Studies of PDFs at Snowmass'2021

Pavel Nadolsky

Southern Methodist University

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

Based on presentations and Letters of Interest in the Snowmass Energy Frontier and EF06 Topical Group

https://snowmass21.org/energy/start

Snowmass 2021 Process

- A long-term planning study for the US particle physics
- Named after a village in Colorado mountains where HEP community meetings took place since 1982
- A wide-ranging community study of particle **physics**. It informs the Particle Physics Project Prioritization Panel (P5) and High Energy Physics Advisory Panel (HEPAP) that recommend research priorities to the US Department of Energy and the US National Science Foundation.
- The previous Snowmass study in 2013 ["Snowmass @ Mississippi"] was mostly virtual. The results were used by P5 to formulate "The Strategic Plan for U.S. Particle Physics in the Global Context."
- The Snowmass 2021 study also follows the virtual format.

How to Snowmass

By Chris Quigg, Aug. 2020 [https://tinyurl.com/HowToSnowmass]

An essay about the goals, history, and process of Snowmass studies

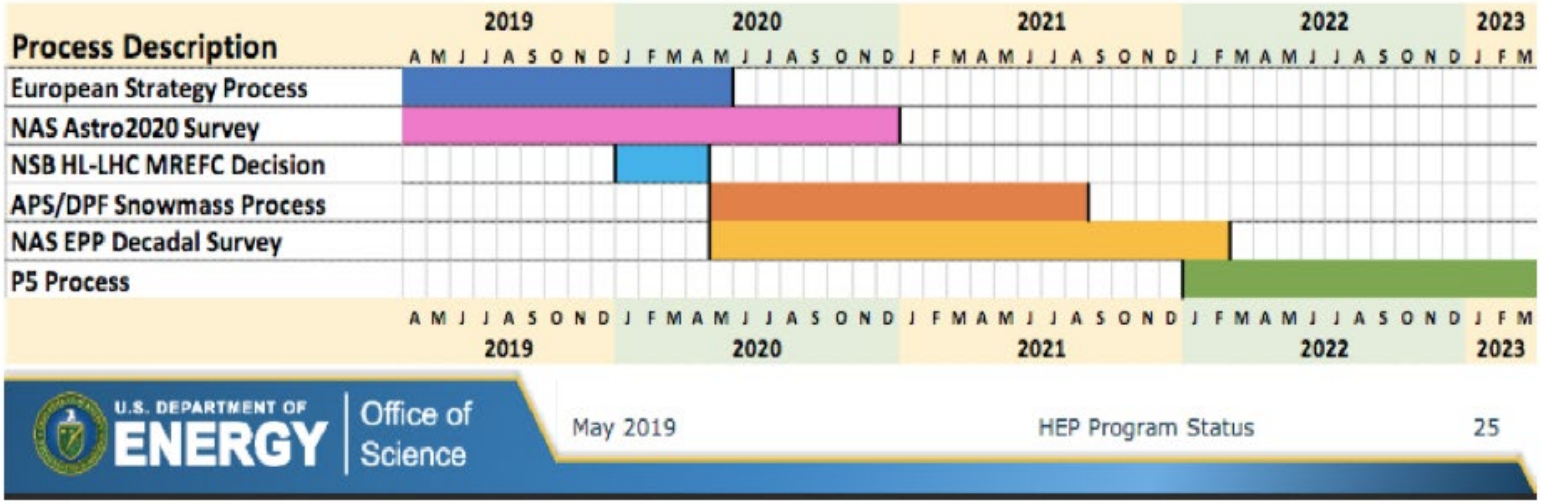
> "The goals of Snowmass—and the outcomes—are defined by individual participants, led by the organizers. This year's announcement speaks of an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. with our international partners."

Snowmass is a comprehensive study of US particle physics **in the global context**

- New horizons in research
- Advocacy for new projects and lines of research
- Resources needed for future studies: infrastructure, computing, etc.
- Human aspects: people, HEP organizations, funding mechanisms, HEP and society, outreach,…

International participants are welcomed and are very active in Snowmass efforts

International Timeline



Snowmass Final Report: Fall 2021

NAS (National Academy of Sciences) Decadal Survey Report: end 2020 or very early 2022

Slide by A. Tricoli, M. Narain, L. Reina

Snowmass'2021 organization, events, and documents

10 Frontiers (topical areas):

Theory Rare processes Neutrino physics Cosmic
Energy **Computational** **Accelerator** Instrumentation
Underground facilities Community engagement

10 EF Topical groups

Events:

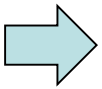
Topical workshops and (bi)weekly group meetings

Frontier workshops

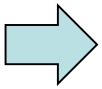
All-frontier meetings
Community Planning Meeting
Oct. 5-8, 2020
Virtual; open to everyone
…
Snowmass Workshop
Seattle, July 11-21, 2021

Documents:

Letters of Interest
(due by 2020-09-01)



Snowmass Proceedings
(due by 2021-07-31)



Final report
(Oct. 2021)

Energy Frontier Topical Groups

Topical Group	Co-Conveners		
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL)	Andrey Korytov (U Florida)	Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook)	Isobel Ojalvo (Princeton)	
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU)	Doreen Wackeroth (Buffalo)	
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland)	Ayres Freitas (Pittsburgh)	Junping Tian (Tokyo)
EF05: QCD and strong interactions: Precision QCD	Michael Begel (BNL)	Stefan Hoeche (FNAL)	Michael Schmitt (Northwestern)
EF06: QCD and strong interactions: Hadronic structure and forward QCD	Huey-Wen Lin (MSU)	Pavel Nadolsky (SMU)	Christophe Royon (Kansas)
EF07: QCD and strong interactions: Heavy Ions	Yen-Jie Lee (MIT)	Swagato Mukherjee (BNL)	
EF08: BSM: Model specific explorations	Jim Hirschauer (FNAL)	Elliot Lipeles (UPenn)	Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin-Madison)	Zhen Liu (Maryland)	Simone Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund)	LianTao Wang (Chicago)	

Physics Charges of Topical Groups

QCD and strong interactions

- **EF05: Precision QCD**

QCD higher-order corrections, jets, event generators, alphas, quark masses, **PDF for precision physics.**

- **EF06: Hadronic Structure and forward QCD**

PDF fits, **Generalized PDF**, Forward QCD, hadron spectroscopy at colliders.

- **EF07: Heavy Ions**

Impact of heavy-ion physics on EF physics (ex.:EIC physics).

Many PDF-related topics are pursued jointly by EF05, 06, and 07

Energy Frontier Topical Group 6 (EF06)

Conveners: Huey-Wen Lin, Pavel Nadolsky, Christophe Royon

Weekly meetings in three topical tracks:

1. **Hadron structure and Parton Distribution Functions**
   - In-depth tests of QCD -- the unique QFT accessible in both perturbative and nonperturbative regimes
   - Essential input for EW precision and BSM studies in hadron scattering
   - 3-dimensional hadron structure, new PDF types (TMD's, GPD's, polarized, nuclear,…)

2. **QCD at small momentum fractions, saturation, diffraction**
   - Transition to the high-density regime of QCD
   - Increasingly relevant at the HL-LHC, FCC-hh, LHeC
   - Impact on the design of new detectors at FCC, etc.

