Constraining heavy flavor PDFs at hadron colliders: updates

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Snowmass2021 LoI: Constraining heavy flavor PDFs at hadron colliders

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Thematic Areas:

(EF03) EW Physics: Heavy flavor and top quark physics,

(EF06) QCD and strong interactions: Hadronic structure and forward QCD

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Abstract

In this letter of interest, we discuss the possibility of constraining heavy-flavor parton distribution functions (PDFs) in the proton using heavy-flavor initiated processes at hadron colliders in global QCD analyses.

The LoI discusses how heavy-flavor (HF) PDFs can in principle be constrained in new global PDF analyses that use high-precision hadron collider data together with an amended version of the factorization formula able to capture HF dynamics over the wider kinematic range of x and Q covered by modern and future colliders.

GOALS

- To Have a GMVFN scheme able to capture HF dynamics (and interplay between nf=4 and nf=5, etc.) in PP collisions. Special focus on the S-ACOT family

- New ways to access HFs (perturbative and intrinsic) to improve current constraints.

- Precision measurements at the LHC run II offer the possibility of probing HFs using novel processes: (e.g. Z/W boson in association with charm or bottom quark jets at the LHC).

To make this happen… Activities:

- Dedicated set up of the theory calculation (scheme selection/validation) and its numerical implementation within a specific fitting package;

- Production of reliable fast tables for theory predictions to allow for short CPU runtime in global PDF analyses;

- Statistical analysis to assess the compatibility of experimental measurements for these processes within the fit.

Theory

A lot of work has been done in trying to understand the interplay between 4FS and 5FS in single and double bottom-quark initiated processes relevant for Higgs and Z production.

The list here is of course not exhaustive (apologies if someone is missing):

- Gauld, Gehrmann-De Ridder, Glover, Huss, Majer 2005.03016:
  (FO calculation for Z+ b-jet at O(α_s^3) in QCD, combines ZM NNLO and FFNS NLO)
- Forte, Giani, Napoletano EPJC 2019: (massive b-scheme)
- Figueroa, Honeywell, Quackenbush, Reina, Reuschle, Wackeroth, PRD 2018:
  (massive b-scheme, Z + b-jet at O($\alpha_s^2\alpha$) and O($\alpha_s\alpha^2$) within ACOT and S-ACOT)
- Forte, Napoletano, Ubiali EPCJ 2018:
  (FONLL method to match 5FS with massless b to 4FS with massive b)
- Krauss, Napoletano, Schumann, PRD 2017: (Z/H + b with SHERPA);
- Lim, Maltoni, Ridolfi, Ubiali JHEP 2016: (b-bbar-initiated processes at the LHC);
- Bonvini, Papanastasiou, Tackmann, JHEP 2015, JHEP 2016: (4 matched calculation b-bar-H);
- Forte, Napoletano, Ubiali, PLB 2015;
- Maltoni, Ridolfi, Ubiali JHEP 2012: (b-initiated processes at the LHC);
- Campbell, Caola, Cordero, Reina, Wackeroth, PRD 2012;
- Campbell, Ellis, Cordero, Maltoni, Reina, Wackeroth, Willenbrock, PRD 2009;
- Dawson, Jackson, Reina, Wackeroth PRD 2004;
- Maltoni, Sullivan, Willenbrock, PRD 2003;
- ……

Theory (closely related to the LoI)

Z+1b-jet: 5FS NLO QCD (S-ACOT) and m5FS NLO + NLO EW with massive b (ACOT).
Figueroa, Honeywell, Quackenbush, Reina, Reuschle, Wackeroth PRD(2018), 1805.01353.

Obtained with NLOX. Honeywell, et al., CPC(2020)

