The Phenomenology of Glueball and Hybrid Mesons*

Workshop on Future Physics with COMPASS

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1. Why?
2. Glueballs
3. Hybrids
4. Summary

*For a recent review see Godfrey and Napolitano, Rev Mod Phys 71, 1411(1999)

Why is this important?

The New York Times
ON THE WEB

August 15, 2000

10 Physics Questions to Ponder for a Millenium or Two

One of those questions:

How can we understand quark and gluon confinement in Quantum Chromodynamics?

Meson Spectroscopy is the ideal laboratory to accomplish this

A fundamental question to this is end is

"How does glue manifest itself in the soft QCD regime?"

Models of hadron structure

- Lattice QCD (C. McNeille)
- Bag Model
- Flux tube model
- Sum rules approach

predict new forms of hadronic matter with the glue degree of freedom manifest explicitly:

- Glueballs
- Hybrids

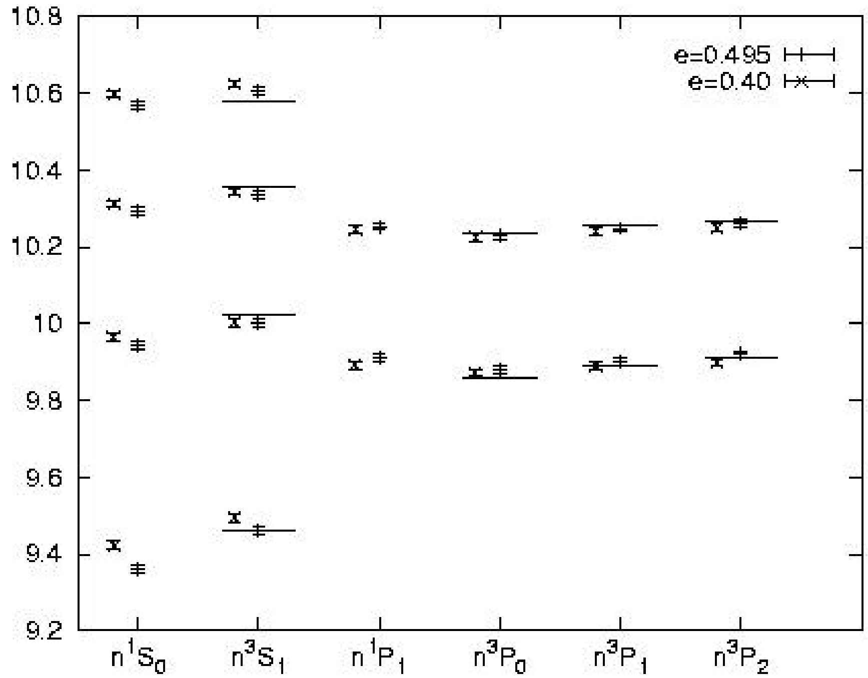
and in addition: Multiquark States

Much theoretical progress:

- Lattice QCD is a first principles calculation starting from the QCD lagrangian (C. McNeille)

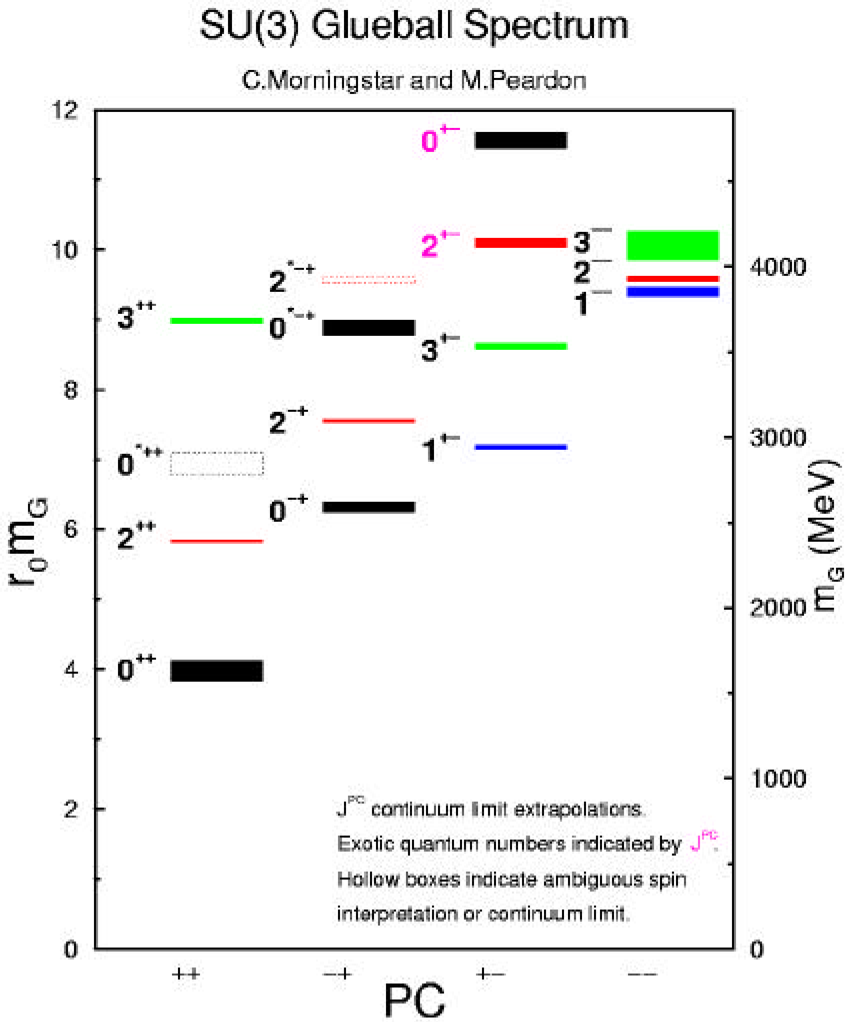
- Gives a good description of the observed spectrum or heavy quarkonium

- Potential description works well



Bali, Schilling and Wachter
hep-ph/9611226

Glueballs:



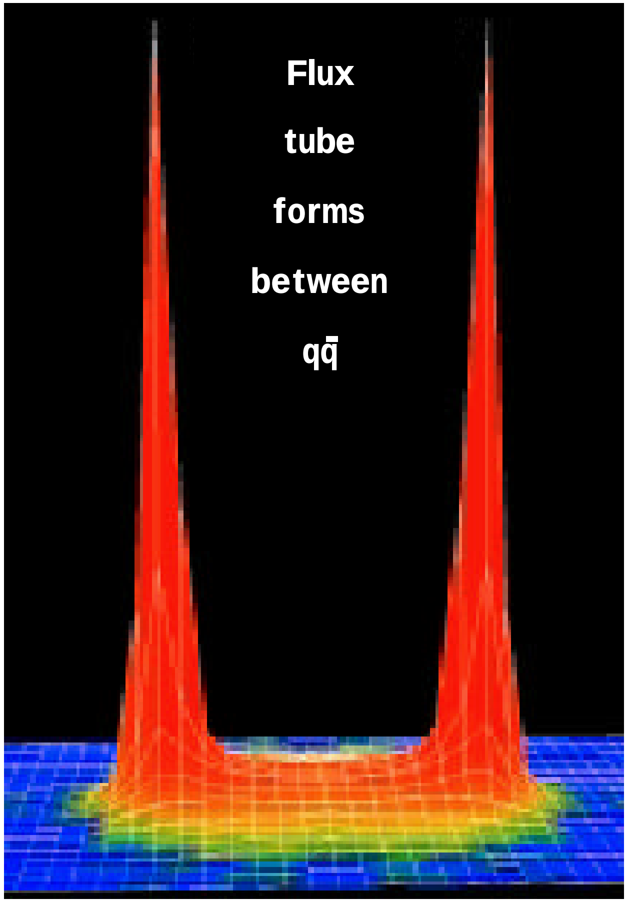
- Need to unambiguously observe glueballs and measure their properties

