Heavy-flavor production in central and forward LHC processes

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EF03: EW Physics: Heavy flavor and top quark physics
EF06: QCD and strong interactions: Hadronic structure and forward QCD

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 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 Scheme 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 PDF analyses.

S-ACOT schemes

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

Our goal is to use an amended version of the S-ACOT GMVFN scheme and to apply it
to heavy-flavor hadroproduction. We dub this new scheme as S-ACOT-MPS (massive phase space).

We use S-ACOT-MPS to describe D-meson measurements at LHCb at 7 and 13 TeV

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 are shown at NLO in QCD.

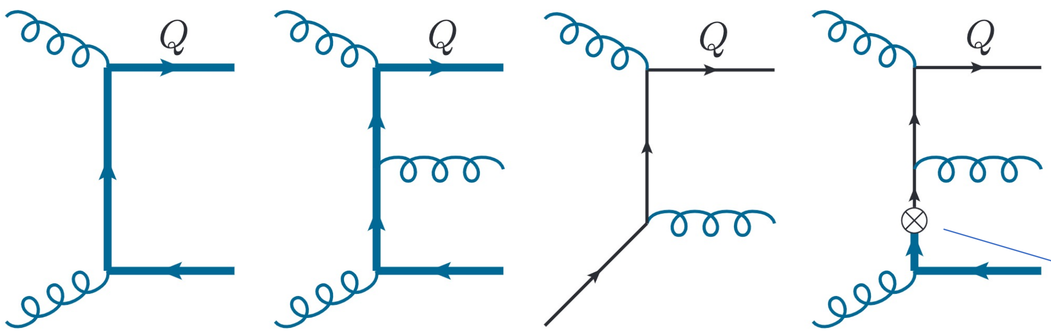
New NNLO predictions made available recently:

- 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 if we have K-factors (NNLO/NLO) at hand. EF06/03 participants maybe helpful.

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

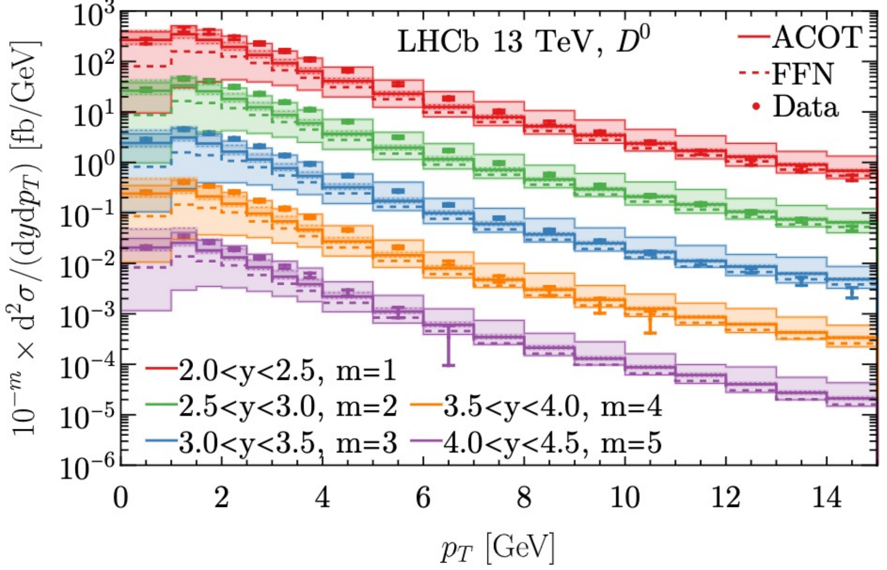
More details in: K. Xie, “Massive elementary particles in the standard model and its supersymmetric triplet higgs extension.” https://scholar.smu.edu/hum_sci_physics_etds/7, 2019. PhD Thesis

