Heavy quark production at HERA and the LHC

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- Introduction, motivation and theory
- Measurements and description of beauty production
- Charm production and proton structure
- Universality of fragmentation
- Diffractive charm production
- Summary

Introduction and motivation

Why study heavy quarks?

New particles often decay to beauty (and charm) quarks

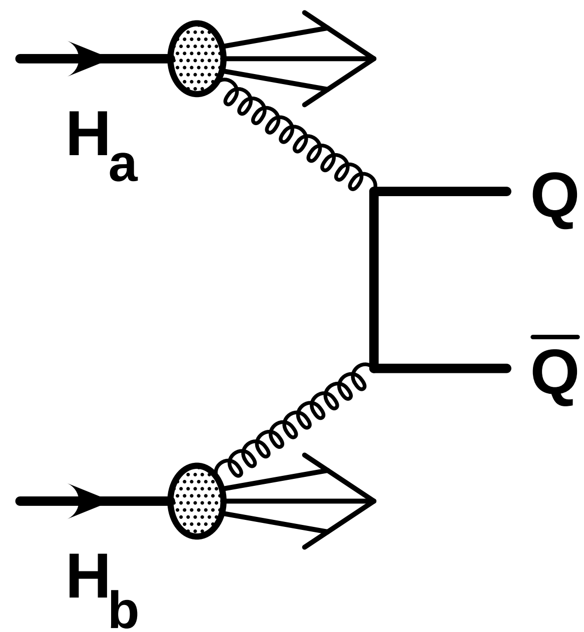
Make measurements of CP violation

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?

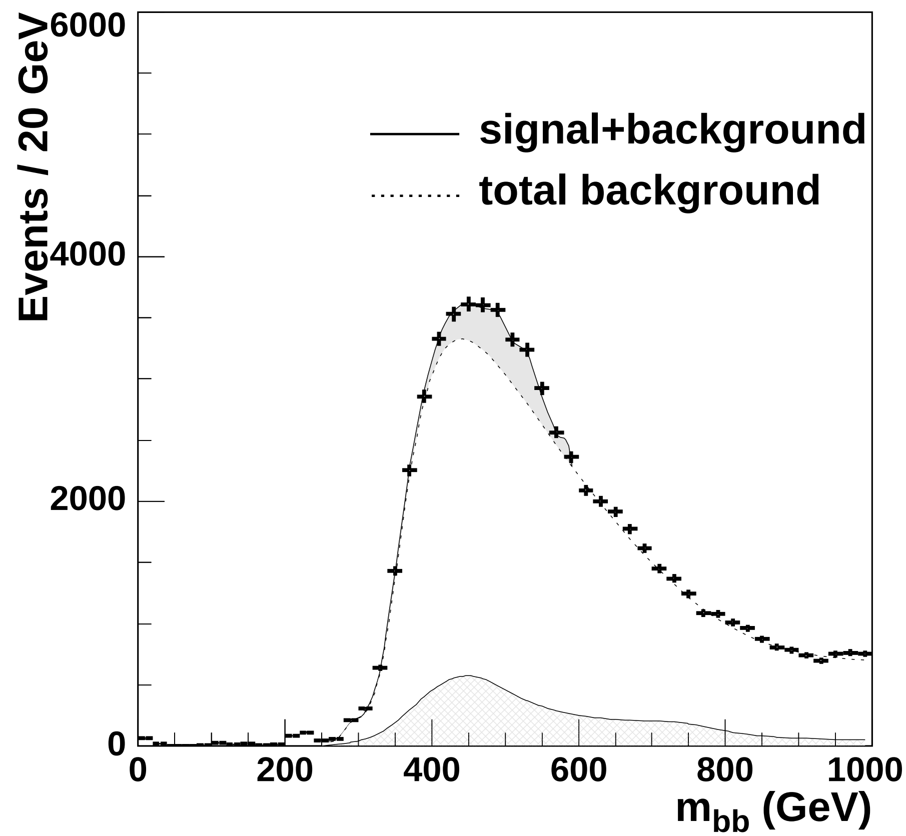
Example of why the heavy quark production rate needs to be understood (ATLAS TDR)

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,

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

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

Fixed-order (FO) scheme - $p_T^2 \sim m^2$, no heavy quarks in hadron ($gg \rightarrow Q\bar{Q}$)

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

FONLL scheme which matches the two

Theoretical calculations

Fixed order:

- **Frixione et al. (FMNR) used for charm and beauty in photoproduction.**
- **Harris and Smith (HVQDIS) used for charm and beauty in deep inelastic scattering.**

Next-to-leading log:

- **Cacciari et al. and Kniehl et al. used for charm and beauty in photoproduction. NB. only inclusive production, cannot do e.g. dijets**
- **No program for deep inelastic scattering.**

Combined, FONLL (Cacciari et al.), used for charm in photoproduction.

New program, MC@NLO (Frixione and Webber), which is the fixed-order program with parton showers and hadronisation from HERWIG - not available for HERA.

Fragmentation of heavy quarks

Sprays of hadrons and leptons are measured in the detector

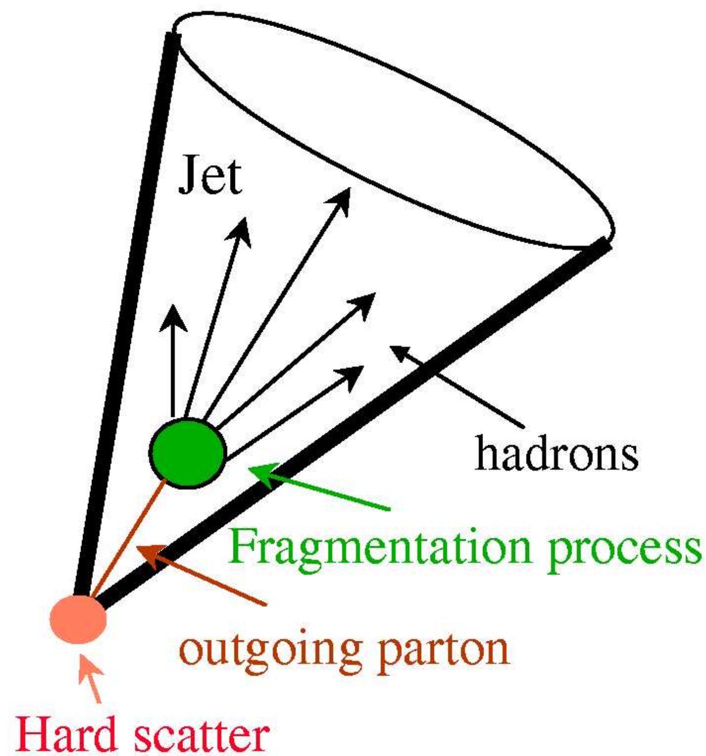
Tag B/D mesons ($D^* \to K\pi\pi_s$) and $Q \to \mu, e$

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

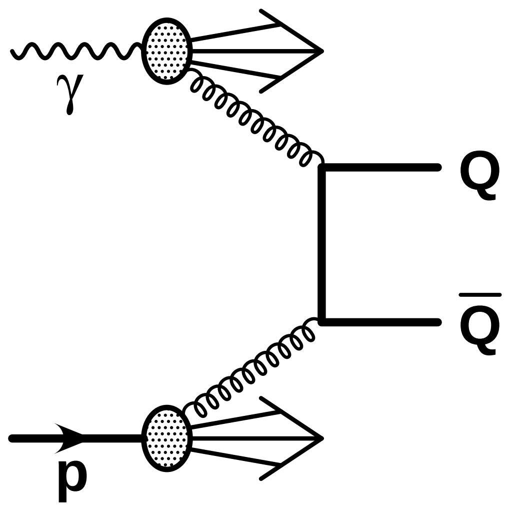


Are the models and current parametrisations correct?

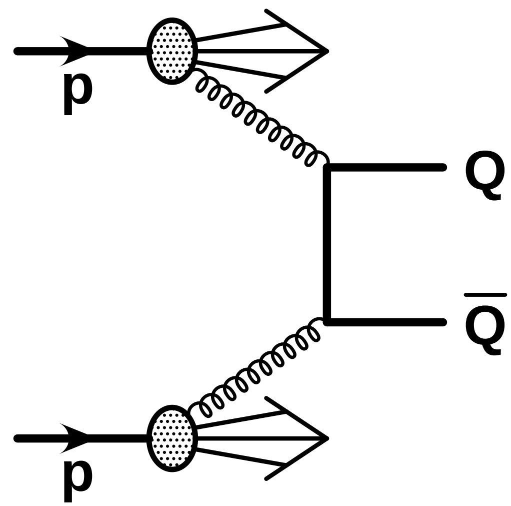
- Measure the fragmentation function
- Make measurements where the effects are reduced; jets, high energy

Generic nature of production

HERA



Tevatron/LHC



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.

What can HERA provide and the LHC want to know?

General state of description (by MC, NLO) of heavy quark production processes:

- **where the heavy quark is produced in the hard scatter**
- **no direct information on gluon splitting**

Information on the proton PDFs:

- **gluon content information is good**
- **heavy quark content is for the future**

Details of the fragmentation in a hadronic environment; fragmentation functions, fractions, etc..

No information yet on mulitparton interactions in heavy quark processes.

Can provide information on topology of events and jets useful for designing algorithms/triggers.

