Heavy-flavor production at hadron colliders

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with
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Also with L. Reina and D. Wackeroth

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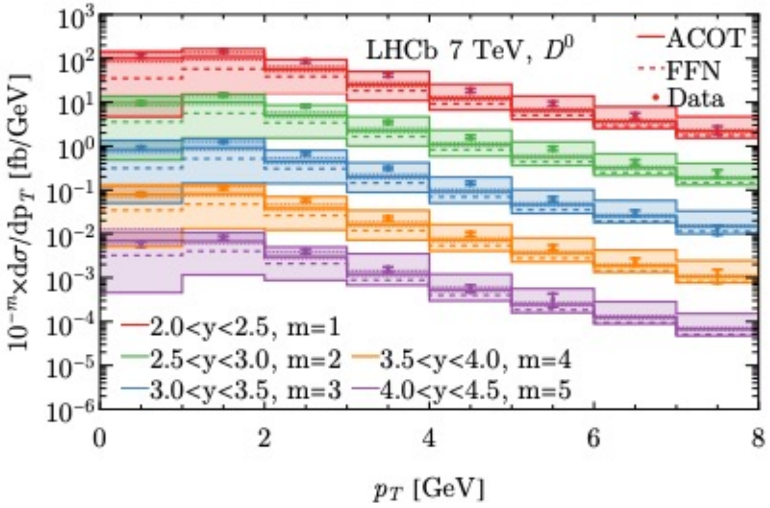
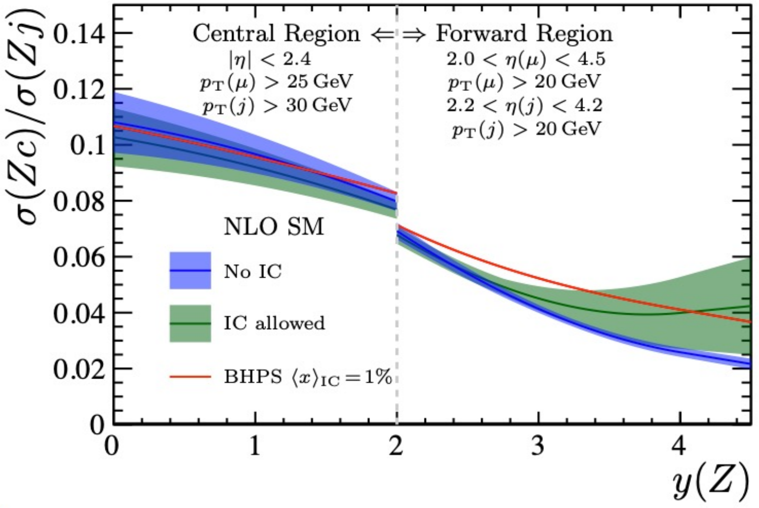
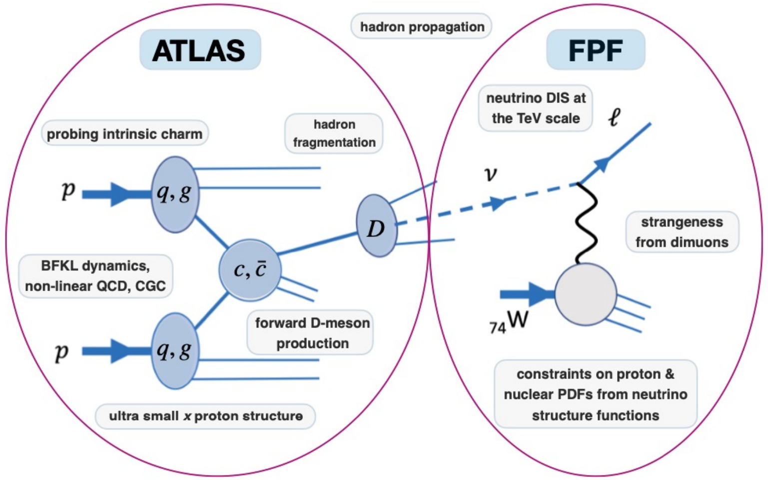
Motivations

- Experimental data
  - D/B meson production LHCb, ALICE, ect
  - Z+c/b production, especially at LHCb
- Intrinsic charm/bottom content of proton
- Test the QCD factorization involving heavy flavors
  - treat the heavy-flavor partons consistently!
- Neutrino measurement at FPF







HF treatments in theory calculations

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

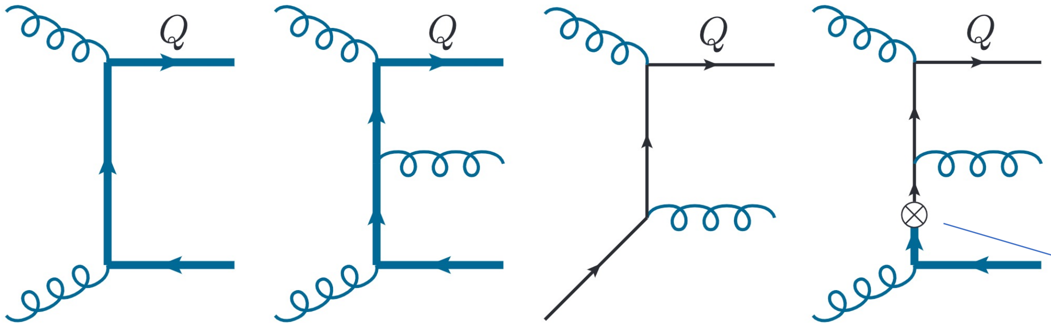
Massive Schemes: final-state HQ with $p_T \leq m_Q \Longrightarrow p_T$-spectrum can be obtained in the **fixed-flavor number (FFN) scheme**.
- No heavy-quark PDF in the proton. Heavy flavors generated as massive final states. m_Q is an infrared cut-off.
- Power terms $\left(p_T^2/m_Q^2\right)^p$ are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

Main idea behind a GMVNS (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

Mass fully retained in dPS

$\sigma = \mathrm{FC} \ + \mathrm{FE} - \mathrm{SB}.$ 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: $\delta f_Q(x,\mu^2) = f_Q(x,\mu^2) - \frac{\alpha_s}{2\pi} \log\left(\frac{\mu^2}{m_Q^2}\right) \ f_Q(x,\mu^2) \otimes P_{Q\leftarrow g}(x)$

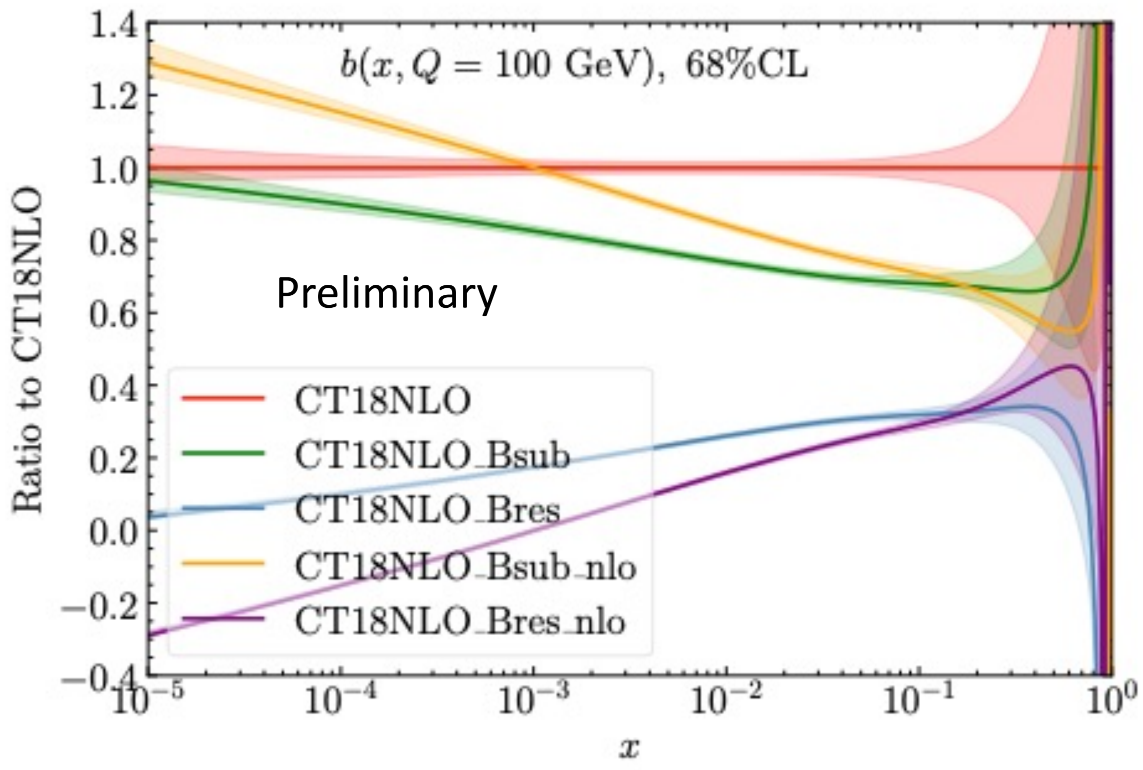
More details in K. Xie PhD Thesis: “Massive elementary particles in the standard model and its supersymmetric triplet higgs extension.” https://scholar.smu.edu/hum_sci_physics_etds/7, 2019.

