c/b production in central and forward LHC processes

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Motivations I (the big picture)

Goals:

- ➢Constrain heavy-flavor PDFs in global QCD analyses;
- ➢Probe QCD dynamics at small and large x.

- Extend the S-ACOT GMVFN scheme to 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.

Motivations II

- 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

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

- In this kinematic region PDFs are poorly constrained by other experiments in global PDF fits.

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

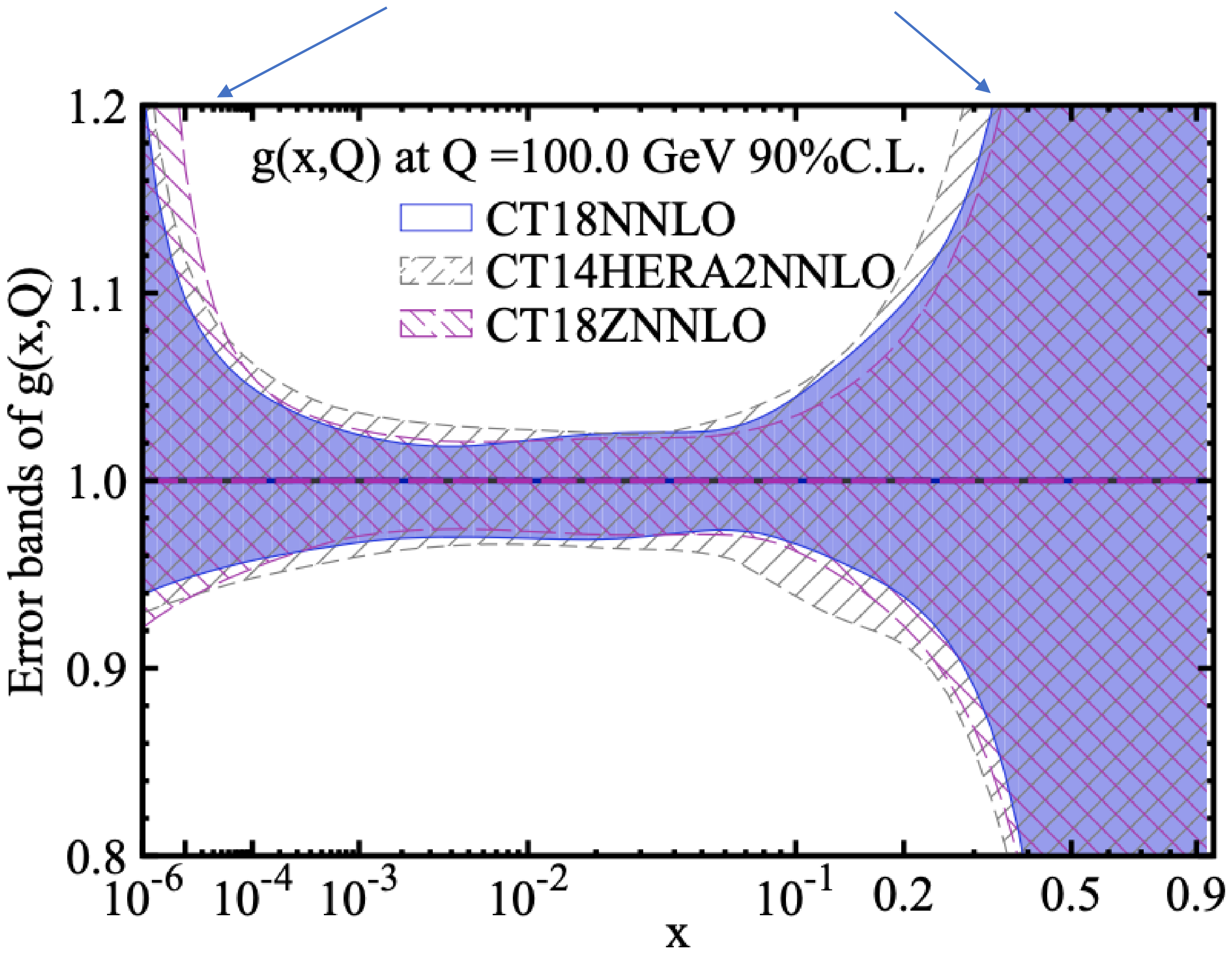

Figure: CT18 gluon PDF *Phys.Rev.D* 103 (2021). Small- and large-x regions have wide uncertainty bands.
See also: The PDF4LHC21 combination of global PDF fits for the LHC Run III, 2203.05506 [hep-ph]

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- 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, (e.g., D-meson prod. at **LHCb**).

