Excited meson spectroscopy and transitions from lattice QCD

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Jefferson Lab

Outline

- Introduction and motivation
- Excited spectra from LQCD – method outline
- Isovector meson spectra
- Multi-meson states and scattering
- Photocouplings in charmonium
- Summary and outlook

PR D79 094504 (2009)
PRL 103 262001 (2009)
PR D82 034508 (2010)
arXiv:1011.6352

Motivation

Renaissance in excited charmonium spectroscopy

BABAR, Belle, BES, CLEO-c, ...

Upcoming experimental efforts (charmonium and light mesons)

GlueX (JLab), BESIII, PANDA, ...

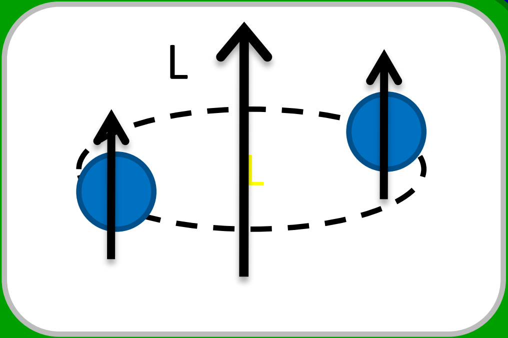
Exotics (J^{PC} = **1**$^{-+}$, **2**$^{+-}$, ...)? – can't just be a $q\bar{q}$ pair

e.g. hybrids, multi-mesons

Quark-antiquark pair: $^{2S+1}L_J$

Parity: $P = (-1)^{(L+1)}$

Charge Conj Sym: $C = (-1)^{(L+S)}$



$J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{++}, 1^{+-}, 2^{--}, 2^{++}, 2^{-+}, \ldots$

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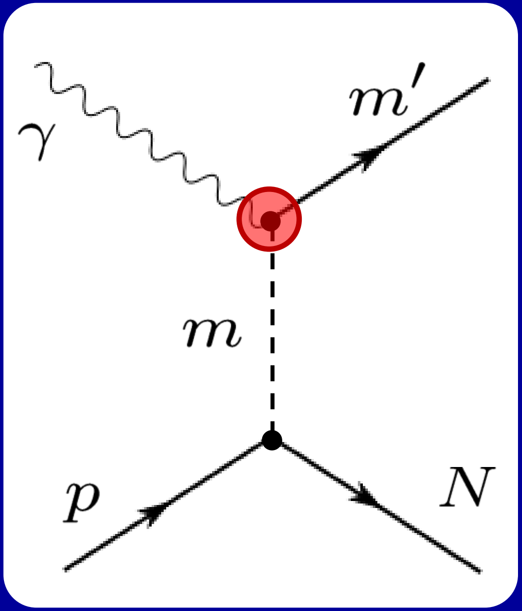
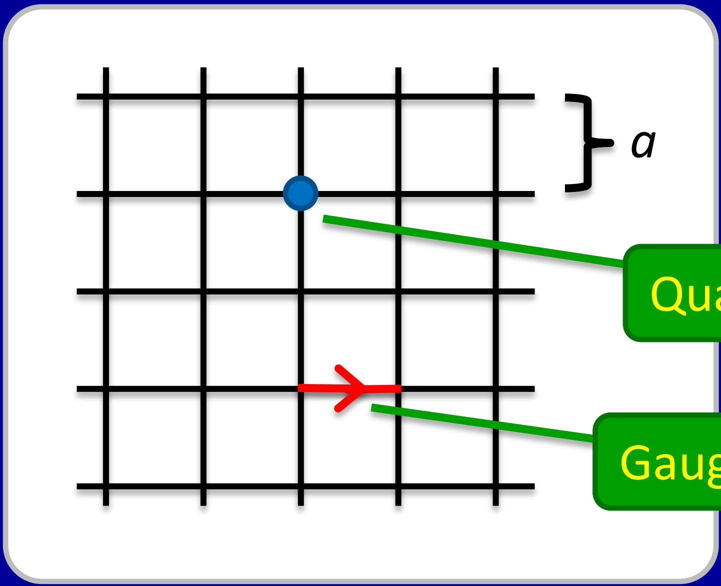


Photoproduction at GlueX (JLab 12 GeV upgrade)

Use Lattice QCD to extract excited spectrum...

... and photocouplings (tested in charmonium)

QCD on a Lattice



Discretise on a grid (spacing = *a*) – regulator

Finite volume → finite no. of d.o.f.

Quarks fields on lattice sites $\psi(x) \longrightarrow \psi_x$

Gauge fields on links $A_\mu(x) \longrightarrow U_{x,\mu} = e^{-aA_{x,\mu}}$

Path integral formulation

$$\int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}U \, f(\psi, \bar{\psi}, U) e^{iS[\psi,\bar{\psi},U]}$$

Euclidean time: t → i t

$$\int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}U \, f(\psi, \bar{\psi}, U) e^{-\tilde{S}[\psi,\bar{\psi},U]}$$

Do fermion integral analytically then use importance sampling Monte Carlo

Spectroscopy on the lattice

Calculate energies and matrix elements ("overlaps", Z's) from correlation functions of meson interpolating fields

$$C_{ij}(t) = <0|O_i(t)O_j(0)|0>$$

Construct operators which only overlap on to one spin in the continuum limit

$$O(t) = \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}} \; \bar{\psi}(x)\Gamma_i \overleftrightarrow{D}_j \overleftrightarrow{D}_k \ldots \psi(x)$$

'Distillation' technology for constructing on lattice PR D80 054506 (2009)

(p = 0)

definite J^{PC}

$$Z_i^{(n)} \equiv <0|O_i|n>$$

$$C_{ij}(t) = \sum_n \frac{e^{-E_n t}}{2E_n} <0|O_i(0)|n><n|O_j(0)|0>$$

Variational Method

Large basis of operators → matrix of correlators

$$C_{ij}(t) =< 0|O_i(t)O_j(0)|0 >$$

Generalised eigenvector problem:

$$C_{ij}(t)v_j^{(n)} = \lambda^{(n)}(t)C_{ij}(t_0)v_j^{(n)}$$

Eigenvalues → energies

$$\lambda^{(n)}(t) \rightarrow e^{-E_n(t-t_0)}$$

($t >> t_0$)

Eigenvectors → optimal linear combination of operators to overlap on to a state

$$\Omega^{(n)} \sim \sum_i v_i^{(n)} O_i$$

$Z^{(n)}$ related to eigenvectors

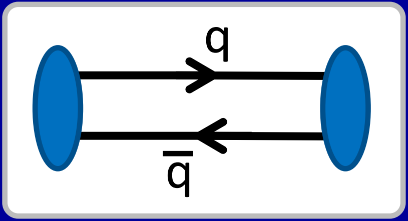
$$Z_i^{(n)} \equiv< 0|O_i|n >$$

Var. method uses orthog of eigenvectors; don't just rely on separating energies

Isovector spectra

- Dynamical (unquenched) calculation
- Anisotropic – finer in temporal dir (a_s/a_t = 3.5), $a_s \sim 0.12$ fm
- Two volumes: 16^3, 20^3 ($L_s \approx 2.0$, 2.4 fm)