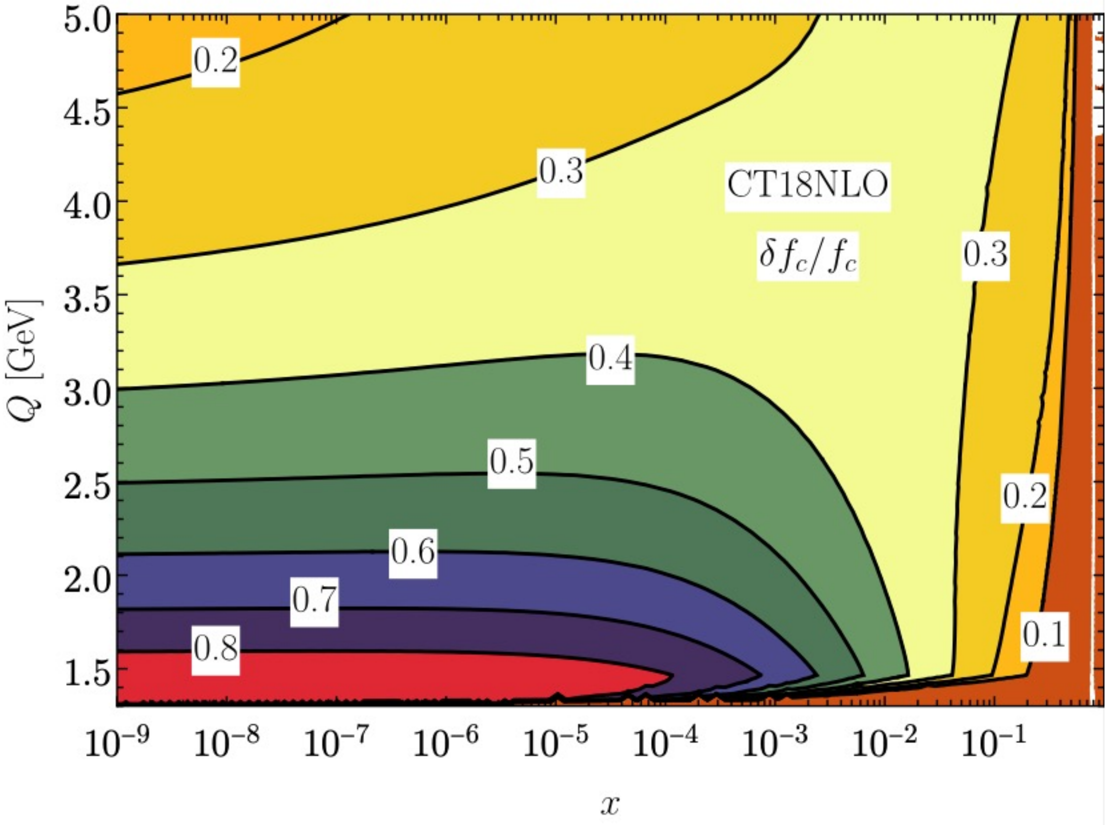
The subtraction scheme

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

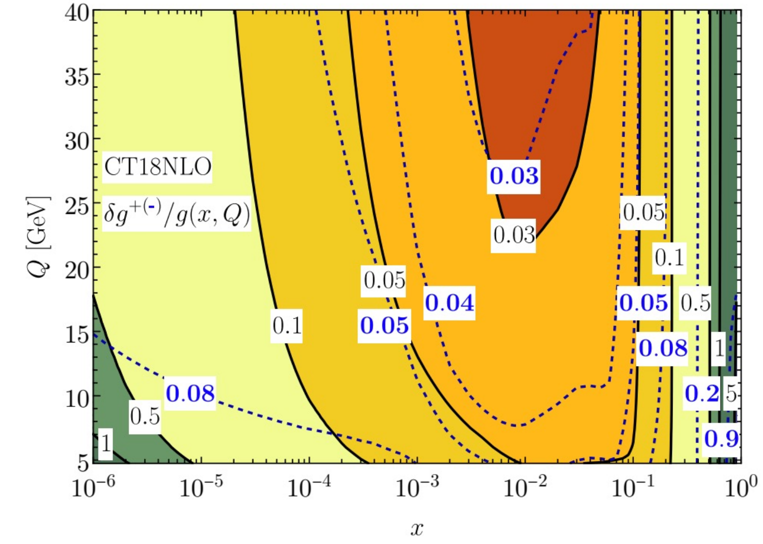
Define subtracted and residual PDFs

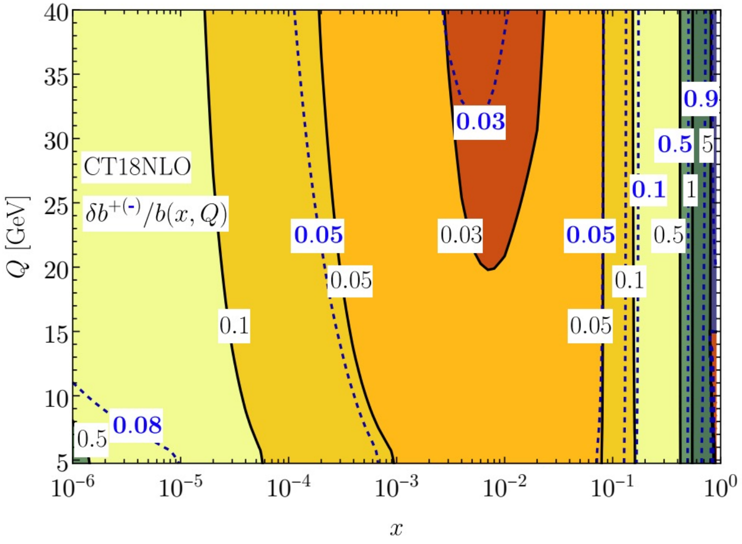
$$\tilde{f}_Q(x,\mu^2) = \sum_j [P_{Qj} \otimes f_j](x,\mu^2)$$
$$\delta f_Q(x,\mu^2) = [f_Q - \tilde{f}_Q](x,\mu^2)$$