Applications and Results

Prompt charm production at central and forward rapidity

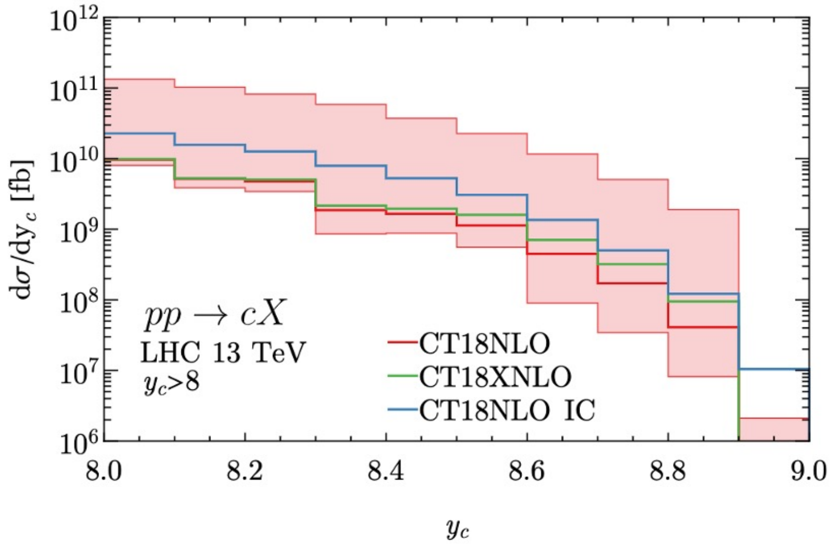
LHCb 13 TeV JHEP 03 (2016) 159

Preliminary



Transverse momentum at central rapidity at LHCb 13TeV.
Error bands are scale uncertainties.

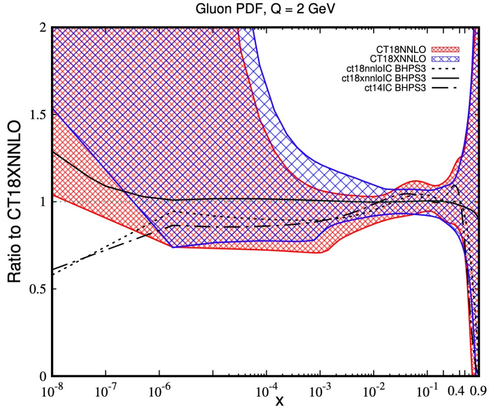
Preliminary



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.

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.

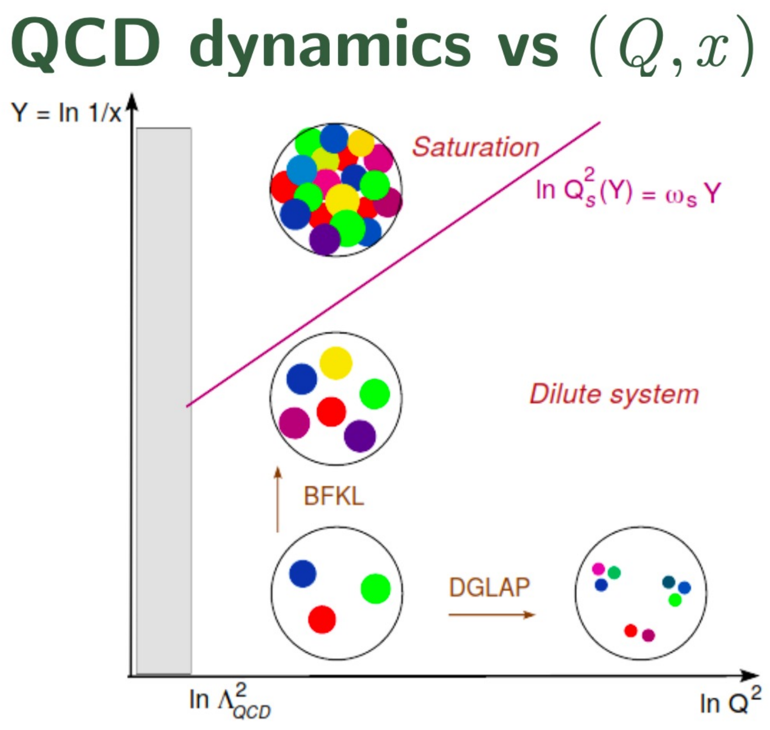
For small x below 10^{-4}, higher-order QCD terms with $\ln(1/x)$ dependence grow quickly at factorization scales of order 1 GeV. FPF facilities like FASERν will access a novel kinematic regime where both large-x and small-x QCD effects contribute to charm hadroproduction rate.

