Heavy quark production in *pp*, charm/beauty/top

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with input from: S. Alekhin, M. Benzke, A. Geiser, T. Gaisser, B. Kniehl, G. Kramer, R. Laha, K. Lipka, S.O. Moch, G. Sigl, O. Zenaiev + PROSA collaboration

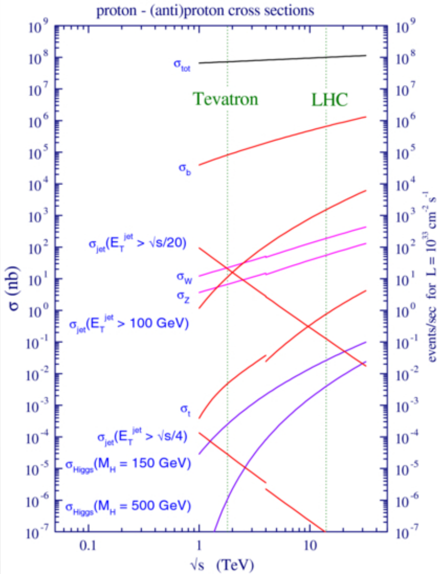
+ further authors in the literature

+ LHCb papers

See also talks by M.W. Winn, R. Gauld, P. Nason, H. Shao, all complementary to my one.

LHCb Workshop on "Implications of LHCb measurements and future prospects", 8 - 10 November 2017

Heavy-flavour hadroproduction at LHC



∗ huge cross-sections for charm and bottom hadroproduction:

at $\sqrt{S} = 13$ TeV,
$\sigma(pp \to c\bar{c}) \sim \mathcal{O}(10mb)$,
$\sigma(pp \to b\bar{b}) \sim \mathcal{O}(600\mu\text{b})$,
$\sigma(pp \to t\bar{t}) \sim \mathcal{O}(700 \text{ pb})$.

∗ Charm, bottom and top hadroproduction are studied by LHCb, ALICE, ATLAS, CMS, in different kinematical regions.

The LHCb experiment allows to probe large rapidities $(2 < y < 4.5)$.

Status of theory for $pp/p\bar{p} \rightarrow c\bar{c}$ + X, $b\bar{b}$ + X, $t\bar{t}$ + X

$*$ NLO QCD + EW corrections available
(Nason et al., 1988, Beenakker et al., 1989....., Kuhn et al. 2006....)

$*$ NLO matched to Parton Shower (+ hadronization + MPI)

$*$ NNLO QCD + NLO EW accuracy:

– at the differential level, exact predictions only for $t\bar{t}$ (Czakon et al., 2016 - 2017)
– for the total σ, approximate N^{3}LO QCD predictions (Muselli et al, 2015)

$*$ Predictions including resummations of various kinds of large logarithms
(matched to fixed-order cross-sections):

– heavy-quark hadroproduction close to threshold,
– high-energy (small-x) log resummation
– resummation of (p_T/m_Q) logs at high p_T,
– ....

Status of theory for single-inclusive open heavy-flavour production ($pp \rightarrow H + \mathbf{X}$)

∗ p_T spectrum finite for $p_T \rightarrow 0$ in the FFNS (thanks to $m_Q \neq 0$).

∗ Logarithms of p_T/m_Q can be large in the high-p_T tail of p_T distributions, depending on kinematics and E_{CM}.

∗ At small p_T, FFNS works; however, at large p_T one needs to resum the logs.
Open question: how large ?

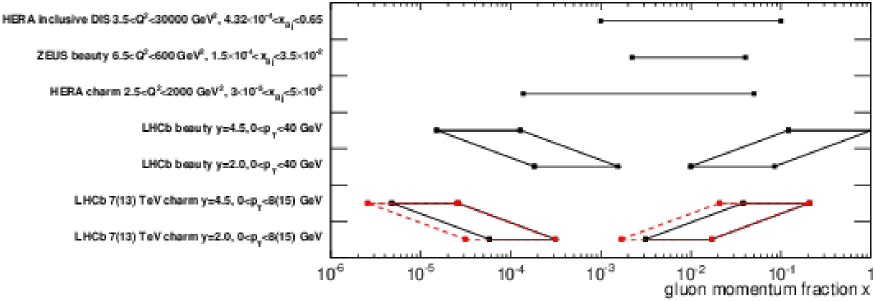
∗ ZM-FNS: massless quarks. LL and NLL contribution effectively resummed through evolution of PDF/FF.
Works at large p_T, but divergence at $p_T \rightarrow 0$. Powers of m_Q/p_T missing !

∗ GM-VFNS: ideal combination of FFNS at low p_T with ZM-FNS at large p_T.
But some arbitrariness in the way the combination is done.

Two approaches: FONLL (Nason et al.) and GM-VFNS (Kniehl et al.),
which both combine fixed-order (NLO) predictions
with LL+NLL resummation,
but differ in the way the combination is done.

Both used in LHCb studies!

Heavy-flavour hadroproduction at LHCb vs. HERA:



LHCb data allows to cover x regions uncovered by HERA data, both at low x's (especially open charm data) and at large x's (especially open bottom data).