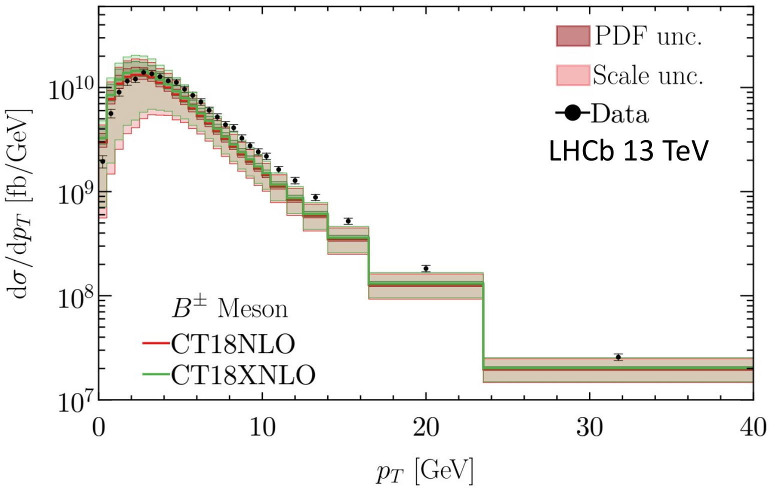


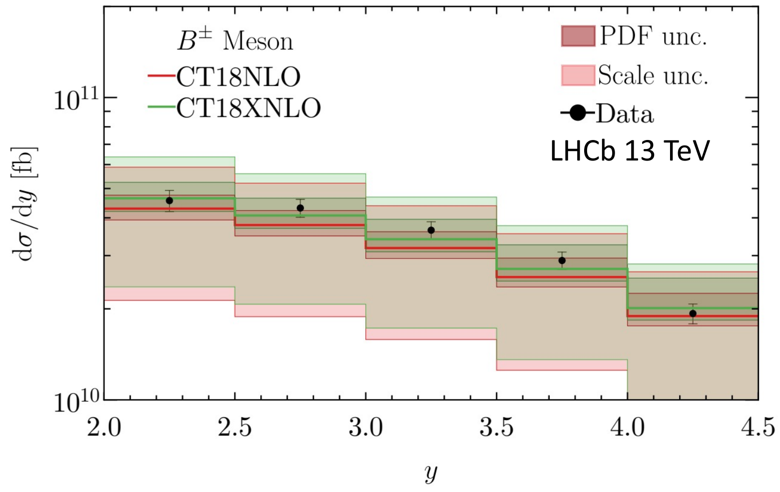
Inclusive b-production





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]



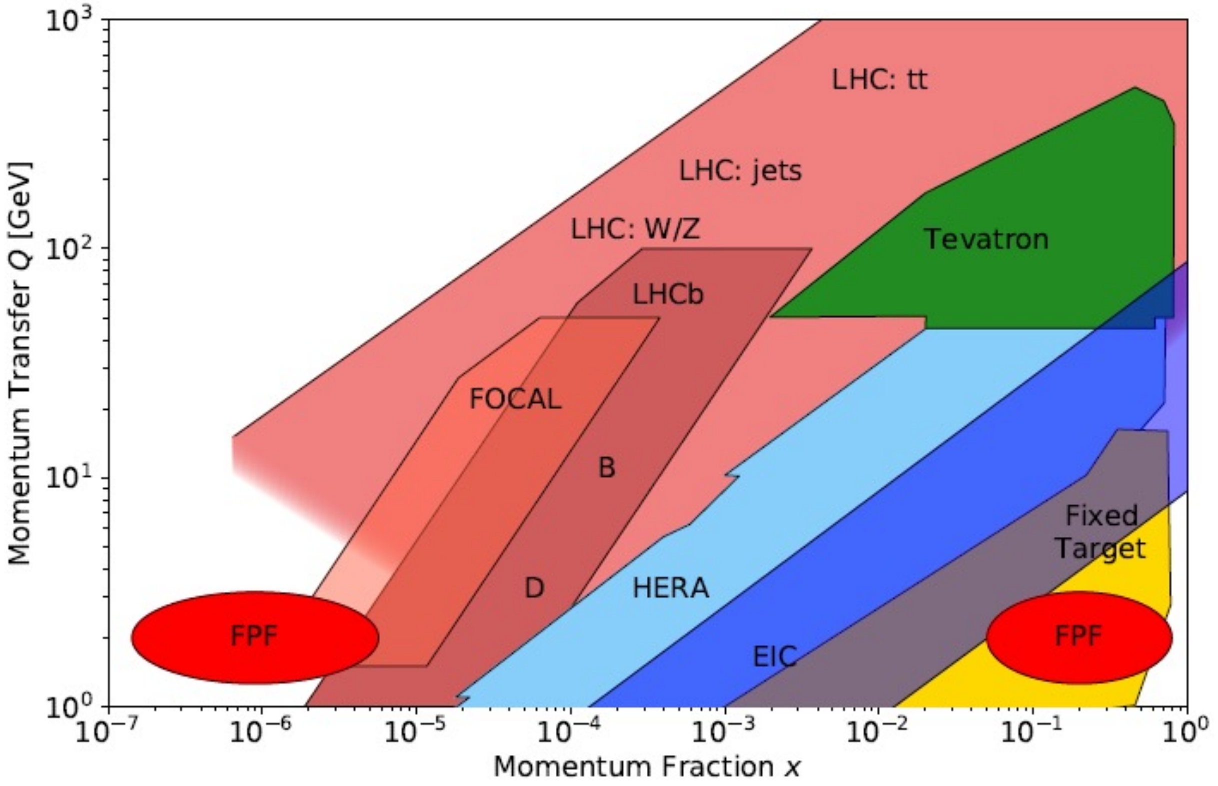


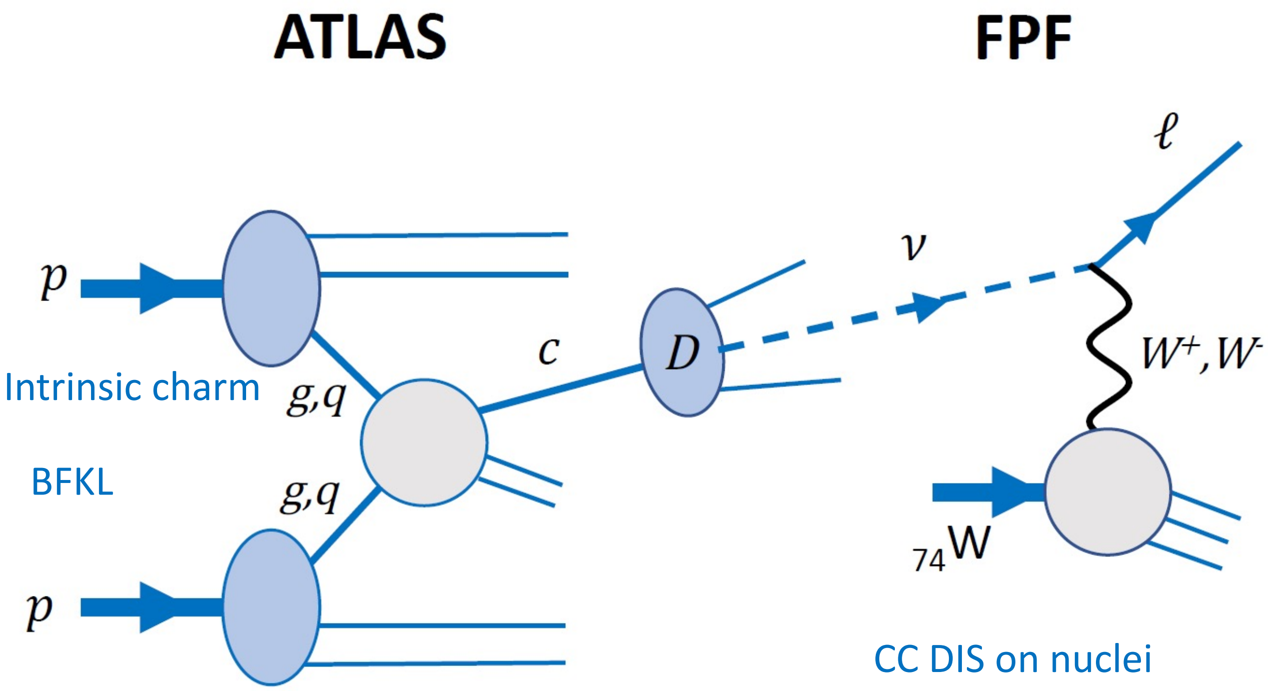
NLO theory predictions for the pT and y distributions obtained with CT18NLO and CT18XNLO PDFs compared to B± production data from LHCb 13 TeV
[Xie, M.G., Nadolsky, 2203.06207]

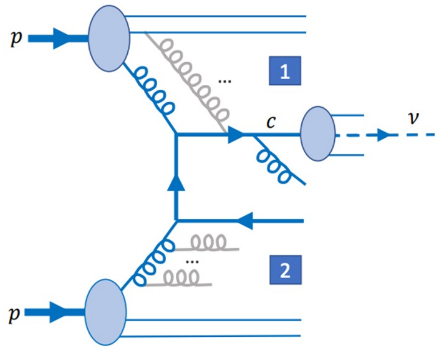
Theoretical uncertainties at NLO are large (O(50%)) and mainly ascribed to scale variation. This can be improved by including higher-order corrections which imply an extension of the S-ACOT-MPS scheme to NNLO

