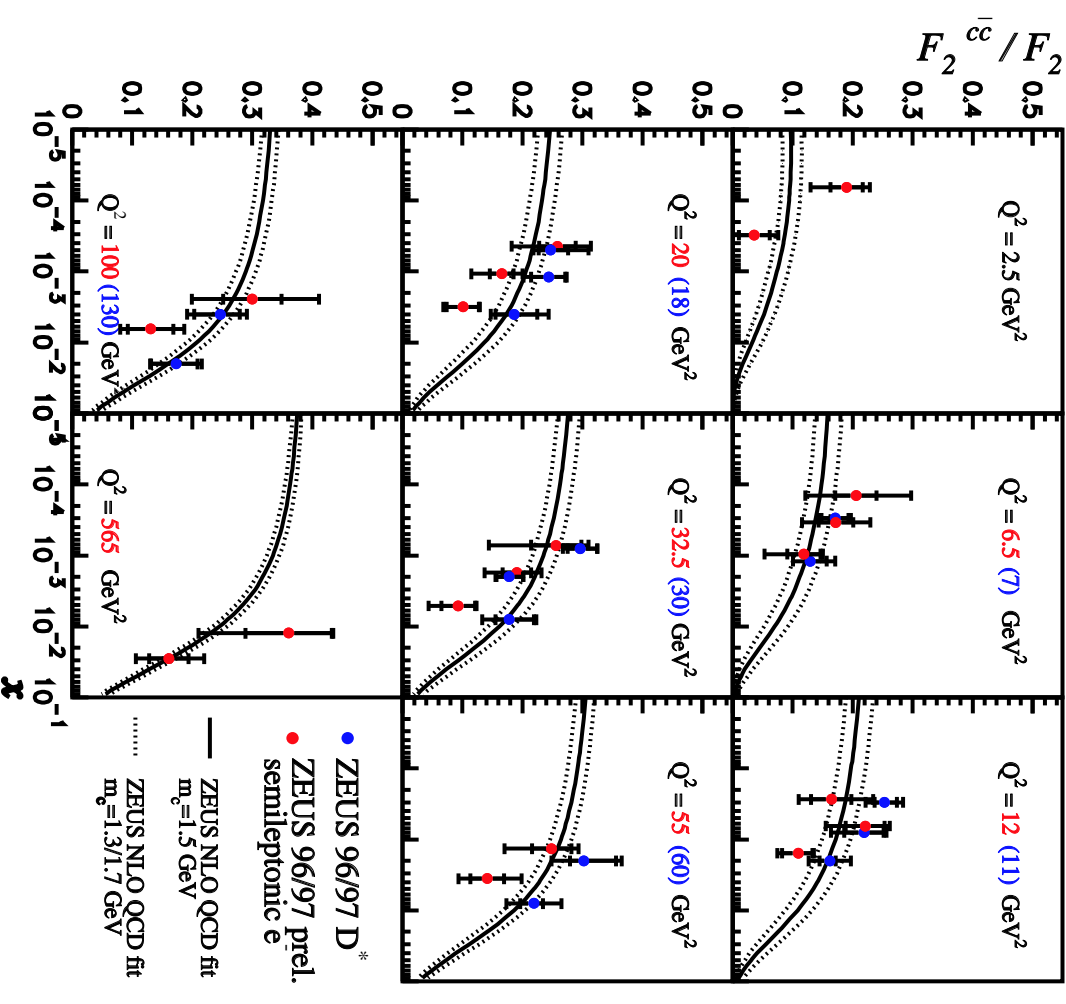


# Charm contribution to the proton structure function

$F_2^c$  in the NLO DGLAP scheme

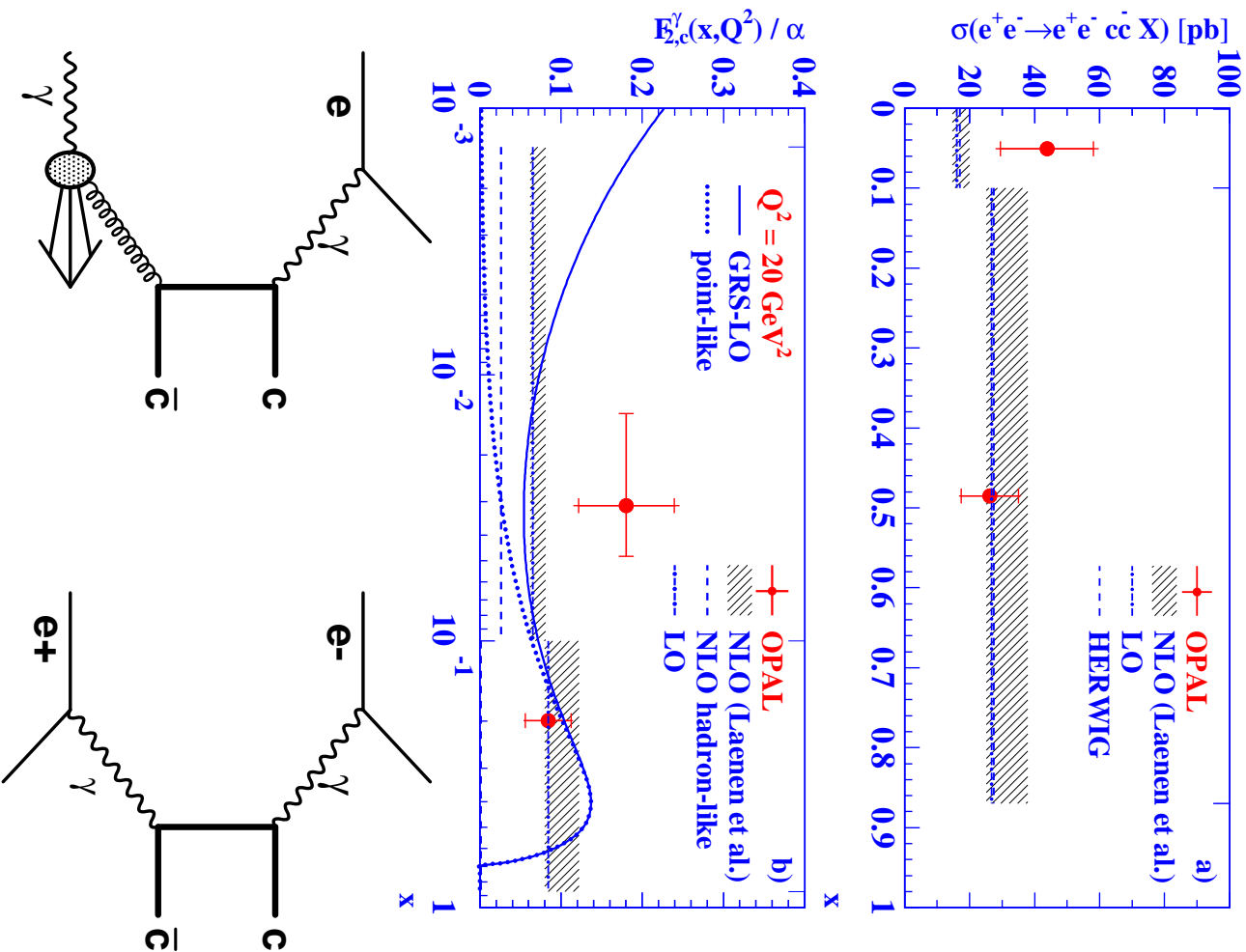


ZEUS Preliminary



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

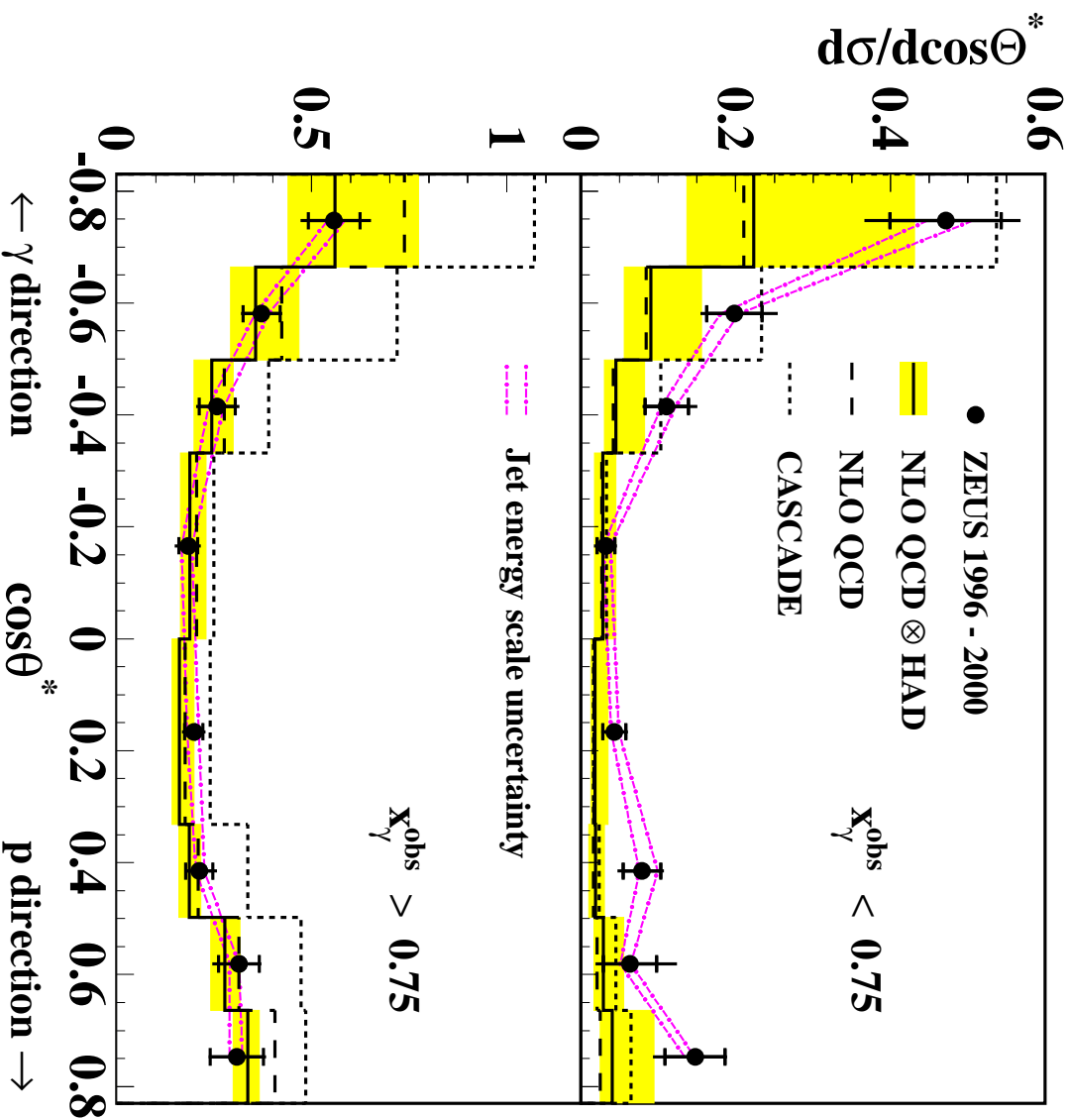
$$(\sigma_{\text{tot}})_{\text{meas}} = \frac{(\sigma_{p_{T^*}, \eta})_{\text{meas}}}{(\sigma_{p_{T^*}, \eta})_{\text{MC}}} \cdot (\sigma_{\text{tot}})_{\text{MC}}$$

