

The small- x dynamics in the CTEQ-TEA PDFs

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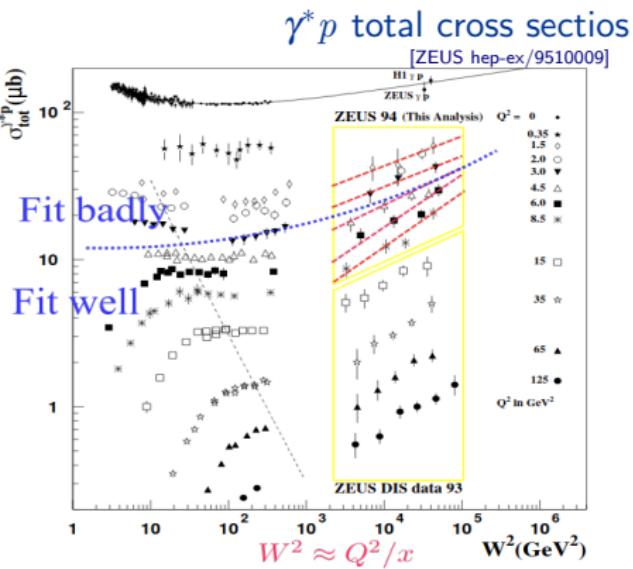
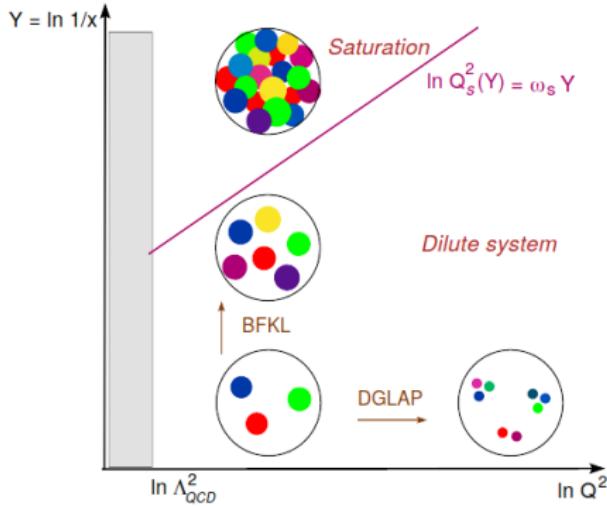
DIS 2023, March 27, 2023



In collaboration with
P. Nadolsky (SMU) and M. Guzzi (Kennesaw State U.)

Snowmass studies:
Phys.Rept. 968 (2022) 1-50 [2109.10905],
J.Phys.G 50 (2023) 3, 030501 [2203.05090]

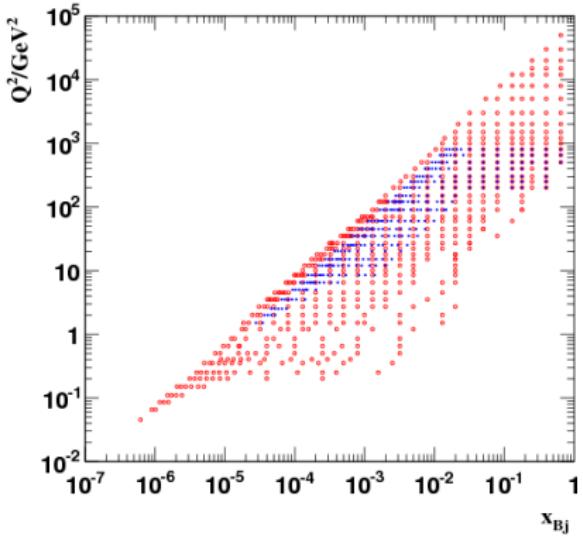
QCD dynamics vs (x, Q^2)



