PROSA analyses

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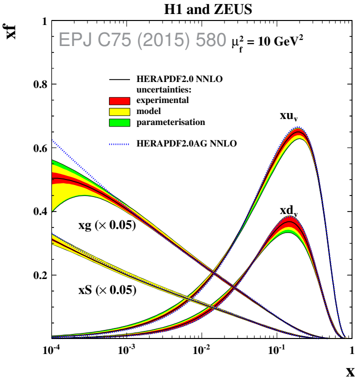
for PROSA Collaboration
[EPJ C75 (2015) 396]
[JHEP05 (2017) 004]
[arXiv:1911.13164]

xFitter workshop, DESY Hamburg
26 Feb 2020

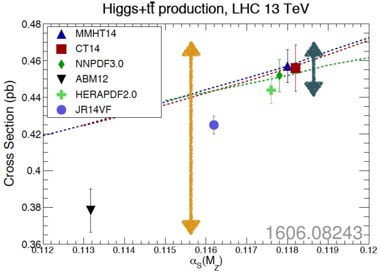
QCD factorisation:

$$\sigma_X = \sum_{a,b} \int \mathrm{d}x_1 \mathrm{d}x_2 \underline{f_a(x_1, Q^2) f_b(x_2, Q^2)} \hat{\sigma}_{ab\to X}(x_1, x_2, Q^2, \ldots)$$



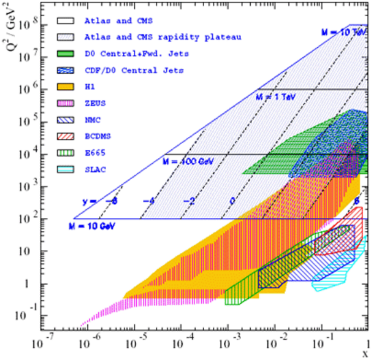
$\underline{f_{a,b}(x_1, Q^2)}$ are PDFs:

- probability to find parton a, b at scale Q^2 with momentum fraction x
- not yet calculable: perturbarive QCD predicts $\hat{\sigma}_{ab\to X}$ and $f_{a,b} = f_{a,b}(Q^2)$, but x-dependence of PDFs has to be extracted using experimental data



PDFs are essential for precision QCD tests, determination of fundamental theory parameters (α_s, m_t, m_b, m_c, m_W ...), and even *predicting background for astrophysical neutrinos*

Experimental data and PDF determination

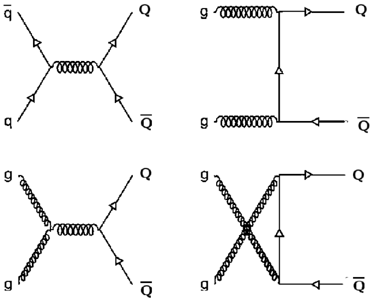


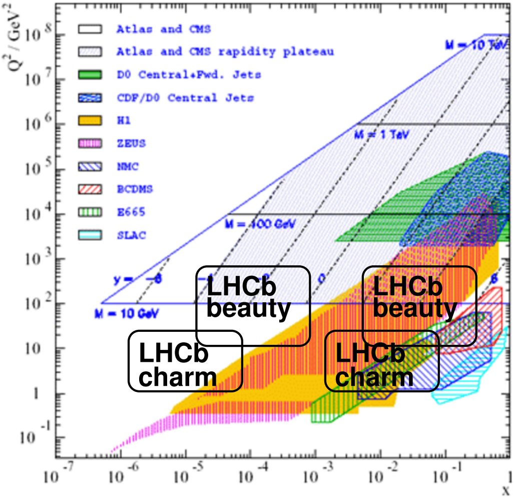
- *ep* HERA collider and fixed-target experiments: deep inelastic scattering is backbone of PDF determination
  - valence and sea quarks in large *x* range
  - gluon only indirectly via scaling violation
  - further information come from jet data, heavy quarks, prompt photons etc.
- Tevatron and LHC:
  - W, Z: improves flavour separation
  - W+c: information on strange PDF
  - jets, heavy quarks (HQ): improves gluon
  - prompt photons, single top ...
  - LHCb plays very special role by covering forward region → constraining PDFs at low *x*

