Heavy Flavour and PDFs

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From an experimentalist's point of view

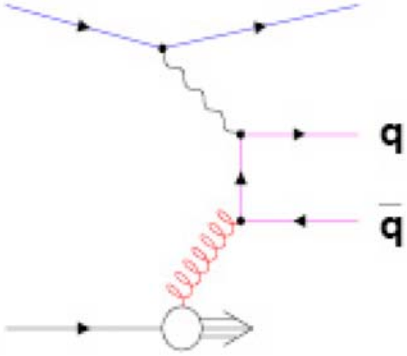
- Brief motivation
- QCD schemes (ZM-VFNS,FFNS,VFNS)
- Reminder of experimental techniques
- Compare results from Tevatron/HERA on beauty/charm
- What else can we learn from HERA and implications for LHC?

Motivation

• Gluon density/heavy flavour PDFs essential for understanding QCD and calculating cross sections/uncertainties at LHC.

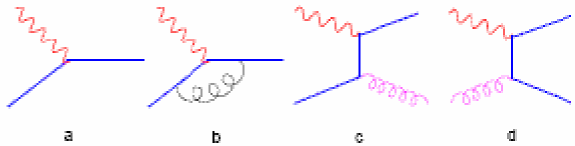
•Heavy flavours offer direct probe of gluon density of the proton. Test models/schemes/PDFs.

•Statistically limited. Offer weak constraint. Chance to learn more at HERA-II?



Massless Scheme

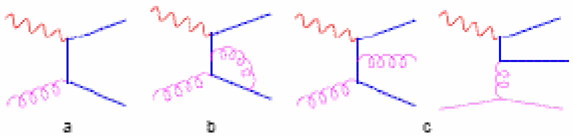
"massless" - Zero Mass Variable Flavour Number Scheme $Q^2 \gg M^2$



ZM-VFNS: $\sigma_{ep\to CX} = \sum_{a\,=\,\text{all active partons}} f_p^a(x_a,\mu)\otimes\hat{\sigma}_{ea\to CX}(\hat{s},Q,\mu)\,\Big|^{\overline{MS}}_{m_a=0}$

- Heavy flavour mass neglected
- Resummed valid for $Q^2 \gg m^2$
- Number of flavours increases across threshold (VFNS)
- Heavy flavour densities are zero below threshold (clearly incorrect)
- Simple to implement. Massless NLO calculations for other processes make ideal for QCD fits (CTEQ6M)

Massive Scheme



FFNS: $$\sigma_{ep \to HX} = \sum_{a = \text{light partons only}} f_p^a(x_a, \mu) \otimes \hat{\sigma}^{FFNS}_{ea \to HX}(\hat{s}, Q, m_H, \mu)$$

- Heavy quark has mass. Correct treatment around threshold $Q^2 \sim M^2$
- Number of flavours fixed to light n=3 (FFNS)
- Heavy Flavour produced from gluon. LO (α_s) NLO (α_s^2)
- Problems at high scales ($Q^2 >> M^2$) due to large $\ln(Q^2/M^2)$

•Massive NLO calculations do not exist for many processes e.g. CC. Limited global fits. Last one CTEQ5F(4)3

VFNS schemes

• Schemes which resum large logarithms at high Q^2 matched to massive treatment at low Q^2 around threshold

•Most favoured scheme by PDF fitters. Allows global fit valid at low/high Q^2

• MRST/CTEQ schemes based on original ACOT(χ) although different ideas on how to treat different terms across threshold region.

• Thorne-Roberts scheme (MRST, ZEUS). CTEQ6HQ.
Final state calculations (FO-NLL,GM-VFNS).

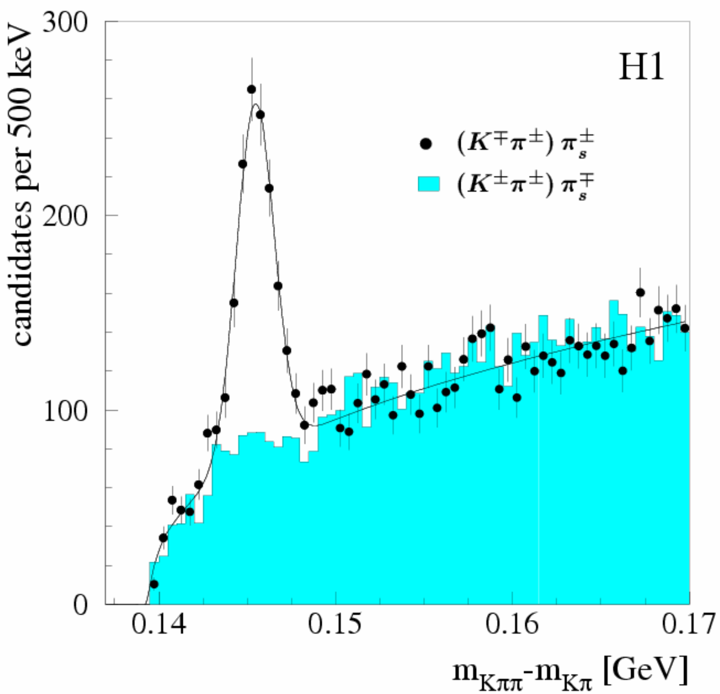
NNLO

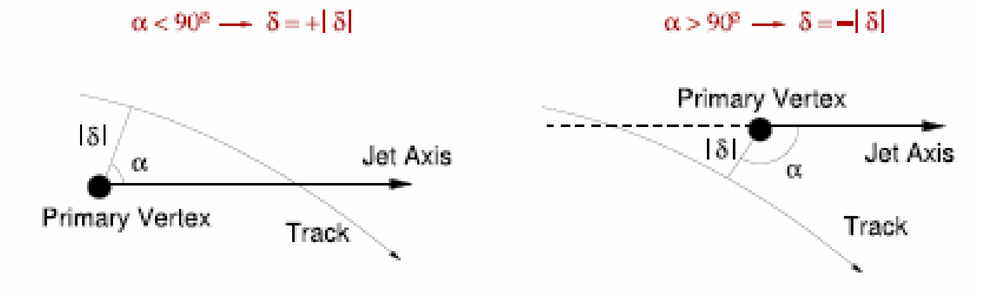
- MRST NNLO fit available which uses VFNS scheme
- massive α_s^3 matrix elements not yet calculated so same approximations that were successful for light flavours are used.
- Heavy Flavour structure functions are made continuous across mass threshold. Consequence from the fact that they are infra-red unsafe at NNLO.

