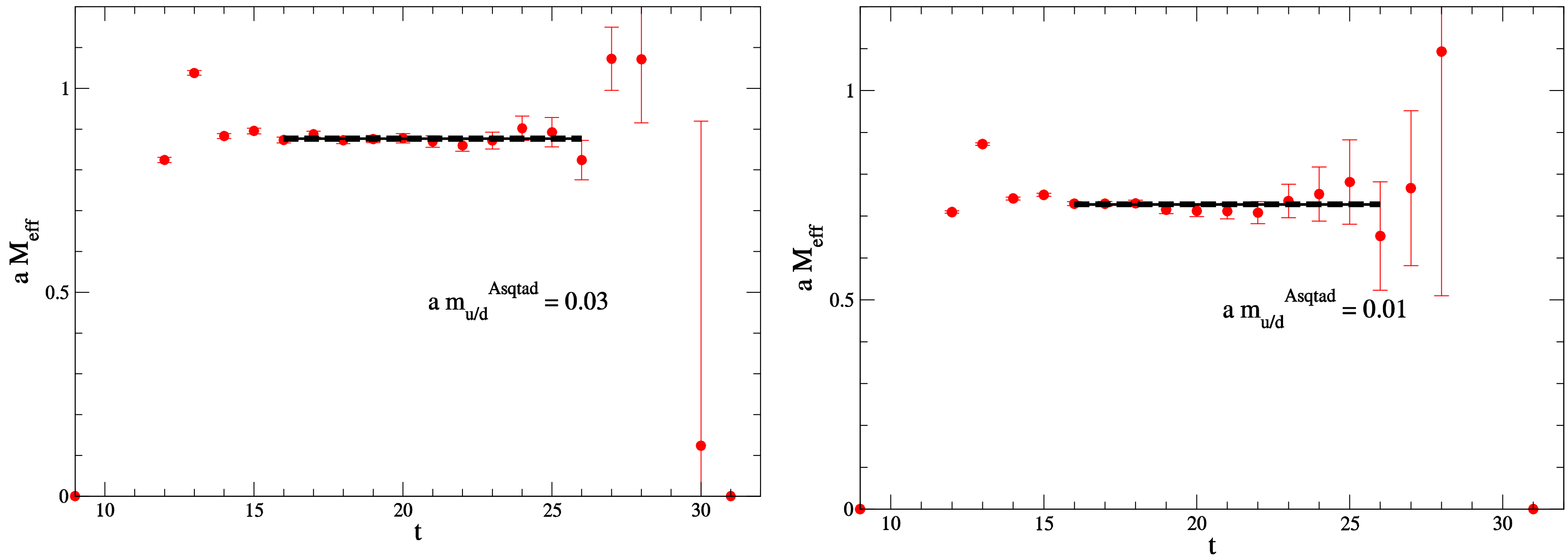
Lecture 2: Spectroscopy and Lattice QCD

- A spectrum recipe book
- Resonances
  - pure-gauge glueball spectrum
  - Spectrum of mesons and baryons
- Unstable Particles and Hadronic interactions

Effective Masses

- Effective mass provides visual tool for seeing domination by single state

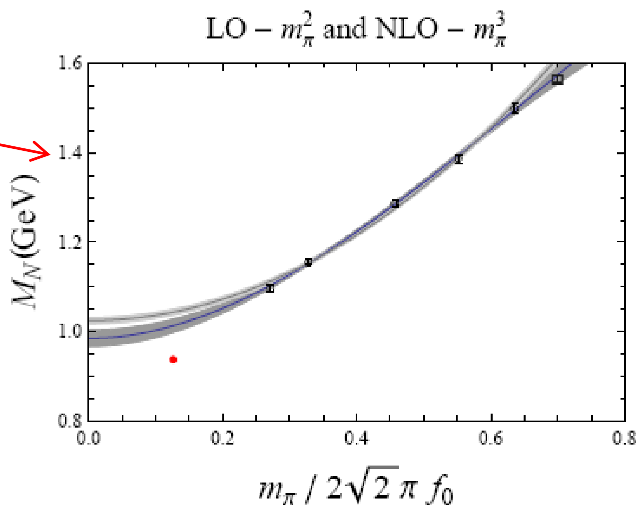


Decreasing pion mass

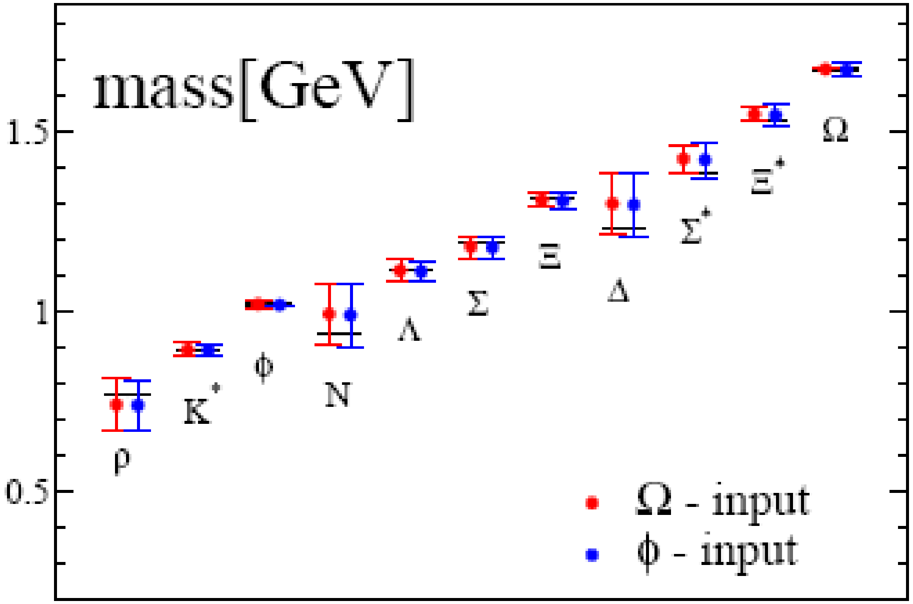
$$M_{\mathrm{eff}} = \ln C(t)/C(t+1)$$

Light-hadron Spectrum

LHPC/MILC, Preliminary



Benchmark of Lattice QCD

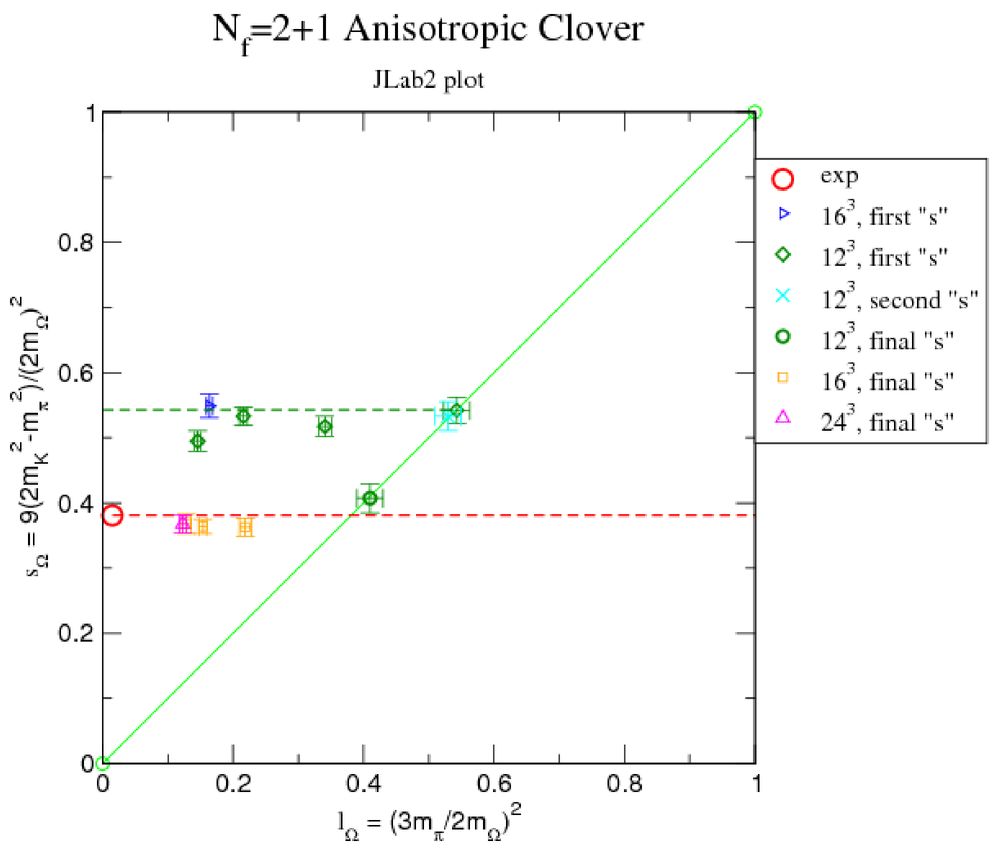


PACS-CS, arXiv:0710.3462

Setting Quark Masses

- **Non-perturbative determination of parameters of three-flavor anisotropic-clover action completed.**

