In search of the elusive glue of Quantum Chromodynamics

Robert Edwards

Jefferson Lab

Hadron Spectrum Collaboration

JEFFERSON LAB

Jozef Dudek
Robert Edwards
Balint Joo
David Richards
Frank Winter

TRINITY COLLEGE, DUBLIN

Mike Peardon
Sinead Ryan

TATA, MUMBAI

Nilmani Mathur

CAMBRIDGE UNIVERSITY

Christopher Thomas

U. OF MARYLAND

Steve Wallace

& postdocs, students

MESON SPECTRUM

PRL103 262001 (2009)	$I=1$
PRD82 034508 (2010)	$I=1, K^\star$
PRD83 111502 (2011)	$I=0$
JHEP07 126 (2011)	$c\bar{c}$
PRD88 094505 (2013)	$I=0$
JHEP05 021 (2013)	D, D_s

BARYON SPECTRUM

PRD84 074508 (2011)	$(N,\Delta)^\star$
PRD85 054016 (2012)	$(N,\Delta)_{\text{hyb}}$
PRD87 054506 (2013)	$(N\ldots\Xi)^\star$
PRD90 074504 (2014)	$\Omega^\star_{ccc}$
PRD91 094502 (2015)	$\Xi^\star_{cc}$

HADRON SCATTERING

PRD83 071504 (2011)	$\pi\pi\ I=2$
PRD86 034031 (2012)	$\pi\pi\ I=2$
PRD87 034505 (2013)	$\pi\pi\ I=1,\ \rho$
PRL113 182001 (2014)	$\pi K, \eta K$
PRD91 054008 (2015)	$\pi K, \eta K$

“TECHNOLOGY”

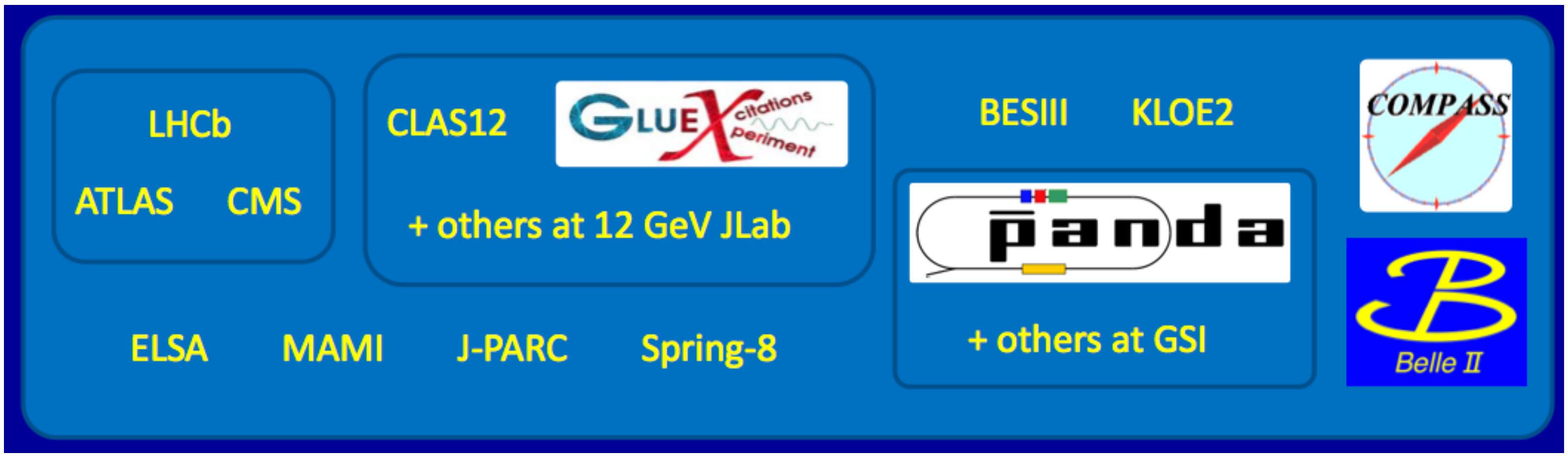
PRD79 034502 (2009)	lattices
PRD80 054506 (2009)	distillation
PRD85 014507 (2012)	$\vec{p}>0$

MATRIX ELEMENTS

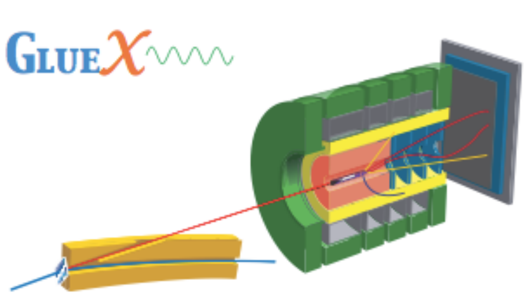
PRD91 114501 (2015)	$M' \to \gamma M$
PRD90 014511 (2014)	$f_{\pi^\star}$

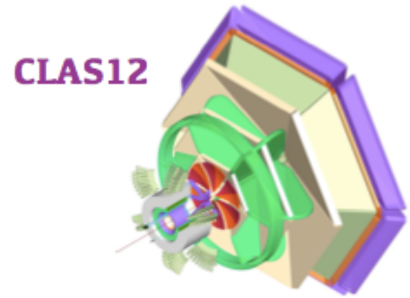
Hadron spectroscopy

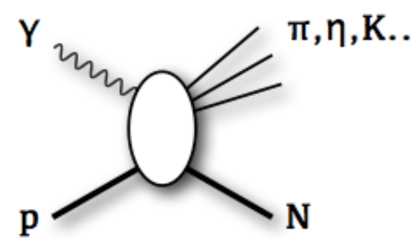
- Determination of hadron spectrum of Quantum Chromodynamics (QCD) a central goal in NP
- Several experiments worldwide

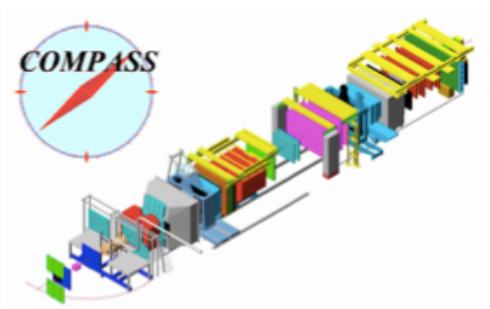


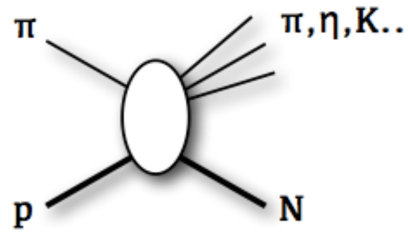
Spectrum - light meson experiments

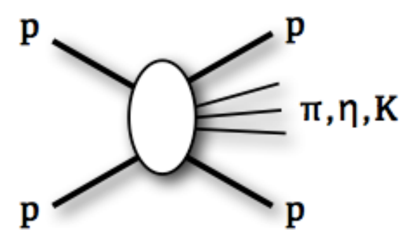


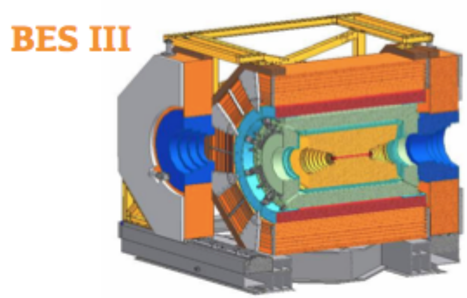


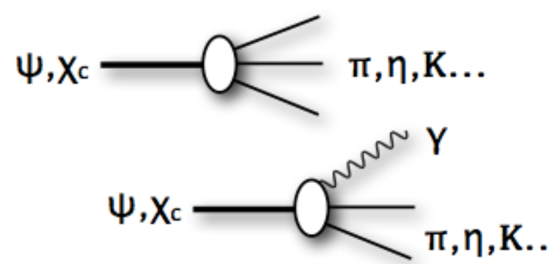






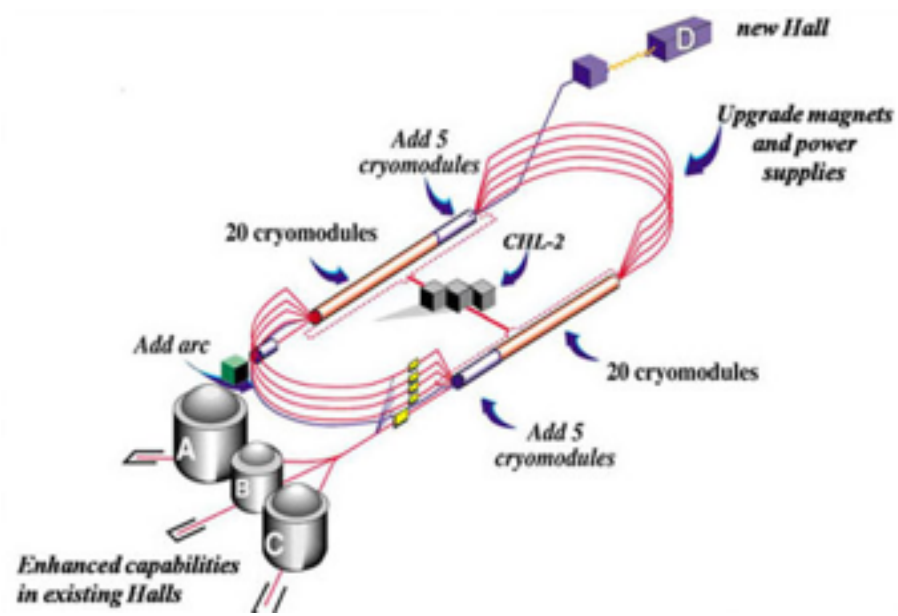






Nuclear Physics & Jefferson Lab

- JLab finishing a $338M upgrade

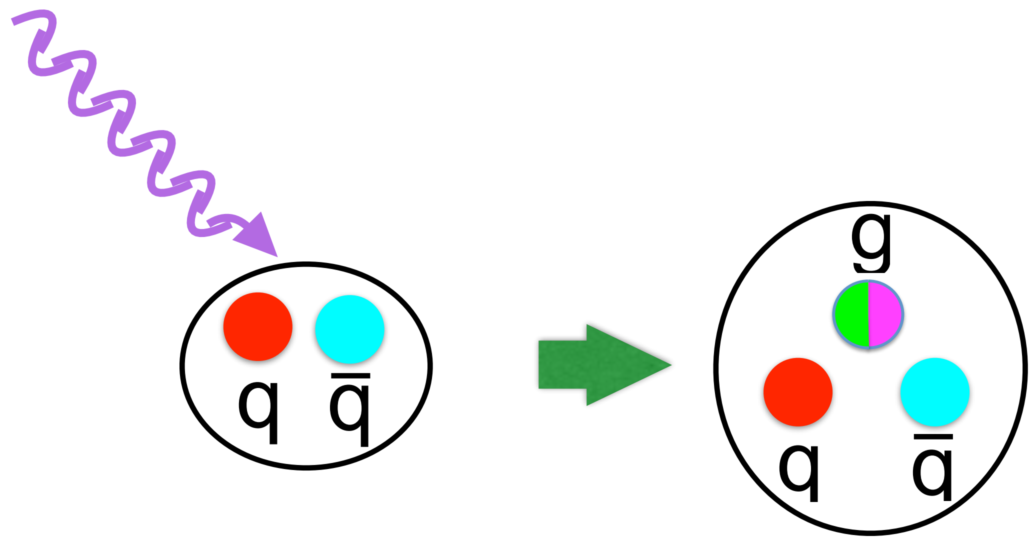


  - Doubled beam energy
  - Added new Hall D (GlueX)

A spectroscopy analogy

Quantum Chromodynamics (QCD) suggests fundamental particles composed of quarks

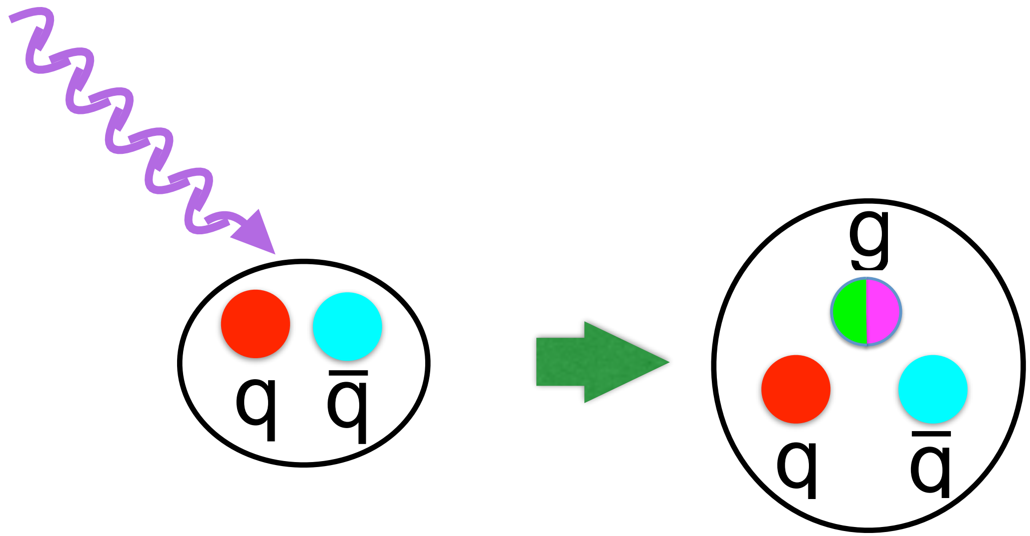
Photon "twacking" a quark-antiquark pair excites the quarks and the glue



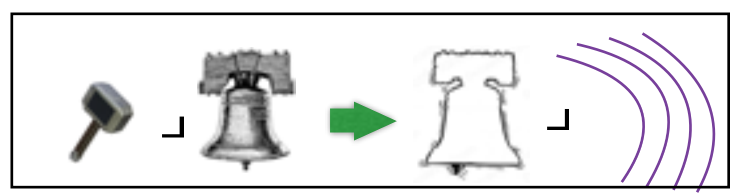
A spectroscopy analogy

Quantum Chromodynamics (QCD) suggests fundamental particles composed of quarks

Photon “twacking” a quark-antiquark pair excites the quarks and the glue



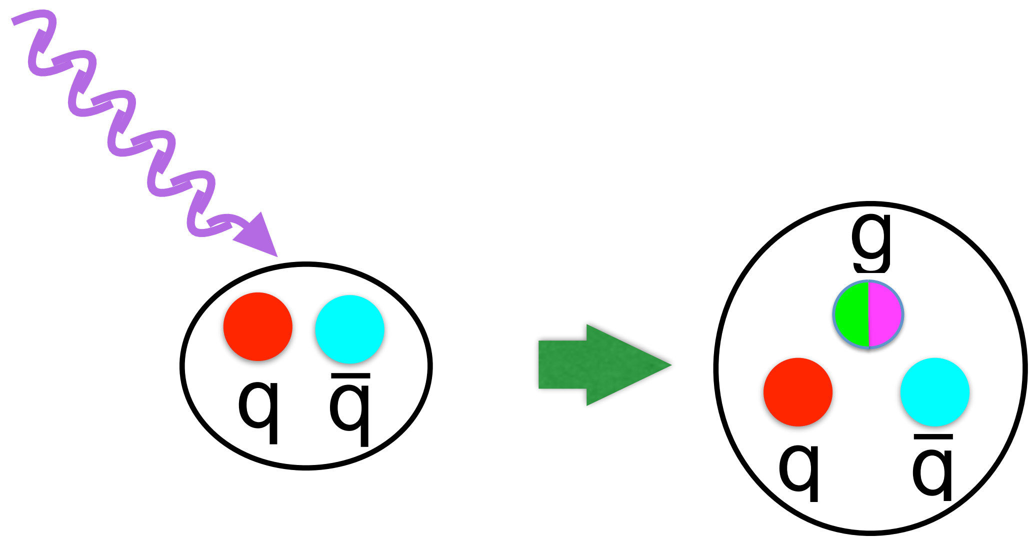
- Analogous to ringing a bell



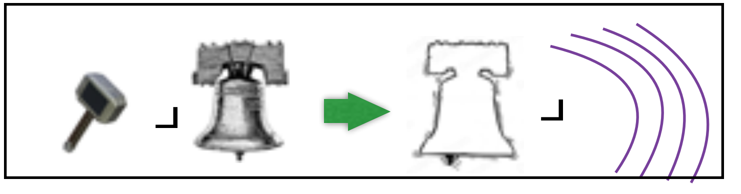
A spectroscopy analogy

Quantum Chromodynamics (QCD) suggests fundamental particles composed of quarks

Photon “twacking” a quark-antiquark pair excites the quarks and the glue



- Analogous to ringing a bell

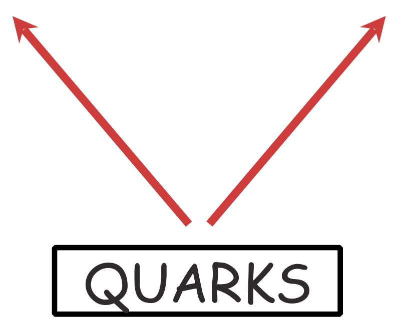


- Can produce an unseen state of matter of quarks and gluons - *exotics*

Experimental spectrum of hadrons

- Hadrons classified by their conserved quantum numbers
  - Spin, isospin, parity, strangeness, charm, …

