meson spectroscopy & lattice QCD

not a review !

phenomenology ?

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work under the auspices of the
Hadron Spectrum Collaboration

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on the results I'll present:

Jozef Dudek
Robert Edwards
Mike Peardon
David Richards
Christopher Thomas

meson spectroscopy

ideally want to explore all aspects of the meson spectrum

resonance properties (mass, widths)

resonance couplings to electromagnetic and weak couplings

lattice QCD offers a somewhat controlled approximation to QCD and the possibility of explicit calculations

current reality

calculations with quarks heavier than in nature

extracting many excited states only recently possible

true 'resonance' physics only recently possible

- ***excited states***
- ***phenomenology & interpretation***
- ***'resonances'***
- ***coupling to photons***

spectrum from LQCD

LQCD offers a way to numerically approximately compute QCD correlation functions

e.g. a pseudoscalar two-point function

$$C_{\gamma_5\gamma_5}(t) = \langle 0 | \sum_{\vec{x}} \bar{\psi}(\vec{x},t)\gamma_5\psi(\vec{x},t) \cdot \sum_{\vec{y}} \bar{\psi}(\vec{y},0)\gamma_5\psi(\vec{y},0) | 0 \rangle$$

general two-point function

$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t) \cdot \mathcal{O}_j(0) | 0 \rangle \qquad \mathcal{O} = f(\psi, \bar{\psi}, A_\mu)$$

if the operator has meson quantum numbers then it can be that

$\langle M_{\mathfrak{n}} | \mathcal{O}_i(0) | 0 \rangle$ takes a non-zero value for various mesons ***M_n***

and hence we can show that

$$C_{ij}(t) = \sum_{\mathfrak{n}} \langle 0 | \mathcal{O}_i(0) | M_{\mathfrak{n}} \rangle \langle M_{\mathfrak{n}} | \mathcal{O}_j(0) | 0 \rangle e^{-m_{\mathfrak{n}} t}$$

$$C_{ij}(t) = \sum_{\mathfrak{n}} Z_i^{\mathfrak{n}} Z_j^{\mathfrak{n}*} e^{-m_{\mathfrak{n}} t}$$

spectrum from LQCD

$$C_{ij}(t) = \sum_{\mathfrak{n}} Z_i^{\mathfrak{n}} Z_j^{\mathfrak{n}*} e^{-m_{\mathfrak{n}} t}$$

so in principle the entire spectrum of QCD with the right quantum numbers is in this correlator

but some states might not overlap well with the operator used

and fitting to a sum of exponentials is ***very*** unstable

a smart solution is to use a basis of several operators, $\mathcal{O}_i = \{\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3 \ldots\}$

& form a correlator matrix, $C_{ij}(t)$

the spectrum can be extracted from this by a ***variational procedure***

corresponds to solution of a certain linear algebra problem

think of Rayleigh-Ritz method in quantum mechanics, it's very similar

spectrum from LQCD

each operator will have different 'overlap' on to the tower of states

some linear combination of the operators is optimal for a certain state

$$\Omega_{\mathfrak{n}} = v_1^{\mathfrak{n}} \mathcal{O}_1 + v_2^{\mathfrak{n}} \mathcal{O}_2 + \ldots$$

this is what is provided by the variational method solution, along with the mass spectrum

derivative-based ops

we cooked up a very simple, but versatile operator set:

form operators which in the continuum limit look like only a single spin

$$\overline{\psi}\Gamma\psi$$ ***J = 0,1***

covariant derivatives are ideal to go beyond this, e.g.

$$\langle 1, m_1; 1, m_2 | J, m \rangle \, \overline{\psi}\Gamma_{m_1} \overleftrightarrow{D}_{m_2} \psi$$ ***J = 0,1,2***

use simple ***SO(3)*** Clebsch-Gordan coefficients

at two derivatives

$$\langle 1, m_1; J_D, m_D | J, m \rangle \langle 1, m_2; 1, m_3 | J_D, m_D \rangle \overline{\psi}\Gamma_{m_1} \overleftrightarrow{D}_{m_2} \overleftrightarrow{D}_{m_3} \psi$$ ***J = 0,1,2,3***

can extend to as many derivatives as you like

our patience ran out at three derivatives

lattice symmetries

in fact the cubic lattice we use does not have the full rotational symmetry

we have to jump through numerous hoops to account for this

consider those hoops jumped through - i'll try to hide these complications from you

explicit computation

3-flavour degenerate lattices (***m_π ~ 700 MeV***)

16^3 / ***20^3*** anisotropic lattices, ***a_s ~ 0.12 fm***, ***a_t^{-1} ~ 5.6 GeV***

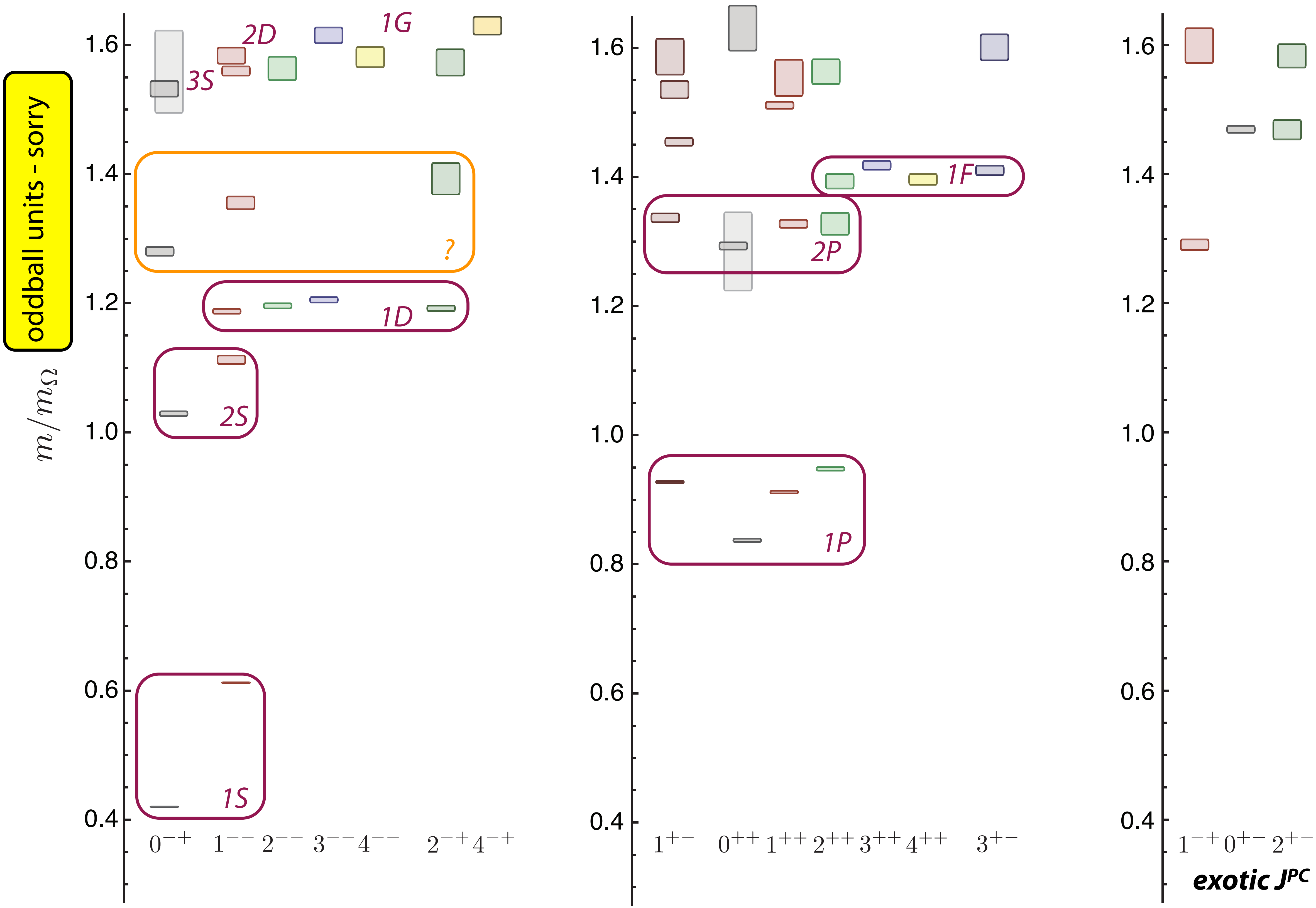
connected correlators - "isovector" (octet of ***$SU(3)_F$***)

