

# Energy Frontier Topical Group 6 (EF06)

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

## 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/>  
Ongoing work on contributions on N3LO PDFs, EIC, LHC Forward Physics Facility, tests of QCD in forward production, lattice calculations of PDFs, ...

**Please see reports from EF03 and EF05 for the summaries of our joint sessions at this workshop**

# 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 N<sup>3</sup>LO 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 N<sup>X</sup>LO 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?**

# EF06 Topical Group status, 2021-09-03

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

In Fall 2021, EF06 will meet every two weeks primarily to track progress on whitepapers. EF06 whitepapers must be on arXiv by March 15, 2022.

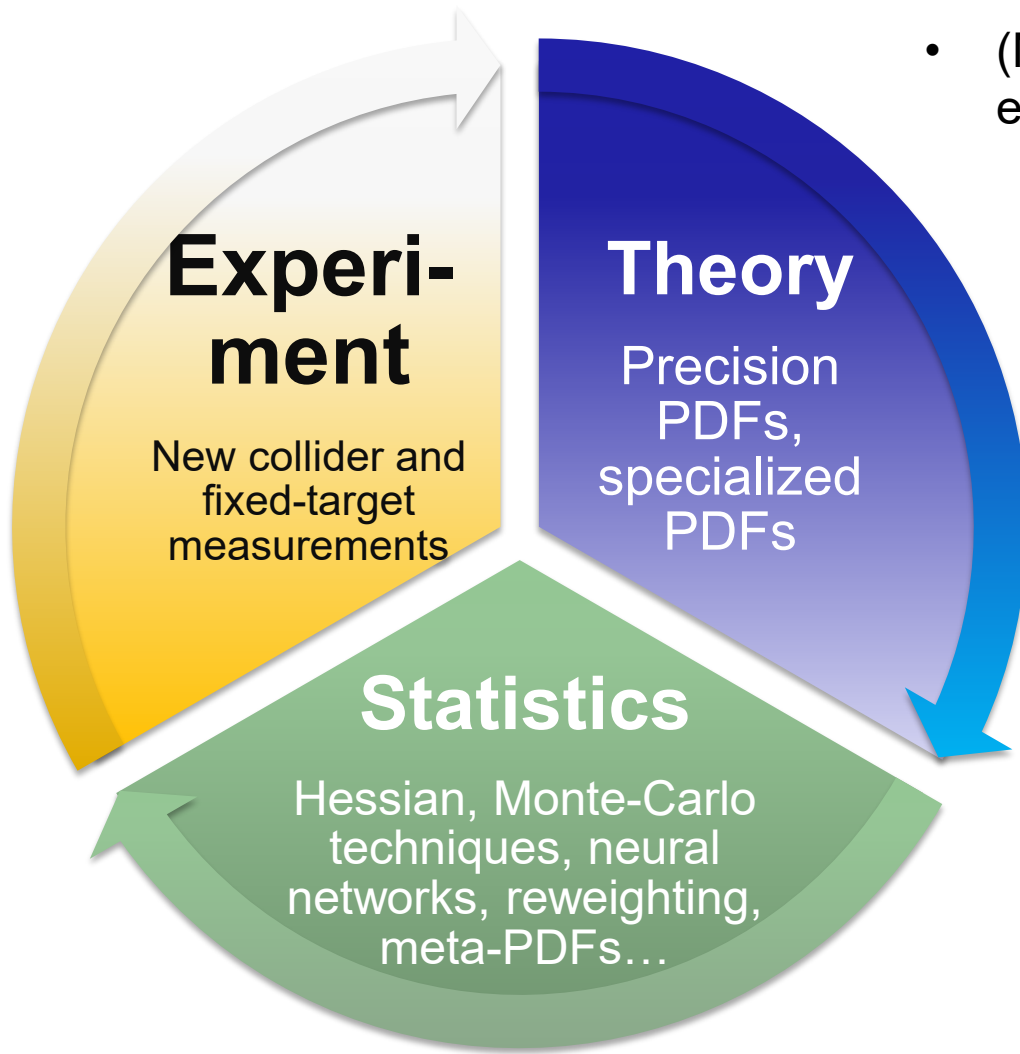
Several ongoing studies are open to new participants, especially to early career researchers

EF06 conveners are interested in your ongoing work on Snowmass contributions or if you are looking for a project to join

# EF06 whitepapers in progress, examples

1. Proton structure at the precision frontier (EF05/EF06/TF06)
2. LHC Forward Physics Facility – Maria Garzelli
3. Hadron structure at the Electron-Ion Collider (with EF07) – Tim Hobbs
4. Hadronic structure and factorization at small momentum fractions
5. QCD tests in the forward region...
6. PDFs on Lattice QCD (with TF05)
7. Hadron spectroscopy
8. ...

