Fundamental nuclear physics at the exascale and beyond

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Fundamental nuclear physics at the exascale and beyond

LQCD ASCR/NP SciDAC-5

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- Brookhaven:
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- JLab
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- Oak Ridge:
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  - Henry Monge Camacho
- William & Mary:
  - Kostas Orginos
  - Andreas Stathopoulos
- NVIDIA:
  - Kate Clark
  - Balint Joo

Local PIs

Publicity and useful repositories

GitHub: https://github.com/LQCDSciDAC Website: https://lqcdscida.github.io

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SciDAC
Scientific Discovery through Advanced Computing

ASCR/NP LQCD SciDAC Project

Home About SciDAC Highlights People Publications

ASCR/NP LQCD SciDAC Project

The Lattice Quantum Chromo-Dynamics (LQCD) ASCR/NP SciDAC Project is supported by the U.S. Dept. of Energy Office of Nuclear Physics and the Office of Advanced Scientific Computing Research. This SciDAC project focuses on an ambitious program of theoretical, algorithmic and software development which will enable calculations using lattice Quantum Chromodynamics (LQCD) methods to exploit the new generation of leadership-class resources and dedicated hardware to address fundamental questions in nuclear science. Specifically, our project will impact our understanding of results from current heavy ion experiments at the Relativistic Heavy-Ion Collider (RHIC), the study of excited and exotic states of hadrons at CLAS-12 and GlueX at Jefferson Lab (JLab) and the hadron and nuclear structure programs at RHIC-spin and JLab. The calculations that are enabled by the proposed developments will also look forward to experiments on protons and nuclei at the upcoming Electron-Ion Collider (EIC).

Scientific goals of project

Science areas recognized in the 2023 NSAC Long Range Plan

- Hadron spectroscopy
  - *Determine spectrum and internal structure of QCD exotic states*
  - Impact CLAS12 & GlueX @ JLab, and possible CEBAF upgrade

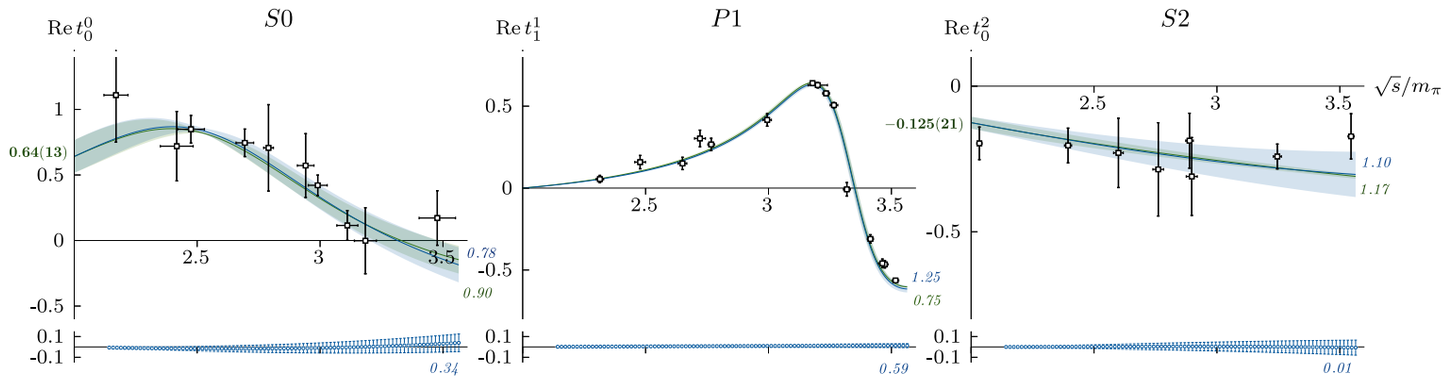
- Hadron structure
  - *Build 3D image of proton in its entirety*
  - JLab 12 & future EIC @ BNL

- Partonic structure of nuclei
  - *Improve constraints on distribution functions of nuclei though A=7*
  - Future EIC, future DUNE (FNAL) & HyperK (Japan)

- Extreme matter - quark gluon plasma
  - *Characterize quark gluon plasma via spectrum of heavy quarks*
  - sPHENIX @ BNL and LHC @ CERN

