Heavy quark production and NPDFs

Ingo Schienbein
Université Grenoble Alpes/LPSC Grenoble

GDR Workshop "Partons and Nuclei"
Orsay, June 1-2, 2017

Motivation

- Charm and beauty production in pp has been shown to be useful to constrain the small-x gluon and quark sea
- Improved knowledge of small-x PDFs:
  - Important for studies of parton dynamics, non-linear effects and saturation
  - Important for physics of atmospheric showers, cross section predictions for UHE neutrino DIS, calculation of prompt lepton fluxes in the atmosphere
- What about charm and beauty production data in pA?

Motivation

- Top quark production in pp has been shown to be useful to constrain the (poorly known) large-x gluon
- Improved knowledge of large-x PDFs important
  - Test models of nucleon structure
  - New physics searches
    - Accurate description of the SM background
    - Improved predictions of new physics signals
- Won't discuss top quark case in the following

Outline

- Heavy quark production: Theory
- Comparisons with data
- PROSA study: constraining the small-x gluon of the proton with LHCb D/B data
- Some thoughts on the impact of heavy quark data in pA on NPDFs

Hadroproduction of heavy quarks: Theory

Different theoretical approaches

- **FFNS (Fixed Flavor Number Scheme = Fixed Order)**
- ZM-VFNS
- **GM-VFNS (General Mass Variable Flavor Number Scheme)**
- FONLL
- NLO Monte Carlo generators
- [k_T factorization]
- [Double parton scattering]
- [Diffractive production]

FFNS/Fixed Order

Factorization formula for inclusive heavy quark (Q) production:

PDFs

$$d\sigma^Q \simeq \sum_{a,b} f_a^A \otimes f_b^B \otimes d\tilde{\sigma}_{ab\to Q+X}$$

sum over all possible partonic subprocesses
NO heavy quark PDF

Calculable short distance cross section;
log(pT/m) terms kept in **fixed order**

FFNS/Fixed Order

Factorization formula for inclusive heavy quark (Q) production:

PDFs

$$d\sigma^Q \simeq \sum_{a,b} f_a^A \otimes f_b^B \otimes d\tilde{\sigma}_{ab\to Q+X}$$

sum over all possible partonic subprocesses
NO heavy quark PDF

Calculable short distance cross section; log(pT/m) terms kept in **fixed order**

Inclusive heavy-flavored hadron (H) production:

$$d\sigma^H = d\sigma^Q \otimes D_Q^H(z)$$

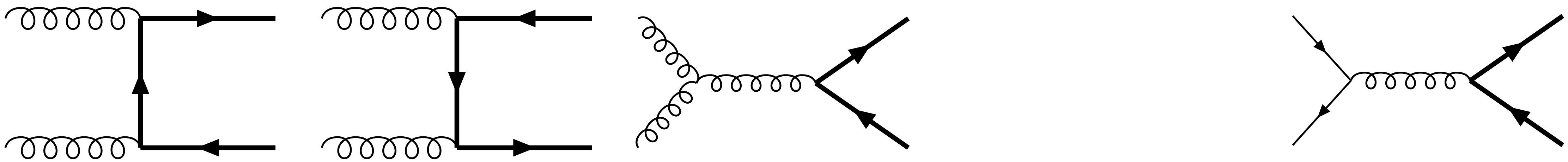
Convolution with a **scale-independent** FF

* non-perturbative
* describes hadronization
* not based on a fact. theorem

Leading Order (LO)

Leading order subprocesses:

1. $gg \to Q\bar{Q}$
2. $q\bar{q} \to Q\bar{Q} \quad (q = u, d, s)$



- The gg-channel is dominant at the LHC ($\sim$ 85% at $\sqrt{S} = 14$ TeV).
- The total production cross section for heavy quarks is fi nite.
  The minimum virtuality of the t-channel propagator is m^2. Sets the scale in α_s.
  Perturbation theory should be reliable.
- Note: For $m^2 \to 0$ total cross section would diverge.

[See M. Mangano, hep-ph/9711337; Textbook by Ellis, Stirling and Webber]

Next-to-leading Order (NLO)

Next-to-leading order (NLO) subprocesses:

1. $gg \to Q\bar{Q}g$
2. $q\bar{q} \to Q\bar{Q}g \quad (q = u, d, s)$
3. $gq \to Q\bar{Q}q$, $g\bar{q} \to Q\bar{Q}\bar{q}$ [new at NLO]
4. Virtual corrections to $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$

Next-to-leading Order (NLO)

Next-to-leading order (NLO) subprocesses:

1. $gg \to Q\bar{Q}g$
2. $q\bar{q} \to Q\bar{Q}g \quad (q = u, d, s)$
3. $gq \to Q\bar{Q}q$, $g\bar{q} \to Q\bar{Q}\bar{q}$ [new at NLO]
4. Virtual corrections to $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$

NLO known since ~20 years

Next-to-leading Order (NLO)

Next-to-leading order (NLO) subprocesses:

1. $gg \to Q\bar{Q}g$
2. $q\bar{q} \to Q\bar{Q}g \quad (q = u, d, s)$
3. $gq \to Q\bar{Q}q$, $g\bar{q} \to Q\bar{Q}\bar{q}$ [new at NLO]
4. Virtual corrections to $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$

NLO known since ~20 years

NLO corrections for $\sigma_{\rm tot}$ and differential cross sections $d\sigma/dp_T dy$ known since long:

- Nason, Dawson, Ellis, NPB303(1988)607; Beenakker, Kuif, van Neerven, Smith, PRD40(1989)54 [$\sigma_{\rm tot}$]
- NDE, NPB327(1989)49; (E)B335(1990)260; Beenakker *et al.*,NPB351(1991)507 [$d\sigma/dp_T dy$]

Well tested by recalculations and zero-mass limit:

- Bojak, Stratmann, PRD67(2003)034010 [$d\sigma/dp_T dy$ (un)polarized]
- Kniehl, Kramer, Spiesberger, IS, PRD71(2005)014018 [$m \to 0$ limit of diff. x-sec]
- Czakon, Mitov, NPB824(2010)111 [$\sigma_{\rm tot}$, fully analytic]

Next-to-next-to-leading Order (NNLO)

Channels: $q\bar{q}$, gg, qg

- Two-loop virtual most difficult $M_2^{(0)} + M_2^{(1)} + M_2^{(2)}$
  - Analytic approach: Bonciani, Ferroglia, Gehrmann, Maitre, Studerus, von Manteuffel ('08-'10)
  - Numeric approach: Czakon, Mitov et al.
- Virtual + Real $M_3^{(0)} + M_3^{(1)}$
  Dittmaier, Uwer, Weinzierl ('08)
- Subtraction method for IR singularities in double real $M_4^{(0)}$
  Czakon ('10-'11)

Next-to-next-to-leading Order (NNLO)

- Available for top pair production!
- Total cross section — Czakon, Mitov, PRL110(2013)252004
- Differential distributions — Czakon, Mitov, arXiv:1411.3007

Very large scale uncertainties at NLO in c,b production

NNLO will be crucial to make progress!