distillation technology for correlator construction

up to three derivatives in the op. construction

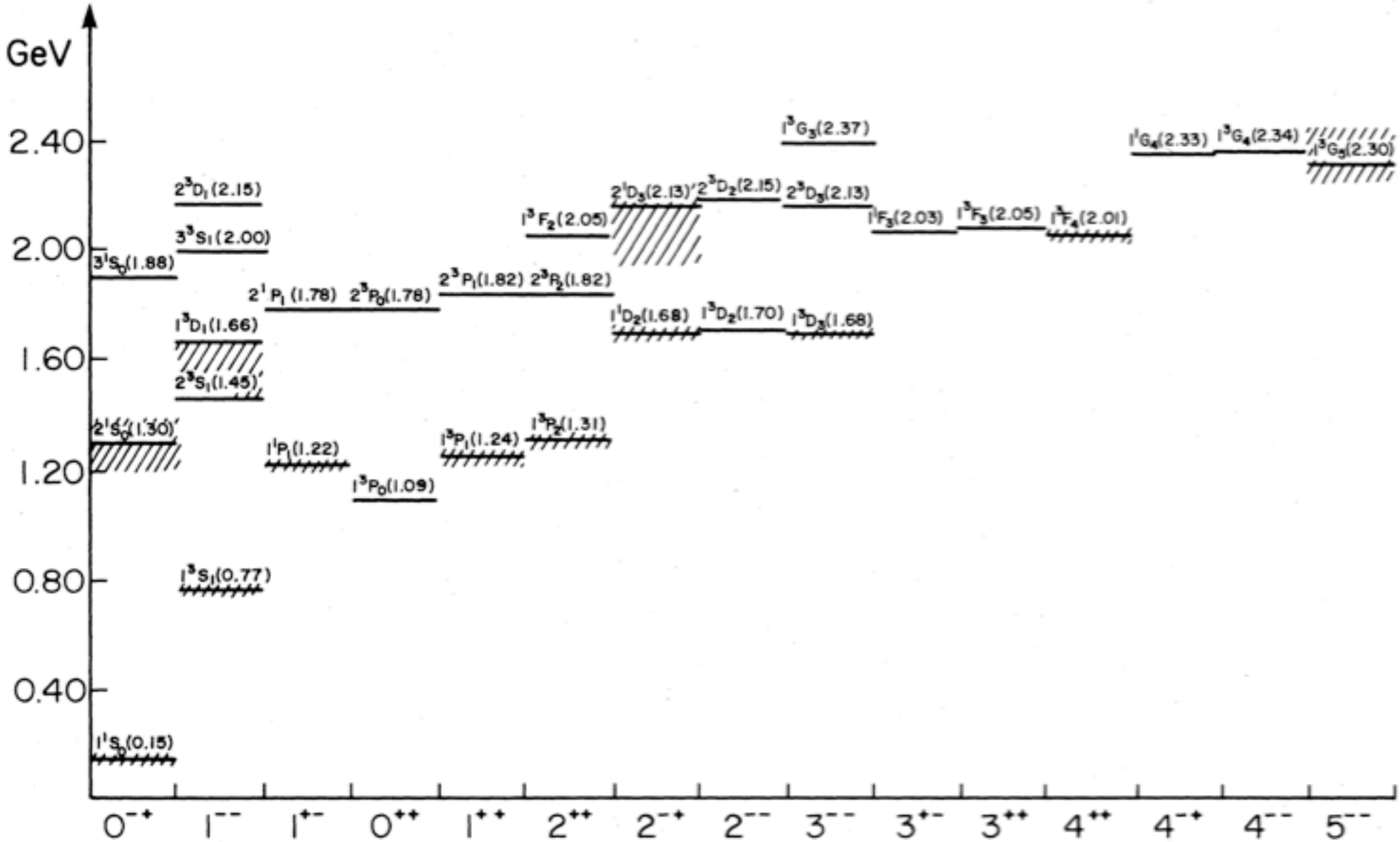
$J \leq 4$, all ***PC***, up to ~25 operators per symmetry channel spin-identified spectrum

3-flavour degenerate lattices (**m_π ~ 700 MeV**)