Discontinuities/infra-red unsafe needs to be solved by theorists. Clear what experimentalist measure!

Experimental Techniques(HERA)

For inclusive c and b cross sections



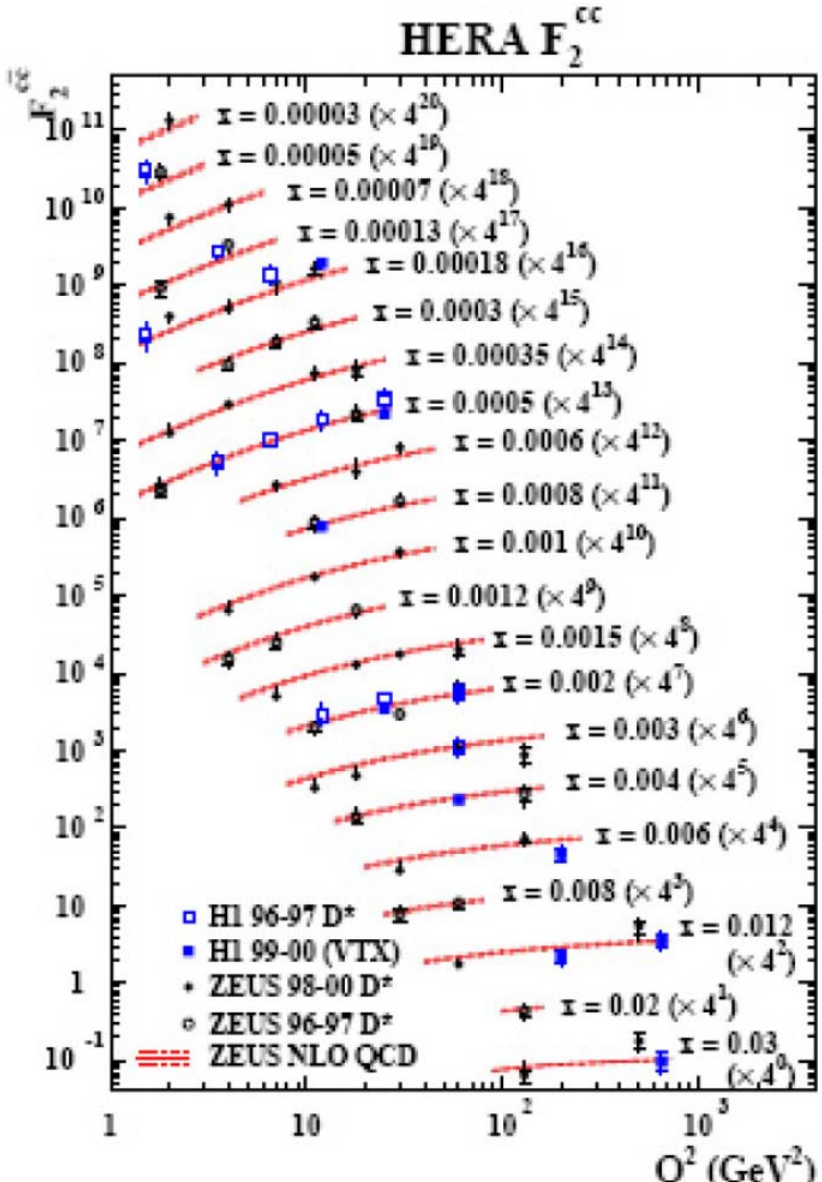


Impact parameter of all tracks using silicon trackers. Access to lower p_t and wider angles reduces extrapolations allows to quote F_2^{cc} and F_2^{bb}.

Explicit reconstruction (D*). Extrapolation to full phase space (factor 5-1.5)

For charm similar overall stat.+syst. errors in methods. b is a large background for the impact parameter method

F_2^{cc}



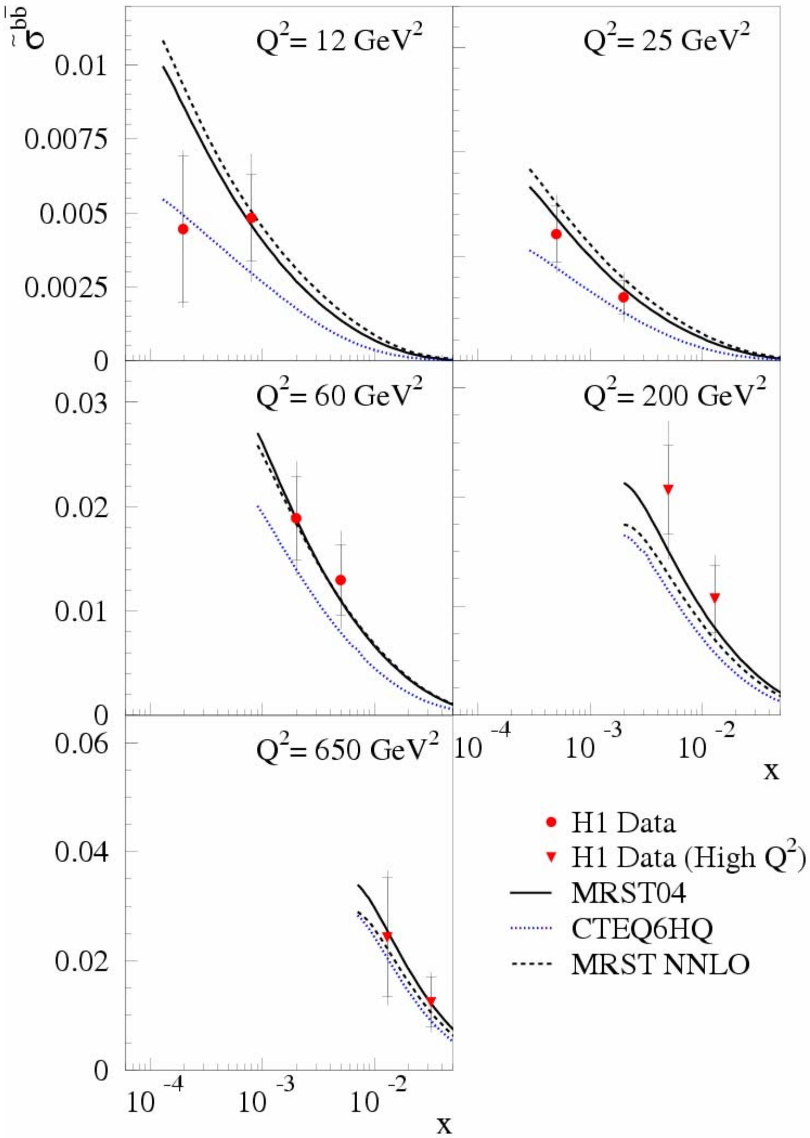
HERA charm data starts to look like early F_2 data