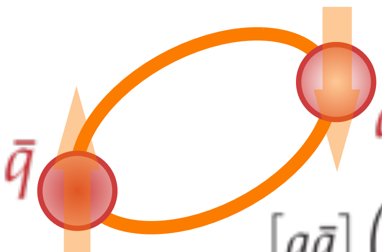
MESONS	BARYONS
J=0,1,2,…	J=1/2, 3/2, 5/2, …
Isospin ≤ 1	Isospin ≤ 3/2
|strangeness|≤ 1	|strangeness|≤ 3
$q\bar{q}$	qqq



u, d, s

Experimental meson spectrum

- Mesons classified by their conserved quantum numbers
  - Spin, isospin, parity, charge-conjugation J^{PC}



$$[q\bar{q}]\left(n\,{}^{2S+1}L_J\right)$$

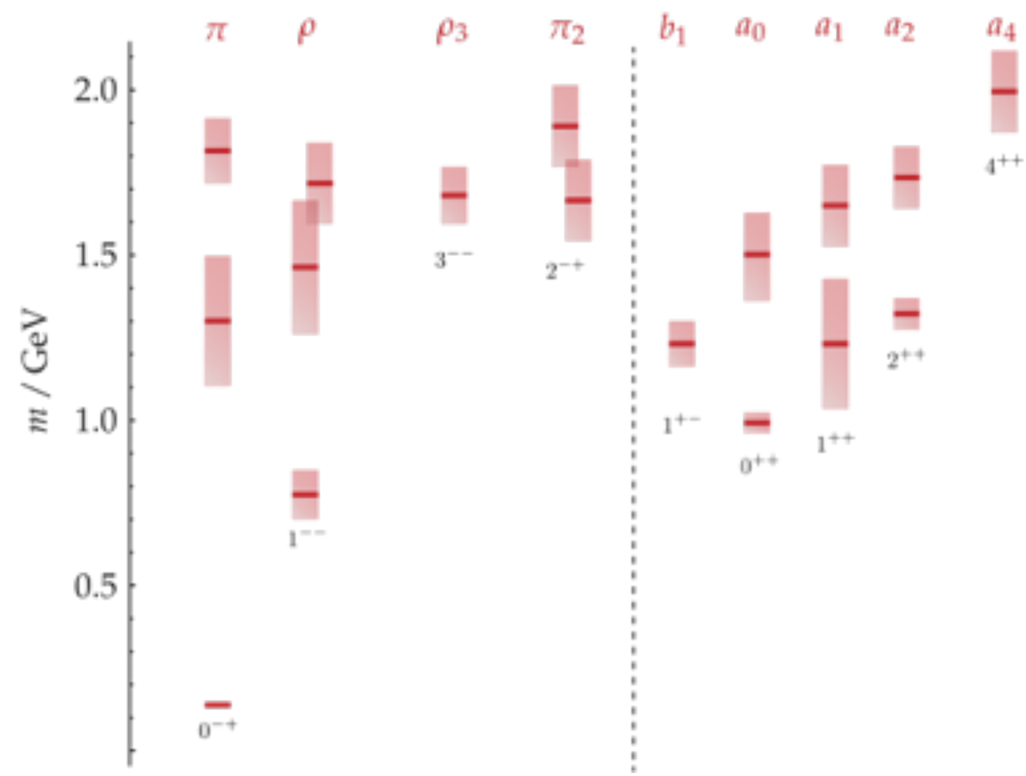
$$L = 0 \,:\, 0^{-+}, 1^{--}$$

$$L = 1 \,:\, 1^{+-}, (0,1,2)^{++}$$

$$L = 2 \,:\, 2^{-+}, (1,2,3)^{--}$$

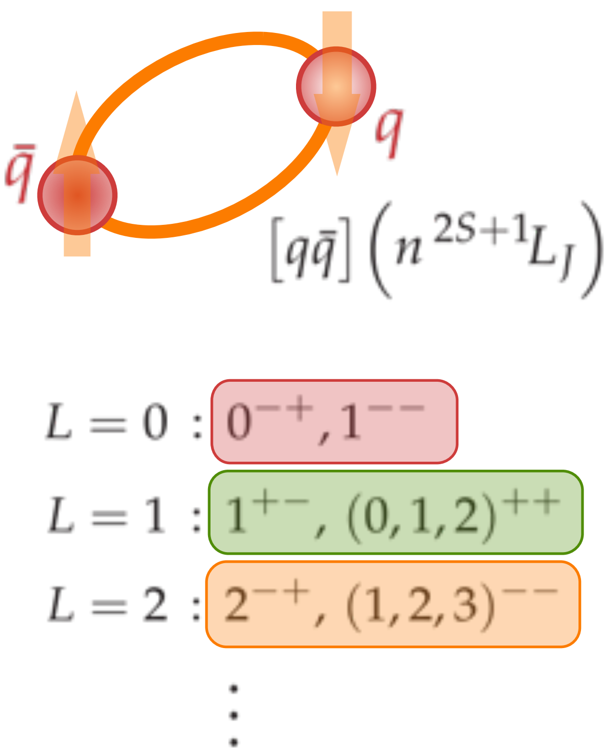
$$\vdots$$

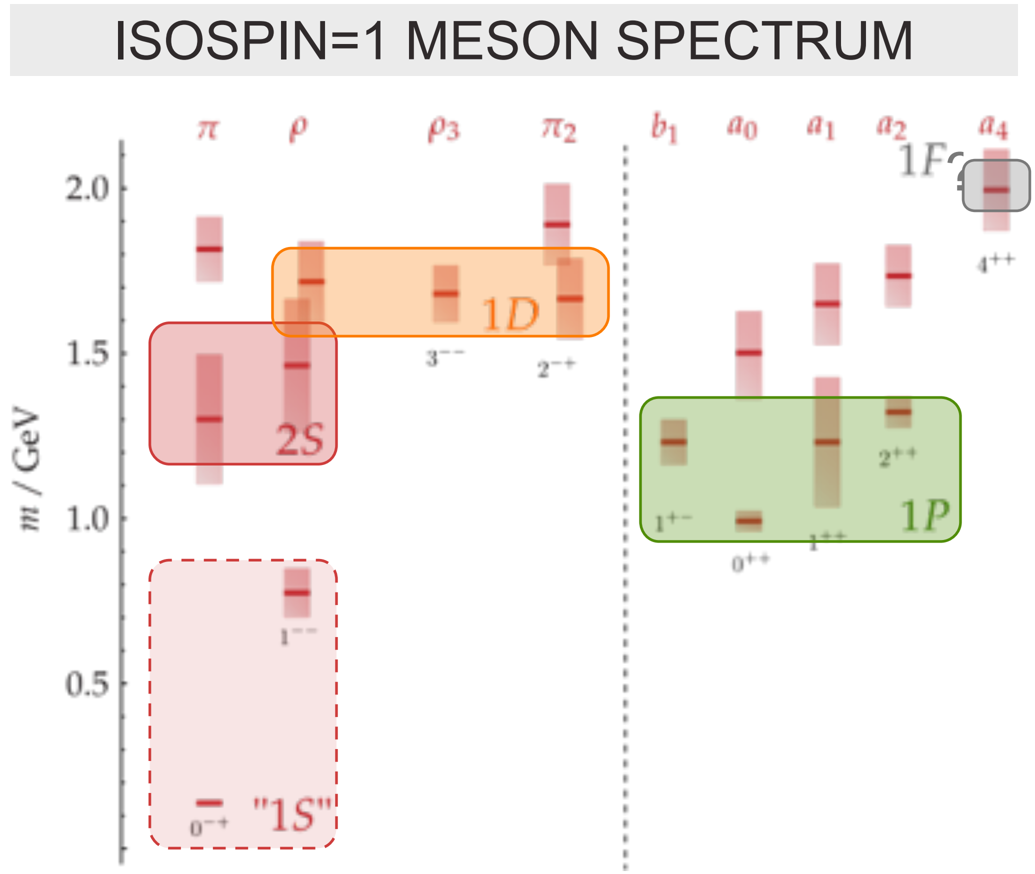
ISOSPIN=1 MESON SPECTRUM



Experimental meson spectrum

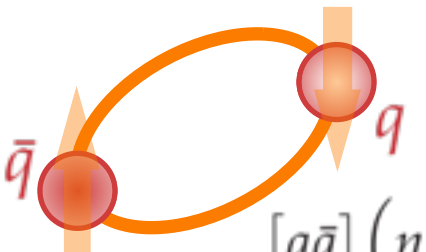
- Mesons classified by their conserved quantum numbers
  - Spin, isospin, charge-conjugation J^{PC}





Experimental meson spectrum

- Mesons classified by their conserved quantum numbers
  - Spin, isospin, charge-conjugation J^{PC}



$$[q\bar{q}]\left(n\,^{2S+1}L_J\right)$$

$$L = 0 : 0^{-+}, 1^{--}$$

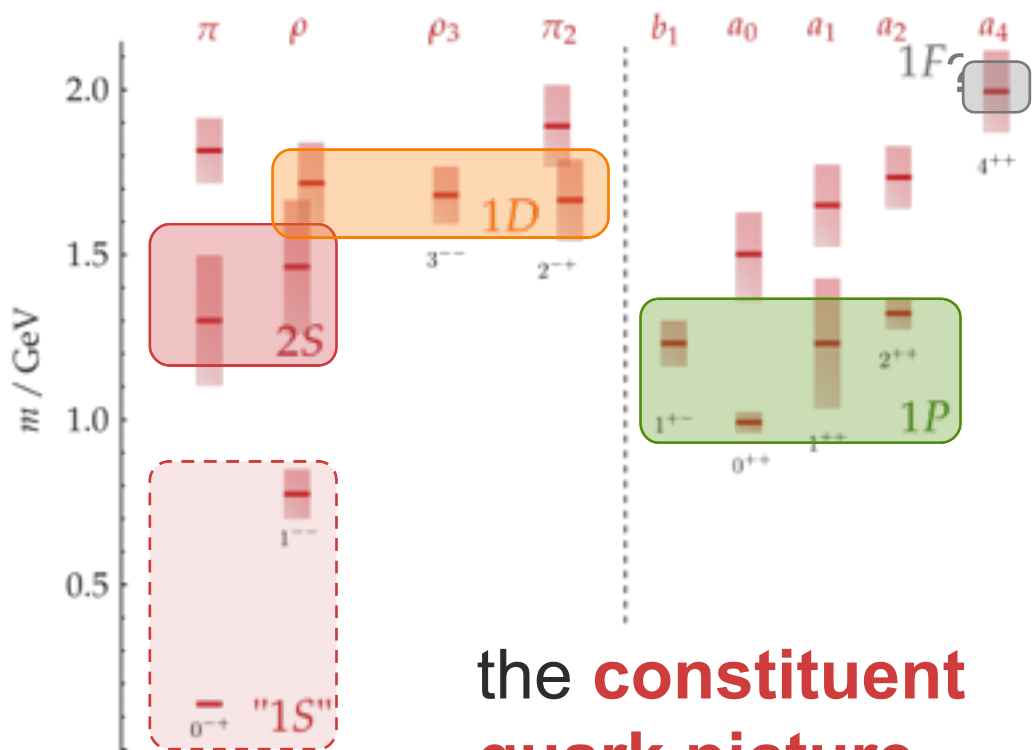
$$L = 1 : 1^{+-}, (0,1,2)^{++}$$

$$L = 2 : 2^{-+}, (1,2,3)^{--}$$

$$\vdots$$

n.b. absent: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \ldots$

ISOSPIN=1 MESON SPECTRUM

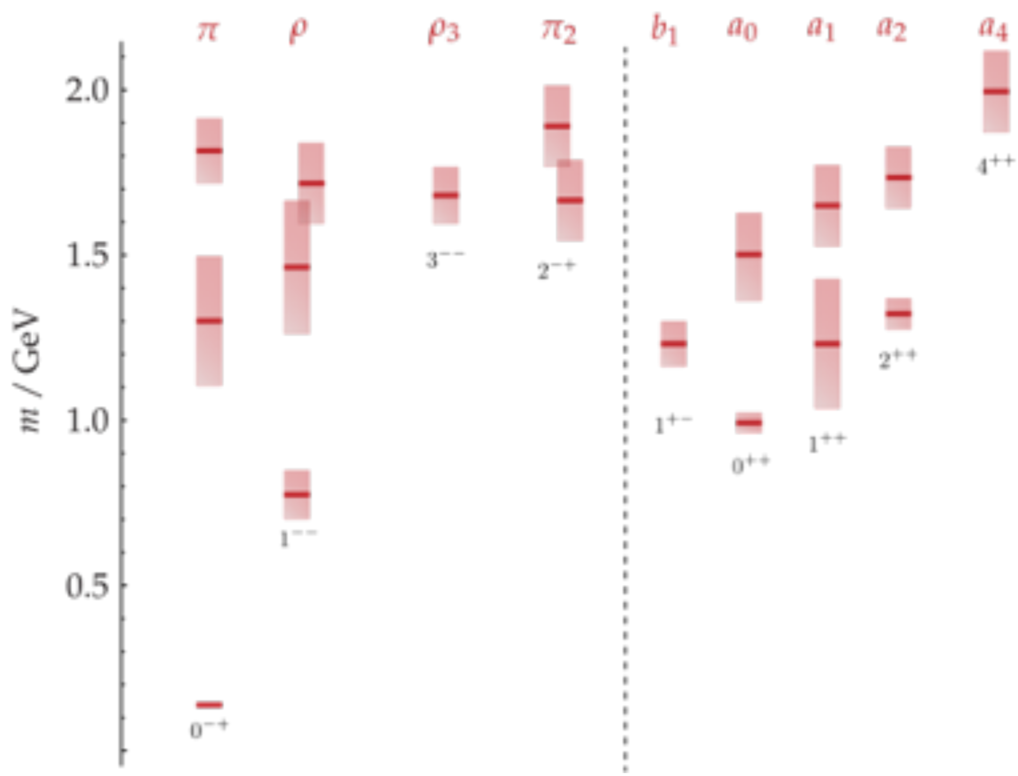


the **constituent quark picture**

Exotic mesons

If we can find $\mathbf{J^{PC}}$ $\mathbf{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}}$ *"Smoking gun signature"*

NON-EXOTIC MESONS

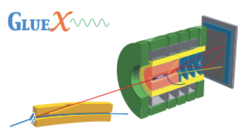


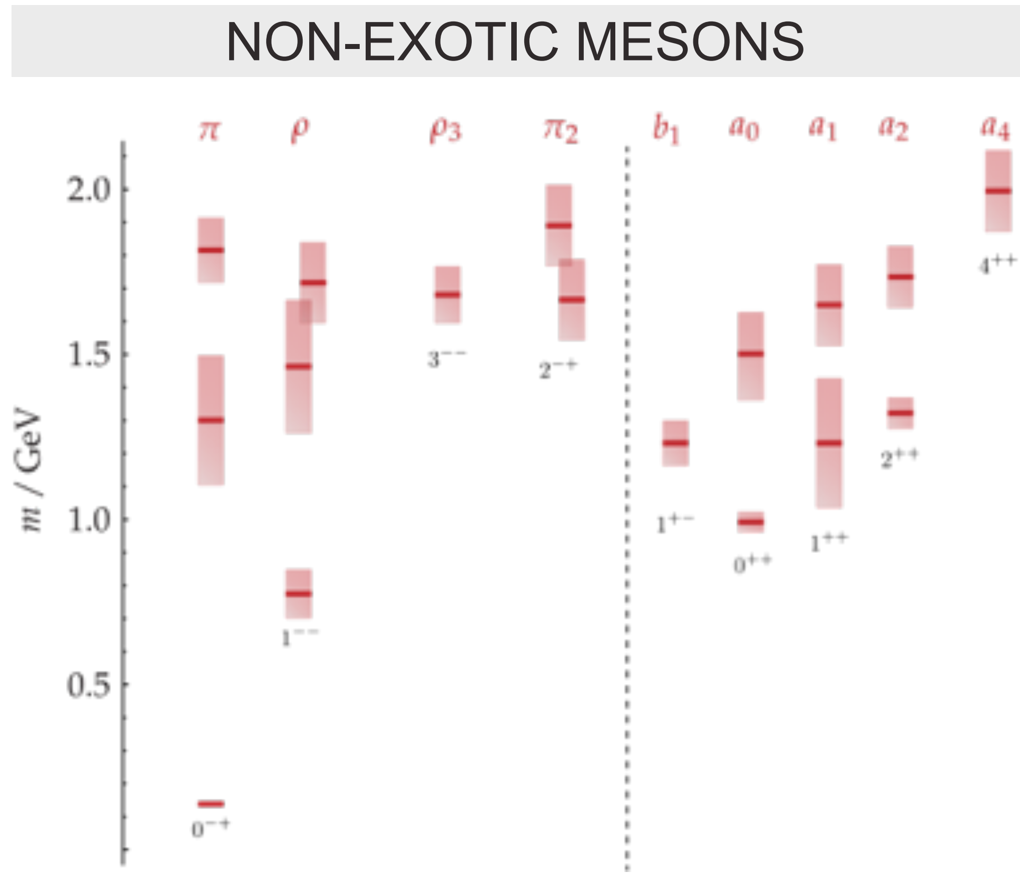
Exotic mesons

If we can find $\mathbf{J^{PC}}$ $\mathbf{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}}$ *"Smoking gun signature"*

