Experimental Status of Meson Resonances

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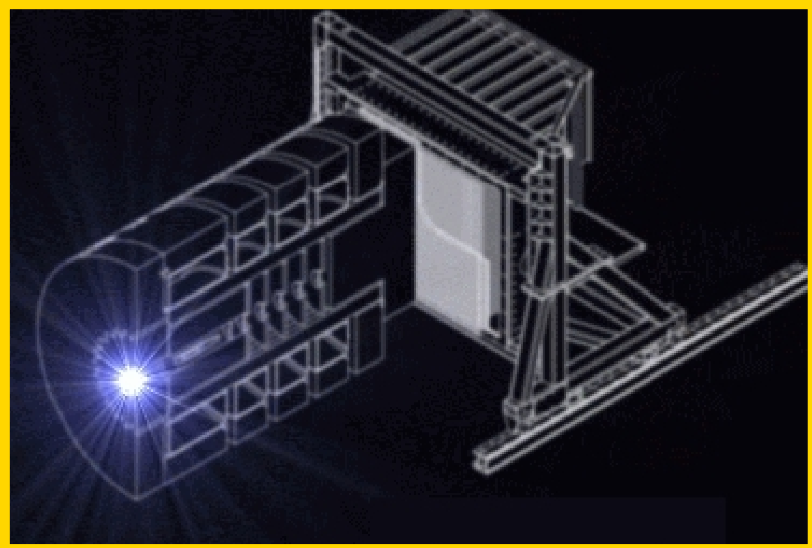


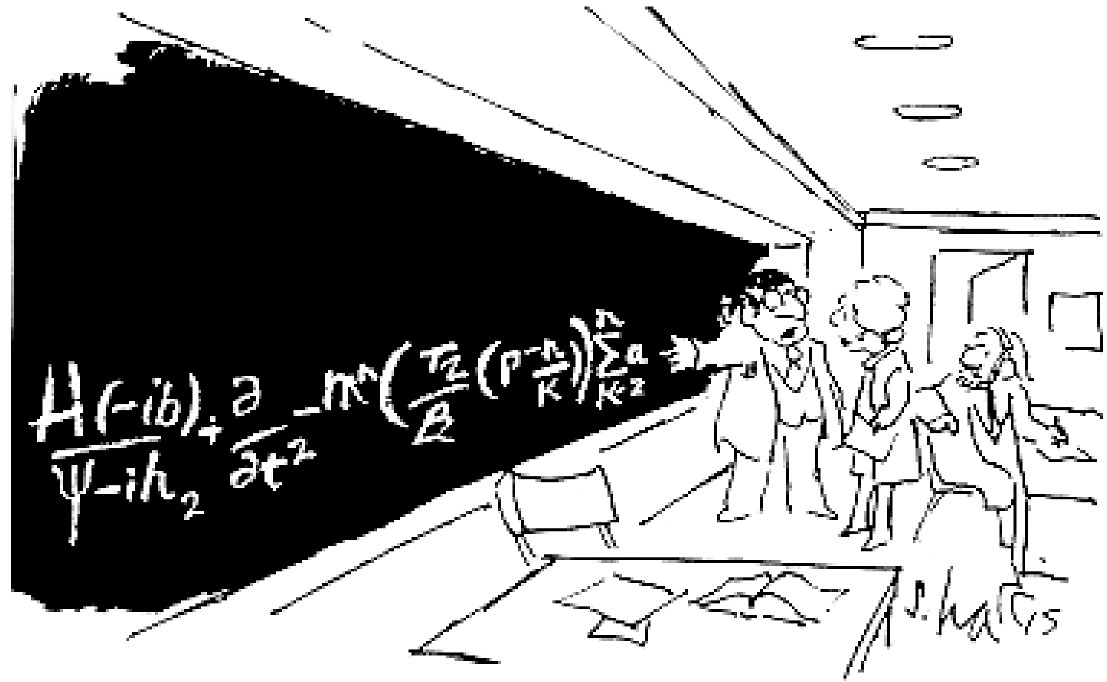
National Nuclear Physics Summer School

Outline

- Motivation for study of exotic mesons.
- Exotic meson properties.
- Introduction to analysis techniques.
- Evidence for exotic mesons and perspectives.
- The next generation −− requirements for detailed spectroscopy.
- The design of the GlueX experiment.
- Summary and conclusions.

The Lighter Side of Physics

"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them."



"But this is the simplified version for students"

THE FUNDAMENTAL SCIENCE ISSUE

- The failure to observe isolated quarks or gluons provides overwhelming experimental evidence that they are confined in nature.

- A quantitative understanding of the confinement of quarks and gluons in quantum chromodynamics (QCD) is one of the outstanding fundamental questions in physics.

- QCD is our pre−eminent example of a strongly−coupled field theory.

- Understanding QCD in this long−distance regime −− as a strongly coupled field theory −− is an outstanding challenge, not only for hadronic physics, but also for all theoretical physics.

- For example, it is likely that physics at the LHC and beyond has strongly coupled sectors, and QCD provides an analogy for constructing new theories (such as technicolor).

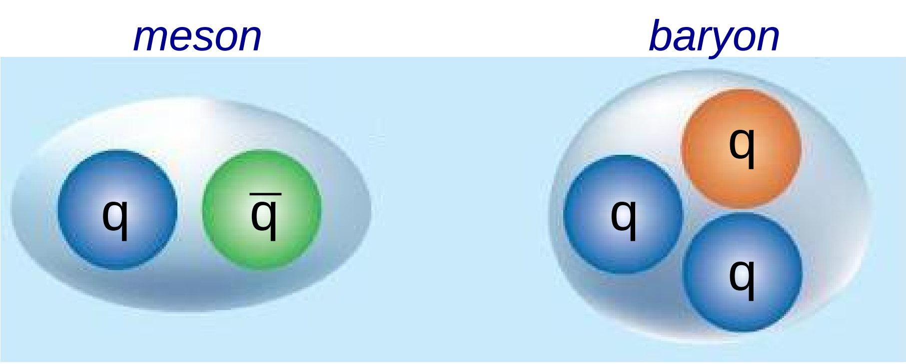
Motivation

- A detailed understanding of the nature of the strong interaction is the goal of studying baryon and meson resonances.

- A fundamental field theory known as quantum chromodynamics (QCD) describes the strong force between quarks mediated by gluons.

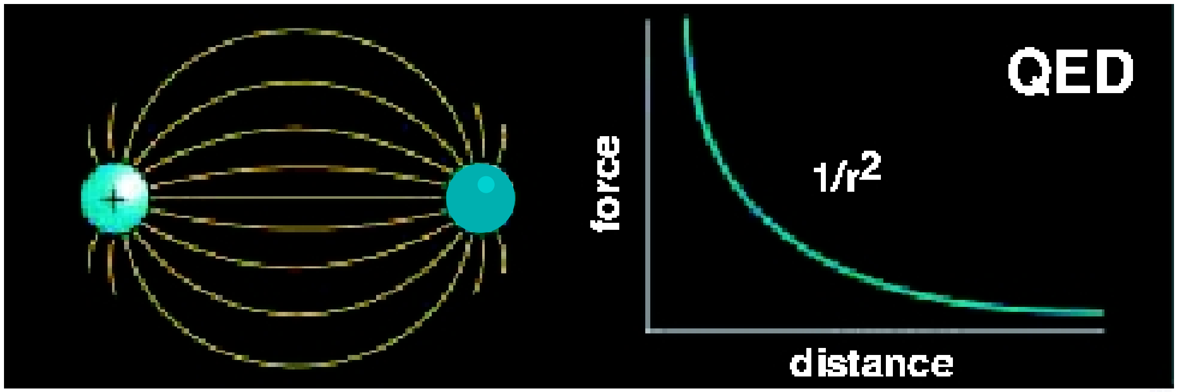
$$L_{QCD} = \bar{\psi}(i\gamma\cdot\partial - m_q)\psi - \frac{1}{4}F^{\mu\nu a}F_{\mu\nu a} - g_s\bar{\psi}\gamma\cdot A\psi$$

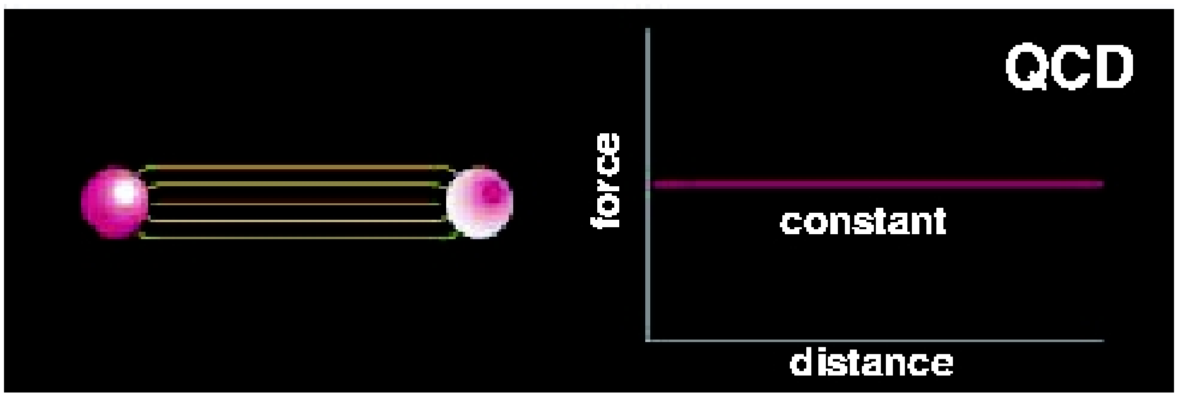
- Studies of mesons and meson resonances are critical to unravel a quantitative understanding of the nature of confinement.