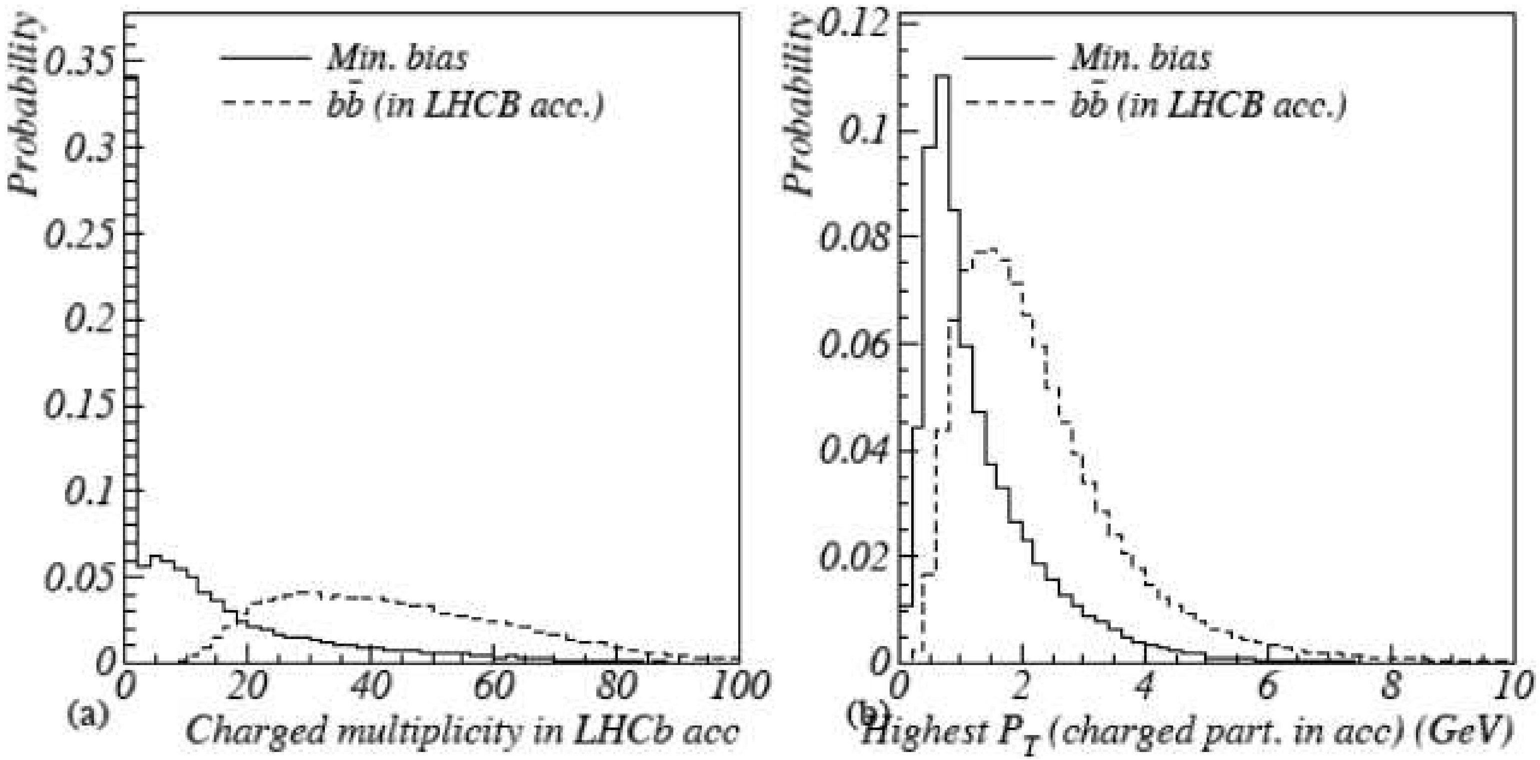
Heavy quarks at LHCb

N. Tuning, H. Dijkstra, N. Brook

Minimum bias cross section much larger than $b\bar{b}$.

Minimum bias and $b\bar{b}$ events have different topologies.

Can cut on event properties to achieve a pure sample.



Reliant on accurate simulation; improving MCs for both minimum bias and $b\bar{b}$ important.

Heavy quarks at LHCb

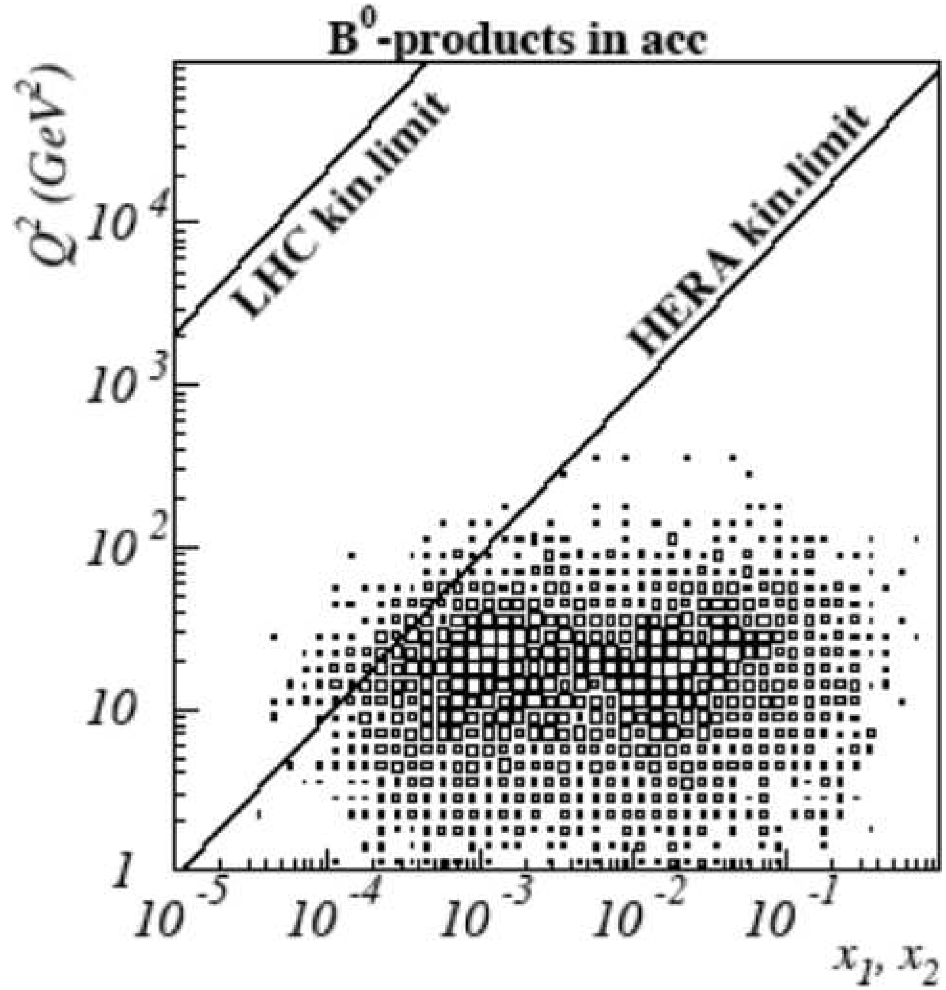
B^0-products in acceptance of LHCb detector.

Kinematic range covered by HERA.

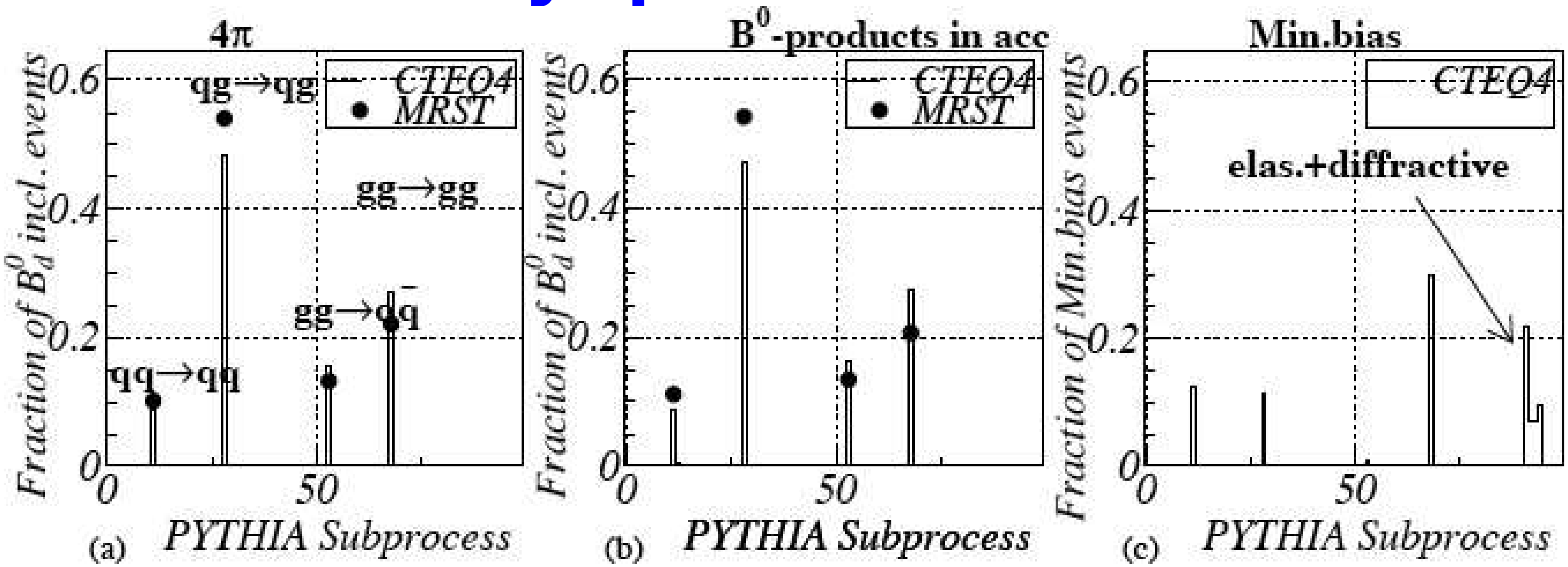
In principle, HERA measurements will constrain PDFs in the range of LHCb measurements.

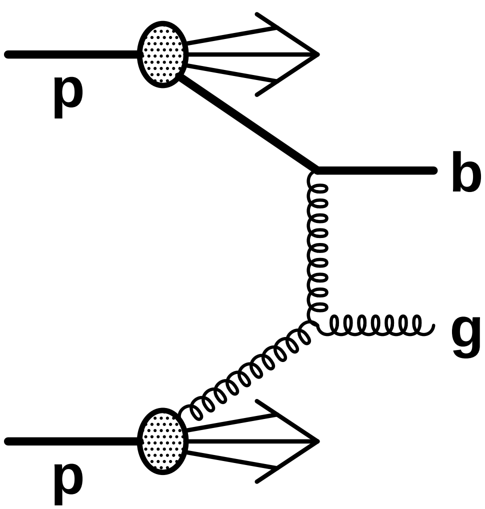
Uncertainties will increase outside the HERA kinematic region.

Type of process involved?



Heavy quarks at LHCb





Dominance of b quark from the proton. Do not have direct constraints from HERA.

But this is model dependent, i.e. using PYTHIA.

At NLO some of this will summed in to the gluon distribution of the proton.

Should measure directly all flavours in the proton at HERA.

However, PYTHIA should be a realistic simulation of the final state for trigger optimisation, etc.. Also b-correlations and production asymmetry.

