PDFs at small x: resummation or saturation?

Keping Xie

PITT PACC, University of Pittsburgh

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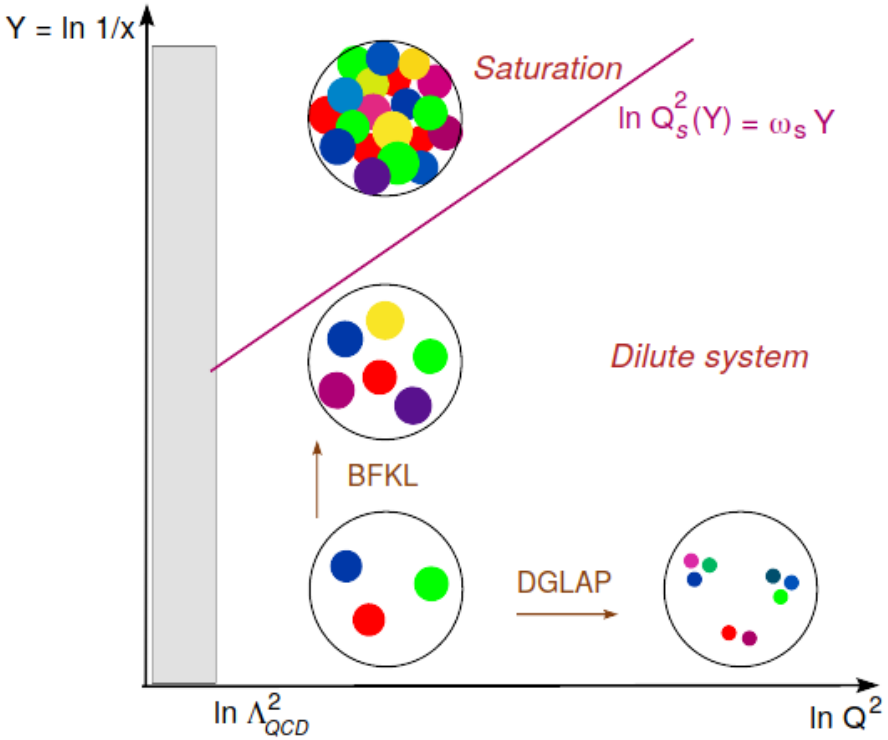
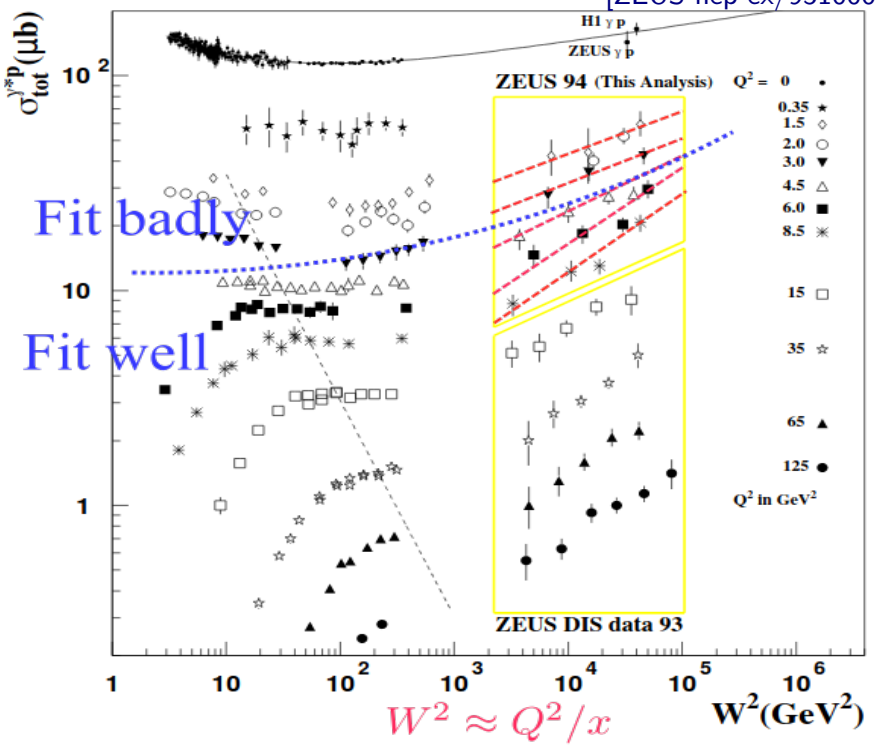
In collaboration with
P. Nadolsky (SMU) and M. Guzzi (Kennesaw State U.)
Some results can be found in arXiv:2108.06596.
More are coming in a near future.

QCD dynamics vs (x, Q^2)