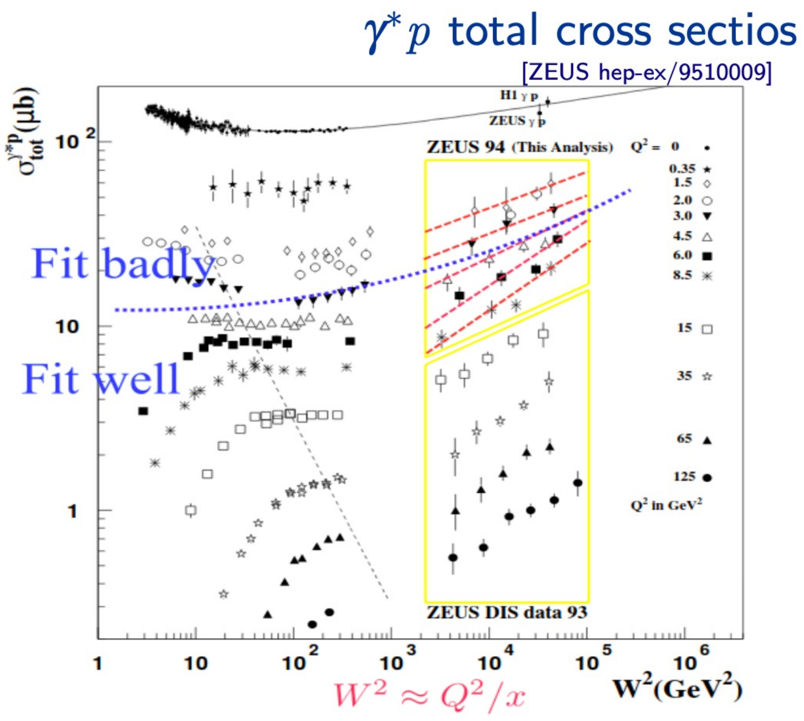


NNLO gluon PDF in CT18/CT18X with IC.
Error PDFs at 90% C.L. FPF paper 2109.10905

Campbell, M.G., Nadolsky, Xie, in preparation

PDFs at small x: resummation or saturation?