Measurement of open beauty production

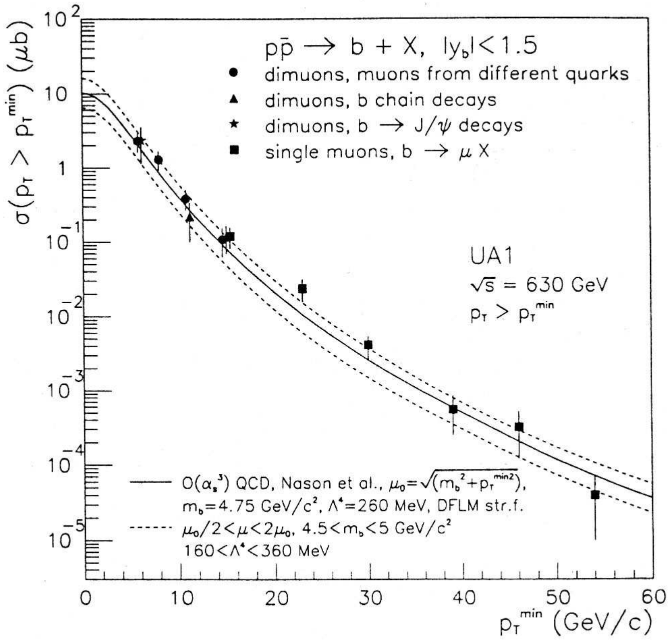
Beauty production at the Tevatron Run I

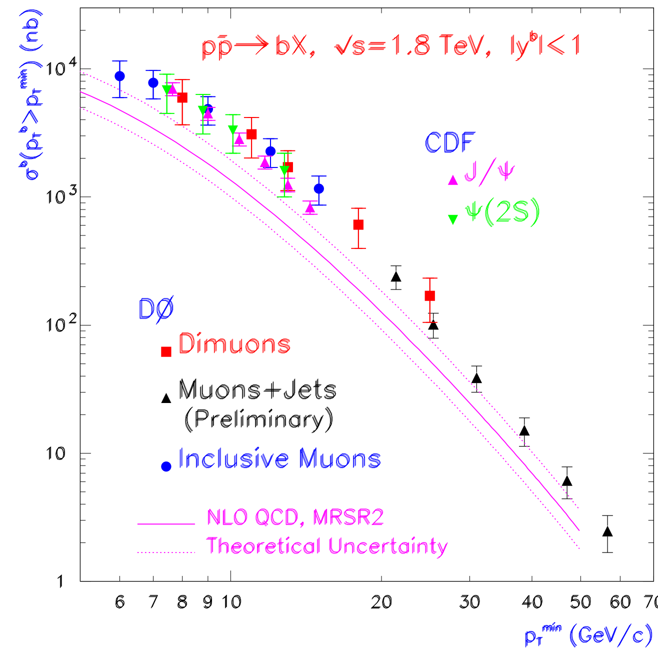
Significant disagreement with QCD

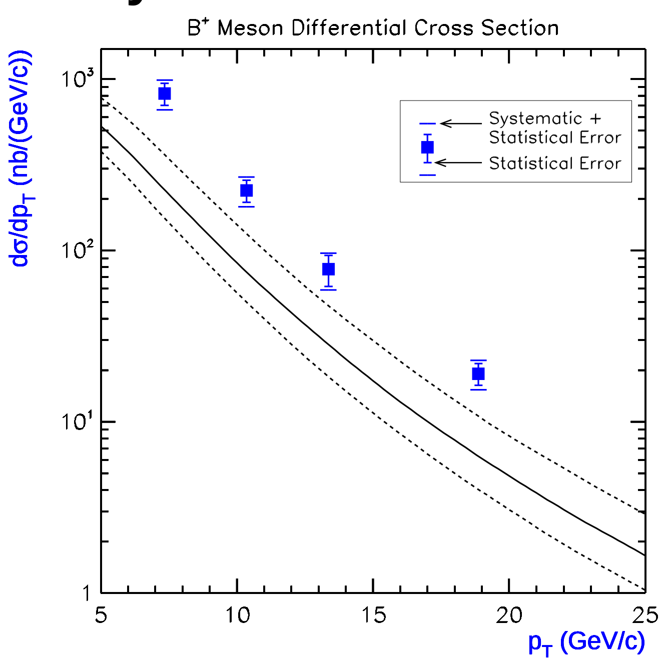
Extrapolation to the the b quark level →

Measurement of B mesons gives more reliable results

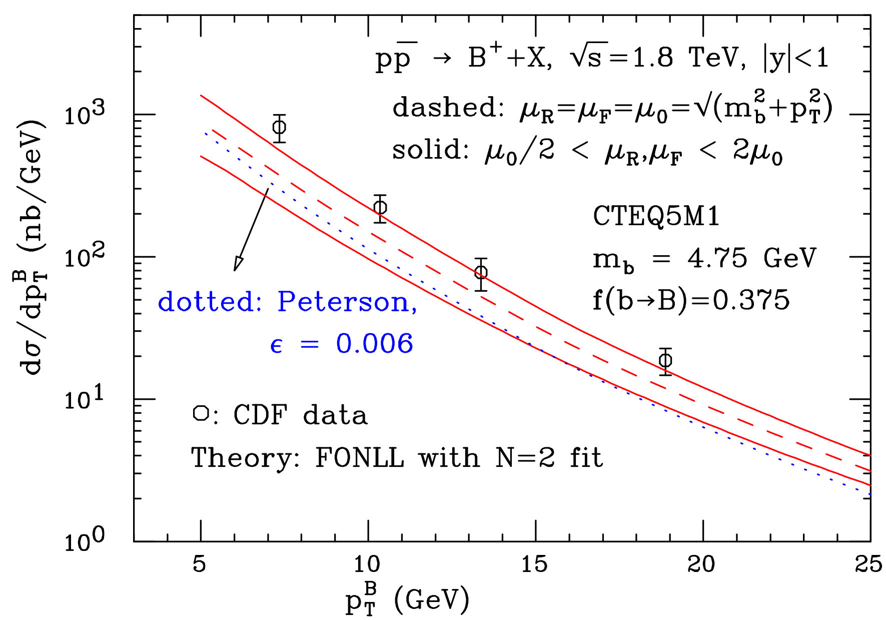
Led to improvement in theory







Fragmentation → in theory → tuned to data

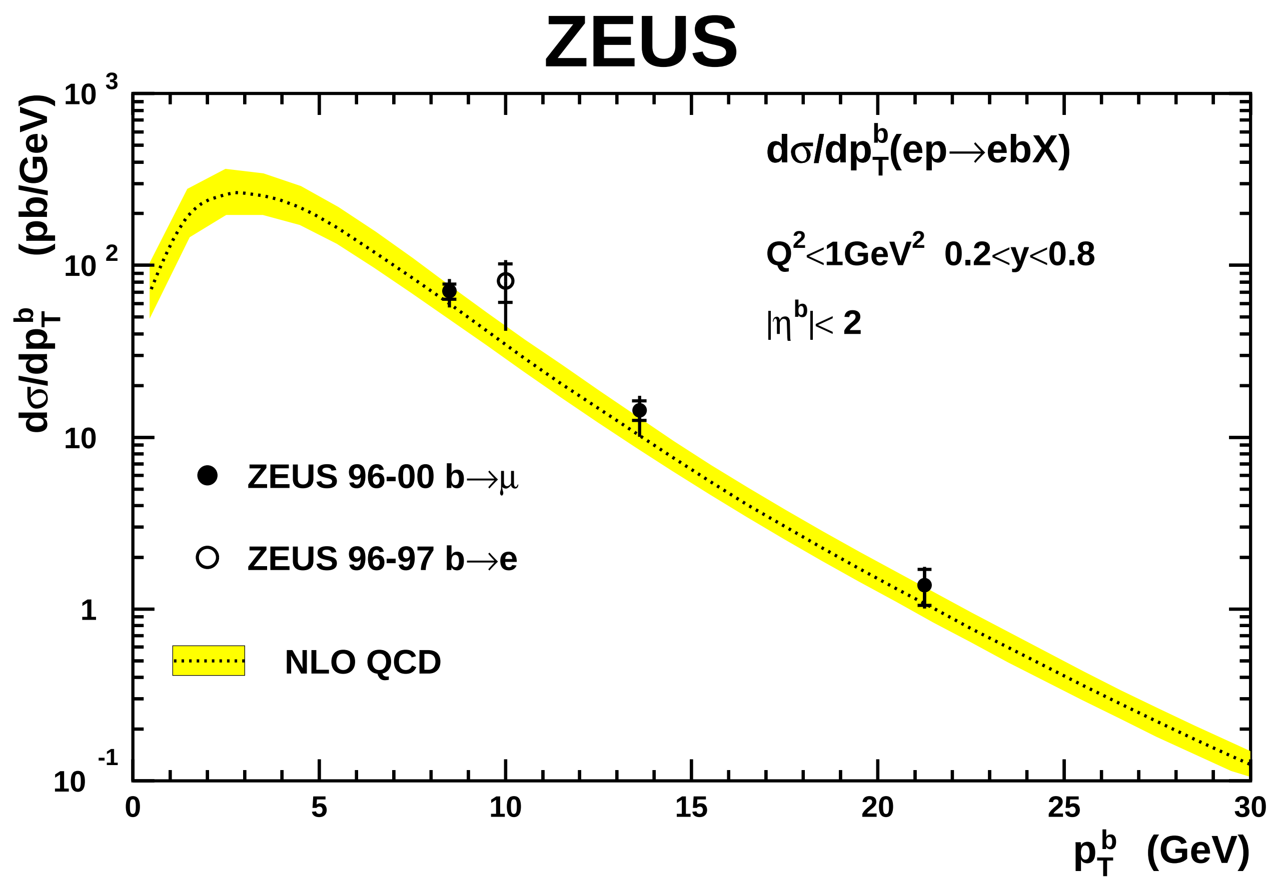


Open beauty measurements in PHP at HERA

Again, measurements in acceptance of detector.

Thorough extrapolation done, above a certain p_T, with a theory that describes the data.