Data described from threshold to higher scales by massive QCD fit.

Consistent results between displaced tracks (VTX) and D^* methods

Expect increased precision from HERA-II

F_2^{bb}



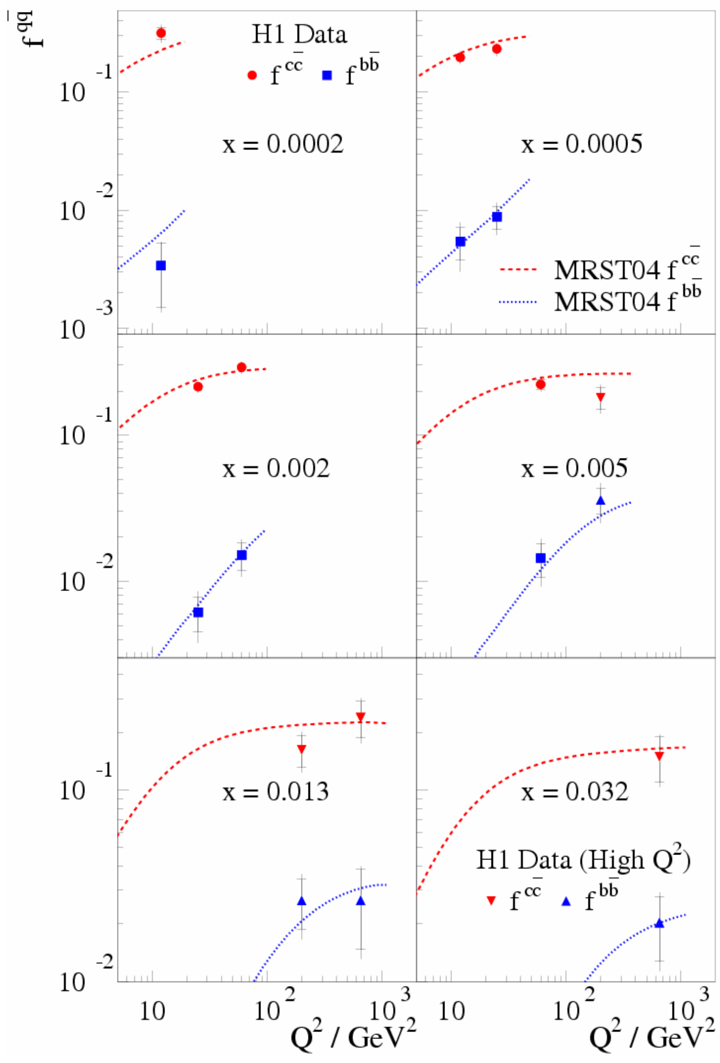
Final HERA-I low Q^2 data

Displaced tracks method allows access to lower p_T reducing extrapolation

Large uncertainty in QCD

Large uncertainties on data - consistent with all predictions

Quark Fraction



Measure fraction of DIS cross sections which are from heavy quarks

Charm large fraction of DIS cross section away from threshold (massless limit 4/11 ~ 36%)

Threshold effect important for beauty.

Recent Developments

• NLO QCD Final state programs at HERA only available for massive calculations (FMNR/HVQDIS)

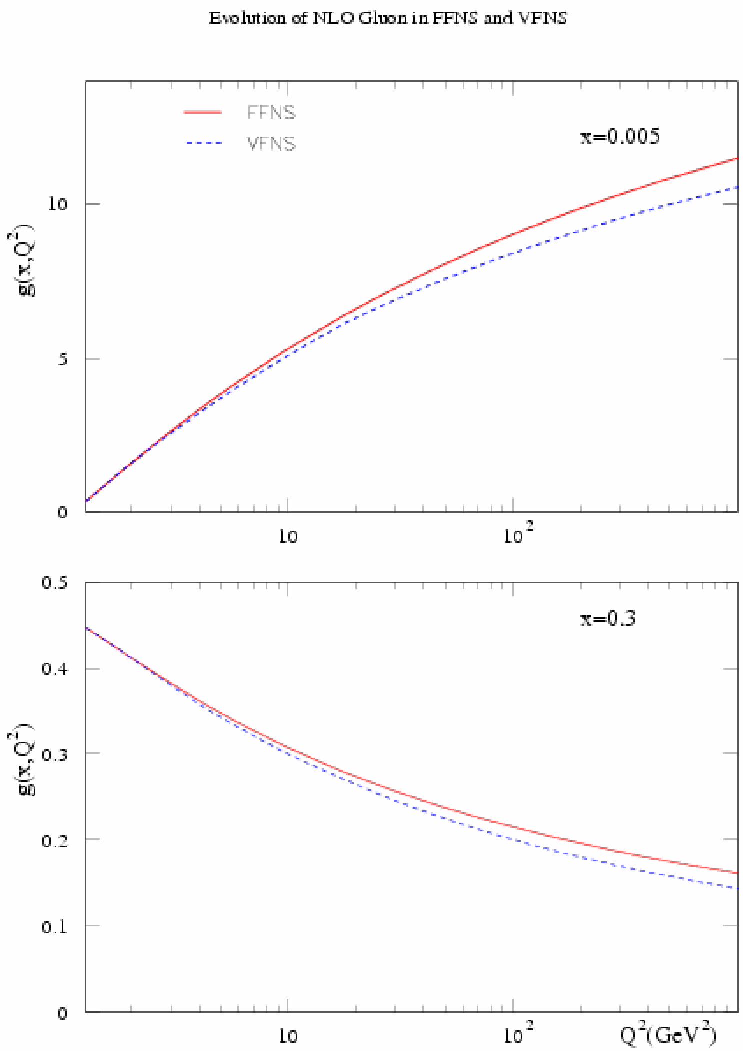
• MRST (hep-ph/0603143) produced a FFNS compatible set of partons from standard VFNS partons. Matched partons at charm threshold

• Not a `true' FF fit but helps to illustrate differences in evolution of massless/massive schemes.

