# Heavy-flavor production in central and forward LHC processes

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SnowMass2021

**Energy Frontier Workshop - March 30, 2022**
EF03 and EF06

Based on the whitepaper contribution, 2203.06207.

# Executive Summary

- Development of a new GMVFN scheme for PP collisions: S-ACOT-MPS
- Currently at NLO. NNLO needed.
- Implemented for inclusive charm [FPF, 2109.10905, 2203.05090] and bottom [2203.06207] production
- S-ACOT-MPS can easily be extended to other processes
- Ultimate goals:

➢ Constrain heavy-flavor PDFs in global QCD analyses;

➢ Probe QCD dynamics at small and large x

# Motivations

- Charm and bottom production at the LHC at small $p_T$ and large rapidity $y$ of the heavy quark: sensitive to PDFs at both small and large $x$

$$x_{1,2} \approx \frac{\sqrt{p_T^2 + m_Q^2}}{\sqrt{S}} e^{\pm y}$$

- here PDFs are poorly constrained by other experiments in global PDF fits.

- c/b production in the $4 < |y| < 4.5$ range in pp collisions at the LHC 13 TeV can probe $x \leq 10^{-5}$, and when $p_T \geq 40$ GeV, it can probe $x \geq 0.2$

- Probing this regime (and beyond, at future facilities) helps us shed light on the **intrinsic heavy-flavor content** of the proton and on **small-x dynamics**.

- LHC delivered precise measurements for these observables, especially **LHCb** (D-meson prod.).

# Theory calculation & HF production dynamics

Heavy flavor production dynamics is nontrivial due to the interplay of massless and massive schemes which are different ways of organizing the perturbation series

**Massive Schemes:** final-state HQ with $p_T \leq m_Q \Longrightarrow p_T$-spectrum can be obtained in the **fixed-flavor number (FFN) scheme**.
- No heavy-quark PDF in the proton. Heavy flavors generated as massive final states. $m_Q$ is an infrared cut-off.
- Power terms $\left(p_T^2/m_Q^2\right)^p$ are correctly accounted for in the perturbative series.

**Massless schemes**: $p_T \gg m_Q \gg m_P \Longrightarrow$ appearance of log terms $\alpha_s^m \log^n\left(p_T^2/m_Q^2\right)$ that spoil the convergence of the fixed order expansion. Essentially, a **zero mass (ZM) scheme**.
- Heavy quark is considered essentially massless and enters also the running of $\alpha_s$.
- Need to resum these logs with DGLAP: initial-state logs resummed into a heavy-quark PDF, final-state logs resumed into a fragmentation function (FF)

**Interpolating (GMVFN) schemes** : composite schemes that retain key mass dependence and efficiently resum collinear logs, so that they combine the FFN and ZM schemes together. They are crucial for:

- a correct treatment of heavy flavors in DIS and PP,
- accurate predictions of key scattering rates at the LHC,
- global PDF analyses.

# Theory calculation & HF production dynamics

- In DIS, perturbative convergence of QCD calculations in the ACOT and other GM-VFN schemes at small momenta comparable to $m_Q$ can be significantly improved by physical treatment of kinematics in flavor-excitation and subtraction terms.

- This is the motivation behind the S-ACOT-MPS (S-ACOT with massive phase space) factorization framework for heavy-quark scattering processes in proton-proton collisions.

- S-ACOT-MPS is equivalent to S-ACOT-χ but applied to proton-proton collisions.

- As for S-ACOT-χ , S-ACOT-MPS evaluates integrals of the Flavor Excitation and Subtraction terms using massless hard-scattering matrix elements combined with the mass-dependent, rather than massless, phase space.

# S-ACOT GMVFN schemes

The literature related to development of GMVFN schemes is vast and will not be discussed here.

We use S-ACOT-MPS to describe D-meson measurements at LHCb at 7 and 13 TeV [arXiv:2108.03741]

Another version named S-ACOT-$m_T$ was developed by Helenius & Pakkunen (*JHEP* 05 (2018)) to describe D-meson data at LHCb and ALICE.

