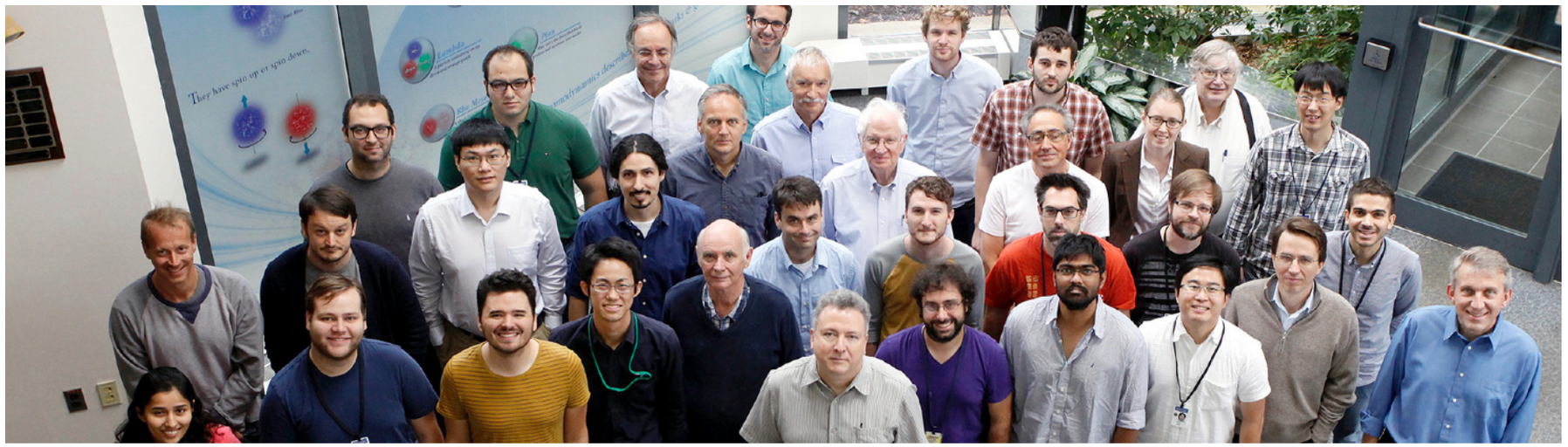
JLab Theory Center future program and impact

C. Weiss, 2023 JLab User Organization Meeting, 28-Jun-2023

Jefferson Lab



JLab Theory Center

Mission / Organization / Impact on experimental program and community

Future program

Nuclear physics research / Connection with JLab & EIC / Initiatives in computational science

This presentation: Brief summary based on 2023 Comparative Review Proposal.
Further information can be provided in discussion and follow-up

JLab Theory Center

Director: J. Qiu
Deputy Director: R. Edwards

Senior staff
W. Melnitchouk
D. Richards
N. Sato
C. Weiss

Joint staff
A. Accardi
I. Balitsky
J. Dudek
J. Goity
K. Orginos
A. Radyushkin
F. Ringer
T. Rogers
R. Schiavilla
A. Szczepaniak

Bridge staff
Y.-T. Chien

Postdoc staff
F. Aslan
P. Barry
C. Costa
O. Fedkevych
R. Jha
J. Karpie
J.-Y. Kim
Z.-Y. Li
G. Montana Faiget

Isgur Fellow
A. Rodas

Grad students
Presently 13

Status: June 2023

Mission

Conduct world-recognized research in theoretical NP

Support/develop JLab and EIC experimental programs

Lead initiatives in broader NP and Computing communities

Train next-gen NP researchers and perform outreach

Organization

Core of lab senior staff

Joint appointments: Lab staff + university faculty
(Old Dominion, Hampton, William & Mary, Indiana)
Highly leveraged, typically 50% at lab

Bridge appointments: Partially funded by JLab for 3-5 years, transition to university-only position

Postdocs and graduate students: Supported by JLab and university funds

Importance of joint appointments

Cover all areas of JLab science program cost-effectively

Realize training opportunities for students at JLab

Deepen JLab/NP connections with broader community

JLab Theory Center: Research directions

Hadron spectrum — Lattice QCD	Edwards, Dudek, Rodas
Hadron spectrum — Amplitude analysis (JPAC)	Rodas, Szczepaniak
Hadron structure — Lattice QCD	Orginos, Qiu, Radyushkin, Richards
Hadron structure — Partonic analysis and high-energy processes	Accardi, Balitsky, Chien, Melnitchouk, Qiu, Ringer, Rogers, Sato
Hadron structure — Low-energy properties and effective field theories	Goity, Melnitchouk, Weiss
Nuclear few-body systems	Schiavilla, Weiss
New initiatives — Machine learning, artificial intelligence, quantum computing	Ringer, Sato

Underlined: Area leaders

Evolving organization, not axiomatic

Many synergies and connections (→ following)