Previous expt. searches conflicting

- Motivation for GlueX



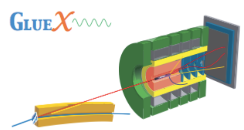


Exotic mesons

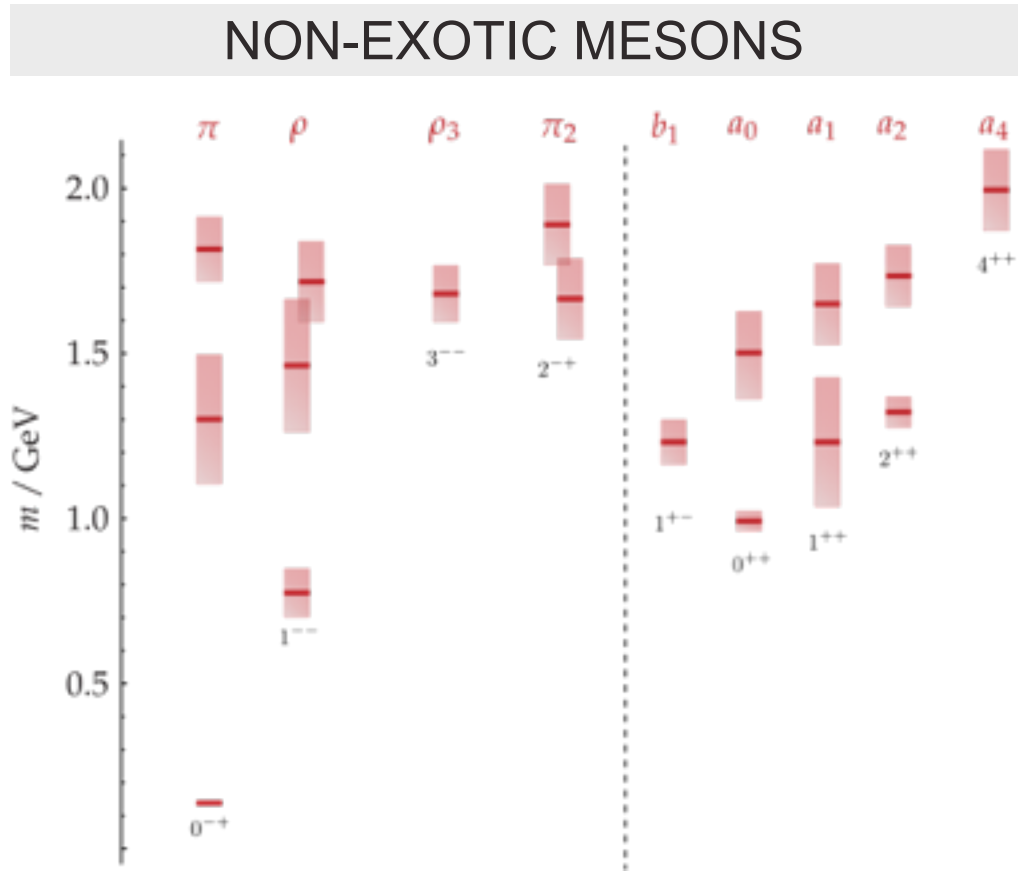
If we can find $\mathbf{J^{PC}}$ $\mathbf{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}}$ *"Smoking gun signature"*

Previous expt. searches conflicting

- Motivation for GlueX



Many models - different/conflicting predictions

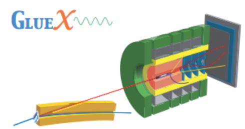


Exotic mesons

If we can find $\mathbf{J^{PC}}$ $\mathbf{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}}$ *"Smoking gun signature"*

Previous expt. searches conflicting

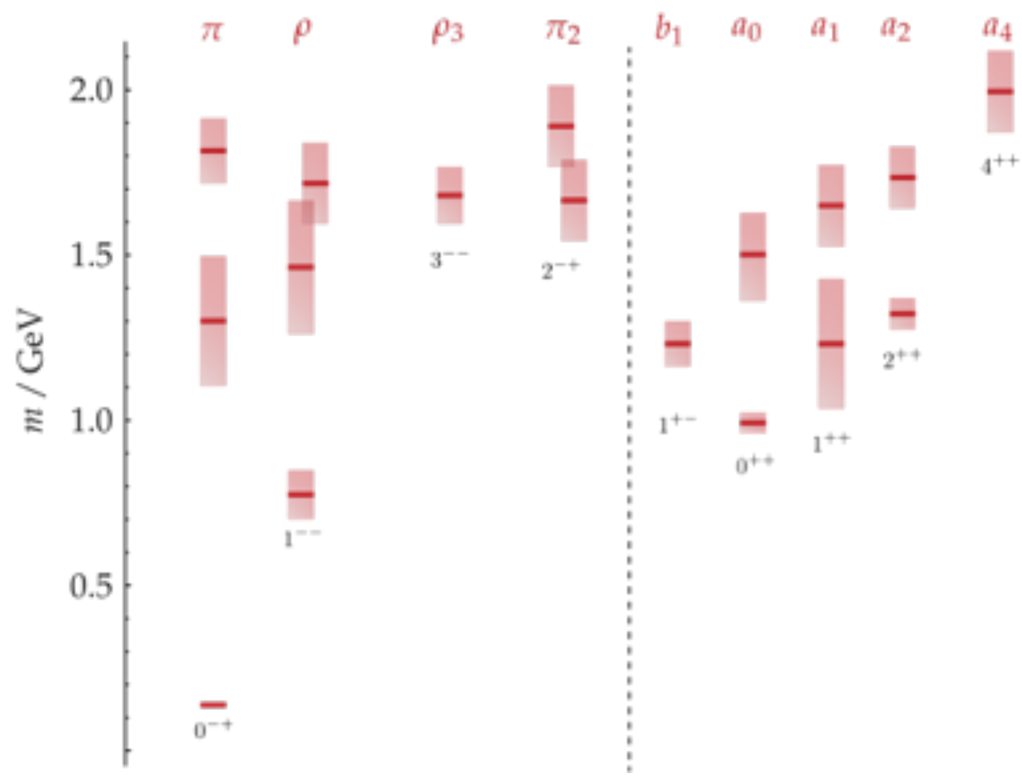
- Motivation for GlueX



Many models - different/conflicting predictions

Need theoretical guidance from QCD

NON-EXOTIC MESONS



Lattice QCD

- First-principles numerical approach to the field-theory
  - Evaluate **correlation functions** e.g $\int \mathcal{D}\psi\mathcal{D}\bar{\psi}\mathcal{D}A_\mu \; \bar{\psi}\Gamma\psi(t)\; \bar{\psi}\Gamma\psi(0)\; e^{-\int d^4x\, \mathcal{L}_{\text{QCD}}(\psi,\bar{\psi},A_\mu)}$

    ‘sum ‘field ‘probability

    via **Monte-Carlo** sampling of path-integral

    on a **finite cubic grid**

» in principle recover physical QCD as

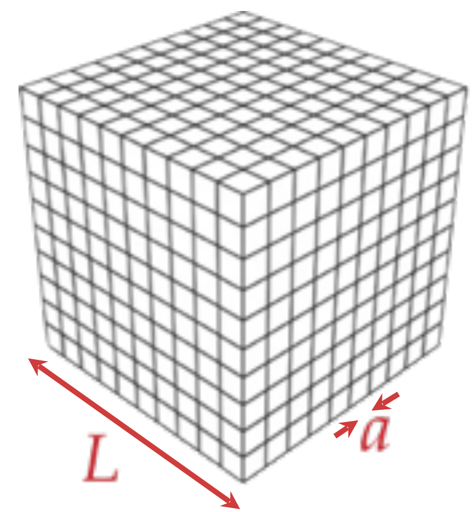
$$a \to 0 \qquad L \to \infty$$

» practical calculations often use

$$m_q^{\text{calc.}} > m_q^{\text{phys.}}$$

» large scale computational problem ...

CUBIC LATTICE



Excited states from correlators

- How to get at excited QCD eigenstates ?
  - optimal operator for state $|\mathfrak{n}\rangle$: $\Omega_{\mathfrak{n}}^{\dagger} \sim \sum_i v_i^{(\mathfrak{n})} \mathcal{O}_i^{\dagger}$

    for a basis of meson operators $\{\mathcal{O}_i\}$

  - can be obtained (in a variational sense) from the matrix of correlators

$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t)\, \mathcal{O}_j^{\dagger}(0) | 0 \rangle$$

  - by solving a generalized eigenvalue problem

'diagonalize the correlation matrix'

$$C(t) v^{(\mathfrak{n})} = C(t_0) v^{(\mathfrak{n})} \lambda_{\mathfrak{n}}(t)$$

eigenvalues $\lambda_{\mathfrak{n}}(t) \sim e^{-E_{\mathfrak{n}}(t-t_0)}$

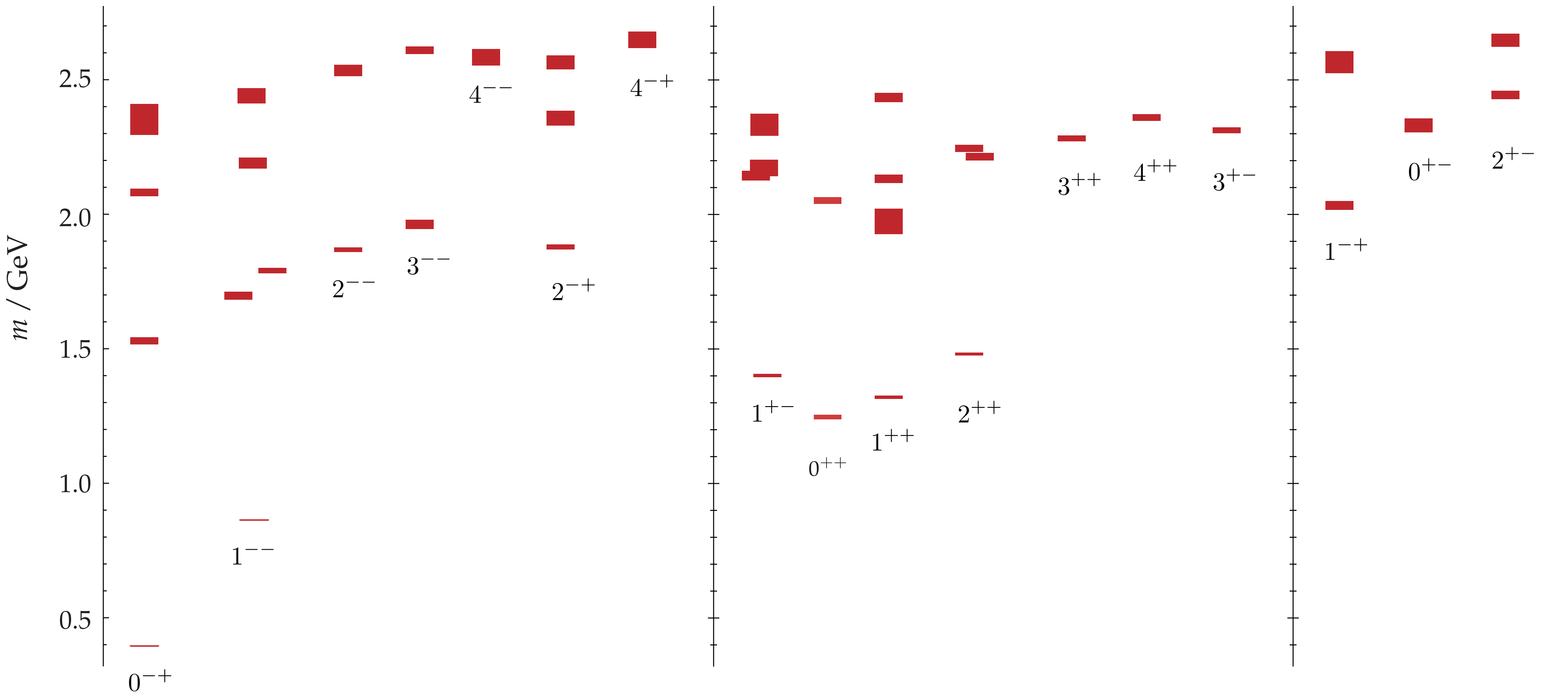
  - a large basis can be constructed using covariant derivatives :

$$\mathcal{O} \sim \bar{\psi} \Gamma \overleftrightarrow{D} \dots \overleftrightarrow{D} \psi$$