- Extrapolation factors vary; up to  $\sim 10$ - $20$

But they are intuitive...

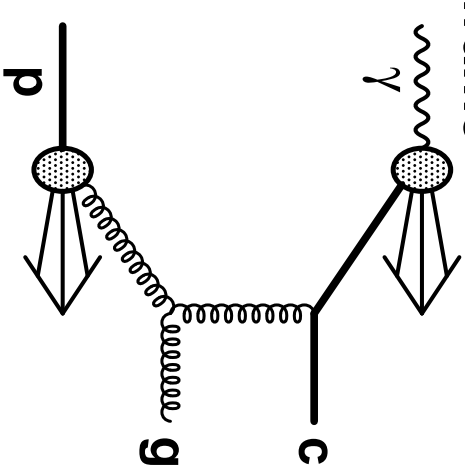
# Charm from the photon

## ZEUS



Angular distribution in dijet centre-

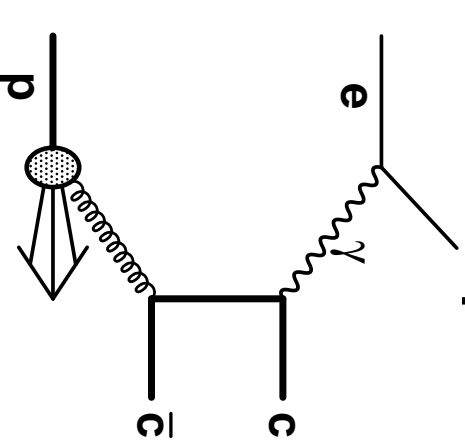
of-mass frame



Similar to Rutherford scattering.

$q$  propagator  $\Rightarrow$  shallow rise

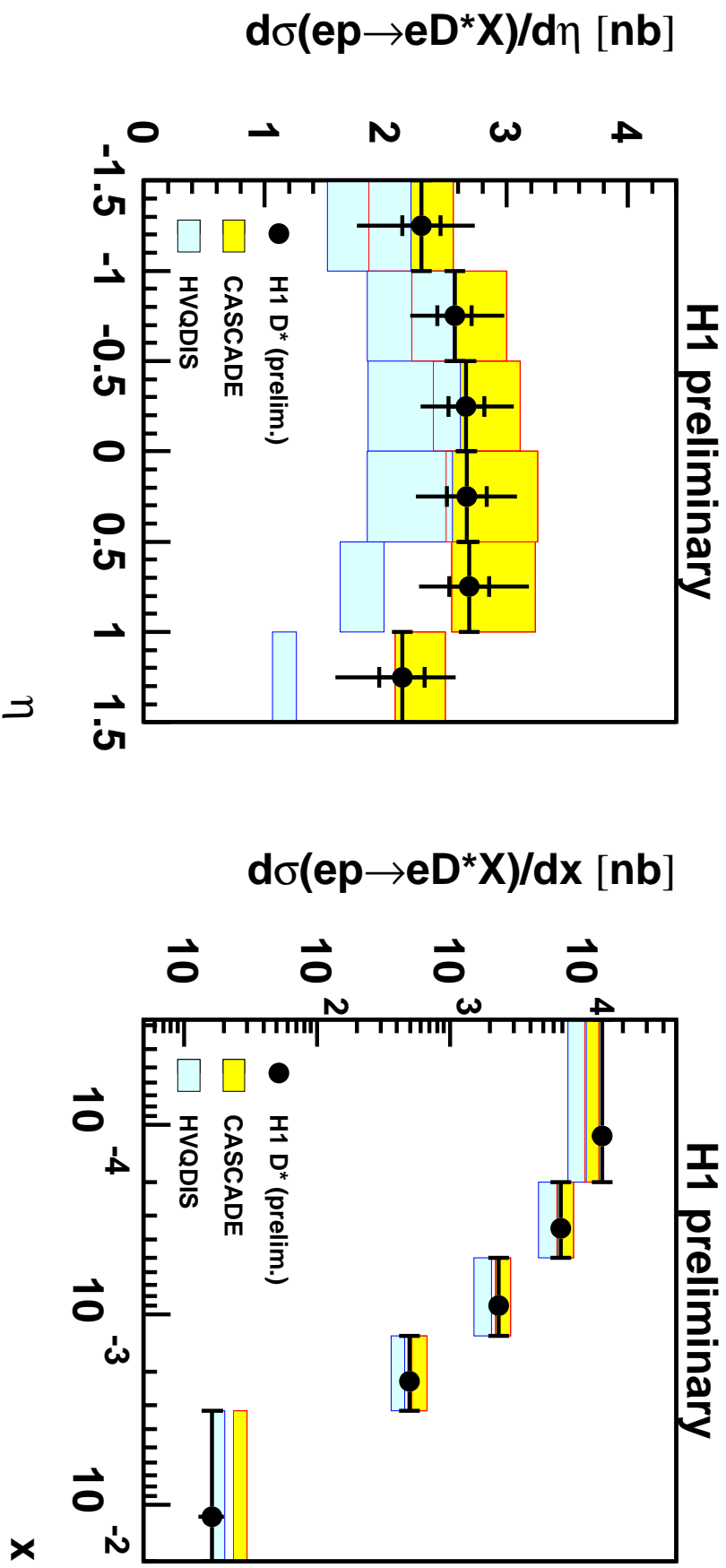
$g$  propagator  $\Rightarrow$  steep rise



