Energy Frontier Topical Group 6 (EF06)

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

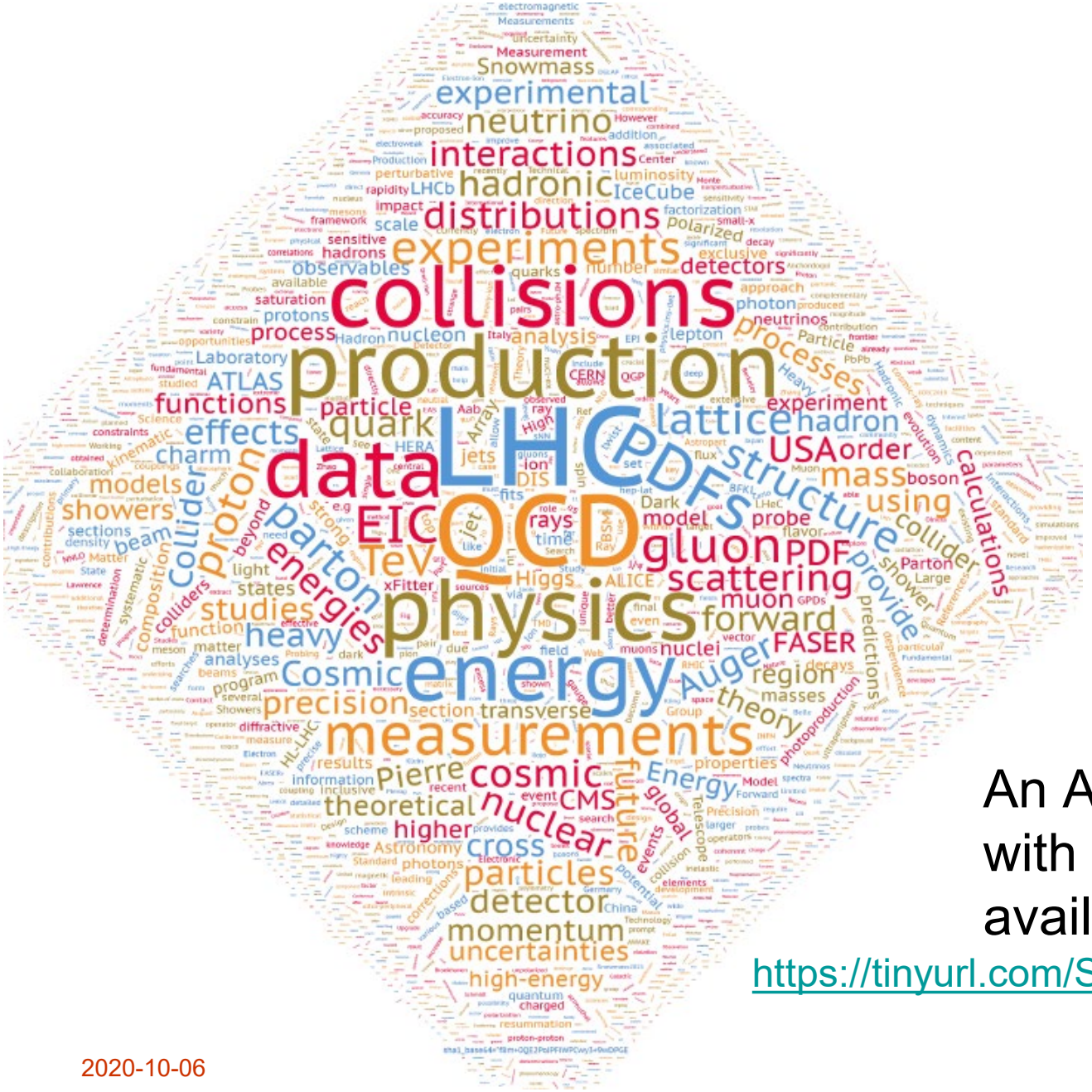
Three topical tracks:

1. Hadron structure and Parton Distribution Functions
2. QCD at small momentum fractions x
3. Nonperturbative models of hadrons and hadron spectroscopy

Agendas and slides from presentations at
https://indico.fnal.gov/category/1140/
Group meetings on Wednesdays, 9am CDT/10am EDT/16h00 CERN time
Overlapping topics with EF03, 04, 05, 07

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?



