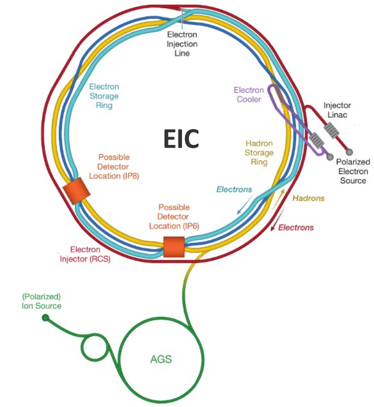
Precision frontiers from the Electron-Ion Collider to the LHC

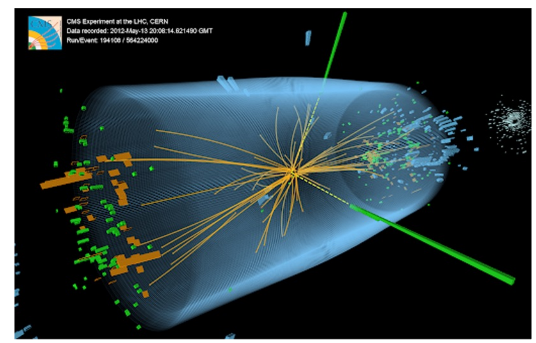
from entanglement to parton densities

Tim Hobbs, Argonne National Lab

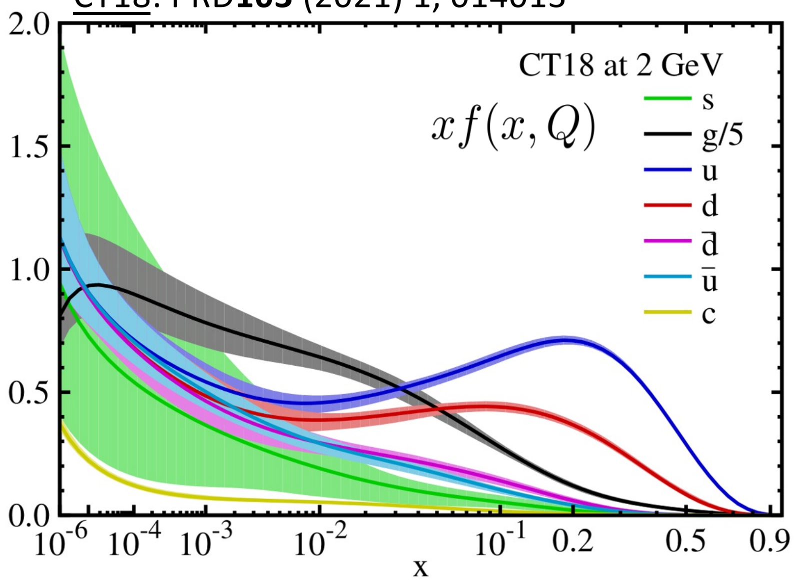
Argonne NATIONAL LABORATORY

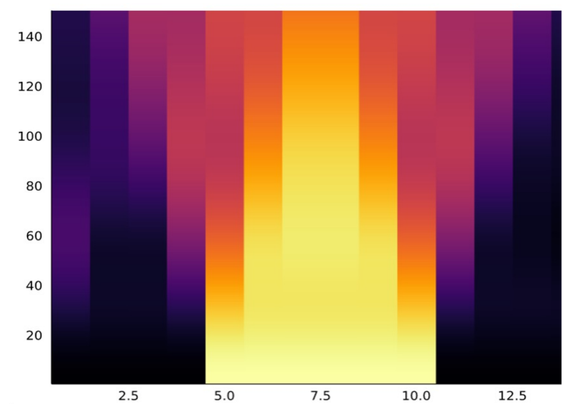
CTEQ





CT18: PRD**103** (2021) 1, 014013

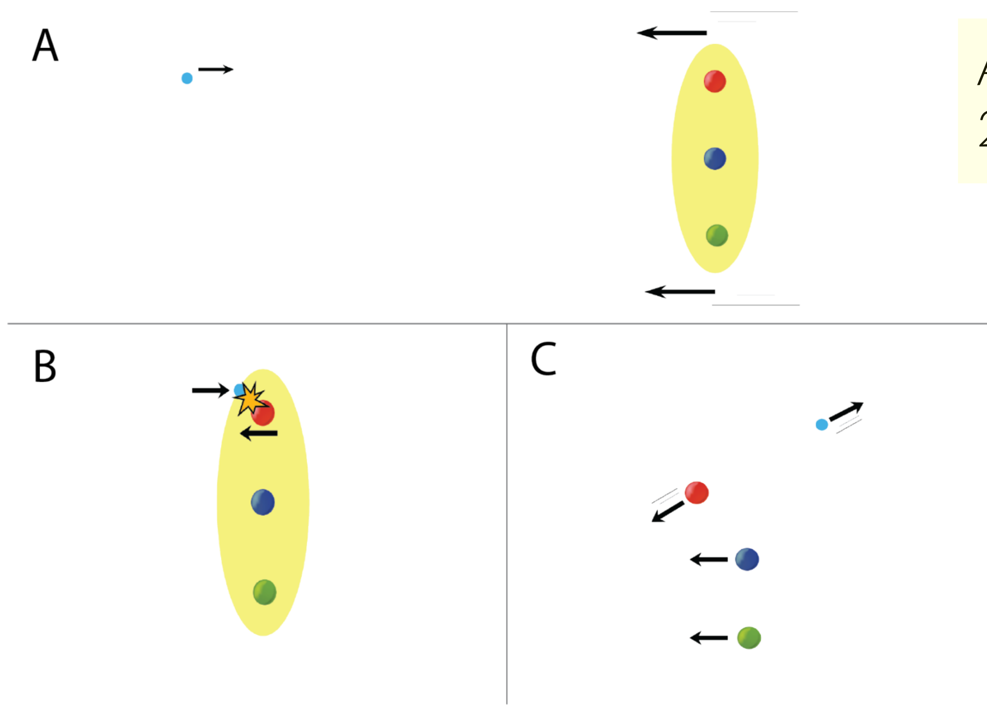




fundamental physics in a quantum-information language

→ broad reimagining of HEP in QIS terms is underway; applies to QCD

- ‘simplest’ scenario – factorization in DIS exploits a **sequential, semi-classical** picture of scattering interaction



Aidala and Rogers, 2108.12319 [quant-ph]

external lepton interactions with one constituent quark (leading twist) at short distance (B); fragments fly away asymptotically (C); only lepton observed

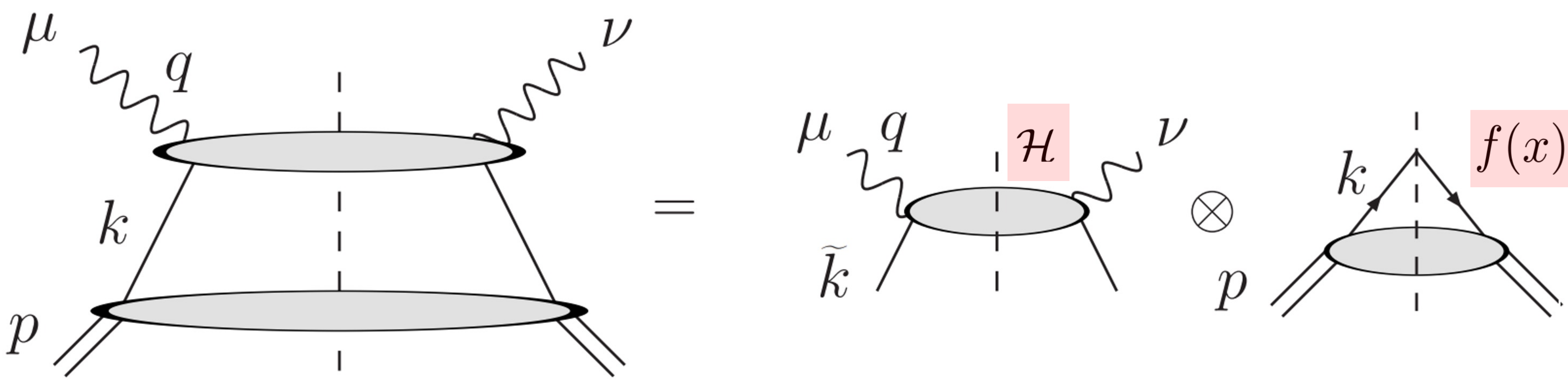
fully inclusive processes: DIS

$$d\sigma \sim W^{\mu\nu}(p,q) = \frac{1}{8\pi}\int d^4z\, e^{-iq\cdot z}\langle p|J^{\dagger\mu}(z)J^{\nu}(0)|p\rangle$$

- previous picture implies scale separation; resolution into subprocesses with classical, probabilistic interpretation

$$W^{\mu\nu}(p,q) = \sum_f \int \frac{dx}{x}\,\mathcal{H}_f^{\mu\nu}(\tilde{k},q)\,\varphi_{f/N}(x,Q^2,m_N^2) + O(\Lambda^2/Q^2)$$

$\rightarrow$ $d\sigma = \mathcal{H} \otimes f(x)$



→ systematic breakdown of coherence; power-suppressed corrections: residual entanglement; complicated in less inclusive processes

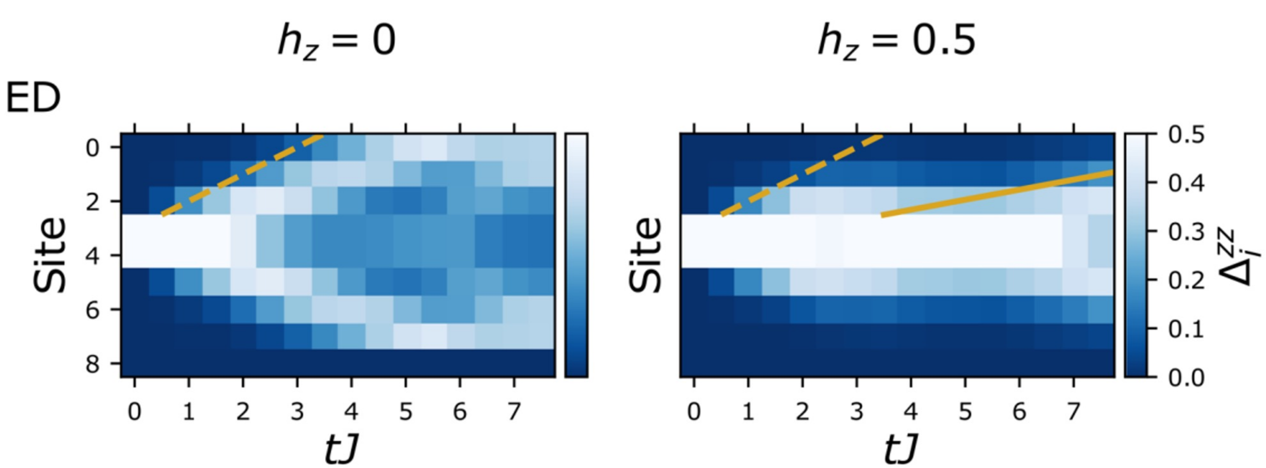
confinement dynamics from (simplified) model Hamiltonians

Vovrosh, Knolle: Nature (2021) 11:11577

- e.g., confinement in 2-fermion systems; Transverse-Field Ising Model:

$$H = -J\left\{\sum_{i=0}^{L-2}\sigma_i^z\sigma_{i+1}^z + h_x\sum_{i=0}^{L-1}\sigma_i^x + h_z\sum_{i=0}^{L-1}\sigma_i^z\right\} \qquad h_x = 0.5$$

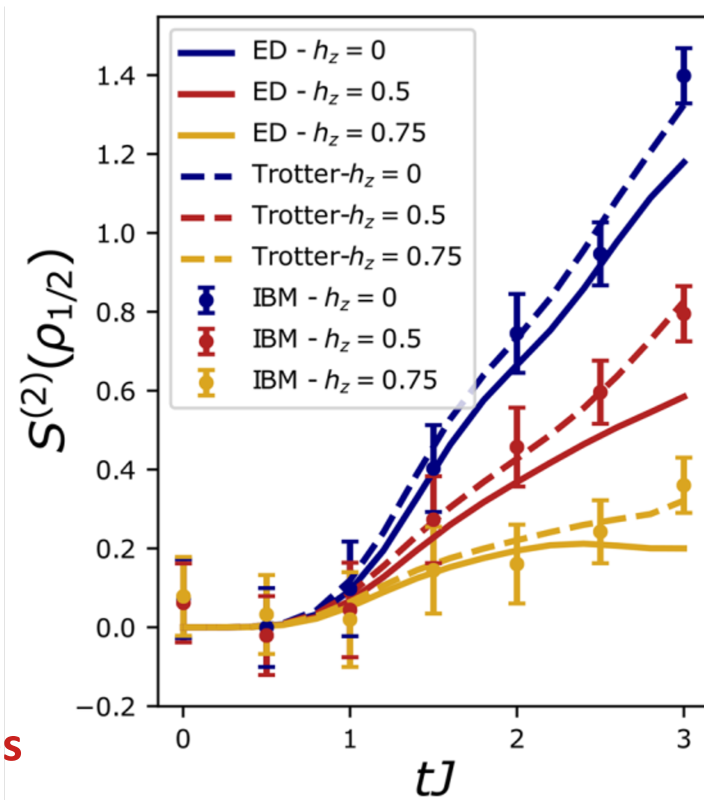
- quark-antiquark → mesons; examine "binding" effects as external potential varied



de-confined

confined

- sample system config → evaluate Réyni entropy



entropy suppression signals confinement at long times

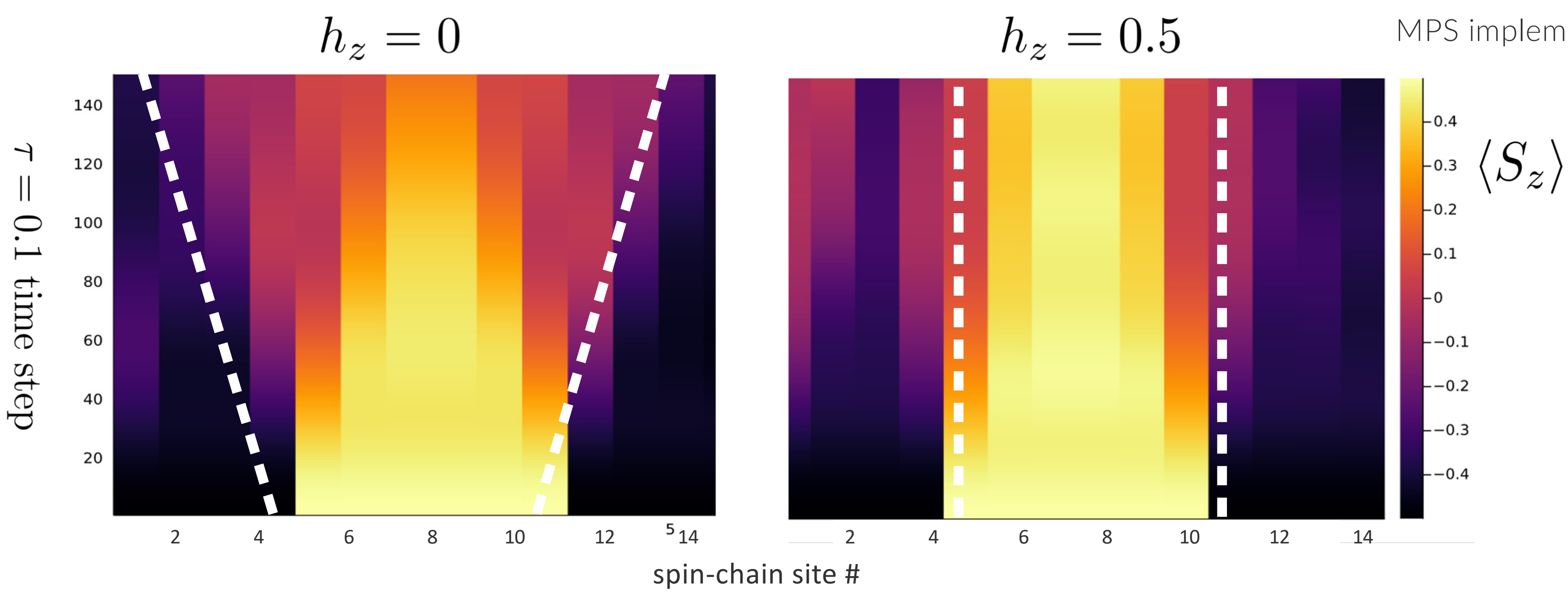
tensor network simulation is informative

- build initial understanding: Matrix Product States (MPS) with Tensor Networks

$$H = -J\left\{\sum_{i=0}^{L-2}\sigma_i^z\sigma_{i+1}^z + h_x\sum_{i=0}^{L-1}\sigma_i^x + h_z\sum_{i=0}^{L-1}\sigma_i^z\right\}$$

Khor, Klich, Kurkcuoglu, TJH, Perdue et al., in prep.

