The exotic spectrum of quarks and gluons

Robert Edwards
Jefferson Lab

Big questions in Nuclear Physics

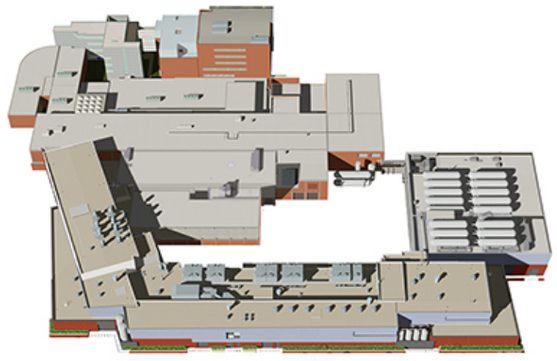
- What is the origin of mass and spin?
- What is the mechanism for confinement of matter?
- What are the limits of nuclear existence?
- How does matter behave under extreme temperatures & pressures?

Focus of new experiments at JLab, BNL, FRIB

Jefferson Lab

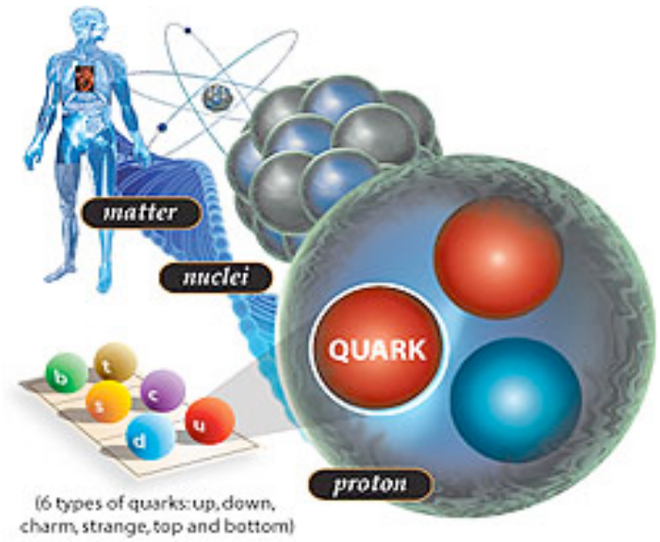
Brookhaven National Lab

Facility for Rare Isotope Beams



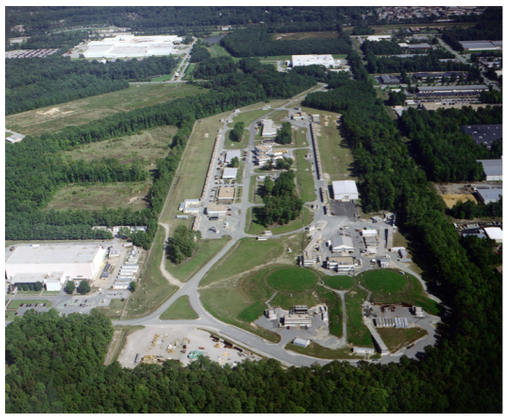
Strong nuclear force

- Fundamental building blocks of matter are ***quarks*** bound by ***gluons*** via ***strong nuclear force***.
- Quantum Chromodynamics (QCD) is the theory which describes the strong interactions
- How does QCD predict confinement and mass/spin?
  - Seems only ~5% of mass of a proton comes from mass of quarks
  - Can we observes presence of gluons?

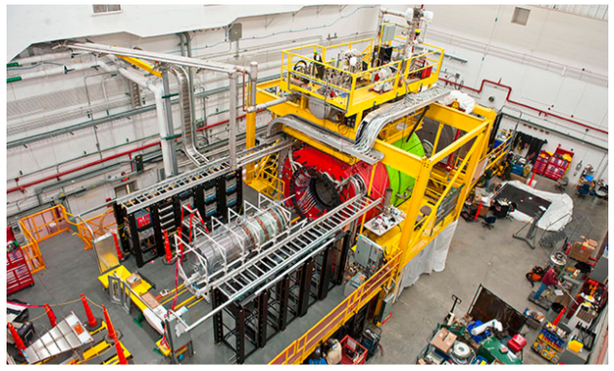


(6 types of quarks: up, down, charm, strange, top and bottom)

Jefferson Lab



GlueX

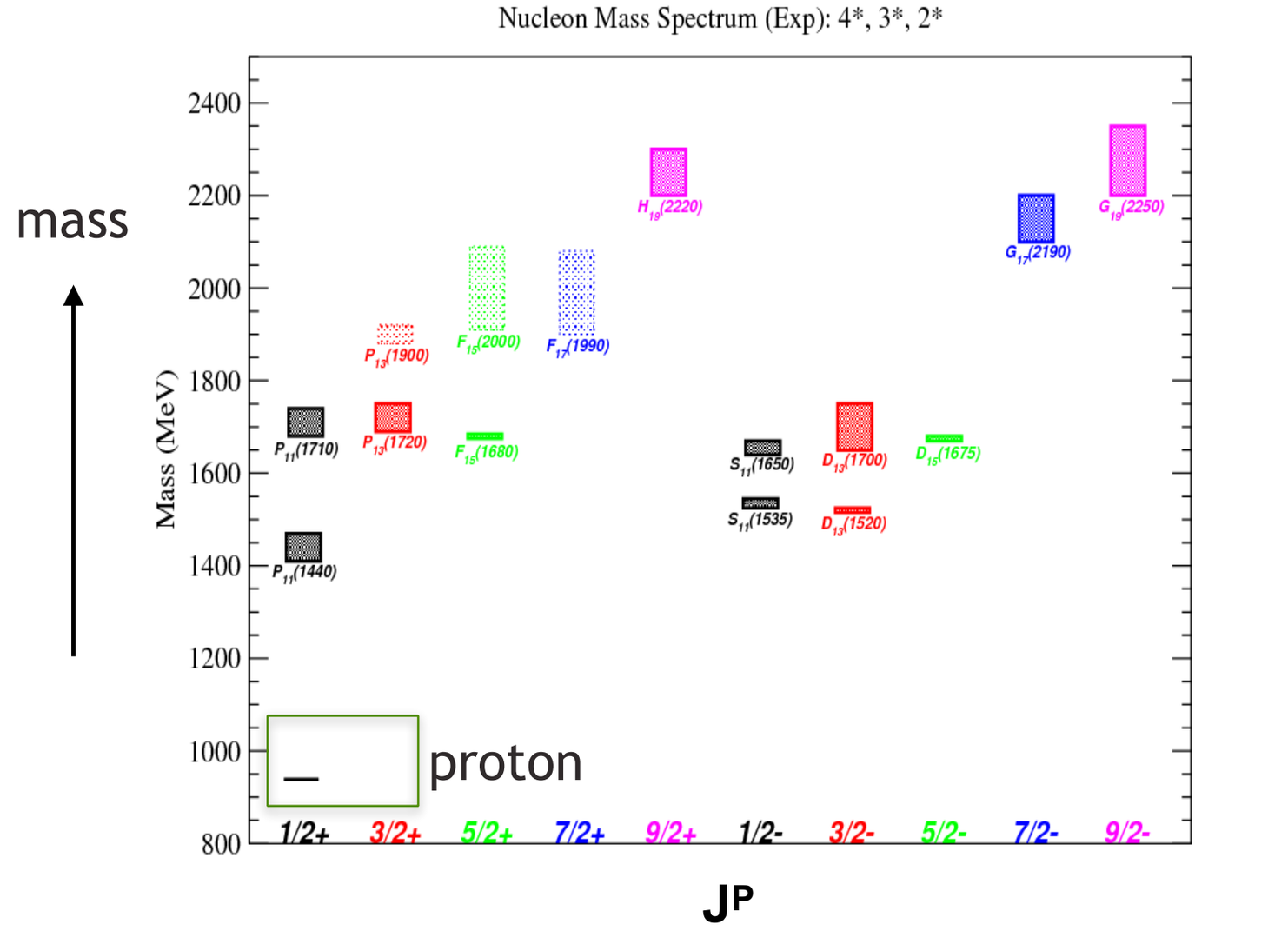


CLAS12

Experimental baryon spectrum

- Elementary particles classified by their conserved quantum numbers
  - Spin, parity **J^P**
- Familiar proton is spin 1/2 particle
- Expt. suggests excitations. How?

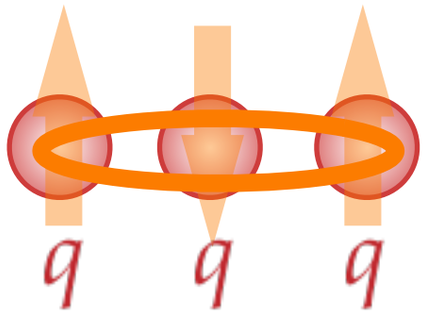
LIGHT QUARK BARYON SPECTRUM



Experimental baryon spectrum

- "Quark model" (circa 1960-s) suggests patterns of spin 1/2 "quarks"
  Similar to chemistry of hydrogen atom