. . . very naive indeed

QCD vs. QED





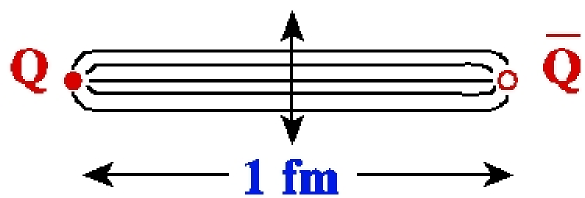
- The self−interacting nature of gluons gives rise to a tube−like field (called a flux−tube) between the quarks.

This flux−tube holds the key to understanding confinement.

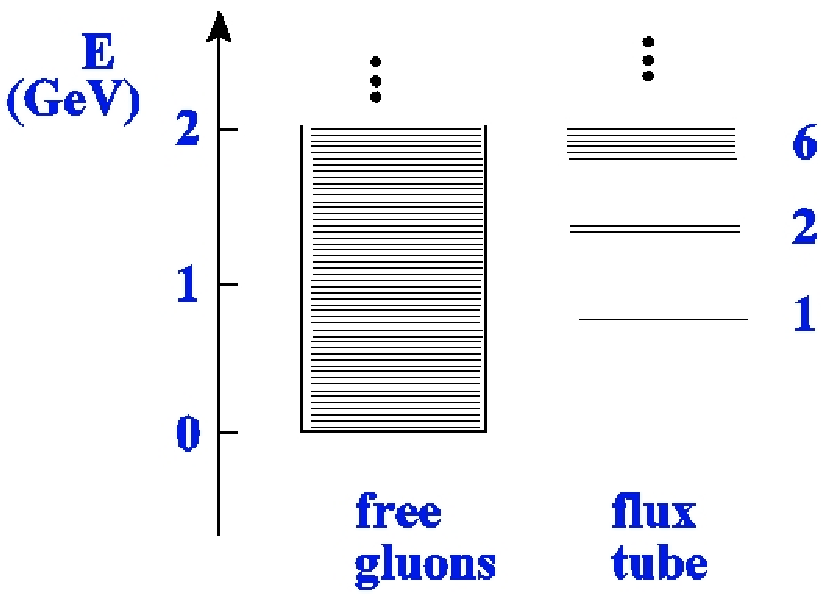
Confinement

Confinement (kən − fīn’ mənt) n. 1. The phenomenon that color charged particles (such as quarks) cannot be isolated.