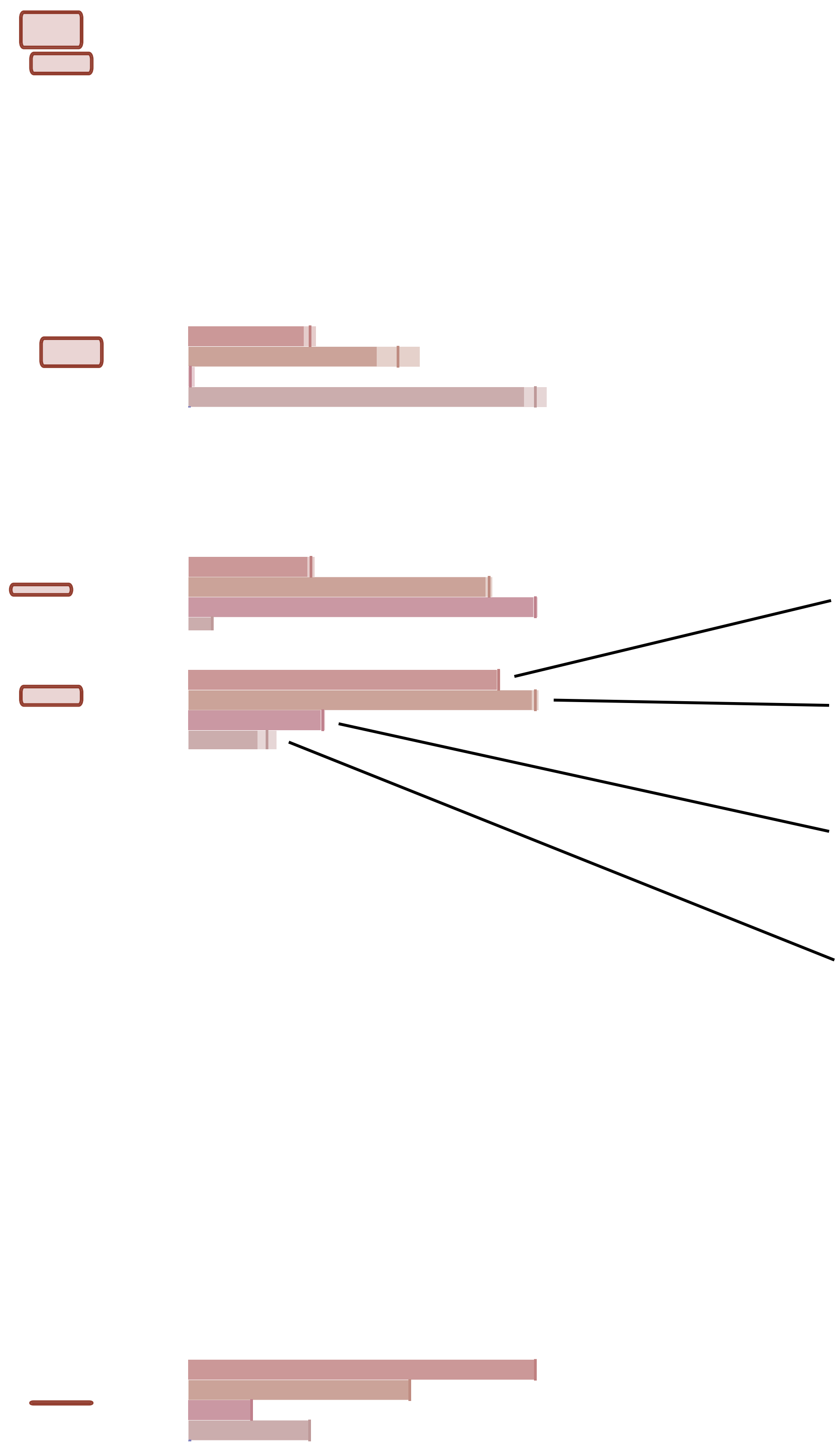
Godfrey & Isgur

isovector spectrum @ "physical pion mass"



... lattice is 25 years behind

operator overlap phenomenology

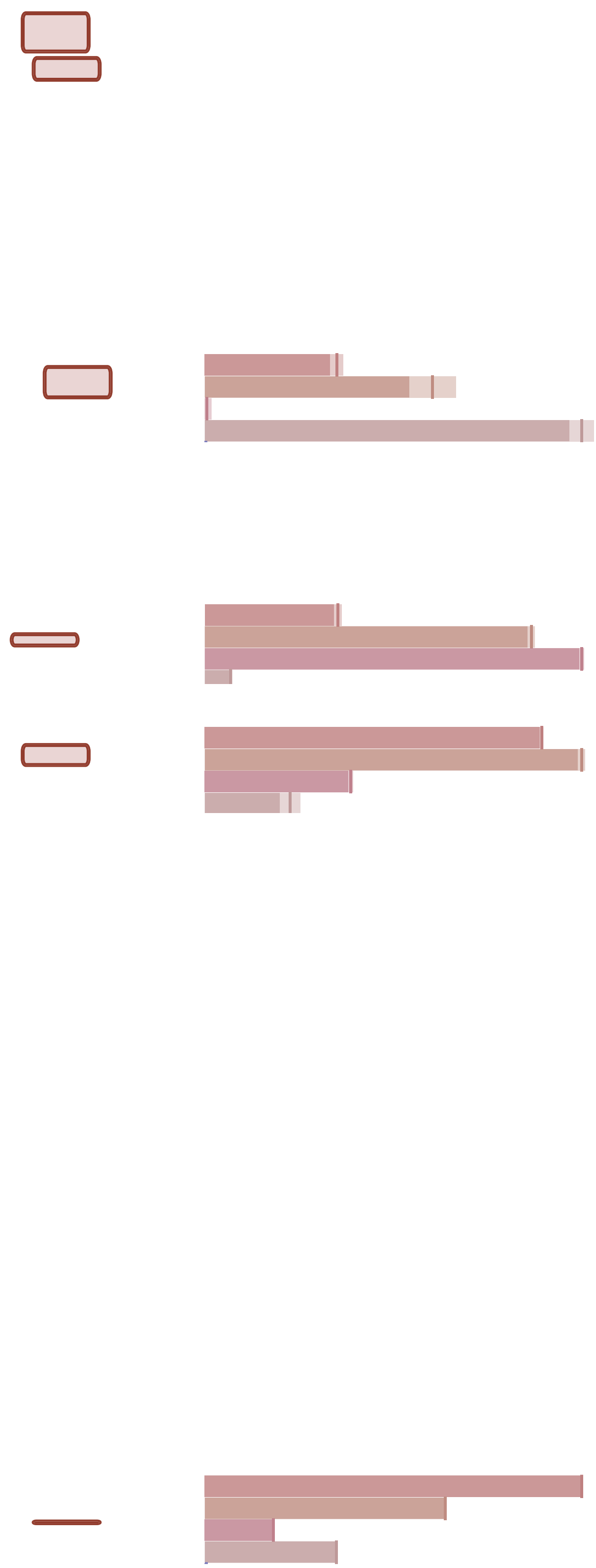


1^{--}

	quark model
$\bar{\psi}\gamma\psi$	$n\,^3S_1$
$\bar{\psi}\gamma_5\,\gamma\,\overleftrightarrow{D}\,\psi$	$n\,^3S_1\,/\,n\,^3D_1$
$\bar{\psi}\gamma Y_2(\overleftrightarrow{D})\psi$	$n\,^3D_1$
$\bar{\psi}\gamma_5[\overleftrightarrow{D},\overleftrightarrow{D}]\psi$	***nothing***