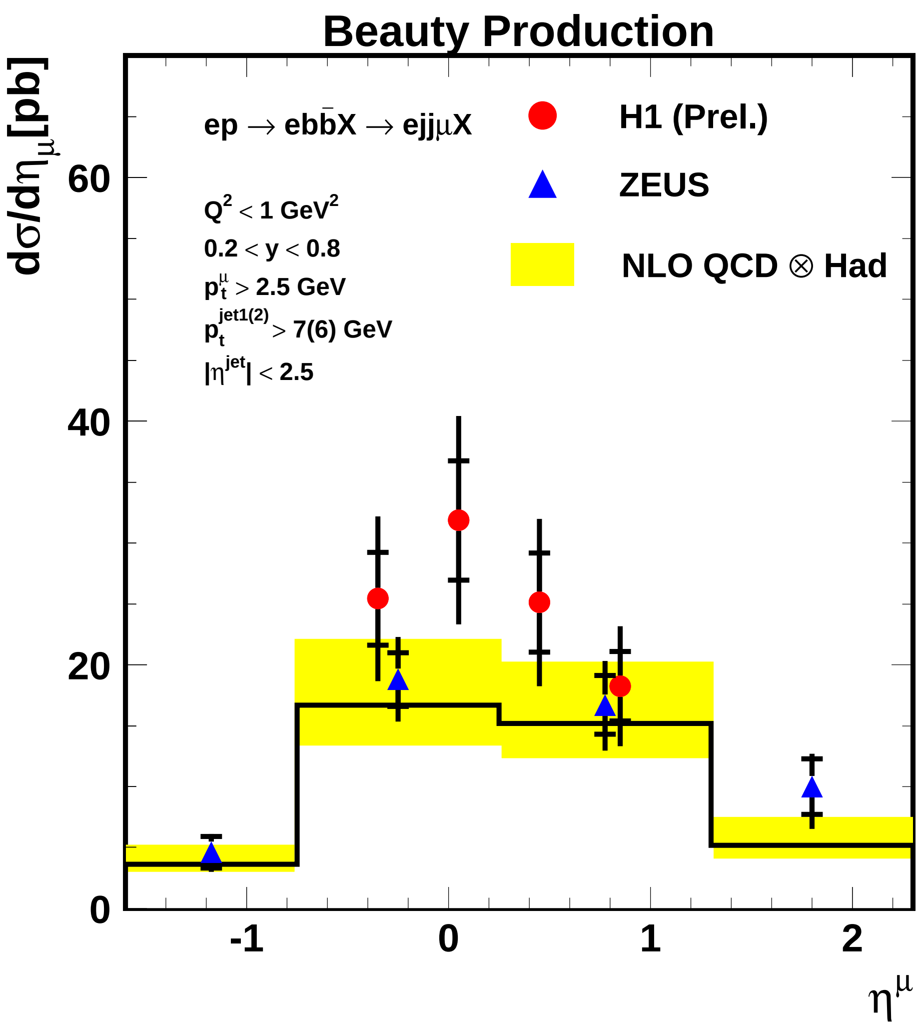
NLO QCD describes the data well.

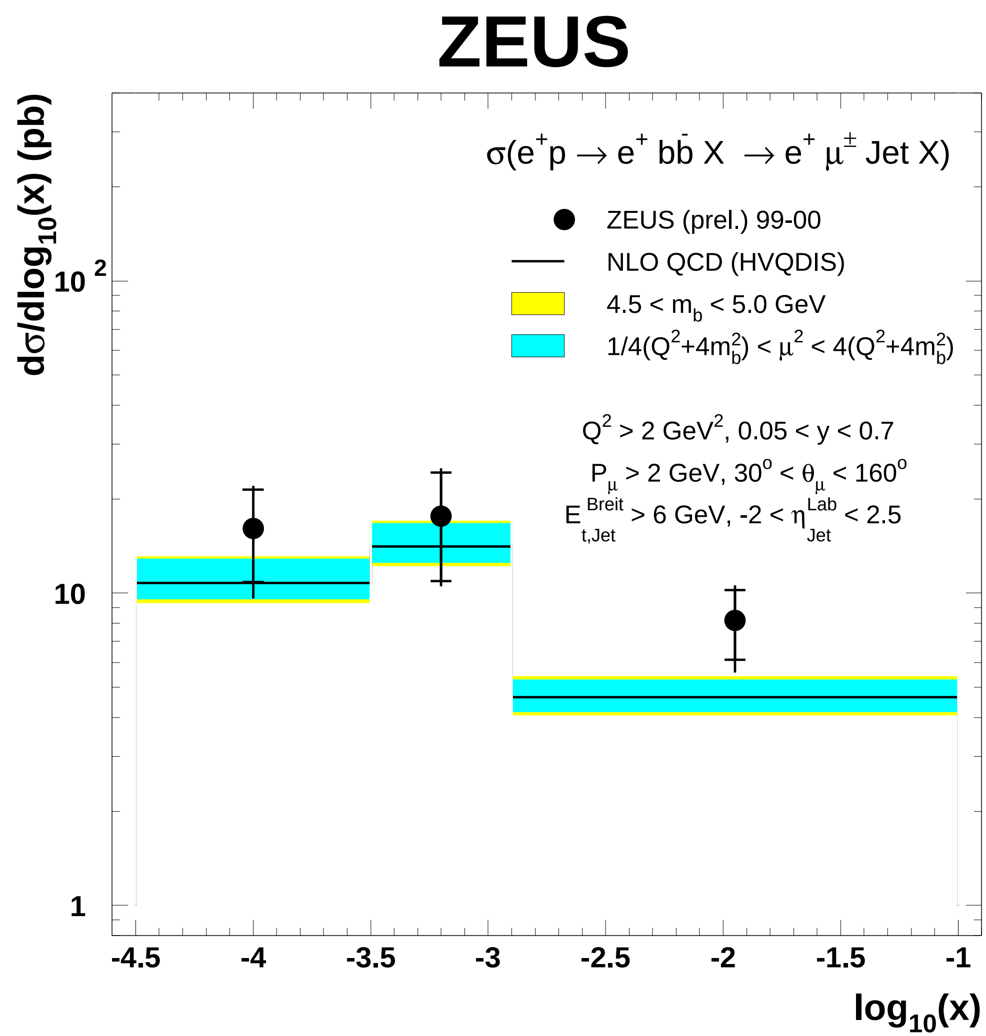


First really good description of b production for a long time.

Now QCD seems to be in a good state.

Open beauty measurements at HERA





Measurements in acceptance of detector

Data from both experiments agrees okay; NLO QCD describes the data reasonably well...

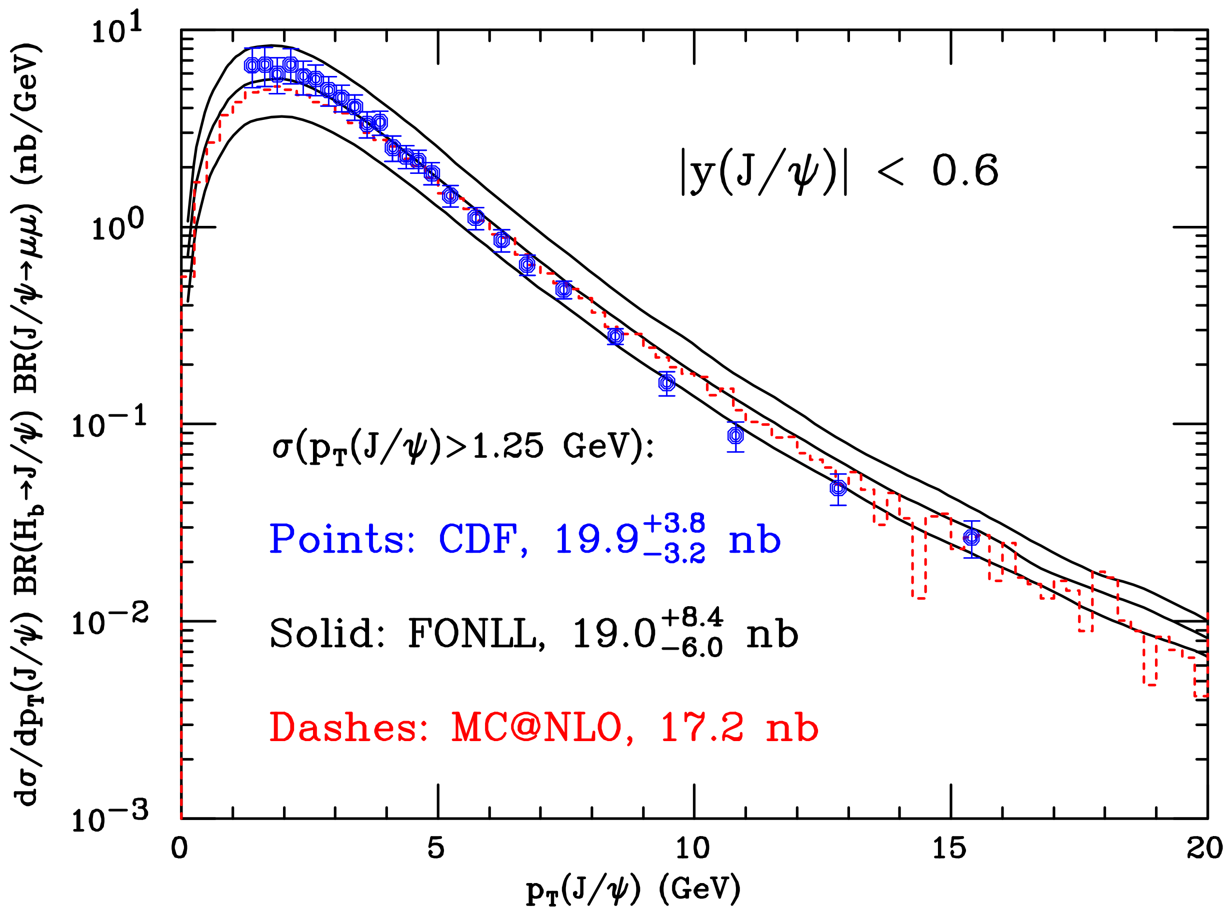
New TeVatron beauty measurement

Run II preliminary data compared with latest theory.
Data go to very low p_T. Valuable to have inclusive measurements.

Improved theory, FONLL and MC@NLO, describe the data well.

Consistency with previous TeVatron results?

Clearly defined measured cross section



Predictions of FONLL and MC@NLO at HERA would useful.

Beauty discussion

Situation is developing rapidly and conclusions changing, but converging

Many different kinematic regions measured and assumptions made

Significant work on fragmentation issues

Data are starting to be described by NLO QCD, but issues remain

Should treat any extrapolation with caution; large extrapolation factors, into unmeasured regions, uncertainties considered...

More data is needed and is coming...

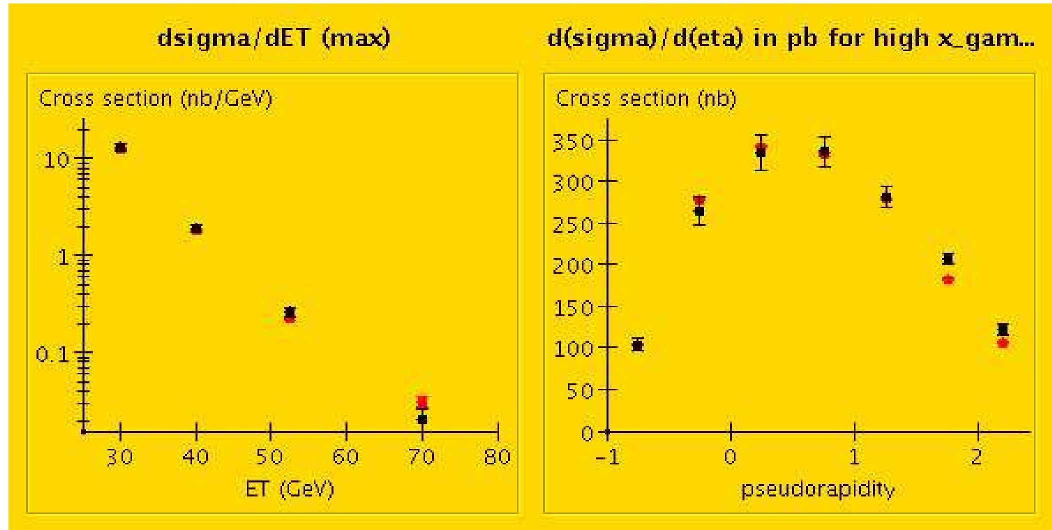
More calculations needed and improved phenomenological understanding

Global fits to all data would be useful for checking consistency

Need programs which can describe all reactions e.g MC@NLO should be able to calculate all cross sections

Consistency of all data?