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 α_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 analyses to determine proton PDFs.

Theory calculation & HF production dynamics

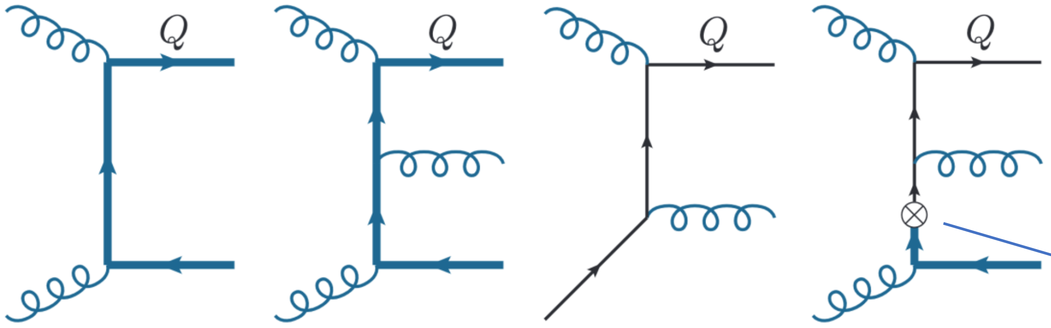
- In DIS, perturbative convergence of QCD calculations in the ACOT and other GM-VFN schemes at small momenta comparable to m_Q can be significantly improved by physical treatment of kinematics in flavor-excitation and subtraction terms.

- 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.

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

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

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

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

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.

S-ACOT-MPS results here are shown at NLO in QCD.

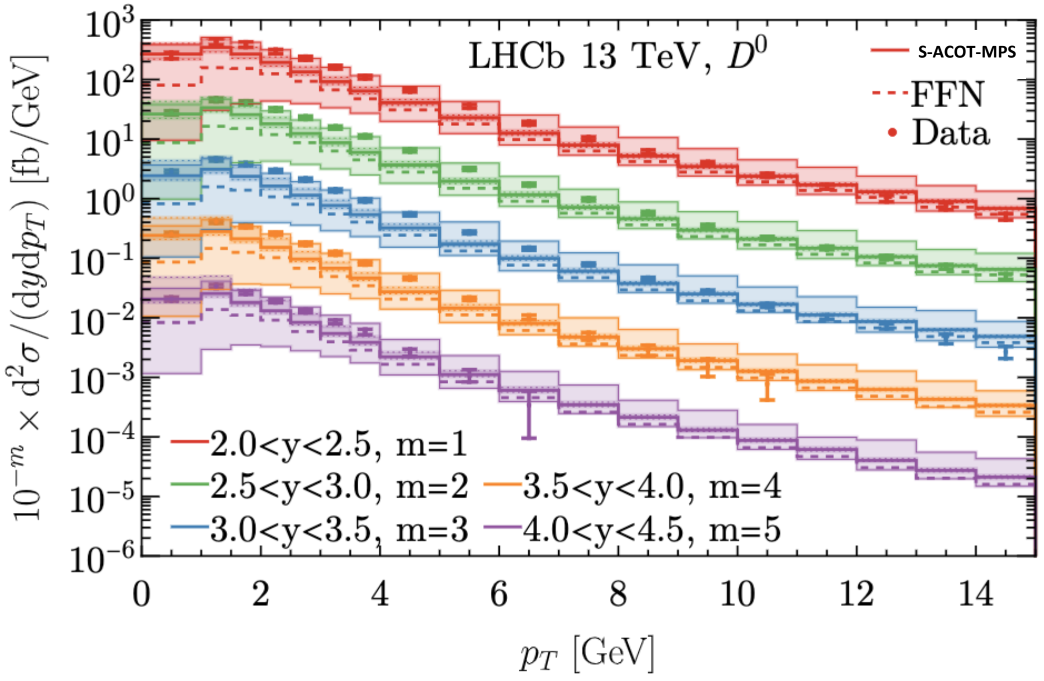
New NNLO predictions were recently made available:

