EF05, EF06, and TF06 topical groups

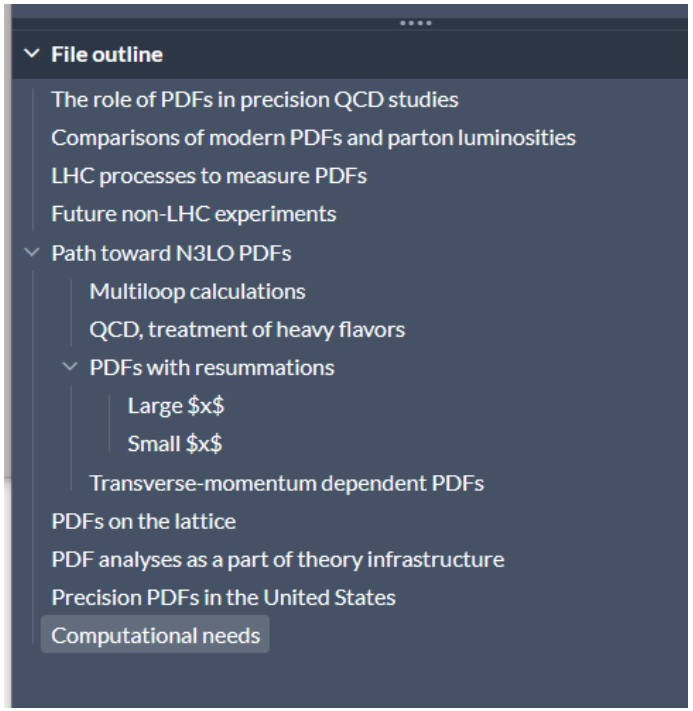
A Snowmass Whitepaper on PDFs

Creating a useful Snowmass document based on interesting LOIs and talks dedicated to PDFs

Pavel Nadolsky

Southern Methodist University

Co-convener, EF06 topical group
“Hadron structure, forward QCD, and hadron spectroscopy”



https://www.overleaf.com/read/tsbdgncmrjpb

EF06 Focus Questions

1. **What is the best approach to reduce systematic uncertainties in LHC measurements to achieve the accuracy of PDFs envisioned by electroweak precision studies at the high-luminosity LHC?**
2. **What is the feasible strategy for obtaining accurate PDFs for N3LO QCD computations? Which theoretical advances and computational tools will be necessary?**
3. **What is the potential of new deep inelastic scattering facilities (EIC and LHeC) for probing the hadronic and nuclear structure in the regions relevant for HEP experiments? How can the experience of the HEP community be transferred to enhance the potential of the EIC and LHeC studies?**
4. **How does the knowledge of hadron structure affect measurements of the QCD coupling constant in various processes?**
5. **When do power-suppressed contributions to the hadron structure become important in NXLO QCD calculations? What are the best approaches to predict or measure them?**
6. **What are the best observables to look for low-x resummation effects predicted by the Balitsky-Fadin-Kuraev-Lipatov resummations?** Define less inclusive variables compared to pure Mueller-Navelet jets, and compute predictions on jet gap jet observables at NLO.
7. **What are the prospects of running forward proton detectors at the LHC at high luminosity?** What will be their sensitivity to anomalous couplings between photon, W, Z bosons, top quarks…
8. How to observe saturation effects or high-gluon density regimes at the LHC and the EIC?
9. Which diffractive measurements can be performed at the LHC and the EIC in order to understand better the structure of the Pomeron?
10. Which detectors (including acceptance/resolution) will be needed at the LHC and the EIC in order to perform the best possible measurements of energy, particle production in the very forward region?
11. **How can the LHC, LHeC, and FCC improve our knowledge of the 3-dimensional structure of nucleons and nuclei?**
12. How do excited hadronic states with two or more heavy quarks form and decay?
13. What are the BSM connections for hadron spectroscopy at future facilities?
14. **How will artificial intelligence methods advance extraction of nonperturbative hadronic functions from experimental measurements?**

Precision collinear PDFs for HL-LHC studies

Toward the N3LO accuracy of parton distribution functions

S. Alekhin, R. Ball, V. Bertone, J. Blümlein, A. Cooper-Sarkar, T. Cridge, S. Forte, F. Giuli, A. Glazov, M. Guzzi, C. Gwenlan, L. Harland-Lang, T. J. Hobbs, J. Huston,[1] H.-W. Lin, S.-O. Moch, P. Nadolsky,[2] E. Nocera, F. Olness, K. Rabbertz, J. Rojo, R. Thorne, M. Ubiali, K. Xie, C.-P. Yuan

Our group will explore future opportunities for determination of the PDFs and implications for future studies explored by the Snowmass Frontiers. In addition to the Snowmass proceedings contribution, we plan to pursue physics studies of N2LO/N3LO PDFs, including those described in the companion LOI's [9–12], with an eye on complementing related efforts by the PDF4LHC working group and Les Houches workshop.

