The heavy-flavor production at hadron colliders

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

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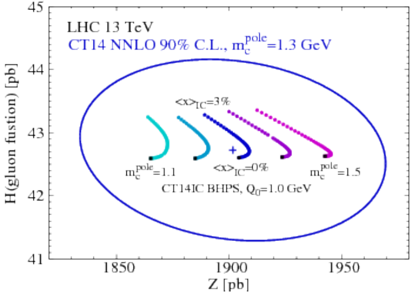
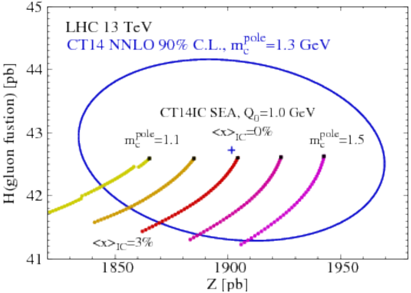
2108.03741, 2109.10905, 2203.05090, 2203.06207

The importance of HF PDFs

- Intrinsic vs extrinsic, *i.e.*, perturbative vs non-perturbative (fitted)? [See Nadolsky's talk]
- Can data tell the difference?
- Heavy flavor mass: dynamics (ME) and kinematics (phase space or threshold)
- Multiple scales: $Q(p_T)$ vs m_Q. PDF resums large logarithms $\alpha_s \log\left(Q^2/m_Q^2\right)$





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HF at hadron colliders

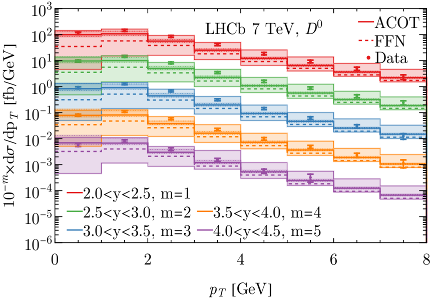
Data:

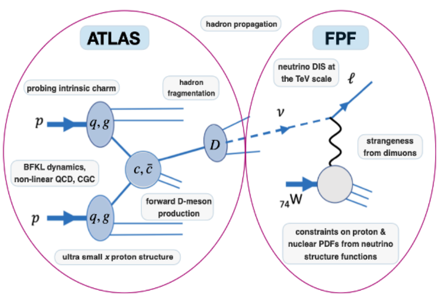
- Heavy-flavor hadron (D, B-meson) production, especially LHCb
- $Z + b/c$ production [See Boettcher's talk]
- Neutrino resource measured at the FASER as well as other FPFs

Theoretical interests:

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

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





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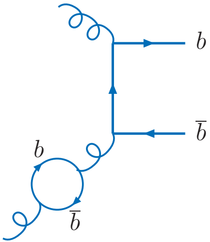
Massive Fixed-Flavor-Number (FFN) scheme

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 (FE) 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.

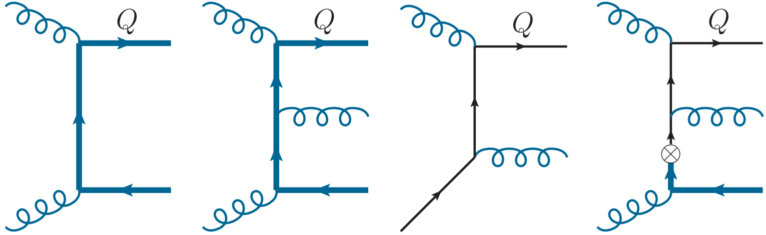
Theory for heavy-flavor production

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

- $Q \lesssim m$ (low energy), Flavor Creation (FC), massive 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 (massless)
- $Q \sim m$, General-mass (GM) variable flavor number (VFN) scheme
  matching: subtracting the double-counted terms

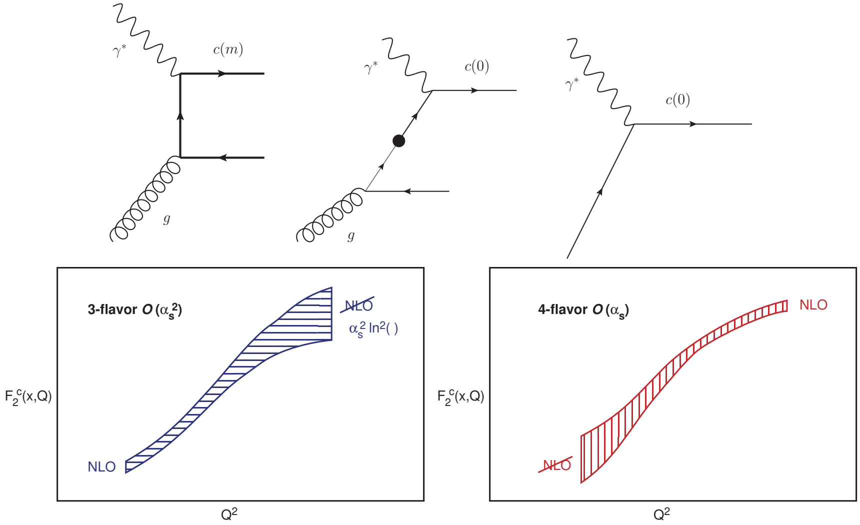
$$\text{VFN} = \text{FC} + \text{FE} - \text{SB}$$