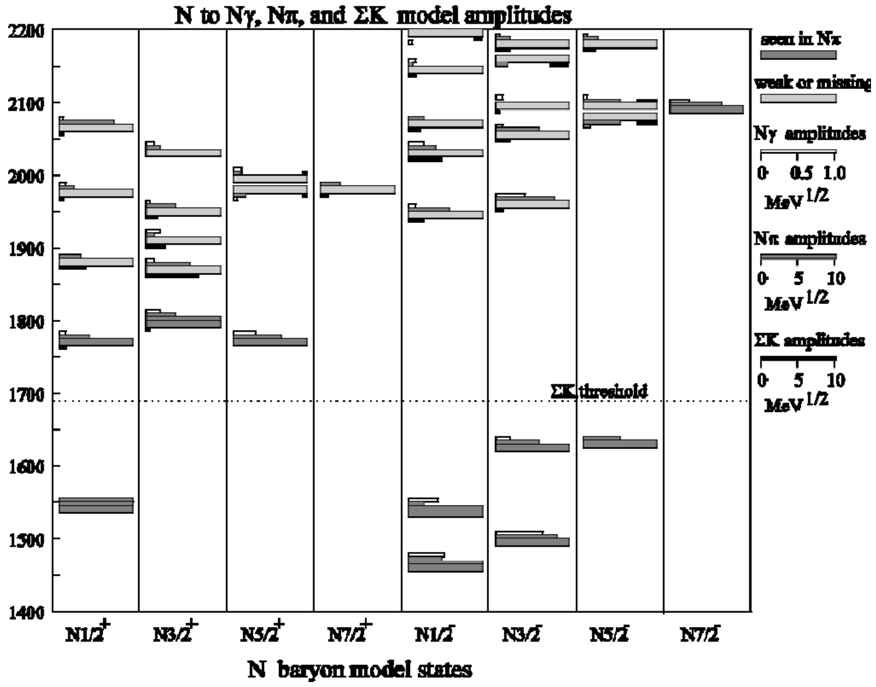
R.G. Edwards, B. Joo, H-W Lin, arXiv:0803.3960



- Improved prescription for setting of strange-quark mass and lattice spacing

Spectroscopy

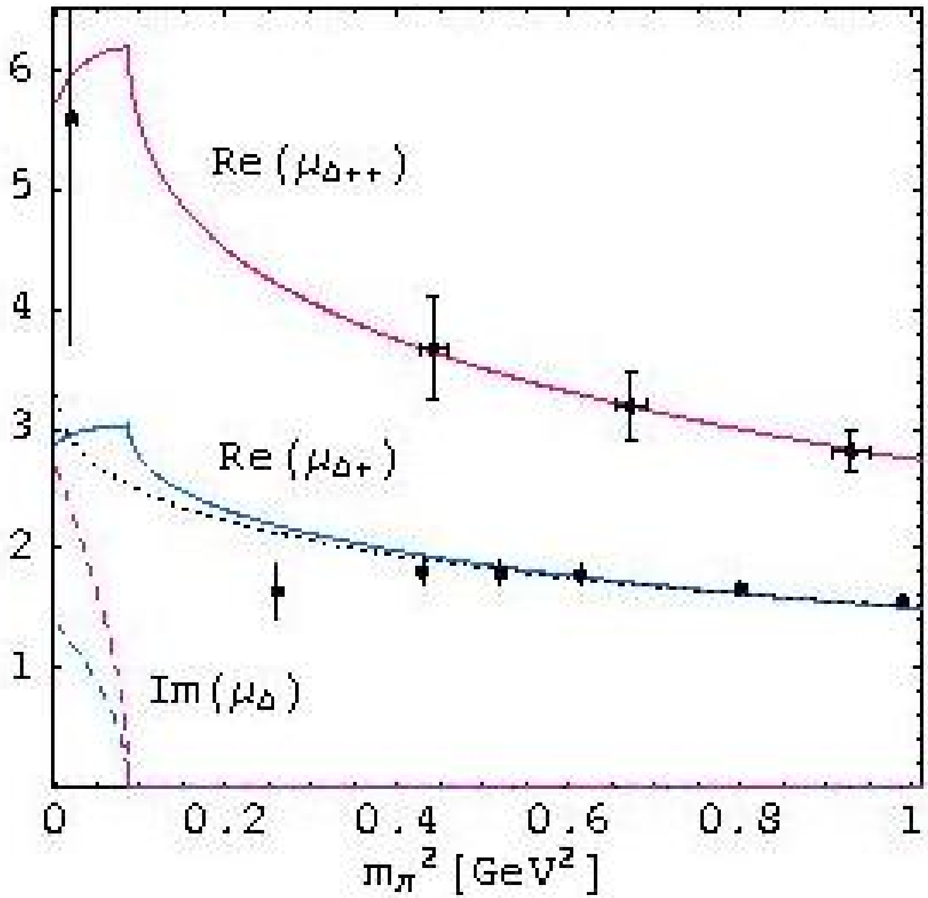
- Classic tool for gleaning information about *degrees of freedom of QCD*
- Experimental and *ab initio* N* and Exotic programs aim at discovering effective degrees of freedom of QCD, and resolving competing low-energy models:



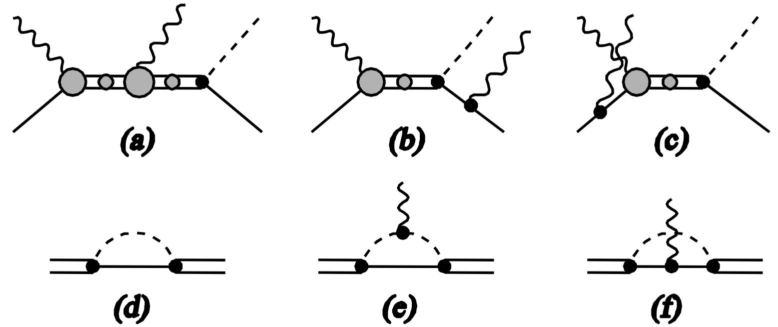
Capstick and Roberts, PRD58 (1998) 074011

Delta

One baryon resonance studied for many years…..



Lattice points from
Leinweber (1992)
Cloet,Leinweber,Thomas (2003)
Lee *et.al*. (2004)