For LHCb, LO formula $x = exp(\pm y \sqrt{p_T^2 + m_Q^2}/E_p\ ) \Rightarrow$

Larger rapidities of the emitted quark and/or larger collision energies correspond to more extreme x's

LHCb data on open heavy hadrons and PROSA PDF fit

Basic idea: use the data on D-meson and B-meson hadroproduction at LHCb to constrain PDFs (especially gluon PDFs) at low x's.

Data sets:

Open charm data at 7 TeV: D-meson p_T distributions in the range [0, 8] GeV, in five rapidity bins between $2 < y < 4.5$. [arXiv:1302.2864]

Open bottom data at 7 TeV: B-meson p_T distributions in the range [0, 40] GeV, in five rapidity bins between $2 < y < 4.5$ [arXiv:1306.3663]

These data are considered together with all HERA data used for the HERAPDF1.0 PDF fit:
– NC and CC inclusive DIS combined HERA data,
– $c\bar{c}$ DIS combined HERA data and $b\bar{b}$ DIS ZEUS data.

Three variants of the PDF fit:

1) one only with HERA data;

2) one also including LHCb absolute differential cross-sections;

3) another one with reduced uncertainties: for each fixed LHCb p_T bin, use the ratios of distributions $(d\sigma/dy)/(d\sigma/dy_0)$ in different rapidity bis (i.e. normalized to the central bin $3 < y_0 < 3.5$): in the ratios theoretical uncertainties partly cancel.

PROSA PDF fit: details of the fit

* Ingredients of the fit (besides data):

– the general methodology used for the HERAPDF 1.0 fit,

– theoretical predictions at NLO accuracy (MNR code),

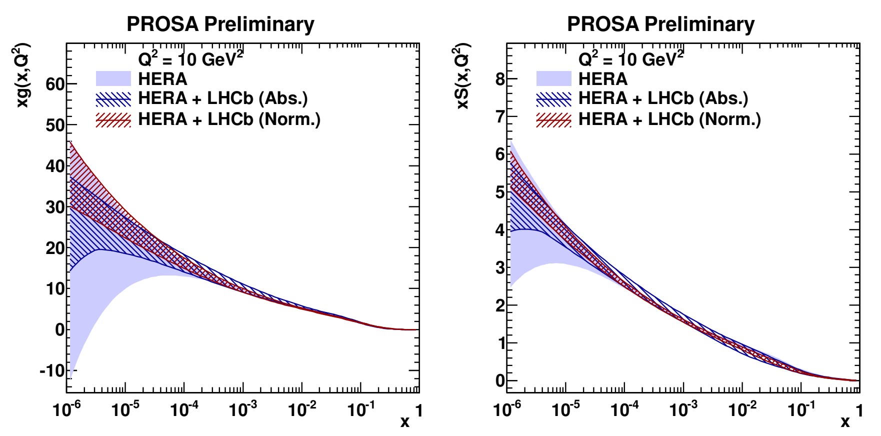
– complemented by non-perturbative FF (already providing good description of the HERA data).

– parameterization: same as in the HERAPDF 1.0 PDF fit, which includes a very flexible gluon PDF functional form (even negative gluon PDFs are allowed)

* Three sources of uncertainties: fit, model, parameterization

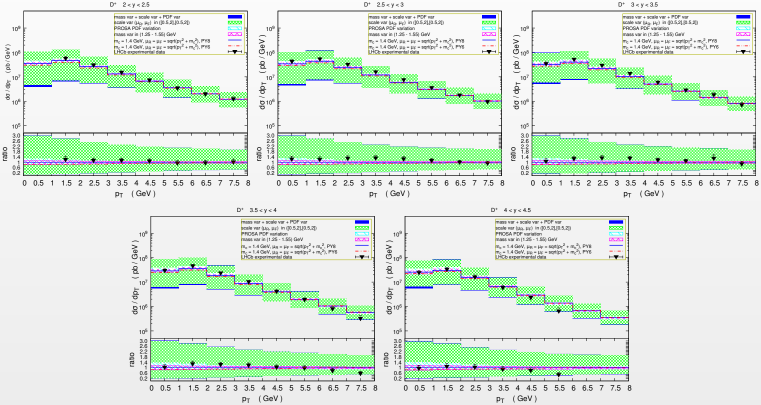
- fit uncertainties: arise from the experimental uncertainties of the measurements used in the fit;
- model uncertainties: related to μ_R and μ_F scale variation, $\alpha_S(M_Z)$, fragmentation parameters, f_s, Q^2_{min} for HERA data used in the fit;
- parameterization uncertainties: starting scale of the QCD evolution at which parameterization is considered, additional parameters varying the functional form of the parameterization.

PROSA PDF fits:
comparison between the three variants of the fit



∗ The gluon and the sea quark distributions are correlated:
a reduction on the uncertainty of the former propagates to the latter.

Theory predictions vs. LHCb experimental data on $pp \to D^{\pm} + X$ at $\sqrt{S} = 7$ TeV



* Here we compare theoretical absolute cross-sections to experimental data, whereas the PROSA PDF fit variant using LHCb data ratios is employed in the predictions.