MPS implementation



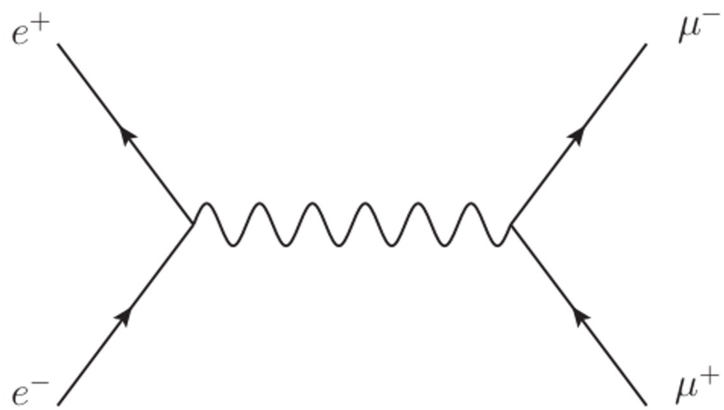
→ explore model space; rapidly compute <u>many</u> metrics (Réyni entropy, arbitrary order, …)

relations among symm breaking, entanglement entropy, confining dynamics in QCD-like systems

entanglement in fundamental 2 → 2 scattering

- many contemporary HEP studies explore utility of MaxEnt to connect properties of specific systems to structure, dynamics

Cervera-Lierta, SciPost Phys. 3, 036 (2017)



$$\mathcal{M}_{RL} \sim \alpha_{RL}|RR\rangle + \beta_{RL}|RL\rangle + \gamma_{RL}|LR\rangle + \delta_{RL}|LL\rangle$$

$$\Delta = 2|\alpha\delta - \beta\gamma| \text{ (concurrence)}$$

→ represent entanglement in 2 → 2 scattering via *concurrence*; examine conditions maximum entanglement place on couplings

→ is there a connection between MaxEnt and fundamental symmetries?

- photon-electron interactions *without* gauge symmetry: MaxEnt → QED

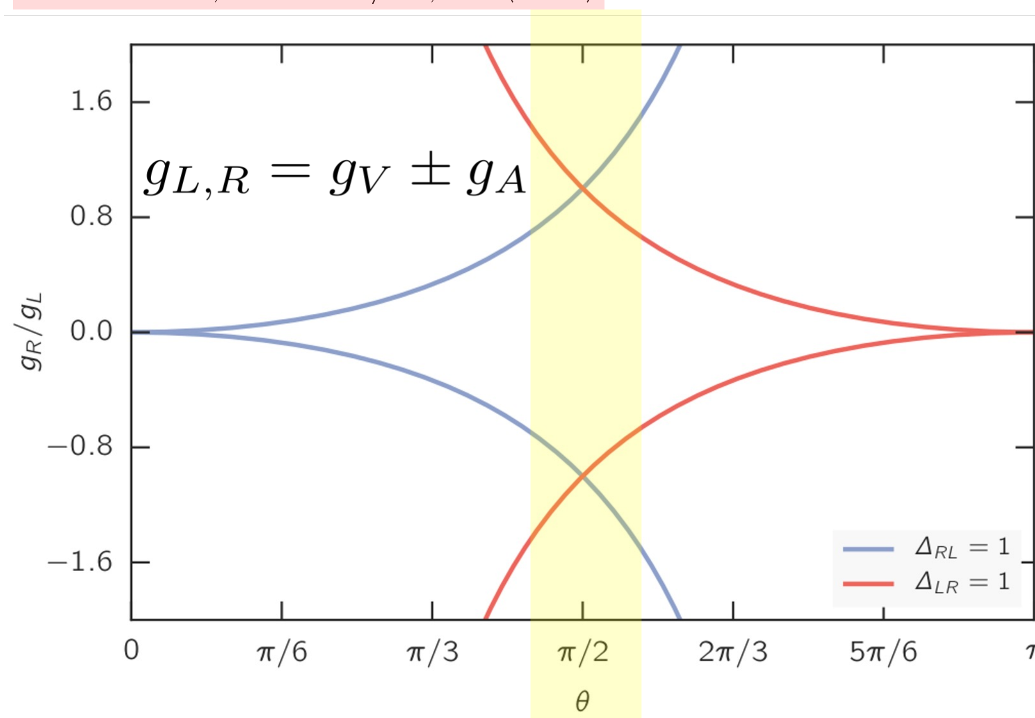
entanglement in fundamental 2 → 2 scattering

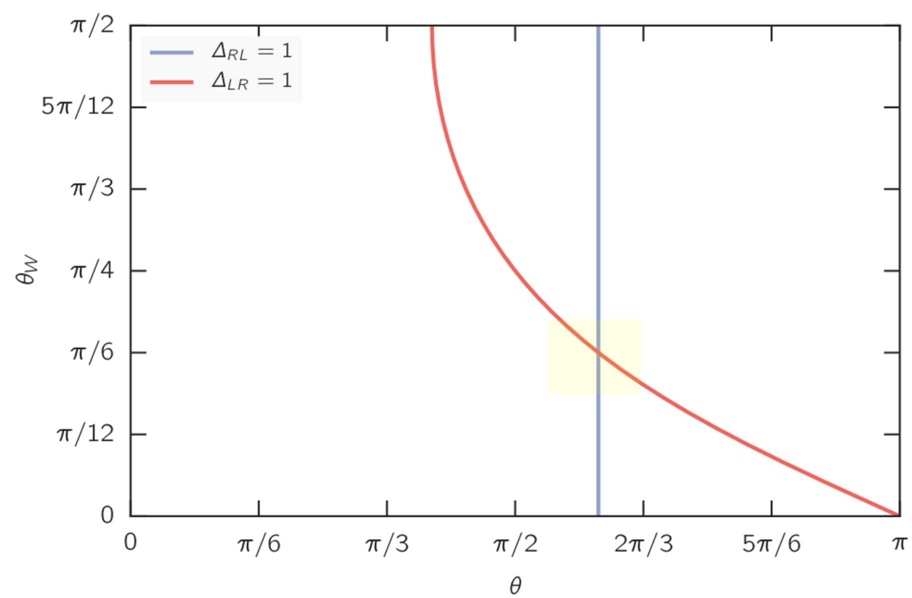
- this method can be extended to the electroweak sector

→ consider weak scattering mediated by *Z* exchange: $e^- e^+ \to \mu^- \mu^+$

$$c_Z^f = i \frac{g}{\cos \theta_W} \gamma^\mu \left(g_V^f - g_A^f \gamma^5 \right)$$

Cervera-Lierta, SciPost Phys. 3, 036 (2017)





- MaxEnt realized for $g_L = g_R \to g_A = 0$ (QED) OR $g_V = 0,\ \sin^2 \theta_W = 1/4$

entanglement in fundamental 2 → 2 scattering (ii)

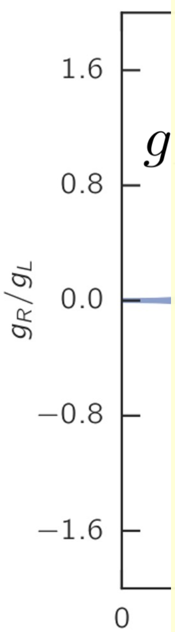
- this method can be extended to the electroweak sector

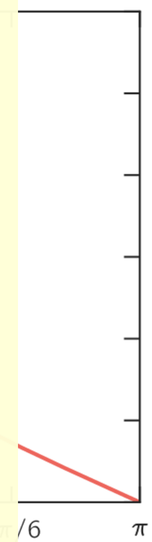
  → consider weak scattering mediated by *Z* exchange

$$c_Z^f = i\frac{g}{\cos\theta_W}\gamma^\mu\left(g_V^f - g_A^f\gamma^5\right)$$

Cervera-Lierta, SciPost Phys. 3, 036 (2017)

$g_{L,R} = g_V \pm g_A$





- **very suggestive** → MaxEnt can serve as a constraining principle;

  ...reflects fundamentally quantum nature of these processes...

- extendable to other HEP pheno., QCD bound states

  → *n.b.:* conclusions will shift at higher orders

  → top sector is an obvious application

- MaxEnt realized for $g_L = g_R \to g_A = 0$ (QED) OR $g_V = 0,\ \sin^2\theta_W = 1/4$

- analogous concurrences, Bell's inequality tests possible in top sector

→ high **QCD accuracy** is essential to robustness of QM tests

Entanglement and Bell Inequality Before Integration

talk yesterday: **Yoav Afik**

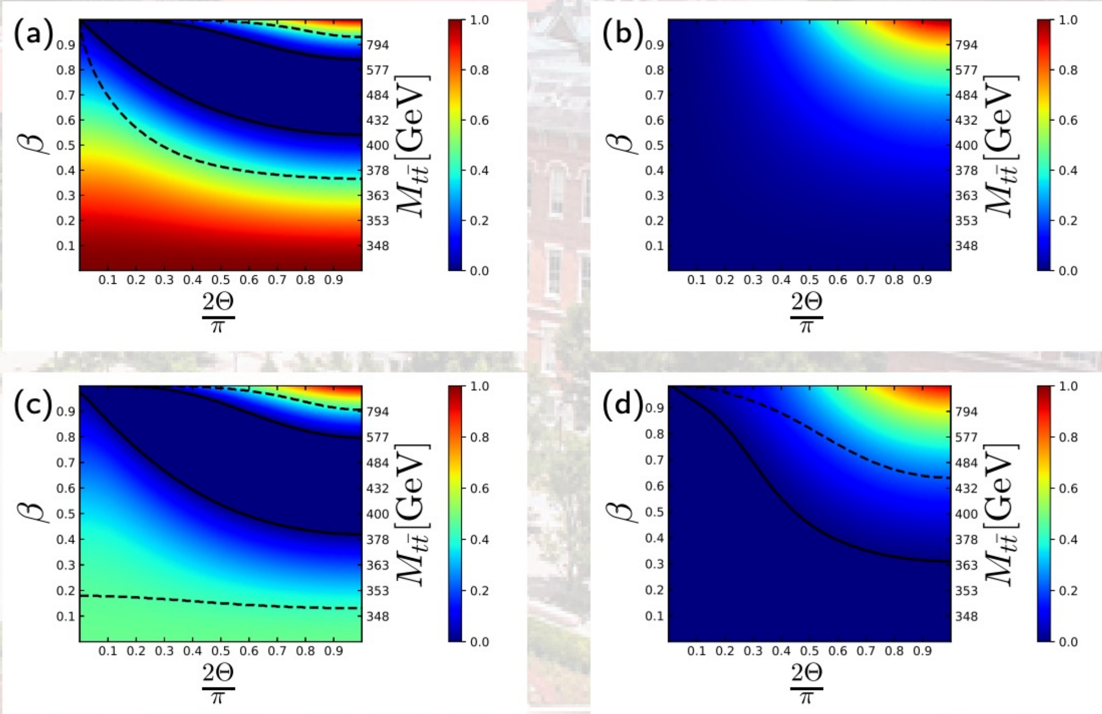
a) $gg \to t\bar{t}$ Concurrence.

b) $q\bar{q} \to t\bar{t}$ Concurrence.

c) Full LHC $\rho(M_{t\bar{t}}, \hat{k})$ Concurrence.

d) Full Tevatron $\rho(M_{t\bar{t}}, \hat{k})$ Concurrence.

- Solid line: entanglement boundary; Dashed line: Bell non-locality boundary.



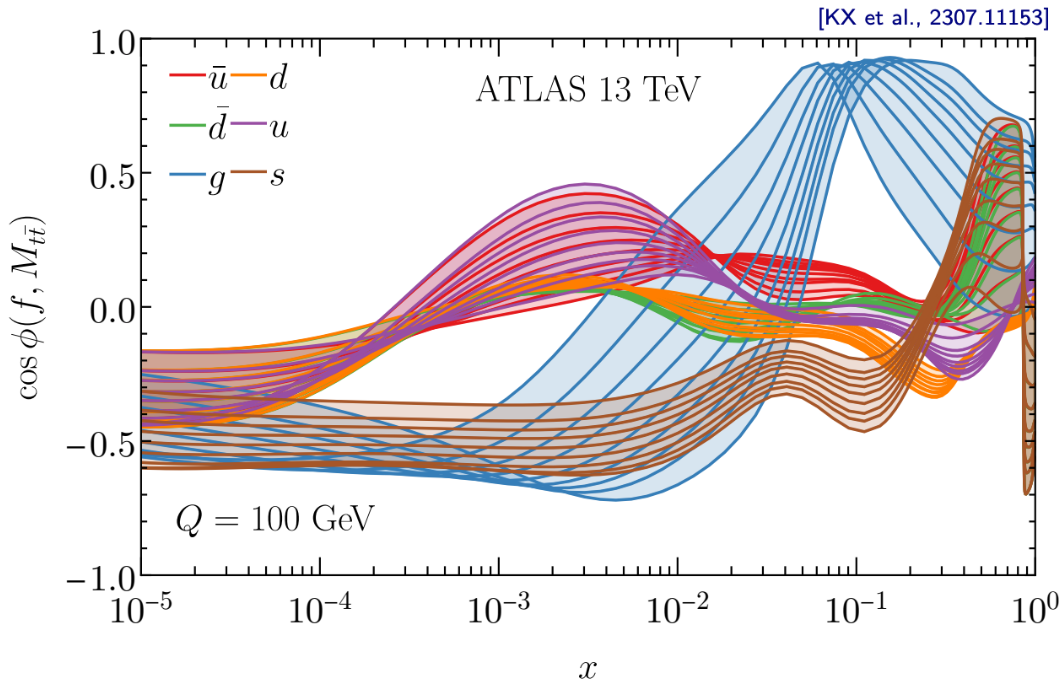
- It is possible to control the $gg/q\bar{q}$ fraction by further selections ($\beta_{t\bar{t}}$), see Aguilar-Saavedra, Casas, EPJC (2022).