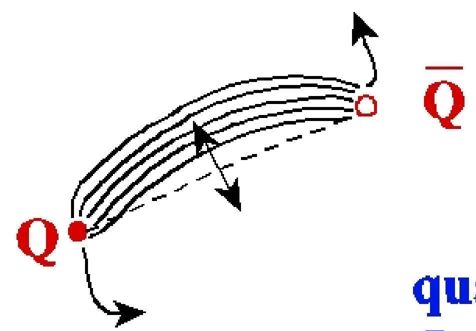
The Ideal Experiment



quarks fixed

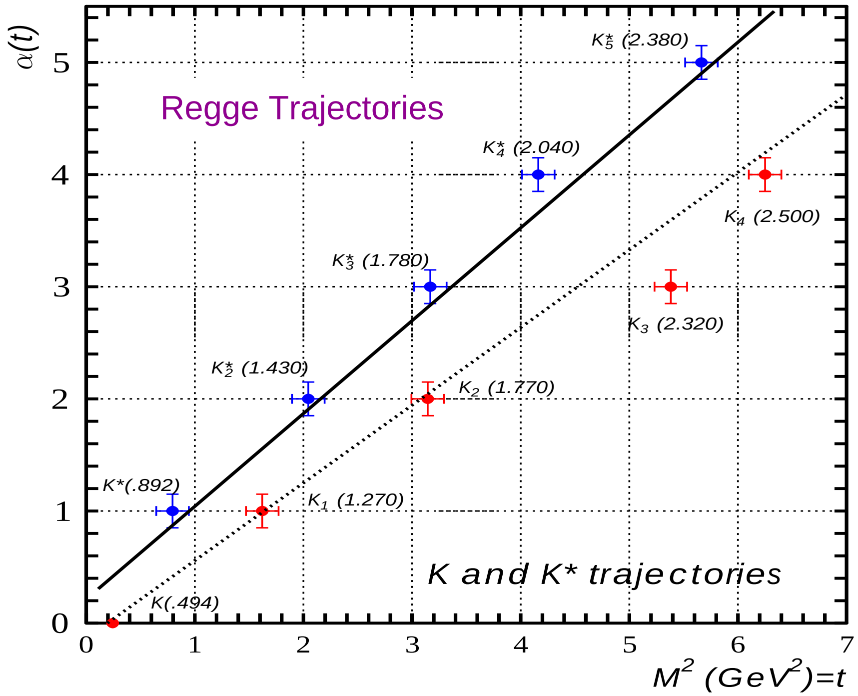


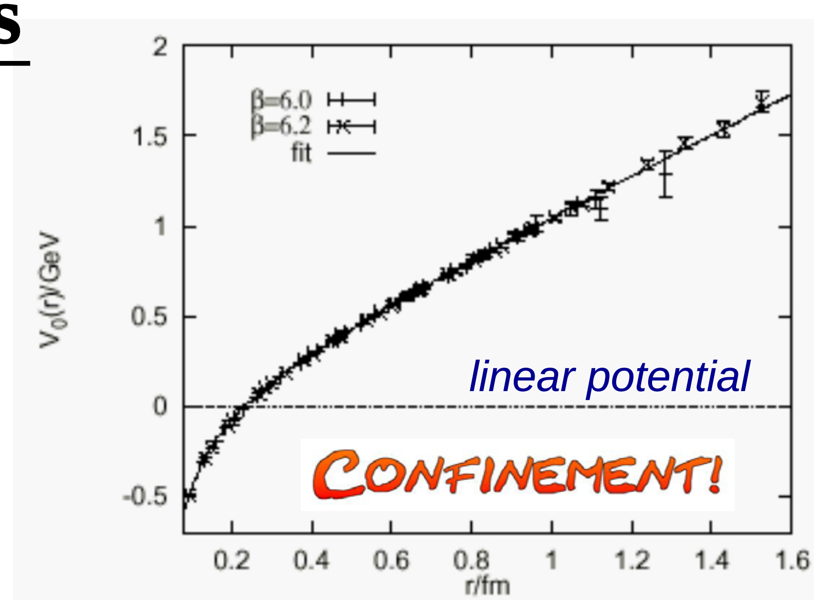
The Real Experiment



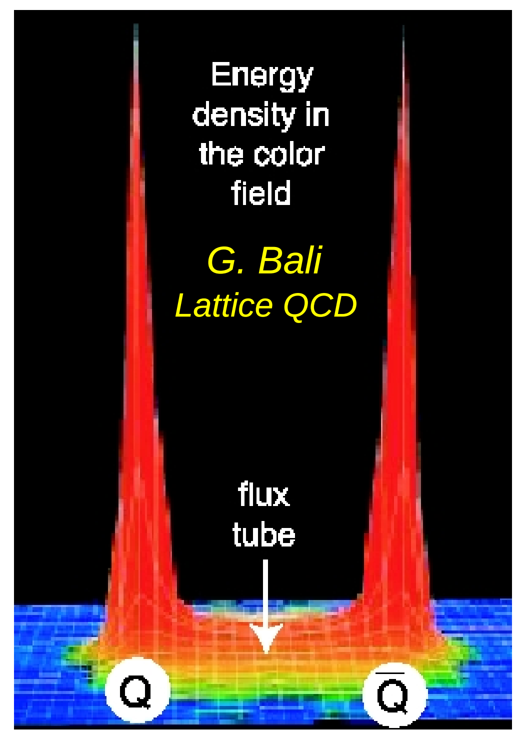
quark motion plus
flux tube excitation

The Evidence for Flux Tubes



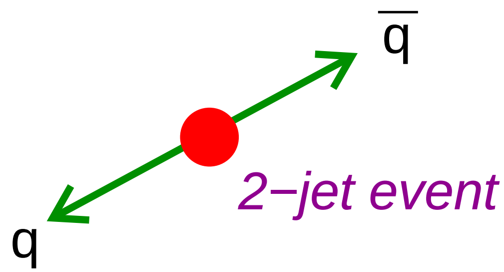


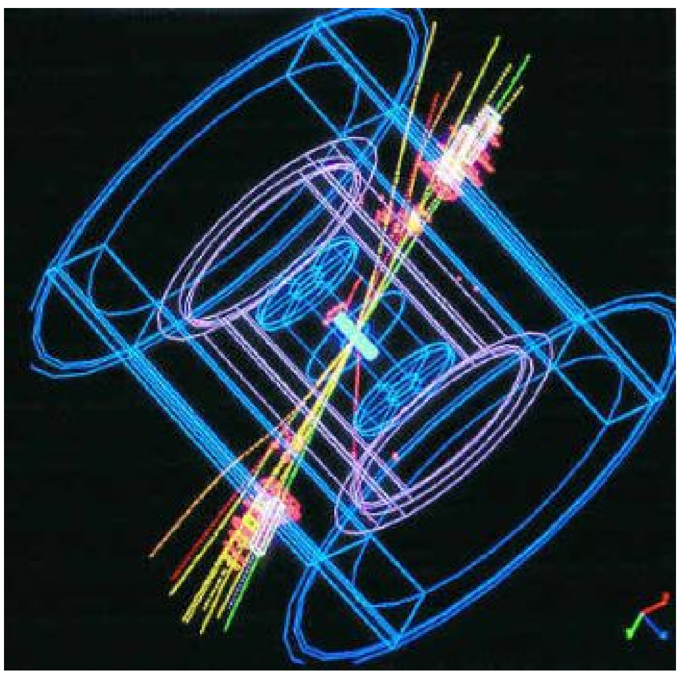
- Evidence since the 70s indicates that the mass of strongly interacting particles increases as the internal angular momentum increases.
- The observed linear dependence of mass squared with spin arises when the string has constant mass per unit length.
- Numerical calculations of QCD tell us the properties of the flux−tube lead to V(r) ~ a + br.

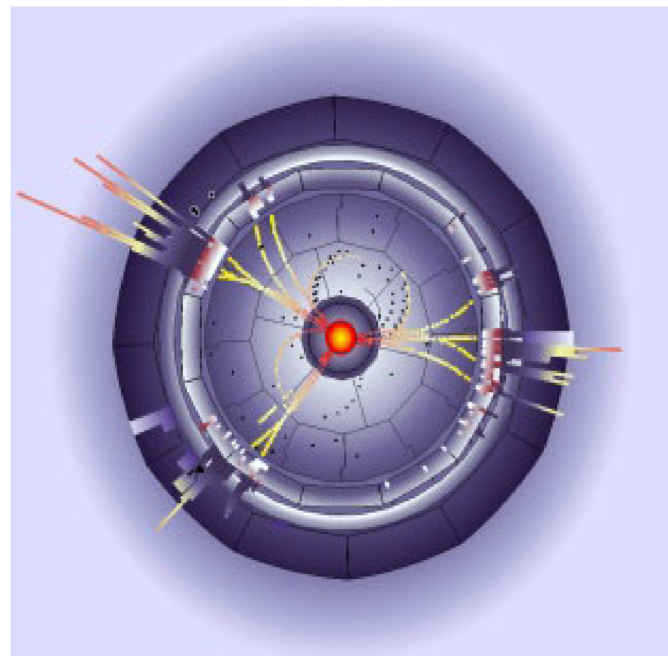


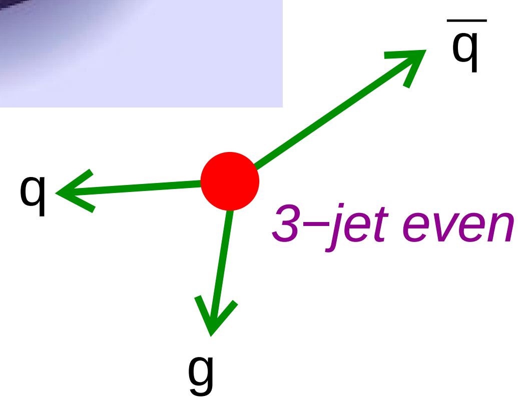
"Jets" at High Energy

- Direct evidence for gluons comes from high−energy jets.
  - *This tells us nothing about the fundamental properties of the glue, only about the strong coupling constant α_s.*

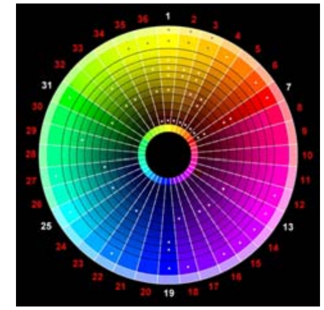






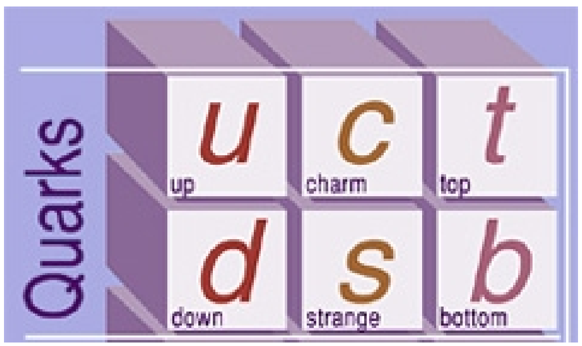


QCD and Strong Interactions



- The fundamental theory of the strong interaction.

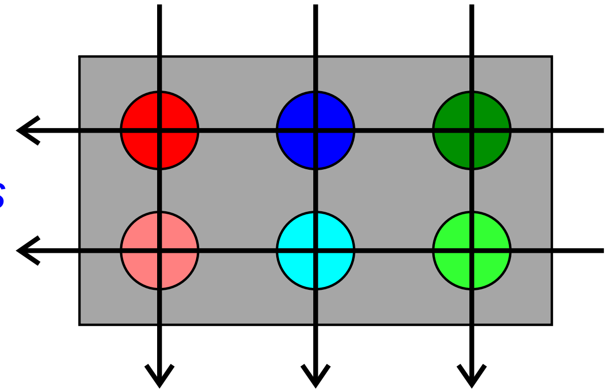
- Building blocks:



6 quarks + 6 anti−quarks

color mixing analogy

white baryons



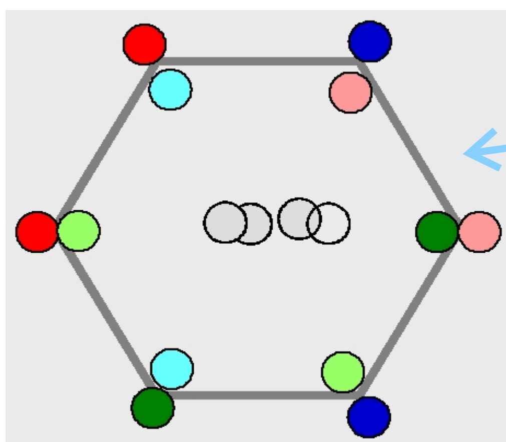
white mesons

strong color charge

8 colored gluons

+

8 anti−colored gluons

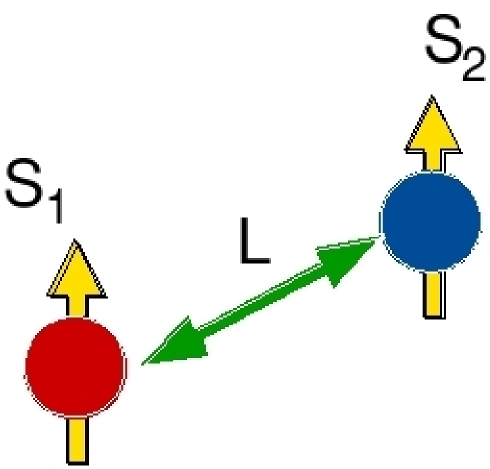


All particles are constructed so that they are colorless.

"Ordinary" Meson Properties

- Spin/angular momentum configurations and radial excitations generate the known spectrum of light quark mesons.

Starting with u, d, s quarks, we expect to find mesons grouped in nonets, each characterized by a given J, P, and C.