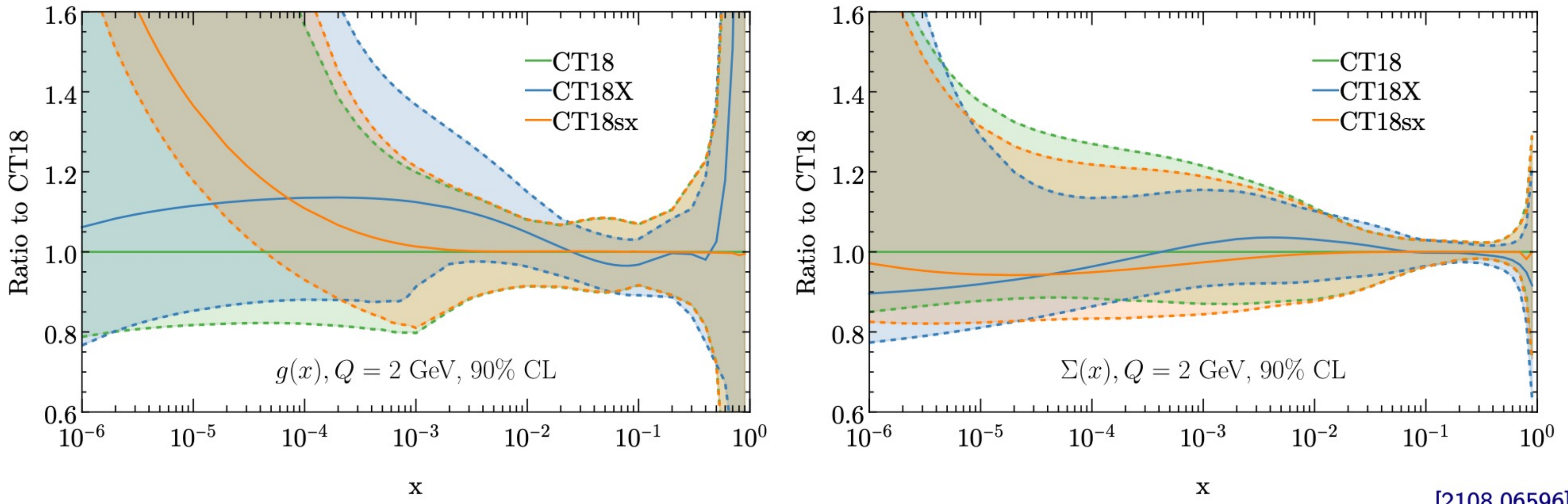


- Red lines "fit" $\sigma_{tot}^{\gamma^* p}$ for a fixed Q
- The slope $\sigma \sim 1/x$ changes as a function of (x, Q), predicting the rapid growth of PDFs at $x \to 0$
- For points below the blue line, expectations are consistent with DGLAP. Above, we see deviations.
- The boundary has not been located precisely.

How to treat the low-Q and low-x data?

- NNPDF/xFitter: BFKL to resum the small-x log's [1710.05935, 1802.00064]
- CT: x-dependent scale, motivated by saturation effect [Golec-Biernat & Wusthoff, PRD1998]

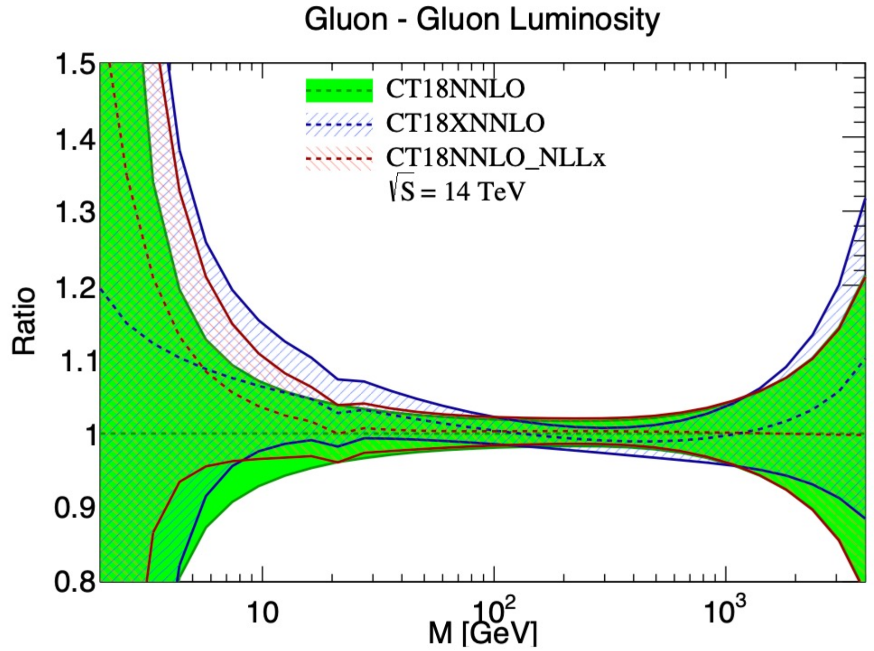
$$\mu^2_{\mathrm{DIS},x} = a_1(Q^2 + a_2/x^{a_3})$$