Quark mass dependence of the lightest resonance of QCD

S, P, D - wave $\pi\pi$ partial waves



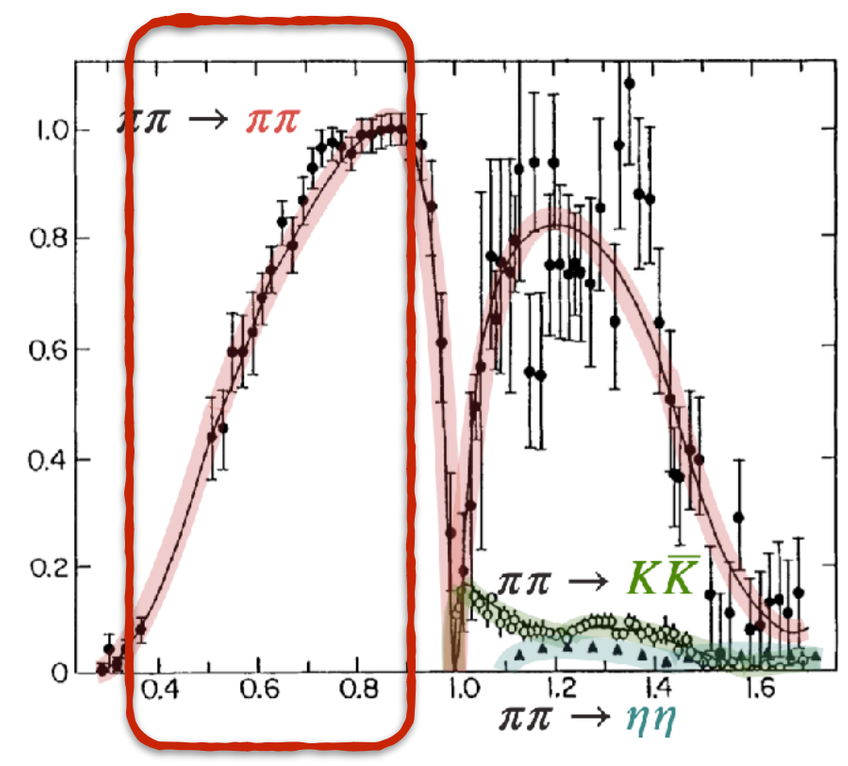
Accomplishment: First full QCD characterization of the lightest resonance.

Methods: Graph evaluation techniques developed in partnership with SciDAC RAPIDS.

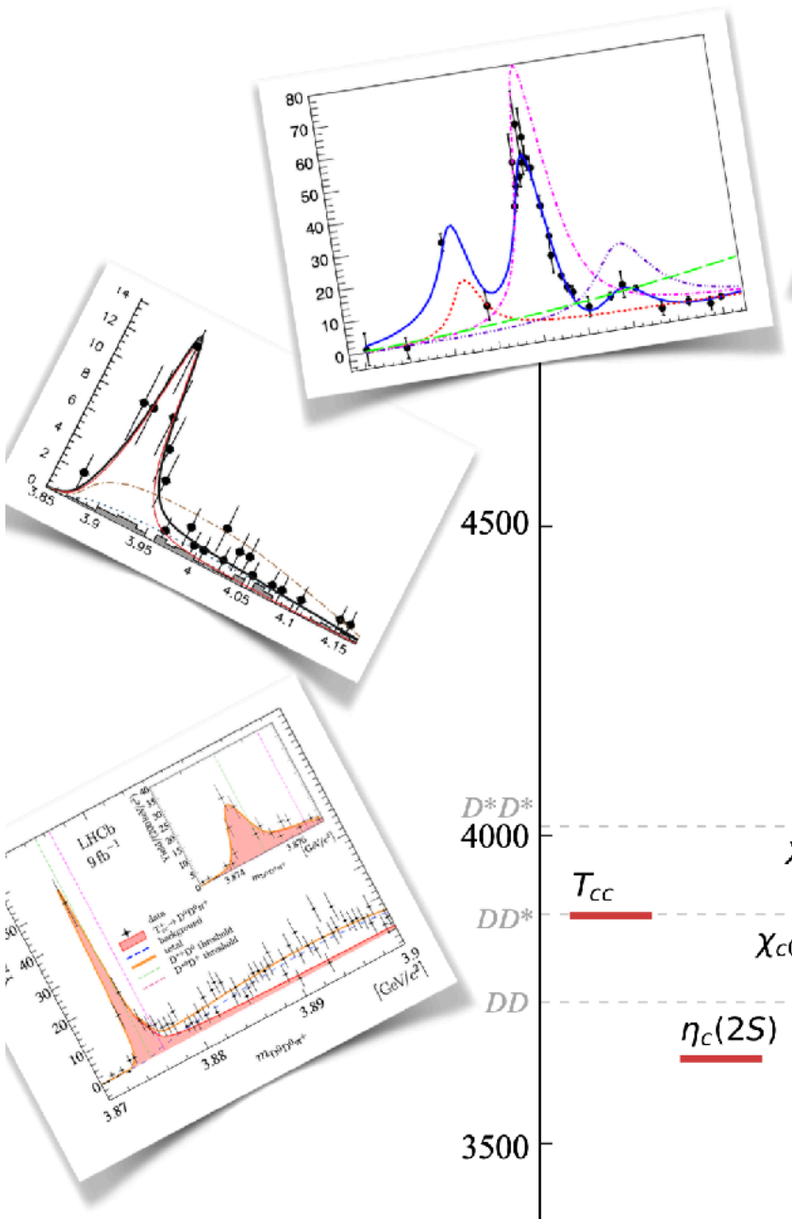
Impact: Provide guidance to analysis campaign of K-long experiment at JLab12

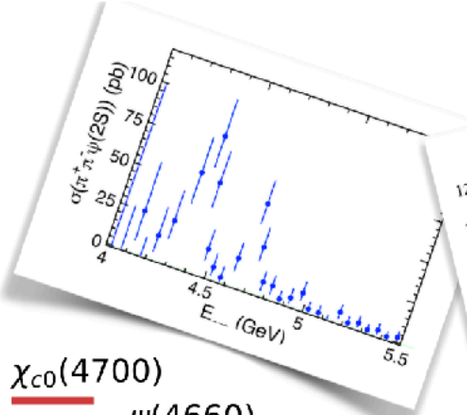
JLab Highlight:
A combination of supercomputing and traditional techniques allowed Jefferson Lab theorists to better describe the unstable sigma meson particle, contributing to our comprehension of the strong interaction