GM-VFNS

Factorization Formula: [1]

$$d\sigma(p\bar{p} \to D^\star X) = \sum_{i,j,k} \int dx_1\, dx_2\, dz\, f_i^p(x_1)\, f_j^{\bar{p}}(x_2) \times$$
$$\mathrm{d}\hat{\sigma}(ij \to kX)\, D_k^{D^\star}(z) + \mathcal{O}(\alpha_s^{n+1}, (\tfrac{\Lambda}{Q})^p)$$

Q: hard scale, $p = 1, 2$

- $\mathrm{d}\hat{\sigma}(\mu_F, \mu'_F, \alpha_s(\mu_R), \frac{m_h}{p_T})$: hard scattering cross sections free of long-distance physics $\longrightarrow$ m_h kept
- PDFs $f_i^p(x_1, \mu_F)$, $f_j^{\bar{p}}(x_2, \mu_F)$: $i, j = g, q, c$ $\quad [q = u, d, s]$
- FFs $D_k^{D^\star}(z, \mu'_F)$: $k = g, q, c$

$\Rightarrow$ need short distance coefficients including heavy quark masses

---

[1] J. Collins, 'Hard-scattering factorization with heavy quarks: A general treatment', PRD58(1998)094002

List of subprocesses in the GM-VFNS

#	Only light lines	Heavy quark initiated ($m_Q = 0$)	Mass effects: $m_Q \neq 0$
1	$gg \to qX$	-	$gg \to QX$
2	$gg \to gX$	-	-
3	$qg \to gX$	$Qg \to gX$	-
4	$qg \to qX$	$Qg \to QX$	-
5	$q\bar{q} \to gX$	$Q\bar{Q} \to gX$	-
6	$q\bar{q} \to qX$	$Q\bar{Q} \to QX$	-
7	$qg \to \bar{q}X$	$Qg \to \bar{Q}X$	-
8	$qg \to \bar{q}'X$	$Qg \to \bar{q}X$	$qg \to \bar{Q}X$
9	$qg \to q'X$	$Qg \to qX$	$qg \to QX$
10	$qq \to gX$	$QQ \to gX$	-
11	$qq \to qX$	$QQ \to QX$	-
12	$q\bar{q} \to q'X$	$Q\bar{Q} \to qX$	$q\bar{q} \to QX$
13	$q\bar{q}' \to gX$	$Q\bar{q} \to gX$, $q\bar{Q} \to gX$	-
14	$q\bar{q}' \to qX$	$Q\bar{q} \to QX$, $q\bar{Q} \to qX$	-
15	$qq' \to gX$	$Qq \to gX$, $qQ \to gX$	-
16	$qq' \to qX$	$Qq \to QX$, $qQ \to qX$	-

$\oplus$ charge conjugated processes

Limiting cases

- **GM-VFNS → ZM-VFNS for p_T >> m**
  (this is the case by construction)

- **GM-VFNS → FFNS for p_T ~ m**
  (formally this can be shown; numerically problematic, requires appropriate scale choice)

Termes in the perturbation series

$L = \ln(m/p_T)$
$a = \alpha_s/(2\pi)$

Resummed ↓

Fixed Order →

	LL	NLL	NNLL	...
LO	1			
NLO	aL	a		
NNLO	$(aL)^2$	$a(aL)$	a^2	
...	...	...	...	...

FFNS/Fixed Order NLO

Resummed ↓

Fixed Order →

	LL	NLL	NNLL	...
LO $m \neq 0$	1			
NLO $m \neq 0$	aL	a		
NNLO	$(aL)^2$	a(aL)	a^2	
...	...	...	...	...

ZM-VFNS/Resummed NLO

Resummed ↓

Fixed Order →

	LL m=0	NLL m=0	NNLL	...
LO	1			
NLO	aL	a		
NNLO	$(aL)^2$	$a(aL)$	a^2	
...	...	...	...	...

GM-VFNS/FONLL (NLO+NLL)

Resummed ↓

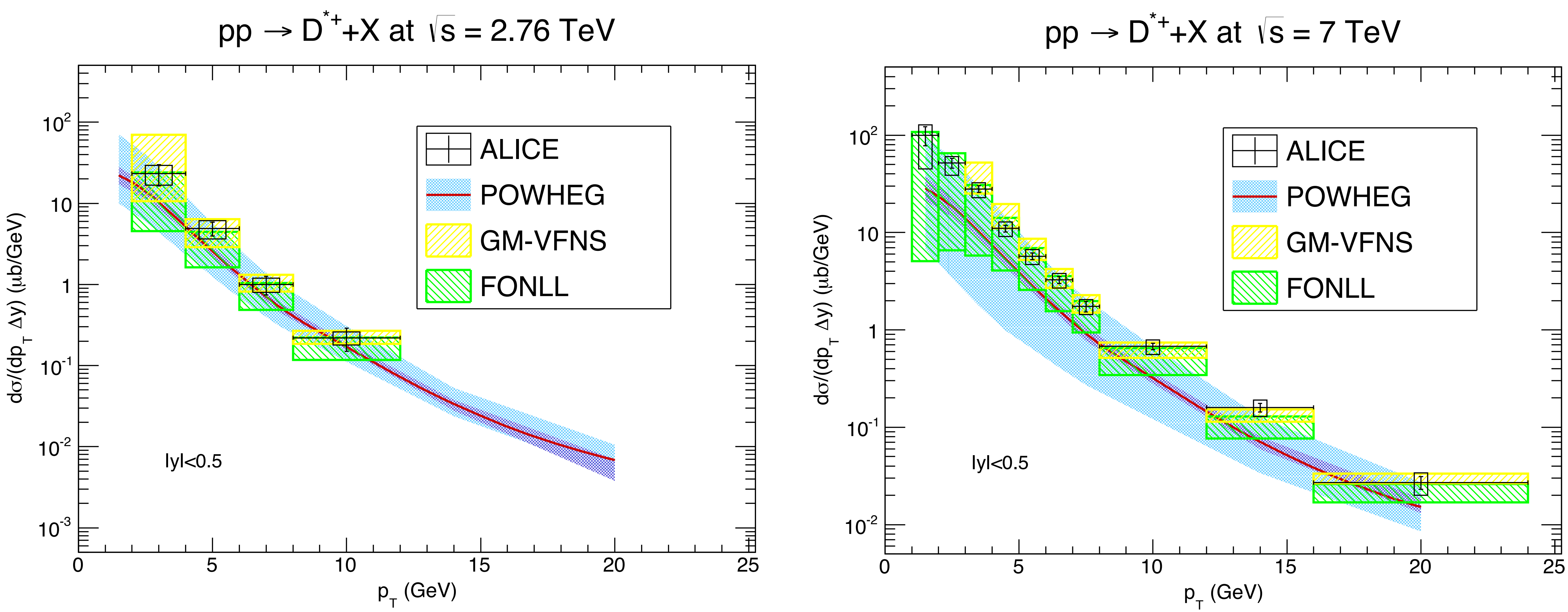
Fixed Order →

	LL	NLL	NNLL	...
LO	1 m≠0			
NLO	aL m≠0	a m≠0		
NNLO	$(aL)^2$ m=0	a(aL) m=0	a^2	
...	... m=0	... m=0	...	...