Evidence for charm from the photon

# **Charm cross section measurements**

# Charm in deep inelastic scattering at HERA

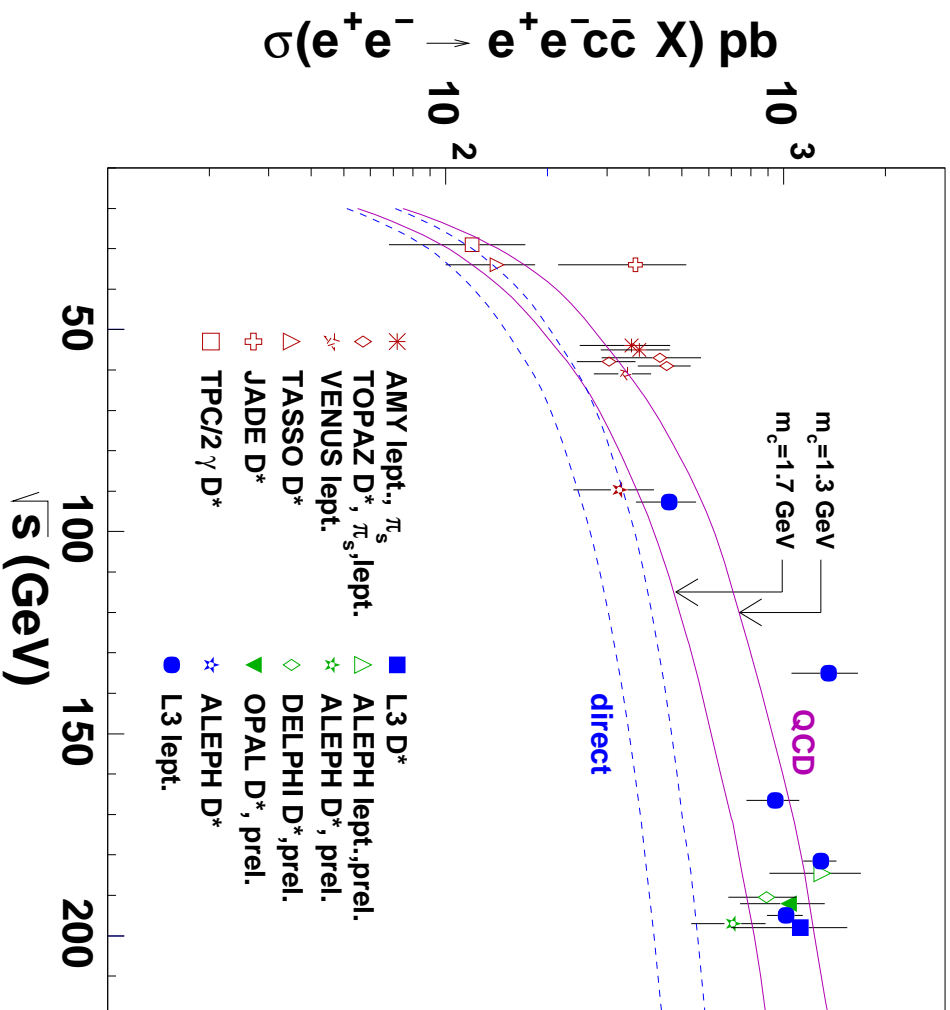


NLO (HVQDIS) prediction does not give complete description of the data

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

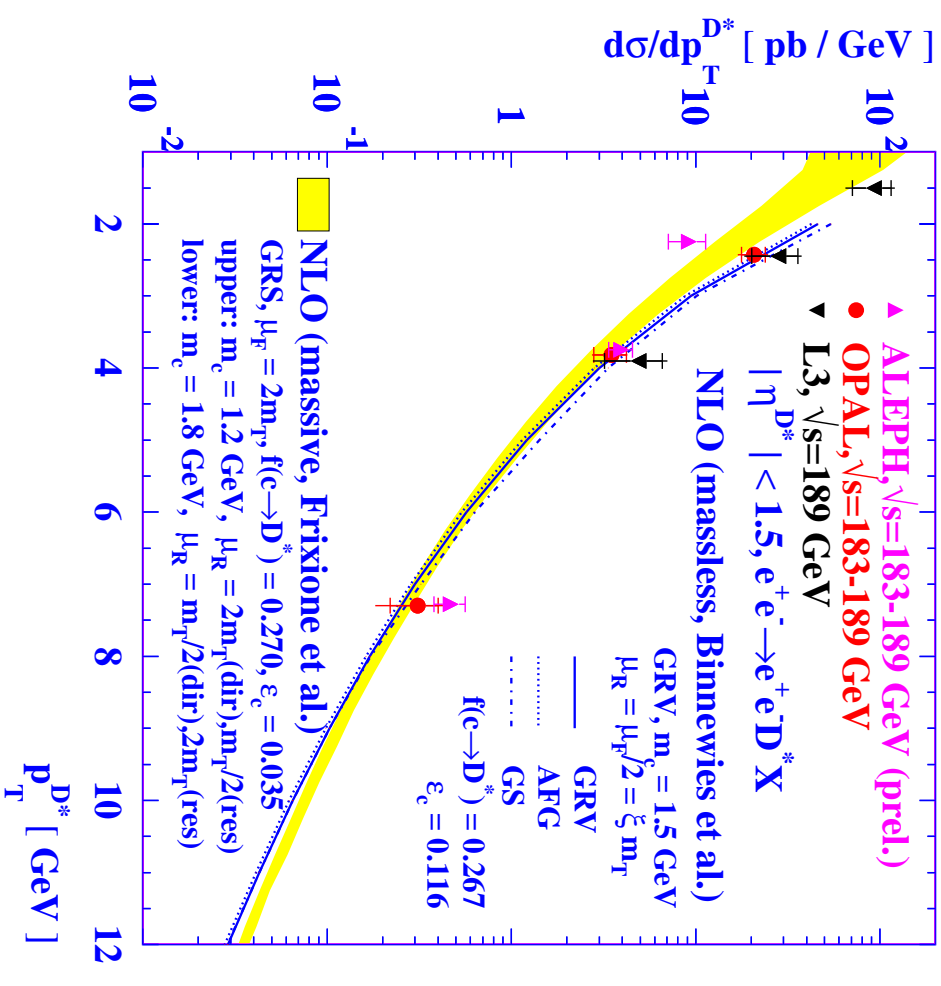
ZEUS collaboration gets better agreement...

