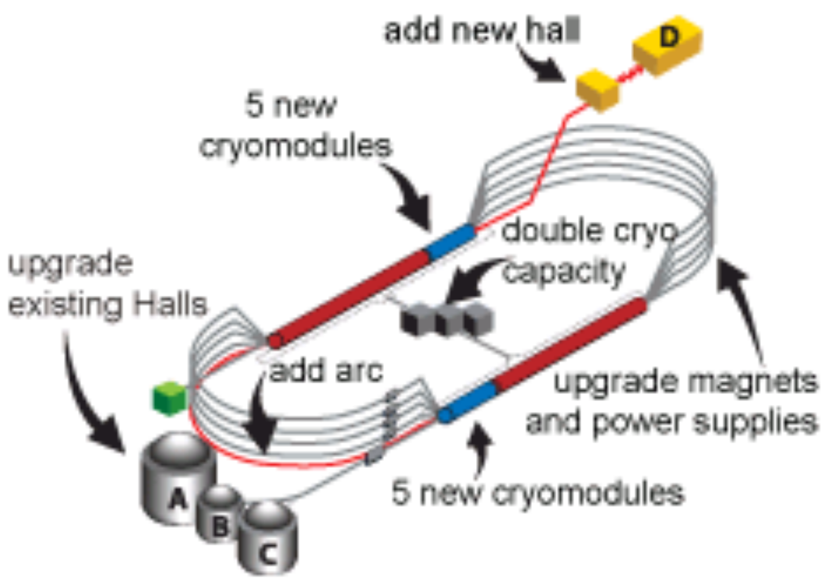
Hadron Spectroscopy from Lattice QCD

Robert Edwards
Jefferson Lab

ORNL 2013

Nuclear Physics & Jefferson Lab

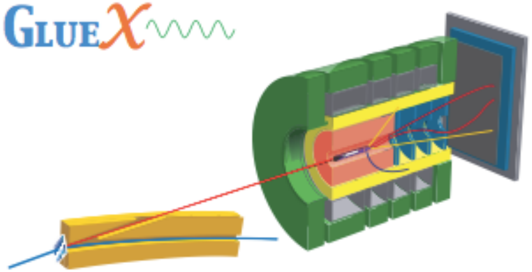
JLab undergoing a $310M major upgrade



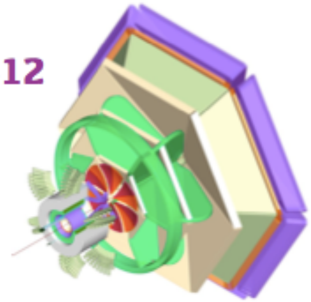
- **Lab doubling beam energy to 12GeV**
- **Adding new experimental Hall**

