Heavy Flavour Production at HERA and the LHC

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- Motivation
- QCD schemes
- experimental techniques
- Results from Tevatron/HERA on beauty/charm
- Compare data with different PDFs
- What else can we learn from HERA?

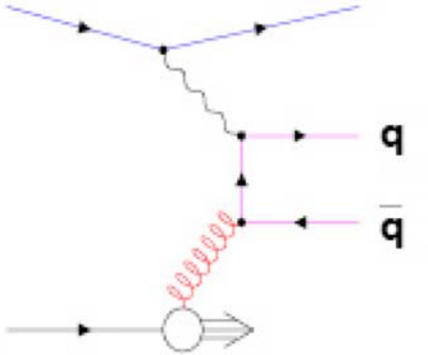
Motivation

• 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. Gluon density measured indirectly from F_2 scaling violations.

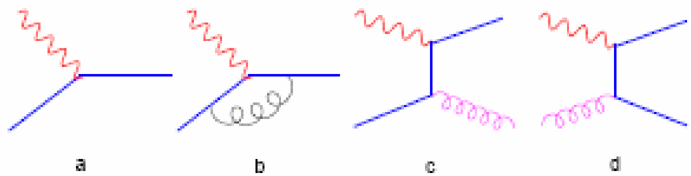
•Test models/schemes/PDFs. Multi-scale problem. $Q^2, p_T, M_{c,b}$

•Statistically limited. Data provide test but only weak constraint. Chance to learn more at HERA-II?



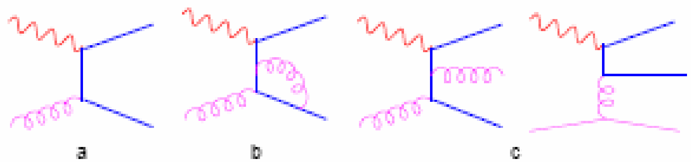
Theoretical Approaches

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



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

"massive" - Fixed Flavour Number Scheme $Q^2 \sim M^2$



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

Page 6

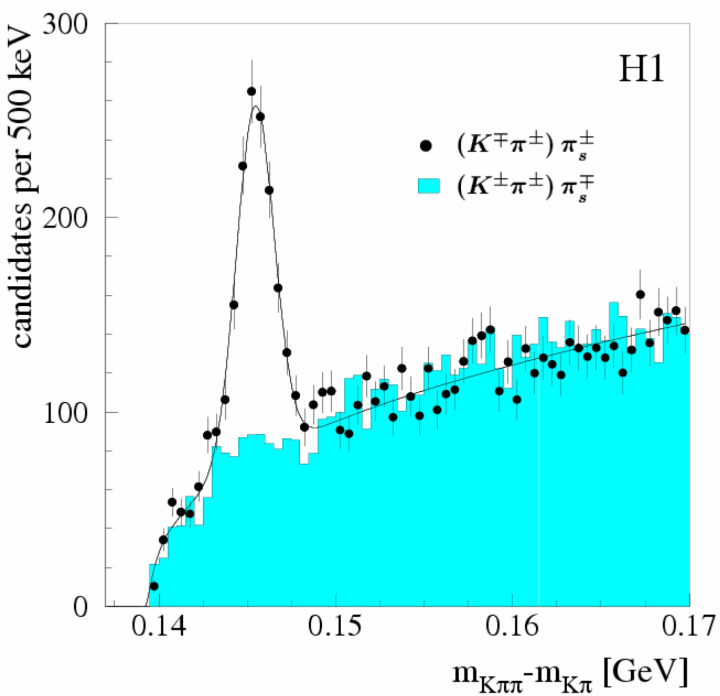
Variable FNS: Interpolate between massive and massless avoiding double counting etc. ACOT(CTEQ), MRST.

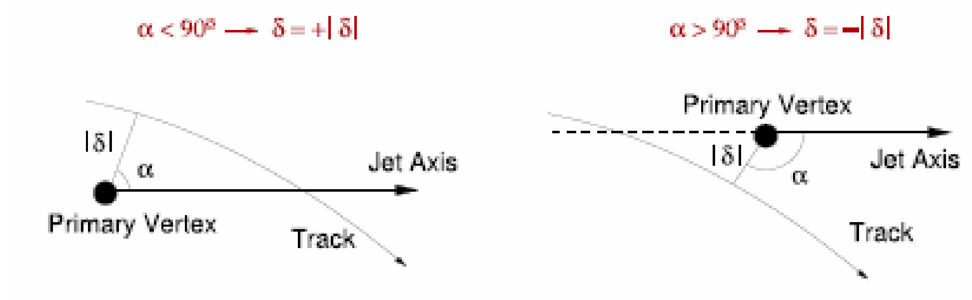
VFNS schemes

- Most favoured by PDF fitters. Thorne-Roberts (MRST,ZEUS). CTEQ6HQ. Final state resummed (p_t^2/m^2) calculations (FO-NLL).
- Completely massless scheme does not describe threshold!
- Massive scheme has theoretical problems at large scales p_t^2/m^2 or Q^2/m^2. Partonic NLO calculations unavailable for many processes in massive scheme e.g. CC (limited data samples to fit).
- Controversial subject. Requires decisions on how to treat different terms across threshold region.
- MRST use VFNS for NNLO (only scheme with continuous $F_2^{c,b}$ at this order).

Experimental Techniques(HERA)

For inclusive c and b cross sections (F_2^{cc}, F_2^{bb})

