CTEQ-TEA Precision PDFs for the EIC Physics

Bridge the LHC and EIC

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Physics Opportunities at an Electron-Ion Collider XI
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On behalf of the CTEQ-TEA (Tung Et Al.) Collaboration

Outline

CT18 $\to$ CT25?

CT18(A/X/Z) PDFs [Hou, KX+, PRD'21]

- Inclusion of new LHC data: Drell-Yan [Sitiwaldi, KX+, PRD'23], top-quark pair [Ablat, KX+, PRD'24], jets [Ablat, KX+, PRD'25]
- Experimental tensions: Representative samplings [Courtoy, KX+, PRD'23], L_2 sensitivity [Jing, KX+, PRD'23]
- Advanced polynomial and AI/ML: Bézier curves [Kotz+, PRD'24], latent representation [Hobbs+, PRD'25], `XAL4PDF` [Hobbs+, JHEP'25]
- Non-perturbative charm: CT18FC [Guzzi, KX+, PLB'23]
- QED photon PDF: proton [KX+, PRD'22], neutron [KX+, JHEP'24]
- Neutrino-nucleus scattering: GM NNLO [Gao+, PRD'22] and ZM N3LO [KX+, PRD'24], trident [KX+, PRD'24] and di-muon [incoming]
- Nuclear corrections: deuterium [Accardi, Jing+, EPJC'21]
- Lattice synergy: (dis)connected sea [Hou+, PRD'22], strangeness asymmetry [Hou+, PRD'23], gluon [Ablat, KX+, 2502.10630]

Towards CT25 and a mid/long-term future

- Approximate N3LO and theory uncertainty
- Tolerance quantification
- α_s update from PDF fits
- $\cdots$

A lot of new LHC precision data: Drell-Yan [Sitiwaldi, KX+, PRD'23], $t\bar{t}$ [Ablat, KX+, PRD'24]

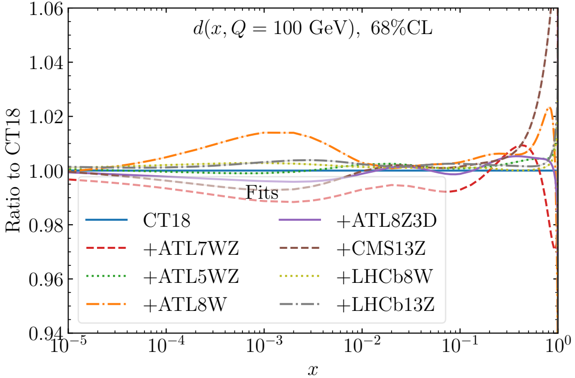
ID	Experiment	N_{pt}	χ^2/N_{pt}					
			CT18	CT18A	CT18As	ATLASpdf21	MSHT20	NNPDF4.0
215	ATLAS 5.02 TeV W, Z	27	0.81	0.71	0.71	–	–	–
211	ATLAS 8 TeV W	22	2.45	2.63	2.51	1.41	2.61	[3.50]
214	ATLAS 8 TeV Z 3D†	188	1.12	1.14	1.18	1.13(184)	1.45(59)	1.22(60)
212	CMS 13 TeV Z	12	2.38	2.03	2.71	–	–	–
216	LHCb 8 TeV W	14	1.34	1.36	1.43	–	–	–
213	LHCb 13 TeV Z	16	1.10	0.98	0.83	–	–	–
248	ATLAS 7 TeV W, Z	34	2.52	2.50	2.30	1.24(55)	1.91(61)	1.67(61)
Total 3994/3953/3959 points			1.20	1.20	1.19	–	–	–

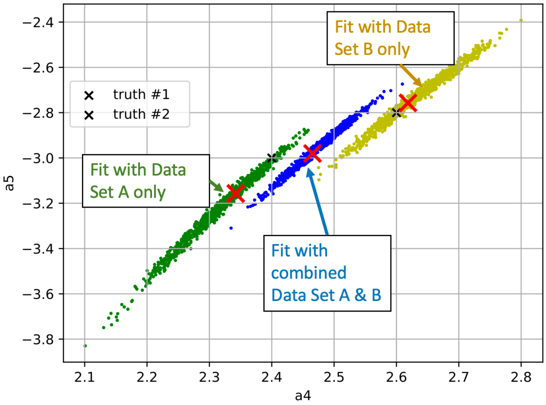
Scale				$H_T/2$	$H_T/2$	$H_T/4$	$H_T/4$
ID#	**Data set**	N_{pt}	CT18	nTT1	nTT2	nTT1	nTT2
573	CMS 8 TeV 2D norm. (p_T, y)	16	1.2	1.2	1.2	1.1	1.1
580	ATLAS 8 TeV $p_T^t, m_{t\bar{t}}$ comb.	15	0.6	0.7	0.7	0.7	0.7
521	ATLAS 13 TeV all-hadronic $y_{t\bar{t}}$	12	-	1.0	1.0	1.1	1.1
528	CMS 13 TeV dilepton $y_{t\bar{t}}$	10	-	0.8	0.8	0.5	0.7
532	ATLAS 13 TeV l+j $y_{t\bar{t}}$	10	-	0.7	-	0.8	-
587	ATLAS 13 TeV l+j comb.	34	-	-	0.7	-	1.1
581	CMS 13 TeV l+j $m_{t\bar{t}}$	15	-	1.1	1.1	1.6	1.7