JetWeb project: WWW interface database for MC tuning using HZTool.



Can use current data and fit MCs to get best possible description

Use HERA, LEP, Tevatron, UA1,... data spanning as much phase space as possible

Tune parameters in MC: PDF, underlying event, proton and photon radius,...

Use general-purpose MCs: PYTHIA and HERWIG.

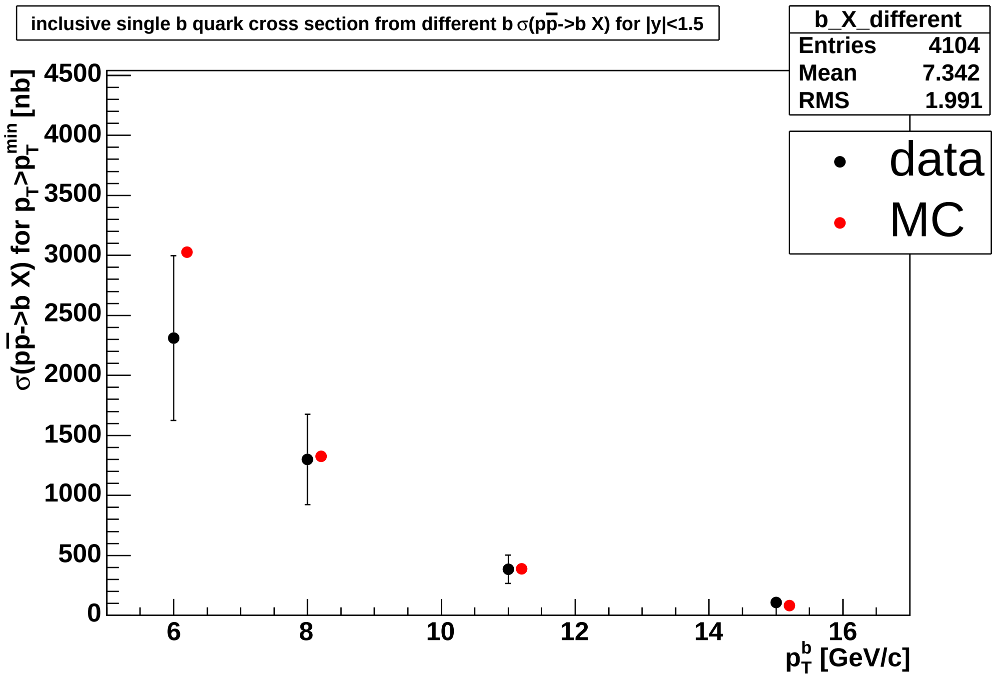
Normalisation from high-precision HERA jet data.

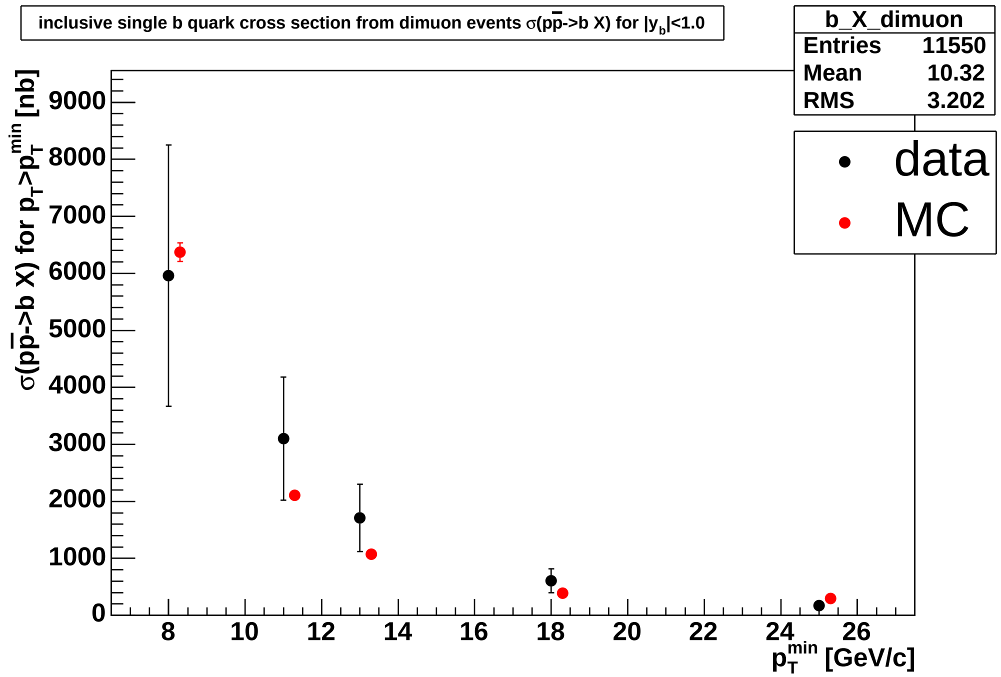
Can use parameters and predict for a future collider

J.M. Butterworth, S. Butterworth, "JetWeb: A WWW Interface and Database for Monte Carlo Tuning and Validation" hep-ph/0210404, http://jetweb.hep.ucl.ac.uk/

Comparison with hadron colliders

O.Gutsche, J. Butterworth, A. Geiser, B. Waugh



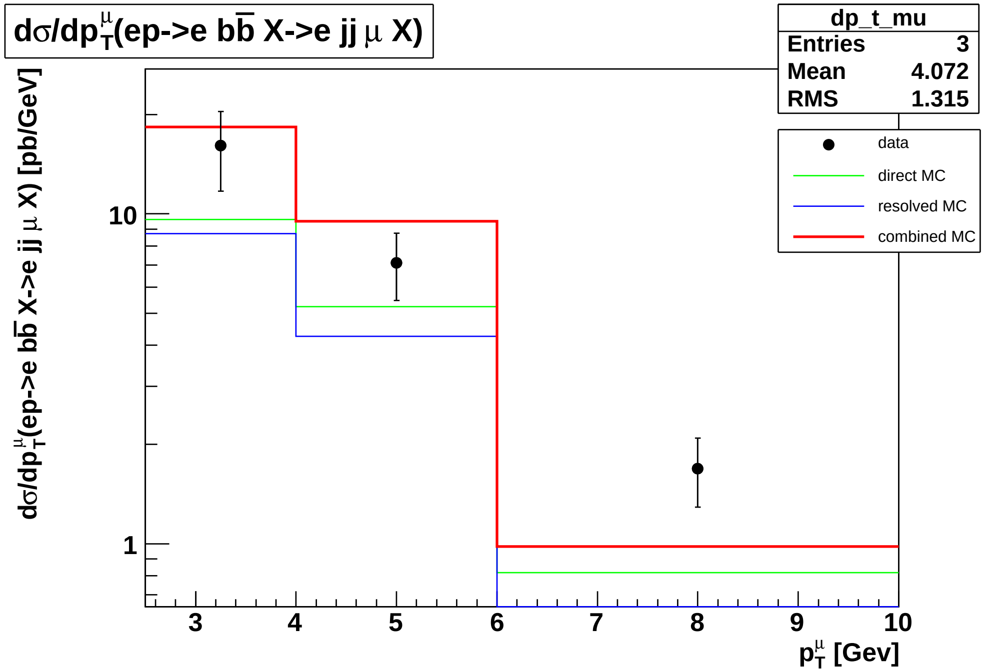


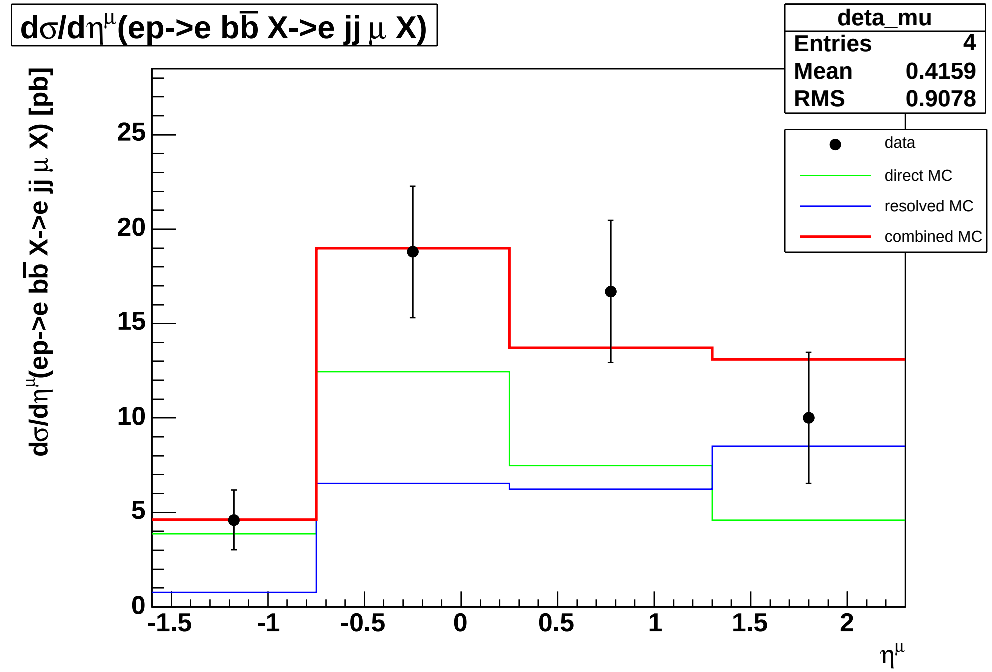
Good description of UA1 (630 GeV) and D0 (1800 GeV) data using same model.

Good MC model to use for LHC predictions: normalisation is good, complete final state.

Need to compare to all hadron-hadron data; being built up.

Comparison with HERA





Good description of HERA data.

Shows the value of general-purpose calculations.

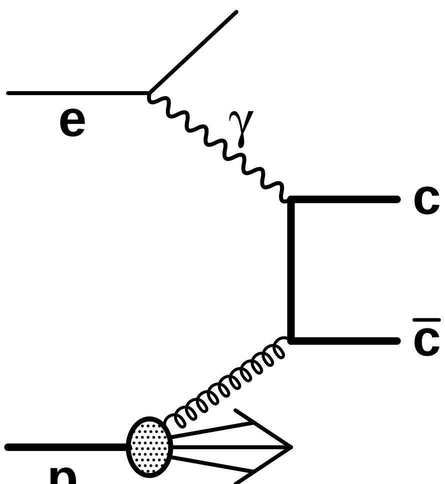
Have shown examples of where the procedure works. Not perfect description of all variables (yet).