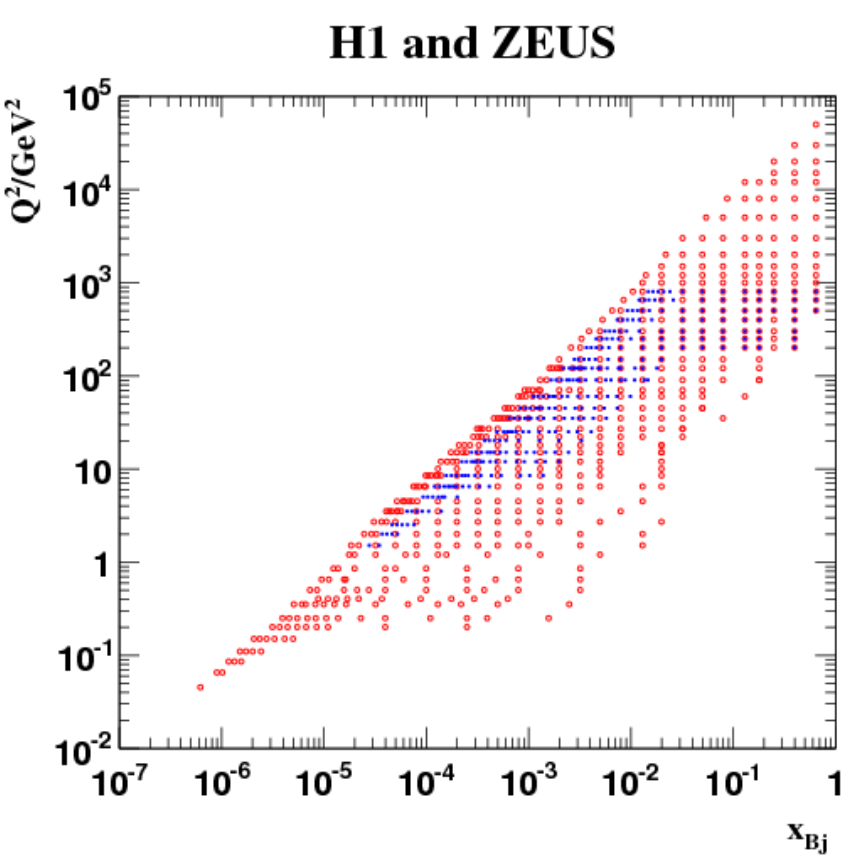
$\gamma^* p$ total cross sectios

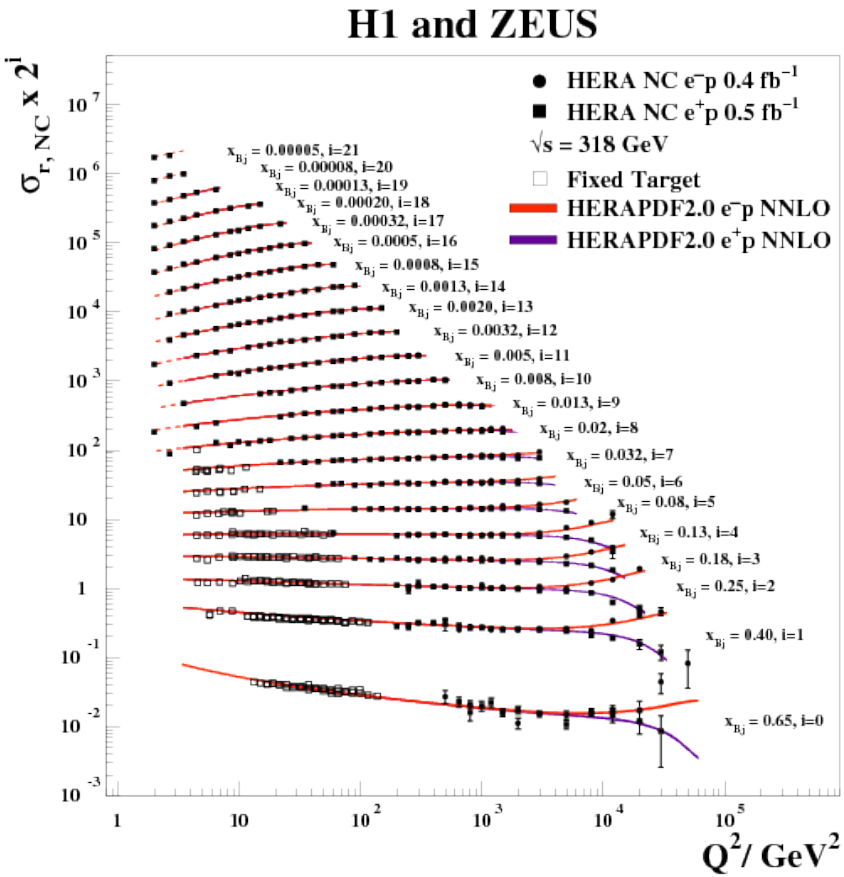
[ZEUS hep-ex/9510009]



- 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 $x \to 0$
- 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]





- 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.