New LHC data (continued): inclusive jets and di-jet [Ablat, KX+, PRD'25]

ID	Expt.	$\sqrt{s}$	$\mathscr{L}_{\text{int}}$	N_{pt}	R	Observable	$\mu_R,\ \mu_F$	Decorrelation
				New inclusive jet data				
553	ATLAS	8	20.3	171	0.4,0.6	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}\lvert y\rvert}$	$p_T^j, \hat{H}_T$	Yes
554	ATLAS	13	3.2	177	0.4	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}\lvert y\rvert}$	$p_T^j, \hat{H}_T$	Yes
555	CMS	13	33.5	78	0.4,0.7	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T\mathrm{d}\lvert y\rvert}$	$p_T^j, \hat{H}_T$	No
				New dijet data				
546	ATLAS	7	4.5	90	0.4,0.6	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{12}\mathrm{d}y^*}$	m_{12}	No
547	CMS	7	5.0	54	0.7	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{12}\mathrm{d}\lvert y_{\max}\rvert}$	m_{12}	No
548	CMS	8	19.7	122	0.7	$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{T,\text{avg}}\mathrm{d}y^*\mathrm{d}y^b}$	$m_{12}, p_{T,1}\, e^{0.3y*}$	No
549	ATLAS	13	3.2	136	0.4	$\frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{12}\mathrm{d}y^*}$	m_{12}	No

More data, more precise PDFs?





Not realy!

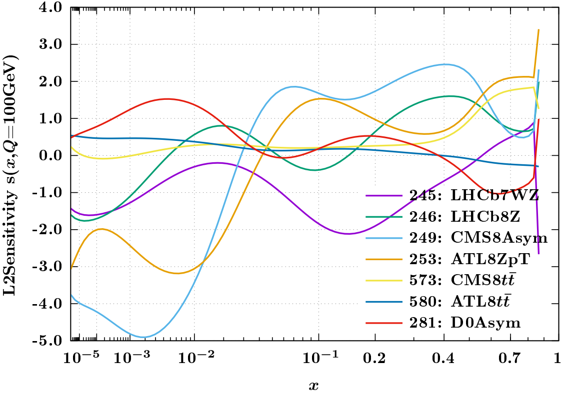
- Different data might be not consistent with each other [CT18, Hou, KX+, PRD'21]
- The in tension data pull the PDFs to different directions [Sitiwaldi, KX+, PRD'23]
- As a balance, the PDF uncertainty might not decrease as much as what we expect [Mohan+, 2406.01664].

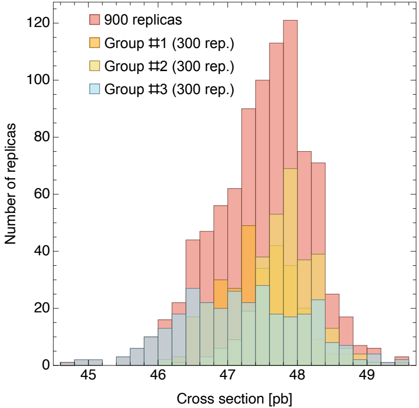
How to quantify the tension or interplay?

Representative sampling [Courtoy, KX+, PRD'23]

$$\Delta_E = \underbrace{\mathrm{Corr}_p[R, G]}_{\text{confounding correlation}} \cdot \underbrace{\sqrt{\frac{N_p}{Ns} - 1}}_{\text{measure discrepancy}} \cdot \underbrace{\mathrm{Var}[G]}_{\text{population variation}}$$

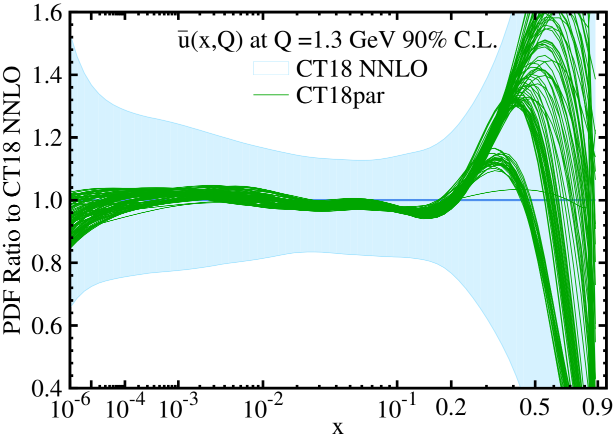
L_2 sensitivity [Jing, KX+, PRD'23]