Some comparisons of the GM-VFNS with data

Comparison with ALICE data

arXiv:1405.3083



Central scale choice: $\mu_R=\mu_F=\mu_F'=m_T$

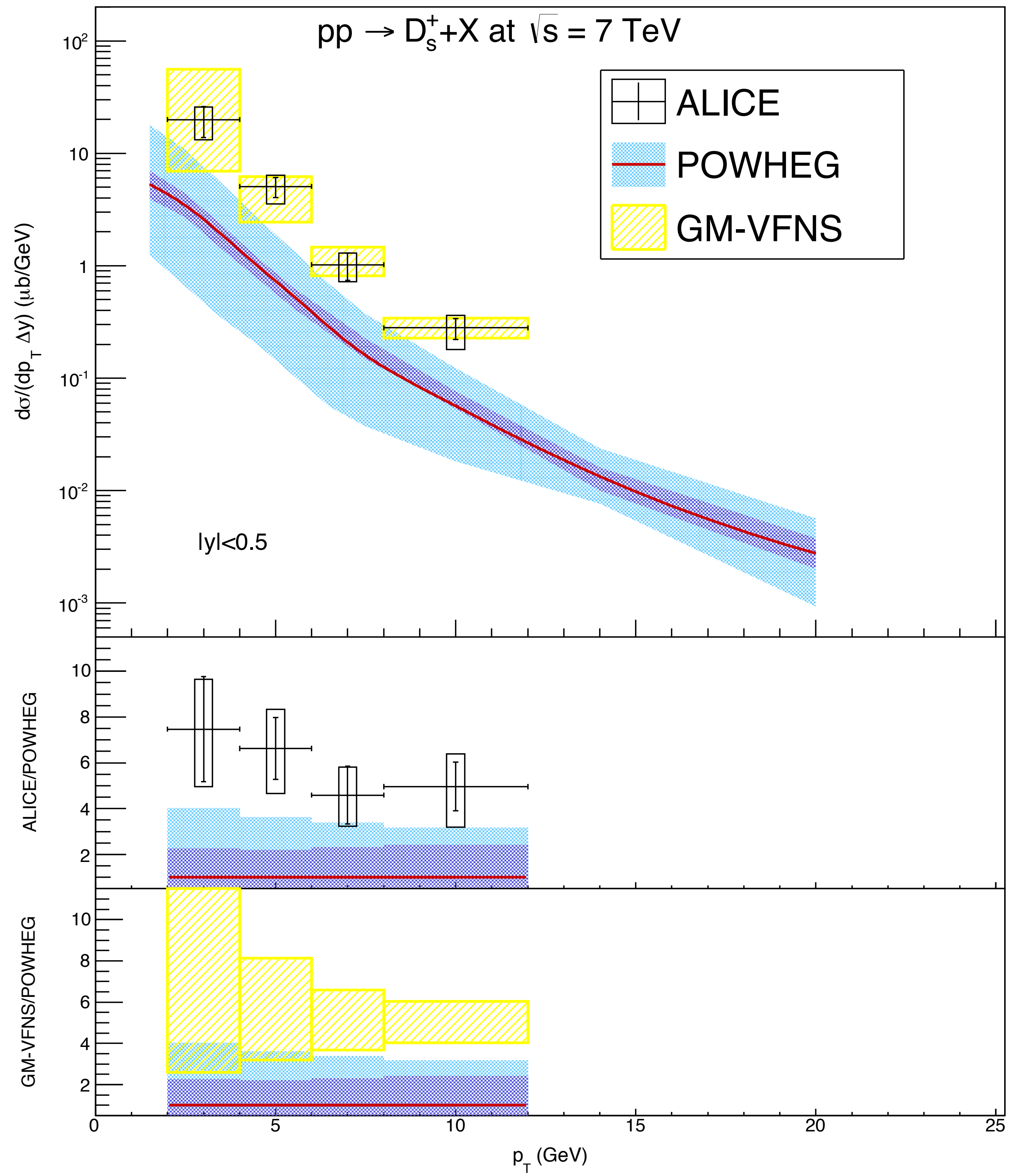
Uncertainty band: varying the scales by a factor 2 up/down