• Can use to compare PDF uncertainty for HERA final state programs (CTEQ5F3(4))

N.B. the NLO calculations for fixed flavour fits should be used with a fixed flavour coupling definition of $\alpha_{s.}$ Take care with heavy flavours and F_L in massive fits!

FF/VFNS gluons



gure 3: The evolution of the gluon distribution in the 3-flavour FFNS and the VFNS, for
pical low and high values of x.

Compare Fixed Flavour (FF) and Variable flavour (VF) schemes

FF gluon is larger due to more heavy flavour `carried’ by partoin density in VF scheme.

FF/VFNS Evolution

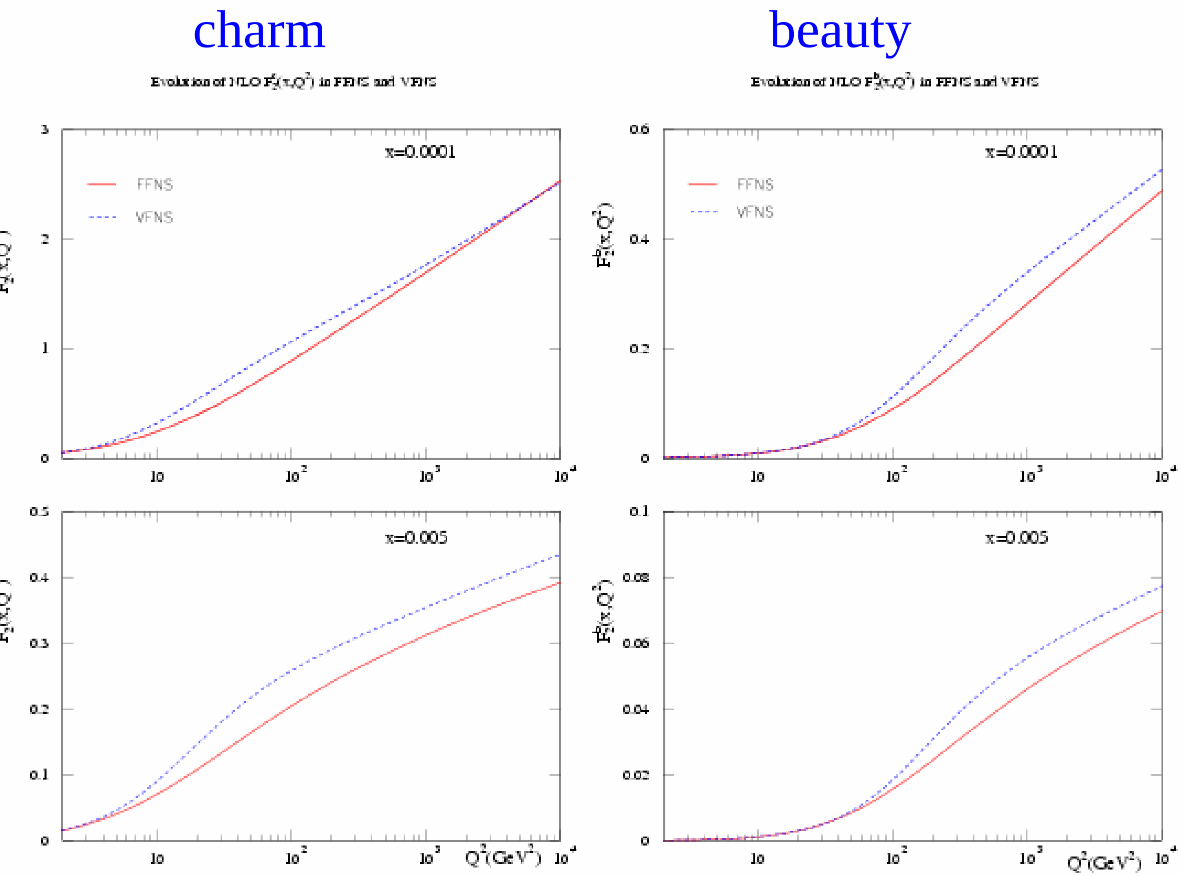
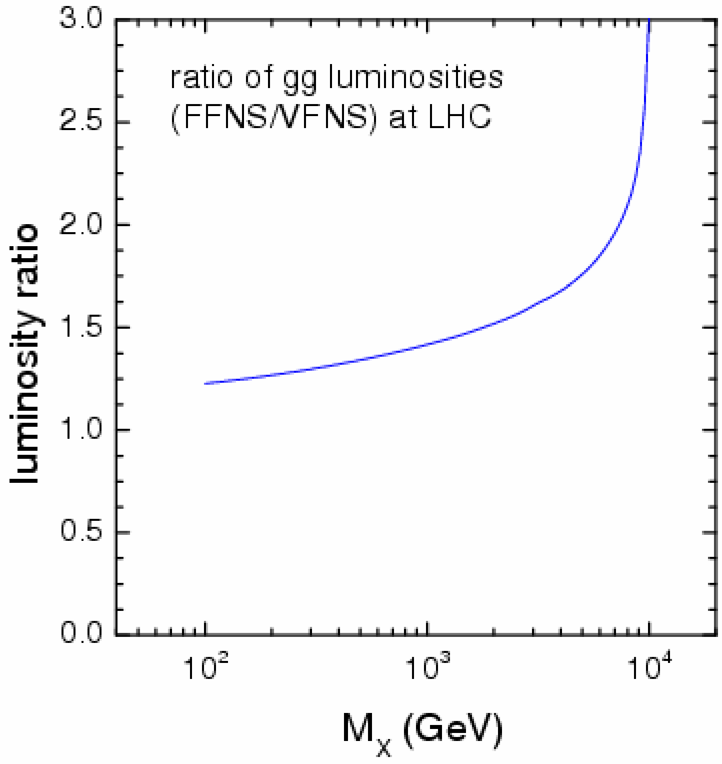


Figure 5: The evolution of $F_2^c(x, Q^2)$ in the 3-flavour FFNS and VFNS (left). The evolution of $F_2^b(x, Q^2)$ in the 3-flavour FFNS and VFNS (right).