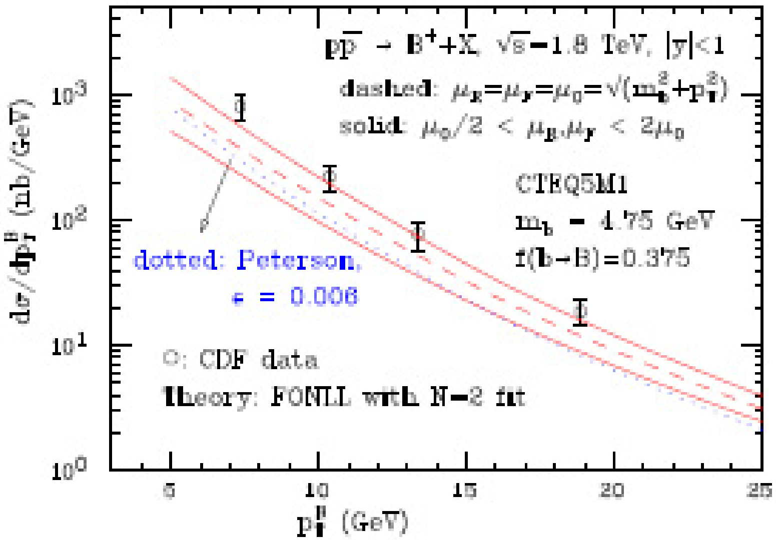




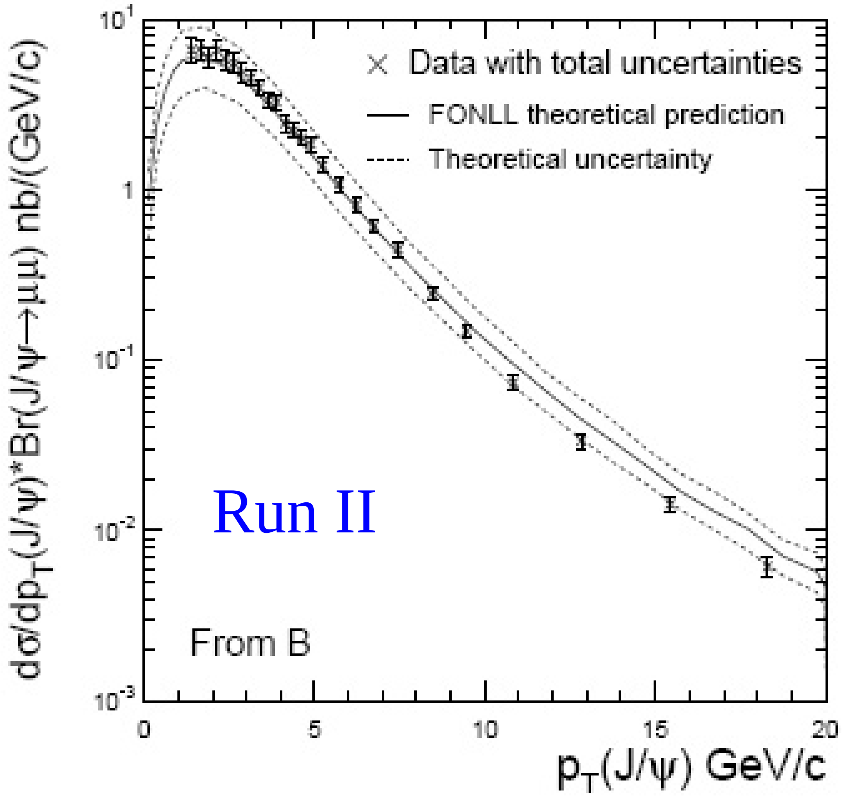
Impact parameter of all tracks using silicon. Access to lower p_t and wider η reduces extrapolations and allows to quote F_2^{cc} and F_2^{bb}.

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

b production at Tevatron



Run I



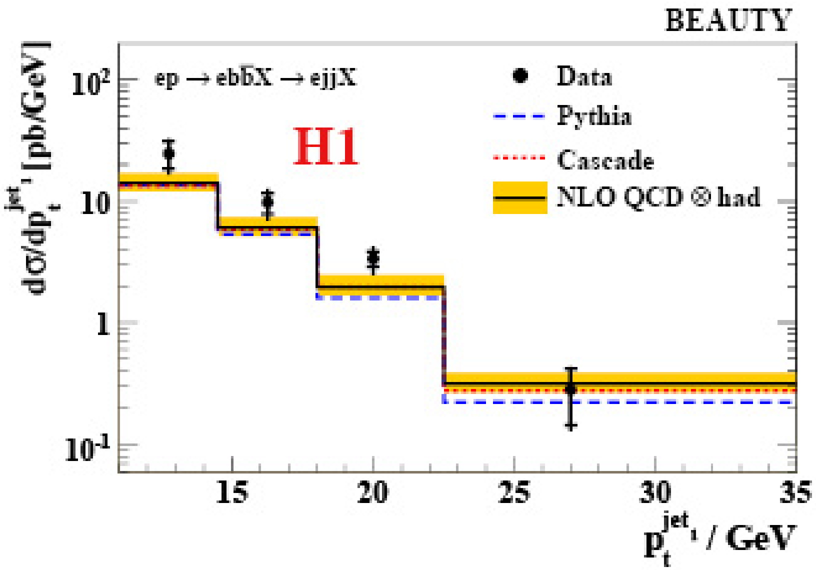
Run II

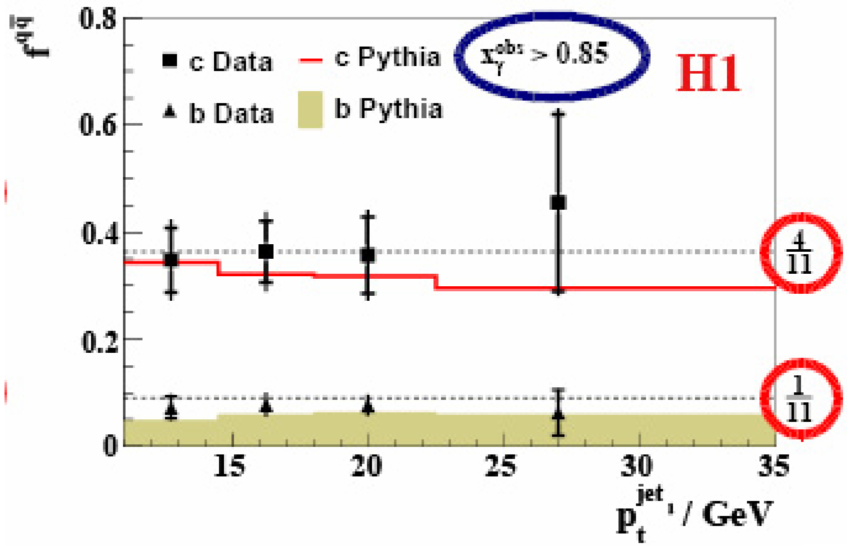
Tuned fragmentation

Data often higher but description within scale uncertainties (difference between Run-I/II?)

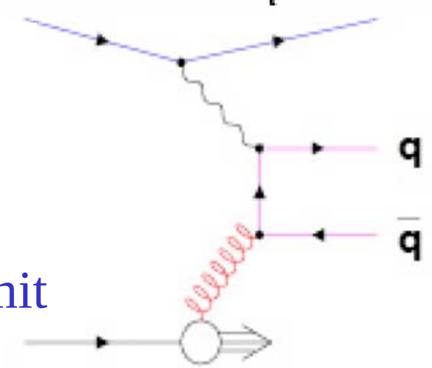
b jets at HERA

Using impact parameter of tracks in jets





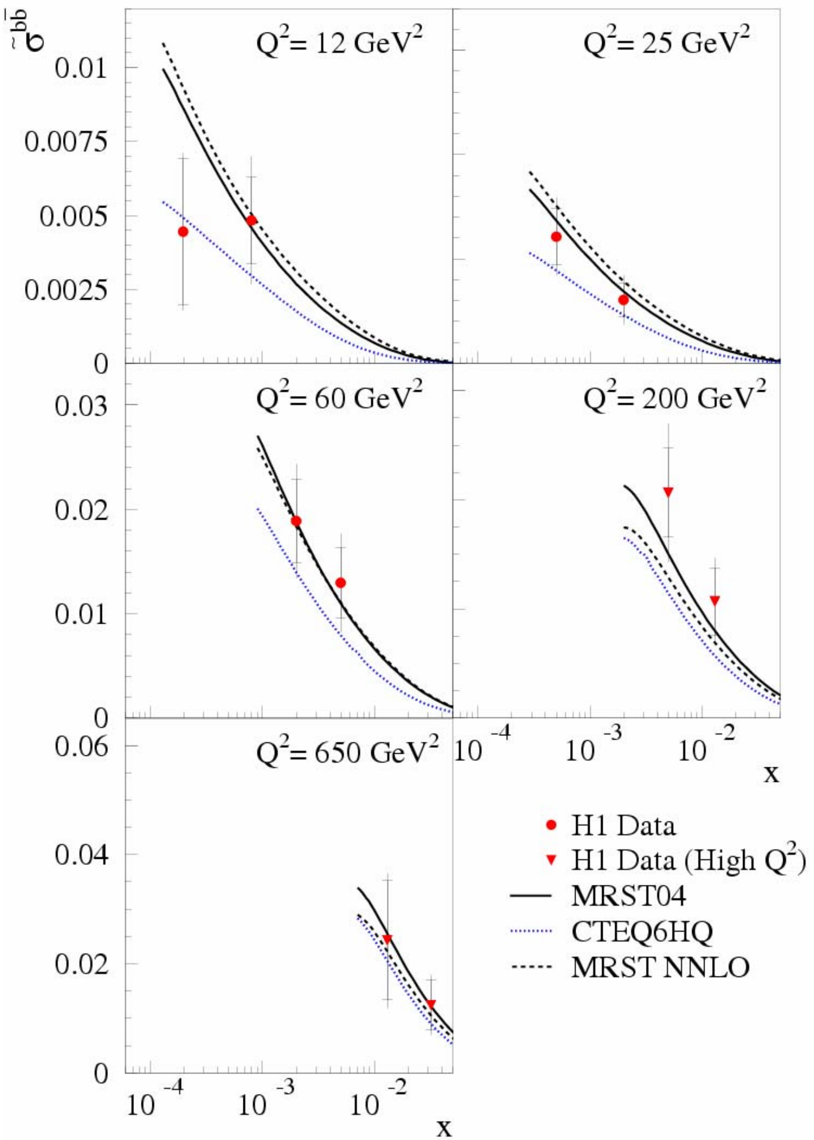
$Q^2 < 1$ GeV^2, $0.15 < y < 0.8$, $p_t^{jet} > 11$ (8) GeV, $-0.9 < \eta^{jet} < 1.3$