- FO calculation for Z + b-jet at O(α_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

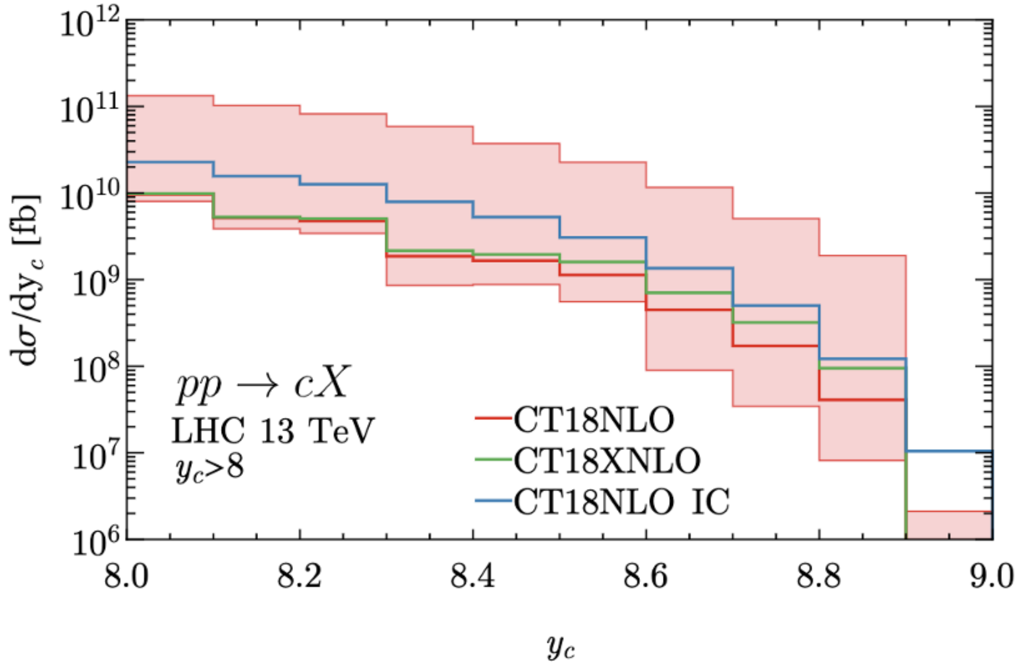
At this stage, it is already technically possible to generate predictions within the S-ACOT-MPS scheme at NNLO with suitable K-factors (NNLO/NLO) at hand.

Charm production at central and forward rapidity

LHCb 13 TeV JHEP 03 (2016) 159



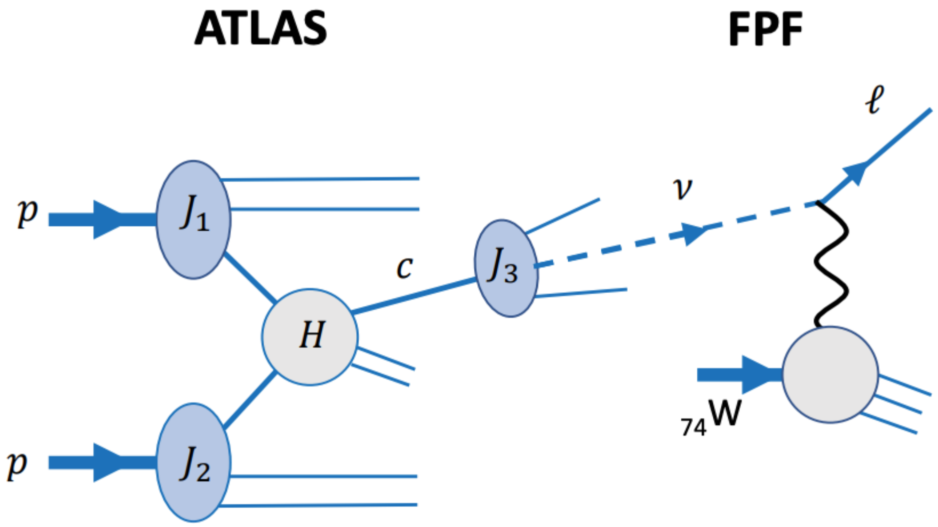
Transverse momentum at central rapidity at LHCb 13TeV.
Error bands are scale uncertainties.
[Xie, Campbell, Nadolsky, 2108.03741]