Charm FFNS/VFNS diverge at low Q^2 and converge at high Q^2/low x. Converge due to missing terms in FFNS.

Beauty mainly diverges in HERA kinematical range. More chance to distinguish schemes experimentally with beauty?

Effect of gluon at LHC



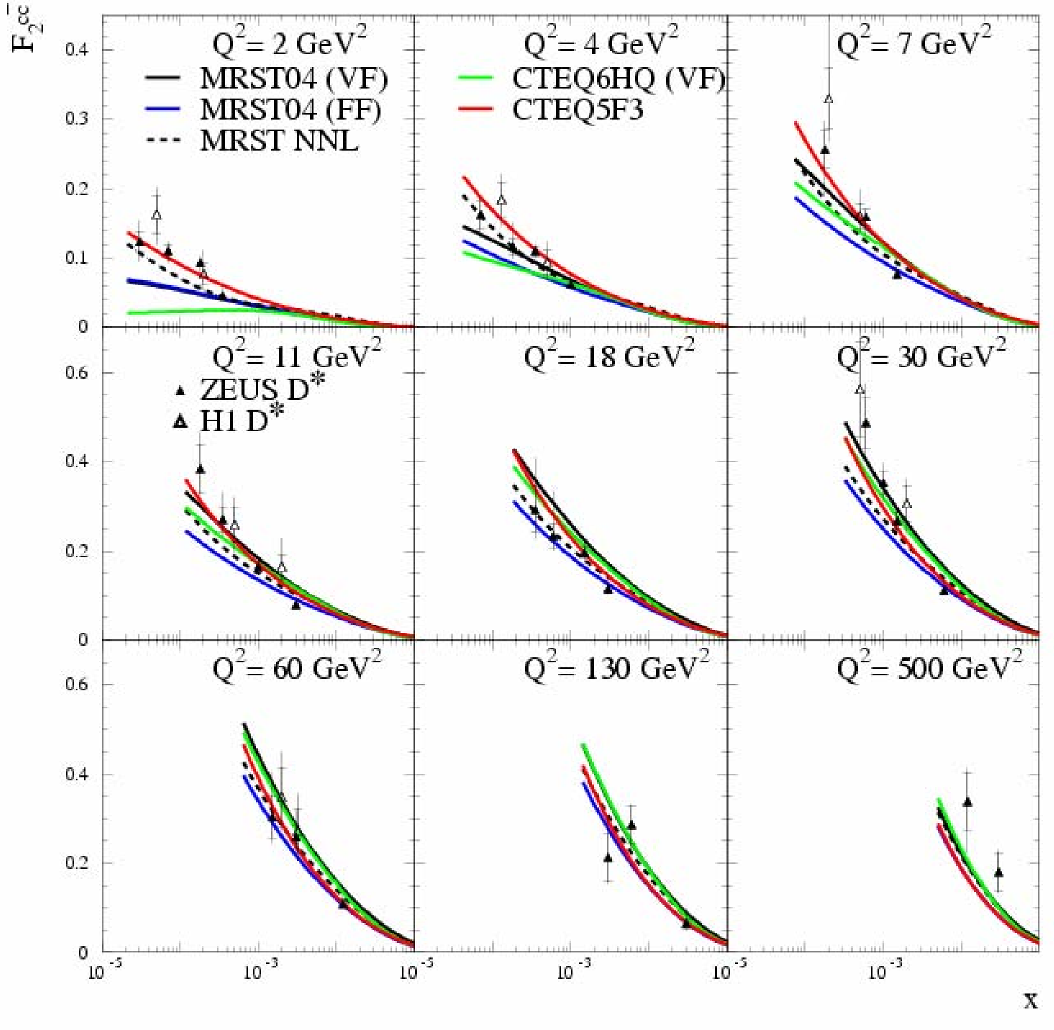
re 4: The effect on the luminosity distribution for $gg \to X$ of using FFNS or VFNS partons.

Scheme dependence introduces large QCD uncertainty at LHC (>20% increasing with x).

No strong experimental evidence to favour VFNS over FFNS despite theoretical advantages

Can HERA-II data help to reduce this? Heavy flavour measurements/F_L?