Compatibility with theory although data are higher

b fraction consistent with (massless) charge counting limit

F_2^{bb}



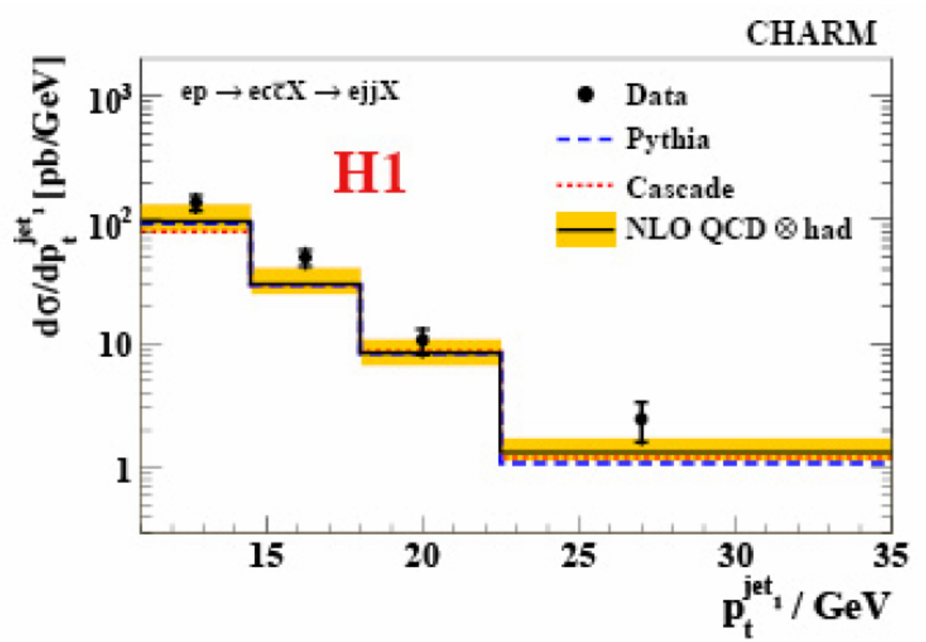
Displaced tracks method allows access to lower p_T reducing extrapolation

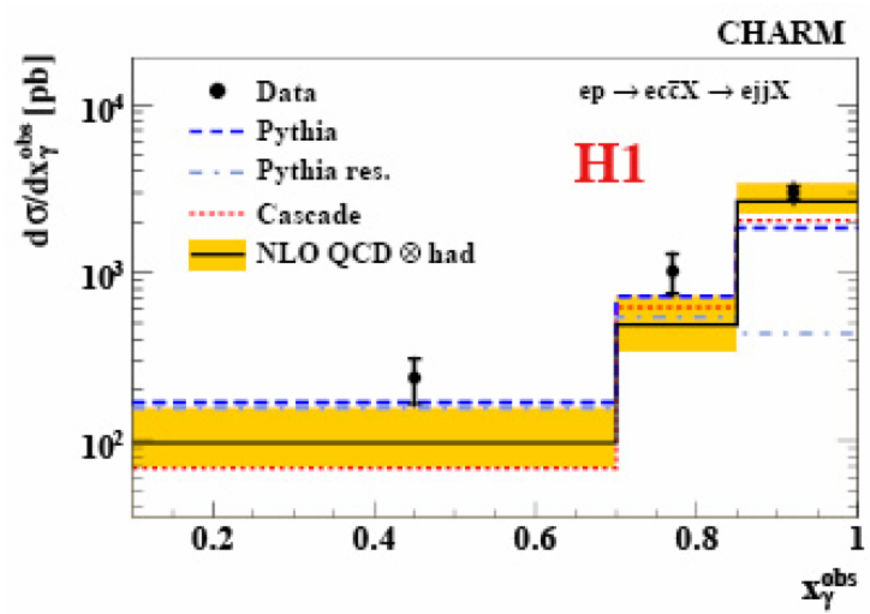
Large uncertainty in QCD (VFNS schemes)

Data consistent with all predictions

Require HERA-II data to improve precision and constrain schemes/PDFs

Open charm production

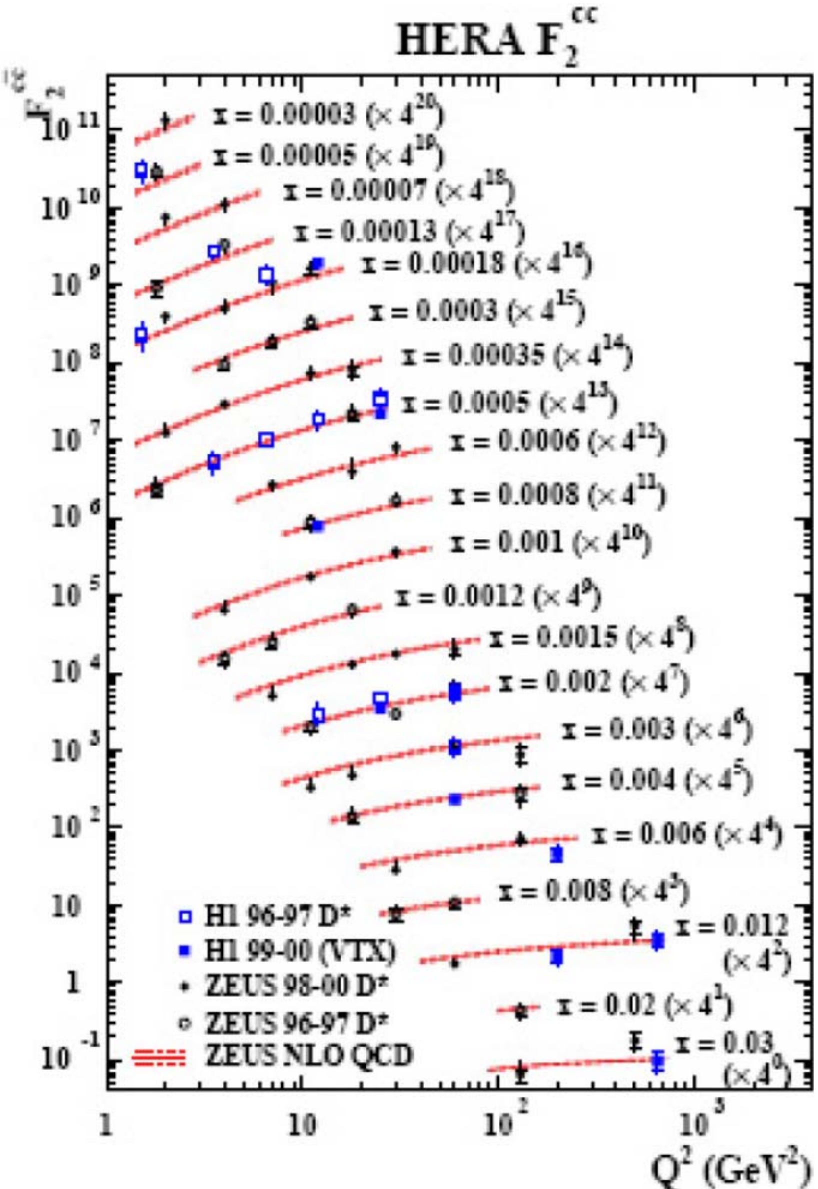




NLO consistent with data within theoretical uncertainties. Similar picture at the Tevatron.