- PDFs are regularly provided by several groups (ABM, CT, MMHT, NNPDF ...)
- PROSA (PROton Structure Analysis) is not a PDF group: collaboration of theorists and experimentalists focused on new ideas [https://prosa.desy.de]
  - 2015: first PDF fit with pp heavy-flavour data [EPJ C75 (2015) 396]
  - 2016: followup with predictions for prompt neutrino fluxes [JHEP 1705 (2017) 004]
  - 2019: followup with new LHCb (13 TeV, 5 TeV) and ALICE data [arXiv:1911.13164]
    → not just quantitative, but qualitative improvement: *even lower x*

Heavy quark production

LO diagrams:

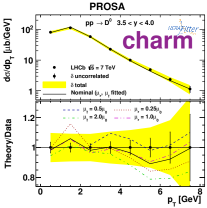


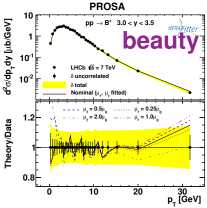


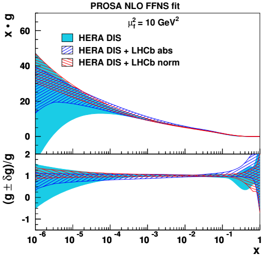
- At LHC, HQ pairs ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$) are predominantly produced via gluon-gluon fusion ($\approx 90\%$)
- at LO: $x_{1,2} \approx e^{\pm y} \frac{\sqrt{p_T^2 + m_Q^2}}{E_p} \approx e^{\pm y} \frac{m_Q}{E_p}$
  - LHCb charm and beauty data are sensitive to low-x gluon ($x \sim 10^{-6}$)

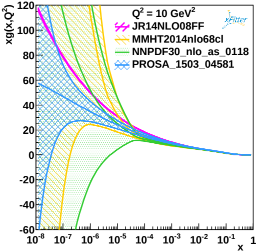
PROSA 2015 results [EPJ C75 (2015) 396]

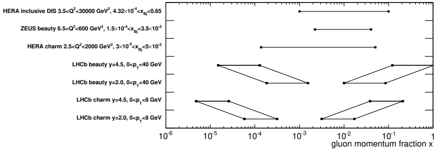
- Before 2015 the only available LHCb heavy-flavour data:
  - charm $0 < p_T < 8$ GeV, $2 < y < 2.5$ [NPB871 (2013) 1]
  - beauty $0 < p_T < 40$ GeV, $2 < y < 2.5$ [JHEP 1308 (2013) 117]
- Improved gluon and sea-quark distributions up to $x \approx 10^{-6}$ (not covered by other experimental data)
  - *realistic* gluon uncertainties at low x (constrained by data)
  - similar studies were published later by Gauld et al. [JHEP11 (2015) 009, PRL 118 (2017) 072001, JHEP01 (2019) 217] + other related publications [EPJ C75 (2015) 610, EPJ C77 (2017) 182]











Why it was not done before?

- For *almost 30 years*, state-of-the-art fixed-order theoretical calculations for charm/beauty hadroproduction production differential cross sections is **NLO** [NPB373 (1992) 295] (MNR)
  - recent calculations for differential $t\bar{t}$ at NNLO [PRL 116 (2016) 082003] were not tried for charm/beauty yet
- NLO predictions for charm *are affected by large scale variations uncertainties* (large missing higher order corrections), order of factor 2 (due to small value of m_c)