The Forward Physics Facility at CERN

L.A. Anchordoqui et al., ``The Forward Physics Facility: Sites, Experiments, and Physics Potential'', *Phys. Rep. 968 (2022), arXiv:*2109.10905
J.L. Feng et al., `` The Forward Physics Facility at the High-Luminosity LHC'', *arXiv:*2203.05090



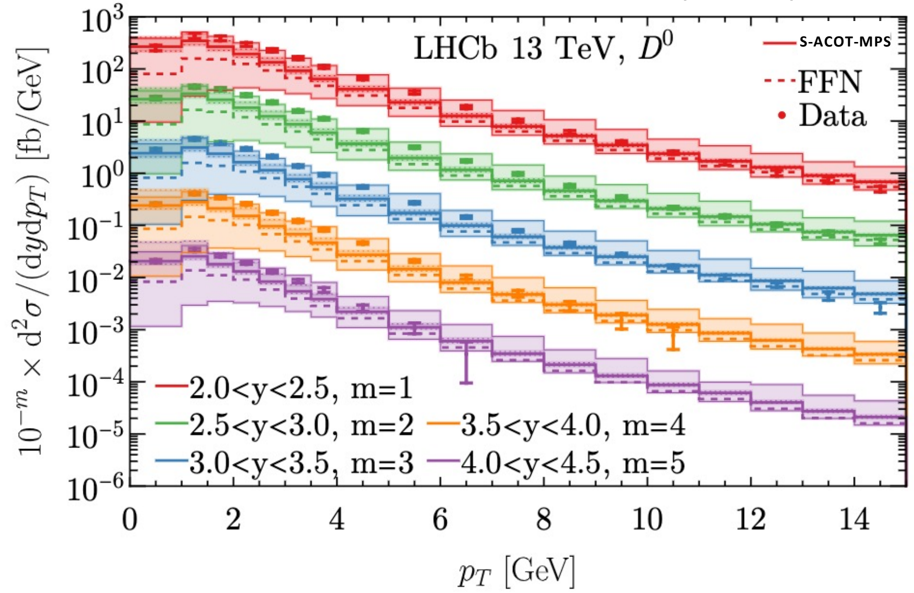




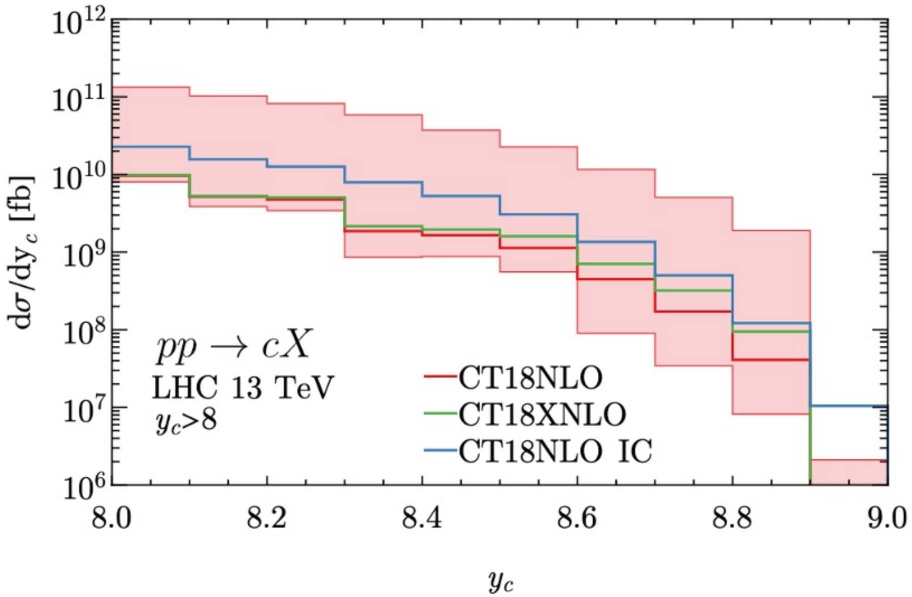
The FPF can clarify multiple aspects of QCD in the new forward region **in coordination** with the HL-LHC and EIC.

Charm production at central and forward rapidity

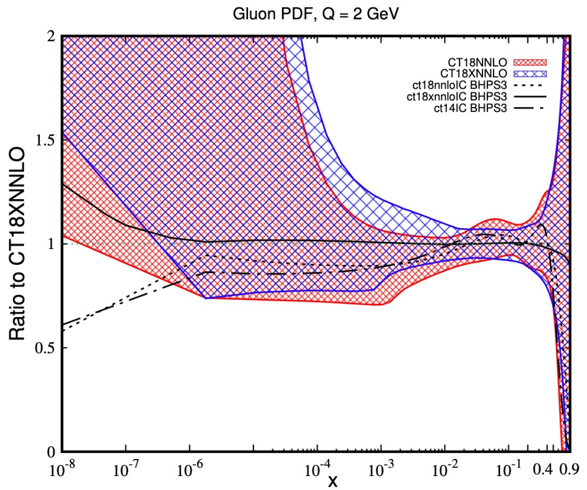
LHCb 13 TeV data: JHEP 03 (2016) 159



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 Intrinsic Charm.
Error PDFs at 90% C.L. (*Phys. Rep. 968 (2022)* 2109.10905)

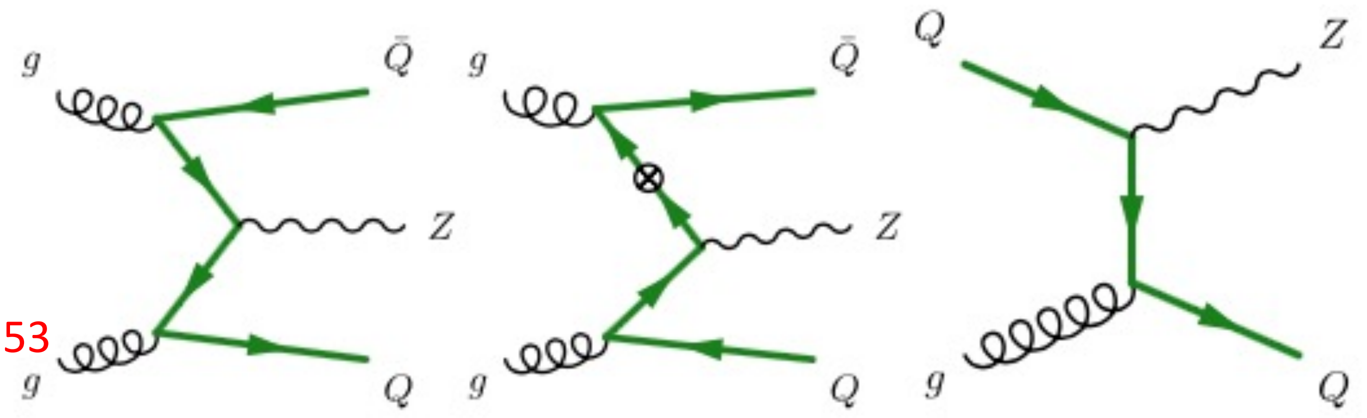
Charm hadroproduction and Z + c production at the LHC can constrain the IC contributions.
In CT14IC, we looked at Z+c at LHC 8 and 13 TeV. LHCb Z+c data deserve attention as they can potentially discriminate gluon functional forms at $x \geq 0.2$ and improve gluon accuracy.

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.