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



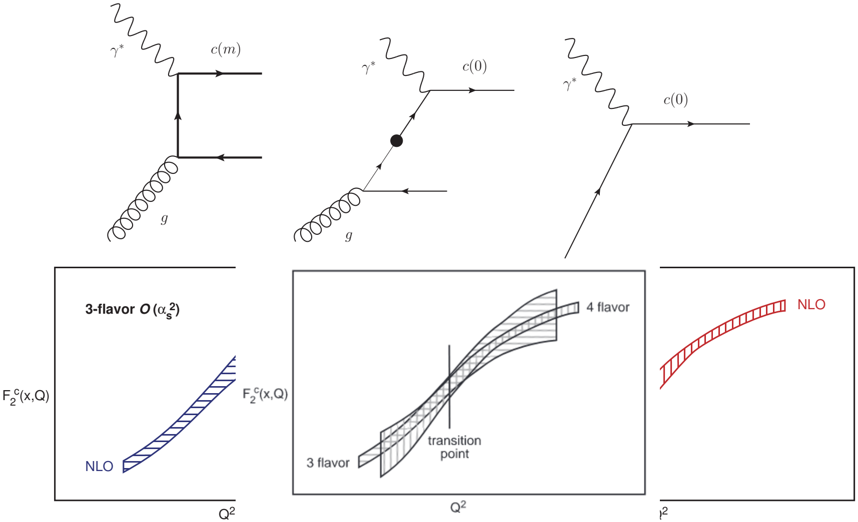
(a) FC LO (b) FC NLO (c) FE (d) SB

ACOT scheme



[W. Tung, et al., 0110247]

ACOT scheme



[W. Tung, et al., 0110247]

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

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

  - $Q \gtrsim m_Q$, SB $\simeq$ FE, ACOT $\to$ FFN 3-flv scheme;
  - $Q \gg m_Q$, SB $\simeq$ FC, ACOT $\to$ 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 scheme [W. Tung et al., 0110247] 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-m_T scheme [I. Helenius et al., 1804.03557]
- The S-ACOT-MPS [K. Xie et al., 2108.03741] scheme extends the S-ACOT-χ method to hadron-hadron collisions.

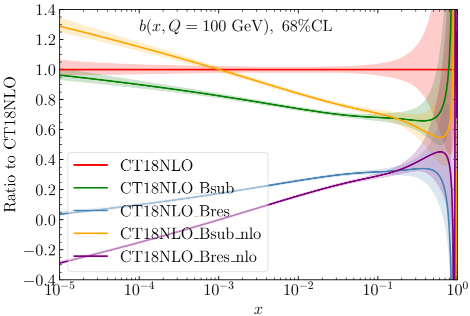
Formulation of the S-ACOT-MPS scheme

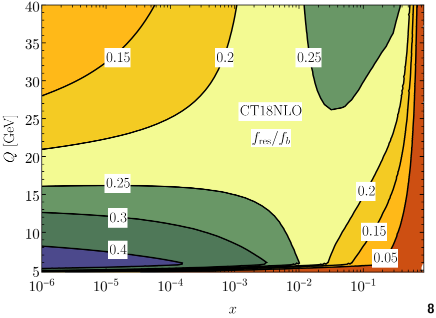
- FC+FE-SB

$$\sigma_{\rm FC} = \sum_{i,j} f_i(x_i,\mu^2) f_j(x_j,\mu^2)\widehat{\sigma}_{ij\to QX},$$
$$\sigma_{\rm FE} = \sum_{i} f_i(x_i,\mu^2) f_Q(x_Q,\mu^2)\widehat{\sigma}_{iQ\to QX} + (i\leftrightarrow Q),$$
$$\sigma_{\rm SB} = \sum_{i,j} f_i(x_i,\mu^2) [P_{Qj}\otimes f_j](x_Q,\mu^2)\widehat{\sigma}_{iQ\to QX} + (i\leftrightarrow Q).$$