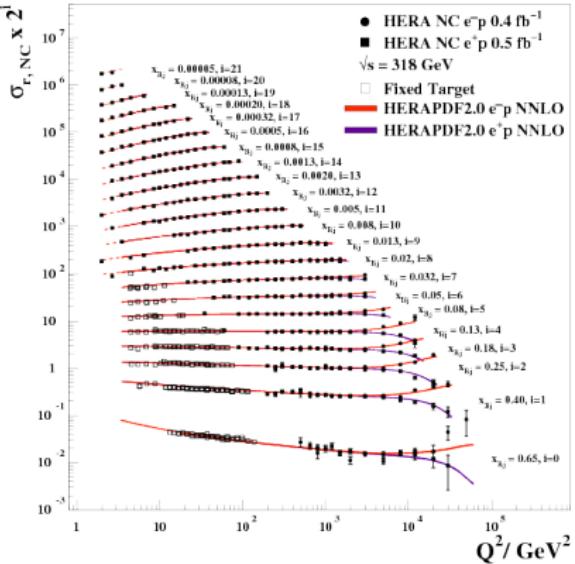
- Red dashed lines “fit” $\sigma_{tot}^{\gamma^* p}$ for a fixed Q
- The slope $\sigma \sim 1/x$ changes as a function of (x, Q) , predicting the rapid growth of PDFs at $x \rightarrow 0$
- For points below the blue line, expectations are consistent with DGLAP. Above, we see deviations.
- The boundary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

HERA I+II data [1506.06042]

H1 and ZEUS



H1 and ZEUS



- HERA data have a broad coverage in (x, Q^2) .
- It's possible to test **DGLAP/BFKL/Saturation**, especially in the low- Q^2 and low- x region.

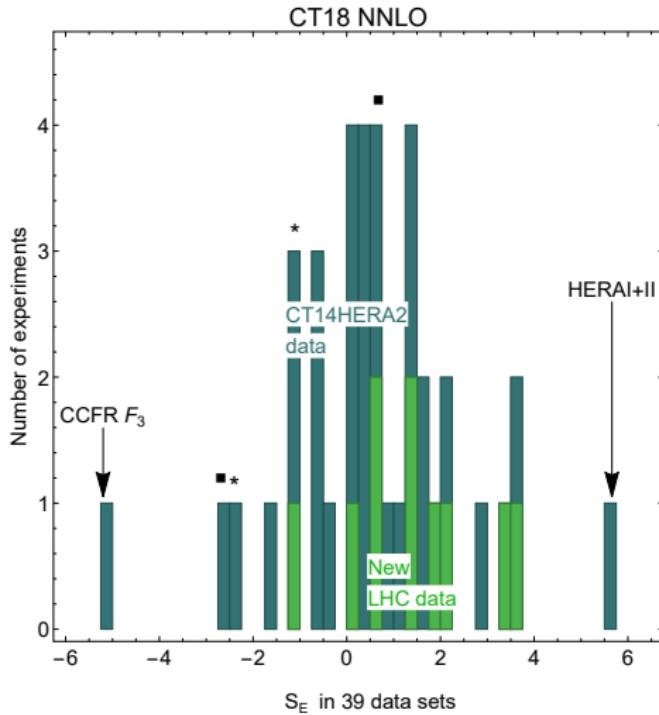
Global fitting

- $e^+ p$ data are fitted well.
- $e^- p$ data are fitted poorly.

Separate the four HERA II DIS processes
($Q_{\text{cut}} = 2 \text{ GeV}$)

	N_{pt}	$\chi^2_{\text{red}}/N_{\text{pt}}$
NC $e^+ p$	880	1.11
CC $e^+ p$	39	1.10
NC $e^- p$	159	1.45
CC $e^- p$	42	1.52
$\chi^2_{\text{red}}/N_{\text{pt}}$	1120	1.17
R^2/N_{pt}	1120	0.08
χ^2/N_{pt}	1120	1.25

- $\chi^2 = \chi^2_{\text{red}} + R^2$
- The quadratic penalty for 162 systematic errors is 87.5.
- χ^2/N_{pt} is fair, while not perfect!



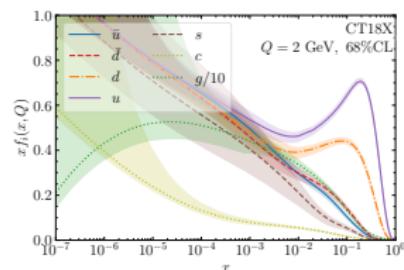
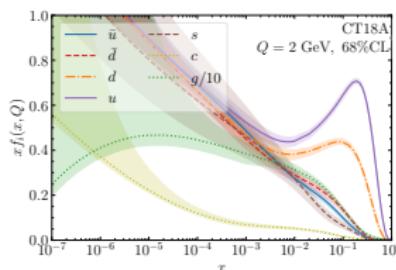
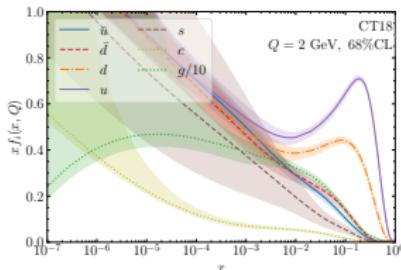
$$S_E = \sqrt{2\chi^2} - \sqrt{2N - 1}$$