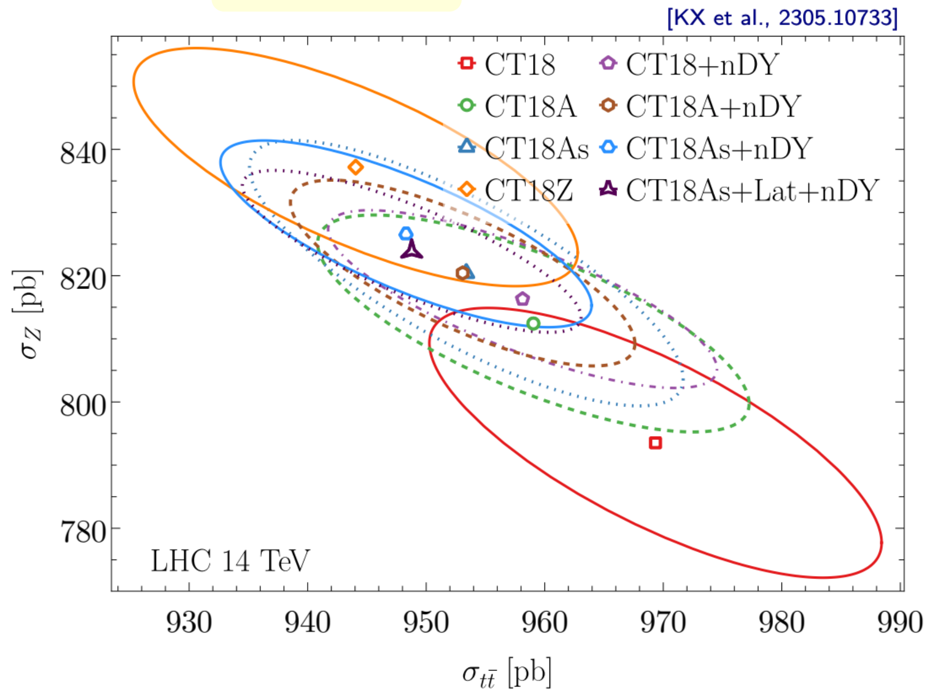
$t\bar{t}$ production has strong PDF dependence

see talks: Hoeche, Kidonakis

Connection to the top pair production

Keping Xie





- 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

- theoretical predictions for top are limited by high-x gluon PDF
- at same time, top data PDF pulls, depend on expt precisions, fit methodology

Top-pair production & basic QM

- If we control t-pair production (per event) => isolate entanglement:

Near threshold $(t\bar{t})_{gg\to t\bar{t}} \Rightarrow$ J=L=0 state, hence spin of the 1st determines the 2nd (spin entanglement). It is testable for instance via spin-spin correlation See for instance: Affik & Nova (21)

- We can in principle work harder and even perform Bell-inequality test

Tue.: Cheng; Thu.: Gonçalves; Severi; Baker; Negro; Afik

- This line of research raise however several questions:

(i) Been tested in multiple system - at low energies with photons/electrons to intermediate energies $B^0 - \bar{B}^0$; is it significant?

Nobel Prize (22)

(ii) Seems non-robust as "normal" BSM can modify For instance: Aoude, Madge, Maltoni & Mantani (22)

(iii) Is there any sensible theory in which there's energy dependence ?

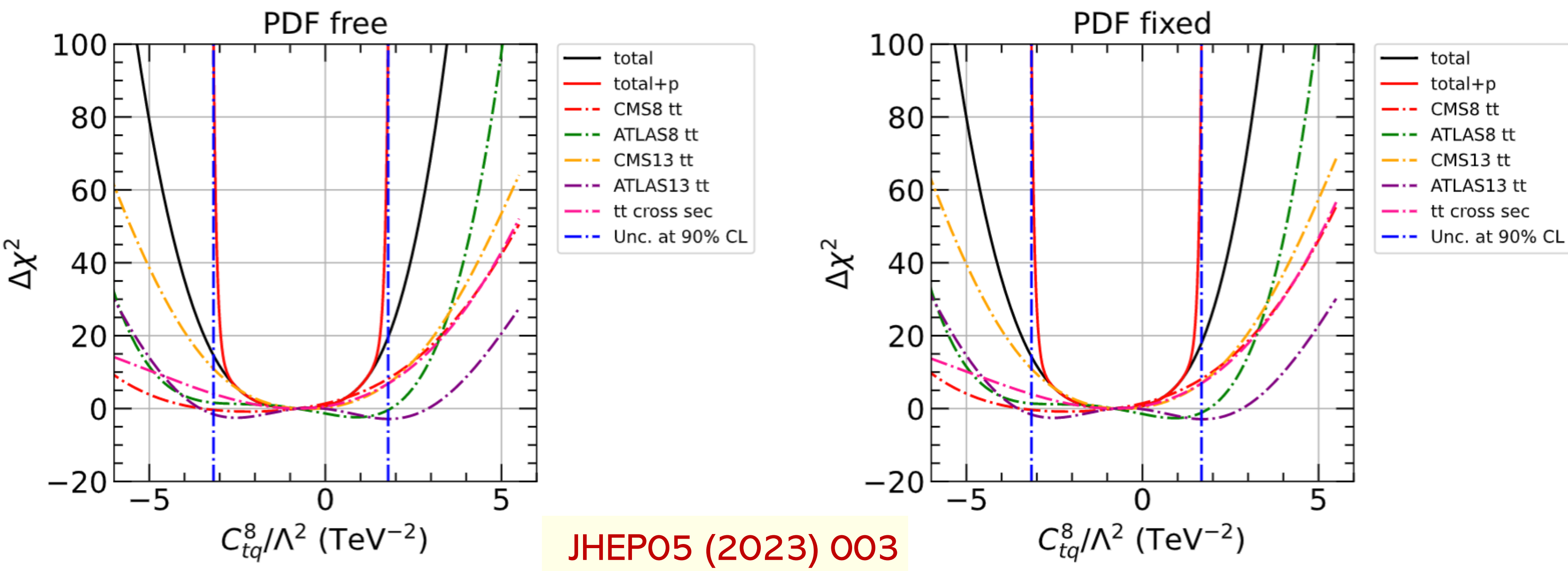
see slides, Alan Barr

- also natural to worry about BSM effects in PDF analyses of top data (?)...

back in Michigan…

SMEFT uncertainties in joint PDF fit $t\bar{t}$ data

- quantify SMEFT uncert. through Lagrange Multiplier (LM) scans:



JHEP05 (2023) 003

→ constraints to top-associated Wilson coefficient, C^8_{tq}/Λ^2

- modest increase in uncertainty when co-fitted with PDFs
- predominantly *quartic* shapes for $\Delta\chi^2$ reflect pure SMEFT contributions $\sim\frac{1}{\Lambda^4}$

… *i.e.*, importance of quadratic EFT terms in limit-setting

entanglement in top production: status

- for now, improving QM tests in $t\bar{t}$ served by controlling PDF, QCD uncertainties; independent EFT analyses acceptable…

…*i.e.*, possible BSM-PDF 'cross-contamination': sub-leading effect

→ quantify, tame PDF dependence

→ improve fixed-order, resummed calculations

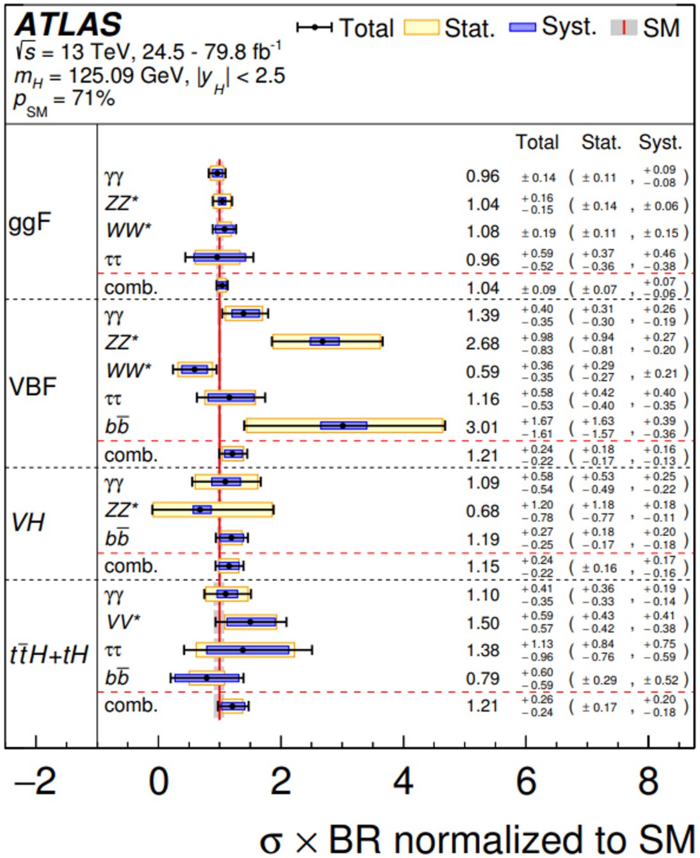
→ event generation

→ experimental systematics

… SM phenomenological bread & butter are essential.

meanwhile, view from HEP: testing the SM at colliders

Higgs prod·decay/SM (PDG)



generically, for EW boson production:

$$\sigma(PP \to W/Z+X) = \sum_n \alpha_s^n \sum_{a,b} \int dx_a dx_b$$

$$\times\, f_{a/P}(x_a)\, \hat{\sigma}^{(n)}_{ab\to W/Z+X}(\hat{s})\, f_{b/P}(x_b)$$

pQCD matrix elements

→ "precision" searches

or, testing the Standard Model through extremely fine measurements...

(deviations could reveal presence of new particles/interactions!)

→ precision depends on pQCD + **parton distribution functions (PDFs)**

BUT standard-candle measurements are limited by PDF uncertainties

→ includes many observables: $\sigma_H\,,\;\sin^2\theta_W\,,\;m_W\,,\;\ldots$

→ this dependence NOT simply another 'theory uncertainty'

example:

ATLAS, 1701.07240

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

→ recent CDF M_W measurement: significant PDF dependence

2205.03942 [hep-ph]

→ frontier efforts at the HL-LHC, LBNF, …, seek percent-level precision

→ confronting these effects will be a primary need of HEP

→ **importance only grows as SM tests become more systematics-dominated**

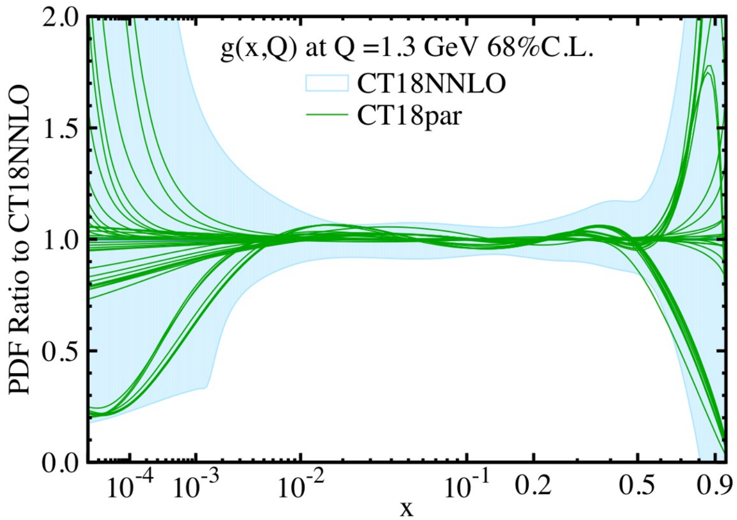
PDFs are extracted from complex global analyses of QCD

PDFs (& analogous distributions) are nonperturbative hadronic matrix elements,

$$f_{q/p}(x,Q^2) = \int \frac{d\xi^-}{4\pi} e^{-i\xi^- k^+} \langle p \, | \overline{\psi}(\xi^-) \gamma^+ \mathcal{U}(\xi^-, 0) \psi(0) \, | p \rangle$$

↓

challenging to compute from QCD!



→ practice agnosticism w.r.t. initial parametrization

(some guidance from QCD, QCD-inspired models)

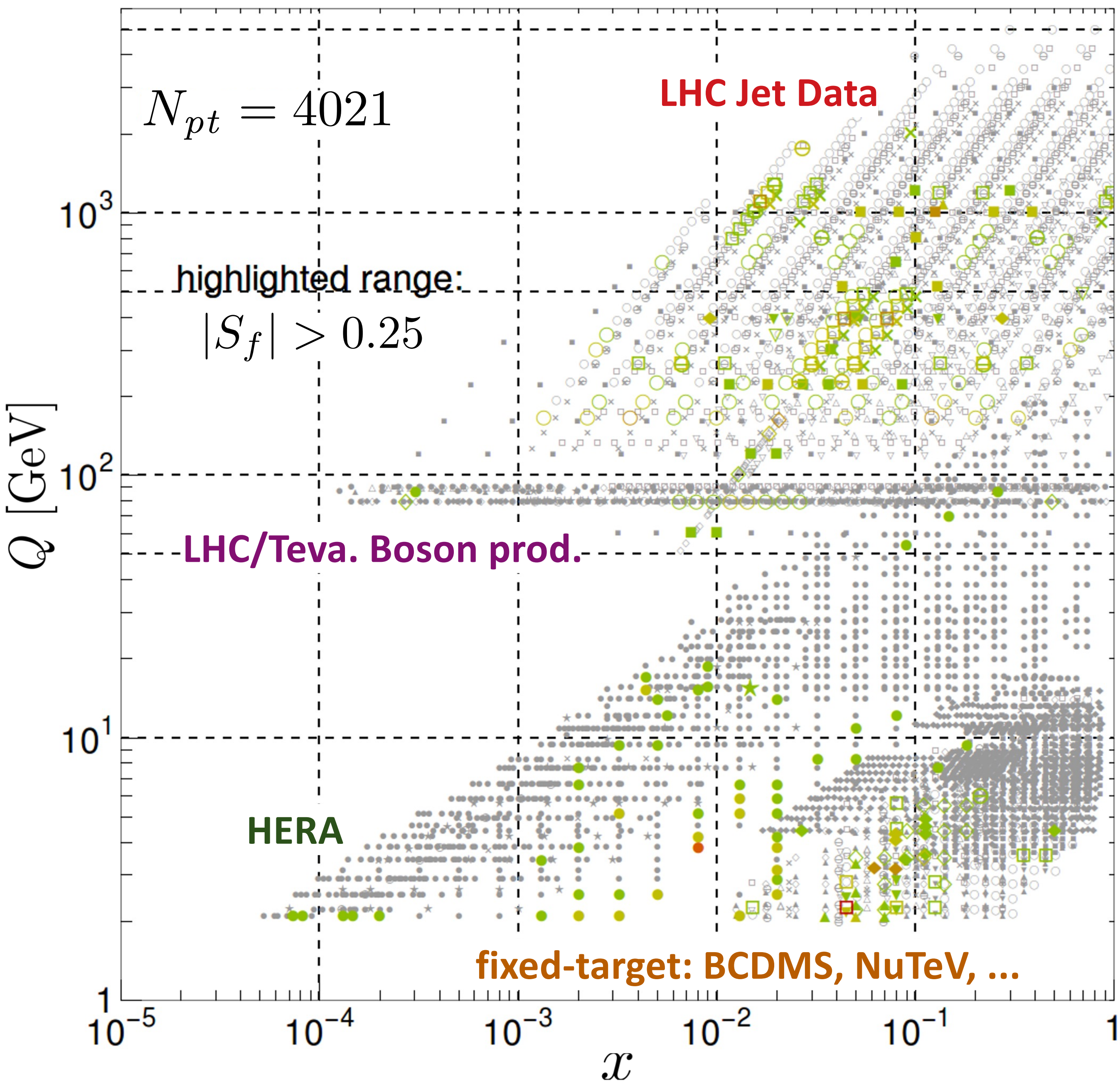
philosophy: lacking a first-principles calculation, fit a flexible parametrization at a suitable boundary condition for QCD evolution:

$$f_{q/p}(x, Q^2 = Q_0^2) = a_{q0}\, x^{a_{q1}} (1-x)^{a_{q2}}\, P[x, \{a_{qn-3}\}]$$