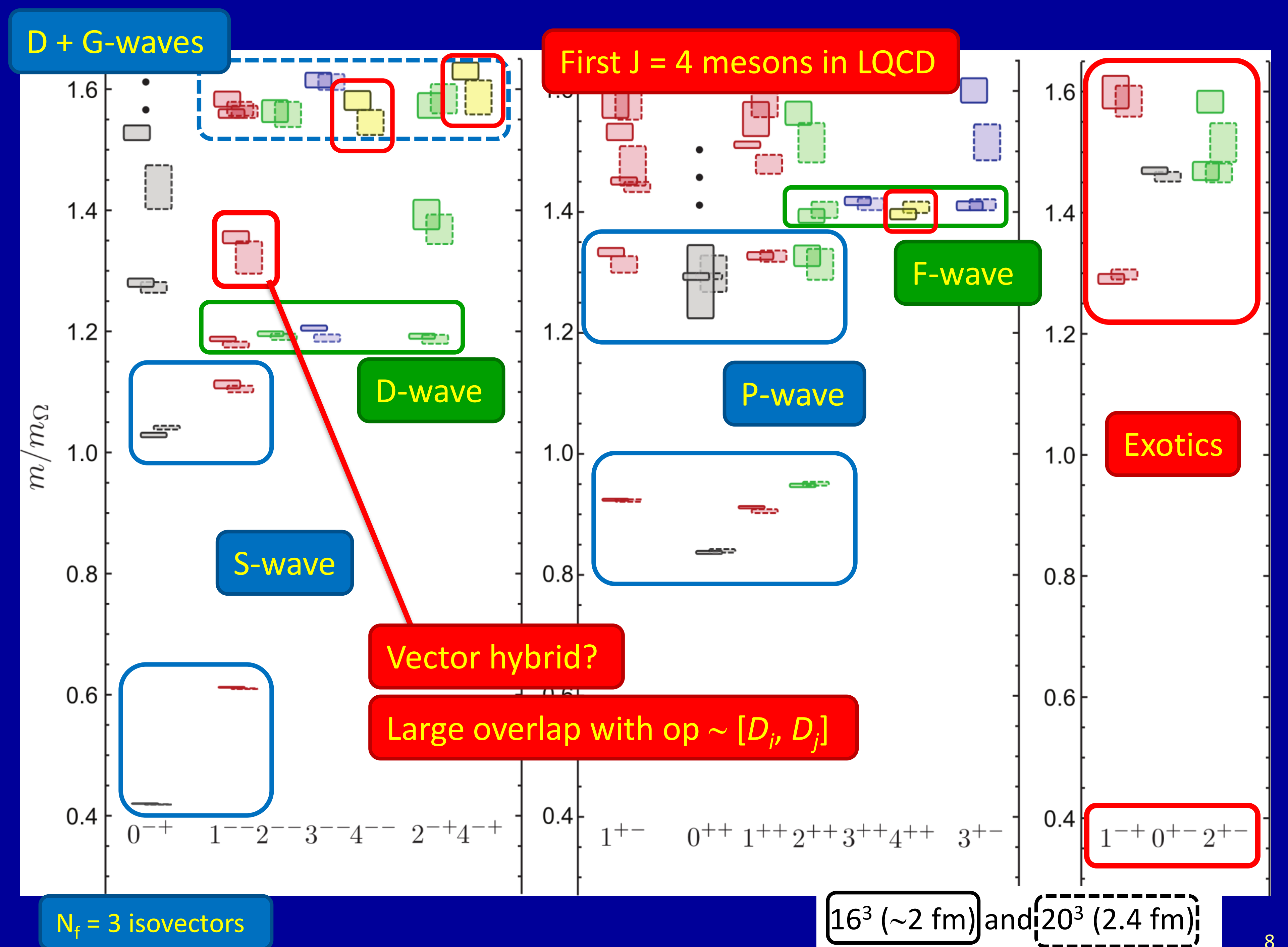
Lattice details in: PR D78 054501, PR D79 034502



- Only connected diagrams – Isovectors (I=1) and kaons
- As an example: three degenerate 'light' quarks ($N_f = 3$, $M_\pi \approx 700$ MeV)
- Also (N_f = 2+1) $M_\pi \approx 520, 440, 400$ MeV

