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

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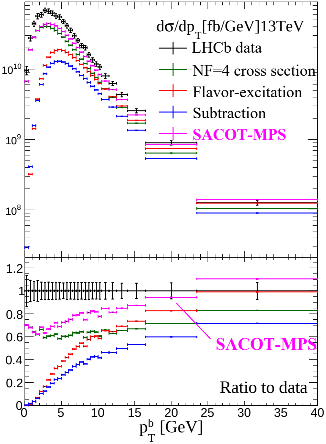
Based on the work with J. Campbell (Fermilab) and P. Nadolsky (SMU)
18xx.xxxxx.

What is S-ACOT-MPS?

Simplified-ACOT scheme with Massive Phase Space:
A QCD factorization approach for heavy-quark scattering at hadron-hadron colliders at (N)NLO in α_s.



Heavy-Flavor Production in DIS

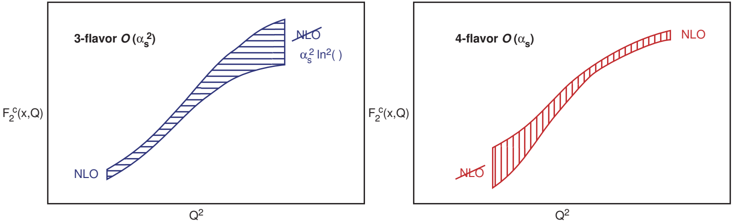


Figure: Expected uncertainty of Fixed Flavor Number Scheme for the Heavy-Flavor structure function in DIS T. Tung et. al. JPG2002.

- $Q \gtrsim m_Q$, m_Q matters, $Q(x,\mu) \approx 0$, Flavor Creation (N_f scheme).
- $Q \gg m_Q$, $m_Q \approx 0$, $Q(x,\mu)$ matters, Flavor Excitation ($N_f + 1$ scheme).

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

$$\mathrm{FC} + \mathrm{FE} - \mathrm{SB} \tag{1}$$

- $Q \gtrsim m_Q$, $\mathrm{SB} \simeq \mathrm{FE}$, return back to N_f scheme.
- $Q \gg m_Q$, $\mathrm{SB} \simeq \mathrm{FC}$, switch to $N_f + 1$ scheme.

ACOT series

- Simplified-ACOT scheme [J. Collins PRD1998, M. Kramer et. al. PRD2000] treats heavy-quark as massless in Flavor Excitation.
  Drawback: instability of the cancellation between SB and FE around the switching point.
- The S-ACOT-χ sheme [W. Tung et.al. JPG2002] introduces rescaling variable $\chi = \mathrm{x}(1 + 4\mathrm{m}_{\mathrm{Q}}^2/\mathrm{Q}^2)$ 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

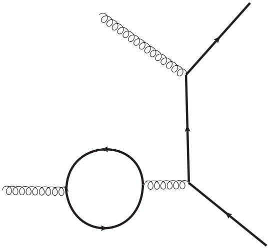
Lots of related experimental data such as D,B mesons at LHCb, b-quark jets at UA1, D0, CDF, ATLAS, and CMS.

- Forward heavy-quark productions at the LHCb are sensitive to gluon-PDF at small-x, because of $\mathrm{x}_{1,2} \sim \frac{\sqrt{\mathrm{m}^2+\mathrm{p}_\mathrm{T}^2}}{\sqrt{\mathrm{s}}}\mathrm{e}^{\pm \mathrm{y}}$ [PROSA arXiv:1503.04581].
- Physical observable: $\mathrm{p}_\mathrm{T}^\mathrm{Q}$
  - $\mathrm{p}_\mathrm{T}^\mathrm{Q} \ll \mathrm{m}_\mathrm{Q}$, N_f Fixed Flavor Number Scheme [P. Nason et. al. NPB1989, W. Beenakker NPB1991],
  - $\mathrm{p}_\mathrm{T}^\mathrm{Q} \gg \mathrm{m}_\mathrm{Q}$, Zero-Mass Scheme $(\mathrm{N}_\mathrm{f}+1)$,
  - $\mathrm{p}_\mathrm{T}^\mathrm{Q} \sim \mathrm{m}_\mathrm{Q}$, 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. 18xx.xxxxx].