Aligned with experimental programs of JLab 12 GeV + upgrades and EIC

Many opportunities for deploying computational science techniques

JLab Theory Center: Impact on experimental program

First LQCD calculation of hadronic decays of lightest 1^{-+} exotic hybrid meson, motivating GlueX's on-going search of $\pi_1 \to \pi\pi\omega$ [PRD 103 (2021) 054502]	GlueX
Showed that single exotic 1^{-+} hybrid meson candidate can describe existing $\pi\eta$, $\pi\eta'$ data, solving longstanding puzzle [PRL 122 (2019) 042002]	GlueX, CLAS12
First LQCD computation of isovector nucleon PDF using distillation and extraction of x-dependent transversity/helicity distributions [JHEP 11 (2021) 148; PRD 105 (2022) 034507; JHEP 03 (2023) 086]	PDF/Spin Hall A/C, CLAS12, EIC
First global analysis of polarized DIS, SIDIS, and e^+e^- data using iterative MC method, providing solution to the "strange quark polarization puzzle" [PRL 119 (2017) 132001]	PDF/Spin Hall A/C, CLAS12
First joint QCD-QED factorization for DIS and SIDIS, critically impacting data analysis and extraction of TMDs at JLab and EIC [PRD 104 (2021) 094033, JHEP 11 (2021) 157]	TMD Hall A/C, CLAS12, EIC
Theory-guided extraction of proton charge and magnetic radii from ep scattering data combining chiral EFT with dispersion theory [PRC 99 (2019) 044303; PRC 102 (2020) 035203].	PRad, JLab form factors, MUSE μp
Excellent description of low-lying spectra of light nuclei up to ^{12}C and their electron- and photo-nuclear properties, validating chiral EFT-based NN interactions and many-body calculations [PRL 120 (2018) 052503, PRC 99 (2019) 034005 , PRC 106 (2022) 044001]	eA/vA program, Hall C hypernuclear
Machine Learning-based event generator for ep scattering using generative modeling [PRD 106 (2022) 096002]	JLab/EIC event-by-event analysis

Here: Highlights from 2018-2023 Comparative Review report. Many more examples!

JLab Theory Center: Community leadership

PAC Theory Review: Assures feasibility, motivation and impact of proposed JLab experiments. Covers full scope of JLab program [all staff]

Theory support in planning and analysis of experiments: JLab Theory staff provide close support for analysis of experiments across entire program (meson/baryon spectroscopy, 3D partonic structure, nuclei, fundamental symmetries) through informal interactions or formal collaboration [all staff]

Theory support for JLab upgrades: Essential contributions to K(long) facility, SoLID, positron program, and CEBAF 22 GeV energy upgrade [Accardi, Goity, Melnitchouk, Qiu, Rodas, Sato, Szczepaniak, Weiss]

EIC program development: Leadership roles in EIC-related LDRD projects, science studies, program development, 2019-2021 Yellow Report, and community building [Accardi, Melnitchouk, Qiu, Sato, Szczepaniak, Weiss]

DOE Topical Collaborations: Essential roles in 2022 Topical Collaborations in Exotic Hadron Spectroscopy [Edwards, Dudek, Szczepaniak PI], Quark-Gluon Tomography [Accardi, Goity, Melnitchouk, Orginos, Richards, Sato, Weiss], Nuclear Theory for New Physics [Schiavilla], and Heavy Flavor Theory for QCD Matter [Qiu]

Scientific computing: Leading national computing efforts in the ASCR/NP SciDAC projects [Lead PI Edwards], DOE/LQCD Exascale Computing [Co-PI Edwards], and USQCD Executive Committee [Edwards, Richards]

NSAC: Membership in NSAC [Dudek 2018-2021], role in 2022 long-range planning process articulating vision of JLab community [Dudek, Qiu]

Training and outreach: Managing HUGS Graduate Summer School and JSA/HUGS fellowships for developing countries [Accardi], creation of REYES outreach program [Briceno]

These functions are made possible by the unique setup with staff + joint + bridge appointments

JLab Theory Center: Future program

Goals (next ~5 years):

- Deliver physics results of JLab 12 GeV program,
  esp. in meson spectrum (GlueX) and 3D parton structure (Hall A/C, CLAS12)

- Develop EIC science program and community,
  esp. new applications in QCD jets and light ion physics

- Provide theory leadership for future programs at JLab
  including K(long), SoLID, positron program, and CEBAF 22 GeV energy upgrade

- Explore opportunities in AI/ML and Quantum Computing for nuclear physics applications

Future: Hadron spectrum in QCD

Lattice QCD Edwards, Dudek, Rodas

Employ/extend unique suite of distillation and finite-volume methods to:

Compute spectrum of hybrid mesons in QCD → GlueX

Explore structure of hadron resonances through coupling to external currents

Implement 3-body channels in LQCD finite-volume analysis → all resonance experiments

Amplitude analysis (JPAC) Szczepaniak + JPAC Collaboration

Analyze multiparticle final states and extract meson resonances → GlueX, CLAS12

Develop/apply amplitude analysis techniques for heavy-quark XYZP states → JLab 22 GeV, EIC, LHC, e+e-