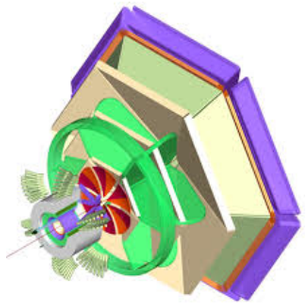
1969 Nobel



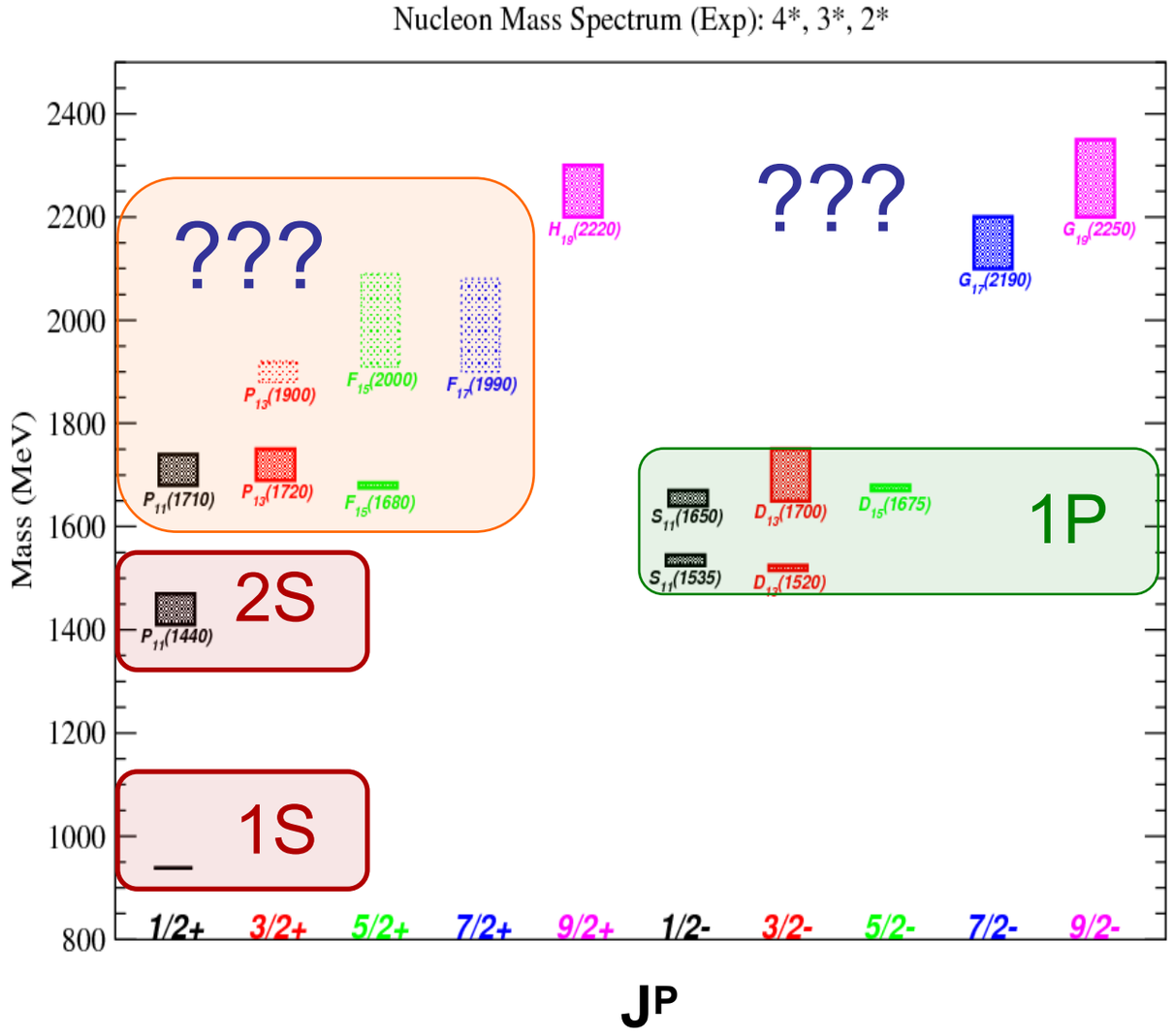
Reasonable description for low mass states

Suggests more states than observed

CLAS12



LIGHT QUARK BARYON SPECTRUM

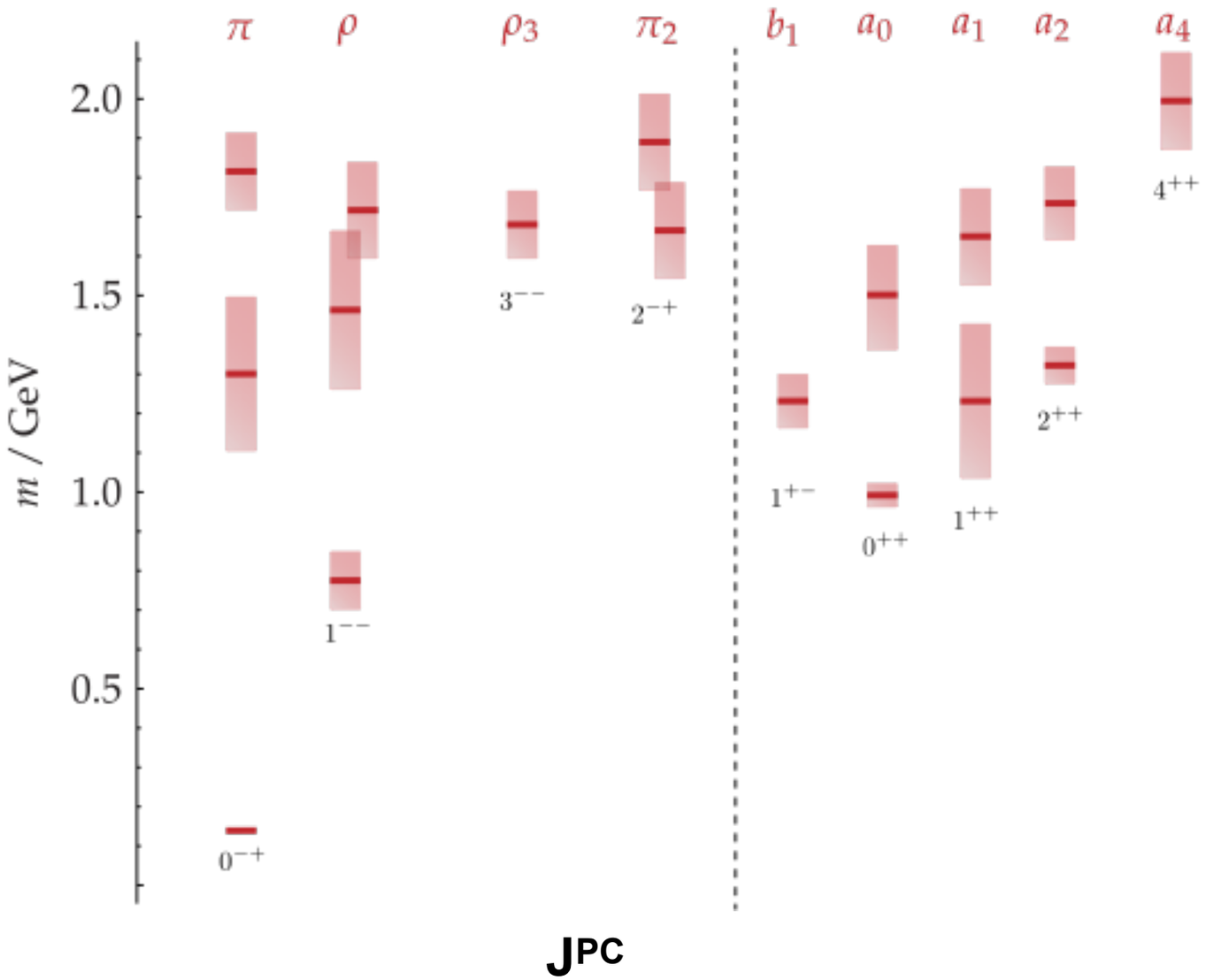


the **constituent quark picture**

Experimental meson spectrum

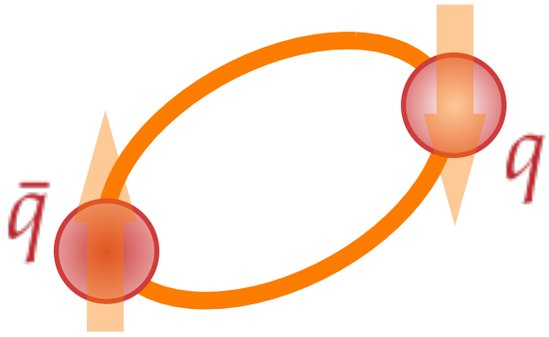
- Mesons classified by Spin, parity, charge-conjugation **J^{PC}**