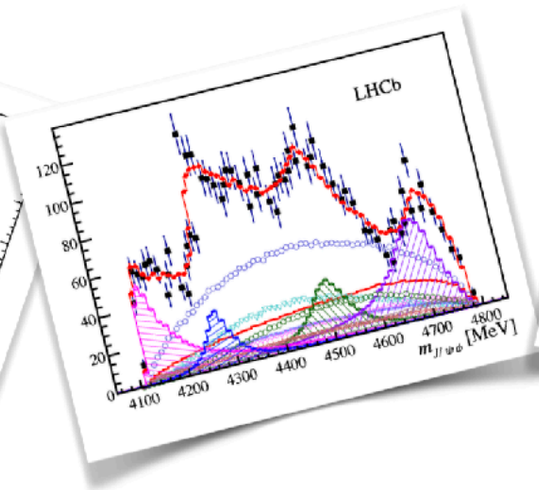
Phys.Rev. D 109 (2024) 3,3
Phys.Rev. D 108 (2023) 034513
Submitted as a DOE highlight

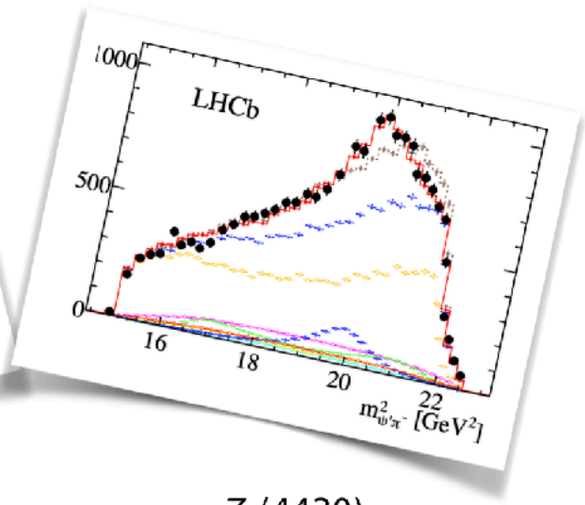


Renewed motivation - the XYZ explosion - tetraquarks?