→ perturbative evolution then specifies dependence on $Q^2 > Q_0^2$

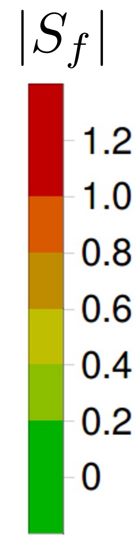
→ **fit the world's data from a diverse range of scales and processes**

modern PDF analysis: constraints from MANY data



B.-T. Wang, TJH et al.,
Phys.Rev. D98 (2018) 094030

(magnitude of PDF pull of each datum)



PDF sensitivity to $\sigma_H(14\,\mathrm{TeV})$

require many data, which have different sensitivities to fitted quantities

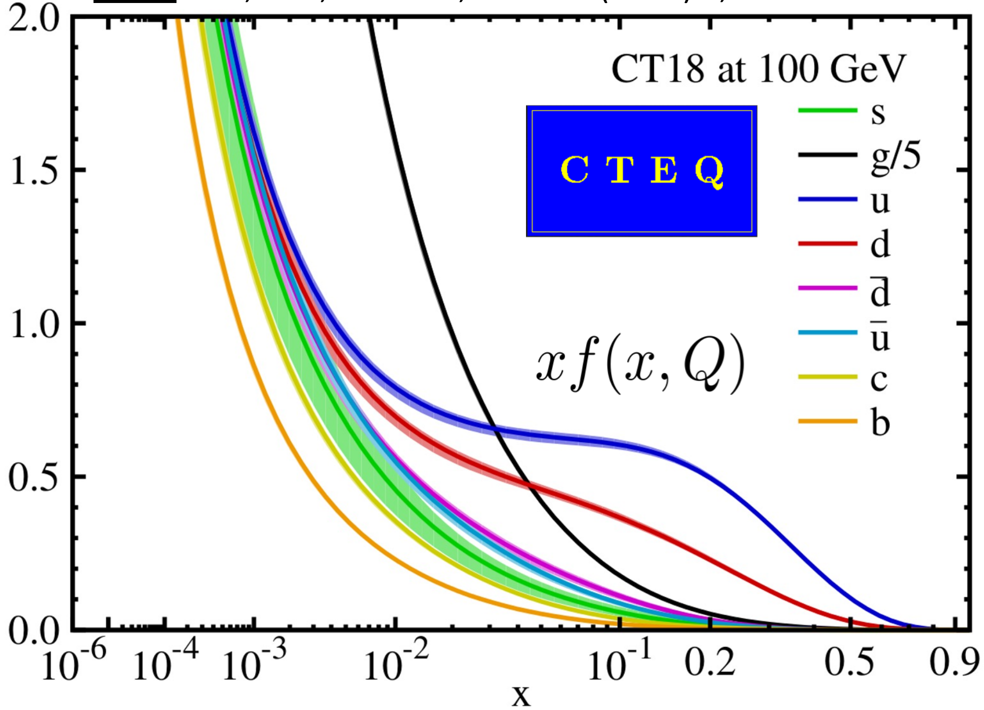
dedicated **NNLO+** theory needed for each

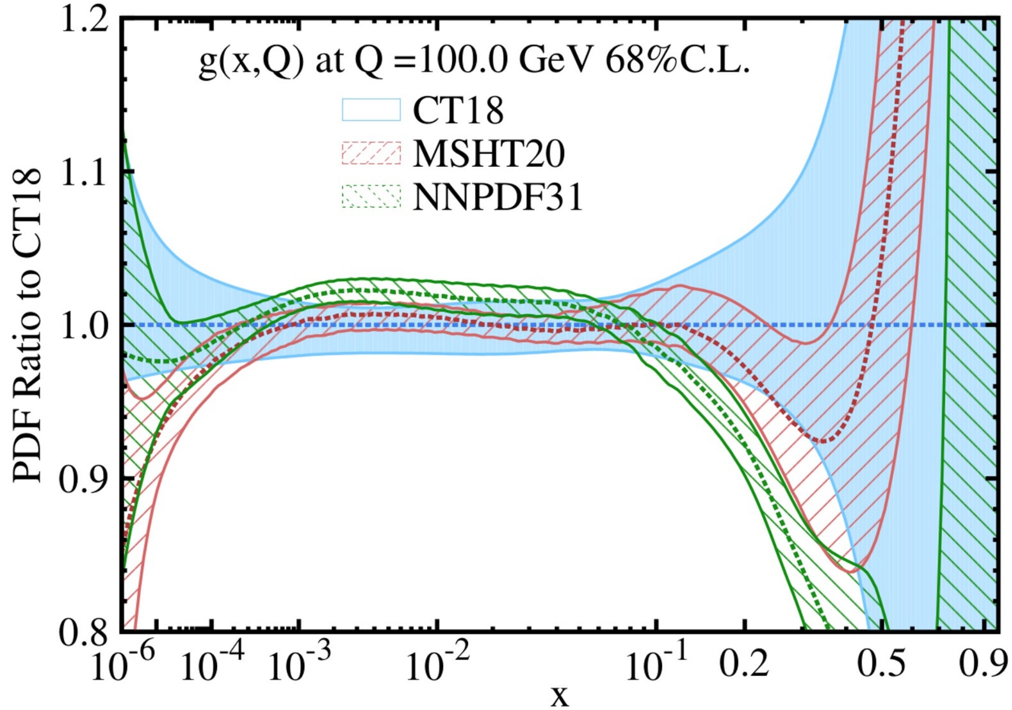
result: QCD global fits – precision for HEP from diverse data

upcoming programs need high-precision → reductions to PDF uncertainties

→ necessary to match (N)NNLO theory accuracy; MC improvements

CT18: Hou, Gao, TJH et al, PRD**103** (2021) 1, 014013



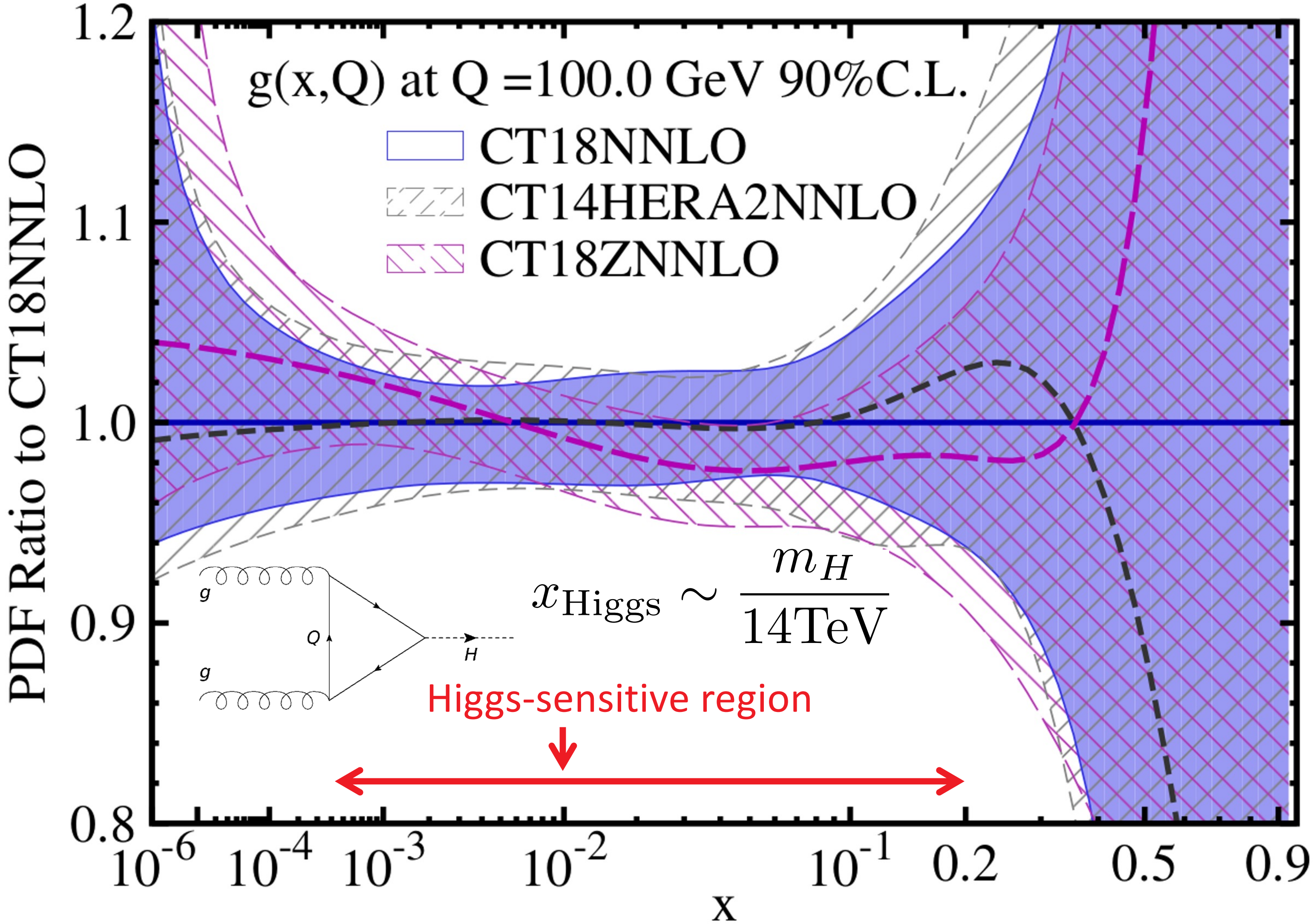


→ NLO EW corrections, especially for LHC data

→ extensive benchmarking for HEP; PDF4LHC21

J. Phys. G 49 (2022) 8, 080501

LHC Run-1 gluon PDF impact in CT14 → CT18(Z)

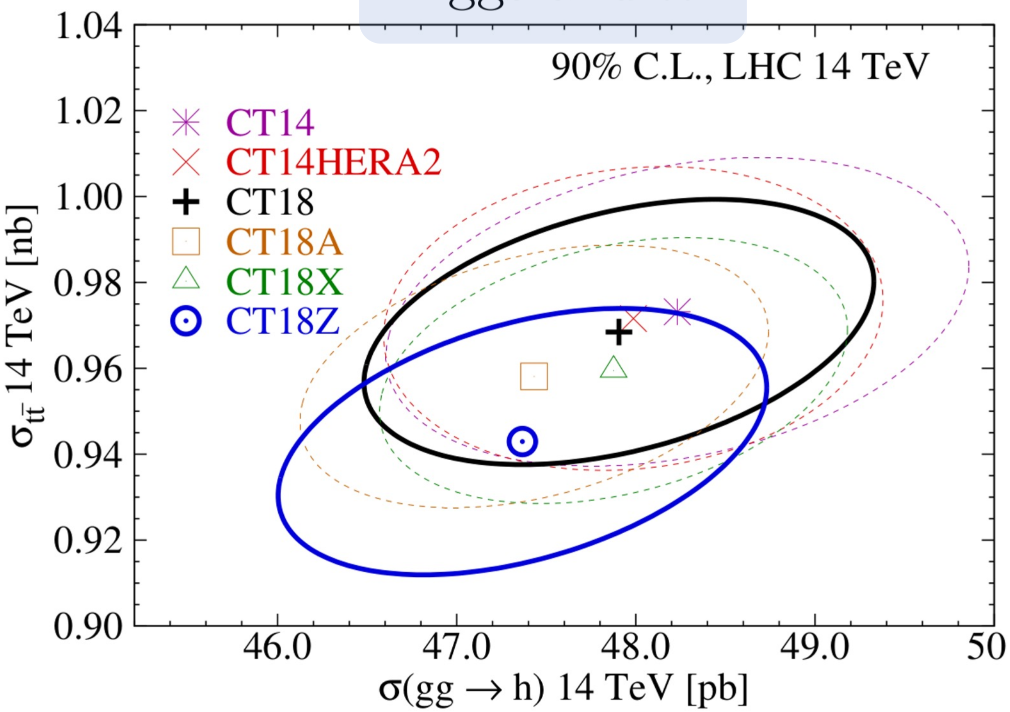


knowledge of the gluon content of the nucleon directly translates into constraints on SM Higgs production