* Big uncertainties on the theoretical predictions, dominated by μ_R and μ_F scale variations.

New data from LHCb at $\sqrt{S}$ at 5 and 13 TeV

Open charm data at $\sqrt{S} = 5$ and 13 TeV have been published after our PROSA fit.

Charm Data at 5 TeV: p_T distributions between [0, 10] GeV, in five rapidity bins between $2 < y < 4.5$ [arXiv:1610.02230]

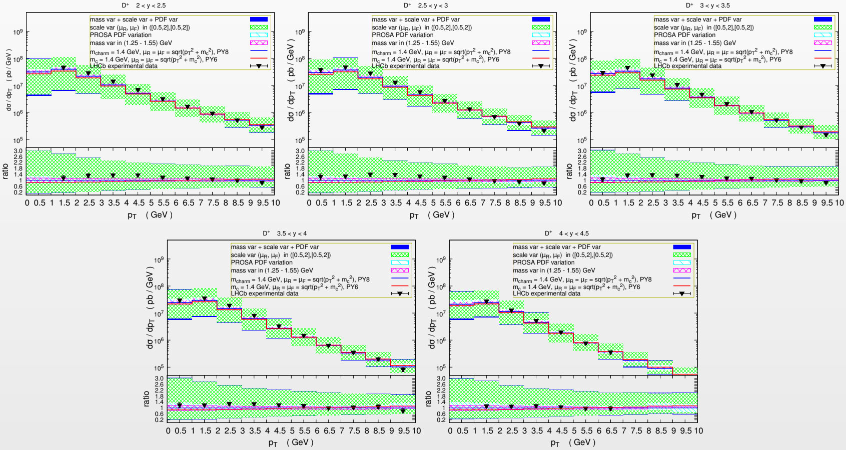
Charm Data at 13 TeV: p_T distributions between [0, 15] GeV, in five rapidity bins between $2 < y < 4.5$ + 13 / 5 distribution ratios + 13 / 7 distribution ratios.
See [arXiv:1510.01707], at the sixth revision!

Latest revision of both these datasets: May 2017.

Additionally:
Data on $pp \rightarrow b\bar{b} + X$ at $\sqrt{S} = 13$ and 7 TeV:
pseudorapidity distributions in six pseudorapidity bins between $2 < \eta < 5$
+ 13 / 7 distribution ratios [arXiv:1612.05140], at the seventh revision!

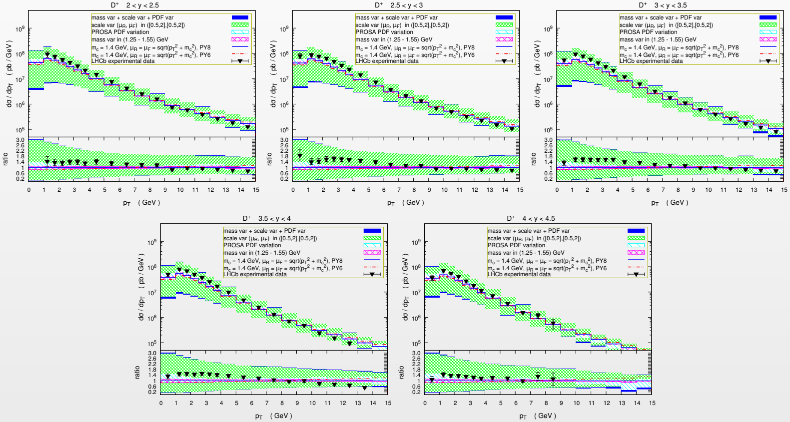
Latest revision: September 2017.

Theory predictions vs. LHCb experimental data on $pp \to D^{\pm} + X$ at $\sqrt{S} = 5$ TeV



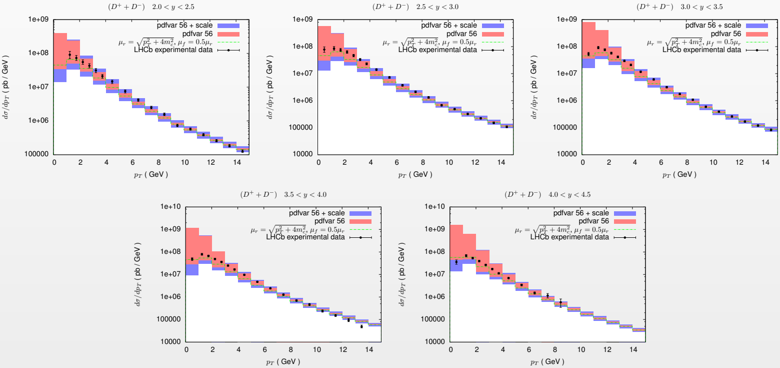
These data are not included in the PROSA PDF fit:
good agreement theory/experiment.