- This will test QCD

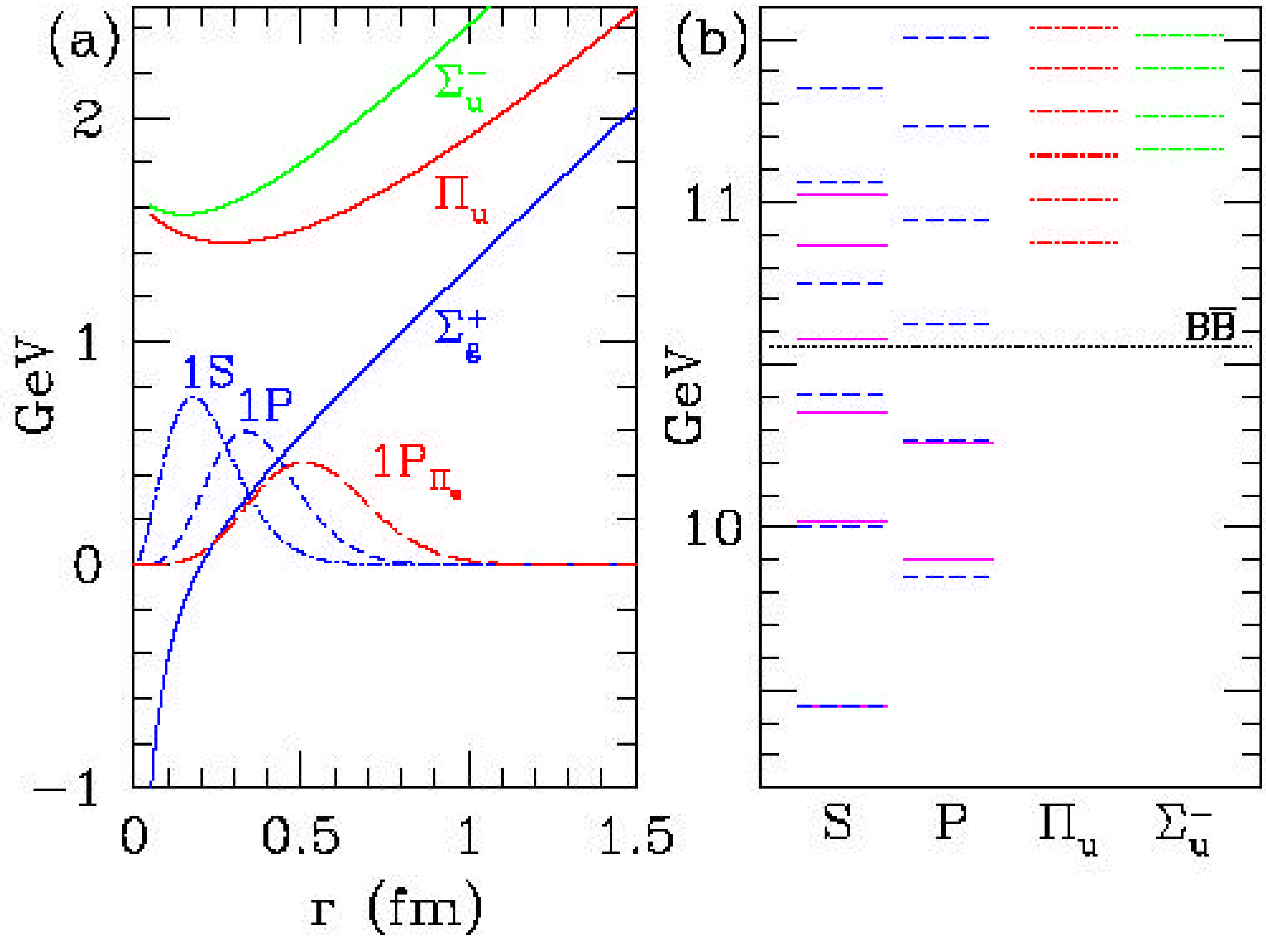
- But deeper than this it builds up confidence that we really can do nonperturbative field theory calculations

Hybrids:

Lattice calculations supports the flux tube picture:



From G. Bali

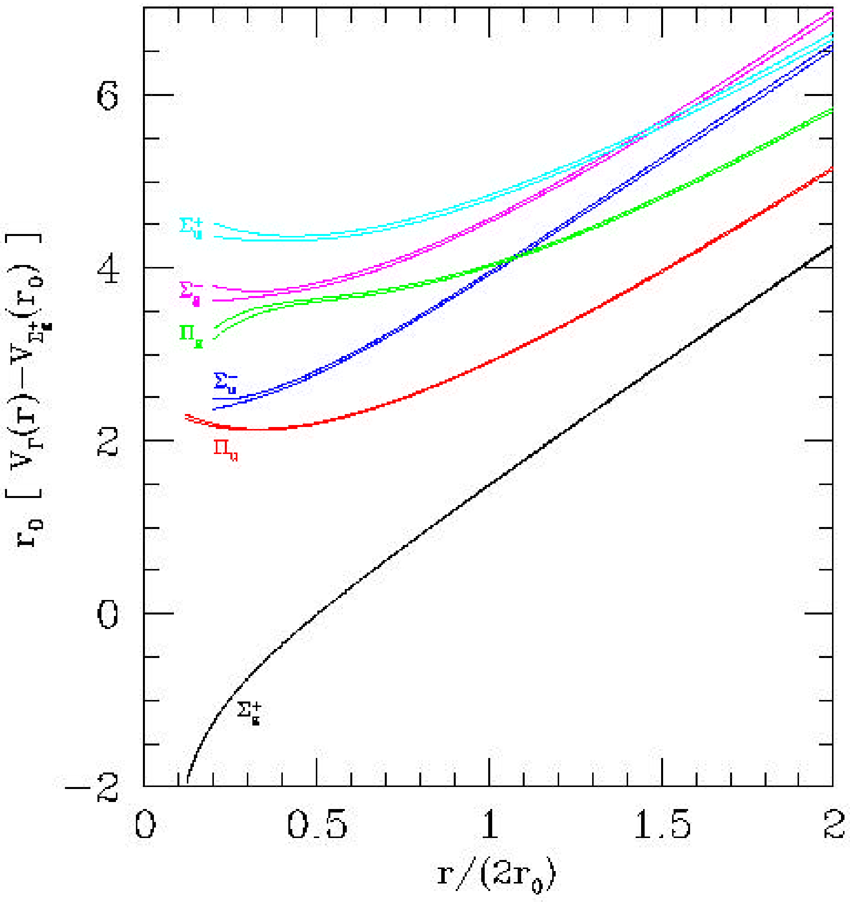


- Excited states have non-trivial representation of the flux tube symmetry
- Similar to electron wavefunctions in diatomic molecules

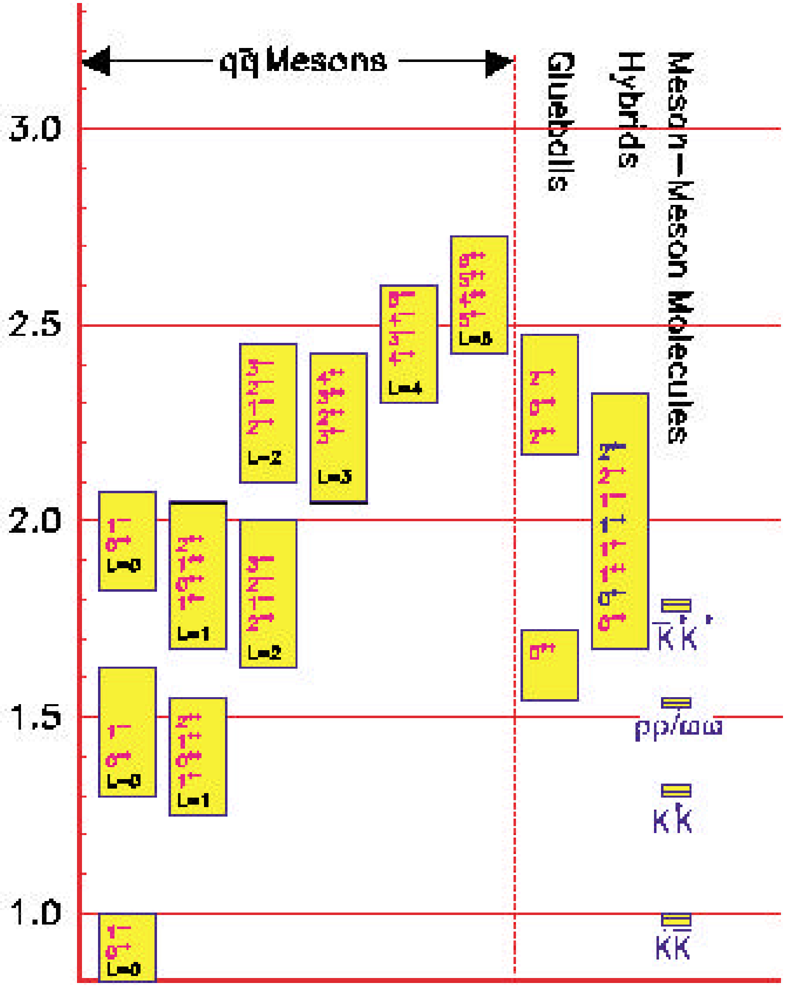
- ***Need to map out the higher adiabatic surfaces to test our understanding of "Soft QCD"***

- ***Not enough to discover one meson with exotic quantum numbers***

- ***Need to find enough excited states to map out the excited surfaces***



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



Lattice calculations not yet enough.