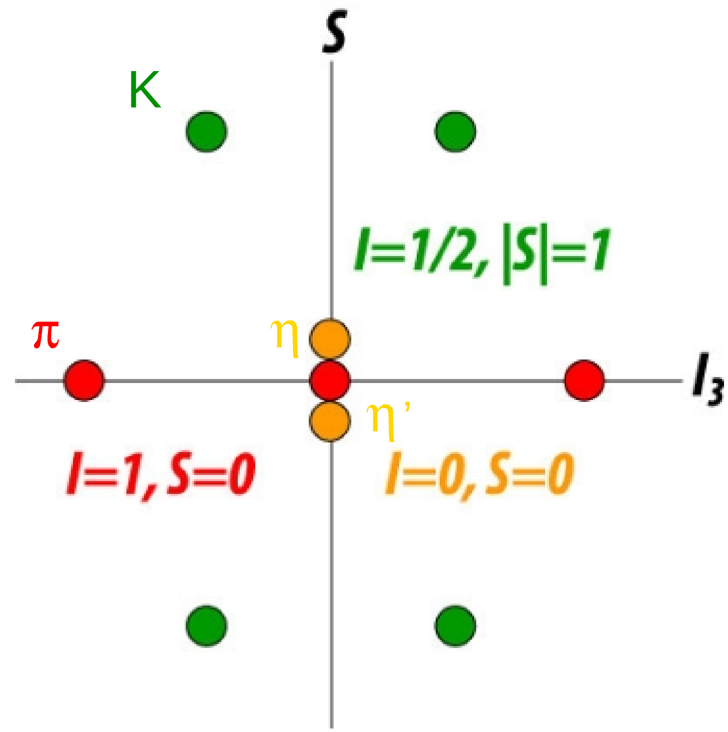


$S = S_1 + S_2$

$J = L + S$

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

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



$q\bar{q}$ color singlet bound states

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

Allowed combinations

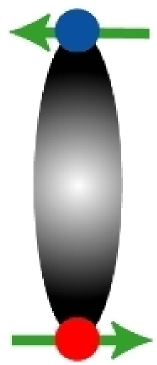
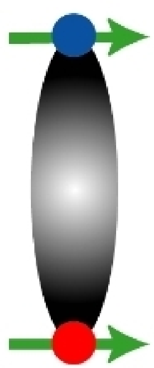
$J^{PC} = 0^{--}\ 0^{+-}\ 1^{-+}\ 2^{+-} \ldots$

Not-allowed: exotic

No need for gluons here!

Hybrid Mesons

Hybrids are quark−antiquark states with excitation energy in the gluonic flux tube.

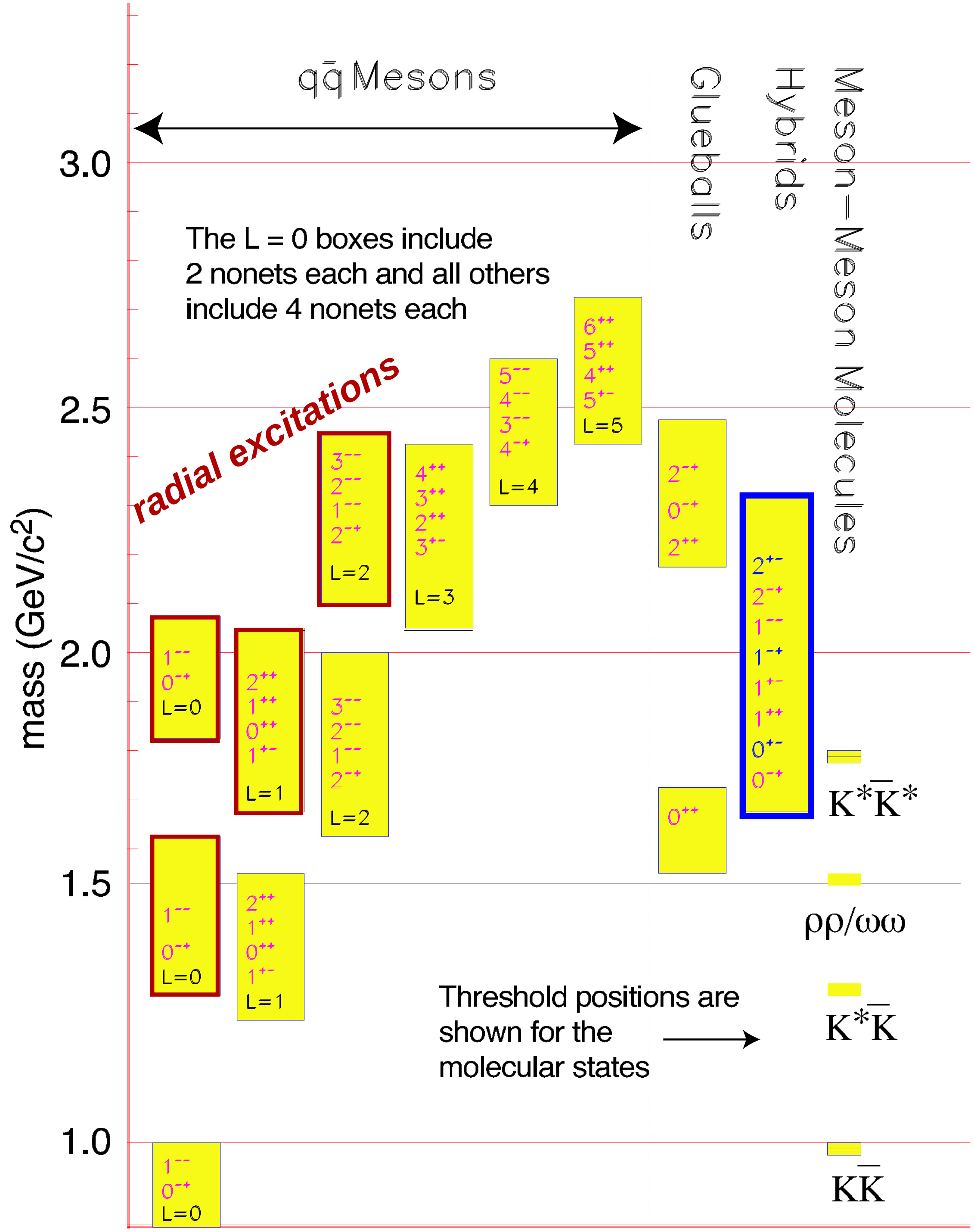
Quarks	⊕	Excited Flux Tube	→	Hybrid Meson
$S=0$ $L=0$ $J^{PC}=0^{-+}$ like π, K		$J^{PC}=\begin{cases}1^{+-}\\1^{-+}\end{cases}$		$J^{PC}=\begin{cases}1^{--}\\1^{++}\end{cases}$
$S=1$ $L=0$ $J^{PC}=1^{--}$ like γ, ρ		$J^{PC}=\begin{cases}1^{+-}\\1^{-+}\end{cases}$		Exotic $J^{PC}=\begin{cases}0^{-+} & 1^{-+} & 2^{-+}\\0^{+-} & 1^{+-} & 2^{+-}\end{cases}$

Flux tube excitation (and parallel quark spins) lead to exotic J^{PC}

Light Meson Spectrum

Exotic quantum numbers imply a deeper structure than simple $q\bar{q}$.

No mixing with those states!