Meson spectrum from lattice QCD

- Appears to be some $q\bar{q}$-like near-degeneracy patterns

$m_\pi \sim 391\,\mathrm{MeV}$

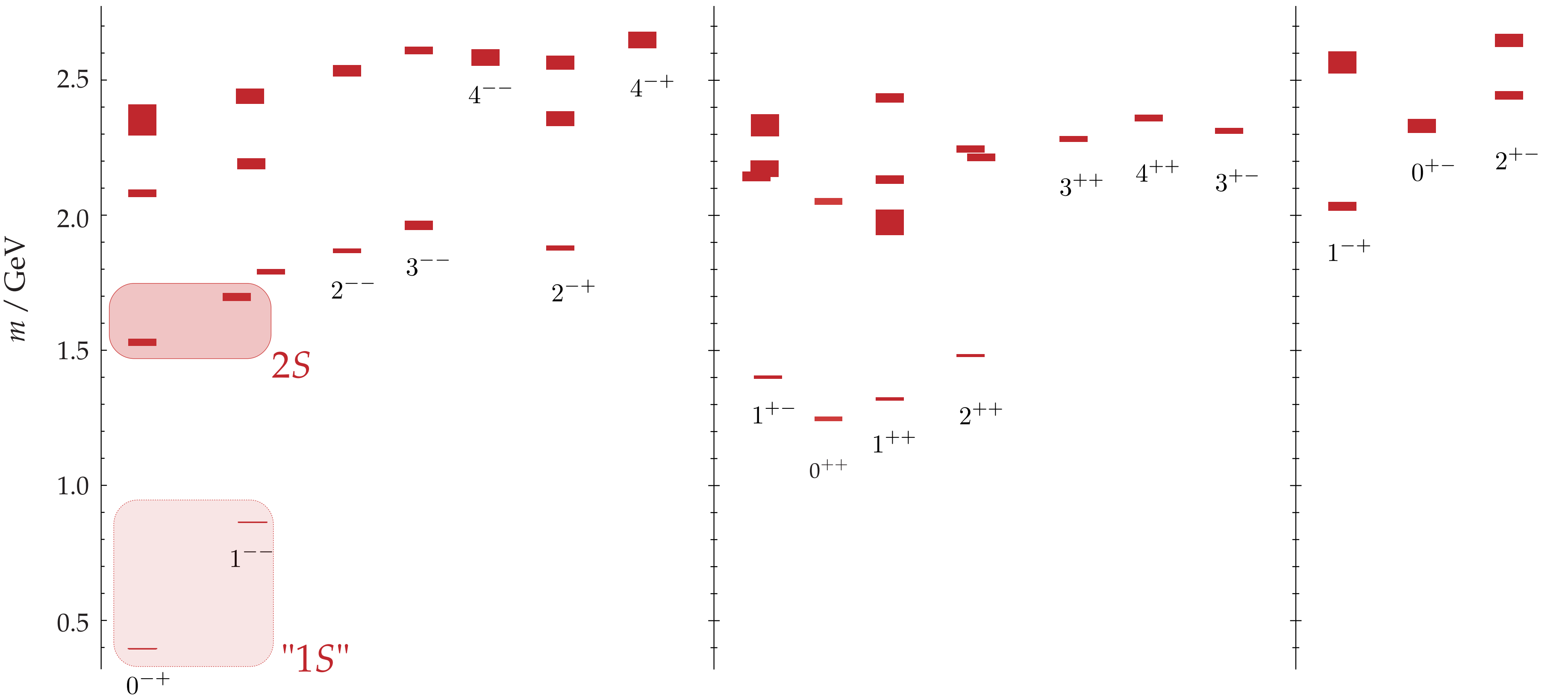


PRL 103; PRD 82, 88

Meson spectrum from lattice QCD

- Appears to be some $q\bar{q}$-like near-degeneracy patterns

$m_\pi \sim 391\,\mathrm{MeV}$

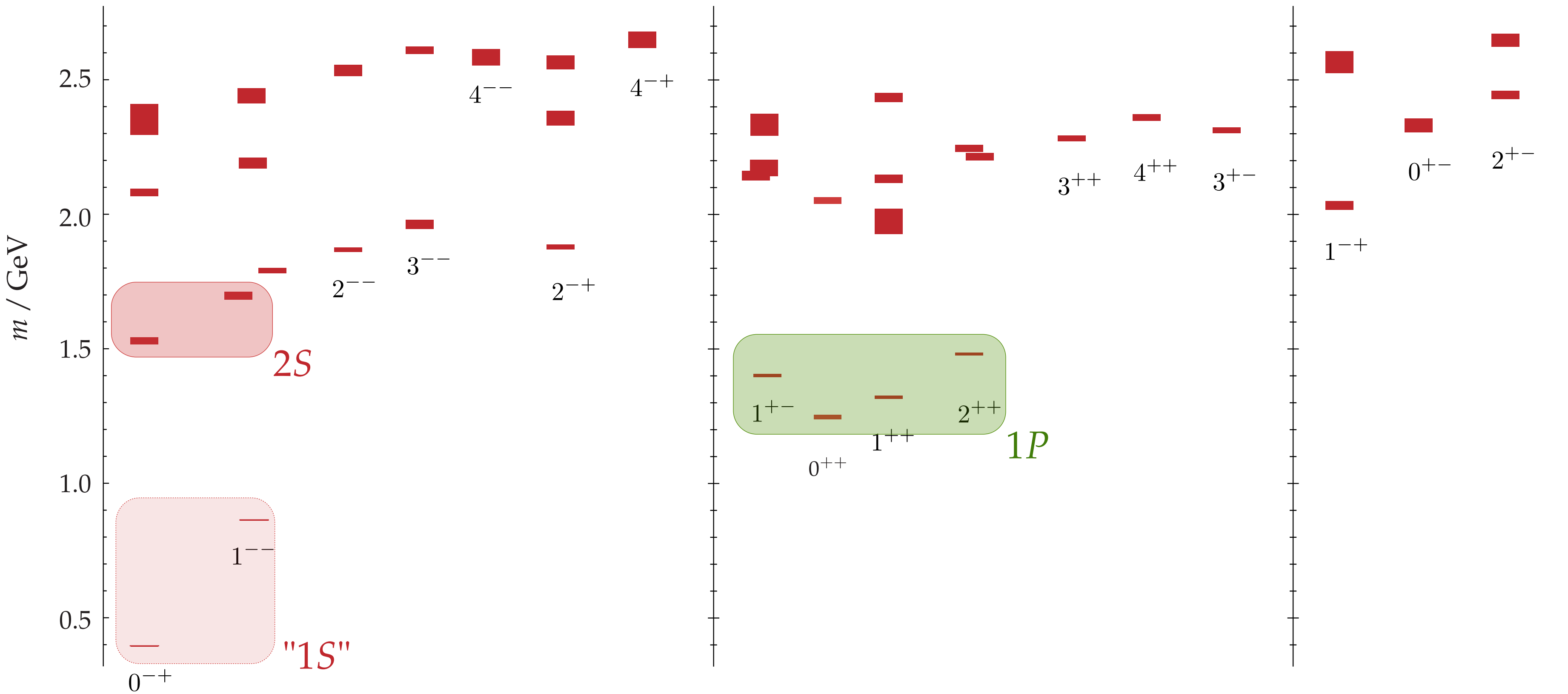


PRL 103; PRD 82, 88

Meson spectrum from lattice QCD

- Appears to be some $q\bar{q}$-like near-degeneracy patterns

$m_\pi \sim 391\,\mathrm{MeV}$

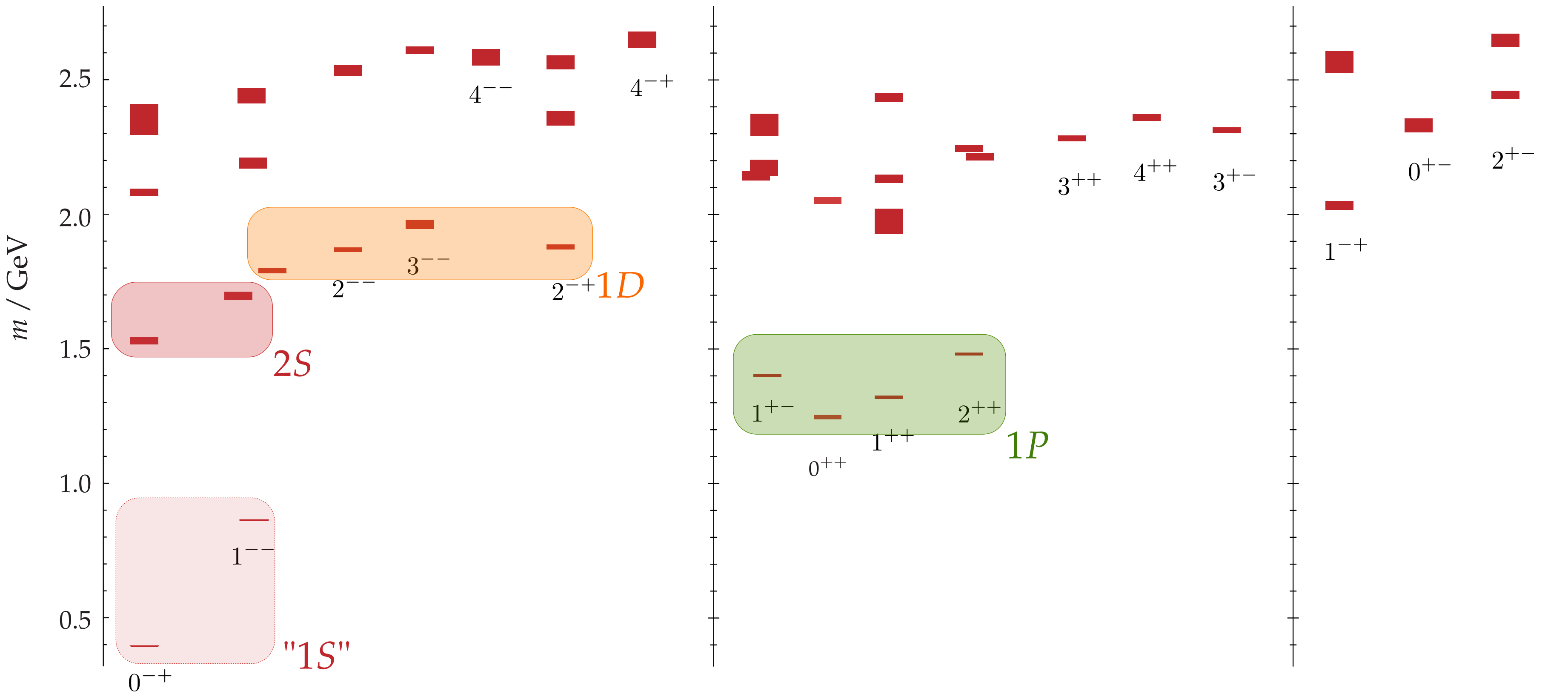


PRL 103; PRD 82, 88

Meson spectrum from lattice QCD

- Appears to be some $q\bar{q}$-like near-degeneracy patterns

$m_\pi \sim 391\,\text{MeV}$

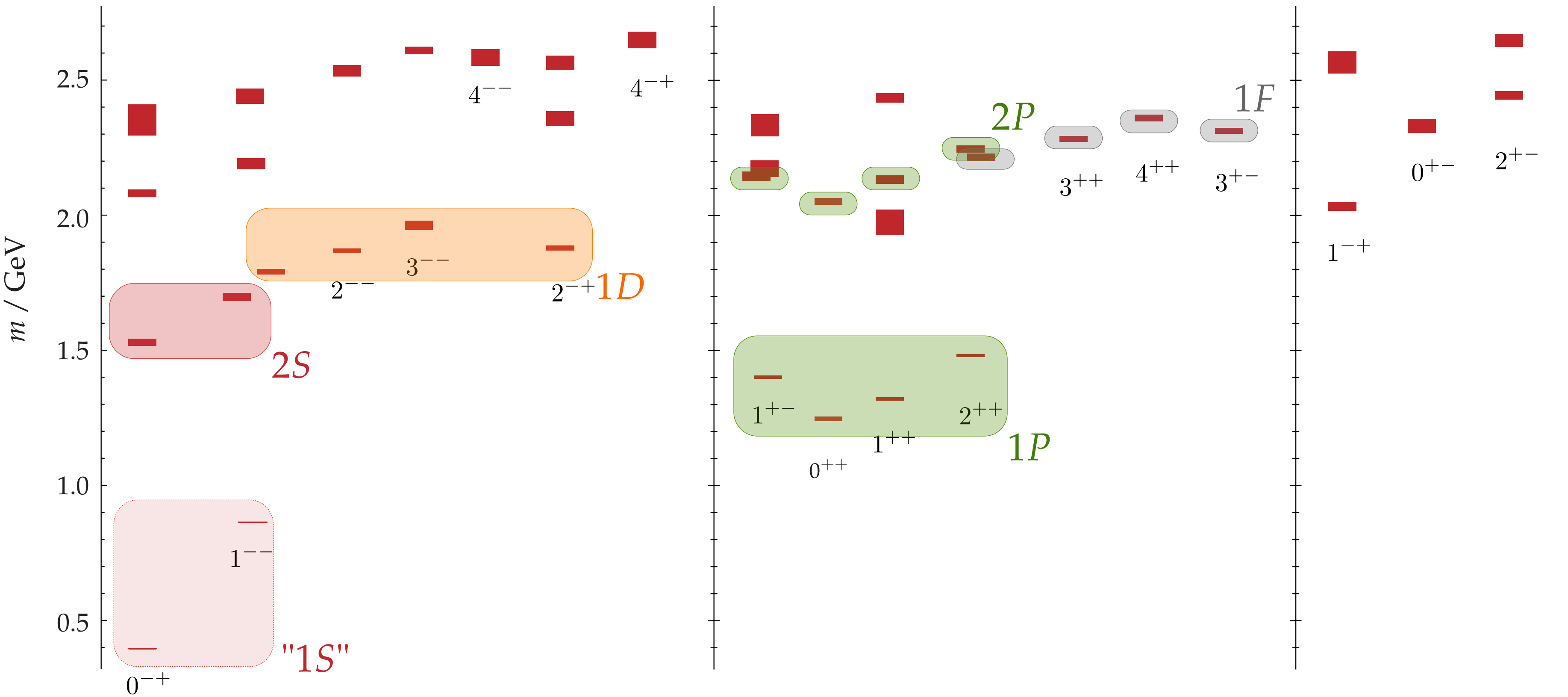


PRL 103; PRD 82, 88

Meson spectrum from lattice QCD

- Appears to be some $q\bar{q}$-like near-degeneracy patterns

$m_\pi \sim 391\,\mathrm{MeV}$

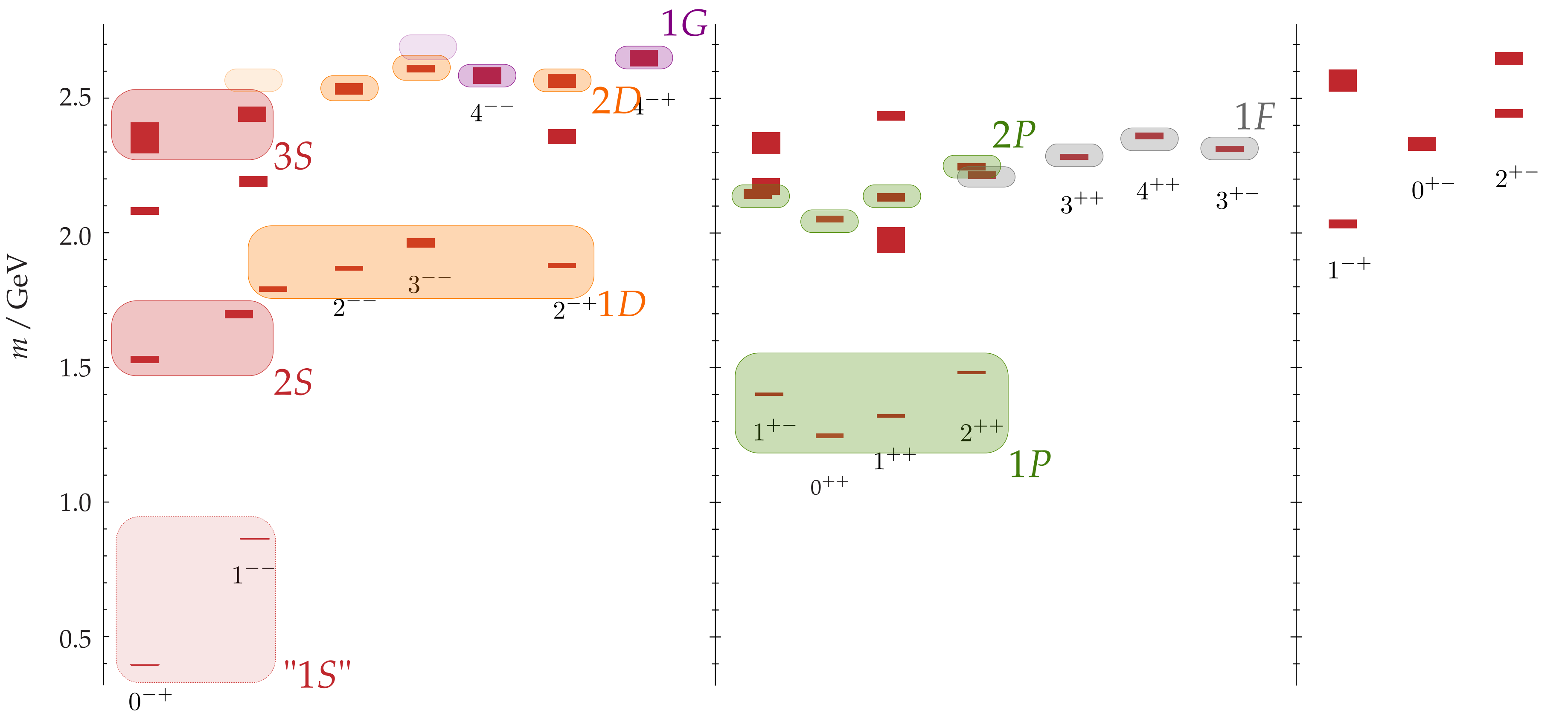


PRL 103; PRD 82, 88

Meson spectrum from lattice QCD

- Appears to be some $q\bar{q}$-like near-degeneracy patterns

$m_\pi \sim 391\,\mathrm{MeV}$

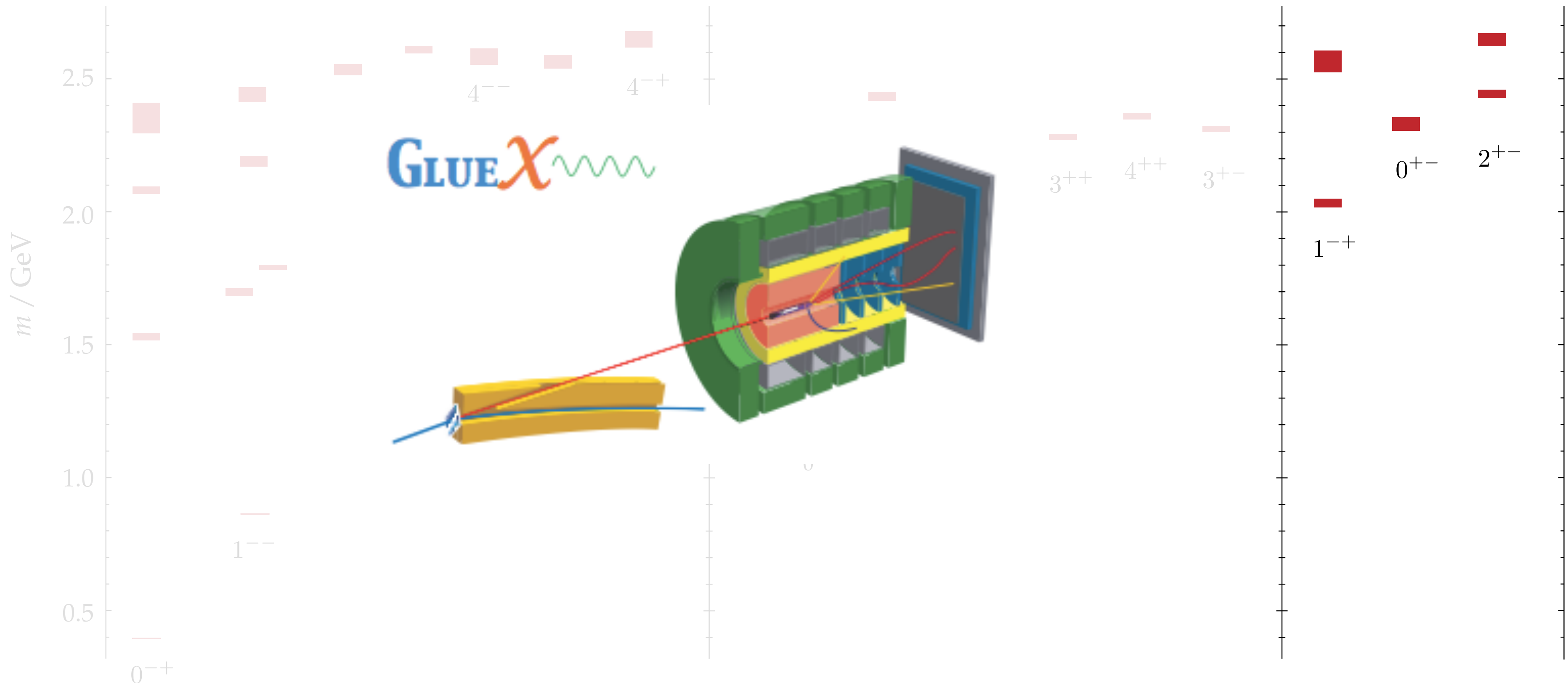


PRL 103; PRD 82, 88

Meson spectrum from lattice QCD

Multiple exotic mesons within range of GlueX

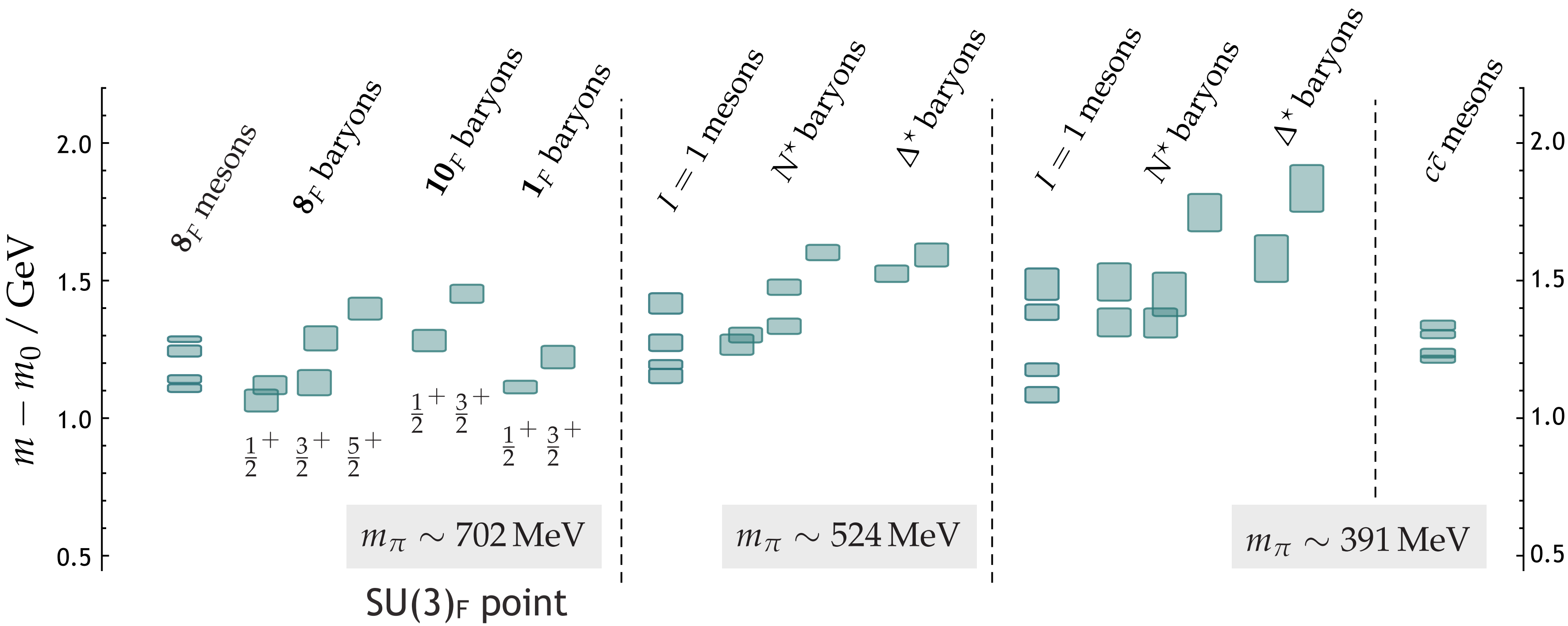
EXOTIC MESONS



PRL 103; PRD 82, 88

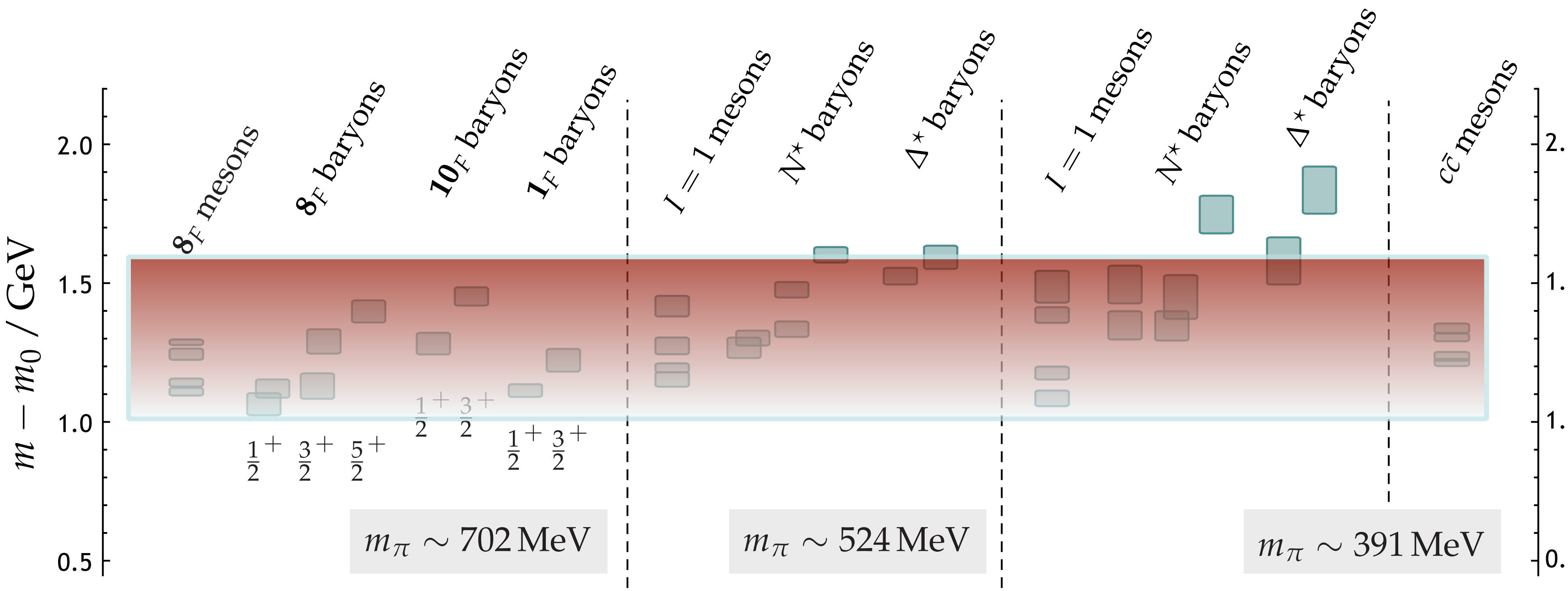
Chromo-magnetic excitation

- Subtract the ‘quark mass’ contribution



Chromo-magnetic excitation

- Subtract the 'quark mass' contribution