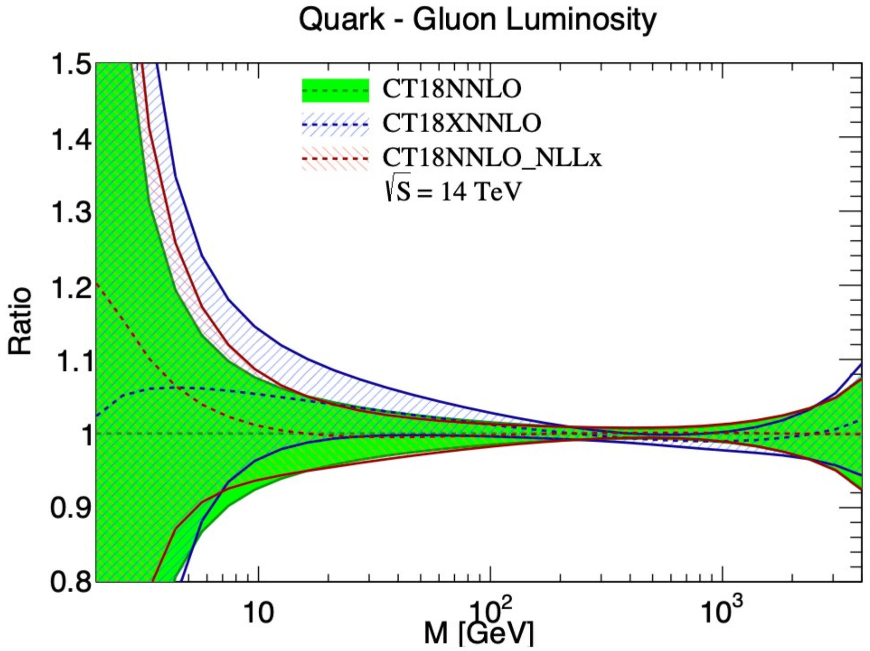


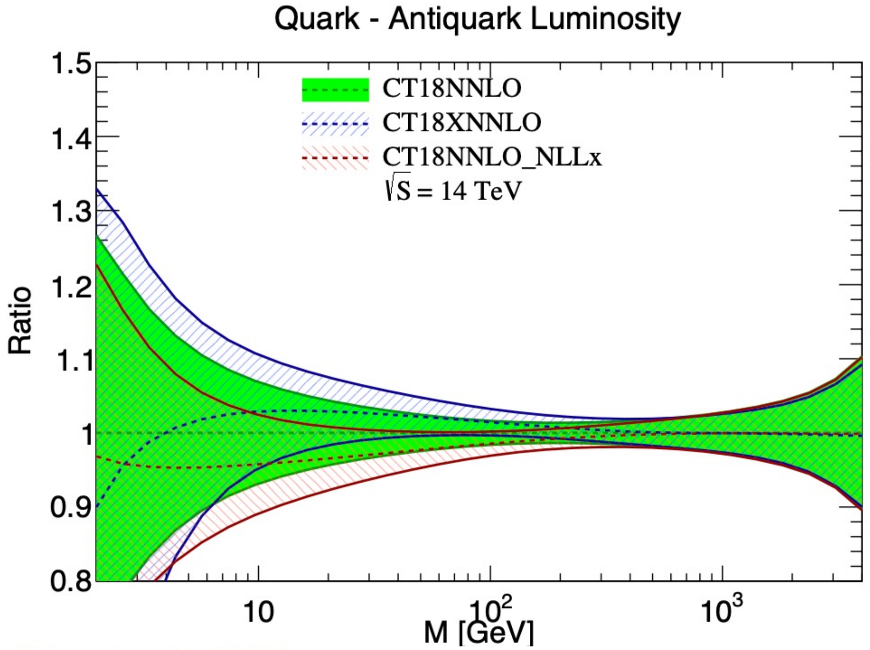
[2108.06596]

- We obtain the same level of agreement between data and theory
- Both approaches enhance (reduce) the gluon (singlet) PDF at small x and Q.
- At a higher Q, the small-x effect disappear.
- Within the currently accessible experimental region, the PDFs and predicted cross sections agree well between the two approaches.
- Higher-twist effects can also play a similar role [1707.05992].