operator overlap phenomenology

$\bar{\psi}\gamma\psi$	n^3S_1
$\bar{\psi}\gamma_5\,\gamma\,\overleftrightarrow{D}\,\psi$	$n^3S_1\,/\,n^3D_1$
$\bar{\psi}\gamma Y_2(\overleftrightarrow{D})\psi$	n^3D_1
$\bar{\psi}\gamma_5[\overleftrightarrow{D},\overleftrightarrow{D}]\psi$	***hybrid ?***



mostly ***hybrid***, some ***n³S₁*** ?

mostly ***1³D₁***, some ***2³S₁*** ?

mostly ***2³S₁***, some ***1³D₁*** ?

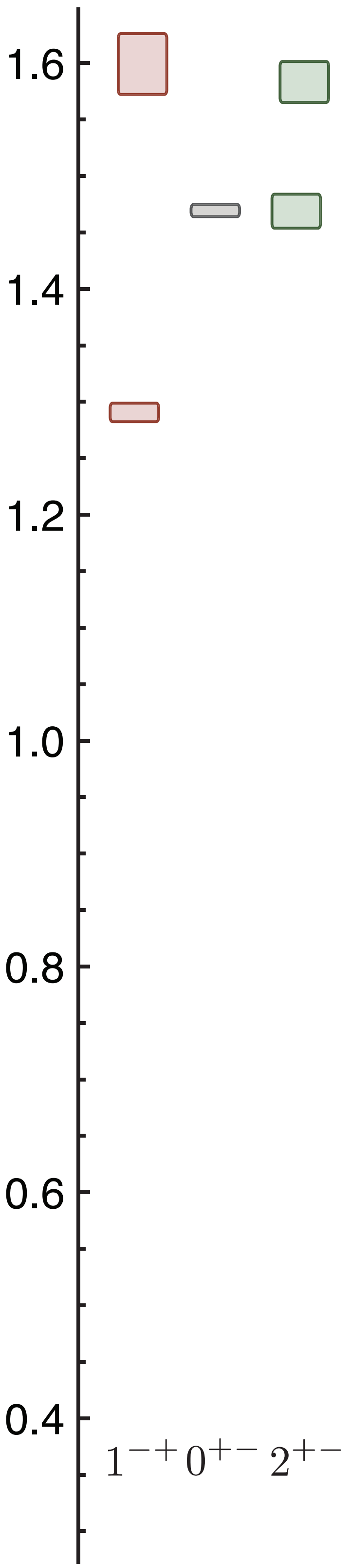
mostly ***1³S₁*** ?