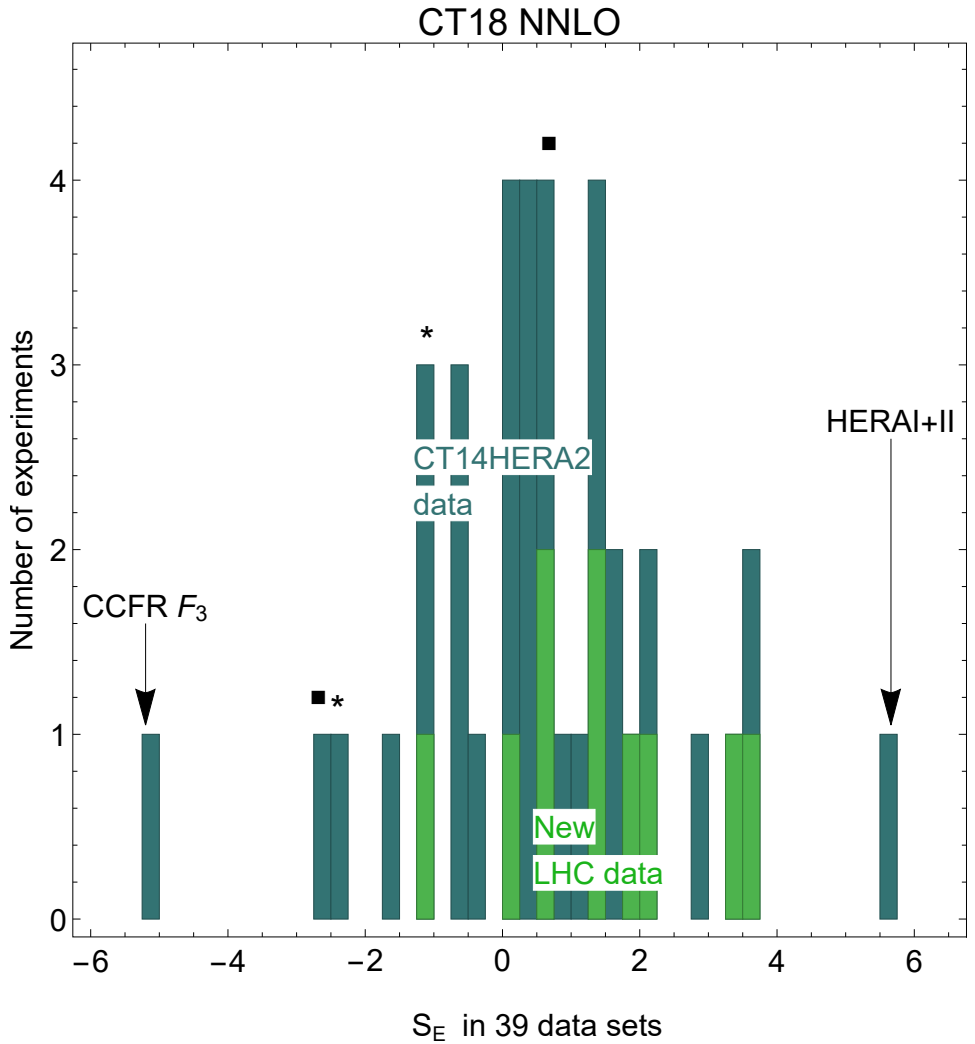
Global fitting

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

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

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

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



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

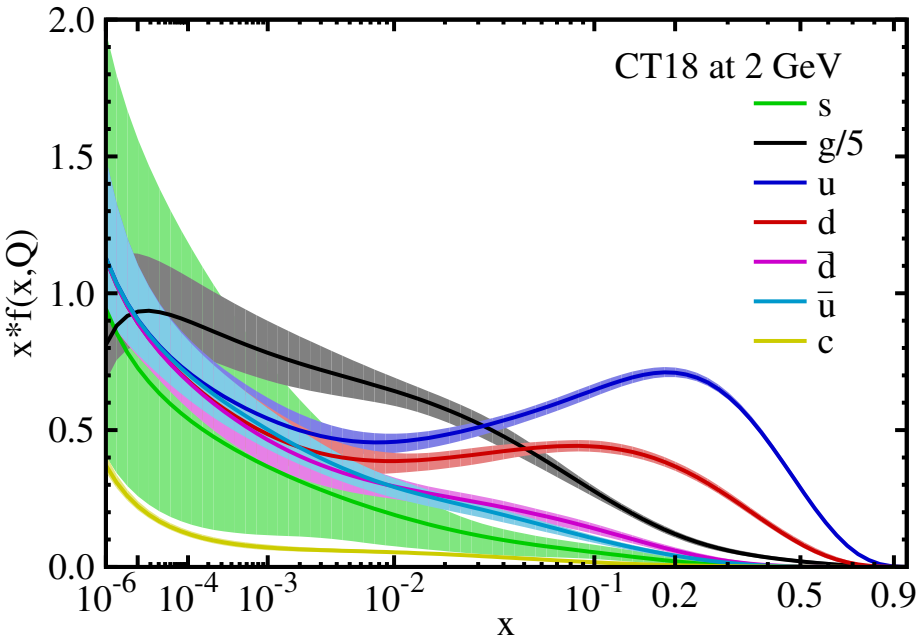
Dealing with low-Q^2 and low-x data

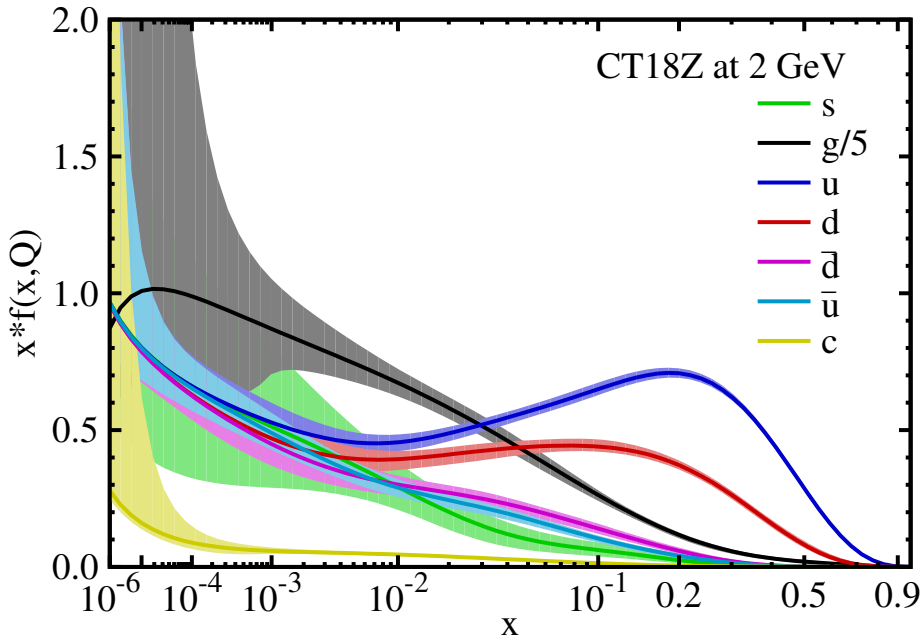
- NNPDF/xFitter: BFKL to resum the small-x log's [1710.05935, 1802.00064]
- CT: x-dependent scale, motivated by saturation effect [Golec-Biernat & Wusthoff, PRD1998]

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

Ensemble [1912.10053]	DIS factorization scale	ATLAS 7 TeV WZ data included ?	CDHSW $F_2^{p,d}$ data included?	Pole 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 PDFs