But the best model so far?

Open charm production and proton structure

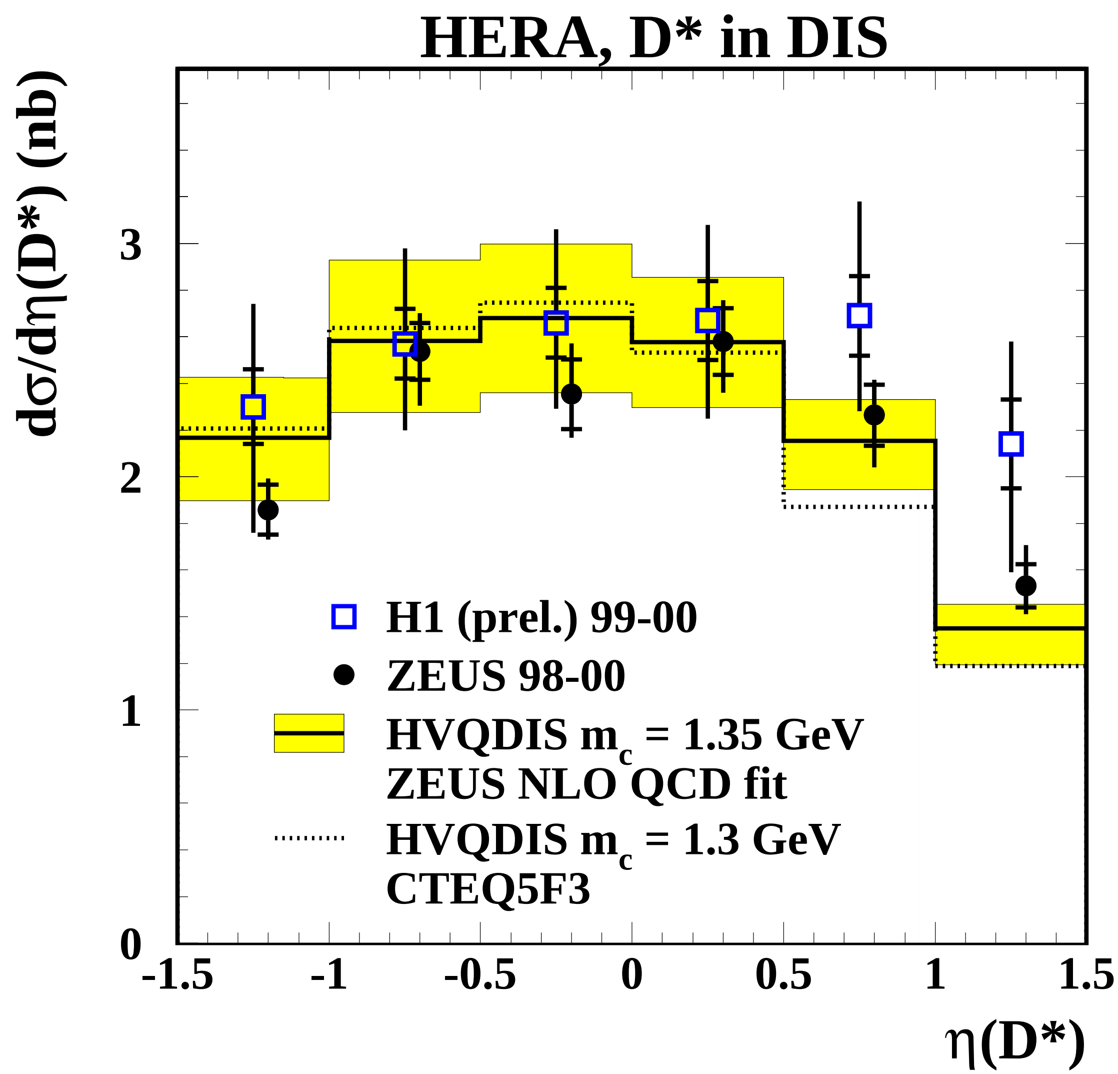
Charm in deep inelastic scattering at HERA

Measurement a convolution of PDF $\otimes$ ME $\otimes$ FRAG, but photon is probe of proton structure



NLO (HVQDIS) prediction gives reasonable description of the data

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



Proton structure

$$\frac{d^2\sigma^{c\bar{c}}\left(x,Q^2\right)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left\{\left[1+(1-y)^2\right]F_2^{c\bar{c}}\left(x,Q^2\right) - y^2F_L^{c\bar{c}}\left(x,Q^2\right)\right\}$$

Extraction of (extrapolation to) $F_2^{c\bar{c}}$ performed by:

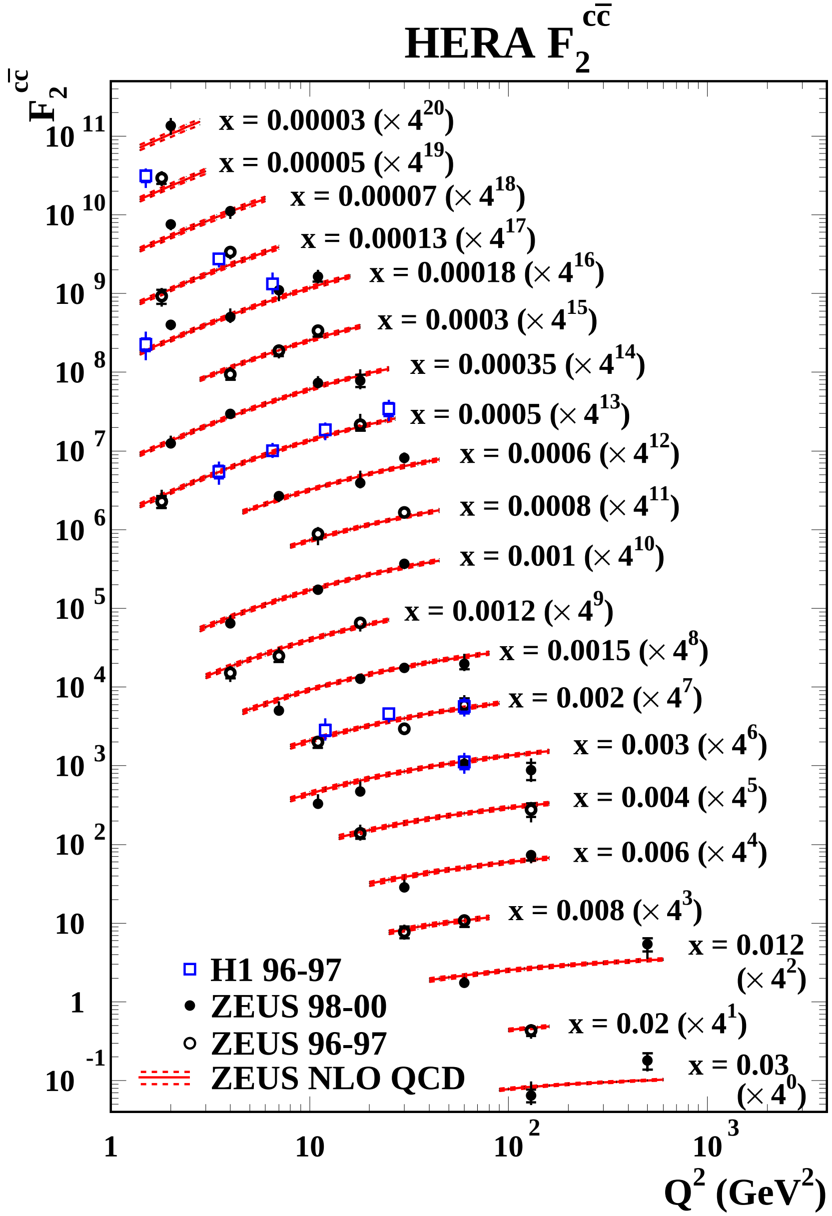
$$F_{2,\text{meas}}^{c\bar{c}}(x_i,Q_i^2) = \frac{\sigma_{i,\text{meas}}(ep \to D^*X)}{\sigma_{i,\text{theo}}(ep \to D^*X)}F_{2,\text{theo}}^{c\bar{c}}(x_i,Q_i^2)$$

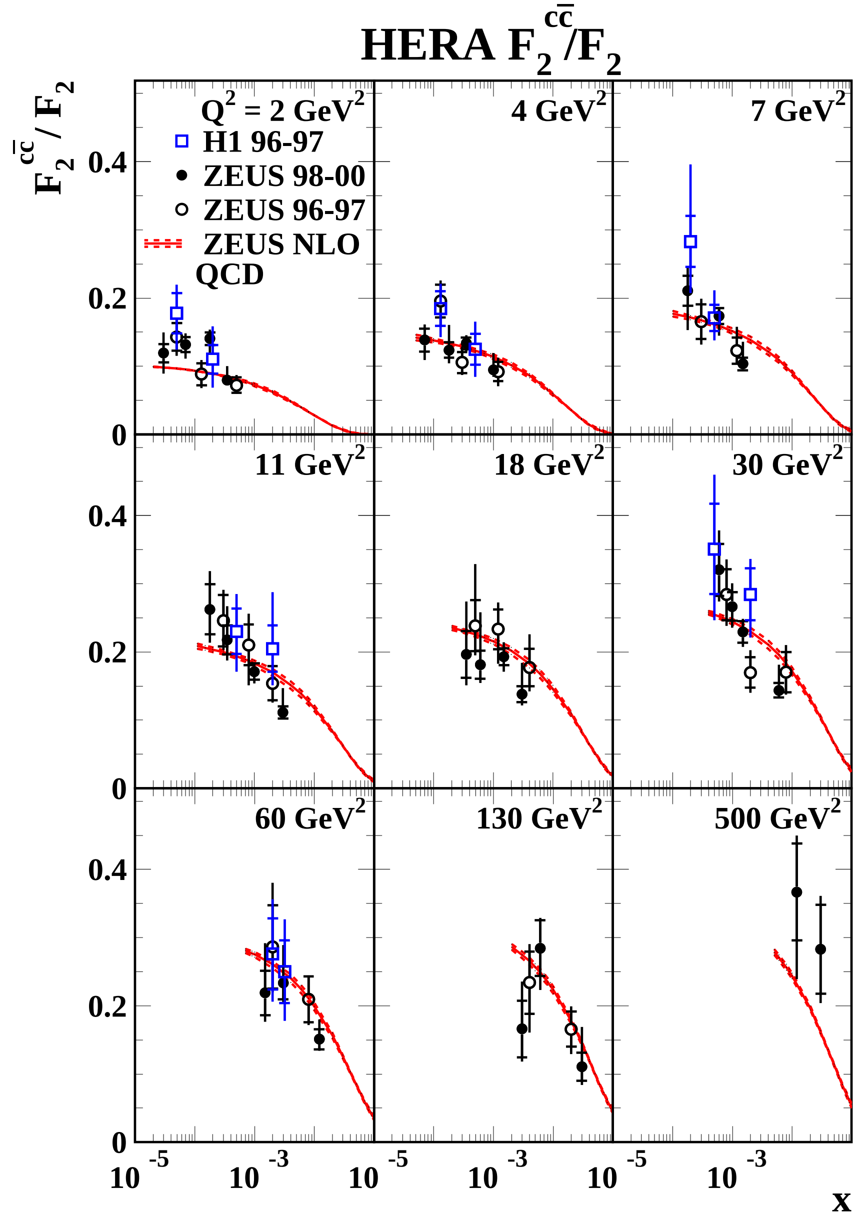
Extraction of $F_2^{c\bar{c}}\left(x,Q^2\right)$ is dependent on the scheme.