LIGHT QUARK MESON SPECTRUM



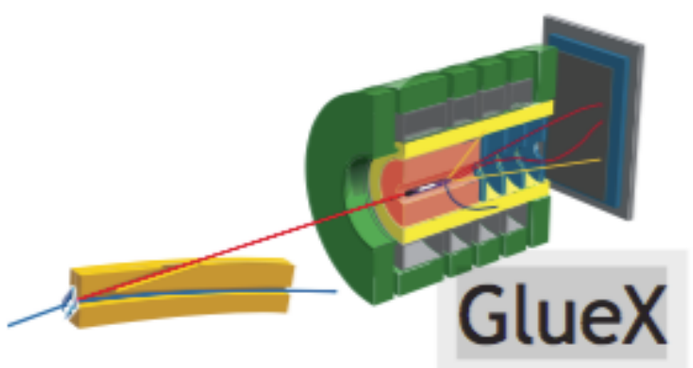
Experimental meson spectrum

- Mesons reasonably described by two “constituent” quarks

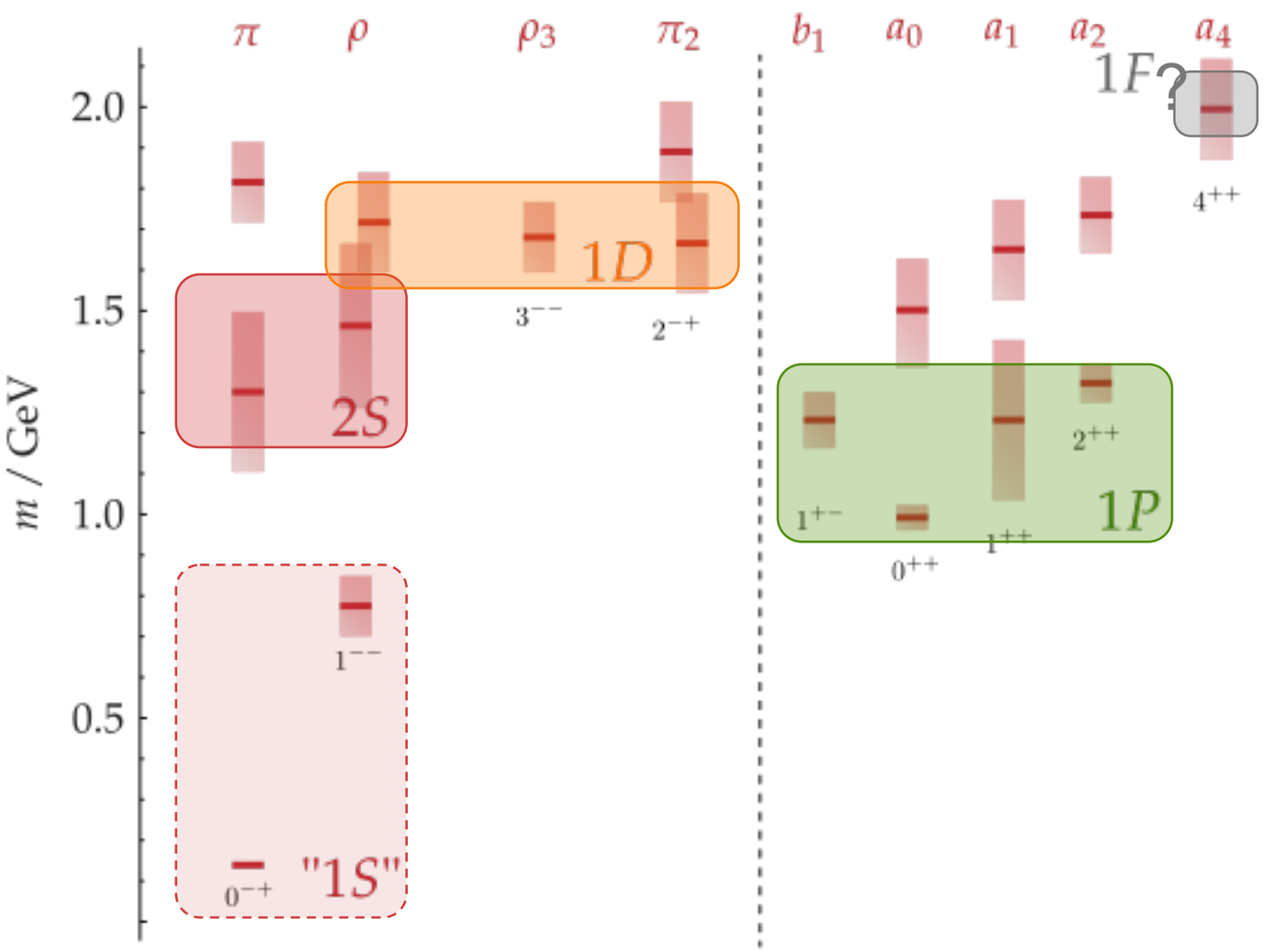


Rules restricts patterns of J^{PC}

Violations are “smoking gun” signatures of gluons



LIGHT QUARK MESON SPECTRUM

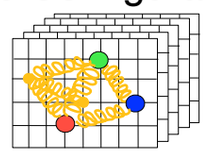


Will directly compute from QCD

Lattice QCD Calculation Workflow

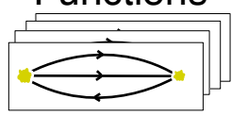
Gauge Generation

Gauge Configurations

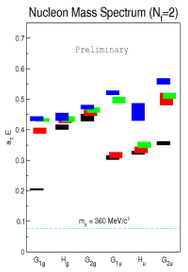


Measurement

Propagators, Correlation Functions



Fitting



Physics Result

- Core computational unit is solution of Dirac equation - large sparse linear system

- Gauge Generation: Few independent chains. Strong scaling challenge
  - Carried out on leadership computing facilities

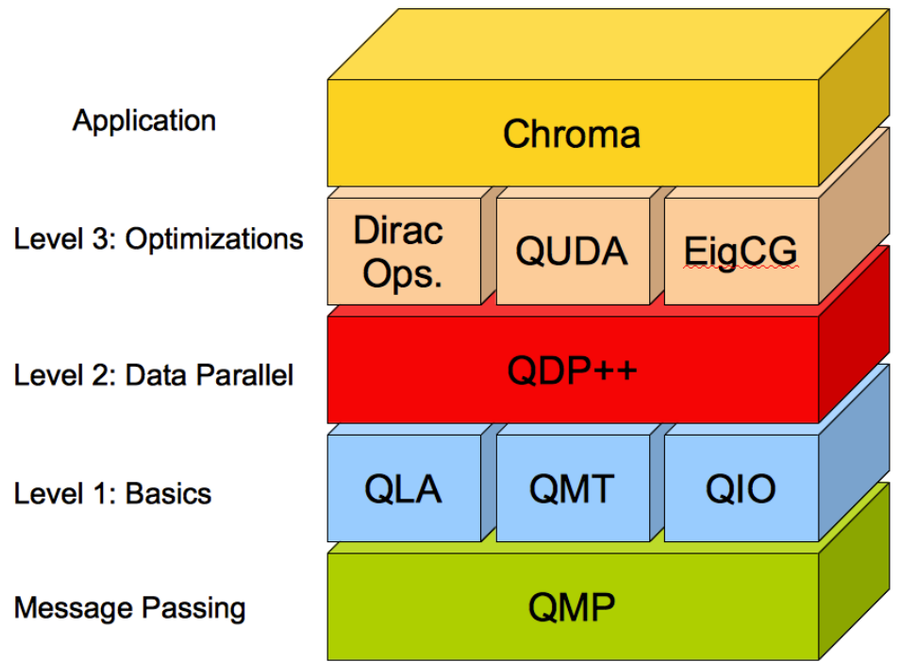
- Measurement: Propagator Calculations & Correlation Function Construction (Contractions)
  - Many independent solves, throughput challenge
  - Most cost effective on capacity/midrange systems, tho LCFs can also be used

Made possible by improved algorithms and adaptation under SciDAC

Software infrastructure

SciDAC-1: developed new code base – used C++

- QDP++:
  - Data parallel interface – well suited for QCD (called Level 2)
  - Hides architectural details
  - Supported threading & comms (e.g., Hybrid/MPI model)
  - Thread package: customized – outperformed OpenMP
  - Parallel file I/O support
- Chroma:
  - Built over QDP++
  - High degree of code modularity
  - Supports gauge generation
  - Task based measurement system
- Modern CS/software-engineering techniques
  - Portable expression templates



SciDAC-2/3: extension to GPUs

- Code generation/Just-In-Time compilation - collab. with SUPER

The Chroma software system for lattice QCD #2

SciDAC and LHPC and UKQCD Collaborations • Robert G. Edwards (Jefferson Lab) et al. (Sep, 2004)

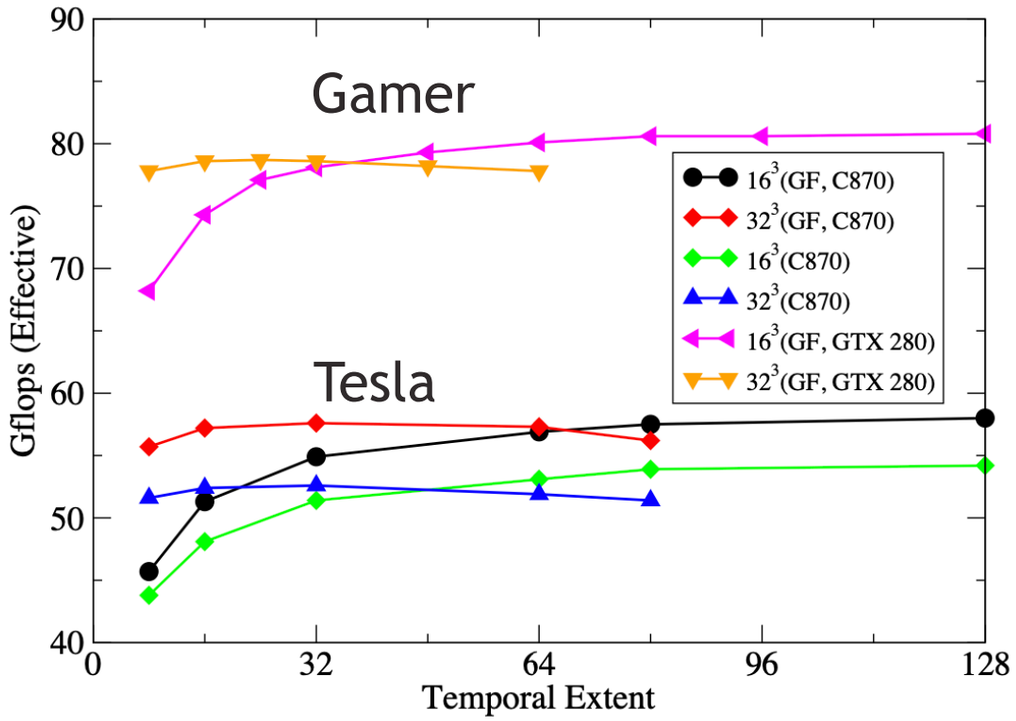
Published in: *Nucl.Phys.B Proc.Suppl.* 140 (2005) 832, • Contribution to: 22nd International Symposium on Lattice Field Theory (Lattice 2004), 832-834 • e-Print: hep-lat/0409003 [hep-lat]

pdf links DOI cite 787 citations

Architectures: GPU - disruptive technology

SciDAC-2 innovation

- In 2008: 5-GFlops per Dirac solve on SSE cpus
- High performance GPU solvers: QUDA library
  - Impressive 32-bit performance for Dirac solves
  - Tesla cards ~ 50 GFlops/solve
  - Gamer cards very cost effective
    - Fraction cost of ECC based GPUs
    - ~80 GFlops/solve for $450/card