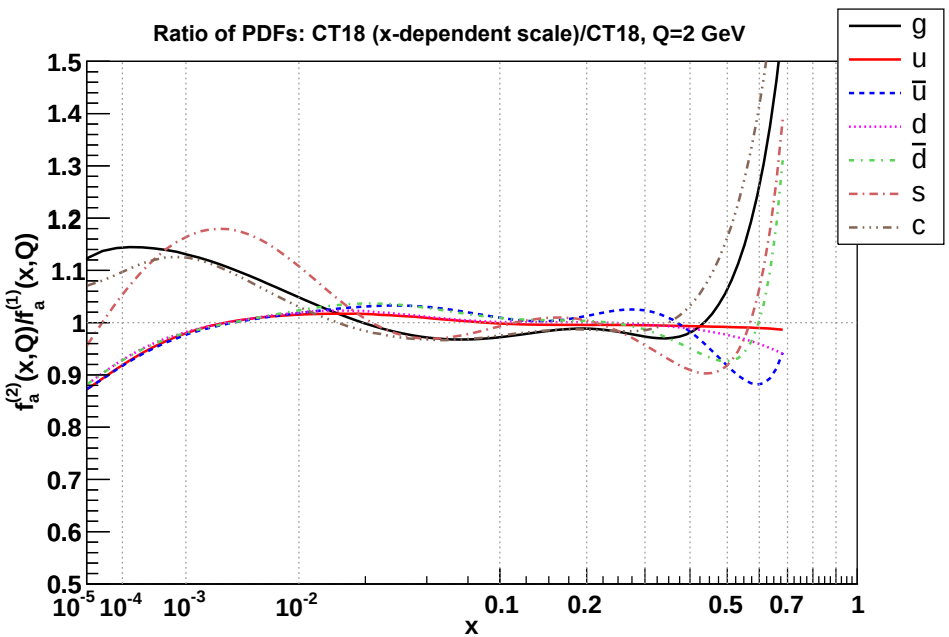


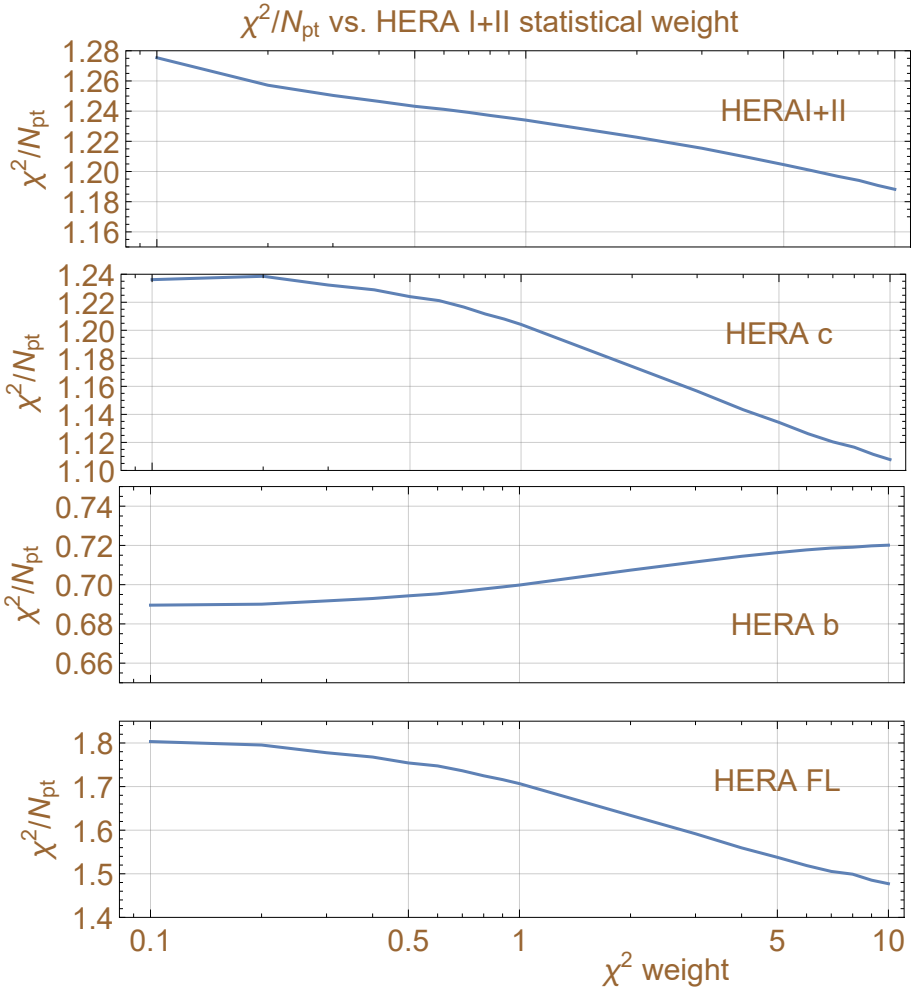
- CT18A/Z enhances strangeness due the ATLAS 7 TeV W/Z data.
- CT18X/Z enhances gluon PDF at $x \sim 10^{-4}$ due to the x-dependent scale, and reduces light-quark PDFs at $x < 10^{-2}$, as a balance.
- CT18Z accumulates the difference from CT18 PDFs, while preserves about the same goodness-of-fit.

CT18X and Z with a x-dependent DIS scale

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

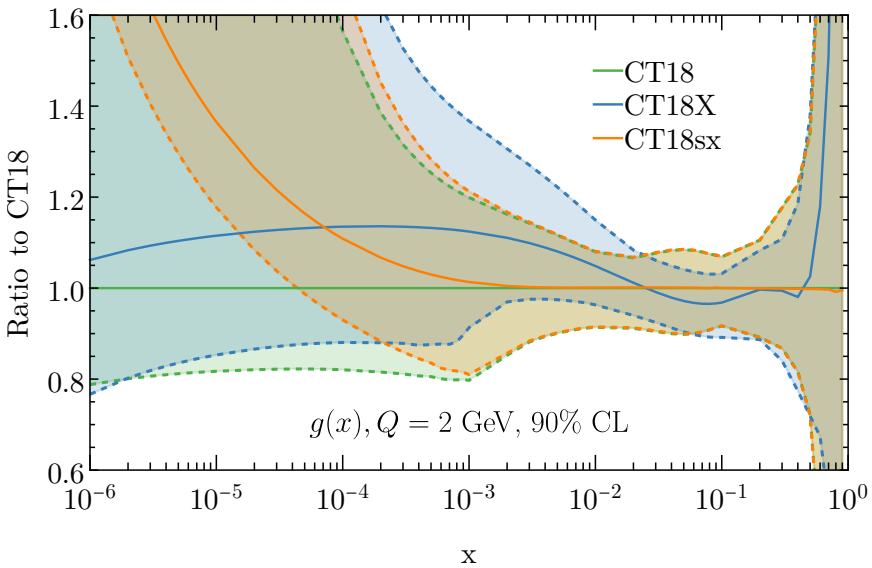
$$\mu^2_{\mathrm{DIS},x} = 0.8^2 \left(Q^2 + \frac{0.3\ \mathrm{GeV}^2}{x^{0.3}} \right)$$

