PDFs from future colliders for precision physics

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On behalf of the CTEQ-TEA Collaboration

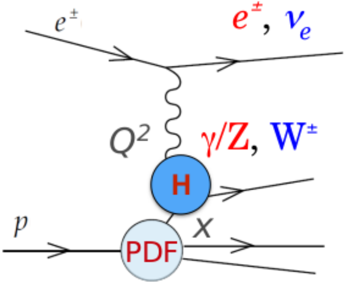
Disclaimer

- My assigned topic is so broad, including PDFs, precision physics, and future colliders. Sorry for my ignorance to miss many works.
- Many thanks to many colleagues contributing to this talk
  - Jun Gao, DIS 2022, MBI 2022
  - Tim Hobbs, DIS 2021, xFitter 2023
  - Many Snowmass 2021 studies
  - FPF series meetings
  - PDF4LHC Working Group

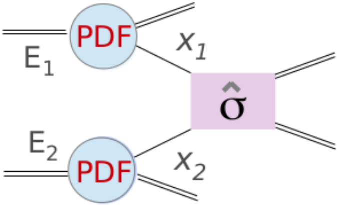
Outline

QCD collinear factorization

DIS structure functions



hadron-hadron collision



The QCD collinear factorization theorem separates long-distance and short-distance contributions in high-energy scatterings involving initial-state hadrons, and gives the predictions as

$$F_a(x,Q^2) = \sum_{i=q,\bar{q},g} C_a^i\left(\frac{x}{\xi},\frac{Q^2}{\mu_R^2},\frac{\mu_F^2}{\mu_R^2},\alpha_s(\mu_R^2)\right)\otimes f_{i/h}(\xi,\mu_F^2) + \mathscr{O}(\Lambda_{\rm QCD}^2/Q^2).$$

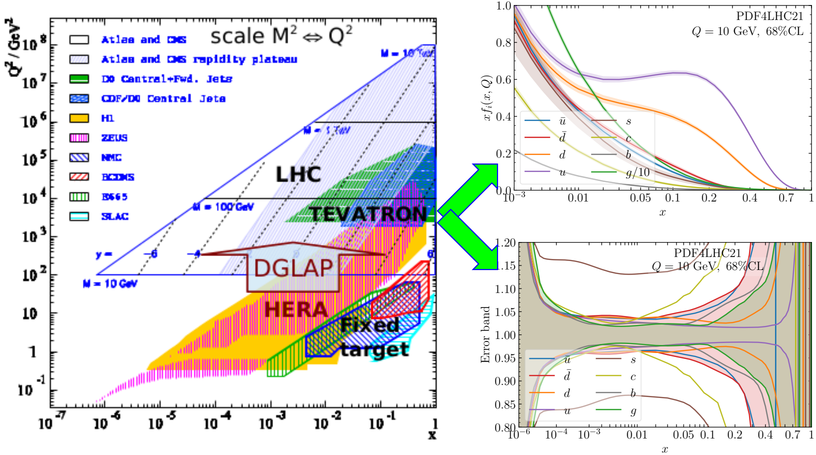
[Collins, Soper, Sterman, 1989]

- C_a^i: Coefficient functions, hard scattering, infrared (IR) safe, calculable in pQCD, independent of hadrons
- $f_{i/h}$: PDFs, reveal inner structure of hadrons, non-perturbative (NP) origin, universal, *e.g.*, for DIS and pp collisions.
- μ_F factorization scale
- PDFs run in terms of the DGLAP equation

Normally, we choose $\mu_R = \mu_F = Q$, thus, Q dependence (scaling violation) of F_2 mainly resulted from PDFs, predicted by the DGLAP equation.

Global analysis of PDFs

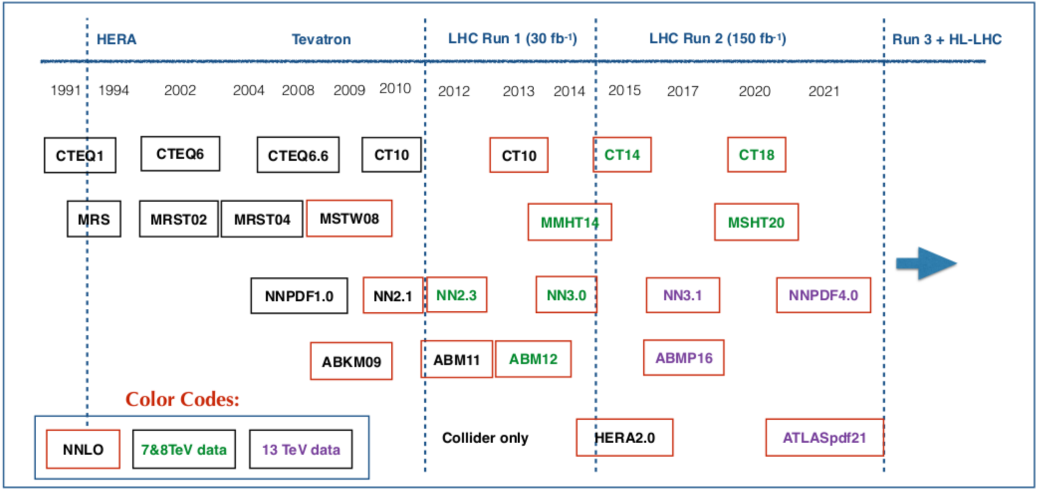
- PDFs are usually extracted from global analyses on variety of experimental data, *e.g.*, DIS, Drell-Yan, jets and top quark production at fixed-target and collider experiments, with increasing impact from the LHC, as well as the precise SM parameters. [See 1709.04922,1905.06957 for recent reviews.]



- Diversity of the analyzed data are important to separate flavors and to avoid theoretical and experimental bias.
- Can be extended to include EW ($\sin^2\theta_W$) and new physics (SMEFT) parameters simultaneously.
- Alternative extracted from lattice QCD simulations, through quasi- or pseudo-PDFs.