FFNS calculations

In FFNS for b production, we should take $\mathrm{N_f} = 4$ 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 $\mathrm{N_f} = 5$ PDF in `MCFM`, `MadGraph_aMC@NLO`, `POWHEG`,

- $\mathrm{N_f} = 5$ in the α_s running, e.g. reading directly from `LHAPDF`;
- No FE contributions, equivalent to $\mathrm{N_f} = 4$ in the PDFs.

GM-VFNS's: Adding the Flavor Excitation terms and subtracting the double-counted terms (FC+FE-SB).

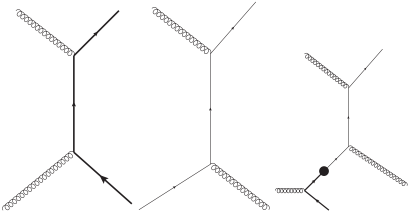


Figure: Representative diagrams for Flavor Creation, Flavor Excitation and SuBtraction terms.Thick (thin) lines indicate massive (massless) quark propagators. The dot means convolution.

Ideally, we have

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

Comparisons with 2 existing codes

- 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].

$$\mathrm{FONLL} = \mathrm{FO} + (\mathrm{RS} - \mathrm{FOM0}) \times \mathrm{G}(\mathrm{m}, \mathrm{p_T}). \tag{2}$$

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

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

$$\sigma = \mathrm{FC} + \mathrm{FE} - \Delta\sigma, \quad \text{where} \quad \lim_{\mathrm{m}\to 0} \sigma_{\mathrm{m}} = \sigma_0 + \Delta\sigma. \tag{3}$$

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

- 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],

$$\mathrm{SB} = \hat{\sigma}_{\mathrm{gQ}} \otimes \mathrm{P}_{\mathrm{Q}\leftarrow\mathrm{g}} \otimes \mathrm{g}(\mathrm{x}) \tag{4}$$

  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.

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

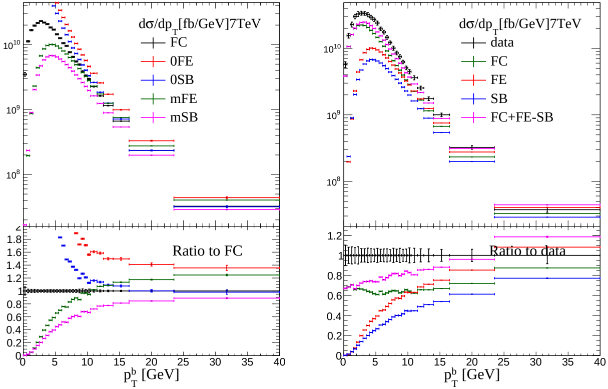


Figure: The FC is calculated with `MCFM`, which is cross-checked with `MadGraph_aMC@NLO` and `FONLL` online web. The $\mathrm{B}^{\pm}$ is corrected back to the b-quark with fragmentation ratio $\mathrm{f}(\mathrm{b} \to \mathrm{B}^{\pm}) = 0.403$ [PDG2016].

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

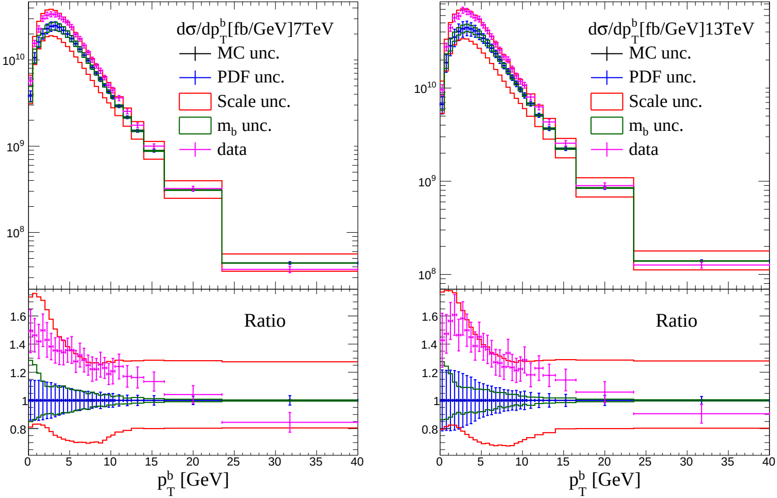


Figure: We choose CT14 PDF. The scale and m_b uncertainties are calculated by varying $\mu_R = \mu_F = (1/2, 1, 2)\sqrt{p_T^2 + m_Q^2}$ and $m_b = 4.75 \pm 0.25$ GeV.