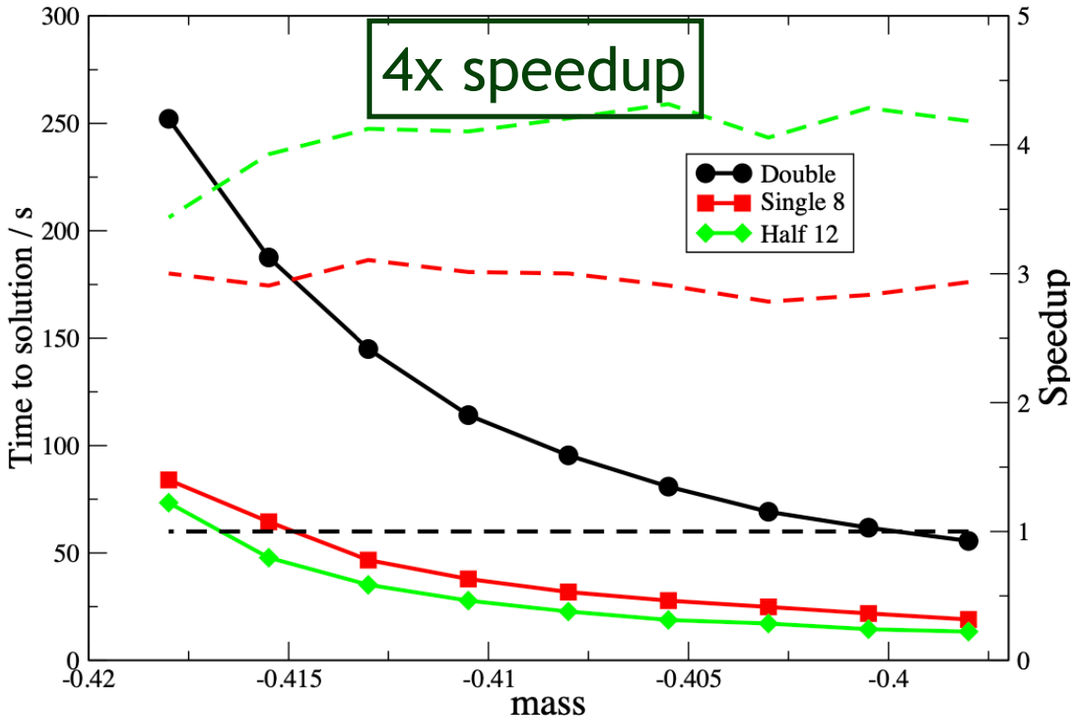
- Innovation: mixed precision solvers
- 4 GPUs/box: >***30x*** in price-performance over CPUs

Solving Lattice QCD systems of equations using mixed precision solvers on GPUs #56

M.A. Clark (Harvard-Smithsonian Ctr. Astrophys. and Harvard U.), R. Babich (Boston U., Ctr. Comp. Sci. and Boston U.), K. Barros (Northwestern U.), R.C. Brower (Boston U., Ctr. Comp. Sci. and Boston U.), C. Rebbi (Boston U., Ctr. Comp. Sci. and Boston U.) (Nov, 2009)

Published in: *Comput.Phys.Commun.* 181 (2010) 1517-1528 • e-Print: 0911.3191 [hep-lat]

pdf DOI cite 258 citations

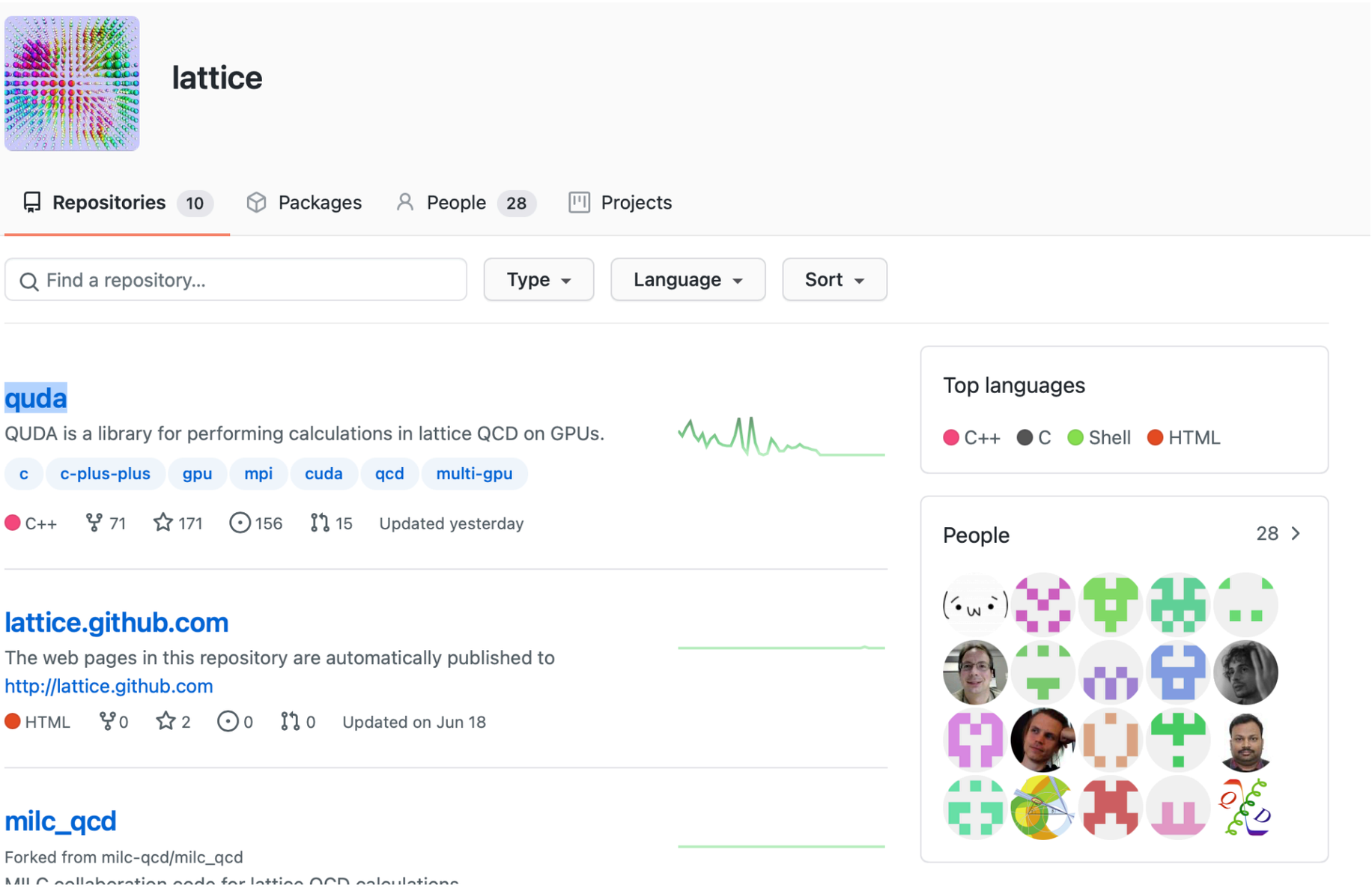


Jefferson Lab

QUDA/NVIDIA+(AMD+Intel) - strong industrial collaboration

Main developers now @ NVIDIA - some members in Future Technologies group

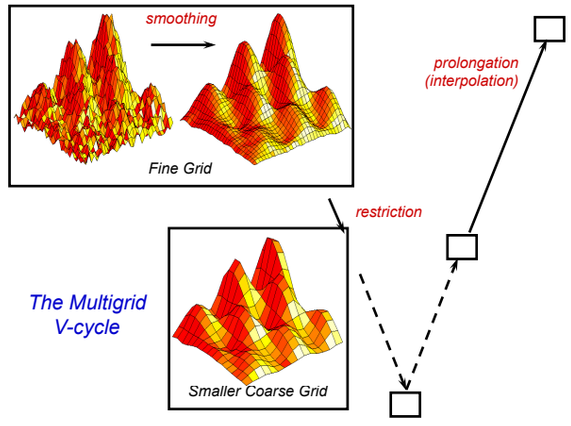
Codes used an Exemplar as well as to guide product development



New contributors from AMD & Intel!

Algorithms: Multi-Grid

- Adaptive Aggregation Algebraic Multi-Grid
  - Developed in collab. with TOPS, Applied Math. & SciDAC along with NSF funding
  - Implementation initially on CPUs
  - Provides 10x improvement over previous solver
- Collaboration with FASTMath
  - Extended HYPRE to allow QCD implementations
- Now supported on GPUs - again 10x speedup



Adaptive Multigrid Algorithm for the Lattice Wilson-Dirac Operator

R. Babich, J. Brannick, R. C. Brower, M. A. Clark, T. A. Manteuffel, S. F. McCormick, J. C. Osborn, and C. Rebbi
Phys. Rev. Lett. **105**, 201602 – Published 11 November 2010