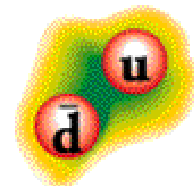
Also need phenomenological models to help to find these states:

- Disentangle their properties
- Build up a physical picture

Conventional Mesons:

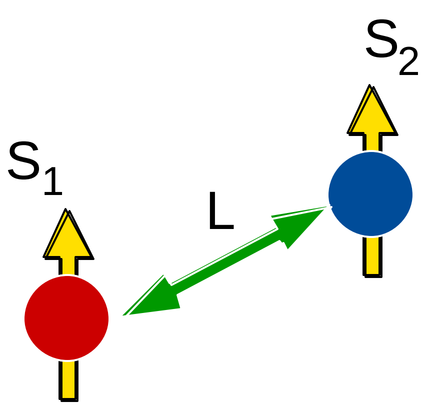
Mesons are composed of a quark-antiquark pair

Combine u,d,s,c,b quark and antiquark to form various mesons:



p **meson**

Meson quantum numbers characterized by given J^{PC}



$$S = S_1 + S_2$$

$$J = L + S$$

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

$$C = (-1)^{L+S}$$

Allowed:

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

Not allowed: exotic combinations:

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

- Although goal is to discover exotics can't ignore conventional states
- Need to understand them to disentangle exotics from $q\bar{q}$

- Couplings of states are sensitive to the internal structure

- An important tool in disentangling the observed spectrum
  - Strong decays modeled by
    - $^3P_0$ Model
    - Flux tube breaking model
  - em couplings:
    - 2γ couplings

$$\Gamma_{gg}(f_2)\cdot B(f_2 \to p^0 p^0)$$

    - single photon transitions

$$\Gamma[(q\bar{q})_i \to g\,(q\bar{q})_f\,]$$ (via Primakoff?)

Godfrey & Isgur, PR D32, 189 (1985); Barnes et al, PR D55, 4157 (1997)

2. Glueballs

Mass predictions by Lattice QCD are fairly robust.

Lowest mass glueballs have conventional quantum numbers:

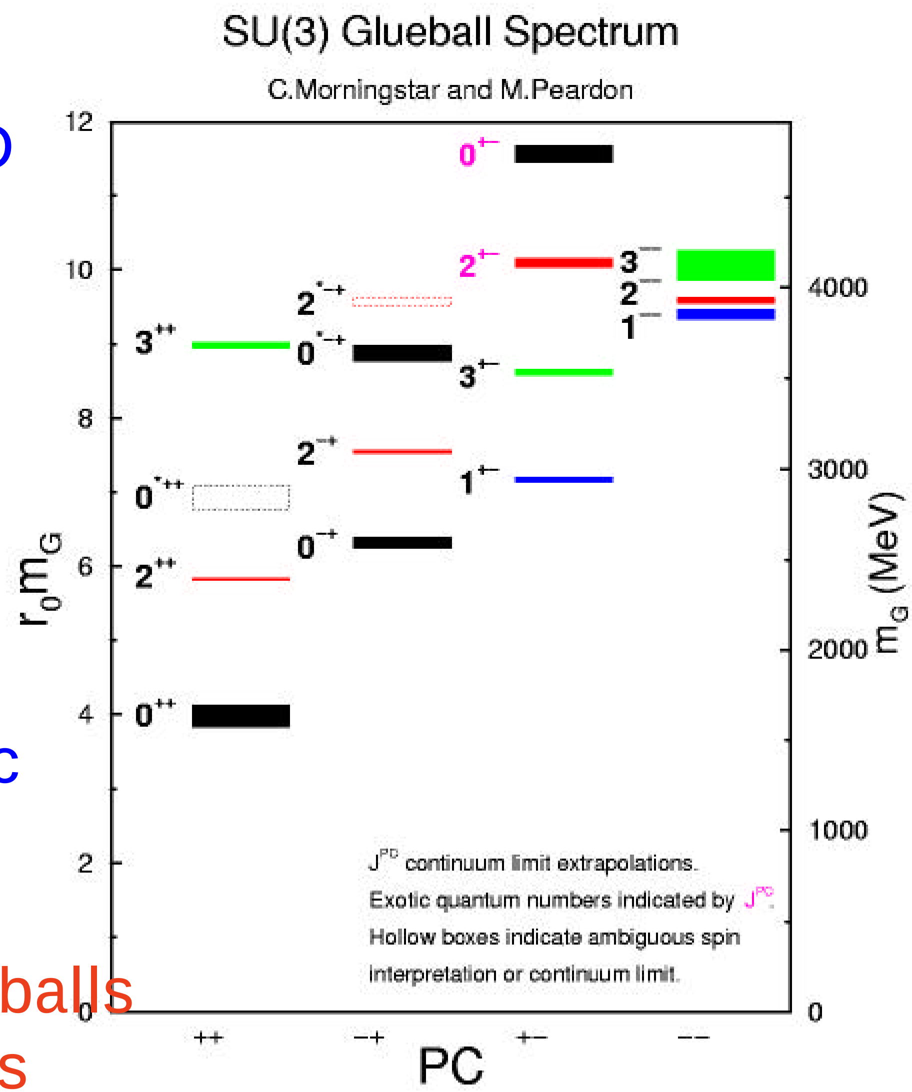
$M_{O}^{++} \sim 1.6$ GeV

$M_{2}^{++} \sim 2.3$ GeV

$M_{O}^{-+} \sim 2.5$ GeV

Lowest lying glueballs with exotic quantum numbers 0^{+-}, 2^{+-}, 1^{-+} are much higher in mass

- Difficult to produce exotic glueballs
- Difficult to disentangle glueballs with conventional Q#'s from dense background of conventional states



Expect glueball decays to have flavour symmetric couplings to final state hadrons:

$$\frac{\Gamma(G \to pp : K\bar{K} : hh : hh' : h'h')}{\text{Phase Space}} = 3{:}4{:}1{:}0{:}1$$

But situation complicated by mixing with

$$q\bar{q} \text{ and } q\bar{q}q\bar{q}$$

Physical states are linear combinations:

$$|f_0\rangle = a|n\bar{n}\rangle + b|s\bar{s}\rangle + g|G\rangle + d|q\bar{q}q\bar{q}\rangle$$

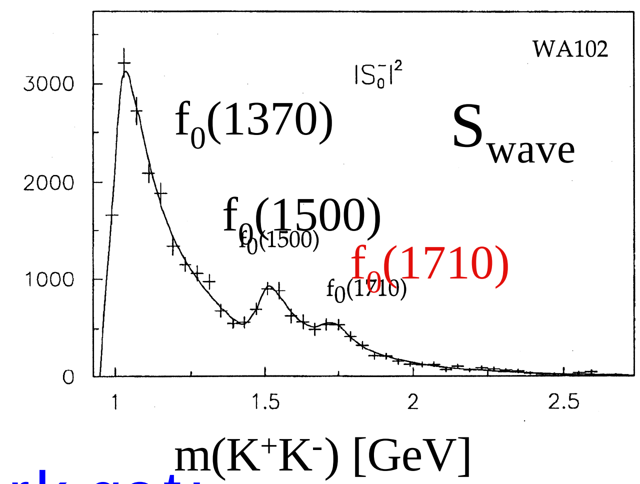
Will shift unquenched glueball mass and distort naïve couplings