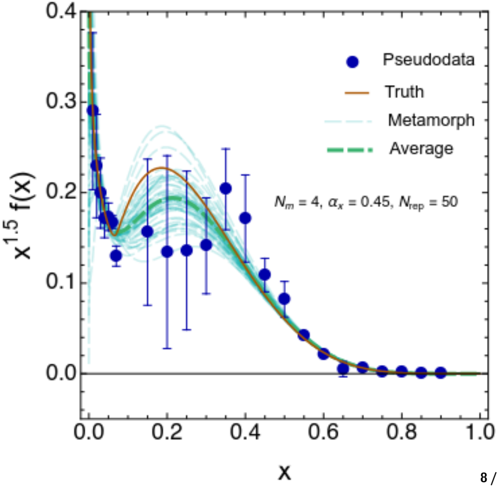




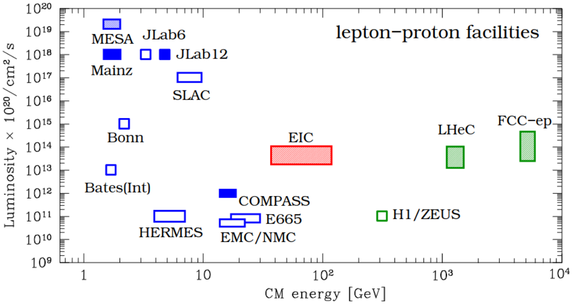
PDF parametrization: flexibility

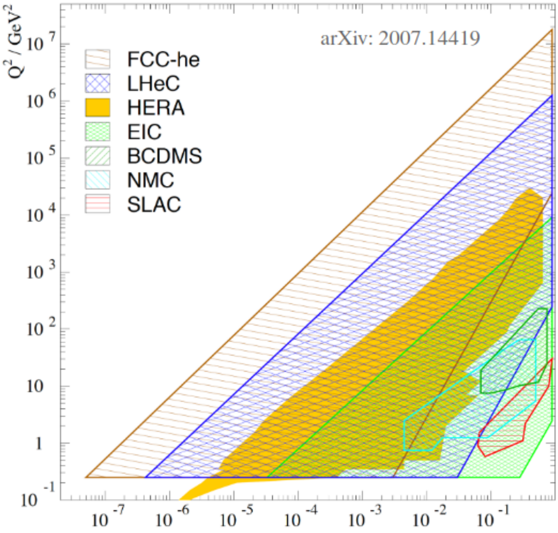
- $f_q = a_0 x^{a_1}(1-x)^{a_2} P(x)$, where $P(x)$ is polynomials
- We have tried out $\mathcal{O}(100)$ parameterizations for the CT18 PDFs [CT18, Hou, KX+, PRD'21]
- More flexible parameterization: Bézier curves [Kotz+, PRD'24] and AI/ML [Hobbs+]





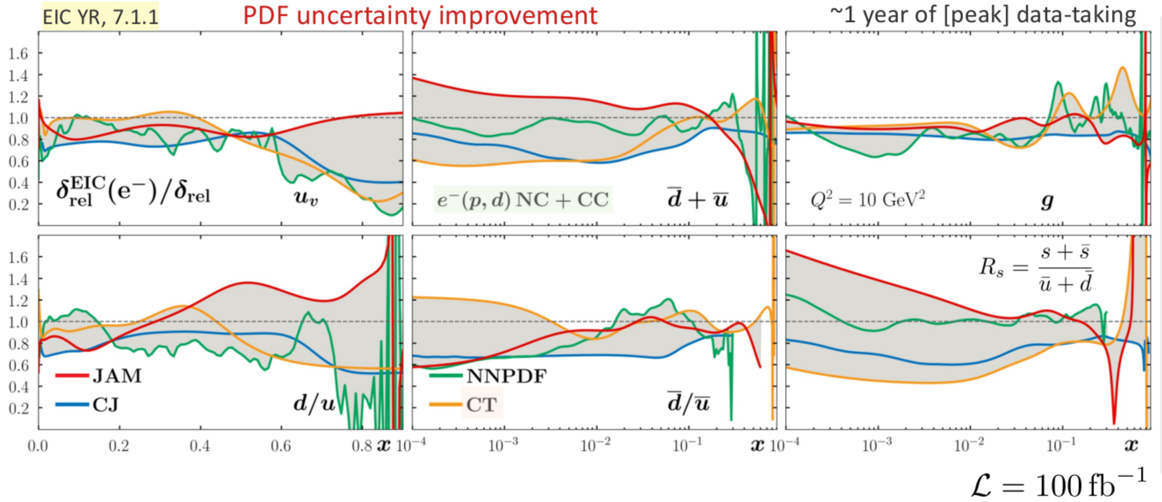
EIC precision QCD, complementary to LHC





- A high-luminosity DIS collider: $\mathscr{O}(10^2 \sim 10^3)$ cf. HERA [EIC YR]
- EIC will probe complementary kinematical space to LHC in (x, Q^2)
- Wide battery of "clean" precision QCD measurements

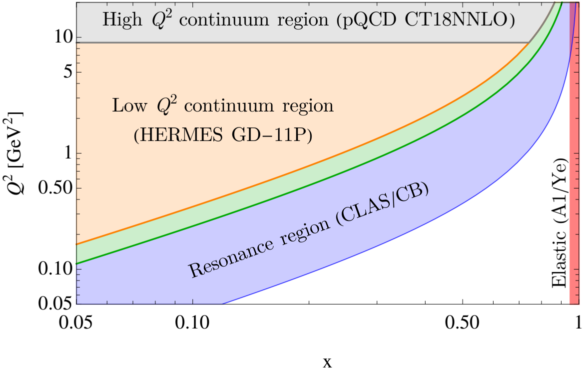
EIC: sensitive to large-x PDFs

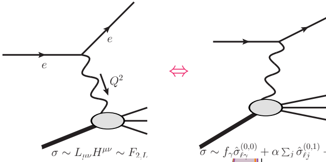


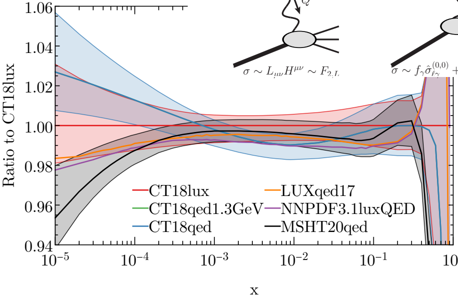
- 1-yr inclusive EIC dataset drives steep reductions in PDF uncertainties [EIC YR]
- Sensitive to large-x PDF, where LHC data is not precise enough