AUTHORS & AFFILIATIONS

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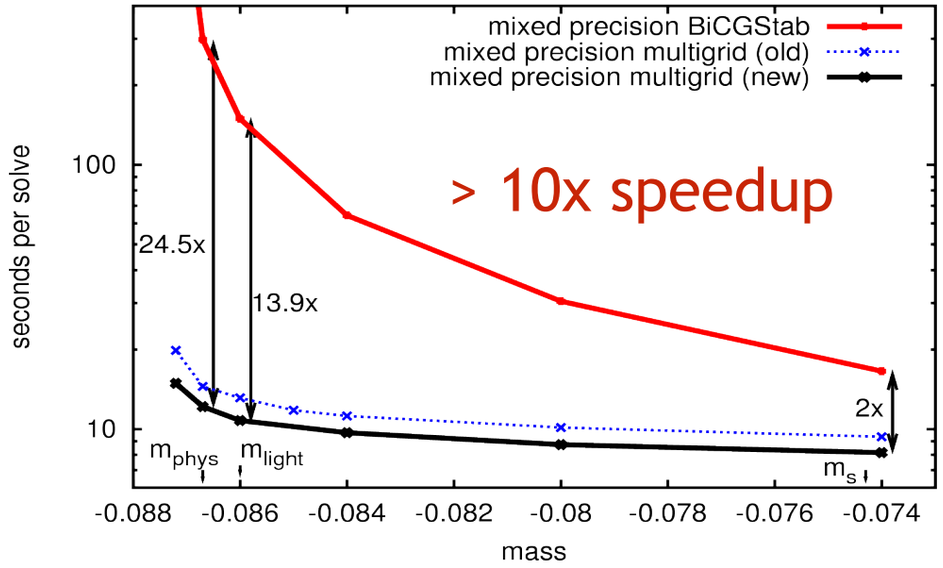
[1]Center for Computational Science, Boston University, 3 Cummington Street, Boston, Massachusetts 02215, USA
[2]Department of Physics, Boston University, 590 Commonwealth Avenue, Boston, Massachusetts 02215, USA
[3]Department of Mathematics, The Pennsylvania State University, 230 McAllister Building, University Park, Pennsylvania 16802, USA
[4]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA
[5]Department of Applied Mathematics, Campus Box 526, University of Colorado at Boulder, Boulder, Colorado 80309, USA
[6]Argonne Leadership Computing Facility, Argonne National Laboratory, Argonne, Illinois 60439, USA

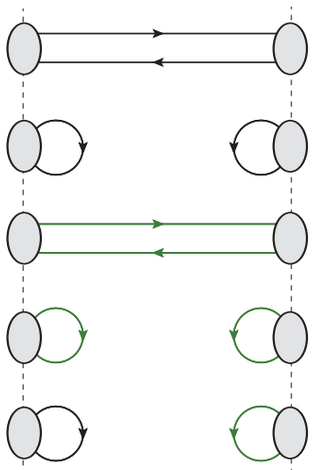
32^3x256 aniso clover on 1024 BG/P cores



Algorithms for Measurements

Foundation for all our LQCD calculations

- Distillation
  - Implement ‘smearing’ to enhance low energy states
  - A way of constructing quark line graphs for contractions
  - O(10,000) graphs, O(100K-1M) propagator solves per config
  - Supports reuse of propagators
- Extensive “operator” technology used with variational method
- Methods efficiently factorizes calculations
  - propagator calculations from contractions



high precision calculation of **disconnected diagrams**

Ideally suited to GPU systems

2010: JLab adopters of GPUs

A Novel quark-field creation operator construction for hadronic physics in lattice QCD #3

Hadron Spectrum Collaboration • Michael Peardon (Trinity Coll., Dublin) et al. (May, 2009)

Published in: *Phys.Rev.D* 80 (2009) 054506 • e-Print: 0905.2160 [hep-lat]

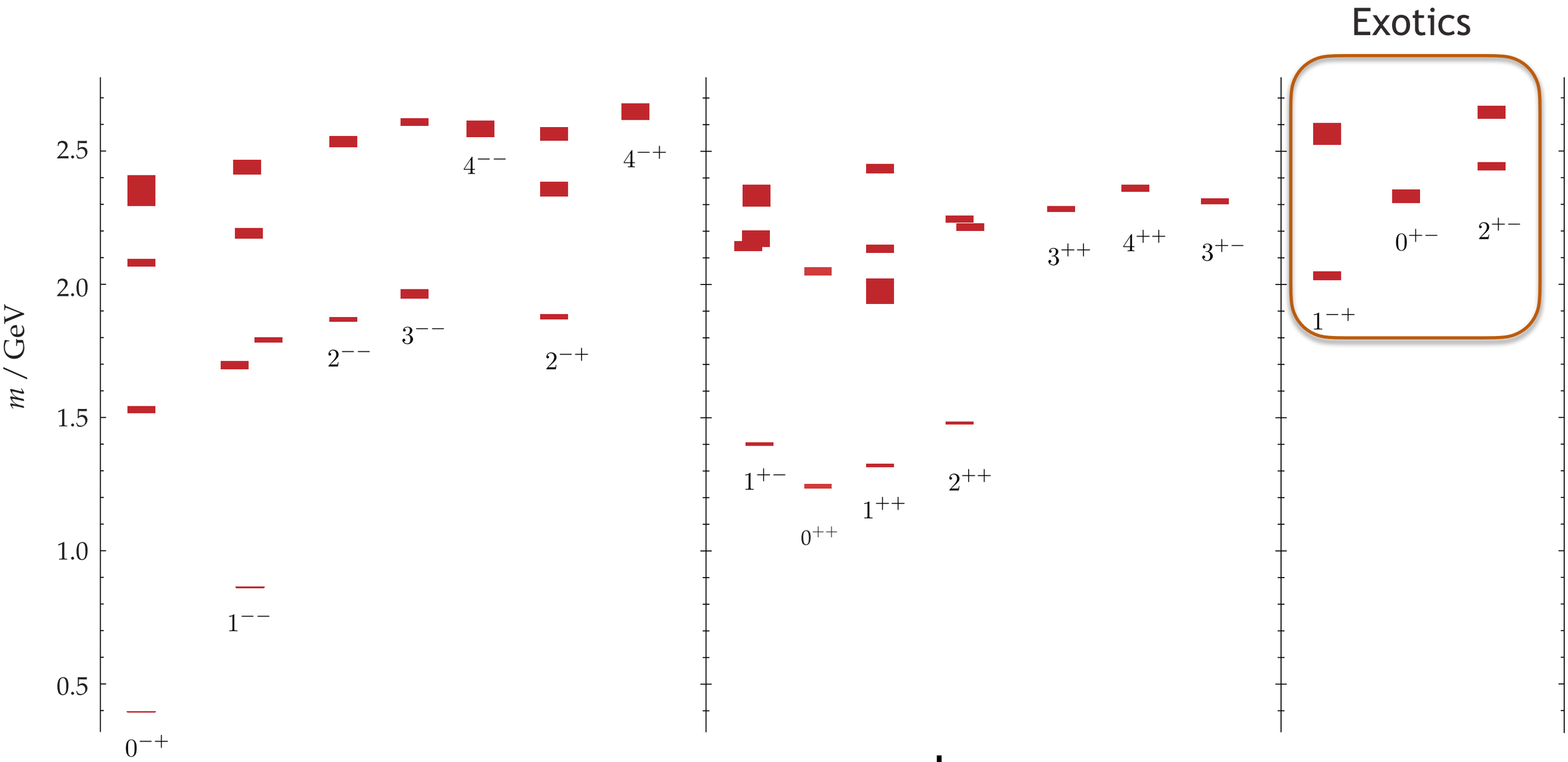
pdf links DOI cite 303 citations

Joint ASCR/NP supported members

Lattice QCD & the excited meson spectrum

- Rich spectrum of mesons - including clear indication of **exotics**

'Toward the excited isoscalar meson spectrum from lattice QCD'
PRD 88 094505 (2013)