Dealing with low- Q^2 and low- x data

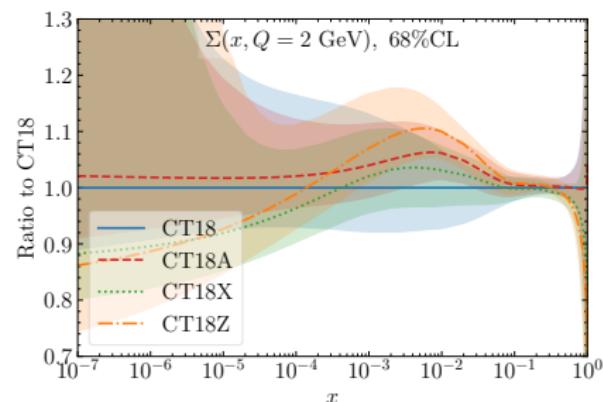
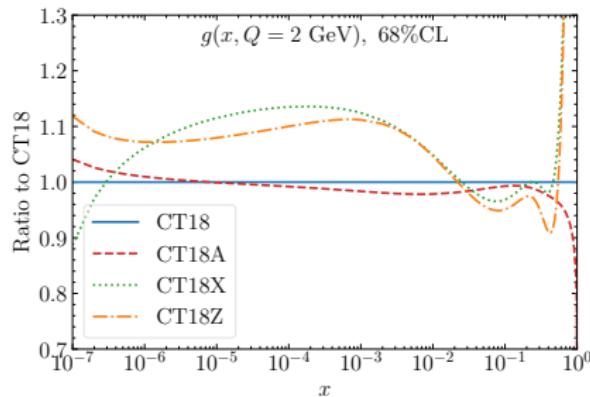
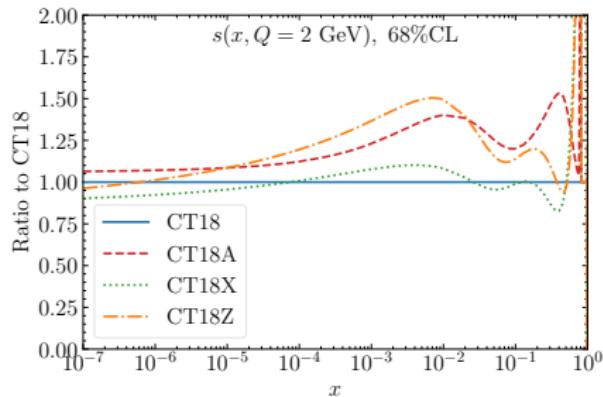
- NNPDF/xFitter: BFKL to resum the small- x log's [1710.05935, 1802.00064]
- CT: x -dependent scale, motivated by saturation effect [Golec-Biernat & Wusthoff, PRD1998]

$$\mu_{\text{DIS},x}^2 = a_1(Q^2 + a_2/x^{a_3})$$

Ensemble [1912.10053]	DIS factorization scale	ATLAS 7 TeV WZ data in- cluded ?	CDHSW $F_2^{p,d}$ data included?	Pole mass [GeV]	charm mass [GeV]
CT18	Q^2	No	Yes	1.3	
CT18A	Q^2	Yes	Yes	1.3	
CT18X	$a_1(Q^2 + a_2/x^{a_3})$	No	Yes	1.3	
CT18Z	$a_1(Q^2 + a_2/x^{a_3})$	Yes	No		1.4