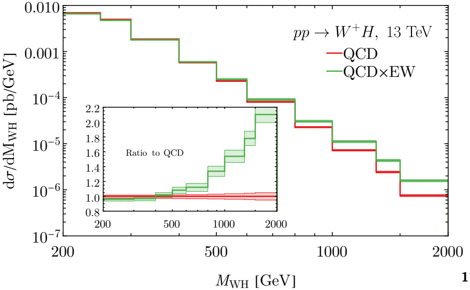
Precision photon: LUXqed formalism [Manohar+, PRL'16, JHEP'17]

$$x\gamma(x,\mu^2) \sim \mathscr{F}[F_2(x,Q^2),F_L(x,Q^2)] + \text{matching.}$$





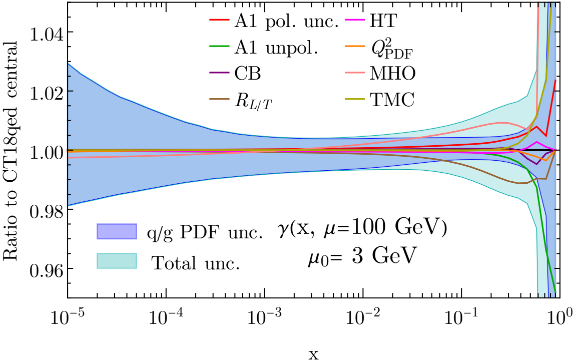




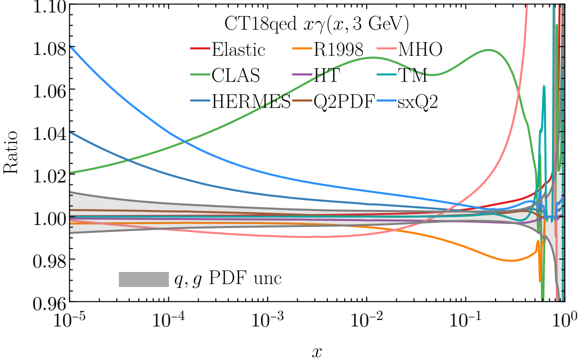
- QED photon PDF is vital for LHC, due to both the EW corrections and photon initiated processes [KX+, PRD'22]
- Photon PDF is very precised determined, up to $\mathcal{O}(1\%)$

Non-perturbative uncertainties

Proton [KX+, PRD'22]



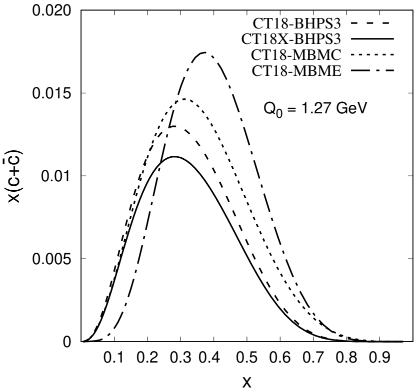
Neutron [KX+, JHEP'24]

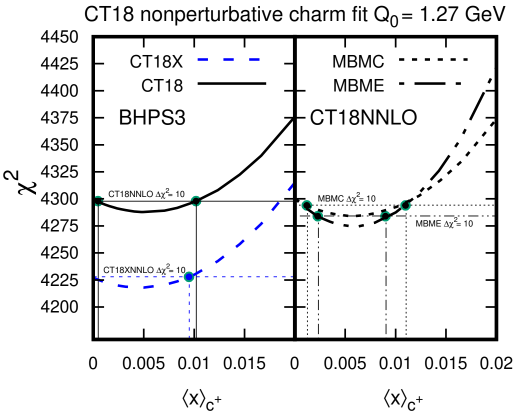


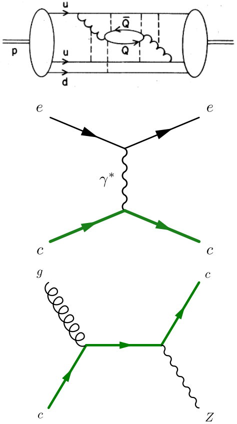
- Remaining uncertainties at large x: Higher-twist, target-mass corrections, etc [KX+, PRD'22]
- The low-Q^2 structure functions: CB/CLAS, HERMES, $R = \sigma_L/\sigma_T$
- The neutron's photon PDF suffers for a large uncertainty, due to the imprecise of SF extraction, and nuclear corrections [KX+, JHEP'24]
- Can be generated to the heavy-nuclei's photon.