PRL 103; PRD 82, 88

Lattice QCD & the excited meson spectrum

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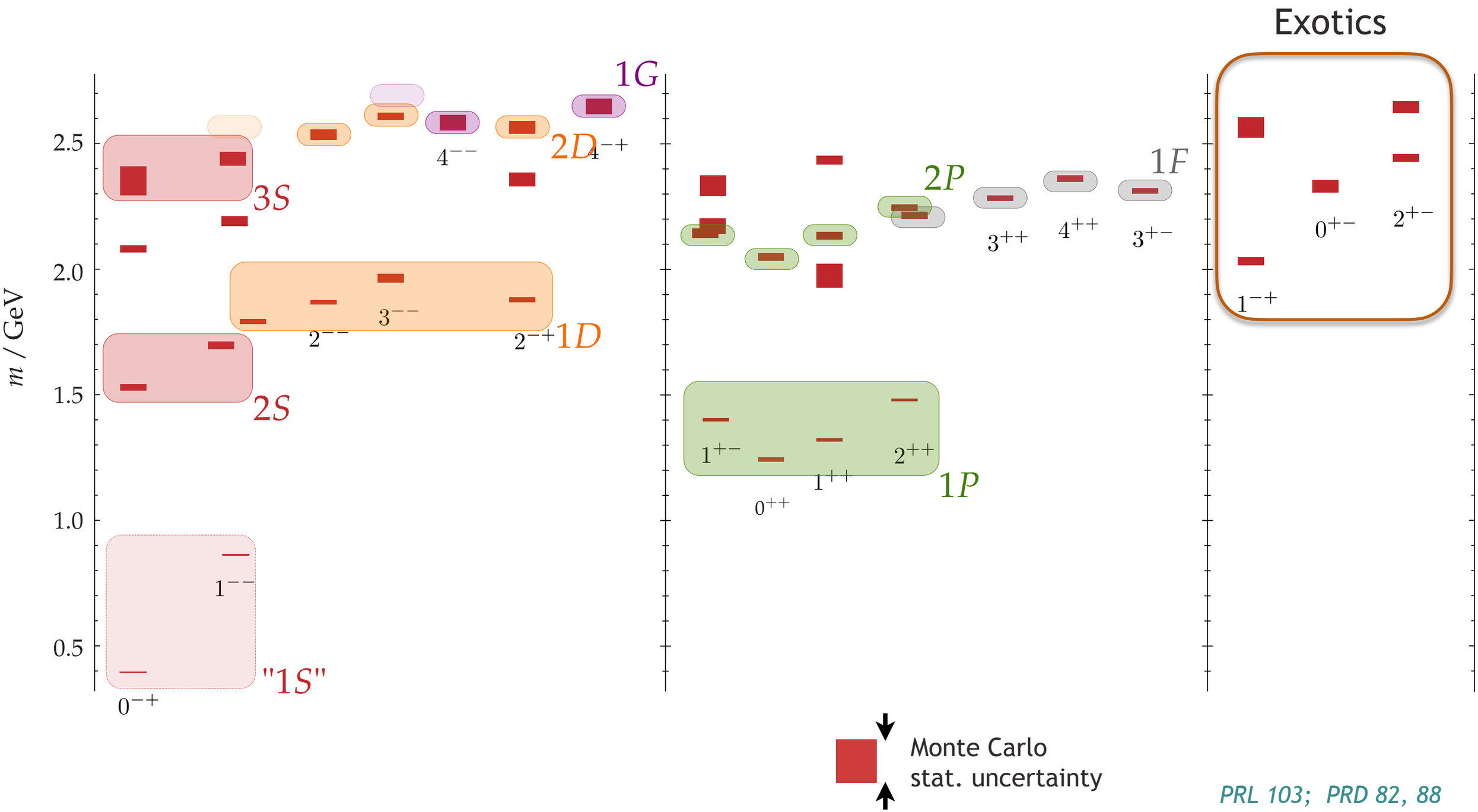
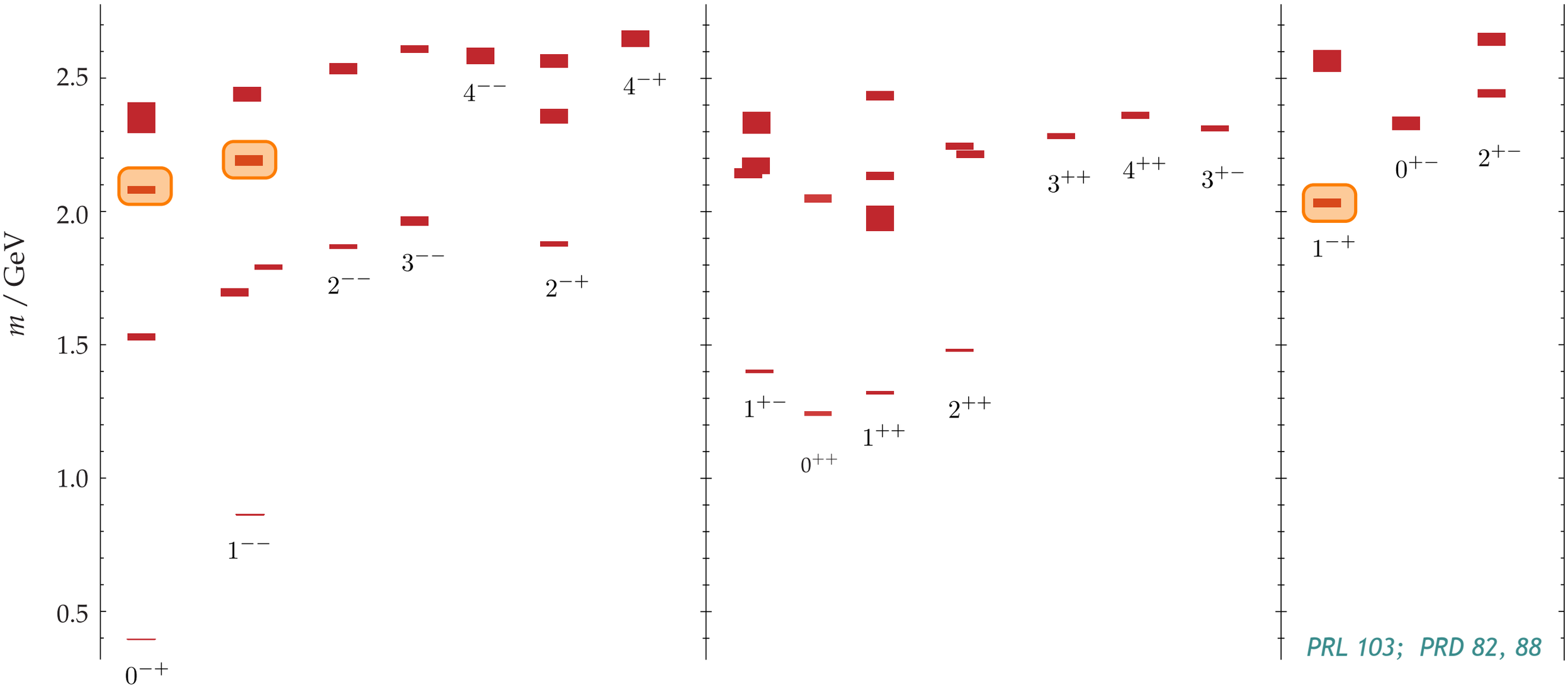


PRL 103; PRD 82, 88

Hybrids and well as exotic mesons

- ‘super’-multiplet of **hybrid mesons** roughly 1.2 GeV above the ρ



- Operator overlaps suggest gluon in color chromo-magnetic configuration

More extensive spectrum computation

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

Featured in Particle Data Group

clear indication of a spectrum of **hybrid mesons**

Joint ASCR/NP supported members

Isoscalar meson spectroscopy from lattice QCD
PRD 83 111502 (2011)

‘Toward the excited isoscalar meson spectrum from lattice QCD’
PRD 88 094505 (2013)

More extensive spectrum computation

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

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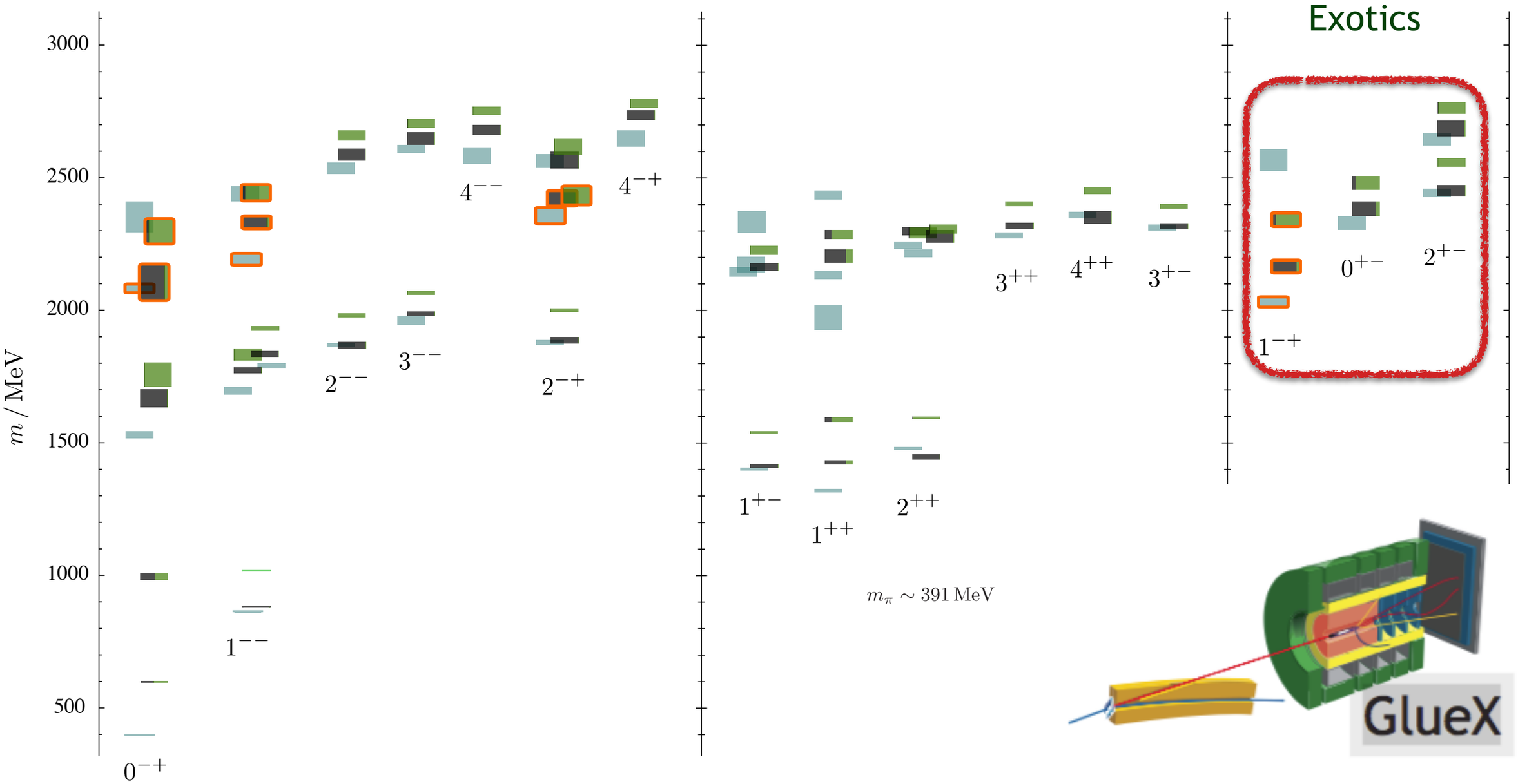
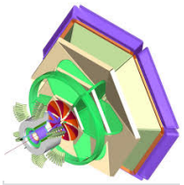