# 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...

# 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 ( $\Rightarrow$ PDF4LHC21)

## Proton structure at the precision frontier

S. Alekhin, R. Ball, V. Bertone, J. Blümlein, R. Boughezal, A. Cooper-Sarkar, T. Cridge, C. Duhr, S. Forte,  
 F. Giuliani, A. Glazov, M. Guzzi, C. Gwenlan, L. Harland-Lang, T. J. Hobbs, S. Hoeche, J. Huston, K. Lipka,  
 H.-W. Lin, B. Mistlberger, S.-O. Moch, P. Nadolsky, E. Nocera, F. Olness, F. Petriello, K. Rabbertz, C. Royon,  
 J. Rojo, M. Sutton, R. Thorne, M. Ubiali, K. Xie, C.-P. Yuan,  
 OTHER AUTHORS

## CONTENTS

10	Editorial matters	2
	A. Authorship	2
	B. Meeting recordings, important dates, technical guidelines	3
	I. Introduction	4
	II. Comparisons of modern PDFs and parton luminosities	6
15	III. Experiments	6
	A. LHC processes to measure PDFs	6
	B. The Electron-Ion Collider	6
	C. PDFs for neutrino phenomenology	6
	D. Other experiments	6
20	IV. Theory for N3LO PDFs	6
	A. Conceptual developments	7
	B. Multiloop calculations	7
	C. QCD	7
	D. Electroweak	7
25	E. PDFs with resummations	7
	1. Large $x$	7
	2. Small $x$	7
	3. Transverse-momentum dependent PDFs	7
	V. Methodology	7
30	VI. PDFs on the lattice	7
	A. Strong Coupling Calculations	7
	B. PDFs Calculations	7
	VII. PDF analyses as a part of theory infrastructure	7
	A. PDF implications for searches for Beyond the Standard Model Physics	8
35	VIII. Computing needs and computing tools	8
	A. High-performance computing in PDF fits	8
	B. Fitting codes	8
	C. Fast interfaces	8
	IX. Conclusion: precision PDFs in the United States	8
40	References	8
	A. EF06 focus questions	10

On Overleaf

**General Coordination and Snowmass TG liaisons:** Radja Boughezal (TF06), Stefan Hoeche (EF05), Huey-Wen Lin (EF06), Pavel Nadolsky (EF06), Maria Ubiali

## Section coordinators/writers

Small groups of  $\sim 3 - 8$  people will self-organize to write the bulk of the whitepaper sections first. **Some sections look for volunteers. Let the conveners know if you want to join one of the writing groups (requires to commit real time).**

**2021-12-01:** the whitepaper will be open to the community to comment or sign up as co-authors.

**2022-03-15:** submission to arXiv and a journal

Authors working on individual sections – not exclusive; feel free to add your name:

- 50 1. Introduction and Conclusion: Huston, Nadolsky, Thorne, Ubiali, Ball, Cooper-Sarkar, Hobbs, Sutton
2. PDFs as a part of theory infrastructure (with connection to the other topical groups/Frontiers): Boughezal, Hoeche, Lin, Nadolsky, Ubiali, WHO ELSE
3. Applications of PDFs to Higgs physics, BSM searches, SMEFT tests: Ubiali, Boughezal, Hoeche, Guzzi, Petriello, Xie
- 55 4. High-luminosity LHC requirements for precision nucleon PDFs: Huston, Moch, Thorne, Cooper-Sarkar, Guzzi, Rojo, Sutton, Cridge
5. PDFs at the Electron-Ion Collider: Hobbs, Moch, Nocera, Thorne, Blümlein, Rojo
6. PDFs and neutrino phenomenology: Hobbs, Xie, Bei Zhou, WHO ELSE
7. QCD theory for precision PDF analyses: Boughezal, Huston, Moch, Thorne, Blümlein, Guzzi, Petriello, 60 Mistlberger, WHO ELSE
8. PDFs with electroweak contributions: Thorne, Hobbs, Nocera, Xie, WHO ELSE
9. Transverse-momentum dependent PDFs: Bertone, WHO ELSE
10. Nuclear PDFs: Nocera, Olness, Hobbs, Rojo
11. PDFs and the strong coupling from lattice QCD: Lin, Johannes Weber
- 65 12. Forward and ultra-high energy scattering processes: Guzzi, Rojo, Royon, Xie, WHO ELSE
13. PDFs for parton showering programs (tbd): Hoeche, Huston, MCnet members (tbd) WHO ELSE
14. Experimental systematic uncertainties in PDF fits: Cooper-Sarkar, Huston, Thorne, Cridge
15. Propagating theoretical uncertainties into PDF fits: Nocera, Ball, Thorne, Cooper-Sarkar, Huston, Ubiali
16. Computing needs and high-performance computing for PDF fits: Sutton, Hoeche, WHO ELSE (connect to 70 CompF2 “Theoretical Calculations and Simulation”, conveners Daniel Elvira and Peter Boyle)
17. The LHAPDF library and other user interfaces for PDFs: Sutton, Thorne, Xie, Cridge WHO ELSE
18. Public fitting codes: Olness, Giuli (xFitter), Ubiali (NNPDF)
19. Applgrid and Fast(N)NLO fast interfaces for PQCD computation: Sutton, Gwenlan, Xie, WHO ELSE
20. Machine learning/AI connections: Ubiali, WHO ELSE
- 75 21. PDF4LHC benchmarking and combinations of PDFs: Cridge, Cooper-Sarkar, Huston, Moch, Nadolsky, Thorne, Nocera, Rojo, C.-P. Yuan, Gwenlan, Giuli

**Proton PDFs at the precision frontier**  
**Some sections accept volunteers to write the bulk text. Let the conveners know if you want to join one of the writing groups (requires to commit real time).**



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