Intrinsic Charm (IC) puzzle

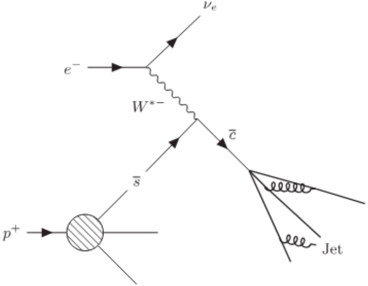
- The proton's intrinsic charm (valence-like) component: BHPS model $|uudc\bar{c}\rangle$ [Brodsky+, PLB'80, PRD'81]
- Both EMC F_2^c [CT14IC, Hou, KX+, JHEP'18] and LHCb $Z+c$ [PRL'22] data prefer an IC component
- We analyzed various uncertainties and IC models $\langle x\rangle_{\rm FC} = (4.8^{+6.3}_{-4.8})\cdot 10^{-3}$, while globally consistent with a zero IC [CT18FC, Hobbs, KX+, PLB'23], contradictory to NNPDF [Nature'22] (Unc. [Nadolsky, KX+, PRD'23])
- Precision measurement of F_2^c at EIC will help

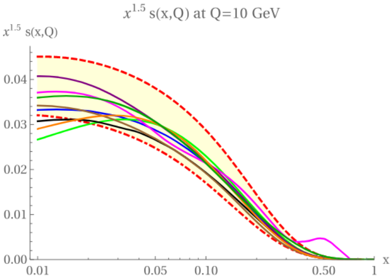


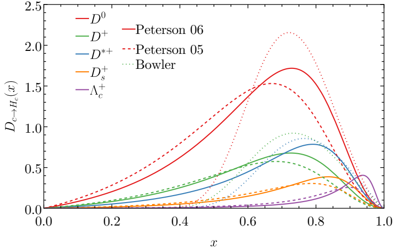


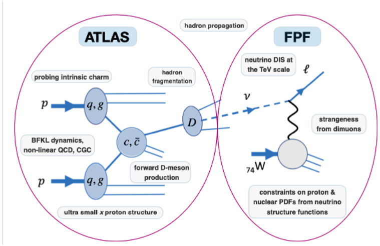


Charged-current charm production and fragmentation



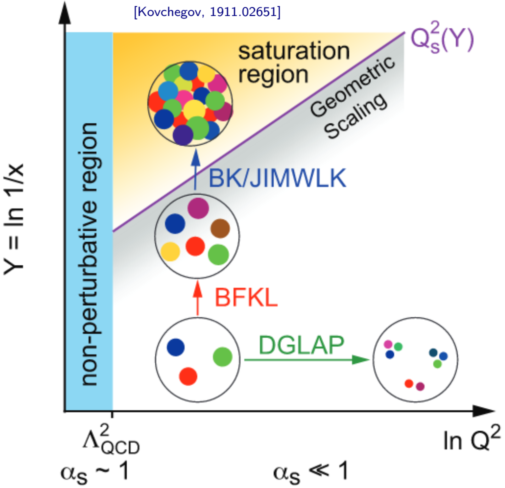






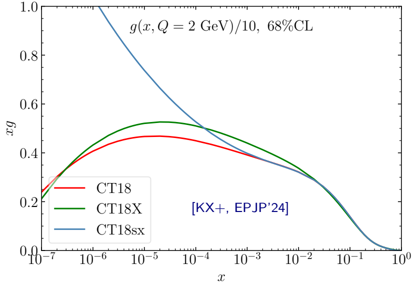
- Besides the neutral-current F_2^c (probe IC), the charge-current $F_2^{c,W}$ can probe the strangeness [Hobbs+, PRD'21]
- HERA data is very imprecise, which awaits to be improved by the EIC
- Also useful for fragmentation function, synergy with many heavy-flavor measurement, such as LHCb [KX+, SciPost'22]
- Important for the neutrino source determination at the Forward Physics Facility [KX+, Phys. Rept.'22, JPG'23]

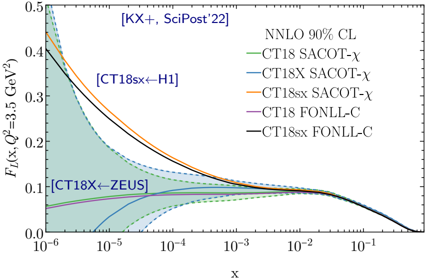
PDFs at small x [also see talks of Li, Kovchegov, Gwenlan]



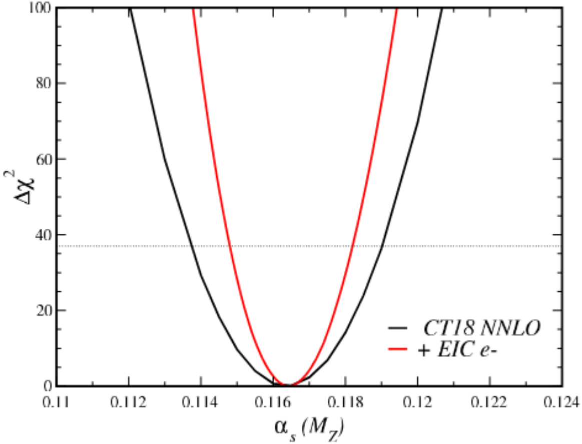
- CT18X takes a saturation model [Hou, KX+, PRD'21]
- CT18sx resum the $\ln(1/x)$ with BFKL [KX+, EPJP'24]