Z+Q(c/b) production

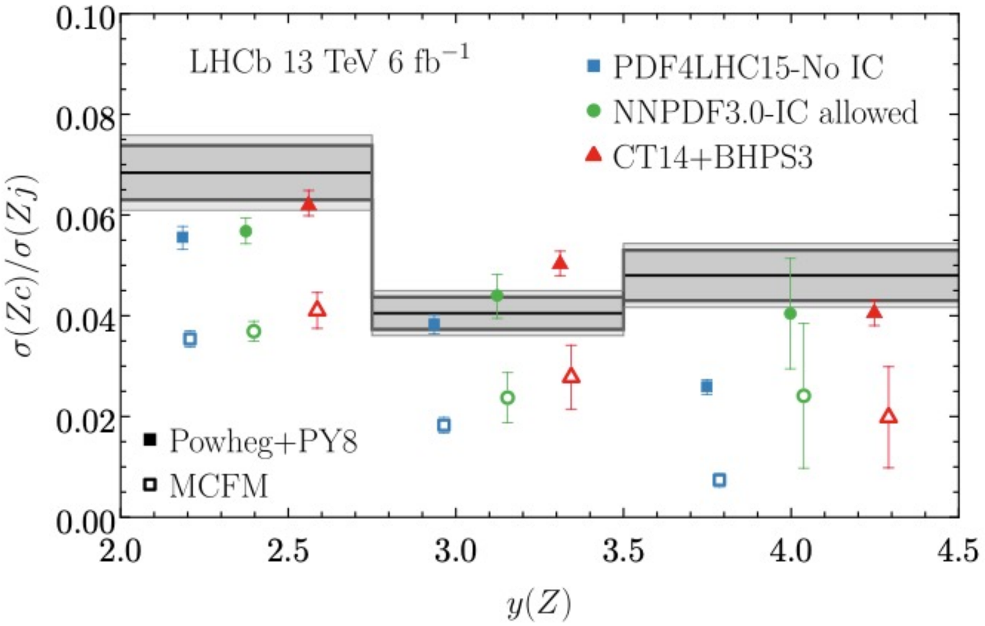
(Work in progress with M Guzzi, P. Nadolsky, L. Reina, and D. Wackeroth)

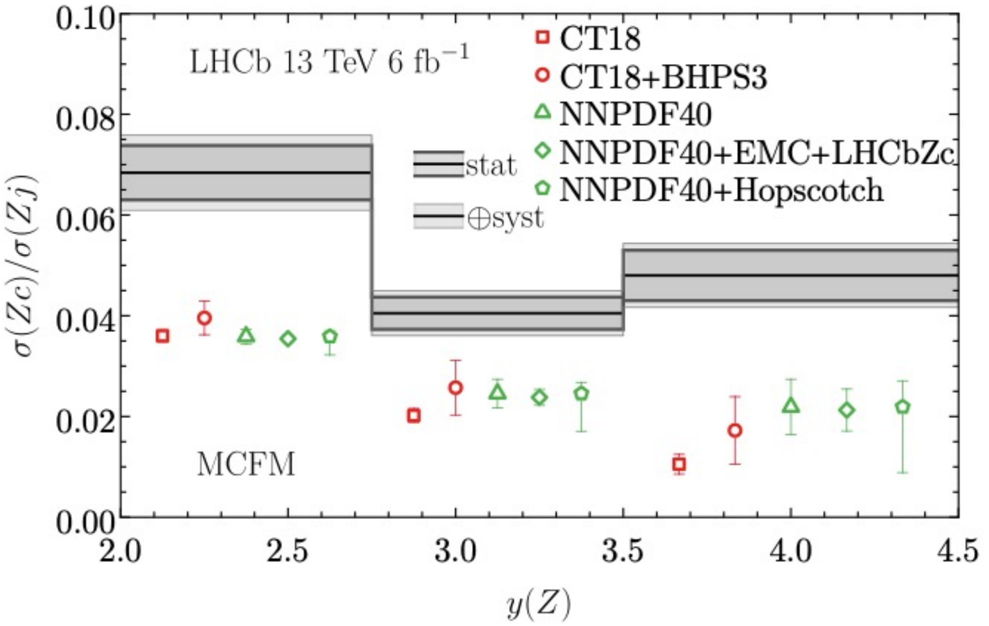
Massive FFNS, L. Reina and D. Wackeroth et al., 1805.01353
GM-VFNS in Progress



$$\sigma = f_g(x_1) f_g(x_2) \hat{\sigma}^{(0)}_{gg\to ZQ\bar{Q}} + f_g(x_1) f_g(x_2) \hat{\sigma}^{(1)}_{gg\to ZQ\bar{Q}g} + f_g(x_1) f_q(x_2) \hat{\sigma}^{(1)}_{gq\to ZQ\bar{Q}q} + f_g(x_1) \delta f^{(1)}_Q(x_2) \hat{\sigma}^{(0)}_{gQ\to ZQ} + f_g \delta f^{(0)}_Q(x_2) \hat{\sigma}^{(1)}_{gQ\to gZQ} + (1 \leftrightarrow 2).$$

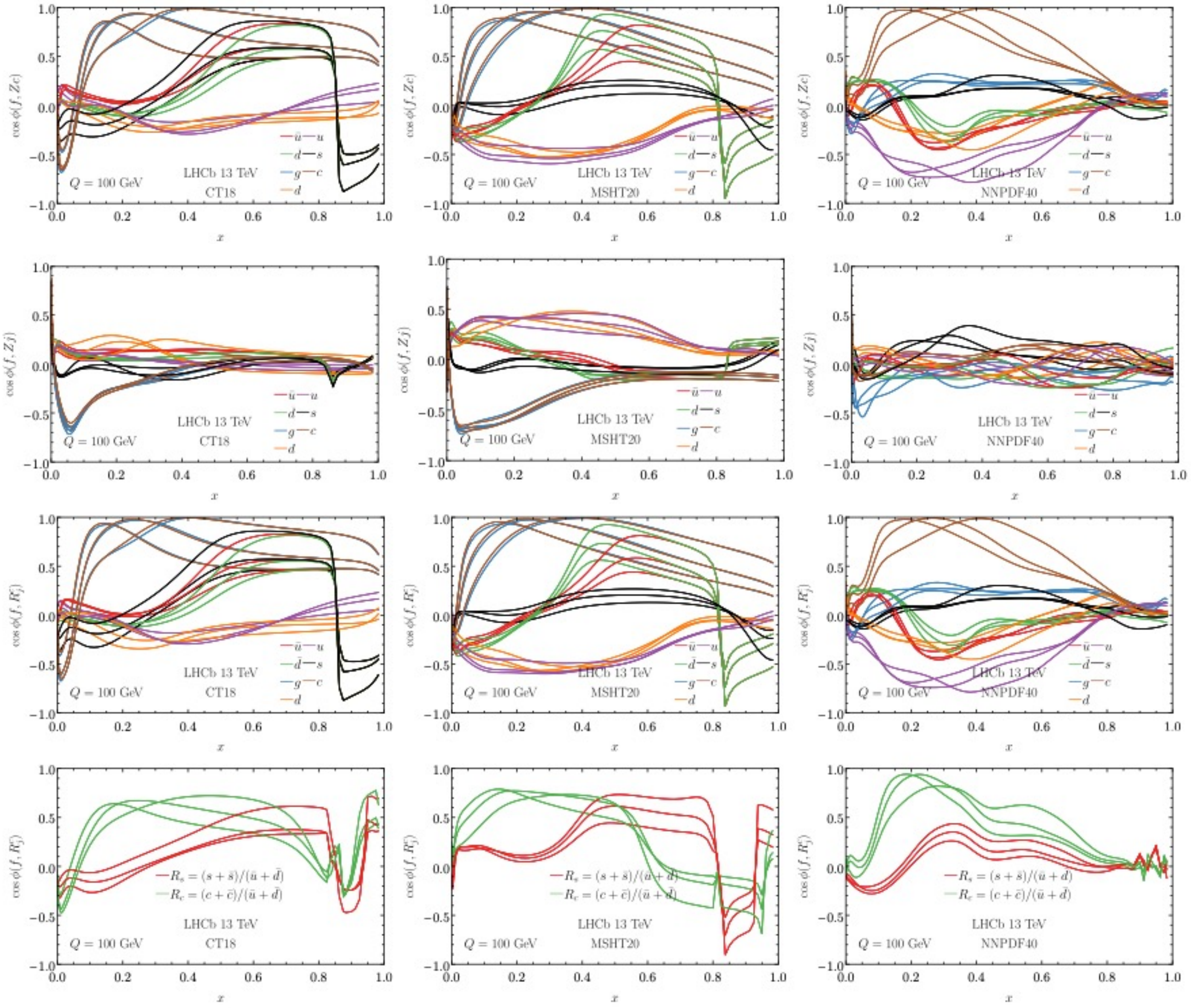
ZM-FFNS scheme + LO FC with MCFM [arXiv:hep-ph/0312024, arXiv:2211.01387]