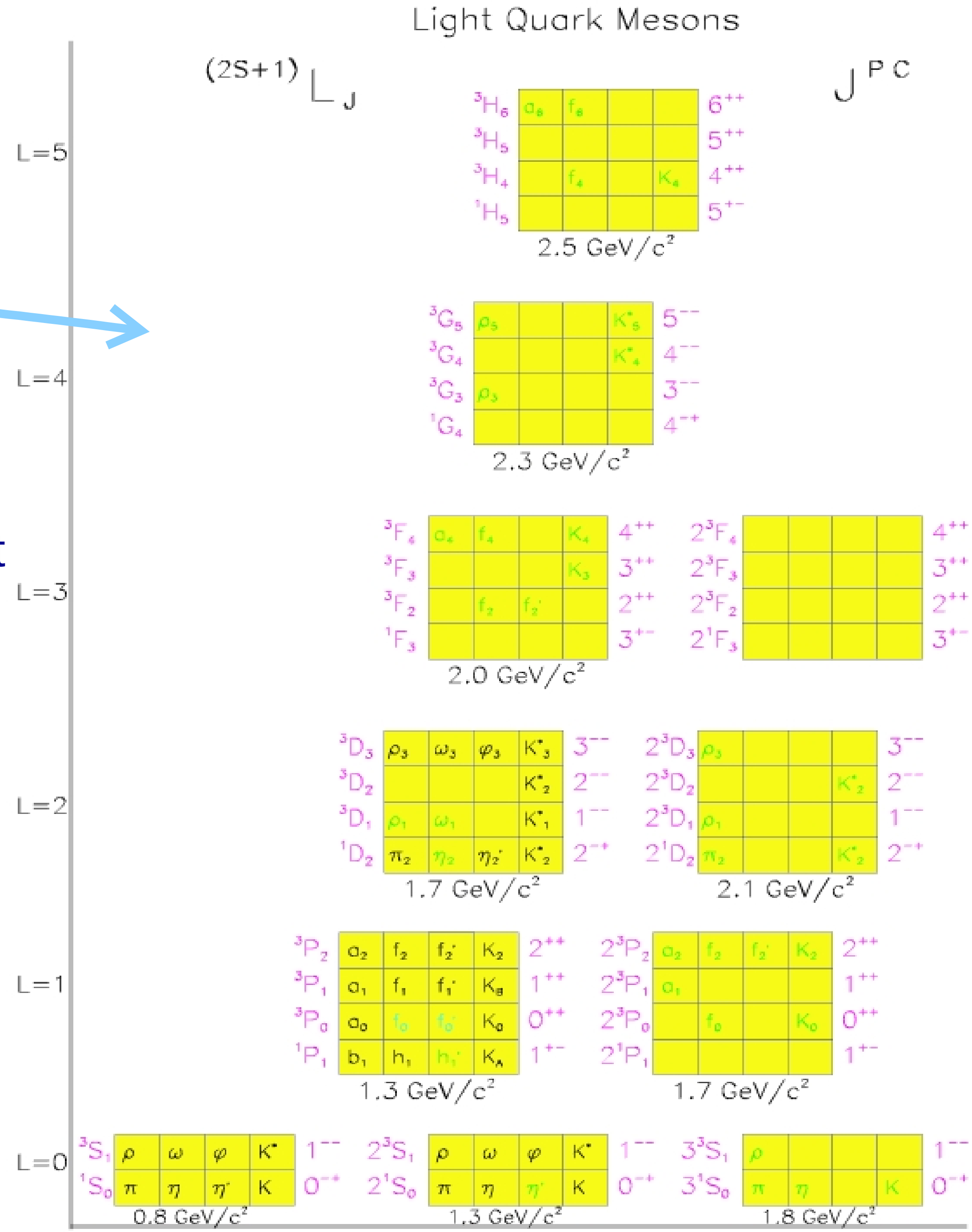


Light Meson Roadmap

What we know experimentally about the light meson spectrum.

Nonet overpopluation used as evidence for hybrid states.

(*tentative assignments)



Families of Exotics

Hybrids

- 2^{+-}
- 2^{-+}
- 1^{--}
- 1^{-+}
- 1^{+-}
- 1^{++}
- 0^{+-}
- 0^{-+}

exotic nonets

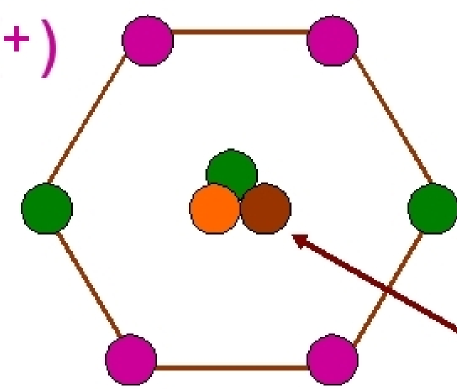
Lattice

1^{-+} 1.9 GeV
2^{+-} 2.1 GeV
0^{+-} 2.3 GeV

- Expect a nonet for each hybrid J^{PC} combination.
  - *Potentially there are a lot of meson states out there yet to be identified.*
  - *Keep in mind that we have not even considered the heavy quarks and what they can allow for.*
  - *Lattice QCD gives us some direction of where to look.*

K_1 $I^G(J^{PC}) = \frac{1}{2}\ (1^{-+})$

π_1 $I^G(J^{PC}) = 1^-(1^{-+})$



1^{-+} nonet

η'_1 $I^G(J^{PC}) = 0^+(1^{-+})$

η_1 $I^G(J^{PC}) = 0^+(1^{-+})$

Search Strategy for Exotics

- Use large−acceptance detector systems:
  - *provide for hermetic coverage for charged and neutral particles*

Typical reactions:

charged

$$\gamma p \to pX \to pK^{*+}K^{*-} \to pK_s^0\pi^+K_s^0\pi^- \to p\pi^+\pi^-\pi^+\pi^+\pi^-\pi^-$$

$$\gamma p \to nX \to n\rho^+\pi^0 \to n\pi^+\pi^0\pi^0\pi^0 \to n\pi^+\gamma\gamma\gamma\gamma\gamma\gamma$$

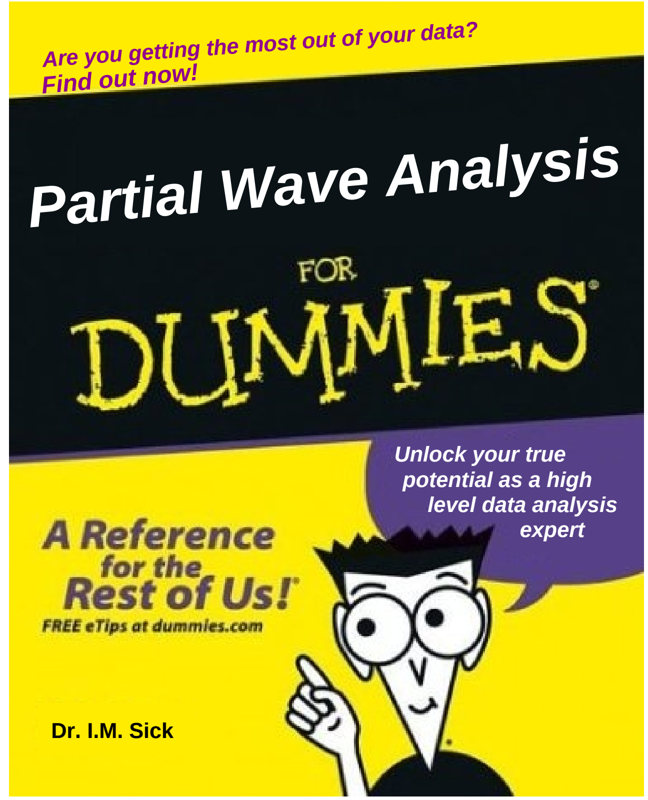
neutrals

  - *require high luminosities and data acquisition rates*

- Perform partial−wave analysis:
  - *identify quantum numbers as a function of mass*
  - *check consistency of results in different decays modes*

Partial Wave Analysis I

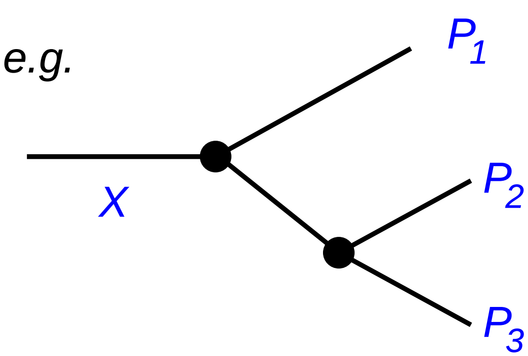
- PWA represents the main tool for "teasing" out the resonant and non−resonant contributions to the mass spectra.
  - *Note: I am one of the "dummies"!*



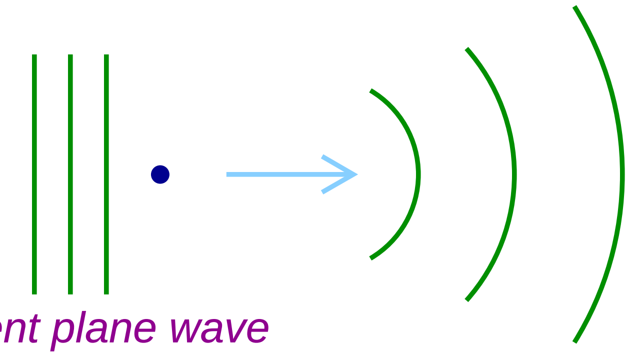
- PWA, amplitude analysis, and partial wave decomposition are all similar terms for this type of fitting.
  - *However, they may mean different things to different folks.*
- How to deal with sequential decays?
  - *Generalize many−body system as a tree of subsequent two−body decays.*

The "Isobar Model"

e.g.



