Topics in Meson Spectroscopy

- S-wave mesons below 1 GeV

  Kaminski, Lesniak and Rybicki [ABS288] hep-ph/0109268

  Van Beveren & Rupp [ABS22] hep-ph/0207022

  Furman and Lesniak [ABS284] hep-ph/0203255
- Heavy Quarkonium
- Exotic Hybrids, present & future
- Summary

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S-wave Mesons below 1 GeV

For a recent review see: Close & Tornqvist hep-ph/0204205

The phenomenology of 0^{++} sector reflects the many different components of the Fock space:

$q\bar{q}$

$qq\bar{q}\bar{q}$

Glueballs

MM molecules

Threshold effects

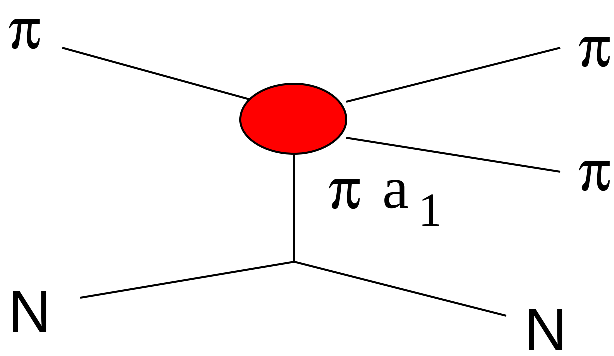
- So it's a real challenge to understand this sector
- 2 steps
  - Analyze the raw data
  - Interpret in terms of underlying models

Information on low energy S-wave ππ scattering from

$p^- p \rightarrow p^+ p^- n$ CERN-Munich experiment [NP B75, 189 (1974)]

CERN-Cracow-Munich [NP B150, 301 (1979); B151, 46 (1979)]

$p^- p \rightarrow p^0 p^0 n$ Brookhaven E852 [PR D64, 07003 (2001)]



- Experiments provide fewer observables than needed to unambiguously describe partial waves
- Therefore make assumptions in PWA
  - Ignore role of nucleon spin
  - Ignore a_1 exchange amplitude
- Results in ambiguities in extraction of phase shifts from PWA

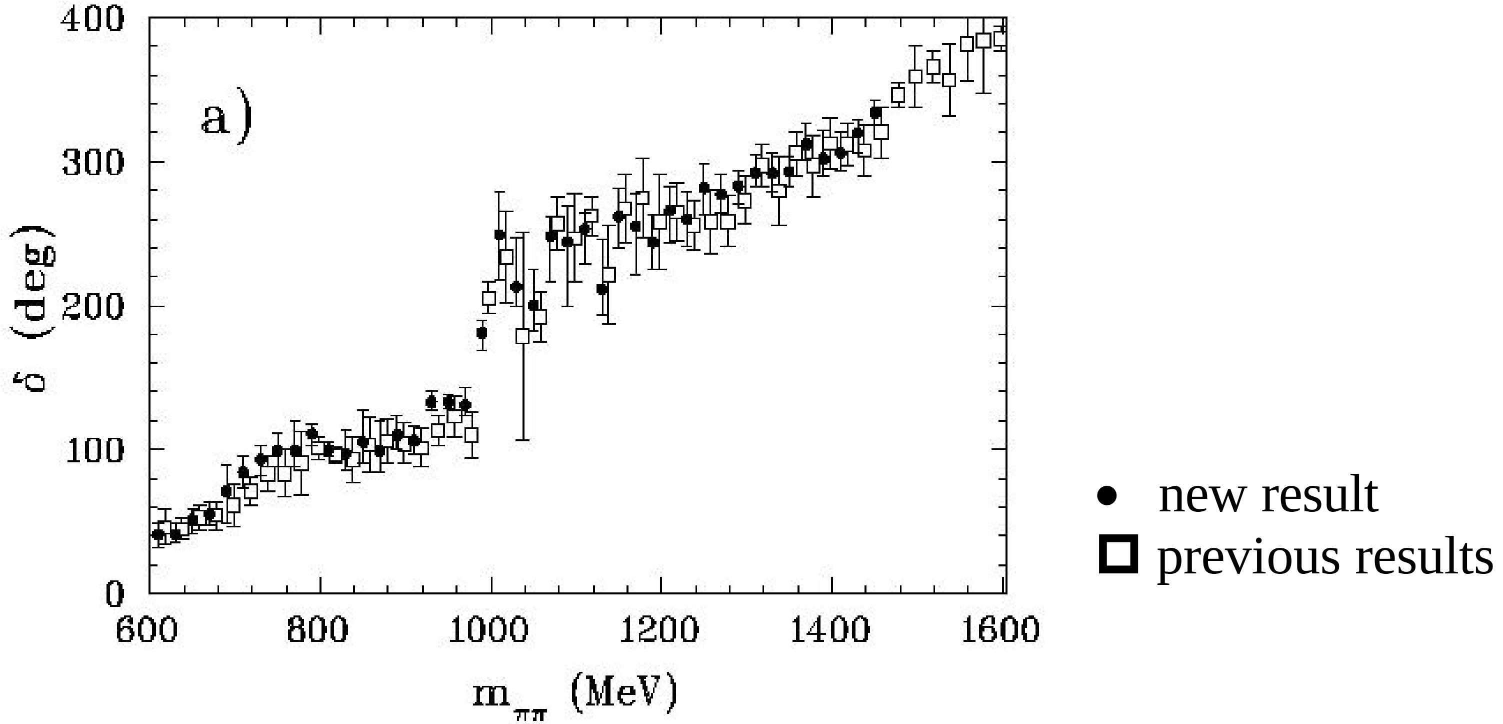
•Kaminski, Lesniak and Rybicki studied this problem