Explore ML/AI applications for spectroscopy analysis

Synergies: 3-body techniques used in finite-volume LQCD and experimental analysis

Topical Collaboration “Exotic hadron spectroscopy” (PI Szczepaniak) enables coordinated approach [→ Talk Rodas]

Future: Partonic structure - LQCD, global analysis

Lattice QCD Orginos, Qiu, Radyushkin, Richards

Employ/extend methods for computing partonic structure using Euclidean correlation functions

Disconnected diagrams for singlets - gluon distributions, quark flavor separation

Improved perturbative matching N2LO → all parton structure experiments

Non-forward matrix elements GPDs (x, ξ dep), distribution amplitudes → JLab & EIC GPD program

Global analysis (JAM, CJ) Accardi, Melnitchouk, Qiu, Sato

TMD extraction from collinear + SIDIS/hadron/e+e- data

Incorporate QED rad corr in DIS/SIDIS, towards event-based analysis → JLab & EIC TMD program

High-x inclusive structure and spin → JLab12 high x program

GPD analysis and nucleon imaging as inverse problem → JLab & EIC GPD program

Synergies: Inclusion of LQCD results in global analysis combines impact with exp data

Expertise with QCD factorization/processes essential for calculation of LQCD matching coefficients

Topical Collaboration “Quark-Gluon Tomography:” Coordinated approach to GPDs combining theory + LQCD + analysis [→ Talk Monahan]

Future: High-energy processes in QCD

Factorization of high-energy processes Balitsky, Qiu, Rogers, Sato

TMD factorization and nonperturbative dynamics → TMD program JLab & EIC

New types of exclusive processes for x-dependence of GPDs → Hall D, JLab 22 GeV

TMD factorization and evolution at small x → EIC

Jets and heavy quarkonia Accardi, Chien, Qiu, Ringer

Jet observables and correlations at EIC → EIC jet physics program

Heavy quarkonium production and use as probe of QCD matter → EIC, heavy ions RHIC LHC

Jets as probes of nonperturbative dynamics → JLab, EIC

Topical Collaboration “Heavy Flavor Theory for QCD Matter” [→ Talk Qiu]

Future: Hadron structure - hadronic scale, EFTs

QCD energy momentum tensor and GPDs Goity, Melnitchouk, Weiss

Energy-momentum tensor in nucleon from 1/Nc expansion → JLab 12/22 GeV, EIC

Generalized form factors from Chiral EFT and dispersion theory

N → Δ, N* transition GPDs

GPD properties at hadronic scale → JLab 12/22 GeV, EIC

Synergies with GPD global analysis effort

Integrated in Topical Collaboration “Quark-Gluon Tomography” [→ Talk Monahan]

Low-energy processes Goity, Weiss

e+N/e-N scattering and two-photon exchange processes in systematic 1/Nc expansion → JLab positron program

πN and Compton scattering from Chiral EFT and 1/Nc expansion

Future: Nuclear few-body systems

Electroweak properties of light nuclei Schiavilla (to retire 2025), Gnech (to join 2027)

Axial currents in ChEFT, beta decay, muon capture → fundamental symmetries, vA interactions

In context of Topical Collaboration “Nuclear Theory for New Physics” [→ Talk Walker-Loud]

Nuclear structure in high-energy scattering processes Weiss

Develop EFT-based description of light-front nuclear structure

Nuclear breakup processes and spectator tagging → JLab 12/22 GeV tagging, EIC far-forward physics

Synergies with high-energy processes and jet physics efforts

Integrated in JLab EIC experimental science effort

Future: Initiatives in Computational Science

Machine learning / artificial intelligence for nuclear physics Ringer, Sato

Generative models for efficient event simulation of collider events

Applications to BSM searches → EIC, LHC

ML-based methods for event-by-event analysis → JLab?

[→ Talks Battaglieri, Gavalian]

Towards quantum computing for nuclear theory Edwards, Orginos, Ringer, Sato, Schiavilla

Explore continuous-variable quantum computing

Explore applications to low-dimensional quantum field theories

Explore quantum machine learning and hybrid discrete-continuous quantum computing

[→ Talks Schram, Ringer]

Summary

- Unique setup (staff + joint + bridge appointments) allows JLab Theory Center to cover JLab's diverse physics program and perform leadership functions in NP community

- JLab Theory Center is playing/will continue to play central role in
  - Physics extraction from JLab 12 GeV data
  - JLab upgrades K(long), SoLID, positrons, CEBAF energy upgrade
  - EIC program development

- Future program (next 5 years) builds on unique suite of tools developed earlier and realizes important synergies between various efforts

- Many opportunities for deploying AI/ML techniques in nuclear theory and data analysis

- JLab Users can/should influence future trajectory of JLab Theory Center through bridge/joint appointments, shared students/postdocs, collaborative research, initiatives

[Not covered here: Outreach and DEIA in JLab Theory: https://www.jlab.org/theory/outreach