3. **Nonperturbative models of hadrons and hadron spectroscopy**
   - PDFs on the lattice
   - New exotic hadronic states at the LHC, B-factories, …
     (overlaps with Rare Processes & Precision Measurements Frontier)
   - …

Agendas and slides from presentations at https://indico.fnal.gov/category/1140/

Overlapping topics with EF03, 04, 05, 07

EF06 Topical Group status, 2020-10-02

197 subscribers to the SNOWMASS-EF-06-HAD_FWD_QCD email list

- Our main communication channel
- To subscribe, email listserv@fnail.gov with a blank subject and the main body containing a single line:
  SUBSCRIBE SNOWMASS-EF-06-HAD_FWD_QCD FIRSTNAME LASTNAME

15 past meetings, including agendas, slides, and meeting recordings, and 9 future meetings can be viewed at https://indico.fnal.gov/category/1140/.

Usually meet on Wednesdays at 9am CDT/10am EDT/16h00 CERN time

Received 60 Letters of Interest (LOIs) – 2-page introductions of new ideas and future projects

An Adobe PDF file with all LOIs is available at https://tinyurl.com/Snowmass21EF06LOIs

Many thanks for excellent PDF-related talks

to EF06 speakers :

N. Armesto, V. Bertone, M. Bonvini, J. Blümlein, S. Chekanov, A. Cooper-Sarkar, C. Duhr, J. Feng, F. Kling, M. Garzelli, T. Hobbs, J. Huston, Z. Kang, P. Kotko, K. Kutak, S.-O. Moch, L. Motyka, E. Nocera, F. Olness, J. Rojo, A. Stasto, M. Ubiali, I. Vitev, K. Xie

as well as to all LOI authors who are too many to be listed here!

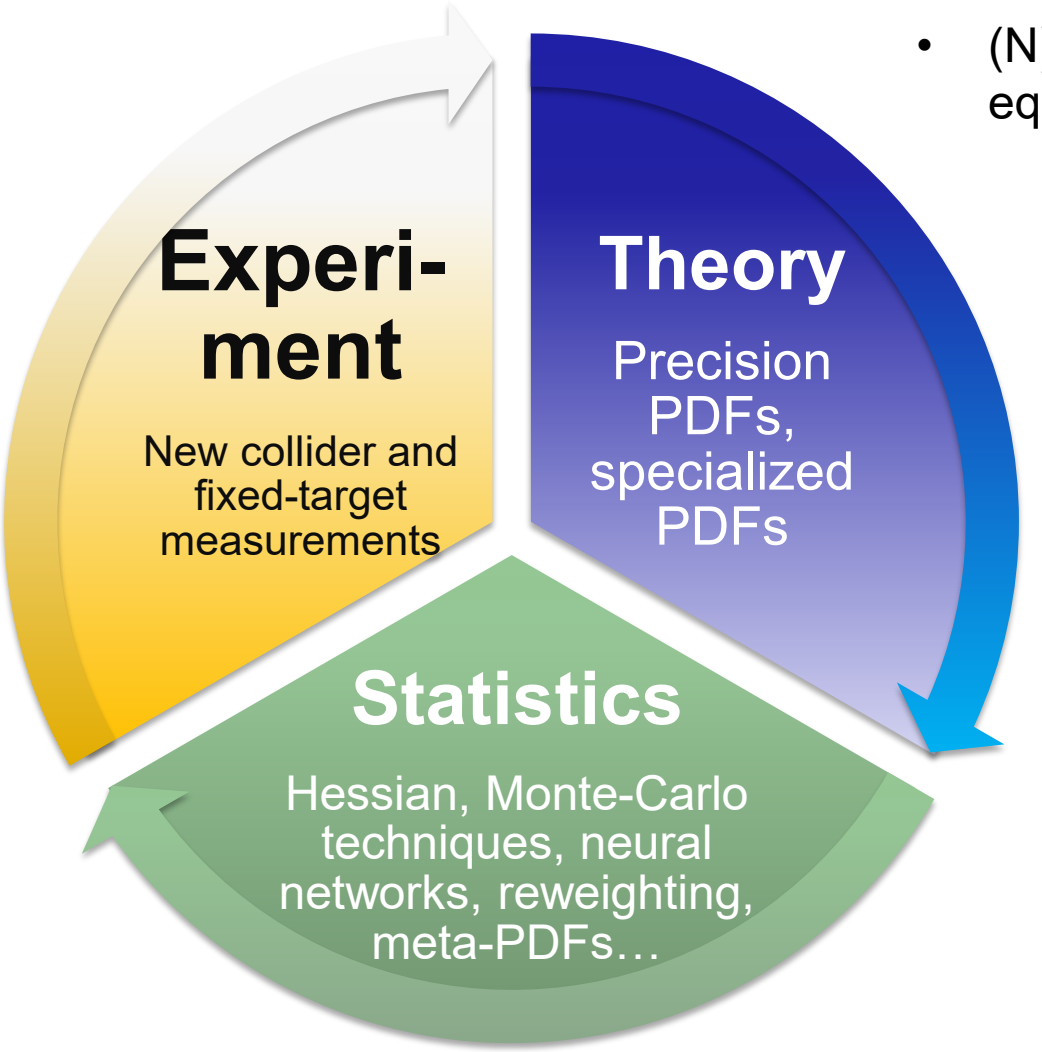
Highly stimulating LOI's on TMDs, GPDs, nuclear PDFs…

Within my short talk, I will focus on unpolarized collinear PDFs.

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?**

Frontiers of the PDF analysis



- (N)NNLO QCD computations require equally accurate PDFs
- Significant advances on all aspects of the proton PDF analysis are necessary to meet physics targets of the HL-LHC program
- Exceptional opportunities to learn about the 3-dim. structure of protons, nuclei, pions at new facilities in the HL-LHC era: EIC, LHeC, AMBER, LHCSpin…

Examples of LOIs in the EF06 Topical Group

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

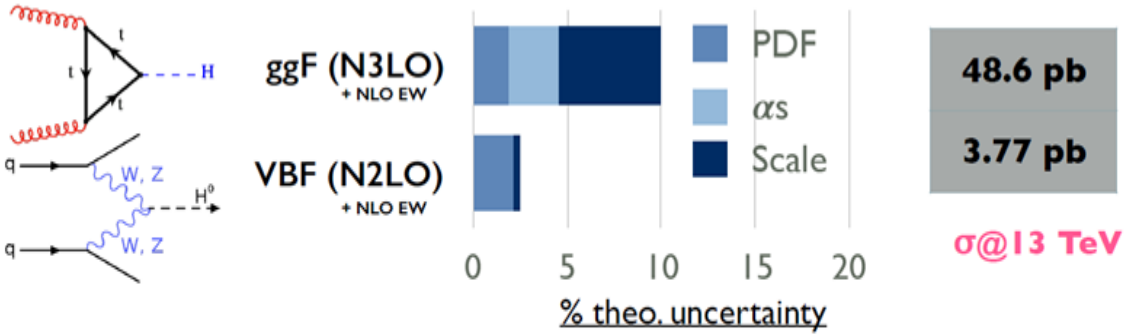
Precision phenomenology at the Large Hadron Collider (LHC) relies upon an accurate estimate of the uncertainty in Standard Model (SM) predictions. Two dominant sources of theoretical uncertainties at hadron colliders are missing higher order uncertainty in perturbative