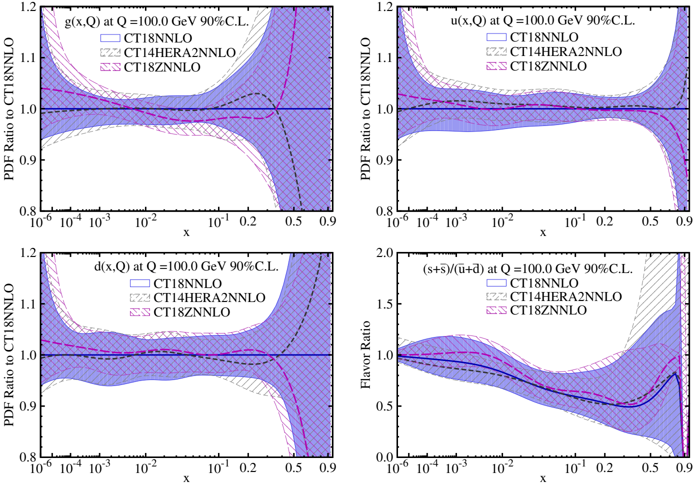
Major PDF analysis groups

- PDFs provided by several major analysis groups, including, CT, MSHT, NNPDF, ABM, HERAPDF, ATLASpdf, CJ, JAM, etc, with slightly different heavy-quark schemes, selections of data, and methodologies. [Jun Gao, DIS 2022]



CTEQ-TEA PDFs

- CT18 PDFs give moderate reductions of PDF uncertainties due to new LHC data sets, agreeing with previous CT14 within uncertainties.
- Alternative CT18A/X/Z fits to deal with small-x saturation and the ATLAS 7 TeV W/Z data

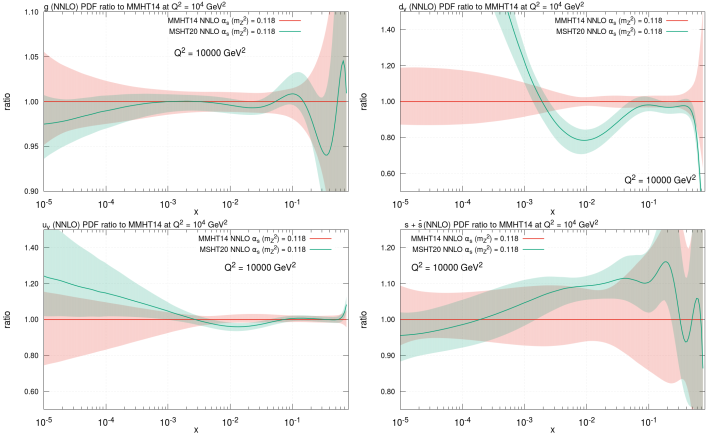


- CT18 vs CT14: gluon unc. reduced everywhere (jets, Z p_T, top), d-quark unc. reduced around $x \sim 0.2$ (LHCb W/Z), s-quark almost unchanged.
- CT18A include ATLAS 7 TeV W/Z as a separate fit due to the tension with other data.
- CT18X include the small-x saturation effect
- CT18Z accumulate both effects, differing from CT18 mostly in gluon and s-quark PDFs

[KX et al., CT18, 1912.10053]

MSHT PDFs

- MSHT20 (Mass Scheme Hessian Tolerance) PDFs adopted an extended parametrization form, as comparison to th MMHT14, to accommodate newly included LHC precision data

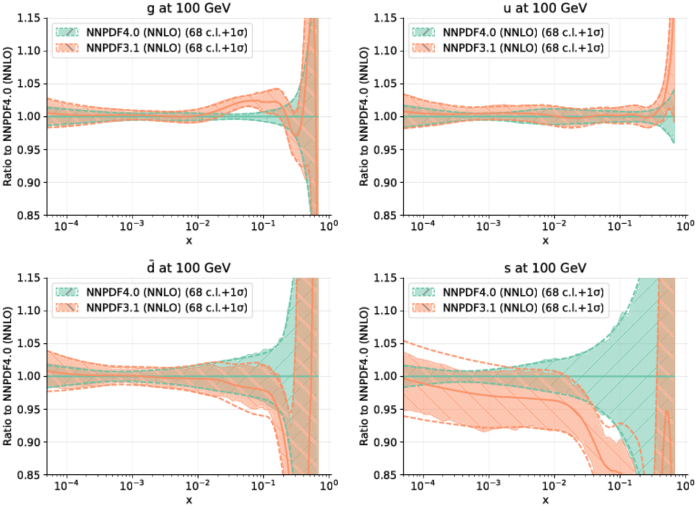


- central of gluon PDF remains mostly unchanged except for a suppression at $x > 0.2$; moderate reduction on gluon uncertainty
- enhancement of s-quark at intermediate x region and large reduction on uncertainty, due to ATLAS 7 TeV W/Z data and update of dimuon theory calculations
- new parametrization allows a change of d-valence shape to better fit LHC W/Z data, and also large uncertainties of isospin asymmetry in small-x region

[MSHT20, 2012.04684]

NNPDFs

- NNPDF4.0 PDFs improves previous NNPDF3.1 with a major update on methodologies and a dedicated global survey and selection of available LHC data

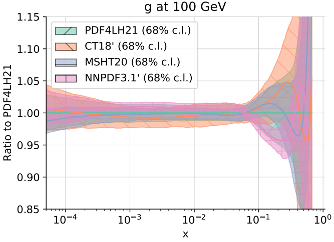


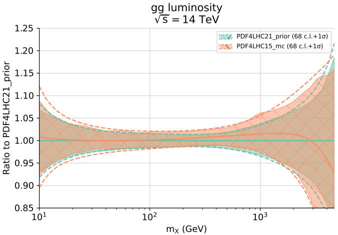
- changes on parametrization and NN architecture, optimization algorithm; additional positivity and integrability constraints and post-fit selections
- central PDF of NNPDF4.0 is generally consistent with NNPDF3.1 except for a notable decrease of gluon PDF at $x \sim 0.1$ and moderate increase of strangeness
- NNPDF4.0 shows PDF uncertainty of $\sim\ 1-2\%$ at data constrained region, largely reduced comparing to NNPDF3.1

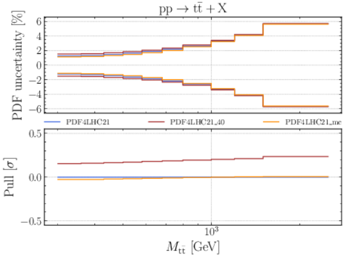
[NNPDF4.0, 2109.02653]

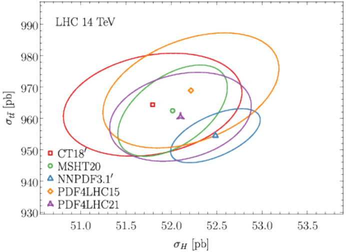
PDF4LHC21 combinations

- The PDF4LHC group performs extensive benchmarks on methodologies of several groups, and present the PDF4LHC21 PDFs as an effective combination of CT18', MSHT20, and NNPDF3.1', as a recommendation for LHC Run3 usage