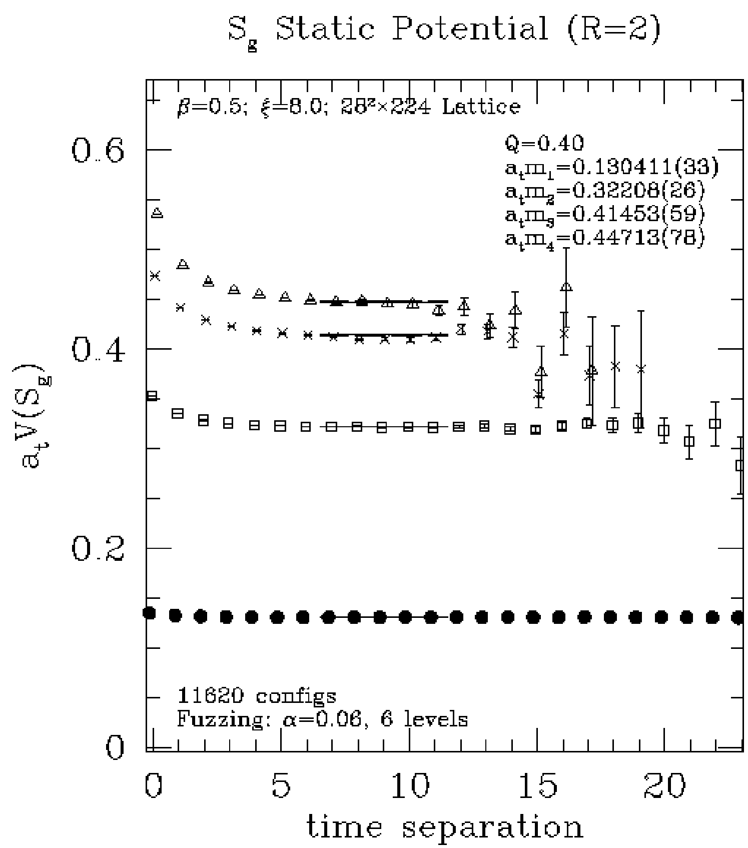


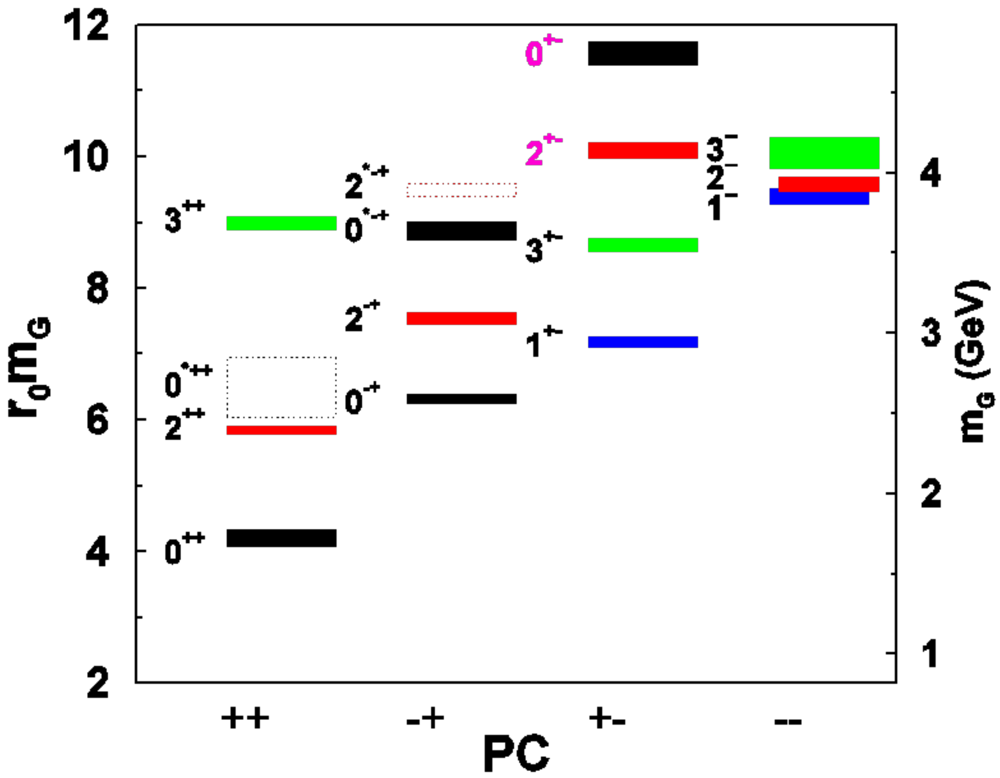
Chiral calculations

Pascalutsa,
Vanderhaeghen (2004)

Thomas, Young (…)

Variational Method: Glueballs





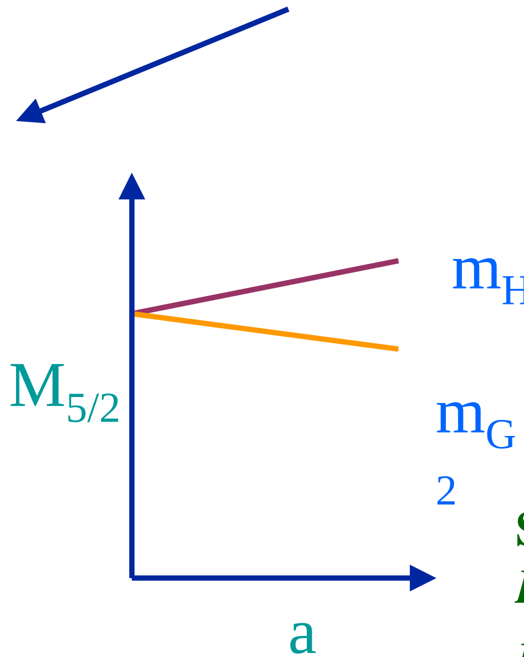
$$E^i_{\text{eff}} = \ln \lambda_i(t)/\lambda_i(t+1)$$

Morningstar and Peardon, PRD60, 034509

Lattice "PWA"

- Do not have full rotational symmetry: $J, J_z \rightarrow \Lambda, \lambda$
- Has 48 elements
- Contains irreducible representations of O, together with 3 spinor irreps G_1, G_2, H: R.C.Johnson, PLB114, 147 (82)

J	$n^J_{G_1}$	$n^J_{G_2}$	n^J_H
$\frac{1}{2}$	1	0	0
$\frac{3}{2}$	0	0	1
$\frac{5}{2}$	0	1	1
$\frac{7}{2}$	1	1	1
$\frac{9}{2}$	1	0	2
$\frac{11}{2}$	1	1	2
$\frac{13}{2}$	1	2	2
$\frac{15}{2}$	1	1	3
$\frac{17}{2}$	2	1	3

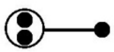
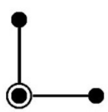
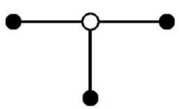
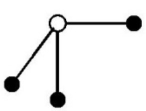