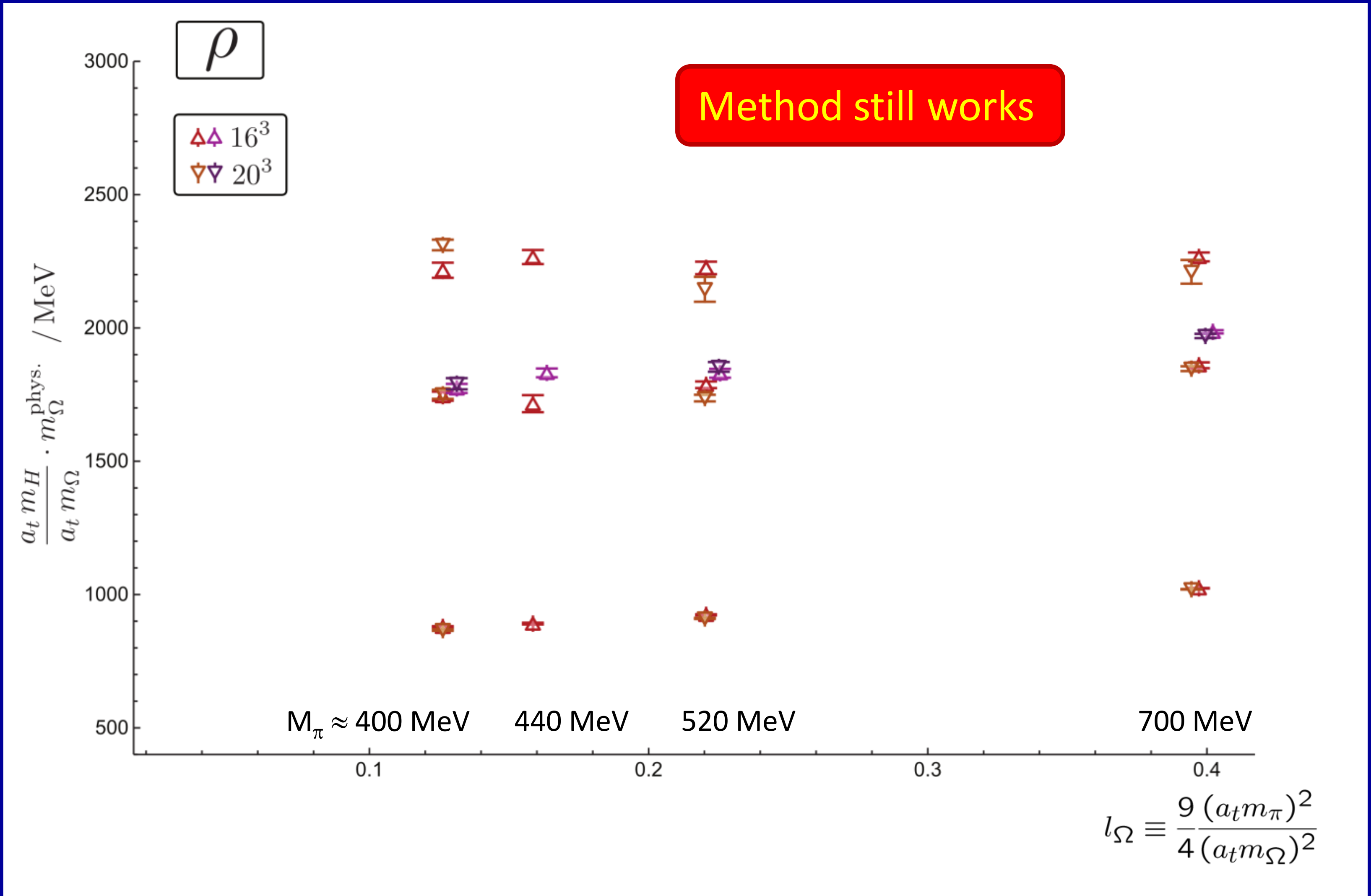
SU(3) sym

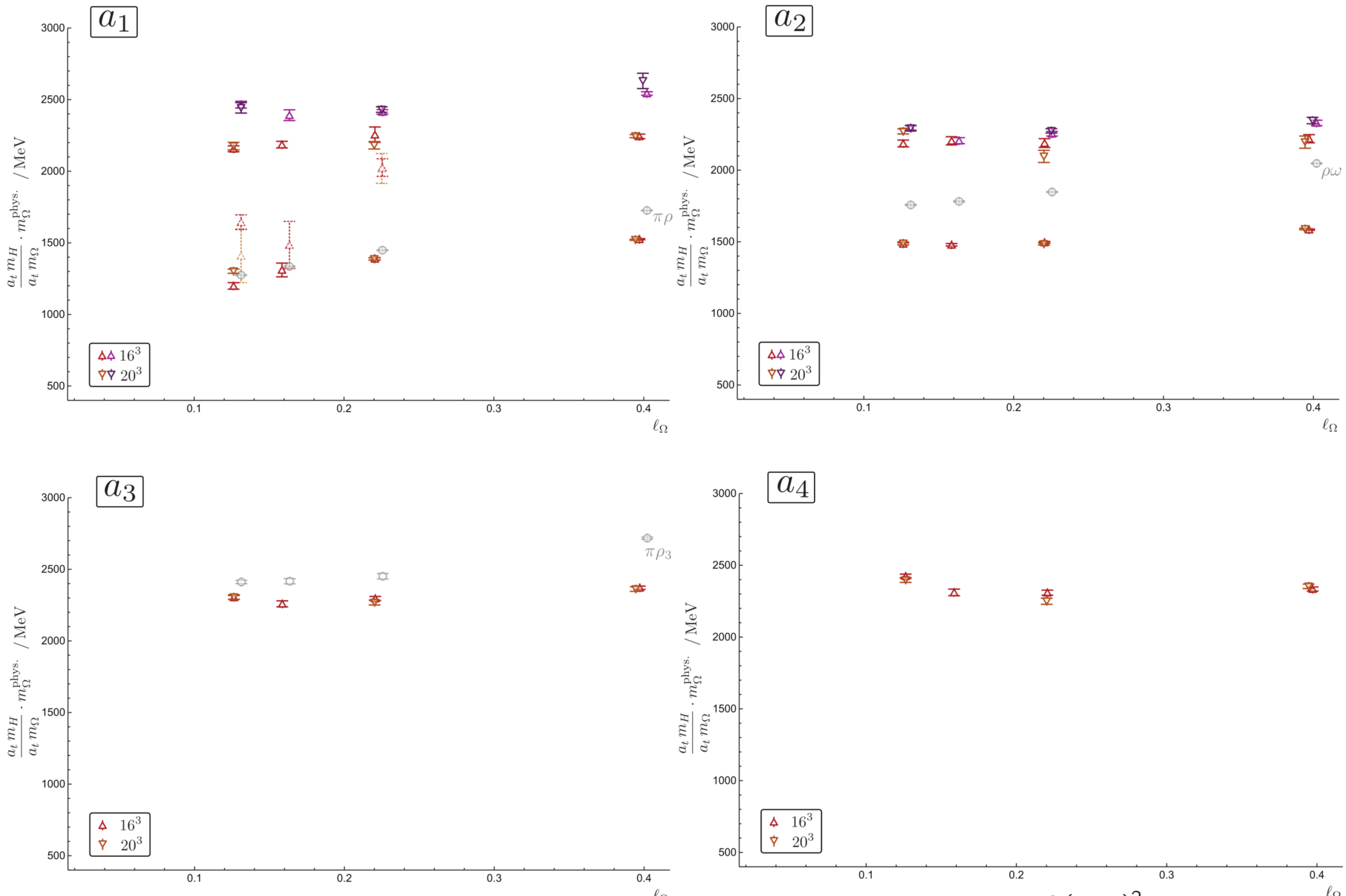
Method details and results: PRL 103 262001 (2009), PR D82 034508 (2010)



D + G-waves
First J = 4 mesons in LQCD
F-wave
D-wave
P-wave
Exotics
S-wave
Vector hybrid?
Large overlap with op ~ [D_i, D_j]
N_f = 3 isovectors
16³ (~2 fm) and 20³ (2.4 fm)
m/m_Ω
0⁻⁺ 1⁻⁻ 2⁻⁻ 3⁻⁻ 4⁻⁻ 2⁻⁺ 4⁻⁺
1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺ 3⁺⁺ 4⁺⁺ 3⁺⁻
1⁻⁺ 0⁺⁻ 2⁺⁻