# Charm in $\gamma\gamma$ collisions



“Dangerous” total cross sections

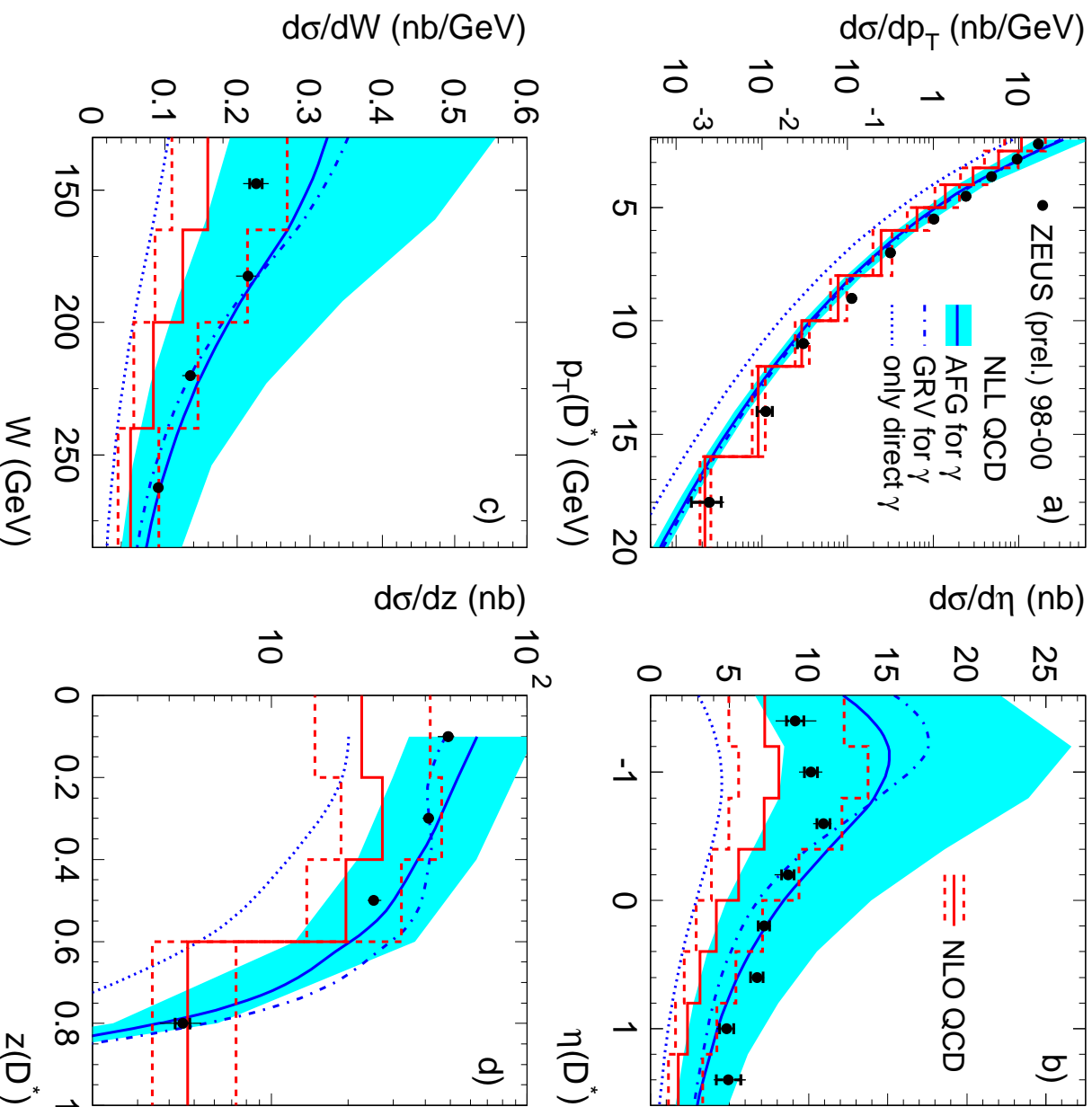
Easy comparison over many experiments



Rigorous comparison possible with cooperation

# Charm in photoproduction at HERA

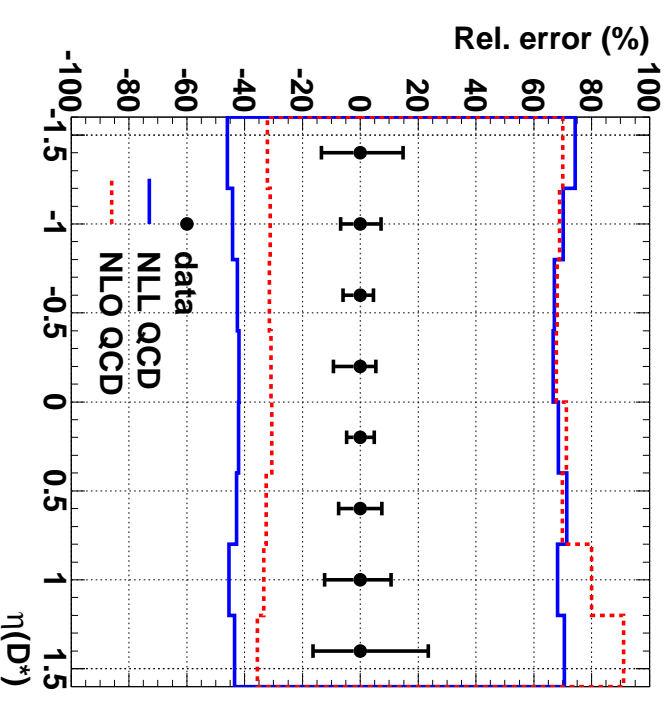
ZEUS



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

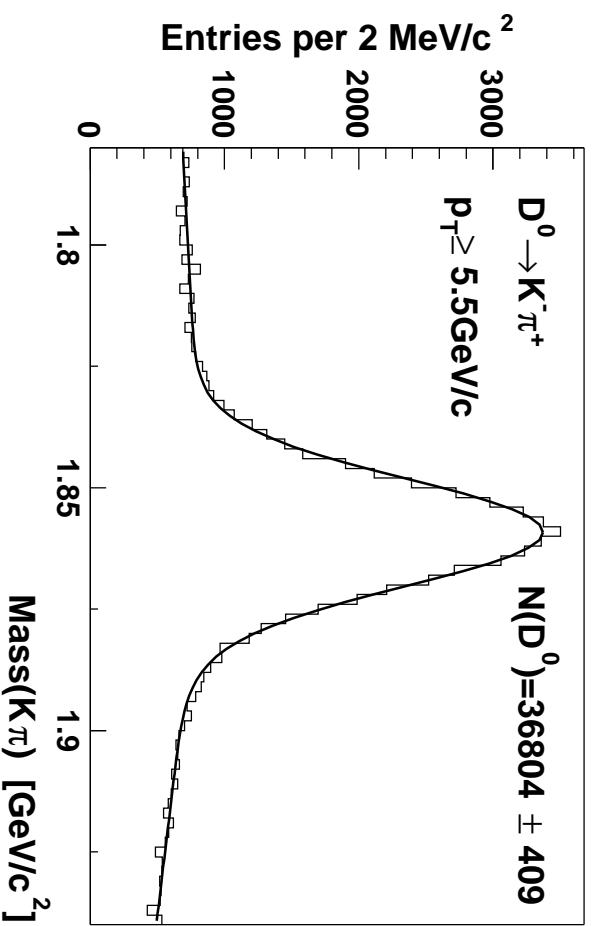
**General description with caveats - double differential cross sections highlight differences**

**Is QCD really predictive?**

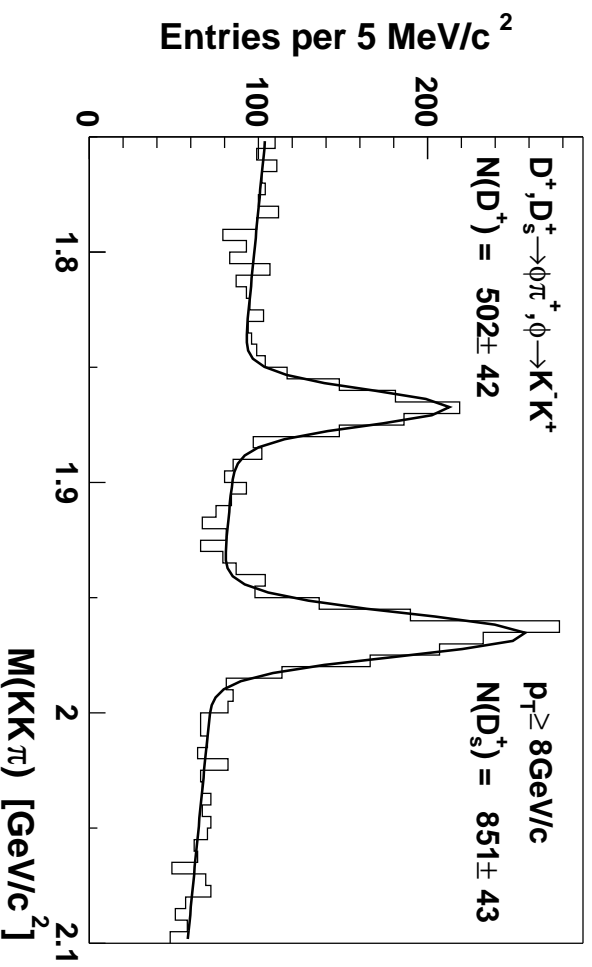


# CDF's impressive charm signals

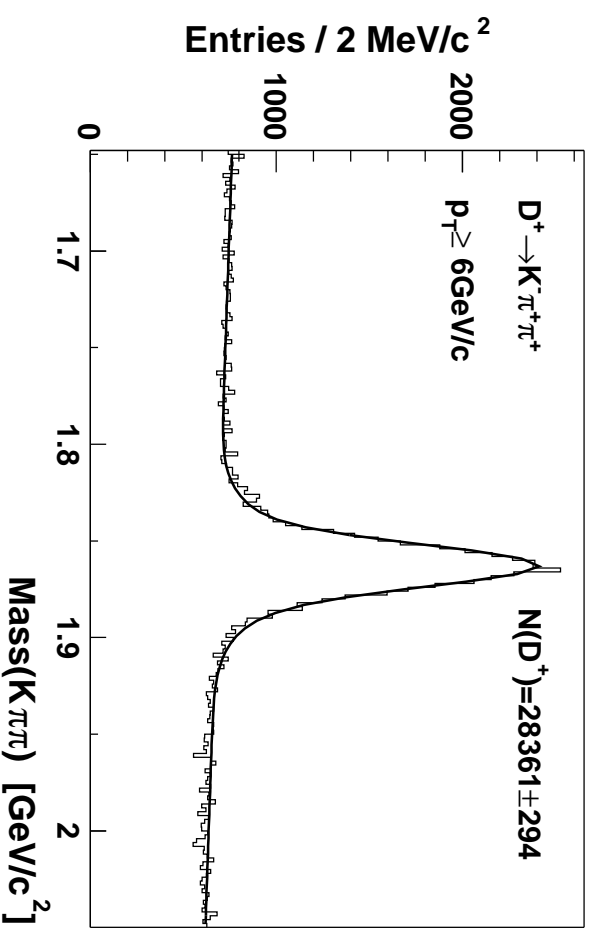
CDF Run II preliminary 5.8pb<sup>-1</sup>



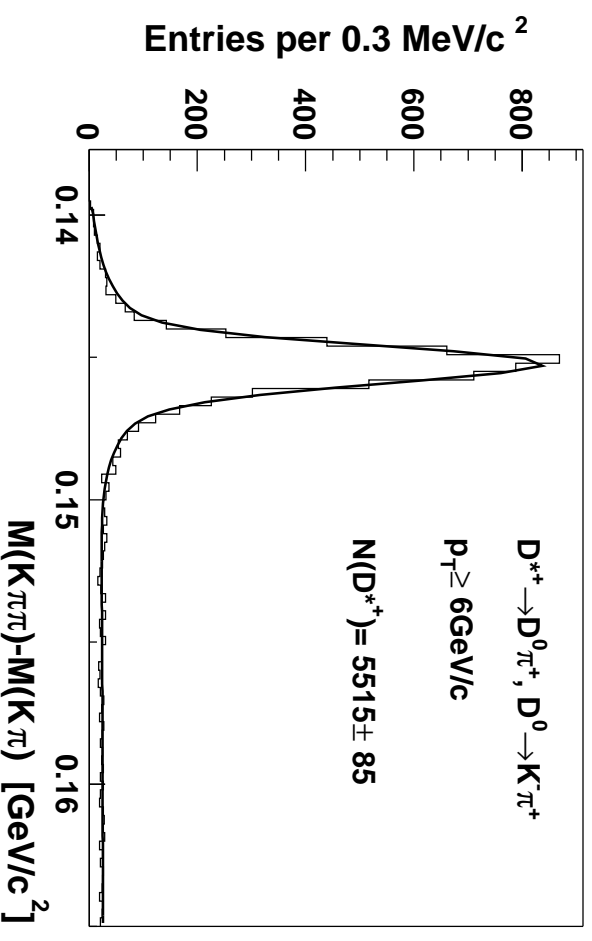
CDF Run II Preliminary 5.8 pb<sup>-1</sup>