Spins identified from degeneracies in contiuum limit

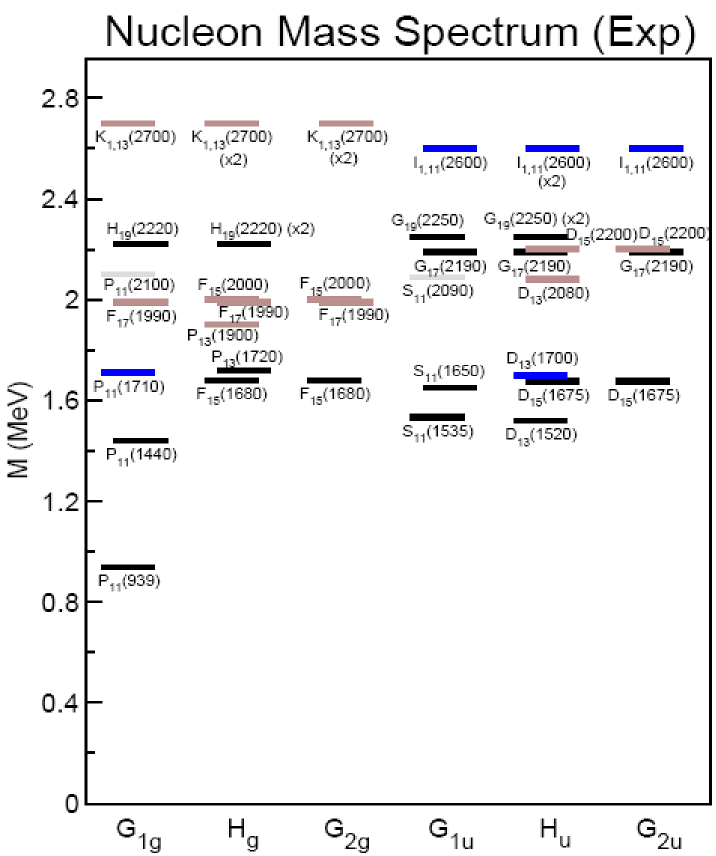
S. Basak *et al.*, *PRD72:074501,2005*

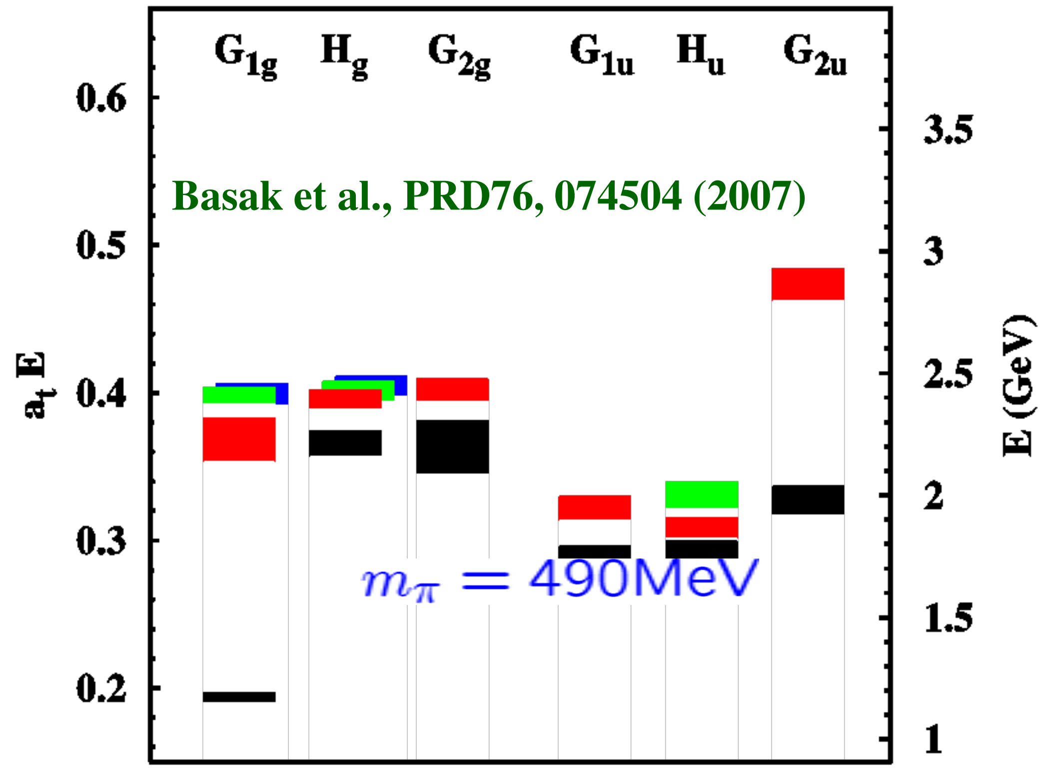
PRD72:094506,2005

Spatial Structures

Illustration	Name	Explicit form ($\|i\| \neq \|j\| \neq \|k\|$)
	single-site	$\phi^F_{ABC}\ \varepsilon_{abc}\ \tilde{\psi}_{Aa\alpha}\ \tilde{\psi}_{Bb\beta}\ \tilde{\psi}_{Cc\gamma}$
	singly-displaced	$\phi^F_{ABC}\ \varepsilon_{abc}\ \tilde{\psi}_{Aa\alpha}\ \tilde{\psi}_{Bb\beta}\ \left(\tilde{D}^{(p)}_j \tilde{\psi}\right)_{Cc\gamma}$
	doubly-displaced-I	$\phi^F_{ABC}\ \varepsilon_{abc}\ \tilde{\psi}_{Aa\alpha}\ \left(\tilde{D}^{(p)}_{-j} \tilde{\psi}\right)_{Bb\beta}\ \left(\tilde{D}^{(p)}_j \tilde{\psi}\right)_{Cc\gamma}$
	doubly-displaced-L	$\phi^F_{ABC}\ \varepsilon_{abc}\ \tilde{\psi}_{Aa\alpha}\ \left(\tilde{D}^{(p)}_j \tilde{\psi}\right)_{Bb\beta}\ \left(\tilde{D}^{(p)}_k \tilde{\psi}\right)_{Cc\gamma}$
	triply-displaced-T	$\phi^F_{ABC}\ \varepsilon_{abc}\ \left(\tilde{D}^{(p)}_{-j} \tilde{\psi}\right)_{Aa\alpha}\left(\tilde{D}^{(p)}_j \tilde{\psi}\right)_{Bb\beta}\left(\tilde{D}^{(p)}_k \tilde{\psi}\right)_{Cc\gamma}$
	triply-displaced-O	$\phi^F_{ABC}\ \varepsilon_{abc}\ \left(\tilde{D}^{(p)}_i \tilde{\psi}\right)_{Aa\alpha}\left(\tilde{D}^{(p)}_j \tilde{\psi}\right)_{Bb\beta}\left(\tilde{D}^{(p)}_k \tilde{\psi}\right)_{Cc\gamma}$

Quenched Baryon Spectrum



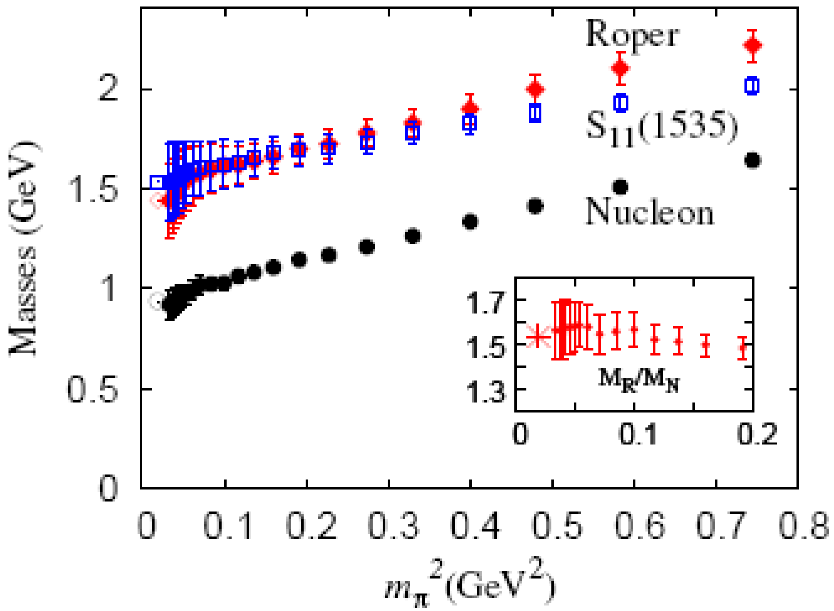


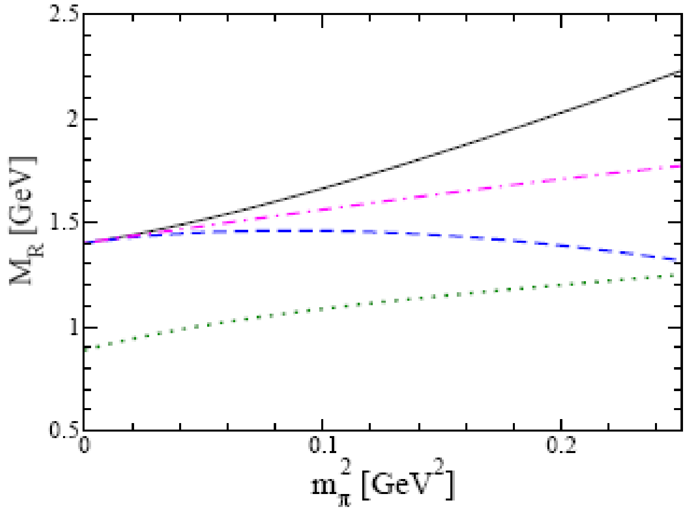
2-flavour calculation in progress: *Eric Engelson*

Roper Resonance

- **Bayesian statistics and constrained curve fitting**
- **Used simple three-quark operator**
-

Dong et al., PLB605, 137 (2005)