Partial Wave Analysis II



$$\psi(r,\theta,\phi) \longrightarrow e^{ikz} + f(\theta,\phi)\frac{e^{ikr}}{r}$$

$$f(\theta,\phi) = \text{scattering amplitude}$$

- Differential cross section: $\frac{d\sigma}{d\Omega} = |f(\theta,\phi)|^2$

$$f(\theta,\phi) = \frac{-m}{2\pi\hbar^2}\int d\vec{r}\, e^{i\vec{q}\cdot\vec{r}/\hbar} V(\vec{r})$$

Fourier transform of potential
(First Born approximation)

- More generally,

phase shifts

$$\psi_s = \psi_f - \psi_i = \frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\frac{\eta_l e^{2i\delta_l}}{2i}P_l(\cos\theta)\frac{e^{ikr}}{r}$$

scattering amplitude

Partial Wave Analysis III

- The cross section can be written as:

$$\frac{d\sigma}{d\Omega} = \frac{1}{k^2}\left|\sum_{l=0}^{\infty}(2l+1)\frac{\eta_l e^{2i\delta_l}-1}{2i}P_l(\cos\theta)\right|^2 = |f(\theta)|^2$$

$$= \frac{1}{k^2}\left|\sum_{l=0}^{\infty}(2l+1)T_l P_l(\cos\theta)\right|^2$$

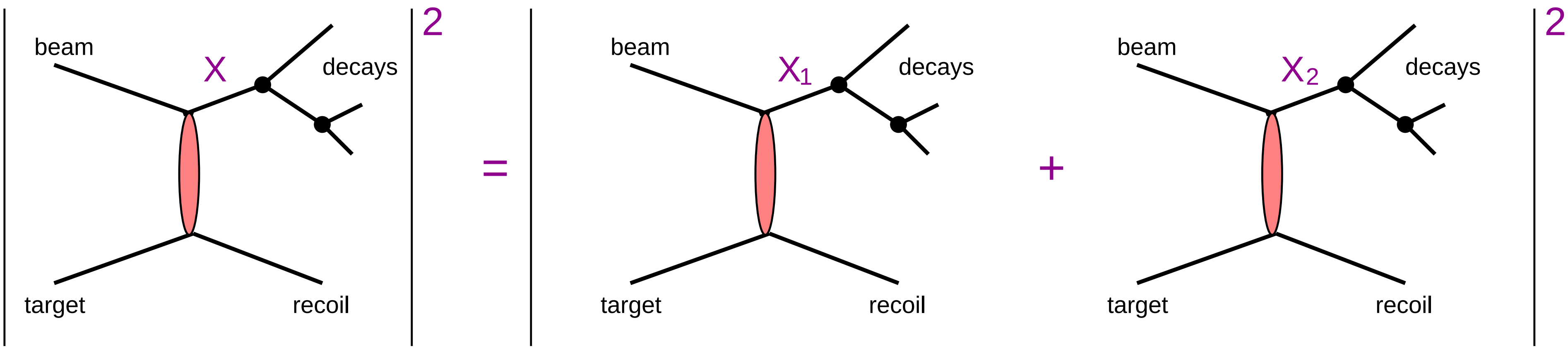
with $T_l = \frac{\eta_l e^{2i\delta_l}-1}{2i}$ T−matrix

- A complete set of phase shifts contains all information about the underlying dynamics.

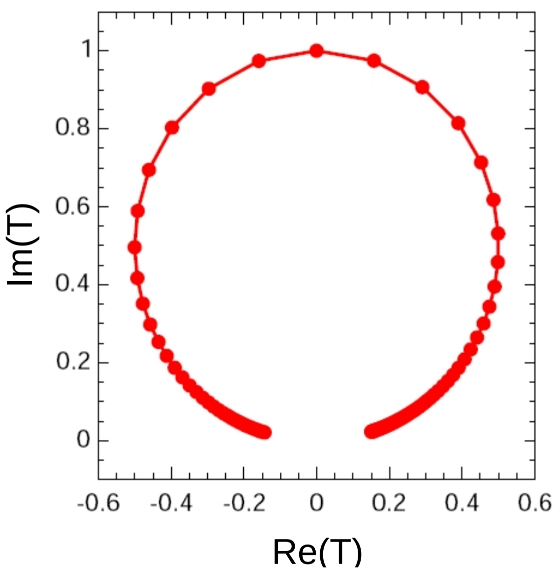
- Typically the analysis is carried out by looking at phase differences between a purported state and a well−known "reference" state.

Partial Wave Analysis IV

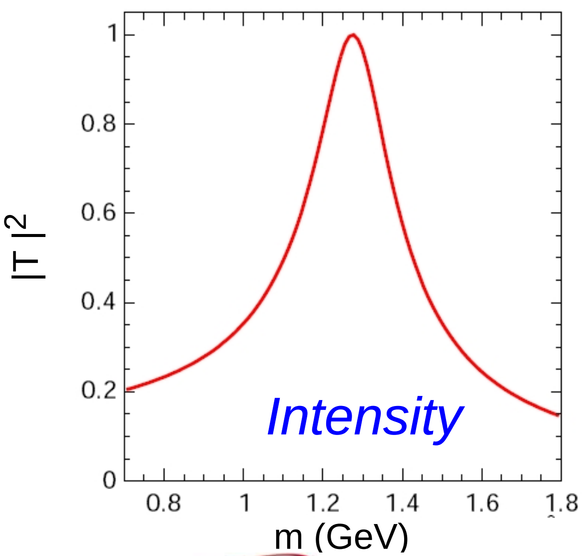
- Amplitude analysis:

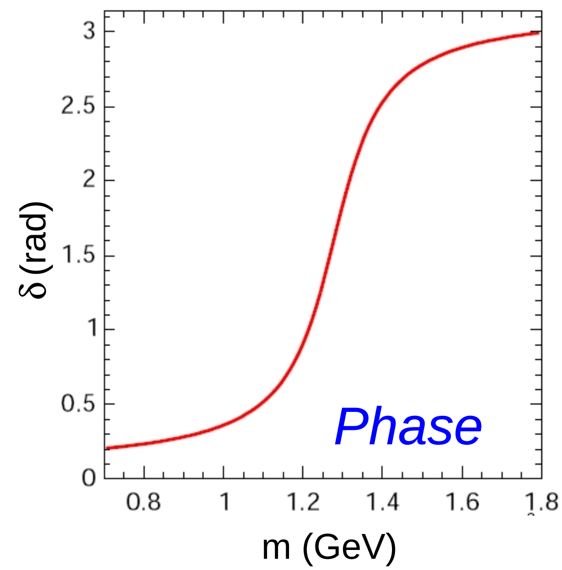


- Argand diagrams:



Relativistic Breit Wigner





Partial Wave Analysis V

- The full amplitude for each partial wave also includes an isospin term, an angular term, proper accounting of spin, and accounting for all channels in a decay tree (as well as accounting for all conservation laws).
- The mass distributions are fit with relativistic Breit−Wigner functions to extract masses and widths.
- The partial wave analysis is carried out on the angular distributions to fit the intensities and phases of each partial wave as a function of mass.

CAVEATS:

The number of counts in a given bin must account for the Poisson fluctuation probability in the number of events.

The true number of counts is not just what we see in the detector. We must count up everything.

account for acceptance of detector and all inefficiencies

(the larger the detector acceptance, the smaller the corrections)

Size Matters

J^{PC} M^{ϵ}	L	Isobar	Wave Set
$0^{-+}0^{+}$	S	$(\pi\pi)_S\pi$	L,H
$0^{-+}0^{+}$	S	$f_0\pi$	L,H
$0^{-+}0^{+}$	P	$\rho\pi$	L,H
$1^{++}0^{+}$	S	$\rho\pi$	L,H
$1^{++}1^{+}$	S	$\rho\pi$	L,H
$1^{++}1^{-}$	S	$\rho\pi$	L
$1^{++}0^{+}$	P	$f_0\pi$	H
$1^{++}0^{+}$	P	$(\pi\pi)_S\pi$	H
$1^{++}1^{+}$	P	$f_2\pi$	H
$1^{++}0^{+}$	D	$\rho\pi$	L
$1^{-+}1^{+}$	P	$\rho\pi$	L,H
$1^{-+}0^{-}$	P	$\rho\pi$	L,H
$1^{-+}1^{-}$	P	$\rho\pi$	L,H
$2^{++}1^{+}$	D	$\rho\pi$	L,H
$2^{++}0^{-}$	D	$\rho\pi$	L,H
$2^{-+}0^{+}$	S	$f_2\pi$	L,H
$2^{-+}1^{+}$	S	$f_2\pi$	L,H
$2^{-+}1^{-}$	S	$f_2\pi$	L
$2^{-+}0^{+}$	P	$\rho\pi$	L,H

J^{PC} M^{ϵ}	L	Isobar	Wave Set
$2^{-+}1^{+}$	P	$\rho\pi$	H
$2^{-+}0^{+}$	P	$\rho_3\pi$	H
$2^{-+}1^{+}$	P	$\rho_3\pi$	H
$2^{-+}0^{+}$	D	$(\pi\pi)_S\pi$	L,H
$2^{-+}0^{+}$	D	$f_0\pi$	H
$2^{-+}1^{+}$	D	$(\pi\pi)_S\pi$	H
$2^{-+}1^{+}$	D	$f_0\pi$	H
$2^{-+}1^{+}$	D	$f_2\pi$	L,H
$2^{-+}0^{+}$	D	$f_2\pi$	L,H
$2^{-+}0^{+}$	F	$\rho\pi$	H
$2^{-+}1^{+}$	F	$\rho\pi$	H
$3^{++}0^{+}$	S	$\rho_3\pi$	L,H
$3^{++}0^{+}$	P	$f_2\pi$	H
$3^{++}0^{+}$	D	$\rho\pi$	H
$4^{++}0^{+}$	D	$\rho_3\pi$	H
$4^{++}0^{+}$	F	$f_2\pi$	H
$4^{++}0^{+}$	G	$\rho\pi$	H
$4^{-+}0^{+}$	P	$\rho_3\pi$	H
$4^{-+}0^{+}$	F	$\rho\pi$	H

$$\pi^- p \longrightarrow (3\pi)^- p$$

- Analysis of E852 data using two different size wave sets.
  - *Low wave set: 20 waves*
  - *High wave set: 38 waves*

Dzierba, PRD 73, (2006)

- Very different physics conclusions can be drawn under different assumptions:
  - *size of wave set*
  - *modeling of detector*
- Leakage: movement of strength from its "real" wave to others due to improper modeling.