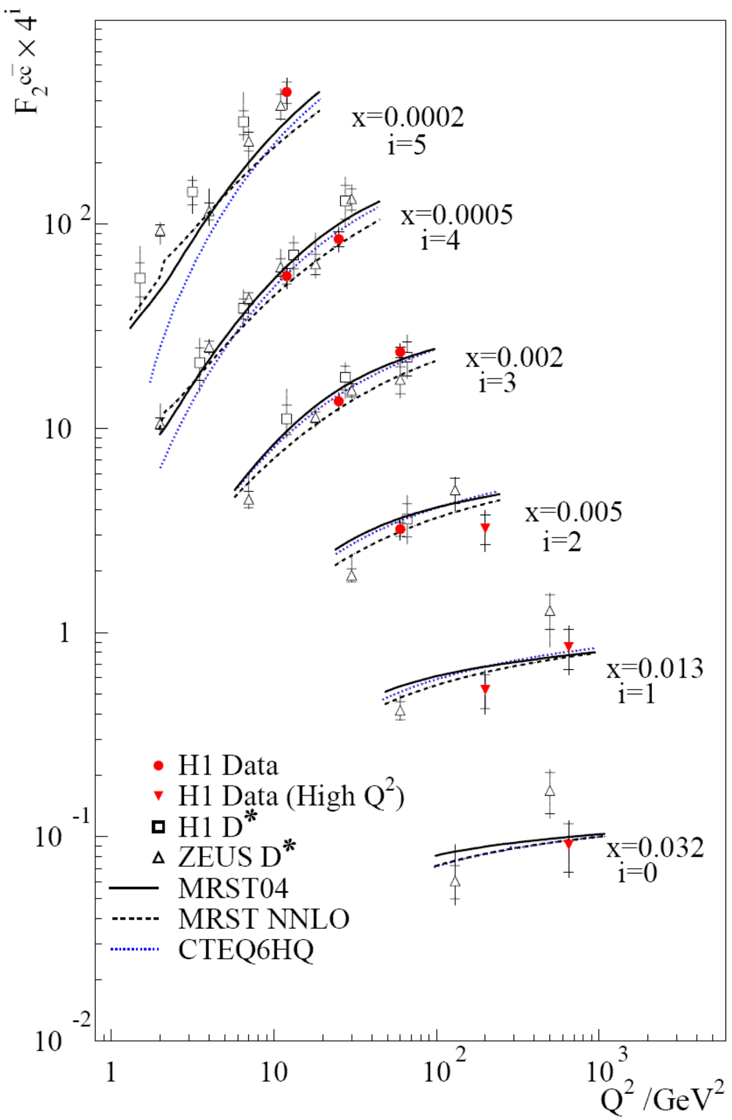
PDFs and charm



Compare data to all the different PDFs

Large difference in PDFs at lowest Q^2. This arises from different schemes and different gluons (see later).

Charm and MRST/CTEQ

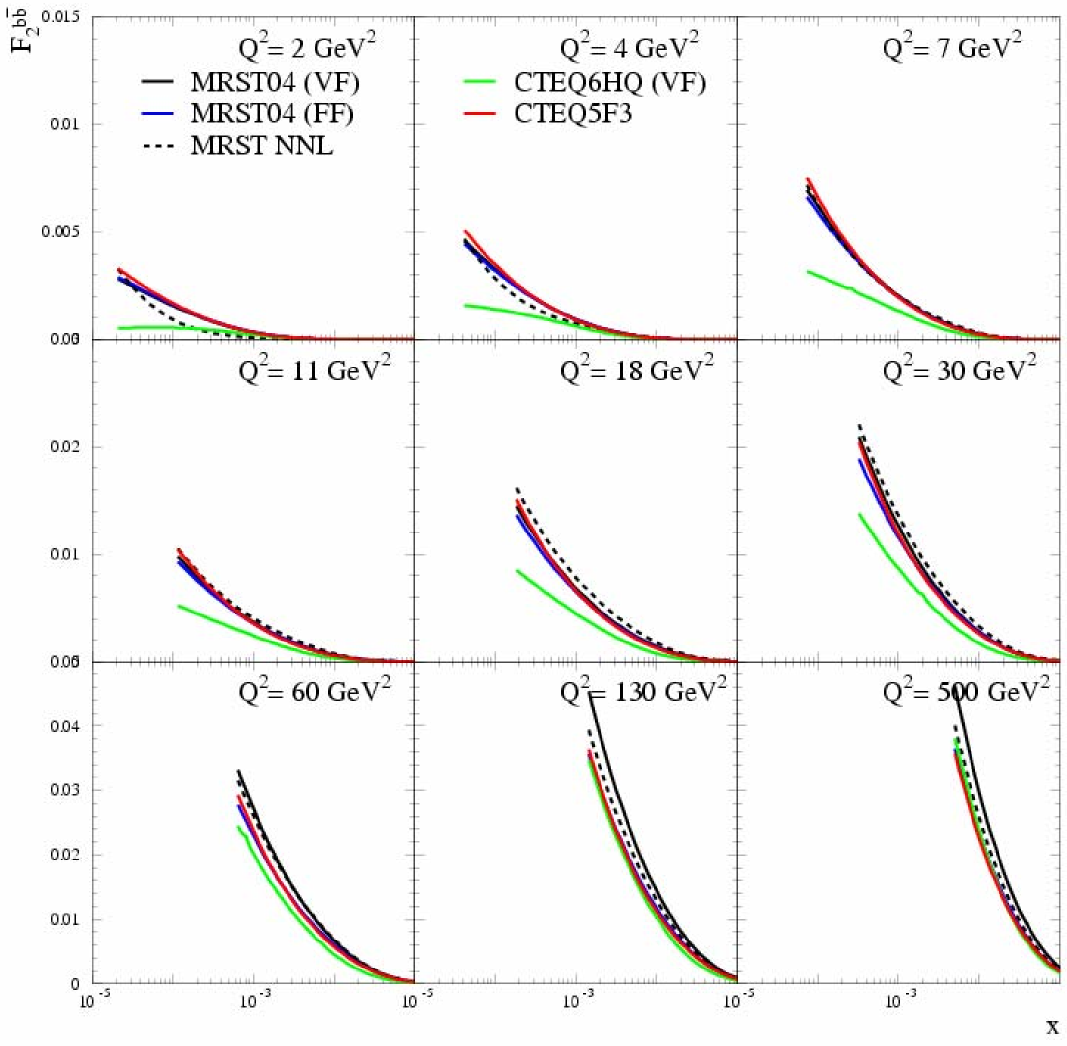


Charm shown in impact parameter method binning.

CTEQ6HQ does not follow CTEQ5F3 at low Q^2 as we would expect. Improved comparison for Q^2>4 GeV^2 at DIS06. More work needed? S. Kretzer has left the field.

MRST try to improve low Q^2 differences at NLO by going to NNLO. Hard to say if it is the order or the gluon?

PDFs and beauty



Higher mass increases effective x range and smaller differences between gluons.