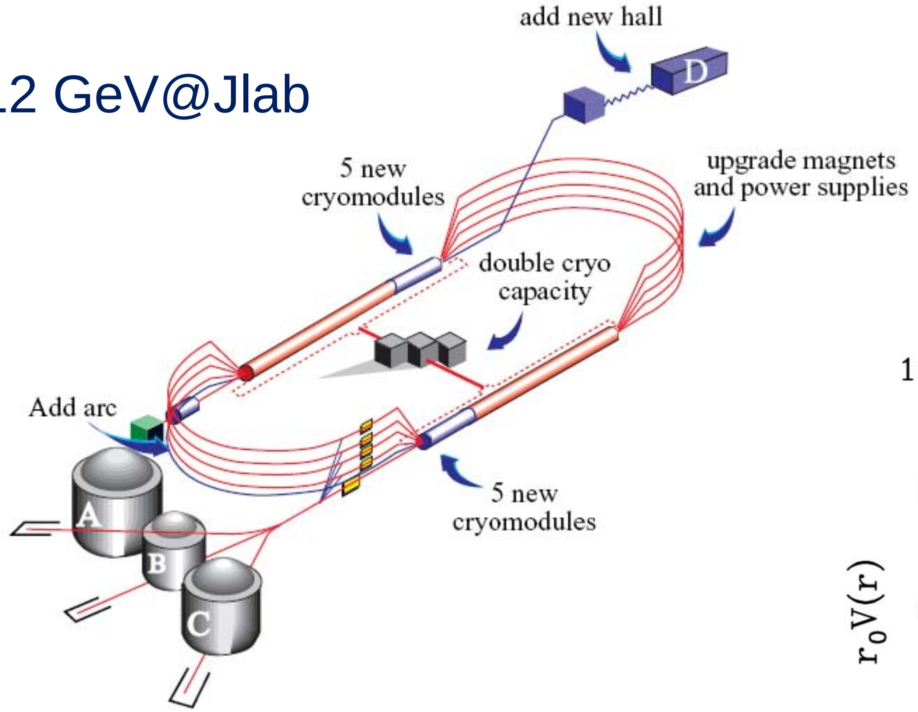




Borasoy et al., Phys.Lett. B641 (2006) 294-300

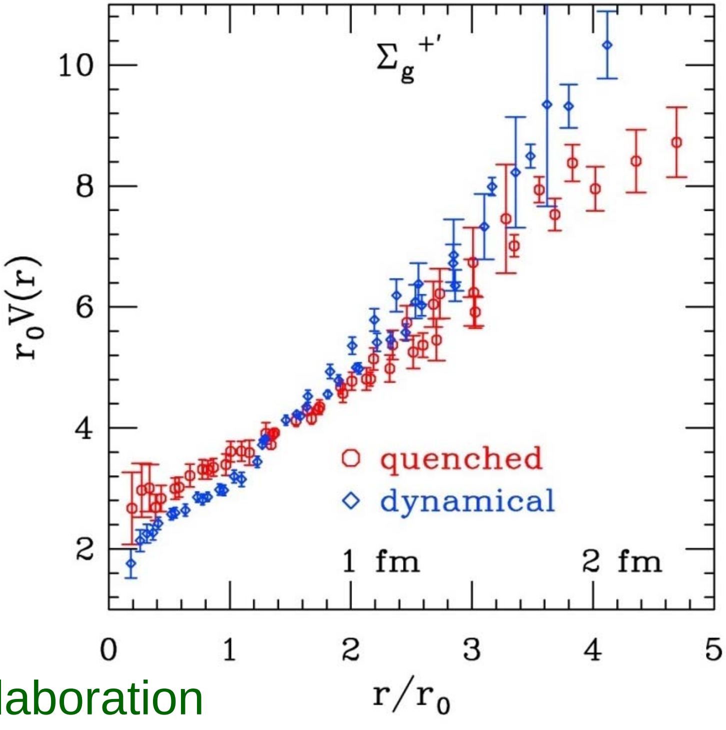
Meson Spectroscopy

12 GeV@Jlab



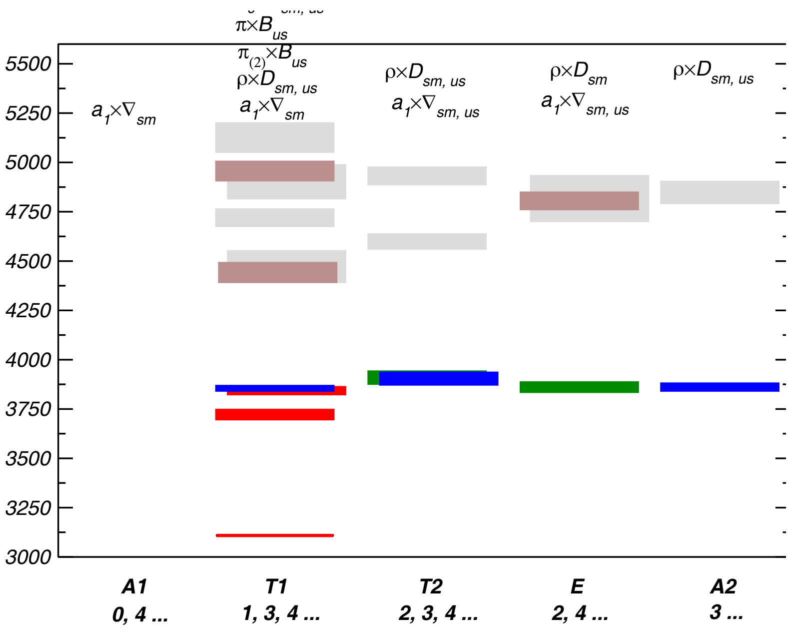
1 GeV Excitation Energy associated with excited string

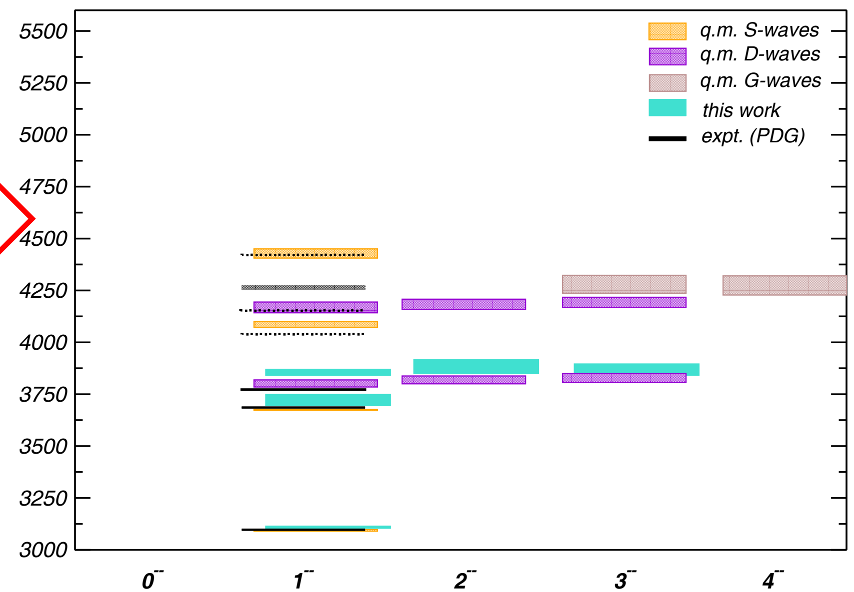
- 1^{-+} lightest hybrid



MILC Collaboration

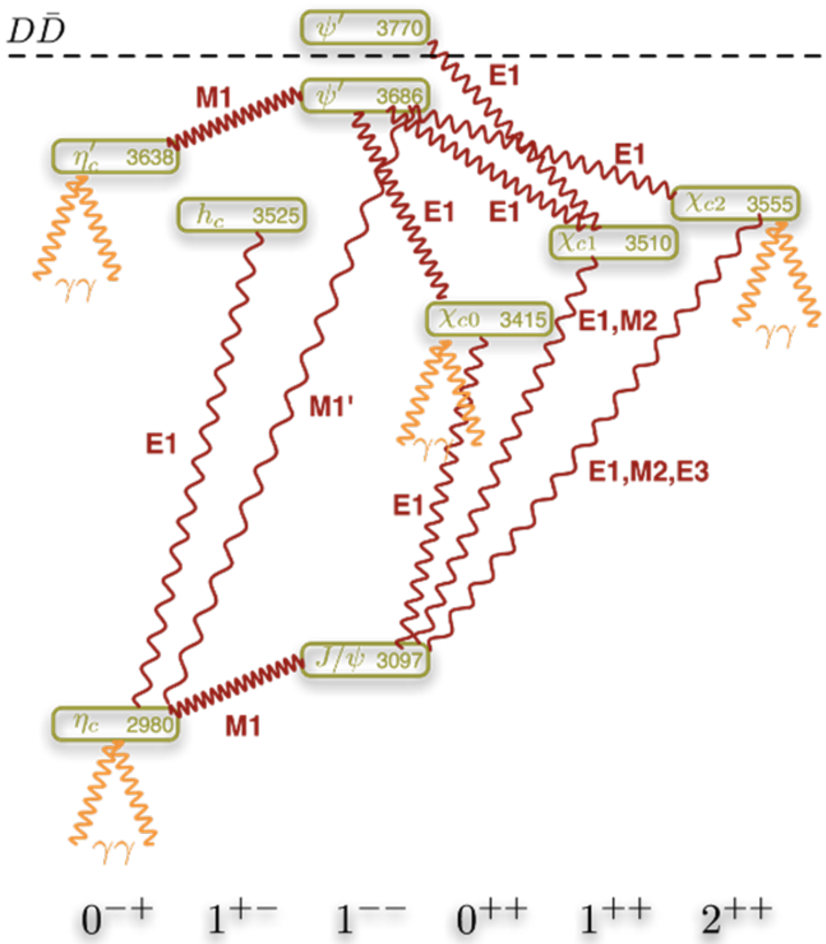
Meson Spectroscopy: Charmonium



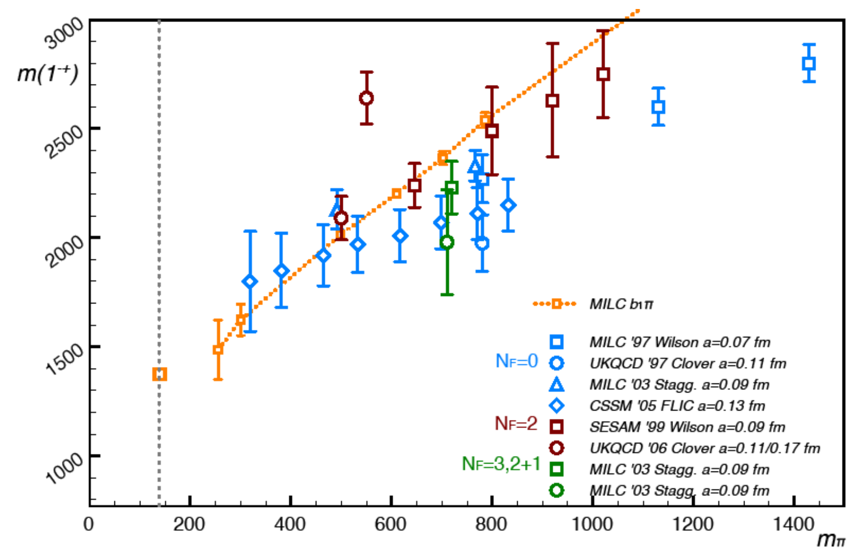


Dudek, Edwards, Mathur, DGR, PRD77, 034501 (2008)