Close & Kirk, PL B483, 345 (2000); Eur. Phys. J. C21, 531 (2001)

Meson properties can be used to extract the mixings and understand the underlying dynamics

$pp \to p_s\,[KK, \pi\pi]\,p_f$ @ 450 GeV

	Ratio	$K\bar{K}/\pi\pi$	
$f_0(1370)$	$\frac{K\bar{K}}{\pi\pi}$	<1	(0.5 ± 0.2)
$f_0(1500)$		<<1	(0.3 ± 0.1)
$f_0(1710)$		>>1	(5.5 ± 0.8)



Using decay information Close and Kirk get:

$$|f_0(1370)\rangle = -0.79|n\bar{n}\rangle - 0.13|s\bar{s}\rangle + 0.60|G\rangle$$

$$|f_0(1500)\rangle = -0.62|n\bar{n}\rangle + 0.37|s\bar{s}\rangle - 0.69|G\rangle$$

$$|f_0(1710)\rangle = +0.14|n\bar{n}\rangle + 0.91|s\bar{s}\rangle + 0.39|G\rangle$$

The point is not the details of the mixing but that mixing is an important consideration in the phenomenology

C. Amsler PL B541 (2002) 22

$$| f \rangle = \cos a | n\bar{n} \rangle - \sin a | s\bar{s} \rangle$$

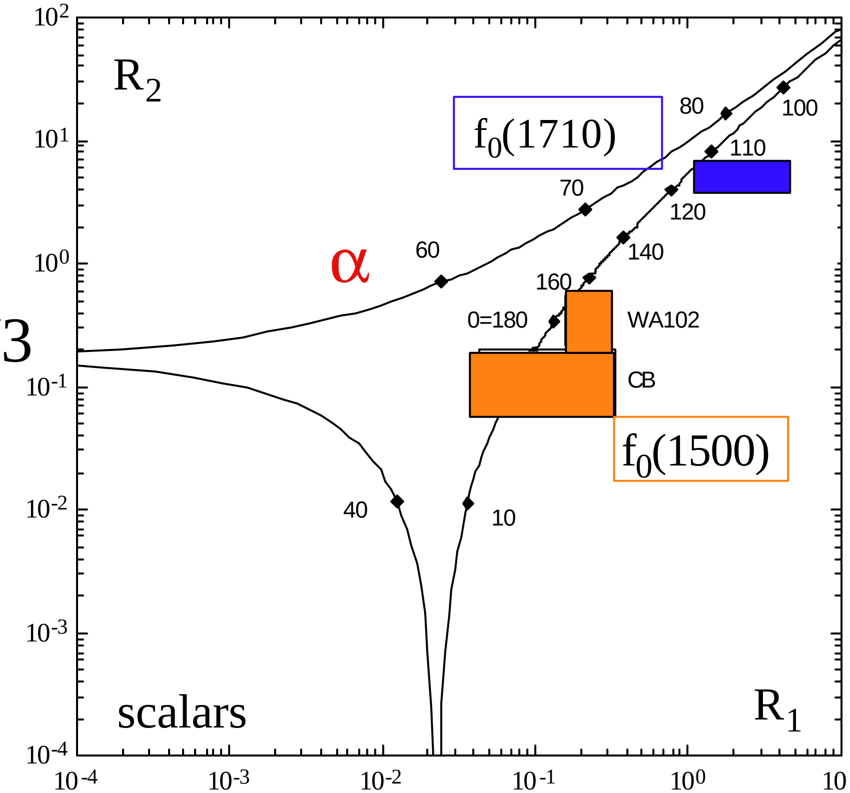
$$R_1 = \frac{\gamma^2(\eta\eta)}{\gamma^2(\pi\pi)}$$

$$R_2 = \frac{\gamma^2(K\bar{K})}{\gamma^2(\pi\pi)}$$

as a function of α

works perfectly for 2^{++} mesons:
$\alpha=82^o$, as from mass formula

1/3



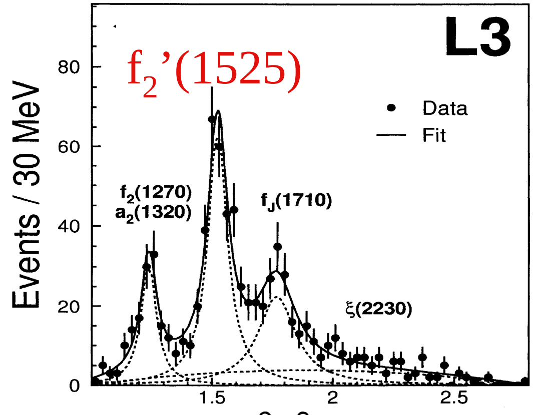
Assuming $q\bar{q}$:

$f_0(1500)$ is $n\bar{n} \rangle$ $\quad -10^o < \alpha < 5^o$

$f_0(1700)$ is dominantly $s\bar{s} \rangle$

$\gamma\gamma$ couplings is a very sensitive probe of $q\bar{q}$ content

$\gamma\gamma \to K_S K_S$



(Acciarri 01,Braccini 01)

no $f_0(1500)$: $\not\to$ KK (?)

$m(K_S K_S)$ [GeV]

An important test of glue content is comparing the gluon rich channel $J/\Psi \to \gamma X$ to $\gamma\gamma$ couplings

$$S = \frac{\Gamma(J/y \to gX)}{PS(J/y \to gX)} \times \frac{PS(gg \to X)}{PS(gg \to X)}$$

large Stickiness reflects enhanced glue content

Production of Glueballs:

1. $\mathrm{J}/y \to g\mathrm{X}$
2. $p\bar{p}$ annihilation
3. $pp \to p_f(G)p_s$ central production (Donskov)

- In central production diffractive process via "*gluonic pomeron exchange*"
- Expect competition with $q\bar{q}$ production
- But kinematic filter discovered which appears to suppress established $q\bar{q}$ states when in P-wave or higher wave

Central Production:

$$pp \to p_f(G)p_s$$

- p_S and p_f represent the slowest and fastest particles
- believe to be dominated by double *Pomeron* exchange
- *Pomeron* believed to have large gluonic content
- Folklore assumed that Pomeron is 0^{++} with flat distribution
- But distributions not flat
- Modelled with J=1 exchange particle:
  - Pomeron transforms as a non-conserved vector current
- Data from WA102 appears to support this hypothesis

Kinematic filter seems to suppress established $q\bar{q}$ when they are in P and higher waves

Close & Kirk PL B397, 333 (1997)

The pattern of resonances depends on the vector difference of the transverse momentum recoil of the final state protons

$$dP_T = \left| \vec{k}_{T_1} - \vec{k}_{T_2} \right|$$

for

- dP_T large well established $q\bar{q}$ states are prominent
- dP_T small, established $q\bar{q}$ states are suppressed while $f_0(1500)$, $f_0(1710)$, $f_0(980)$ survive

ϕ, the angle between k_T vectors

Close Kirk & Schuler give a good account of the data modeling Pomeron as Vector exchange particle:

0^{-+} - parity requires the vector pomeron to be transversely polarized; peaks at 90^o

1^{++} - one transverse the other longitudinal; peaks at 180^o

2^{-+} - similar to 0^{-+} case; peaks at 0^o (helicity 2 suppressed by Bose statistics)

2^{++} - established states peak at 180^o while $f_2(1950)$ at 0^o

0^{++} - peaks at 0^o for some states while others are spread out:

- $f_0(1500)$, $f_0(1710)$, $f_0(980)$ peak at small ϕ
- $f_0(1370)$ peaks at large ϕ

Fact that $f_0(1370)$ and $f_0(1500)$ have different ϕ dependence Indicates not just J dependent phenomena