Snowmass2021 LOI: xFitter: An Open Source QCD Analysis Framework

The xFitter Developers' Team:[1] H. Abdolmaleki, S. Amoroso, V. Bertone, M. Botje, D. Britzger, S. Camarda, A. Cooper-Sarkar, J. Fiaschi, F. Giuli, A. Glazov, C. Gwenlan, F. Hautmann, H. Jung, A. Kusina, A. Luszczak, J. Morfin, I. Novikov, F. Olness, P. Starovoitov, M. Sutton, M. Walt, O. Zenaiev,

New frontiers in PDF analyses in the HL-LHC era

Maria Ubiali (DAMTP, University of Cambridge, UK), M.Ubiali@damtp.cam.ac.uk

Precision phenomenology at the Large Hadron Collider (LHC) relies upon an accurate estimate of the uncertainty in Standard Model (SM) predictions. Two dominant sources of theoretical uncertainties at hadron colliders are missing higher order uncertainty in perturbative

Snowmass2021 LoI: Constraining heavy flavor PDFs at hadron colliders

Authors in alphabetical order: Marco Guzzi, Timothy Hobbs, Pavel Nadolsky, Laura Reina, Doreen Wackeroth, Keping Xie, C.-P. Yuan

To do: write a single document based on the community consensus?

Toward N3LO accuracy in DIS and DGLAP evolution

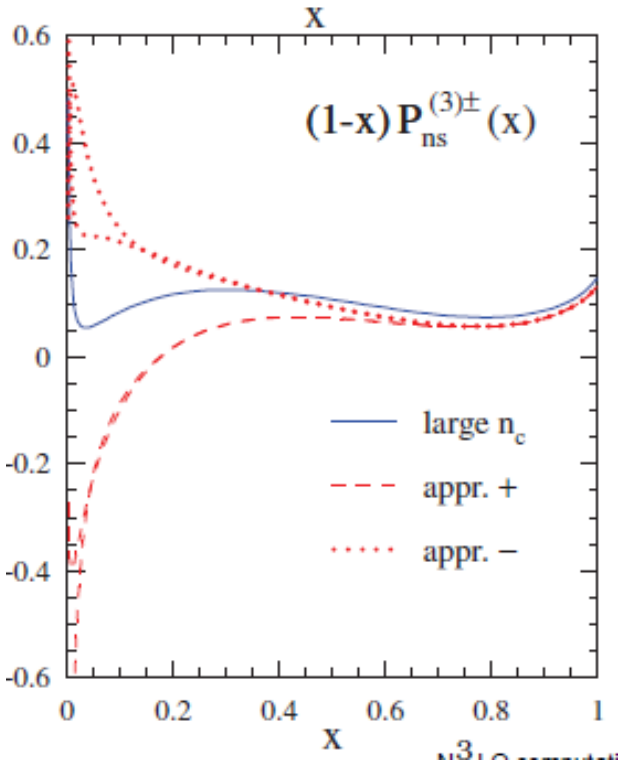
EF06 talks by J. Blümlein and S.-O. Moch

- We are getting close to having full N3LO predictions for DIS and DGLAP evolution
- The remaining unknown N3LO terms are more important at small x. In the fixed-target DIS region, the preliminary N3LO results are already stable.

Terms with massive quarks require more work.
Steady progress in computing them.

To do: summarize the talks in the final document

four-loop $P_{\rm ns}^{(3)\pm}(x)$ and uncertainty bands beyond large-n_c limit with $n_f = 4$