4500

4000

3500

3000

D^*D^*

DD^*

DD

$\chi_{c0}(4700)$

$\psi(4660)$

$\chi_{c0}(4500)$

$\psi(4415)$

$Y(4390)$

$\psi(4360)$

$Y(4230)$

$\psi(4160)$

$\psi(4040)$

$X(3915)$

T_{cc}

$\chi_{c0}(3860)$

$\psi(3770)$

$\psi(2S)$

$\eta_c(2S)$

χ_{c0}

J/ψ

η_c

$\chi_{c1}(4274)$

$X(4140)$

$X(3872)$

$\psi_2(3823)$

$\chi_{c2}(3930)$

h_c

χ_{c1}

χ_{c2}

$Z_c(4430)$

$R_{c0}(4240)$

$Z(4250)$

$Z_{cs}(4220)$

$Z_c(4200)$

$D_s^*D^*$

$Z(4050)$

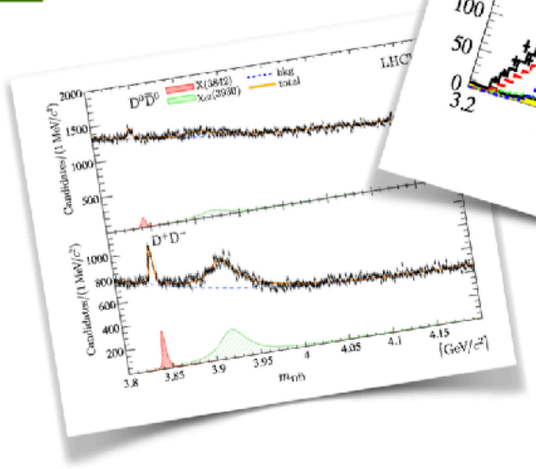
$Z_c(4020)$

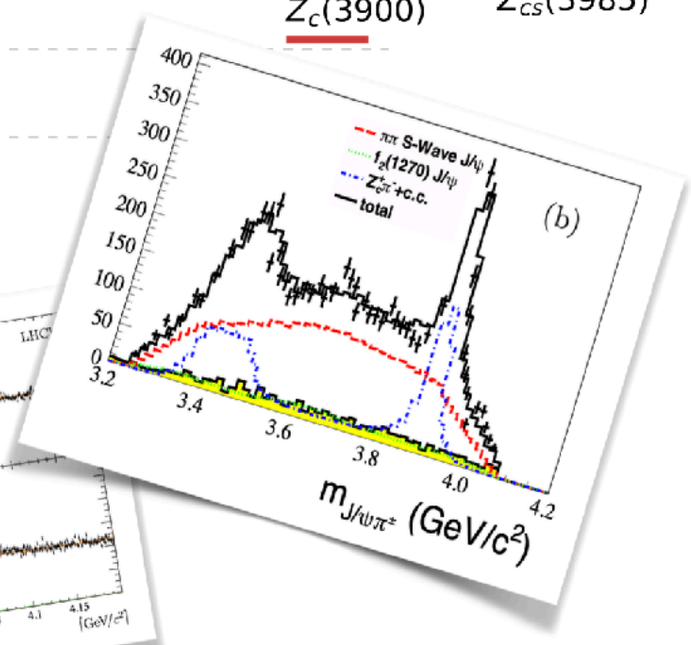
$Z_{cs}(4000)$

$Z_{cs}(3985)$

D_sD^*

$Z_c(3900)$





20th century

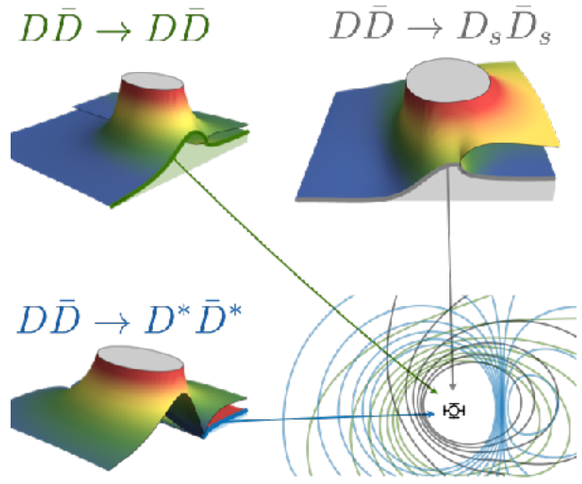
21st century

New insights on a particle physics enigma

JLab Highlight:
Lattice QCD method suggests a simpler spectrum of exotic "XYZ" hadrons

Cambridge & DAMTP Highlights

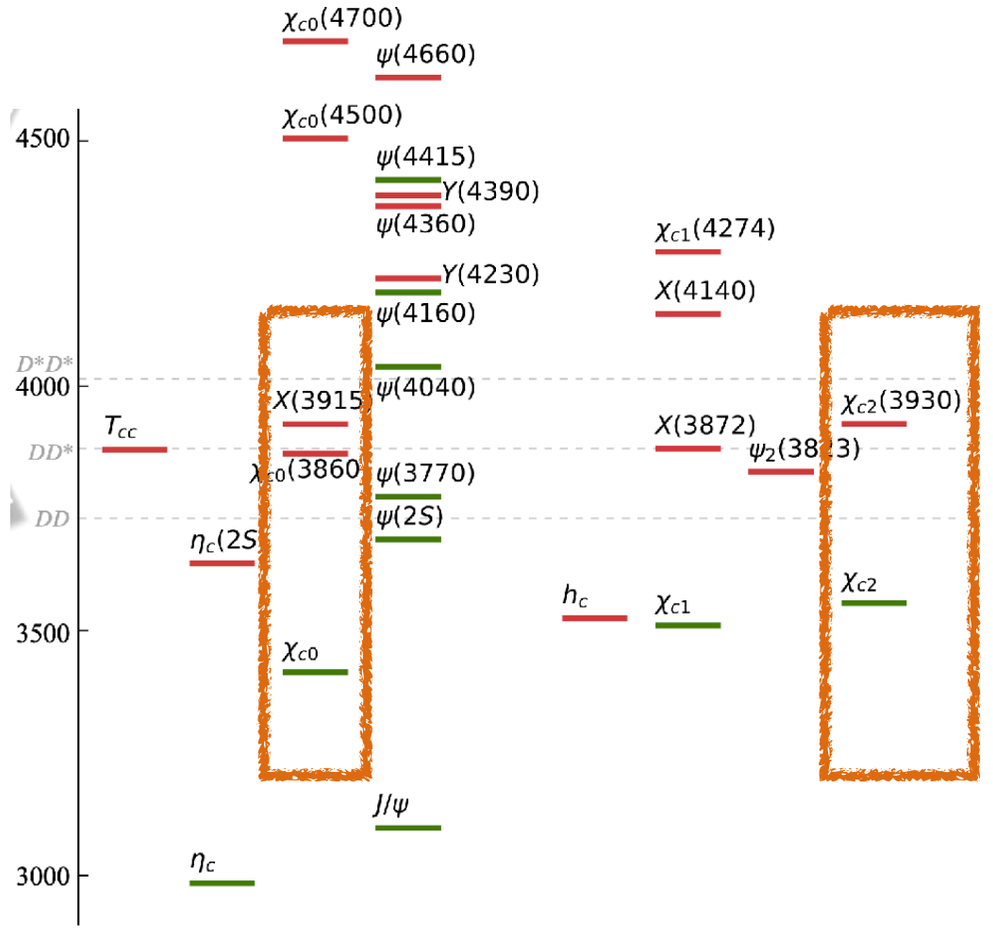
Editor's Suggestion
Phys.Rev.Lett. 132, 241901 (2024)
Phys.Rev.D 109 (2024) 11, 114503
Submitted as a DOE highlight