Theory predictions vs. LHCb experimental data on $pp \to D^{\pm} + X$ at $\sqrt{S} = 13$ TeV



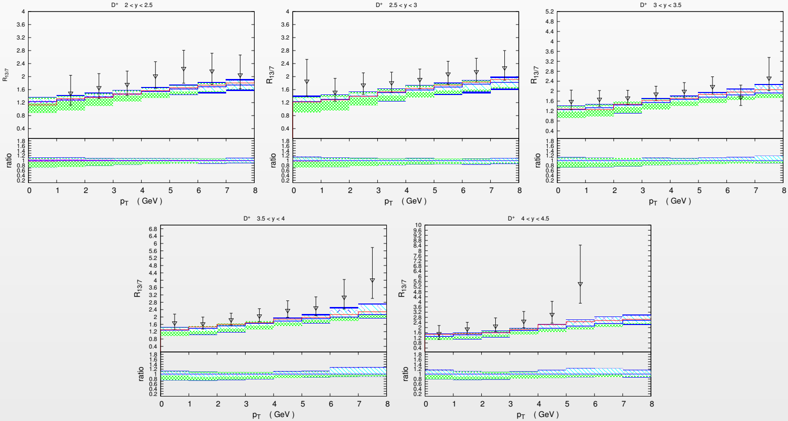
These data are not included in the PROSA PDF fit:
experimental data always within the theory uncertainty bands.

How do other PDF fits (CT14nlo), not including LHCb data, behave ? $pp \to D^{\pm} + X$ at LHCb at 13 TeV

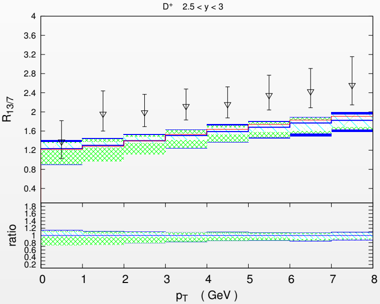


$*$ Large PDF uncertainties, increasing at low p_T / large y.

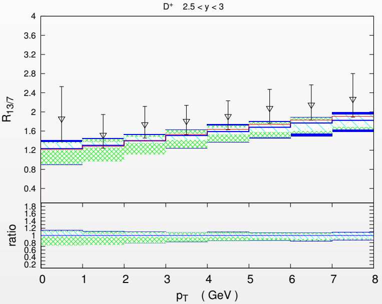
Ratios of theory predictions at different energies vs. 13/7 LHCb experimental data - $pp \to D^{\pm} + X$



Ratios of theory predictions at different energies vs. LHCb 13/7 experimental data



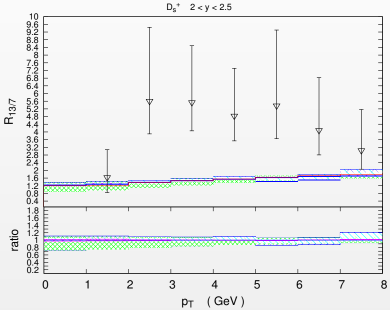
old (wrong) experimental data



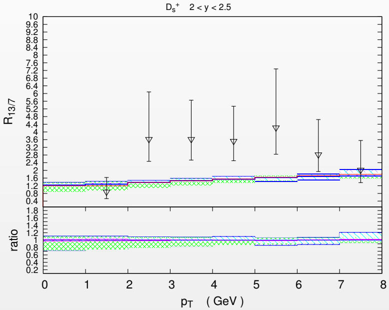
new revised experimental data

* Agreement of theory predictions and experimental data improved after last data revision (May 2017).
* Reduced uncertainties in ratios (compared to the absolute case)
* Theory predictions from two different independent computations and PDF sets are considered (red line: NLO QCD + NLL GM-VFNS, with CT14nlo PDFs, green/blue bands: NLO QCD + PS + hadronization, with PROSA PDFs).

Ratios of theory predictions at different energies vs. LHCb 13/7 experimental data



old (wrong) experimental data



new revised experimental data

∗ There are still ratios for which the agreement theory/experiment is not within 1 σ.

∗ Shortcomings in experimental data or shortcomings in theory predictions ?
Up to which extent are these data useful for a PDF fit ?

Wish-list of the PDF-fitters community to include LHCb open charm and bottom data in their fits

∗ Possibly data correct since the first release (no seven errata)!

∗ LHCb open charm and bottom data even at other energies would be desirable: $\sqrt{s} = 0.9$, 2.76 and 8 TeV.

This offers the chance of additional cross-checks and cross-calibrations both on the experimental and the theory level, and to check PDF evolution in x and Q^2 indipendently.

⇒ (partial) overlap of the x-range covered by different measurements:
open charm at 5 TeV - open beauty at 13 TeV
open charm at 2.76 TeV - open beauty at 7 - 8 TeV
open charm at 0.9 TeV - open beauty at 2.76 TeV
open beauty at 0.9 TeV - top at 13 TeV

∗ In order to use open charm and bottom data in PDF fits: information on bin-to-bin correlations for each separate measurement as well as between different measurements (charm and beauty, and different center of mass energies) is necessary!

Information of correlations between integrated cross-sections is not enough!

→ We need the same information, but for each measured (p_T, y) bin
(see also recent work by R. Gauld).

Why these developments matter ?