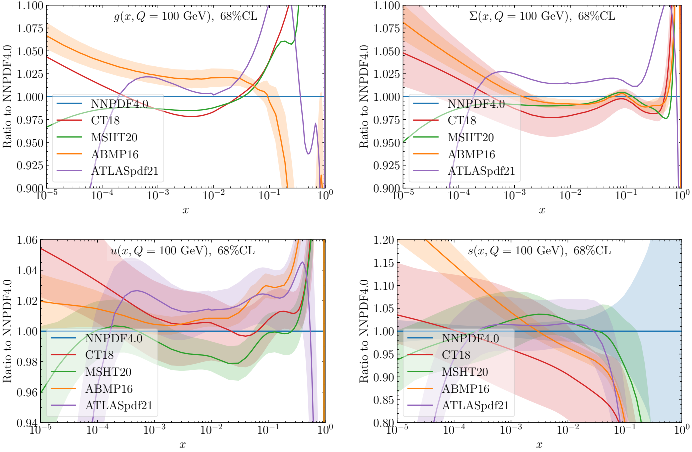


- CT18' differs slightly from CT18 by using $m_c = 1.4$ GeV, NNPDF3.1' differs frm 3.1 by including additional jet and top-quark data
- PDF4LHC21 PDFs are presented in the form of either a MC set of 100 replicas or Hessian 40 sets.
- PDF unc. at the level of $2 \sim 3\%$ for the inclusive cross sections, which increase up to $5 \sim 10\%$ in the multi-TeV region

[KX et al., PDF4LHC21, 2203.05506]

PDF benchmarking

- Many efforts on comparisons and understanding of differences of up-to-date PDFs, in order to have a faithful determination of PDFs and its uncertainties [KX et al., Snowmass 2021, 2203.13923]

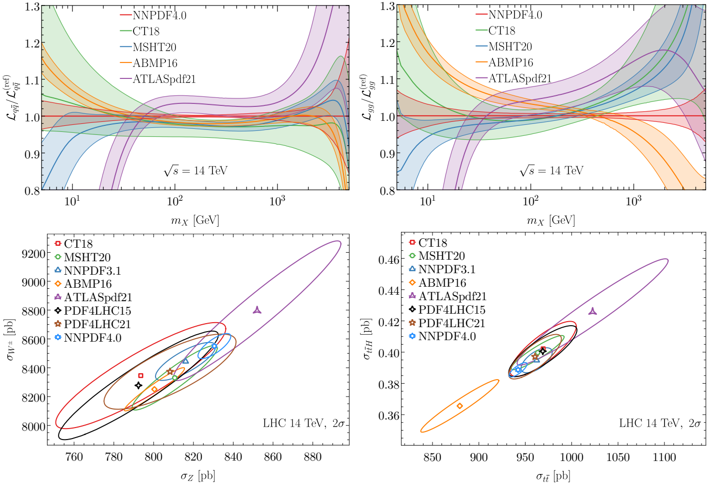


- general agreement among different groups over range $x \sim 10^{-4} - 10^{-1}$ within uncertainties
- gluon notable difference at $x \sim 0.2$ with 2σ for NNPDF4.0 vs CT18 and MSHT20.
- singlet ATLASpdf21 deviate at $x < 10^{-4}$ due to $Q^2 > 10$ GeV^2 applied on HERA data and $x > 0.2$ due to lack of fixed-target data
- NNPDF and ABMP show uncertainty of $1 - 2\%$ in constrained region, mostly due to methodologies; CT18 being conservative among all fits

Phenomenological implications

- Spread of PDFs from different groups propagates into the parton-parton luminosity or cross sections at the LHC 14 TeV and some cases enlarged due to (anti-)correlations between different x-regions/flavors

[KX et al., Snowmass 2021, 2203.13923]

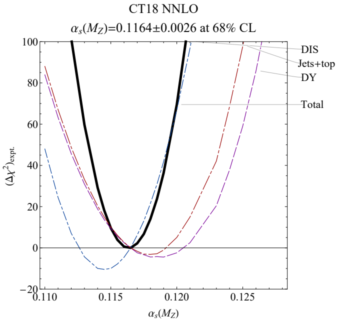


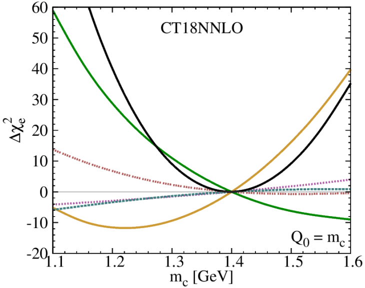
- gg luminosity shows a spread of more then 20% in the multi-TeV region; $q\bar{q}$ agrees better in general, exceptat a mass around 300 GeV.
- 2σ error ellipses show cross sections of standard candle processes; NNPDF4.0 shows an uncertainty of less than 1% CT18 2σ ellipse cover most groups

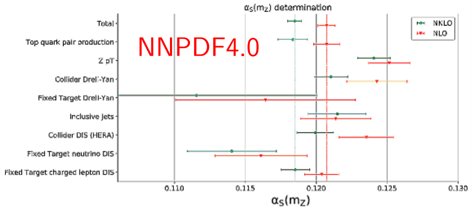
Outline

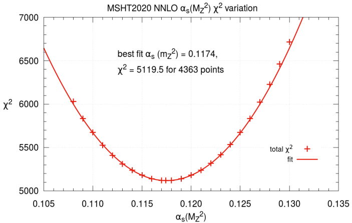
QCD parameter determinations

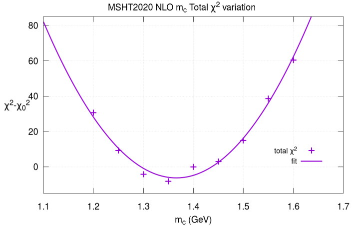
- From global analysis of PDFs, one can also extract QCD parameters, including the strong coupling [KX et al., Snowmass 2021, 2203.08271] at NNLO with compatible precision, and the heavy-quark pole masses.







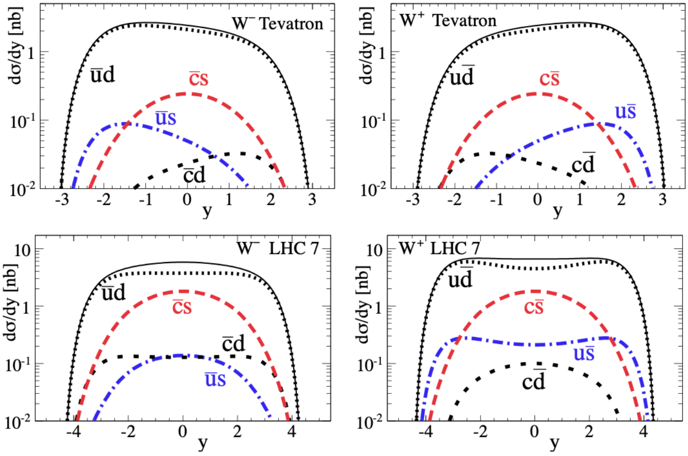




- The 3 most recent global fits gives $\alpha_s(M_Z) = 0.1164, 0.1174, 0.1185$ at NNLO for CT18, MSHT20, and NNPDF4.0, respectively.
- Very mild sensitivity to $m_c = 1.35$ GeV for both CT18Z and MSHT20.

