Impact of heavy-flavour production measurements by the LHCb experiment on the gluon distribution at low x

O. Zenaiev et al, arXiv:1503.04581

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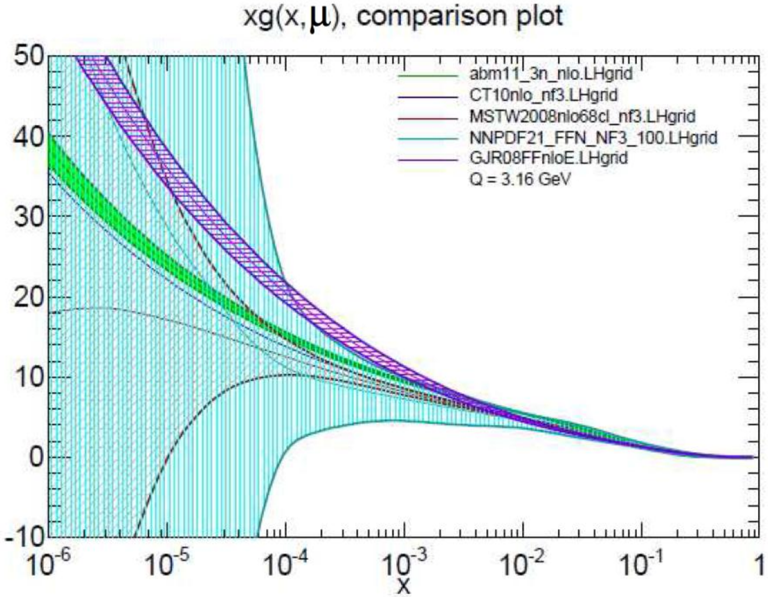
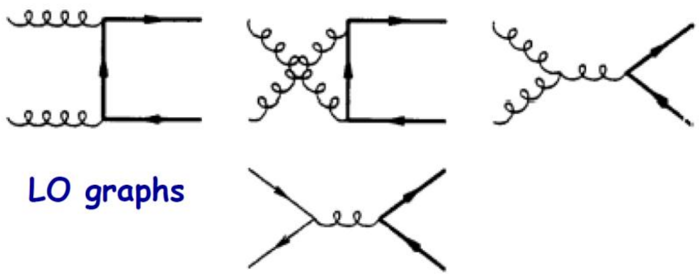
QCD@LHC2015



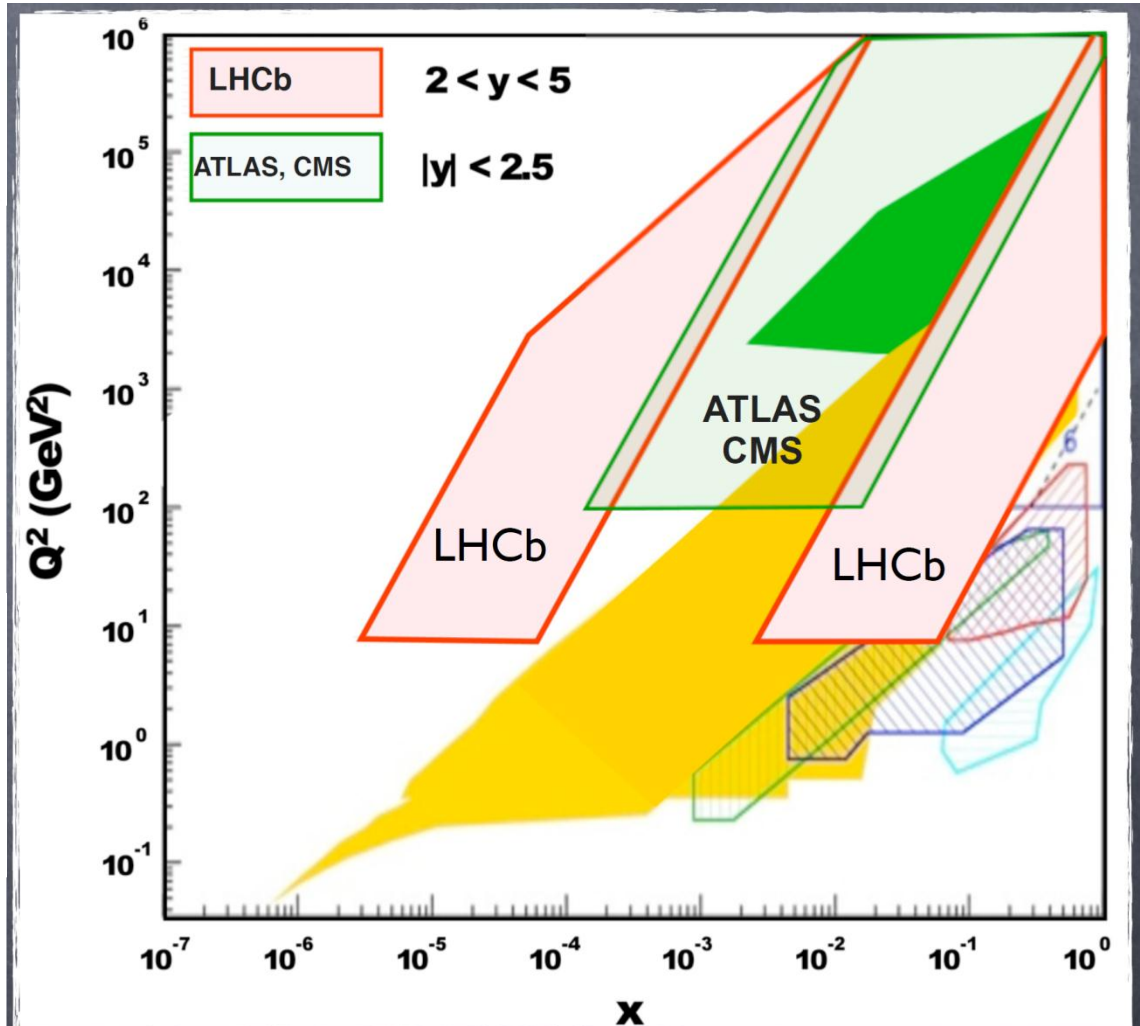
Current level of knowledge of gluon is poor for $x < 10^{-4}$