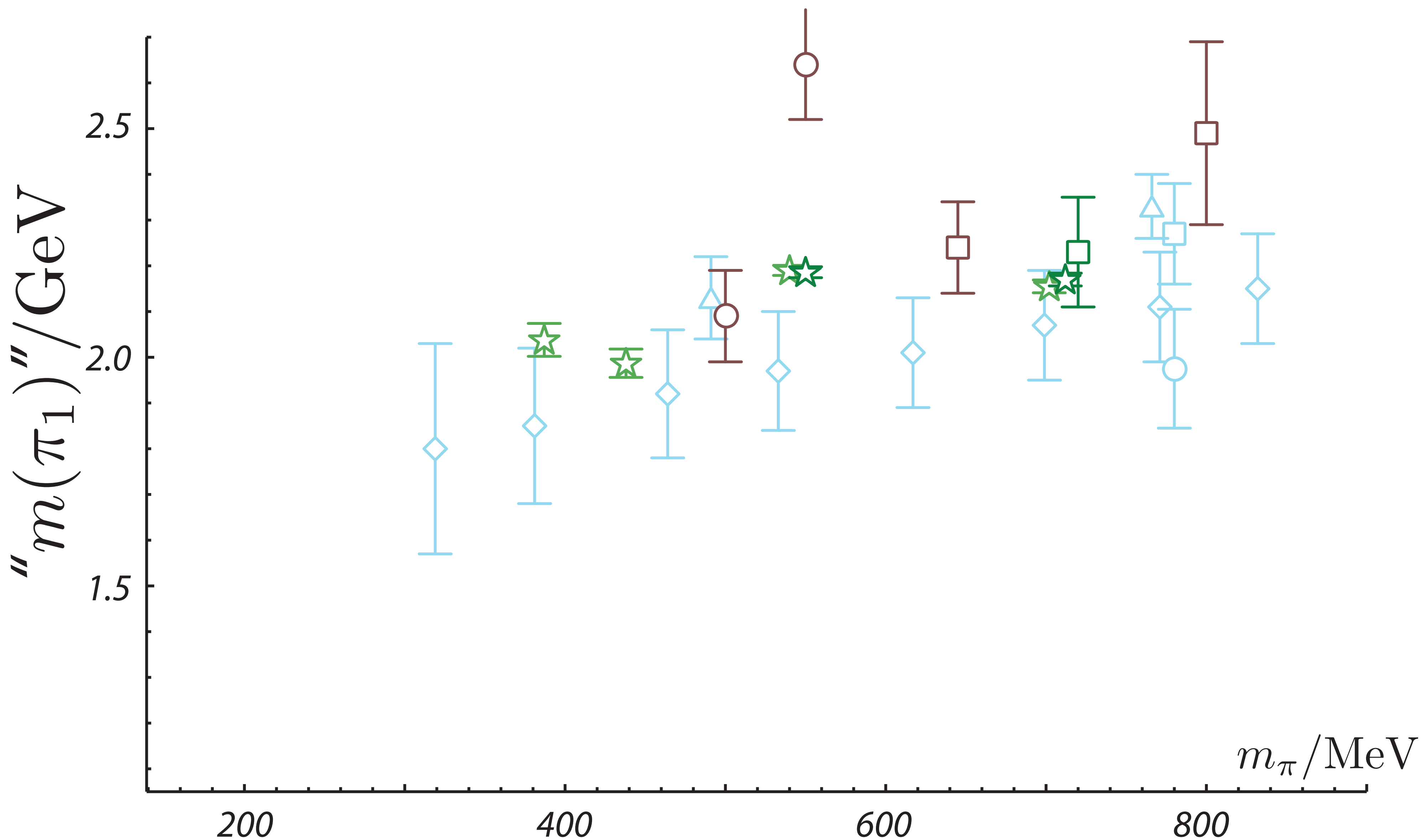
1^{--}

currently working on estimating quark-model style mixing angles

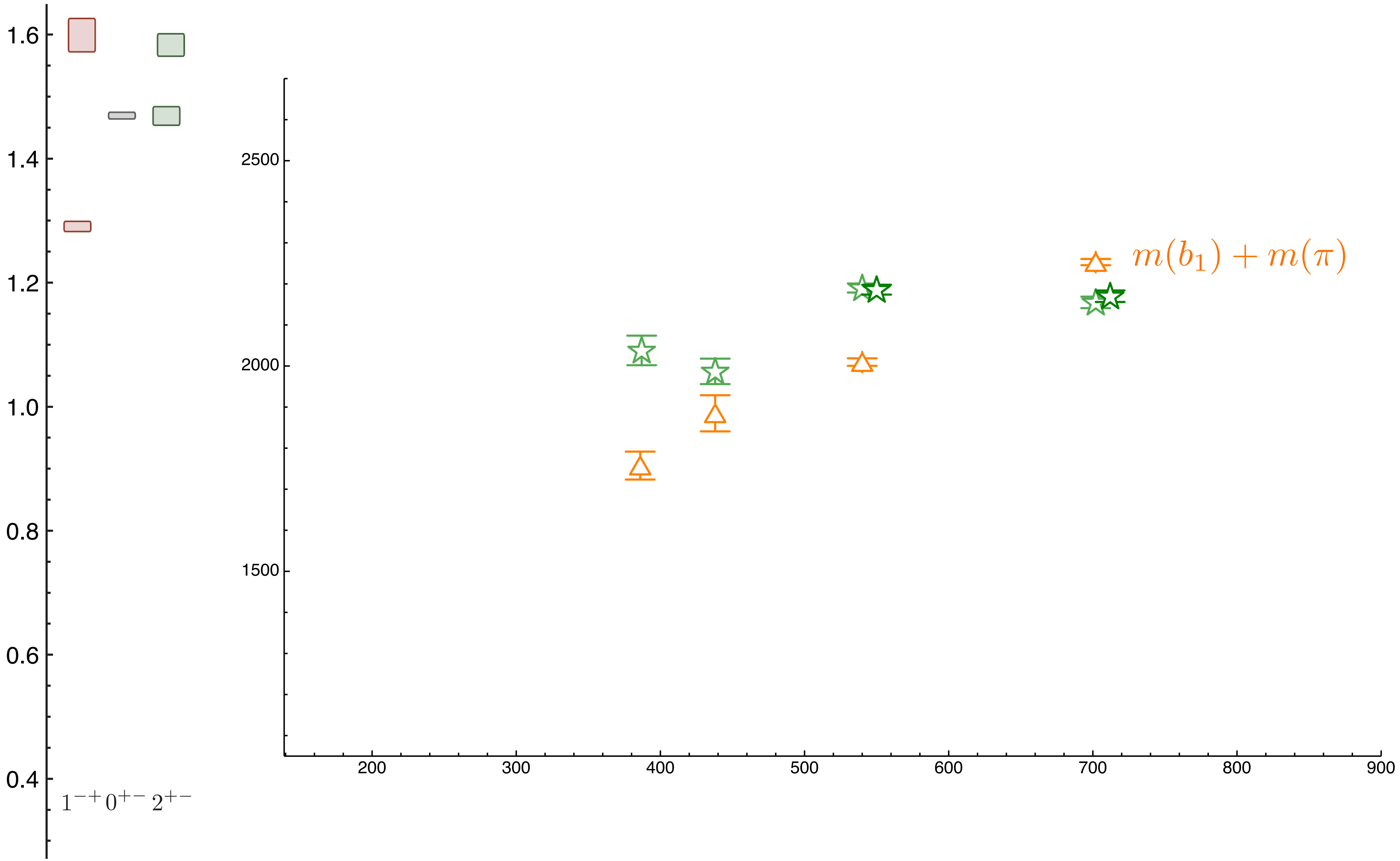
not clear that this continues to make sense as the quark mass reduces !

exotic J^{PC}





resonance ?