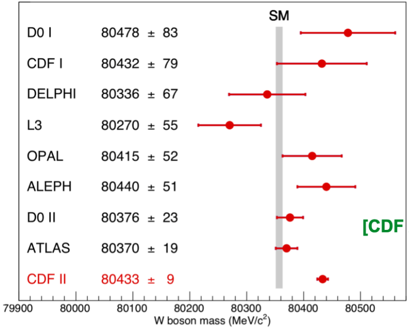
W-boson mass measurement

- PDFs are key inputs for precision programs at hadron colliders, e.g., direct measurements on the W boson mass and the weak mixing angle



[ATLAS 2018]

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

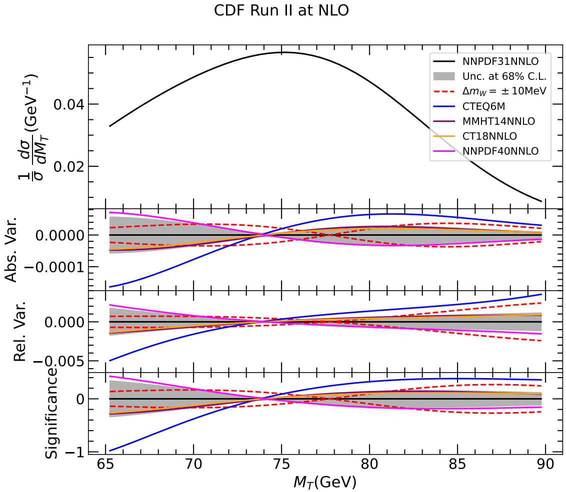


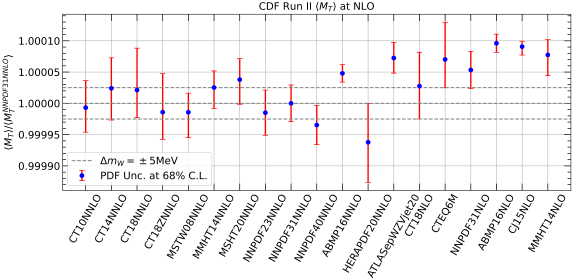
[CDF 2022]

Fig. 5

PDF impact on the m_W measurement

- We estimate shift of extracted W boson mass induced by variation of PDFs, and the associated PDF uncertainty for a variety of PDFs, focusing on the kinematic variable of transverse mass at CDF





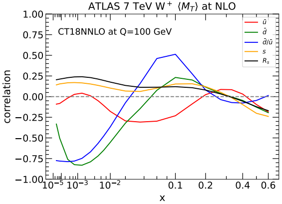
The shift and PDF unc. of W mass

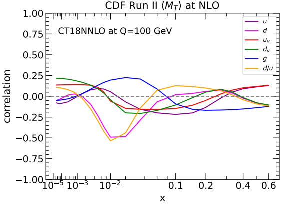
δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT2014	NNPDF4.0	MSHT2020
$\langle M_T \rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$
$\langle M_T \rangle$(NLO)	–	$0^{+5.9}_{-5.9}$	$-4.2^{+8.8}_{-13.3}$	$-5.0^{+6.7}_{-5.3}$	$+6.9^{+6.2}_{-6.2}$	$-7.6^{+7.9}_{-6.7}$
χ^2 fit (NLO)	8.0	$0^{+4.2}_{-4.2}$	$-4.3^{+5.4}_{-10.1}$	$-5.1^{+4.8}_{-3.4}$	$+7.1^{+4.5}_{-4.5}$	$-7.8^{+5.7}_{-4.5}$
CDF	9.2	$0^{+3.9}_{-3.9}$	–	–	–	–

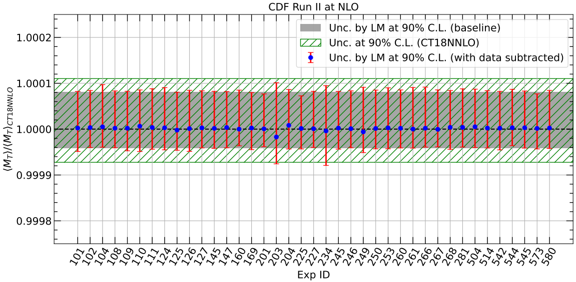
[Gao, Liu, KX, 2205.03942]

PDF variations cannot explain the CDF discrepancy

- We carry out a series of Lagrange multiplier scans to identify the constraints on the transverse mass distribution (using mean m_T) imposed by individual data sets in the CT18 global analysis





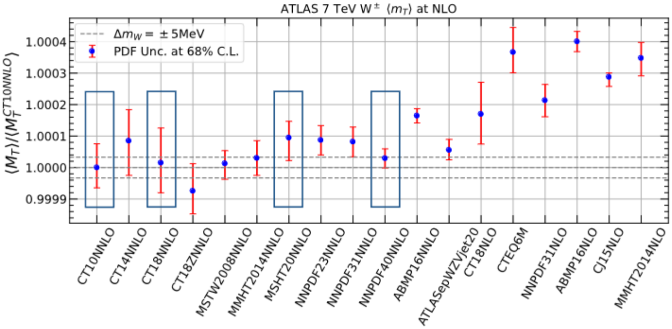


- m_T at CDF (ATLAS) is mostly sensitive to the d-quark (dbar-quark) at x 0.01(0.001); CDF and ATLAS are largely uncorrelated
- m_T at CDF is largely constrained by the DIS and Drell-Yan data on deuteron target, the Tevatron lepton charge asymmetry data; at ATLAS also the CMS charge asymmetry data

[Gao, Liu, KX, 2205.03942]

Transverse mass at ATLAS

- We further investigate PDF variations on transverse mass distribution focusing on the ATLAS 7 TeV measurement; note the transverse momentum distribution has a relatively larger weight in ATLAS



[Gao, Liu, KX, 2205.03942]

- spread of predictions from different PDFs could be much larger than the PDF unc. of a specific set, even for the same group the PDF unc. not necessarily decrease with time

