Heavy flavor production at hadron colliders

Simplified ACOT scheme with Massive Phase Space (S-ACOT-MPS)

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In collaboration with
John Campbell (Fermilab) and Pavel Nadolsky (SMU),
SMU-HEP-18-03, 21xx.xxxxx,
SMU PhD. Thesis [link]

LoI to EF03 & EF06

Snowmass2021 LoI: **Constraining heavy flavor PDFs at hadron colliders**

Authors in alphabetical order: Marco Guzzi, Timothy Hobbs, Pavel Nadolsky, Laura Reina, Doreen Wackeroth, Keping Xie, C.-P. Yuan

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.

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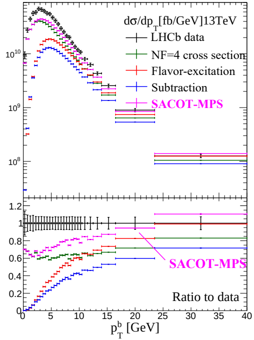
S-ACOT-MPS

The Simplified ACOT scheme with Massive Phase Space

- Keping Xie (PITT PACC)
- John Campbell (Fermilab)
- Pavel Nadolsky (SMU)



HF at hadron colliders

Data:

- heavy-flavor jet production, UA1, D∅, CDF, ATLAS, CMS
- Heavy-flavor hadron (D, B-meson) production, especially LHCb

Theoretical interests:

- pQCD: factorization theorem, scale uncertainty, fragmentation, etc.
- PDF: Forward heavy flavor production probes gluon PDF at small x.

$$x \sim \frac{m}{\sqrt{s}} e^{-y} \sim 10^{-6}.$$

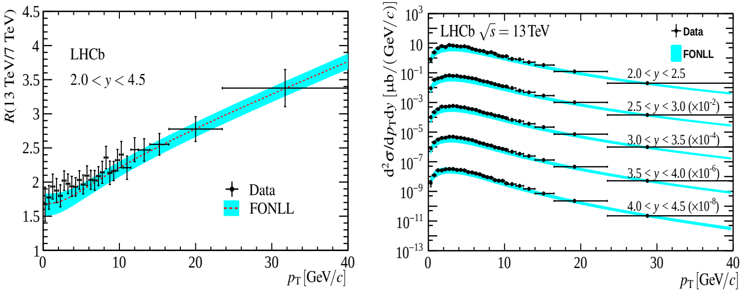
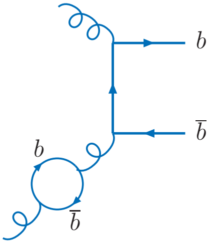


Figure: The D^0 [1510.01707] and $B^{\pm}$ [1710.04921] meson production at the LHCb 13 TeV.

Fixed Flavor Number (FFN) scheme

For consistency, we should take $N_f = 3(4)$ for charm(bottom) flavor production, in both α_s and PDF running.

- The heavy-quark running in the virtual loops is missing.
- No Flavor Excitation contributions as no heavy-flavor PDF.



Inconsistency when using $N_f = 5$ PDF in `MCFM`, `MadGraph_aMC@NLO`, `POWHEG`,

- $N_f = 5$ in the α_s running, e.g. reading directly from `LHAPDF`;
- No FE contributions, equivalent to $N_f = 3(4)$ in the PDFs.

We need treat heavy flavor consistently.

