The Role of the High Luminously Halls in JLab Science
&
How the JLab Theory Center can Help

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OUTLINE

• JLab 12 GeV science program and the role of all Halls

• How the JLab Theory Center can contribute
  – Spectroscopy
  – Hadron structure and properties
  – QCD and nuclei
  – Standard Model and beyond

• Summary
12 GeV CEBAF Upgrade Project is Complete, On-time and On-Budget!

Project Completion Approved September 27, 2017
All four Halls are in physics operations
JLab 12 GeV Science Era is Here!
Future Projects

- **MOLLER experiment:**
  (Possible MIE – FY19-23)
  - Precision Standard Model Test
  - DOE science review (Sept. 2014) – strong endorsement
  - Director’s Cost, Schedule and Technical review held Dec. 2016
    (project **paused** due to budget)
  - Awaiting green light to proceed

- **SoLID:**
  - Large acceptance, high lumi
  - SIDIS and PVDIS
  - CLEO Solenoid ✓
  - International collaboration
  - Director’s review (Feb. 2015)
    → new pre-CDR complete
  - Awaiting science review from ONP
Advantage of Lepton-Hadron Facility

- **Lepton-lepton collisions:**
  - Hadron-hadron collisions:
    - Hadron structure – motion of quarks, …
    - Emergence of hadrons, …
    - Initial hadrons broken – collision effect, …
  - Hard collision without breaking the initial-state hadron – spatial imaging, …

- **Hadron-hadron collisions:**
  - Hadrons
    - Hadron structure – motion of quarks, …
    - Emergence of hadrons, …
    - Initial hadrons broken – collision effect, …

- **Lepton-hadron collisions:**
  - No hadron in the initial-state
  - Hadrons are emerged from energy
  - Not ideal for studying hadron structure

- **Lepton-lepton collisions:**
  - Initial-state hadron}

Diagram showing the setup for Belle II detector and other experimental setups.
Advantage of Lepton-Hadron Facility

- **Lepton-hadron collisions:**
  - **Q^2** → Measure of resolution
  - **y** → Measure of inelasticity
  - **X** → Measure of momentum fraction of the struck quark in a proton
  - \(Q^2 = S \times y\)

Inclusive events: \(e+p/A \rightarrow e'+X\)
Detect only the scattered lepton in the detector
(Modern Rutherford experiment!)

Semi-Inclusive events: \(e+p/A \rightarrow e'+h(\pi,K,p,jet)+X\)
Detect the scattered lepton in coincidence with identified hadrons/jets
(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

Exclusive events: \(e+p/A \rightarrow e' + p'/A' + h(\pi,K,p,jet)\)
Detect every things including scattered proton/nucleus (or its fragments)
(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)
JLab 12 GeV Science Program

- Explore the origin of color confinement:
  - What is the role of gluonic excitations in the spectroscopy of light mesons?
  - Can these excitations elucidate the origin of color confinement?

- Probe the internal structure of hadrons:
  - Can the 3D landscape of nucleon shed some lights on the confinement?
  - How quark/gluon and their 3D confined motion make up hadron’s mass, spin, ..
  - How hadrons are emerged from quarks and gluons – Femtometer detector?

- Understand the emergence of nuclei from QCD:
  - What does a nucleus look like if we only see quark/gluon?
  - How nuclear force emerged from quark/gluon interaction?
  - What is the origin of short-range N-N correlations?

- Test the Standard Model and beyond:
  - Can the precision measurements at JLab help discover evidence for physics beyond the Standard Model of particle physics?
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*Halls: A, B, C, D*

*Hall-B (CLAS12) & Hall D (GlueX)*

All Halls could contribute to JLab 12 Science Program Complementarily
How the JLab Theory Center can Contribute