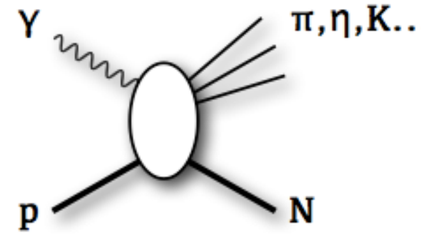
Light meson spectrum - experiments

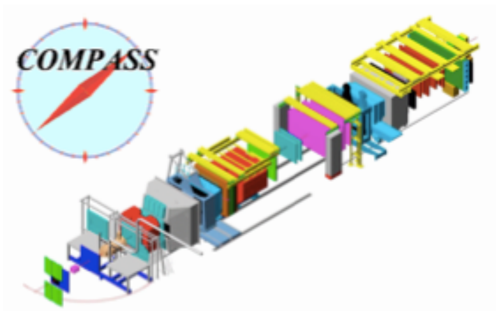
GlueX

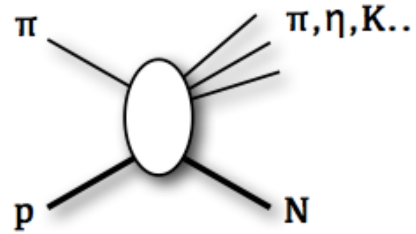


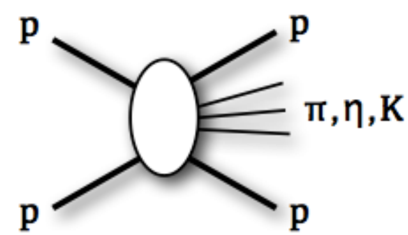
CLAS12



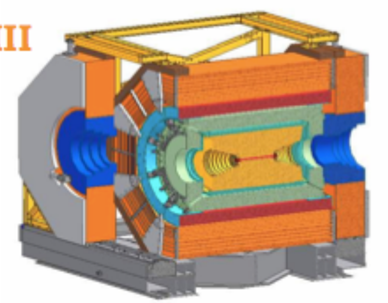


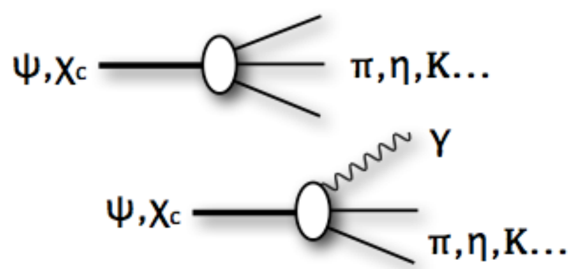






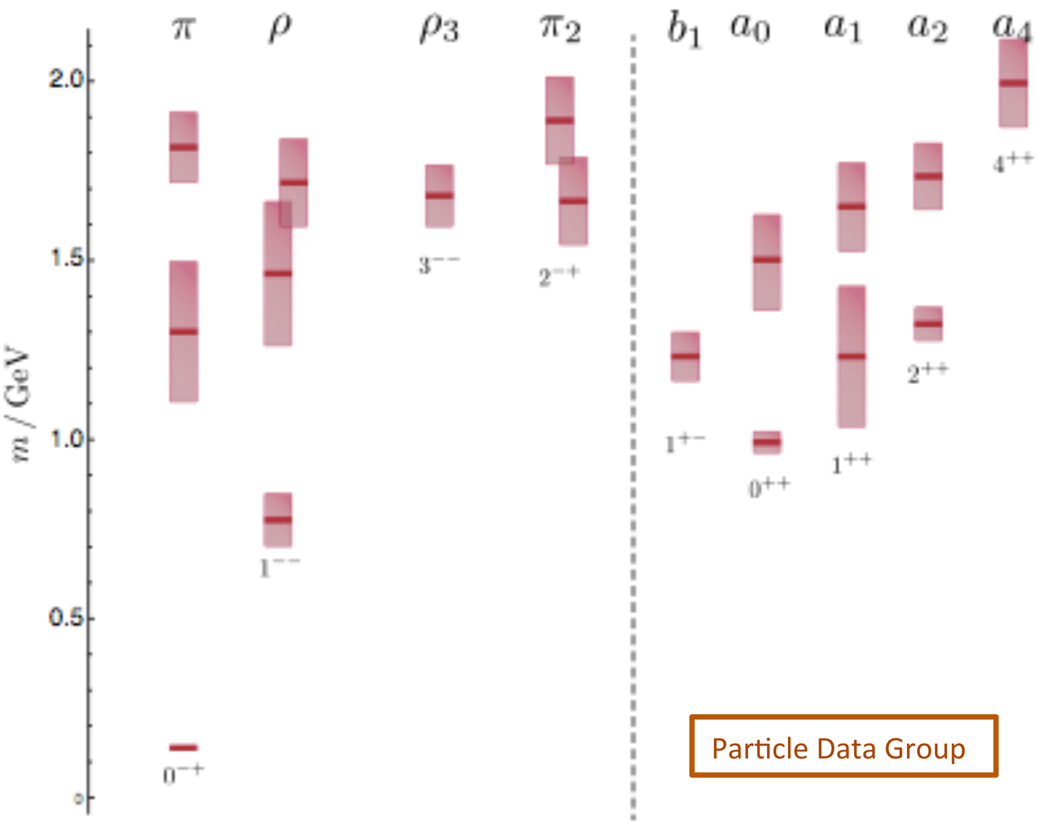
BES III





Experimental meson spectrum

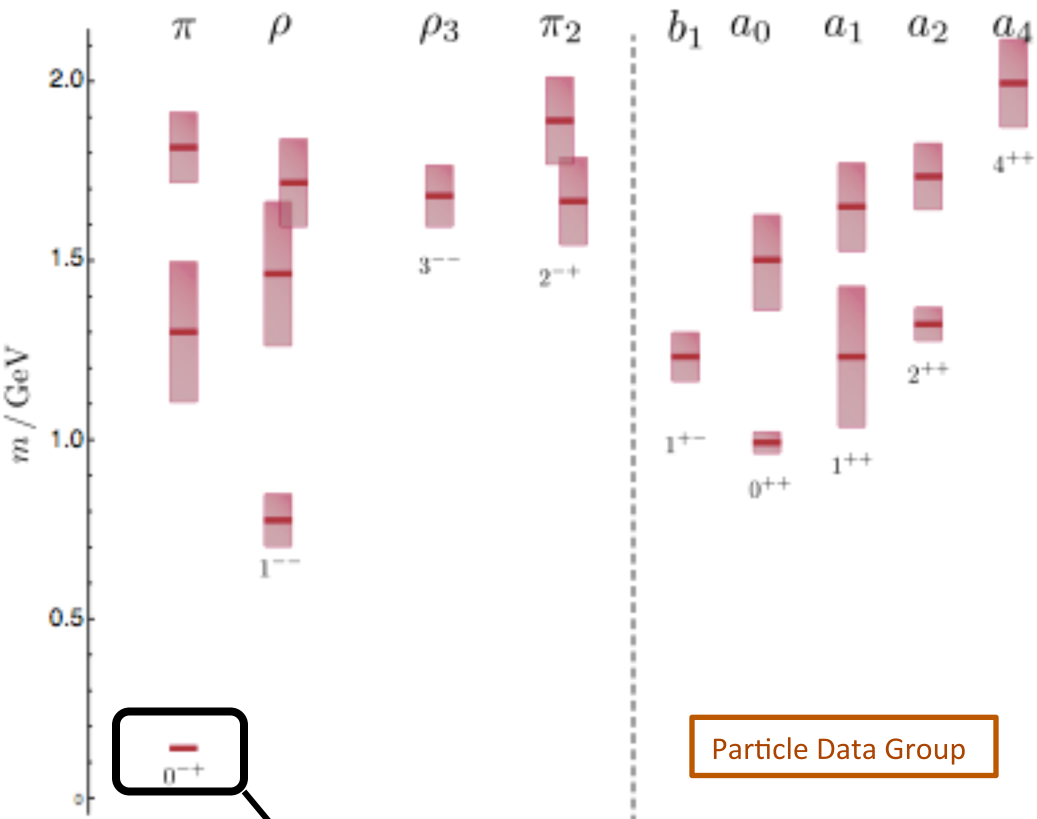
Isospin 1



Particle Data Group

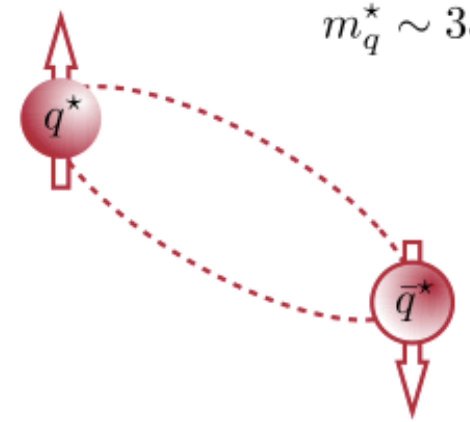
Experimental meson spectrum

Broadly compatible with **spatial excitations** of **constituent** quark-antiquark pair



Pion pseudo Goldsone-boson $m_q \sim \mathcal{O}(1)\ \mathrm{MeV}$

$m_q^\star \sim 350\,\mathrm{MeV}$



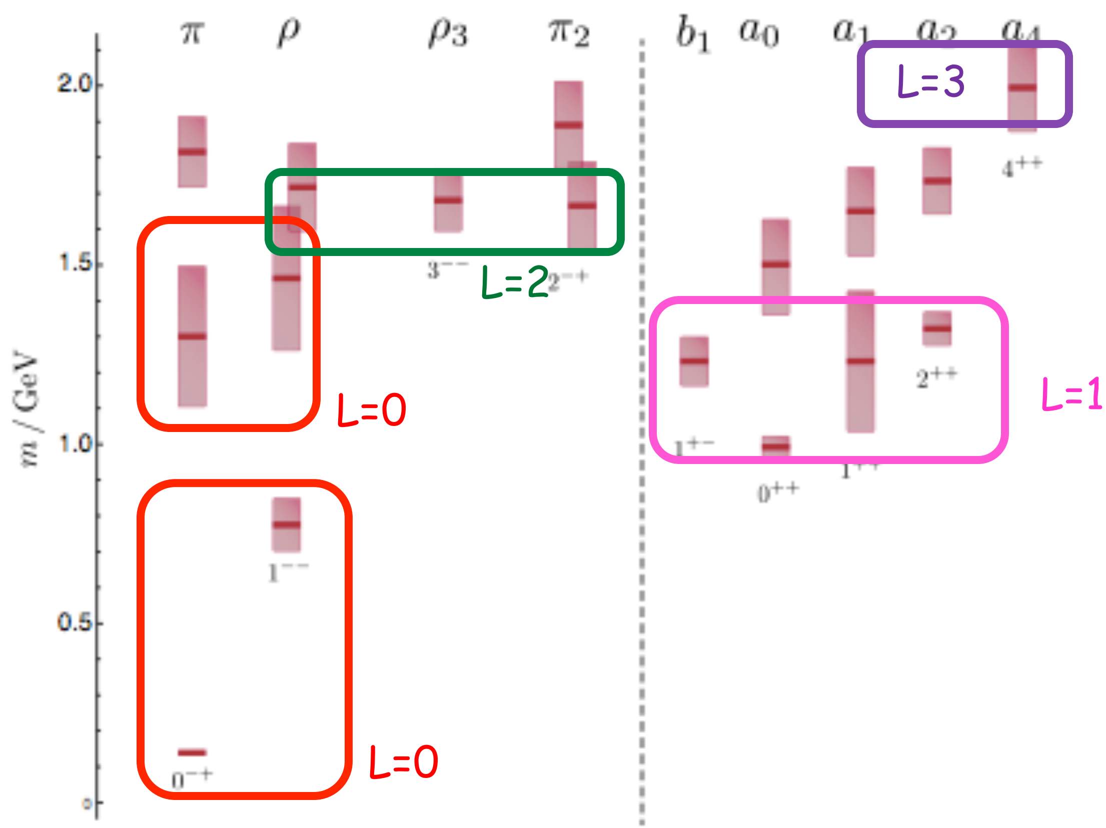
$q^\star \bar{q}^\star (^{2S+1}L_J) \implies J^{PC}$

excluding

$0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$

Experimental meson spectrum

The "quark model" $M \sim q\bar{q} \quad B \sim qqq$



Empirical J^{PC} distribution

I=0, S=0 : η, φ, ω, f_J …

I=1, S=0 : π, ρ, b_1, a_J …

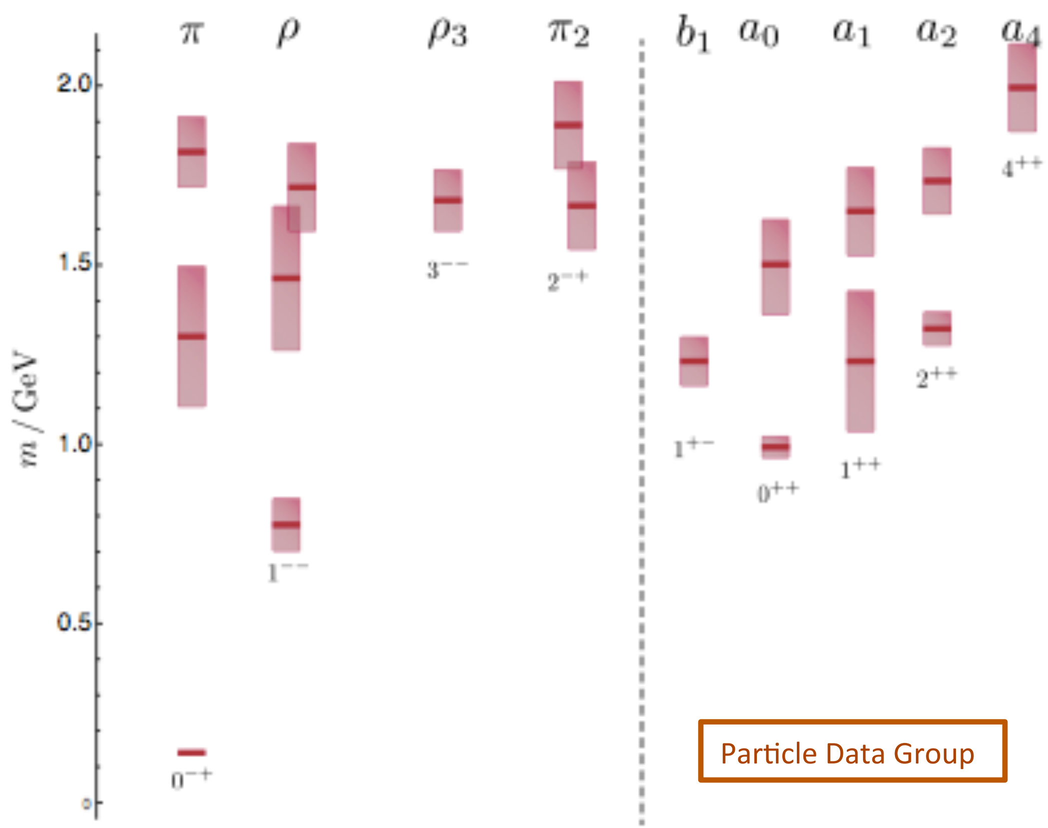
I=½, S=±1 : K, K* …

$I \ngtr 1$, $|S| \ngtr 1$

Exotic mesons

Quark-antiquark spatial (only) excitations exclude $\mathbf{J^{PC}}$ $\mathbf{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}}$