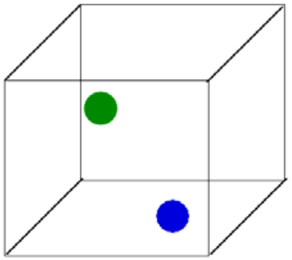
Unstable Resonances



Charmonium: many states below threshold

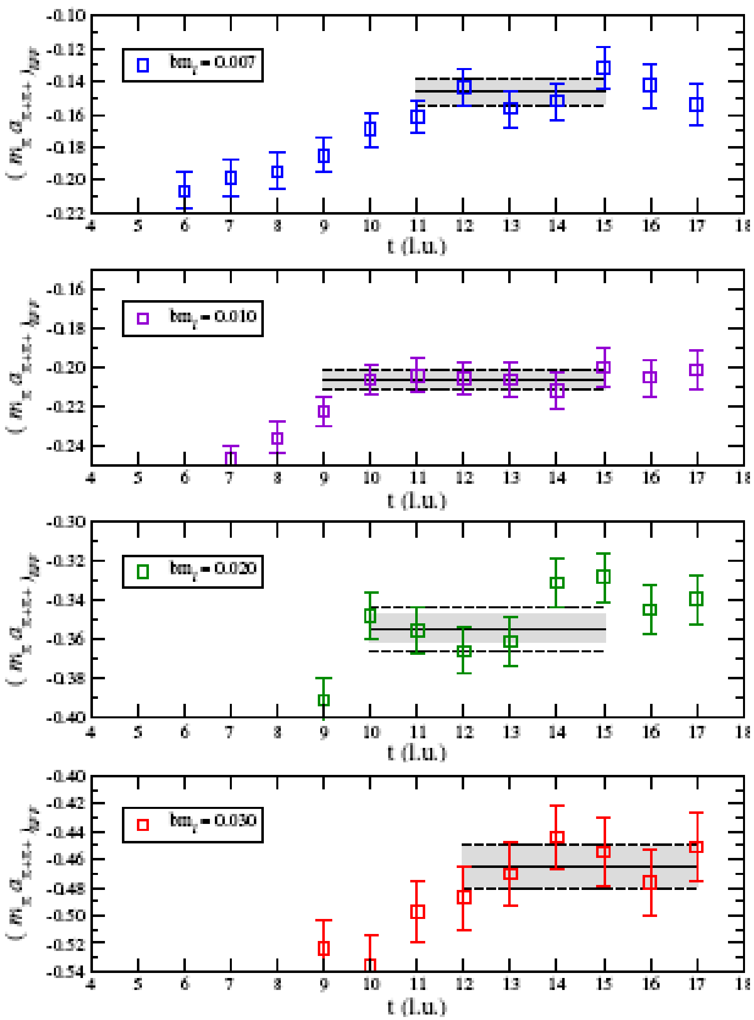


Unstable Particles



- Maiani-Test Theorem
- computations done in a periodic box
  - momenta quantized
  - discrete energy spectrum of stationary states → single hadron, 2 hadron,…
- scattering phase shifts → resonance masses, widths (in principle) deduced from finite-box spectrum
  - B. DeWitt, PR **103**, 1565 (1956) (sphere)
  - M. Luscher, NPB**364**, 237 (1991) (cube)
- Two-particle states and resonances identified by examining behaviour of energies in finite volume
  - **Resonances with milder volume dependence**