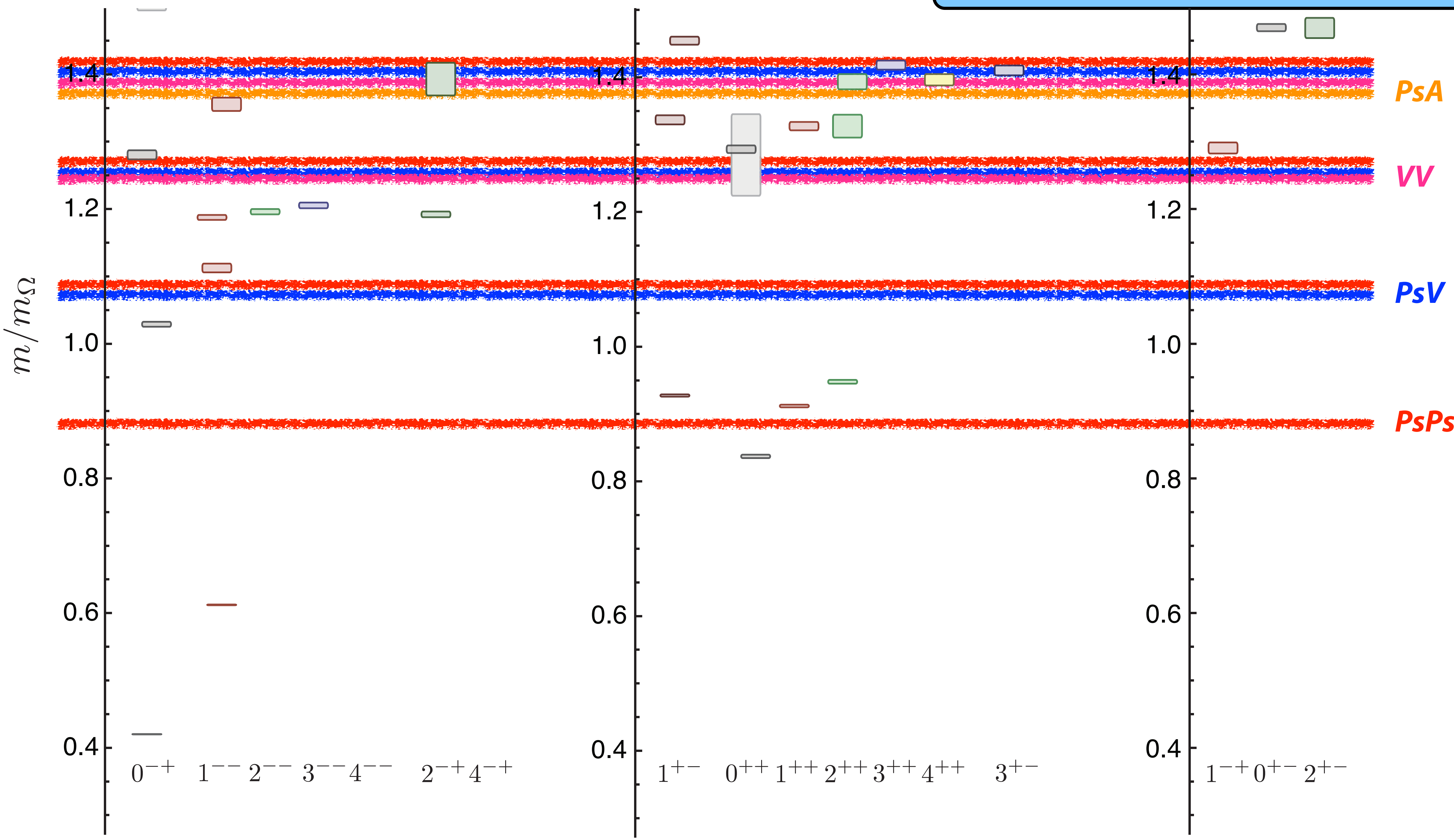


1.6
1.4
1.2
1.0
0.8
0.6
0.4
1^{-+} 0^{+-} 2^{+-}
2500
2000
1500
200
300
400
500
600
700
800
900
$m(b_1) + m(\pi)$

two-particle states ?

$A(n_x, n_y, n_z)\ B(-n_x, -n_y, -n_z)$

$$\sqrt{m_A^2 + n^2 \left(\frac{2\pi}{L}\right)^2} + \sqrt{m_B^2 + n^2 \left(\frac{2\pi}{L}\right)^2}$$



many two-particle states move with changing volume - our extracted spectra don't

no sign of two-particle states

two-particle states ?

probably explanation is that our $\bar{\psi} \ldots \psi$ operators are not good at producing such states

but this is bad news - we need these two-meson states to really extract resonance info

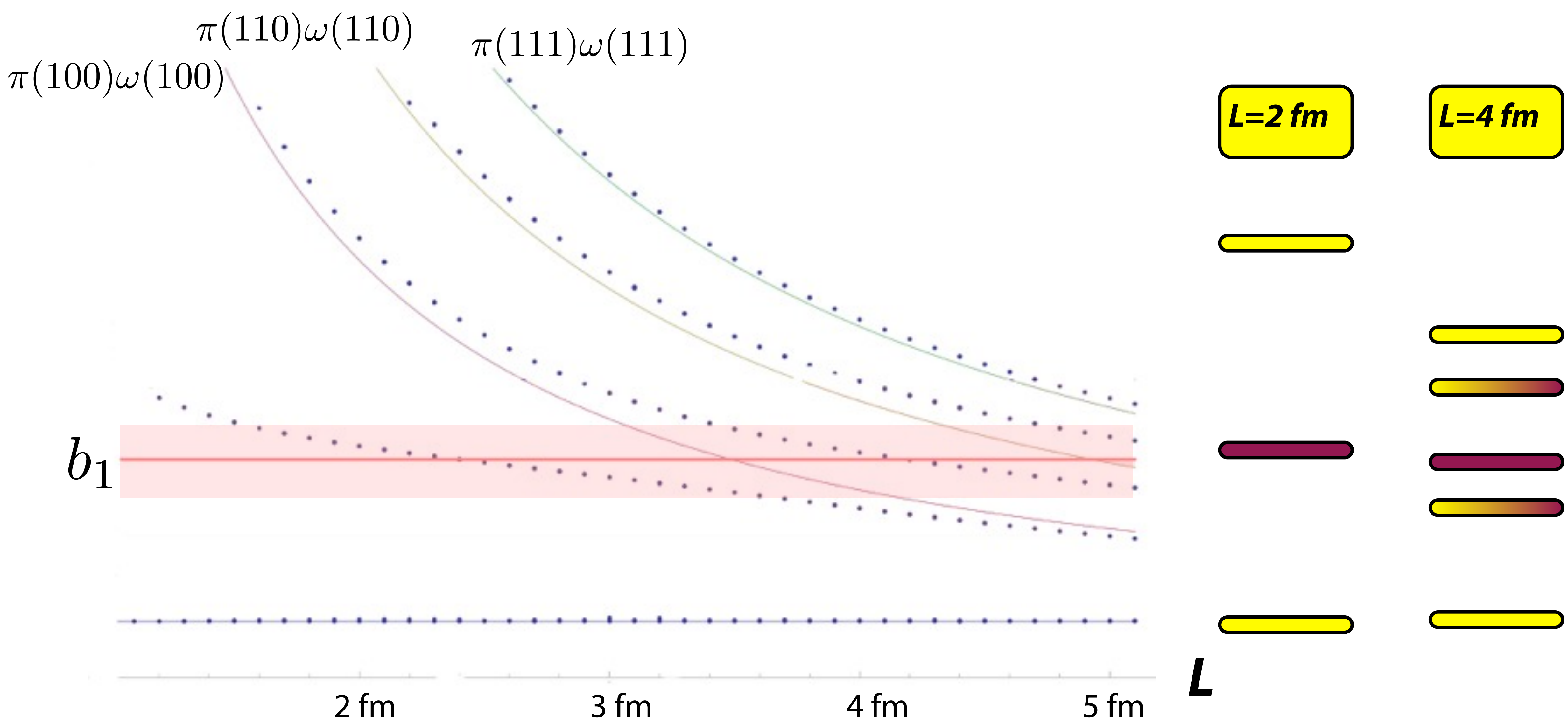
Lüscher & finite volume

in finite volume, two-particle energy states get shifted by the 'interaction' between them