CT18(A/X/Z) global analyzes

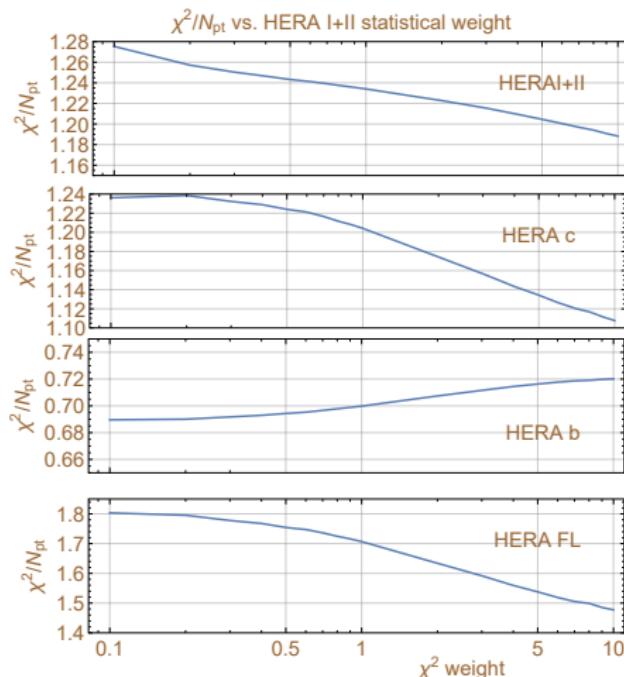
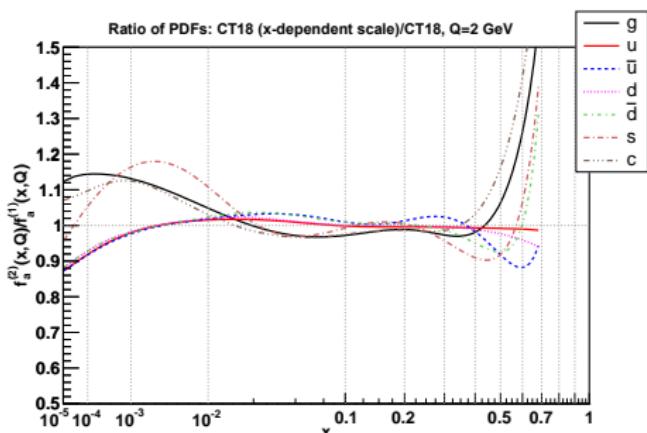


- CT18A/Z enhances strangeness due the ATLAS 7 TeV W/Z data.
- CT18X/Z enhances gluon PDF at $x \sim 10^{-4}$ due to the x -dependent scale, and reduces light-quark PDFs at $x < 10^{-2}$, as a balance.
- CT18Z accumulates the difference from CT18 PDFs, while preserves about the same goodness-of-fit.

CT18X(Z) fits with a x -dependent DIS scale

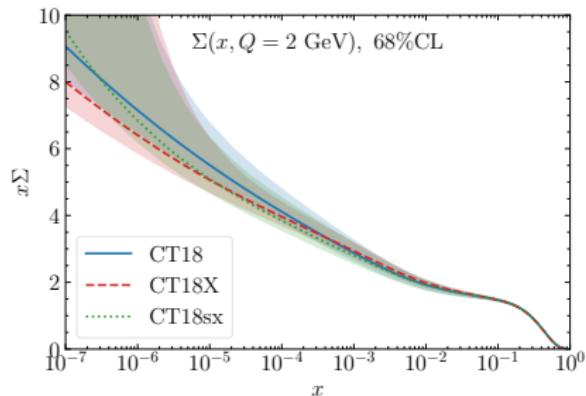
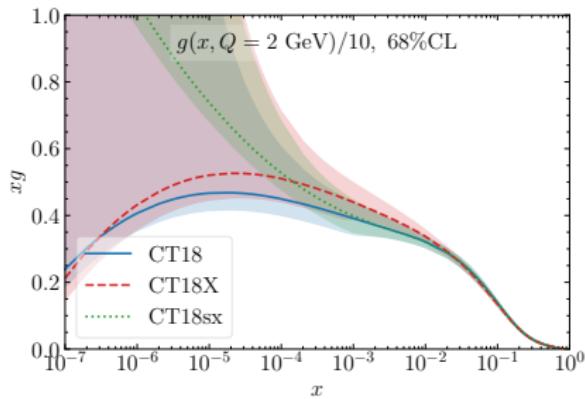
- CT18X and Z fits adopt a $\mu_{\text{DIS},x}$, that reproduces many features of NNLO-NLLx fits with $\ln(1/x)$ resummation by the NNPDF [1710.05935] and xFitter [1802.00064] groups

$$\mu_{\text{DIS},x}^2 = 0.8^2 \left(Q^2 + \frac{0.3 \text{ GeV}^2}{x^{0.3}} \right)$$



A small tension in HERA b data.