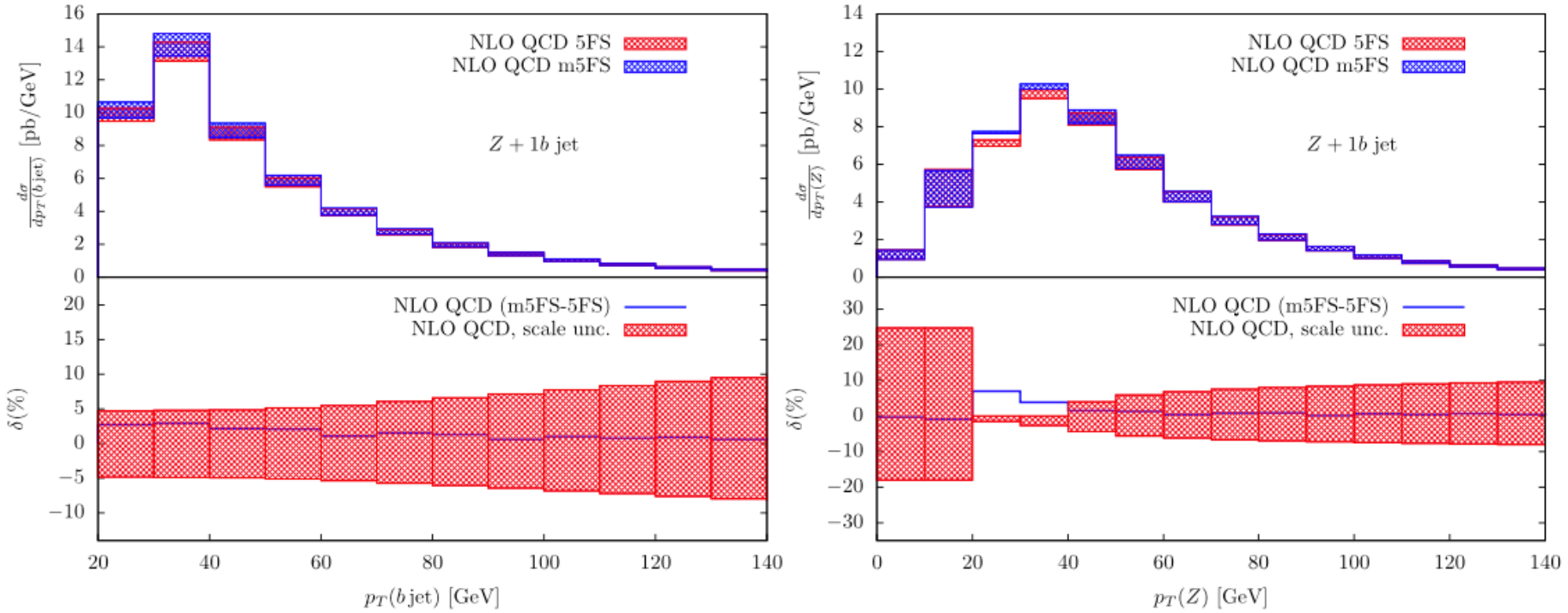


Figure from 1805.01353

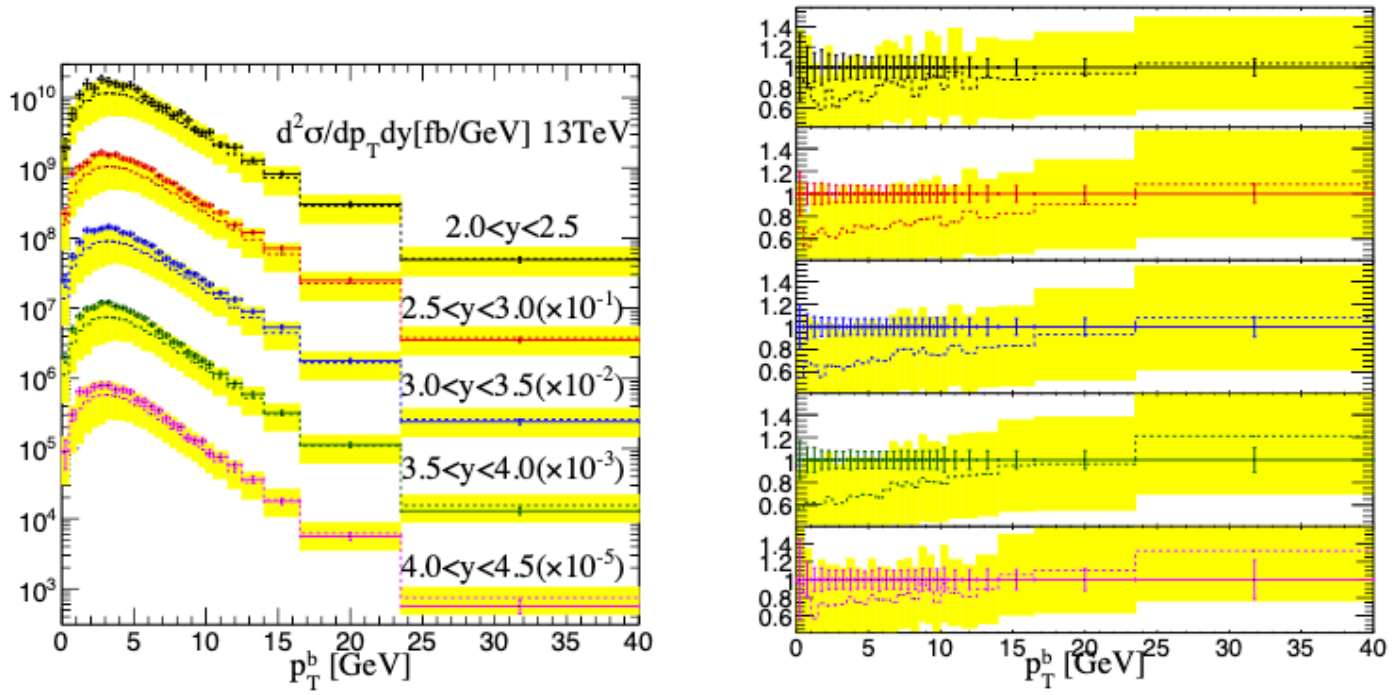
Theory (closely related to the LoI)