PWA can be more an art than a science!

Buyer beware!

Data Set Overview

- Existing data for the evidence of exotic mesons has come from a number of sources.

1). **Brookhaven National Laboratory**: E852 - 18 GeV $\pi^- p$ reactions

2). **Crystal Barrel at CERN**: $\bar{p}p$, $\bar{p}d$ reactions at 1–2 GeV

3). **VES at IHEP**: $\pi^- p$ at 37 GeV

4). **GAMS at Serpukhov**: $\pi^- p$ at 40 GeV

5). **KEK at Japan**: $\pi^- p$ at 6 GeV

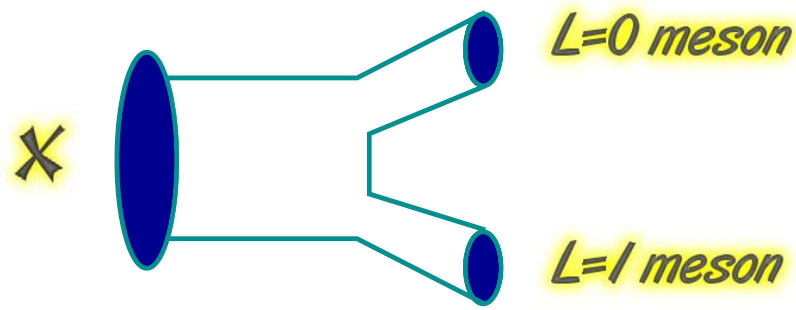
6). **Smattering of photoproduction data**: SLAC (old) and JLab/CLAS

Each experiment has its own limitations, not the least of which is relatively small statistics!

Hybrid Decays

- Decay calculations are model dependent, but it is generally believed that the angular momentum of the flux tube stays in one of the daughters.

Approximate selection rule:



$$\left.\begin{array}{l}\mathrm{L{=}0:}\ \pi,\ \rho,\ \eta,\ \omega,\ \cdots \\ \mathrm{L{=}1:}\ a,\ b,\ h,\ f,\ \cdots\end{array}\right\}\ \eta\pi,\ \rho\pi,\ \cdots\ \text{not preferred.}$$

(partial widths)

e.g. $\pi_1 \rightarrow \pi b_1, \pi f_1, \pi\rho, \eta a_1 \quad 87, 21, 11, 9\ \mathrm{MeV}$

(Heavy quark expansion: Swanson & Szczepaniak)

- Experiment has provided some tantalizing hints for exotic hybrid states.

$\pi_1(1400)$ $\pi_1(1600)$ $\pi_1(2000)$

WHAT CAN WE SAY ABOUT THESE STATES??

$\pi_1(1400)$ [o]

$I^G(J^{PC}) = 1^-(1^{-+})$

Mass $m = 1376 \pm 17$ MeV
Full width $\Gamma = 300 \pm 40$ MeV

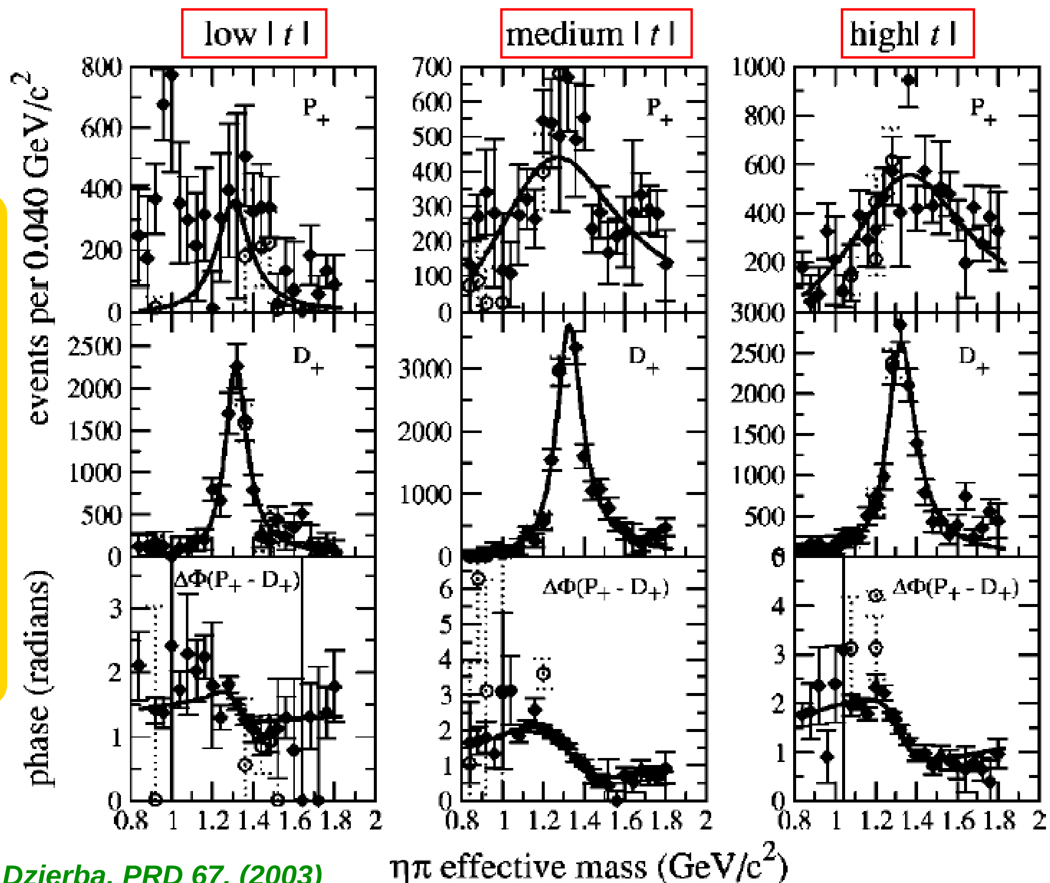
$\pi_1(1400)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\eta\pi^0$	seen	570
$\eta\pi^-$	seen	569

E852 Results:

$$\pi^- p \to \eta\pi^0 n \text{ @ 18 GeV}$$

"No consistent set of P-wave resonant parameters can describe the data while the resonant parameters obtained for the $a_2(1320)$ are consistent for various ranges with PDG."

Exotic is a few % of the dominant $a_2(1320)$.

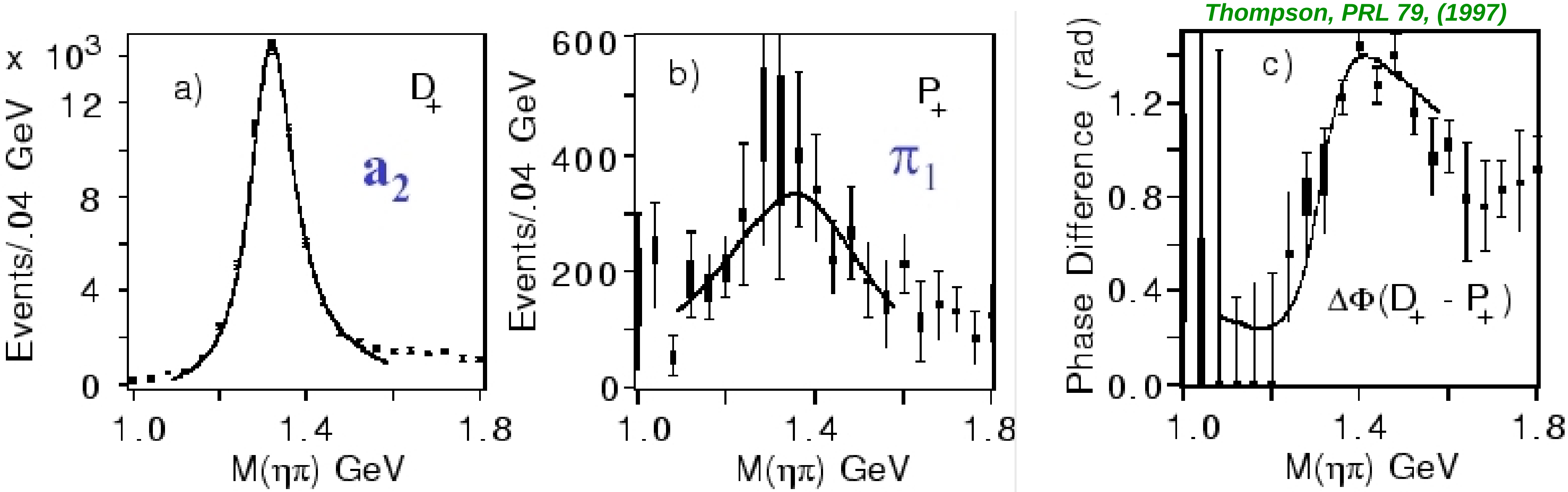


Dzierba, PRD 67, (2003)