Not all details described at low x_γ (consistent with ZEUS D^*+jets)

F_2^{cc}



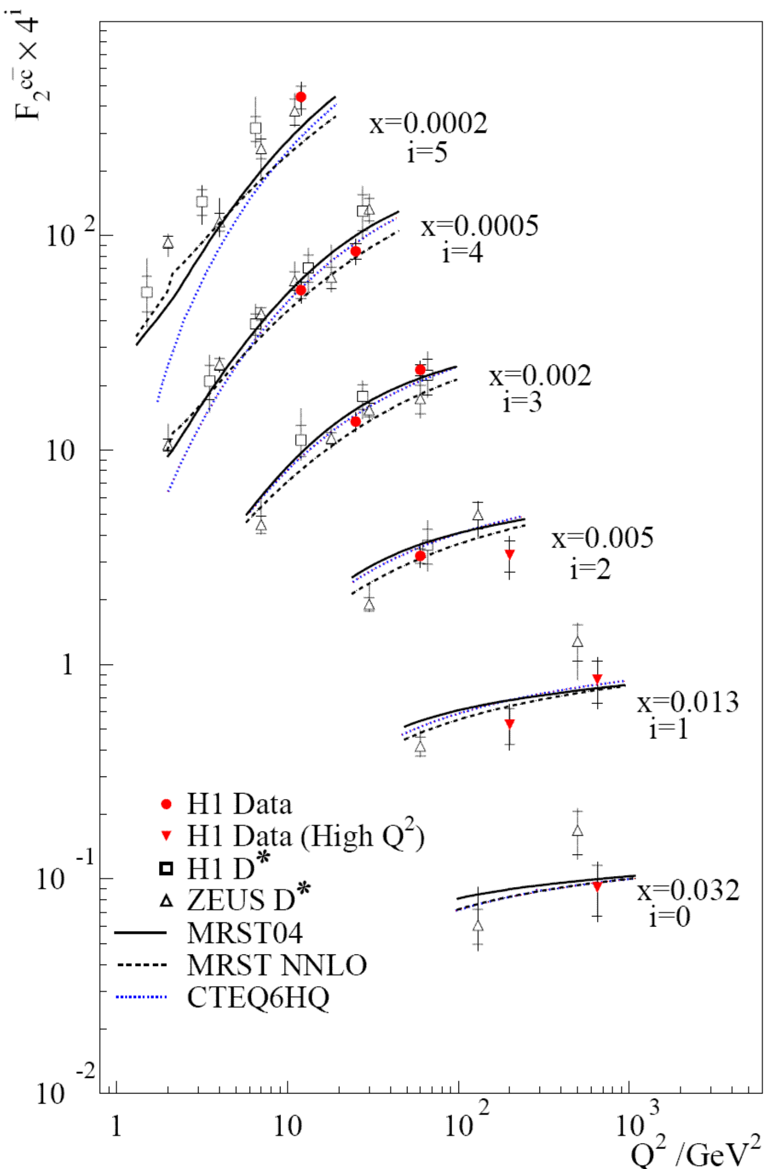
Charm scaling violations – data start to look like (early) inclusive data.

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

Similar overall statistical plus systematic errors for 2 methods

NLO QCD works

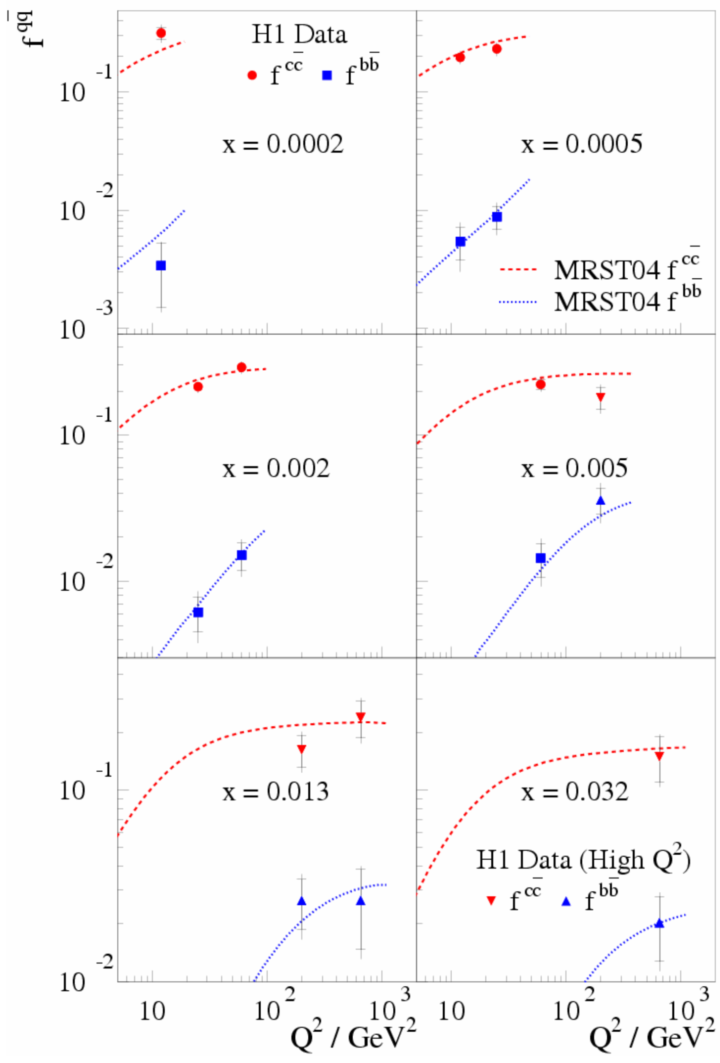
Charm c.f. Theory



Displayed in impact parameter binning method x bins.

CTEQ VFNS scheme looks disfavoured around threshold.

Quark Fraction



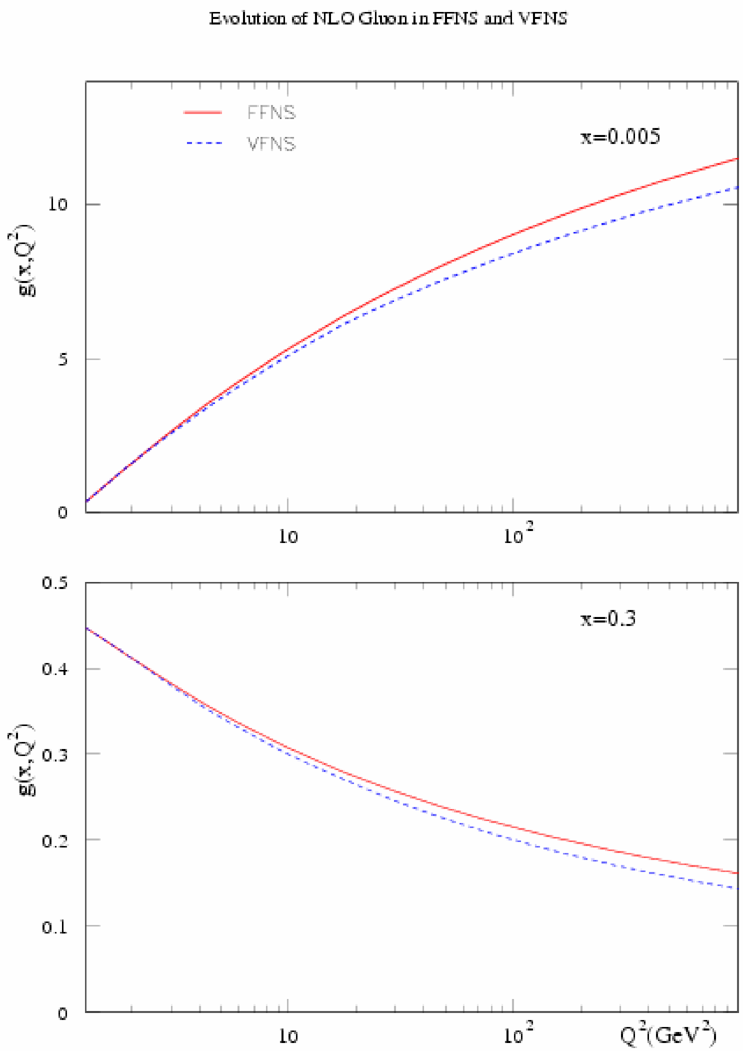
Measure fraction of DIS cross sections which are from heavy quarks