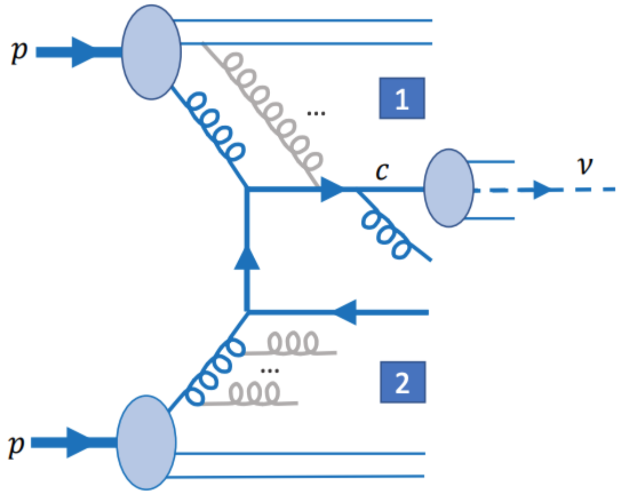
Prompt charm at the LHC 13 TeV in the very forward region ($y_c > 8$).
Error band represents the CT18NLO induced PDF uncertainty
at 68% C.L. [M.G., Xie, Nadolsky. FPF paper I, 2109.10905]

Probing IC content in the proton at FPF

Figure: Forward Physics Facilities I 2109.10905



Forward neutrinos from charmed meson decays in ATLAS



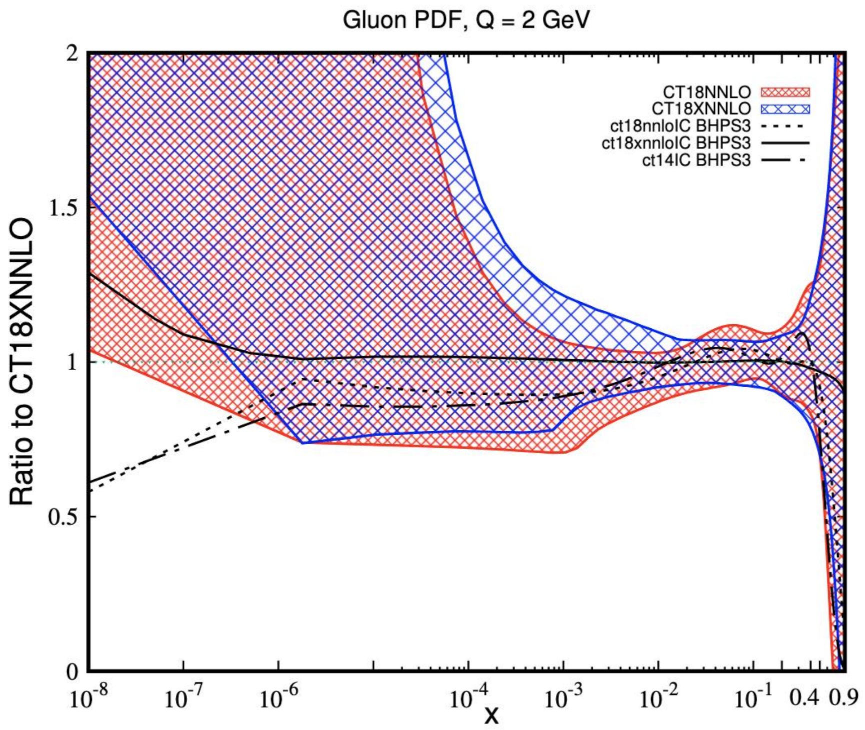
Production of a neutrino in the direction of the FPF. The charm quark escapes close to the beam axis in nearly the same direction as the comoving remnants of proton 1.