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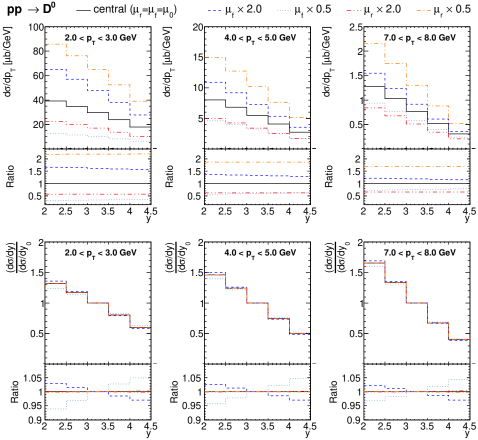
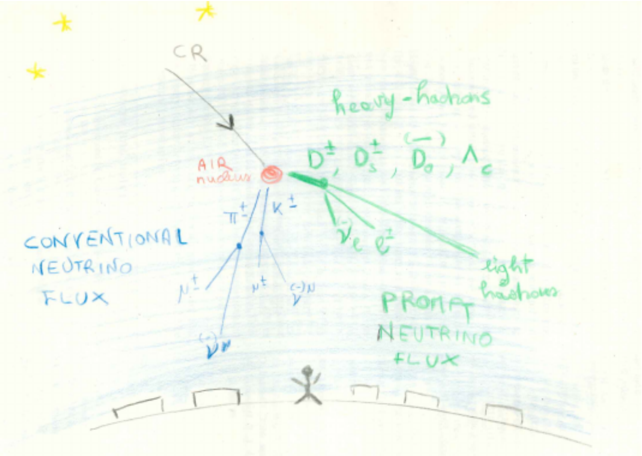
- However, if PDF uncertainties at very low x are *infinitive,* predictions uncertain by factor 2 *are still useful*
- Furthermore, theoretical uncertainties can be reduced by using *rapidity shape of the cross sections only:*
  $\frac{d^2\sigma}{dy dp_T} / \left(\frac{d^2\sigma}{dy dp_T}\right)_0$, where
  $\frac{d^2\sigma}{dy dp_T}$ is x-section in $3 < y < 3.5$ bin
  (the choice of this bin is arbitrary)
  $\rightarrow$ *scale unc. are reduced to % level*
- Alternatively, one can use ratio of cross sections at different energies (but smaller cancellation of scale unc.)



Atmospheric ν **are background for** *astrophysical* ν:



Production of atmospheric ν:

- cosmic rays (CR) $+$ atmospheric nuclei
  $\rightarrow$ light and heavy hadrons $\rightarrow$ conventional and **prompt** ν fluxes
- spectra of conventional and **prompt** ν fluxes are different because of different hadroproduction cross sections and decay properties

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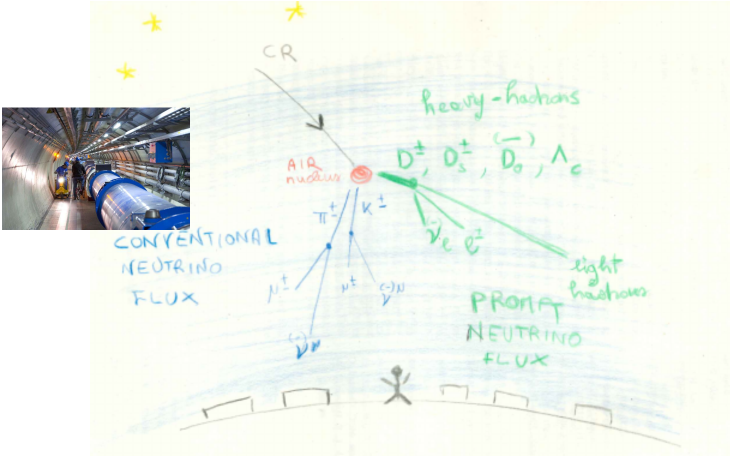