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].

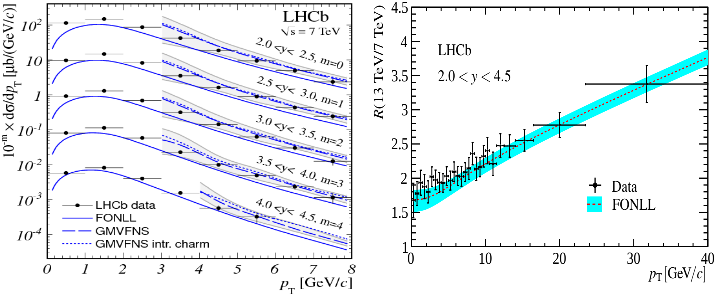
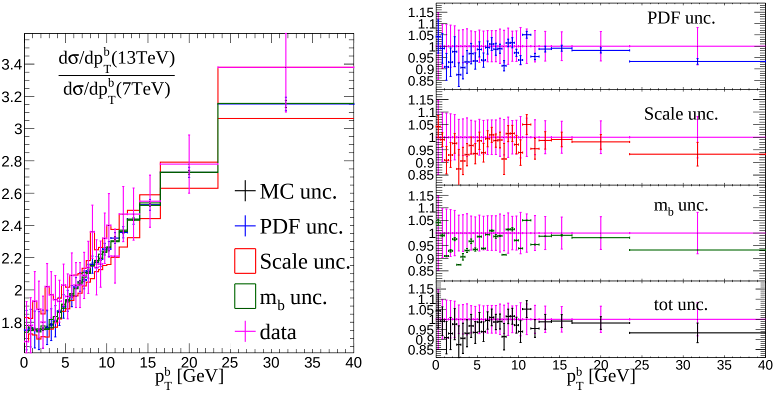


Figure: LHCb measurements of D^0 production at 7 TeV [1302.2864], and the cross section ratio $R(13TeV/7TeV)$ of $B^\pm$ p_T distribution [1710.04921].

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

Theoretical uncertainties cancel, especially the scale uncertainty.



NLO vs. LHCb data: double-differential cross section

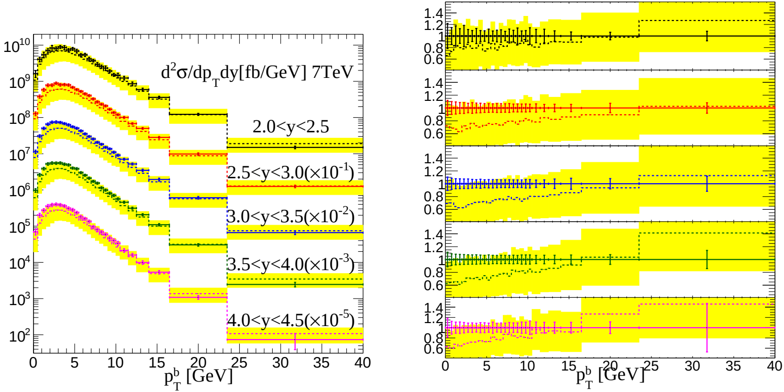


Figure: Double differential cross section for 7 TeV. Yellow bands are the total theoretical uncertainties, added in quadrature. Good overall agreement.

