Meson spectroscopy and the 'missing' valence glue of QCD

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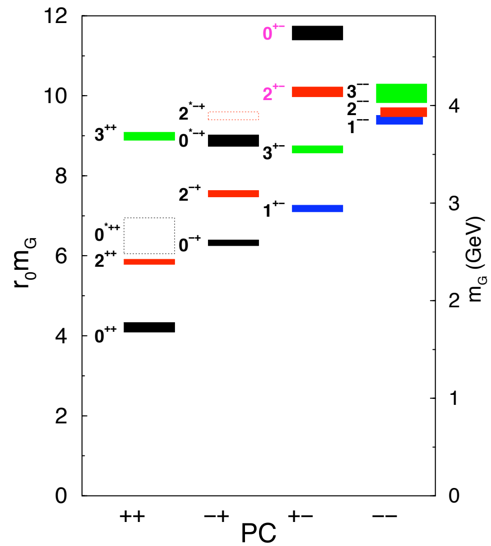
Meson spectrum

- established meson states have J^{PC} quantum numbers of *fermion-antifermion* Fock-state, $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{-+} \ldots$, and no states with isospin > 1 or |strangeness| > 1

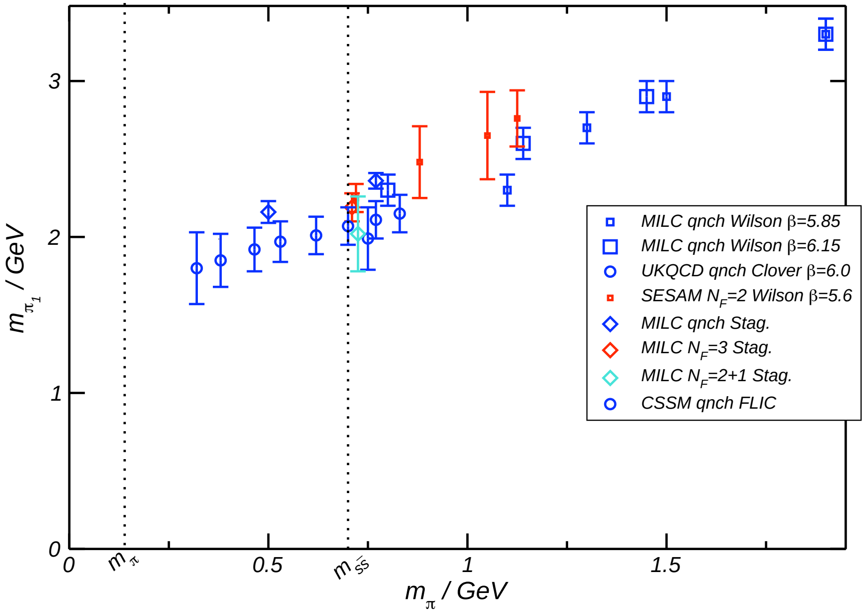
- a reasonable interpretation is quasi-particle quarks and the gluonic ground state
- QCD is non-abelian and non-perturbative at this scale, so where are the excitations of the gluonic field?
  - e.g. glueball spectrum in pure SU(3) Yang-Mills
  - glueball phenomenology cloudy for QCD
    mixing with 'quark'-'antiquark' states



- potentially cleaner sector - *hybrid mesons*: valence quarks + excited glue
  - extra gluonic-field quantum numbers introduces new J^{PC} combinations
    - *"exotic"* $0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \ldots$

J^{PC} exotic mesons

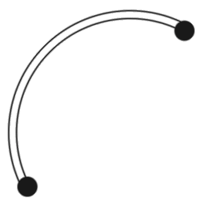
- alternative mechanism for J^{PC} exotic is higher quark Fock state, e.g. $qq\bar{q}\bar{q}$
  - generically lead to flavour exotics - so easy to tell apart from hybrids
  - lattice QCD at heavy quark masses has valence glue states with exotic J^{PC}
- lattice QCD at 'lower' quark masses has addressed the mass of the lightest 1^{-+} state



- extrapolation from this 'bound-state' region to the 'resonance' region not trivial, but indications are for a state in the 1.5-2.5 GeV region
  - in accord with phenomenological flux-tube model

Flux-tube model

- quantum mechanical model, based on the idea that the gluonic field in a meson forms a tube between the quarks
  - hybrids correspond to oscillatory excitation of tube
- prevailing model of hybrids, due somewhat to near 'complete' phenomenology
  - ***spectrum***