the energy shift is related to the **scattering phase shift** ***δ(k²)***

we can reverse engineer this to see what to expect

e.g. ***b_1*** in ***πω***



Lüscher & finite volume

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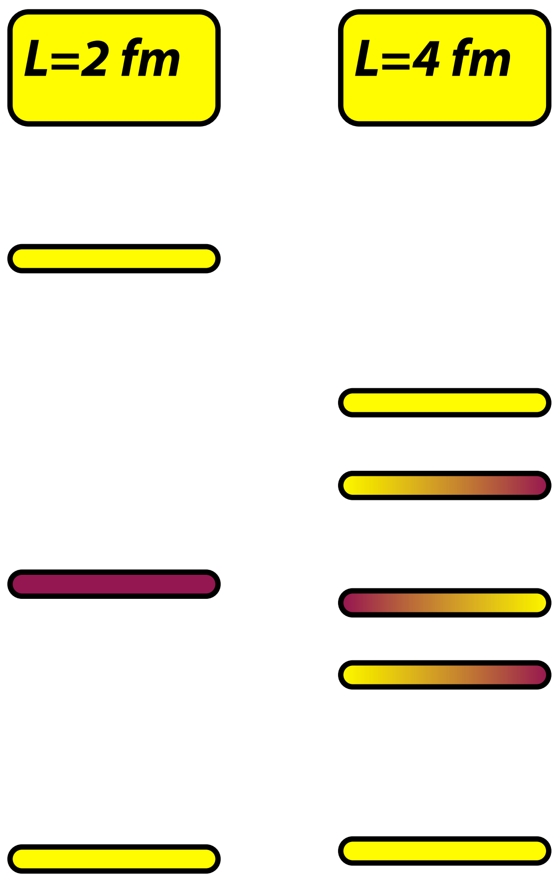
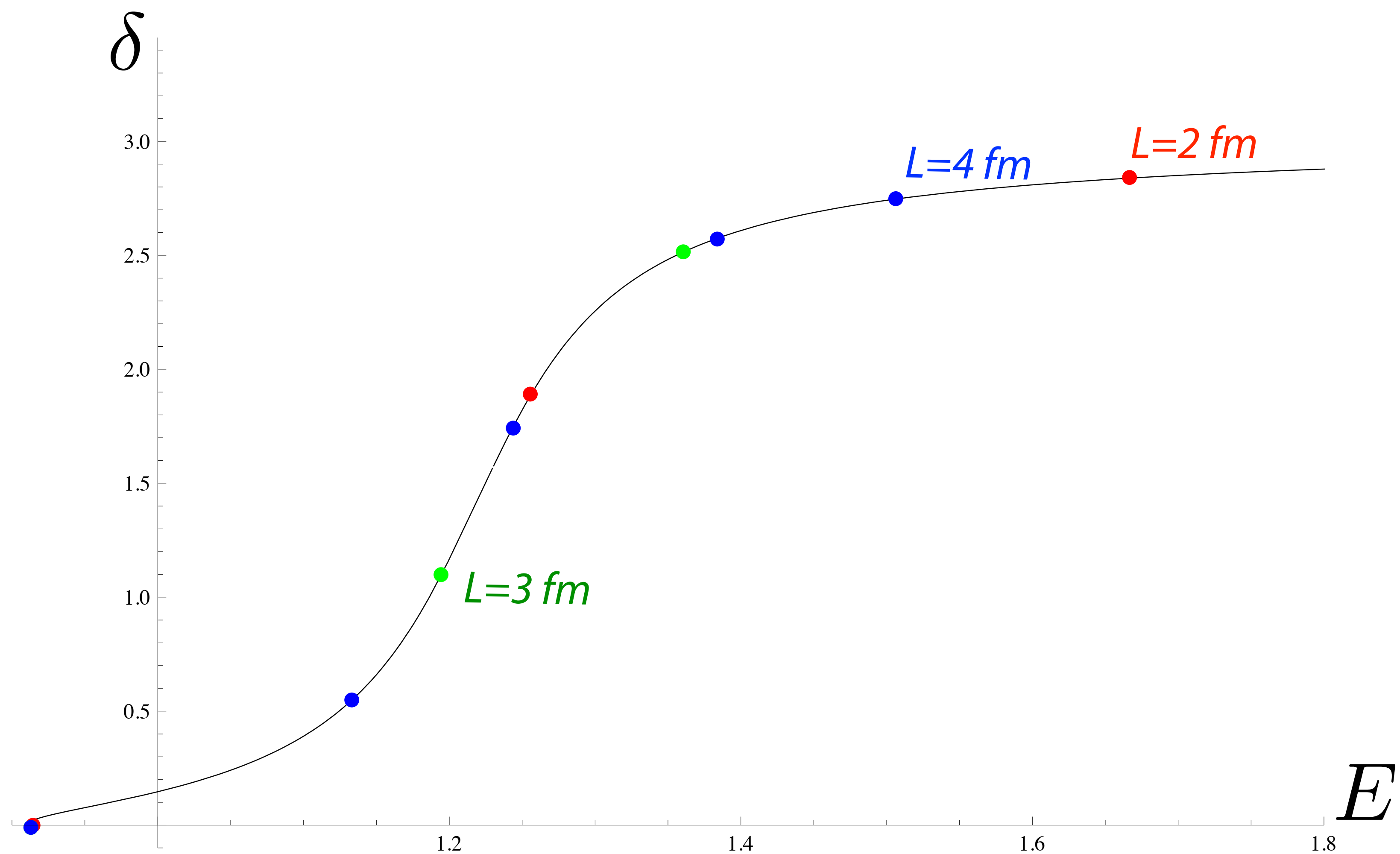
e.g. ***b_1*** in ***$\pi\omega$***





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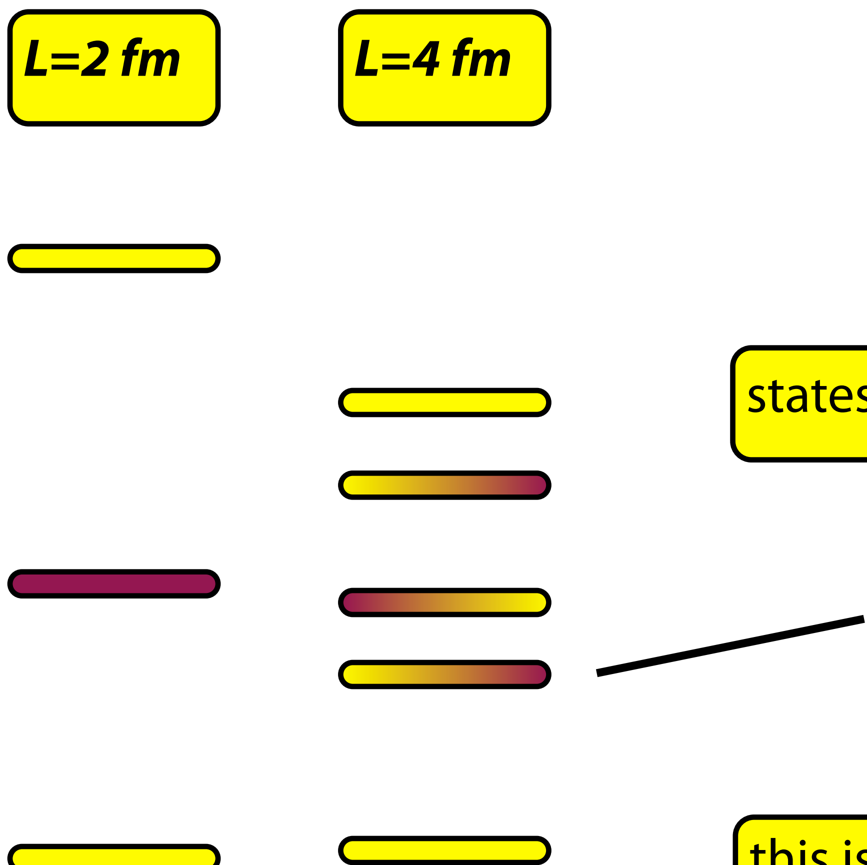