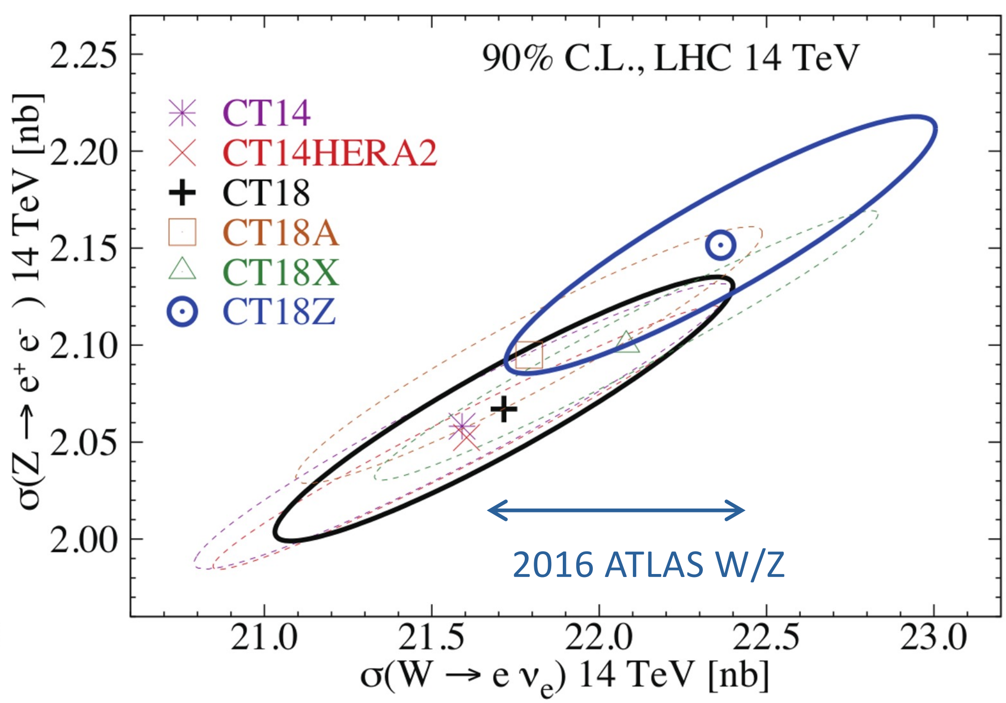
SM theory predictions from global analyses

from this NNLO analysis, state-of-the-art predictions for fundamental LHC observables → *e.g.*, **total cross sections at 14 TeV**

Higgs and $t\bar{t}$



W and Z



Higgs, NNLO QCD: iHixs v1.3

$t\bar{t}$, NNLO+NNLL: Top++ v2.0

$$\mu_R = \mu_F = m_t; m_{W,Z}; m_H$$

NNLO QCD: Vrap v0.9

significant PDF-driven uncertainties; also, systematic effects: W cross sections sensitive to inclusion of 2016 7 TeV ATLAS inclusive W/Z data

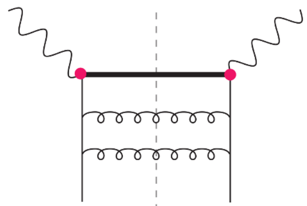
theory ingredients… first thought → higher pQCD accuracy

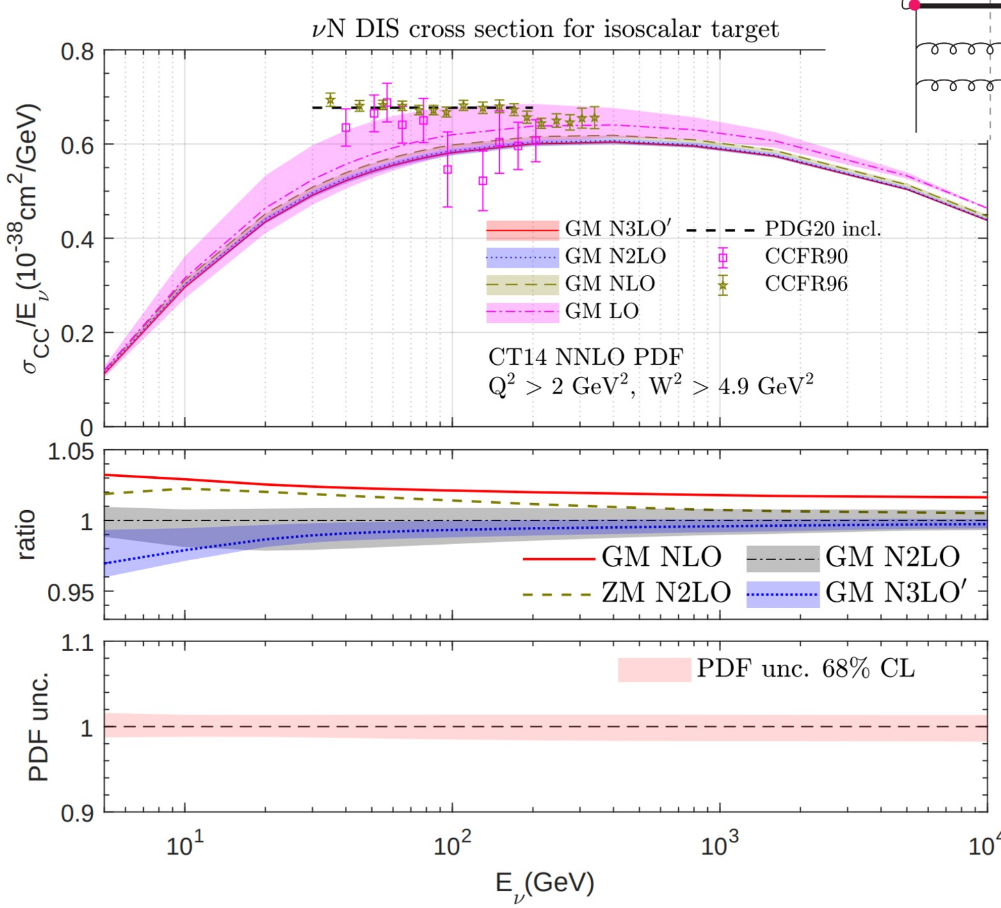
future analyses will witness an interplay between pQCD & other dynamics

NNLO+ necessary to stabilize scale uncertainties; especially over wide scales

charge-current DIS

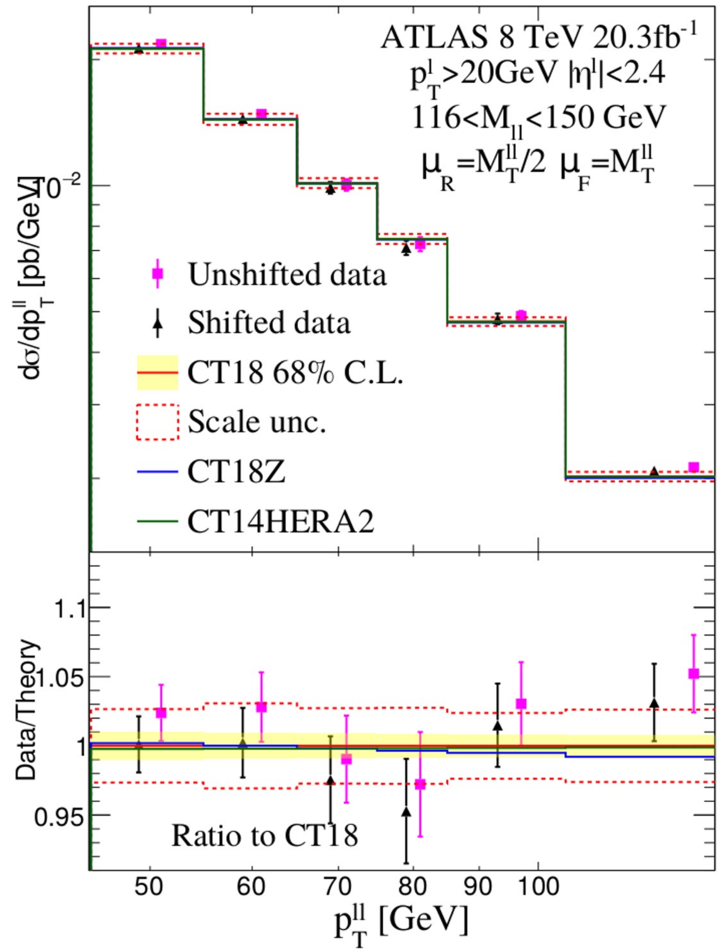
Gao, TJH, Nadolsky, Sun, Yuan: 2107.00460





→ needed for EIC, DUNE, FASERν, … (more later…)

NNLO scale variations at LHC

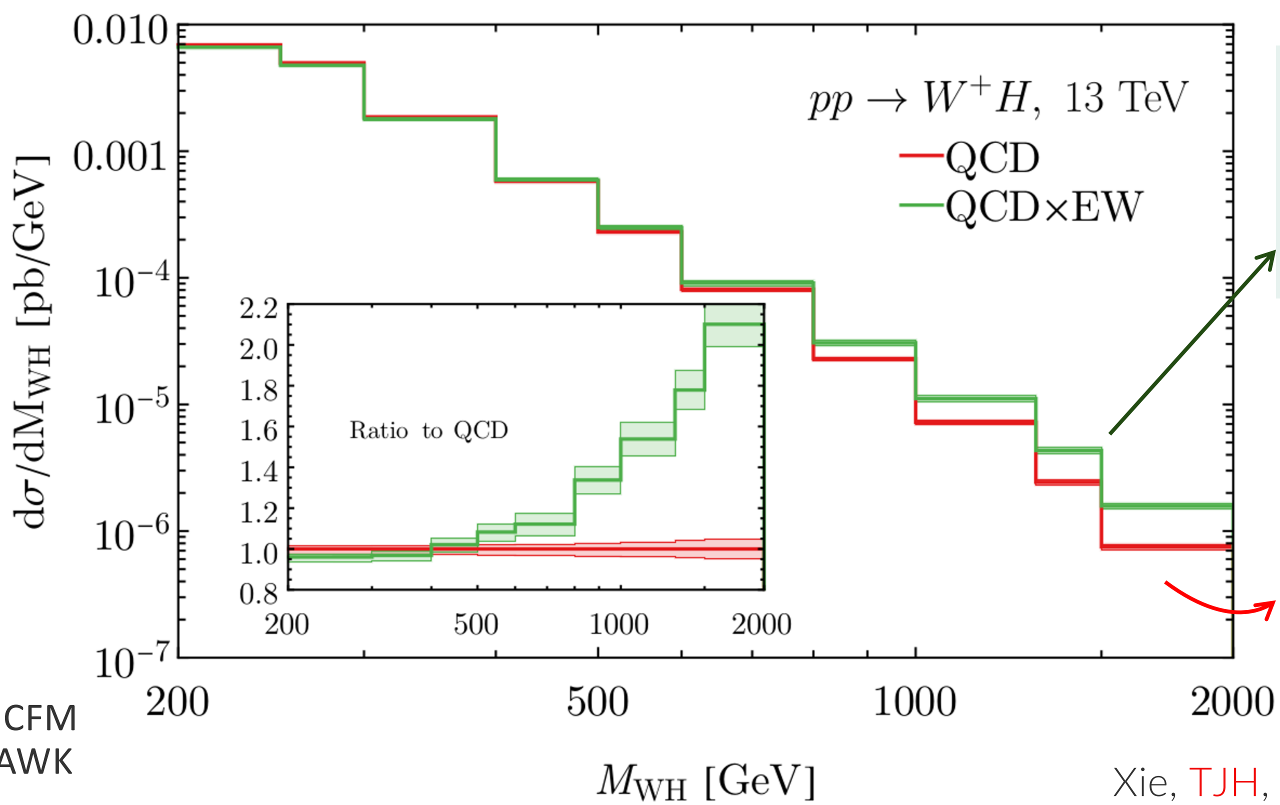


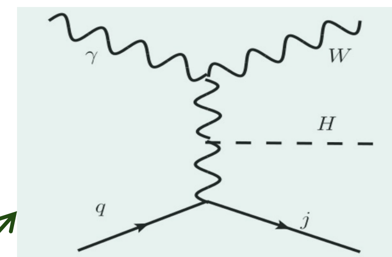
Hou, Gao, TJH et al.: 1912.10053

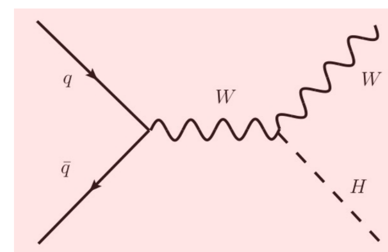
EW corrections for LHC processes

at $\mathcal{O}(\alpha_s^2)$ accuracy, EW corrections and explicit $\gamma(x, \mu^2)$ needed

important for high-energy LHC processes: *e.g.*, 13 TeV W+H production







MCFM
HAWK

Xie, TJH, Hou, Schmidt, Yan, Yuan: 2106.10299

TeV-scale NLO EW corrections dominated (60%) by single-photon (PDF) contributions

→ requires **delicate** treatment along with QCD perturbative effects

photon PDF for precision EW physics (i)

<u>precision EW pheno</u>: must consider photon as partonic degree-of-freedom

photon PDF calculable combination of factorization, hadronic tensor rep.:

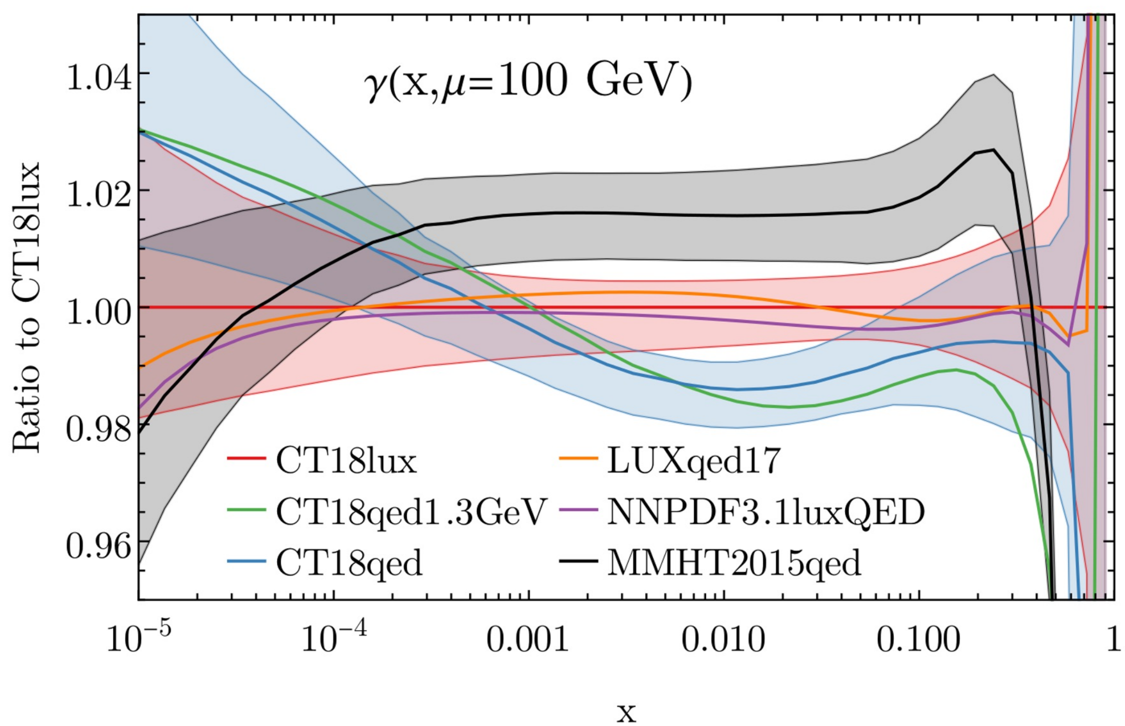
Xie, TJH, Hou, Schmidt, Yan, Yuan: 2106.10299

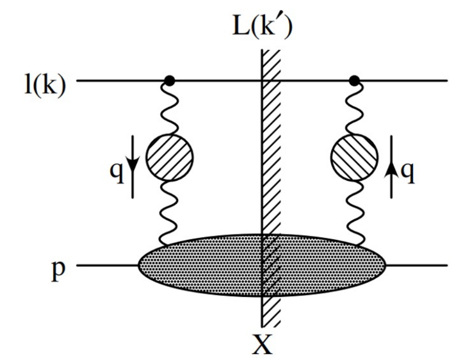
$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{z}{z}\left\{\int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{Q^2}{Q^2}\alpha_{\rm ph}^2(-Q^2)\left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2 F_L(x/z,Q^2)\right]\right.$$

$$\left. -\alpha^2(\mu^2) z^2 F_2(x/z,\mu^2)\right\} + \mathcal{O}(\alpha^2,\alpha\alpha_s)$$

Manohar, Nason, Salam, Zanderighi; JHEP**12** (2017) 046

→ 2 complementary implementations: CT18lux, CT18qed





photon PDF for precision EW physics (ii)

calculation depends on nonperturbative proton-structure inputs!