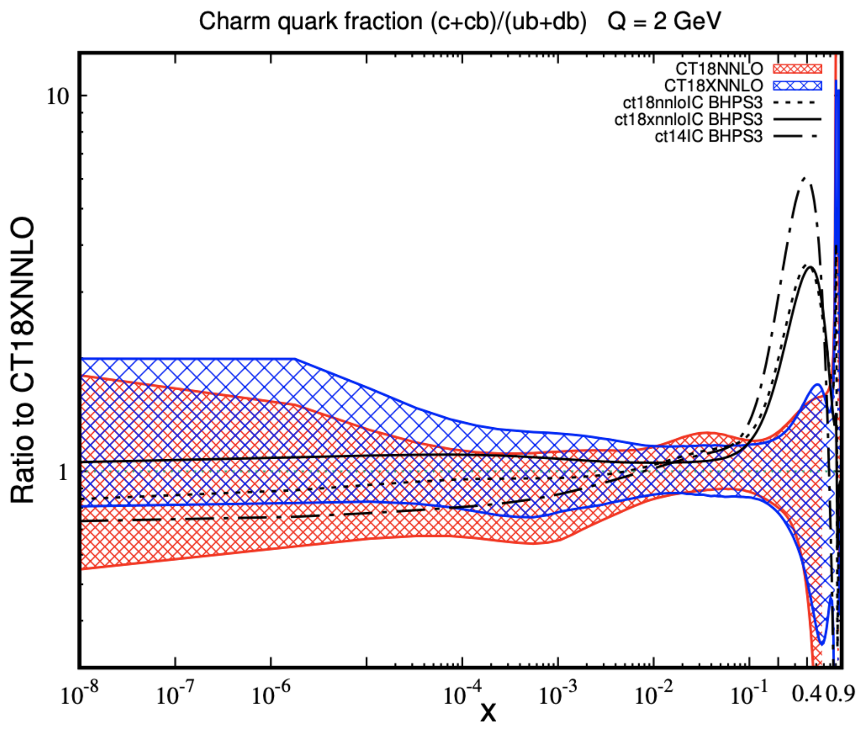
At large rapidity, one can probe QCD factorization beyond its standard formulation:

1. Enhanced power suppressed contributions: intrinsic charm
2. Large logarithms of the form $\ln(s/Q^2) \approx \ln(1/x)$: BFKL resummation framework

Probing IC content in the proton at FPF

NNLO gluon and charm-quark PDF in CT18/CT18X with IC. Error PDFs at 90% C.L. [M.G. Xie, Nadolsky, FPF I paper 2109.10905]