Guiding GlueX searches

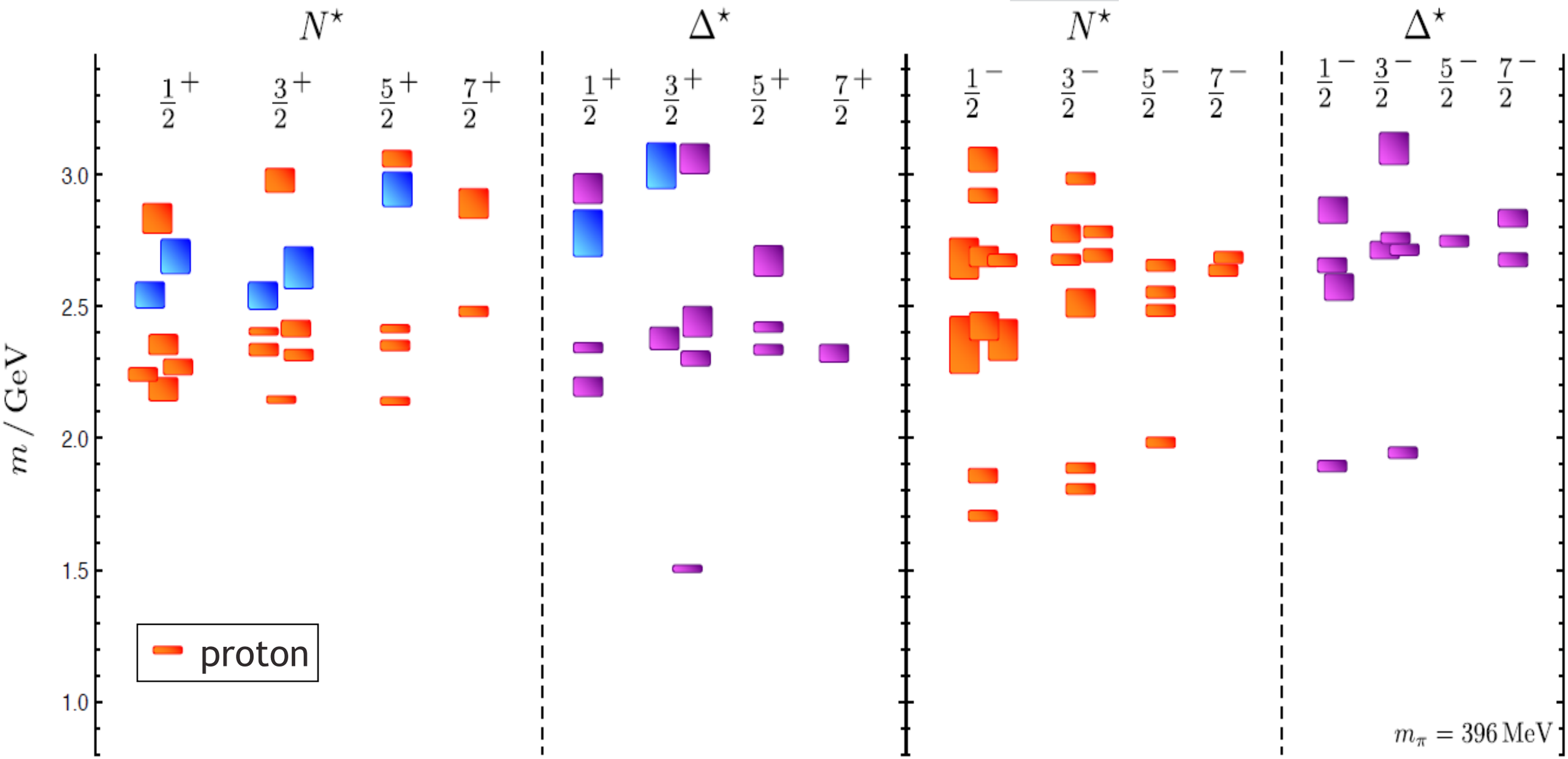
LQCD sees rich spectrum of baryons

Focus of CLAS12 @ JLab & Bonn & Mainz & LHCb @ CERN

Featured in Particle Data Group



CLAS12



Excited state baryon spectroscopy from lattice QCD
PRD 83 074508 (2011)

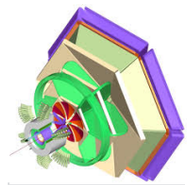
LQCD suggest no “missing" baryon states

Predicts specific multiplicity of states

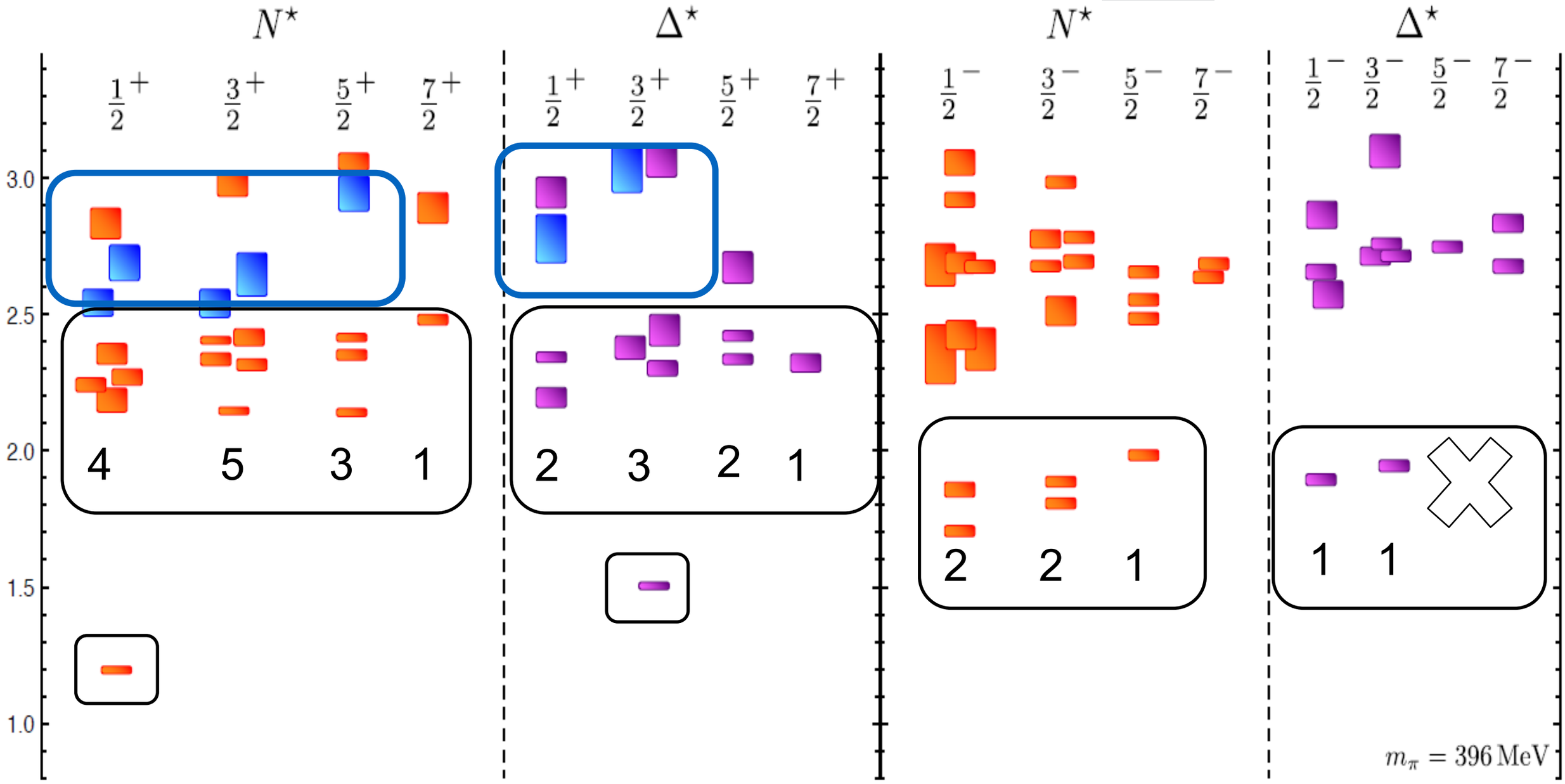
Additional gluonic excitations within baryons

Spurred new expt. search in CLAS12@JLab

Featured in Particle Data Group



CLAS12

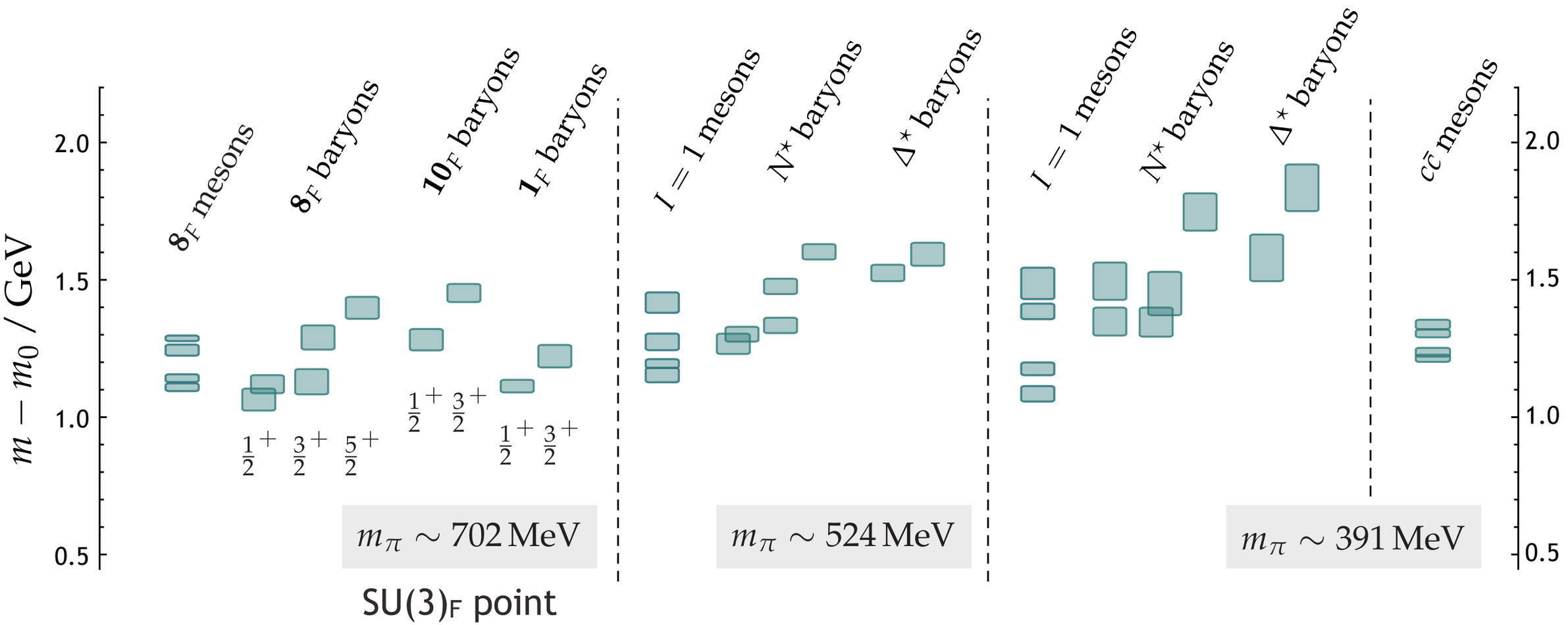


Excited state baryon spectroscopy from lattice QCD
PRD 83 074508 (2011)