Theory for heavy-flavor production

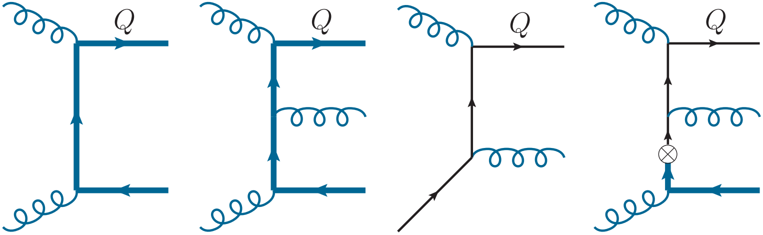
Energy scale Q, such as invariant mass M_{QQ} or p_T

- $Q \lesssim m$ (low energy), Flavor Creation (FC), FFN scheme (N_f)
- $Q \gg m$ (high energy), Flavor Excitation (FE), Zero-mass (ZM) scheme ($N_f + 1$), resum $\alpha_s^m \log^n(Q^2/m^2)$ as heavy-flavor PDF
- $Q \sim m$, General-mass (GM) variable flavor number (VFN) scheme

matching: subtracting the double-counted terms (ACOT idea [PRD1994])

$$\text{VFN} = \text{FC} + \text{FE} - \text{SB}$$

- $Q \lesssim m$, FE $\simeq$ SB, VFN $\to$ FC FFN scheme
- $Q \gg m$, FC $\simeq$ SB, VFN $\to$ FE ZM scheme



(a) FC LO (b) FC NLO (c) FE (d) SB

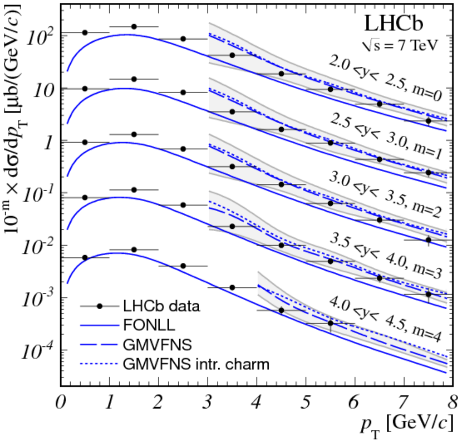
Comparison among different VFN schemes

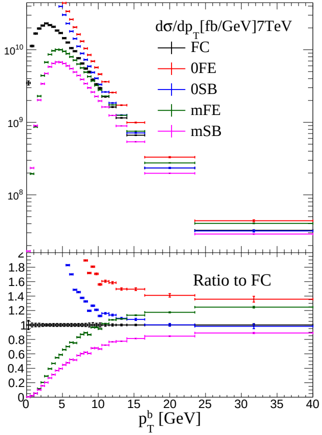
`FONLL`: Tune the matching function $G(m, p_T)$ [9803400,0102134]

`GM-VFNS`: Impose a hard cut $p_T \gtrsim m$ [0410289,11092472]

`SACOT-mT`: Choose a m_T dependence $x_{\min}$ for the FE (SB as well) [1804.03557]

`SACOT-MPS`: Massive phase space tame the matching instability. [KX et al., SMU-HEP-18-03, KX, PhD Thesis], NLO implementation in MCFM in a fully differential way.