"Smoking gun signature"



Particle Data Group

Possible explanation: "hybrid" mesons $q\bar{q}\, G_{\mathbf{8_c}}$

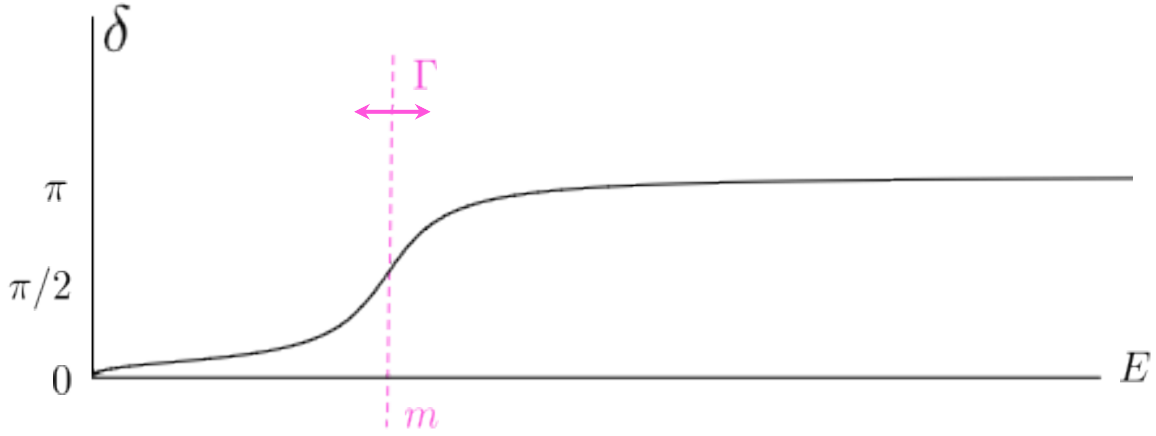
Many models, many different/conflicting predictions

Need theoretical guidance from QCD

Scattering

Experimentally - determine amplitudes as function of energy **E**

E.g. just a single elastic resonance



e.g.

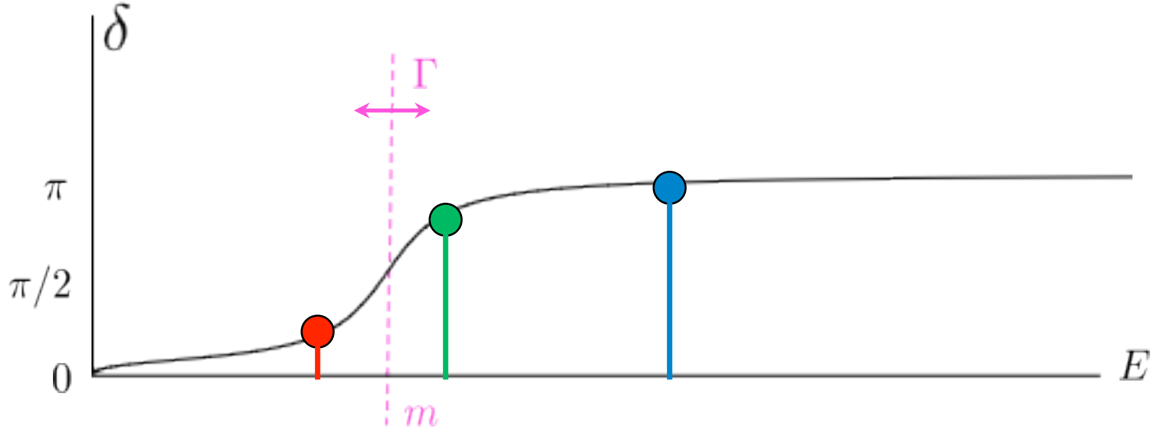
$$\pi\pi \longrightarrow \rho \longrightarrow \pi\pi$$

$$\pi N \longrightarrow \Delta \longrightarrow \pi N$$

Scattering (in finite volume!)

Scattering in a periodic cubic box (length **L**)

E.g. just a single elastic resonance



e.g.

$$\pi\pi \to \rho \to \pi\pi$$

$$\pi N \to \Delta \to \pi N$$

At some **L** , have discrete excited energies

Scattering (in finite volume!)

Scattering in a periodic cubic box (length **L**)

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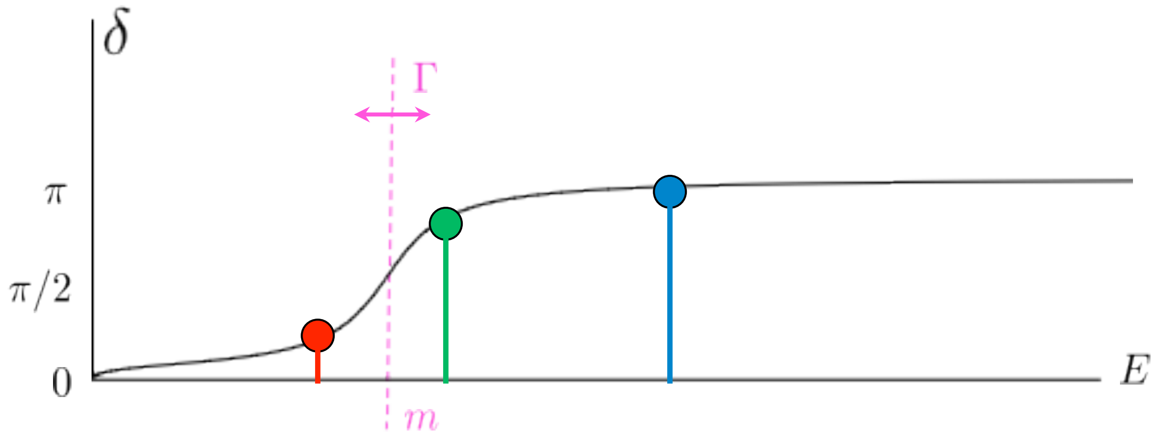


e.g.

$$\pi\pi \to \rho \to \pi\pi$$

$$\pi N \to \Delta \to \pi N$$

At some **L** , have discrete excited energies

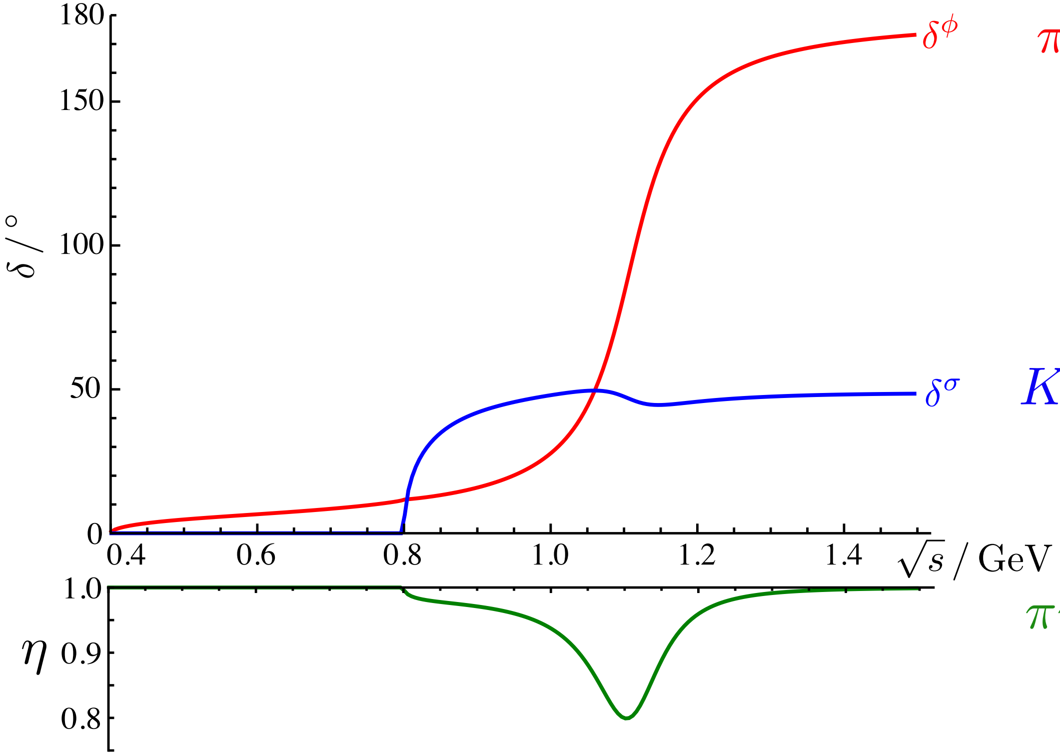
$$E \to k; \quad kL + 2\delta(k) = 0 \mod 2\pi$$

- Scattering matrix amplitudes in partial waves
- Finite volume energy levels **E(L) -> δ(E)**

More realistic scattering

Can have coupled channels

E.g.