LHCb kinematic region extends to low x, for reasonably high Q^2

Use forward heavy flavour data to probe the gluon in this kinematic region

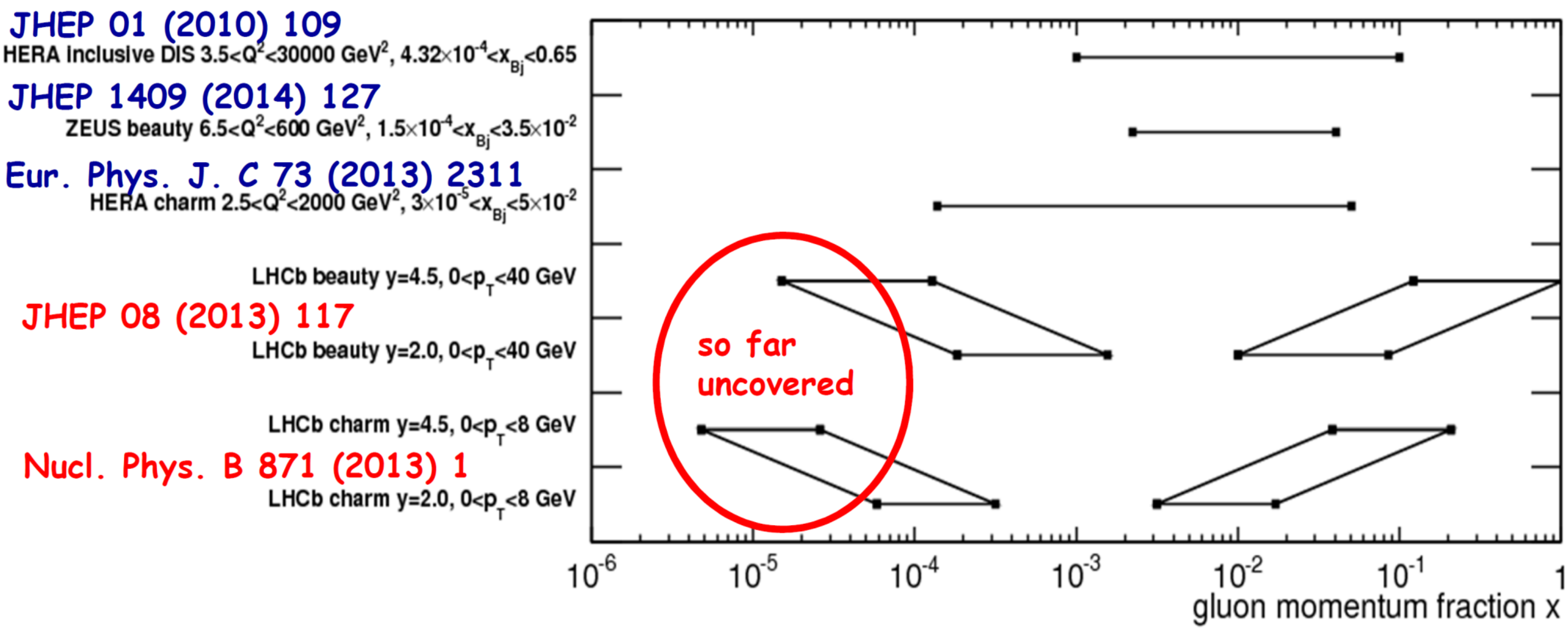


Charm and beauty masses provide hard scales



Input data sets

HERA I combined inclusive + HERA combined charm + ZEUS beauty + LHCb charm + LHCb beauty



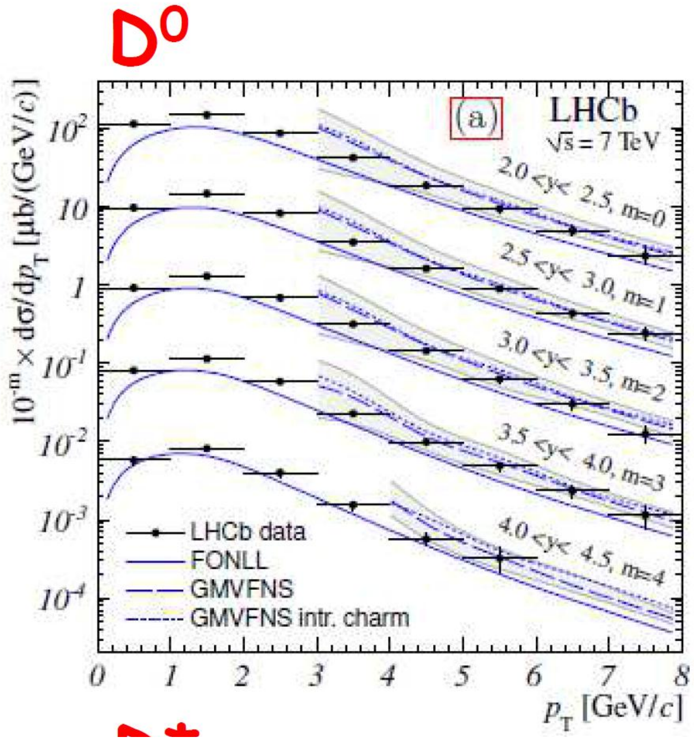
combination of data sets "bridges" complete x range