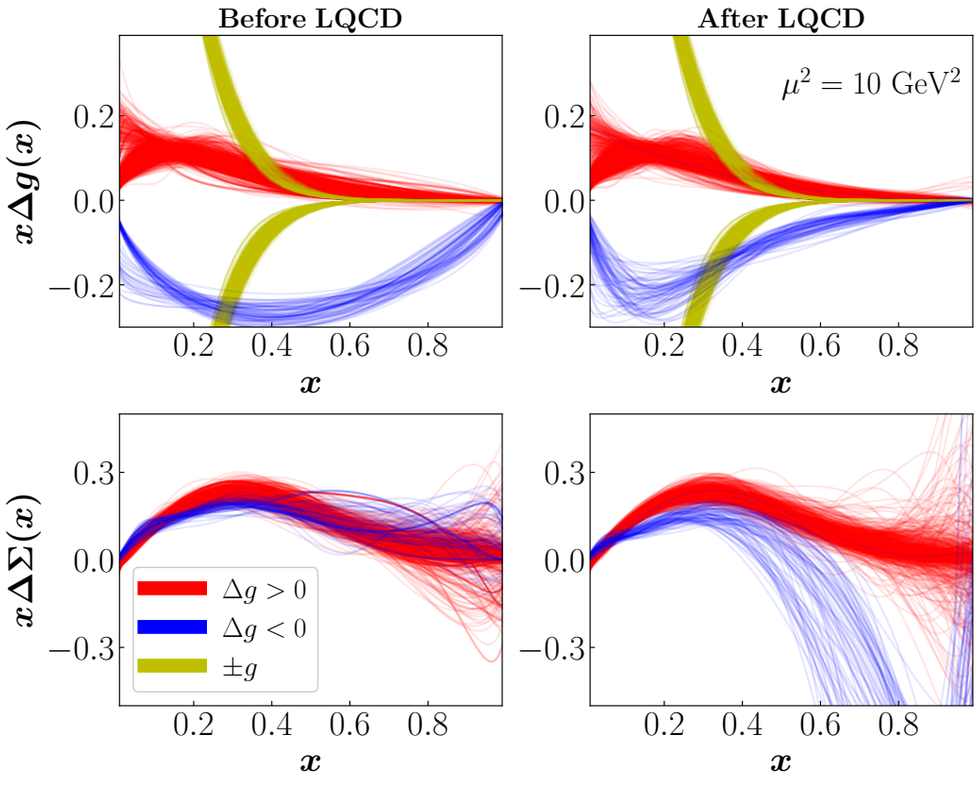
Accomplishment:
First charmonium spectrum calculation including all scattering channels, showing state counting is consistent with simple pictures.

Methods: Graph evaluation techniques developed in partnership with SciDAC RAPIDS

Impact: Suggests many charmonium states claimed by LHCb may not exist, and X(3872) may not be a tetraquark.



Theory & experiment combine to shine a new light on proton spin



JLab Highlight:

A recent study reveals new details of the origins of the proton's spin

Phys.Rev.D 106, 114512

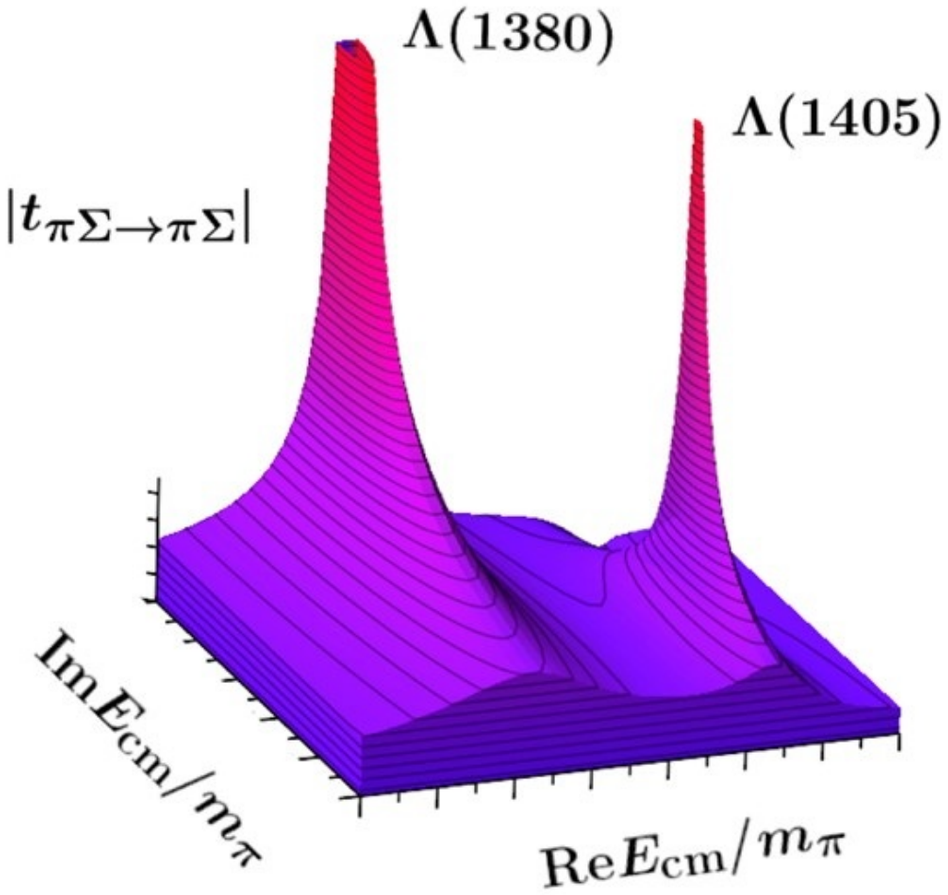
Submitted as a DOE highlight

Accomplishment: Combined analyses LQCD and experimental data providing gluon helicity contributions to proton spin

Methods: Analysis pipeline developed in partnership with SciDAC RAPIDS.

Impact: Insight into origin of proton spin

Two-pole nature of the Λ(1405)



DOE SC Highlight:
Scientists Gain new insights into the nature of the puzzling lambda 1405 hyperon resonance and its controversial partner.