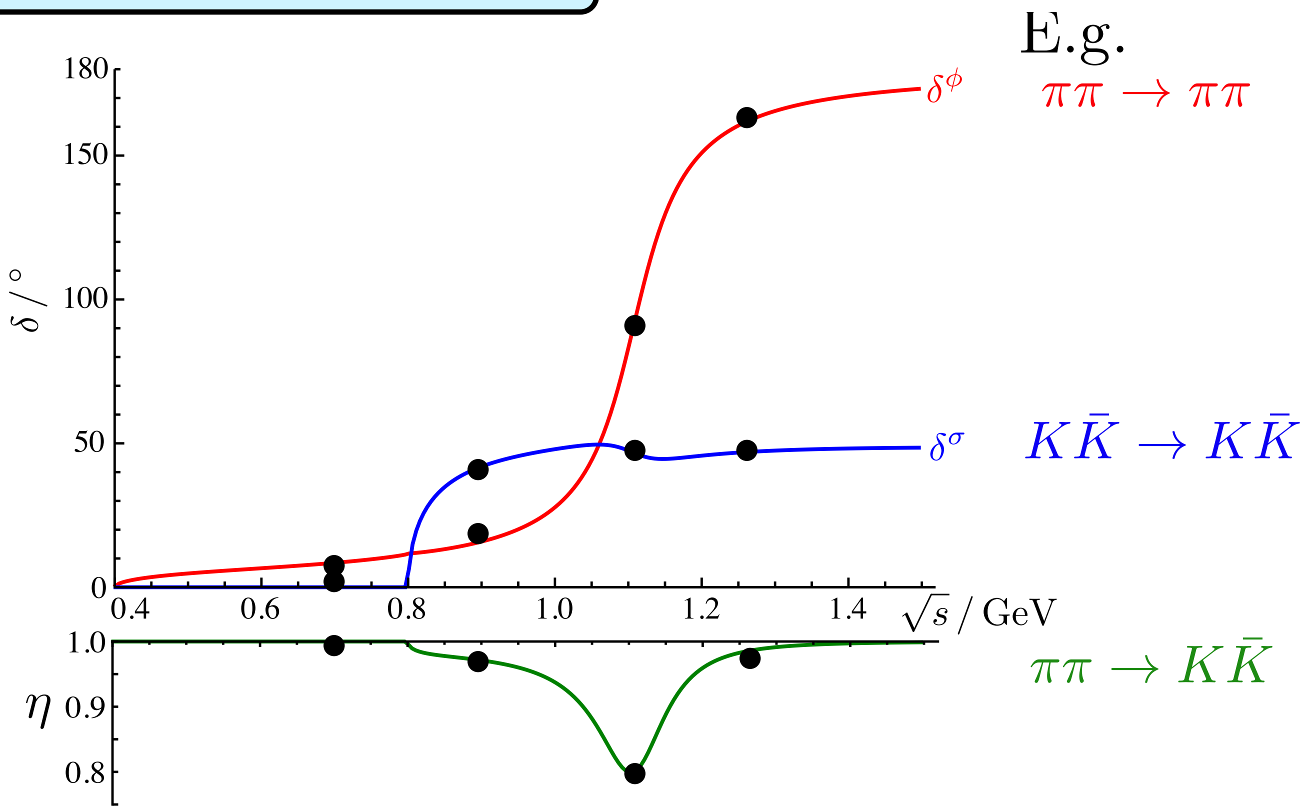
$\pi\pi \to \pi\pi$

$K\bar{K} \to K\bar{K}$

$\pi\pi \to K\bar{K}$

More realistic scattering

Can have coupled channels



Requirements:

- Lattice calculation must map energy dependence
- Need multiple excited states

Spectrum from variational method

Two-point correlator

$$C_{ij}(t) = \langle 0 | \Phi_i(t) \Phi_j^\dagger(0) | 0 \rangle$$

$$C_{ij}(t) = \sum_{\mathfrak{n}} e^{-E_{\mathfrak{n}} t} \langle 0 | \Phi_i(0) | \mathfrak{n} \rangle \langle \mathfrak{n} | \Phi_j^\dagger(0) | 0 \rangle$$

$$Z_i^{\mathfrak{n}} \equiv \langle \mathfrak{n} | \Phi_i^\dagger | 0 \rangle$$

Matrix of correlators

$$C(t) = \begin{pmatrix} \langle 0|\Phi_1(t)\Phi_1^\dagger(0)|0\rangle & \langle 0|\Phi_1(t)\Phi_2^\dagger(0)|0\rangle & \cdots \\ \langle 0|\Phi_2(t)\Phi_1^\dagger(0)|0\rangle & \langle 0|\Phi_2(t)\Phi_2^\dagger(0)|0\rangle & \cdots \\ \vdots & & \ddots \end{pmatrix}$$

"Rayleigh-Ritz method"
Diagonalize:
- eigenvalues -> spectrum
- eigenvectors -> spectral "overlaps" Z_i^n

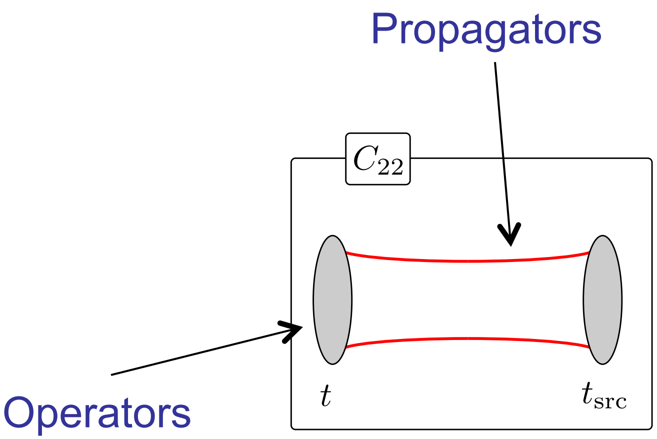
Each state optimal combination of Φ_i

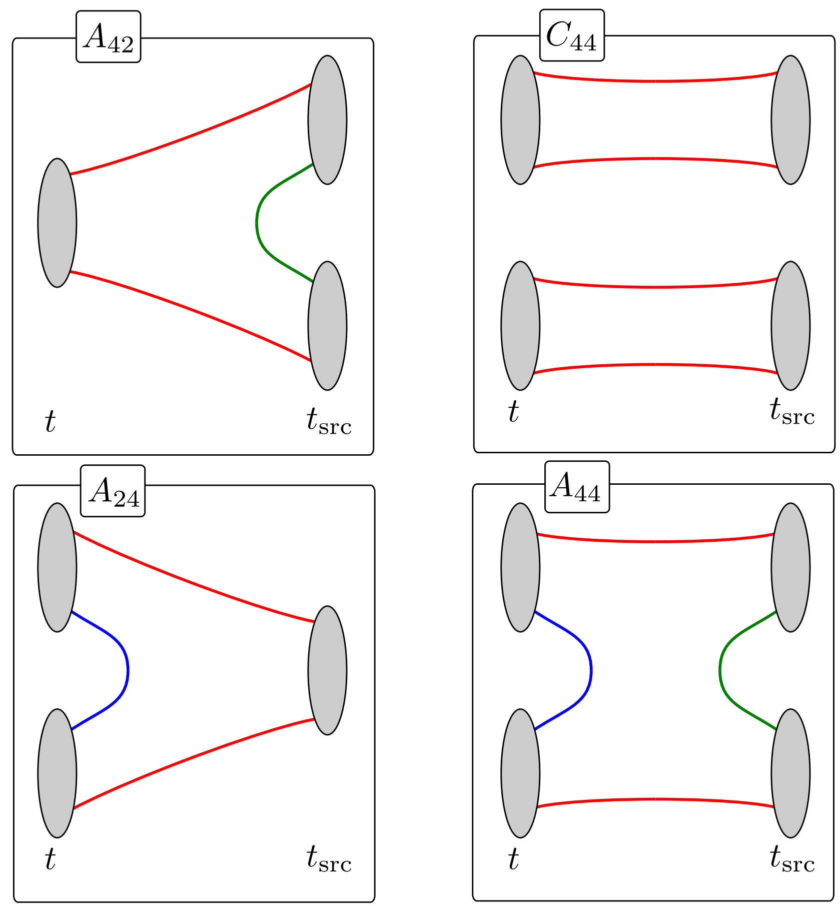
$$\Omega^{(\mathfrak{n})} = \sum_i v_i^{(\mathfrak{n})} \Phi_i$$