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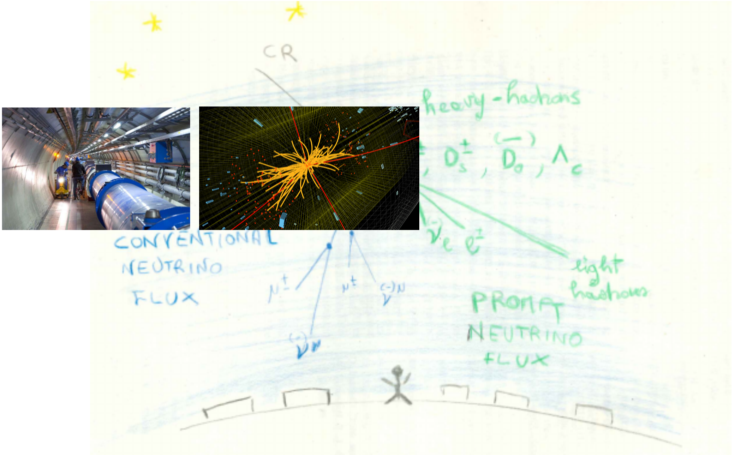

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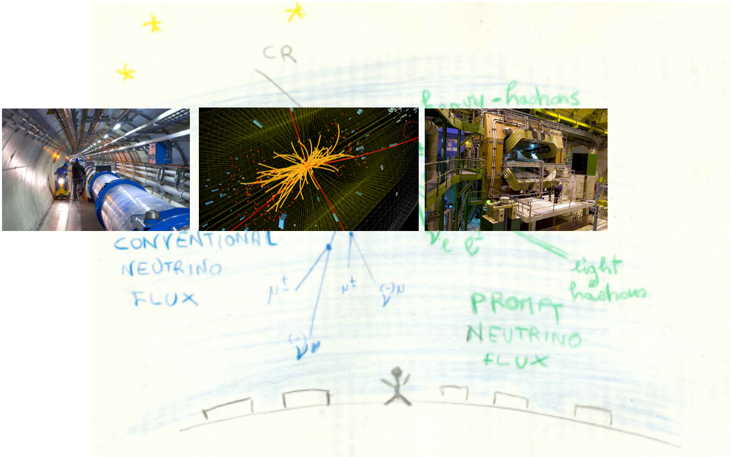

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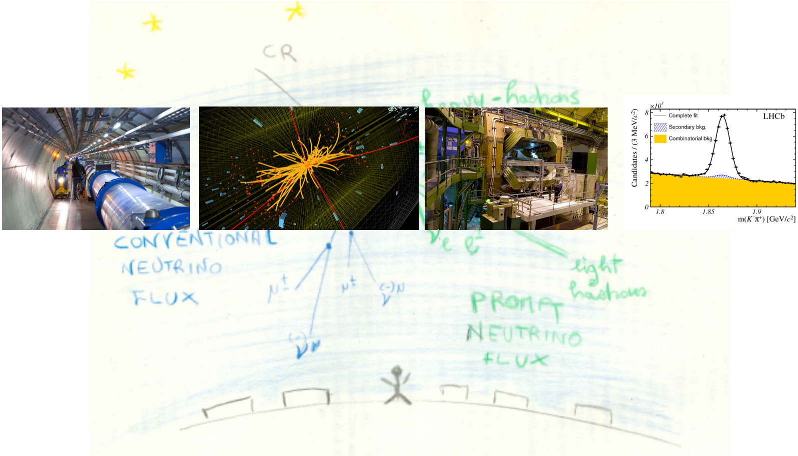