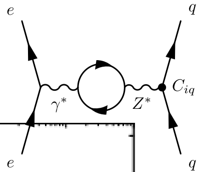
Resolve the F_L puzzle between H1 and ZEUS

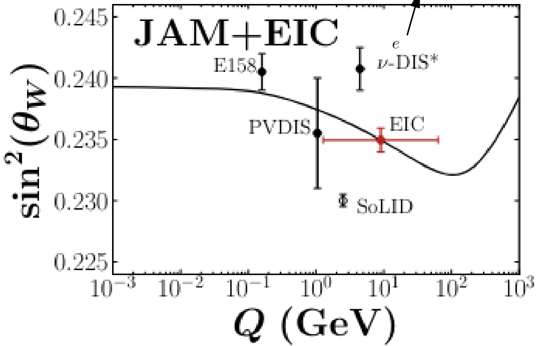




Precision measurements: α_s and $\sin^2\theta_W$ [Also see Gwenlan's talk]





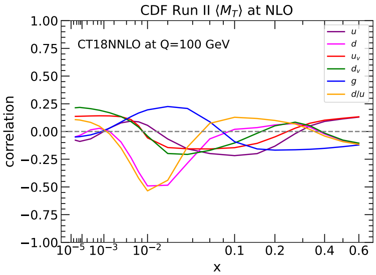


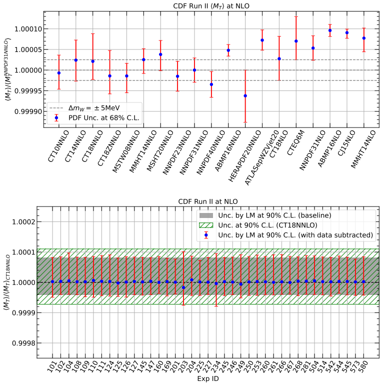
- α_s from event shapes and N-jettiness
- An optimistic 40% precision improvement [EIC YR]
- Similarly for the heavy-quark mass m_Q

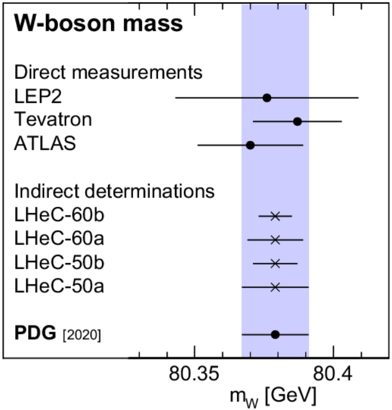
- Weak neutral-current measurements can probe the C_{iq} coupling, and mixing angle [EIC YR]

$$A^e_{PV} = \frac{\mathrm{d}\sigma_L - \mathrm{d}\sigma_R}{\mathrm{d}\sigma_L + \mathrm{d}\sigma_R} \sim C_{iq} \sim \sin^2\theta_W(Q^2).$$

W-boson mass measurement

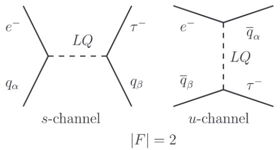


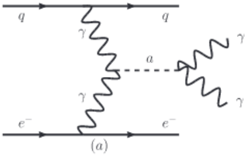




- PDF uncertainty is not enough to explain the CDF anomaly [KX+, Chin. Phys. C'22]
- $\langle m_T \rangle$ at CDF is mostly sensitive to the $d(\bar{d})$ at $x \sim 10^{-2}$, largely constrained by the DIS and Drell-Yan data on deuteron target, the Tevatron lepton charge asymmetry data
- TMD non-perturbative parameters and N3LL resummation effect is explored in [Isaacson, Fu, Yuan, PRD'24]
- Future EIC and LHeC measurement can help improve the M_W measurement [Britzger, EPJC'20]

New physics [Also see Hurley's talk]

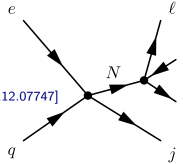


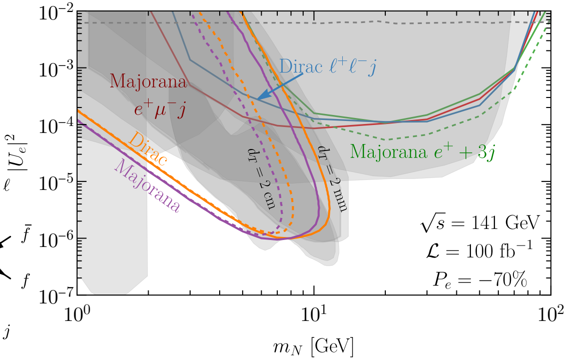


Heavy neutral leptons [KX+, JHEP'23]

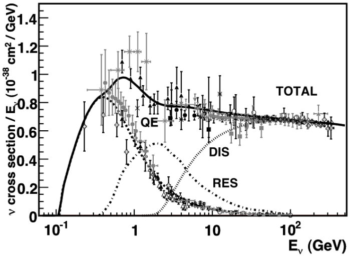
- The displaced vertex search probe small mass and small coupling
- The prompt search probe the large mass and large coupling
- Comparable to the LHC search