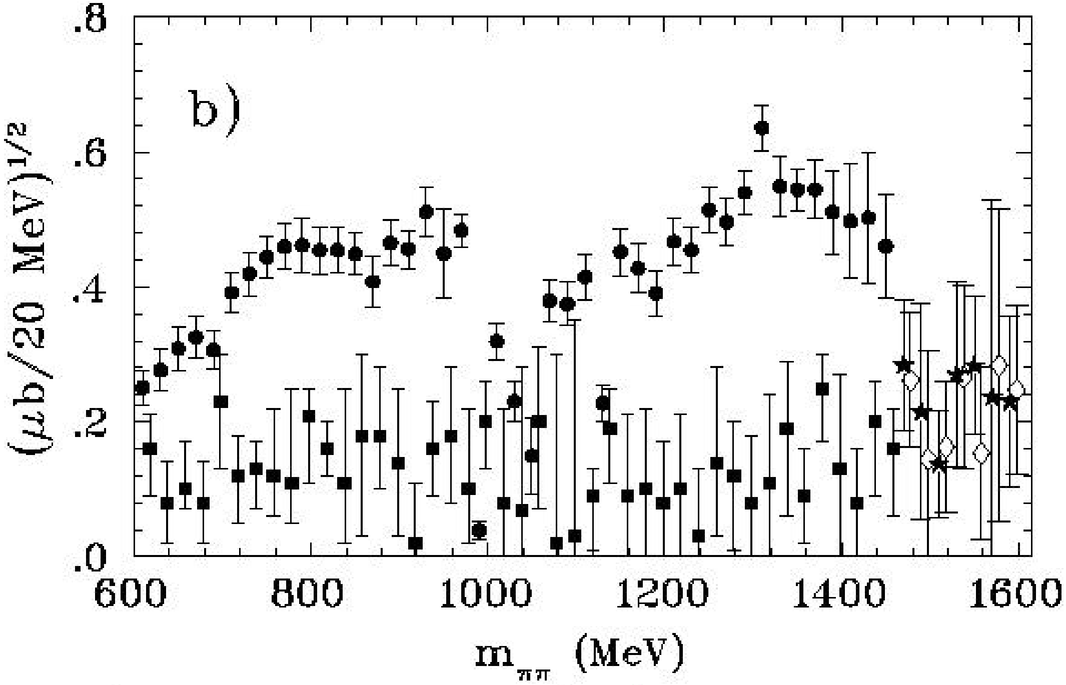
[ABS288: hep-ph/0109268]

•to constrain allowed solutions

- •Apply unitarity
- •Non-observation of inelastic scattering below the $f_0(980)$

•Related $\pi^+\pi^-$ to $\pi^0\pi^0$ amplitudes





Pseudoscalar (circles) and pseudovector (squares) amplitudes

Conclude that a_1 contributions are significantly different from zero (ratio is 0.2-0.3)

- How to describe these phase shifts in terms of true resonances or from the dynamics between KK, $K\pi$, $\pi\pi$?

Van Beveren & Rupp hep-ph/0207022 [ABS22]

- Must look at the meson-meson scattering
- Extract the phase shifts <u>not</u> resonance positions

- Need multichannel approach which includes

  resonances (from constituent qq channels)

  meson-meson interactions

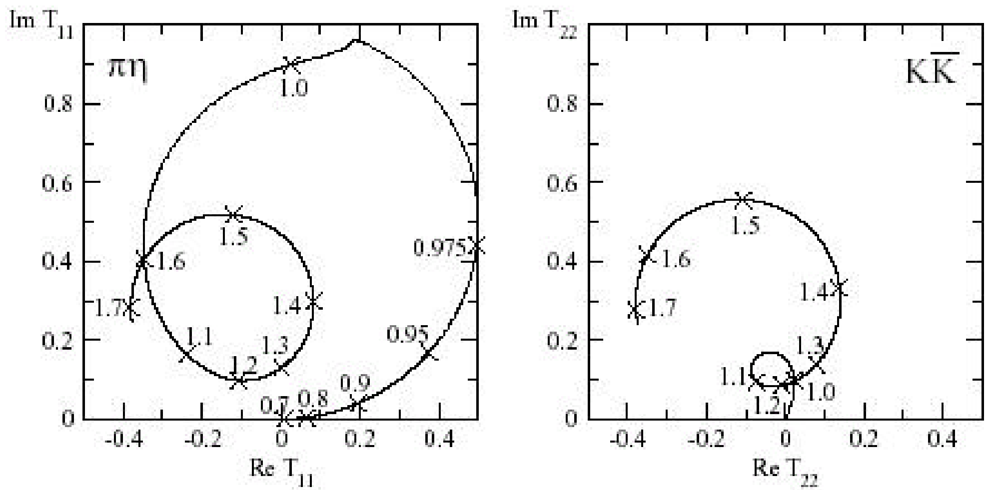
(An interesting and important consequence is that the pole parameters are dependent on the coupling strengths)

Furman and Lesniak, hep-ph/0203255 [ABS284]

Coupled channel model of two a_0 resonances decaying into $\pi\eta$, and KK mesons using Lippman-Schwinger equation:

$$\langle \mathbf{p} \,|\, T \,|\, \mathbf{q} \rangle = \langle \mathbf{p} \,|\, V \,|\, \mathbf{q} \rangle + \int \frac{d^3 s}{(2\pi)^3} \langle \mathbf{p} \,|\, V \,|\, \mathbf{s} \rangle \langle \mathbf{s} \,|\, G \,|\, \mathbf{s} \rangle \langle \mathbf{s} \,|\, T \,|\, \mathbf{q} \rangle$$

where T,V, and G are 2 x 2 matrices



Find significantly different widths in the two channels in agreement with E852 and Crystal Barrel (also used to describe I=0 sector)

- These multichannel approaches
  - Furman & Lesniak hep-ph/0203255 [ABS284]
  - Van Beveren & Rupp hep-ph/0207022 [ABS22]
  - (and others)