Benefit: orthogonality for near degenerate states

Contractions

Cost to produce correlators driven by contractions



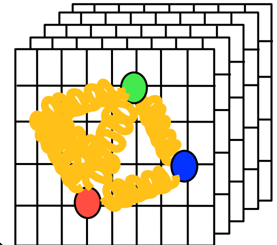


Many permutations

Improving is a current SciDAC activity

LQCD Workflow

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

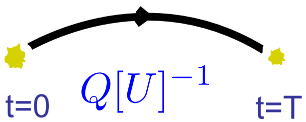


Few big jobs
Few big files

Analyze
10K copies
4 Kepler GPUs

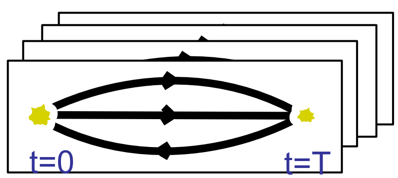
+

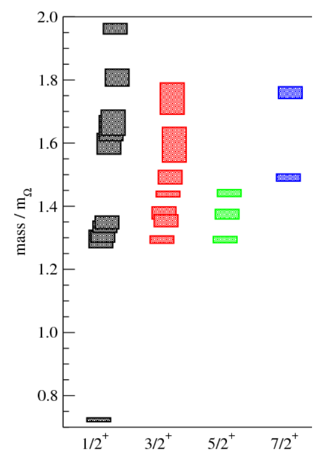
Propagators



Contract (CPUs)`

Correlators
100K – 1M copies



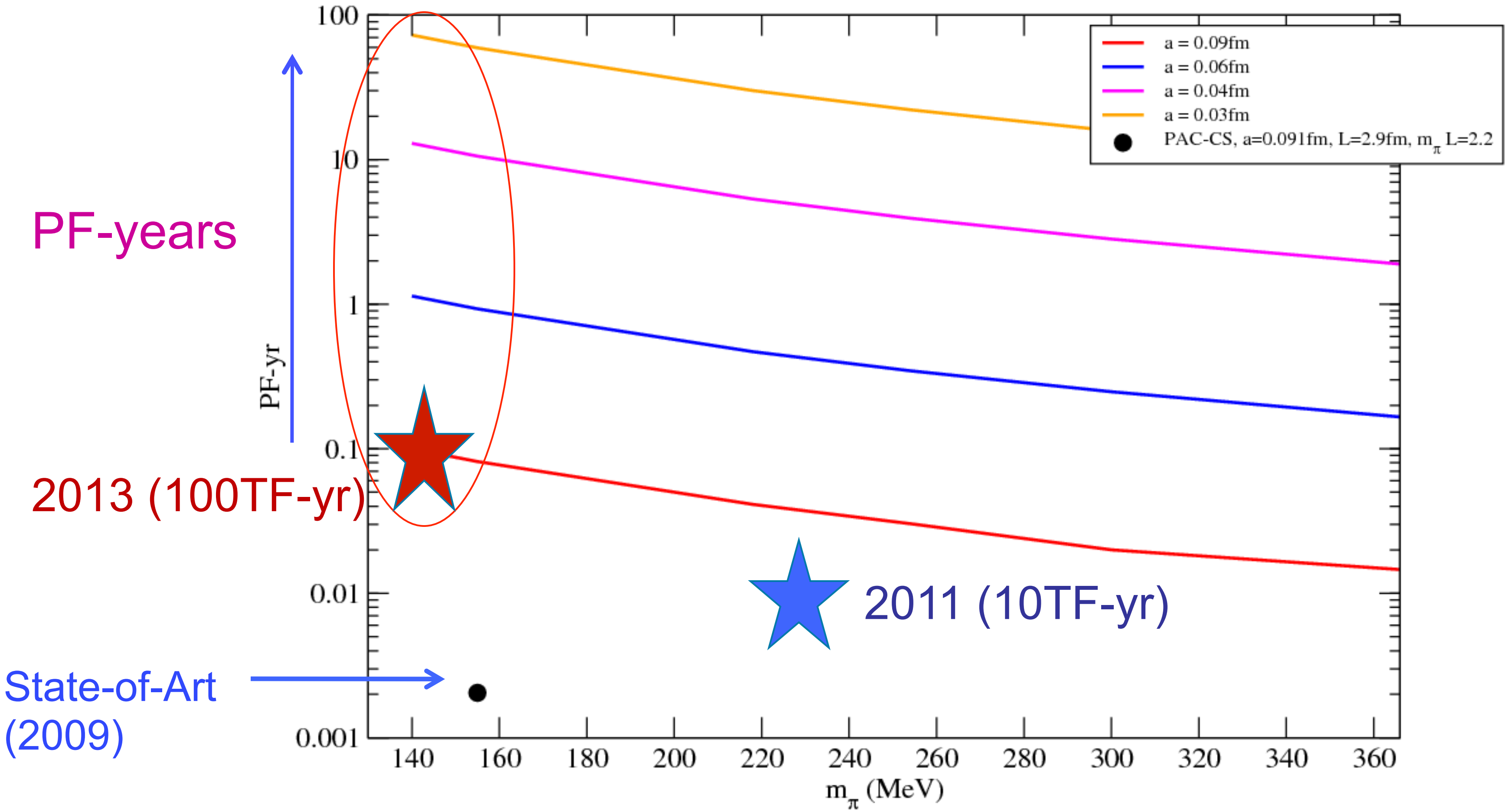


Many small jobs
Many big files

I/O movement

Gauge Generation: Cost Scaling

- Cost: reasonable statistics, box size and “physical” pion mass
- Extrapolate in lattice spacings: 10 ~ 100 PF-yr



Spectroscopy Computational Requirements

Example calculation (24^3x128):

Gauge generation: 6M cr-hr (0.6 TF-yr) + 1 TB
Propagators: 0.34M GPU-hr (10 TF-yr) + 120 TB
Contractions: > 10's M cr-hr + 10's TB [on-going]
Core work: Dirac inverters - use GPU-s

Computational Requirements:

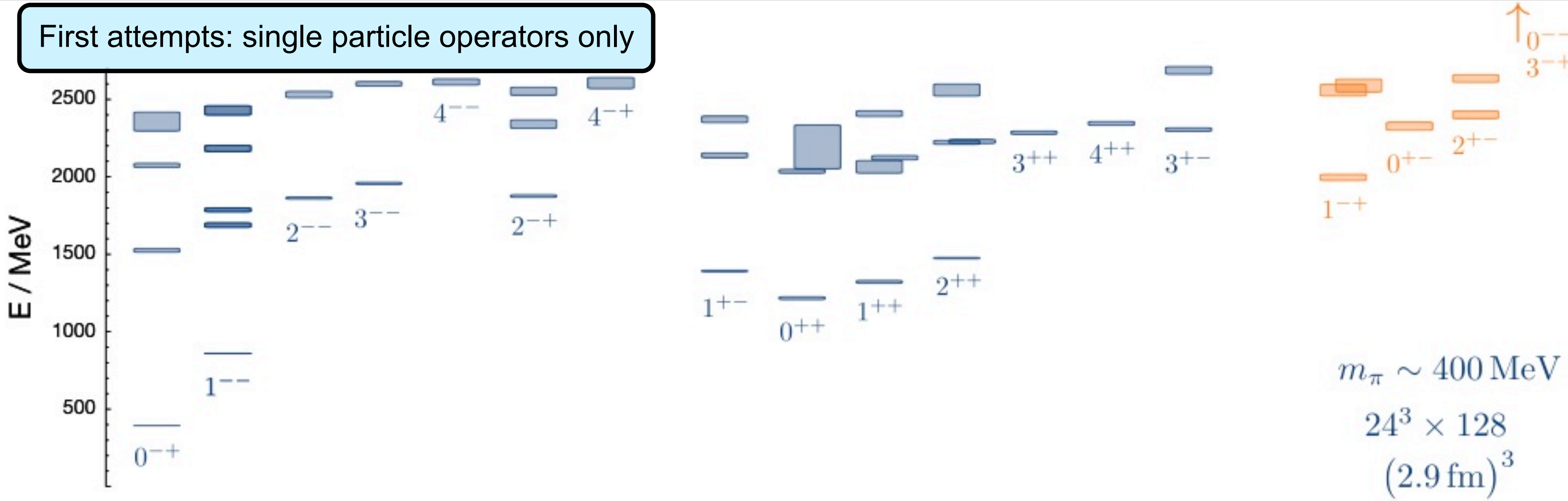
Gauge Generation : Analysis
1 : 0.1 (2005)
1 : 10 (2013)

Gauge generation @ORNL:

Previous: 32^3x256: 78M CPU cr-hr [in analysis]
Current: 40^3x256: 180M CPU cr-hr [need to push to GPU-s!]