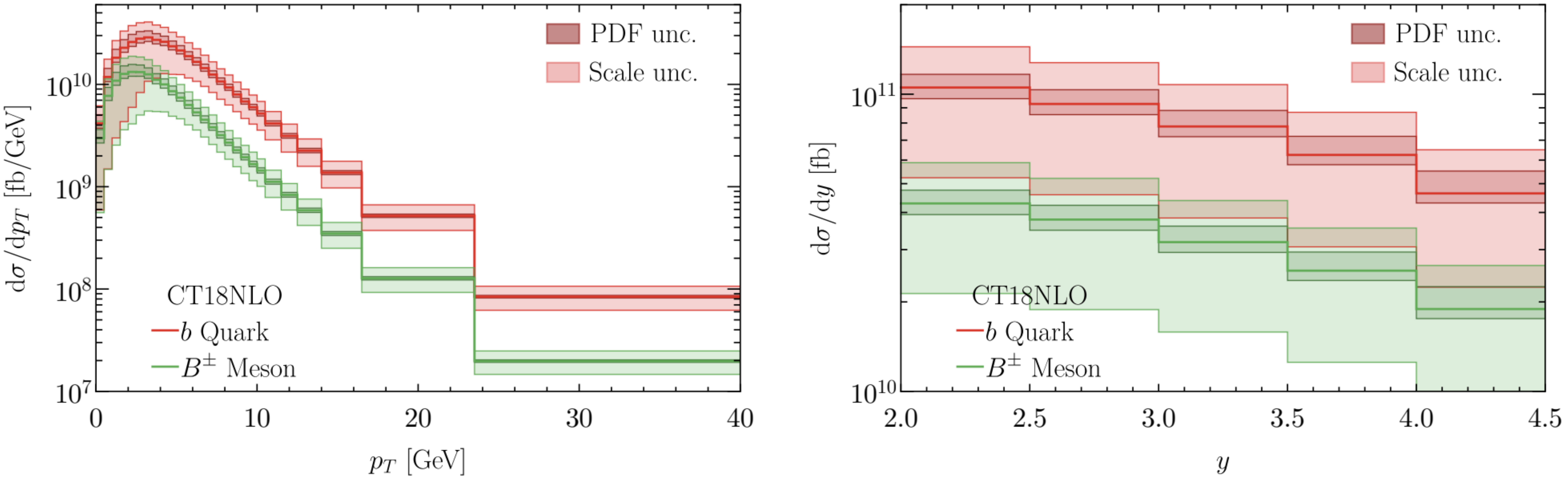


Charm hadroproduction and Z + c production at the LHC can constrain the IC contributions.

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.

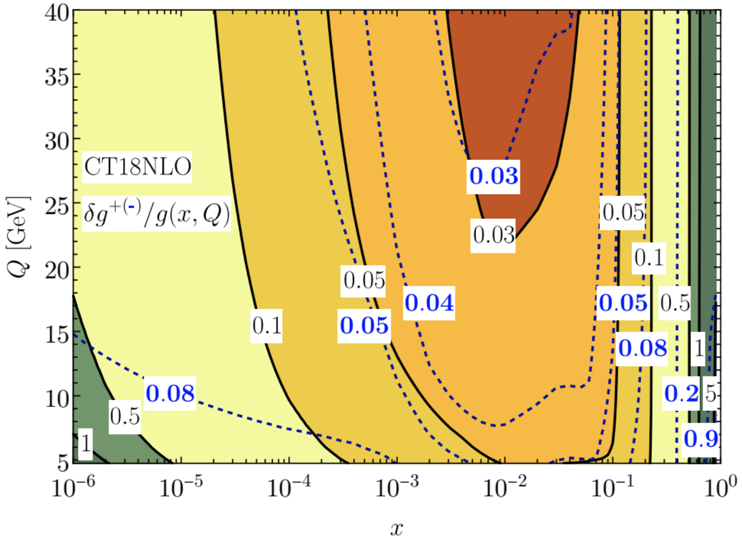
Inclusive b-production: parton and particle level results

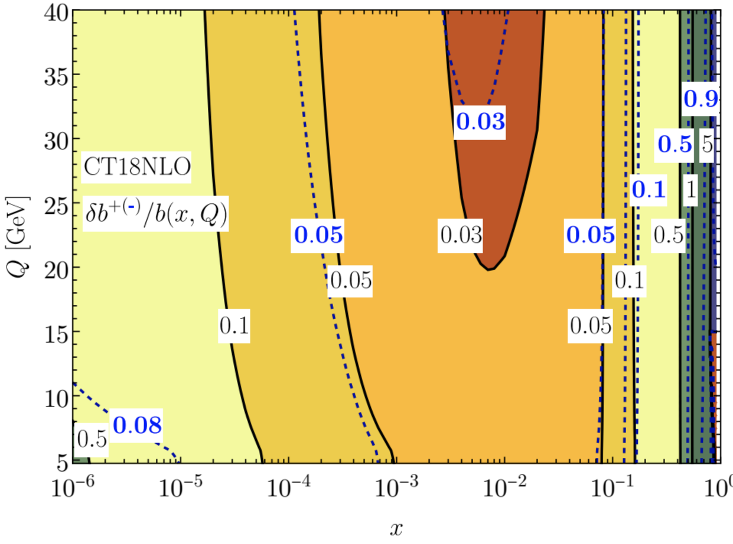


NLO theory predictions for the pT and y distributions obtained with CT18NLO PDFs 90%CL at LHCb 13 TeV.
Parton-level distributions are plotted in red. Particle-level distributions are in green. [Xie, M.G., Nadolsky, 2203.06207]
Scale uncertainty is obtained from the 7-point variation by a factor of 2 using