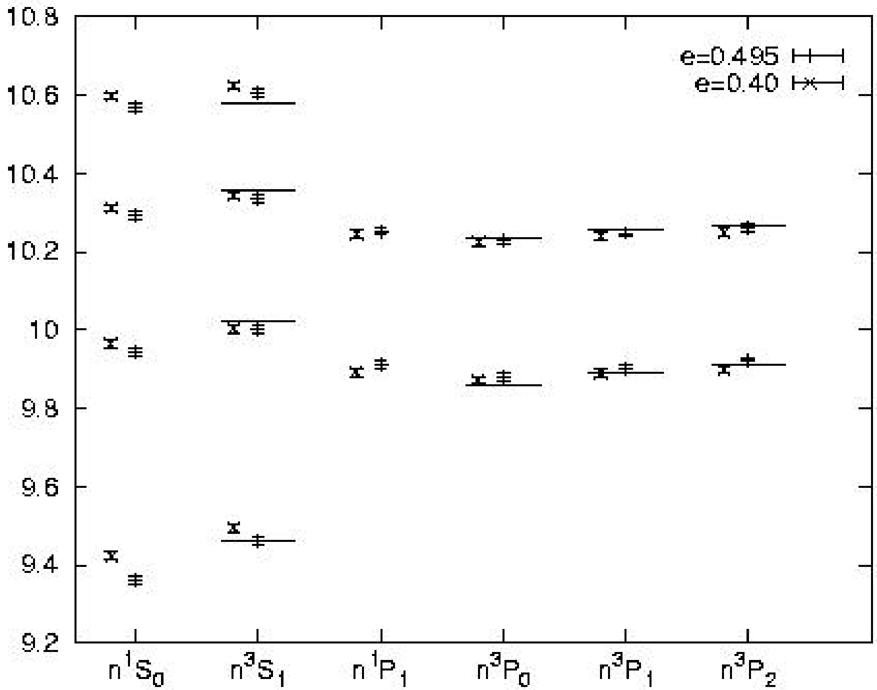
obtain a good description of the low lying S-wave spectrum

My impression is that workers in the field have come to a consensus on the general description if not the details.

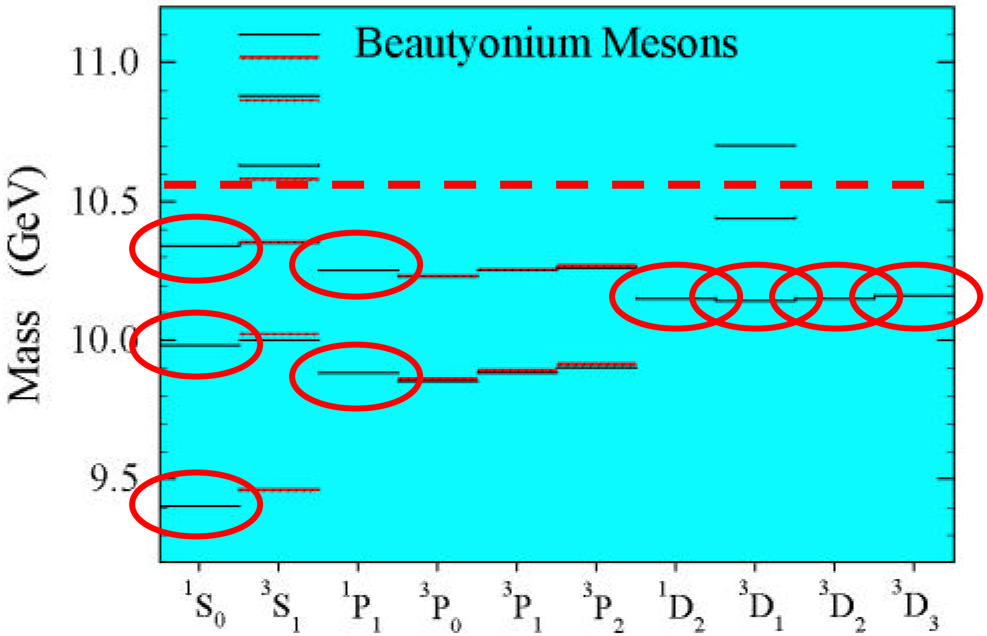
Heavy Quarkonium

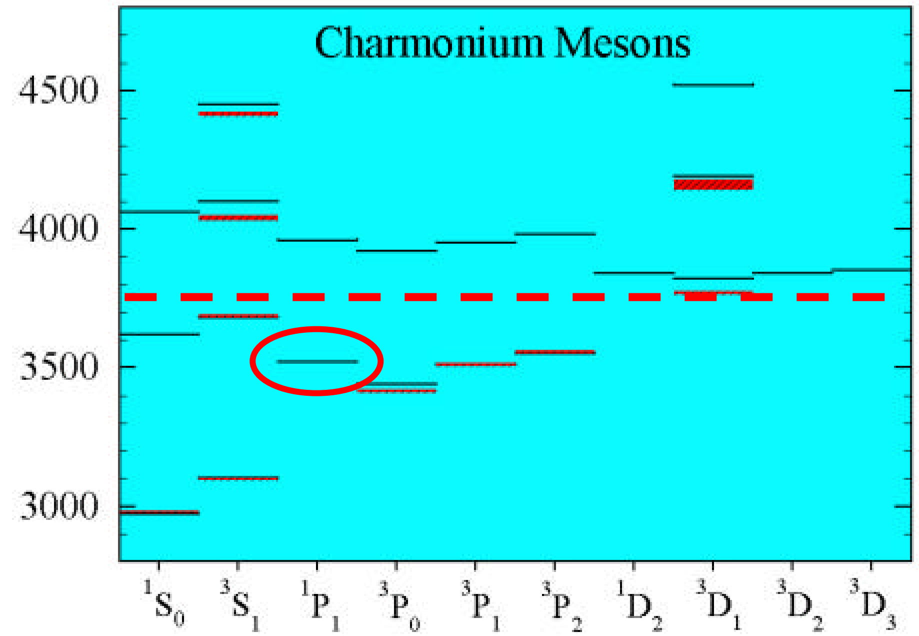
- Recent interest due to
  - CLEO/CESR run on $\Upsilon(3S)$
  - Belle observation of $\eta_c(2S)$ in B decay
- Lattice QCD starting to make quantitative predictions for the hadron mass spectrum
- Need to test Lattice calculations against experiment