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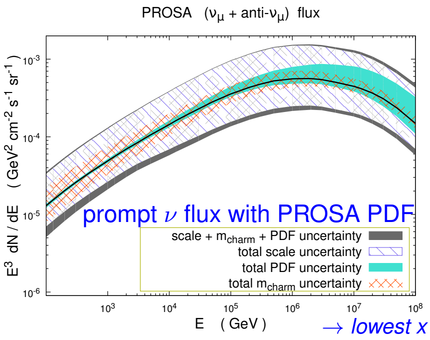
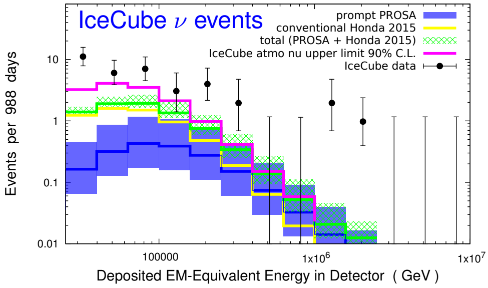
PROSA PDFs and atmospheric ν fluxes [JHEP 1705 (2017) 004]





- Uncertainties for prompt ν flux are dominated *by NLO scale uncertainties*
- PDF uncertainties are under control *owing to LHCb data in PROSA fit*
- Predictions for the number of prompt, conventional and total expected atmospheric neutrino events for the IceCube 988-day HESE analysis, as compared to the IceCube lepton data
- IceCube upper limit lies well inside PROSA uncertainty band at high E_ν

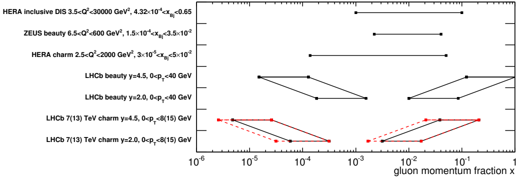
$\rightarrow$ LHC data on hadroproduction and their interpretation are of crucial importance for astrophysical measurements

$\rightarrow$ astrophysical measurements provide complementary information about charm hadroproduction and proton structure

New experimental data on charm hadroproduction published in 2015–2019:

- LHCb **13 TeV** arXiv:1510.01707
- LHCb 5 TeV arXiv:1610.02230
- ALICE 7 TeV arXiv:1702.00766
- ALICE 5 TeV arXiv:1901.07979

  → *stronger constraints on gluon PDF, extended x range (13 TeV data)*



New HERA data for PDF fit:

- HERA I+II inclusive DIS NC and CC arXiv:1506.06042
- HERA i+II charm and beauty DIS NC arXiv:1804.01019

  → *stronger constraints on all PDFs and HQ masses*

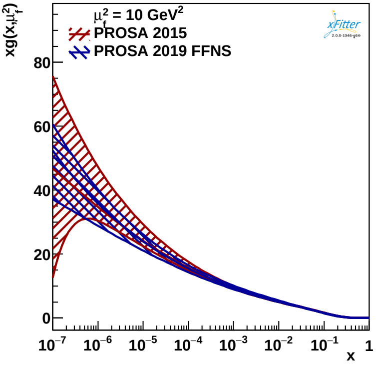
New developments on phenomenology side in xFitter (tool for QCD fits):

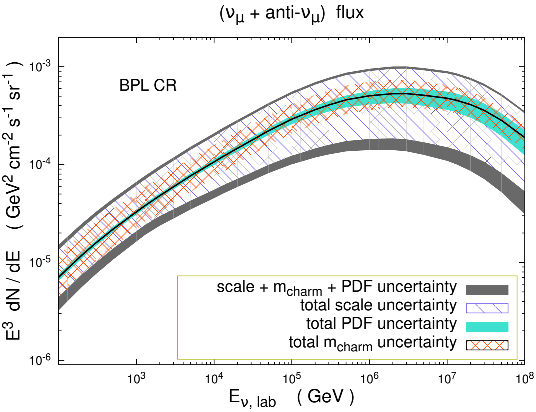
- NLO predictions for HQ hadroproduction using $\overline{\mathrm{MS}}$ running HQ mass [EPJ C74 (2014) 3167]

  → *well defined theory masses in all parts of calculations*
- variable HQ thresholds in PDF evolution $\mu_{c,b} > m_{c,b}$