PDF unc. at LHCb, NNPDF3.1, CT18, MSHT20

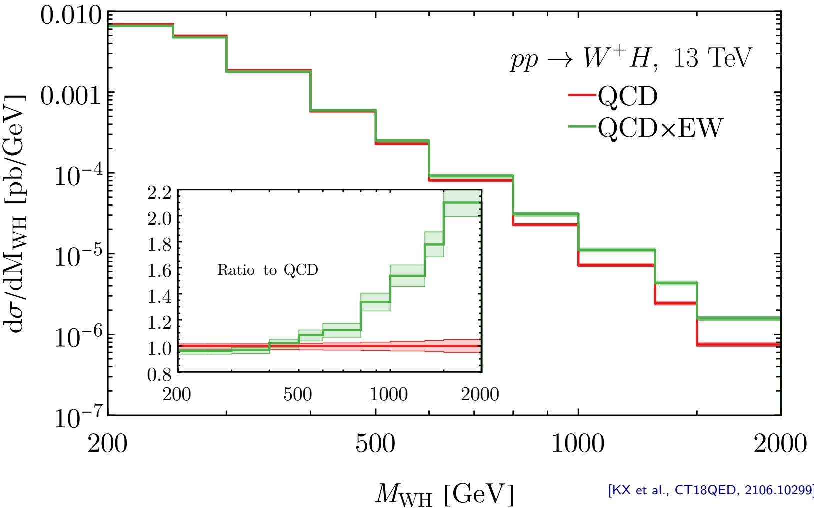
$$m_W = 80362 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 9_{\rm PDF}\ \text{MeV},$$
$$m_W = 80350 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 12_{\rm PDF}\ \text{MeV},$$
$$m_W = 80351 \pm 23_{\rm stat} \pm 10_{\rm exp} \pm 17_{\rm theory} \pm 7_{\rm PDF}\ \text{MeV},$$

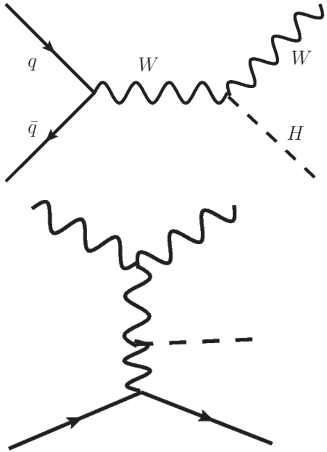
ATLAS, CT10 + 3.8 MeV (MMHT14-CT14)

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5

Electroweak corrections become vita

- At high mass tail, the EW corrections and photon PDF $\gamma(x, \mu^2)$ becomes important

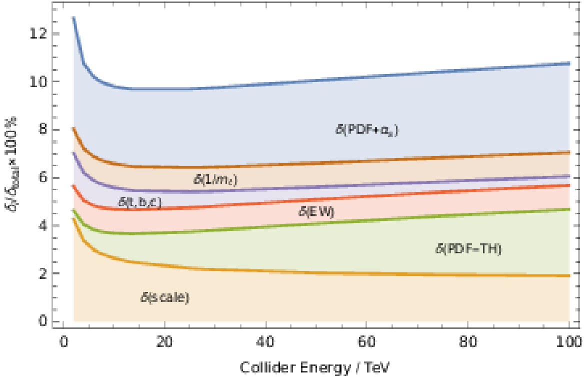


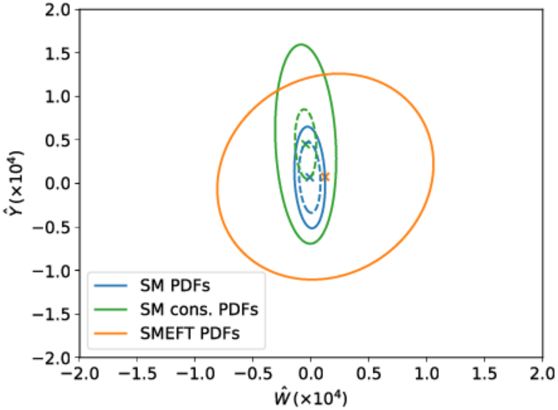


[KX et al., CT18QED, 2106.10299]

PDF impacts on Higgs, BSM, and SMEFT

- PDF uncertainties becomes one of the main theoretical obstacles to explore Higgs and SMEFT as well as other BSM physics



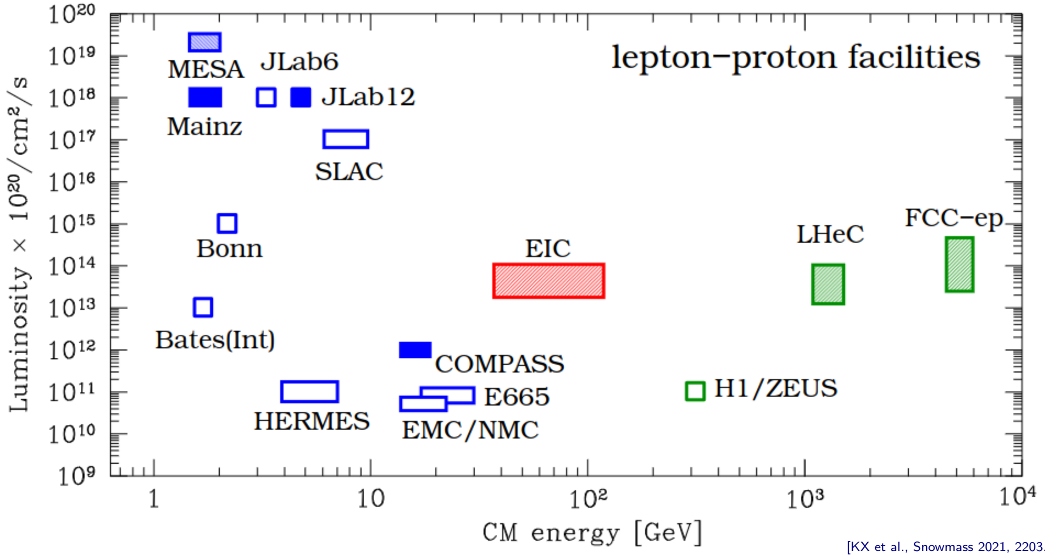


[KX et al., Snowmass 2021, 2203.13923]

[See T. Hobbs' talk tomorrow on SMEFT+PDF joint fit]