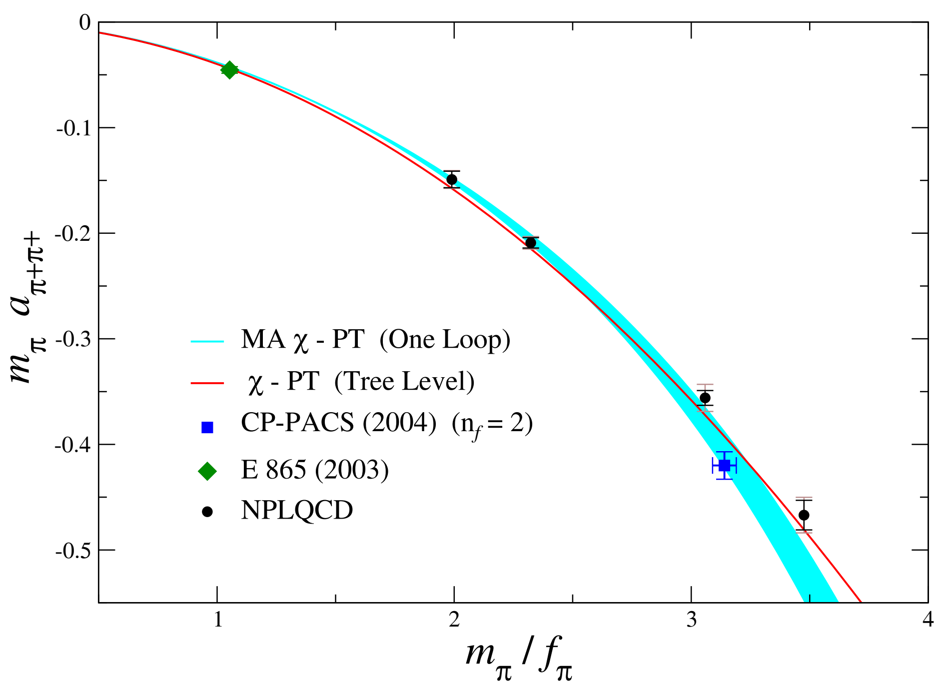
I=2 π-π Scattering Length

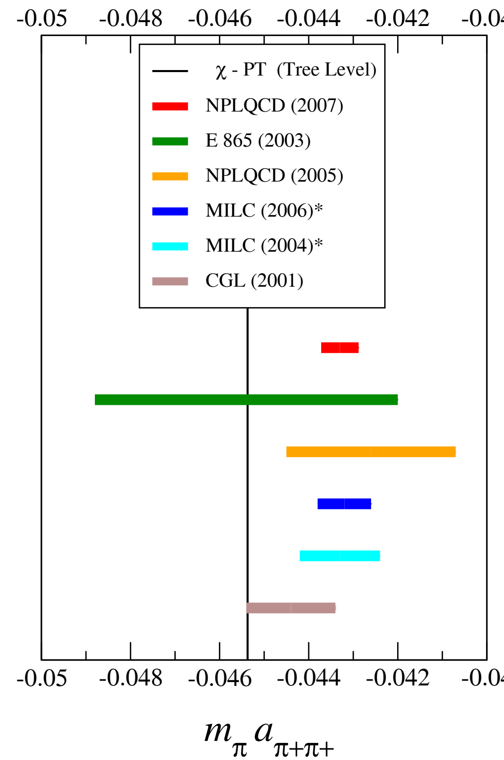


See NPLQCD Review, arXiv:0805.4629

Hadronic Interactions

- **NPLQCD: Amalgam of Lattice QCD + Effective Theory**





Review Article - arXiv:0805.4629

Width of Rho

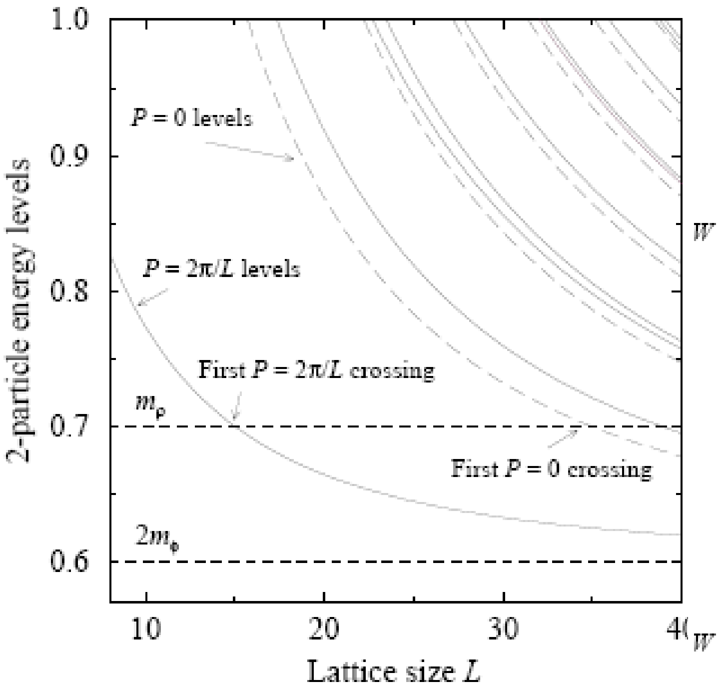
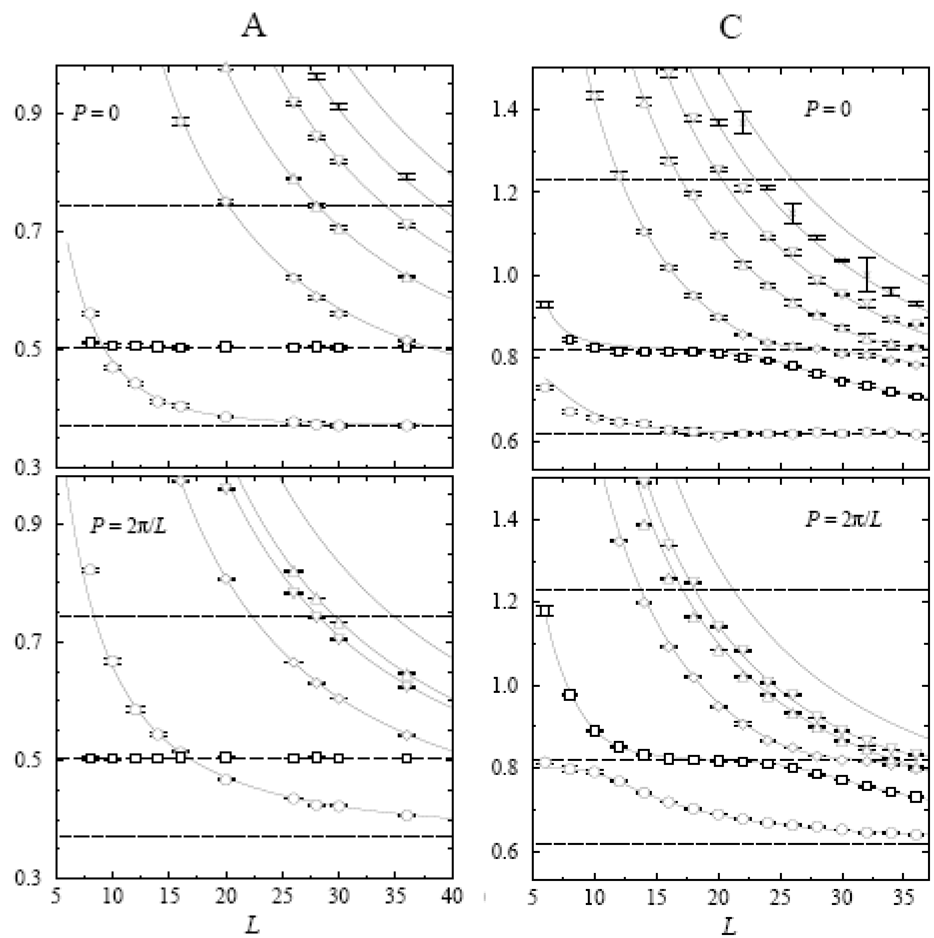


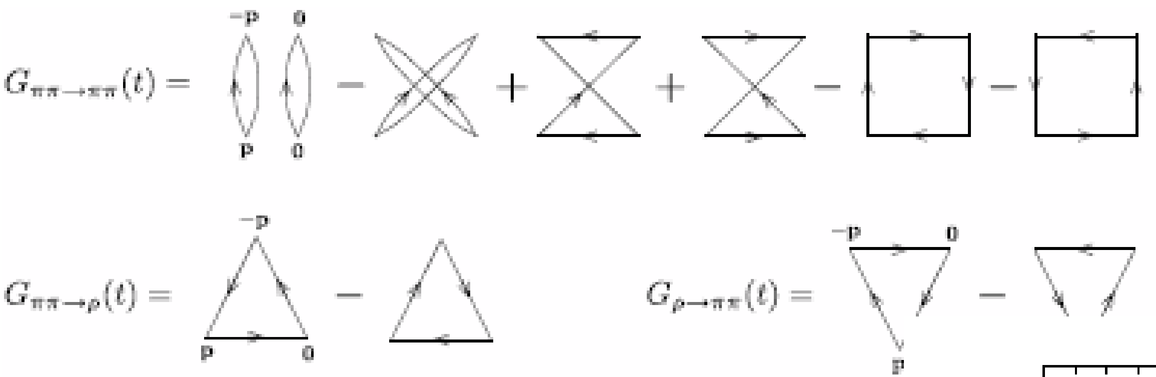
Figure 1. The free particle center of mass energ
levels for the $\vec{P} = 0$ (dashed lines) and $\vec{P} = 2\pi/$
(solid lines) sectors.



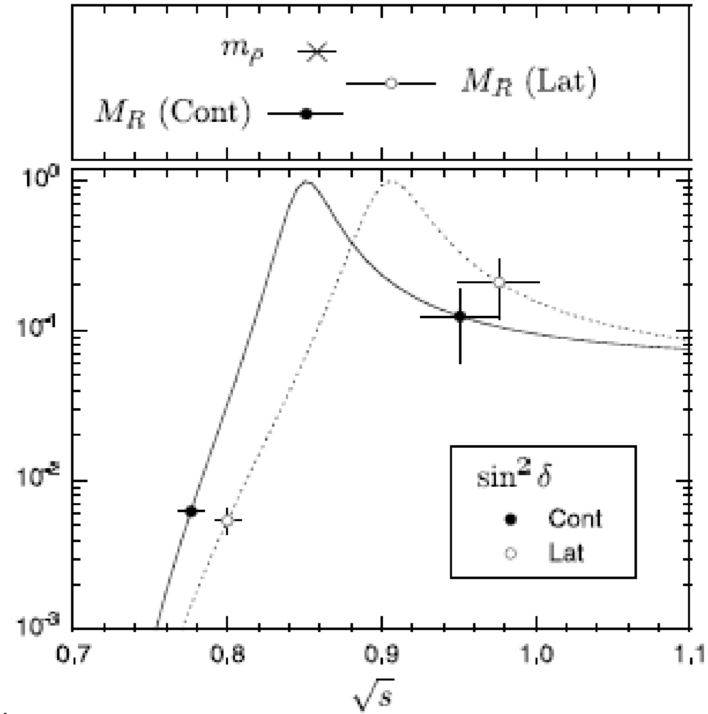
Gottlieb and Rummukainan

Phases shifts related to avoided level crossings.