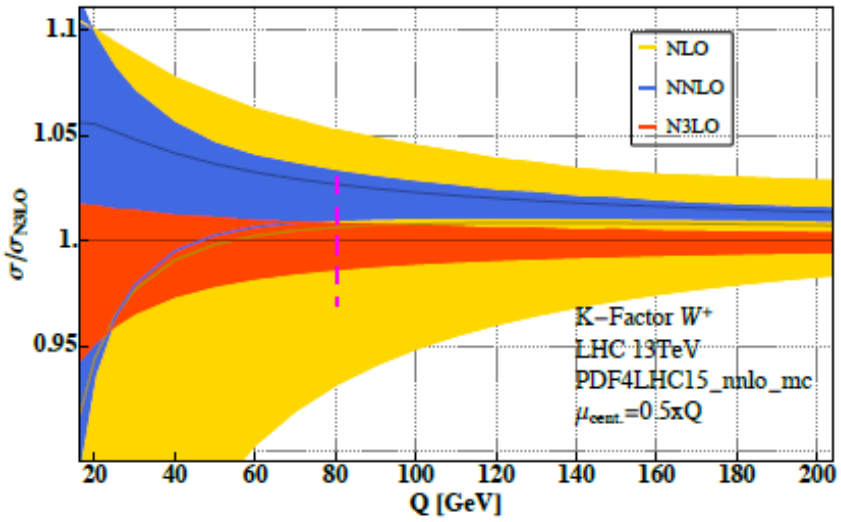


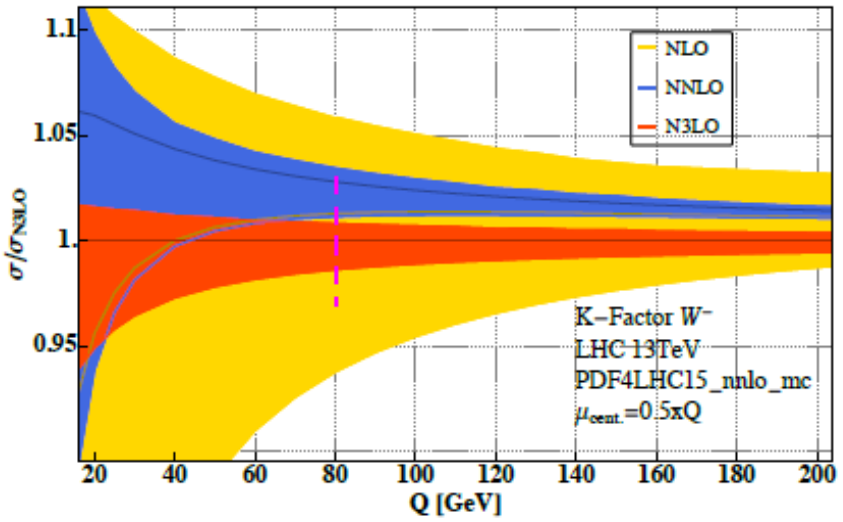
The N^{3}LO Frontier: Precision Predictions with QCD Perturbation Theory

Letter of Interest for Snowmass2021

Claude Duhr [a] , Bernhard Mistlberger[b]

NxLO K-factors for $pp \to W^{\pm}X$





Possible to do: can we estimate dependence of N3LO contributions on PDFs using the existing NNLO PDFs?

PDF-related topics in Snowmass'13 [arXiv:1310.5189] and 21' studies

Topic	Status, 2013	Status and plans, 2020
Benchmarking of PDFs for the LHC	Before PDF4LHC'2015 recommendation	In progress toward PDF4LHC'2X recommendation
PDFs with NLO EW contributions	MSTW'04 QED, NNPDF2.3 QED	Needs an update using LuXQED and other photon PDFs; PDFs with leptons and massive bosons
PDFs with resummations	Small x (in progress)	Needs an update for PDFs with small-x and threshold resummations
Parton luminosities at 14, 33, 100 TeV	CT10, MSTW2008, NNPDF2.3 Update at 100 in CERN YR (1607.01831)	Need an update based on the latest PDFs
LHC processes to measure PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production	updates on these processes + $Q\bar{Q}$, dijet, $\gamma/W/Z$ +jet, low-Q DY, …
Future experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3 DIS: EIC, LHeC, …

NEW TASKS in THE HL-LHC ERA:

Obtain complete NNLO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast NNLO interfaces	Estimate NNLO theory uncertainties	Develop an agreement on comparing and combining PDF fits

Talks by J. Huston, M. Guzzi, J. Rojo,M. Ubiali, K. Xie, P. Nadolsky

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Parton luminosities at 33, 100 TeV	Update at 100 in CERN YR (1607.01831)	date based on the latest PDFs
LHC processes to measure PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production	updates on these processes + $Q\bar{Q}$, dijet, $\gamma/W/Z$ +jet, low-Q DY, …
Future experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3 DIS: EIC, LHeC, …

To-do: We invite volunteers to contribute on these topics

NEW TASKS in THE HL-LHC ERA:

Obtain complete NNLO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
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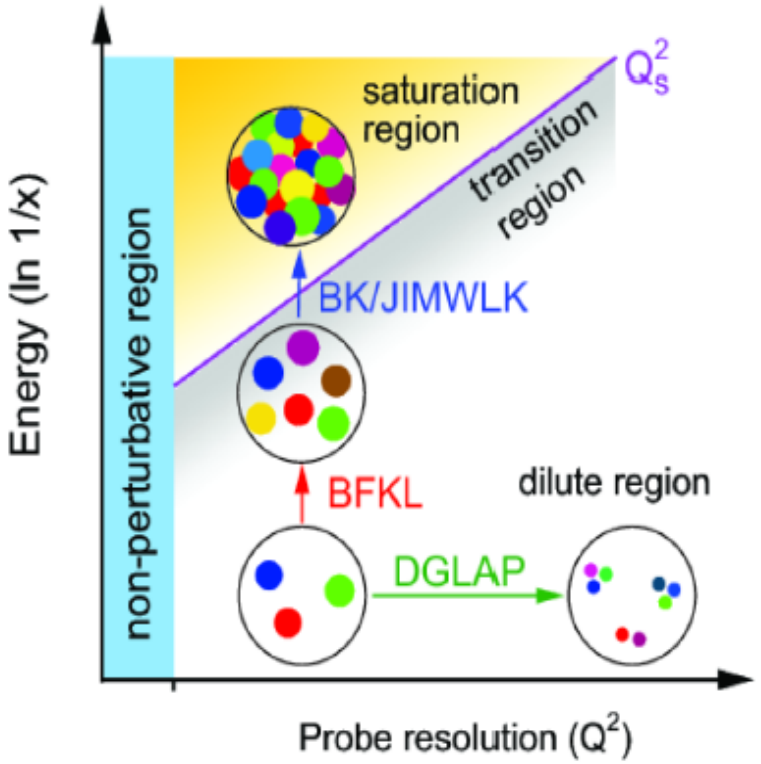
Talks by J. Huston, M. Guzzi, J. Rojo,M. Ubiali, K. Xie, P. Nadolsky