Outline

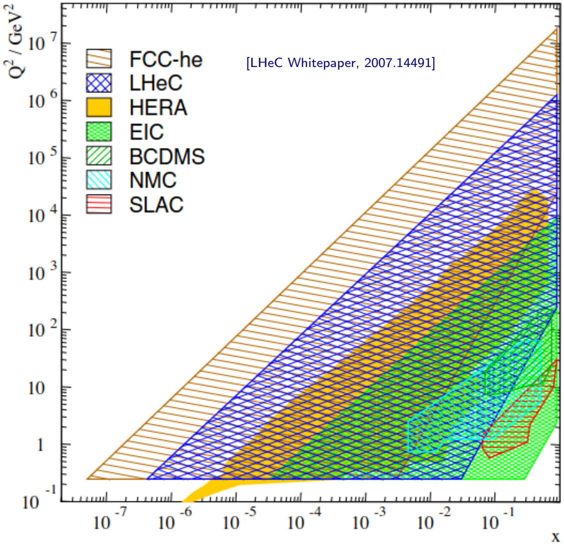
Energy and luminosity reaches for future DIS machines



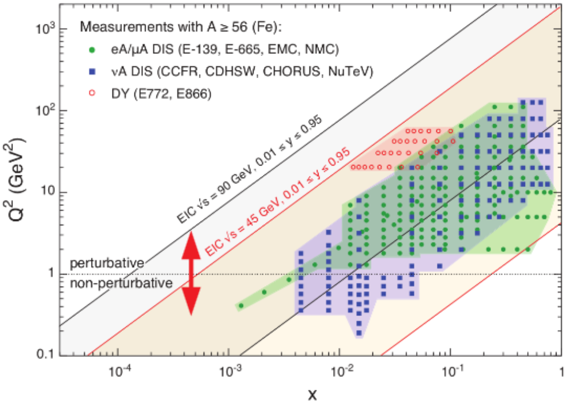
[KX et al., Snowmass 2021, 2203.13199]

Kinematic coverage from future DIS experiments

LHeC and FCC-he probe large Q^2 and small x

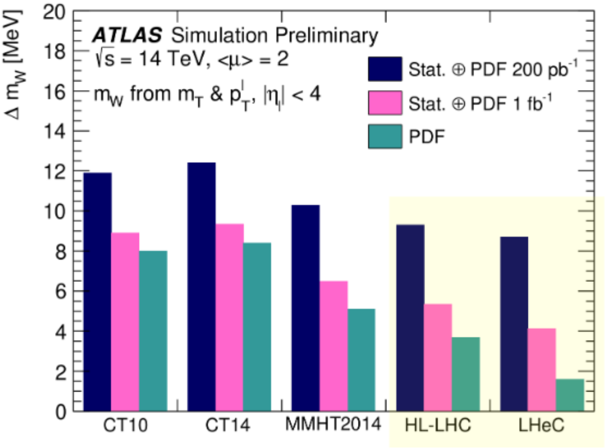


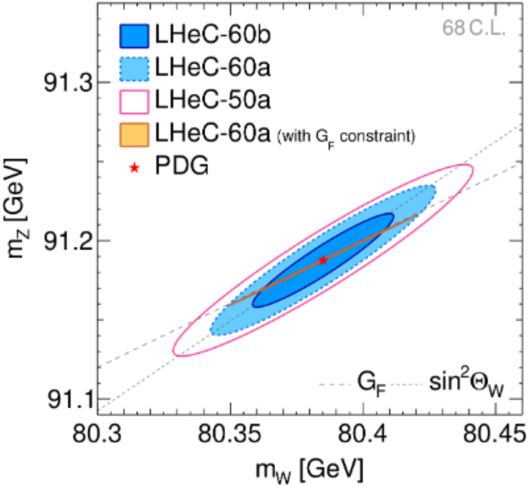
EIC extends the large x and small-Q^2 region



Eur. Phys. J. **A52** (2016) 9, 268.

M_W constraints from the LHeC

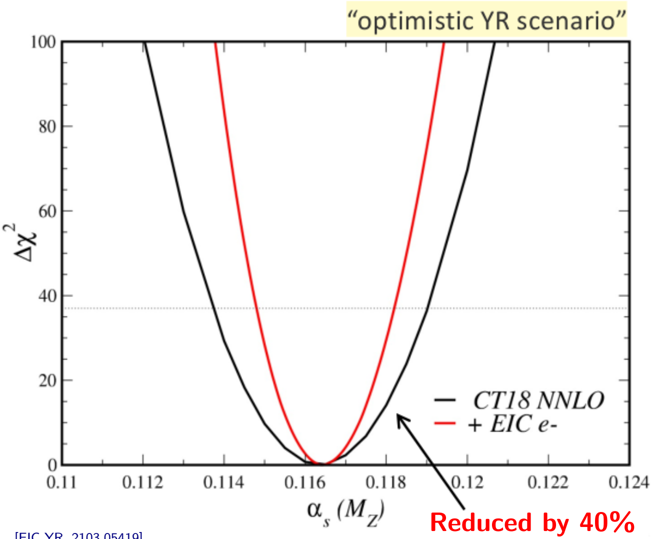




- like the EIC, LHeC could dramatically enhance constraints to M_W: $\delta^{\rm PDF} M_W \lesssim 2$ GeV [LHeC Whitepaper, 2007.14491]

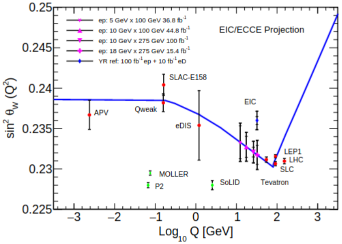
EIC constraints on SM parameters: α_s and $\sin^2\theta_W$

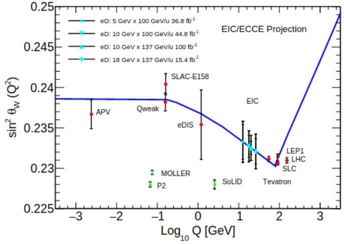
- Precise determination of α_s and $\sin^2\theta_W$. Similar constraints applies to m_Q as well.