CDF Run II Preliminary 5.8 pb<sup>-1</sup>

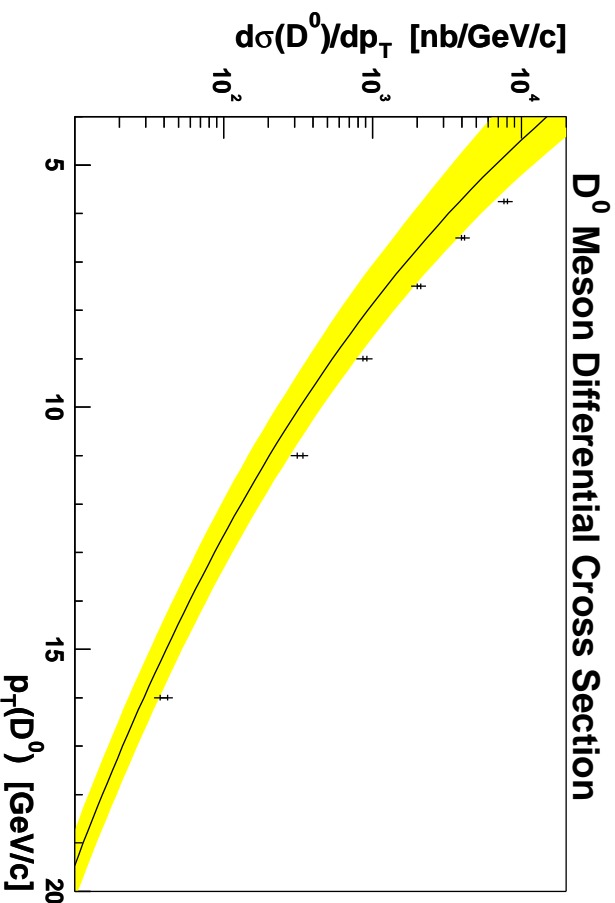


CDF Run II Preliminary 5.8 pb<sup>-1</sup>

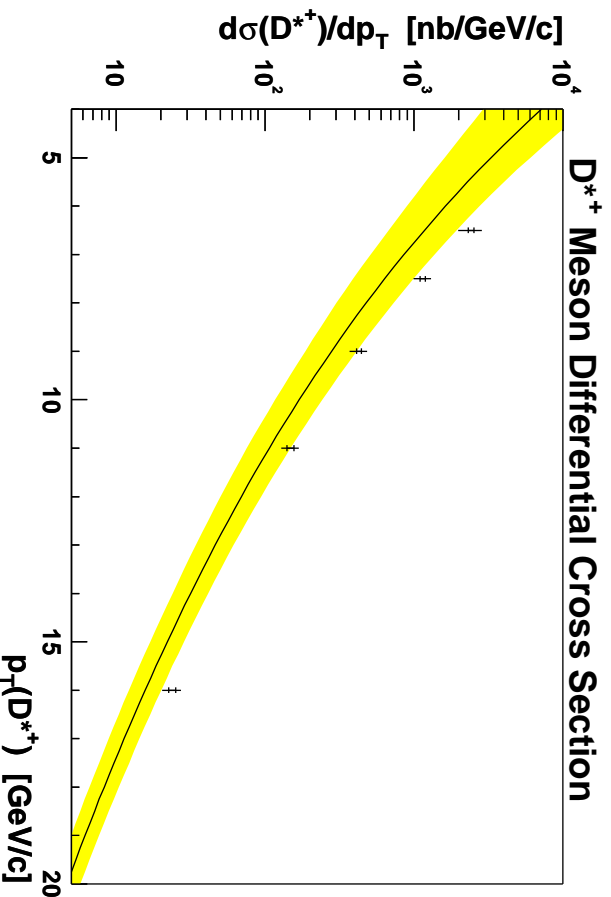


# CDF charm cross sections

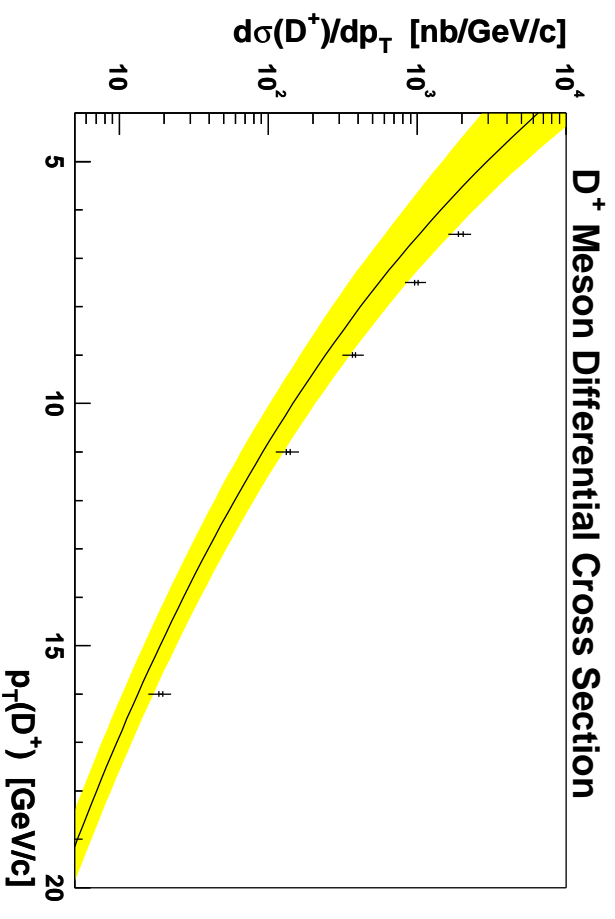
CDF Run II preliminary



CDF Run II preliminary



CDF Run II preliminary



**Comparison with FONLL QCD  
(Cacciari and Nason)**

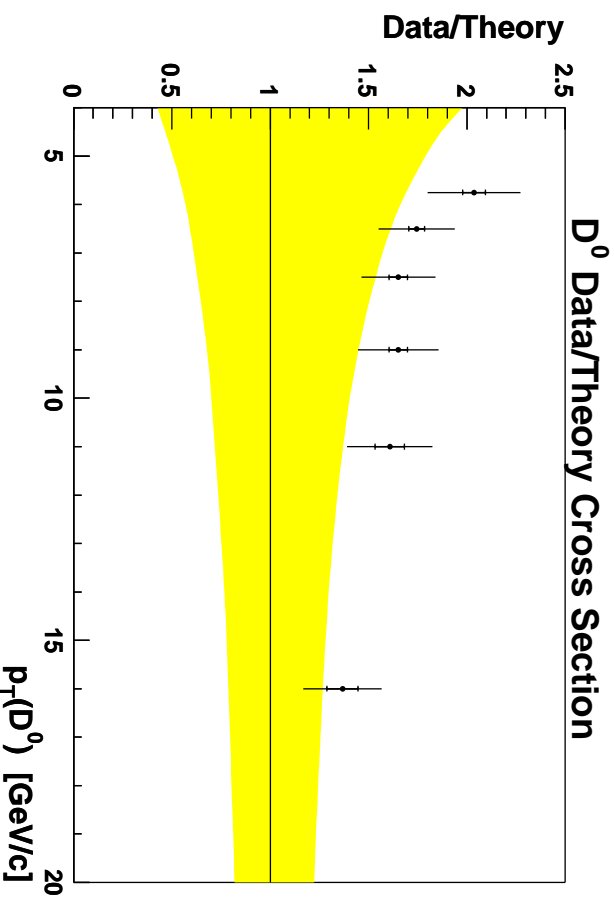
**Inputs: CTEQ6M,  $m_c = 1.5$  GeV,**

$$\mu = \sqrt{m_c^2 + p_T^2}$$

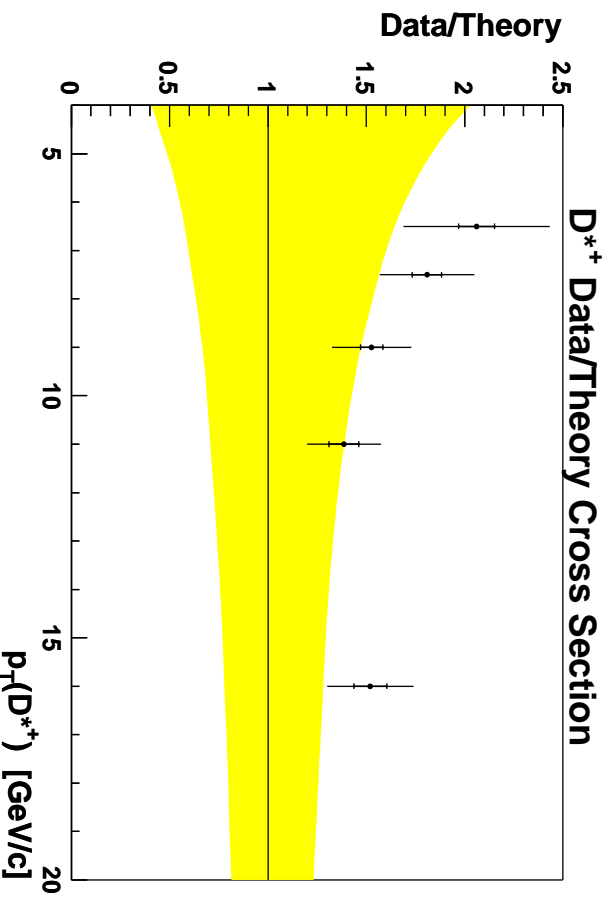
**Uncertainties in scale ( $m_c$ , PDF and fragmentation)**