- Organized in six thrust areas:
  - **Hadron spectroscopy**
    - LQCD: Briceno, Edwards, **Dudek**, Orginos, Richards
    - JPAC: Doring, Passimar, **Szczepaniak**
  - **Nuclear structure & Low energy EFTs**: Goity, Melnitchouk, **Schiavilla**, Van Orden, Weiss
  - **3D hadron & nuclear structure – LQCD**: Briceno, Edwards, Orginos, **Richards**, Shanahan
  - **3D hadron & nuclear structure – Global analyses**: Accardi, **Melnitchouk**, Prokudin, Rogers
  - **3D hadron & nuclear structure – QCD & EFTs**: Accardi, Balitsky, Melnitchouk, Prokudin, Qiu, Radyushkin, Rogers, **Weiss**
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- Initiatives:
  - JLab collaboration with PARTONS – Theory + Hall A/B/C – Data → 3D Images
  - Research with HPC: Exascale & Event generators with “no” theory biases, …
Hadron Spectroscopy – LQCD

- Focus on GlueX & CLAS12 @ JLab & COMPASS, BES, & LHCb

(JLab’s Pioneering Work!)

Light quark meson + “exotics” & “hybrids” spectrum

Predicted

Exotics
Light quark meson + “exotics” & “hybrids” spectrum

Explored at GlueX & CLAS12 @ JLab & COMPASS, BES, & LHCb

Predicted

Exotics

Recognized by Feature review

Searching for the rules that govern hadron construction

Matthew R. Shepherd, Jozef J. Dudek & Ryan E. Mitchell

New development:

(Solving old mysteries – scalar sector)

First Lattice QCD calculation – “discovery” of “$a_0$”, “$\sigma$”, …
Motivation: GlueX looking for exotic hybrid mesons in photoproduction (to theorists) Might appear as enhancement in $\pi\pi\pi \sim \pi\rho$, $\pi\sigma$, $\pi f_0(980)$…

First LQCD resonance identification via flavor tagged decays:

“Editors” Suggestion

In return:
Used as motivation in GlueX PID upgrade proposal GlueX actively calibrating in this channel
Hadron Spectroscopy – LQCD

Even newer development:

Two/three body systems

First development of formalism for coupled two/three-body scattering via lattice QCD

\[ \mathcal{M}_L = \begin{pmatrix} \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots \end{pmatrix} \]


Multi-Hadron Systems from Lattice QCD

Organized workshop

Viewpoint: A Doubly Charming Particle

Briceno, Physics 10 (2017) 100

Lattice QCD prediction of the first doubly-charmed baryon is confirmed by LHCb
Joint Physics Analysis Center:

- Experimental or lattice signatures (real axis data: cross section bump and dips, energy levels)

Reaction amplitudes

- Theoretical signatures (complex plane singularities: poles, cusps)

Microscopic Models

- What is the interpretation (constituent quarks, molecules, ...)?

Jefferson Lab
Hadron Spectroscopy – JPAC

Beam asymmetry:

$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho + \omega|^2 - |b + h|^2}{|\rho + \omega|^2 + |b + h|^2}$$

Separation meson from baryon resonance

Successful predictions for GlueX!

Possible tension between GlueX and SLAC data?

First paper from GlueX and JLab12 upgrades

H. Al Ghoul et al. [GlueX]
Phys. Rev. C95 (2017) no.4, 042201

V. Mathieu et al., PRD92 (2015) 074013
J. Nys et al., PRD95 (2017) 034014
Hadron Spectroscopy – JPAC

- **πΔ-photoproduction:**
  - Stringent test of one-pion-exchange production
  - Possible to make parameter-free predictions

Comparison with preliminary GlueX results

- Confirmation of interference pattern
- High \(-t\): natural, Low \(-t\): unnatural
- Mismatch: oddly behaved \(\pi\) exchange
  - on-going analysis – theory/experiment

\[ \frac{\Gamma(p\gamma\rightarrow\pi^-\pi^+\Delta^{++})}{\Gamma(p\gamma\rightarrow\pi^-\pi^+)} \]

\[ \rho, a_2 \]

\[ \gamma p \rightarrow \pi^-\Delta^{++} \]

\[ (~8.5 \text{ GeV}) \]

\[ \pm 7\% \text{ norm. uncertainty} \]


\[ \text{J. Zarling (GlueX): preliminary} \]

\[ \text{SAID} \]

\[ s_{\pi p} \leq 2 \text{ GeV} \]