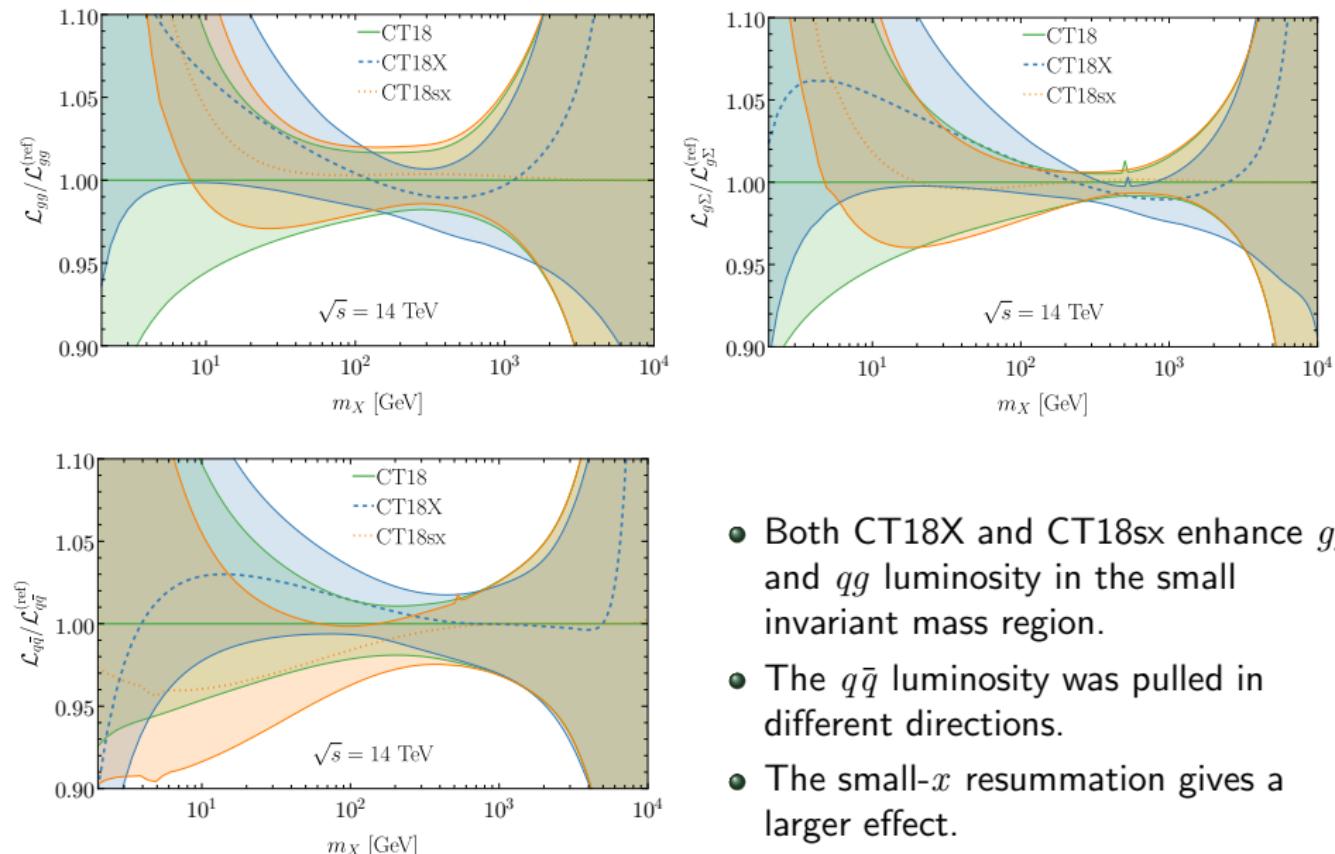
Small- x resummation vs saturation scale



[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].