Meson spectrum from lattice QCD

First attempts: single particle operators only



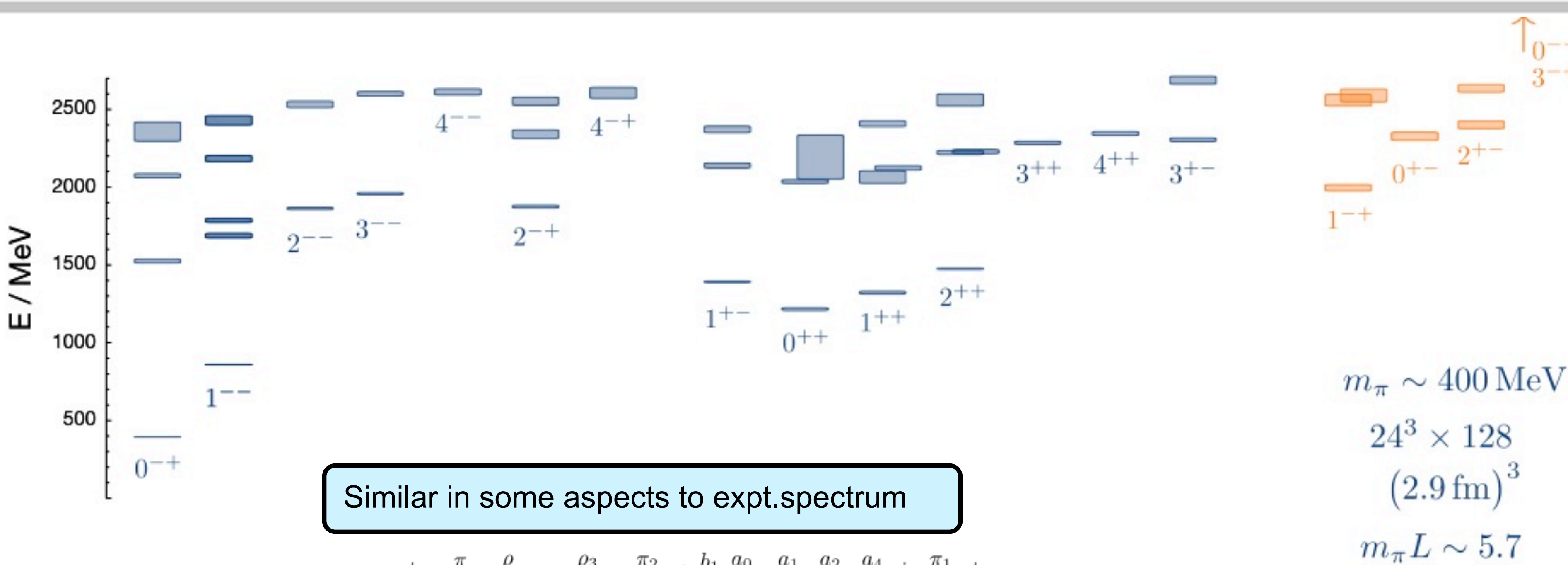
$m_\pi \sim 400$ MeV

$24^3 \times 128$

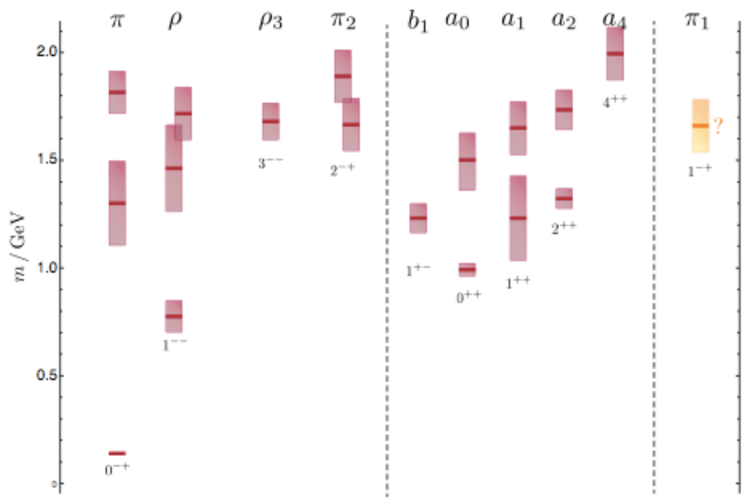
$(2.9\,\mathrm{fm})^3$

$m_\pi L \sim 5.7$

Meson spectrum from lattice QCD



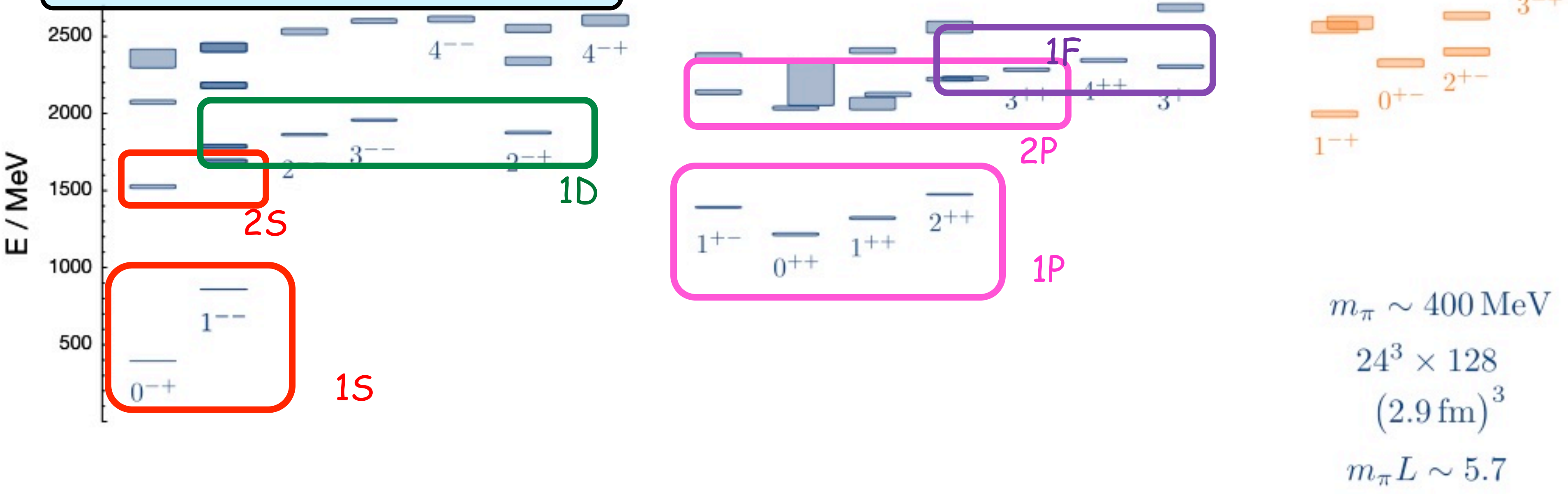
Similar in some aspects to expt.spectrum



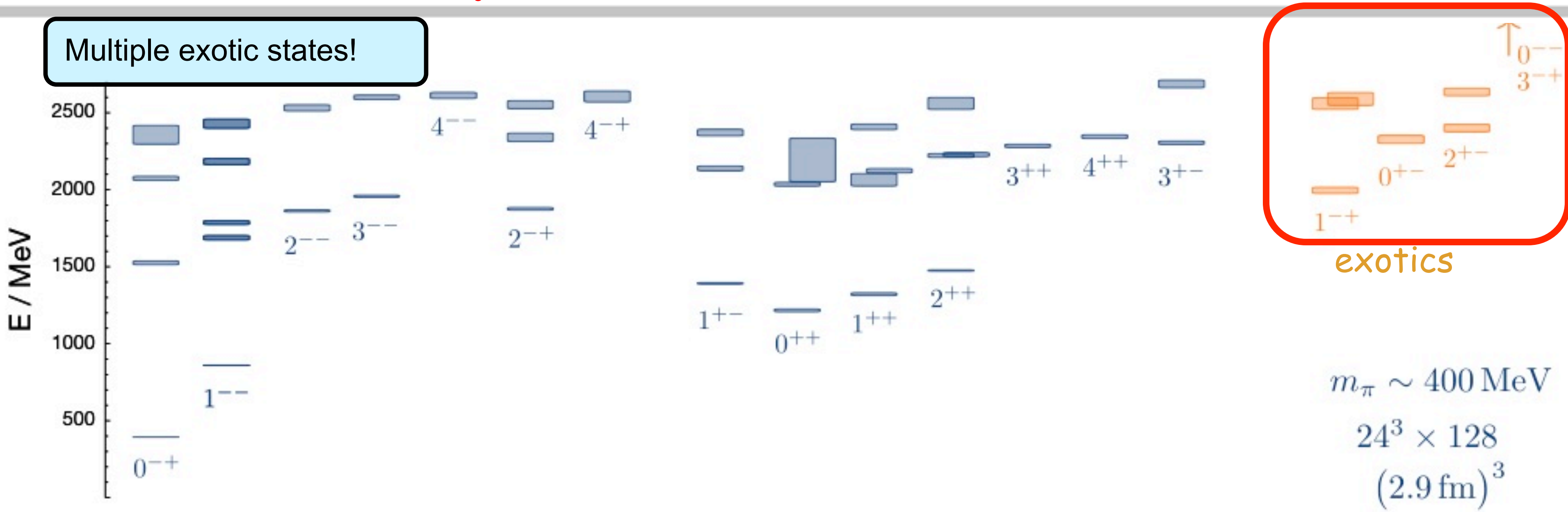
Expt exotic state controversial!!