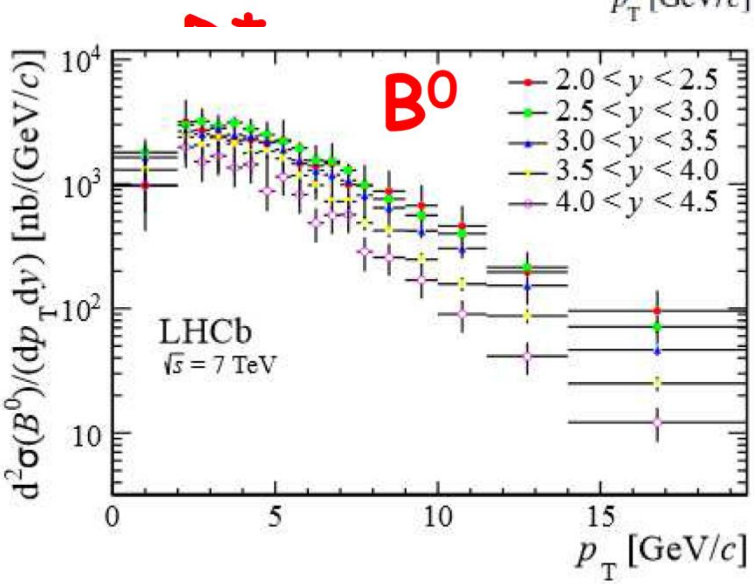
LHCb data in the QCD analysis

$D^0, D^+, D^{*+}, D^+_s, \Lambda_c$
$0 < p_T < 8$ GeV, $2.0 < y < 4.5$

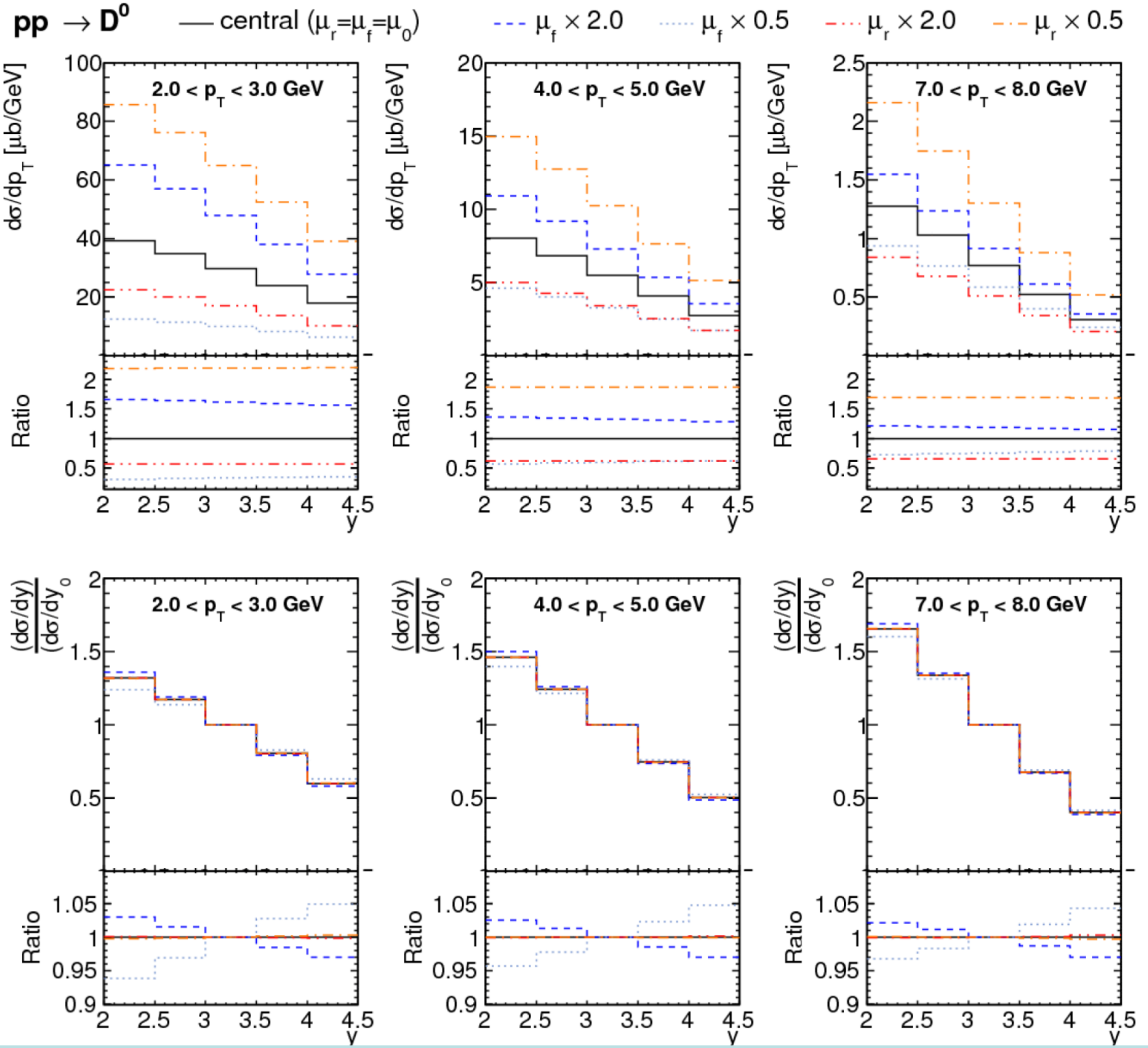
B^0, B^+, B^0_s
$0 < p_T < 40$ GeV, $2.0 < y < 4.5$

Theory describes data well but with large scale uncertainties.
PROSA study uses single differential fixed order NLO calculations for heavy flavours at LHC by Nason, Dawson, Ellis 1989 which are very fast and so can be input directly to QCD fits.
They are available as part of the MNR software package, Mangano, Nason, Ridolfi 1992, which was added to HERAFitter
They are similar to the FONLL predictions.





PROSA



$\mu_0=A\sqrt{(p_T^2+m_Q^2)}$

absolute cross section:

~factor 2

p_T-normalized cross section:

(use shape in y for each p_T bin, normalized to central y bin)

~ few %

Scale dependence of the predictions is much reduced if normalised cross-sections are used

QCD analysis framework

Use open-source QCD analysis framework HERAFitter *Eur.Phys.J. C75 (2015) 7, 304*

DGLAP NLO PDF evolution

Basic parametrization at the starting scale μ^2_0=1.4 GeV^2 (13 free parameters):

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}}, \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.
\end{aligned}
$$

$$
\begin{aligned}
x\,\overline{U} &= x\,\bar{u} \\
x\,\overline{D} &= x\,\bar{d} + x\,\bar{s} \\
B_{\overline{U}} &= B_{\overline{D}} \\
A_{\overline{U}} &= A_{\overline{D}}(1 - f_s) \\
f_s &= \bar{s}/(\bar{d} + \bar{s}) \equiv 0.31 \pm 0.08
\end{aligned}
$$

Normalization parameters A are determined by QCD sum rules

Fit (Hessian) uncertainties: originate from uncertainties of the data, using $\Delta\chi^2$=1

Parametrization uncertainties: originate from variations on assumed parametrization: additional parameters are added one by-one to the functional form; and of starting scale (μ^2_0=1.9 GeV^2). Largest difference of resulting PDFs to the central result (envelope) is assigned as uncertainty.

QCD analysis in FFNS: model input

- ✓ FFNS (Nf=3) for DIS data from openQCDrad *S. Alekhin et al, PRD86 (2012) 054009*

  QCD scales for heavy flavours $\mu_{r,f} = \sqrt{Q^2 + m^2_Q}$, light flavours $\mu_{r,f} = Q$

- ✓ MNR FFNS predictions for LHCb data, *P. Nason et al, NPB303 (1988) 607, NPB327 (1989) 49*

  M. Mangano et al, NPB373 (1992) 295

  QCD scales $\mu_{r,f} = A^Q_{r,f} \sqrt{p^2_T + m^2_Q}$

  .$A^Q_{r,f}$ =1 for the normalised fit but fthe values are free for the absolute fit, to obtain reasonable $\chi 2$

- ✓ m_c, m_b - free parameters in the fit, constrained by heavy-flavour cross section data
- ✓ Fragmentation via Kartvelishvili functions,