# CDF charm cross sections

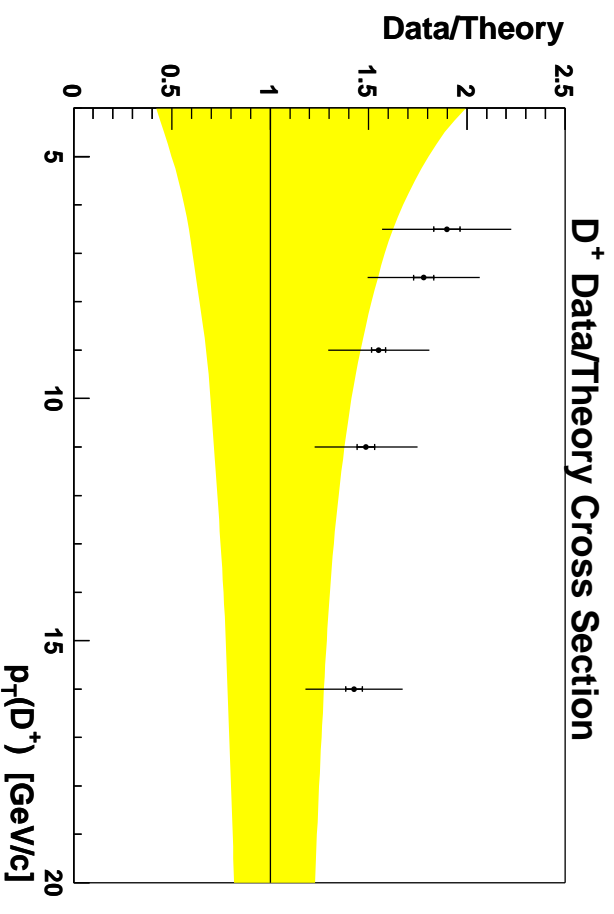
CDF Run II preliminary



CDF Run II preliminary



CDF Run II preliminary



**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 compatibility within uncertainties

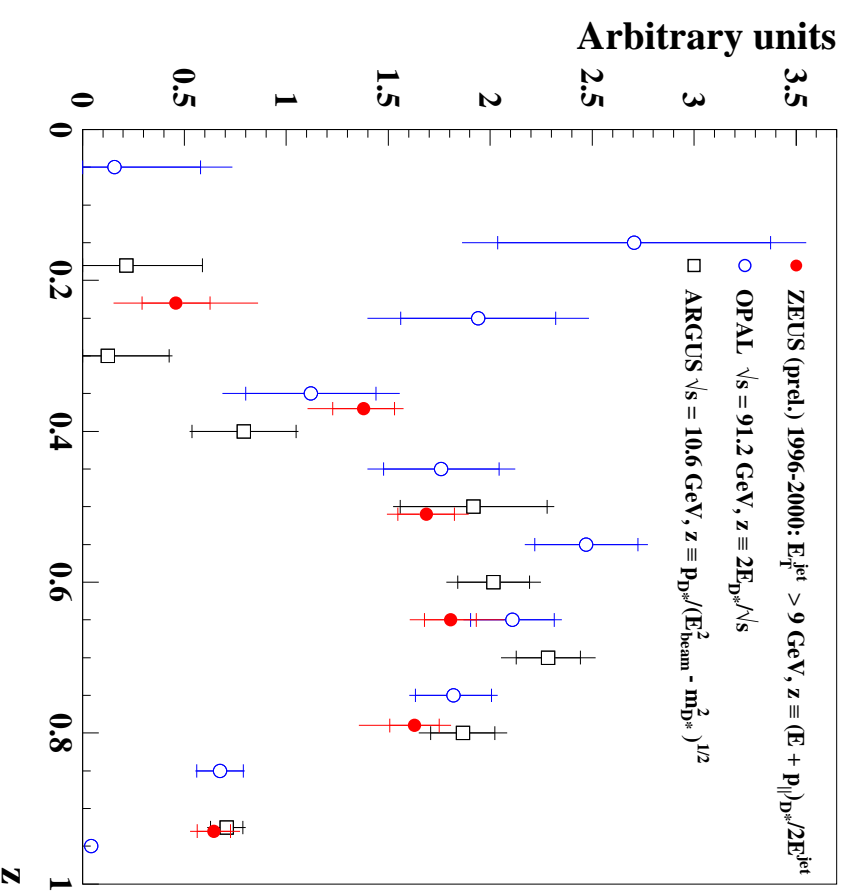
Still complicated convolution (PDF  $\times$  Hard scatter  $\times$  fragmentation)

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

## ZEUS

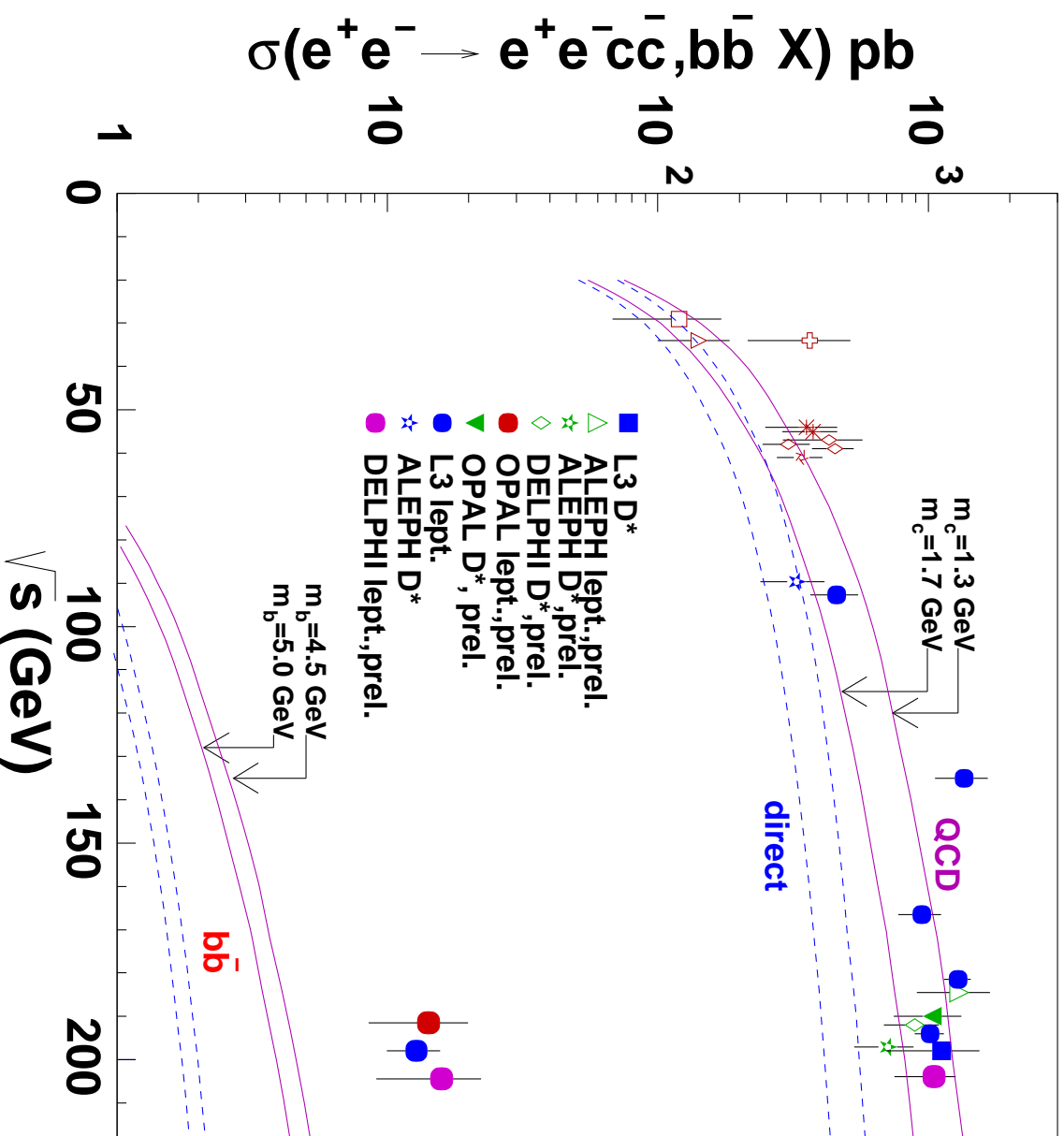
Independent ways of measuring fragmentation

Measurements insensitive to fragmentation (e.g. jets)