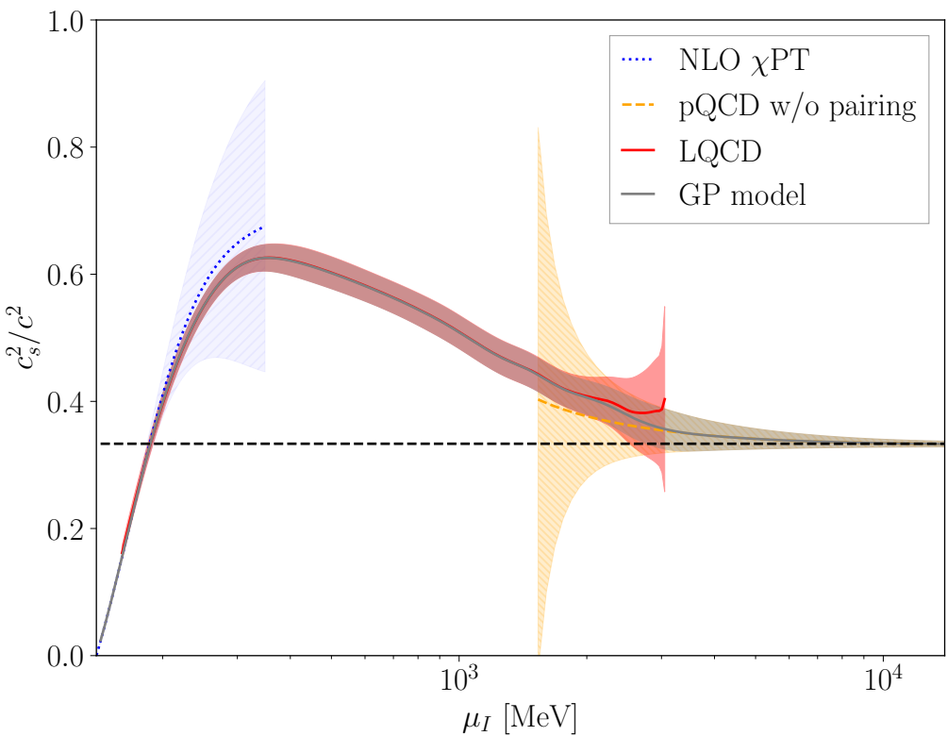
Phys. Rev. Lett., 132(5):051901, 2024.
Phys. Rev. D, 109(1):014511, 2024.

Accomplishment: First LQCD computation of coupled-channel scattering amplitudes and extraction of Λ(1405) resonance structure.

Methods: Analysis methods developed under SciDAC.

Impact: Resolving decades-long debate on origin of lightest states in QCD, and providing guidance to JLab experiments.