- S-ACOT-mPS follows the philosophy of S-ACOT-χ. Flavor-Excitation (FE) terms computed with massless HQ. Full mass dependence retained in the phase space. K. Xie Ph.D. Thesis (2019). Xie, Nadolsky, Campbell, in prep.
  (Pavel Nadolsky will discuss more about the progress on this)

NLO S-ACOT-mPS applied to inclusive b-production at LHCb
Yellow band: quadrature sum of PDF, scale, and mb uncertainties.

Fast table computations available.

Figure from K. Xie's PhD thesis
https://scholar.smu.edu/hum_sci_physics_etds/7/



- S-ACOT-mT applied to D-meson production. Helenius and Paukkunen JHEP (2018)
- m-ACOT applied to top-quark initiated Higgs production. Han, Sayre, Westhoff. JHEP(2015)

Theory

- S-ACOT-(…): generalization to NNLO for PP collisions desiderable

New NNLO predictions made available recently:

- FO calculation for Z + b-jet at O(α_s^3) in QCD, combines ZM NNLO and FFNS NLO. Gauld, Gehrmann-De Ridder, Glover, Huss, Majer, 2005.03016 PRL(2020)

- W + c-jet at NNLO at the LHC. Czakon, Mitov, Pellen, Poncelet, 2011.01011

At this stage, it is already technically possible to generate predictions within the S-ACOT-mPS scheme at NNLO if we have K-factors (NNLO/NLO) at hand and perform a global PDF analysis within the CTEQ framework.

Data

List is not exhaustive here

Need better control on the systematics, but measurement ratios can in principle be used.

Z + b at the LHC

CMS collaboration, A. M. Sirunyan et al., *Measurement of the associated production of a Z boson with charm or bottom quark jets in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. D* **102** (2020) 032007 [2001.06899].

ATLAS collaboration, G. Aad et al., *Measurements of the production cross-section for a Z boson in association with b-jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **07** (2020) 044 [2003.11960].

CMS collaboration, V. Khachatryan et al., *Measurements of the associated production of a Z boson and b jets in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J. C* **77** (2017) 751 [1611.06507].

ATLAS collaboration, G. Aad et al., *Measurement of differential production cross-sections for a Z boson in association with b-jets in 7 TeV proton-proton collisions with the ATLAS detector*, *JHEP* **10** (2014) 141 [1407.3643].

CMS collaboration, S. Chatrchyan et al., *Measurement of the production cross sections for a Z boson and one or more b jets in pp collisions at sqrt(s) = 7 TeV*, *JHEP* **06** (2014) 120 [1402.1521].