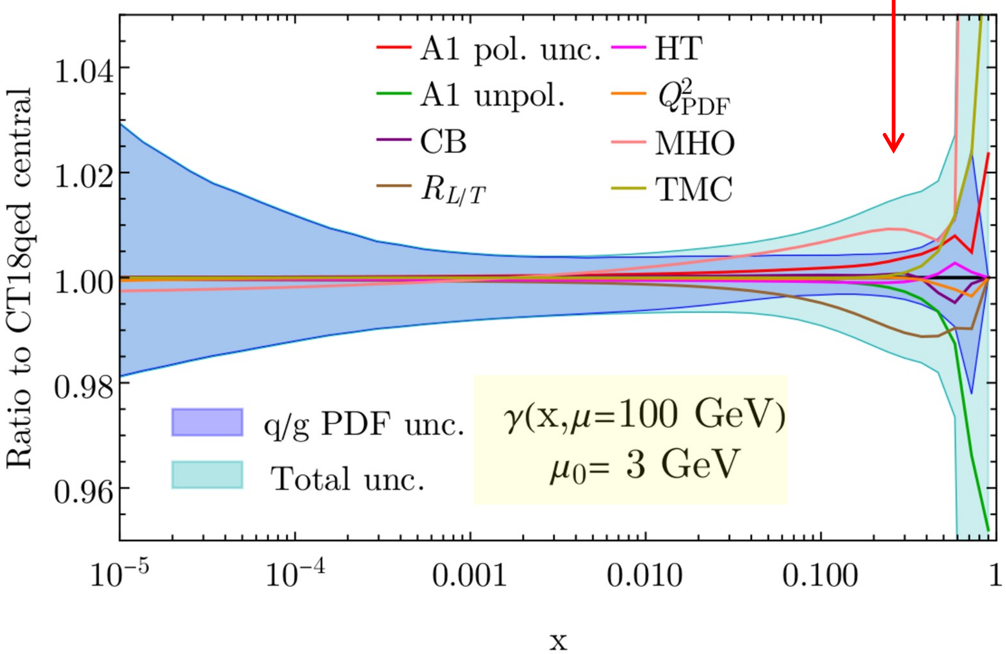
integrated proton SFs include contributions from **low *Q*, high *x***

$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{z}{z}\Bigg\{\int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{Q^2}{Q^2}\alpha_{\rm ph}^2(-Q^2)\Bigg[\Bigg(zp_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2}\Bigg)F_2(x/z,Q^2) - z^2 F_L(x/z,Q^2)\Bigg]$$

$$-\alpha^2(\mu^2) z^2 F_2(x/z,\mu^2)\Bigg\} + \mathcal{O}(\alpha^2,\alpha\alpha_s)$$

dependence on Sachs EM **form factors**; twist-4 (HT), resonance prescriptions; target-mass corrections (TMC); …

[AND **quark-gluon PDFs**, scale uncertainties]



QCD effects induce uncertainties at LHC → *e.g.*, BSM-sensitive tails of rapidity distributions

for higher precision, future analyses must simultaneously incorporate and potentially fit these ingredients

EIC: precision QCD, complementary to LHC

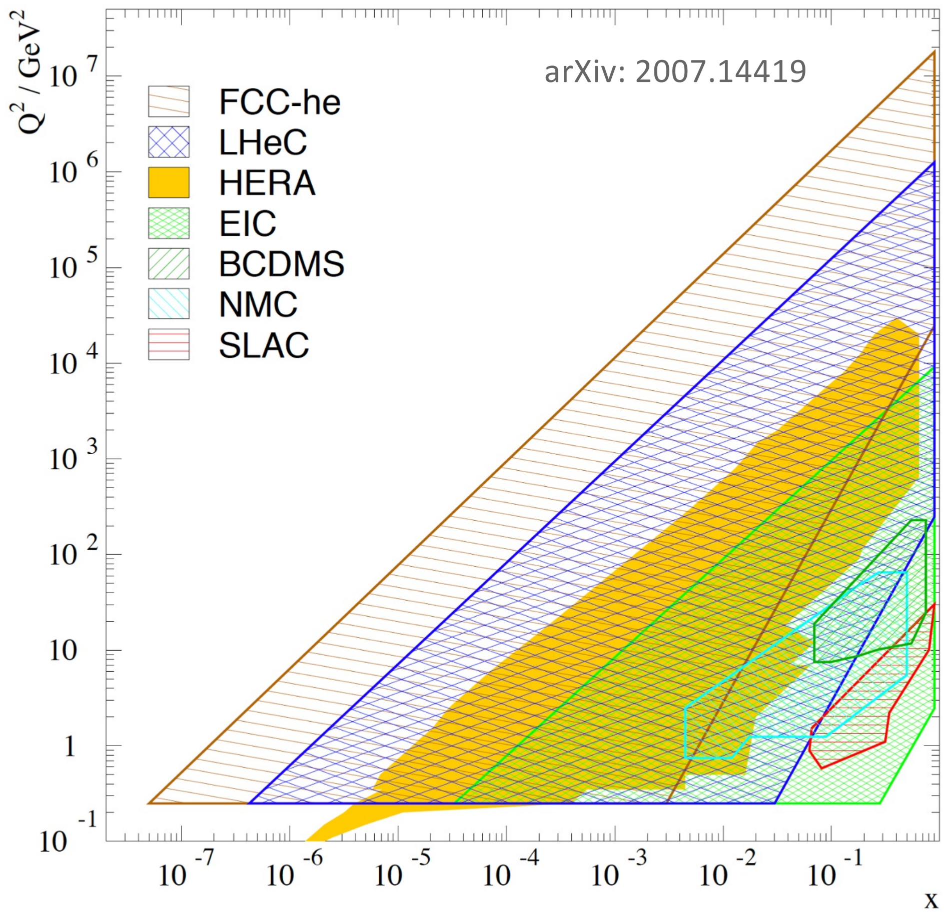
the EIC: a **high-luminosity** DIS collider: ~2-3 orders-of-magnitude cf. HERA

EIC will probe complementary kinematical space to LHC/LBNF in $[x, Q^2]$

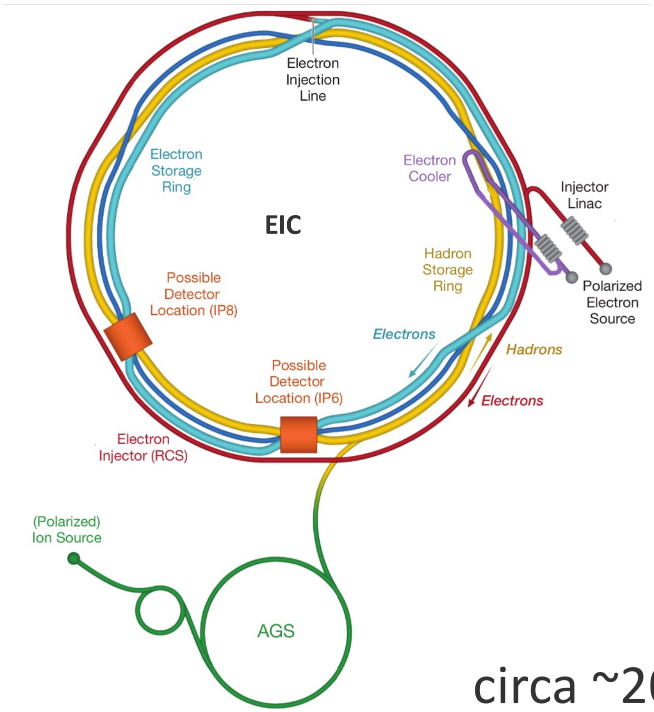
$$20 \leq \sqrt{s} \leq 140\,\text{GeV}$$

wide battery of 'clean' **precision QCD measurements**

→ extensive probe(s) of the quark-to-hadron transition region (for PDFs)



only new US-based collider under planning!

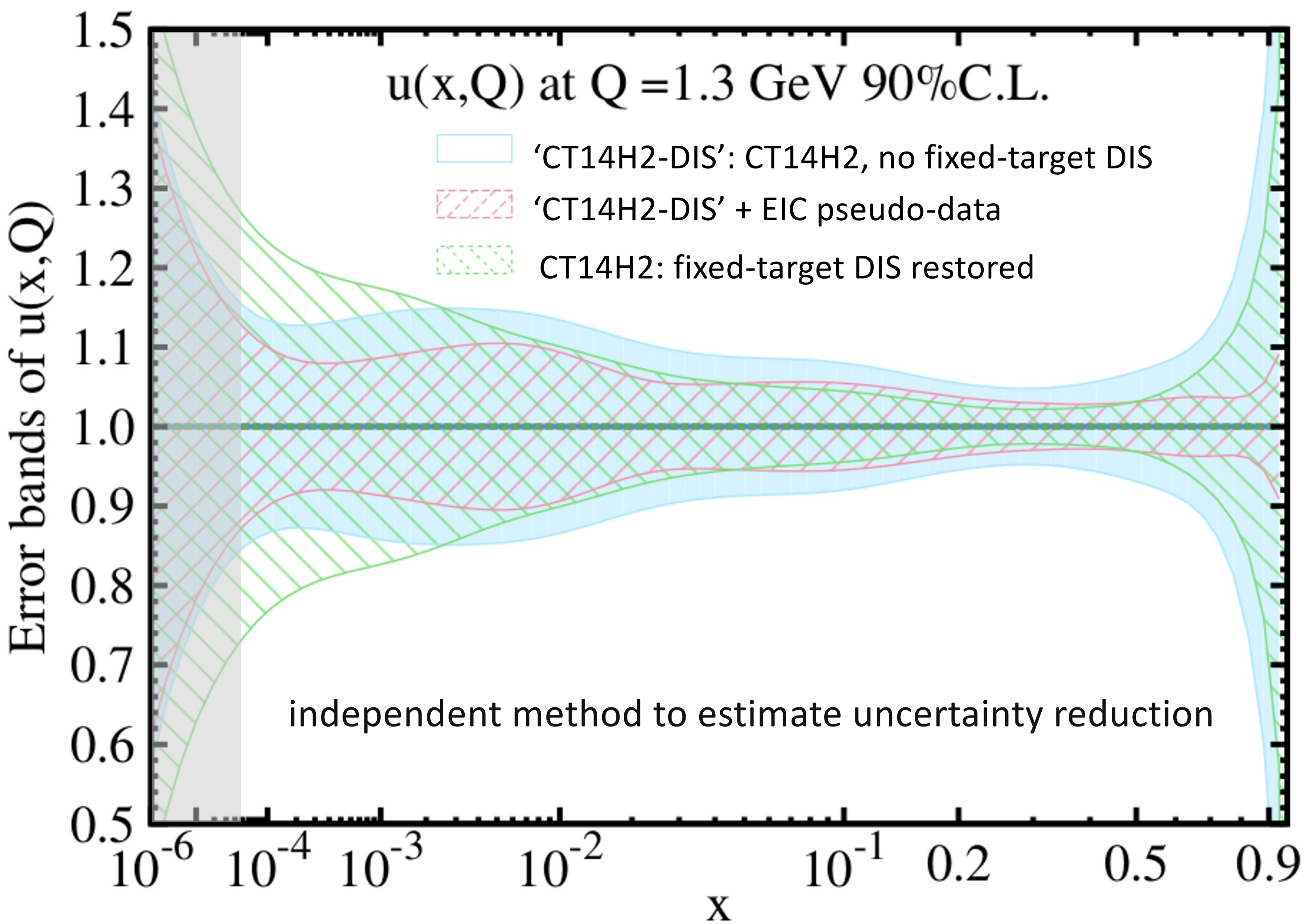


circa ~2034

CD-1; EIC Yellow Report: 2103.05419

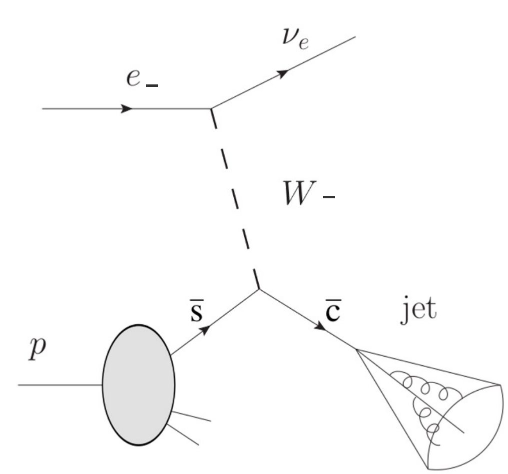
EIC sensitive to PDFs → strong HEP implications

[impact studies made with error profiling methods]



DIS charm-jet prod.