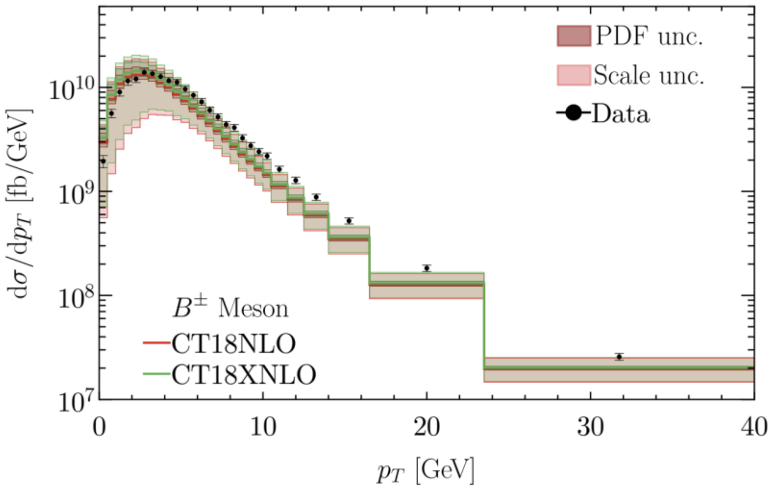
$$\mu_R = \mu_F = \sqrt{m_b^2 + p_T^2}$$

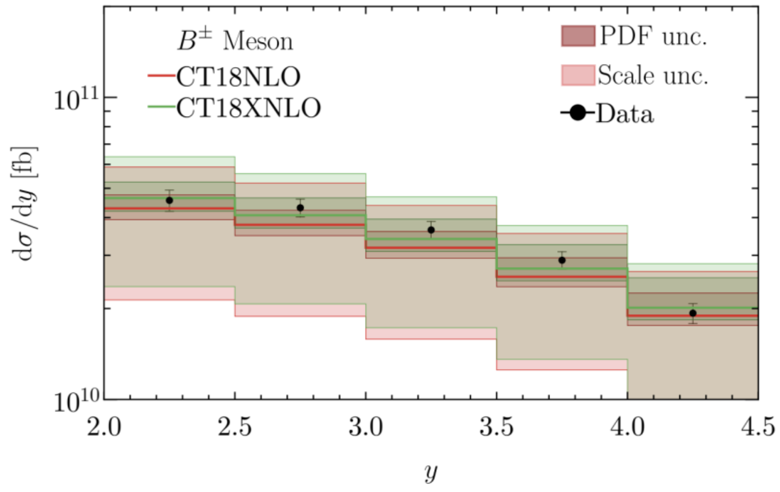
Inclusive b-production





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 [Xie, M.G., Nadolsky, 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 [Xie, M.G., Nadolsky, 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

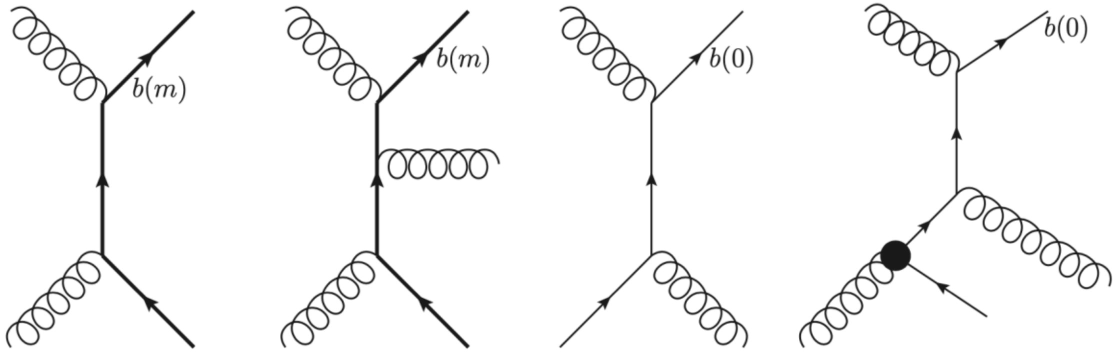
Concluding remarks

- We explored inclusive c/b production at central and (very)forward rapidity
- S-ACOT-MPS 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.
- Very interesting applications at future forward physics facilities to probe QCD factorization beyond its standard formulation