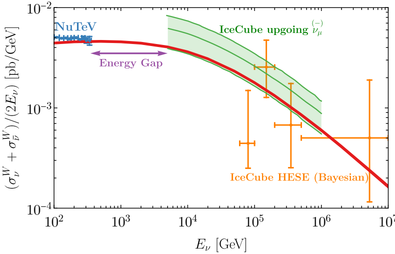
- Charged lepton flavor violation [2102.06176]
- Leptoquark [1006.5063]
- Standard Model Effective filed theory [2107.02134, 2204.07557]
- Axion-like particles [2112.02477, 2310.08827]
- Dark Photon [2203.01510]
- Anomalous $Zb\bar{b}$ coupling [2107.02134, 2112.07747]
- $\cdots$ [EIC YR, Snowmass Whitepaper]

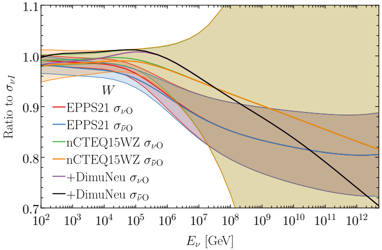




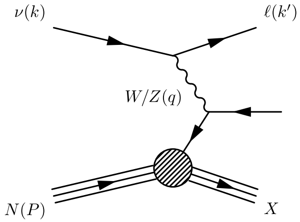
Neutrino scattering



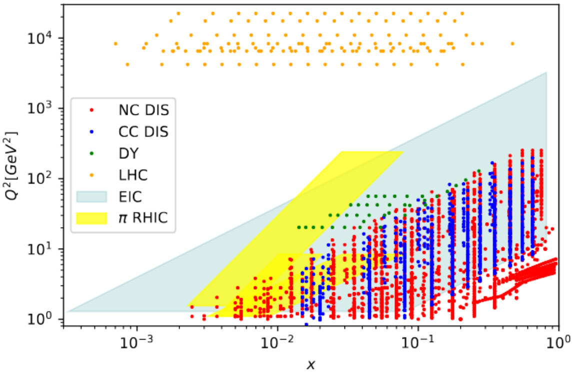


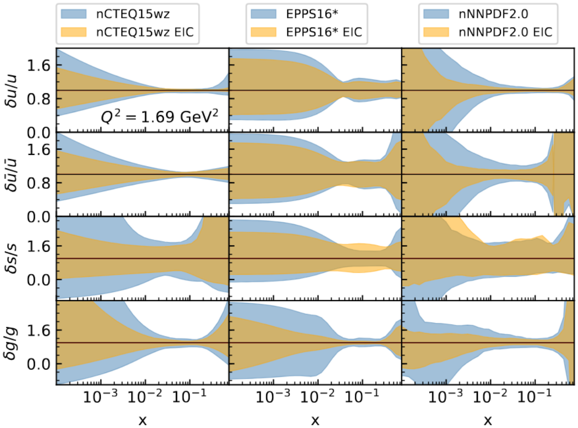


- High-energy neutrino scattering is mainly through Deep inelastic scattering
- We know DIS very well, up to N3LO [KX+, PRD'24]
- However, the biggest uncertainty comes from nuclear corrections
- EIC physics can help, including light C/O and the heavy Pb/W.
- EIC charged-current cross section can also help the cross section measurement at a low E_ν



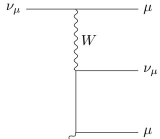
Nuclear PDFs [See Risse's talk]





- EIC Extends the (x, Q^2) range for nuclear scattering data
- EMC effect and (anti-)shadowing
- Improvement of the nuclear PDFs

Photon from heavy nuclei



Heavy nuclei's photon includes the coherent, diffractive (elastic), and inelastic components.

$$\gamma = \gamma_{\rm coh}(Z^2) + \gamma_{\rm diff}(Z) + \gamma_{\rm inel}(Z+N).$$

Coherent photon embraces a Z^2 enhancement

- Neutrino trident [KX+, PRD'24], W-boson production [KX+, JHEP'24]
- Axion-like particles [2310.08827]

Magnetic form factor are normally treated as zero [SuperChic]

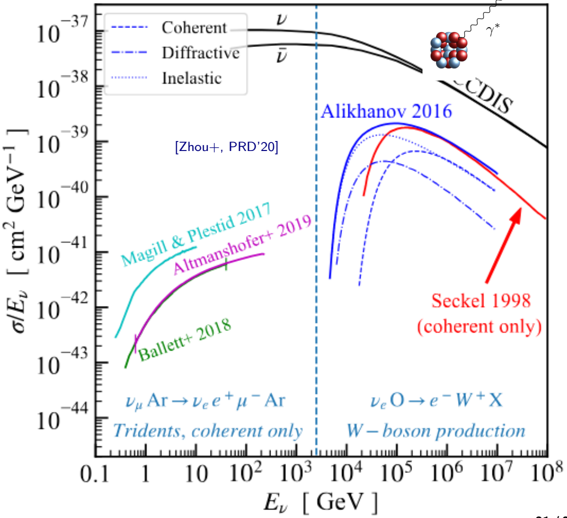
$$F_M(Q^2) = 0,\ F_E(Q^2) = \left[F_p(Q^2) G_E(Q^2)\right]^2.$$