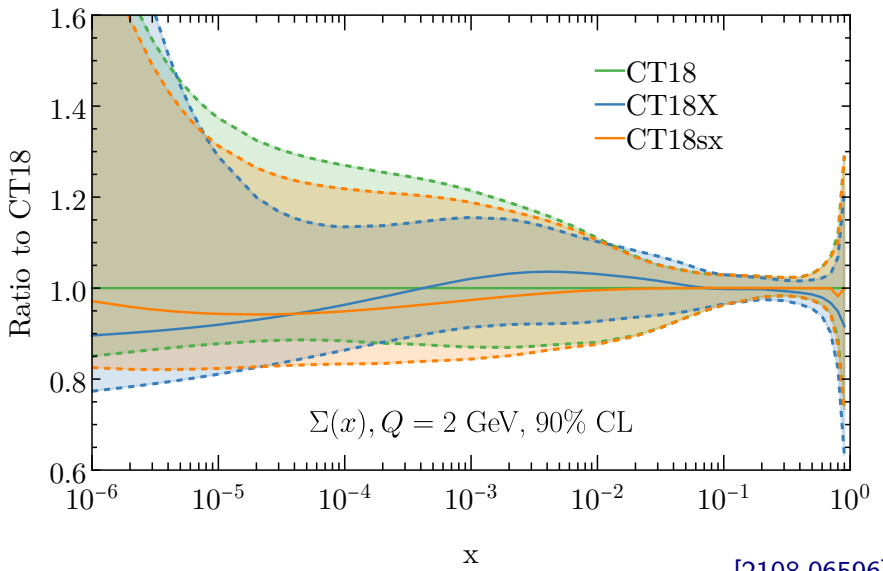




A small tension in HERA b data.