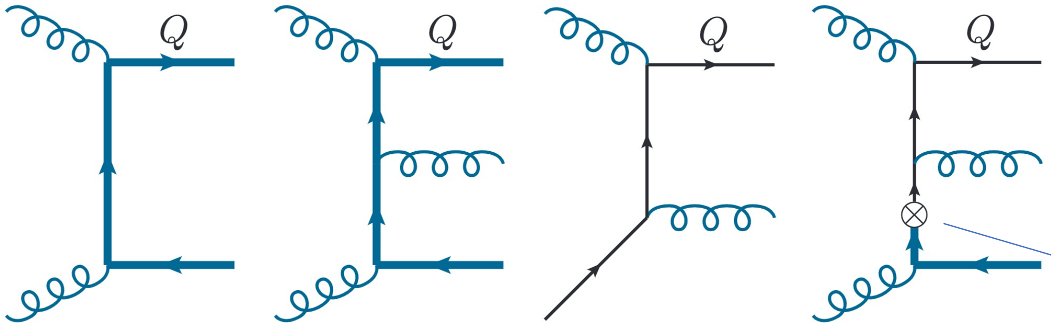
Results here are shown at NLO in QCD.

New NNLO predictions were recently made available:

- FO calculation for Z + b-jet at O($\alpha_s^3$) in QCD, combines ZM NNLO and FFNS NLO. Gauld, Gehrmann-De Ridder, Glover, Huss, Majer, 2005.03016
- 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 with suitable K-factors (NNLO/NLO) at hand.

# Main idea behind S-ACOT-MPS




LO FC | NLO FC | LO FE | Subtraction

The subtraction term avoids double counting and cancels enhanced collinear contributions from FC when $\hat{s} \gg m_Q^2$ or $p_T \gg m_Q$

Collinear splitting $gg \to Q\bar{Q}$

Mass fully retained in $\hat{\sigma}$ and $dPS$ (LO FC, NLO FC)

Mass fully retained in $dPS$ (LO FE, Subtraction)

$\sigma = \mathrm{FC} + \mathrm{FE} - \mathrm{SB}$. Subtraction well defined also in the $p_T \to 0$ limit

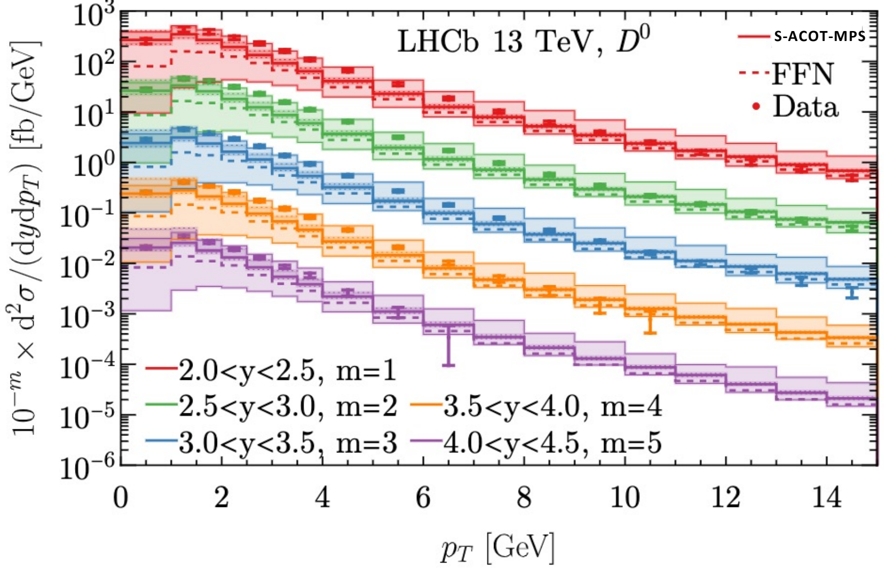
FE and Subtraction ➡ facilitated by introducing Residual PDF: $\delta f_Q(x,\mu^2) = f_Q(x,\mu^2) - \frac{\alpha_s}{2\pi} \log\left(\frac{\mu^2}{m_Q^2}\right) f_Q(x,\mu^2) \otimes P_{Q\leftarrow g}(x)$