Constraining PDFs at low x's is relevant for:

* forward physics and multiple parton interactions, already in the LHC era:
  with increasing precision of the LHC data,
  improving the description of these aspects matters!

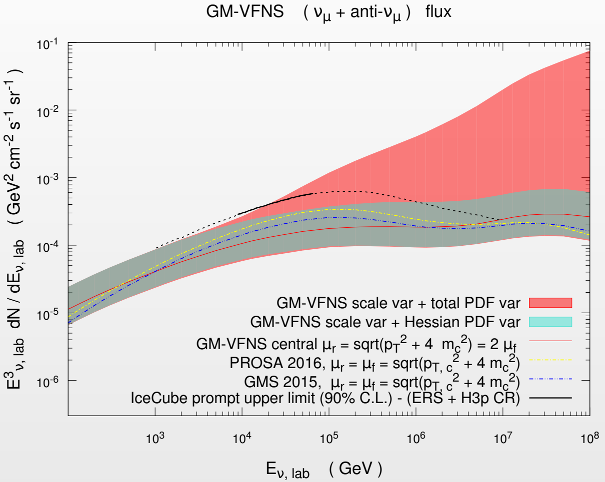
* future high-energy colliders: FCC-hh, etc.....
  (see the study in the FCC-hh SM report [arXiv:1607.01831]).

* high-energy astroparticle physics applications:

  - prompt neutrino fluxes
  - neutrino + N DIS (detection of high-energy neutrinos by VLVνT's)

Prompt neutrino fluxes:

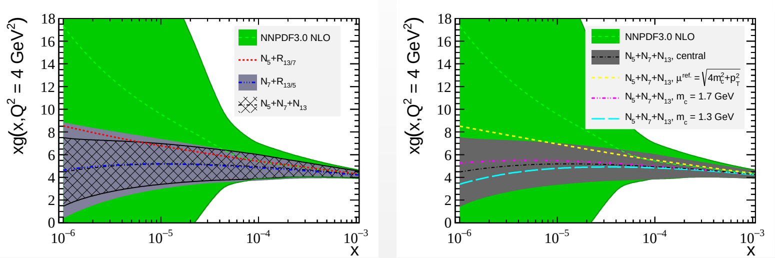
theoretical predictions vs. IceCube upper limits



* IceCube results give clear indication that the CT14nlo gluon PDF uncertainties at low *x*'s (see PDF error sets 53-56) are too large!

The NNPDF3.0 + LHCb PDF fit

(via Bayesian reweighting of the NNPDF3.0 fit.)



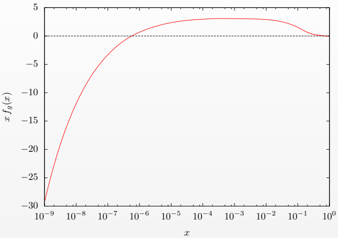
∗ their first fit includes 7 TeV open charm data [arXiv:1511.06346]

∗ most recent fit includes 5, 7, 13 TeV open charm data, as well as 13/7, 13/5 ratios [arXiv:1610.09373 v2]

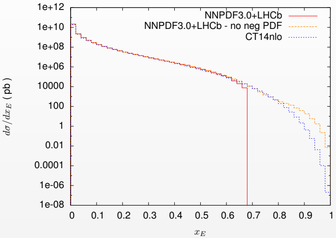
⇒ new version after last LHCb data correction!

∗ still space for improvement.....

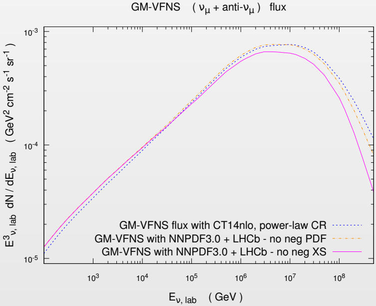
The NNPDF3.0 + LHCb PDF fit and GM-VFNS prompt neutrino fluxes



gluon PDF for $Q = 1.7$ GeV



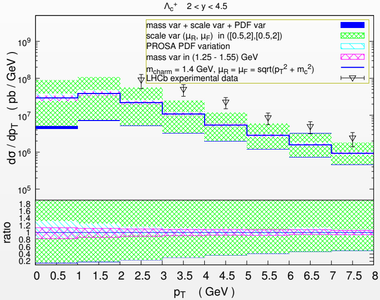
$d\sigma/dx_E$ for $pp \to D^0 + X$ for p with $E_{lab} = 10^5$ GeV



from [arXiv:1705.10386]

Too negative PDFs produce negative (i.e. unphysical) differential cross-sections!

Forward Λ_c hadroproduction

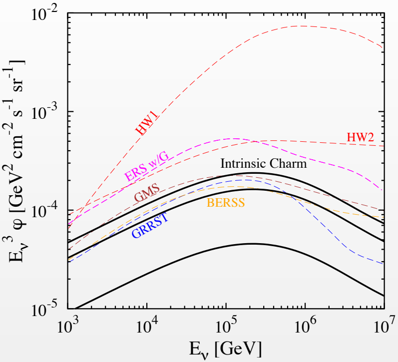


* $*$ LHCb experimental data at $\sqrt{s} = 7$ TeV above the theory bands (differences within 2σ).
* $*$ Update of branching ratios and fragmentation fractions needed: big uncertainties on these elements ($\sim 25\%$ and 8%).
* $*$ What happens at 13 and 5 TeV ?
* $*$ LHCb is measuring Λ_c/D^0 ratios in $p - Pb$ collisions.