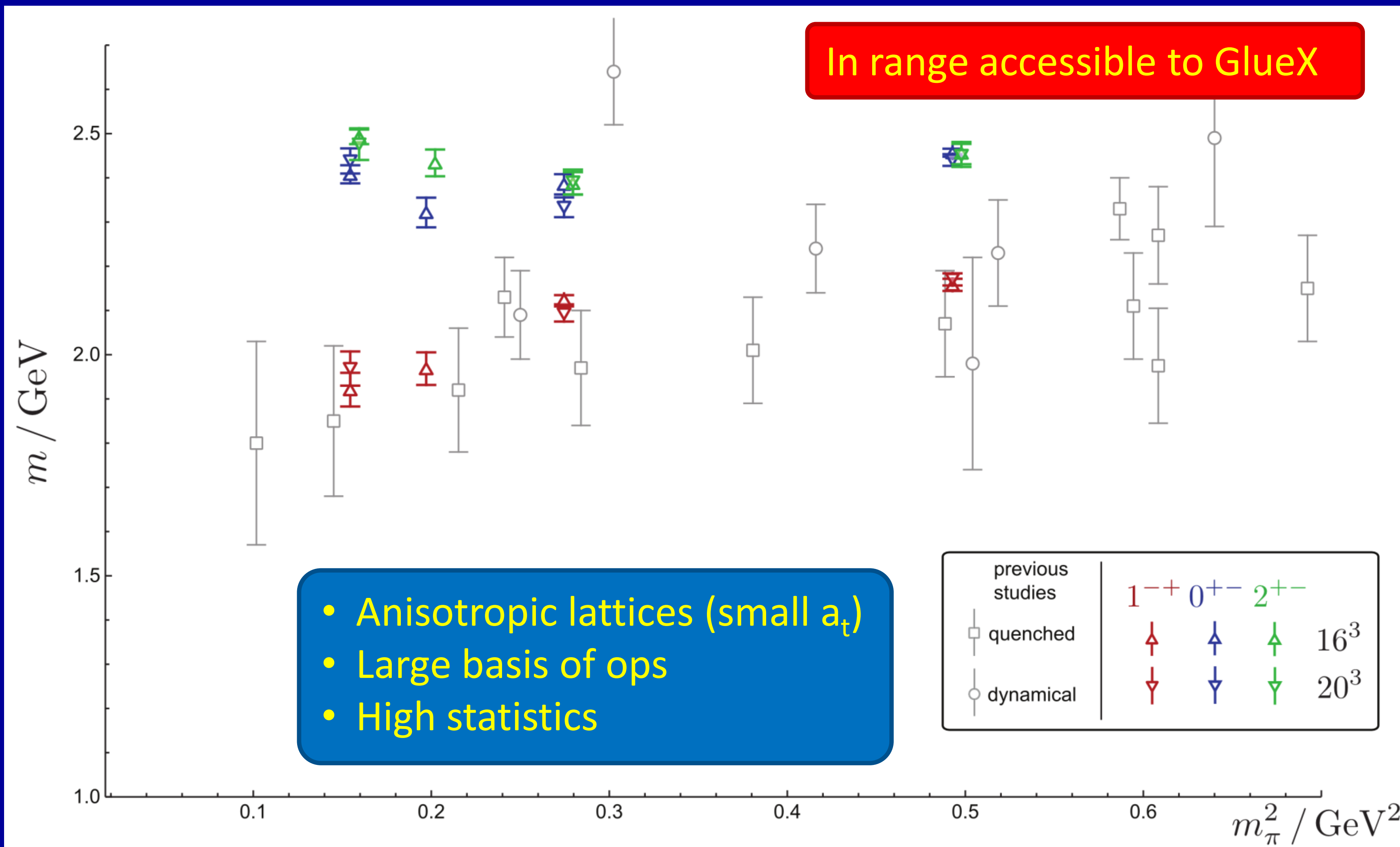
Lower pion masses





$$l_\Omega \equiv \frac{9}{4}\frac{(a_t m_\pi)^2}{(a_t m_\Omega)^2}$$

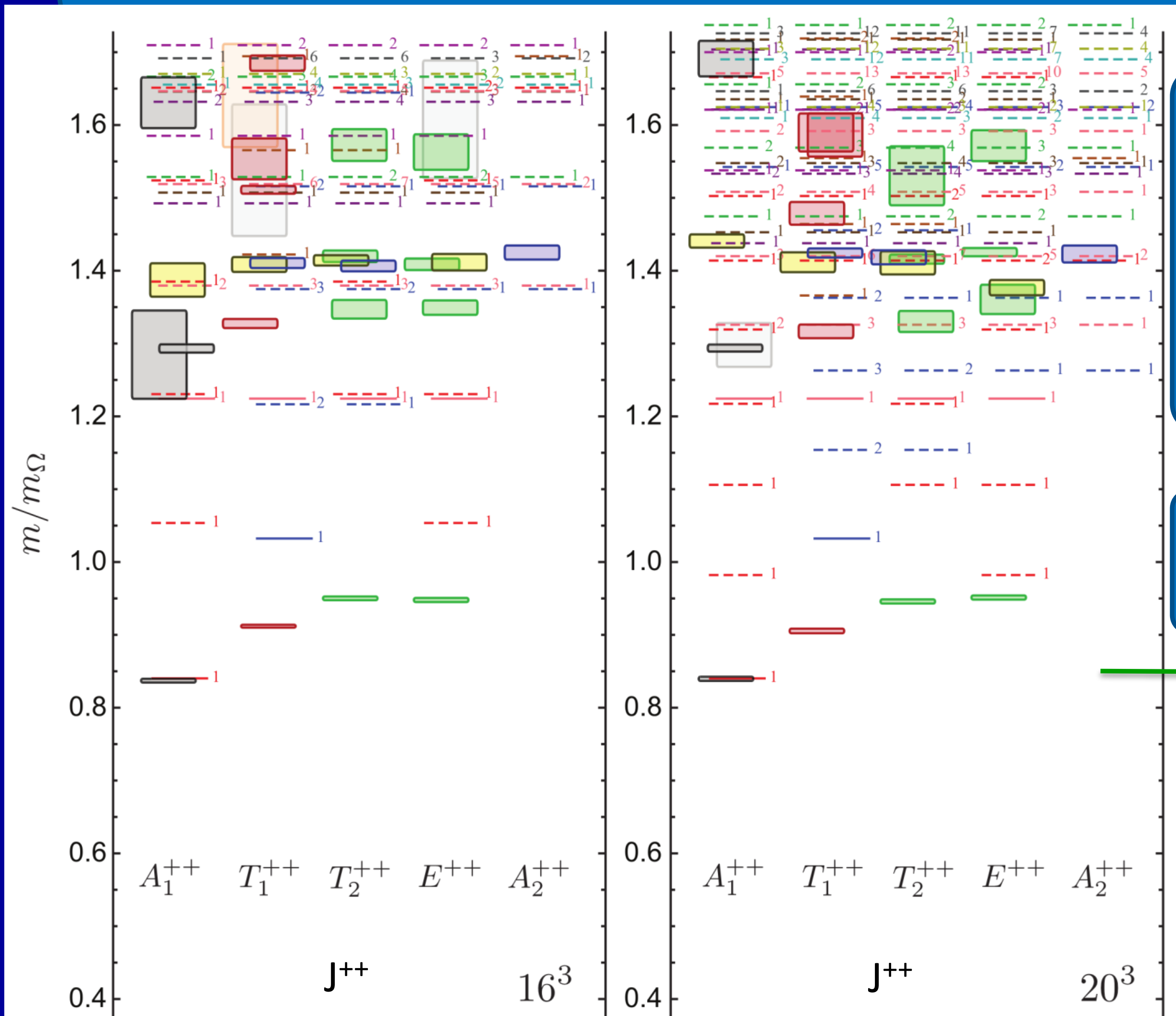
Exotics summary



In range accessible to GlueX

- Anisotropic lattices (small a_t)
- Large basis of ops
- High statistics

Multi-particle states?



Finite box
→ discrete allowed momenta
→ discrete spectrum of multiparticle states

Expect two-meson states above $2m_\pi$

$2m_\pi \sim 0.85\ m_\Omega$

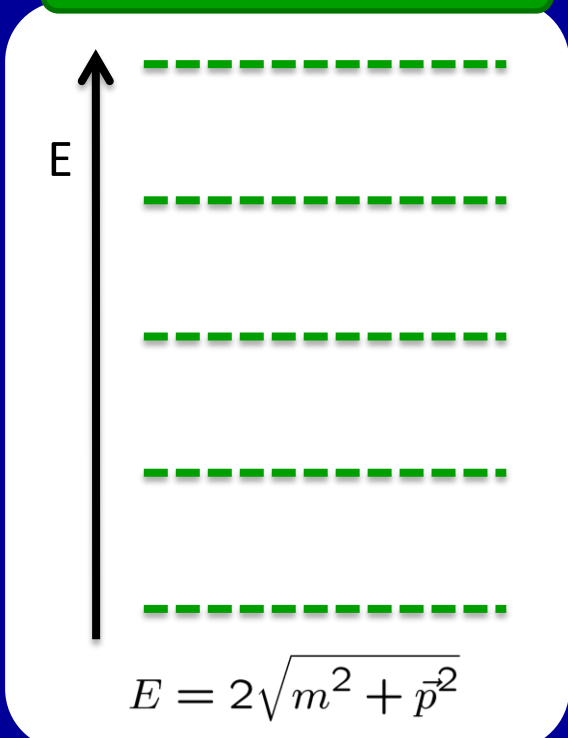
Where are they?

Multi-particle states

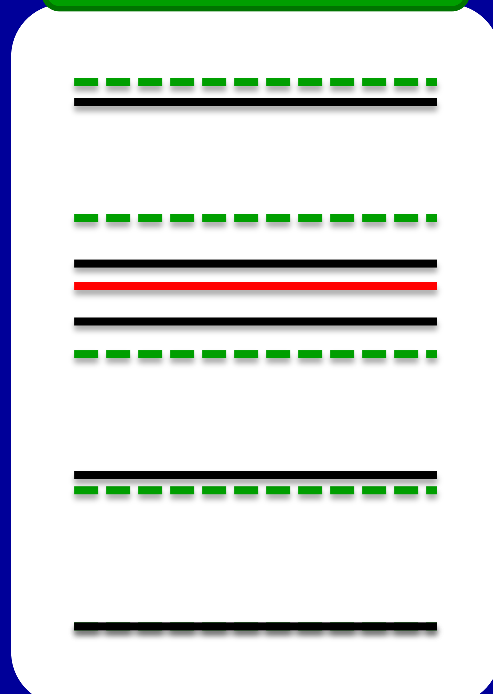
Euclidean time: can’t directly study dynamical properties like widths