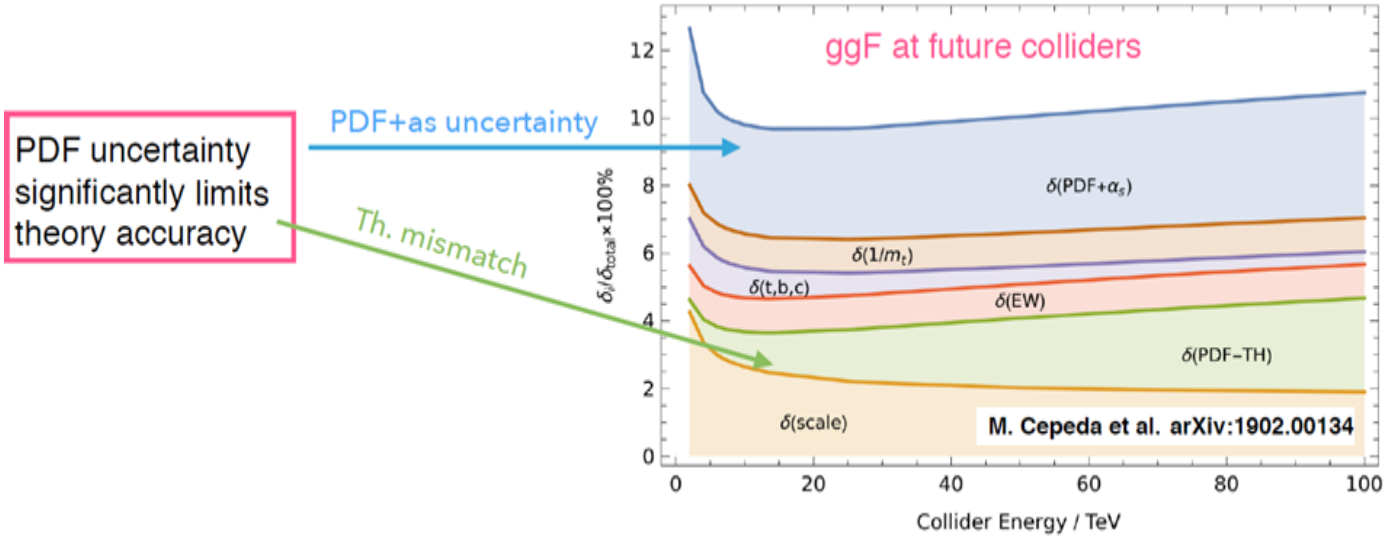
Action items (AIs): we solicit inputs to update the PDF section of the Snowmass'2013 report. We also need satellite proceedings contributions such as physics studies.

PDFs and α_s introduce leading uncertainties in EW/BSM physics at hadron colliders

Talk by M. Ubiali

For example, in Higgs production at the HL-LHC and HE-LHC





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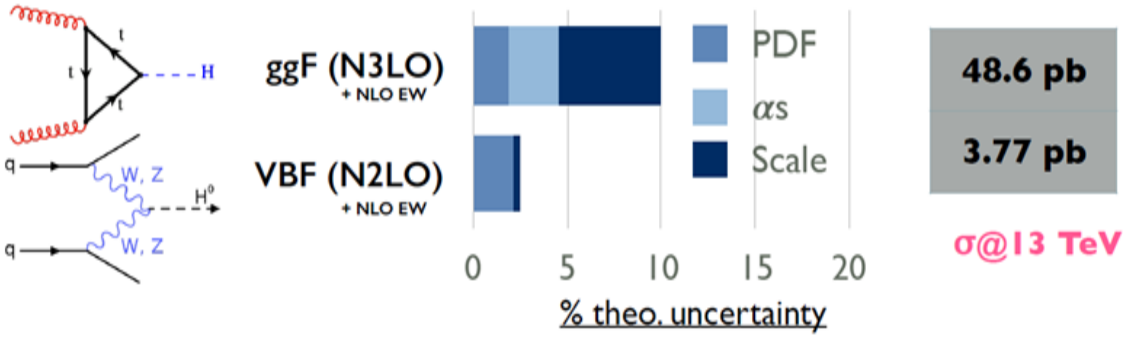
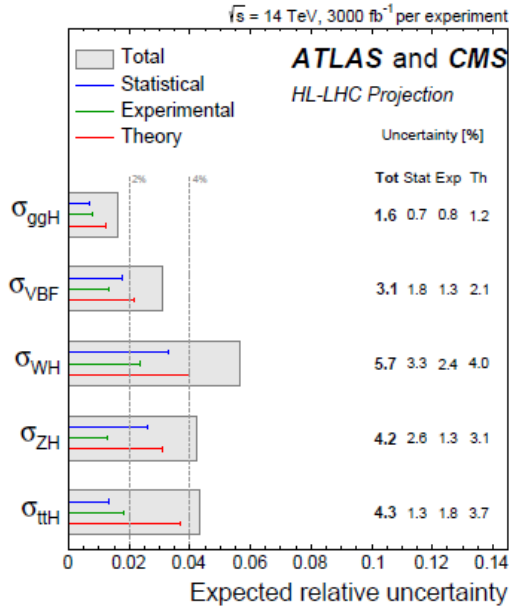


Reaching the targeted accuracy of PDFs at the HL-LHC/HE-LHC is not automatic:

which advancements in QCD theory & PDF determination will be required, as well as new measurements at the LHC and other facilities?



M. Cepeda et al., arXiv:1902.00134

Toward N3LO accuracy in DIS and DGLAP evolution

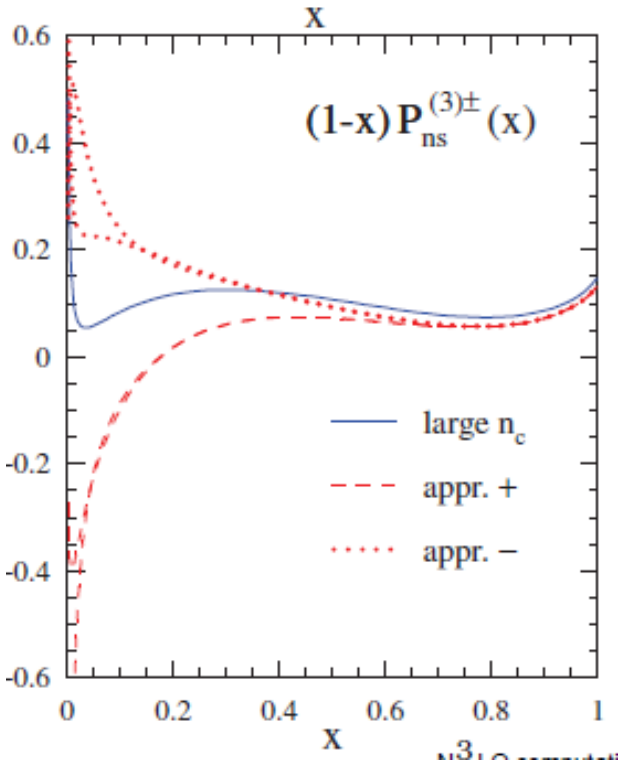
EF06 talks by J. Blümlein and S.-O. Moch

- 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.

