Heavy flavor production at hadron colliders

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

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Pheno 2019 @ Pittsburgh

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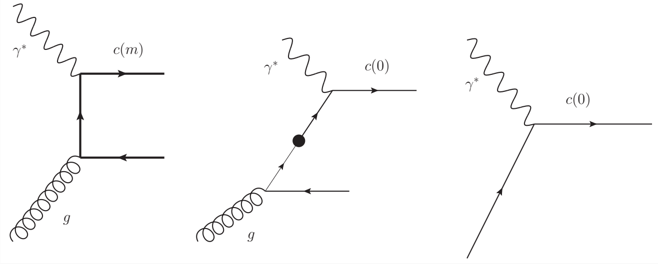
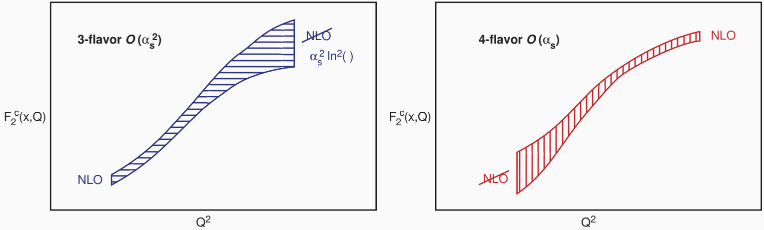
Charm production at DIS: FFN vs ZM schemes





- $Q \gtrsim m_Q$, m_Q matters, $Q(x,\mu) \approx 0$, Flavor Creation (FFN 3-flv).
- $Q \gg m_Q$, $m_Q \approx 0$, $Q(x,\mu)$ matters, Flavor Excitation (ZM 4-flv).

ACOT series

- Aivazis-Collins-Olness-Tung [PRD1994] introduce an asymptotic subtraction (SB) term to get rid of the double-counting between Flavor Creation (FC) and Flavor Excitation (FE), which switches from N_f to $N_f + 1$ scheme (Variable Flavor Number Scheme).

$$\mathrm{FC{-}SB{+}FE}$$

  - $Q \gtrsim m_Q$, $SB \simeq FE$, FFN 3-flv scheme.
  - $Q \gg m_Q$, $SB \simeq FC$, ZM 4-flv scheme.
- Simplified-ACOT scheme [J. Collins PRD1998, M. Kramer et. al. PRD2000] treats heavy-quark as massless in Flavor Excitation. Warning: instability in the cancellation between SB and FE around the switching point.
- The S-ACOT-χ sheme [W. Tung et.al. JPG2002] introduces rescaling variable $\chi = x(1 + 4m_Q^2/Q^2)$ to capture the mass threshold effect.
  It stabilizes the perturbative convergence near the switching point by enforcing energy-momentum conservation in all scattering contributions.
- The S-ACOT-MPS [K. Xie et. al. 18xx.xxxxx] scheme extends the S-ACOT-χ method to hadron-hadron collisions.

heavy-quark production at colliders

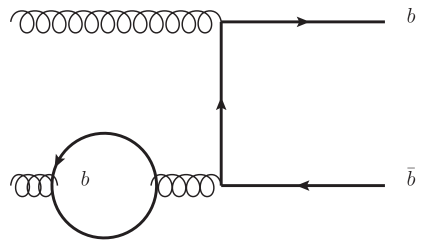
Lots of related experimental data such as D,B mesons at LHCb, b-quark jets at UA1, D0, CDF, ATLAS, and CMS.