Lüscher: energy shifts in finite volume → phase shift

Free 2-particle levels



Measured levels

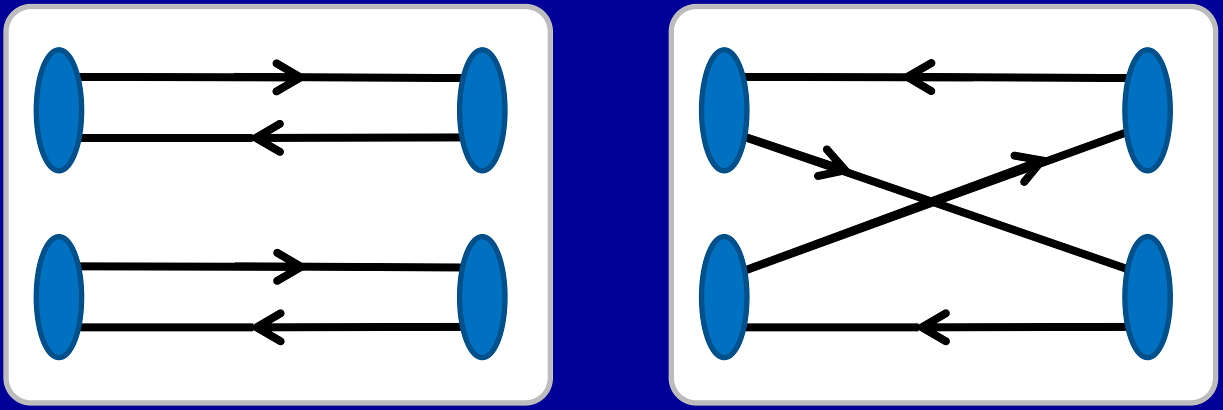


$$\vec{p} = \frac{2\pi}{L_s}(n_x, n_y, n_z)$$

Extract phase shift at discrete E
– Lüscher method

$$\Delta E(L_s) \rightarrow \delta(E, L_s)$$

$\pi\pi$ isospin-2

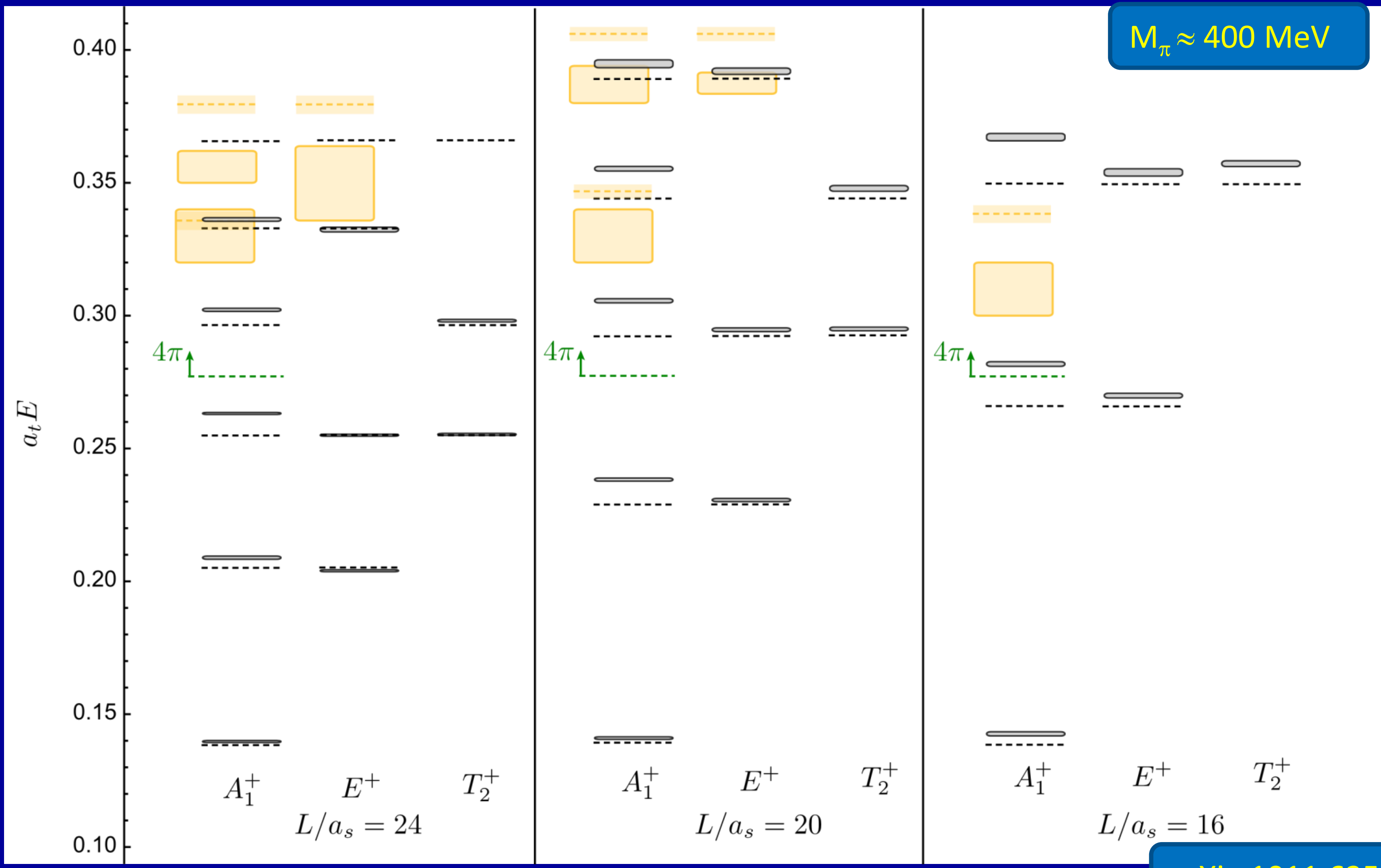


+ similar diagrams

Operators

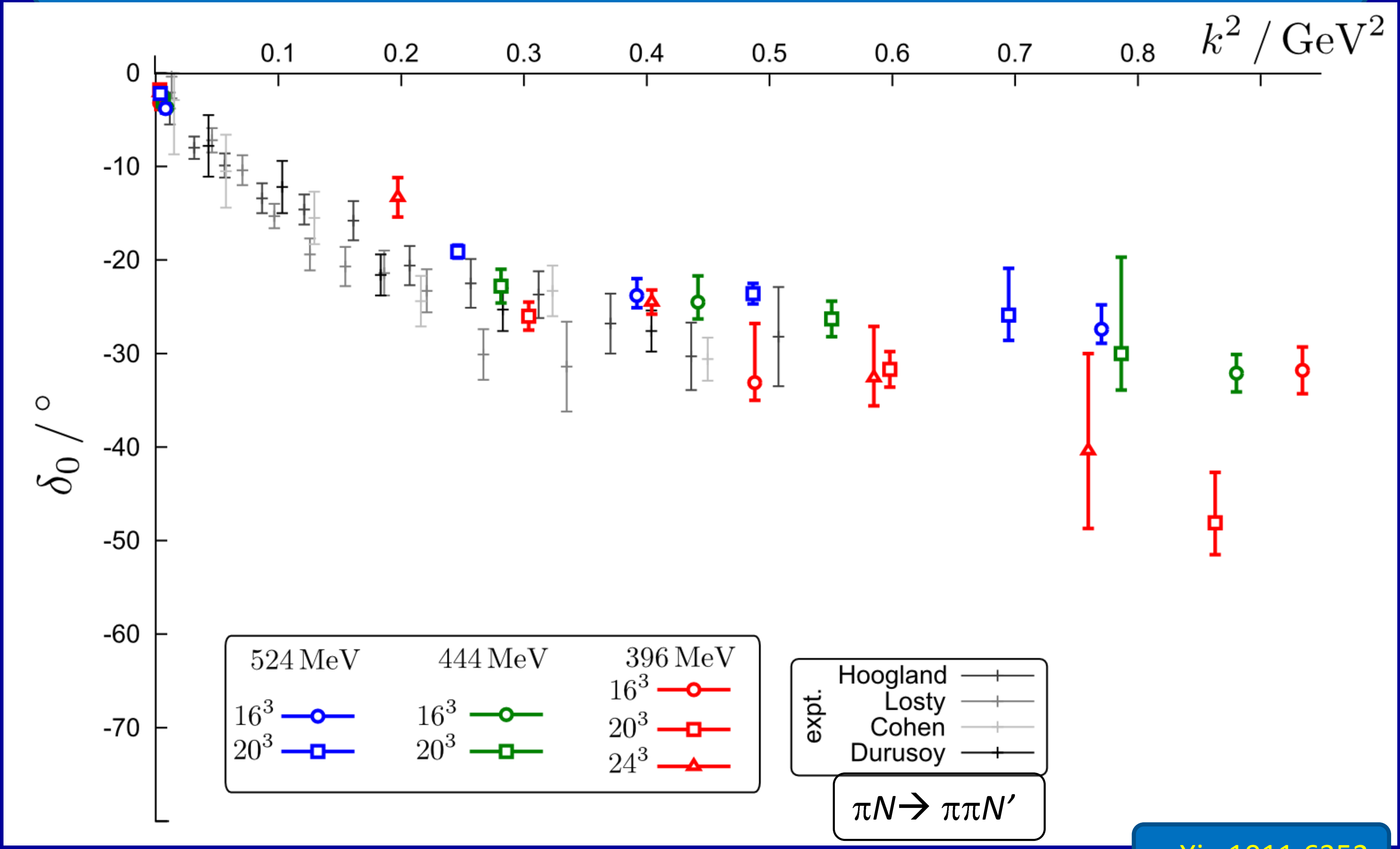
$$\mathcal{O}_{\pi\pi} = \sum_{\Omega_{\vec{p}}} Y_L^M(\Omega_{\vec{p}})\ O_\pi(\vec{p})\ O_\pi(-\vec{p})$$