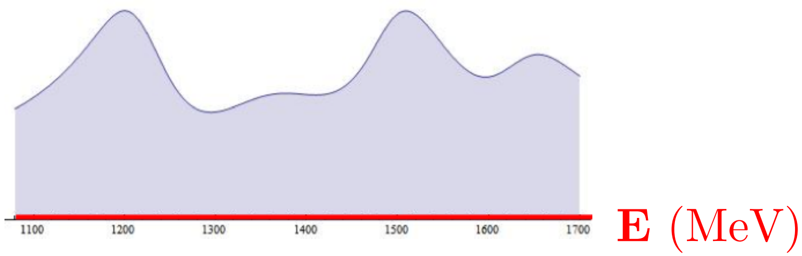


SU(3)$_F$ point

– ***Common energy scale of gluonic excitation*** $\sim 1.3\,\mathrm{GeV}$

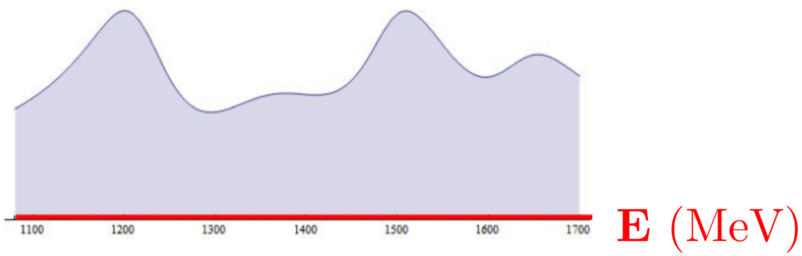
Resonances

- Most hadrons are resonances
- Properties determined from scattering amplitudes of particles
  - E.g., πN πN

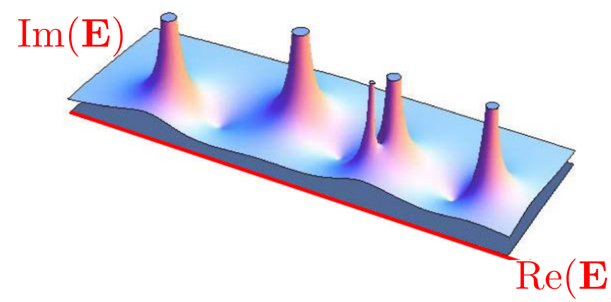


Resonances

- Most hadrons are resonances
- Properties determined from scattering amplitudes of particles
  - E.g., πN πN



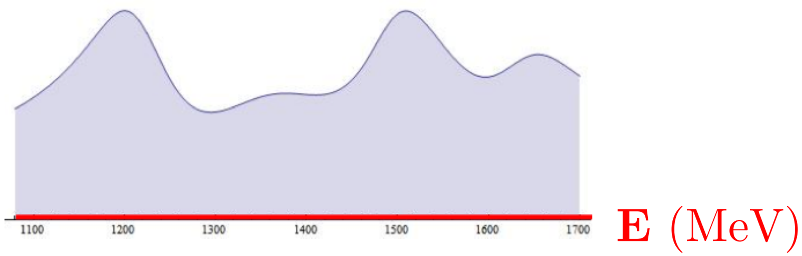
- Amplitudes described by poles in complex plane
  - Pole structure gives decay information



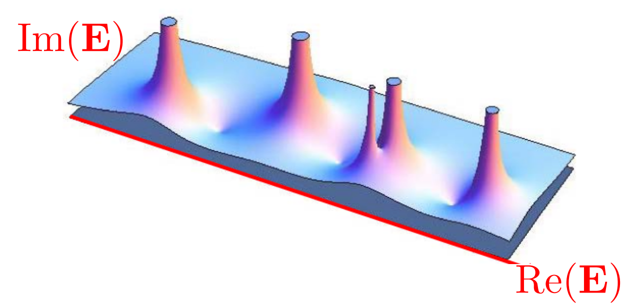
Resonances

- Most hadrons are resonances

- Properties determined from scattering amplitudes of particles
  - E.g., πN πN

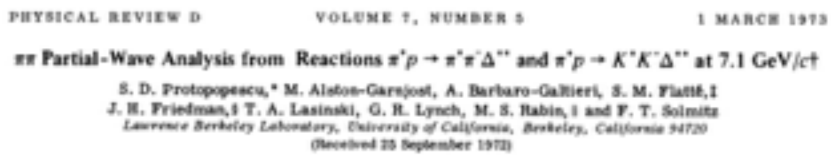


- Amplitudes described by poles in complex plane
  - Pole structure gives decay information



- To compare directly with experiment, must determine decay modes

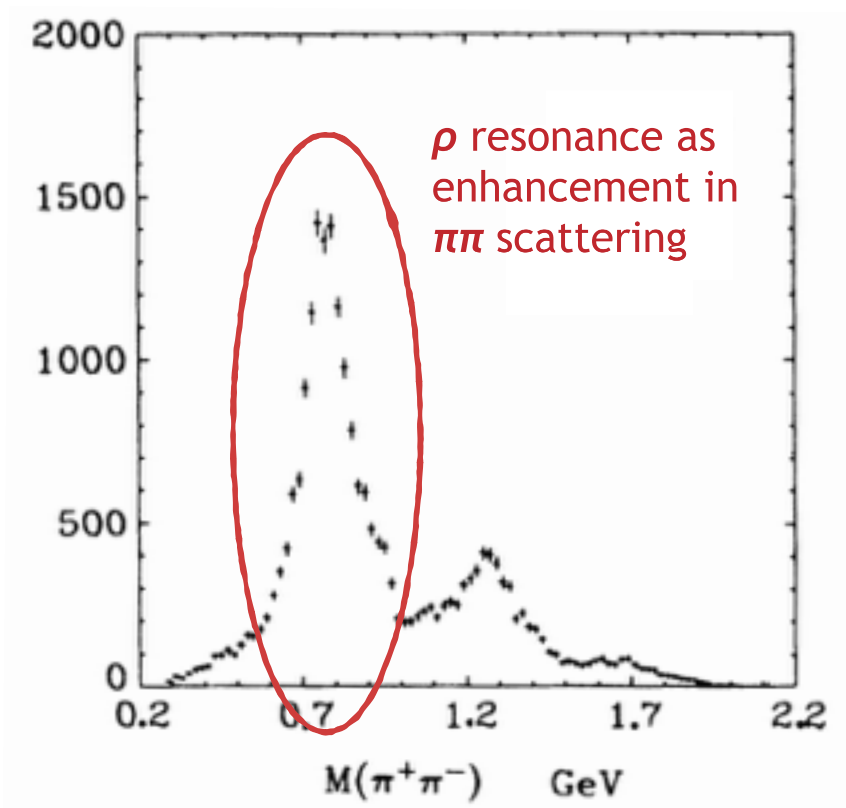
Resonances - the "ρ"



PHYSICAL REVIEW D VOLUME 7, NUMBER 5 1 MARCH 1973

$\pi\pi$ Partial-Wave Analysis from Reactions $\pi^+p \rightarrow \pi^+\pi^-\Delta^{++}$ and $\pi^+p \rightarrow K^+K^-\Delta^{++}$ at 7.1 GeV/c†

S. D. Protopopescu,* M. Alston-Garnjost, A. Barbaro-Galtieri, S. M. Flatté,‡
J. H. Friedman,‡ T. A. Lasinski, G. R. Lynch, M. S. Rabin,‡ and F. T. Solmitz
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 25 September 1972)