CT10 PDFs, KKKS FFs, m_c = 1.5 GeV

Comparison with ALICE data

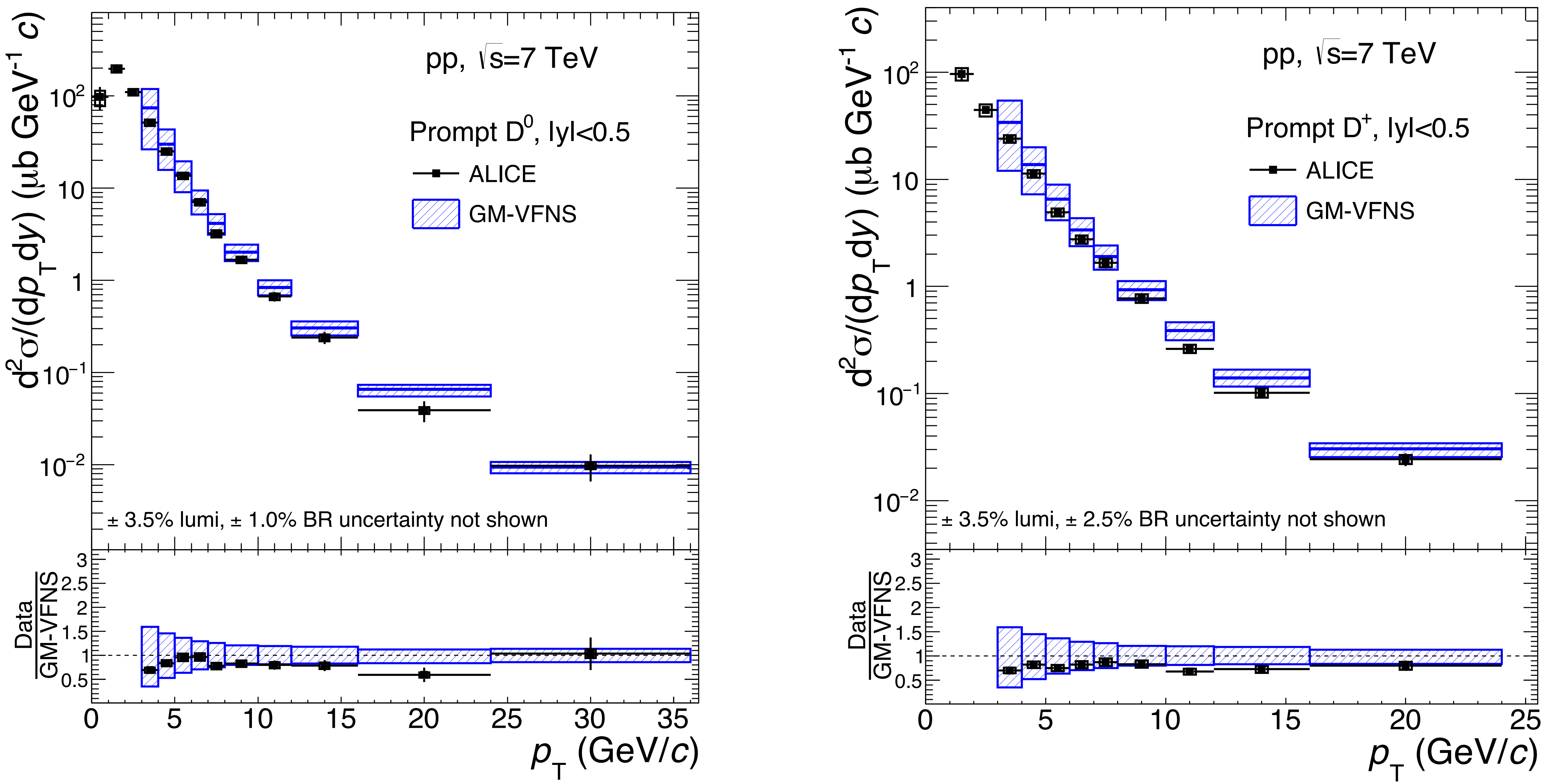
D_s FFs from Kniehl, Kramer'06

arXiv:1405.3083



Comparison with most recent ALICE data

arXiv:1702.00766



Conclusion

- There are many more data in pp both for D and B mesons
- Generally, GM-VFNS in good agreement with data
- Large scale uncertainties!
  To make progress need NNLO
- Results for p-Pb soon to come

Constraining the small-x gluon in the proton

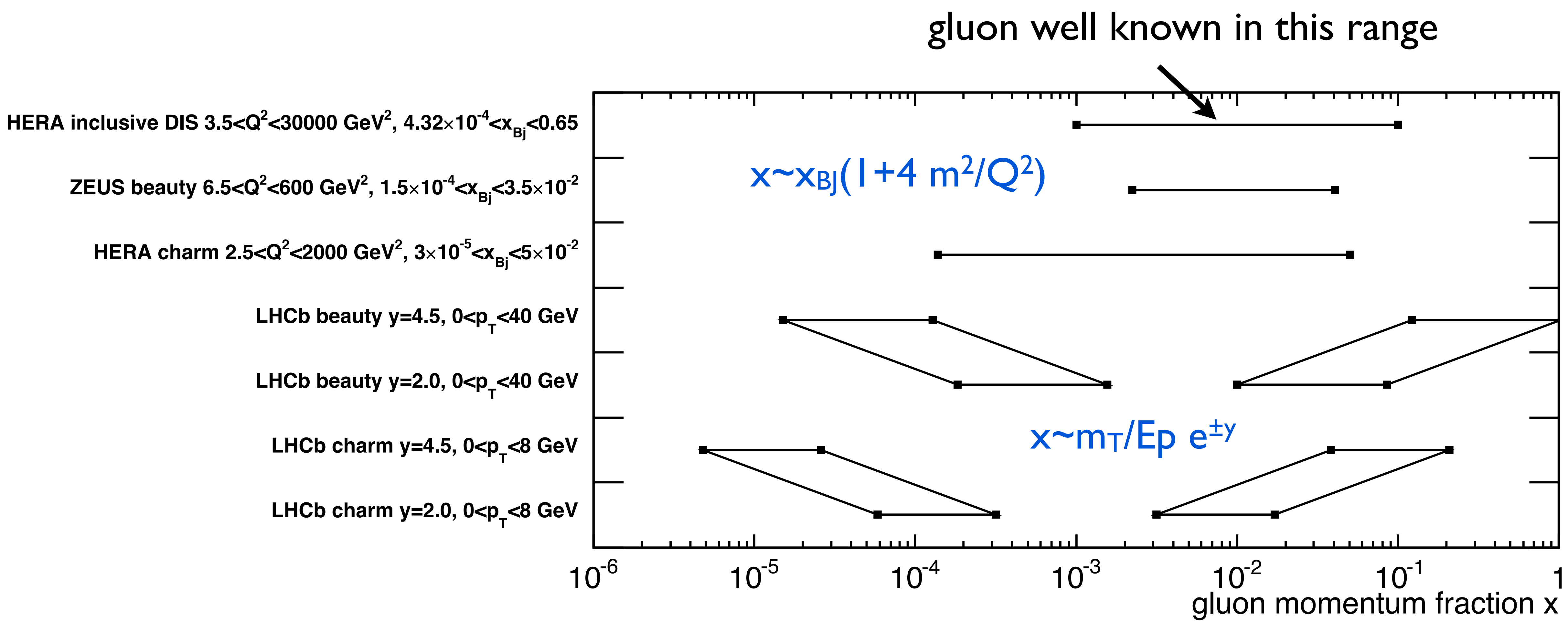
PROSA study

O. Zenaiev et al, EPJC75(2015)396

- NLO QCD analysis of impact of data for heavy quark production in ep and pp collisions on PDFs
- Theory for heavy quark production in ep, pp: FFNS at NLO
- Data:
  - HERA: Inclusive DIS cross sections in ep
  - HERA: Heavy flavour production cross sections in ep
  - LHCb: Differential cross sections for c (D^0, D^+, D^{*+}, D_s^+, Λ_c) and b (B^+, B^0, B_s^0) production in pp at LHC7
- Result:
  LHCb data impose constraints on low-x gluon and quark sea