Probe heavy-flavor PDFs

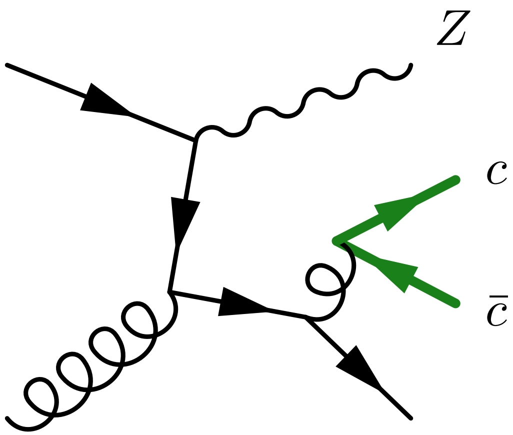
[arXiv:2211.01387]



Higher order splittings

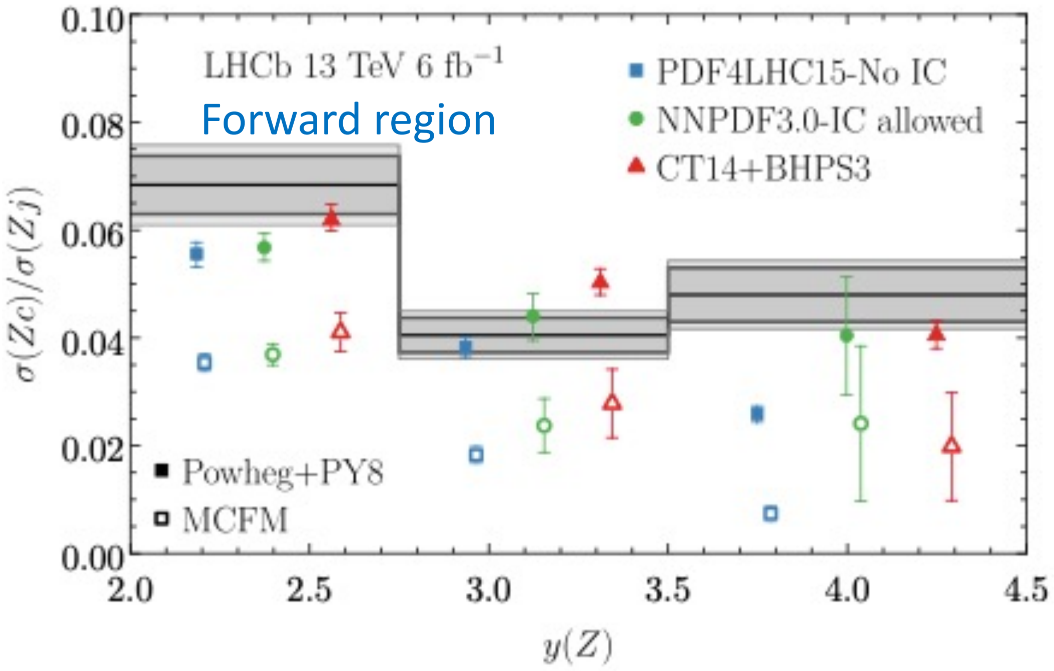
[arXiv:1707.00657]

PDF	Central region		Calculation		
		[ratio to MCFM CT14]		(increase wrt. CT14)	
		MCFM	SHERPA 1J	SHERPA 2J	SHERPA 3J
CT14NNLO		6.04 [1.0]	5.93 [0.982]	6.59 [1.091]	6.64 [1.099]
BHPS3		6.18 (+2.3%)	6.04 (+1.9%)	6.70 (+1.7%)	6.76 (+1.8%)
BHPS2		6.41 (+6.1%)	6.21 (+4.7%)	6.90 (+4.7%)	6.97 (+5.0%)
SEA1		6.51 (+7.8%)	6.29 (+6.1%)	6.97 (+5.8%)	7.03 (+5.9%)
SEA2		7.23 (+19.7%)	6.82 (+15.0%)	7.57 (+14.9%)	7.63 (+14.9%)



- Higher-order splittings to convert light jets to heavy quarks is missing the NLO fixed-order calculations.
- The missing part becomes significant especially in the forward region
- It's important to capture these contribution through NNLO calculation [2005.03016], or with the parton showers approach.
- Infrared safe flavor algorithm is needed to match fixed-order calculation to experimental measurement.

[arXiv:1512.06666]



Conclusions

- New GM-VFNS applied to PP collisions
- Describe c/b production at central and forward rapidity
- Technically possible to generate predictions within the S-ACOT-MPS scheme at NNLO with suitable K-factors (NNLO/NLO) at hand.
- Apply the S-ACOT-MPS to other heavy-flavor processes, such as Z+Q production
- Parton Shower effect is critical to describe the data, especially in the forward region
- In general, HFs: critical to constrain m_Q, α_s, g-PDF correlations (see M. Guzzi's talk)

BACK UP

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 significantly be 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 too 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 differs in the mass treatment in the phase space.

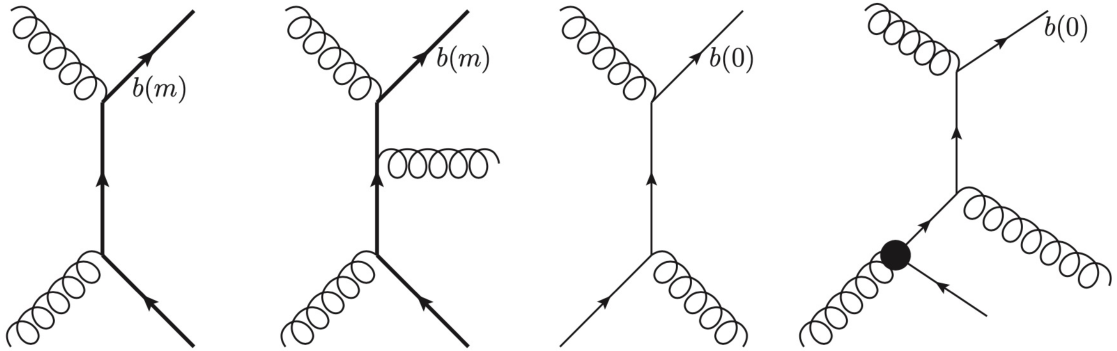
S-ACOT-MPS results here are shown at NLO in QCD.

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.

Subtraction Heavy-flavor PDF



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

Evaluated with DGLAP and stored in the $\tilde{b}$ PDF. Then

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

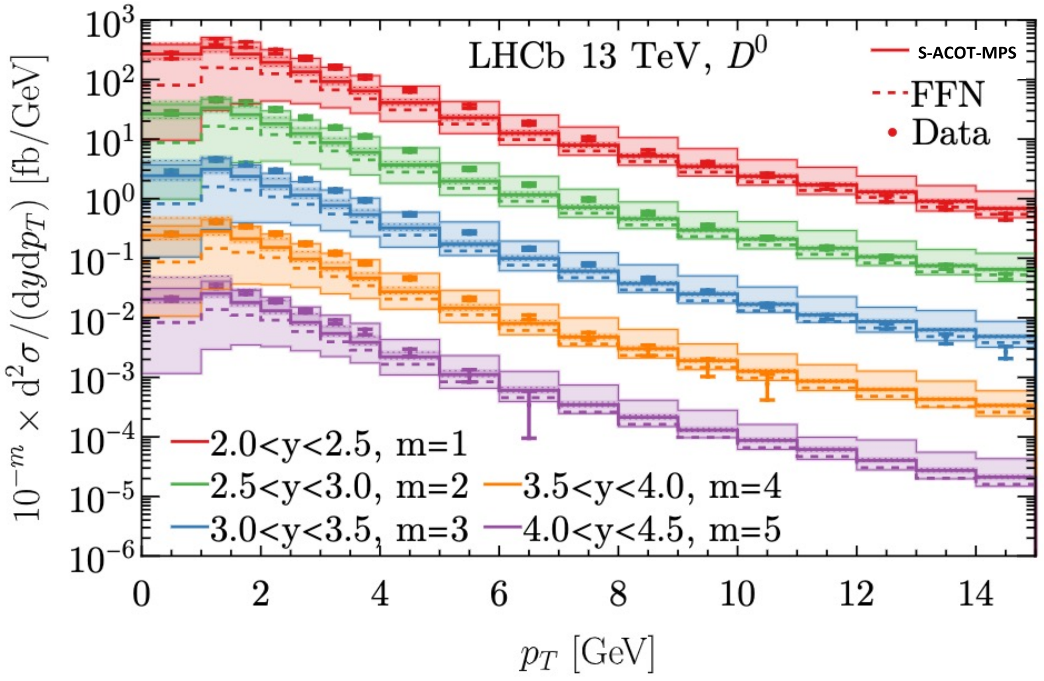
$$\sigma_{\mathrm{SB}} = \tilde{b}(x_1,\mu) f_i(x_2,\mu) \otimes \hat{\sigma}_{bi}^{(0)} + (1 \leftrightarrow 2).$$

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.