A new regime of QCD: low x, BFKL resummation, saturation



Which observables allow access to the high-parton-density regime of QCD at future facilities?

- Measurements of Mueller-Navelet jets (mini-jets), low-x heavy quark, hadron-hadron,Higgs-jet, trijet, vector meson production at LHC, LHeC, FCC-hh…; heavy ions

What is the realistic path toward a unified formalism describing transitions between DGLAP, BFKL, and saturation regimes?

Future DIS facilities, LHeC and FCC-eh

PDFs, α_s and Low-x Physics and at Future DIS Facilities

LHeC/FCC-eh: Future (energy frontier) Electro-Proton and Electron-Hadron Colliders

The LHeC/FCC-eh PDF & Low x Study Group:[1]

Conveners: N. Armesto, D. Britzger, C. Gwenlan, M. Klein, P. Newman, F. Olness, A. Stasto,

with the working group.[2]

LHeC and FCC-eh: Small-x Physics at Energy Frontier Electron-Proton and Electron-Nucleus Colliders[1]

N. Armesto, M. Bonvini, C. Gwenlan, M. Klein, H. Mäntysaari, P. R. Newman, F. Olness, P. Paakkinen, H. Paukkunen, A. M. Stasto, P. Zurita, with the LHeC and FCC-eh Study Group

PDFs, α_s and Low-x Physics and at Future DIS Facilities

LHeC/FCC-eh: Future (energy frontier) Electro-Proton and Electron-Hadron Colliders

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Future DIS, EIC-focused letters

Hadronic Tomography at the EIC and the Energy Frontier

Editors in alphabetical order: S. Fazio, T. J. Hobbs[1], A. Prokudin, A. Vicini
Authors in alphabetical order: H. Abdolmaleki, M. Ahmady, C. Aidala, A. Al-bataineh, A. Aprahamian, M. Arratia, J. Arrington, A. Asaturyan, A. Bacchetta, F. Benmokhtar, P. Bernard, J. Bernauer, C. Bertulani, V. Bertone, M. Boglione, R. Boughezal, R. Boussarie, G. Bozzi, F. Bradamante, V. Braun, A. Bressan, W. Briscoe, D. Bruhwiler, M. Bukhari, C. Cabrera, C. Muñoz Camacho, A. Camsonne, E. G. Celiberto, T. Chetry, M. Chiosso

Impact of the Electron Ion Collider on particle physics at the Energy Frontier

R. Boughezal[a], S.V. Chekanov[a], I. Cloet[b], T. Hobbs[d], J.R. Love[a], F.J. Petriello[c], D. Wiegand[a], R. Yoshida[a]

Letter of Interest: Heavy Flavors at the EIC

H. Abdolmaleki (IPM), M. Arratia (UC Riverside), Y.-T. Chien (SUNY Stony Brook), X. Dong (LBNL), M. Durham (LANL), Y. Furletova (JLab), M. Garzelli (Hamburg U.), V.P. Goncalves (UFPel), T. Hobbs (SMU), J. Huang (BNL), Y. Ji (USTC/LBNL), Z. Kang (UCLA), M. Kelsey (LBNL), X. Li (LANL), H.-

Snowmass 2021 Letter of Interest: Jet Physics at the Electron Ion Collider

The EICjets Community[1]

Jet studies have played a key role in the exploration of QCD since its conception [1]. With the advances in experimental techniques, and theory development over time, jets

Snowmass 2021 Letter of Intent:
EW and BSM physics at EIC

M. Arratia, M. Battaglieri, M. Begel, R. Boughezal, R. Corliss, A. Deshpande, S. Forte, Y. Furletova[1],

EIC Letter of Interest:
Higher twist effects in inclusive and diffractive nuclear structure functions