Role of the glue in hadron spectroscopy

- Subtract the ‘quark mass’ contribution

  Compare over wide range of states and quark mass scales



Predicts observable effects @JLab 12GeV and @Electron Ion Collider

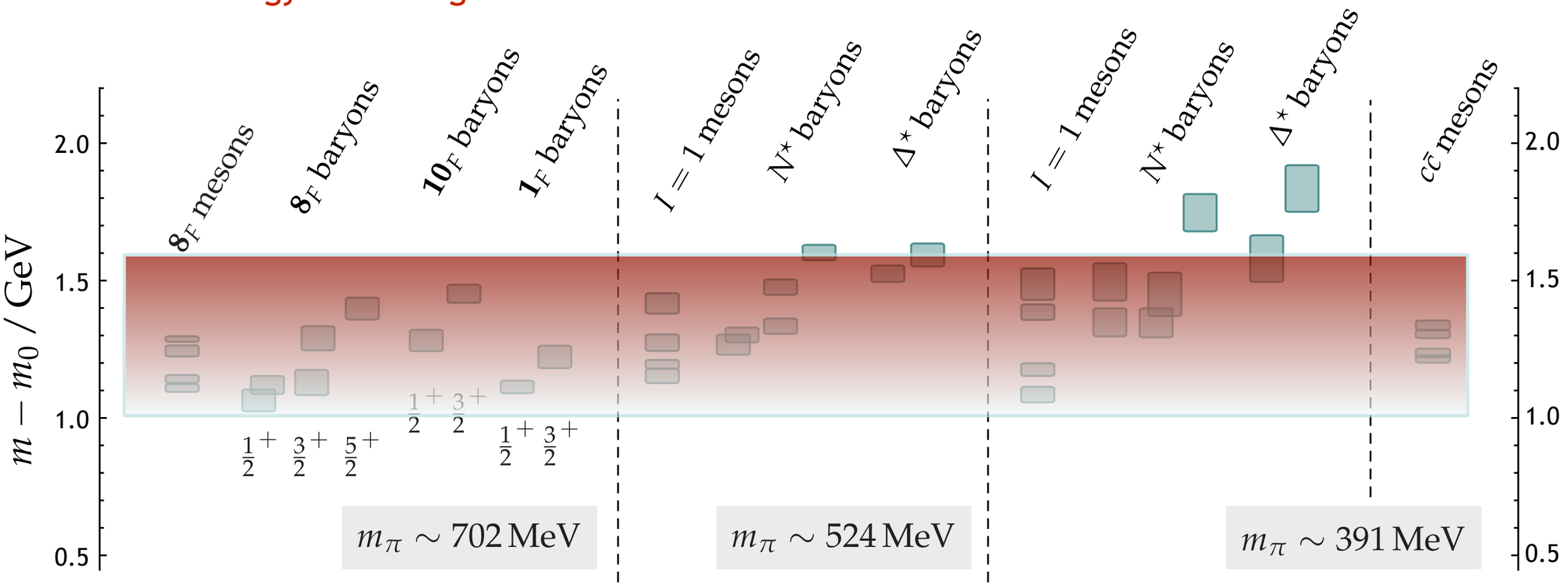
HADRON SPECTRUM: PRD83 (2011); PRD88 (2013)

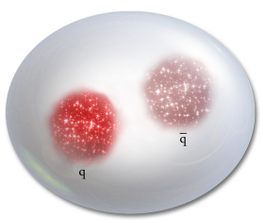
Role of the glue in hadron spectroscopy

- Subtract the ‘quark mass’ contribution

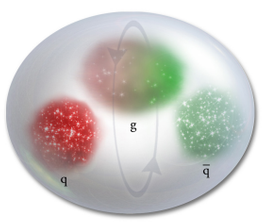
  Compare over wide range of states and quark mass scales

Common energy scale of gluonic excitation ~ 1.3 GeV





Conventional Meson



Hybrid Meson

Predicts observable effects @JLab 12GeV and @Electron Ion Collider

HADRON SPECTRUM: PRD83 (2011); PRD88 (2013)

Involvement with experimental program

Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab

Jozef Dudek, Rolf Ent, Rouven Essig, Krishna Kumar, Curtis Meyer, Robert McKeown, Zein Eddine Meziani, Gerald A. Miller, Michael Pennington, David Richards, Larry Weinstein, Glenn Young

12 GeV science case

A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC

(A proposal to the 42nd Jefferson Lab Program Advisory Committee)

M. Dugger,[1] B. Ritchie,[1] I. Senderovich,[1] E. Anassontzis,[2] P. Ioannou,[2] C. Kourkoumeli,[2] G. Vasileiadis,[2] G. Voulgaris,[2] N. Jarvis,[3] W. Levine,[3] P. Mattione,[3] W. McGinley,[3] C. A. Meyer,[3] R. Schumacher,[3] M. Staib,[3] F. Klein,[4] D. Sober,[4] N. Sparks,[4] N. Walford,[4] D. Doughty,[5] A. Barnes,[6] R. Jones,[6] J. McIntyre,[6] F. Mokaya,[6] B. Pratt,[6] W. Boeglin,[7] L. Guo,[7] E. Pooser,[7] J. Reinhold,[7] H. Al Ghoul,[8] V. Crede,[8] P. Eugenio,[8] A. Ostrovidov,[8] A. Tsaris,[8] D. Ireland,[9] K. Livingston,[9] D. Bennett,[10] J. Bennett,[10] J. Frye,[10] M. Lara,[10] J. Leckey,[10] R. Mitchell,[10] K. Moriya,[10] M. R. Shepherd,[10] O. Chernyshov,[11] A. Dolgolenko,[11] A. Gerasimov,[11] V. Goryachev,[11] L. Larin,[11] V. Matveev,[11] V. Tarasov,[11] F. Barbosa,[12] E. Chudakov,[12] M. Dalton,[12] A. Deur,[12] J. Dudek,[12] H. Egiyan,[12] S. Furletov,[12] M. Ito,[12] D. Mack,[12] D. Lawrence,[12] M. McCaughan,[12] M. Pennington,[12] L. Pentchev,[12] Y. Qiang,[12] E. Smith,[12] A. Somov,[12] S. Taylor,[12] T. Whitlatch,[12] B. Zihlmann,[12]

12 GeV science case

Second phase of GlueX program with BaBar DIRC-s (approved)

Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction

I. G. Aznauryan,[1,2] A. Bashir,[3] V. M. Braun,[4] S. J. Brodsky,[5,6] V. D. Burkert,[2] L. Chang,[7,8] Ch. Chen,[7,9,10] B. El-Bennich,[11,12] I. C. Cloët,[7,13] P. L. Cole,[14] R. G. Edwards,[2] G. V. Fedotov,[15,16] M. M. Giannini,[17,18] R. W. Gothe,[15] F. Gross,[2,19] Huey-Wen Lin,[20] P. Kroll,[21,4] T.-S. H. Lee,[7] W. Melnitchouk,[2] V. I. Mokeev,[2,16] M. T. Peña,[22,23] G. Ramalho,[22] C. D. Roberts,[7,10] E. Santopinto,[18] G. F. de Teramond,[24] K. Tsushima,[13,25] and D. J. Wilson[7,26]

JLab CLAS12 expt (approved)

Exclusive $N^* \to KY$ Studies with CLAS12

Daniel S. Carman *(contact person, spokesperson)*, Victor Mokeev *(spokesperson)*, Harut Avakian, Volker Burkert, Eugene Pasyuk
Jefferson Laboratory, Newport News, VA 23606, USA

Robert G. Edwards, Michael R. Pennington, David G. Richards, Adam Szczepaniak†
Theory Center, Jefferson Laboratory, Newport News, VA 23606, USA
(† *Joint with Indiana University, Bloomington, IN 47405*)

Hybrid baryons
CLAS12 expt (approved)

Searching for the Rules that Govern Hadron Construction

J. Dudek R. Mitchell, M. Shepherd

Expt/Theory Review for Nature 534 (2016)

Jefferson Lab

Nuclear Science Advisory Committee recommendations

NSAC Long Range Plan appeared in 2015

Strong endorsement of LQCD spectroscopy program (page 13)

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

Underscoring this huge progress, LQCD plays an essential role in guiding experimental work. GlueX at JLab, one of the flagship experiments of the 12-GeV Upgrade, is designed to search for exotic particles where the glue is in an energetically excited state. Initial LQCD calculations motivated the experiment and guided its design. Recent LQCD results confirm the mass range of the predicted particles. And in the future, LQCD calculations of hadron dynamics will play a critical role in the analysis of the data.

Formal recommendations for SciDAC

Many thanks to SciDAC for making this progress possible

Jefferson Lab

Large cast of characters

- Paul Mackenzie (FNAL)
- Richard Brower (BU)
- Norman Christ (Columbia)
- David Richards (JLab)
- Robert Falgout (LLNL)
- Robert Fowler (UNC)
- Fritjof Karsch (BNL)
- Balint Joo (ORNL)
- Kate Clark (NVIDIA)
- Robert Babich (NVIDIA)
- Eric Weinberg (NVIDIA)
- Frank Winter (JLab)
- David Keyes (King Abdullah+Columbia)
- Steven McCormick (Colorado)
- Thomas Manteuffel (Colorado)
- James Brannick (Penn State)
- James Osborn (ANL)
- K. Barros (Illinois)
- …