AIs: summarize the status of these efforts for the final document

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

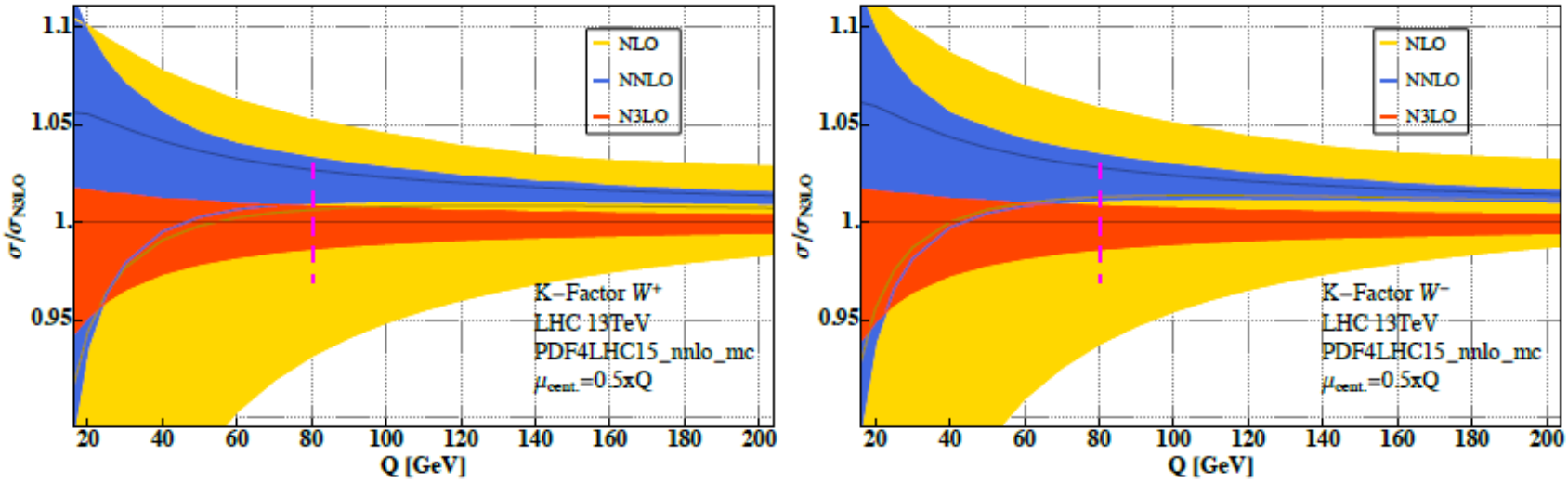


The N^{3}LO Frontier: Precision Predictions with QCD Perturbation Theory

Letter of Interest for Snowmass2021

Claude Duhr [a] , Bernhard Mistlberger[b]

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



Possible A.I.: 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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PDFs with resummations	Small x (in progress)	Needs an update for PDFs with threshold ns
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, …

AI: We invite volunteers to contribute on these topics

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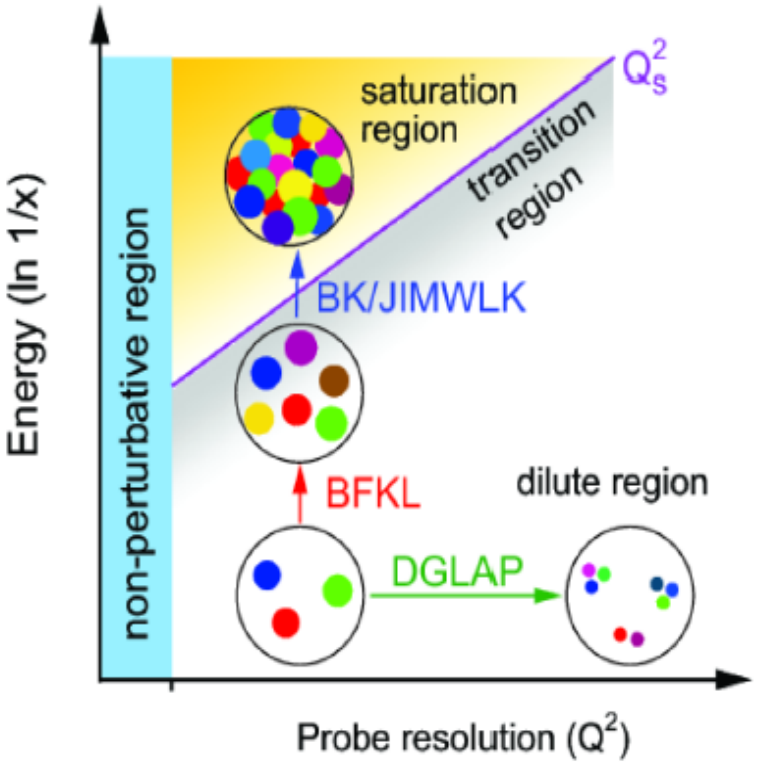
Talks by J. Huston, M. Guzzi, J. Rojo,M. Ubiali, K. Xie, P. Nadolsky

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



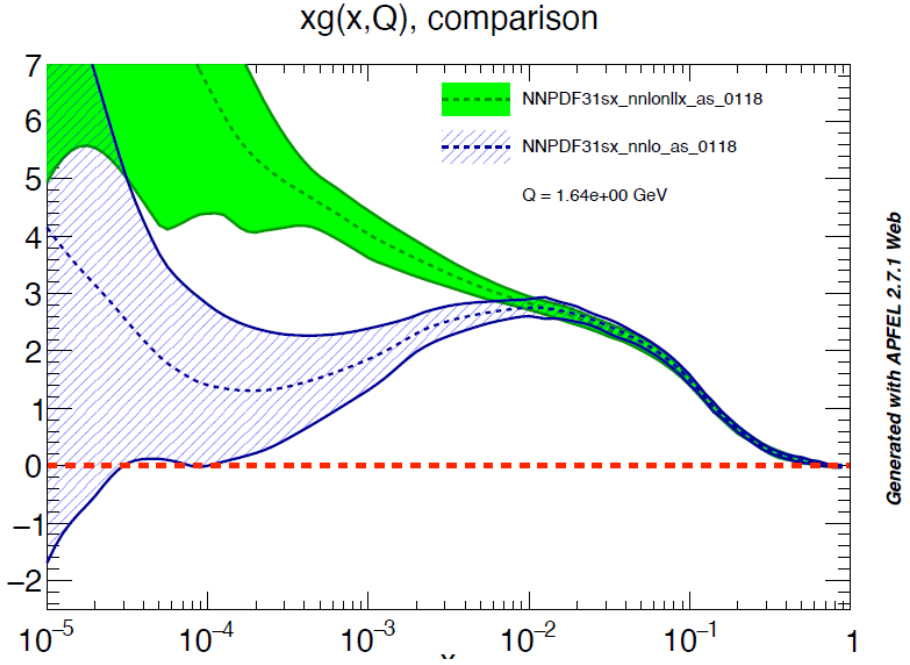
Which observables allow access to the high-parton-density regime of QCD at future facilities?

- 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?