Backup slides

Subtraction Heavy-flavor PDF

$$\tilde{b}(x,\mu) = \frac{\alpha_s(\mu)}{2\pi} \log \frac{\mu^2}{m_b^2} \int_x^1 \frac{d\xi}{\xi} P_{b\leftarrow g}(\frac{x}{\xi}) g(\xi,\mu).$$



Evaluate with DGLAP and store in b-tilde. Then

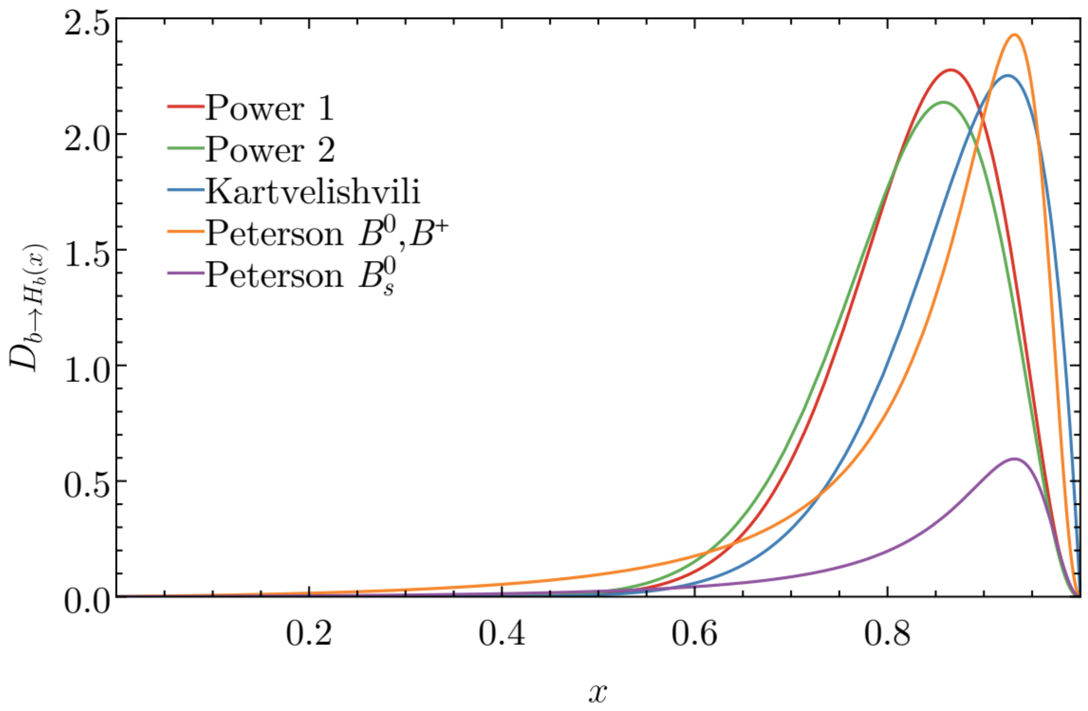
$$\sigma_{\rm FE} = b(x_1,\mu) f_i(x_2,\mu) \otimes \hat{\sigma}_{bi}^{(0)} + (1 \leftrightarrow 2),$$

$$\sigma_{\rm SB} = \tilde{b}(x_1,\mu) f_i(x_2,\mu) \otimes \hat{\sigma}_{bi}^{(0)} + (1 \leftrightarrow 2).$$

Can be done at the same time: the subtraction terms are calculated exactly as the Flavor Excitation terms, just by replacing the heavy flavor PDF by the subtraction PDF.

Using a subtraction/residual PDF, the subtraction terms are much faster to compute

Afew details about b fragmentation



Left: Fragmentation functions for b → H_b, modelled according to the power ansatz in Salajegheh et. al. [1904.08718], Kartvelishvili PLB (1978), and Peterson et. al. PRD (1983) parameterizations. The branch fraction is normalized to B(b → B0/B+) = 0.408

A conservative estimate of the uncertainty associated to the FFs in this work is obtained by considering relative differences between the parametrizations mentioned here. The corresponding branching fraction is normalized to $\mathcal{B}(b \to B_s^0) = 0.100$

A more rigorous estimate of FF uncertainties deserves a dedicated study which will be addressed in a future work.