Meson spectrum from lattice QCD

See patterns like $q\bar{q}$ quark model



Meson spectrum from lattice QCD



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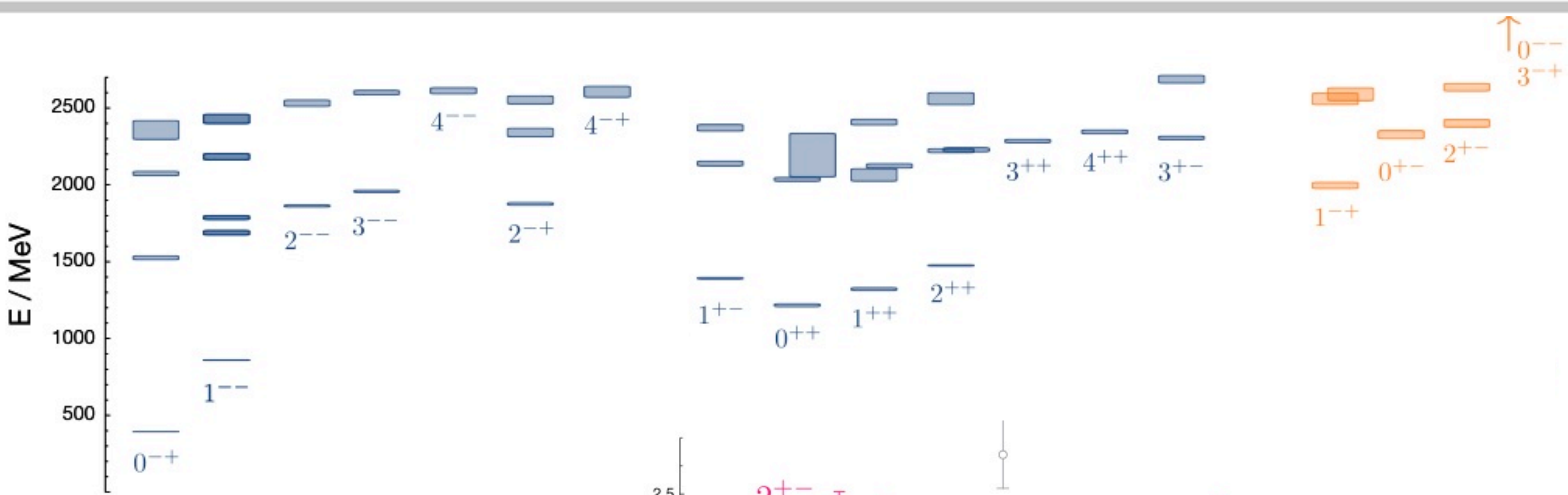
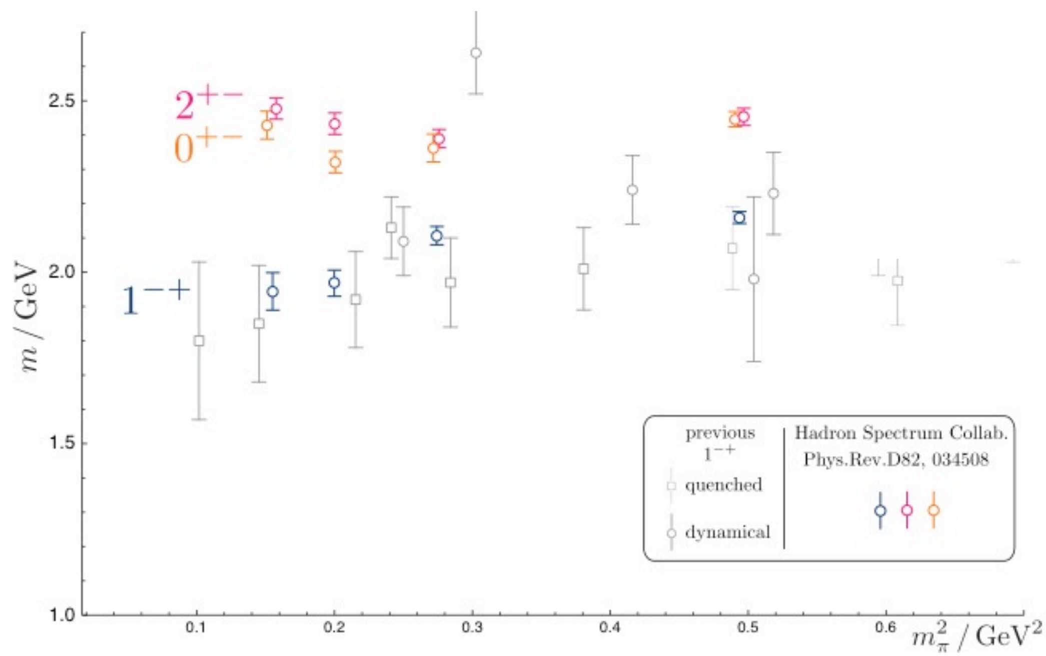
Meson spectrum from lattice QCD