Only available NLO calculation is massive calculation, HVQDIS, i.e. active partons in the proton are gluon and light quarks.

Extrapolation involved; need to improve using a larger phase space.

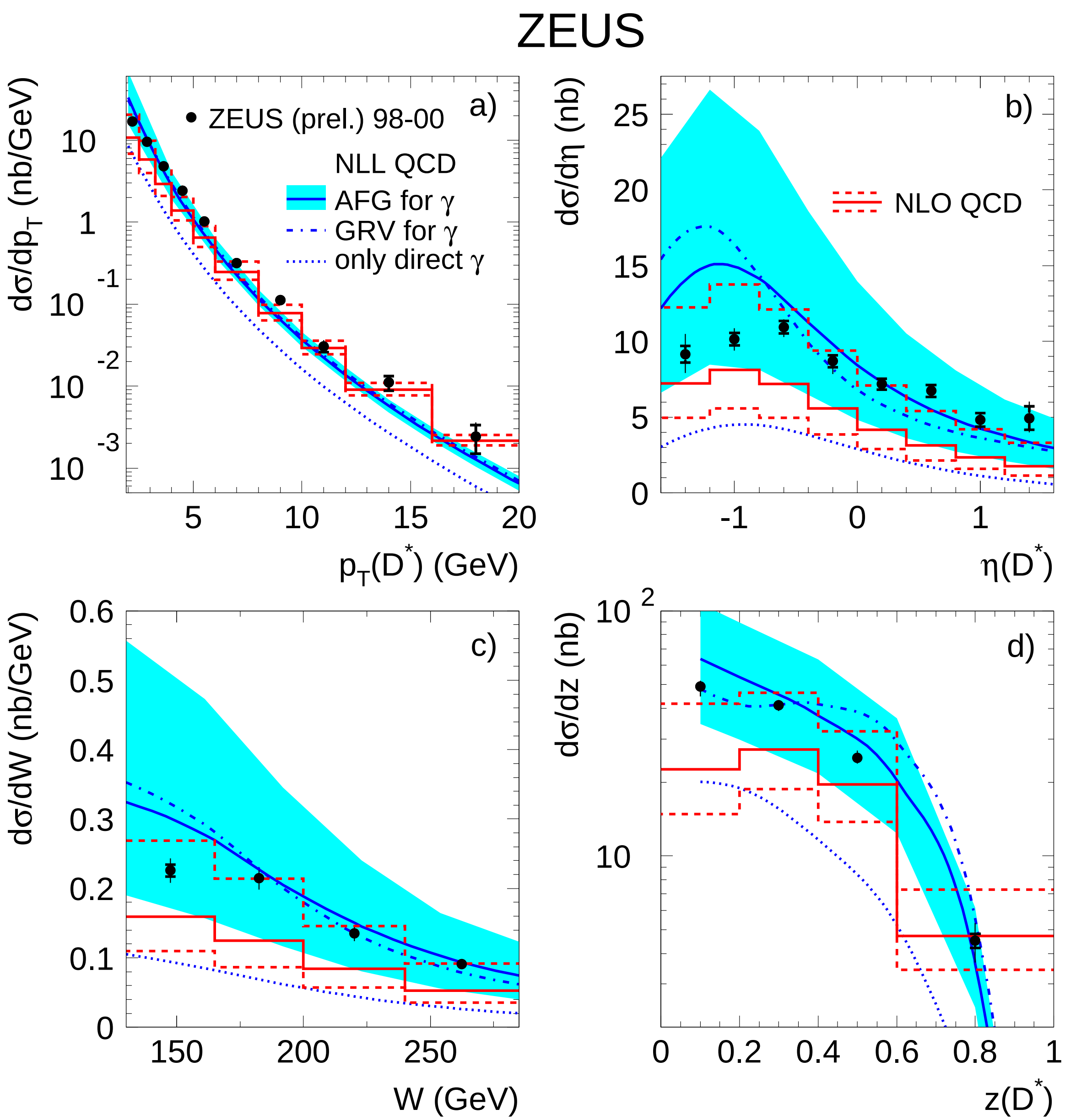
Charm contribution to the proton structure function





Charm production represents a significant amount of the inclusive cross section

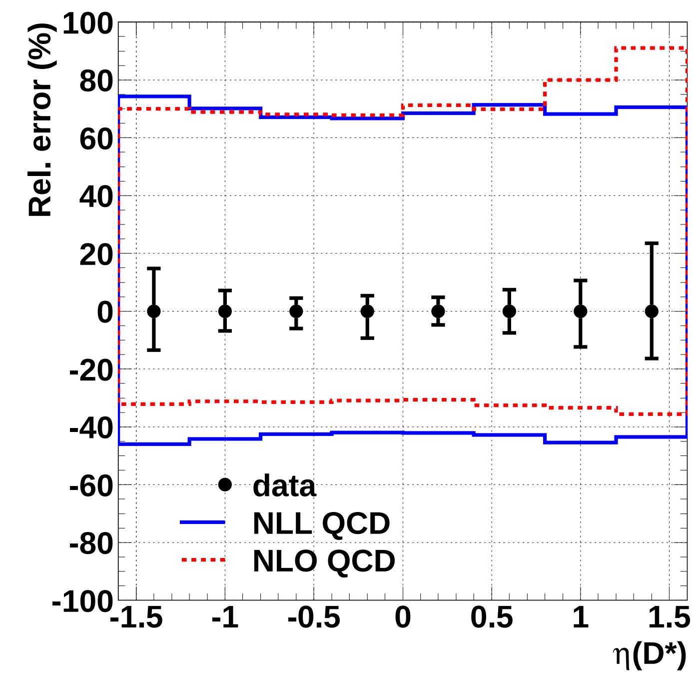
Charm in photoproduction at HERA



Description by NLO/NLL QCD not perfect.

General description with caveats - double differential cross sections highlight differences

Is QCD really predictive?



Data also good for tuning theory

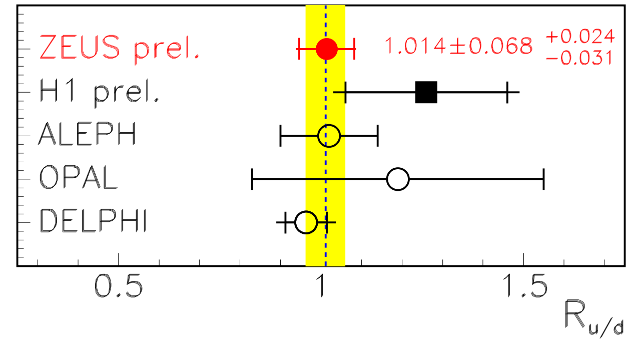
Universality of fragmentation

Charm fragmentation ratios

$R_{u/d}$, γ_s and P_V

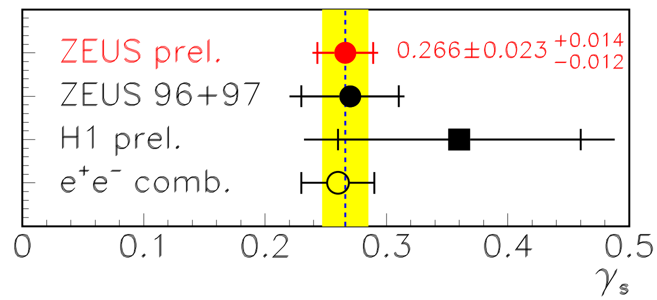
$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} = \frac{\sigma(D^{0,*0})}{\sigma(D^{\pm,*\pm})} = \frac{\sigma^{untag}(D^0)}{\sigma(D^\pm) + \sigma^{tag}(D^0)}$$

The vacuum as seen by the charm quark contains an equal number of *u* and *d* quarks



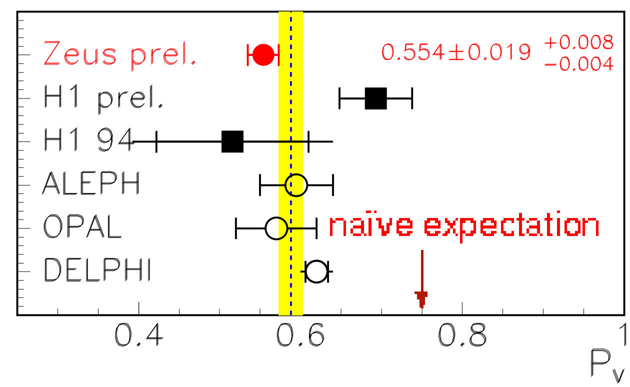
$$\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}} = \frac{2\sigma(D_s^\pm)}{\sigma^{dir}(D^\pm) + \sigma^{dir}(D^0) + 2\sigma(D^{*\pm})}$$

s **quarks are suppressed by a factor of 4**



$$P_V = \frac{V}{V+P} = \frac{\sigma(D^*)}{\sigma(D^*) + \sigma^{dir}(D)} \neq 3/4$$

Naïve spin counting does not work for charm



QCD vacuum seen by charm quarks is independent of the hard physics

Charm fragmentation fractions

Fractions	ZEUS (prel.) γp $p_T(D,\Lambda_c) > 3.8$ GeV $\lvert\eta(D,\Lambda_c)\rvert < 1.6$	Combined e^+e^- data	H1 (prel.) DIS
$f(c \to D^+)$	$0.249 \pm 0.014^{+0.004}_{-0.008}$	0.232 ± 0.010	$0.202 \pm 0.020^{+0.045+0.029}_{-0.033-0.021}$
$f(c \to D^0)$	$0.557 \pm 0.019^{+0.005}_{-0.013}$	0.549 ± 0.023	$0.658 \pm 0.054^{+0.115+0.086}_{-0.148-0.048}$
$f(c \to D_s^+)$	$0.107 \pm 0.009 \pm 0.005$	0.101 ± 0.009	$0.156 \pm 0.043^{+0.036+0.050}_{-0.035+0.046}$
$f(c \to \Lambda_c^+)$	$0.076 \pm 0.020^{+0.017}_{-0.001}$	0.076 ± 0.007	
$f(c \to D^{*+})$	$0.223 \pm 0.009^{+0.003}_{-0.005}$	0.235 ± 0.007	$0.263 \pm 0.019^{+0.056+0.031}_{-0.042+0.022}$