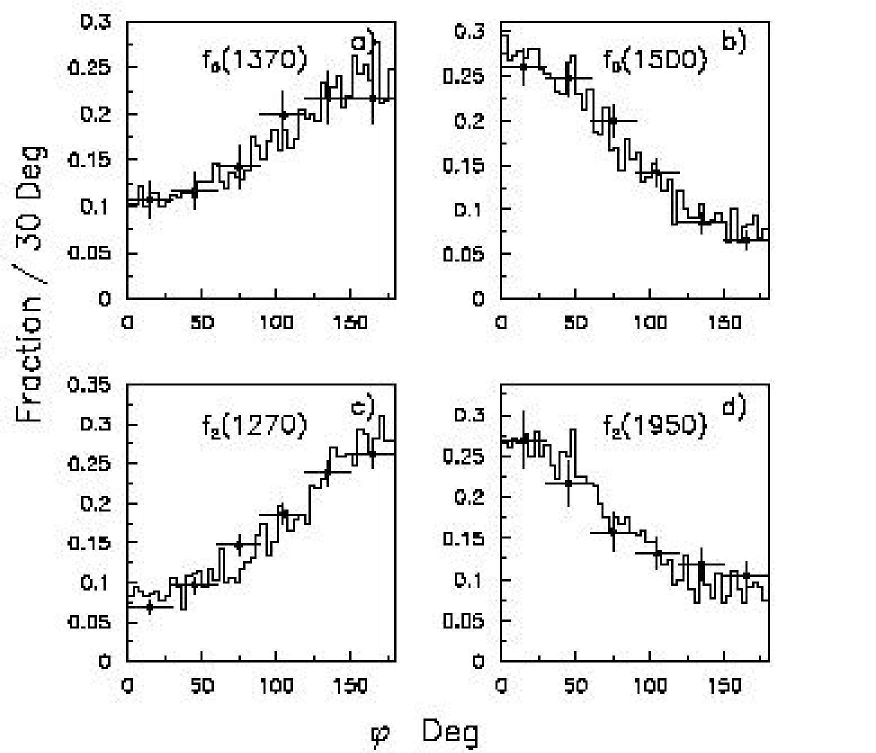
Close, Kirk, & Schuler PL B477, 13 (2000); Close & Schuler PLB 458, 127 (1999); PLB 464, 279 (1999)

0^{++}, 2^{++} expect both TT & LL contributions

$$\frac{ds}{df} \sim \left[1 + \frac{\sqrt{t_1 t_2}}{m^2} \frac{a_T}{a_L} \cos f \right]^2$$

described by varying $m^2 a_L / a_T$

= -0.5 GeV^2 for $f_0(1370)$
= +0.7 GeV^2 for $f_0(1500)$
= -0.4 GeV^2 for $f_2(1270)$
= +0.7 GeV^2 for $f_0(1950)$



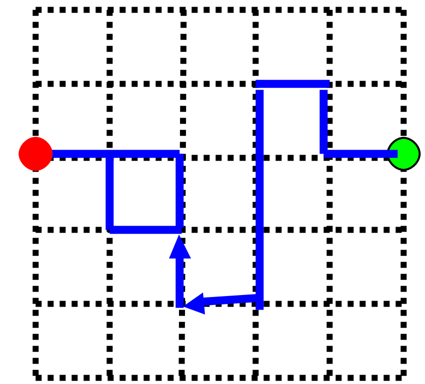
Close, Kirk, & Schuler PL B477, 13 (2000)

φ distributions fitted with only 1 parameter

Hybrid Mesons:

Hybrid mesons are defined as those in which the gluonic component is non-trivial

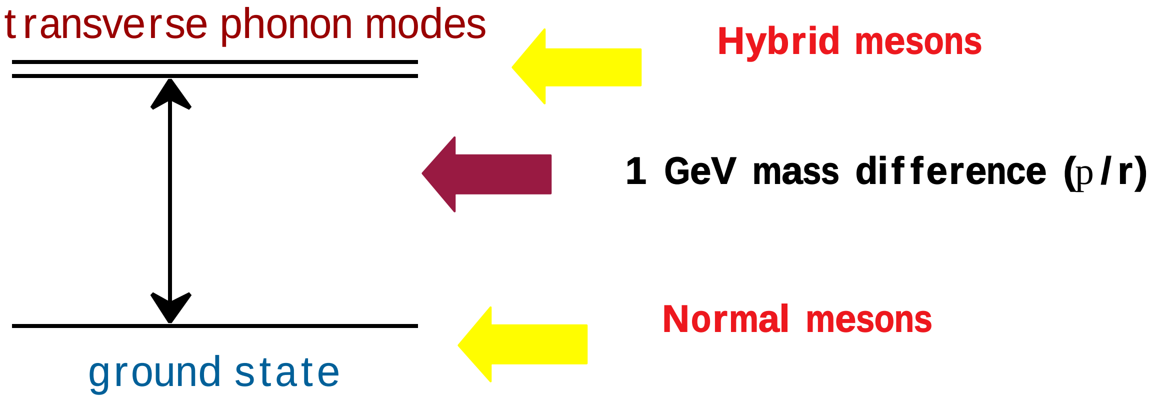
Hybrids



Two types of hybrids:

- **Vibrational hybrids**
- **Topological hybrids**

- Quarks move in effective potentials of adiabatically varying state of flux tubes
- A given *adiabatic surface* corresponds to various string topologies and excitations
- In Flux-Tube model the lowest excited adiabatic surface corresponds to transverse excitations



Lowest mass hybrids at 1.9 GeV

Doubly degenerate:

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

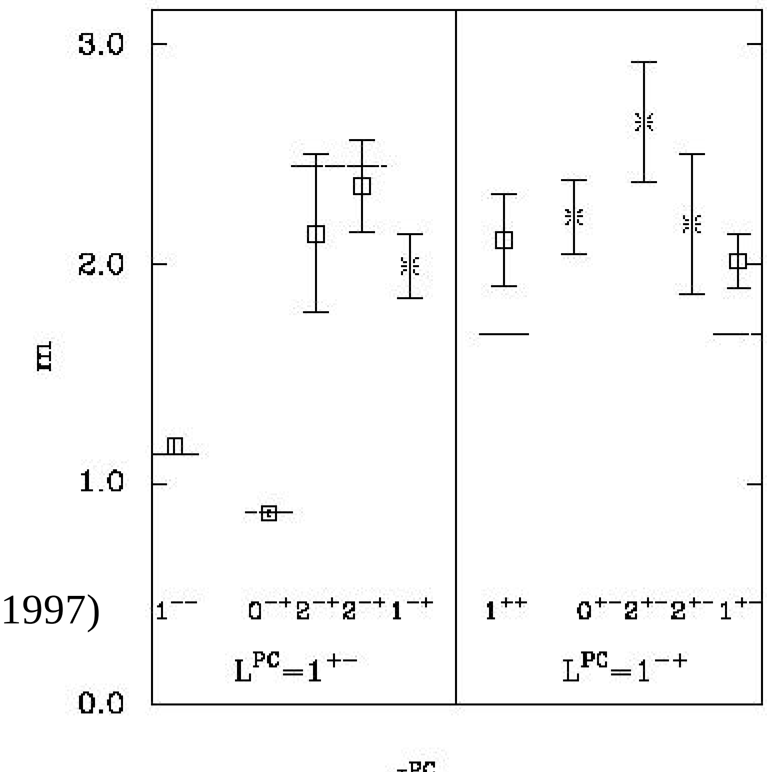
Expect degeneracies to be broken by different excitation energies of flux tube modes, spin dependence, mixings with $q\bar{q}$

Lattice results generally consistent with these predictions

$M(1^{-+})$~1.9 GeV

$M(0^{+-})$~2.1 GeV

$M(2^{+-})$~2.1 GeV



UKQCD; Lacock et al, PR D54, 6997 (1996); PL B401, 308 (1997)

Decay Properties:

Decays need to preserve symmetries

A General Selection Rule:

To preserve symmetries of quark and colour fields about the quarks the Π_u hybrid must decay to Meson in a P-wave

e.g. cannot transfer angular momentum as relative angular momentum but appears as internal angular momentum

This appears to be a universal selection rule

For 1^{-+} exotic expect $\hat{r} \to b_1 p, f_1 p$ modes to dominate

Need model to calculate hybrid properties:

Flux tube model is based on the strong coupling Hamiltonian lattice QCD

- Based on quark and flux-tube degrees of freedom
- Provides a unified framework of:
  - ***conventional hadrons,***
  - ***multiquark states,***
  - ***hybrids***
  - ***glueballs***

Expect strong mixing between non-spin exotic hybrids and conventional mesons

For exotic hybrids:

Isgur, Kokoski and Paton, PRL, 54, 907
Close & Page, NP B443, 233 (1995)