- Forward heavy-quark productions at the LHCb are sensitive to gluon-PDF at small-x, because of $x_{1,2} \sim \frac{\sqrt{m^2+p_T^2}}{\sqrt{s}} e^{\pm y}$ [PROSA arXiv:1503.04581].
- Physical observable: p_T^Q
  - $p_T^Q \ll m_Q$, N_f Fixed Flavor Number Scheme [P. Nason et. al. NPB1989, W. Beenakker NPB1991],
  - $p_T^Q \gg m_Q$, Zero-Mass Scheme (N_f+1),
  - $p_T^Q \sim m_Q$, General-Mass Variable Flavor Number Scheme.
- Existing GM-VFNS's for heavy-quark hadroproduction
  - FONLL [M. Cacciari et. al., hep-ph/9803400, hep-ph/0102134],
  - GM-VFNS code [B. Kneihl et. al. hep-ph/0410289, 1109.2472],
  - S-ACOT-MPS [K. Xie et. al. 19xx.xxxxx].

FFNS calculations for b-quark production

Decoupling theorem of FFNS, we should take $N_f = 4$ 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.



If 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 $N_f = 4$ in the PDFs.

ACOT idea: FC-SB+FE.

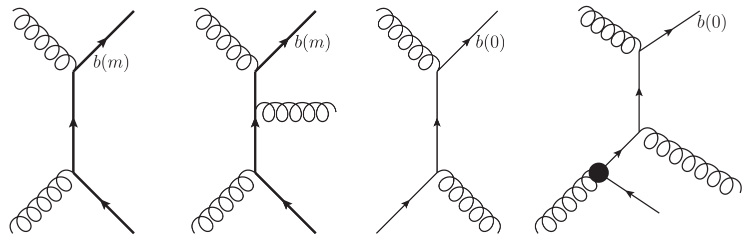


Figure 1: Representative diagrams for Flavor Creation (LO and NLO), Flavor Excitation and SuBtraction terms.Thick (thin) lines indicate massive (massless) quark propagators. The dot means convolution.

Ideally, we have

- $p_T^Q \ll m_Q$, $\mathrm{SB} \simeq \mathrm{FE}$, FC dominates (FFNS),
- $p_T^Q \gg m_Q$, $\mathrm{SB} \simeq \mathrm{FC}$, FE takes over (ZMS).

Comparisons with FONLL and GM-VFNS code

- FONLL resums logarithms as fragmentation functions and subtracts the massless limit of fixed-order where only log terms retained [M. Cacciari et. al., hep-ph/9803400, hep-ph/0102134].

  $$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0}) \times G(m, p_T).$$

  The matching function is tuned to keep $\lim_{m/p_T \to 0} G(m, p_T) = 1$.

- GM-VFNS code [B. Kneihl et. al. hep-ph/0410289, 1109.2472],

  $$\sigma = \mathrm{FC} + \mathrm{FE} - \Delta\sigma, \quad \text{where} \quad \lim_{m\to 0} \sigma_m = \sigma_0 + \Delta\sigma.$$

  The subtraction term $\Delta\sigma$ is logarithms, equivalent to $FOM0$.

- S-ACOT-MPS scheme is equivalent to GM-VFNS, except the subtraction term is calculated with the convolution of splitting function [J. Collins PRD1998, M. Kramer et. al. PRD200],

  $$\mathrm{SB} = \hat{\sigma}_{gQ} \otimes P_{Q\leftarrow g} \otimes g(x).$$

  We introduce the massive phase space to capture the threshold effect in FE and SB by following the idea S-ACOT-χ scheme[W. Tung et.al. JPG2002].

NLO cross section: massless vs. massive phase space.

`SACOT-MPS`:The matching instability is tamed by the massive phase space.
`FONLL` deals it with a tuned a tuned matching function $G(m, p_T)$
`GM-VFNS` has to impose a cut $p_T^Q > m_Q$.