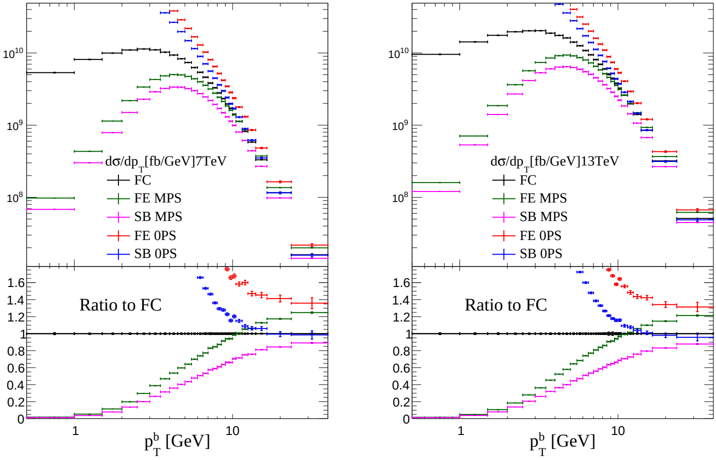
- We can define the subtracted and residual PDFs

$$\tilde{f}_Q(x,\mu^2) = \sum_j [P_{Qj}\otimes f_j](x,\mu^2),\ \delta f_Q(x,\mu^2) = [f_Q - \tilde{f}_Q](x,\mu^2)$$





The massive phase space



Caveat: The Lorentz violation for the heavy parton

$$p_b = x p_{\text{proton}} : \; p_{\text{proton}}^2 = 0 \leftrightarrow p_b^2 = m_b^2 .$$

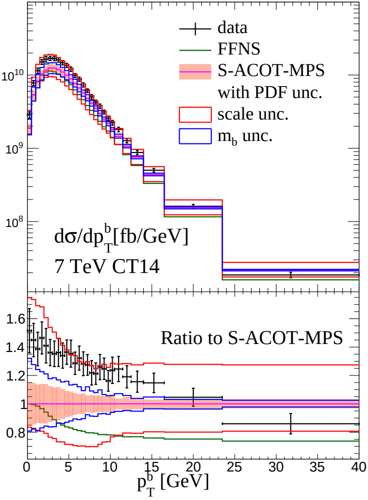
We enforce $E_b = x E_{\text{beam}} > m_b$.

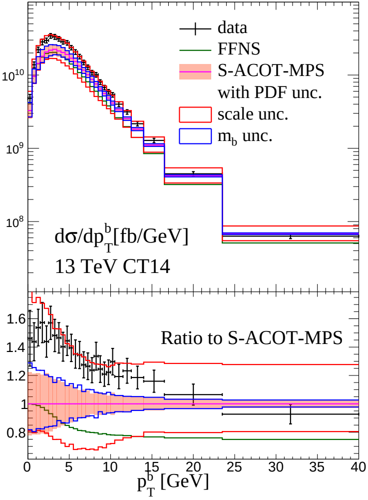
A correction term $\mathcal{O}(m_b^2/Q^2)$ needs to be got back order by order.

Bottom production at LHCb

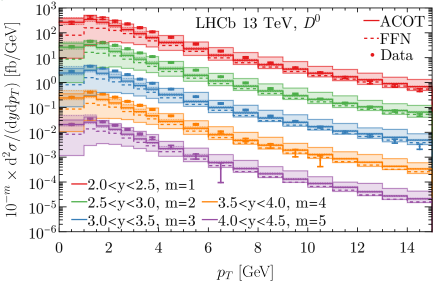
Scale $(\mu_R, \mu_F) = (1/2, 1, 2)\sqrt{p_{T,b}^2 + m_b^2}$ uncertainty is large:

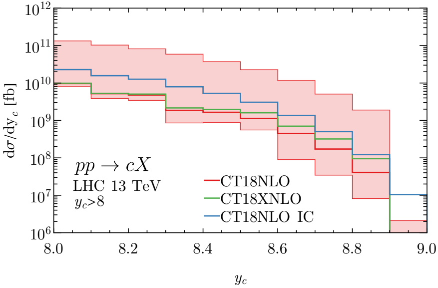
- $\alpha_s(\mu_R)$ is large and varies drastically around $\mu_R \sim m_Q$,
- Heavy-flavor PDF $f_Q(x, \mu_F)$ starts to be generated perturbatively at $\mu_F = m_Q$.