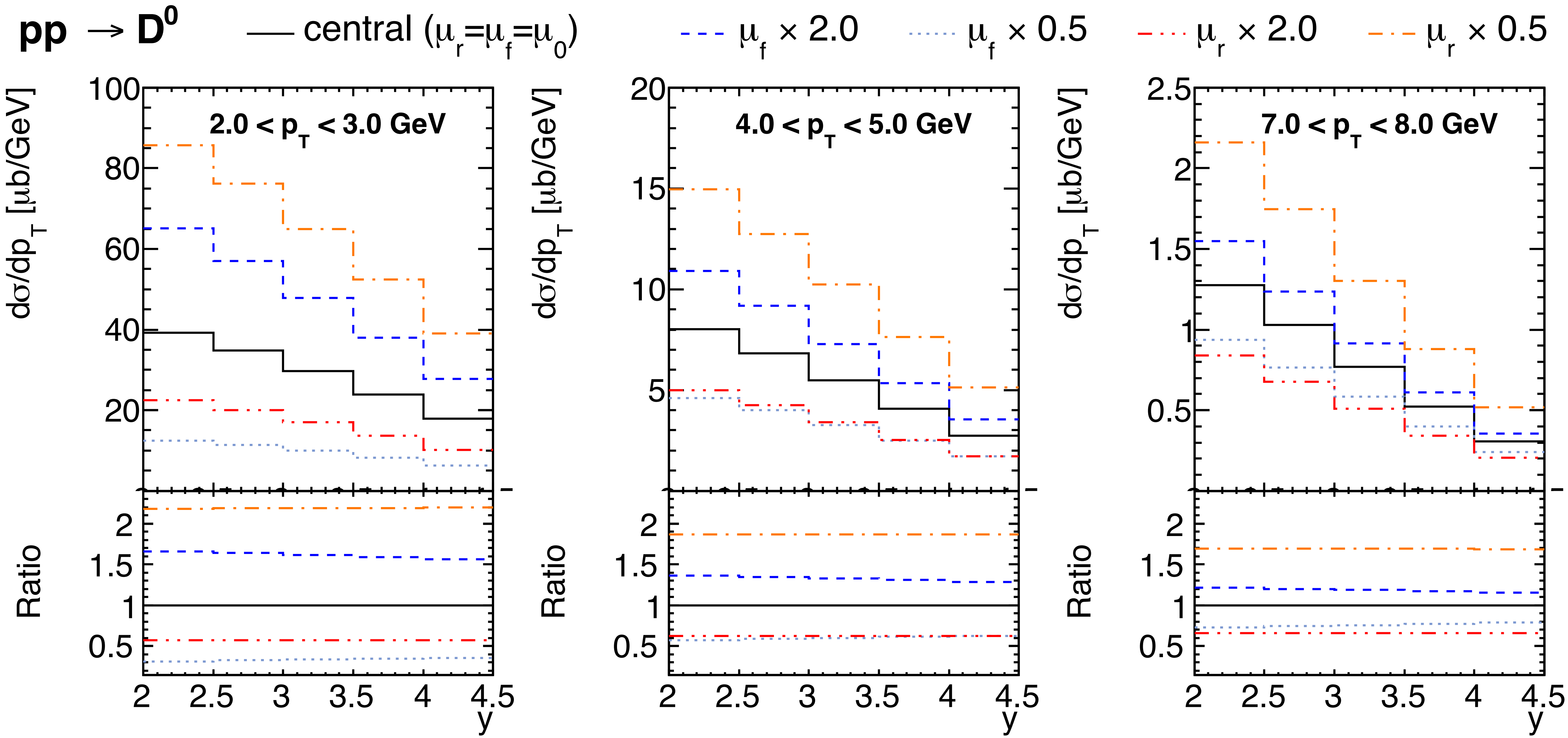
Kinematic range

O. Zenaiev et al, EPJC75(2015)396



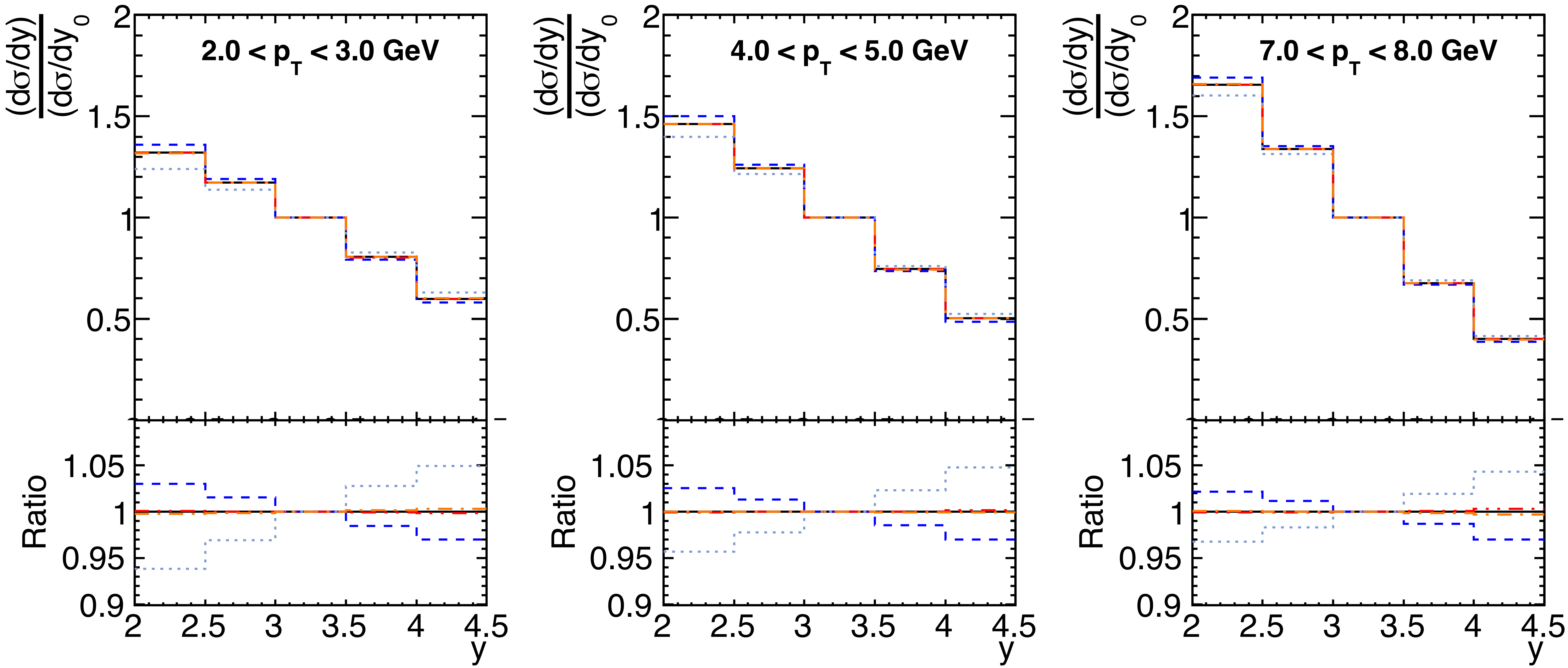
- HERA inclusive DIS data: x-range is indicated where the gluon PDF uncertainties are less than 10% (at $\mu_F^2=10$ GeV^2)
- Mayor impact of LHCb data expected at $5\text{x}10^{-6} < x < 10^{-4}$