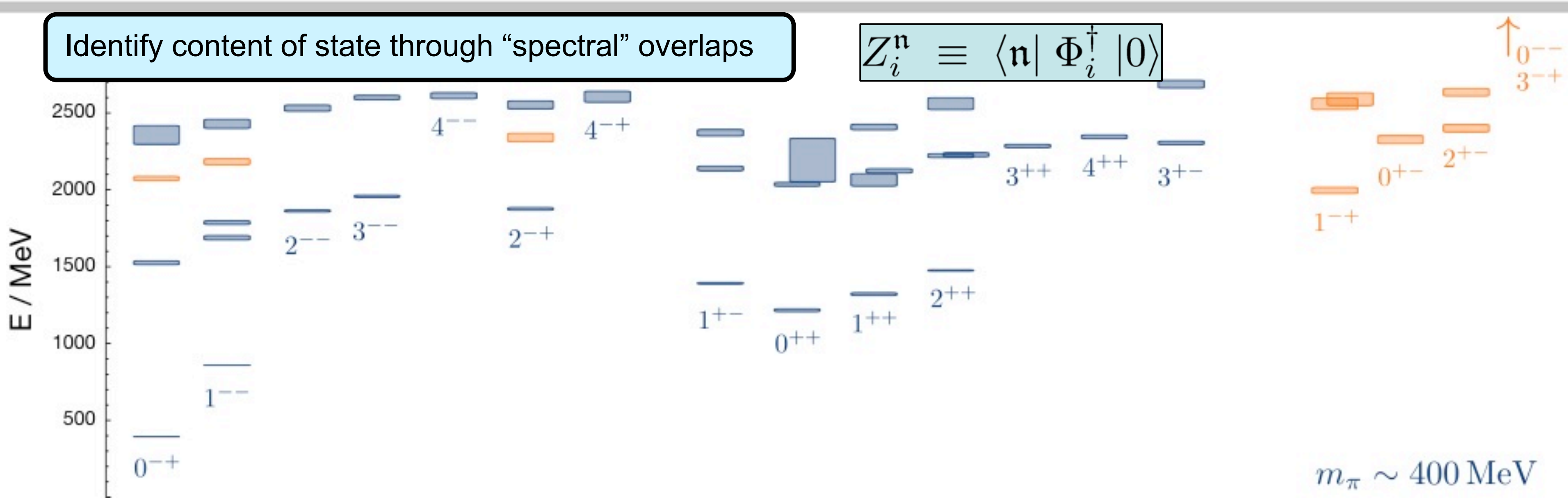


Suggests multiple exotic states within range of JLab 12GeV

Isovector hybrid mesons

Identify content of state through "spectral" overlaps

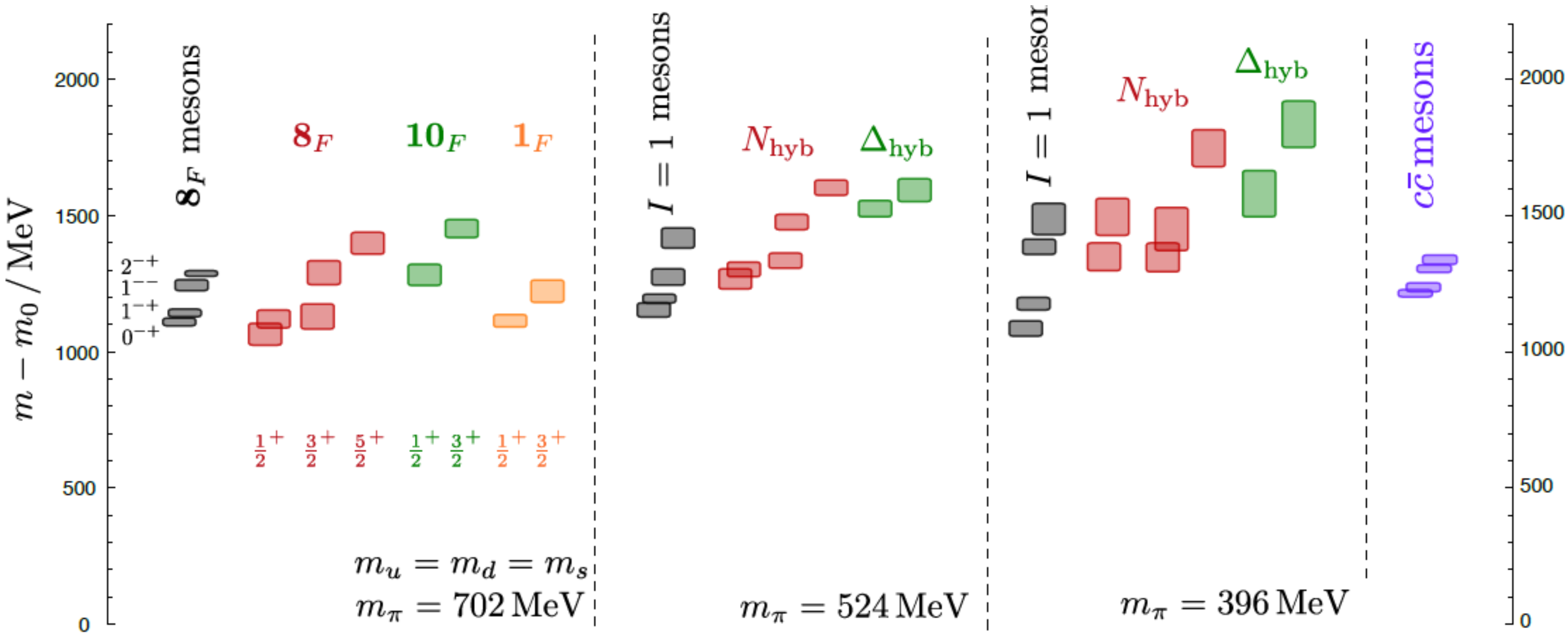
$$Z_i^{\mathfrak{n}} \equiv \langle \mathfrak{n} | \Phi_i^\dagger | 0 \rangle$$



Find significant gluonic contribution to some states

Hybrid hadrons

"subtract off" the quark mass



$$m_0 = \begin{cases} m_\rho & \text{light mesons} \\ m_N & \text{baryons} \\ m_{\eta_c} & \text{charmonium} \end{cases}$$

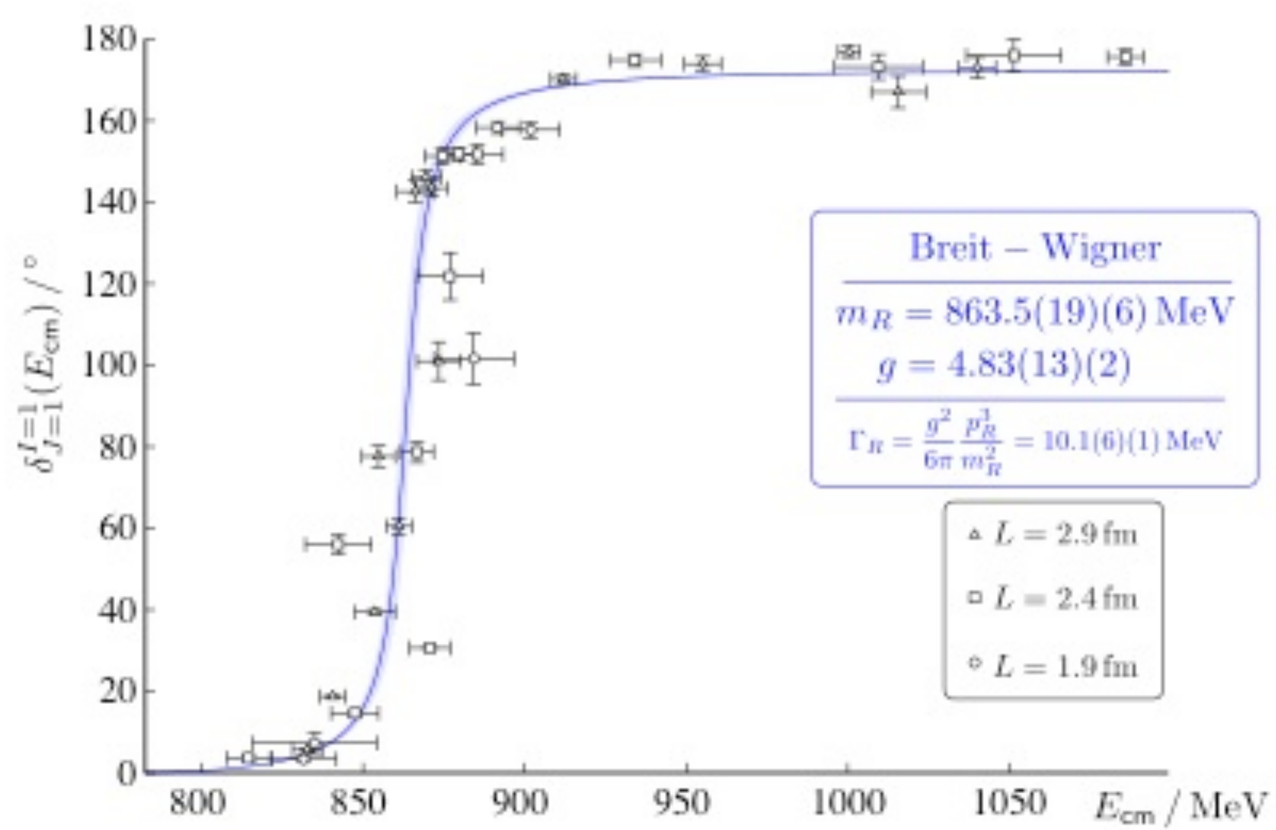
Appears to be a single scale for gluonic excitations **~ 1.2 to 1.4 GeV**

Gluonic excitation transforming like a color **octet** with **$J^{PC} = 1^{+-}$**

First foray - resonance determination

Isospin=1: ππ

$\pi\pi \to \rho \to \pi\pi$



Progress: now move on to the interesting cases!

Impact on experiment

arxiv:1208.1244

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

arxiv:1210.4508 - proposal to build Kaon particle ID chamber

A study of meson and baryon decays to strange final states with GlueX in Hall D

(A proposal to the 39th Jefferson Lab Program Advisory Committee)

M. Dugger,[1] B. Ritchie,[1] E. Anassontzis,[2] P. Ioannou,[2] C. Kourkoumeli,[2] G. Voulgaris,[2] N. Jarvis,[3] W. Levine,[3] P. Mattione,[3] C. A. Meyer,[3,*] R. Schumacher,[3] P. Collins,[4] F. Klein,[4] D. Sober,[4] D. Doughty,[5] A. Barnes,[6]

⋮

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 $q\bar{q}$ ($q = u$, d, or s) states coupled with a gluonic field. A thorough study of the hybrid spectrum, including the identification of the isovector triplet, with charges 0 and ±1, and both isoscalar members, $|s\bar{s}\rangle$ and $|u\bar{u}\rangle + |d\bar{d}\rangle$, for each predicted hybrid combination of J^{PC}, may only be achieved by conducting a systematic amplitude analysis of many different hadronic final states. We propose the development of a kaon identification system, supplementing the existing GlueX forward time-of-flight detector, in order to cleanly select meson and baryon decay channels that include kaons. Once this detector has been installed and commissioned, we plan to collect a total of 200 days of physics analysis data at an average intensity of 5×10^7 tagged photons on target per second. This data sample will provide an order of magnitude statistical improvement over the initial GlueX data set and, with the developed kaon identification system, a significant increase in the potential for GlueX to make key experimental advances in our knowledge of hybrid mesons and Ξ baryons.

Impact on experiment

arxiv:1212.4891 - science case for JLab Hall B 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 features LQCD exotic meson spectroscopy supporting JLab

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

USQCD Resource distribution

1 Jpsi = 1.2 GF

2011-2012	INCITE [with zero]	Cluster	GPU	Total (M-Jpsi)
Available(M-Jpsi)	87M	243M	318M	650M

2012-2013	INCITE [no zero]	Cluster	GPU	Total (M-Jpsi)
Available(M-Jpsi)	571M	283M	385M	1241M

2013-2014 [availability]	INCITE [no zero]	Cluster	GPU	BNL	Total (M-Jpsi)
Available(M-Jpsi)	550M	340M	646M	116M	1652M

Leadership resources crucial – partner to USQCD capacity resources