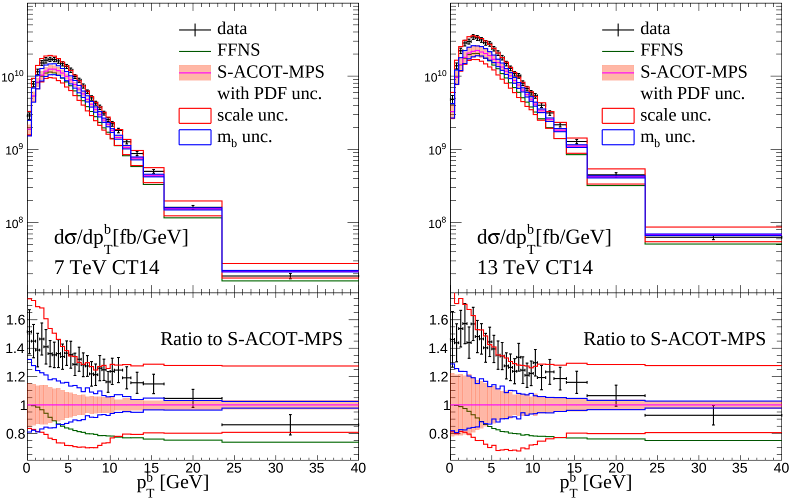




SACOT-MPS vs. LHCb data: the p_T^b distribution

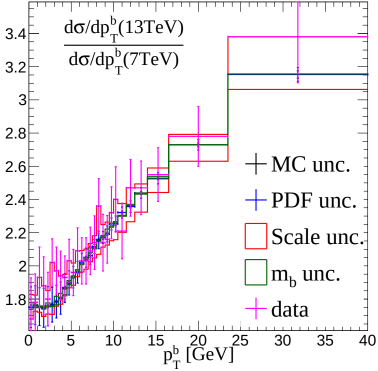
Scale $(\mu_R, \mu_F) = (1/2, 1, 2)\sqrt{p_{T,b}^2 + m_b^2}$ uncertainty is large:

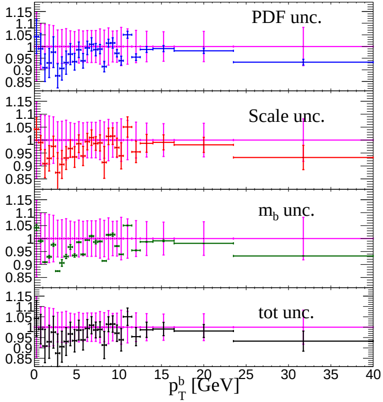
- $\alpha_s(\mu_R)$ is large and varies drastically around $\mu_R \sim m_Q$,
- Heavy-flavor PDF $f_Q(x, \mu_F)$ starts to be generated perturbatively at $\mu_F = m_Q$.



The ratio observable $R(13\text{TeV}/7\text{TeV})$

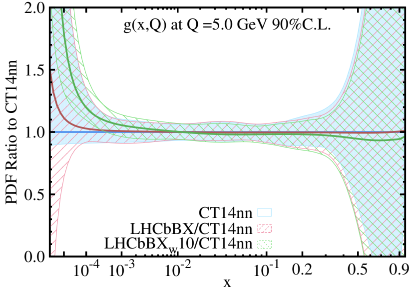
We introduce the ratio observables $R_{\sqrt{s_1}/\sqrt{s_2}}(X) = \frac{\sigma(X,\sqrt{s_1})}{\sigma(X,\sqrt{s_2})}$ [M. Mangano 1206.3557], of which the theoretical uncertainties cancel, especially the scale uncertainty.





CT14 Hessian profiling with ePump [C. Schmidt et al., 1806.07950]

LHCbBX(w10): CT14 PDF updated with wight 1(10) LHCb $B^{\pm}$ data.
Caveat: We treat the systematic errors as uncorrelated, since we do not have the full correlated uncertainties.



We observe the impact on gluon PDF, but still mild, because

- CT14 PDF describe the data very well,
- The experimental uncertainties are still large.

Summary

- We develop SACOT-MPS scheme for the heavy flavor production at hadron collider, which gives a good cancellations behaviors in both asymptotic limits:
  - $p_T \ll m_Q$, the SB cancels the FE term, FFN scheme,
  - $p_T \gg m_Q$, the SB cancels the FC term, ZM scheme.
- The calculation is implemented in `MCFM` in a fully differential way.
- We have obtained the subtraction $\tilde{f}_Q = P_{Q\leftarrow g} \otimes g$ and residual $f_{\text{res}} = f_Q - \tilde{f}_Q$ PDF, available on HEPForge [https://sacotmps.hepforge.org]
- The subtraction and residual PDFs can be easily applied to other heavy-flavor process, such as $H/V + Q$ and extended to NNLO.
- Our calculations agree well with the LHCb $B^\pm$ measurements.
- With theoretical uncertainties cancel significantly, the ratio observables impact the gluon and HF in the small-x region. The precise data in next rounds can potentially provide strong constraints.
- Fast computation grids are generated, to be implemented in global PDF analysis.