$\Rightarrow$ Extension to pp would be important for assessing fragmentation/hadronization mechanisms and for testing the intrinsic charm hypothesis.

A rapidity dependence is to be expected/checked.

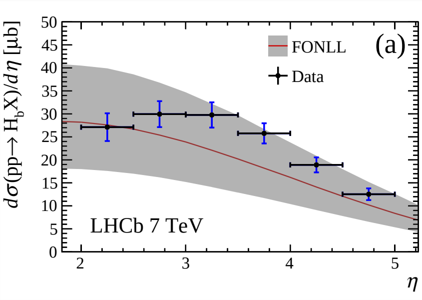
Intrinsic charm and prompt neutrino fluxes

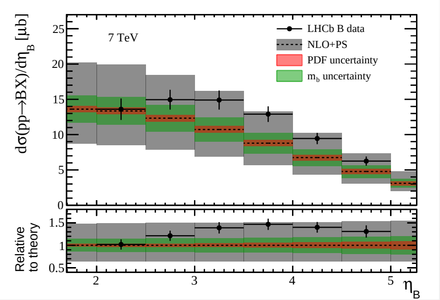


from [arXiv:1607.08240]

* Extrinsic heavy-quarks generated by $g \to Q\bar{Q}$ splittings.
* Intrinsic charm hypothesis testable by LHCb (large x), especially using the fixed-target SMOG apparatus.
* Further possibility: investigate $pp \to Zc$, γc.
* Old results from EMC, ISR, fixed-target experiments (forward Λ_C, asymmetries D - $\bar{D}$, J/ψ J/ψ).

Open bottom production at LHCb, $\sqrt{s} = 7$ TeV: theory vs. experiment



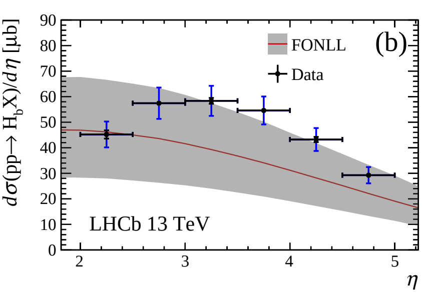


from [arXiv:1612.05140] and from [arXiv:1703.03636]

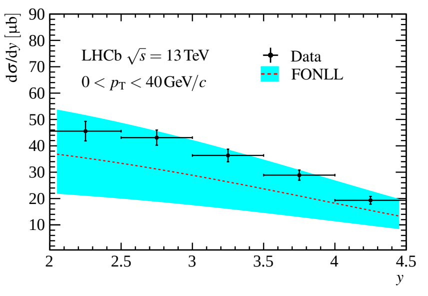
∗ Experimental data compared to FONLL and to NLO QCD + PS computations: big theory uncertainties, but differences in the $d\sigma/d\eta$ shape even after last data revision (only concerning the $\sqrt{s} = 13$ TeV data).

∗ We plan cross-checks with further methods (GM-VFNS).

Open bottom production at LHCb, $\sqrt{s} = 13$ TeV: theory vs. experiment



H_b from [arXiv:1612.05140]



B^+ from [arXiv:1710.04921]

* The corrected data on H_b at 13 TeV exhibit a similar $d\sigma/d\eta$ shape as those at 7 TeV.
* Helpful to have separate results for each H_b (B^+, B^0, B_s^0, Λ_b^0).
* In case of B^+, shape of FONLL predictions more similar to that of data than for H_b.

Double charm/bottom hadron production involving open charm/bottom: kinematic correlations

$*$ open charm-anticharm, charm-charm and open charm-J/ψ correlations have been measured by LHCb at $\sqrt{s} = 7$ TeV in [arXiv:1205.0975v3].

$*$ open bottom-bottom correlations have been reported by LHCb at $\sqrt{s} = 7 + 8$ TeV in [arXiv:1708.05994], following results by ATLAS and CMS at different rapidities.

$*$ Extension to other center-of-mass energies is ongoing.

$\Rightarrow$ Interesting for constraining Double Parton Scattering,
for exploring k_T-factorization, and for understanding $g \rightarrow Q\bar{Q}$ s splittings.

$*$ In case of correlated $(Q, \bar{Q})$,
$\Delta\phi(Q, \bar{Q}) = \pi$ at LO in collinear factorization, but not in k_T-factorization.
$\Delta\phi = 0$ peak at higher orders generated by $g \rightarrow Q\bar{Q}$ splittings.

$*$ Unlike the measurements with open-charm mesons,
no significant contribution from $g \rightarrow b\bar{b}$ splittings is observed at small $\Delta\phi$ for the bottom case.