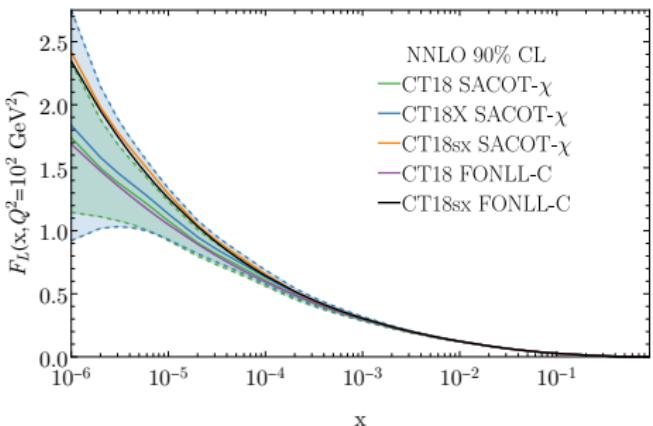
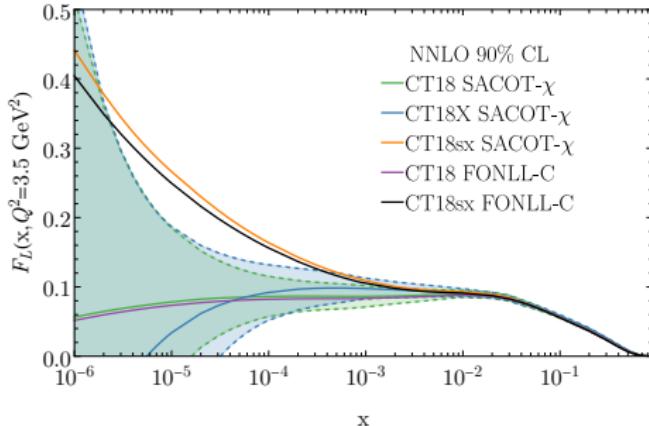
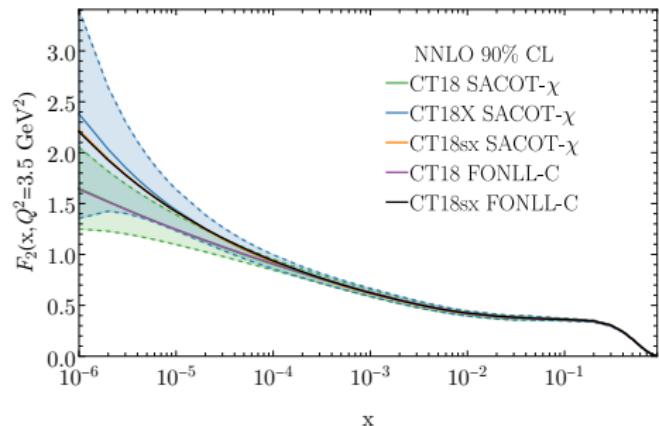
Parton luminosities



[Plotted with APFEL]

Impacts on Structure Functions

[2108.06596]



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

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

Ultra-high energy neutrino cross sections

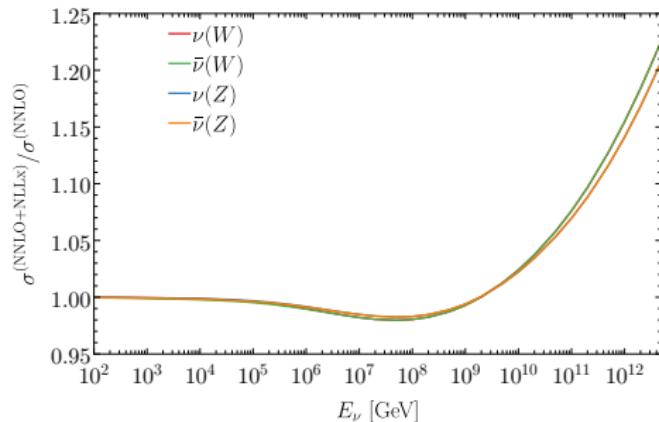
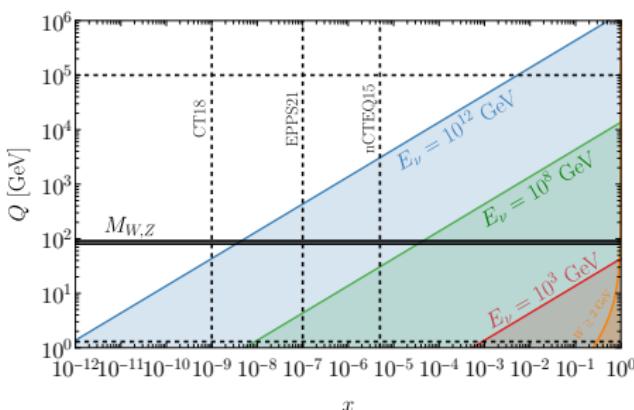
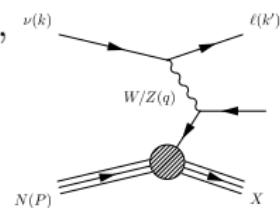
The neutrino DIS inclusive cross section [arXiv:2303.13607, See D. Stump's talk]