where G_E is the proton dipole or elastic form factor

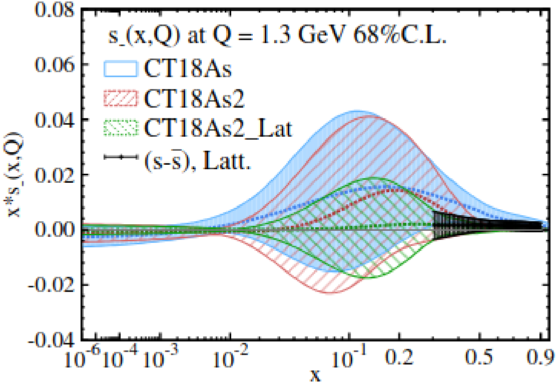
$$F_p(|\vec{q}|) = \int \mathrm{d}^3 r e^{i\vec{q}\cdot\vec{r}} \rho_p(r),$$

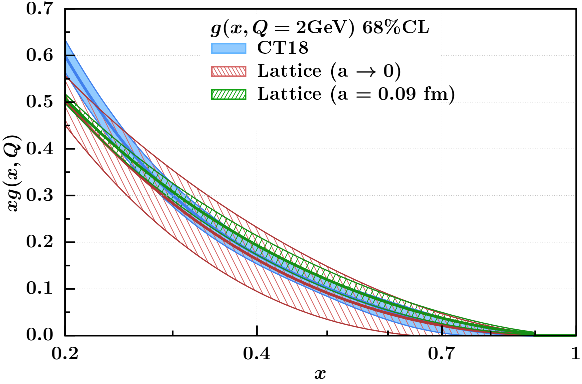
$$\rho_p(r) = \frac{\rho_0}{1+\exp[(r-R)/d]},\ \int \mathrm{d}^3 r \rho_p(r) = Z.$$

- How good is this approximation?
- What is the size of magnetic form factor?
- How to account the nuclear corrections?



Lattice synergy [Also see Lin's talk]



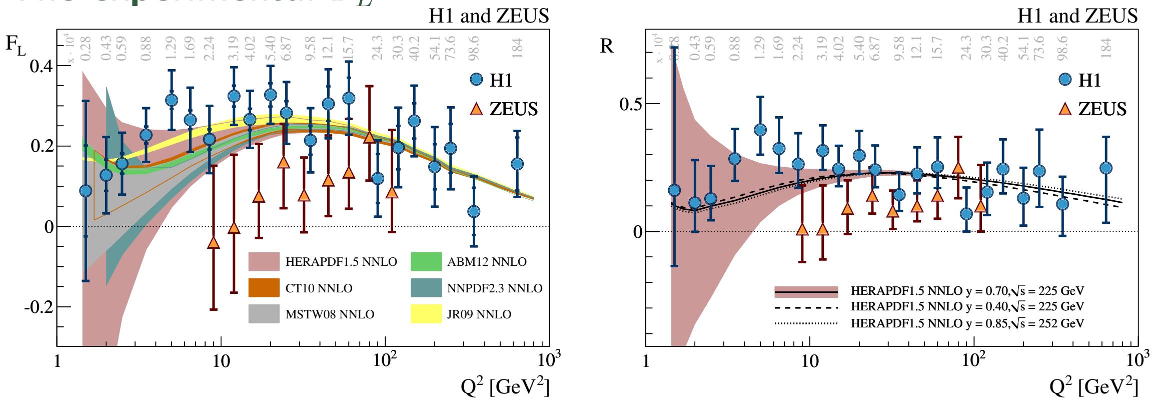


- The lattice strangeness asymmetry is incorporated into the CT18As_Latt global fit [Hou+, PRD'23]
- Recently, we explore the lattice gluon data in the CT18 framework [Ablat, KX+, 2502.10630], and found a similar pull as the latest inclusive jet data from the LHC 13 TeV [Ablat, KX+, PRD'25]
- Many moments $\langle x^n \rangle_{q^\pm}$ are compared between lattice and global fits, which can be included directly in global fitting [Hobbs+, PRD'19].

Summary

- CTEQ-TEA has many updates since the release of the CT18 PDFs
  - We continuously include the latest LHC datasets: Drell-Yan, top-quark pair, inclusive jet.
  - Many tensions show up here and there, due to the precision of the experiemntal data.
  - Many schemes are tried out to resolve or relax the tensions: flexible PDF parametrization, interplay of experimental constraints with L_2 sensitivity, ePump profiling
  - Moving towards to (approximated) N3LO
- The incoming EIC precision QCD data is complementary to LHC, low/intermediate Q^2 and large x
- EIC can reduce the non-perturbative uncertainties of the photon PDF at large x: target-mass corrections, higher twists, and coherent photon.
- EIC can potentially resolve the intrinsic charm puzzle, with the measurement of the F_2^c
- EIC can also help resolve the small-x F_L puzzle between H1 and ZEUS
- Precision measurements: $\alpha_s, \sin^2\theta_W, M_W$
- New Physics searches: Heavy neutral leptons, leptoquarks, etc
- Constrain the high-energy neutrino-nucleus scattering, by reducing the nuclear PDF uncertainties
- Lattice synergies and fragmentation functions

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.