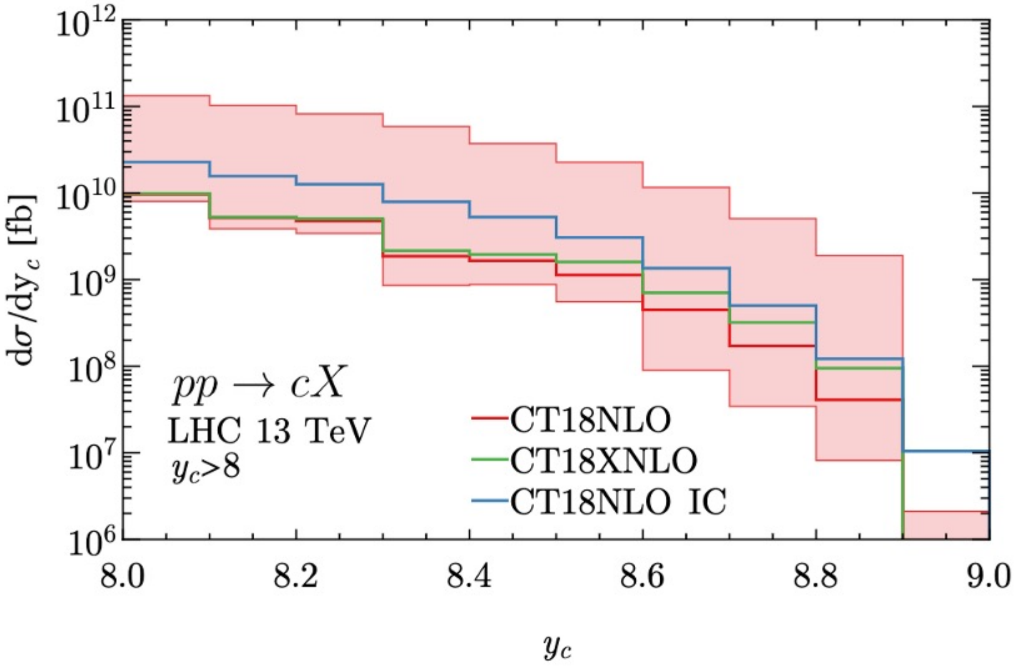
Using a subtraction/residual PDF, the subtraction terms are much faster to compute

Charm production at central and forward rapidity

LHCb 13 TeV JHEP 03 (2016) 159



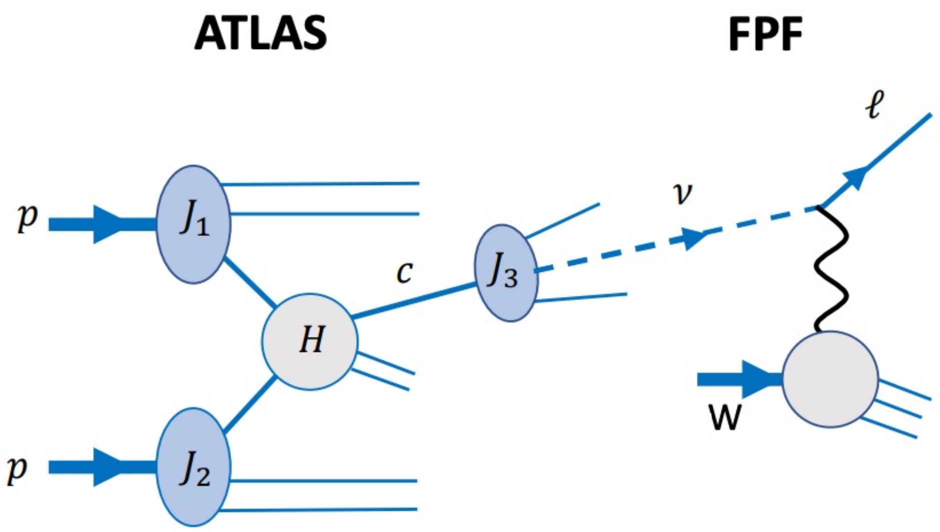
Transverse momentum at central rapidity at LHCb 13TeV.
Error bands are scale uncertainties.
[Xie, Campbell, Nadolsky, 2108.03741]



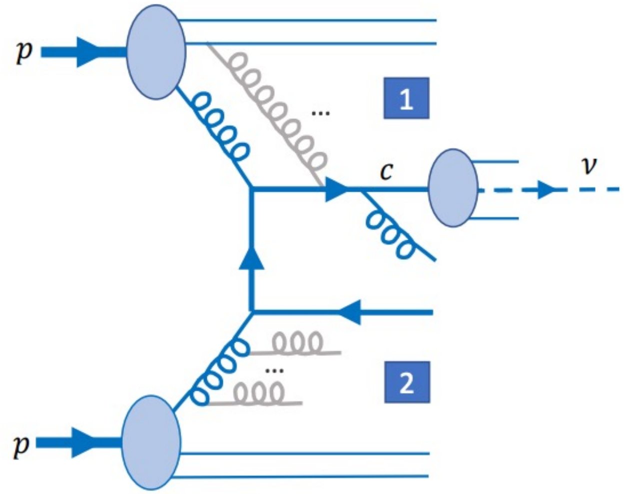
Prompt charm at the LHC 13 TeV in the very forward region (y_c > 8).
Error band represents the CT18NLO induced PDF uncertainty
at 68% C.L. [M.G., Xie, Nadolsky. FPF paper I, 2109.10905]

Probing IC content in the proton at FPF

Figure: Forward Physics Facilities I *Phys. Rep. 968 (2022)* 2109.10905



Forward neutrinos from charmed meson decays in ATLAS



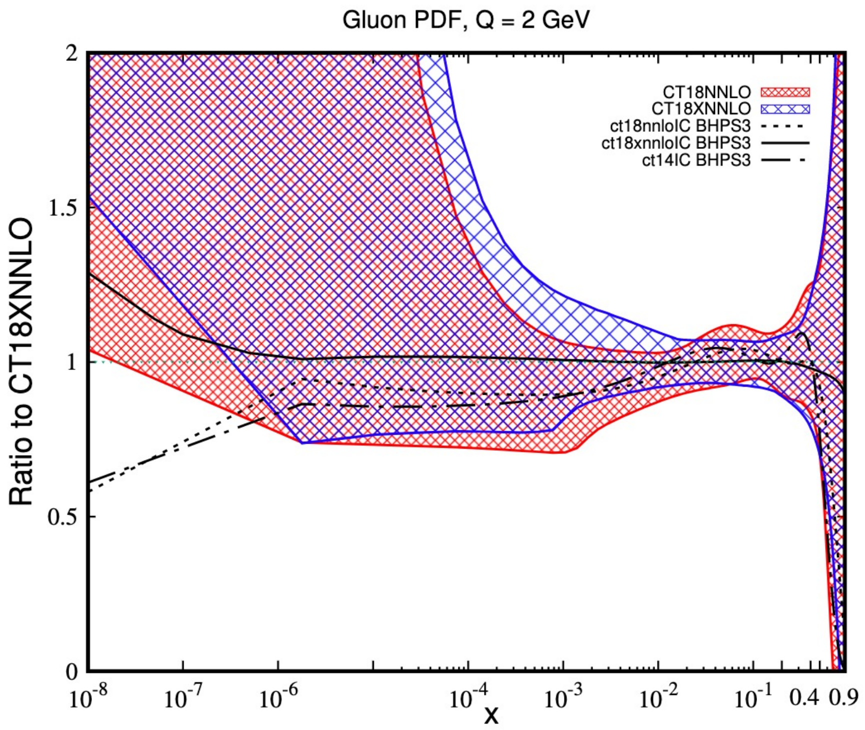
Production of a neutrino in the direction of the FPF. The charm quark escapes close to the beam axis in nearly the same direction as the comoving remnants of proton 1.