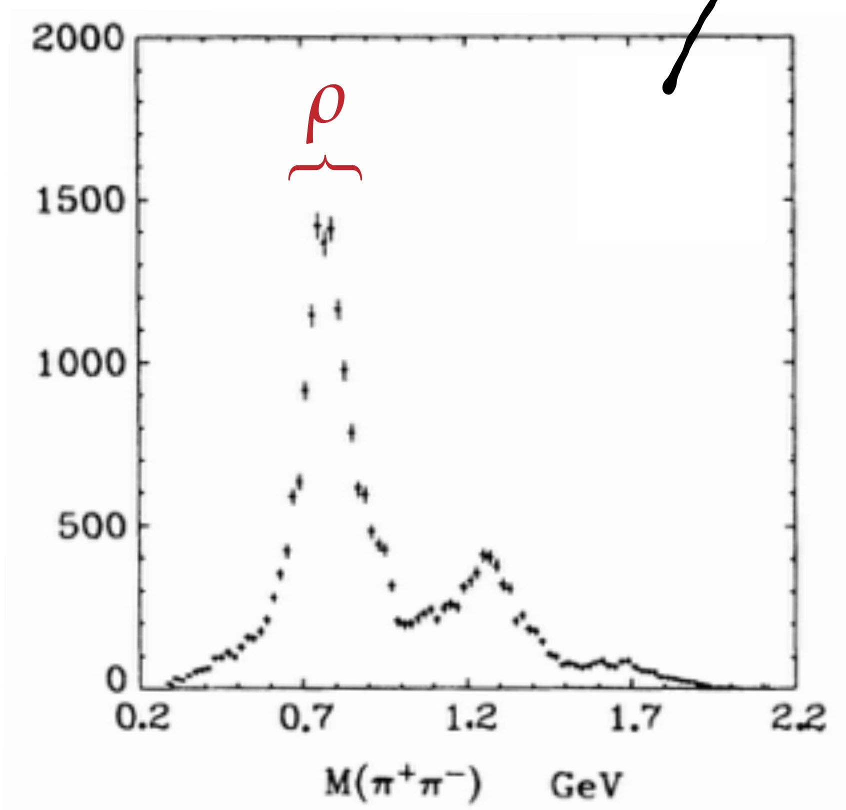


Resonances - the "ρ"

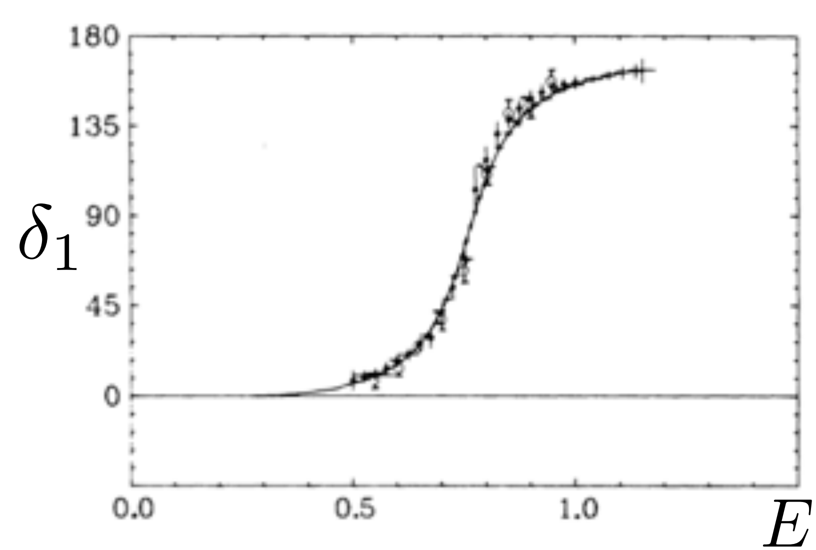
angular
dependence

PARTIAL WAVE AMPLITUDE

$$f_\ell(E) = \frac{1}{2i}\left(e^{2i\,\delta_\ell(E)} - 1\right)$$

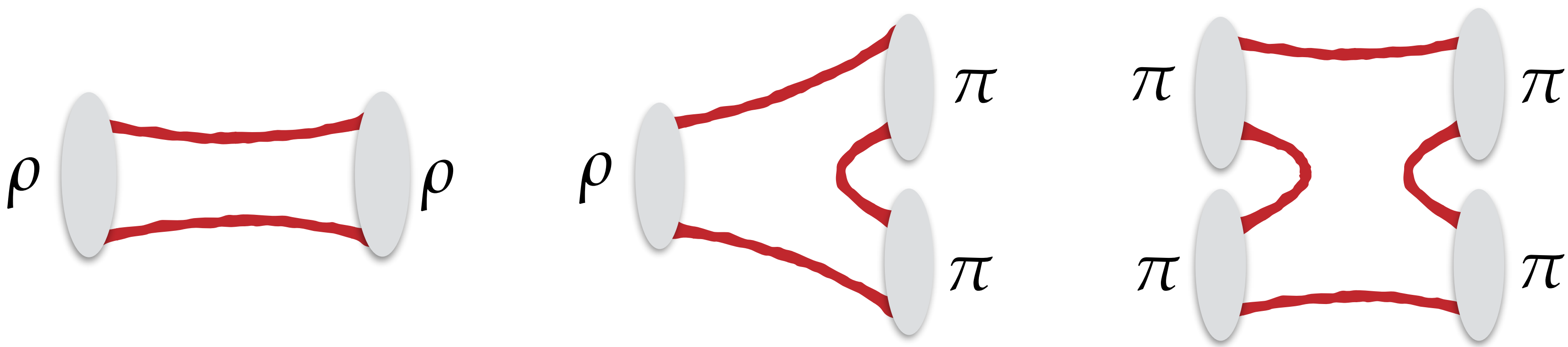


RESONANT PHASE SHIFT



Propagators and contractions

- Need correlation functions - and hence operators - that resemble scattering



- Computing “propagators” (solving large sparse linear system) — expensive
- Large number (combinatorics) of contractions - expensive

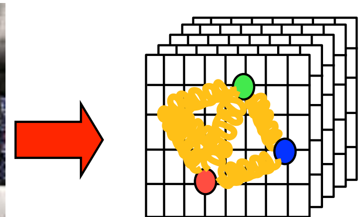
- *ALCC: Solved with new algorithms & lots of flops*
  - *GPU-based inverters*
  - *Algebraic Multigrid inverters for CPUs*
  - *GPU-based contraction codes - pipelined “zgemms”*

LQCD workflow

LQCD workflow

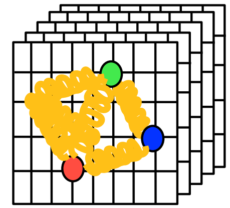
Generate the configurations

- Leadership level
- 60K cores, 10’s TF-yr



LQCD workflow

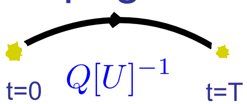
Generate the configurations
- Leadership level
- 60K cores, 10's TF-yr



Analyze
100K copies
4 Kepler GPUs
Now also AMG!

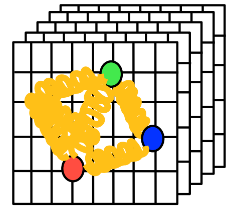
+

Propagators



LQCD workflow

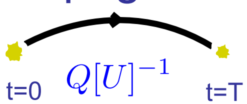
Generate the configurations
- Leadership level
- 60K cores, 10's TF-yr



Analyze
100K copies
4 Kepler GPUs
Now also AMG!

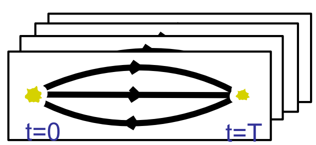
+

Propagators



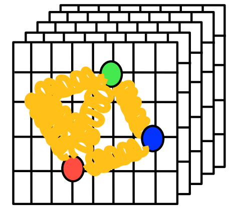
Contract
- 8 cores, CPUs

Correlators
100K – 1M copies



LQCD workflow

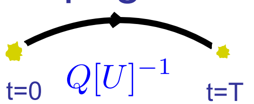
Generate the configurations
- Leadership level
- 60K cores, 10's TF-yr



Analyze
100K copies
4 Kepler GPUs
Now also AMG!

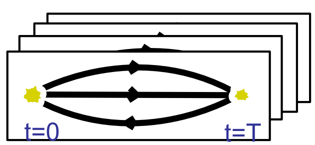

+

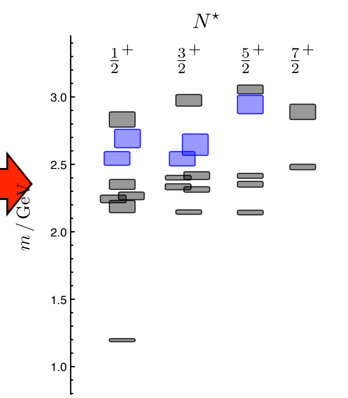

Propagators



Contract
- 8 cores, CPUs

Correlators
100K – 1M copies

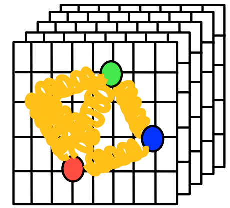




LQCD workflow

Generate the configurations

- Leadership level
- 60K cores, 10's TF-yr

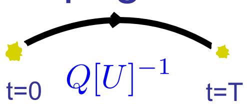


Few big jobs
Few big files

Analyze
100K copies
4 Kepler GPUs
Now also AMG!

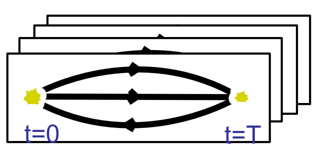
+

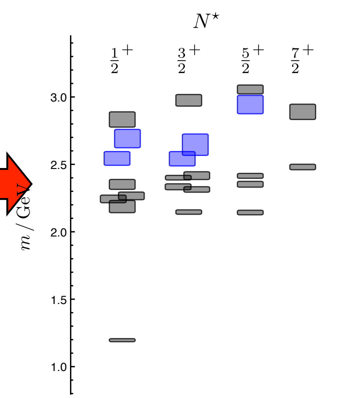
Propagators



Contract
8 cores, CPUs

Correlators
100K – 1M copies



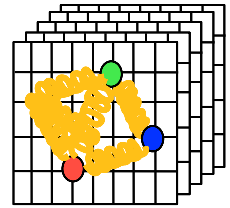


Many small jobs
Many big files

I/O movement

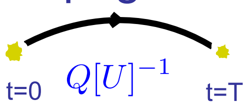
LQCD workflow

Generate the configurations
- Leadership level
- 60K cores, 10’s TF-yr



~25%
Leadership level

Propagators



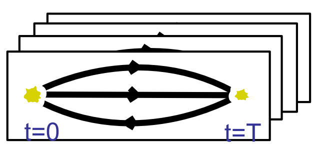
+

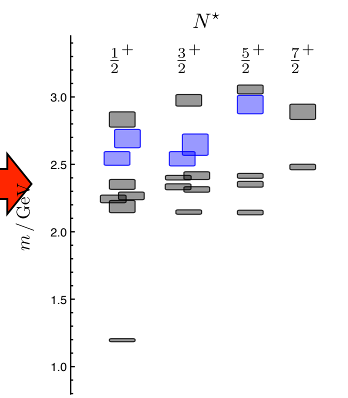
Analyze
100K copies
4 Kepler GPUs
Now also AMG!

~75%
Throughput mode

Contract
8 cores, CPUs

Correlators
100K – 1M copies



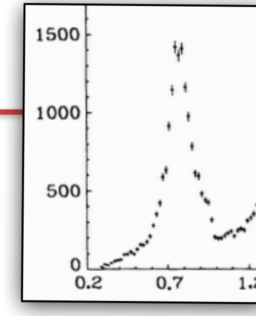


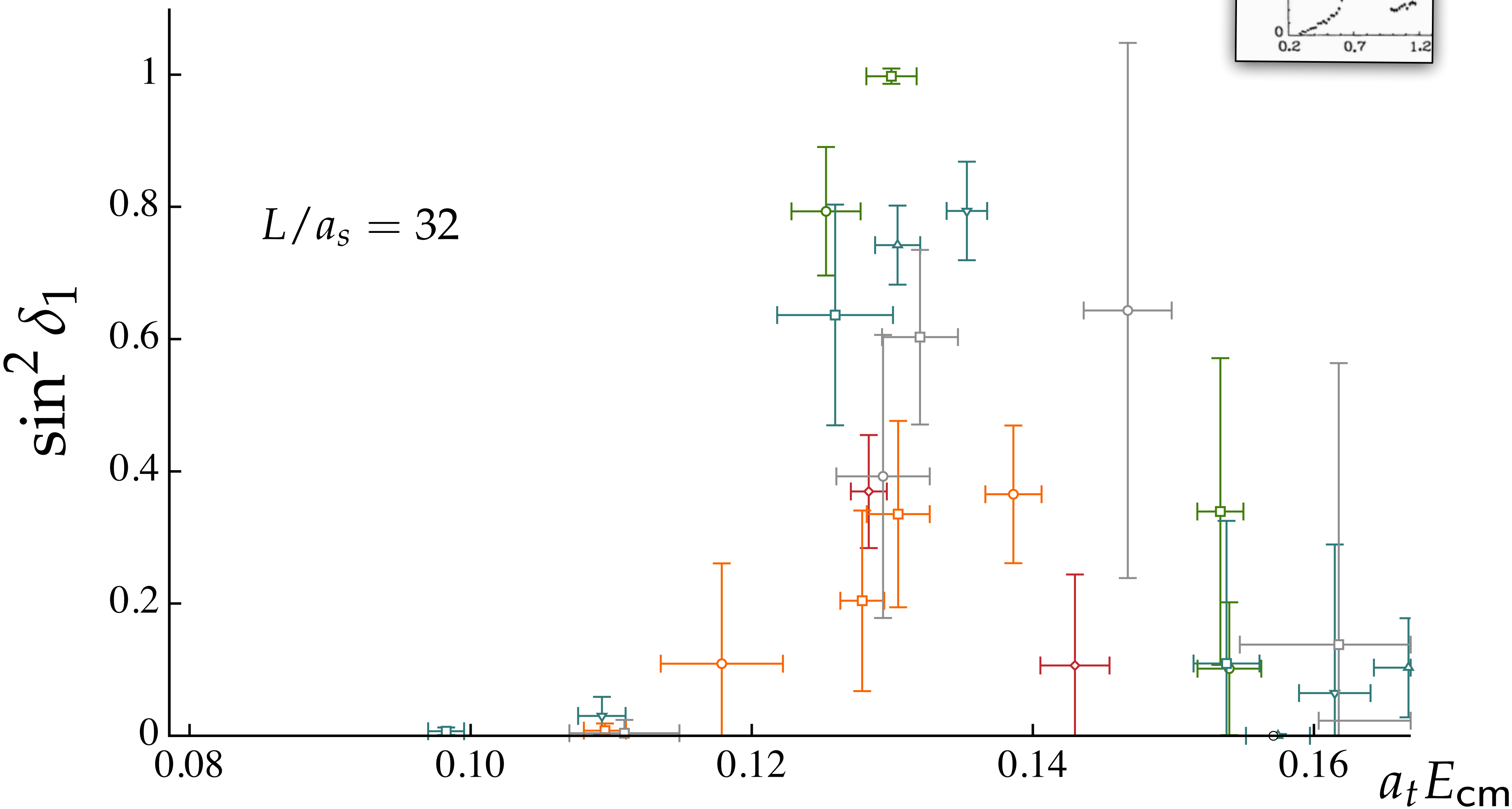
> 5%
New analysis cost

(Previous) state of the art

$m_\pi \sim 230\,\text{MeV}$

Can you find a resonance?