$b\bar{b}$ Mass

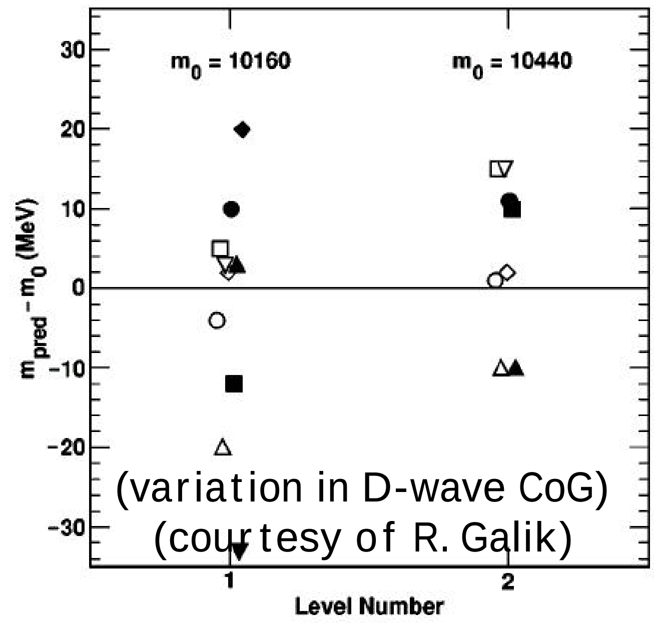


Bali, Schilling and Wachter
Hep-ph/9611226

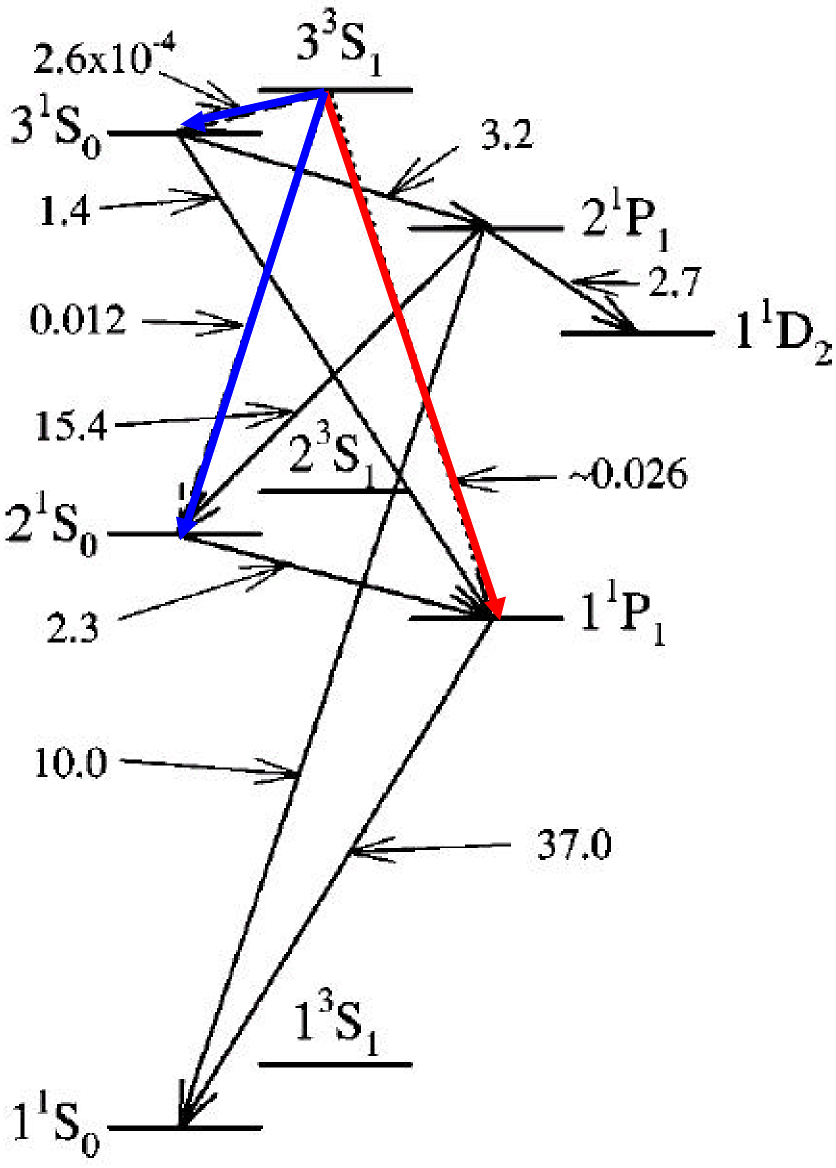




- Numerous states below threshold
- Spin triplet states have been observed
- Few spin singlet states have been seen
- Wide variation in splittings
- Their observation would test the various Calculations
- Expect many of these states to be found in
  - The recent CESR/CLEO run
  - B-decays at B-factories
  - At future CLEO-c/CESR-c



(variation in D-wave CoG)
(courtesy of R. Galik)



- CESR/CLEO has just completed a high statistics run at the $\Upsilon(3S)$
- Expect very rich spectroscopy
- Estimate the radiative widths and BR using quark model

Production of the $h_b(nS)$ states

S.G + J. Rosner, Phys Rev D64, 074011 (2001)

Proceeds via magnetic dipole (M1) transitions:

$$Y(nS) \to \eta(n'S) + \gamma$$

$$\Gamma(^3S_1 \to {}^1S_0 + g) = \frac{4}{3} a \frac{e_Q^2}{m_Q^2} \left| \langle f | j_0(kr/2) | i \rangle \right|^2 w^3$$

- Hindered transitions have large phase space
- Relativistic corrections resulting in differences in $^3S_1$ and $^1S_0$ wavefunctions due to hyperfine interaction

	Transition	BR (10^{-4})
Υ(3S)		
(Γ_{tot}=52.5 keV)	$\rightarrow 3^1S_0$	0.10
	$\rightarrow 2^1S_0$	4.7
	$\rightarrow 1^1S_0$	25
Υ(2S)	$\rightarrow 2^1S_0$	0.21
(Γ_{tot}=44 keV)	$\rightarrow 1^1S_0$	13
Υ(1S)	$\rightarrow 1^1S_0$	2.2
(Γ_{tot}=26.3 keV)		

- Expect substantial rate to produce η_b's
- Also $\Upsilon(3S) \rightarrow h_b(^1P_1)\ \pi\pi \rightarrow \eta_b + \gamma + \pi\pi$

BR=0.1-1% BR = 50%

[Kuang & Yan PRD24, 2874 (1981); Voloshin Yad Fiz 43, 1571 (1986)]

Production of the singlet P-wave states

S.G + J. Rosner, PR D66 in press

Two interesting cascades:

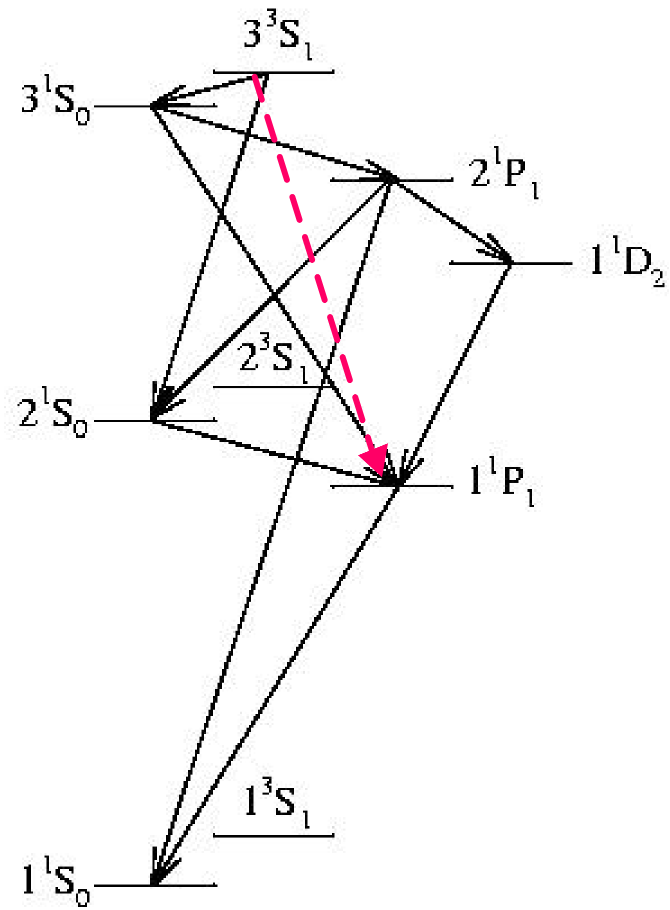
M1 E1 E1

$$\Upsilon(3S) \to \eta_b(2S) + \gamma \to h_b + \gamma\gamma \to \eta_b + \gamma\gamma\gamma$$

$$\psi(2S) \to \eta_c(2S) + \gamma \to h_c + \gamma\gamma \to \eta_c + \gamma\gamma\gamma$$

$$\Upsilon(3S) \to h_b + \pi \to \eta_b + \gamma + \pi$$

$$\psi(2S) \to h_c + \pi \to \eta_c + \gamma + \pi$$



Need branching ratios and hence partial widths

$$\Gamma[h(2^1S_0) \to h_b(1^1P_1) + g\,] = \frac{4}{3} a e_Q^2 \left| \langle {}^1P_1 | r | {}^1S_0 \rangle \right|^2 w^3 = 2.3 \text{ keV}$$

$$\Gamma[h_b(1^1P_1) \to h_b(1^1S_0) + g\,] = \frac{4}{9} a e_Q^2 \left| \langle {}^1S_0 | r | {}^1P_1 \rangle \right|^2 w^3 = 37 \text{ keV}$$

$$\Gamma[h_b(2^1S_0) \to gg] = \frac{27p}{5(p^2 - 9) a_S} \times \Gamma[\Upsilon(2^3S_1) \to ggg] = 4.1 \pm 0.7 \text{ MeV}$$

BR($3^3S_1\ \gamma \to 2^1S_0\ \gamma$)=4.7 x 10^{-4} and BR($2^1S_0\ \gamma \to 1^1P_1\ \gamma$)=5.7x 10^{-5}

BR[$\Upsilon(3S) \to 2^1S_0\ \gamma \to 1^1P_1\ \gamma$] = 2.6 x 10^{-7} $\Rightarrow$ 0.3 events/10^6 $\Upsilon(3S)$'s

Similarly

BR[$\psi(2S) \to 2^1S_0\ \gamma \to 1^1P_1\ \gamma$] = 10^{-6} $\Rightarrow$ 1 event /10^6 $\Upsilon(3S)$'s

(A challenge for the experimentalists!)

A more promising approach utilizes:

$$\mathrm{BR}[\Upsilon(3S) \to \pi\ 1^1P_1] = 0.1\%$$

$$\Gamma[h_b(1^1P_1) \to h_b(1^1S_0) + g] = \frac{4}{9} a e_Q^2 \left| \left\langle {}^1S_0 \middle| r \middle| {}^1P_1 \right\rangle \right|^2 w^3 = 37 \text{ keV}$$

$$\Gamma[h_b(1^1P_1) \to ggg] = \frac{5}{2n_f} \Gamma[\chi_{b1}(1^3P_1) \to q\bar{q}g] = 50.8 \text{ keV}$$

$\mathrm{BR}[\Upsilon(3S) \to \pi\ 1^1P_1 \to 1^1S_0\,\gamma] = 4 \times 10^{-4} \Rightarrow$ 400 events/10^6 $\Upsilon(3S)$'s

Similarly

$\mathrm{BR}[\psi(2S) \to \pi\ 1^1P_1 \to 1^1S_0\,\gamma] = 3.8 \times 10^{-4} \Rightarrow$ ~400 event /10^6 $\psi(2S)$'s

Expect ~400 events!

Production of the D-wave states

- By direct scans in e^+e^- to produce $^3D_1$
- In e.m. cascades: $\Upsilon(3S) \rightarrow \gamma\, \chi'_b \rightarrow \gamma\gamma\, ^3D_J$
- Some 4γ cascades with observable # of events/10^6 $\Upsilon(3S)$'s:

Cascade	Events
$3^3S_1 \rightarrow 2^3P_2 \rightarrow 1^3D_3 \rightarrow 1^3P_2 \rightarrow 1^3S_1$	7.8
$3^3S_1 \rightarrow 2^3P_2 \rightarrow 1^3D_2 \rightarrow 1^3P_1 \rightarrow 1^3S_1$	2.7
$3^3S_1 \rightarrow 2^3P_1 \rightarrow 1^3D_2 \rightarrow 1^3P_1 \rightarrow 1^3S_1$	20
$3^3S_1 \rightarrow 2^3P_1 \rightarrow 1^3D_1 \rightarrow 1^3P_1 \rightarrow 1^3S_1$	3.3

S.G + J. Rosner, Phys Rev D64, 097501 (2001)

Expect ~38 events /10^6 $\Upsilon(3S)$ via ^3D_J

- The e^+e^- final states leads to less background
- $\mu^+\mu^-$ final states also contribute if μ's are identified

In the CESR run just completed expect to see evidence for the

2^1S_0, 1^1S_0, 1^1P_1, 1^3D_2

And maybe the

3^1S_0, 1^3D_1 and 1^3D_3

Would represent a significant increase in our knowledge of quarkonium and provide an important benchmark against which to measure the results of lattice QCD