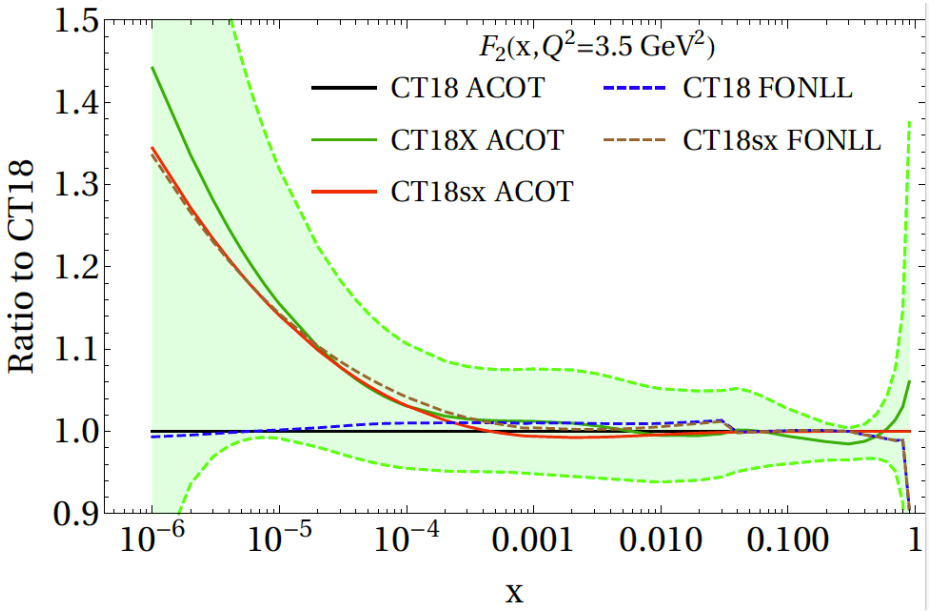
Latest [resummed] NNLO PDFs at $x < 10^{-5}$

NNLO+NLLx NN PDFs v. 3.1
[V. Bertone]



Small-*x* resummation effects make the low-Q^2 and low-*x* gluon PDF look much like a *sea* distribution.

CT18X NNLO PDFs with a factorization scale that models small-x saturation
[K. Xie; based on arXiv:1912.10053]



CT18sx implements NLLx resummation using the HELL code. CT18X and CT18sx predictions for F_2 are indistinguishable down to $x \sim 10^{-5}$, are still close at $x \sim 10^{-6}$.

AI: compare predictions for F2 and FL based on various PDFs at $x = 10^{-9} - 10^{-5}$. At which x and Q^2 do we clearly transit to BFKL, then to saturation?

Future LHC experiments in the far-forward rapidity region

Letter of Intent: A Forward Calorimeter at the LHC

I.G. Bearden[5], R. Bellwied[1], V. Borshchov[10], J. Faivre[12], C. Furget[12], E. Garcia-Solis[2], M.B. Gay Ducati[9], G. Conesa-Balbastre[12], R. Guernane[12], C. Loizides[3], J. Rojo[11], M. Płoskoń[4], S.R. Klein[4], Y. Kovchegov[15], V.A. Okorokov[7], T. Peitzmann[11], M. Protsenko[10], J. Putschke[13], D. Röhrich[8], J.D. Tapia Takaki[6], I. Tymchuk[10], M. van Leeuwen[11], and R. Venugopalan[14]

A Very Forward Hadron Spectrometer for the LHC.
(Expression of Interest: Snowmass EF05,EF06)

D.Cerci, S.Cerci (Adiyaman), F.Gargano, F.Loparco, M.N.Mazziotta (INFN, Bari), B.Bergmann,

FASER 2: Forward Search Experiment at the HL LHC

Henso Abreu,[1] Yoav Afik,[1] Claire Antel,[2] Akitaka Ariga,[3] Tomoko Ariga,[4] Florian Bernlochner,[5] Tobias Boeckh,[5] Jamie Boyd,[6] Lydia Brenner,[6] Franck Cadoux,[2] David W. Casper,[7] Xin Chen,[8]

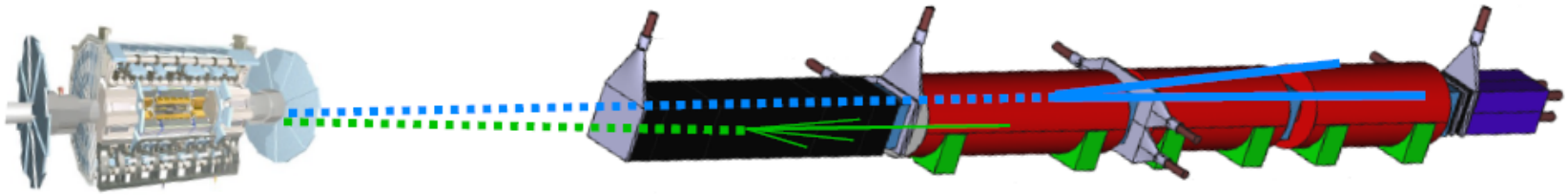
FASERν 2: A Forward Neutrino Experiment at the HL LHC

Henso Abreu,[1] Yoav Afik,[1] Claire Antel,[2] Akitaka Ariga,[3] Tomoko Ariga,[4] Florian Bernlochner,[5] Tobias Boeckh,[5] Jamie Boyd,[6] Lydia Brenner,[6] Franck Cadoux,[2] David W. Casper,[7] Xin Chen,[8]

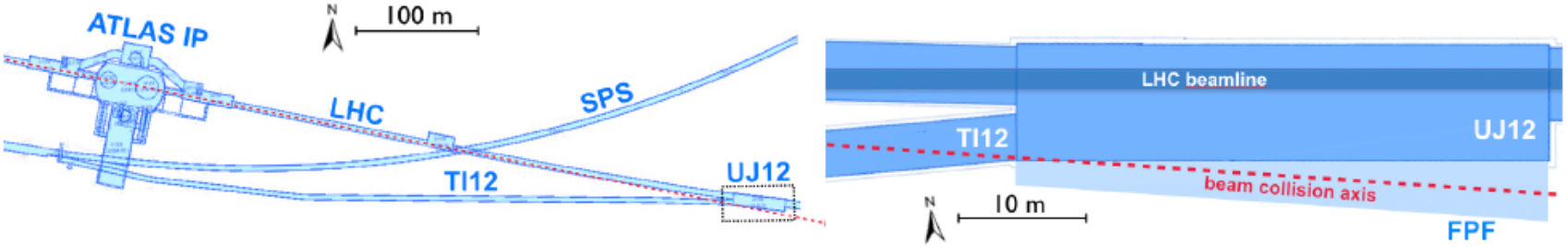
FORWARD PHYSICS FACILITY

Roshan M. Abraham,[1] Henso Abreu,[2] Yoav Afik,[2] Sanjib K. Agarwalla,[3] Juliette Alimena,[4] Luis Anchordoqui,[5] Claire Antel,[6] Akitaka Ariga,[7] Tomoko Ariga,[8] Carlos A. Argüelles,[9] Kento Asai,[10] Pouya

FASER / FORWARD PHYSICS FACILITY



FASER is a new LHC experiment (currently under construction) in the far forward region of the LHC. It consists of a spectrometer to look for light long-lived particles and the **FASERnu** neutrino detector. Snowmass LOIs for FASERnu and FASER were submitted.