Isospin-dense matter and nuclear equation of state



APS Viewpoint:
Drilling into Neutron Stars with Computers

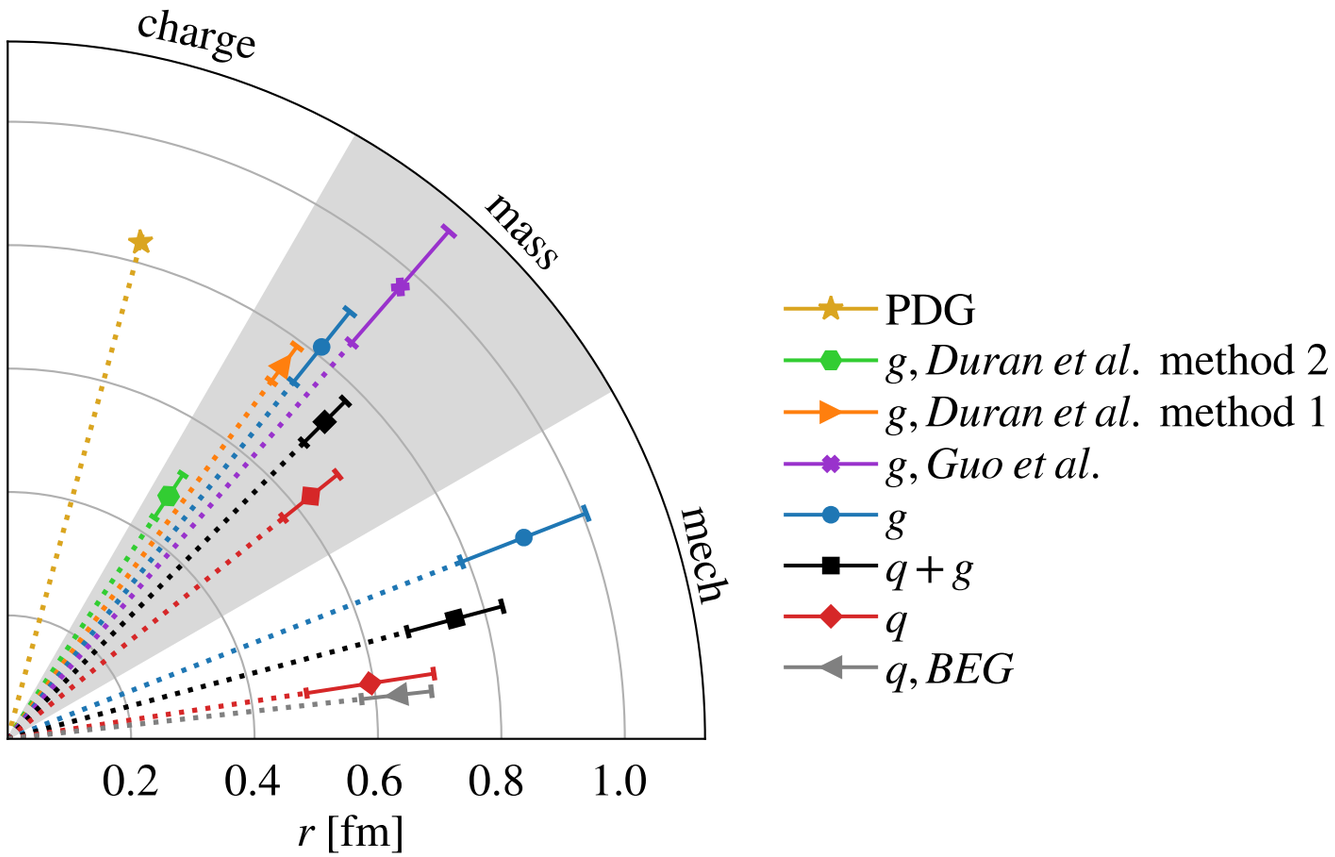
Phys. Rev. Lett. 134:011903, Jan 2025

Accomplishment: Determination of equation-of-state (EoS) for isospin-dense matter and constraints on EoS for symmetric nuclear matter.

Methods: Many pion contractions and code optimizations developed under SciDAC.

Impact: Rigorous bounds on nuclear EoS.

Gravitational Form Factors Illuminate Substructure of the Proton



Berkeley Lab Highlight

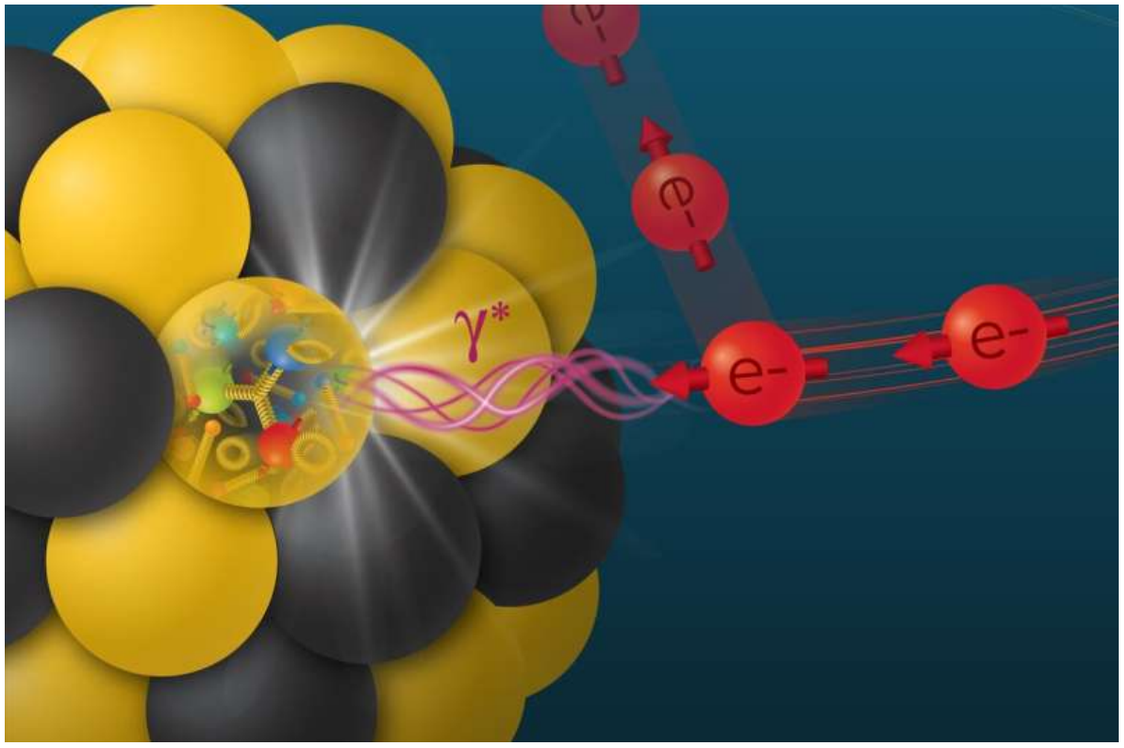
Phys. Rev. Lett. 132, 251904

Accomplishment: First computation of spatial distributions of energy, angular momentum, pressure, and shear forces inside proton.

Methods: Computational techniques for full set of quark, gluon gravitational form-factors developed under SciDAC.