Łukasz Bibrzycki et al. (Cracow,JPAC)
Nuclear structure – EFT approach

Light nuclei spectra from chiral dynamics:

[PIARULLI et al, Phys. Rev. Letts. 120, 052503 (2018)]

GFMC calculations
Internal Structure of Hadrons

- **Structure – “a still picture”**
  - Crystal Structure:
    - NaCl, B1 type structure
    - FeS2, C2, pyrite type structure
  - Nano-material: Fullerene, C60

  *Motion of nuclei is much slower than the speed of light!*

- **No “still picture” for hadron’s partonic structure!**
  - Atomic world:
    - Atom ~ 10^{-8} cm
    - Nucleus ~ 10^{-12} cm
    - Proton (neutron) ~ 10^{-13} cm
    - Quark ~ 10^{-16} cm

  *Motion of quarks/gluons inside hadrons is relativistic!*

  - Partonic Structure:
    - Quantum “probabilities”
    - Quantum Fluctuation

  - Gluon
  - No still Picture!
Internal Structure of Hadrons

- **Landscape of hadrons:**
  - **Momentum Space**
  - **Coordinate Space**
  - **3D Confined motion**
  - **2D Spatial distribution**

In probability distributions

Parton Distribution Functions

Form Factors

Jefferson Lab
Accurate form factors from chiral EFT:


- Controlled accuracy, systematic improvements

- Calculated nucleon electromagnetic FFs and transverse densities, scalar FF. Extending approach to GPDs

- Results used in experimental analysis: Low-Q² electron scattering, proton radius extraction. Higinbotham et al. 18, Horbatsch et al. 18. JLab12 PRAD experiment
Scalar, axial and tensor currents of light nuclei (Halls A/B/C):


\[ R_X^{(f)}(A) = g_X^{(f)}(A)/g_X^{(f)}(p) \]

Nucleon charge radius through coordinate-space moments (Hall B/Prad):

Bouchard, Chang, Orginos, Richards, PoS LATTICE2016 (2016)

Pion Form Factor at High Momenta and Pion Parton Distribution Function (Prad/Hall C): Lattice/QCD Phenomenolog on-going joint effort
Strange quark magnetic moment of the nucleon:
(at physical pion mass with domain wall fermions)

- Ratio 3pt/2pt method
- Z-expansion

Raza Sufian et al, Phys. Rev. Letts. 118, 042001
Hadron structure – JLab webfitter

User friendly setups

Easy data visualization tools
Hadron structure – JAM – Global analysis

- First global QCD analysis of transversity distribution
  - using Monte Carlo methodology with lattice QCD constraints

- Impact of a future SoLID, …


First MC global QCD analysis of pion PDFs:

- significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data
- implications for “TDIS” (Tagged DIS) experiment at JLab

Using Fermilab DY data and HERA leading neutron production data
Valence Quark Structure – Global Analysis

- Inclusive DIS at large x:
  - $d/u \to 1/2$: SU(6) Spin-flavor symmetry
  - $d/u \to 0$: Scalar diquark dominance
  - $d/u \to 1/5$: pQCD power counting
  - $d/u \to \frac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$: Local quark-hadron duality

**Unique JLab strength!**

Newly extracted ratio at $x=1$:

- $d/u \to 0.09 \pm 0.03$

Does not match any models!

CTEQ-Jefferson Lab collaboration

http://www.jlab.org/CJ
PDFs, TMDs, GPDs, … from Lattice QCD:

PDFs: $\propto \langle P | \overline{\psi}(0) U(0, \xi) \psi(\xi) | P \rangle_{\xi^+=0, \xi_T=0}$

Cannot be calculated directly in LQCD!