There is an entire physics program that remains to be explored in the far forward region. We propose to create a **Forward Physics Facility** to house a suite of experiments with capabilities for new physics searches, neutrinos physics, and QCD measurements.

F. Kling in EF06 with J. Feng, M. V. Garzelli

D→ν PRODUCTION and PDFs

Idea: ν_e (at high energy) and ν_τ are produced in charm decays. They are therefore sensitive to forward charm production, which can be described by perturbative QCD.

Opportunities: This could be used to probe

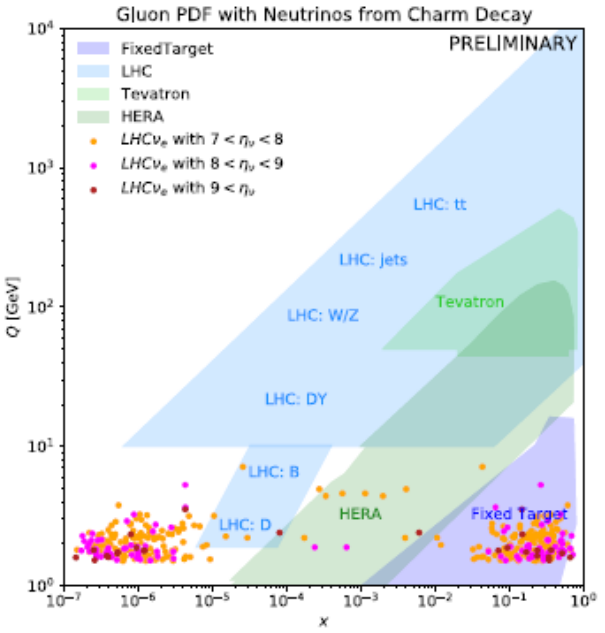
- g g → c c: gluon PDFs at low x ~ 10^{-7}
- g c → g c: intrinsic charm at $x \approx 10^{-7}$ OR $x > 0.1$

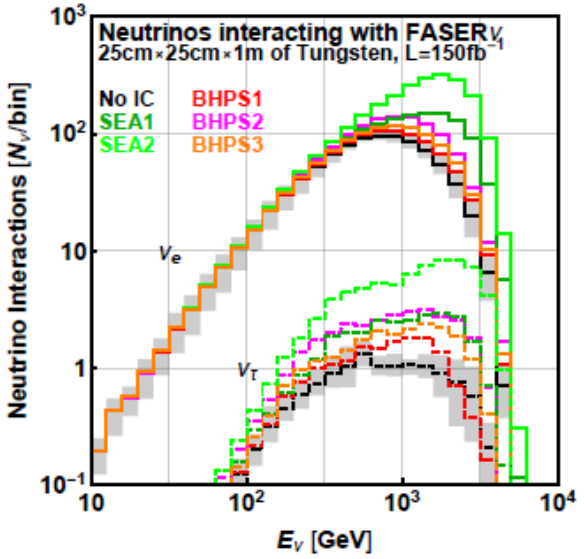
[see scattered points in the figure]

The FASER experiment is strongly sensitive to various models of charm production in unconstrained regions

Running FASER together with the EIC and/or LHeC greatly enhances the FASER's potential for BSM searches

AI: need a study of these issues





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

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,

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]

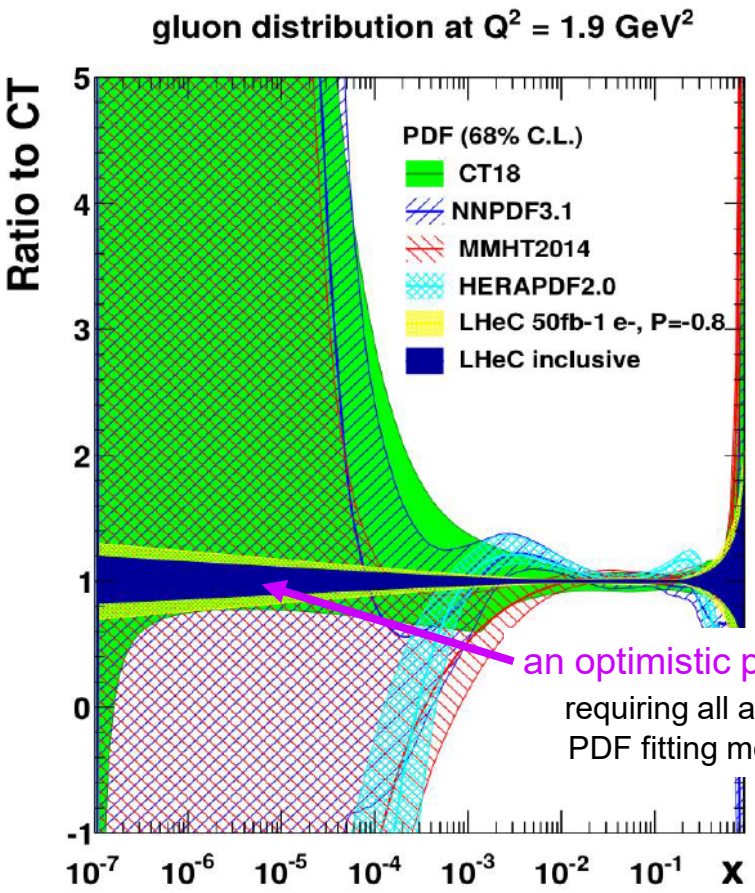
Gluon Saturation at the Electron Ion Collider

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



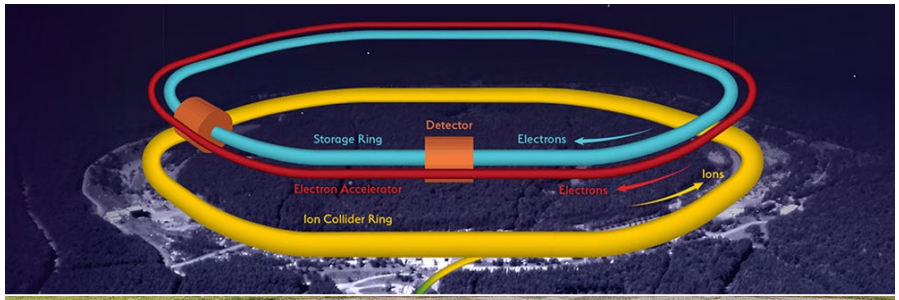
An **Electron-Ion Collider** can replace most of fixed-target and nuclear-target measurements constraining proton PDFs at large x. It will systematically study PDFs for heavy nuclei.
https://indico.fnal.gov/event/44510/