Impact: Provide QCD-based understanding of JLab results

Predictions for Charge Distribution in Mesons for JLab12 and EIC and Test of QCD Factorization



Brookhaven's Top 10 Discoveries of 2024

Scientists calculate predictions for EIC measurements

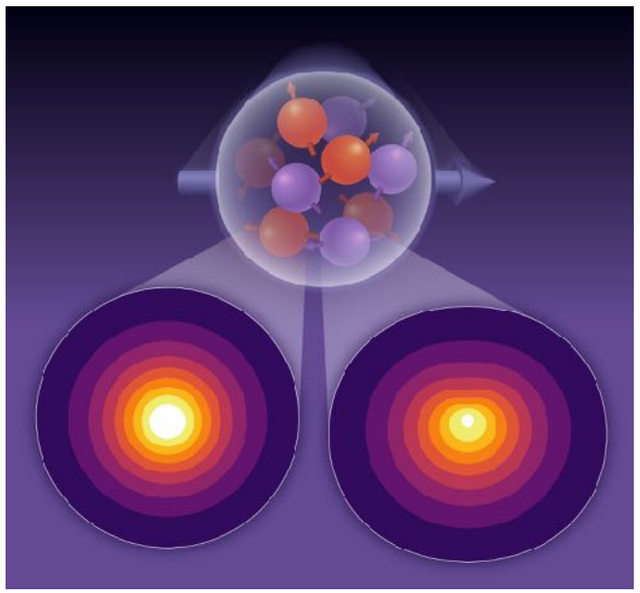
Phys. Rev. Lett. 133, 181902

Accomplishment: Predicted electric charge distributions within mesons and tested the QCD factorization.

Methods: SciDAC project provided critical software and algorithms.

Impact: Predictions for JLab12 and EIC. Demonstrates reliability of QCD factorization in inferring quark, gluon dynamics from observed hadron properties.

High-Resolution Mapping of Quark Distributions in Protons



u-quark spatial dist

d-quark spatial dist

DOE SC Highlight:
Calculations reveal high-resolution view of quarks inside protons

Phys. Rev. D, 106(11):114512, 2022 & PHYS.ORG
Phys. Rev. D, 108(1):014507, 2023.

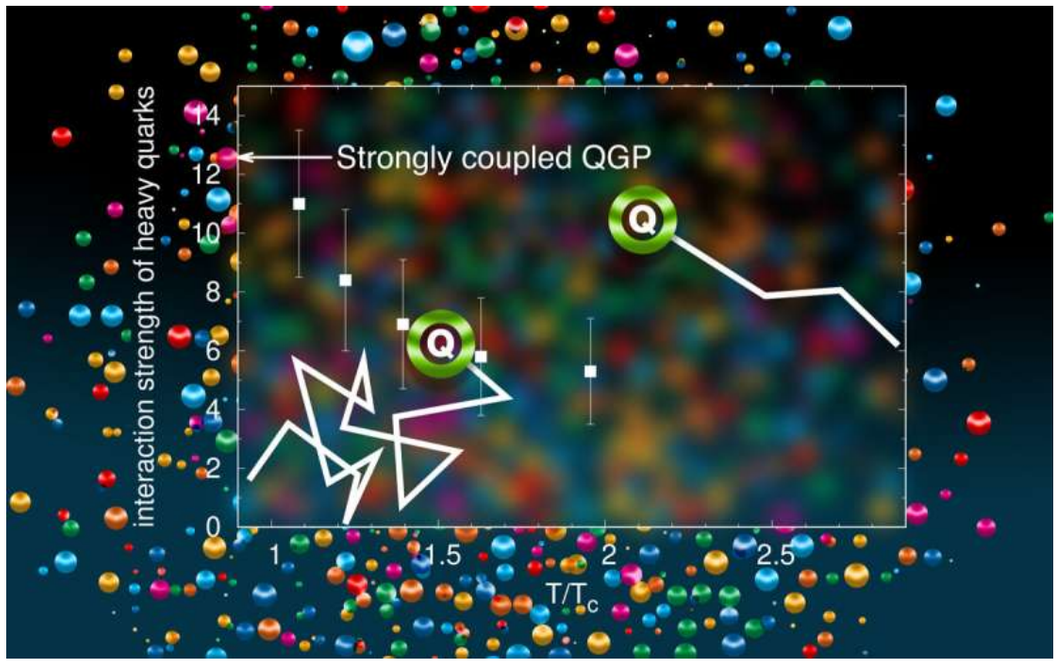
This graphic illustrates a proton moving at nearly the speed of light toward the viewer with its spin aligned along the horizontal direction (large arrow). The two views of concentric circles at the bottom show the spatial distributions of the momentum of up quarks (left) and down quarks (right) within this proton (white is high; violet is low).

Accomplishment: Revealed the differences in spatial distributions of up and down quarks within protons.

Methods: SciDAC developed 10x faster new formalism for LQCD calculations of generalized parton distribution (GPD).

Impact: Provide guidance for interpretation and extraction of GPDs from JLAB12 and EIC experiments.

Rapid Thermalization of Heavy Quarks in Quark-Gluon Plasma



DOE SC Highlight:
Calculation shows why heavy quarks get caught up in the flow

Phys.Rev.Lett. 132 (2024) 5, 051902 & PHYS.ORG

Accomplishment: First calculations of a transport coefficient, the heavy quark diffusion coefficient, for QCD with dynamical light quarks.

Methods: The SciDAC project provided all necessary software and algorithms.

Impact: Shows rapid thermalization of heavy quarks in QGP, and provide QCD input for sPHENIX and LHC heavy-ion experiments.

Lattice QCD Reveals the Hidden Motion of Quarks in Protons

DOE SC Highlight:
Calculation Sharpens Imaging of Protons' Insides

SciTechDaily

Phys. Rev. D, 109(9):094506, 2024.
Phys. Lett. B, 852:138617, 2024

Accomplishment: First precise calculation of 3D transverse motion of quarks using chiral fermions and physical quark masses.

Methods: The SciDAC project provided critical software and algorithms.

Impact: Provide QCD input and reduce model-reliance for 3D imaging of proton at EIC experiments.