  charm as measured at HERA *[EPJ C59 (2009) 589, JHEP04 (2009) 082]*

  beauty as measured at LEP *[NPB565 (2000) 245]*

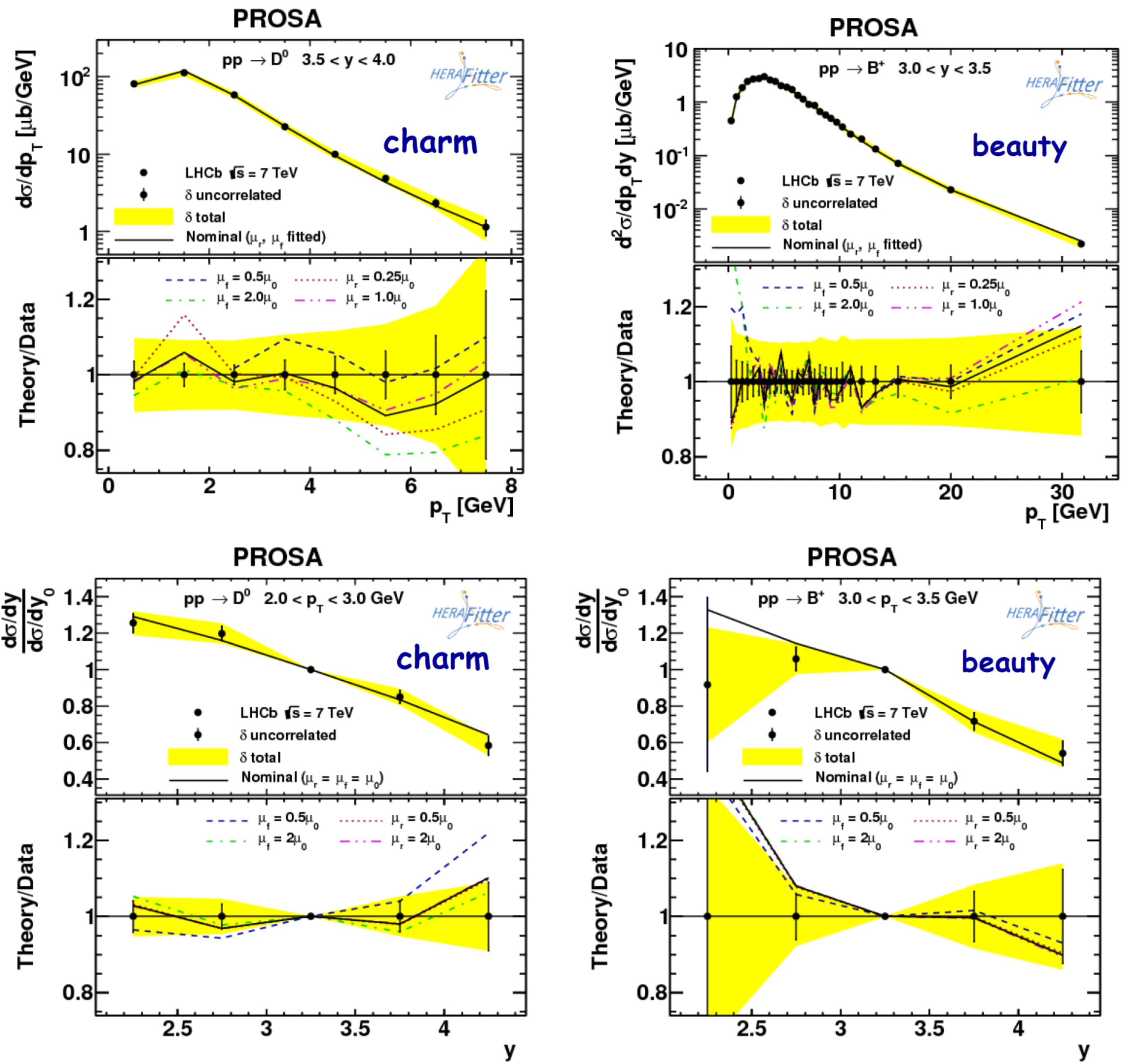
  Fragmentation fractions: combination of LEP and HERA measurements *[arXiv:1112.3757]*

- ✓ $\alpha_S(m_Z)^{Nf=3}$ =0.1059, corresponding to $\alpha_S(m_Z)^{Nf=5}$ = 0.1185

Model Uncertainty originates from following variations:

- QCD scales for heavy-flavour production varied independent by a factor of 2,
- fragmentation parameters varied by their uncertainties
- kinematics of inclusive DIS data: 2.5 GeV^2 < Q^2_{min} < 5 GeV^2
- fraction of strange quarks in the sea 0.23< f_s < 0.50, $\alpha_S(m_Z)^{Nf=3}$ ± 0.0005