b-production at the LHC

Precise →

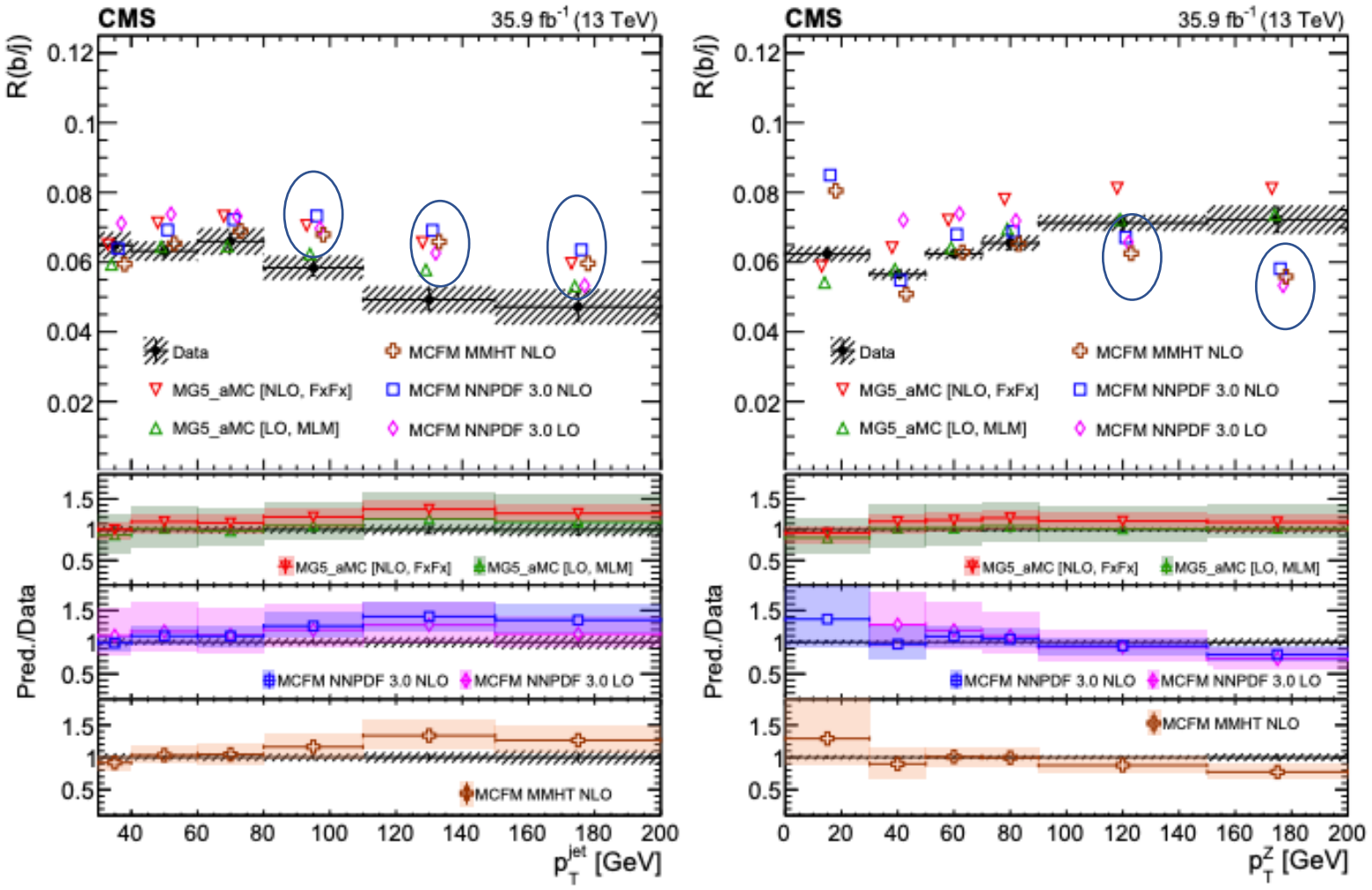
LHCb collaboration, R. Aaij et al., *Measurement of the $B^{\pm}$ production cross-section in pp collisions at $\sqrt{s} = 7$ and 13 TeV*, 1710.04921.

ATLAS collaboration, G. Aad et al., *Measurement of the inclusive and dijet cross-sections of b^{-} jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Eur. Phys. J.* **C71** (2011) 1846, [1109.6833].

CMS collaboration, S. Chatrchyan et al., *Inclusive b-jet production in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **04** (2012) 084, [1202.4617].

Data

Associated production of a Z boson with a c or a b-jet at CMS 13 TeV



$$R(c/j) = \frac{\sigma(Z+c\ jets)}{\sigma(Z+jets)}$$

$$R(b/j) = \frac{\sigma(Z+b\ jets)}{\sigma(Z+jets)}$$

$$R(c/b) = \frac{\sigma(Z+c\ jets)}{\sigma(Z+b\ jets)}$$

Figure from the CMS Analysis 2001.0689

Current activities LoI-related (within KSU, SMU, and MSU)

- Ongoing analysis of the compatibility of new charm and bottom quark production DIS data within CTEQ global analysis (M.G.)

- Ongoing work on S-ACOT-mPS (Xie, Nadolsky, et al.)

- Ongoing work on S-ACOT schemes at NNLO for PP collisions.