Arratia, Furletova, TJH, Olness, Sekula
PRD **103** (2021) 7, 074023



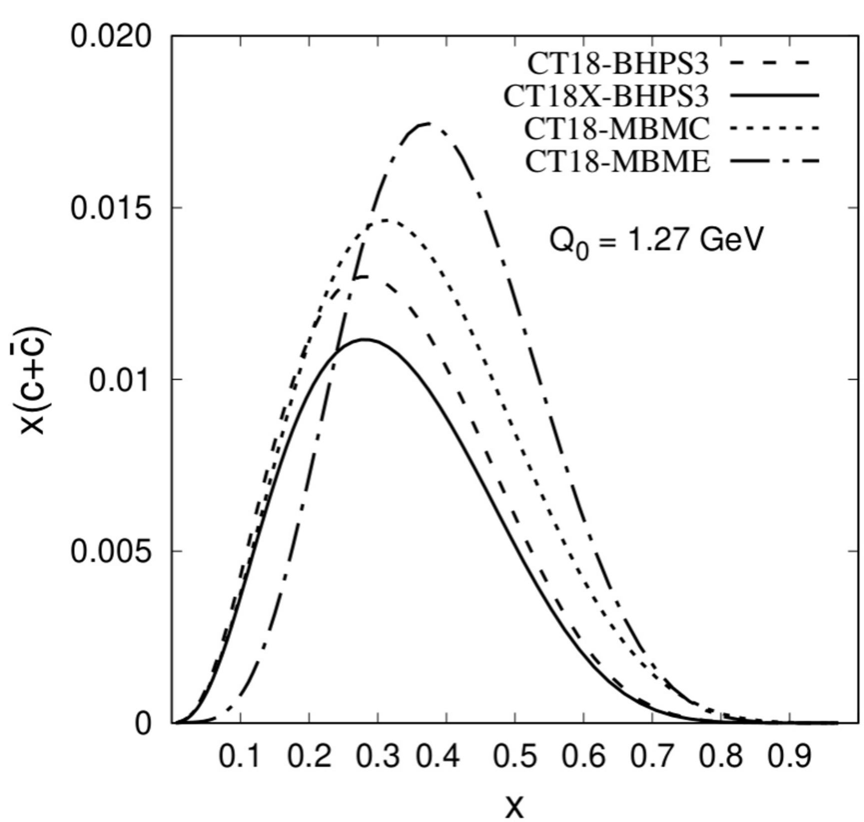
1-yr inclusive EIC dataset drives steep reductions in PDF uncertainties

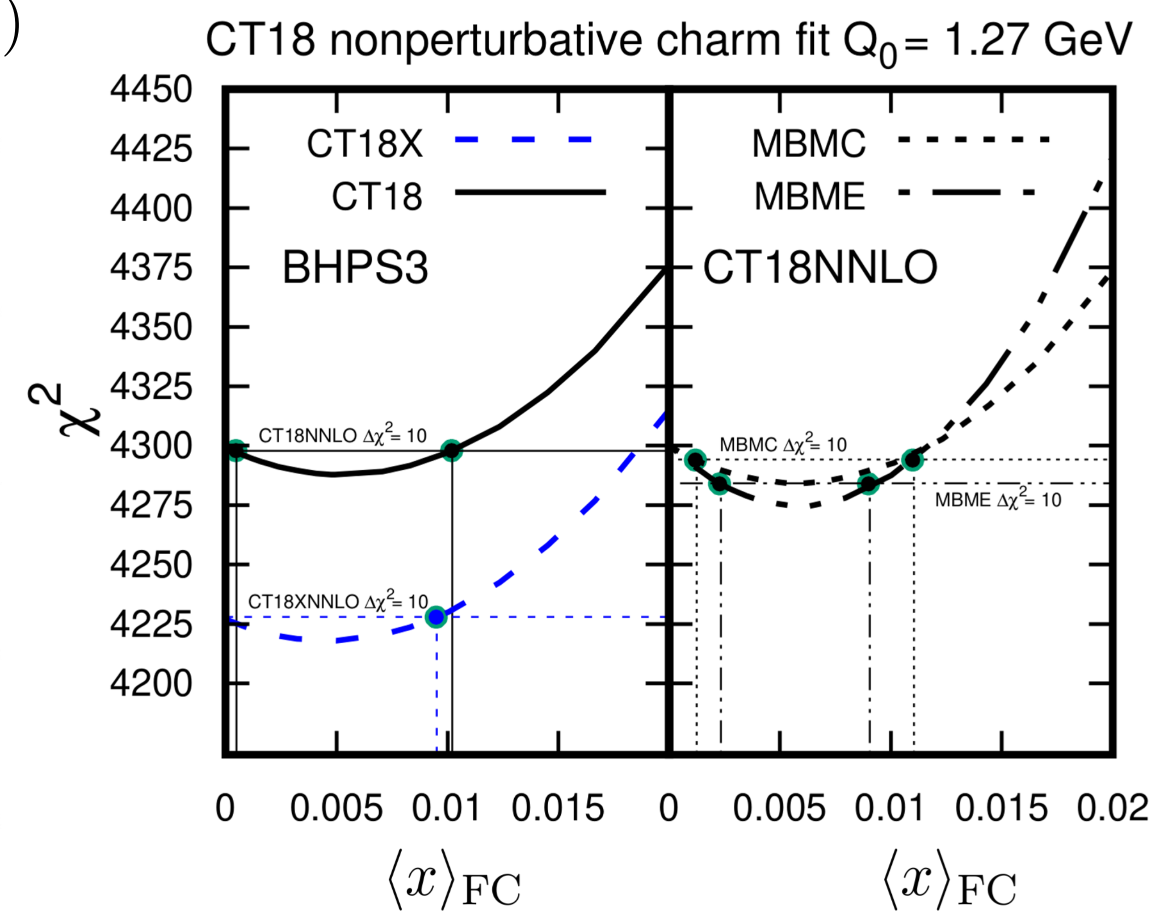
→ just inclusive DIS; many other channels with PDF sensitivity; precision QCD tests

related high-x "precision" PDF effects: 'intrinsic charm'

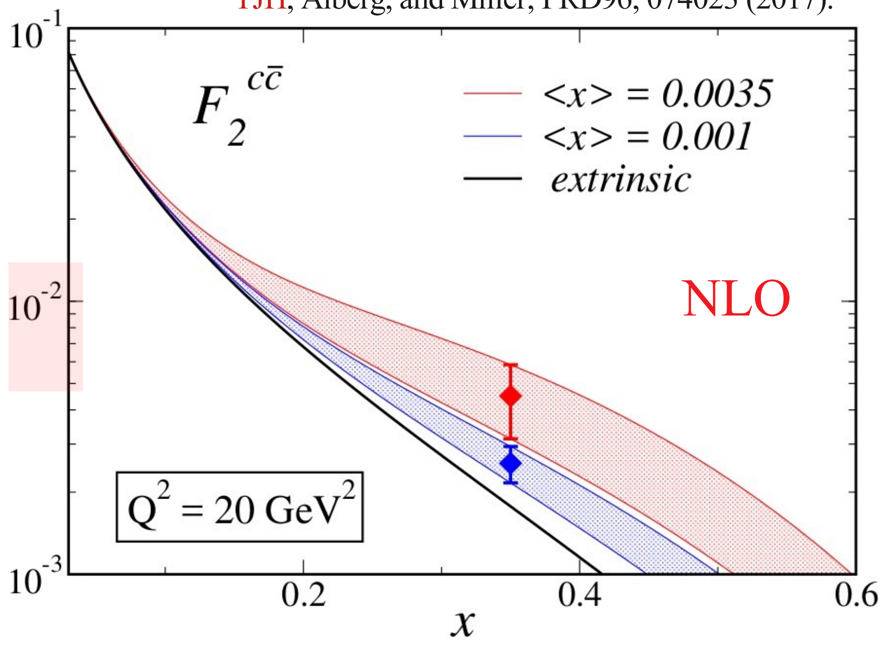
- might the proton contain a nonperturbative charm component? arXiv:2211.01387
  - → prediction of wave function models; distinct from typical, perturbatively-generated charm
  - → <u>uncertainties remain large</u>! need more information to resolve nonzero FC

$$\langle x \rangle_{\rm FC} = 0.0048^{+0.0063}_{-0.0048} \quad ({\rm BHPS3})$$



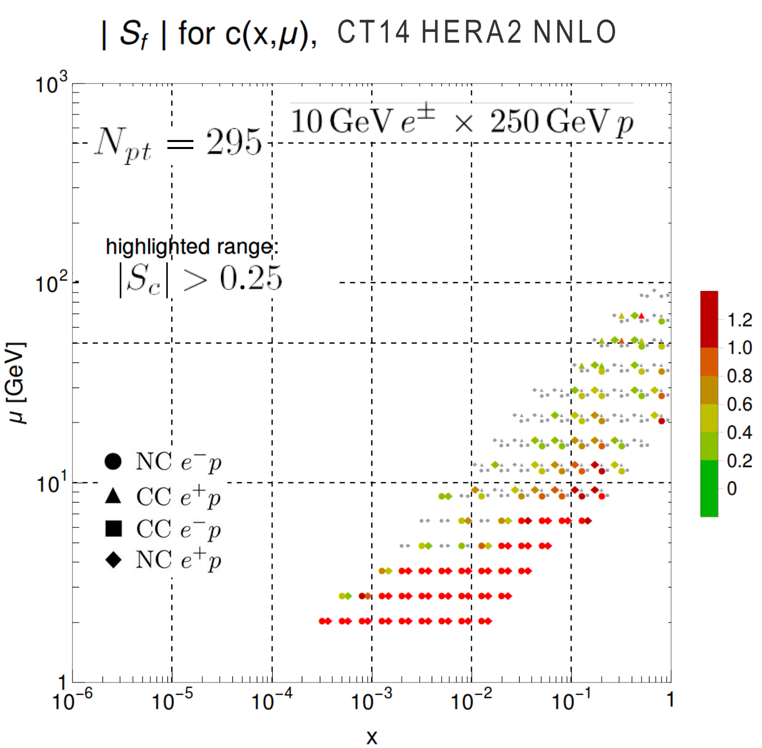


TJH, Alberg, and Miller; PRD96, 074023 (2017).



require more data to resolve nonperturbative charm

EIC + lattice QCD will constrain FC scenarios



enhanced FC momentum implied by EMC data → small high-x effects in structure function; need high precision

- essential complementary input from LHC; CERN FPF

EIC will measure precisely in the few-GeV, high-x region where FC signals are to be expected

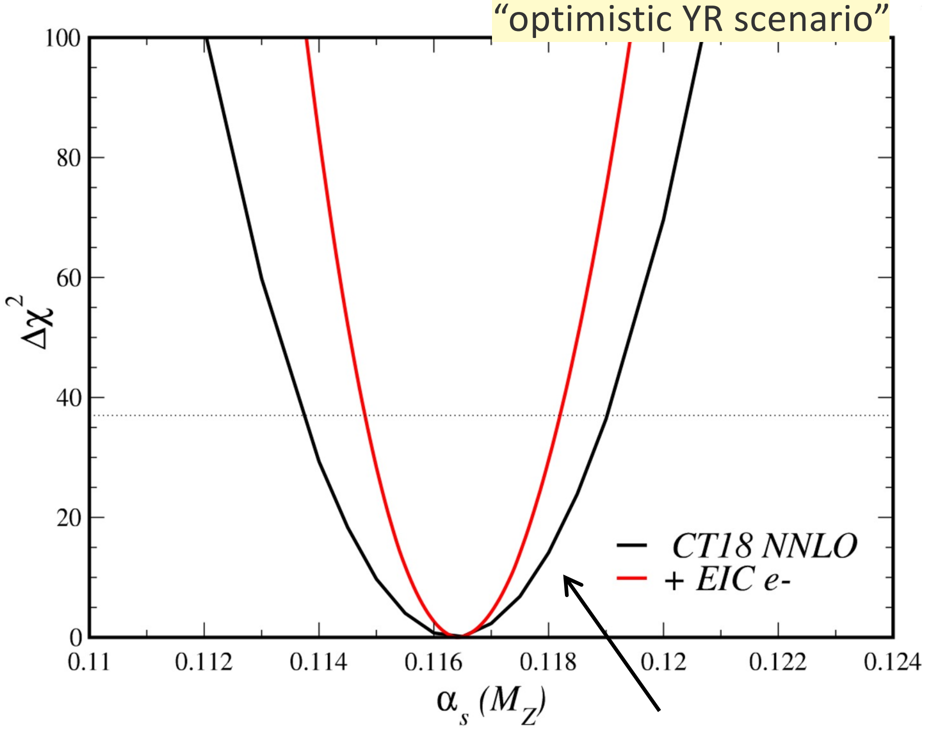
collider DIS and precision QCD: EIC and SM inputs: α_s

part of moving toward N^{3}LO PDFs, precise determinations needed for α_s

similar argument for m_Q

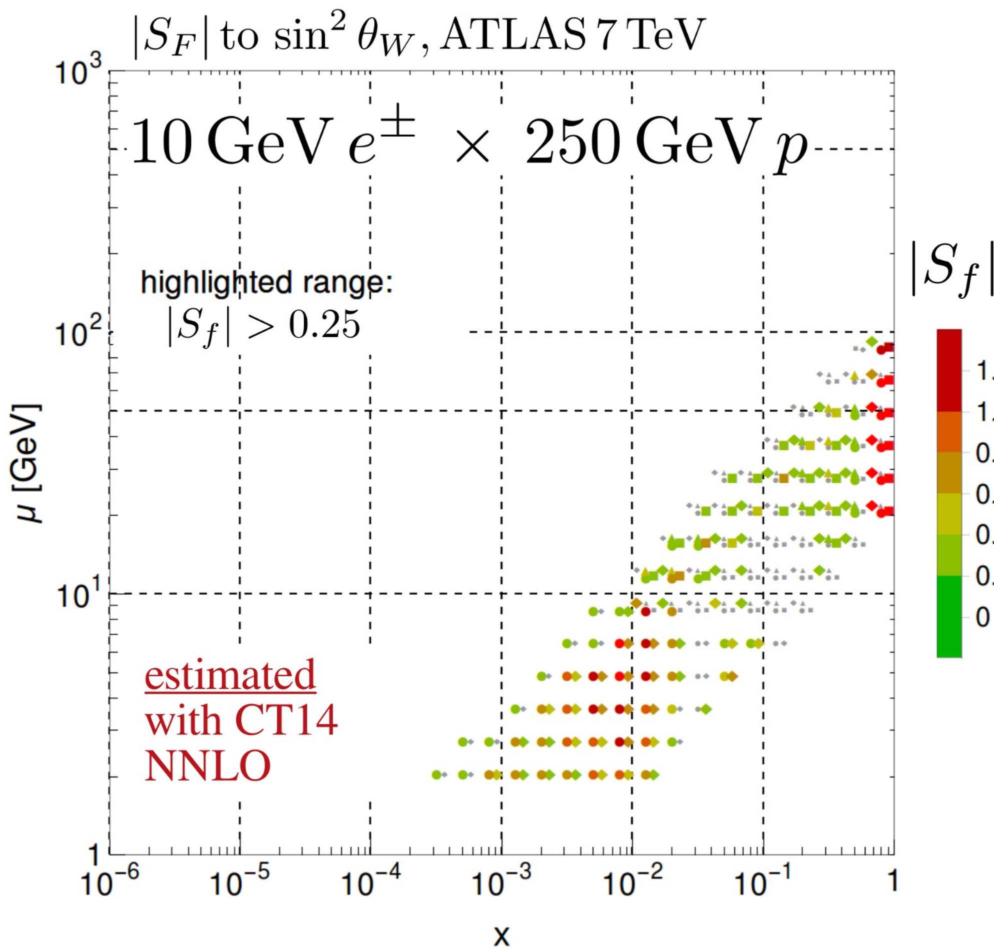
from inclusive data alone

"optimistic YR scenario"



~40% reduction

B.-T. Wang, TJH, et al., PRD **98** (2018) 9.