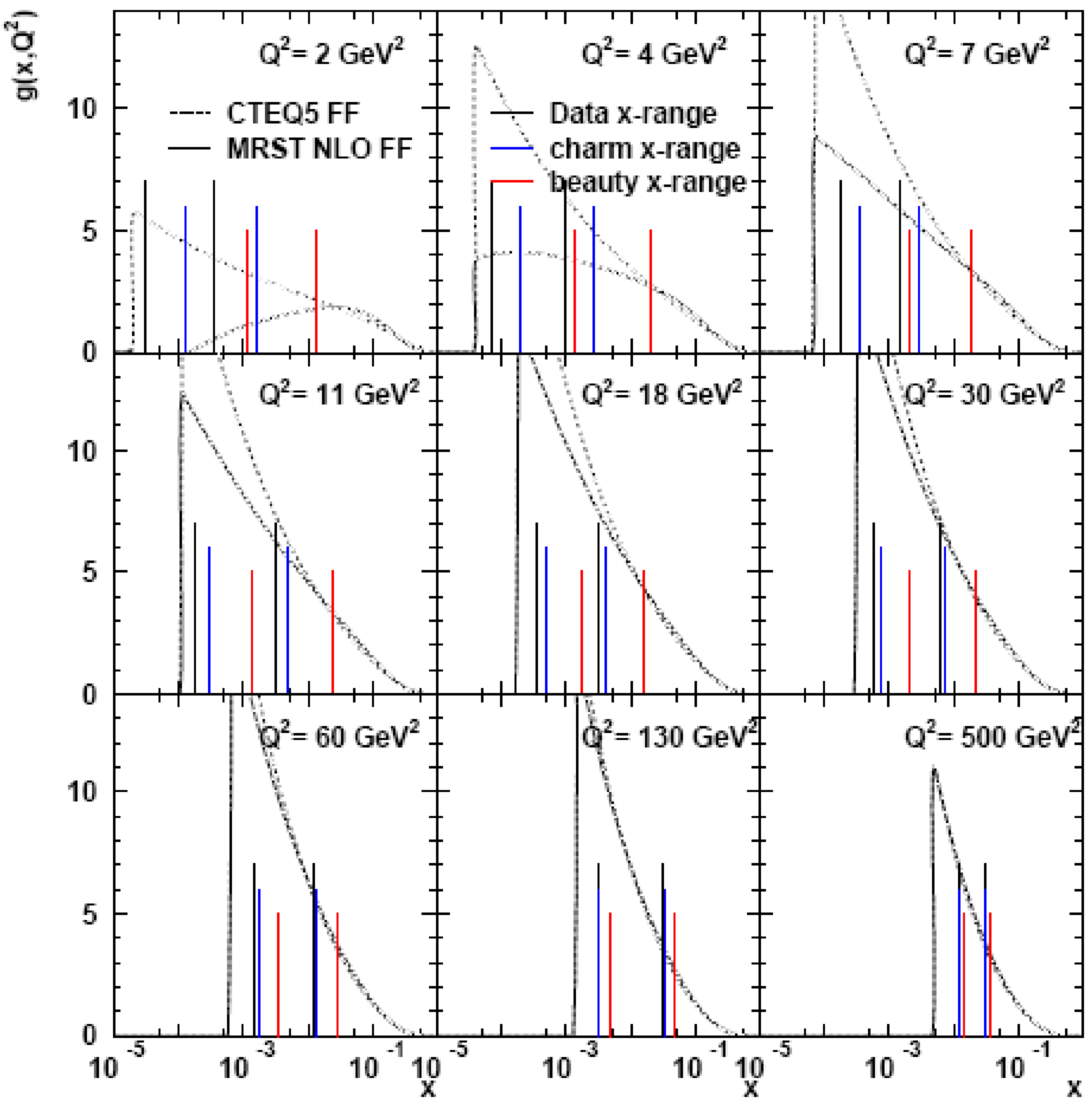
MRST/CTEQ schemes show differences at medium Q^2. Possible to distinguish?

Differences due to evolution at higher Q^2.

Need luminosity!

Scale uncertainties?

CTEQ/MRST FF gluons



Compare CTEQ and MRST FF gluons.

Effective x range increases with quark mass

$x' = x(Q^2+M^2)/Q^2$

Vertical lines show;