A	B, C	L	Γ_1	Γ_2
$\pi 1^{-+}$	$b_1(1235)\pi$	S	100	100
		D	20	30
	$f_1(1285)\pi$	S	30	30
		D	20	20
$\omega 1^{-+}$	$a_1(1260)\pi$	S	90	100
		D	60	70
	$K_1(1400)K$	S	100	100
$\pi 2^{+-}$	$a_2(1320)\pi$	P	350	450
	$a_1(1260)\pi$	P	100	100
	$h_1(1170)\pi$	P	125	150

A	B, C	L	Γ_1	Γ_2
$\phi 1^{-+}$	$K_1(1270)K$	D	90	80
	$K_1(1400)K$	S	200	250
$\pi 0^{+-}$	$a_1(1260)\pi$	P	600	800
	$h_1(1170)\pi$	P	100	100
$\omega 0^{+-}$	$b_1(1235)\pi$	P	250	250
$\phi 0^{+-}$	$K_1(1270)K$	P	500	800
	$K_1(1400)K$	P	70	50
$\omega 2^{+-}$	$b_1(1235)\pi$	P	350	500
$\phi 2^{+-}$	$K_2^*(1430)K$	P	300	250
	$K_1(1400)K$	P	250	200

$\hat{a}_0, \hat{f}'_0$ too broad

$\hat{w}_1$ decays to $[a_1 p]_S$

with $\Gamma \approx 100$ MeV

similarly for $\hat{f}_1$

Best bets:

$\hat{r}_1 \rightarrow [b_1 p]_S, \; [f_1 p]_S$

$\hat{f}_2 \rightarrow [b_1 p]_P \quad (\Gamma \approx 350 \text{ MeV})$

$\hat{f}_2' \rightarrow [K_2^* \overline{K}]_P \quad (\Gamma \approx 300 \text{ MeV})$

$\rightarrow [K_1 \overline{K}]_P \quad (\Gamma \approx 250 \text{ MeV})$

But there is variation in model predictions

For non exotic hybrids:

Close & Page, NP B443, 233 (1995); PR D56, 1584 (1997)

To distinguish non-exotic hybrids from conventional states need detailed predictions of properties:

p (1800)

TABLE III. Decay of quark model and hybrid $\pi(1800)$.

	Partial widths to final states					
State	$\pi\rho$	$\omega\rho$	$\rho(1465)\pi$	$f_0(1300)\pi$	$f_2\pi$	K^*K
$\pi_{3S}(1800)$	30	74	56	6	29	36
$\pi_H(1800)$	30	—	30	170	6	5

$\rho\omega$ can be used as discriminator between possibilities observed in $\pi f_0(1300)$

(but recent paper by Swanson and Szczepaniak [PR D56, 5692] predicts small $\rho\omega$ partial width)

r' and w'

Close & Page, PR D56, 1584 (1997)
Barnes et al, PR D55, 4157 (1997)

Expect mixing: $|V\rangle = a|2^3S_1\rangle + b|1^3D_1\rangle + g|V_H\rangle$

	$\pi\pi$	$\omega\pi$	$\rho\eta$	$\rho\rho$	KK	K^*K	$h_1\pi$	$a_1\pi$	Total
$\rho_{2S}(1465)$	74	122	25	-	35	19	1	3	279
$\rho_{1D}(1700)$	48	35	16	14	36	26	124	134	435
$\rho_H(1500)$	0	5	1	0	0	0	0	140	$\approx$150

the πh_1 and πa_1 can discriminate between ρ_{2S}, ρ_{1D} and ρ_H or to disentangle the mixings

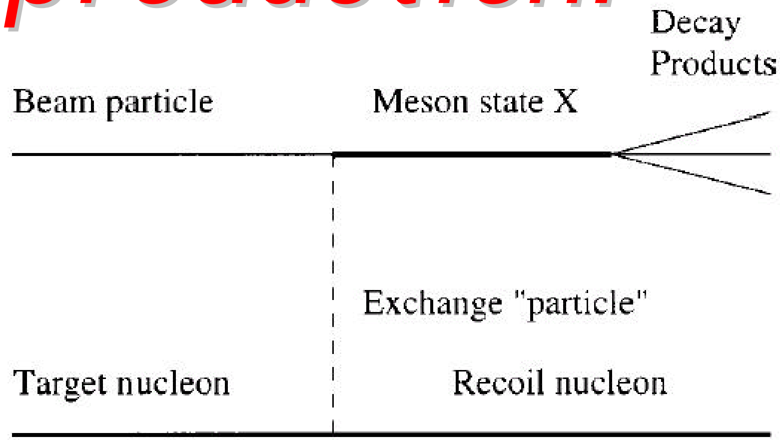
	$\rho\pi$	$\omega\eta$	KK	K^*K	$b_1\pi$	Total
$\omega_{2S}(1419)$	328	12	31	5	1	378
$\omega_{1D}(1649)$	101	13	35	21	371	542
$\omega_H(1500)$	20	1	0	0	0	$\approx$20

$w(1420) \to pb_1$ and $w(1600) \to pb_1$ are observed to be small so both unlikely to be pure 1^3D_1 state implying ω_H admixture

Production of Hybrids:

1. $\mathrm{J}/y \rightarrow g\mathrm{X}$
2. $p\bar{p}$ annihilation
3. peripheral production (Dorofeev)
4. photoproduction (Moinester)

Peripheral production:



Beam particle is excited and continuous to move forward exchanging momenta and quantum #'s with recoiling nucleus

eg: LASS, E852, BENKEI, VES, GAMS

Evidence for $\hat{r}(1600)$ (Dunnweber, Dorofeev)

Serpukhov: $p^- N \rightarrow (p^+ p^- p^-) N$ 40 GeV / c p beam

in $r^0 p^-$, ph and pb_1

BNL E852: $p^- p \rightarrow p^- p^+ p^- p$ at 18 GeV / c p beam

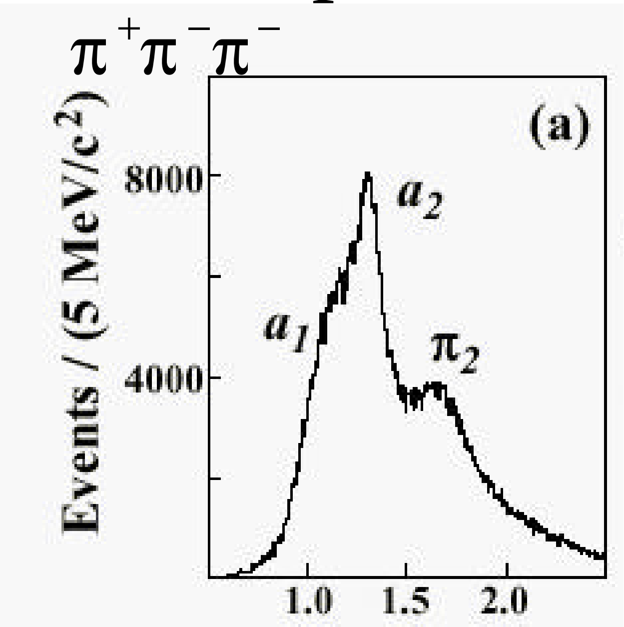
signal in $pf_1(1285)$

- No reason a priori to expect that any type of hadron is preferred over any other in this mechanism