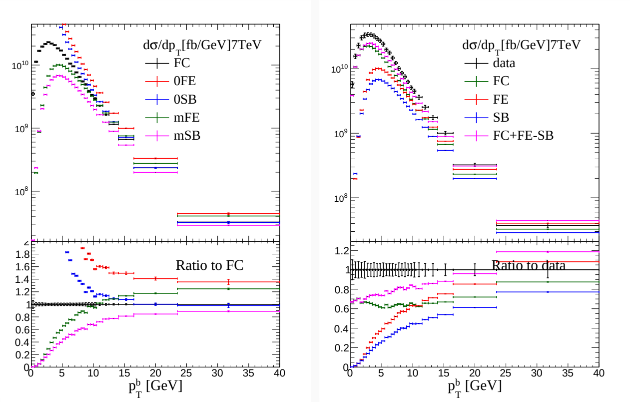


Figure 2: The FC is calculated with `MCFM`, which is cross-checked with `MadGraph_aMC@NLO` and `FONLL` online web. The $B^{\pm}$ is corrected back to the b-quark with fragmentation ratio

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

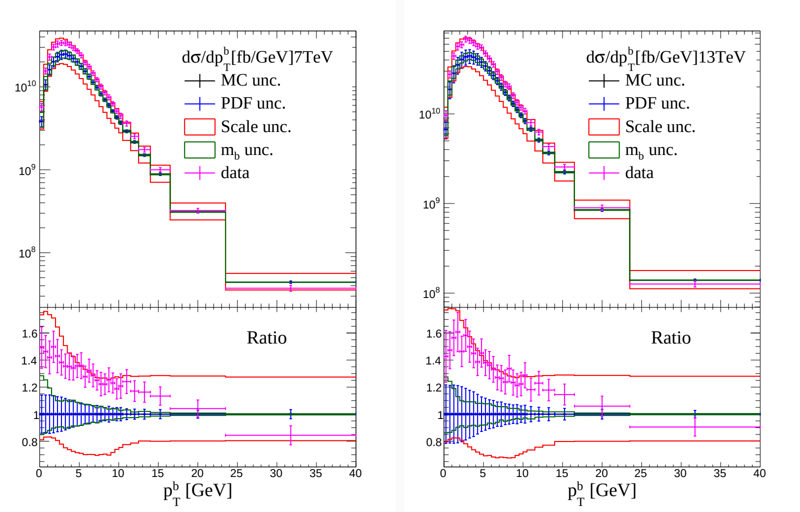


Figure 3: We choose CT14 PDF. The scale and m_b uncertainties are calculated by varying $\mu_R = \mu_F = (1/2, 1, 2)\sqrt{p_T^2 + m_Q^2}$ and $m_b = 4.75 \pm 0.25$ GeV.

NLO scale uncertainties are large.

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

We can introduce the ratio observables $R_{E_1/E_2}(X) = \frac{\sigma(X,E_1)}{\sigma(X,E_2)}$, in which theoretical uncertainties cancel significantly [M. Mangano 1206.3557].

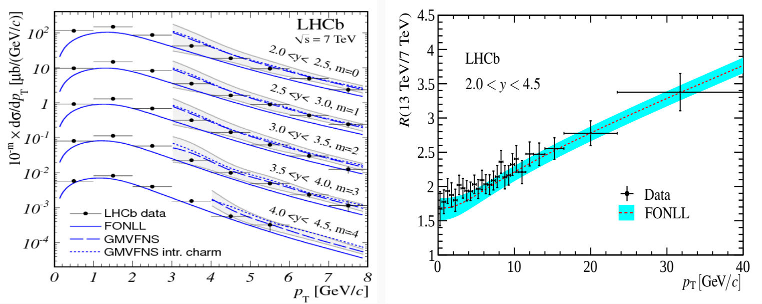
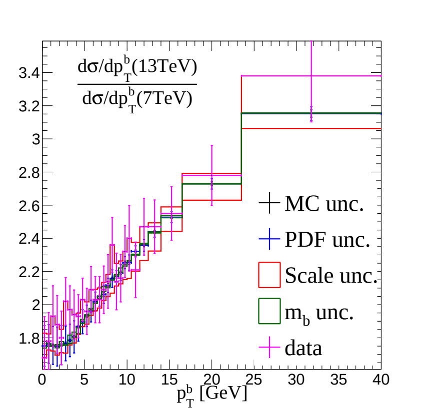
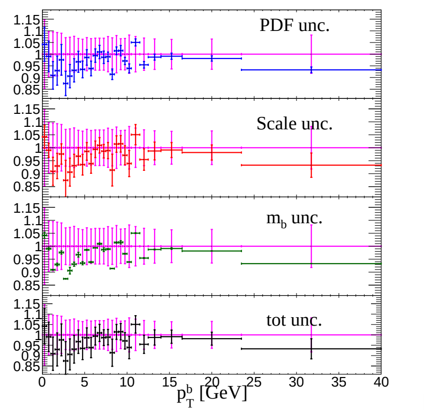