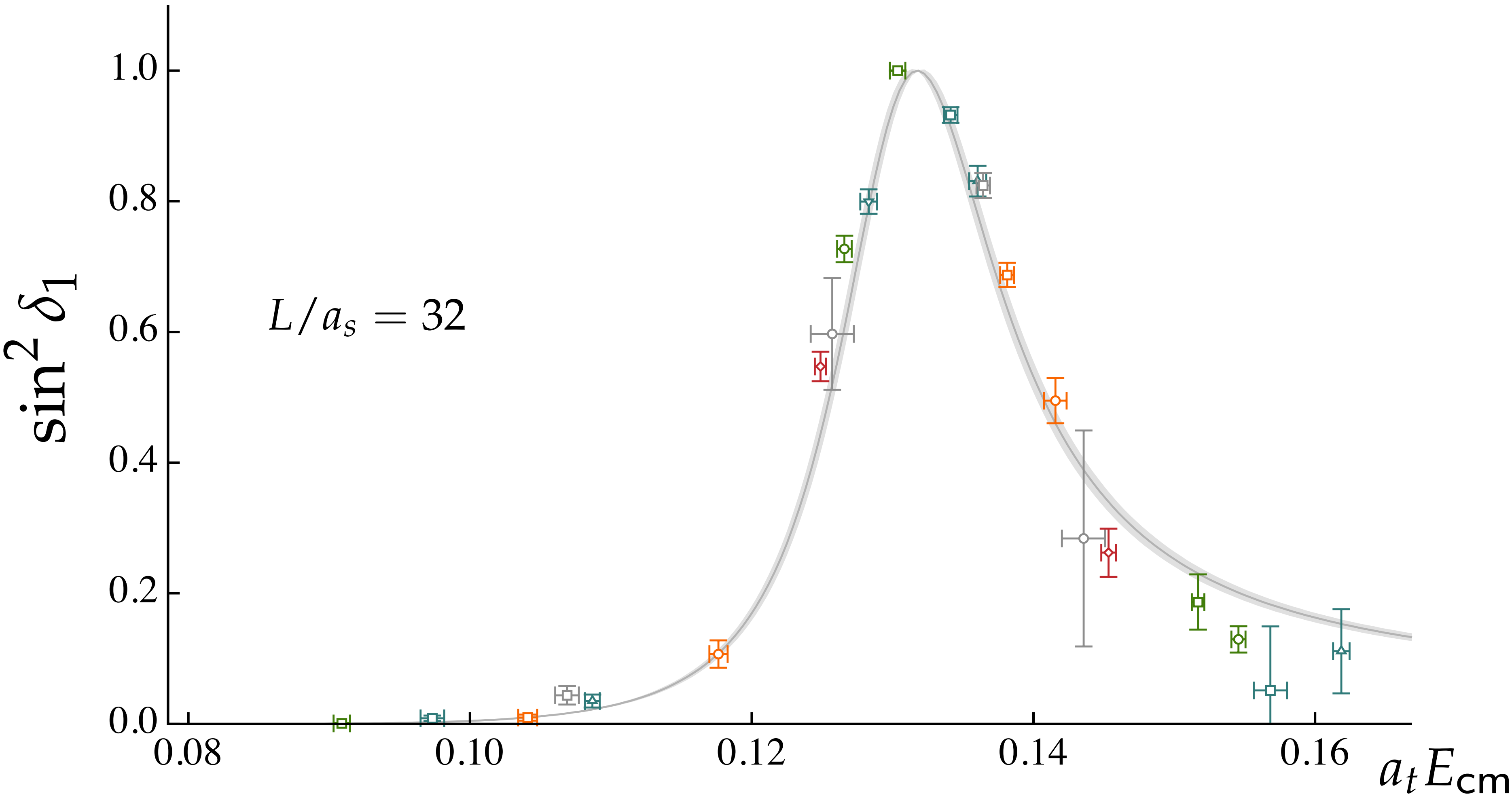


Fahy, et.al. arXiv:1410.8843

Result of ALCC

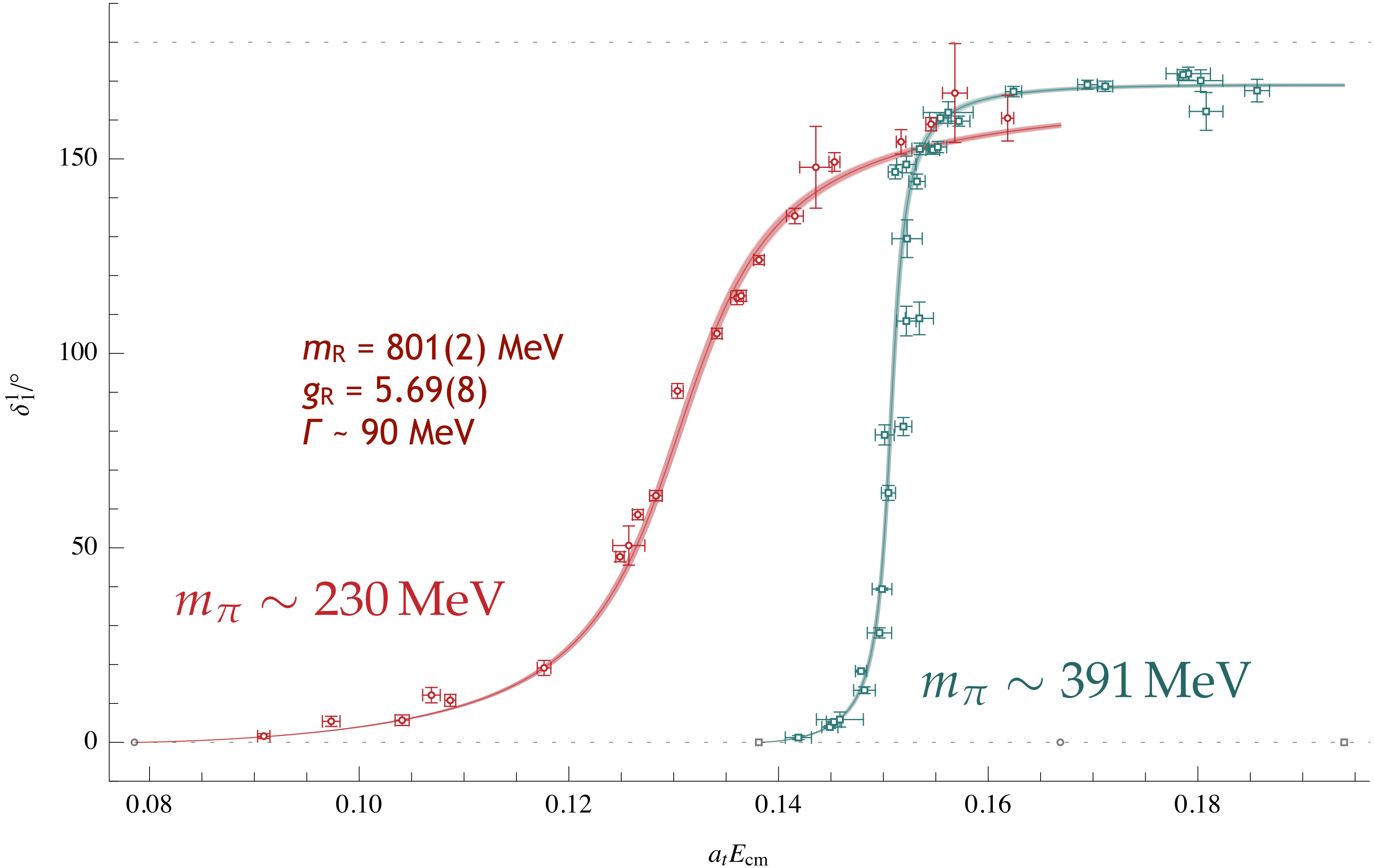
$m_\pi \sim 230\,\mathrm{MeV}$

Clearly a resonance!



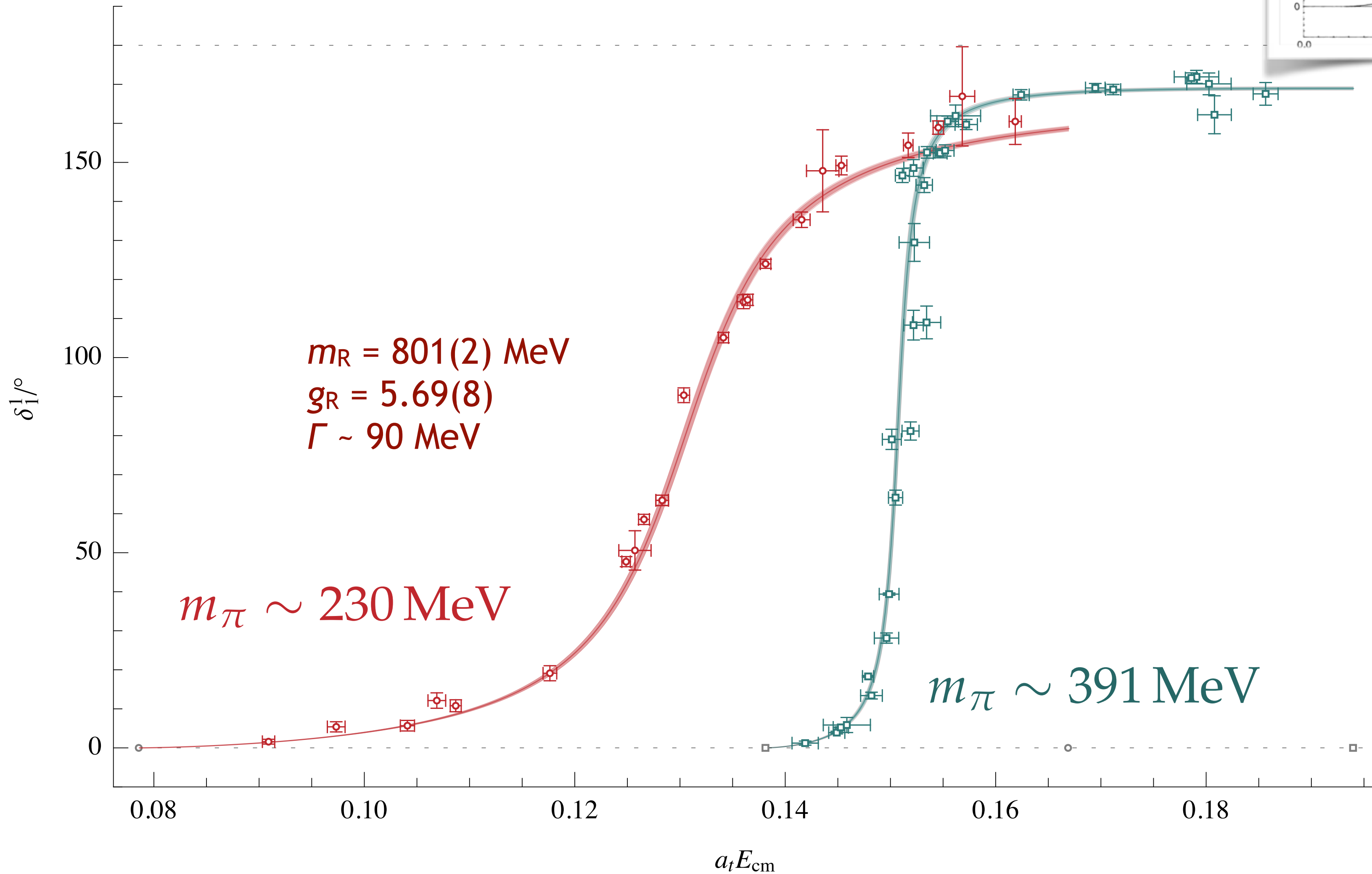
PRELIMINARY … to appear soon

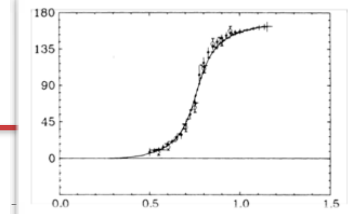
And at different quark masses …



Extracting resonances from finite-volume spectra computed in lattice QCD looks promising …

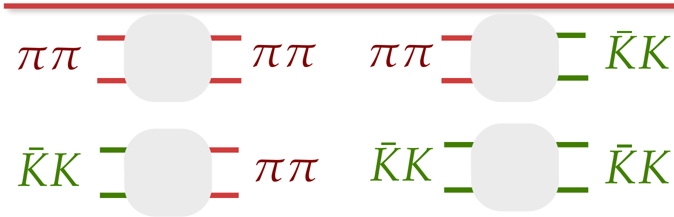
And at different quark masses …

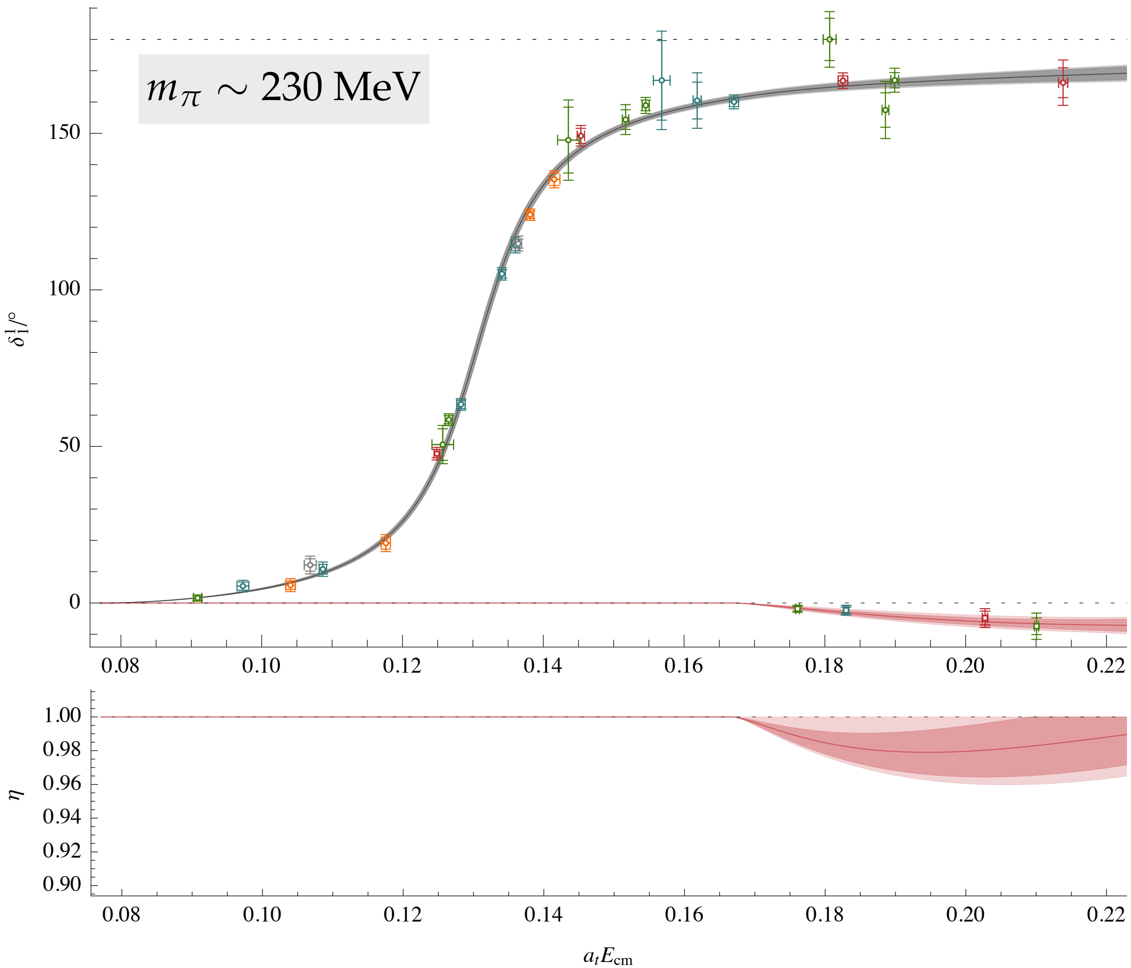




Extracting resonances from finite-volume spectra computed in lattice QCD looks promising …

ρ resonance as a coupled channel system

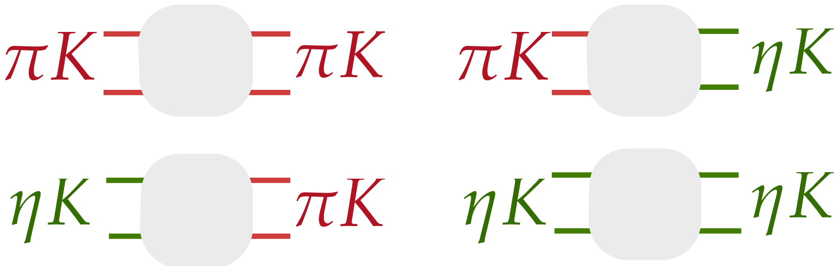




m_R = 801(2) MeV
g_R = 5.69(8)
Γ ~ 90 MeV

$\pi K/\eta K$ scattering & kaon resonances

- Example of coupled-channel scattering



- More extended basis of operators

$$\bar{u}\boldsymbol{\Gamma}s$$

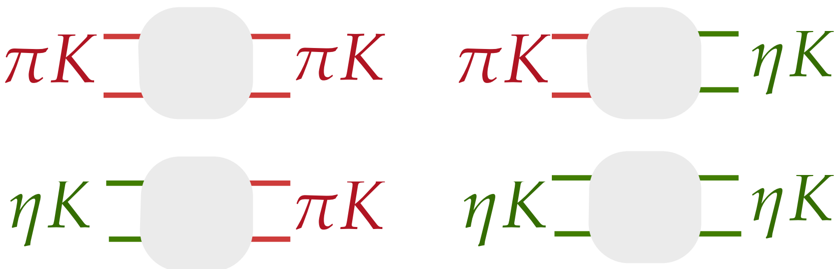
$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\ \pi^\dagger(\vec{k}_1)\ K^\dagger(\vec{k}_2)$$

$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\ \eta^\dagger(\vec{k}_1)\ K^\dagger(\vec{k}_2)$$