Parton luminosities



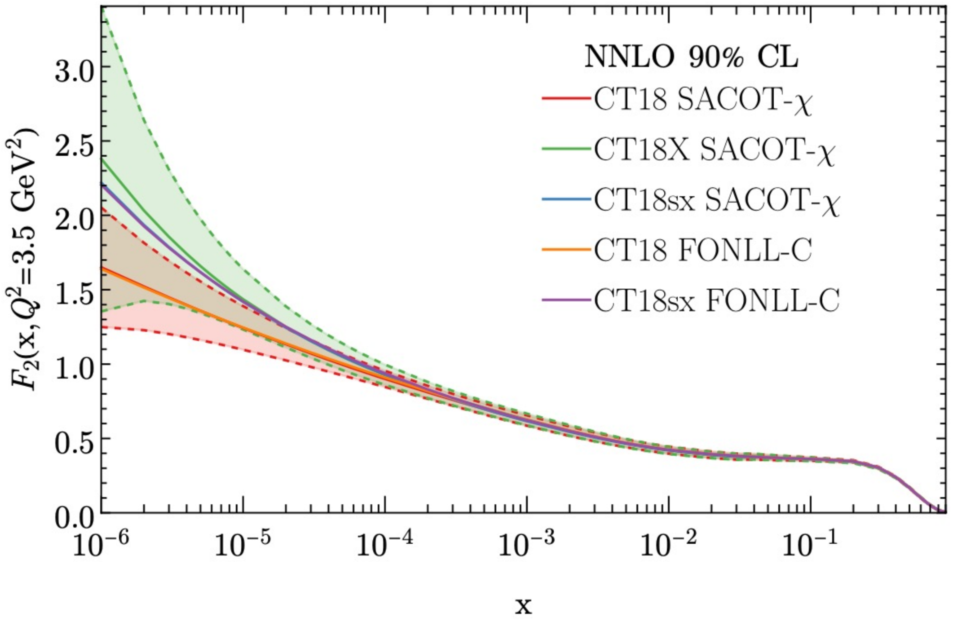


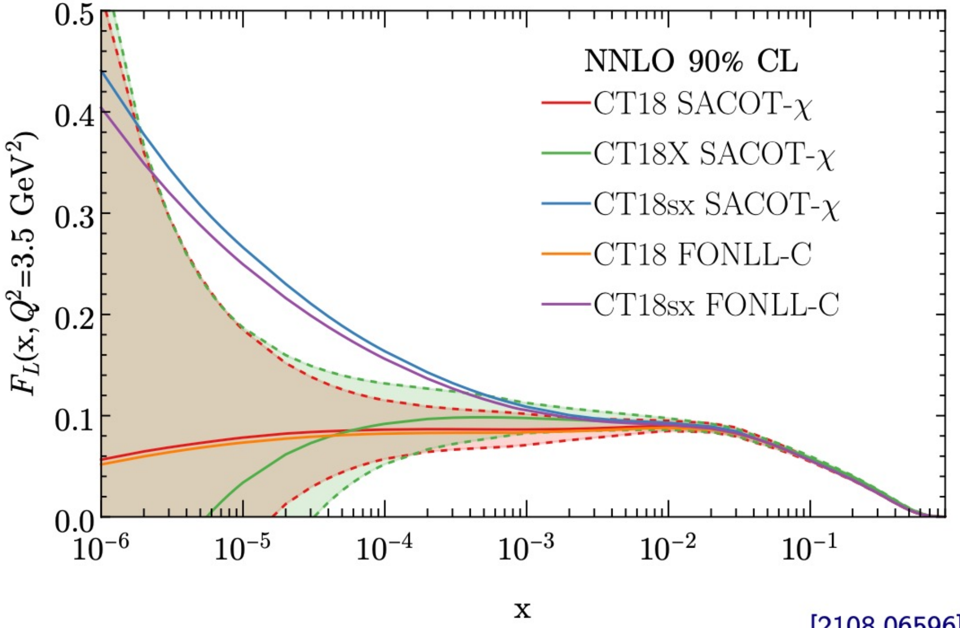


[Plotted with APFEL]

- Both CT18X and CT18sx enhance gg and qg luminosity in the small invariant mass region.
- The $q\bar{q}$ luminosity was pulled to different directions.
- The small-x resummation gives a larger effect.

Impact on Structure Functions





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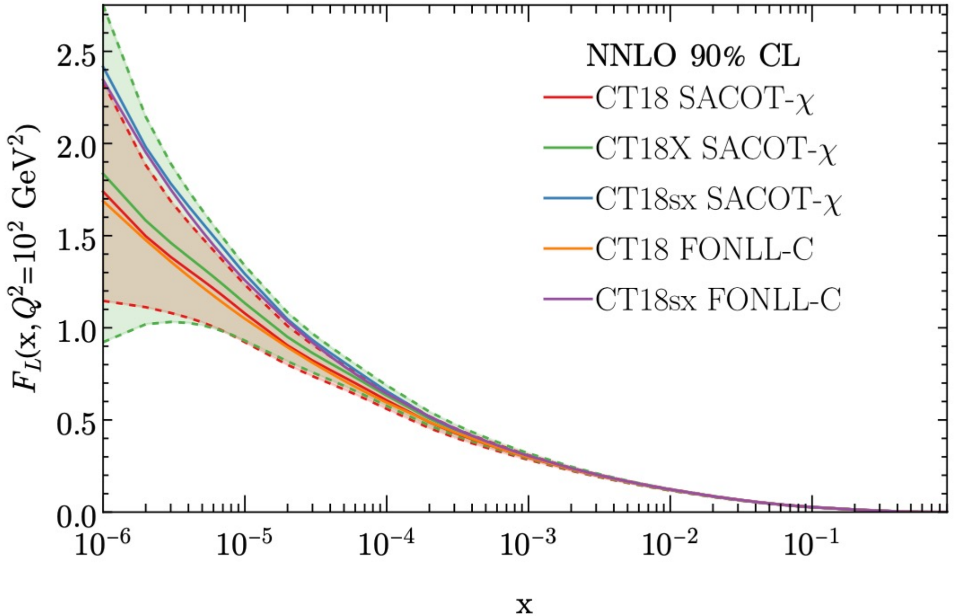

- Both CT18X and CT18sx enhance the F_2 at small x and Q.
- CT18X reduces F_L at small x while CT18sx enhances.
- Both effects disappear at Q.

$$F_2^{\mathrm{NLLx,SACOT}} = \underbrace{\frac{C(\mathrm{NLLx})\otimes f(\mathrm{CT18sx})}{C(\mathrm{NNLO})\otimes f(\mathrm{CT18})}}_{K:\ \mathrm{FONLL-C}} \underbrace{C(\mathrm{NNLO})\otimes f(\mathrm{CT18})}_{F_2^{\mathrm{SACOT}}(\mathrm{CT18})}$$

Concluding remarks

- 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.
- EF06/03 participants may be helpful.

Small-x dynamics:

- Both BFKL resummation and saturation scale provide enhancement to the gluon and reduction to the singlet PDFs.
- The small-x effect disappears at high Q.

- BFKL and saturation scale give a comparable description of the HERA I+II combined data
- At extremely small x, the BFKL gives enhance FL while saturation gives reduction
- This study would benefit from additional EF06 contributors who could compare these predictions based on CT18X with other small-x QCD formalisms