  (S-ACOT-χ generalized to NNLO for neutral current in DIS. (Guzzi, Nadolsky, Lai, Yuan, PRD 2012). Default scheme for CTEQ NNLO global analyses)

- Within the CTEQ group, we are interested in external collaborations on new calculations for processes with HQs that can be used for PDF analyses.

Concluding remarks

- After LoI submission, many activities are going on.
- Fast table theory predictions are mandatory for PDF analyses
- There is work ahead to be done, but precision measurements at the LHC will be the key to unlock HQ dynamics and improve current constraints on HQ PDFs.
- Several spinoffs may be accomplished in the near future

For example

Possible spinoffs

Measurement of associated production of a W boson and a charm quark in proton-proton collisions at 13 TeV at CMS. CMS Coll. Eur.Phys.J.C 79 (2019) 3, 269, 1811.10021 [hep-ex]

PDF analysis at CMS to constrain the strange quark PDF

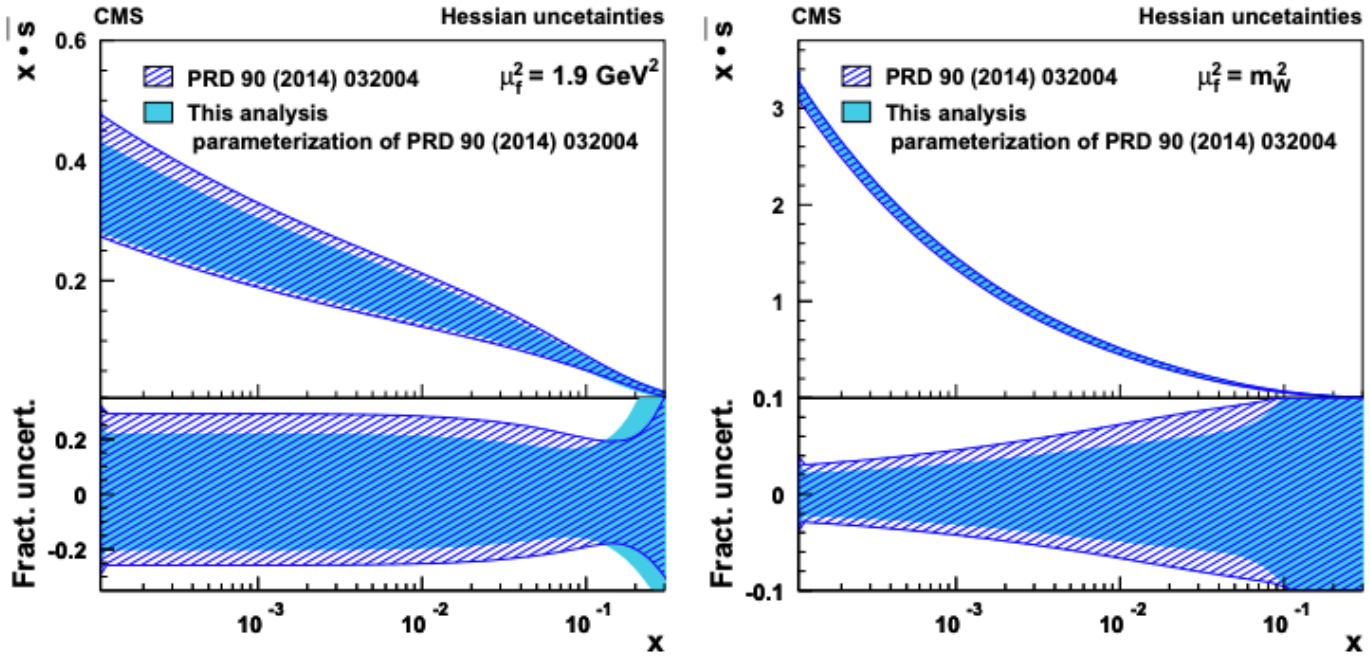


Figure from 1811.10021

A possible spinoff of the LoI is a novel strange anti-strange asymmetry study at NNLO

Possible spinoffs

- Hadron collider-based HF analyses will be complementary to DIS, especially direct to measurements at EIC: better understanding of processes at the EIC.
- Interplays between FFN schemes (Nf=4 and Nf=5) have been extensively studied in different processes: Z-production, Higgs, single top, etc. These schemes are compatible, but complementary information can be gathered by using a GMVFNS over the whole kinematic range.
- W+c-jet at NNLO will allow for a new strange asymmetry analysis
- Important for many Beyond the Standard Model searches (2HD models, Z's, etc.)

THANK YOU