Charm fragmentation fractions are universal

Same measurements at the TeVatron could be made

Correct values being used in NLO calculations

Charm fragmentation function

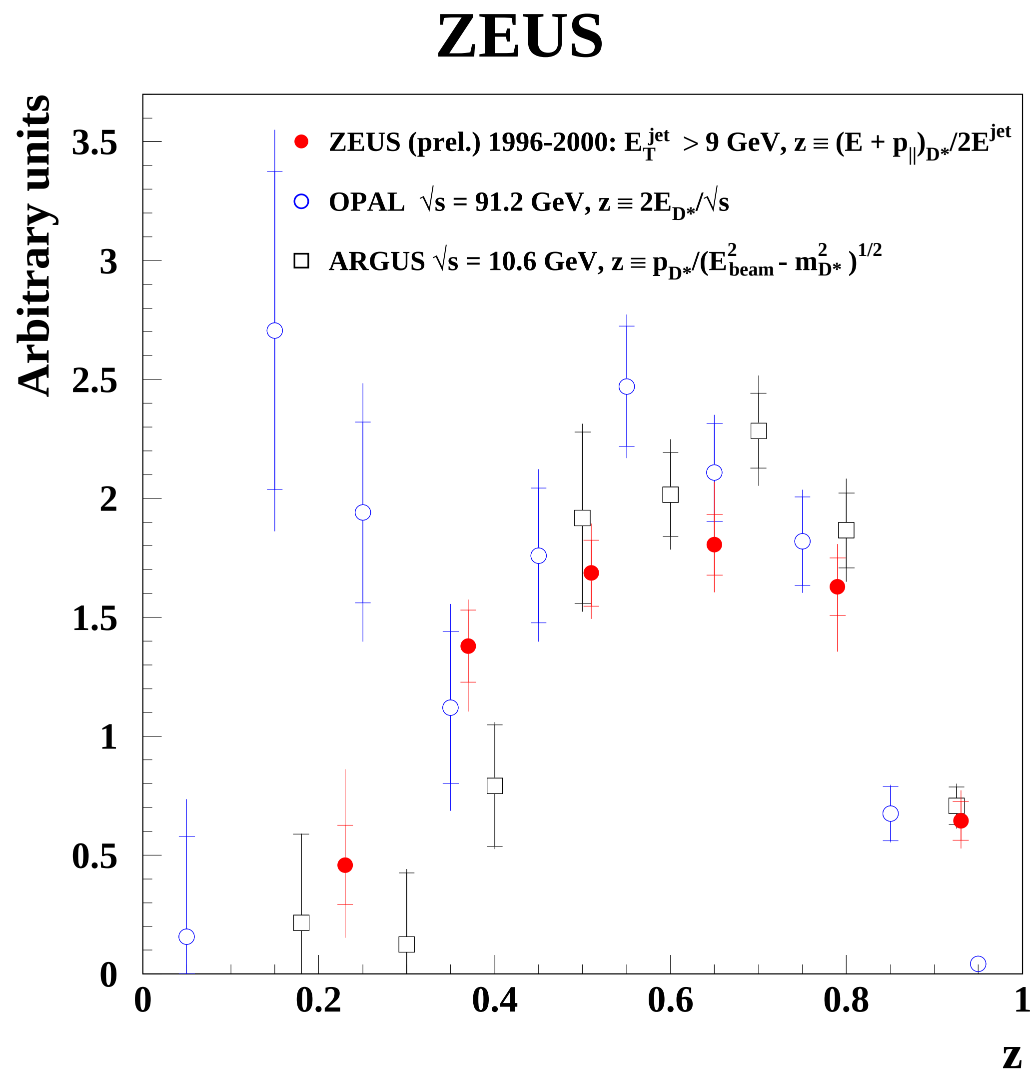
Measurements at hadronic colliders are important:

- Independent ways of measuring fragmentation
- Extra constraints and precision on fragmentation function
- Consistency in more complicated environment - hadron remnant?

General trend is similar for LEP/HERA

Different processes, energies, z-definitions.

$\longrightarrow$ need consistent fit to all data in MC and NLO.



Improve measurements at HERA and hopefully have measurements at the TeVatron $\rightarrow$ useful input for the LHC.

Charm in diffraction

Diffractive open-charm production

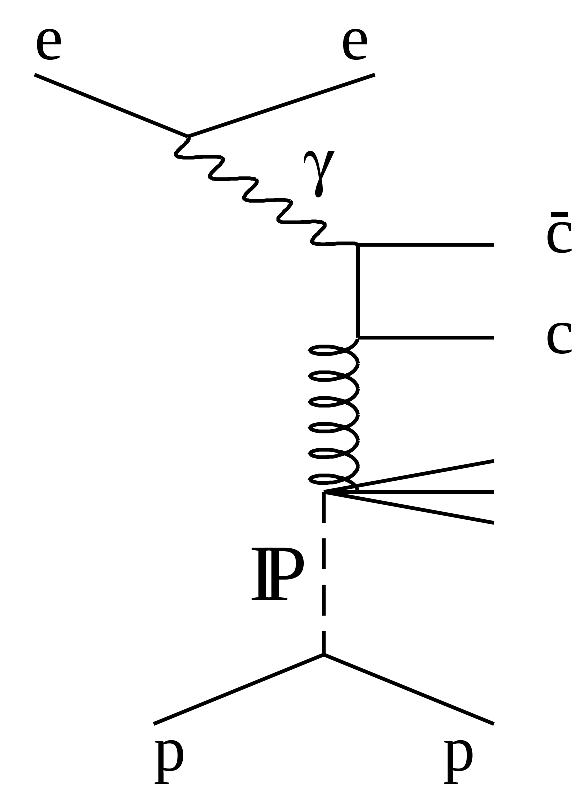
Diffractive processes contribute $\sim 10\%$ to the total DIS cross section

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

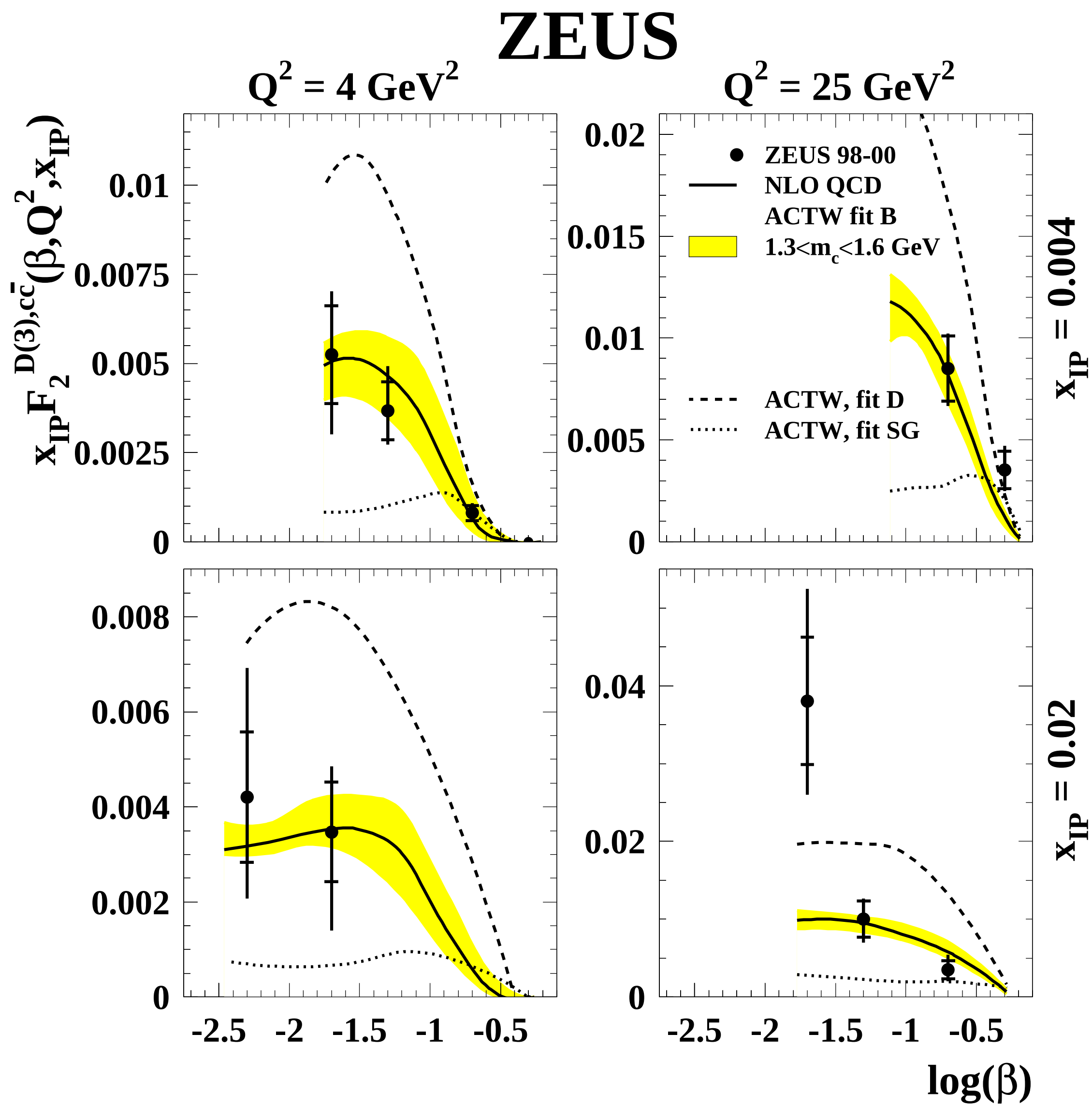
Data show sensitivity to the parton density parametrisations

Some parametrisations are ruled out

One parametrisation consistent with data

Factorisation approach works

Charm in photoproduction, i.e. hadronic environment?



Summary

Increasing number of high precision measurements of heavy quark production from HERA.

HERA is providing valuable information on:
$\longrightarrow$ **parton densities**
$\longrightarrow$ **overall production rates**
$\longrightarrow$ **universality of fragmentation**

Work is ongoing in tuning MC predictions to describe all known data.

Precise and well-defined measurements have allowed phenomenological improvements.

Calculations need to be global, i.e. predict all processes under study.

HERA will produce a lot more data and more will be known about heavy quark production.