Charm production in the forward region





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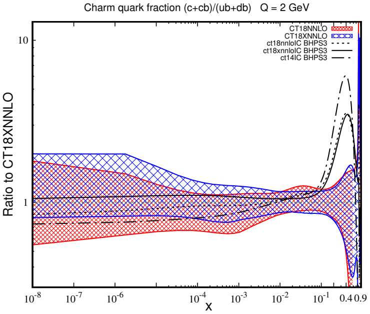
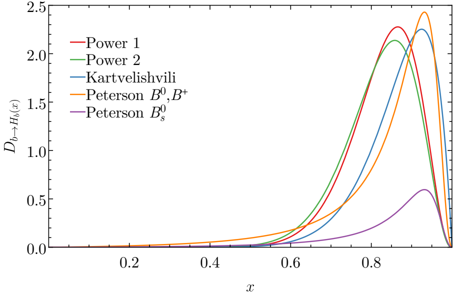
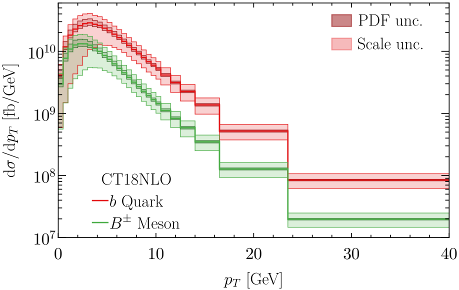
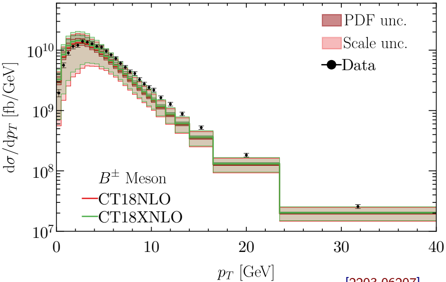


- Charm production in the forward region are sensitive to both small and large x charm and gluon PDFs.
- Intrinsic charm can potentially show up in the large x region.
- Both the LHCb and the FASER measurement can provide probe to the gluon at small x and intrinsic charm at large x.

Final-state fragmentation







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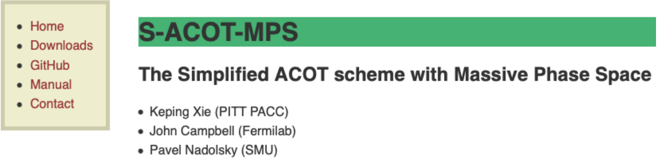
- The overall size gets reduced roughly by a factor of fragmentation fraction $\mathscr{B}(b \to B)$
- Fragmentation shift the p_T spectrum to a lower value.
- Our calculation gives a good description of the LHCb data, which can provide constraints on gluon and heavy-flavor PDFs.

Towards a global analysis of heavy-flavor data

- Generalize the S-ACOT-MPS to NNLO for proton-proton collisions
- NLO tables for fast computation are available on HEPForge



- Need the NNLO/NLO K-factors
- At this stage, it is already technically possible to perform a global PDF analysis within the CTEQ framework.
- Data: $Z + b$ and b/c production at the LHC (not exhaustive) [See Boettcher's talk].

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].

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].

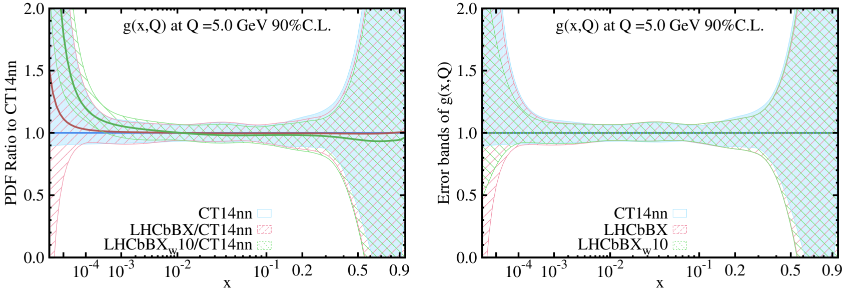
CMS collaboration, S. Chatrchyan et al., *Inclusive b-jet production in pp collisions at $\sqrt{s} = 7$ TeV*, JHEP **04** (2012) 084, [1202.4617].

B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, *Inclusive Charmed-Meson Production at the CERN LHC*, Eur. Phys. J. **C72** (2012) 2082, [1202.0439].

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

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 S-ACOT-MPS scheme for the heavy flavor production at hadron colliders
  - Inclusive heavy quark production 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 term, FFN scheme,
  - $p_T \gg m_Q$, the SB cancels the FC term, ZM scheme.
- 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.
- We have obtained the subtraction $\tilde{f}_Q = P_{Qg} \otimes g$ and residual $\delta f_Q = f_Q - \tilde{f}_Q$ PDF, which can be easily applied to other heavy-flavor process, such as $H/V + Q$. Available on `HEPForge`.
- Fast computation tables are generated, to be implemented in global analysis.