  π exchange only provides access to natural parity states

- Advantage is high statistics

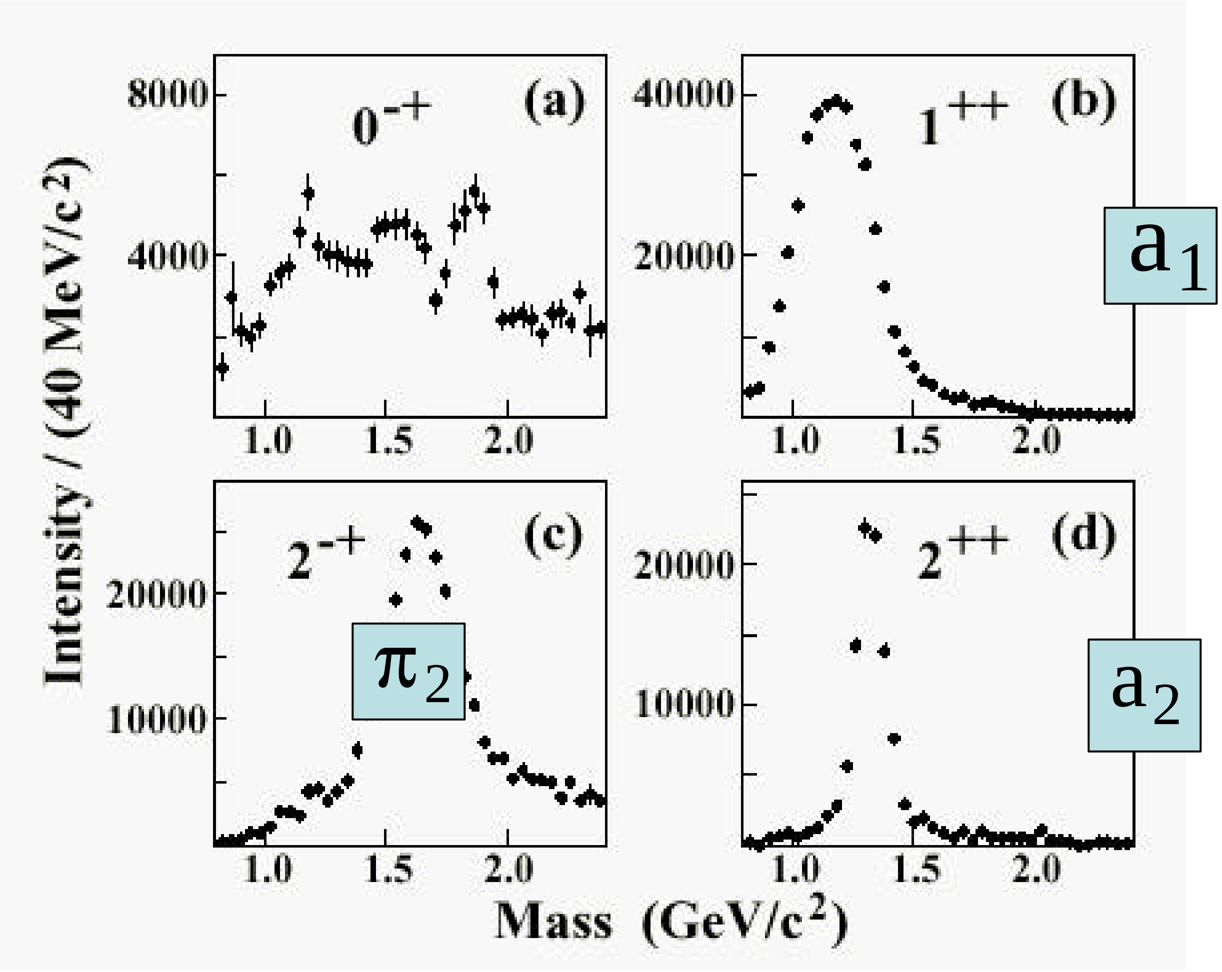
E852 Results: $\pi^- p \to \pi^+ \pi^- \pi^- p$ **At 18 GeV/c**



$M(\pi^+\pi^-\pi^-)$ $[GeV / c^2]$

to partial wave analysis

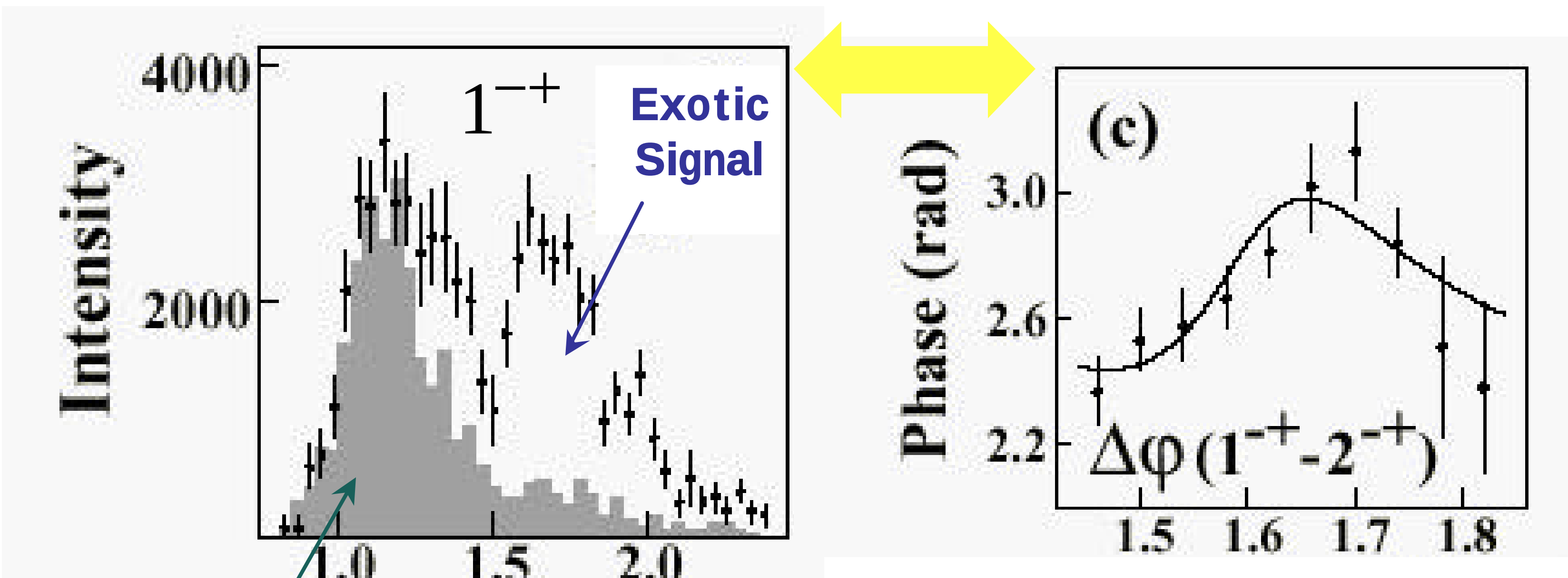
Results of Partial Wave Analysis



Benchmark resonances

An Exotic Signal in E852

Correlation of Phase & Intensity



$M(\pi^+\pi^-\pi^-)\ [GeV/c^2]$

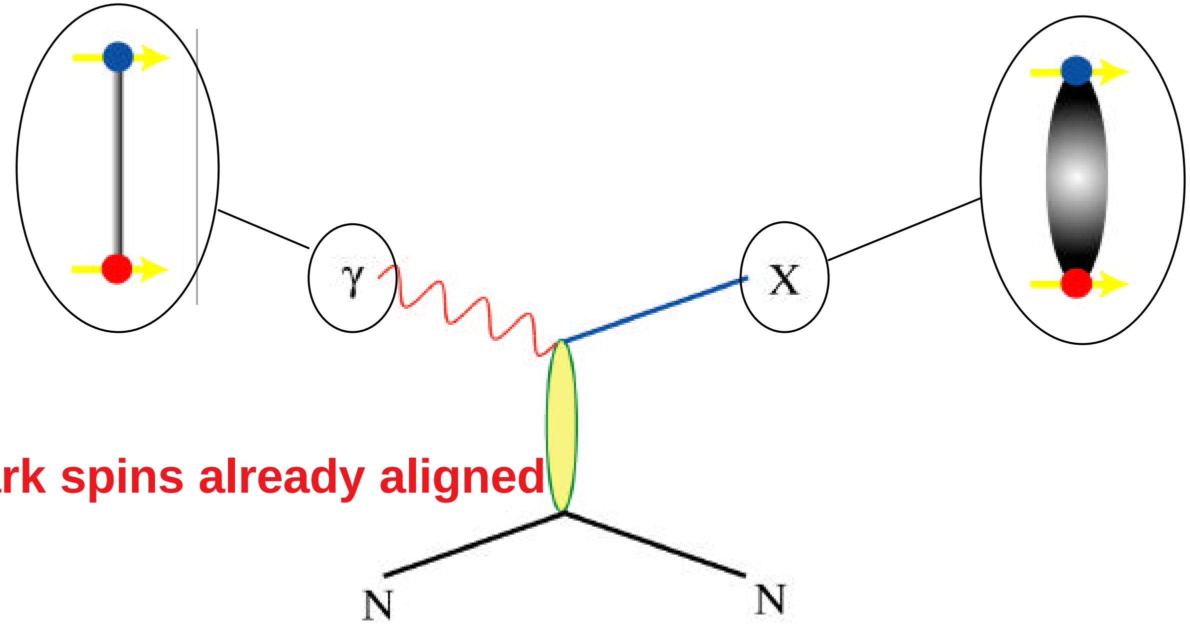
Leakage From Non-exotic Wave

due to imperfectly understood acceptance

Photoproduction:

Qualitative alternative to hadronic peripheral production

- series of preferred excitations is likely to be different
- strong source of ss states



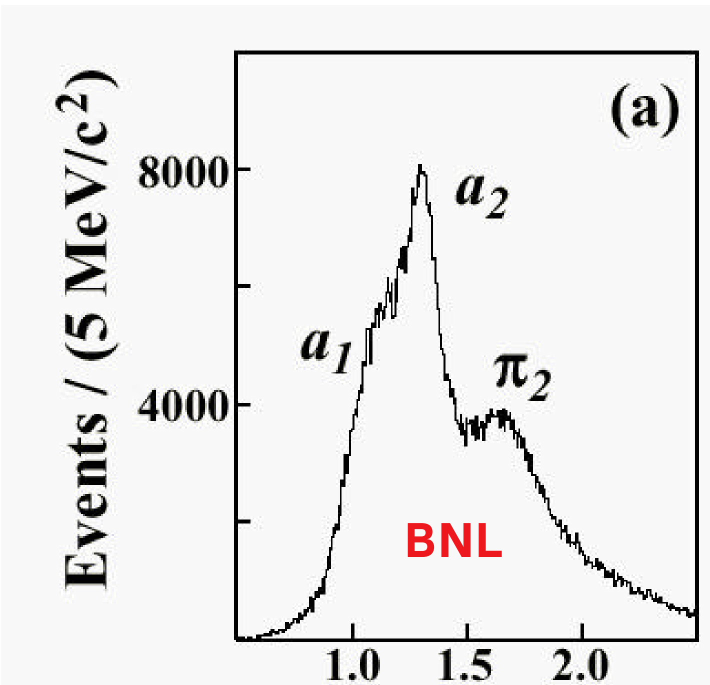
- Production of exotic hybrids is favoured
- Almost no data is available

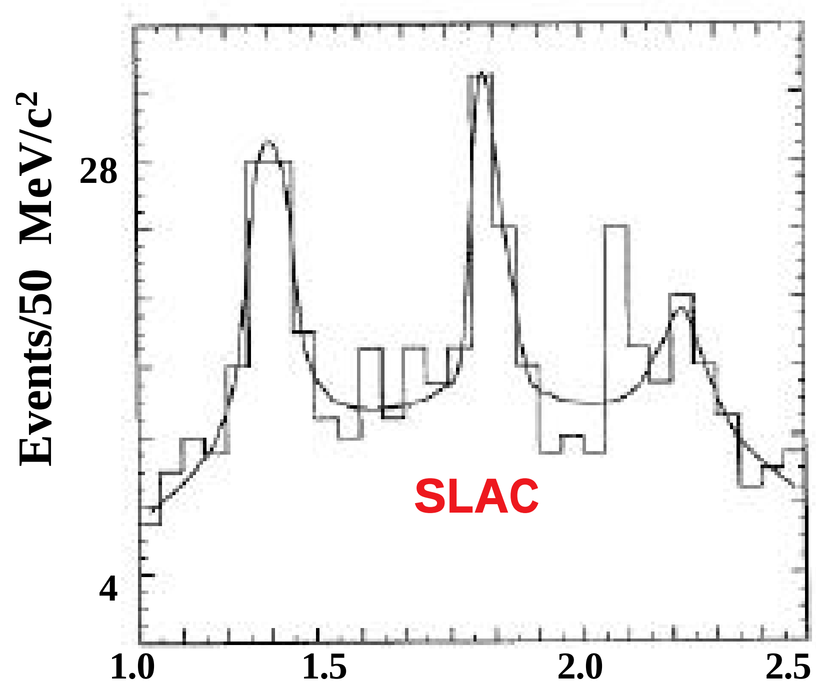
Compare pþ and gþ Data

Compare statistics and shapes

$$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p \qquad\qquad \gamma p \rightarrow \pi^+ \pi^+ \pi^- n$$

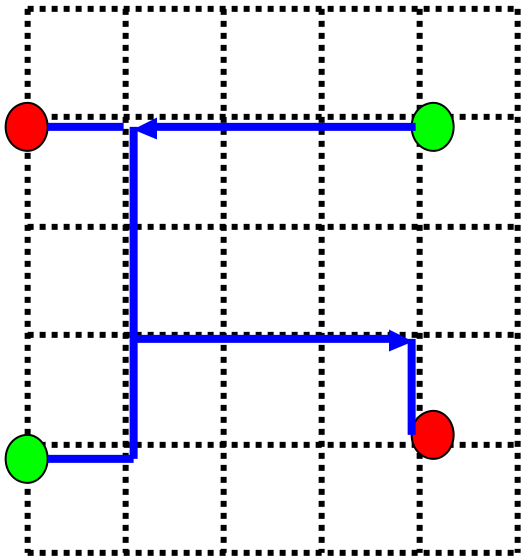
ca. 1998 **@ 18 GeV** **ca. 1993** **@ 19 GeV**

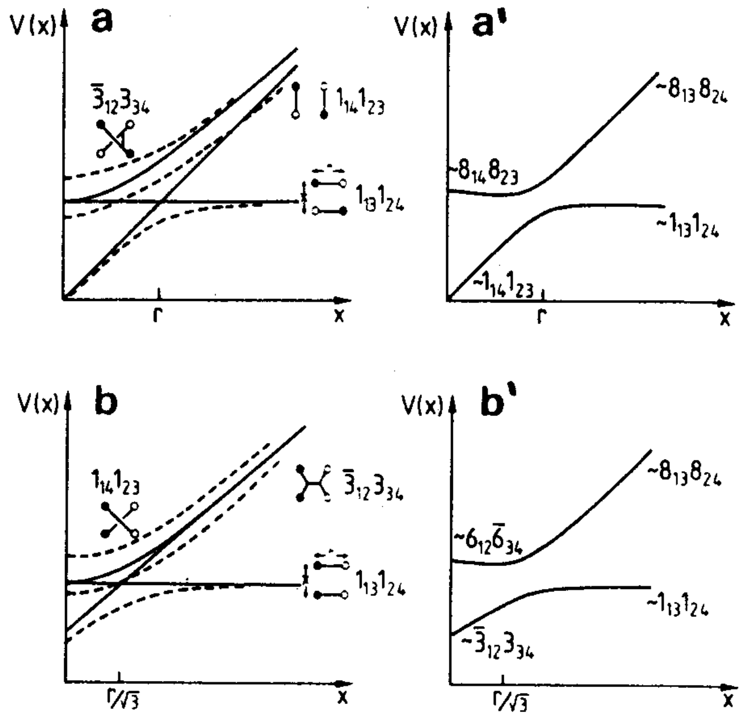




$$M(3\pi) \ \left[\mathrm{GeV}/c^2\right]$$

Multiquark Mesons:





- No time to discuss but mention as another ingredient
  - $f_0(980)$, $a_0(980)$ believed to be multiquark states
  - $f_1(1430)$ long standing puzzle (E/ι puzzle)
  - $f_J(1710)$ also open to interpretation
- Could also have multiquarks with exotic quantum #'s
- Best bets are fractional or doubly charged mesons

Summary

- The discovery and mapping out of the glueball and hybrid meson spectrum is a crucial test of QCD
- It will help validate Lattice QCD as an important computational tool for non-perturbative field theory
- It will take detailed studies to distinguish Glueball and Hybrid candidates from conventional $q\bar{q}$ states
- This will require extremely high statistics experiments
  - To measure meson properties
    - Partial widths
    - Production mechanisms
      - t-channel exchange
      - central production distributions
- COMPASS is unique: It has numerous tools to do this:

  π, K, p, and μ beams

COMPASS can make important advances in this field

I strongly encourage you to do so