states can be viewed as a mixture of non-interacting basis states

$$a\left|\text{“}b_1\text{“}\right\rangle + b\left|\pi_{100}\omega_{100}\right\rangle$$

this is probably why we're not resolving everything
- we're only able to produce the ***b_1*** bit

we need to construct two-meson operators to include in our basis

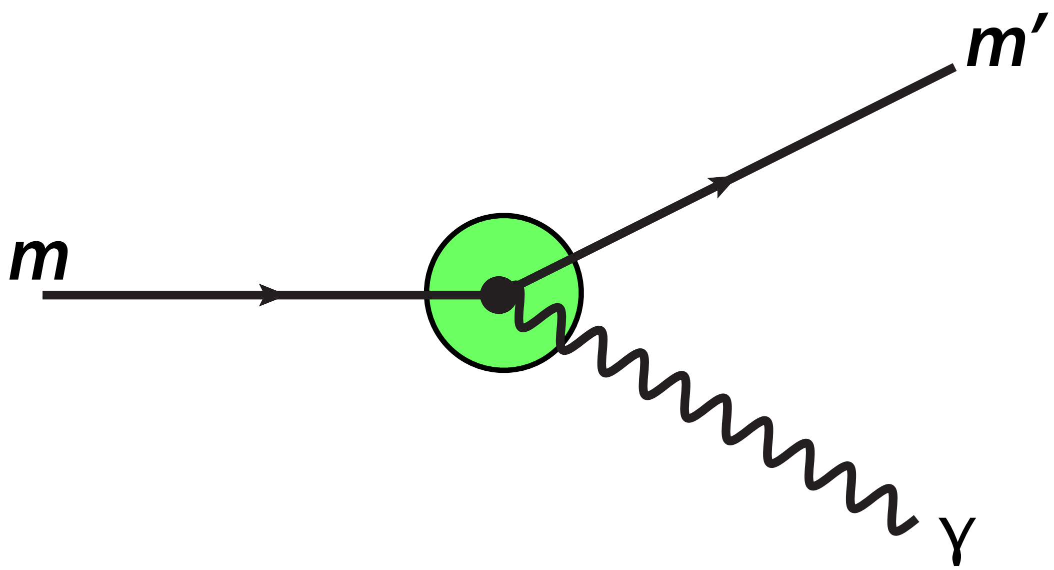
expect a delay before this is done

ππ *isospin =2* as a test-bed

photocouplings

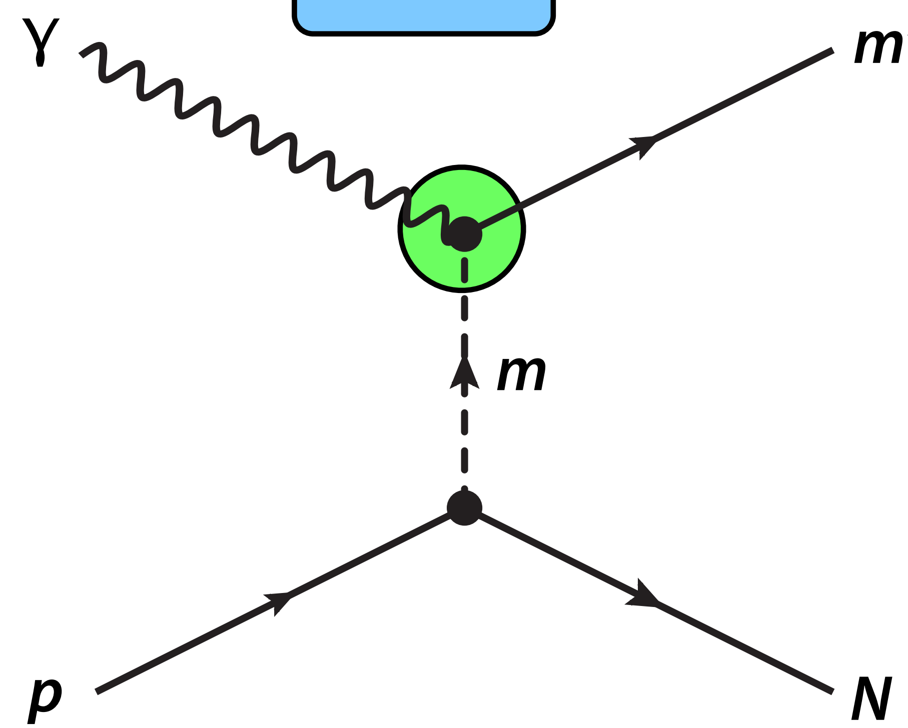
radiative transitions

CLEO-c, BES III



peripheral photoproduction

GlueX



basic object: $\langle \gamma\, m' | m \rangle$

$$\langle m' | \bar{\psi} \gamma^{\mu} \psi | m \rangle \, \langle \gamma | A_{\mu} | 0 \rangle$$

see Christopher Thomas's talk on Friday
- will present charmonium results,
GlueX relevant results coming soon

summary

have dealt with a lot of technical issues such that multiple excited states can be extracted

spin can be identified

need more operators to capture the required multi-meson states

with these in hand, some hope of extracting resonance params

need more theory progress too though - inelasticity

developing a lattice-result-based phenomenology of non-exotics and exotics

mixing of 'non-exotic hybrid' basis states into regular spectrum

kaon mixing angles - as a function of quark mass

other useful quantities like photo-couplings coming soon

spin-identified spectrum

3-flavour degenerate lattices (***m_π ~ 700 MeV***)