Width of ρ

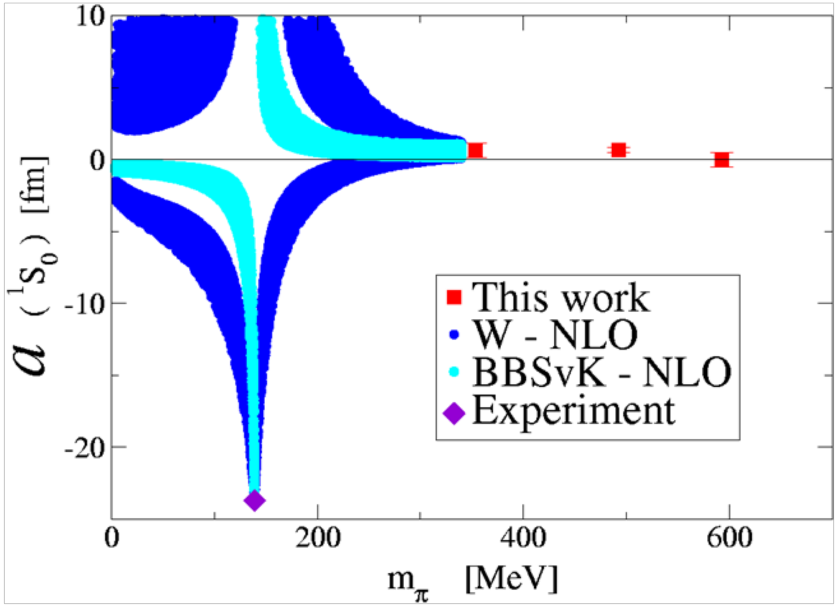


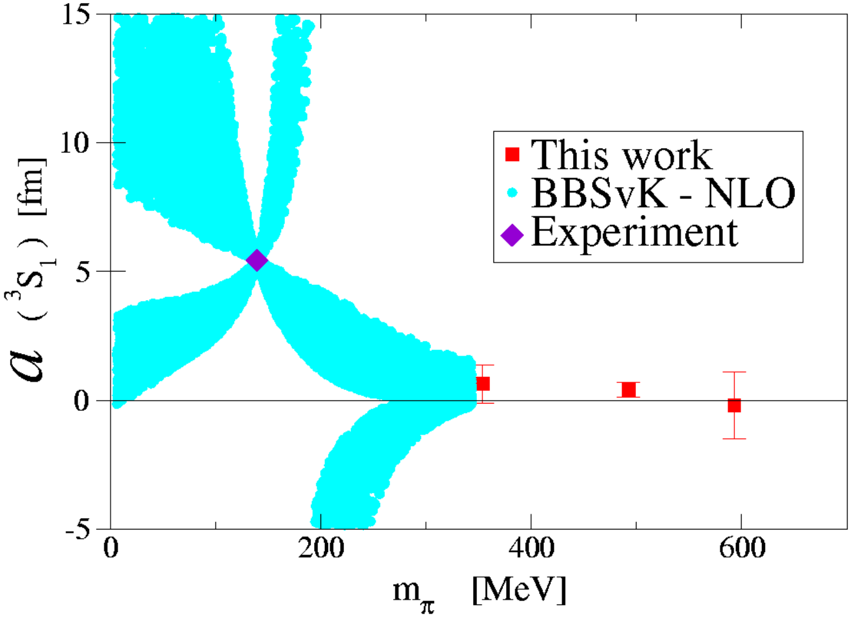
CP-PACS, arXiv:0708.3705



NN Scattering

NPLQCD: S. Beane, P. Bedaque, K. Orginos, M. Savage ; PRL97, 012001 (2006))



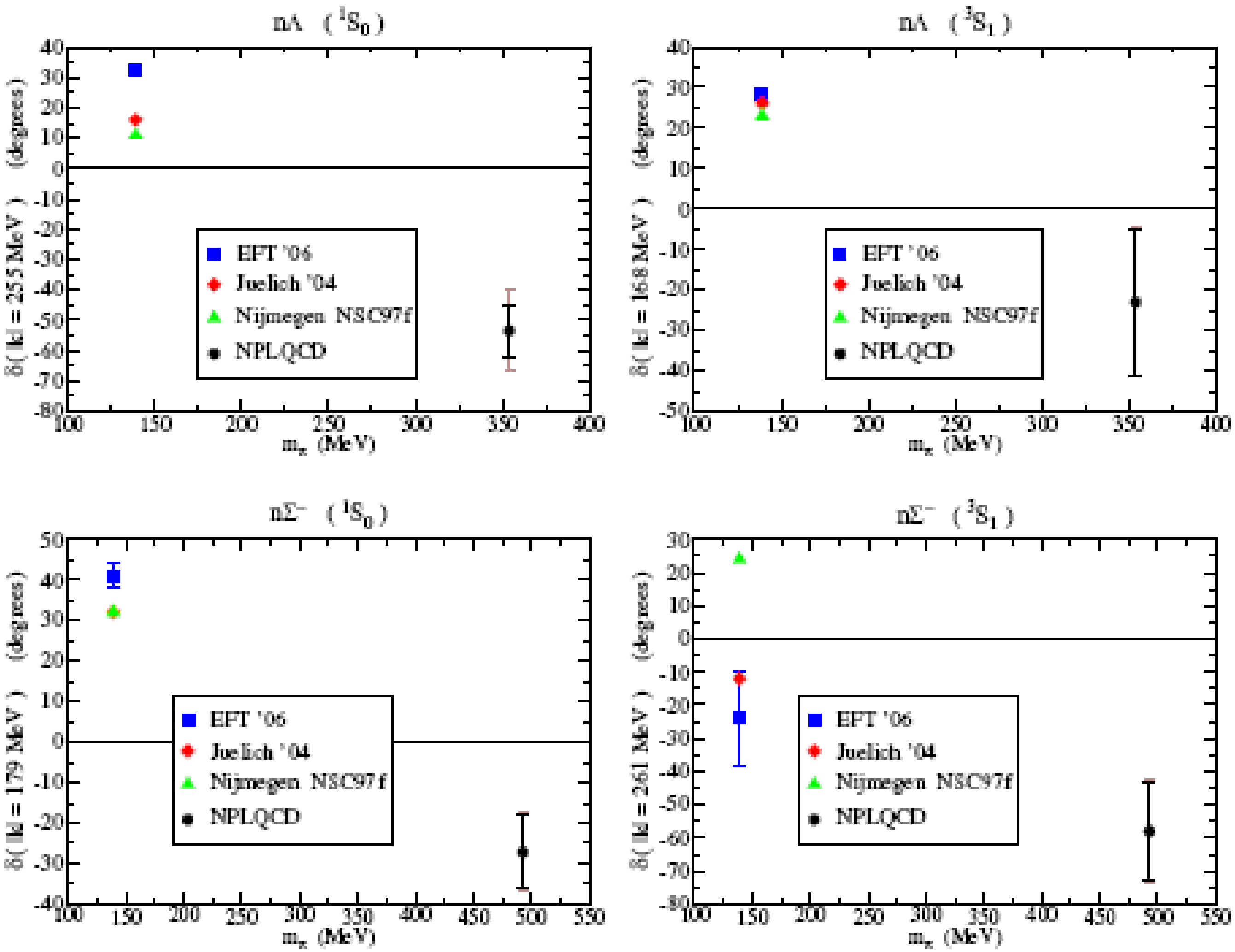


Calculations at lower m_π to constrain scattering length at physical quark masses

$^1S_0$: pp , pn , nn

$^3S_1$-$^3D_1$: pn : deuteron

YN Interaction



Spectroscopy – Outlook

- **Anisotropic *$N_f = 2$* Wilson and *$N_f = 2 + 1$* Clover gauge configurations designed for spectroscopy: 2007 INCITE, 2008 INCITE, LQCD**
- **Investigate new methods of computing hadron correlation functions: all-to-all propagators and eigenvector methods – *multi-particle states***
- **Physics goals**
  - **Low-lying baryon spectrum for states composed of u/d and s quarks, with scattering states delineated**
  - **Low-lying exotic meson spectrum; first calculation of photo-couplings involving conventional and exotic mesons**

L_s(fm)	1.92fm	2.4fm	2.9fm	3.8fm
m_π(MeV)	$16^3 \times 128$	$20^3 \times 128$	$24^3 \times 128$	$32^3 \times 128$
875	10k, JLab[0.20M](8.4)			
580	20k, JLab[0.48M](5.6)			
400		20k, JLab[1.35M](4.8)		
315		30k, JLab[2.35M](3.8)	30k, ORNL[4.66M](4.5)	30k, X[13.7M](6.0)
250			30k, TACC[5.44M](3.6)	30k, ?[16.0M](4.8)

Summary

- Low-lying light hadron spectrum is benchmark calculation of LQCD
- LQCD can also compute the masses of excitations of the theory, and in principle their widths
- Exciting program of computations that are tuned to the experimental program

BACKUP

HADRON SPECTRUM

- University of Pacific
  - J Juge
- JLAB
  - S Cohen
  - J Dudek
  - R Edwards
  - B Joo
  - H-W Lin
  - D Richards
- BNL
  - A Lichtl
- Yale
  - G Fleming
- CMU
  - J Bulava
  - J Foley
  - C Morningstar
- UMD
  - E Engelson
  - S Wallace
- Tata (India)
  - N Mathur

Spectroscopy - Roadmap

- First stage: a ~ 0.12 fm, spatial extents to 4 fm, pion masses to 220 MeV
  - –Spectrum of exotic mesons
  - –First predictions of π_1 photocoupling
  - –Emergence of resonances above two-particle threshold
- Second stage: two lattices spacings, pion masses to 180 MeV
  - –Spectrum in continuum limit, with spins identified
  - –Transition form factors between low-lying states
- Culmination: Goto a=0.10fm computation at two volumes at physical pion mass
  - –Computation of spectrum for direct comparison with experiment
  - –Identification of effective degrees of freedom in spectrum

* Resources: USQCD clusters, ORNL/Cray XT4, ANL BG/P, NSF centers, NSF Petaflop machine (NCSA-2011)/proposal