Examples of the fit to LHCb data

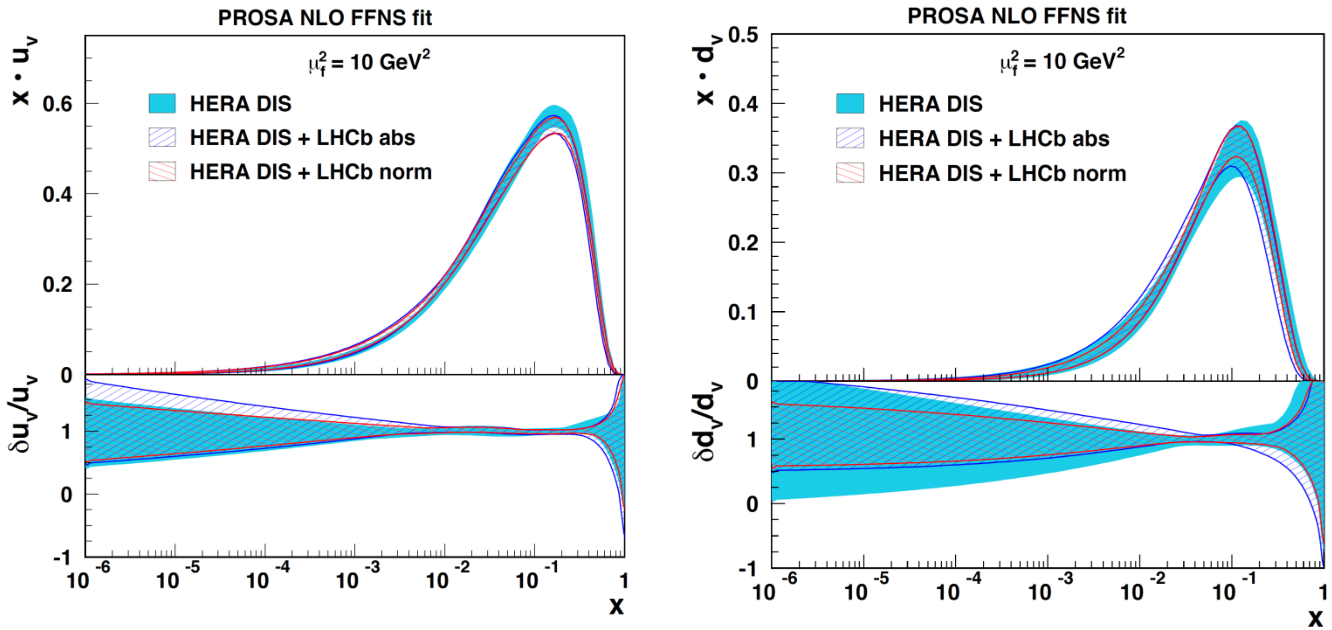


absolute

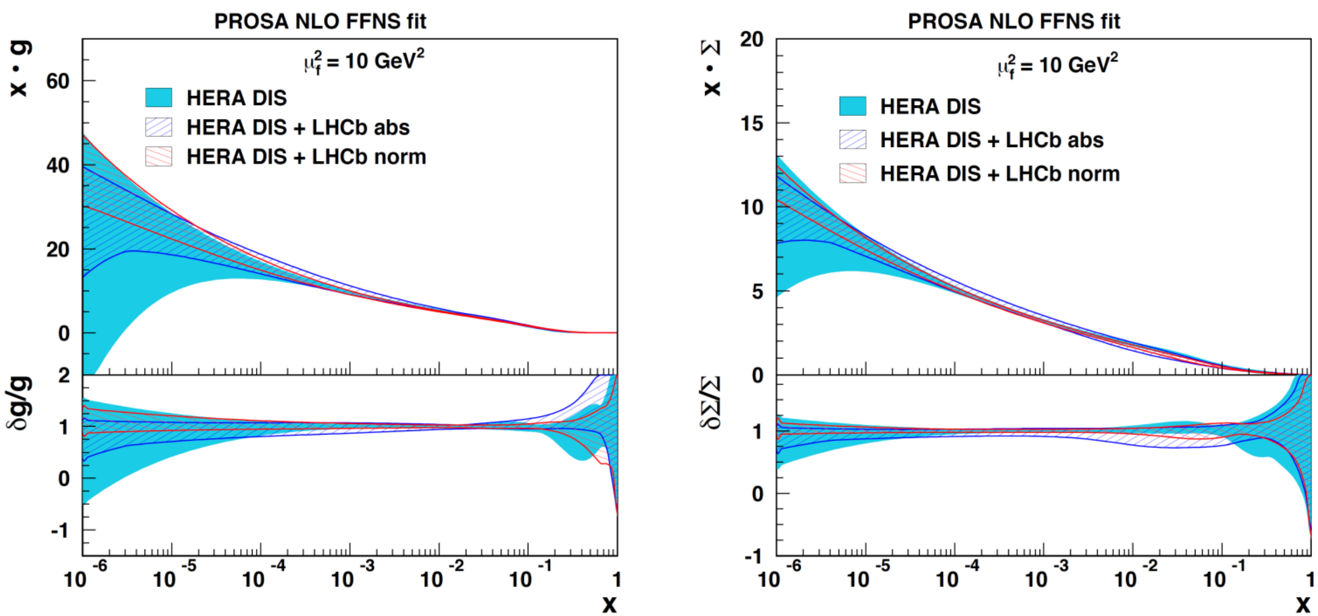
normalised

It is clear that scale sensitivity is reduced when fitting normalised spectra

Representation of the LHCb measurements	absolute	normalised
Global χ^2/n_{dof}	1073 / 1087	958 / 994
Global χ^2 p-value	0.61	0.79
χ^2-contribution from correlated uncertainties	73	49
χ^2-contribution from logarithmic correction	-129	48
Data set	partial χ^2/n_{dof}	
NC DIS HERA I combined $e^- p$	108 / 145	108 / 145
NC DIS HERA I combined $e^+ p$	419 / 379	419 / 379
CC DIS HERA I combined $e^- p$	26 / 34	26 / 34
CC DIS HERA I combined $e^+ p$	39 / 34	41 / 34
$c\bar{c}$ DIS HERA combined	78 / 52	47 / 52
$b\bar{b}$ DIS ZEUS Vertex	16 / 17	12 / 17
LHCb D^0	68 / 38	17 / 30
LHCb D^+	53 / 37	18 / 29
LHCb D^{*+}	50 / 31	19 / 22
LHCb D_s^+	24 / 28	11 / 20
LHCb Λ_c^+	5.3 / 6	4.9 / 3
LHCb B^+	99 / 135	81 / 108
LHCb B^0	66 / 95	35 / 76
LHCb B_s^0	78 / 75	23 / 60

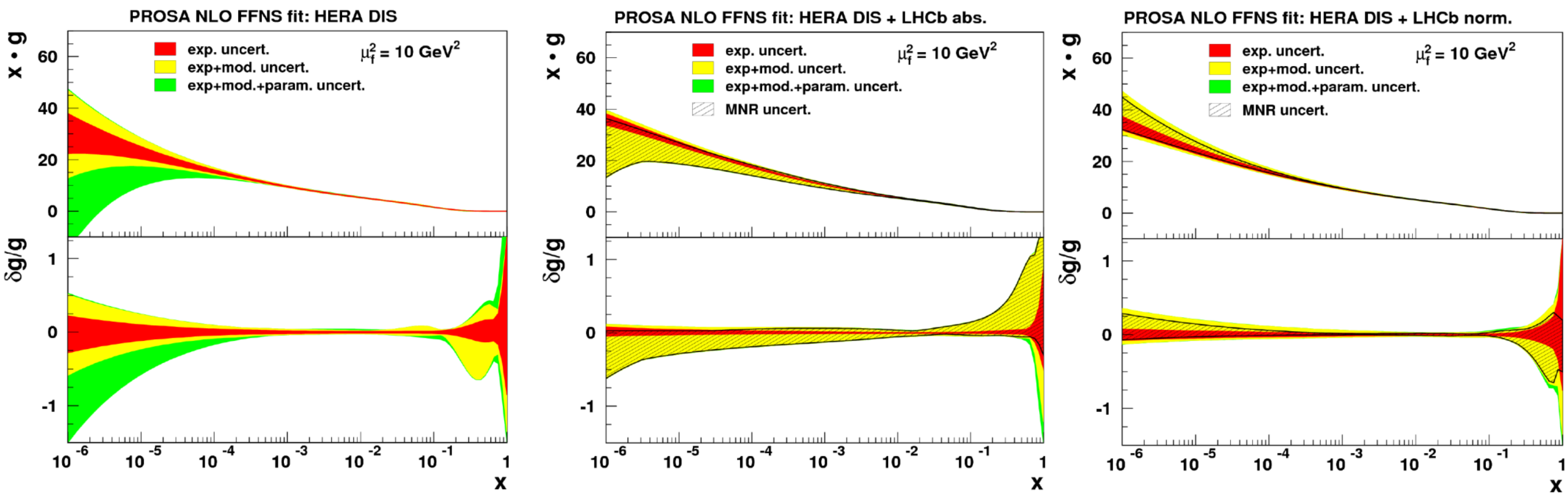


The results are consistent for the normalised and absolute cross sections



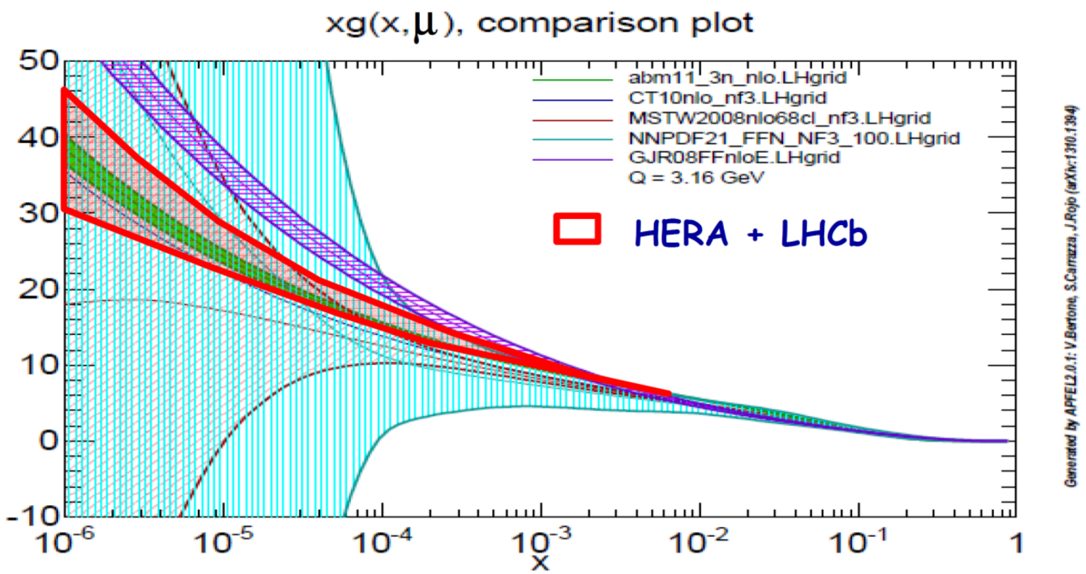
The gluon and sea uncertainties are significantly reduced at low x