Charm large fraction of DIS cross section and approaches massless limit away from threshold.

Threshold effect important for beauty.

QCD describes data

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.

MRST produced a FFNS compatible set of partons from standard VFNS partons.

Matched at c threshold

Not a FF fit but helps to illustrate differences in evolution of schemes.

FFNS gluon is larger (c,b quarks in VFNS carry missing gluon momentum)

FF/VFNS Evolution

charm beauty

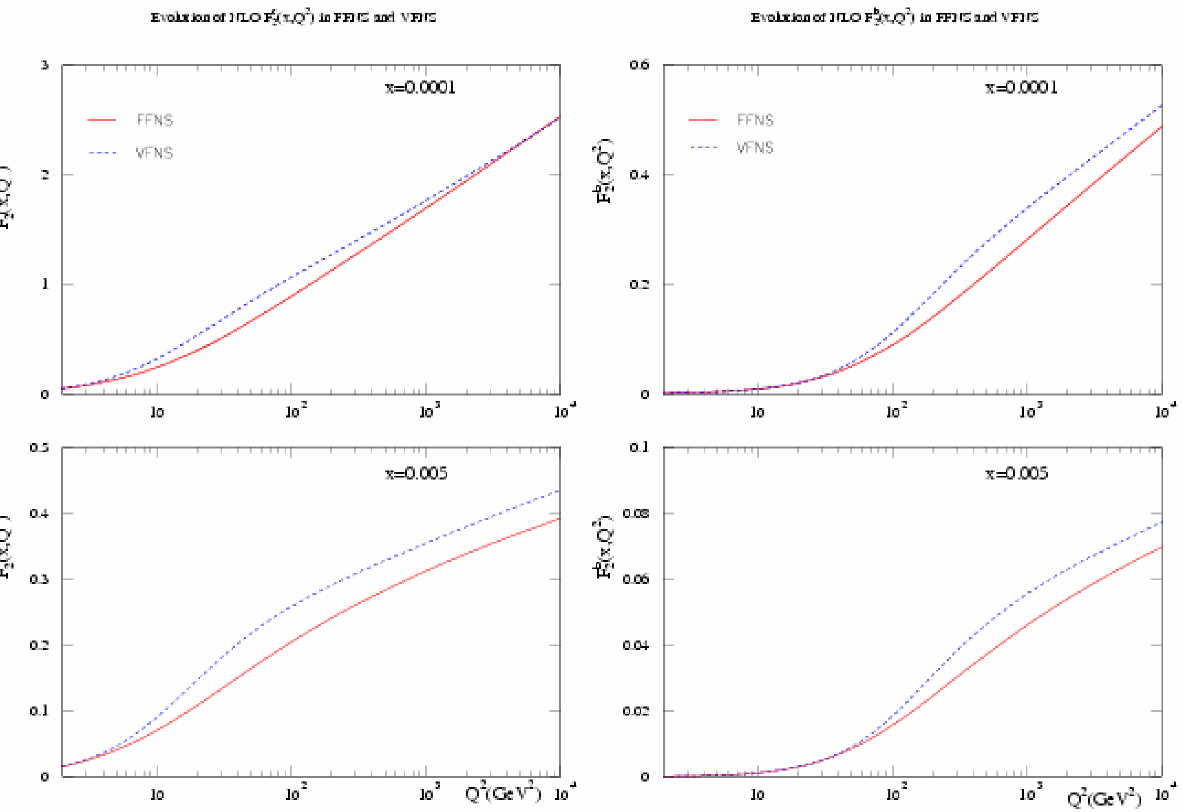
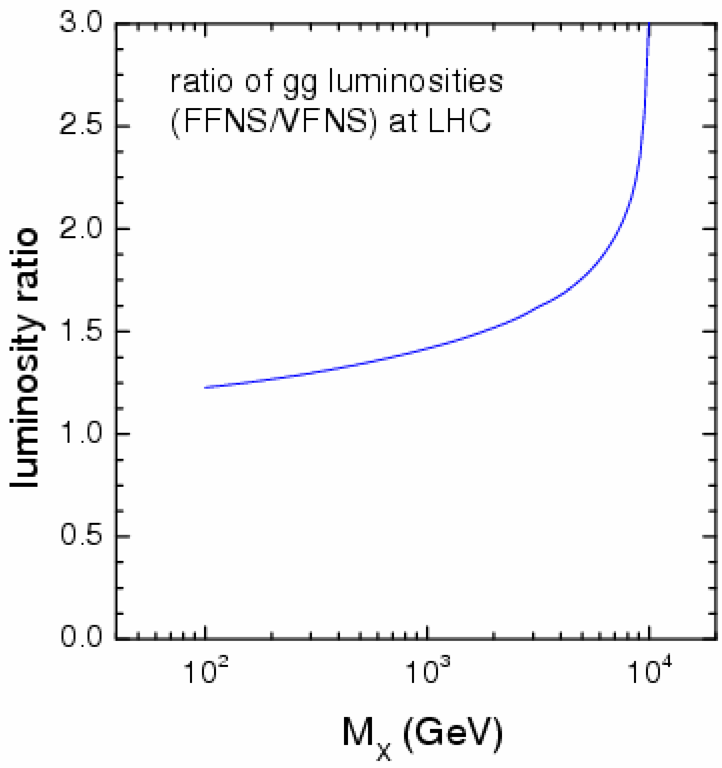


Figure 5: The evolution of $F_2^c(x, Q^2)$ in the 3-flavour FFNS and VFNS (left). The evolution of $F_2^b(x, Q^2)$ in the 3-flavour FFNS and VFNS (right).