An Adobe PDF file with EF06 LOIs is available at

https://tinyurl.com/Snowmass21EF06LOIs

Big questions about nonperturbative QCD dynamics in the next decade

Precision collinear PDFs for HL-LHC studies
[M. Ubiali]

Measurements of α_s and quark masses
[J. Huston]

QCD at small momentum fractions

Future DIS experiments
[T. Hobbs]

Forward hadron production
[M. Garzelli]

Nuclear structure

3-dimensional hadron structure
[TMDs, GPDs, …]

QCD for cosmic ray physics

Hadron spectroscopy at colliders

PDFs from lattice QCD

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

Snowmass LOI Les Houches Wishlist: placeholder

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

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

Examples of LOIs

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.

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

Future DIS facilities: EIC, LHeC, FCC-eh

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

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

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,§]

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]

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,

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,*]

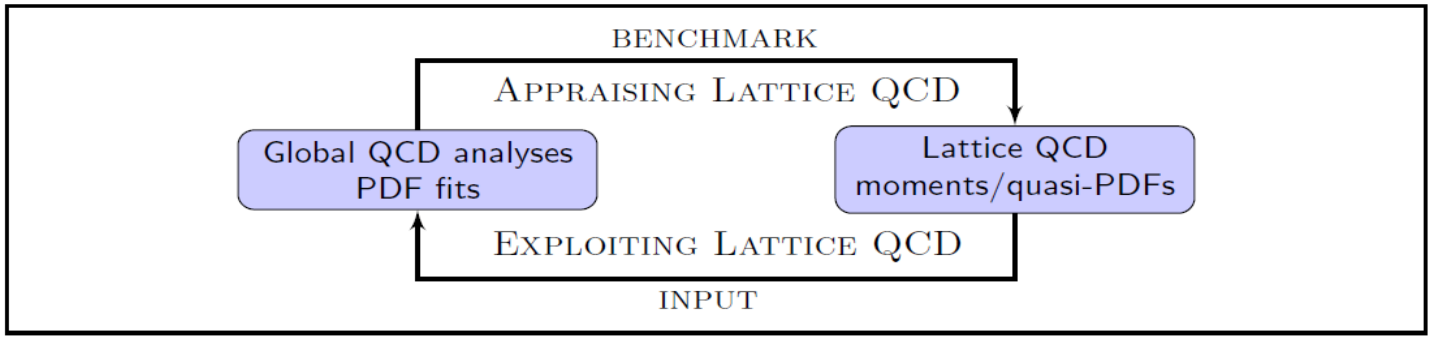
Lattice-QCD Determinations of Quark Masses and the Strong Coupling α_s

Fermilab Lattice, MILC, and TUMQCD Collaborations

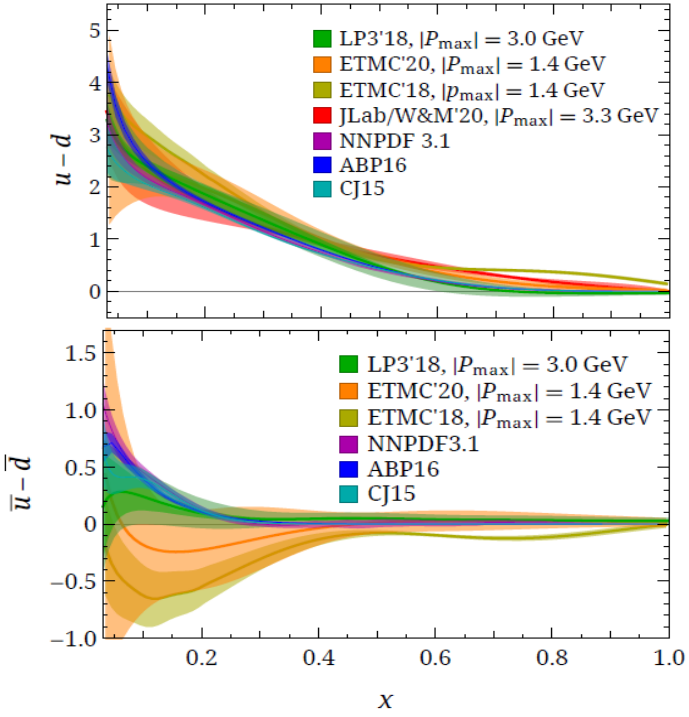
Letter of Interest for EF06: Parton distribution functions from lattice QCD

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.

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

Stay tuned!
Get involved!

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