Figure 4: LHCb measurements of D^0 production at 7 TeV [1302.2864], and the cross section ratio $R(13\text{TeV}/7\text{TeV})$ of $B^\pm$ p_T distribution [1710.04921].

S-ACOT-MPS vs. LHCb data: the ratio $R(13\text{TeV}/7\text{TeV})$

Theoretical uncertainties cancel, especially the scale uncertainty.





NLO vs. LHCb data: double-differential cross section

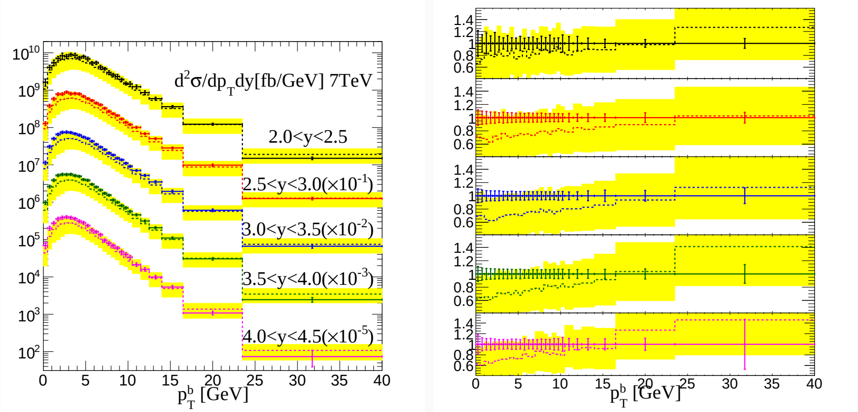


Figure 5: Double differential cross section for 7 TeV. Yellow bands are the total theoretical uncertainties, added in quadrature. Good overall agreement.

13 TeV case

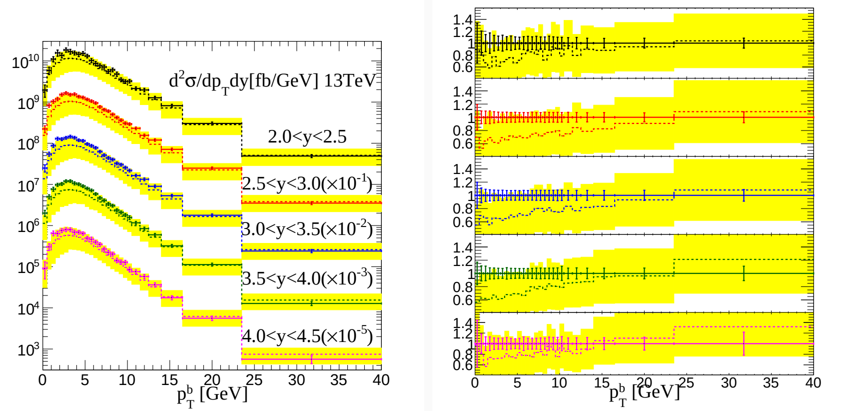
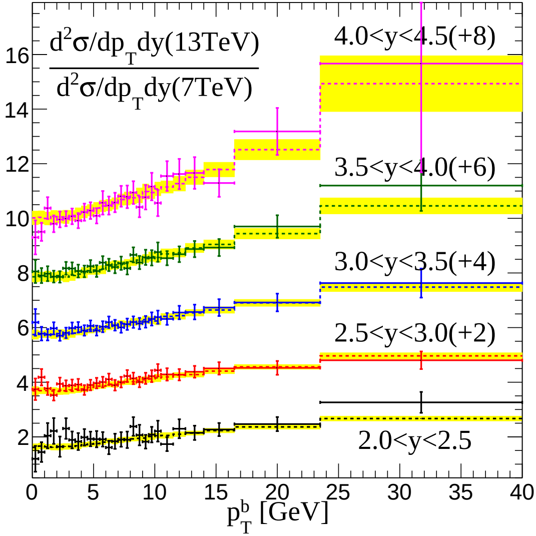


