JLab Theory Center future program and impact

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

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
## 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

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**Director:** J. Qiu  
**Deputy Director:** R. Edwards

<table>
<thead>
<tr>
<th>Senior staff</th>
<th>Joint staff</th>
<th>Postdoc staff</th>
<th>Bridge staff</th>
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<tbody>
<tr>
<td>W. Melnitchouk</td>
<td>A. Accardi</td>
<td>F. Aslan</td>
<td>Y.-T. Chien</td>
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<td>D. Richards</td>
<td>I. Balitsky</td>
<td>P. Barry</td>
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<td>N. Sato</td>
<td>J. Dudek</td>
<td>C. Costa</td>
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<td>C. Weiss</td>
<td>J. Goity</td>
<td>O. Fedkevych</td>
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<td>K. Orginos</td>
<td>A. Radyushkin</td>
<td>R. Jha</td>
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<td>A. Radyushkin</td>
<td>F. Ringer</td>
<td>J. Karpie</td>
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<td>T. Rogers</td>
<td>T. Rogers</td>
<td>J.-Y. Kim</td>
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<td>R. Schiavilla</td>
<td>R. Schiavilla</td>
<td>Z.-Y. Li</td>
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<td>A. Szczepaniak</td>
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<td>G. Montana</td>
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<td>Isgur Fellow</td>
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<td>A. Rodas</td>
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<td></td>
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<td>Grad students</td>
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<td>Presently 13</td>
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**Status:** June 2023
### JLab Theory Center: Research directions

| Hadron spectrum — Lattice QCD                  |
| Hadron spectrum — Amplitude analysis (JPAC)   |
| Hadron structure — Lattice QCD                |
| Hadron structure — Partonic analysis and high-energy processes |
| Hadron structure — Low-energy properties and effective field theories |
| Nuclear few-body systems                      |
| New initiatives — Machine learning, artificial intelligence, quantum computing |

- Edwards, **Dudek**, Rodas
- Rodas, **Szczepaniak**
- Orginos, Qiu, Radyushkin, **Richards**
- Accardi, Balitsky, Chien, Melnitchouk, Qiu, Ringer, Rogers, Sato
- Goity, Melnitchouk, **Weiss**
- **Schiavilla**, Weiss
- 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

<table>
<thead>
<tr>
<th>Impact</th>
<th>Program/Project</th>
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<tbody>
<tr>
<td>First LQCD calculation of hadronic decays of lightest $1^{-+}$ exotic hybrid meson, motivating GlueX's on-going search of $\pi_1 \rightarrow \pi \pi \omega$ [PRD 103 (2021) 054502]</td>
<td>GlueX</td>
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<tr>
<td>Showed that single exotic $1^{-+}$ hybrid meson candidate can describe existing $\pi \eta, \pi \eta'$ data, solving longstanding puzzle [PRL 122 (2019) 042002]</td>
<td>GlueX, CLAS12</td>
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<tr>
<td>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]</td>
<td>PDF/Spin Hall A/C, CLAS12, EIC</td>
</tr>
<tr>
<td>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]</td>
<td>TMD Hall A/C, CLAS12, EIC</td>
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<tr>
<td>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]</td>
<td>PRad, JLab form factors, MUSE $\mu p$</td>
</tr>
<tr>
<td>Machine Learning-based event generator for $ep$ scattering using generative modeling [PRD 106 (2022) 096002]</td>
<td>JLab/EIC event-by-event analysis</td>
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**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*
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
- Explore structure of hadron resonances through coupling to external currents
- Implement 3-body channels in LQCD finite-volume analysis

→ GlueX
→ all resonance experiments

**Amplitude analysis (JPAC)**
Szczepaniak + JPAC Collaboration

- Analyze multiparticle final states and extract meson resonances
- Develop/apply amplitude analysis techniques for heavy-quark XYZP states
- Explore ML/AI applications for spectroscopy analysis

→ GlueX, CLAS12
→ JLab 22 GeV, EIC, LHC, e+e-

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

Non-forward matrix elements GPDs (x, ξ dep), distribution amplitudes → all parton structure experiments

→ 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

<table>
<thead>
<tr>
<th>Topic</th>
<th>Authors</th>
<th>Programs and Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMD factorization and nonperturbative dynamics</td>
<td>Balitsky, Qiu, Rogers, Sato</td>
<td>TMD program JLab &amp; EIC</td>
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<tr>
<td>New types of exclusive processes for x-dependence of GPDs</td>
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<td>Hall D, JLab 22 GeV</td>
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<tr>
<td>TMD factorization and evolution at small x</td>
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<td>EIC</td>
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### Jets and heavy quarkonia

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<tr>
<th>Topic</th>
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<th>Programs and Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet observables and correlations at EIC</td>
<td>Accardi, Chien, Qiu, Ringer</td>
<td>EIC jet physics program</td>
</tr>
<tr>
<td>Heavy quarkonium production and use as probe of QCD matter</td>
<td></td>
<td>EIC, heavy ions RHIC LHC</td>
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<tr>
<td>Jets as probes of nonperturbative dynamics</td>
<td></td>
<td>JLab, EIC</td>
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<tr>
<td>Topical Collaboration “Heavy Flavor Theory for QCD Matter”</td>
<td></td>
<td>Talk Qiu</td>
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### QCD energy momentum tensor and GPDs

<table>
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<tr>
<th>Topic</th>
<th>Authors</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy-momentum tensor in nucleon from 1/Nc expansion</td>
<td>Goity, Melnitchouk, Weiss</td>
<td>→ JLab 12/22 GeV, EIC</td>
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<tr>
<td>Generalized form factors from Chiral EFT and dispersion theory</td>
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<td>N → Δ, N* transition GPDs</td>
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<td>GPD properties at hadronic scale</td>
<td></td>
<td>→ JLab 12/22 GeV, EIC</td>
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Synergies with GPD global analysis effort

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

### Low-energy processes

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<tr>
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<tbody>
<tr>
<td>e+N/e-N scattering and two-photon exchange processes in systematic 1/Nc expansion</td>
<td>Goity, Weiss</td>
<td>→ JLab positron program</td>
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<tr>
<td>πN and Compton scattering from Chiral EFT and 1/Nc expansion</td>
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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  \[ \rightarrow \) 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  \[ \rightarrow \) 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**

Generative models for efficient event simulation of collider events

Applications to BSM searches

ML-based methods for event-by-event analysis

[Ringer, Sato]

[→ Talks Battaglieri, Gavalian]

**Towards quantum computing for nuclear theory**

Explore continuous-variable quantum computing

Explore applications to low-dimensional quantum field theories

Explore quantum machine learning and hybrid discrete-continuous quantum computing

[Edwards, Orginos, Ringer, Sato, Schiavilla]

[→ 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]