PRL 113 182001
PRD 91 054008

$\pi K/\eta K$ scattering & kaon resonances

- Example of coupled-channel scattering



- More extended basis of operators

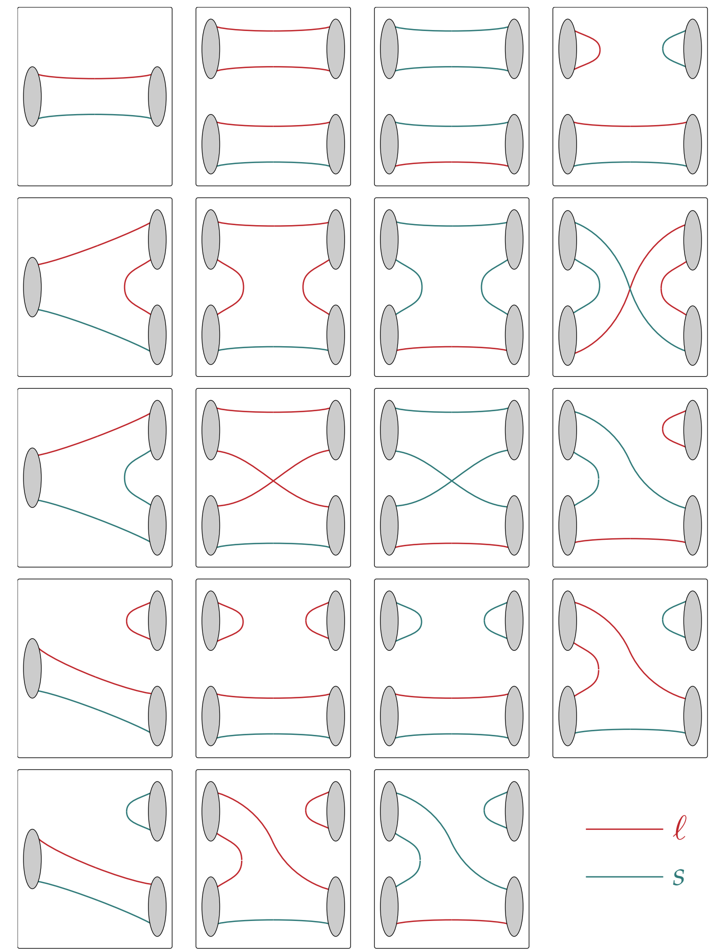
$$\bar{u}\mathbf{\Gamma}s$$

$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\,\pi^\dagger(\vec{k}_1)\,K^\dagger(\vec{k}_2)$$

$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\,\eta^\dagger(\vec{k}_1)\,K^\dagger(\vec{k}_2)$$

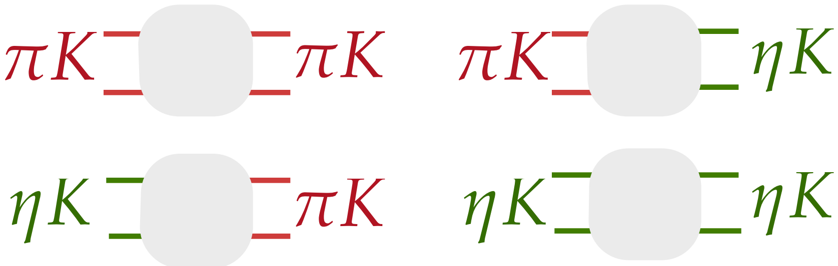
PRL 113 182001
PRD 91 054008

WICK CONTRACTIONS



$\pi K/\eta K$ scattering & kaon resonances

- Example of coupled-channel scattering



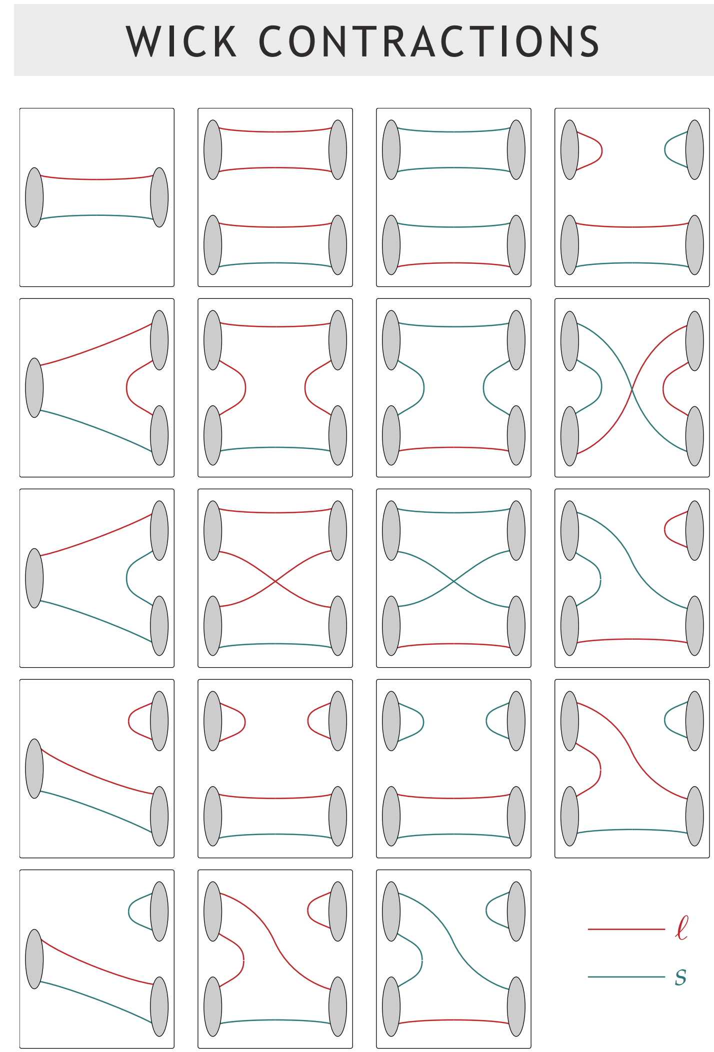
- More extended basis of operators

$$\bar{u}\mathbf{\Gamma}s$$

$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\,\pi^\dagger(\vec{k}_1)\,K^\dagger(\vec{k}_2)$$

$$\sum_{\hat{k}_1,\hat{k}_2} C(\Lambda,\vec{P};\vec{k}_1,\vec{k}_2)\,\eta^\dagger(\vec{k}_1)\,K^\dagger(\vec{k}_2)$$

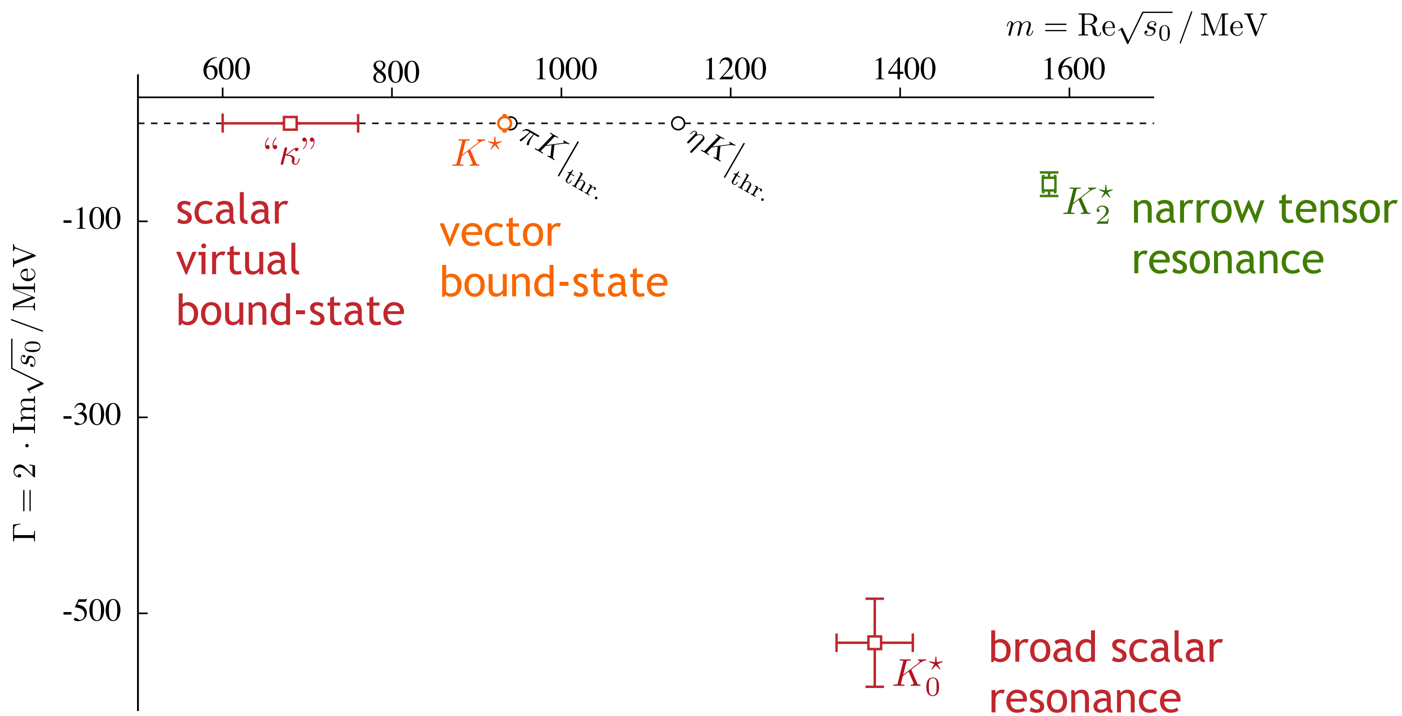
PRL 113 182001
PRD 91 054008



Large combinatoric factors – contractions expensive

Singularity content

- Resonance pole locations extracted as well as decay amplitudes



$m_\pi \sim 391\,\mathrm{MeV}$

PRL 113 182001
PRD 91 054008

- Must carry this on to smaller pion masses - closer to "reality"

Hunt for exotic mesons - lessons from experiment

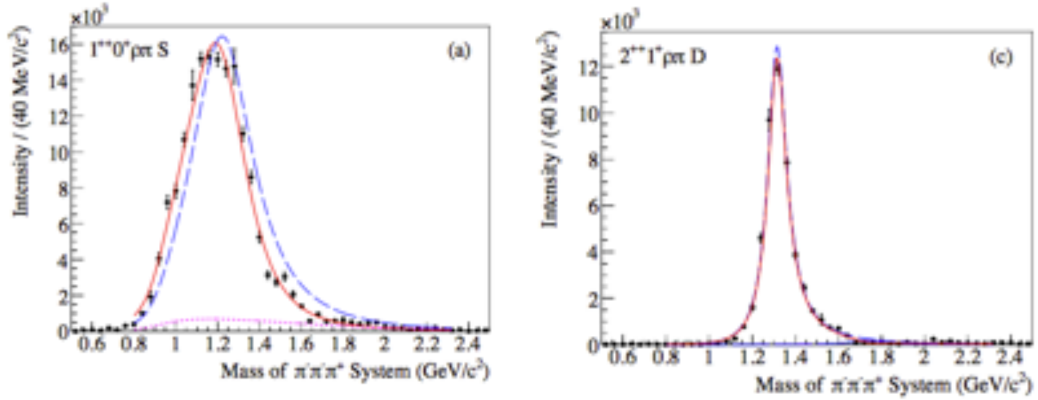
COMPASS

- Experiments have to look at many decay channels

Non-exotic

Scale ~ 10000

E.g., scattering of $\pi\pi\pi$



Hunt for exotic mesons - lessons from experiment

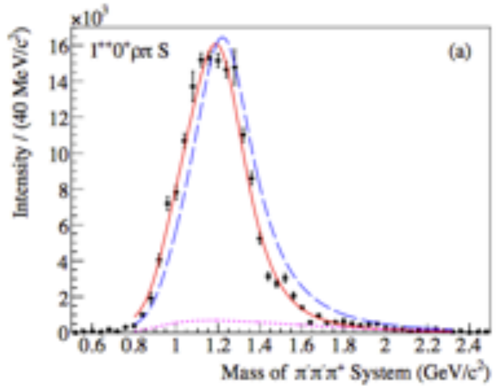
COMPASS

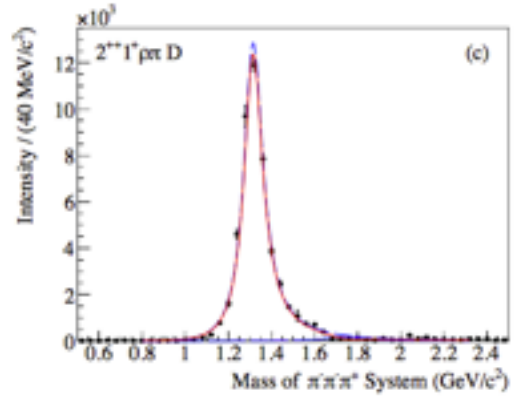
- Experiments have to look at many decay channels

Non-exotic

Scale ~ 10000

E.g., scattering of $\pi\pi\pi$



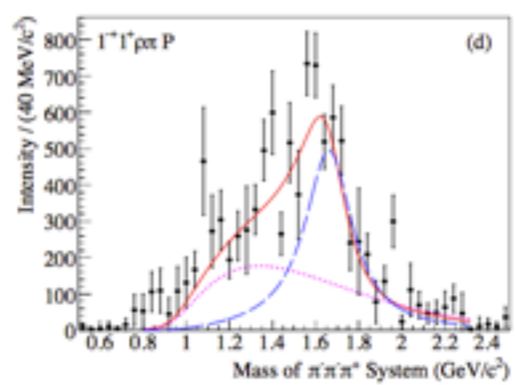


- Amplitude for exotics are very tiny compared to background ~ 5%

Exotic

Scale ~ 800

Goal - compute decay amplitudes!



Impact on experiment

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

Approved expt: second phase of GlueX program

PR12-13-003

An initial study of mesons and baryons containing strange quarks with GlueX

(A proposal to the 40^{th} Jefferson Lab Program Advisory Committee)

A. AlekSejevs,[1] S. Barkanova,[1] M. Dugger,[2] B. Ritchie,[2] I. Senderovich,[2] E. Anassontzis,[3] P. Ioannou,[3] C. Kourkoumeli,[3] G. Voulgaris,[3] N. Jarvis,[4] W. Levine,[4] P. Mattione,[4] W. McGinley,[4] C. A. Meyer,[4,*]

⋮

The primary motivation of the GlueX experiment is to search for and ultimately study the pattern of gluonic excitations in the meson spectrum produced in γp collisions. Recent lattice QCD calculations predict a rich spectrum of hybrid mesons that have both exotic and non-exotic J^{PC}, corresponding to $q\bar{q}$ states ($q = u$, d, or s) coupled with a gluonic field. A thorough study of the

Impact on experiment

Science case for JLab CLAS12 expt

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]

NSAC report prominently featuring exotic meson spectroscopy project

Report to the
Nuclear Science Advisory Committee
Implementing the 2007 Long Range Plan
January 31, 2013

New NSAC report in writing now…

Summary

Summary

- Spectroscopy program maturing (I was told many times

Summary

- Spectroscopy program maturing (I was told many times
- First phase:
  - Unphysical pion masses, have a glimpse of the QCD spectrum
  - See evidence of non-exotic and exotic mesons - suggests *hybrids*
  - ➡ Has had direct impact on JLab expt. program

Summary

- Spectroscopy program maturing (I was told many times
- First phase:
  - Unphysical pion masses, have a glimpse of the QCD spectrum
  - See evidence of non-exotic and exotic mesons - suggests *hybrids*
  - ➡ Has had direct impact on JLab expt. program

Summary

- Spectroscopy program maturing   (I was told many times
- First phase:
  - Unphysical pion masses, have a glimpse of the QCD spectrum
  - See evidence of non-exotic and exotic mesons - suggests *hybrids*
  - ➡ Has had direct impact on JLab expt. program

- Have demonstrated viability to determine decays in fairly simple systems

Summary

- Spectroscopy program maturing (I was told many times
- First phase:
  - Unphysical pion masses, have a glimpse of the QCD spectrum
  - See evidence of non-exotic and exotic mesons - suggests *hybrids*
  - ➡ Has had direct impact on JLab expt. program

- Have demonstrated viability to determine decays in fairly simple systems

Summary

- Spectroscopy program maturing   (I was told many times
- First phase:
  - Unphysical pion masses, have a glimpse of the QCD spectrum
  - See evidence of non-exotic and exotic mesons - suggests *hybrids*
  - ➡ Has had direct impact on JLab expt. program

- Have demonstrated viability to determine decays in fairly simple systems

- Near term goals
  - Use multiple volumes at m_π ~230MeV and 391MeV to help disentangle decays
  - Tackle exotics as a part of our new ALCC
  - ➡ Knowledge of even size of branching fractions useful for expt. analysis