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

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

Effect of gluon at LHC



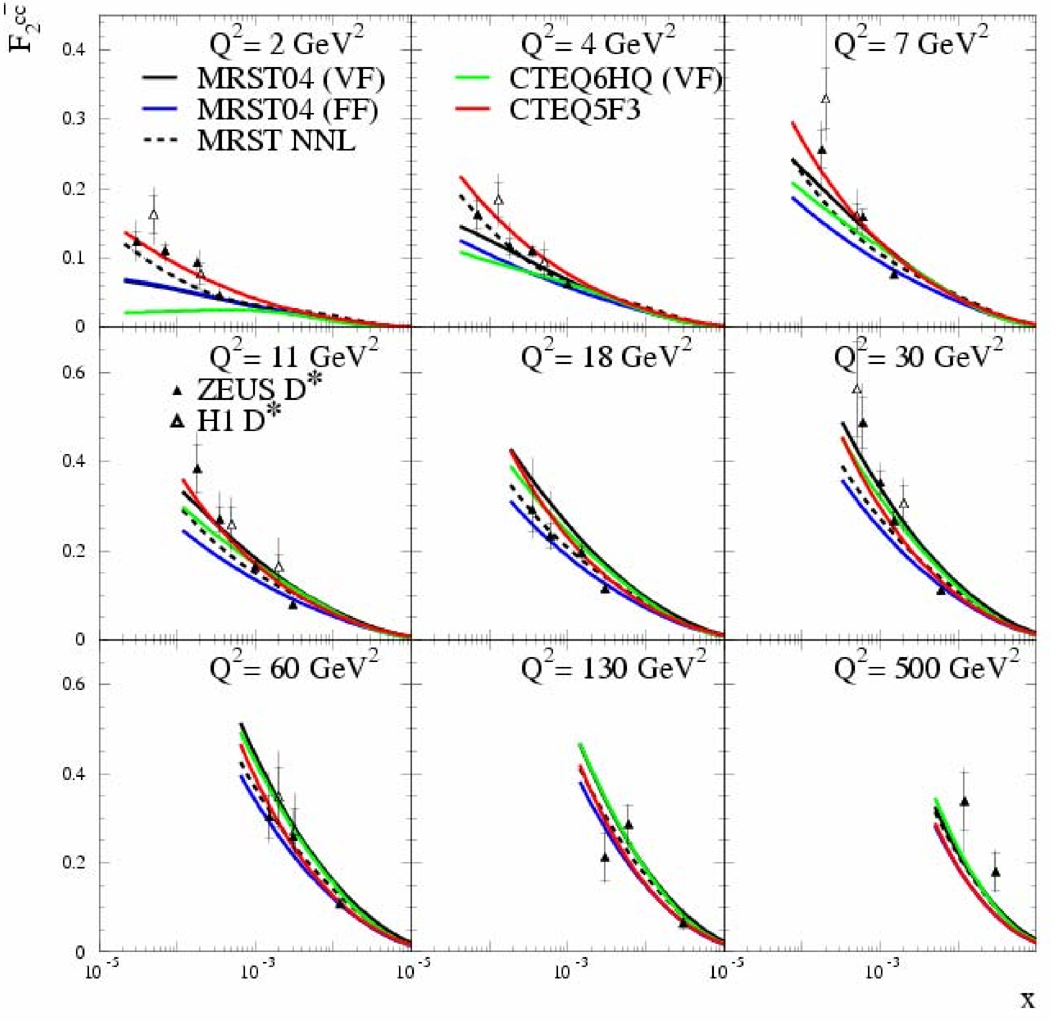
re 4: The effect on the luminosity distribution for $gg \to X$ of using FFNS or VFNS partons.

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

No strong experimental evidence to disfavour FFNS (VFNS theoretically more convenient)

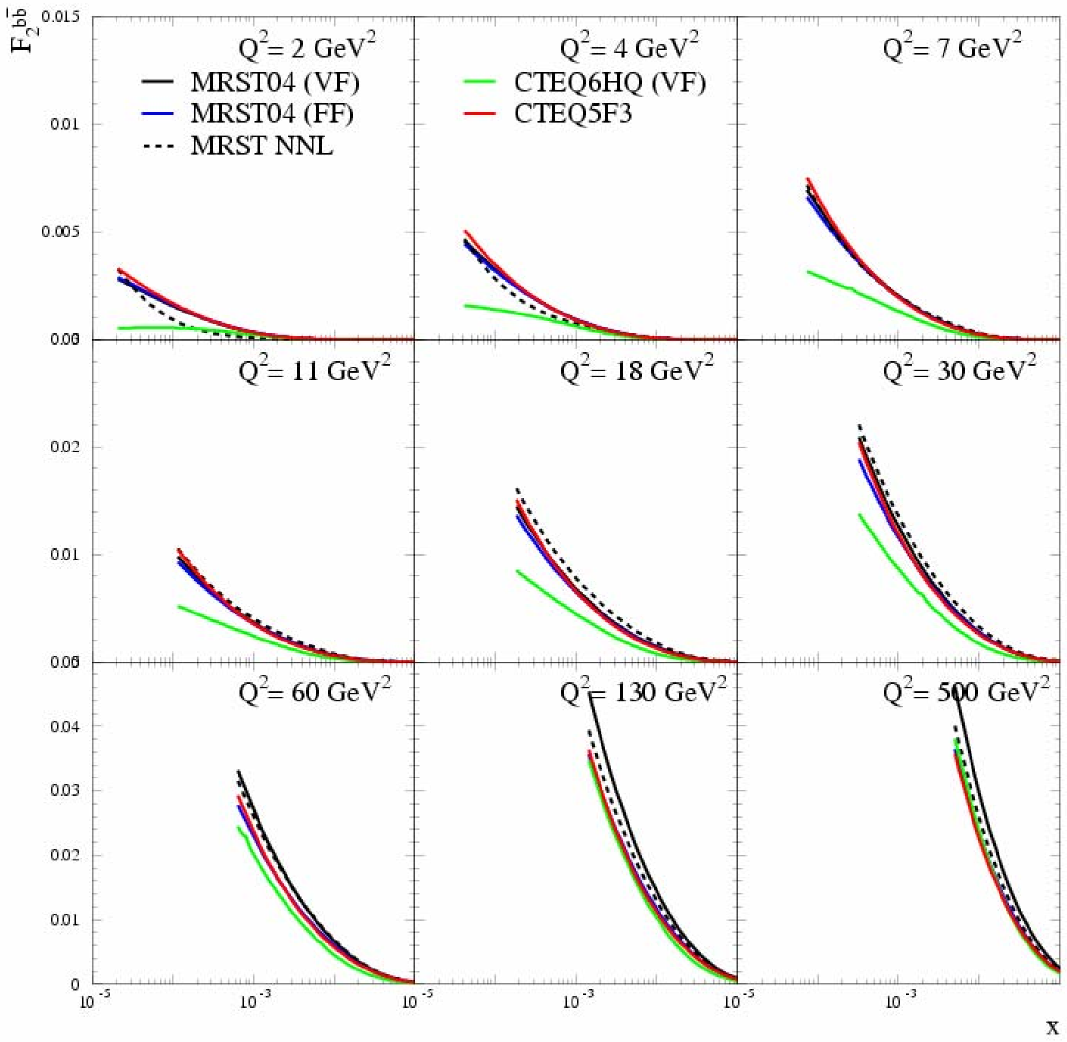
Can HERA-II data help to reduce this? Heavy flavour/jet measurements/F_L?

PDFs and charm



Large difference in PDFs at low Q^2. This arises from different schemes and different gluons.