K. Golec-Biernat[a,1], L. Motyka[b,2], M. Sadzikowski[b,3] and W. Słomiński[b,4]

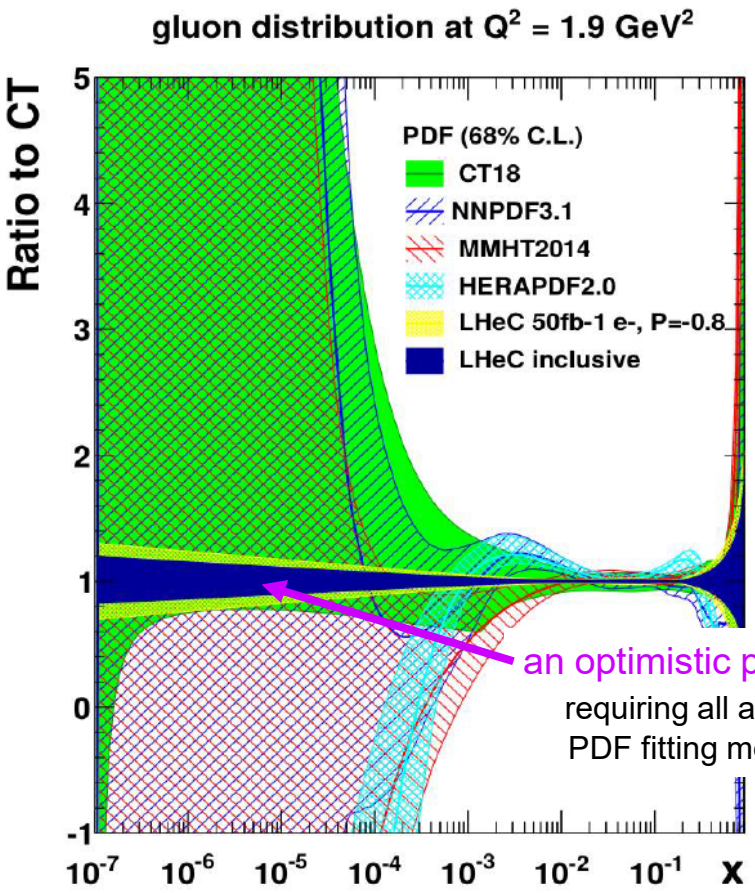
Gluon Saturation at the Electron Ion Collider

Renaud Boussarie,[1,*] Tuomas Lappi,[2,3,†] Björn Schenke,[1,‡] and Sören Schlichting[4,§]

What can we learn about PDFs at future ep/eA colliders?

Talks by N. Armesto, T. Hobbs, F. Olness, A. Stasto; EIC@Snowmass meeting on Aug.4

An ep collider operating concurrently with the HL-LHC can contribute critical **complementary** measurements of PDFs that are **independent** of the LHC systematic effects and free from high-mass BSM contributions



An **Electron-Ion Collider** can replace most of fixed-target and nuclear-target measurements constraining proton PDFs at large x. It will systematically study PDFs for heavy nuclei.
https://indico.fnal.gov/event/44510/

The **Large Hadron-Electron Collider** will supersede the HERA DIS measurements and extend the kinematic reach of DIS to very small x and large Q

To do: update projections for the LHeC and EIC constraints on PDFs using consistent reweighting methods

Select LOI's on lattice PDFs

Charm Parton Distribution Functions from Global Analysis and Lattice QC

Tie-Jiun Hou,[1,*] Joey Huston,[2,†] Huey-Wen Lin,[2,3,‡] Carl Schmidt,[2,§] C.-P. Yuan,[2,¶] and Rui Zhang[2]
[1]*Department of Physics, College of Sciences, Northeastern University, Shenyang 110819, China*

Towards global fits of three-dimensional hadron structure from lattice QCD

Christopher Monahan[1,2*], Luigi Del Debbio[3], Huey-Wen Lin[4], Kostas Orginos[1,2]

Precision Moments of Strange Parton Distribution Functions from Lattice QCD

Tanmoy Bhattacharya,[1] Rajan Gupta,[1] Huey-Wen Lin,[2,3] Santanu Mondal,[1] Boram Yoon,[1] and Rui Zhang[2,3]

Transverse-momentum-dependent parton distributions from lattice QCD

Markus Ebert,[1,*] Jian Liang,[2,†] Yizhuang Liu,[3,‡] Phiala Shanahan,[1,§]
Iain Stewart,[1,¶] Michael Wagman,[4,**] Wei Wang,[5,††] and Yong Zhao[6,‡‡]

Small-x parton physics on lattice

(Letter of Interest for Snowmass 2021)

Xiangdong Ji,[1] Luchang Jin,[2] Bo-Wen Xiao,[3] and Feng Yuan[4,*]