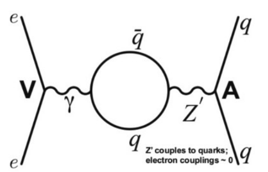
also: precise α_s extractions based on global event shapes; N-jettiness, τ_N

robust PDF sensitivity to $\sin^2\theta_W$ from A_{FB}

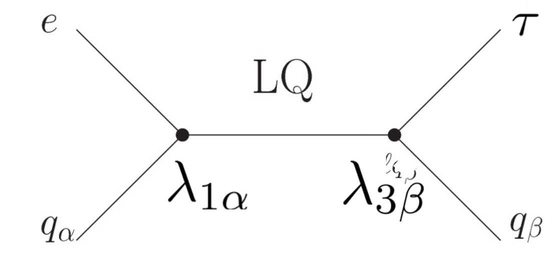
EW and BSM opportunities

potentially BSM-sensitive extractions of EW quark couplings, through **parity violation**

$\sin^2\theta_W$

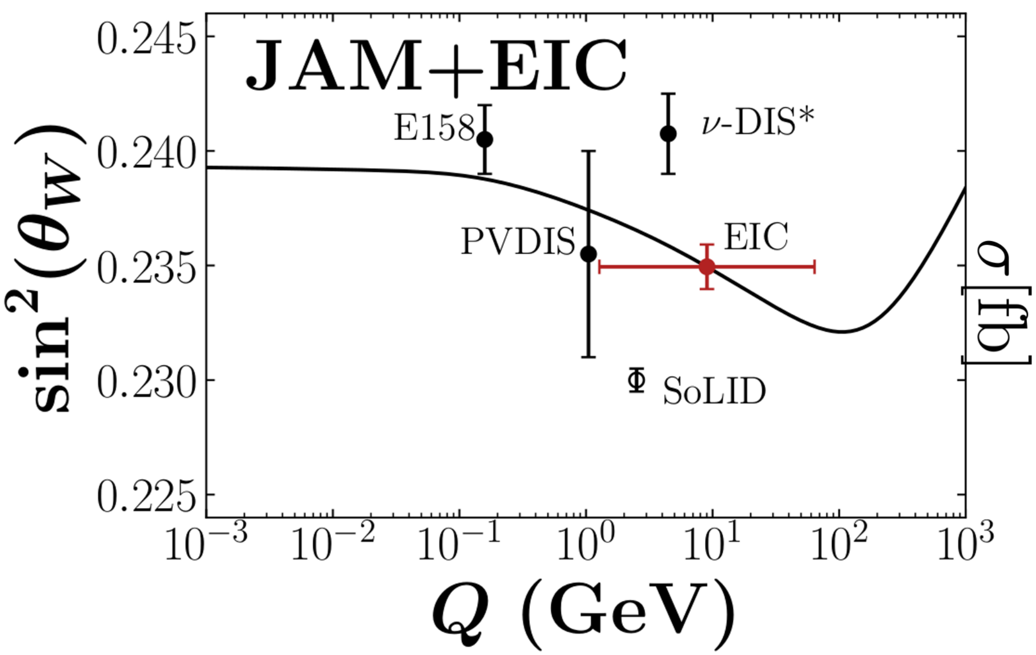


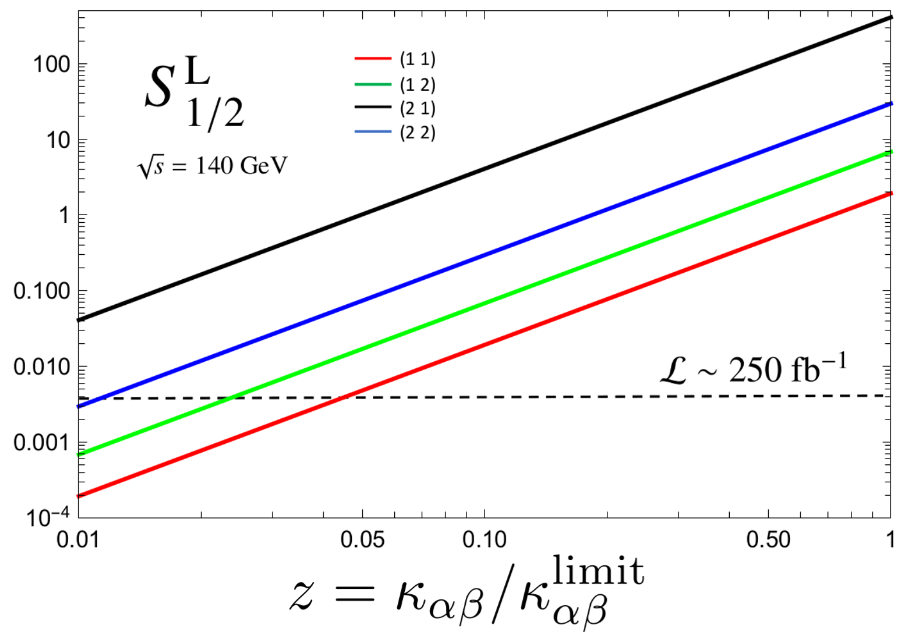
$$A^e_{\rm PV} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



$$\kappa_{\alpha\beta} = \lambda_{1\alpha}\lambda_{3\beta}/M^2_{LQ}$$

EIC YR, 7.5.1



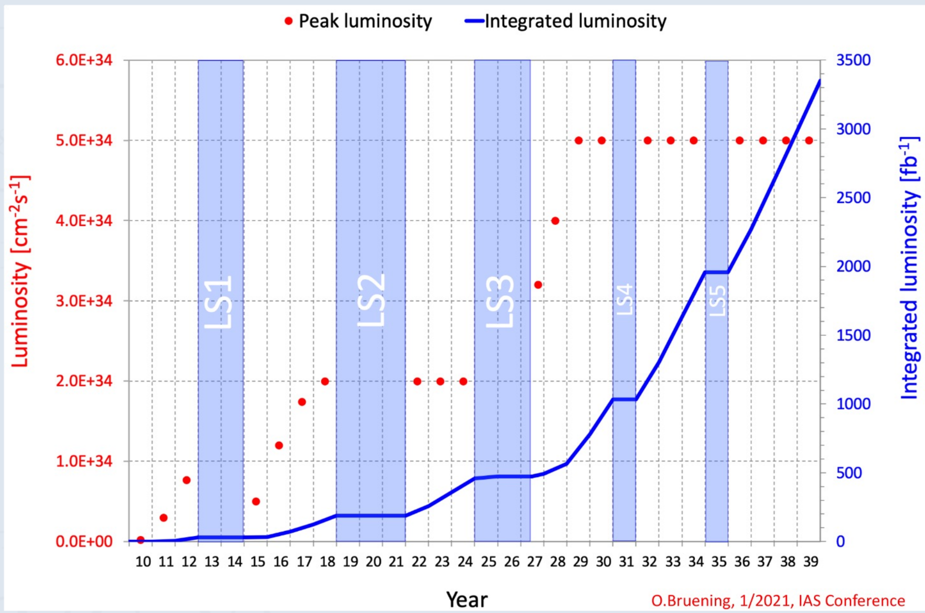


more direct SM tests also possible: searches for charged-lepton flavor violation (CLFV) $e^- + N \to \tau^- + X$

also, (SM)EFT impact

EW and BSM opportunities

have highlighted a large number of **theory issues** & **experiments** engaging with these



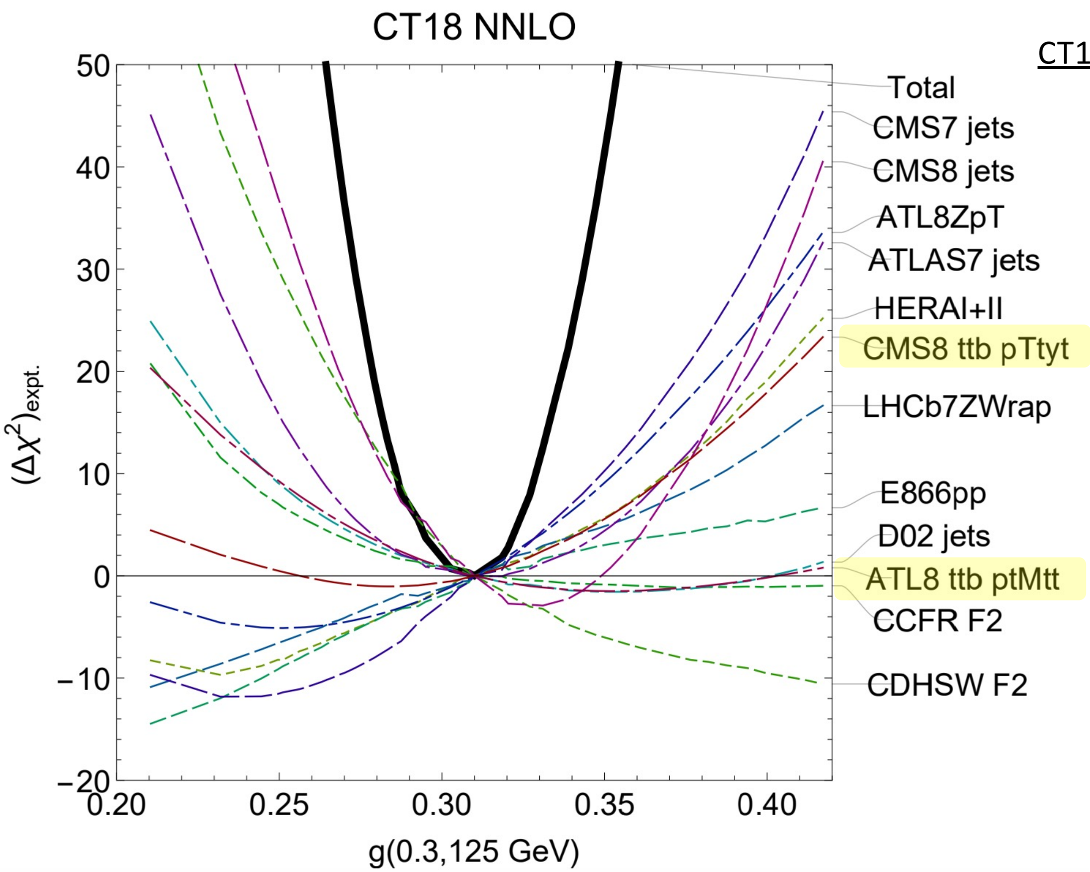
how do we put these together in light of the expected in-flux of data?

SO: many current/future experiments: ***more global*** <u>analyses</u> vital

why? → **compatability** of data sets is a crucial issue

data must be harmonized in global fits; else, ***tensions***

Lagrange Multiplier scan



CT18: Hou, Gao, TJH et al, PRD**103** (2021) 1, 014013

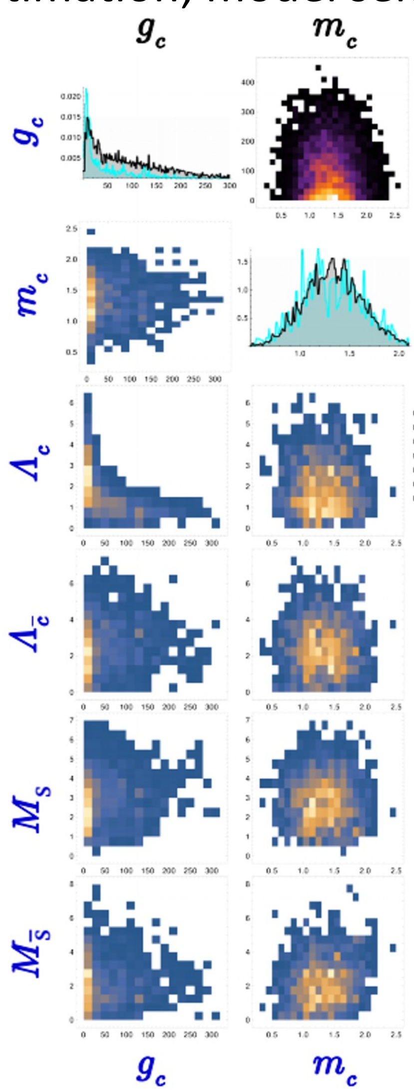
serious impediment to higher precision in PDF/SM predictions

tools: examine change in χ^2 as PDF continuously varies away from fitted central value

→ analysis elements must be treated and assessed comprehensively

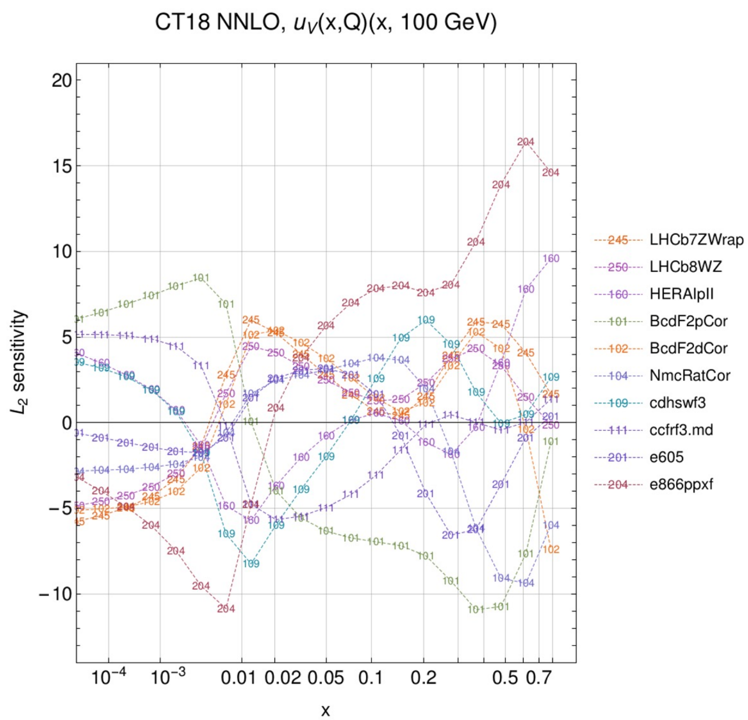
negotiating this landscape: big data tools will be vital

advanced parameter estimation; model selection



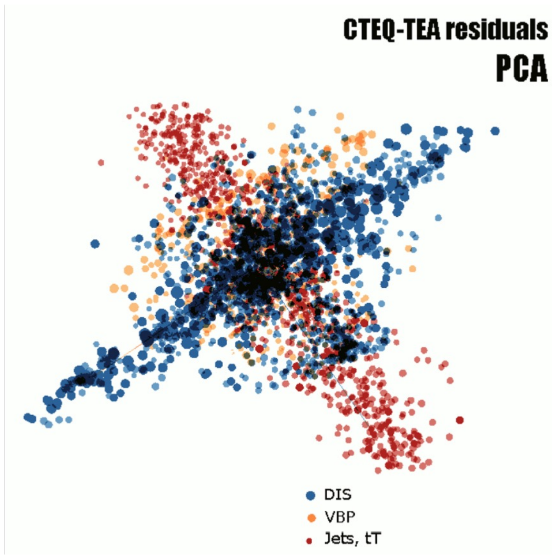
MCMC

fast statistical methods



data embedding

[principal-component analyses]



TensorFlow

→ techniques marry to computationally-intensive analyses; scale on computational clusters

→ deploy cumulatively to resolve tensions, understand theory space

conclusion: next-gen QCD for precision HEP

top, LHC data: unprecedented opportunity to **test QM and the SM**

→ requires precision in QCD: PDFs, QCD theory

→ the EIC is targeted at high-x physics and will be consequential in this area

EIC's privileged position: precision in non/perturbative transition region

exploiting EIC will require more comprehensive QCD/EW analyses

→ augmented theoretical QCD (non)perturbative accuracy; EW ingredients

→ crucial synergy with advanced computation for highly multi-dimensional analyses

HL-LHC, EIC are still being planned → **critical theory preparation needed now** to maximize physics impact