New Idea and great potential:

Calculate quasi-PDFs $\Rightarrow$ Normal PDFs when $P_z \rightarrow \infty$

Major challenges:

- Ability to calculate in LQCD
- Renormalization of quasi-DPFs
- Factorization to PDFs

Renormalization:

Complete proof for the renormalization of quasi-DPFs

$$\tilde{F}_{i/p}^R(\xi_z, \tilde{\mu}^2, p_z) = e^{-C_i|\xi_z|} Z_{wi}^{-1} Z_{vi}^{-1} \tilde{F}_{i/p}^b(\xi_z, \tilde{\mu}^2, p_z).$$

Completely multiplicative - No mix with other flavors or gluon!
Pseudo-PDFs:

- Lattice calculation with $\alpha = 0$:
  \[ \mathcal{M}^\alpha (\nu = p \cdot \xi, \xi^2) \equiv \langle p | \overline{\psi}(0) \gamma^\alpha \Phi_\nu(0, \xi, v \cdot A) \psi(\xi) | p \rangle \]
  \[ \equiv 2p^\alpha \mathcal{M}_p(\nu, \xi^2) + \xi^\alpha (p^2/\nu) \mathcal{M}_\xi(\nu, \xi^2) \approx 2p^\alpha \mathcal{M}_p(\nu, \xi^2) \]

- Model quasi-PDFs:
  \[ \mathcal{P}(x, \xi^2) \equiv \int \frac{d\nu}{2\pi} e^{ix \nu} \frac{\mathcal{M}_{p=p^0}(\nu, \xi^2) / \mathcal{M}_{p=p^0}(0, \xi^2)}{\mathcal{M}_p(\nu, \xi^2)} \]
  with $\xi^\mu = (0, 0_\perp, \xi_z)$

First numerical results:

- Orginos, et al, PRD96, 094503 (2017) at $Q = 2.15$ GeV
- One-loop matching recently Completed!
- A. Radyushkin, arXiv:1801.02427
Hadron structure – LQCD

- **Lattice “cross sections”**:  
  - Go beyond quasi- or pseudo-PDFs  
  - Any single-hadron matrix elements satisfies:

\[
\sigma_n(\xi^2, \omega, P^2) = \langle P | T\{O_n(\xi)\} | P \rangle
\]

- **Lattice calculable, reliable continuum limit, pQCD factorizable**

\[
\tilde{\sigma}_{\text{Lattice}}(\tilde{x}, Q, P \sim \sqrt{s}) \approx \sum_f \int \frac{dx}{x} C_f \left( \frac{x}{\tilde{x}}, \frac{\mu^2}{Q^2}, \alpha_s(\mu); P \right) f(x, \mu^2) + \mathcal{O} \left[ \frac{1}{Q^2} \right]
\]

- **Key: controllable hard scale!**

- **Many choices for the operator**:  
  - Doing experiments on the lattice!

\[
O_{j_1j_2}(\xi) \equiv \xi^{d_{j_1} + d_{j_2} - 2} \frac{Z_{j_2}^{-1}}{Z_{j_1}^{-1}} j_1(\xi) j_2(0)
\]

\[
j_{V'}(\xi) = \xi Z_{V'}^{-1} [\bar{\psi}_q \gamma \cdot \xi \psi_{q'}](\xi),
\]

\[
j_G(\xi) = \xi^3 Z_G^{-1} \left[ -\frac{1}{4} F^c_{\mu\nu} F^c_{\mu\nu} \right] (\xi)
\]

\[
O_q(\xi) = Z_q^{-1}(\xi^2) \bar{\psi}_q(\xi) \gamma \cdot \xi \Phi(\xi, 0) \psi_q(0)
\]

\[
\Phi(\xi, 0) = \mathcal{P} e^{-ig \int_0^1 \xi \cdot A(\lambda \xi) d\lambda}
\]

- PDFs
- DGLAP-Evolution
- Module $O(\alpha_s)$ corrections
- And HT corrections

\[
\omega = -\tilde{\xi} |\vec{P}| \cos(\theta)
\]
3D hadron structure – TMDs

- Confined motion:
  - Non-perturbative confined motion!