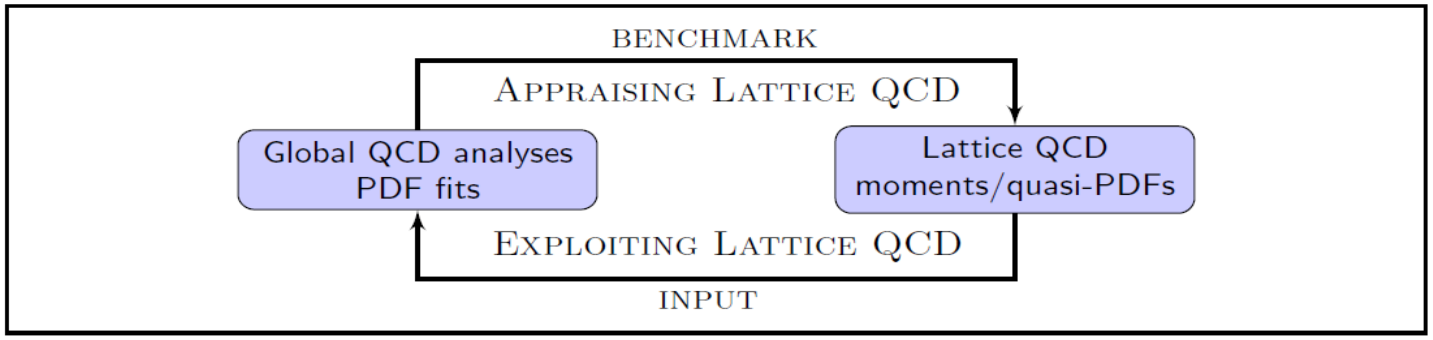
Lattice-QCD Determinations of Quark Masses and the Strong Coupling α_s

Fermilab Lattice, MILC, and TUMQCD Collaborations

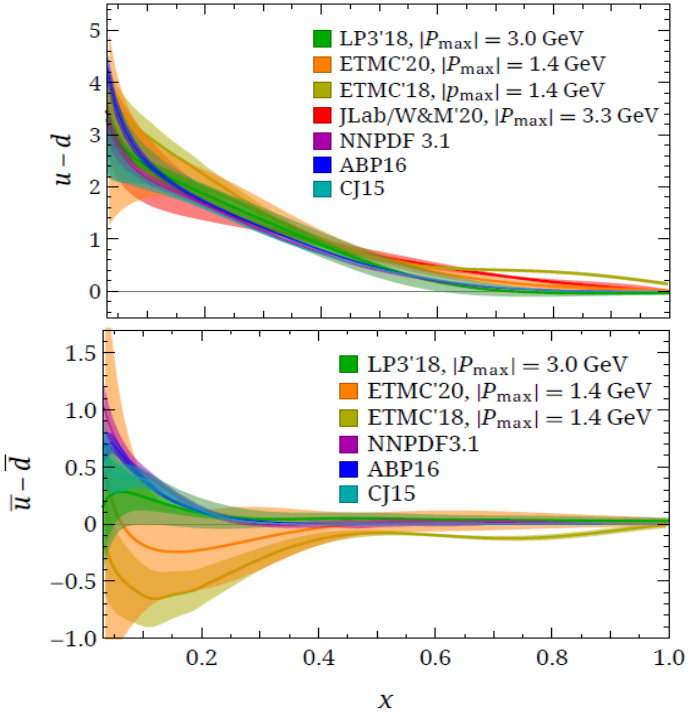
Letter of Interest for EF06: Parton distribution functions from lattice QCD

Peter Boyle[1,2], Taku Izubuchi[1,3], Luchang Jin[3,4], Peter Petreczky[1], Swagato Mukherjee[1], and Sergey Syritsyn[3,5]

Lattice QCD: ab initio computations of PDFs



Talk by E. Nocera
Snowmass EF06
Topical group



Lattice QCD computes nonperturbative functions for the hadron structure (Mellin moments, quasi-PDFs, pseudo-PDFs) by discretizing the QCD Lagrangian density