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME_\nu}{\pi \left(1 + Q^2/M_{W,Z}^2\right)^2} \left[\begin{array}{l} \frac{y^2}{2} 2xF_1(x, Q^2) + \left(1 - y - \frac{Mxy}{2E}\right) F_2(x, Q^2) \\ \pm y \left(1 - \frac{y}{2}\right) xF_3(x, Q^2) \end{array} \right]$$

$$\implies \sigma = \int_{Q_{\min}^2}^{2ME_\nu} dQ^2 N(Q^2) \int_{Q^2/(2ME_\nu)}^1 \frac{dx}{x} \mathcal{F}[F_{i=1,2,3}](x, Q^2),$$

with integration limits

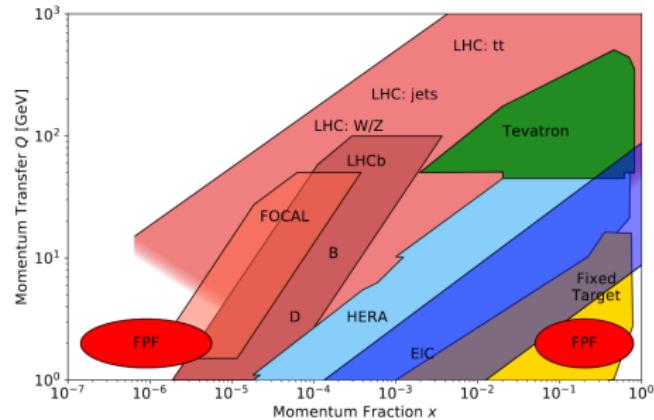
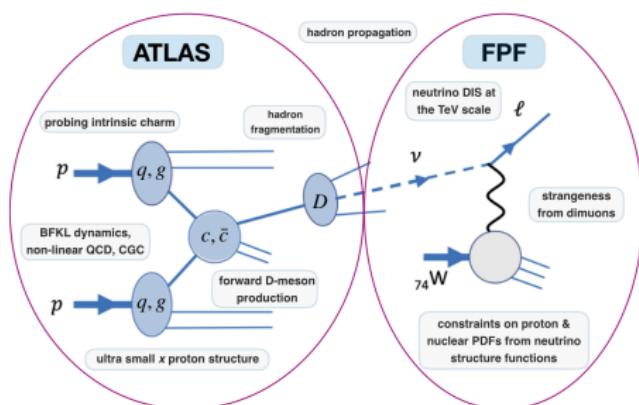
$$Q^2 \in [Q_{\min}^2, 2ME_\nu], \quad x \in [Q^2/(2ME_\nu), 1].$$



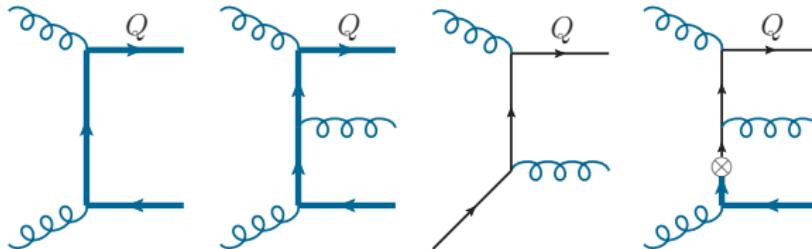
The Forward Physics Facility at HL-LHC

[L.A. Anchordoqui et al., "The Forward Physics Facility: Sites, Experiments, and Physics Potential", Phys. Rep. 968 (2022), arXiv:2109.10905]

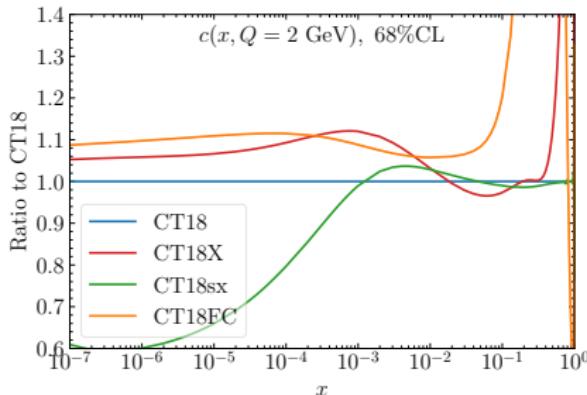
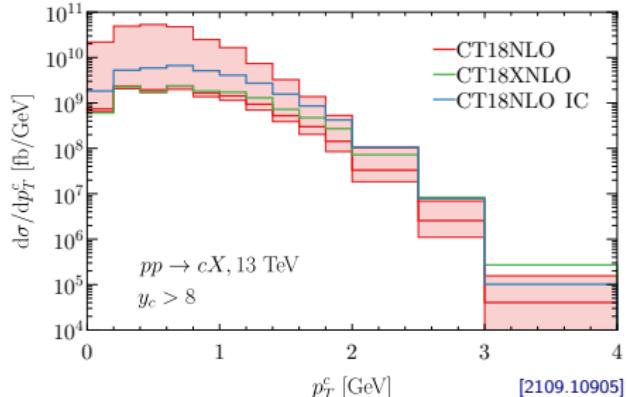
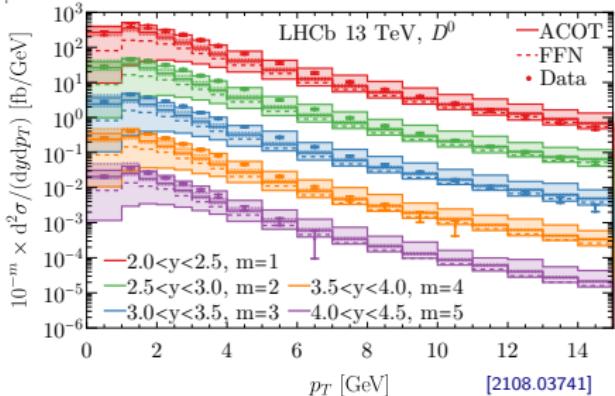
[J.L. Feng et al., "The Forward Physics Facility at the High-Luminosity LHC", J.Phys.G 50 (2023) 3, 030501, arXiv:2203.05090]