And if we decompose this decrease in the gluon uncertainty we can see that both experimental and parametrisation uncertainty have decreased

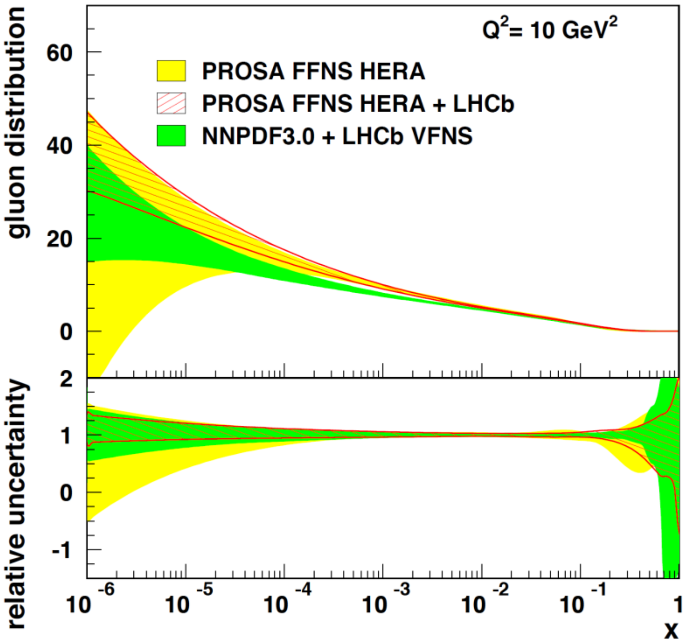


However there is still a significant scale uncertainty for the fits to absolute cross sections, which is reduced when normalised cross sections are used

So in comparison to the plot of global PDFs shown earlier



And in comparison to other recent work on the subject- see talk of R Gauld



Summary and Conclusions

Use of LHCb open heavy flavour data constrains PDFs at $x < 10^{-4}$

The gluon is constrained down to $x \sim 5 .10^{-6}$

This can yield improved precision for the estimation of neutrino fluxes produced by cosmic rays interacting in the atmosphere– of interest to IceCube

Fits to normalised cross sections have reduced scale uncertainty

Currently using QCD to fixed order at NLO in the FFN scheme– improvements to theory to NNLL /beyond fixed order? What are the implications for ln(1/x) resummation?

Back-up

Charm

at LHCb

Nucl.Phys. B871 (2013) 1-20

down to p_T = 0 GeV

large theory uncertainty at NLO (~factor 2) but also strong m_c dependence

directly sensitive to gluon down to $x \sim 10^{-5}$!

FONLL fits well (factor 2 scale uncertainty not shown)