allows us to get (FE-Subtraction) in one step

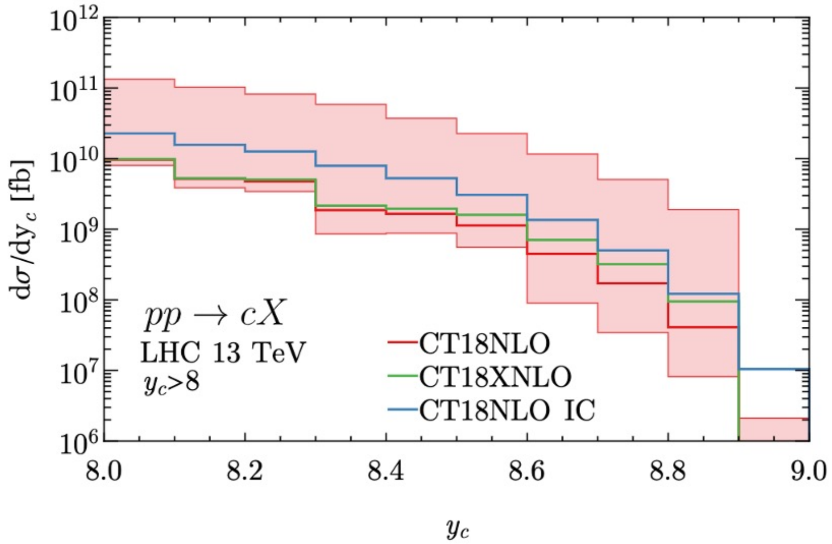
More details in: K. Xie, "Massive elementary particles in the standard model and its supersymmetric triplet higgs extension."
https://scholar.smu.edu/hum_sci_physics_etds/7, 2019. PhD Thesis

# Applications and Results: **Charm production at central and forward rapidity**

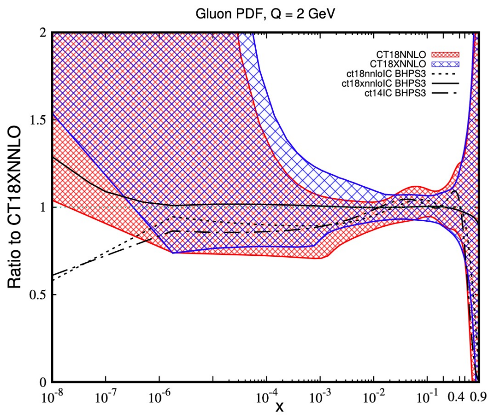
LHCb 13 TeV JHEP 03 (2016) 159




Transverse momentum at central rapidity at LHCb 13TeV.
Error bands are scale uncertainties. [arXiv:2108.03741]




Rapidity distributions of prompt charm at the LHC 13 TeV in the very forward region (yc > 8).
Error band represents the CT18NLO induced PDF uncertainty at 68% C.L. [arXiv:2109.10905]



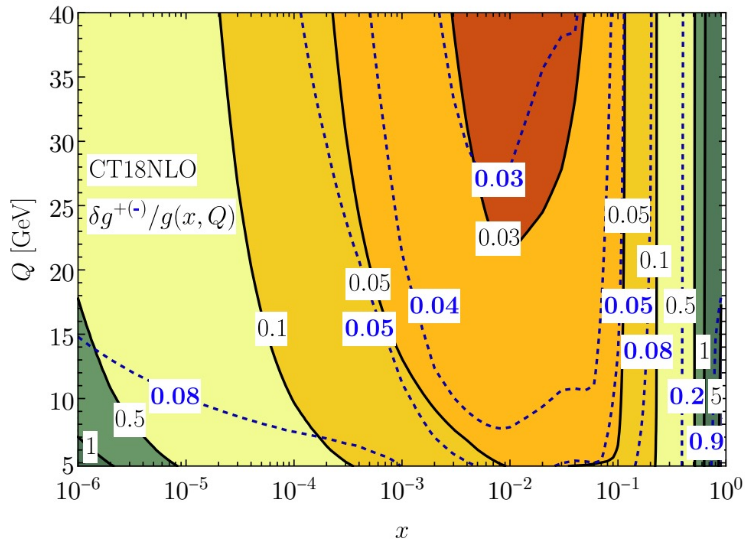

NNLO gluon PDF in CT18/CT18X with IC.
Error PDFs at 90% C.L. FPF paper 2109.10905

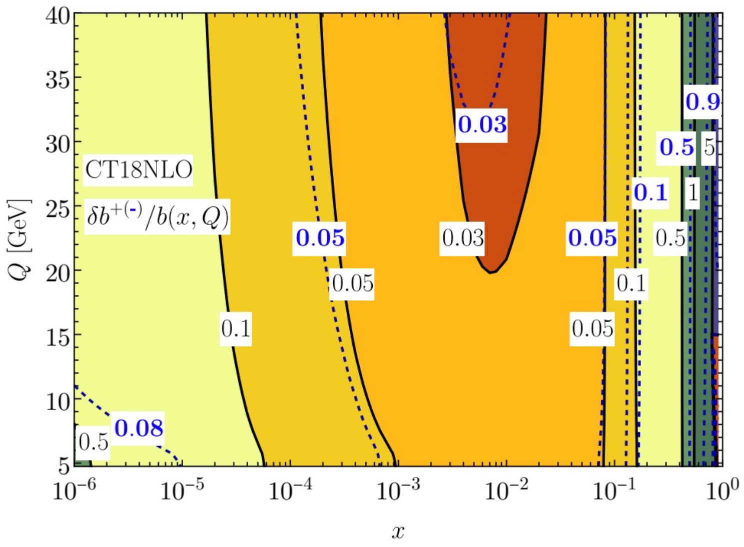
Charm hadroproduction and Z + c production at the LHC can constrain the IC contributions.
In CT14IC, we looked at Z+c at LHC 8 and 13 TeV. LHCb Z+c data deserve attention as they can potentially discriminate gluon functional forms at $x \geq 0.2$ and improve gluon accuracy.