Small-x resummation vs saturation scale

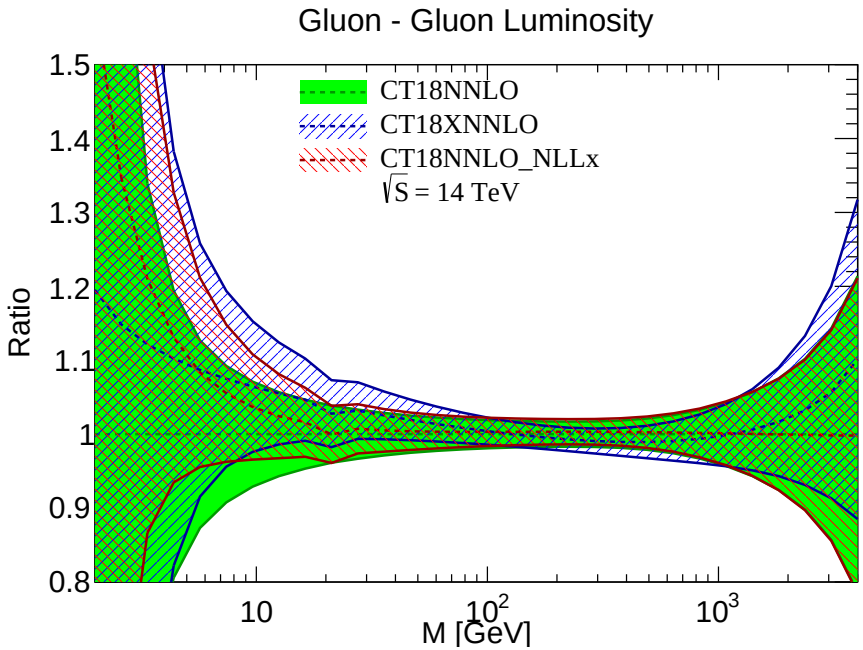


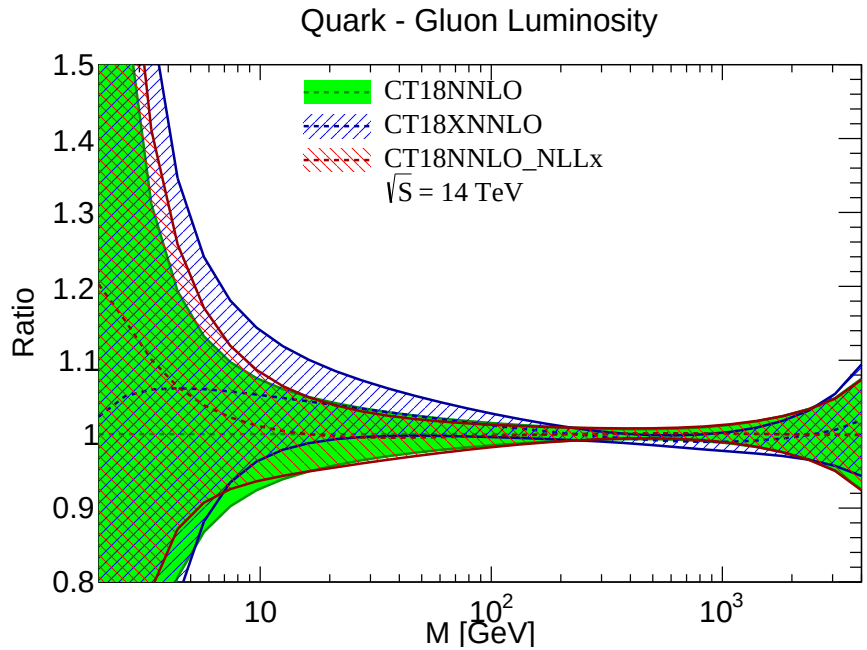


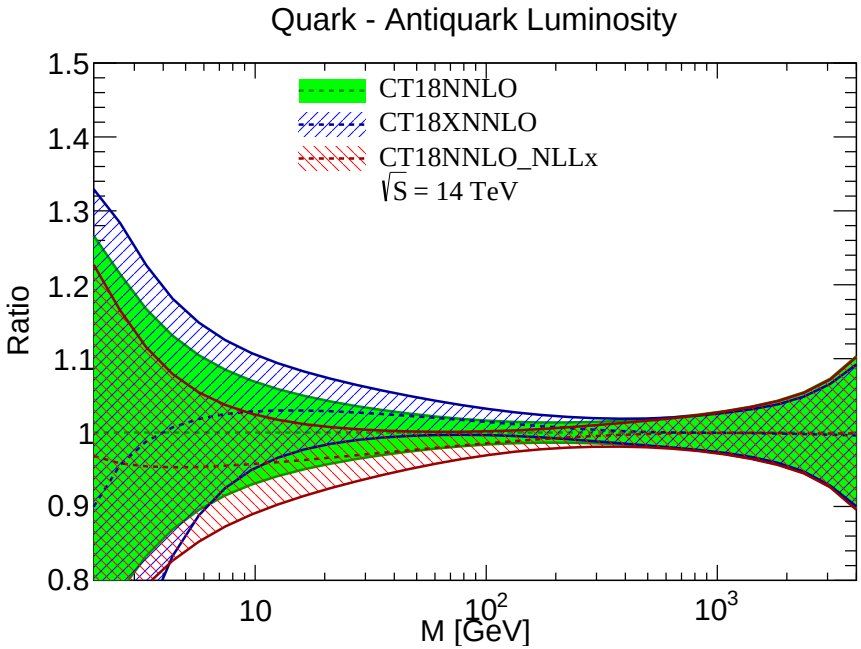
[2108.06596]

- 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





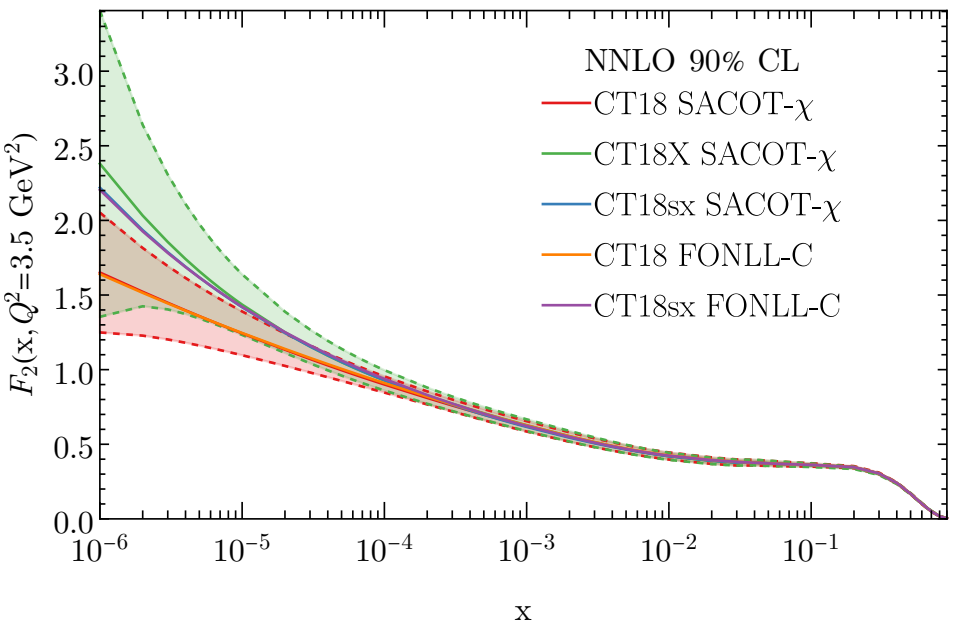


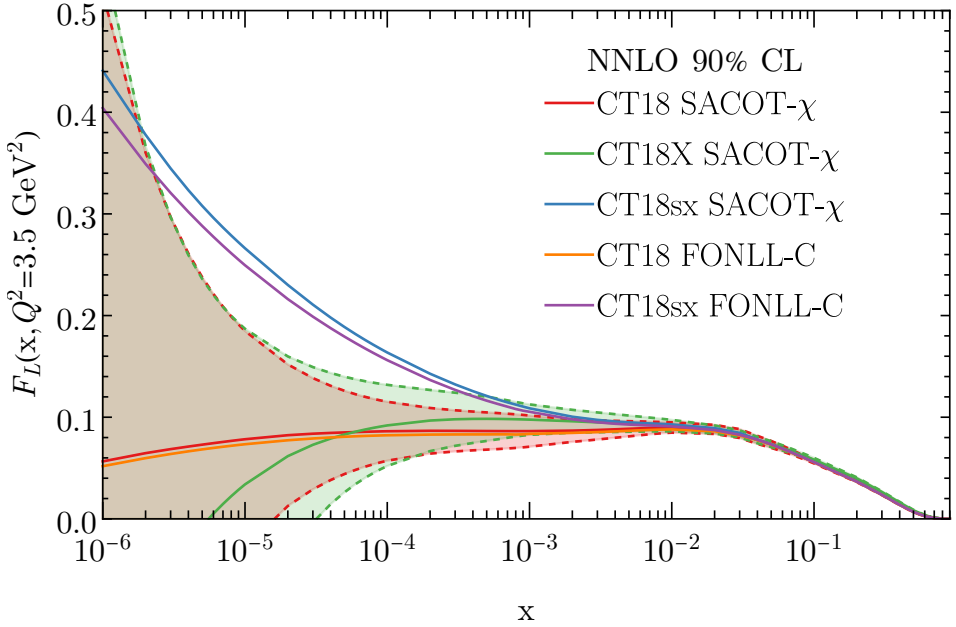
[Plotted with APFEL]