# **Open beauty measurements**

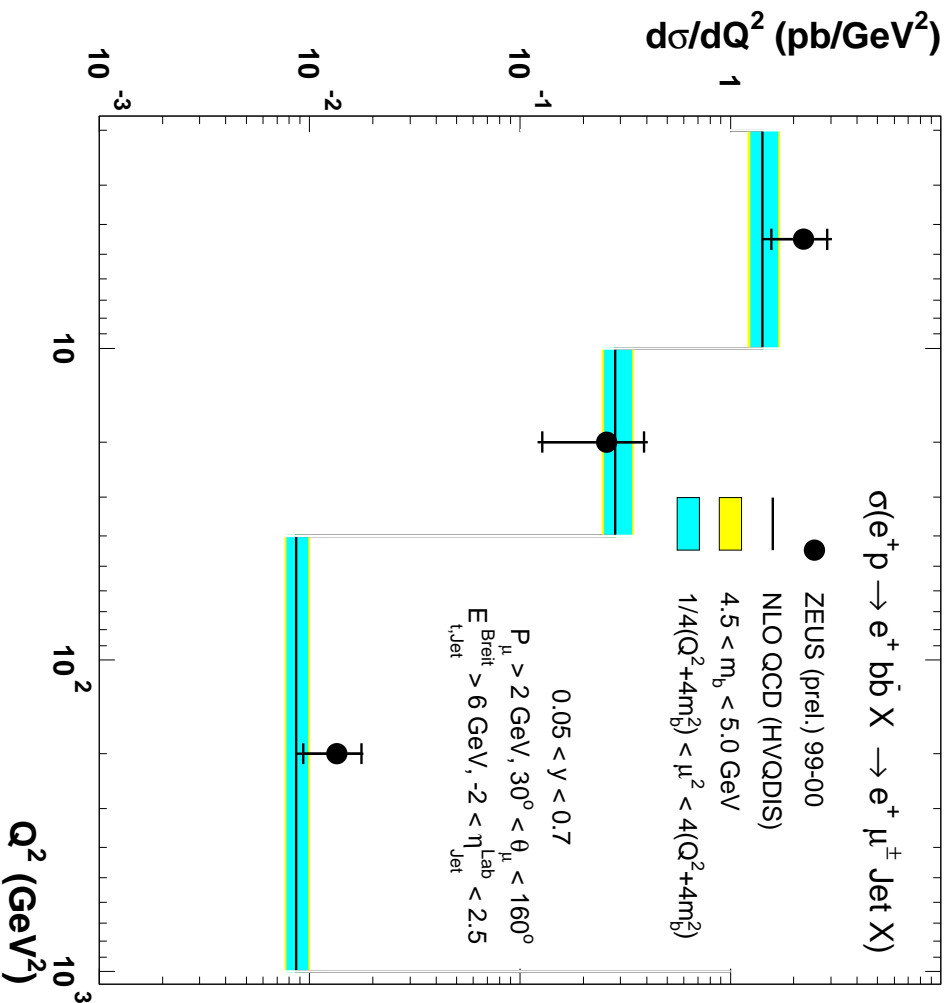
# Beauty in $\gamma\gamma$ collisions



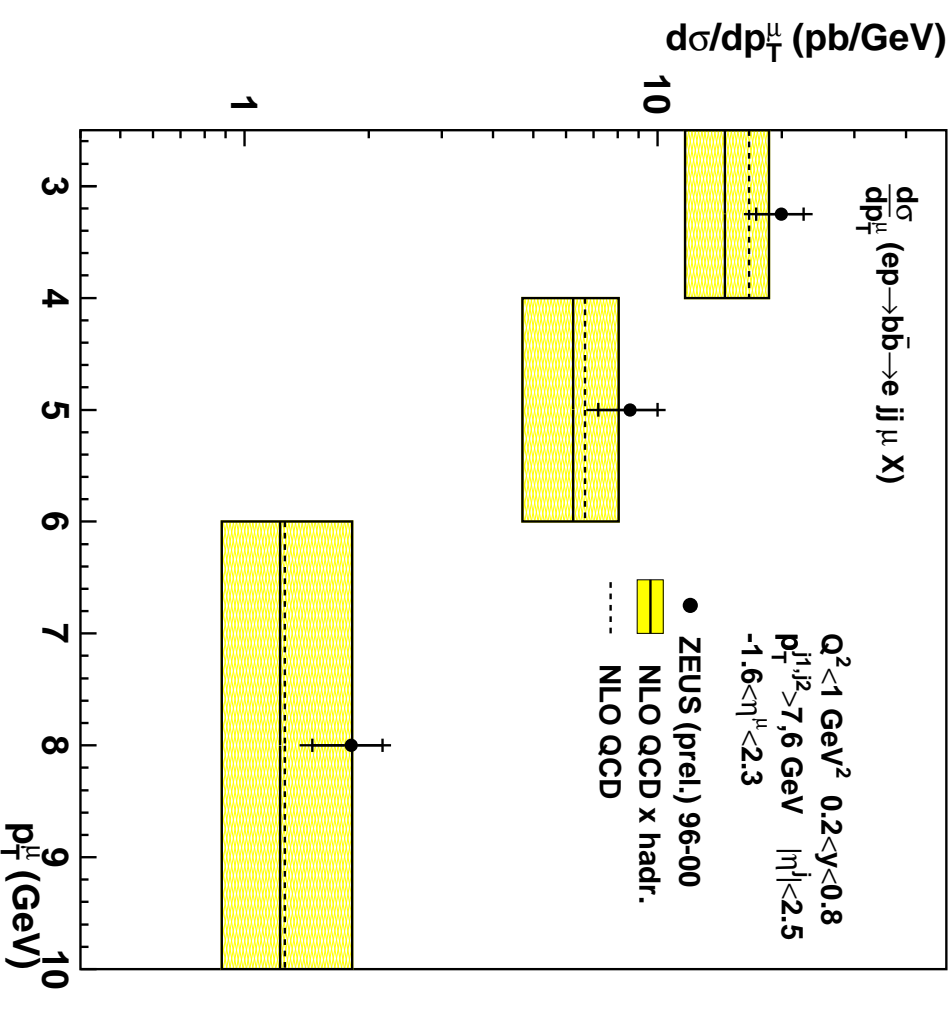
NLO significantly below the data  
 Data undergone large  
 extrapolation  
 Similar to old results from  
 TeVatron Run I