NLO QCD predictions for charm LHCb data



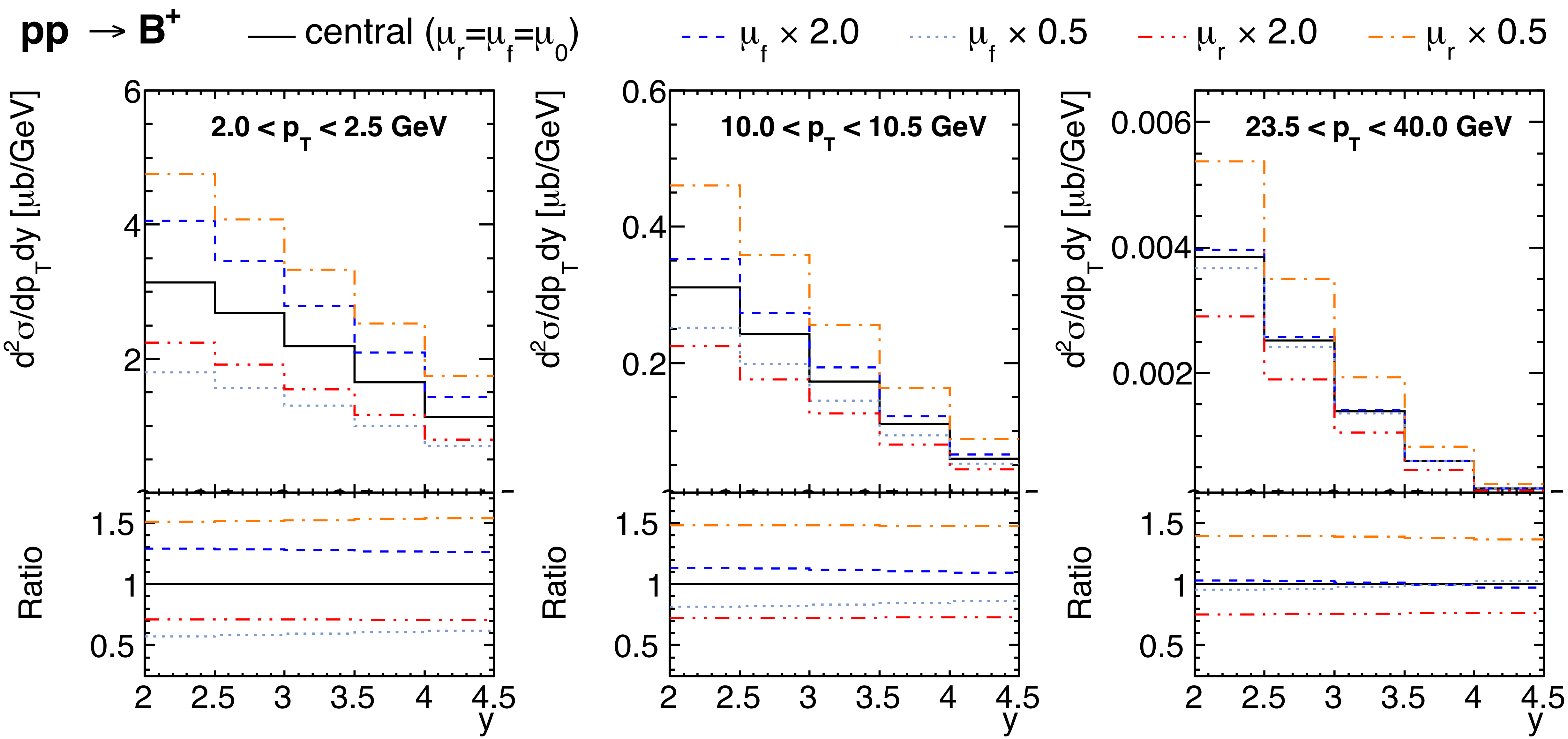
- Central scale $\mu_0 = m_T$
- Large scale uncertainties!
- Mostly change the normalization, shape less affected

NLO QCD predictions for charm LHCb data



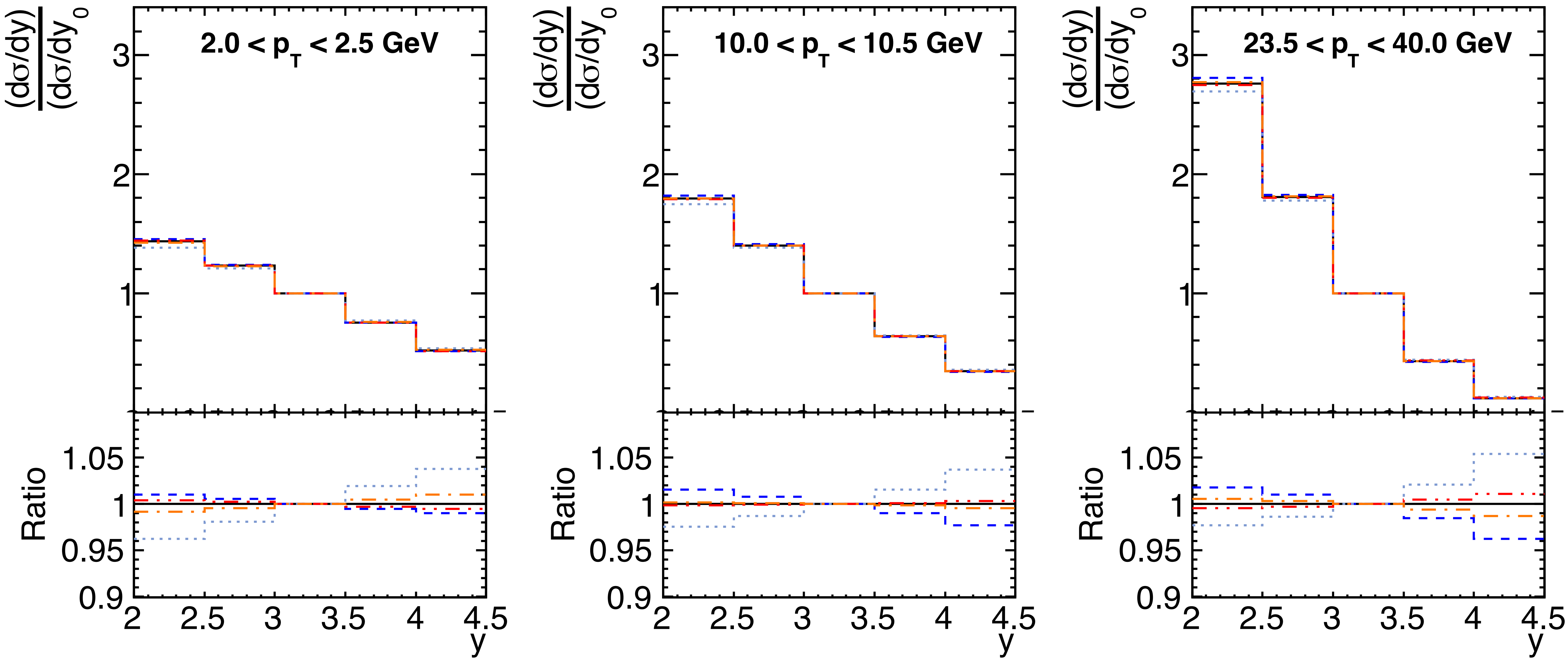
- Normalized cross sections w.r.t. dσ/dy in the bin 3<y<3.5
- Very small scale uncertainties now!
- Shape remains sensitive to gluon