[EIC YR, 2103.05419]

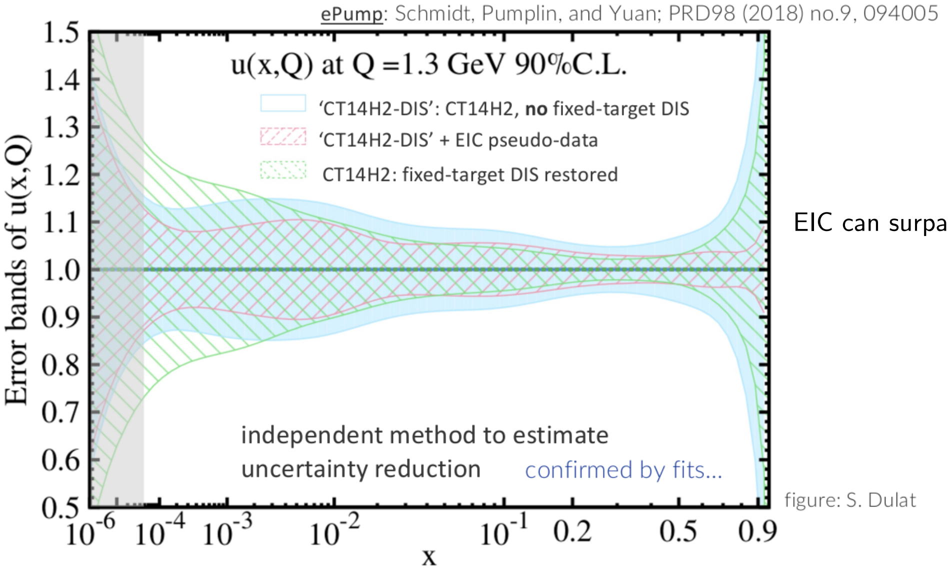
[KX et al., Snowmass 2021, 2203.13199]





[See R. Boughezal et al. for many works on SMEFT at EIC]

EIC constraint on PDFs at both high and small x

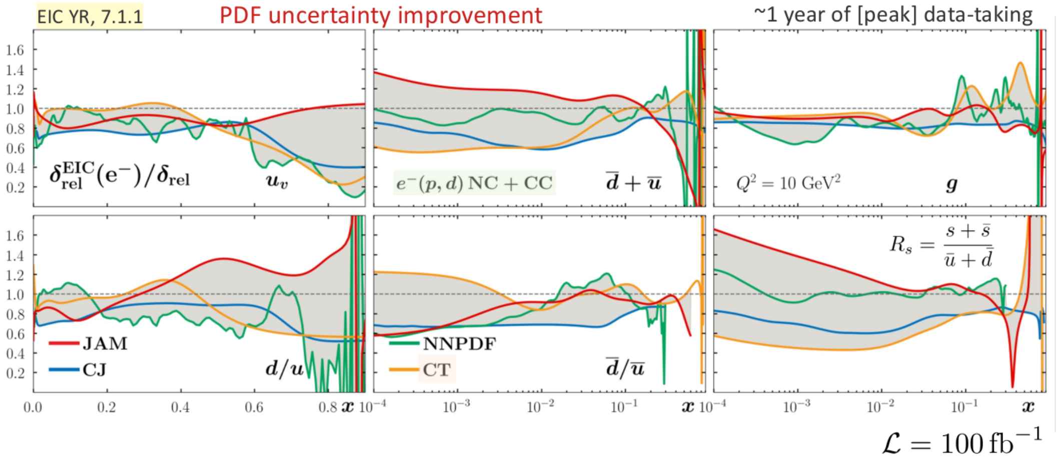


EIC can surpass fixed-target DIS

figure: S. Dulat

Reduction to PDF uncertainties

Impact from simulated pseudodata, estimated by various methods and groups



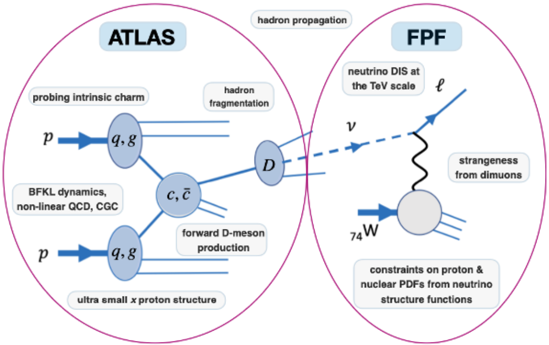
- Broad impacts: high-x u,d-PDFs, gluon and sea quarks at low-x.
- Systematics limitations: to be investigated

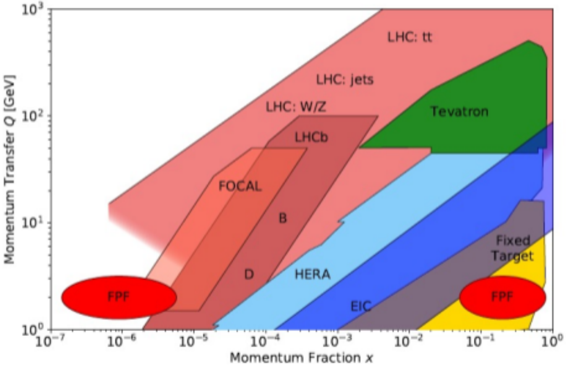
Many other helps from the EIC

- Heavy Flavors
- Small-x
- TMD PDFs and GPDs
- Nuclear effects

Please refer to the EIC Yellow Report [2103.05419] and Snowmass whiterpaper [KX et al., 2203.13199] for details.

Forward Physics Facility

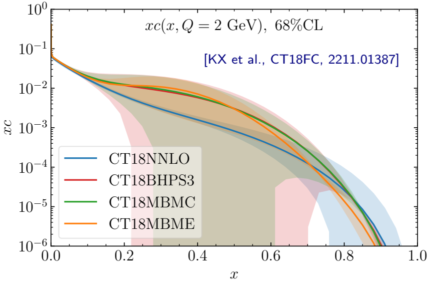


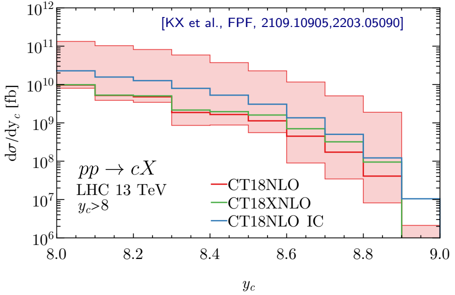


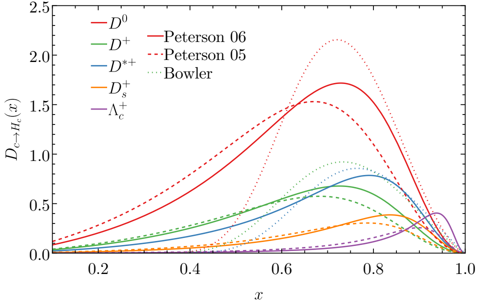
The neutrino measurement in the ongoing FASER and future FPF probe both large and small Bjoken x.