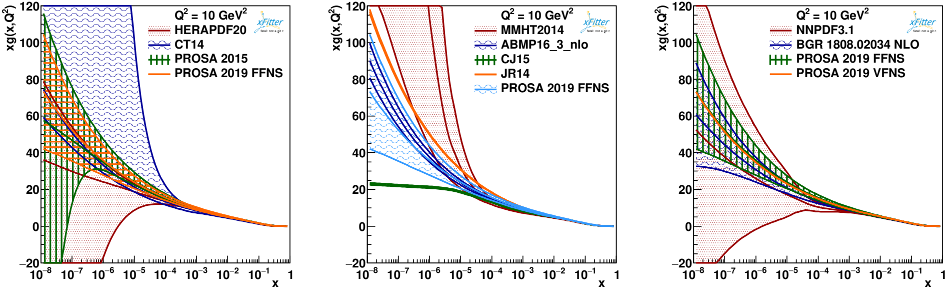
  → *more reliable PDFs at higher energies*
- flexible PDF parametrisation in xFitter

  → *less parametrisation bias*





- Stronger constraints on gluon PDF at low x in PROSA2019
- Reduced PDF uncertianties for prompt ν flux at high energies

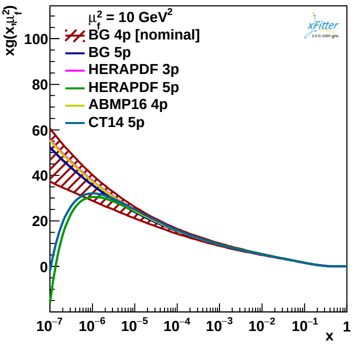


- In general, reduced gluon uncertainties at low x compared to most of other global PDF fits (MMHT, CT, NNPDF, HERAPDF)
    - most of other fits do not use LHCb heavy-flavour data
- Though some other PDF fits have smaller uncertainties purely because of rigid gluon parametrisation at low x
    - ABMP16 turns out to be compatible with PROSA2019
- Good agreement with results from Bertone, Gauld, Rojo [1808.02034] (also using LHCb charm data), both for central values and uncertainties

The new PROSA analysis heavily exploited many new features of xFitter
(thanks to I. Novikov and S. Glazov for help with `PionCeres` and `test_ceres` branches):

- flexible PDF parametrisation
  - we decided to use Bonvini-Giuli (BG) parametrisation for gluon as nominal, provided as xFitter example (see talk "xFitter examples" today)
  - we compared with different gluon parametrisation used by other PDF groups
- APFEL PDF evolution with displaced heavy-quark mass thresholds (thanks V. Bertone)
- new reaction 'cbdiff' was implemented (more flexible calculation of NLO for heavy-quark hadroproduction)
- KMatrix to manipulate with bins and calculate normalised cross sections
- finally, numerous improvements, like fitting extra parameters, producing LHAPDF output etc.

Check of gluon parametrisation



We decided to not use parametrisations which produces sharp negative gluon at low x, because:

- they predict negative total charm hadroproduction cross sections at $\sqrt{s} \gtrsim 30$ TeV
- at $x \lesssim 10^{-6}$ gluon is not probed by data directly: it is momentum sum rule which makes it negative

Other parametrisations are consistent with out uncertainty band (some other, like MMHT2014, was not possible to use because of very flexible gluon at high x)

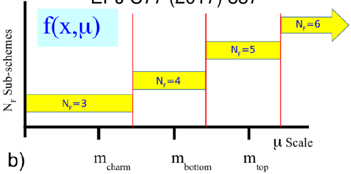
Nominal
($D = E = 0$ for $f = g$):