PDFs and beauty



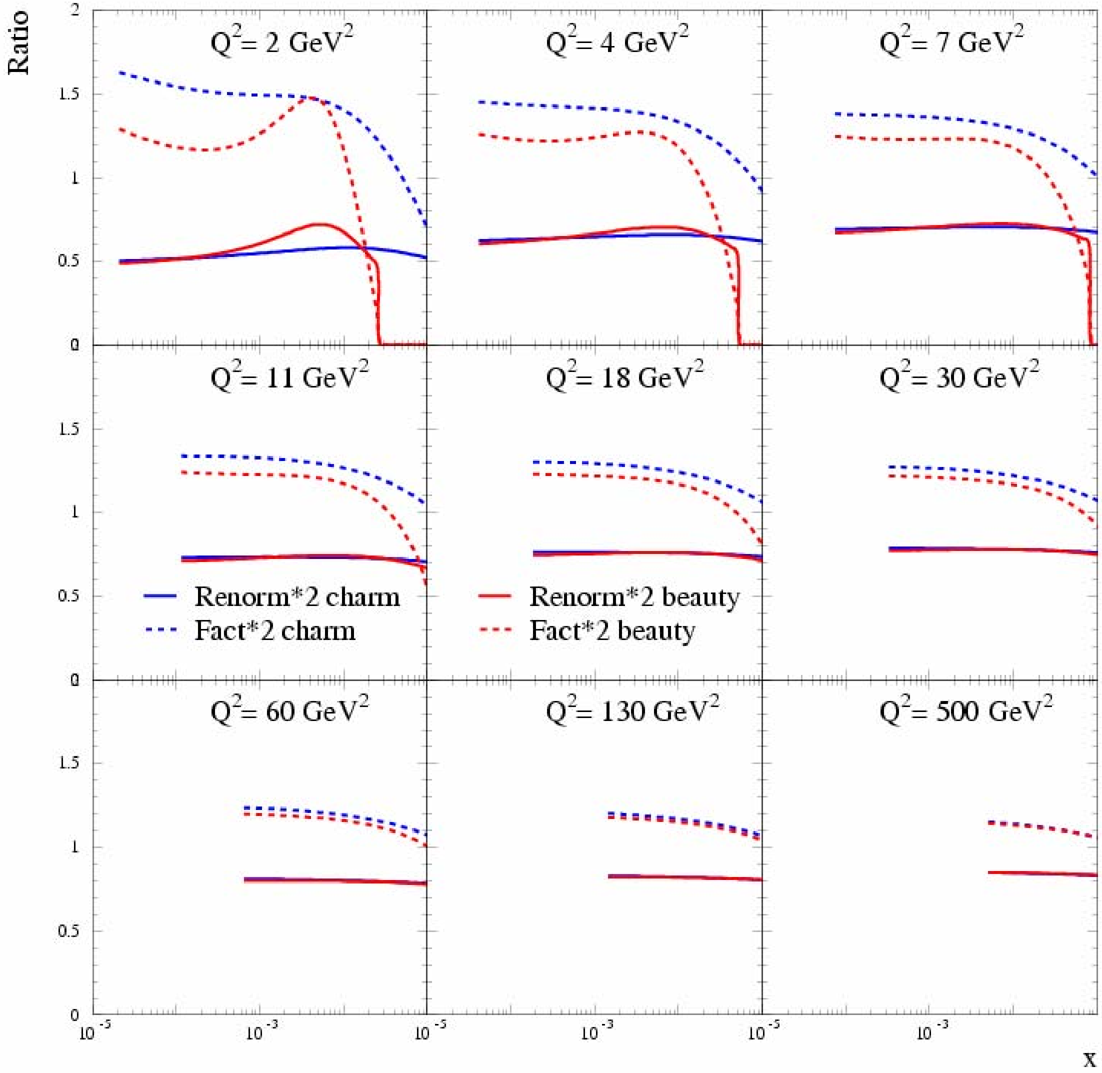
Higher mass increases effective x range and smaller differences between gluons.

HF schemes show differences. Possible to distinguish?

Need luminosity!

Scale uncertainties?

Scale Uncertainty



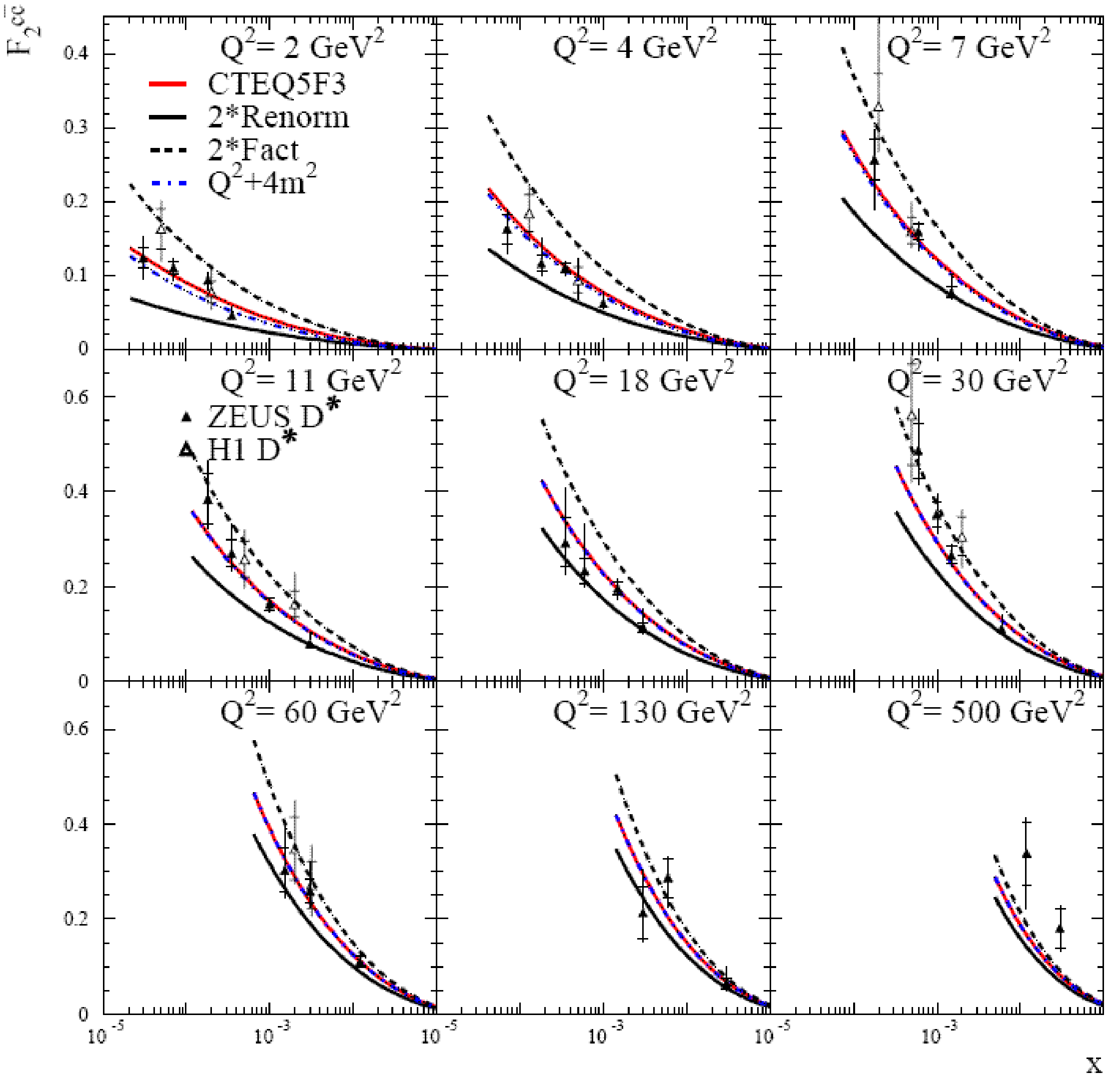
Renormalisation scale selects different α_s

Factorisation scale different gluon density.

Large uncertainties at low scales.

Uncertainties smaller for beauty.