NLO QCD predictions for beauty LHCb data



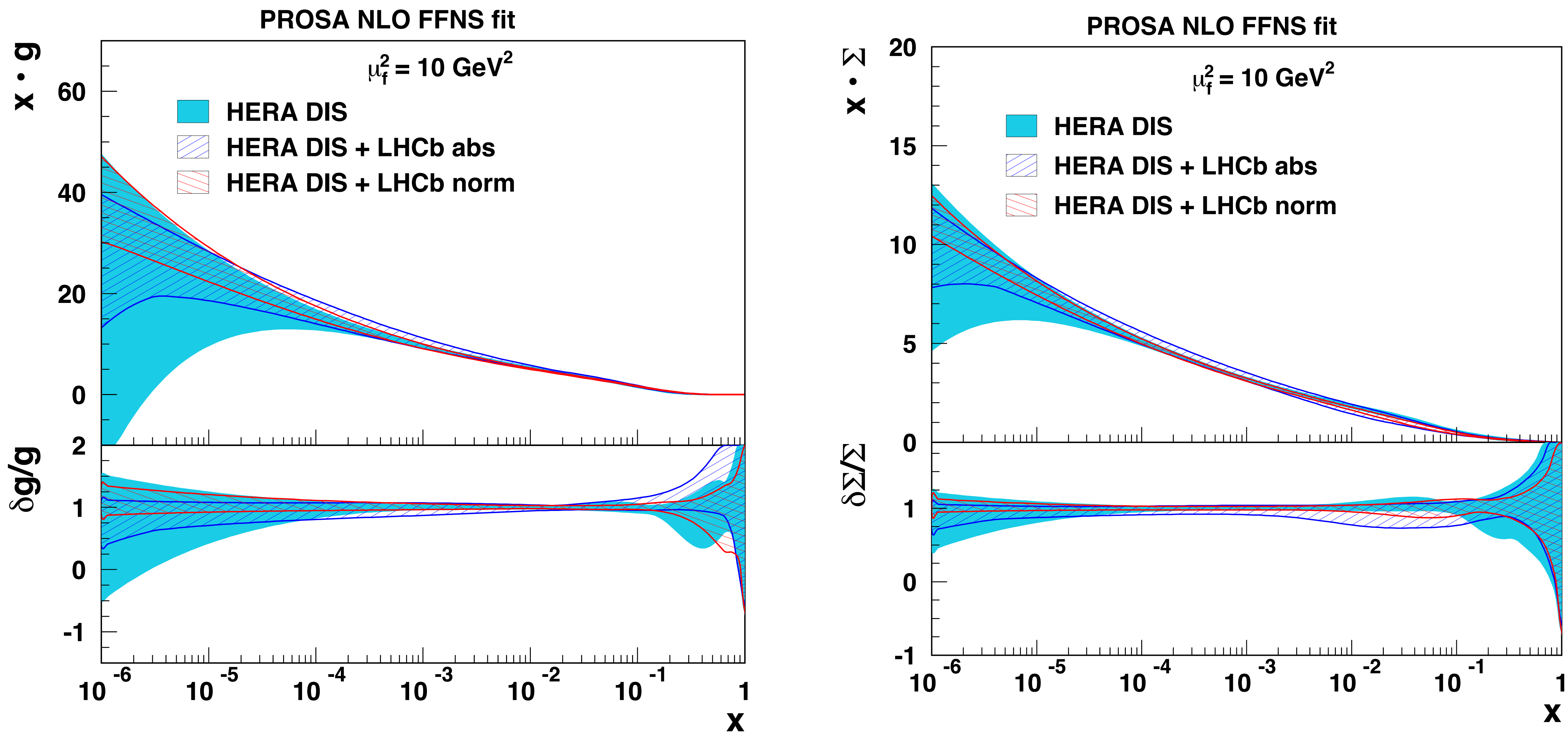
- Central scale $\mu_0 = m_T$
- Large scale uncertainties!
- Mostly change the normalization, shape less affected

NLO QCD predictions for beauty LHCb data



- Normalized cross sections w.r.t. $d\sigma/dy$ in the bin $3<y<3.5$
- Very small scale uncertainties now!
- Shape remains sensitive to gluon