Top production at LHCb

* $t\bar{t}$ + single-top hadroproduction ((75% + 25%) in the forward region)

* $t\bar{t}$ dominated by gg fusion, but at increasing rapidities, the contribution of qg and $q\bar{q}$ channels increase. $\rightarrow$ enhanced opportunity to study charge asymmetries.

* Total cross-section first measured in the $t \rightarrow Wb \rightarrow \mu b$ channel [arXiv:1506.00903]. Background: direct Wb production.

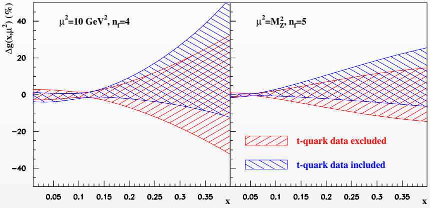
* More recently $t\bar{t}$ cross-section determined at $\sqrt{s} = 8$ TeV in the $e/\mu + 2$ jets channel [arXiv:1610.0842].

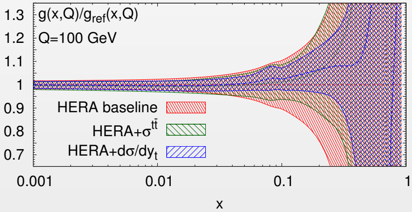
Differential cross-sections (e.g. as a function of rapidity) and separation of single-top wanted! $\Rightarrow$ Useful for PDF and (PDF + α_S + m_{top}) fits ($t\bar{t}$ especially for gluons at large x, single-top especially for d/u ratio at large x).

Limits of usability: the statistics in the restricted phase-space region explored by LHCb.

Warning: when going differential, a proper theoretical or experimental estimate of the $W+b$ differential cross-section is important to extract correctly the signal.

Top quark measurements and constraints on PDFs





from [arXiv:1611.08609] and from [arXiv:1701.05838]

* Including information on $\sigma^{t\bar{t}}$ and on various differential distributions $d\sigma/dp_{T,t}$, $d\sigma/dy_t$, $d\sigma/dy_{t\bar{t}}$, $d\sigma/dm_{t\bar{t}}$ in PDF fits constrains gluons especially in the region $0.08 < x < 0.5$.

$W+b$, $W+c$ hadroproduction

* So far, LHCb has produced ratios of total cross-sections $\sigma(Wc)/\sigma(Wj)$, $\sigma(Wb)/\sigma(Wj)$ at $\sqrt{s} = 7$ and 8 TeV in their fiducial region [arXiv:1505.04051], looking at the $\mu{+}b$ and $\mu{+}c$ decay channels. They also have $\sigma(Wb\bar{b})$ and $\sigma(Wc\bar{c})$ at 8 TeV [arXiv:1610.08142].

Limited sample → large uncertainties, agreement with MCFM calculations at NLO.

LHCb complement Wc, Wb experimental measurements from CMS and ATLAS.

* Important to go differential and compare with differential theoretical predictions (theoretical uncertainties on the latter are big).

* Wb: important to better understand it because this is background to HW hadroproduction (with $H \to b\bar{b}$) and to top and SUSY processes.

* Wc: important measurement to get information on the strange content of the proton (dominance of the initial state sg channel with respect to the Cabibbo-suppressed dg). Separate measurements of W^-c and $W^+\bar{c}$ allow to compute (s-$\bar{s}$). Large theoretical uncertainties.

* Data on Wc together with the existing data on muon charge asymmetry allow for a determination of the ratio $R_s = (s+\bar{s})/(\bar{u}+\bar{d})$. Data from LHCb can help to better investigate the behaviour of this ratio, especially at small x (plateau ?).

$Z/\gamma^* + b \to \mu^+\mu^- b$ hadroproduction

$*$ So far, LHCb has produced results for the total cross-section at $\sqrt{s} = 7$ TeV in their fiducial region [arXiv:1411.1264].

Results in agreement with `MCFM` predictions in the 4 FNS and 5 FNS.

$*$ Process interesting from the theory point of view:

- It is irreducible background for HZ with $H \to b\bar{b}$.
- It allows to investigate $g \to b\bar{b}$ splitting (important for constraining Parton Shower).
- It helps in the determination of the b-quark PDFs.
- It allows to test the validity of 5 FNS wrt 4 FNS calculations.
- It allows to test resummation scale choices in the context of NLO computation matched to Parton Shower.

$\Rightarrow$ It would be interesting to have differential cross-sections from LHCb!