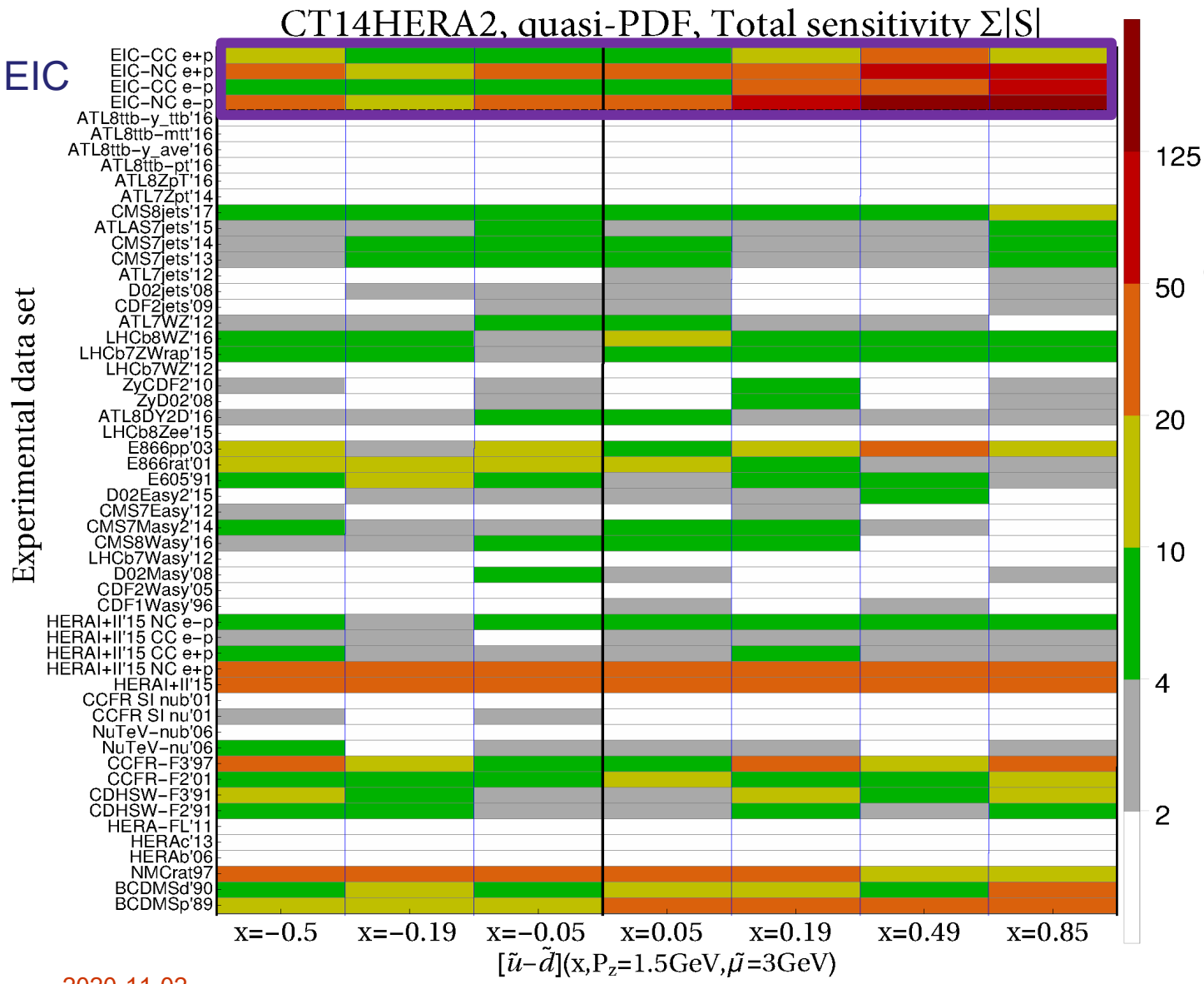
This is a rapidly progressing field: computations of PDFs in several lQCD approaches have been compared against phenomenological PDF models at two workshops:

- PDFLattice2017, Oxford, March 2017
- PDFLattice2019, Michigan State University, Sept. 2019

[Prog.Part.Nucl.Phys. 100 (2018) 107; arXiv:2006.08636]

Pheno PDFs provide empirical benchmarks for lattice QCD computations. Lattice QCD has the potential to predict PDF combinations not accessible in the experiment.

Total sensitivity to lattice quasi-PDFs



$$\tilde{q}(x) \equiv \begin{cases} q(x), & x > 0; \\ -\bar{q}(|x|), & x < 0 \end{cases}$$

$Q = 3$ GeV,
$P_z = 1.5$ GeV

T. Hobbs et al.,
arXiv: 1904.00022

Many interesting LOI's…

Precision measurements of α_S and its running at future colliders

S. Amoroso,[1] R. Ball,[2] M. Begel,[3] S. Bhattacharya,[4] D. d'Enterria,[5] M. Feickert,[6] S. Forte,[7] A.

Uncertainties in perturbative QCD calculations and Monte-Carlo simulations

S. Amoroso,[1] R. Ball,[2] M. Begel,[3] S. Bhattacharya,[4] M. Campanelli,[5] M. Diefenthaler,[6] S. Forte,[7]

Recommendations for more precise and robust assessment of experimental and systematic QCD uncertainties

S. Amoroso,[1] M. Begel,[2] S. Bhattacharya,[3] M. Campanelli,[4] M. Diefenthaler,[5] S. Forte,[6] A. Grohsjean,[1] S. Hoeche,[7] J. Huston,[8] F. Krauss,[9] T. LeCompte,[10] S. Liuti,[11] CH McLean,[12] S-O Moch,[13] B. Nachman,[14] P. Nadolsky,[15] S. Plätzer,[16] S. Prestel,[17] J. Rojo,[18] M. Schmitt,[3] and M. Vos[19]

[1] *DESY*

Synergy of astro-particle physics and collider physics

Contact Information:
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Authors:

Rana Adhikari, Markus Ahlers, Michael Albrow, Roberto Aloisio, Luis A. Anchordoqui, Ignatios Antoniadis, Vernon Barger, Jose Bellido Caceres, David Berge, Douglas R. Bergman, Mario E. Bertaina, Lorenzo