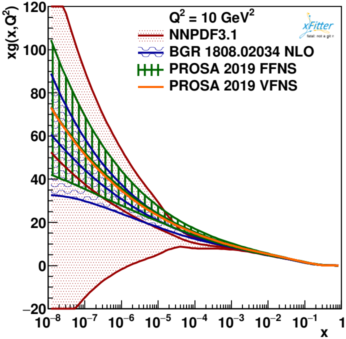
$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2+F\log x), \quad f = g$$
$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2), \quad f = u_v, d_v, \overline{U}, \overline{D} \qquad (2)$$

$$\text{ABMP16:} \quad xg(x) = A(1-x)^b x^{a(1+\gamma_1 x)},$$
$$\text{CT14:} \quad xg(x) = Ax^{a_1}(1-x)^{a_2}(e_0(1-y)^2 + e_1(2y(1-y)) + y^2), y = 2\sqrt{x} - x,$$
$$\text{HERAPDF2.0:} \quad xg(x) = A_g x^{B_g}(1-x)^{C_g} + A'_g x^{B'_g}(1-x)^{25},$$
$$\text{HERAPDF2.0 no flex. } g\text{:} \quad xg(x) = A_g x^{B_g}(1-x)^{C_g},$$
$$\text{BG:} \quad xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+F_g \log x + G_g \log^2 x), \qquad (3)$$

We produced also VFNS fit with charm and beauty thresholds $\mu_{c(b)} > m_{c(b)}$:

EPJ C77 (2017) 837





- important e.g. for MC tuning
- fit LHC HQ data with $p_T < \mu_{c,b}$ (no pp VFNS implementation available suitable for fits)
- use VFNS (FONLL-B) for HERA data
- HQ matching thresholds: $\mu_{c(b)} = k m_{c(b)}$
  - $k = 4.5$:
    $p_T^c < 5$ GeV, $p_T^b < 16$ GeV
  - varied $3.1 < k < 6$: almost no sensitivity

PROSA PDFs below μ_c are almost identical in FFNS and VFNS fits

Certain things could be improved by experimentalists...

Typical description of correlated syst. unc. [LHCb 5 TeV JHEP 1706 (2017) 147]

Table 2: Fractional systematic uncertainties, in percent. Uncertainties that are computed bin-by-bin are expressed as ranges giving the minimum to maximum values. Ranges for the correlations between p_T-y bins and between modes are also given, expressed in percent.

	Uncertainties (%)				Correlations (%)	
	D^0	D^+	D_s^+	D^{*+}	Bins	Decay modes
Luminosity		3.8			100	100
Tracking	3–5	5–7	4–7	5–7	90–100	90–100
Branching fractions	1.2	2.1	5.8	1.5	100	0–95
Simulation sample size	0–10	0–10	2–9	1–10	0	0
Simulation modelling	0.3	0.7	0.6	2	0	0
PID sample size	0–1	0–1	0–2	0–2	0–100	0–100
PID binning	0–30	0–10	0–20	0–20	0	0
Fit model shapes	0–3	0–3	0–3	0.0–1.0	0	0

- This information is not really sufficient: need to know contributions of different systematic uncertainties for each bin (not just ranges)
- After presenting these results in LHCb, they pointed us to HepData records*, where they do provide correlations for measurements at 5 TeV and 13 TeV (thanks D. Muller), but...
  - it is really complicated to find those matrices there
    → HepData interface could be better (`'Download All'` should download them)
  - some of these correlation matrices are not positive definite (rounding issue?)
    → could HepData implement a simple check that any provided correlation (or covariance) matrix is positive definite?
  - feedback to LHCb was provided

*https://www.hepdata.net/record/74708?version=2
*https://www.hepdata.net/record/73066?version=2

Summary

- Heavy-flavour hadroproduction data are currently *unique* to constrain low x gluon in PDF fits, and global PDF fits start to include these data (NNPDF, preliminary ABMP)
- Such PDFs are important for astriphysical applications, e.g. predicting atmospheric ν flux
- Once NNLO predictions will be available for charm and beauty (currently only for top), these data will be even more important
- Recent developments in xFitter were very important for latest PROSA paper
- FFNS and VFNS PDFs from PROSA paper arXiv:1911.13164 are available at PROSA web page `https://prosa.desy.de` (as well as supplementary materials)