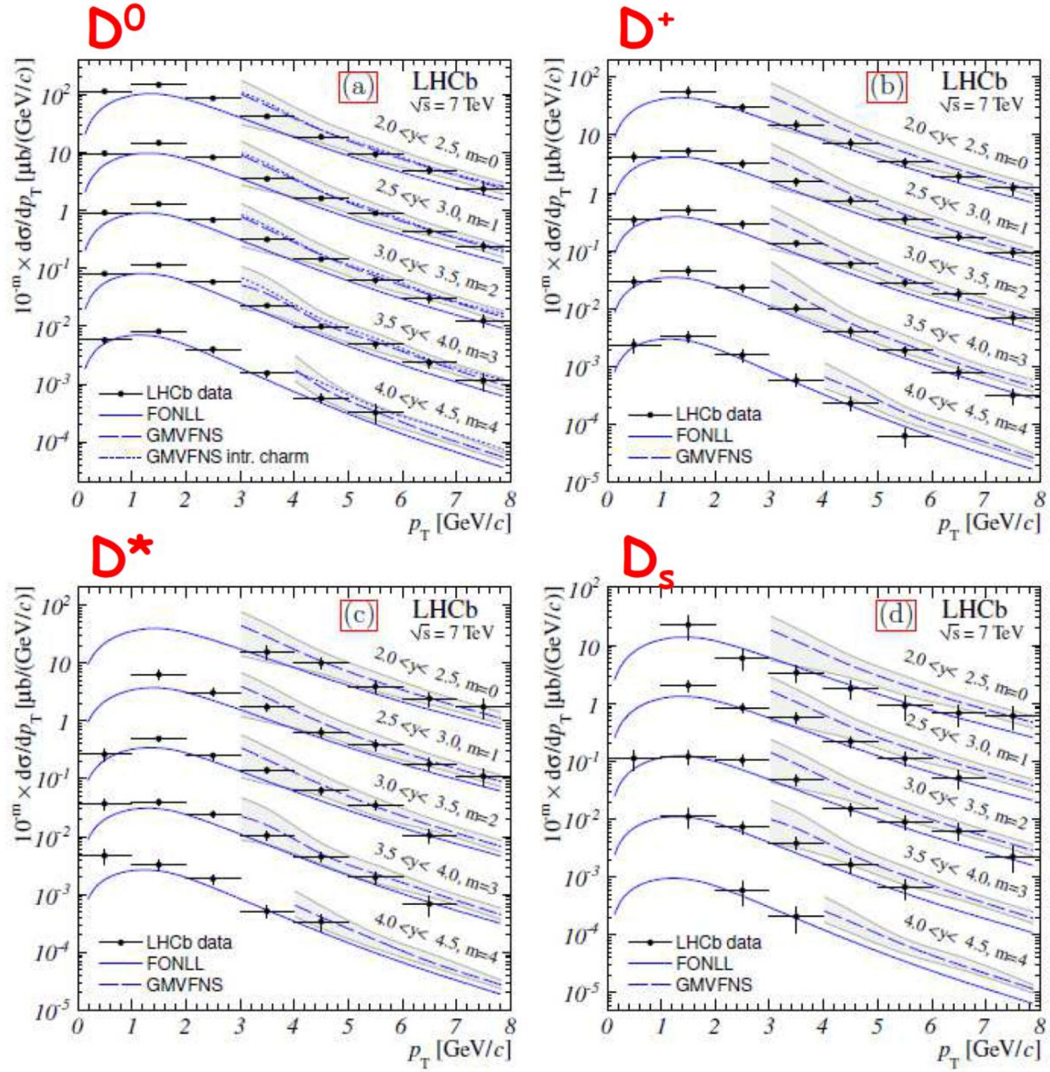
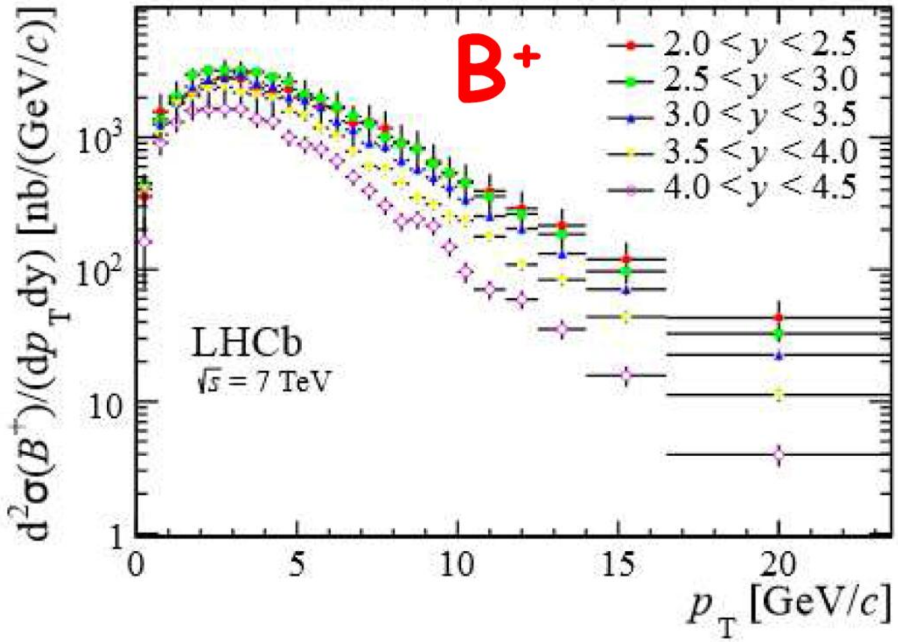
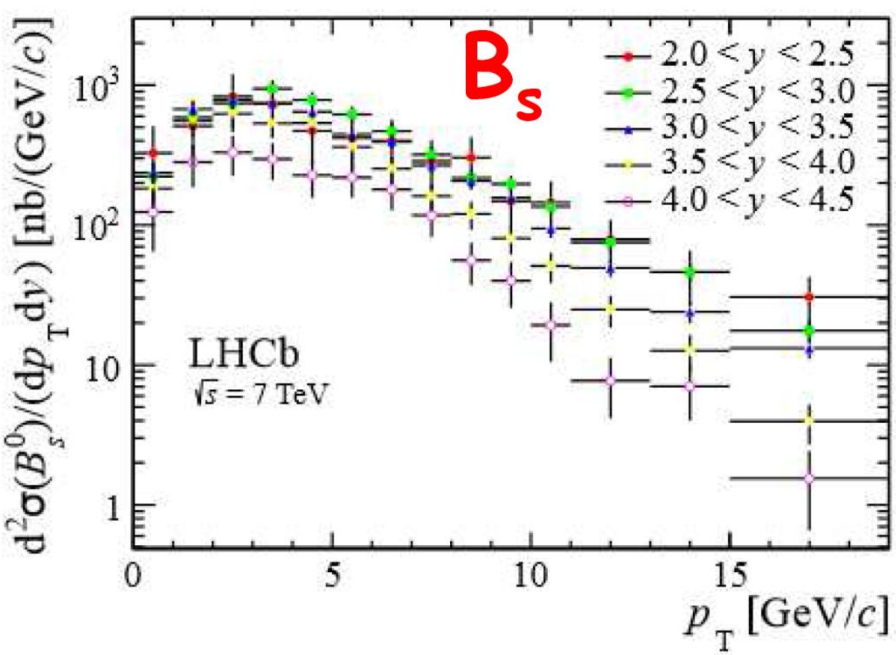


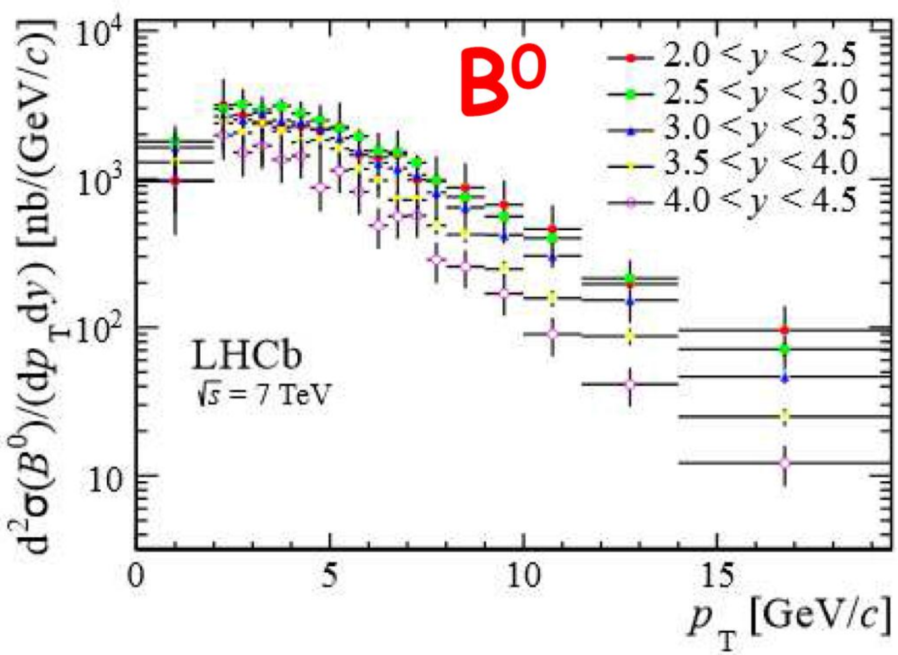
Figure 4: Differential cross-sections for (a) D^0, (b) D^+, (c) D^{*+}, and (d) D_s^+ meson production compared to theoretical predictions. The cross-sections for different y regions are shown as functions of p_T. The y ranges are shown as separate curves and associated sets of points scaled by factors 10^{-m}, where the exponent m is shown on the plot with the y range. The error bars associated with the data points show the sum in quadrature of the statistical and total systematic uncertainty. The shaded regions show the range of theoretical uncertainties for the GMVFNS prediction.