13 TeV case

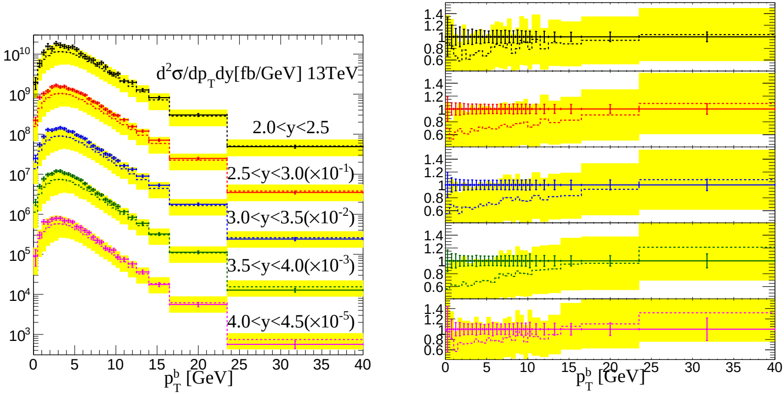
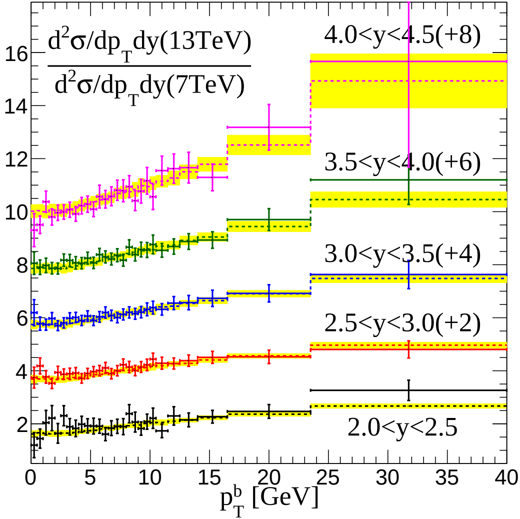


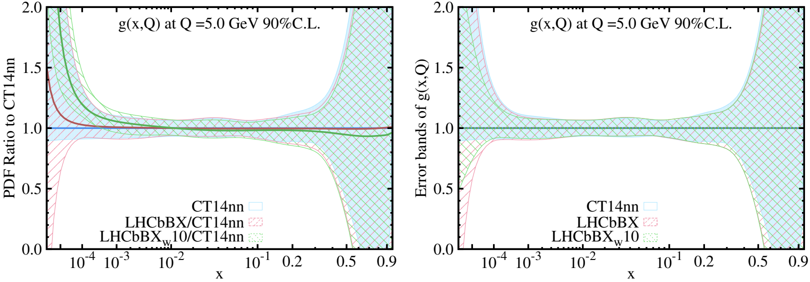
Figure: Double differential cross section for 13 TeV.

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



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

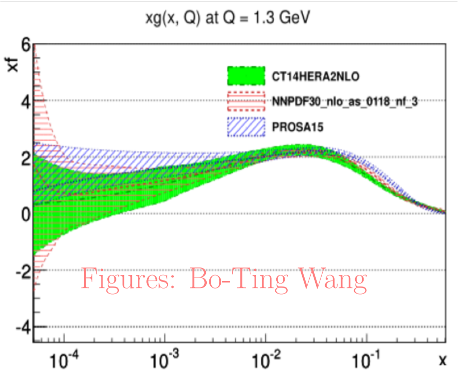
LHCbBX(w10): CT14 PDF updated with wight 1(10) LHCb $\mathrm{B}^{\pm}$ data. Caveat: We treat the systematic errors as uncorrelated, since we do not have the full correlated uncertainties.



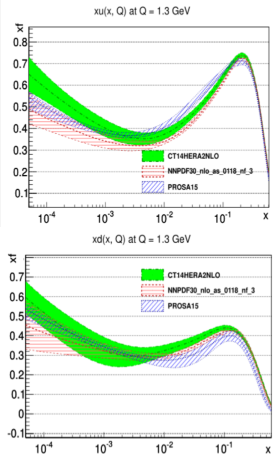
We observe the impact on gluon PDF, but still mild, because

- 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 $\mathrm{N_f = 3}$.



Figures: Bo-Ting Wang



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:
  - $\mathrm{p_T} \ll \mathrm{m_Q}$, the SB cancels the FE terms,
  - $\mathrm{p_T} \gg \mathrm{m_Q}$, the SB cancels the FC terms.
- Our calculations agree well with the LHCb $\mathrm{B}^{\pm}$ 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 $\mathrm{H/V+Q}$.