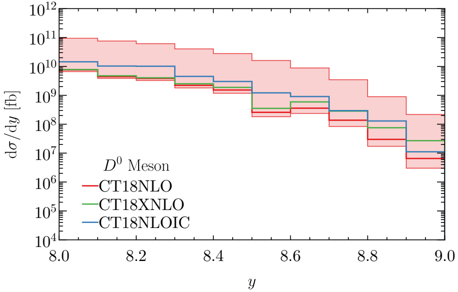
[KX et al., FPF, 2203.05090]

The charm production at the FPF

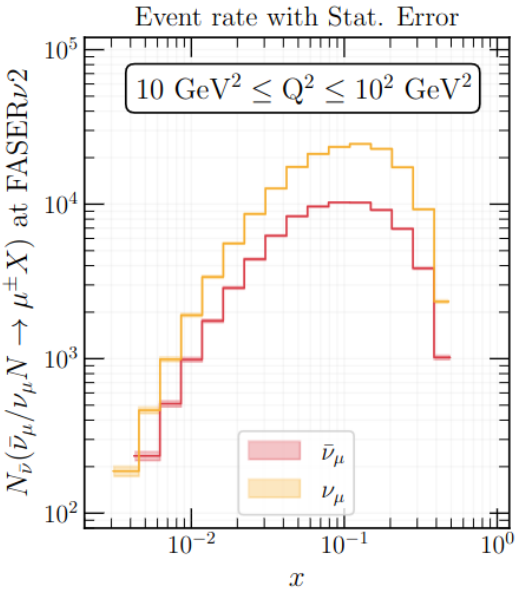


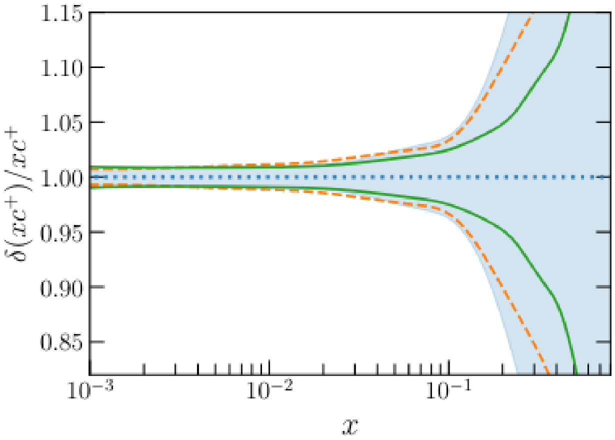






LHC (FPF) as a neutrino-ion collider

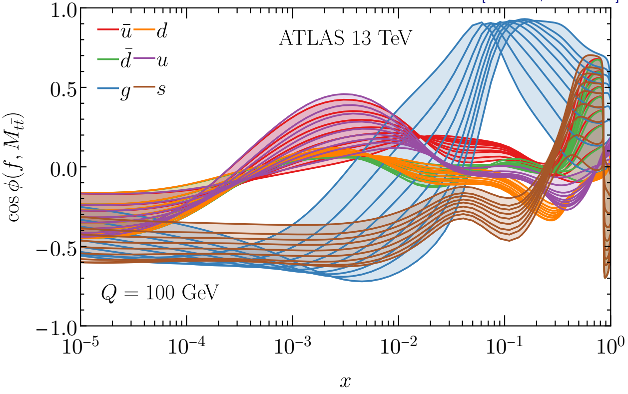




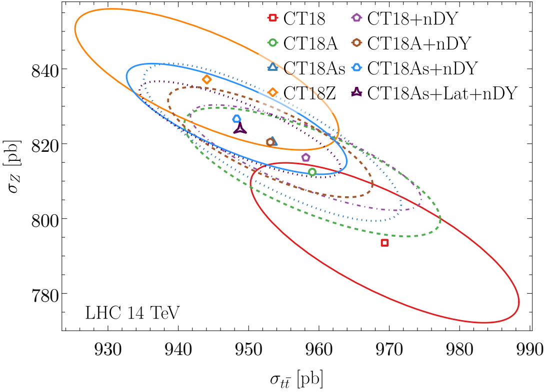
Neutrino cross section measurement constrains the charm and gluon PDFs [NNPDF, 2309.09581]

Connection to the top pair production

[KX et al., 2307.11153]



[KX et al., 2305.10733]



- Top quark pair cross section is largely correlated with gluon PDF at large $x(\sim M_{t\bar{t}}/\sqrt{s})$ at LHC
- Inputs from future colliders for the large-x gluon can both shift central value and shrink uncertainty.
- More extensive studies are needed

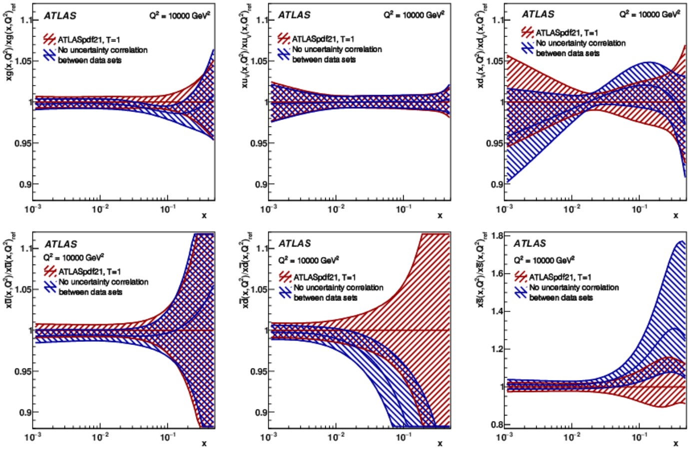
Summary

- Global analyses of parton distributions demonstrate great success of QCD and on understanding internal structures of proton, and phenomenologically become more and more prominent for electroweak precision test and searches for new physics at the (HL-)LHC EIC. LHeC, FPF and other future machines.
- EIC as well as other future DIS machines (LHeC, FCC-eh) help constrain precision physics
- FPFs provide excellent probes to both for large-x and small-x PDFs, which helps but is not limited to the top-quark physics
- **Sorry for missing many many related studies!**

Thanks for your attention!

ATLAS PDFs

- ATLAS releases the most recent 2021 PDFs based on a NNLO analysis of HERA combined data and a variety of ATLAS data from 7,8, 13 TeV with several new features explored



- Consistent pull from 7, 8 TeV inclusive W, Z data on strangeness
- W/Z+jet data stabilize sea quarks at large x closed to preferences from fixed-target experiments
- impact of correlation of experimental uncertainties across different data sets, and of scale variations are investigated

[ATLASpdf21, 2112.11266]

Towards aN3LO PDFs

- MSHT20aN3LO PDFs [2207.04739]
- NNPDF preliminary PDFs [Giacomo Magni, DIS2023]
- Ongoing aN3LO PDF benchmarking