Scale Uncertainty

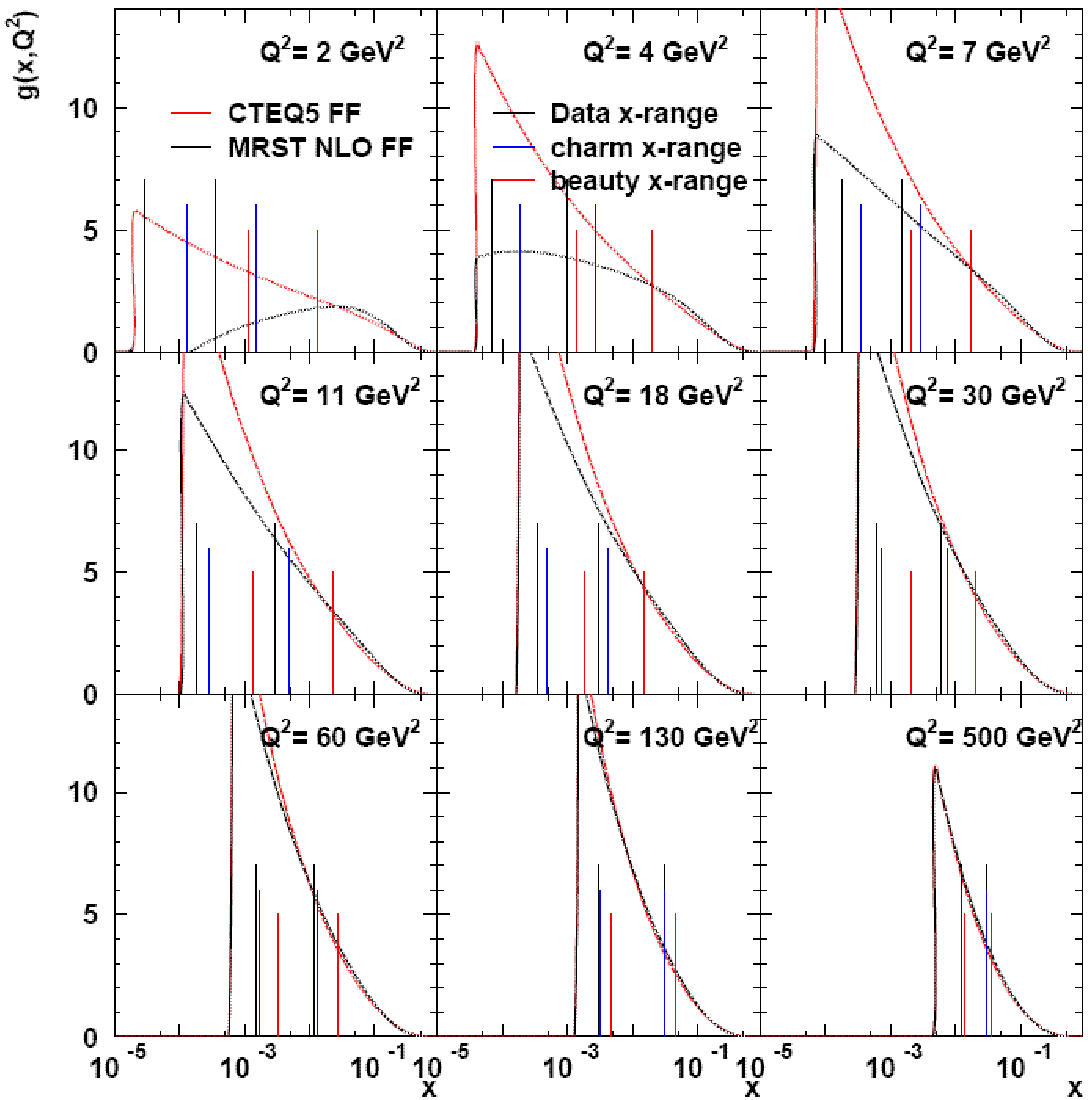


Small charm mass in scale has small effect

Scale uncertainties larger than data allow?

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

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

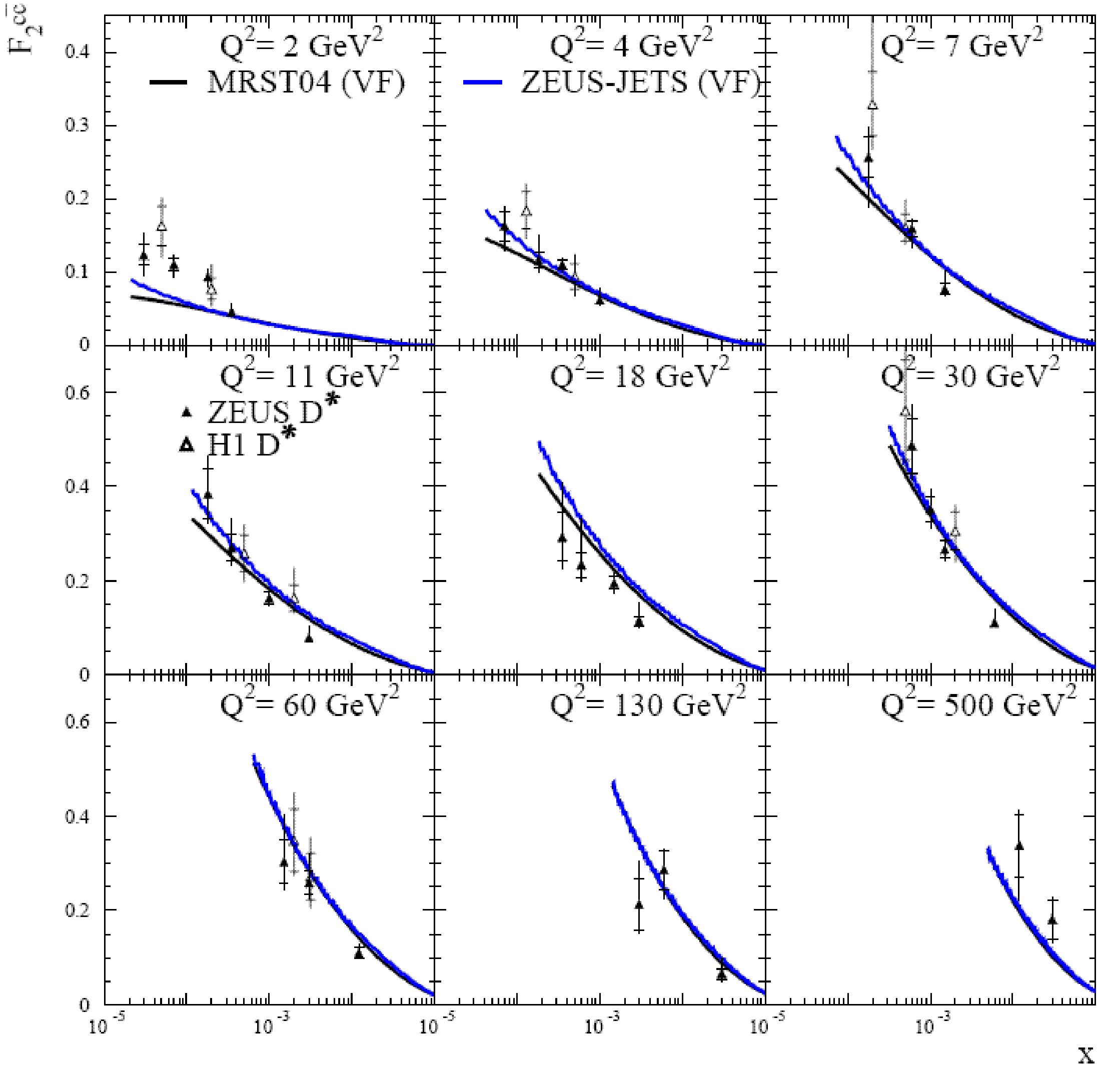
Blue – effective charm x

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

MRST/ZEUS PDF



Compare MRST/ZEUS PDFs

Which use Thorne-Roberts VFNS scheme

Low Q^2 region has large PDF/scale/scheme uncertainties plus data extrapolation uncertainties

Focus on beauty!

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. Beauty may be more useful for scheme testing. Need luminosity!