Charmonium in B decays

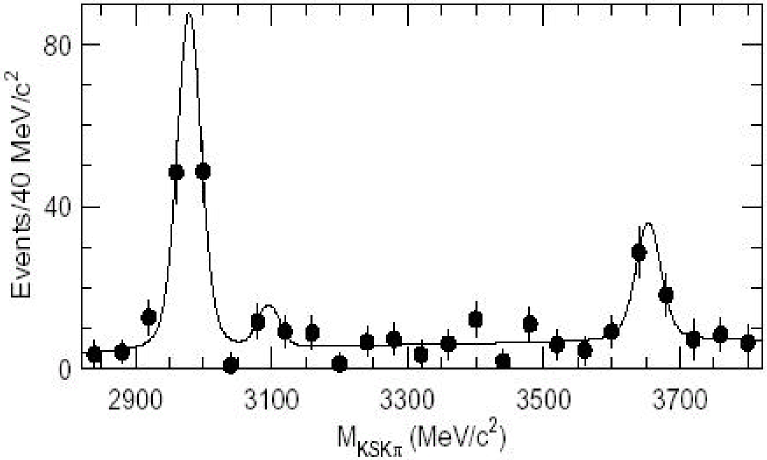
Recent observation by Belle of

$\eta_c(2S)$ in: $B \to \eta_c(2S) K \to K K_S K^- \pi^+$

M=3654 ±6 (stat) ± 8 (sys) MeV

Γ<55 MeV (90% C.L.)

[hep-ex/0206002]



Belle had previously reported the observation of

$B^+ \to \chi_{c0} K^+$ PRL 88, 031802 (2002)

$B \to \chi_{c2} X$ hep-ex/0202038

And $B \to \chi_{c1} K$ has been observed by both BaBar and Belle

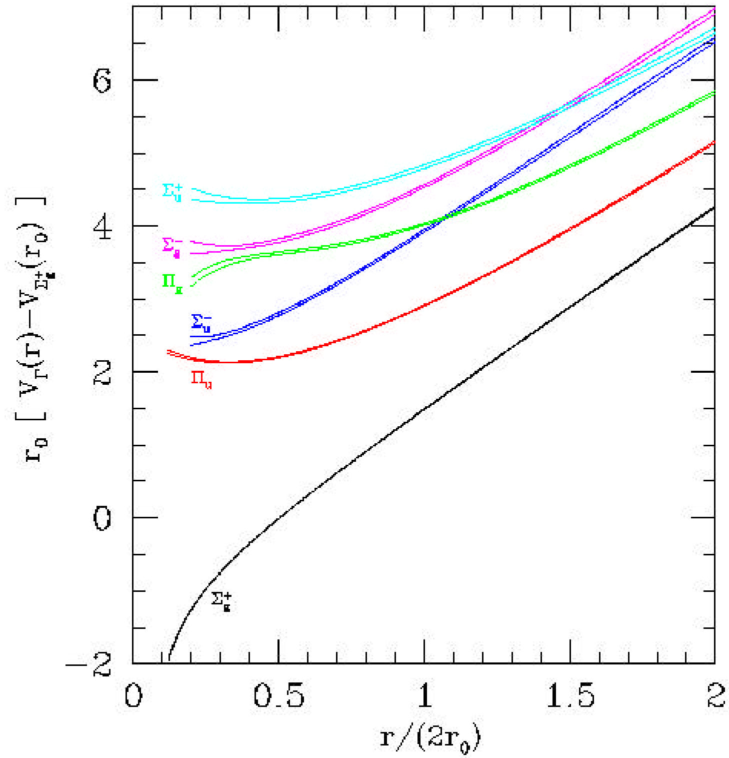
Suzuki proposed to search for the h_c in $B \to h_c X$ [hep-ph/0204043]

[see also Eichten Lane & Quigg hep-ph/0206018; Gu hep-ph/0206002]

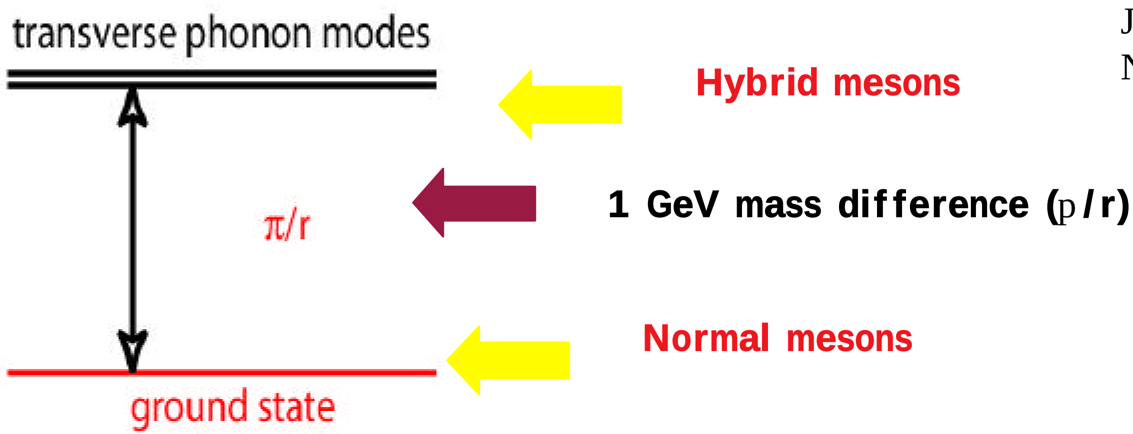
Other related work by Hao Liu & Chao hep-ph/0206226

Exotic Hybrids

- Quarks move in effective potentials of adiabatically varying state of flux tubes
- Lowest excited adiabatic surface corresponds to transverse excitations



Juge, Kuti, and Morningstar,
Nucl. Phys. (Proc. Suppl.) **63A-C**, 326 (1998)