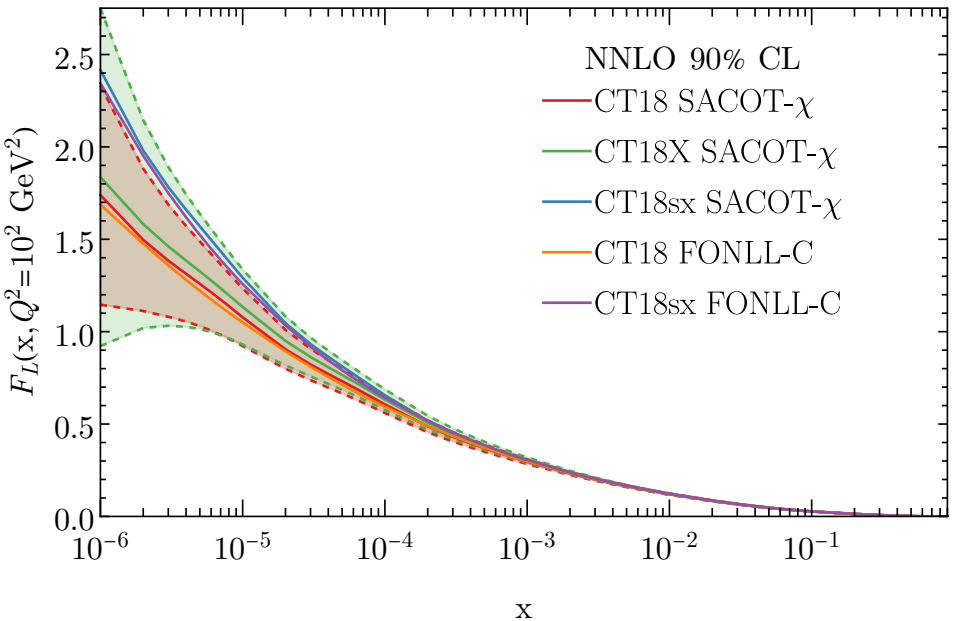
- Both CT18X and CT18sx enhance gg and qg luminosity in the small invariant mass region.
- The $q\bar{q}$ luminosity was pulled to different directions.
- The small-x resummation gives a larger effect.

Impacts on Structure Functions

[2108.06596]



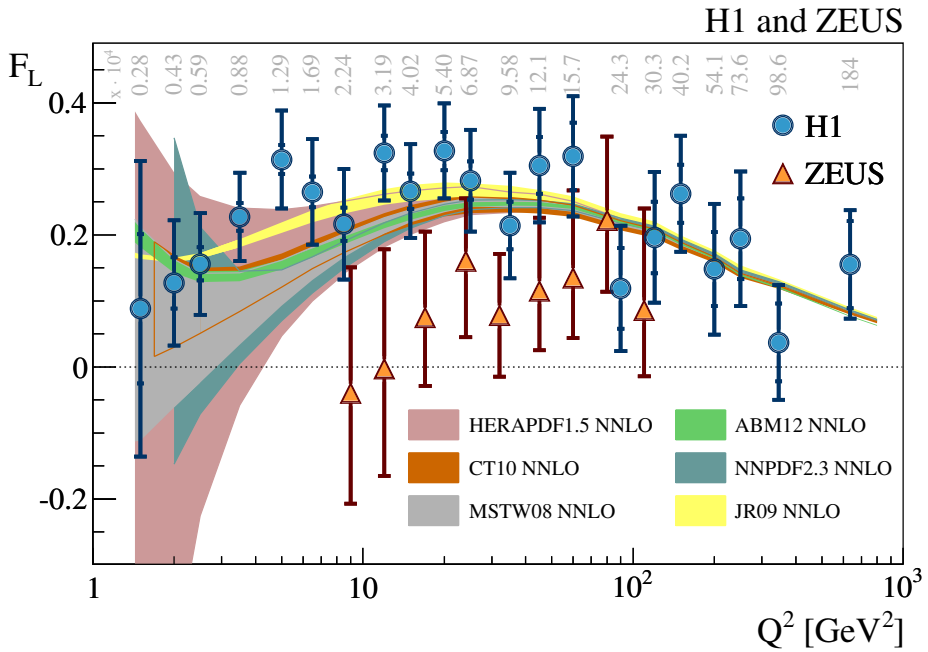


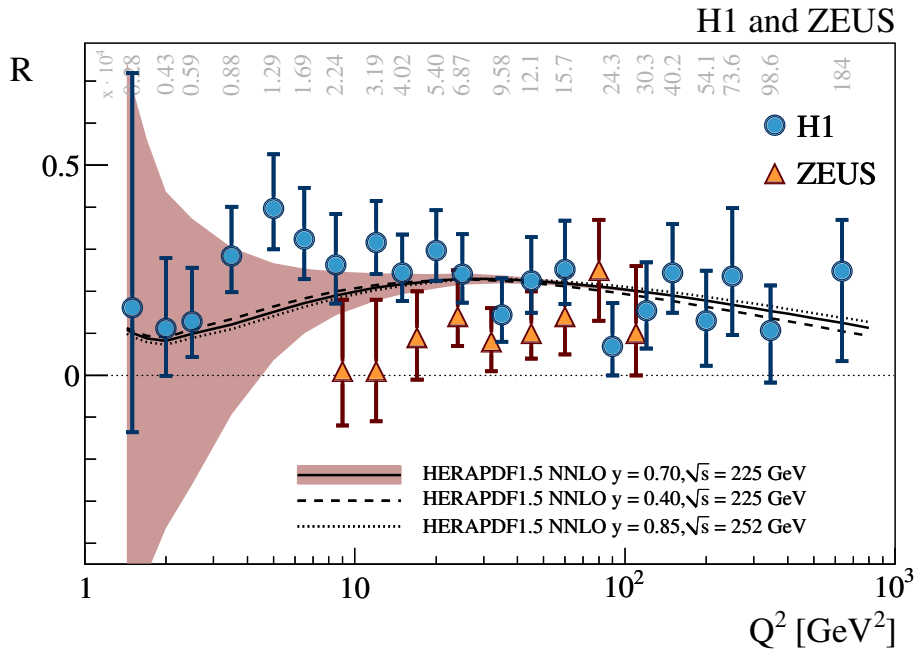


- Both CT18X and CT18sx enhance the F_2 at small x and Q.
- CT18X reduces F_L at small x while CT18sx enhances.
- Both effects disappear at Q.