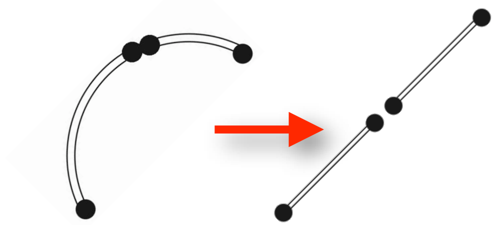


$$\delta m = \left\langle \frac{\pi}{r} \right\rangle$$

$$m_{\mathcal{H}} \sim 2\,\mathrm{GeV}$$

$1^{-+}, 0^{+-}, 2^{+-}$ *+ non-exotics*

  - ***hadronic decays***

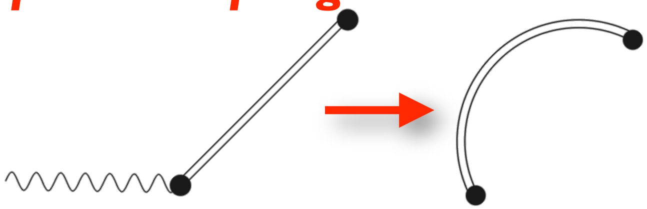


$\Rightarrow$ *"S+P" rule*

$\pi_1 \to \pi\, b_1$

$\pi_1 \not\to \pi\, \rho$

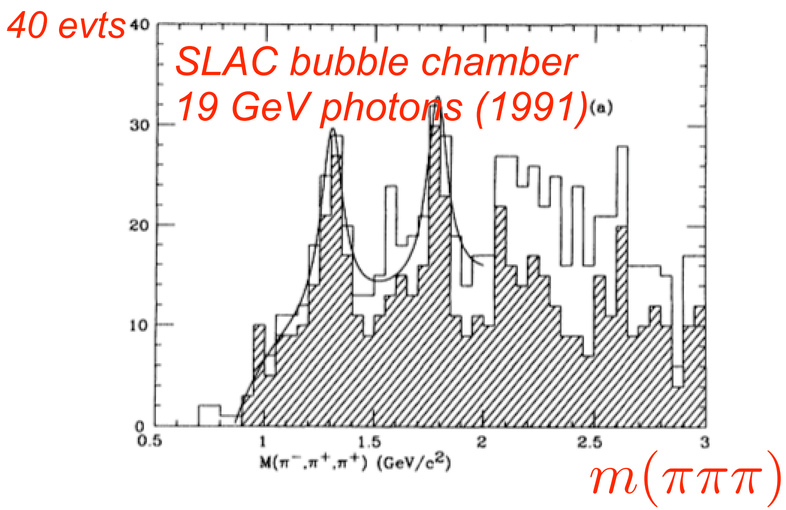
  - ***photocouplings***

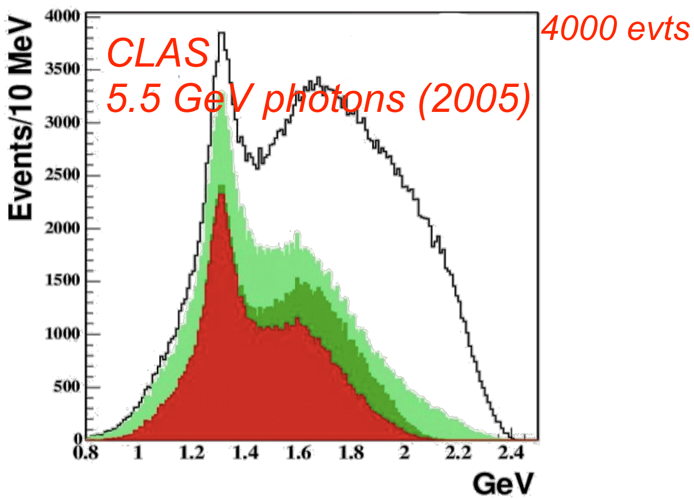


$$\frac{A_{\mathcal{H}}}{A_{\mathcal{C}}} \sim \frac{\sqrt{b}}{m_q} \sim \mathcal{O}(1)$$

Photoproduction

- Next talk will inform you of the status of pion beam experiments
  - results have been tantalising, but inconclusive
- Photoproduction as a meson factory not previously considered