Results for the gluon and the sea

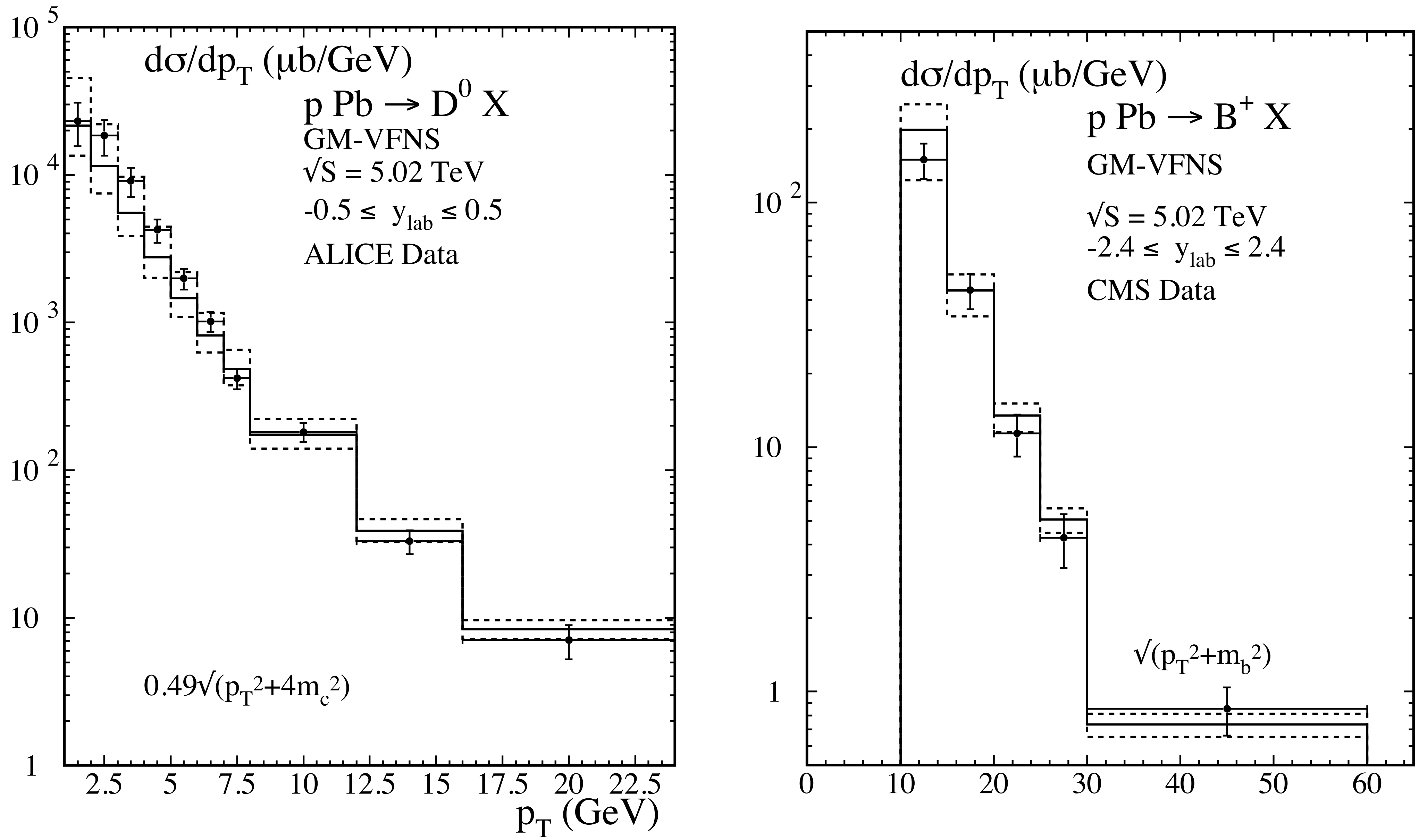


- The uncertainties on the gluon and the sea are significantly reduced using LHCb data

- In the normalised case by a factor 3 at $x \sim 5 \times 10^{-6}$

Impact of heavy quark measurements on NPDFs?

p-Pb data

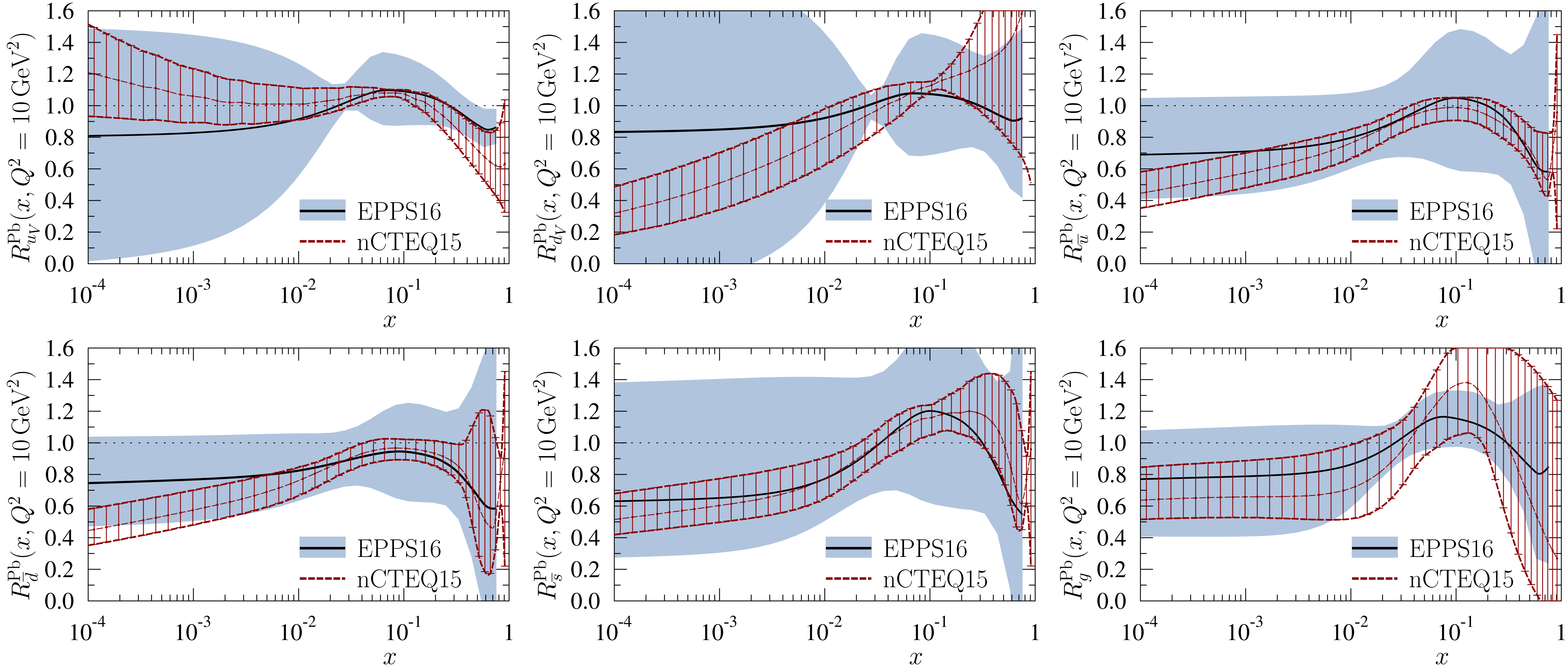


figures from
arXiv:1703.04754

- There are p-Pb data from ALICE and CMS for D's and B's, with the potential to constrain the nuclear gluon and sea

EPPS'16 vs nCTEQ'15 @Q^2=10 GeV^2

Eskola, Paukkunen, Paukkunen, Salgado, arXiv:1612.0574



- The data are at more central rapidities. The probed x-range will be larger than in the pp case with forward LHCb data

- However, nPDFs are less constrained than the proton PDFs even at larger x.
  (The proton gluon at x~10^{-2}...10^{-3} has less than 10% uncertainty.)

Ratios

- The differential cross sections have very large scale uncertainties

- Use normalized cross sections
  $R_y = (d\sigma^{pPb}/dy)/(d\sigma^{pPb}/dy(y_0))$

- Directly sensitive to nuclear gluon and sea PDF

- Advantage: a lot of experimental systematics cancel

Ratios

- Another ratio is (of course)
  $R_{pA} = d\sigma^{pA}/(A\ d\sigma^{pp})$
- This ratio provides additional information on the correlations between the uncertainties of the nuclear PDFs and the proton PDFs
- Should also have much reduced scale dependence and experimental systematics cancel (but less perfectly as in the R_y ratio)

What about charmonium production?

- Obviously very interesting! Also probes small-x, lots of data
- **Theory under control?**
- Interesting idea: (Lansberg & Shao arXiv:1610.05382)
  - Choose a proton PDF (e.g. CT14)
  - Fit a parametrization for the hard part to charmonium data (dominated by gluon channel).
  - This gives the hard part corresponding to the order and scheme of the chosen proton PDF
  - Compare to pA data and reweight the NPDFs

Thank you