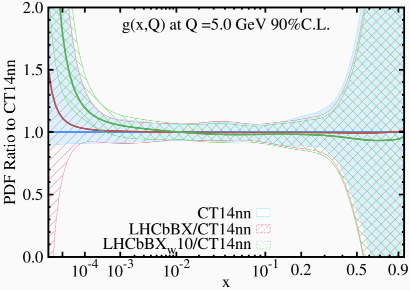
Figure 6: Double differential cross section for 13 TeV.

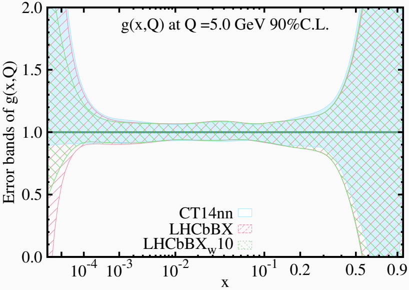
NLO vs. LHCb data: ratios of double-diff. cross sections



CT14 Hessian profiling with `ePump` [C. Schmidt et. al. 1806.07950, see talk by Zhite Yu]

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.

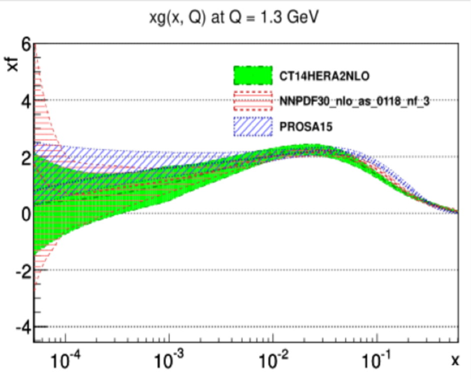


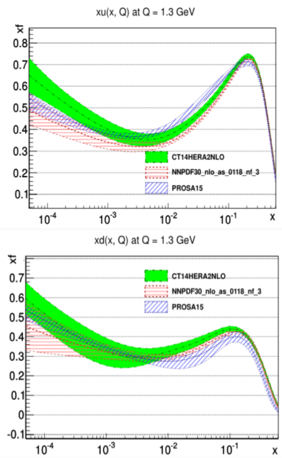


We observe the impact on gluon PDF, but still mild, because

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

PROSA15 PDFs fitting 7 TeV LHCb charm data [1503.04581], compatible with CT14HERA2NLO $N_f = 3$.





Next rounds of LHCb measurements may help constrain the small-x gluon.

Summary

- We develop S-ACOT-MPS scheme calculations to the heavy-flavor hadroproduction.
  - Contributions to inclusive heavy quark from both Flavor Creation and Flavor Excitation;
  - The double-counted term from gluon splitting is subtracted;
  - We introduce massive phase space to capture the threshold effect.
- We obtain good cancellations behaviors in both asymptotic limits:
  - $p_T \ll m_Q$, the SB cancels the FE terms,
  - $p_T \gg m_Q$, the SB cancels the FC terms.
- Our calculations agree well with the LHCb $B^{\pm}$ measurements.
- With theoretical uncertainties cancel significantly, the ratio observables impact the gluon-PDF in the small-x region. The precise data in next rounds can potentially provide strong constraints.
- Implementation in `MCFM` can be easily extended to NNLO, and applied to other heavy-quark processes, such as $H/V+Q$.