$\pi\pi$ isospin-2



arXiv:1011.6352

ππ I=2 phase shift



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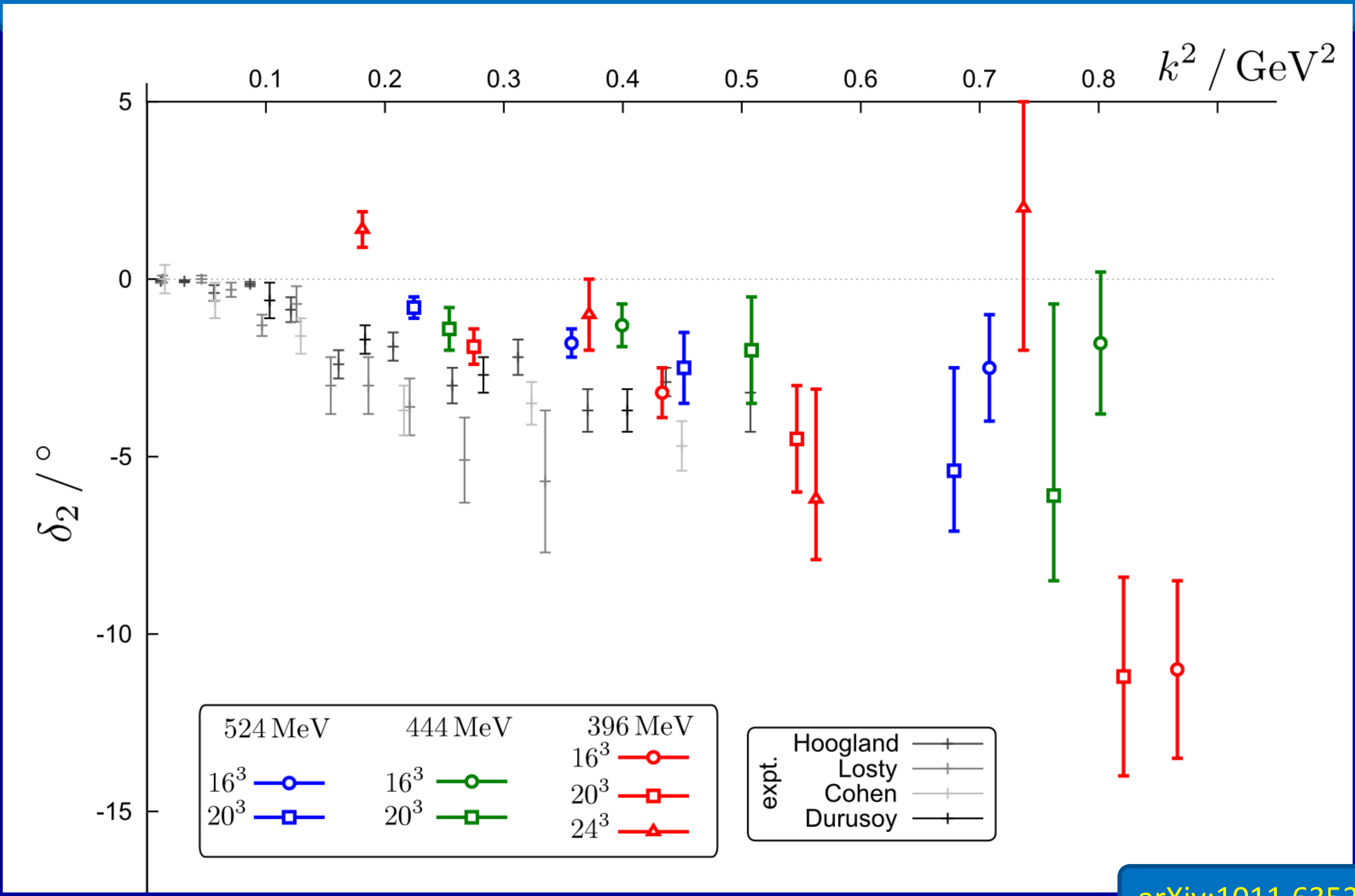
$\pi\pi$ I=2 phase shift



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Charmonium

"Hydrogen atom" of meson spectroscopy

Potential models, effective field theories, QCD sum rules, ...

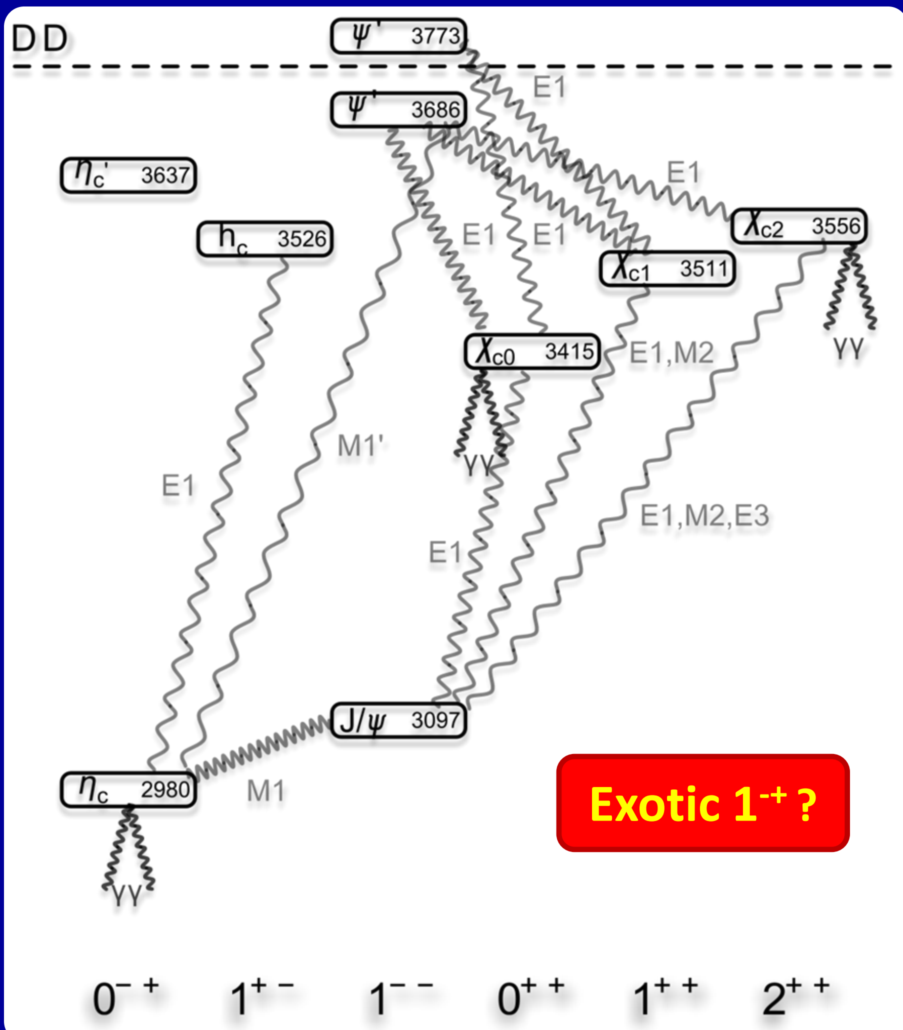
New and improved measurements at BABAR, Belle, BES, CLEO-c

New resonances not easily described by quark model

Theoretical speculation: hybrids, multiquark/molecular mesons, ...