- JLab strength & efforts:
  - Theory: Match the measured hadron to QCD quarks/gluons
  - Phenomenology: Extract the physics of “confined motion” from data
  - Lattice QCD: Calculate the role of the non-perturbatives
3D hadron structure – TMDs

- **SIDIS at JLab:**
  
  \[
  \frac{d\sigma}{dx_B \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos2\phi_h} + \lambda_\varepsilon \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h}\right\}
  \]

- **Hall B (E12-06-112):**

  Boer-Mulders functions & Collins FFs – how does spin influence hadronization?
Global Effort on TMDs – TMD Collaboration

Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD (TMD Collaboration)

Co-spokespersons: W. Detmold, J.W. Qiu
3D hadron structure – GPDs

- Confined spatial imaging:
  - Generalized version of Form Factor
  - F.T. of t-dependence
  - Spatial imaging!
  - Hadron EM charge radius

- Theoretical progress:
  - GPD parametrizations, evolution, power corrections in hard processes (virtuality distributions)
  - Peripheral 3D nucleon structure from chiral EFT: Charge/current densities, GPDs
  - $1/N_c$ expansion of GPDs: Spin-flavor structure

Radyushkin PRD93 (2016) 056002, ...
3D hadron structure – GPDs

发起人：JLab – PARTONS 合作项目 – 3D 影像:

- DOE 批准了 JLab – PARTONS 合作项目的 ICRADA
- 理论 – C. Weiss – 是 JLab 和 PARTONS 之间的联络点
- 他协调 JLab 努力与所有实验大厅

首次视频会议 – 于今天 (8:30-12:30) 进行，会议内容概述了 JLab 实验大厅需要什么，以及 PARTONS 可以提供什么。

- 如何更快、更少理论偏见地从 JLab12 数据中提取物理结果？

<table>
<thead>
<tr>
<th>测量类型</th>
<th>JLab 实验大厅</th>
<th>PARTONS 可提供</th>
<th>GPDs</th>
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<td>p, n</td>
<td>CLAS12</td>
<td>GPDs $H, E, \bar{H}, \bar{E}$</td>
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- JLab 实验大厅的需求，以及 PARTONS 可提供的内容？
- 如何更快、更少理论偏见地从 JLab12 数据中提取物理结果？
Emergence of hadrons

- **Production of light hadrons (All Halls):**
  - high $p_T$ photoproduction of mesons
    - **SIDIS (Halls A/B/C):**
      ![Diagram of SIDIS process]
      Impact TMD extraction!
    - **Photo-production (Hall D):**
      ![Diagram of photo-production process]
      Similar phenomena appeared in heavy quarkonium production

- **Heavy flavor physics (All Halls):**
  - production of charm mesons, $J/\Psi$, $P_c$, ... near the threshold
    
    *Challenge to Theory for developing a reliable prediction near the threshold!*
Emergence of Nuclear Phenomena

- **Short-range structure of nuclei (Halls A/B/C):**
  - No one is actively investigating this phenomenon in Theory Center now (man power)
  - Reaching out experts to get support (visits)

- **Femtometer size detectors (Halls A/B/C):**
  - Probing color neutralization by medium effect of color propagation
  - Color transparency, ...

  Theory Center does have expertise on nuclear medium effects, ...
  (Andres, Accardi, Qiu, ...)

  *Similar situation for physics BSM effort!*
Summary and outlook

- All four Halls are in operation, and have had the successful data taking runs.
- JLab 12 GeV Science era is started, and will be exciting for many years to come.
- Theory Center is fully engaged with JLab12 GeV program,
  having the sense of the urgency and working with experimental colleagues
  to help analyze and interpret the data to publish physics results, …
- Theory Center is lack of man power for some science goals of JLab12 program,
  reaching out expertise in the field to establish a strong network to provide
  the necessary support to for reaching these goals.
- Theory Center is a part of the JLab12 science program, and will continue
  ✦ Help motivate, promote, stimulate, justify, and support the JLab12 experimental program
  ✦ Help analyze, interpret, and model JLab12 experimental data

Thank you!