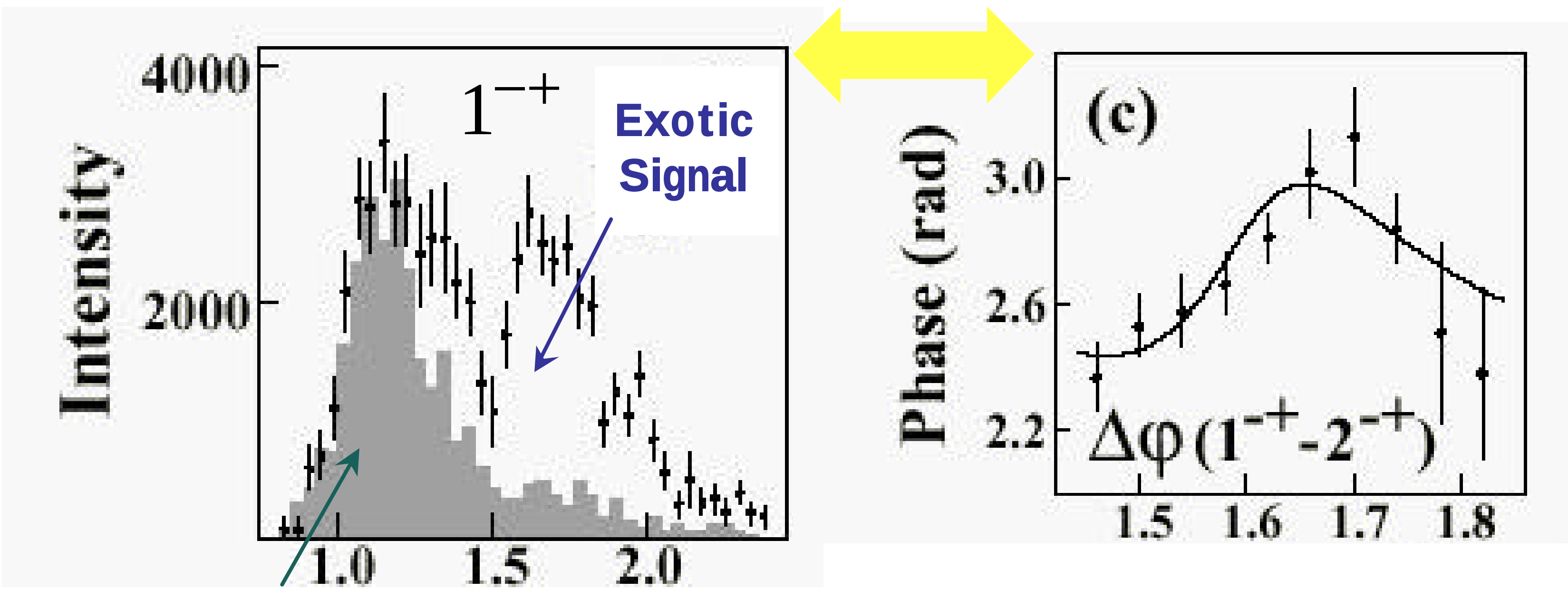
Lowest mass hybrids at ~1.9 GeV

Doubly degenerate:

J^{PC} = 0^{+-} 0^{-+} 1^{+-} 1^{-+}
2^{+-} 2^{-+} 1^{++} 1^{--}

An Exotic Signal in E852

Correlation of Phase & Intensity



$M(\pi^+\pi^-\pi^-)\ \left[\mathrm{GeV}/c^2\right]$

Leakage From Non-exotic Wave

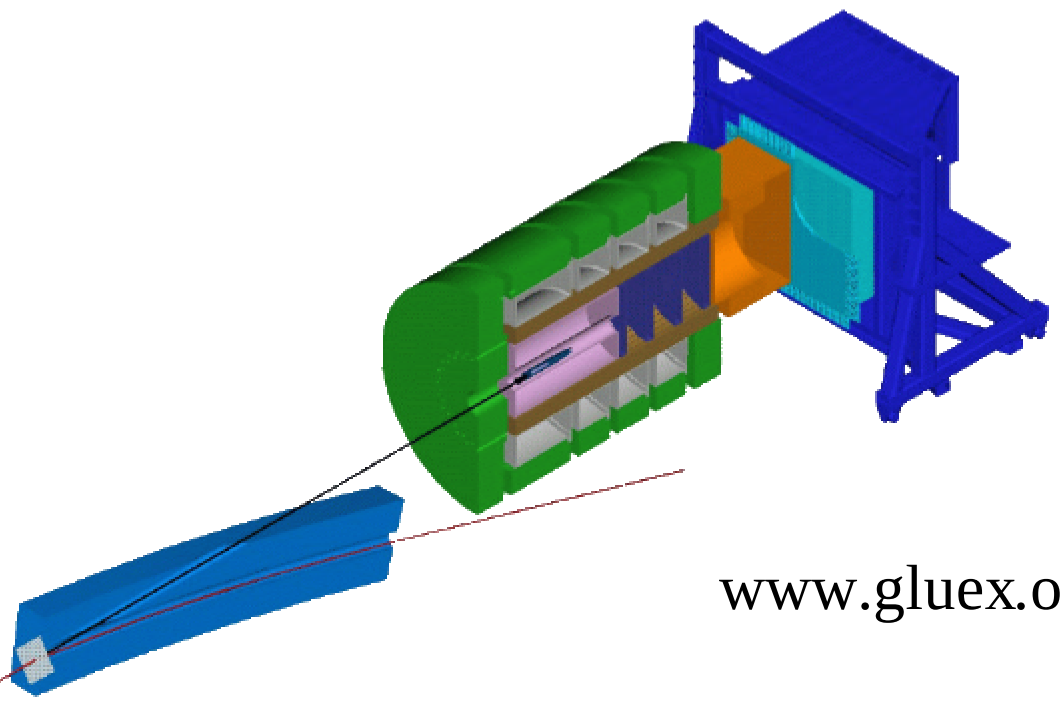
due to imperfectly understood acceptance

What about the future?