For small x below $10^{-4}$, higher-order QCD terms with $\ln(1/x)$ dependence grow quickly at factorization scales of order 1 GeV. FPF facilities like FASERν will access a novel kinematic regime where both large-x and small-x QCD effects contribute to charm hadroproduction rate.

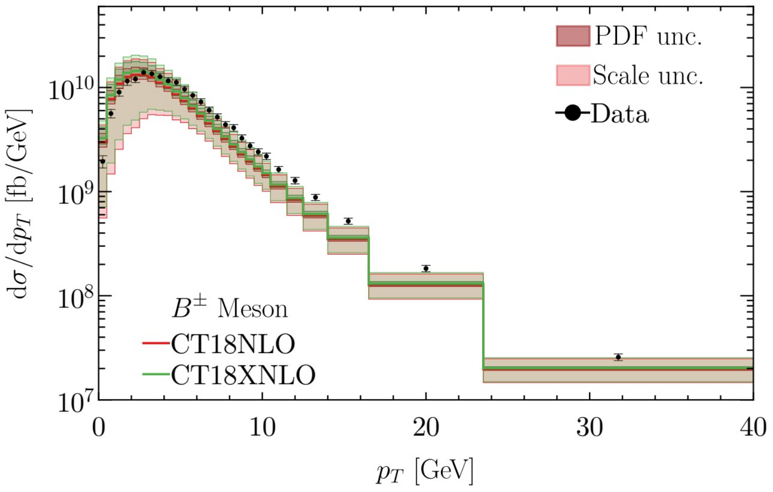
Campbell, Guzzi, Nadolsky, Xie, in preparation

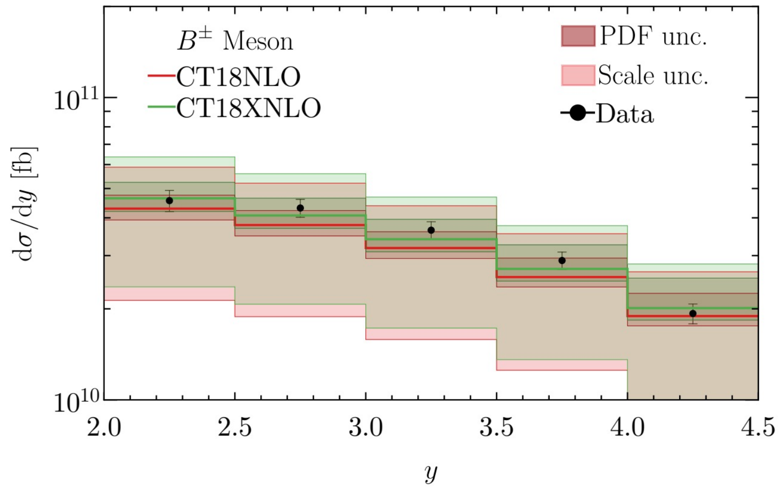
# Applications and Results: **inclusive b-production**




Strong sensitivity to the gluon and the b-quark PDFs. Corresponding PDF uncertainties obtained with the asymmetric Hessian approach at the 90% CL, with positive (negative) direction denoted as black solid (blue dashed) lines [arXiv:2203.06207]




NLO theory predictions for the pT and y distributions obtained with CT18NLO and CT18XNLO PDFs compared to B± production data from LHCb 13 TeV [arXiv:2203.06207]

Theoretical uncertainties at NLO are large (O(50%)) and mainly ascribed to scale variation. This can be improved by including higher-order corrections which imply an extension of the S-ACOT-MPS scheme to NNLO

# Concluding remarks

- S-ACOT-MPS is developed at NLO: used to describe HF production at central and forward rapidity
- Technically possible to generate predictions within the S-ACOT-MPS scheme at NNLO if we have K-factors (NNLO/NLO) at hand.
- Easy to extend to other heavy-flavor processes, such as Z+c/b.
- Important to constrain heavy-flavor PDFs.
- EF06 EF03 synergy will be helpful.