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

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

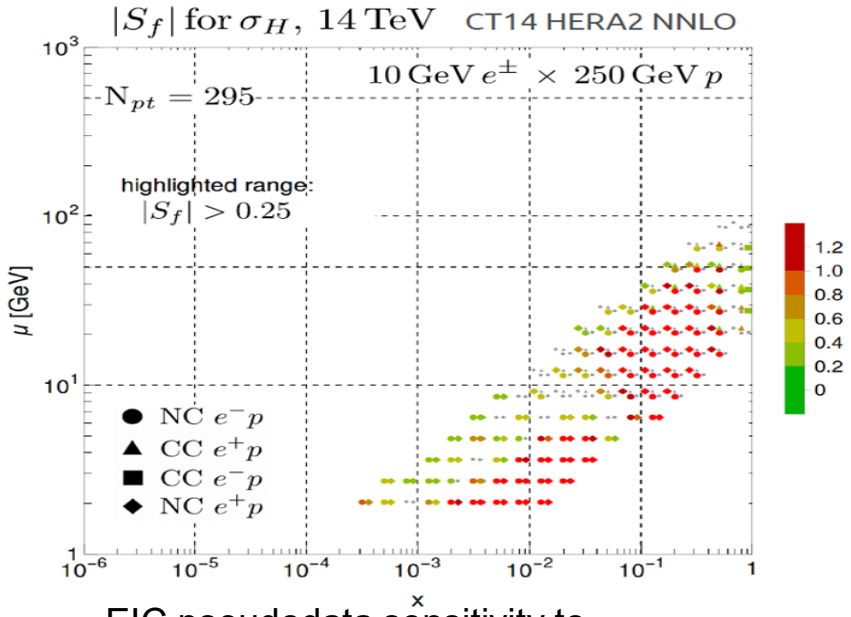
Electron-Ion Collider at Brookhaven

A frontier lab for 3-dimensional hadron tomography



September 18, 2020. The Electron-Ion Collider project launch ceremony [https://tinyurl.com/EICLaunch2020]

- Jan. 2020: stage 0 approval
- Will operate after 2030, possibly
- concurrently with the HL-LHC
- Major improvements in large-x PDFs



EIC pseudodata sensitivity to PDFs in $gg \to H$ production @ 14 TeV

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,*]

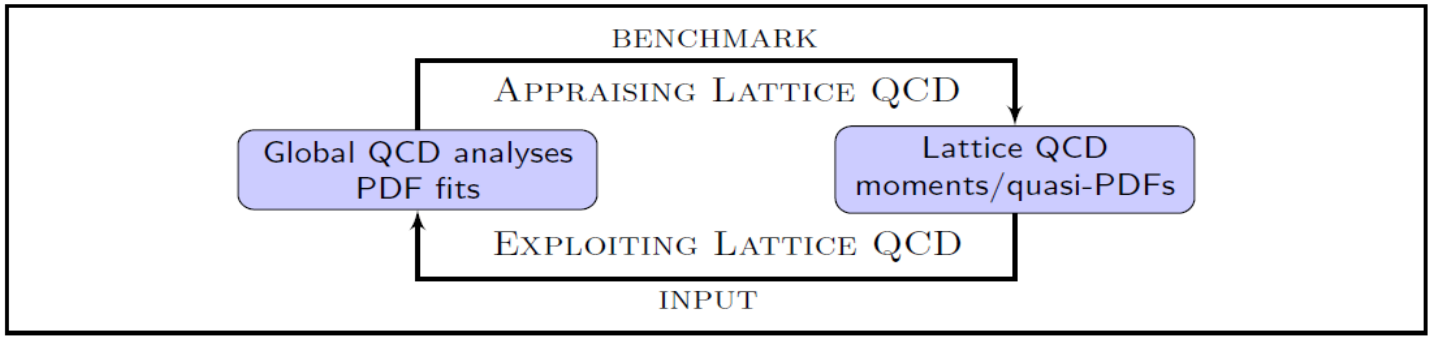
Lattice-QCD Determinations of Quark Masses and the Strong Coupling α_s

Fermilab Lattice, MILC, and TUMQCD Collaborations

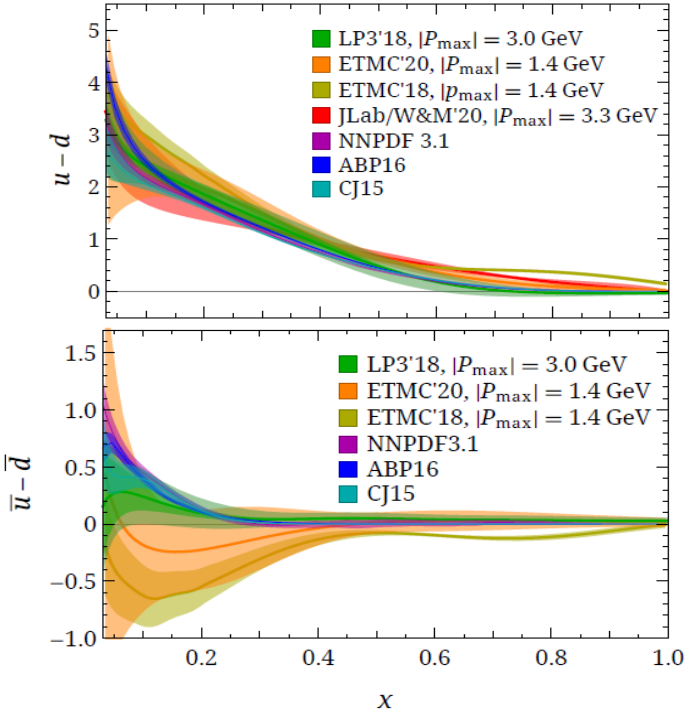
Letter of Interest for EF06: Parton distribution functions from lattice QCD

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

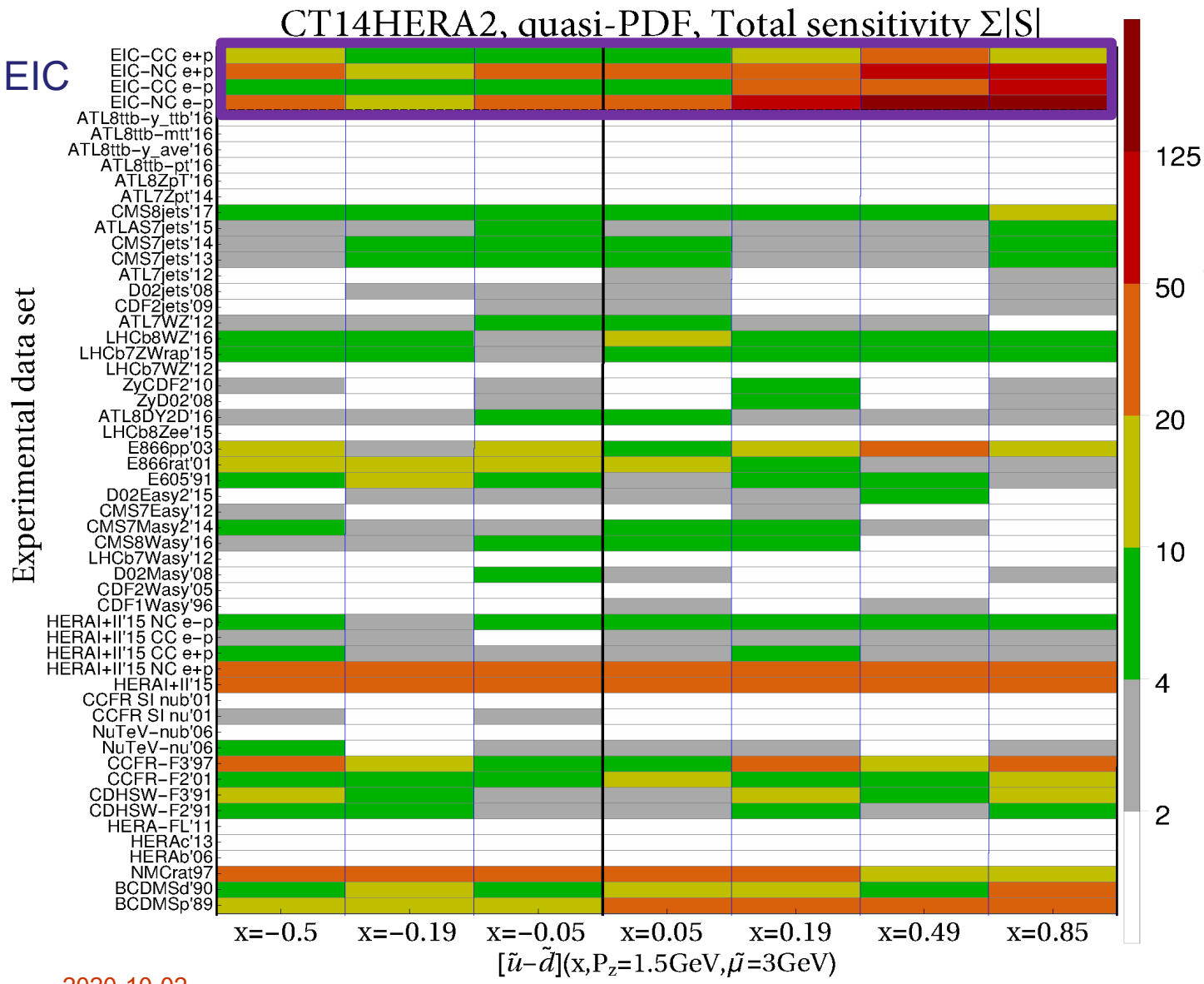
This is a rapidly progressing field: computations of PDFs in several lQCD approaches have been compared against phenomenological PDF models at two workshops:

- 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

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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

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

Status and prospects of nuclear PDFs at the LHC

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

Generative, Explainable Artificial Intelligence for Nuclear Physics and HEP

The Femtography Project

Contact person: Simonetta Liuti

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

Snowmass LOI Les Houches Wishlist: placeholder

T. Hobbs, A. Huss, J. Huston, S. Jones, S. Kallweit

AIs:
Which new (N)NNLO predictions impose elevated requirements on PDFs?
Which new processes can be used to constrain PDFs?

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!

SMU ManeFrame II HPC cluster

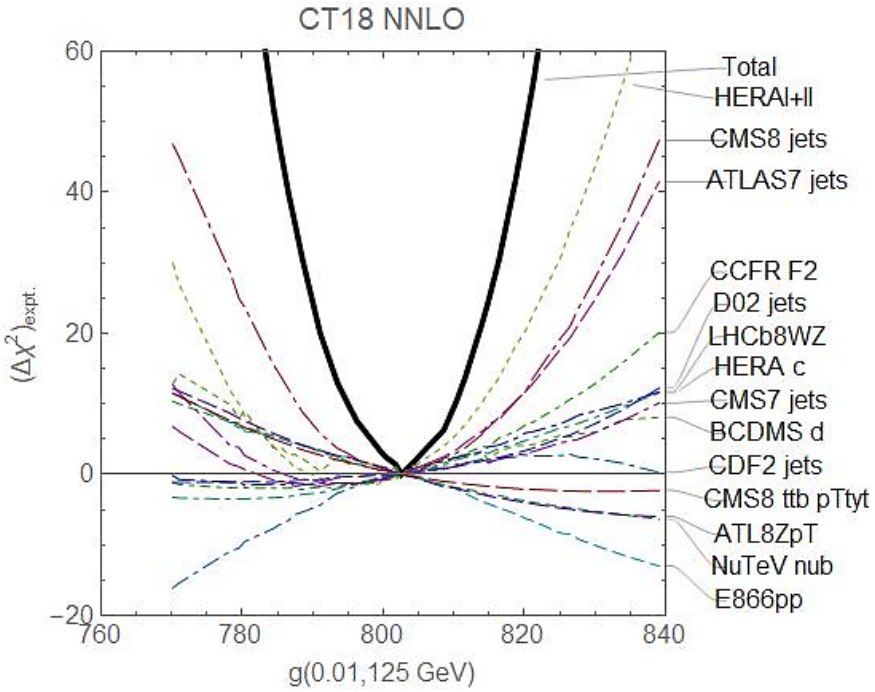
https://www.smu.edu/OIT/Services/HPC

HPC infrastructure at SMU and MSU was essential for completion of the CT18 global PDF analysis

Availability of HPC opens avenues for generating PDFs with alternative assumptions (resummations, EW corrections, alternative selections of experimental data,…) and detailed studies of PDF uncertainties

Computational Ability	870 TFLOPS
Number of Nodes	354
Intel CPU Cores (AVX2)	11,276
Total Accelerator Cores	275,968
Total Memory	120 TB (122,880 GB)
Node Interconnect Bandwidth	100 Gb/s
Scratch Space	2.8 PB (2,867 TB)
Archive Capabilities	Yes
Operating System	CentOS 7

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=$1.8 \cdot 10^6$

AI: 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

Snowmass Community Planning meeting

Virtual; October 5-8, 2020

- #92. Non-perturbative QCD dynamics at colliders

Tue. 11:30-12:30 CDT/12:30-13:30 EDT (Zoom 11)

- #124. Lattice Gauge Theory for High Energy Physics

Tue. 1:30-14:30 CDT/14-15:30 EDT (Zoom 11)

- #128 Precision calculations and techniques

Tue. 13:30-14:30 CDT/14:30-15:30 EDT (Zoom 6)

- #138. Synergy of astro-particle physics and collider physics

Wed. 14-15 CDT/15-16 EDT (Zoom 14)

- #28 Theory Challenges in Precision Measurements

Wed. 13-14:30 CDT/14-15:30 EDT (Zoom 11)

- #99 Advances in Event Generation and Detector Simulation

Wed. 13-14:30 CDT/14-15:30 EDT (Zoom 12)

- #1 EF Introduction (Overview of ongoing activities, including LOIs received, very brief introduction to EF goals for this workshop)

Tue. 11:00-11:30 CDT/12-12:30 EDT (Zoom 1)

- #201 EF Planning (MC Task force summary and plans for production, more on LOIs, planning towards final report) Wed. 15:00-16:00 CDT/16:00-17:00 EDT (Zoom 1)

The call to explore new QCD frontiers remains strong!

Snowmass 1984, Wu-Ki Tung (picture by speaker)

Backup

Toward N3LO accuracy of collinear nucleon PDFs

Shown at the EF06 kick-off meeting on May 25

N3LO predictions are becoming available for Higgs and DY pair production, etc. and will eventually require N3LO PDFs

Some physics questions will require N3LO accuracy in QCD and NLO accuracy in EW: HL-LHC Higgs and EW precision studies, measurement of m_{charm} in DIS, determination of sea PDFs at large x

The progress toward N3LO accuracy requires numerous advancements beyond the current frameworks for global QCD fit, on the top of implementing N3LO radiative contributions.

Many of these advancements will take time and are already necessary at NNLO to satisfy goals of the HL-LHC physics program.

Recall that it took >10 years after implementing the first NNLO contributions in global fits to obtain benchmark PDF fits at NNLO accuracy in ~2015