- The FPF can explore multiple aspects of QCD in the new forward region.
- The charm-meson production provides an important neutrino source.
- It probes small- x dynamics as well as non-perturbative charm PDF [See T. Hobbs' talk].



Forward charm production

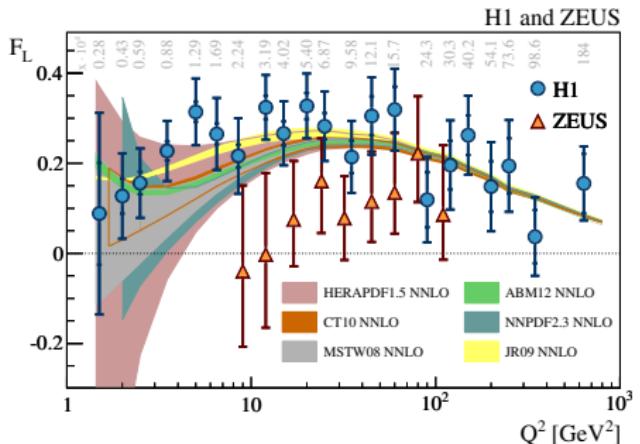


- The far-forward charm production ($y_c > 8$) probe the gluon and charm PDF at $x \sim 10^{-7}$ and $x \sim 0.5$.
- No data available to constrain PDFs in such small x region.
- The PDF uncertainty mainly comes from the extrapolation of PDF parameterization.
- Small- x resummation is technically achievable at the moment [2211.10142].

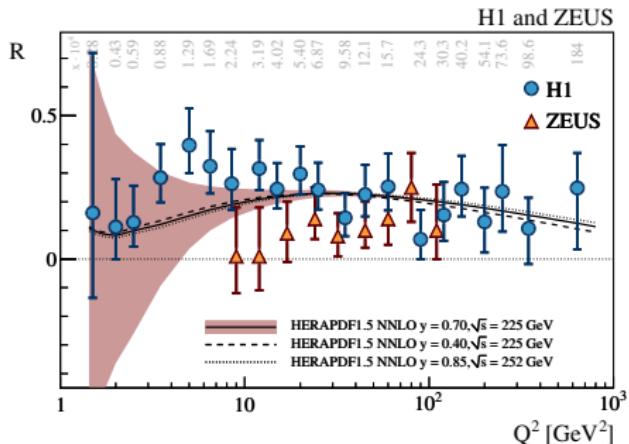
Conclusions

- 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 .
- Both BFKL and the saturation scale give a comparable description of the HERA I+II combined data.
- At extremely small x , the BFKL gives enhance F_L while saturation reduces it.
- Many current and future experiments, such as FASER, EIC, and LHeC, can test the small- x dynamics.

The experimental F_L



[EPJC 2014]



$$R = F_L / (F_2 - F_L) \approx \sigma_L / \sigma_T \quad [\text{PRD 2014}]$$

- H1 and ZEUS do not fully agree with each other in the F_L measurement.
- H1 gives enhanced F_L , which is preferred by small- x resummation [1710.05935, 1802.00064].
- ZEUS gives an opposite pull, preferred by x -scale description.
- It awaits to be resolved by the future precision measurements.