Beauty at LHCb

JHEP 08 (2013) 117

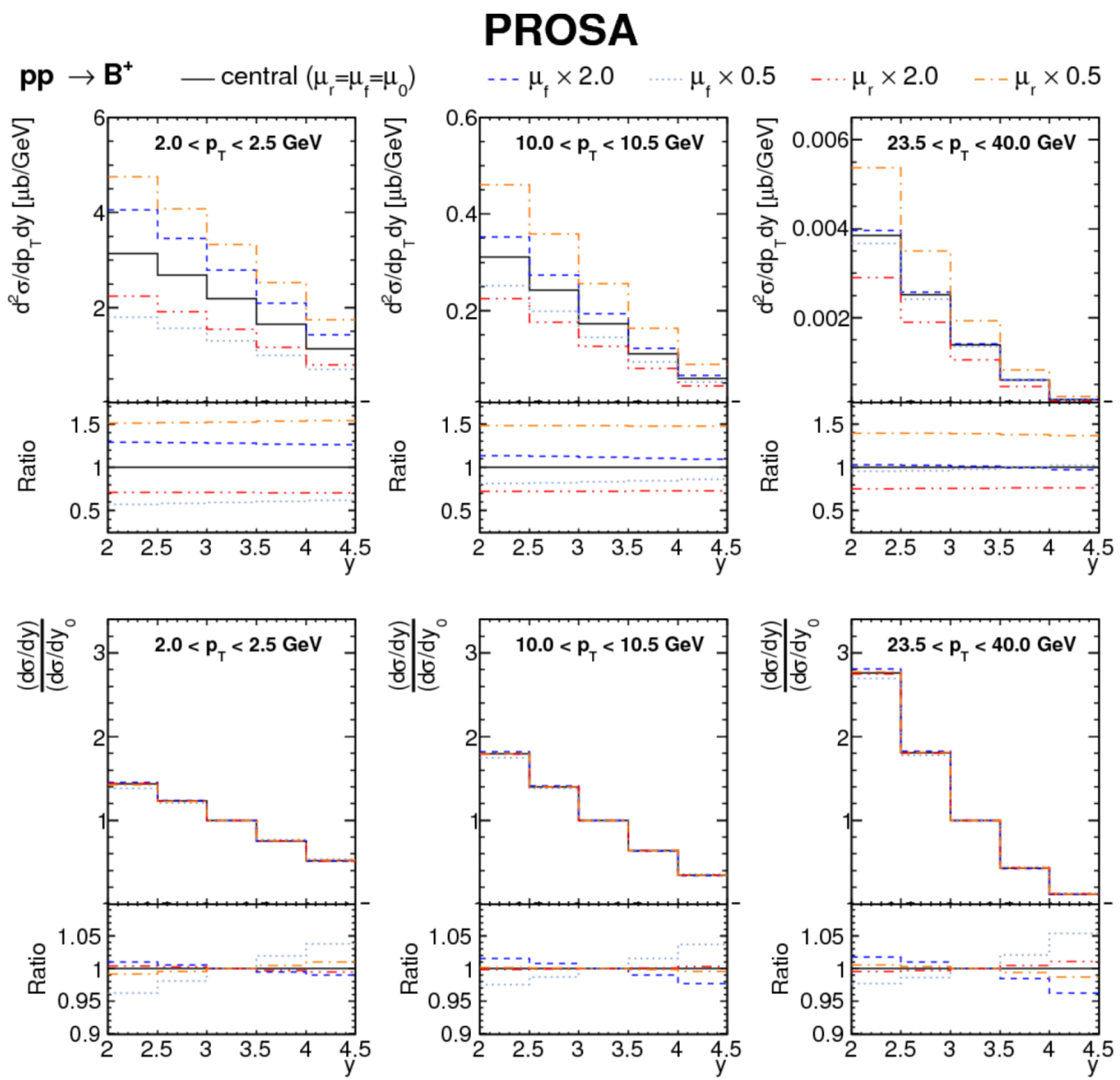






beauty at LHCb

similar to charm



- The scales are parametrised as:

$$\mu_f^c = A_f^c \sqrt{p_T^2 + m_c^2} \qquad (1)$$

$$\mu_r^c = A_r^c \sqrt{p_T^2 + m_c^2} \qquad (2)$$

$$\mu_f^b = A_f^b \sqrt{p_T^2 + m_b^2} \qquad (3)$$

$$\mu_r^b = A_r^b \sqrt{p_T^2 + m_b^2} \qquad (4)$$

  (4 free parameters for the nominal fit)
- Fragmentation function:
  - charm: $\alpha_k = 4.4 \pm 2.7$ (covers whole spread measured at HERA) (EPJC **59** (2009) 589, JHEP **0904** (2009) 082)
  - beauty: $\alpha_k = 11 \pm 4$ (from LEP) (PRD **55** (1997) 7134, NPB **565** (2000) 245)
- Fragmentation fractions:
  - charm: averaged LEP and HERA from [arXiv:1112.3757]
  - beauty: from the orig. LHCb paper JHEP 08 (2013) 117

PDFs: uncertainties estimation

Following procedure used for HERAPDF1.0:

Fit unc.:

- $\chi^2 = \chi^2 \pm 1$

Model unc.:

- $f_s = 0.31^{+0.07}_{-0.08}$
- m_c,m_b —free parameters (to be contrained by the HERA HF data), unc. included in the $\chi^2 = \chi^2 \pm 1$
- $Q^2_{min} = 3.5^{+1.5}_{-1.0}\ GeV^2$
- $\alpha_s(M_Z) = 0.1059 \pm 0.0005$; FFNS $n_f = 3$ running ($\alpha_s(M_Z) = 0.1185 \pm 0.0006$ for $n_f = 5$)
- HQ μ_f, μ_r varied simult. by a factor 2

Parametrisation unc.:

- $D_{u_v} \neq 0$
- $D_{\bar{D}} \neq 0$
- $D_{\bar{U}} \neq 0$
- $Q^2_0 = 1.9\ GeV^2$

(take the largest deviation)

Parameter	absolute	normalised
B_g	-0.14 ± 0.07	-0.08 ± 0.10
C_g	6.83 ± 0.31	5.23 ± 0.34
A'_g	1.74 ± 0.22	1.29 ± 0.32
B'_g	-0.19 ± 0.04	-0.16 ± 0.05
B_{u_v}	0.668 ± 0.020	0.649 ± 0.021
C_{u_v}	4.99 ± 0.23	4.98 ± 0.23
E_{u_v}	12.2 ± 2.4	13.5 ± 2.7
B_{d_v}	0.93 ± 0.09	0.96 ± 0.09
C_{d_v}	5.50 ± 0.56	5.59 ± 0.55
$C_{\overline{U}}$	1.63 ± 0.21	1.63 ± 0.24
$A_{\overline{D}}$	0.173 ± 0.007	0.158 ± 0.007
$B_{\overline{D}}$	-0.146 ± 0.006	-0.155 ± 0.007
$C_{\overline{D}}$	10.4 ± 2.5	15.1 ± 4.2
m_c	1.709 ± 0.024	1.257 ± 0.014
m_b	4.67 ± 0.08	4.19 ± 0.13
A^c_f	0.659 ± 0.020	1.0
A^b_f	0.262 ± 0.007	1.0
A^c_r	0.444 ± 0.021	1.0
A^b_r	0.335 ± 0.024	1.0