As yet, no exotic J^{PC} observed (1^{-+}, 0^{+-}, 2^{+-})

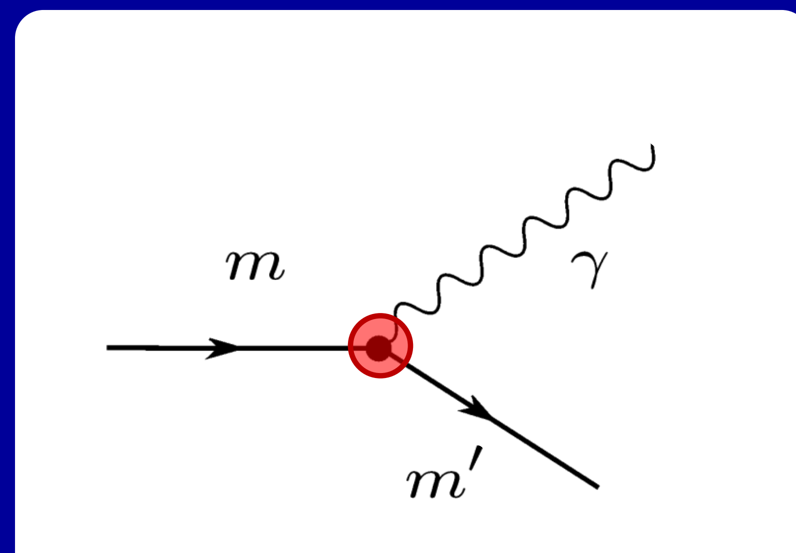
Charmonium radiative transitions



Exotic 1^{-+} ?

Below DD threshold radiative transitions have significant BRs

Meson – Photon coupling

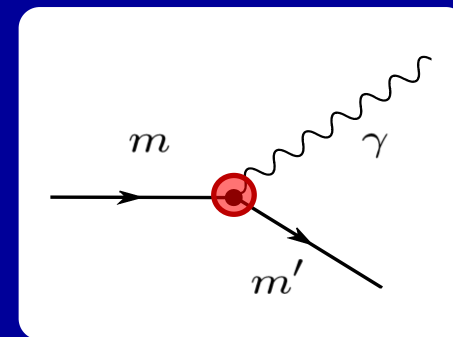


$$< m'|\bar{\psi}(t)\gamma^{\mu}\psi(t)|m >$$

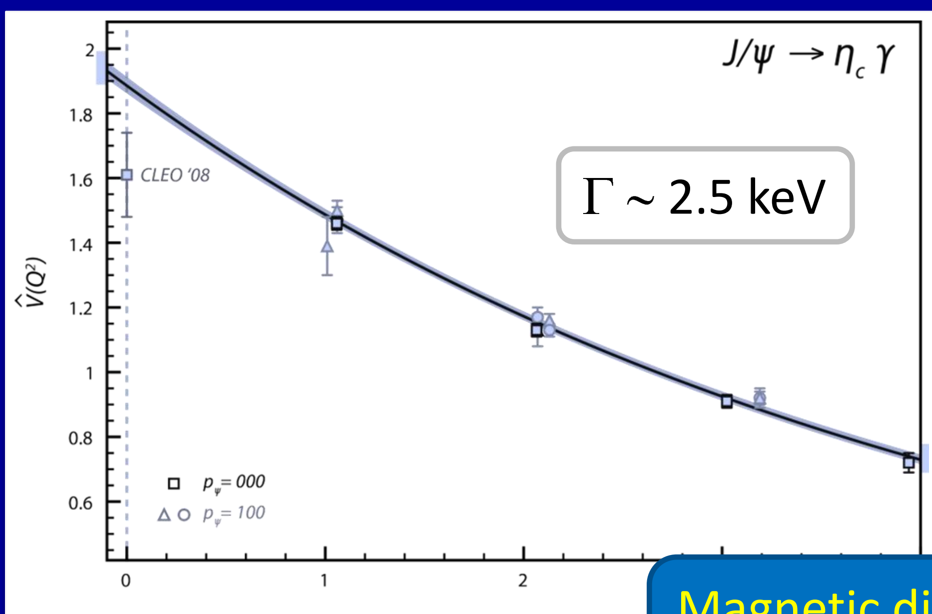
Photocouplings

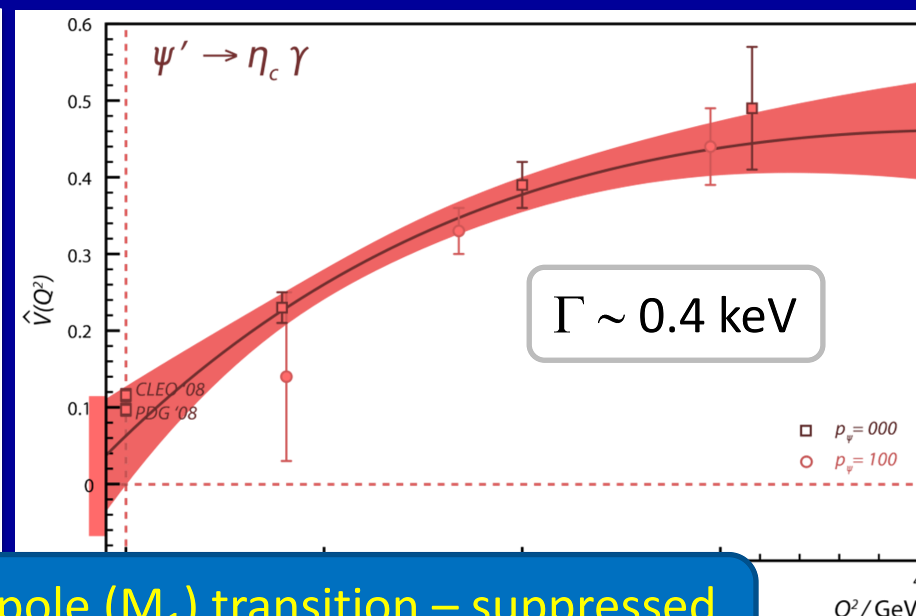
Charmonium (quenched) – testing method

$$C_{ij}(t_f, t, t_i) = < 0|O_i(t_f)\ \bar{\psi}(t)\gamma^\mu\psi(t)\ O_j(t_i)|0 >$$