Generative, Explainable Artificial Intelligence for Nuclear Physics and HEP

Status and prospects of nuclear PDFs at the LHC

Georgios K Krintiras,[1,*] Émilien Chapon,[2,†] and Hannu Paukkunen[3,‡]

The Femtography Project

Contact person: Simonetta Liuti

Authors: P. Alonzi (UVA), M. Boer (Virginia Tech), M. Burkardt (NMSU), G. Cates

Computing needs of PDF fits

With the Computational Frontier

PDF fits require speed and accuracy;
critically depend on…

…high-performance computing

(N)NNLO QCD, NLO EW computations

Development of fast (N)NNLO interfaces

Benchmarking of multithreaded fitting codes (Fortran, C++, Python,…)

…data science & machine learning

Probability distributions with hundreds of parameters

Shapes of PDFs presented by flexible functions (ABM, CTEQ, HERA, MMHT, …) or CNNs (NNPDF)

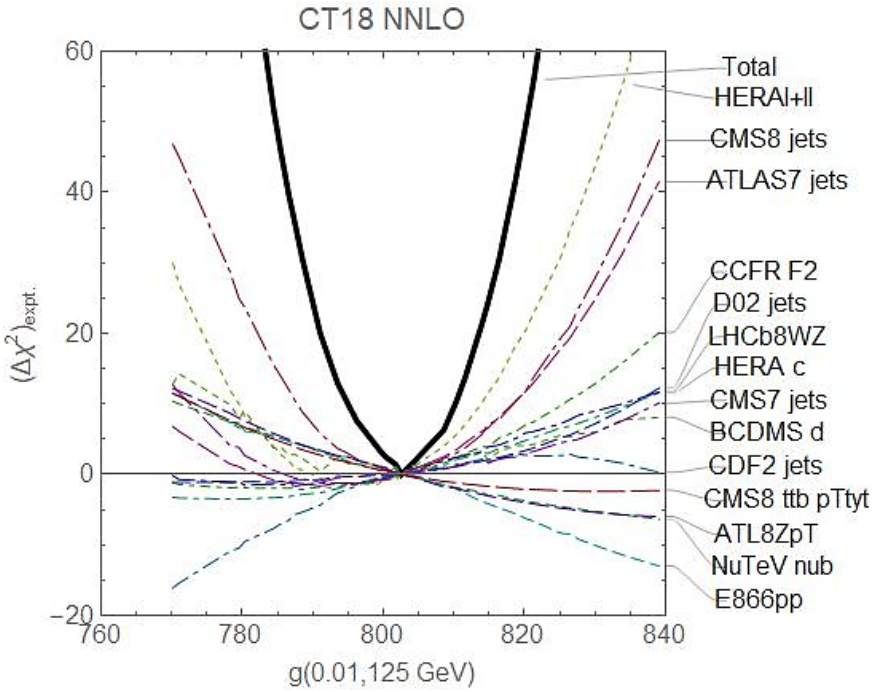
Global fits to >40 heterogenous measurements in collider and fixed-target experiments

Minimization/learning with MINUIT, TensorFlow, genetic algorithms…

Algebraic marginalization of labyrinthine experimental systematic uncertainties

PDF4LHC combinations of PDF sets for LHC applications. Dimensionality reduction in METAPDF/compressed PDF methods. The majority of LHC publications use PDF error sets!

Example, computing requirements, CT18 study



A Lagrange Multiplier scan…

…offers a detailed picture of pulls from experiments on the CT18 gluon PDF in the Higgs production region

…instrumental for reducing PDF uncertainties

Intel Xeon E5-2695 v4 workstations, 18 cores/48 GB RAM per 1 fit

Memory management issues to read large ApplGrid/FastNLO tables

Task	Approximate core-hours
1 candidate NNLO fit	300-430
1 NNLO error set	1300
1 LM scan, for 1 point in x and Q	6500
6000+ fits we performed to study parametric, theoretical, methodological uncertainties	> 6000*300=$1.8 \cdot 10^6$

To do: what are computing requirements for future PDF studies by various global analysis groups?

The next steps

- Get involved in physics studies! If you are interested to work on the action items, let me know! The list of the action items is not exhaustive.
- Let us know about your relevant work.
- Volunteer to give a talk.
- Participate in the weekly meetings and (all-)frontier workshops.
- Let your colleagues know about the Snowmass.
- Encourage students and postdocs to participate. We have projects for them!
    - October 14: An EF06 meeting for Early Career Researchers

We will have the skeleton draft of the EF06 section in November (based on the focus questions)

In April 2021, the EF will invite the participants to send us 2-paragraph summaries for their Snowmass Proceedings Contributions

July 11-21, 2021: in-person meeting in Seattle

The submission of Proceedings by July 31, 2021

Backup