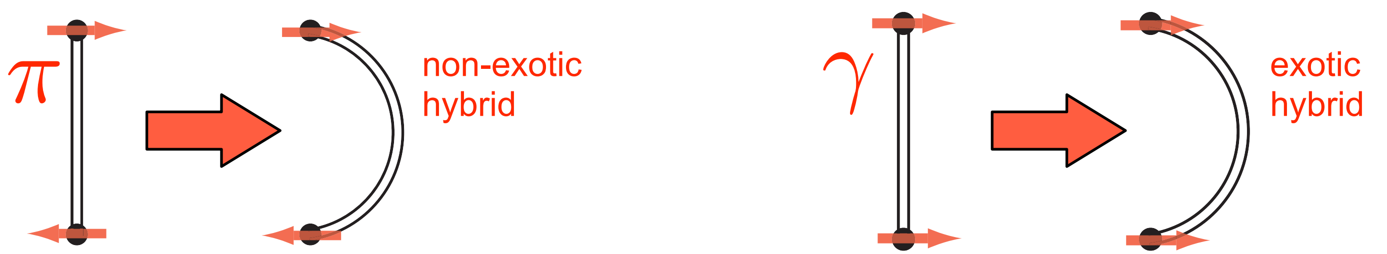


- photocouplings (vs pion couplings) likely to lead to different weighting of meson states - new spectroscopic lever-arm

- several arguments suggest photoproduction may be favourable for exotic hybrid mesons

Photoproduction of exotic J^{PC}

- at the hadron-level, using a beam with $J^{PC} = 1^{--}$ we'd expect diffractive production of exotic 2^{+-}
- at the quark-level, we note that the flux-tube model (and many others) have exotic hybrids with $S_{q\bar{q}} = 1$
  - to the extent that spin-flip is suppressed, using a photon (virtual vector meson) beam with $S_{q\bar{q}} = 1$, is preferred to a pion beam with $S_{q\bar{q}} = 0$



- explicit calculations in the flux-tube model, coupling photons to quarks indicates hybrid photocouplings unsuppressed relative to conventional photocouplings
  - conventional radiative decay rate (measured) $\Gamma(b_1^+ \to \pi^+\gamma) = 230(80)\,\mathrm{keV}$
  - exotic hybrid radiative decay rates (flux-tube model)
    - $\Gamma(\pi_1^+ \to a_2^+\gamma) \sim 90\,\mathrm{keV}$
    - $\Gamma(b_{0,2}^+ \to \rho^+\gamma) \sim 2000(800)\,\mathrm{keV}$
- lattice QCD calculations of photocouplings underway at Jefferson Lab

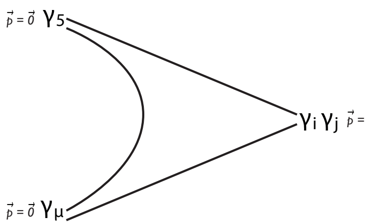
Exotic hybrid decay widths

- several flux-tube model variants make predictions for hadronic widths

$\Gamma_{tot}/\mathrm{MeV}$	PSS (alt)	PSS (std)	PSS (2.0)	IKP
π_1/η_1	121 / 73	81 / 59	168 / 158	117 / 107
b_0/h_0	108 / 115	247 / 59	429 / 262	665 / 94
b_2/h_2	7 / 5	5 / 12	11 / 74	248 / 166

  - note that mainly these numbers are reasonably small

- recent relevant lattice QCD result from C.Michael & C.McNeile
  - compute a hadronic three-point function 'on-shell', e.g. $b_1 \to \omega\pi$ with $m(b_1) \approx m(\omega) + m(\pi)$
  - extract an 'on-shell' coupling - difficultly is in extrapolation to the physical decay kinematics



    - Close & Burns applied flux-tube model style form-factors and found

$$\Gamma = |\vec{k}|\,\bar{g}^2 \left(1 - \frac{2|\vec{k}|^2}{9\beta^2}\right)^2 e^{-\frac{|\vec{k}|^2}{6\beta^2}} = 150(80)\,\mathrm{MeV}$$

      - similarly for exotic decays:

$$\Gamma(\pi_1 \to b_1\pi) \approx 70(40)\,\mathrm{MeV}$$
$$\Gamma(\pi_1 \to \text{"}f_1\text{"}\pi) \approx 20(15)\,\mathrm{MeV}$$

- general large N_c result from Cohen - exotic hybrid widths are same order as conventionals

Summary

- photoproduction as a meson factory has not hitherto been explored
- it is likely to offer a different weighting to meson states to the traditional pion beam production, and may well help disentangle some confused regions of spectroscopy
- one of the most exciting possibilities is the production of exotic hybrid mesons
  - flux-tube model predictions have been made, suggest healthy production rates and manageable total width
  - lattice QCD now reaching the stage where phenomenologically relevant statements can be made

- a custom designed experiment coupled with a strong analysis program will realise the possibilities in photoproduction
  - ***GlueX***