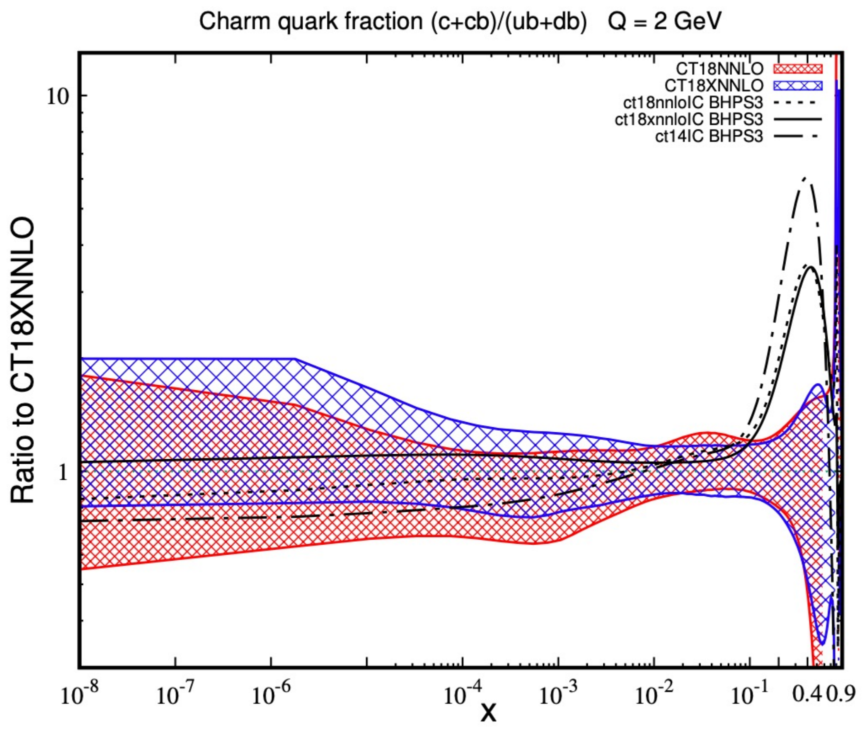
At large rapidity, one can probe QCD factorization beyond its standard formulation:

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]





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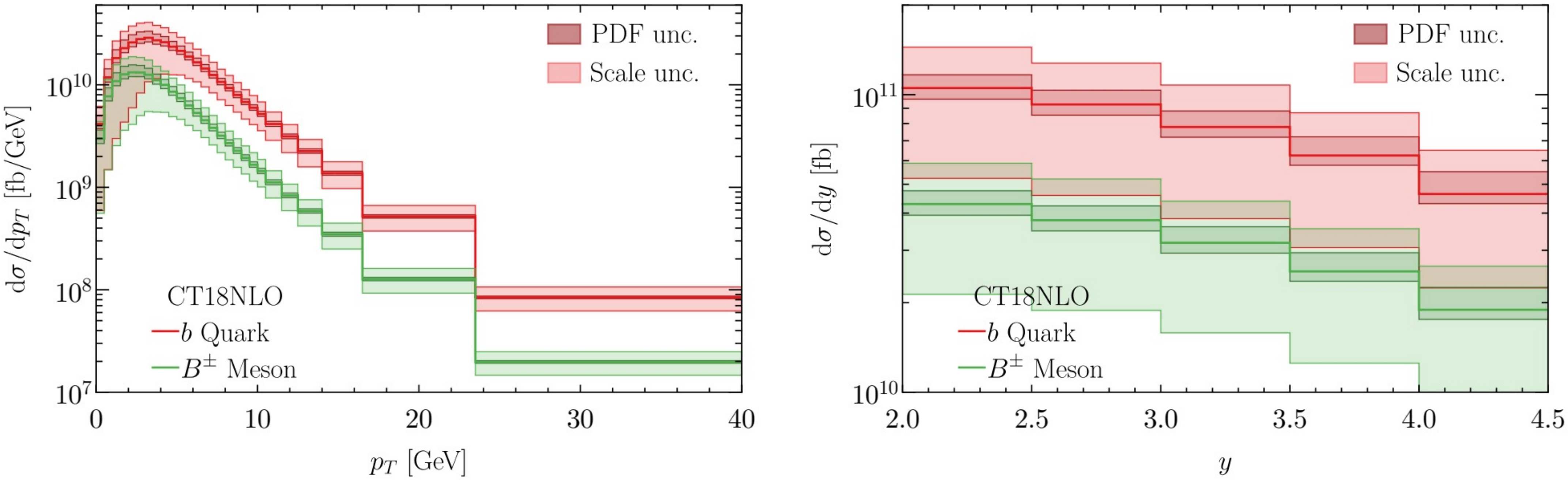
For small x below 10^{-4}, higher-order QCD terms with $\ln(1/x)$ dependence grow quickly at factorization scales of order 1 GeV.
FPF facilities like FASERν will access a novel kinematic regime where both large-x and small-x QCD effects contribute to charm hadroproduction rate.

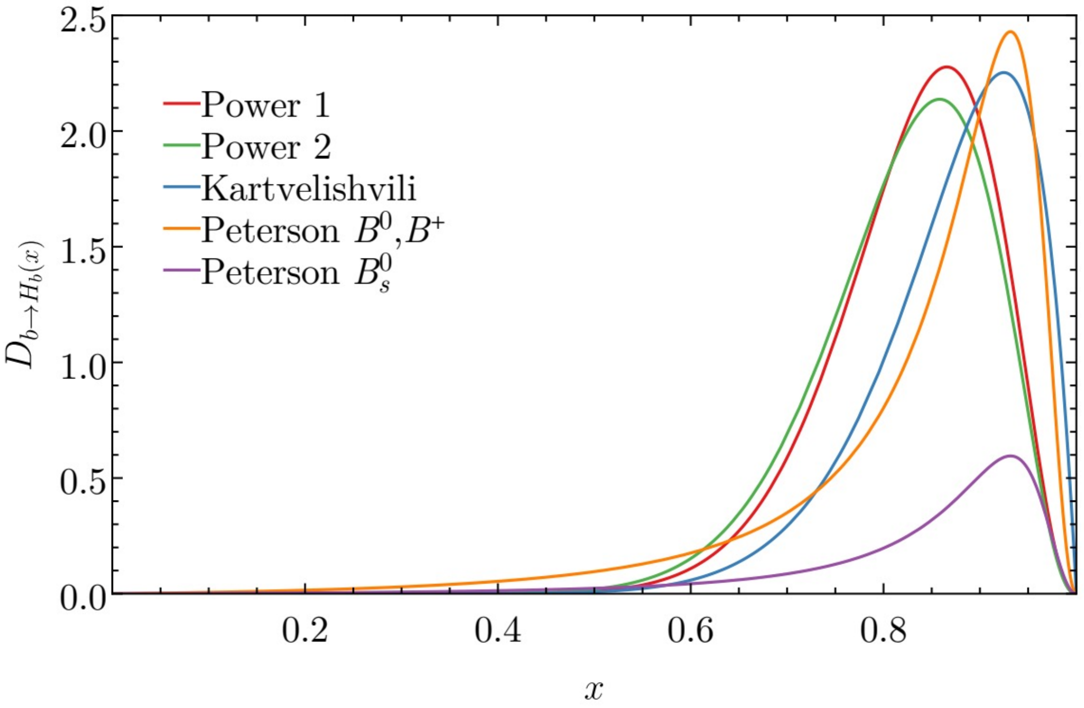
Inclusive b-production: parton and particle level results



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

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

A few 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.