# Open beauty measurements at HERA

**ZEUS**



**ZEUS**

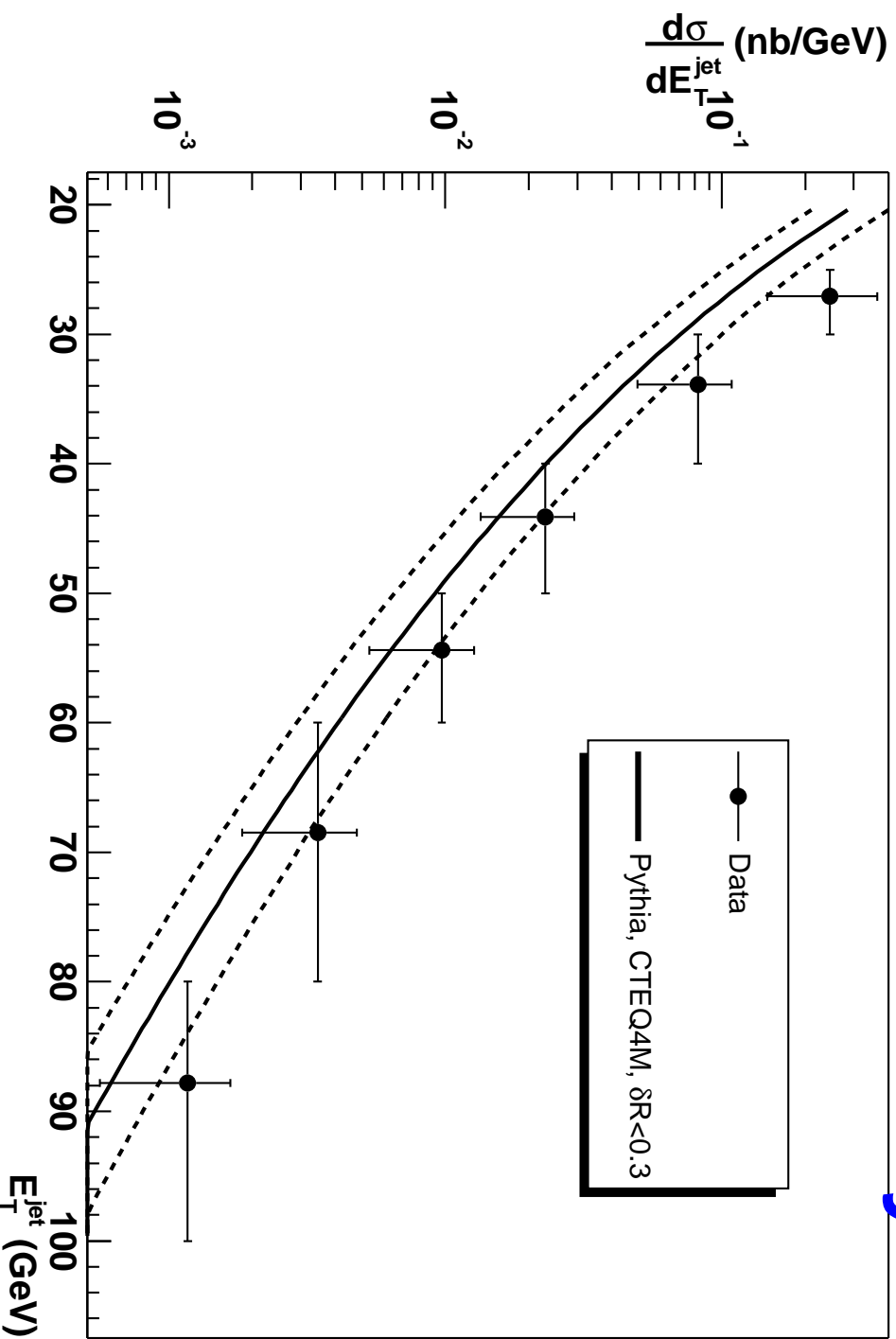


**Measurements in acceptance of detector**

**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

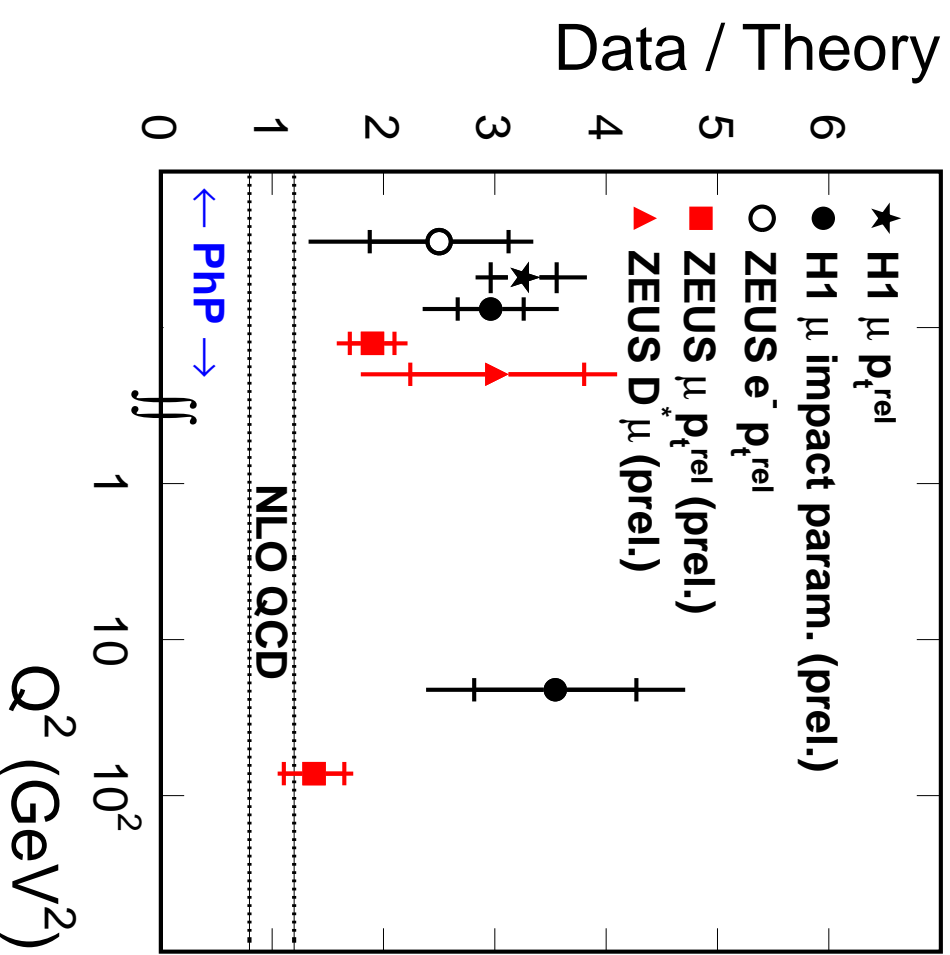
Situation not as clear as a few years ago

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

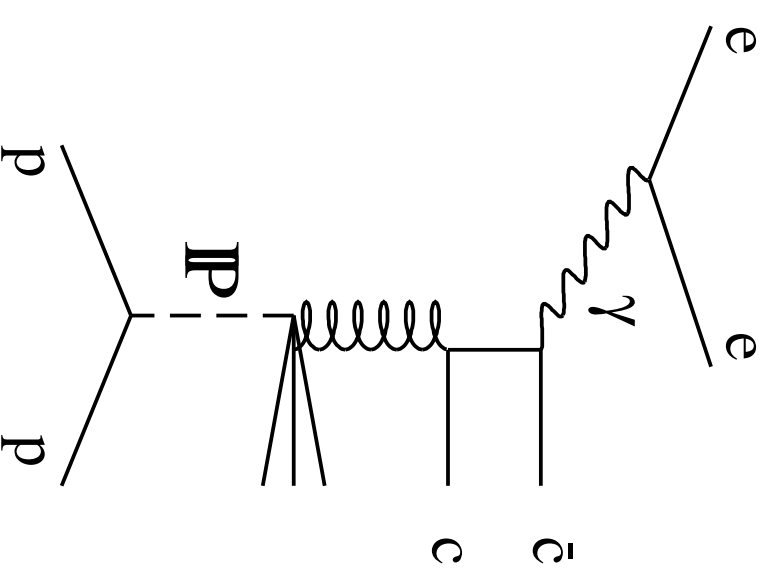
Diffractive processes contribute  $\sim 10\%$  to the total DIS cross section

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



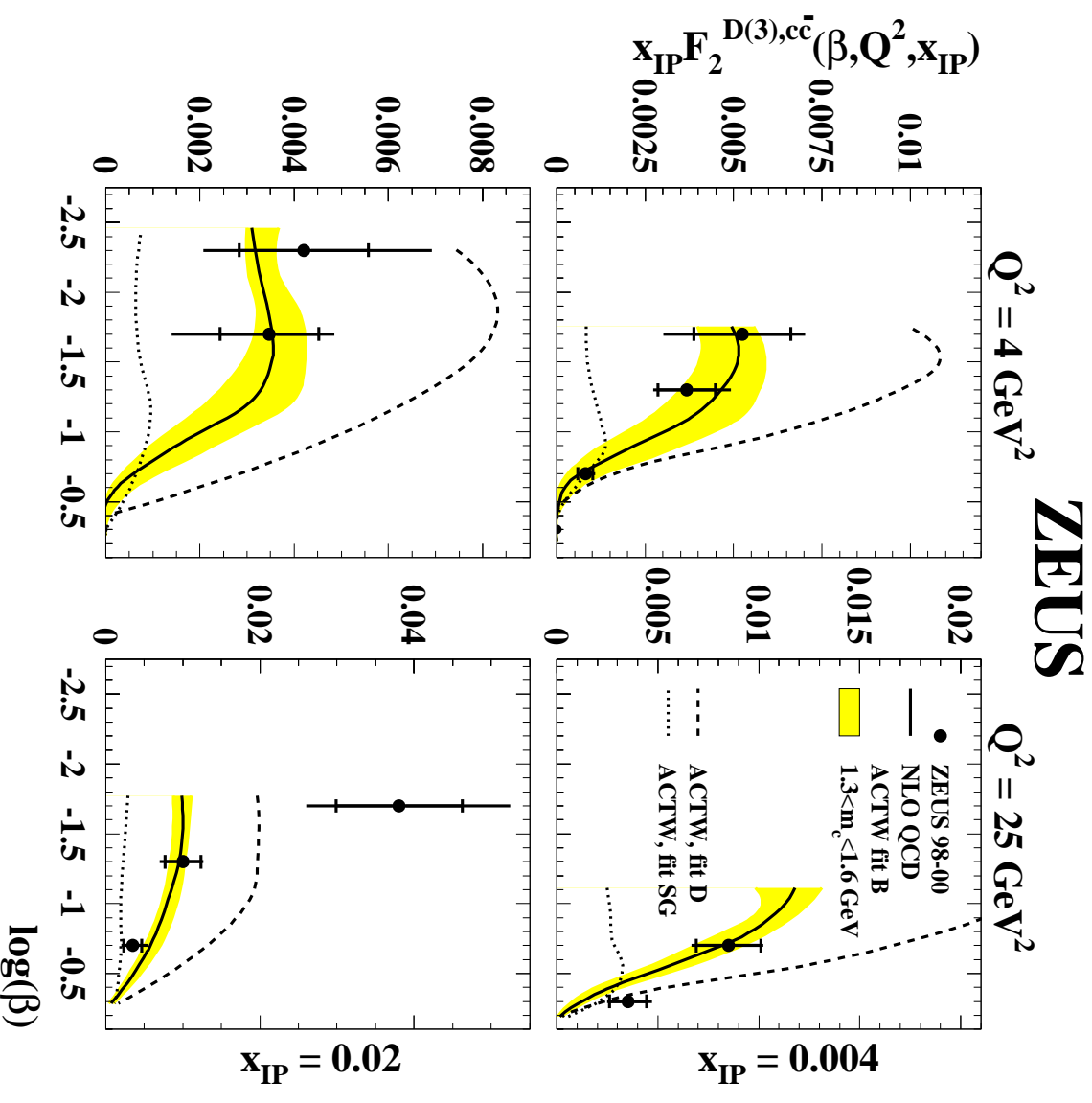
# Charm contribution to diffractive structure function

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?**