Conventional vector – pseudoscalar transition

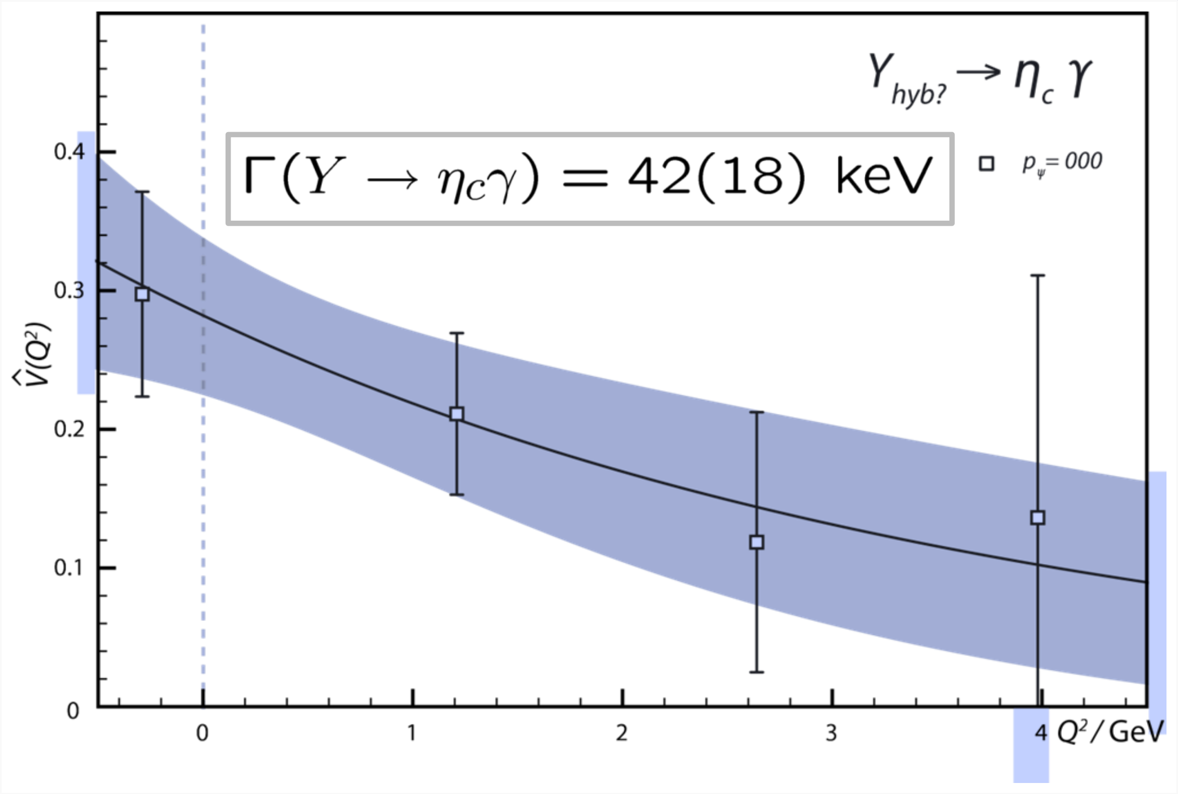




Magnetic dipole (M_1) transition – suppressed (in quark model spin flip ~ $1/m_c$)

PR D79 094504 (2009)

Photocouplings



Much larger than other $1^{--} \rightarrow 0^{-+}$ M_1 transitions

$\Gamma(J/\psi \to \eta_c\gamma) \sim 2$ keV

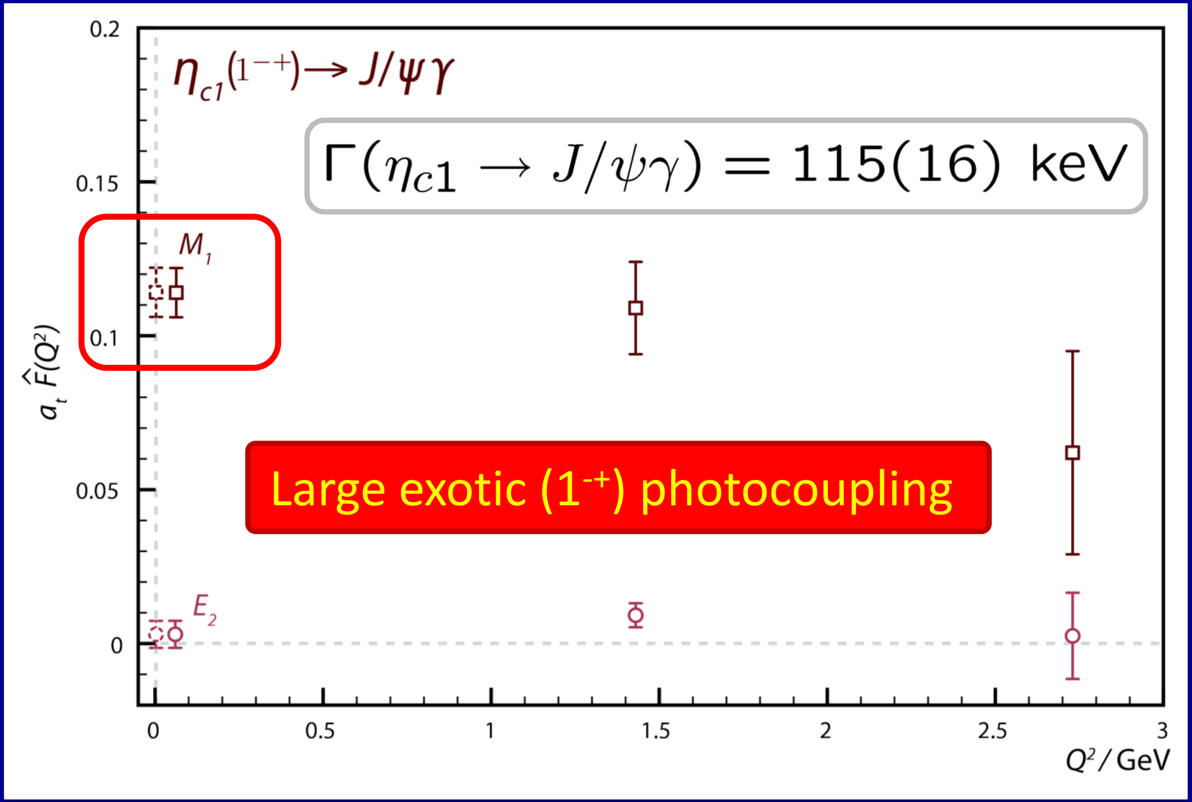
Spectrum analysis suggests a vector hybrid (spin-singlet)

c.f. flux tube model 30 – 60 keV

- Usually M_1 → spin flip (e.g. $^3S_1 \rightarrow {}^1S_0$) → $1/m_c$ suppression
- Spin-singlet hybrid → extra gluonic degrees of freedom

  → M_1 transition without spin flip → not suppressed

Exotic meson photocoupling



Same scale as many measured conventional charmonium transitions

BUT very large for an M_1 transition

$\Gamma(J/\psi \to \eta_c\gamma) \sim 2$ keV

Suggests a spin-triplet hybrid

- Usually M_1 → spin flip (e.g. $^3S_1$ → $^1S_0$) → $1/m_c$ suppression
- Spin-triplet hybrid → extra gluonic degrees of freedom

  → M_1 transition without spin flip → not suppressed

More charmonium results

Tensor – Vector transitions $\chi_{c2}, \chi'_{c2}, \chi''_{c2} \to J/\psi\gamma$

Identify 1^3P_2, 1^3F_2, 2^3P_2 tensors from hierarchy of multipoles E_1, M_2, E_3

Vector – Psuedoscalar $J/\psi, \psi', \psi'' \to \eta_c\gamma$

Scalar – Vector $\chi_{c0} \to J/\psi\gamma$ $\psi', \psi'' \to \chi_{c0}\gamma$

Axial – Vector $\chi_{c1}, \chi'_{c1} \to J/\psi\gamma$

PR **D79** 094504 (2009)

Summary and Outlook

Summary

- **Technology** and **method work**; **spin identification** is possible
- **First spin 4 meson** extracted and confidently identified on lattice
- Isovectors and kaons: **exotics** and non-exotic **hybrids**
- Our first results on **scattering** – map out *E*-dependent phase shift
- **Photocouplings** of excited charmonia

Outlook – ongoing work

- Disconnected diagrams – isoscalars and multi-mesons (I=0,1)
- Multi-meson operators – map out **resonances**
- Baryons
- Photocouplings
- Lighter pion masses and larger volumes

Jefferson Lab