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

The experimental F_L





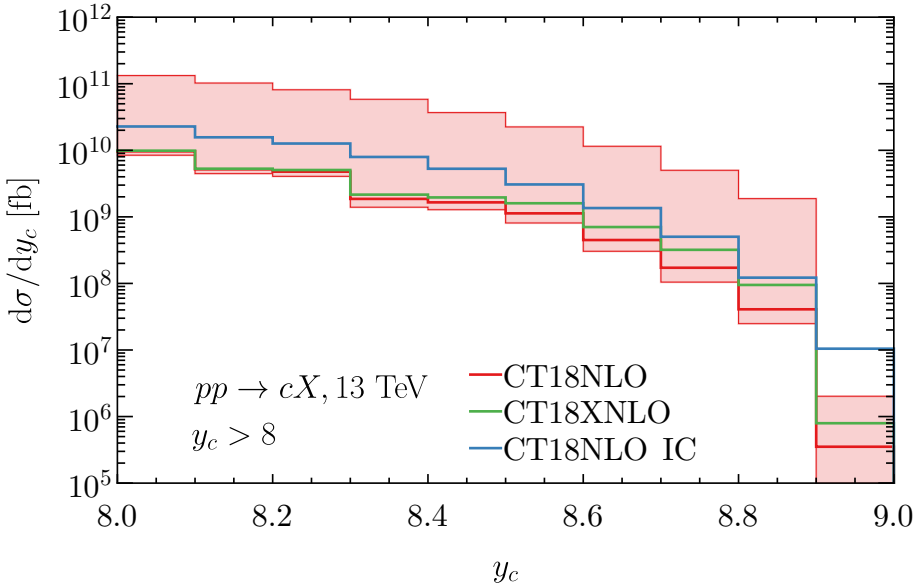
[EPJC 2014]

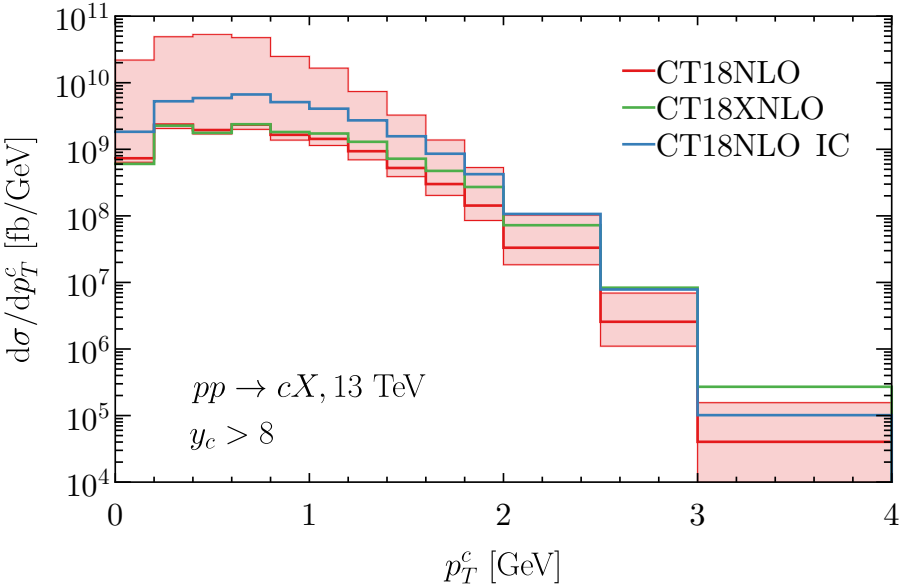
$$R = F_L/(F_2 - F_L) \approx \sigma_L/\sigma_T$$ [PRD 2014]

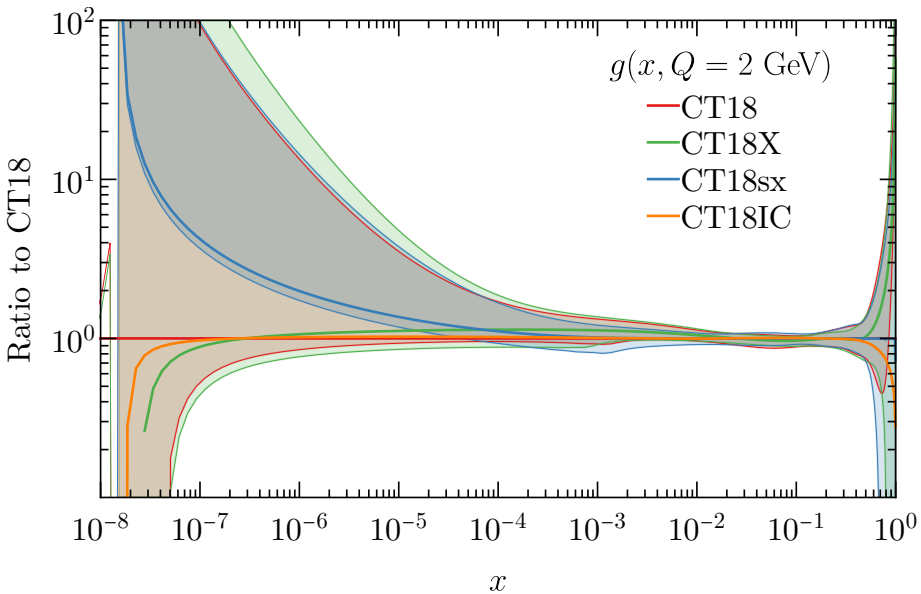
- H1 and ZEUS do not fully agree with each other in the F_L measurement.
- H1 gives enhanced F_L, which is preferred by small-x resummation [1710.05935,1802.00064].
- ZEUS gives an opposite pull, preferred by x-scale description.
- It awaits to be resolved by the future precision measurements.

Far-forward charm production

[2109.10905]







- The far-forward charm production ($y_c > 8$) probe the gluon and charm PDF at $x \sim 10^{-7}$ and $x \sim 0.5$.
- We don't have any data to constrain the PDFs in such small x region.
- The PDF uncertainty mainly comes from the extrapolation of PDF parameterization.
- In the small-x resummation, we are missing Wilson coefficients.

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.
- BFKL and 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 gives reduction.
- Future experiments, such as EIC, LHeC and FASER, can test the small-x behavior.
- The x-scale approach gives a simpler treatment of the small-x description. While, in the small-x resummation, we need to the corresponding Wilson coefficients for hadron colliders, which are missing.