Black – HERA charm data

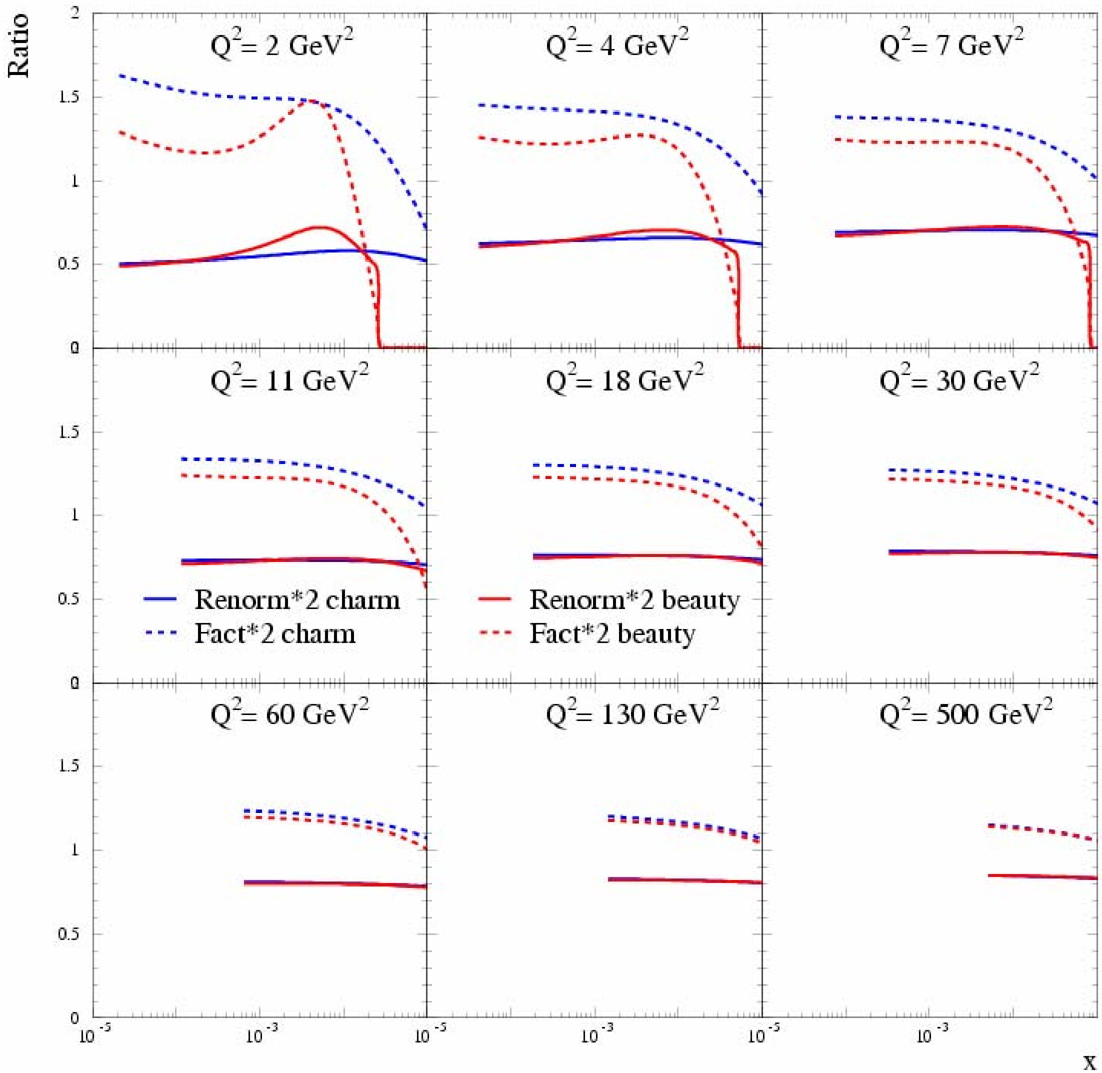
Blue – effective charm x

Red – effective beauty x

Large difference at low Q^2.

N.B. HF cross section is not proportional to gluon but a convolution of coeff. and gluon density

Scale Uncertainty



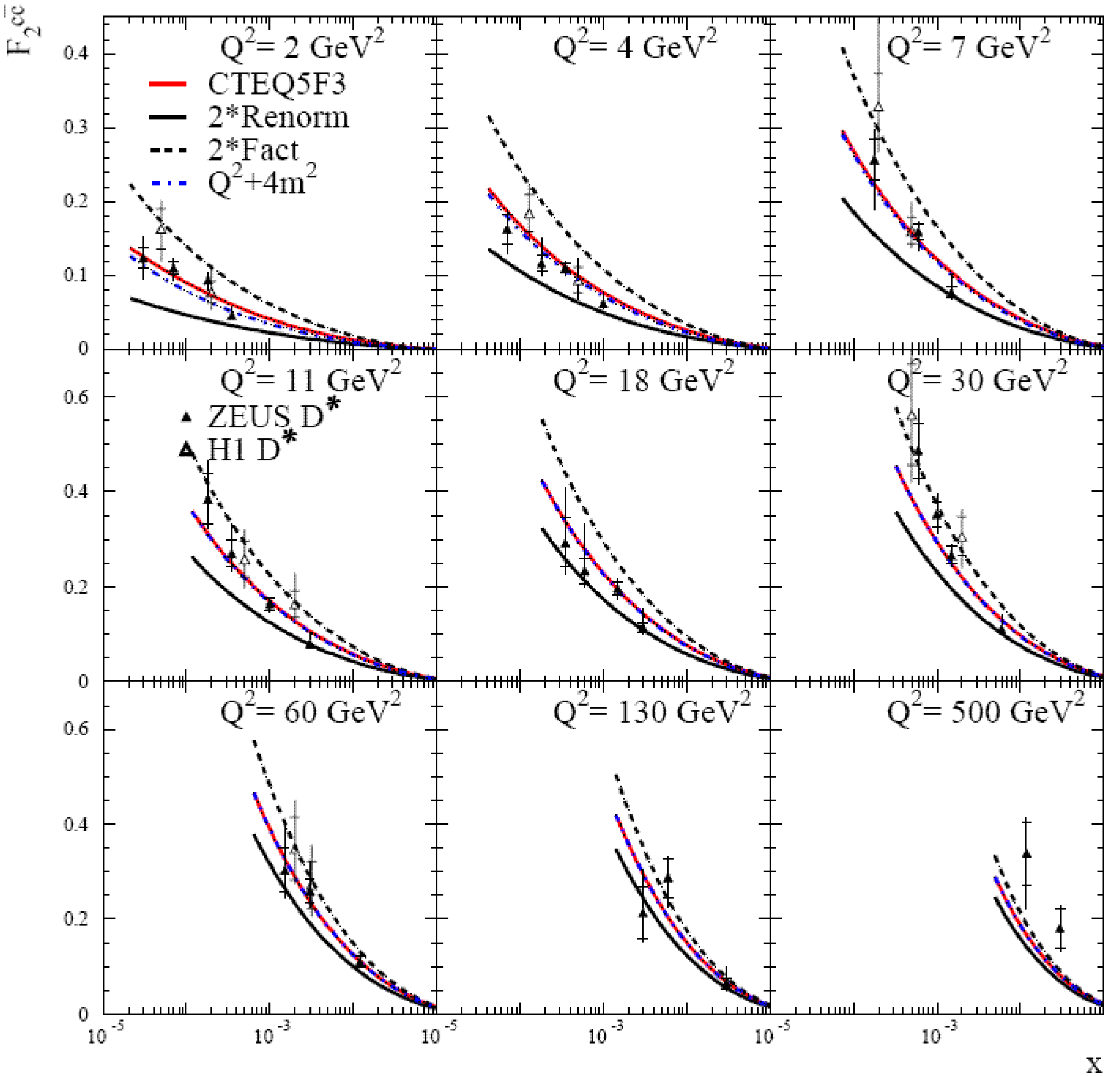
Renormalisation scale selects different α_s (same uncertainty for c and b with same scale Q^2)

Factorisation scale selects different gluon density.

Large uncertainties at low scales.

Uncertainties smaller for beauty (samples higher x where gluon varies less).

Scale Uncertainty for charm



Small charm mass in scale has small effect

Scale uncertainties larger than data allow?

Mainly come from gluon density – should each scale variation use a different PDF?

Probably not because QCD is uncertain!

Summary

- Heavy flavours provide direct access to gluon measured indirectly from fits to inclusive data.

- QCD is a success (within uncertainties)!

- Progress in understanding different schemes/gluons.

- With more F_2^{cc}/F_2^{bb} data is it possible to distinguish different schemes/gluons in time for the LHC?

- Charm is difficult to unfold gluon/scheme/scale at low Q^2. Beauty may be more useful for scheme testing. Need luminosity!