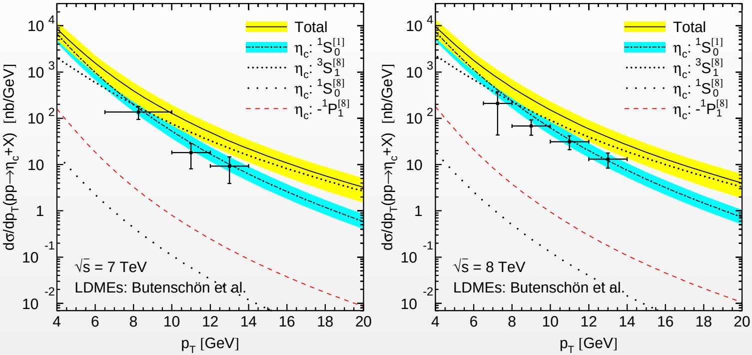
Quarkonium production and NRQCD

The NRQCD effective field theory allows to calculate cross-section for quarkonium production via the factorization:

$$\sigma_{A+B\to H+X} = \sum_n \sigma^{partonic}_{A+B\to Q\bar{Q}[n]+X} < 0|\mathcal{O}^H_n|0 >$$

* further folding with PDFs understood (in case of initial-state hadrons)
* Short-distance partonic cross-section (perturbative)
* Long-distance matrix elements (LDME) (non-perturbative):
  determine the evolution of $Q\bar{Q}$ color-singlet and color-octet states in quarkonium.
  Fit to experimental data (various NLO fits available) and assumed to be universal.
* Sum over quantum numbers n.
* Double expansion in α_S and in v.
* Color-octet operators suppressed by powers of v with respect to color-singlet ones.
* Full calculations up to NLO in both are available.

Prompt η_c hadroproduction at mid-p_T at $\sqrt{s} = 7$ and 8 TeV



Full NRQCD NLO calculation in [arXiv:1411.5287] (see also [arXiv:1411.7350] et al.)

NRQCD challenged by LHCb experimental data:

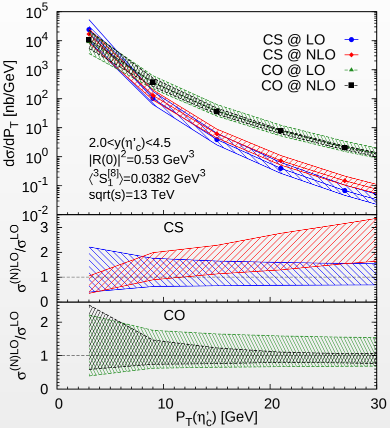
∗ LDME are not universal, but process dependent ?

∗ some of the data used for LDME global fits are not correct ?

∗ NRQCD factorization is not valid for states as light as charmonium ($v^2 \sim 0.3$) ?

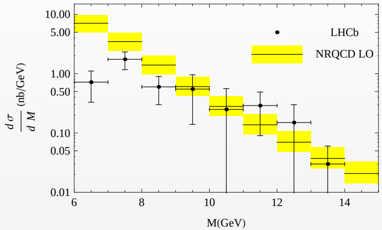
∗ heavy-quark spin symmetry (relating η_c LDME to J/ψ ones) does not apply ?

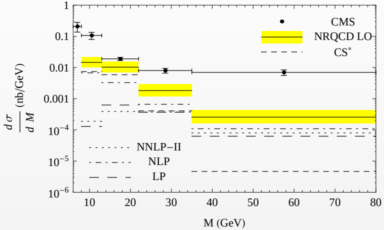
η_c' prompt hadroproduction at $\sqrt{s} = 13$ TeV



* First complete 1-loop analysis in [arXiv:1711.00265]
* big differences between color singlet and color octet
* η_c' LDME from ψ' LDME: ψ' LDME NLO fits + Heavy-quark spin symmetry
* process in the ball-park of LHCb, relevant to constrain ψ' production (no data from ep and e^+e^- collisions)

$J/\psi J/\psi$ hadroproduction





full NRQCD LO calculation in [arXiv:1609.02786]

* Predictions by NRQCD not in agreement with LHCb and CMS experimental data.
* Is there room for a large DPS component ?
* Need to complete a full NLO calculation before a clear assessment.

⇒ Important that LHCb produce further measurements on $d\sigma/dM_{J/\psi J/\psi}$ and $d\sigma/d(\Delta y_{J/\psi J/\psi})$ in order to further cross-check the results of CMS.

Conclusions

∗ LHCb has provided a lot of experimental data on open and hidden charm and bottom hadroproduction. General-purpose detector in this respect.

∗ Unique kinematic domain, complementary to the one explored by ATLAS, CMS, ALICE. Important to test the compatibility of LHCb data with those from the other experiments. Theoretical studies should possibly include/explain data from all sources.

∗ Data on single-inclusive open charm/bottom: useful for PDF fits at low and large x's. At present experimental uncertainties below the theoretical ones, need for more accurate theoretical description, but can we really trust the data (after so many revisions) ?

∗ LHCb has provided some data on top: in line of principle useful for PDF fits at large x's, but present usability limited by low statistics.

∗ Data on (c,c) and (b,b) correlations: more severe test for theoretical description than data on single-inclusive open heavy-quark. Useful for testing the limits of collinear vs. k_T-factorization, DPS, g $\rightarrow Q\bar{Q}$ splittings.

∗ Data on associated production of $(W, Z) + c$, $(W, Z) + b$: useful for PDF fit and for better understanding these processes background for top and SUSY and Higgs searches.

∗ Data on quarkonium challenge NRQCD: theory efforts needed to complete full NLO calculations before drawing firm conclusions on topics like DPS. Simultaneous description of polarized J/ψ hadroproduction and other unpolarized quarkonium data still problematic.