GLUEX CITATIONS PERIMENT

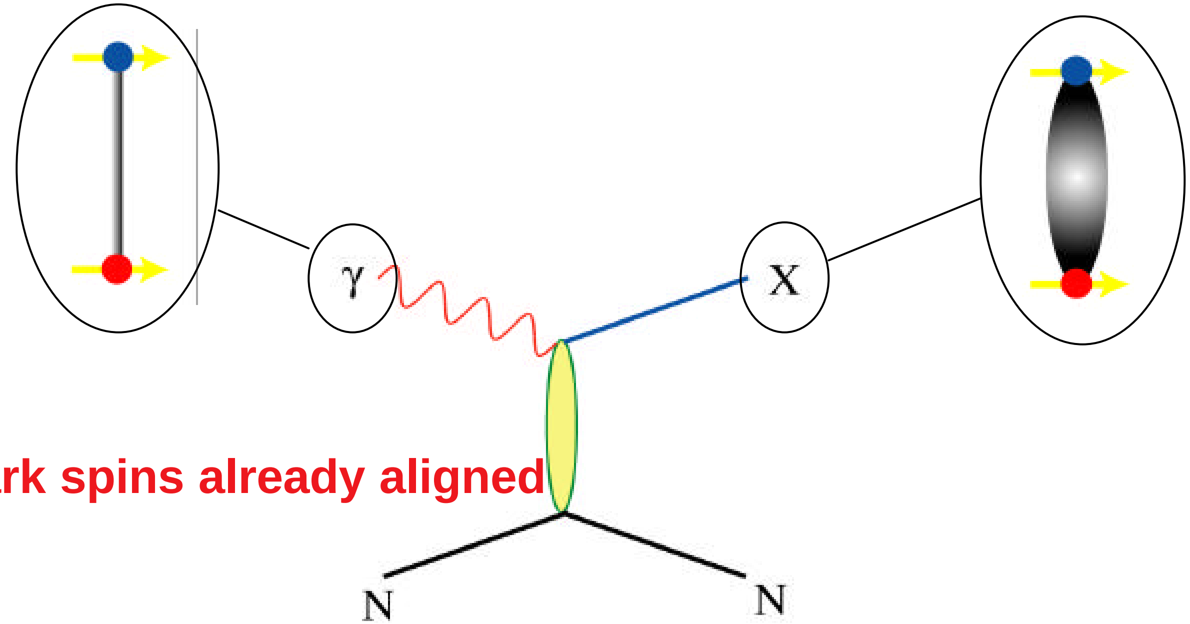
Hall D at Jefferson Lab

"Searching for Exotic Gluonic Excitations"



www.gluex.org

Photoproduction:



Quark spins already aligned

Production of exotic hybrids favored. Almost no data available

Optimum photon energy is about 9 GeV

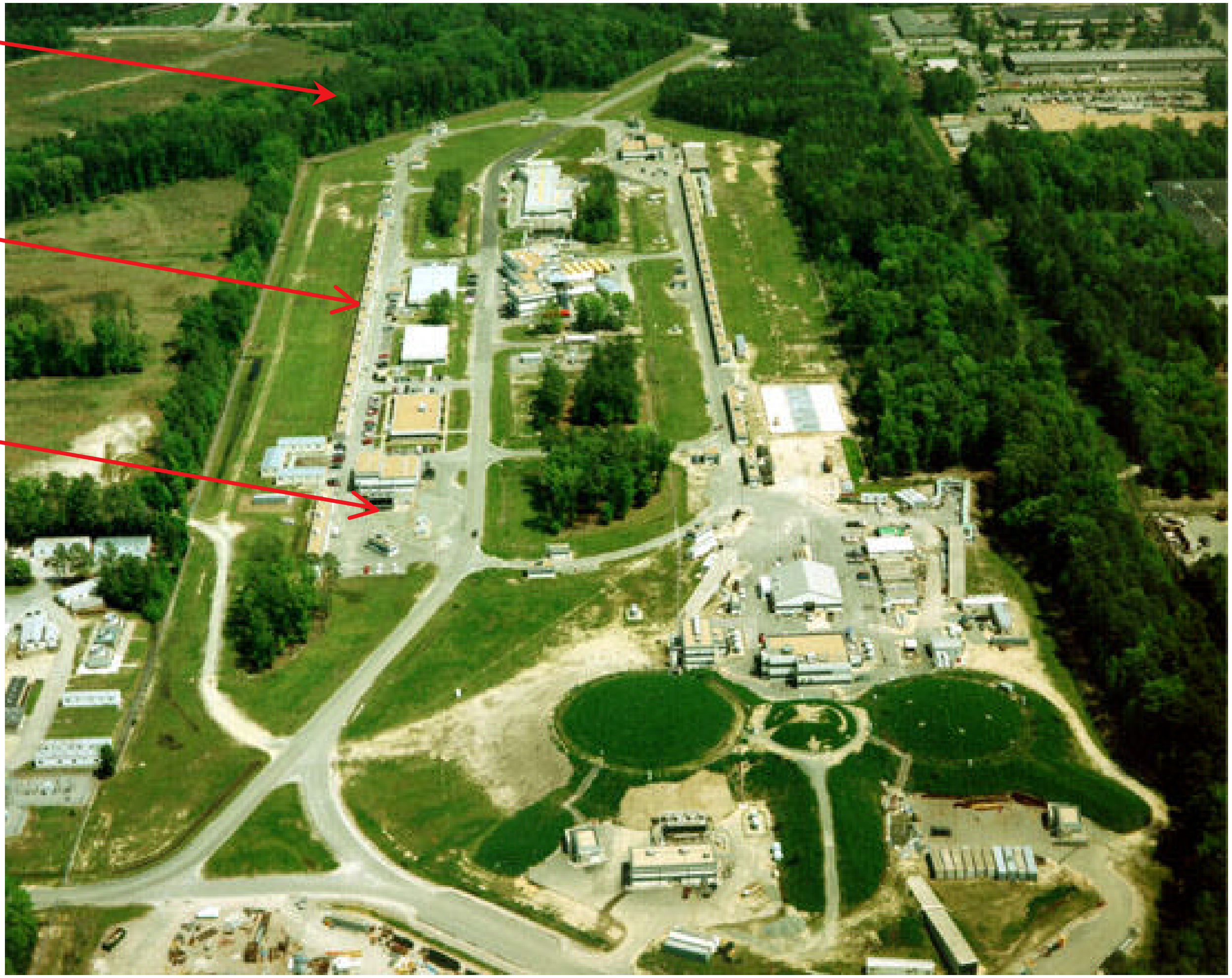
Proposal to upgrade CEBAF to 12 GeV
Produce photons through coherent bremsstrahlung

The JLab Accelerator Complex

Hall D will be located here

Linac

Arc



Construction start – 2004   Physics - 2008

Summary

- S-wave $\pi\pi$ scattering far from a closed book but definite progress in our understanding
- Expect great progress in heavy quarkonium spectroscopy
- Confirmation and mapping out of hybrid-meson spectrum is one of the most important qualitative question facing hadron spectroscopy
- Theory and Experiment go hand in hand to fully understand ***Soft QCD***