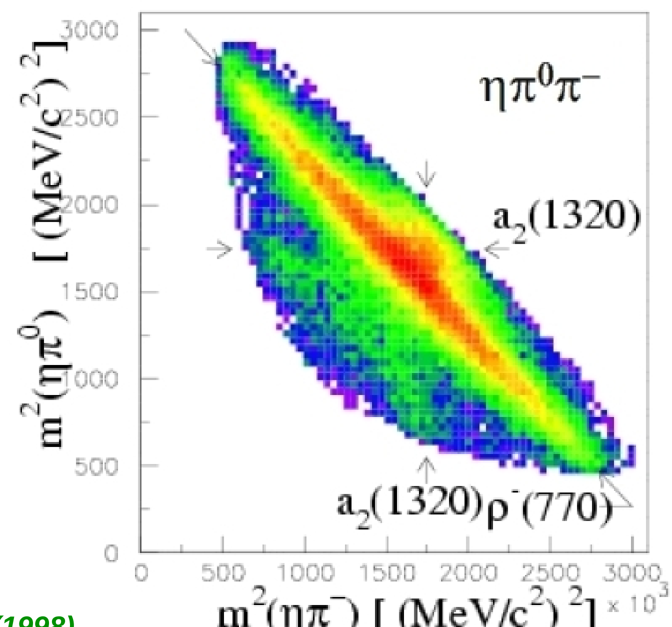
E852 Results:

$\pi^- p \to \eta \pi^- p$ @ 18 GeV

Thompson, PRL 79, (1997)



$\bar{p}n$



Abele, PLB 423, (1998)

Crystal Barrel Results:

PWA Results

- Without exotic P−wave resonance:

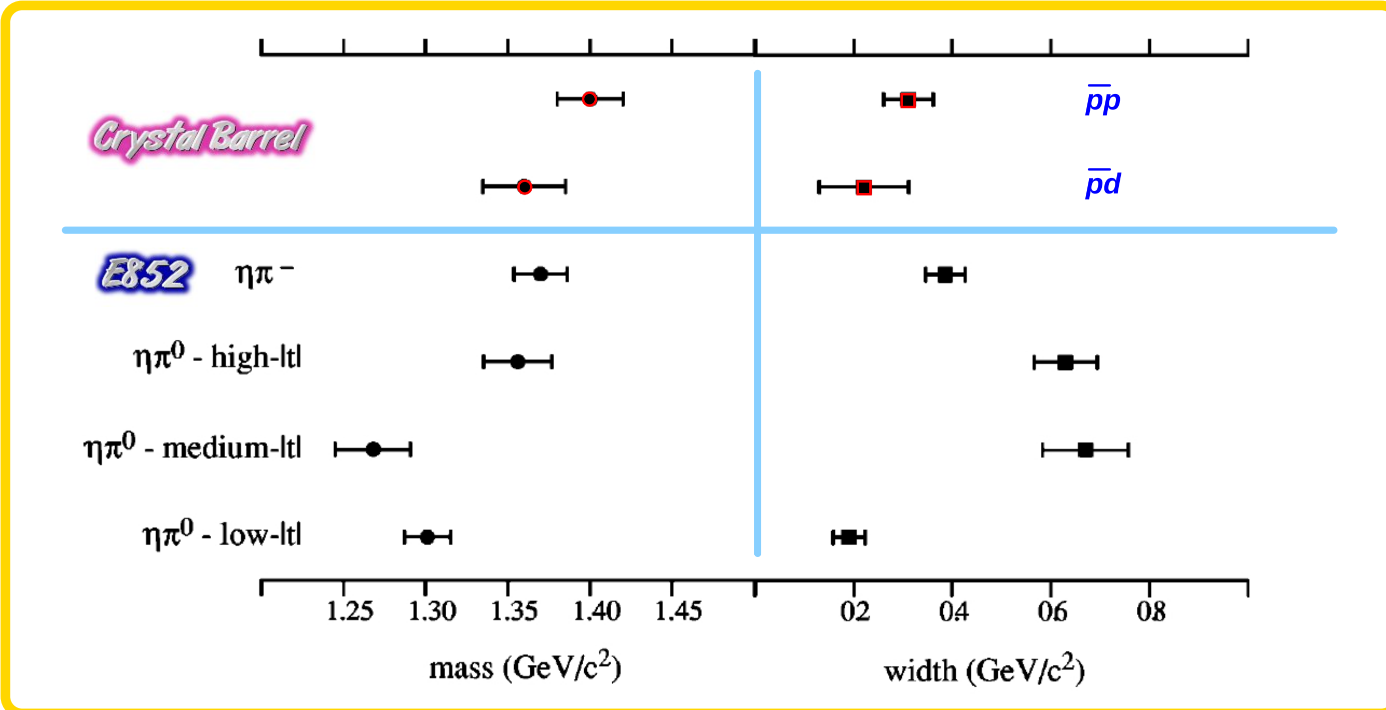
  χ^2/d.o.f. = 3

- With exotic P−wave resonance:

  χ^2/d.o.f. = 1.4

  (~400 d.o.f.)

Exotic strength is comparable to the a_2(1320)!!



- *Decays modes not "hybrid−like".*
- *The signal is too light to be a hybrid by any (reasonable) model.*
- *Could be a meson−meson molecule.*
- *Szczepaniak shows that exotic wave is non−resonant (rescattering effect).*
- *Data quality poor and results inconsistent.* **Leakage??** *(VES,GAMS,KEK)*

EVIDENCE IS CONTROVERSIAL!

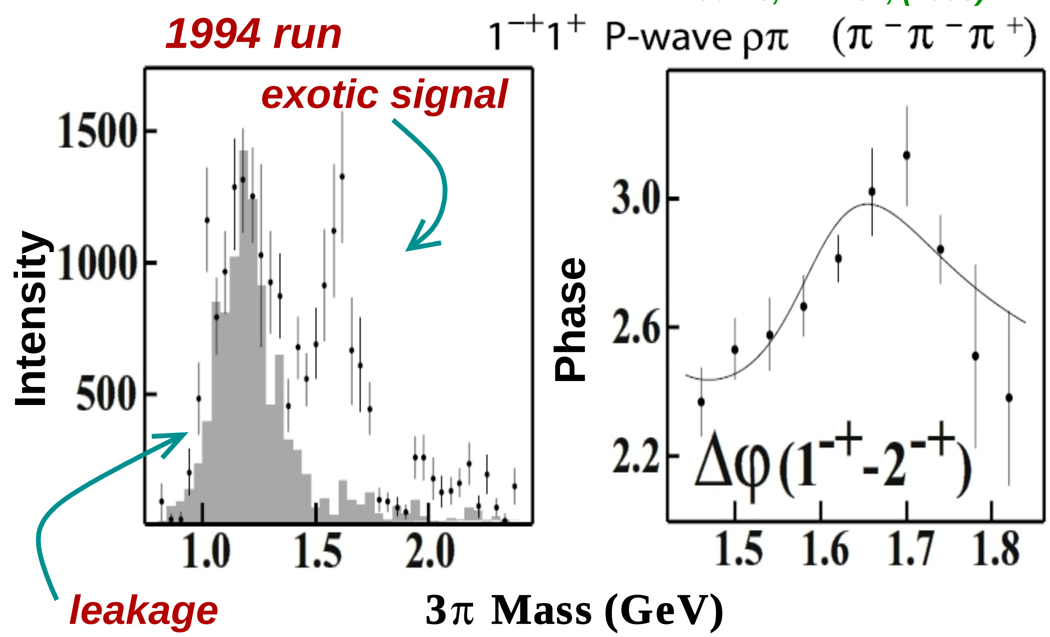
π_1 (1600)

E852 Results:

- Evidence based on 250k events from $\pi^- p \rightarrow Xp \rightarrow \rho\pi p$.

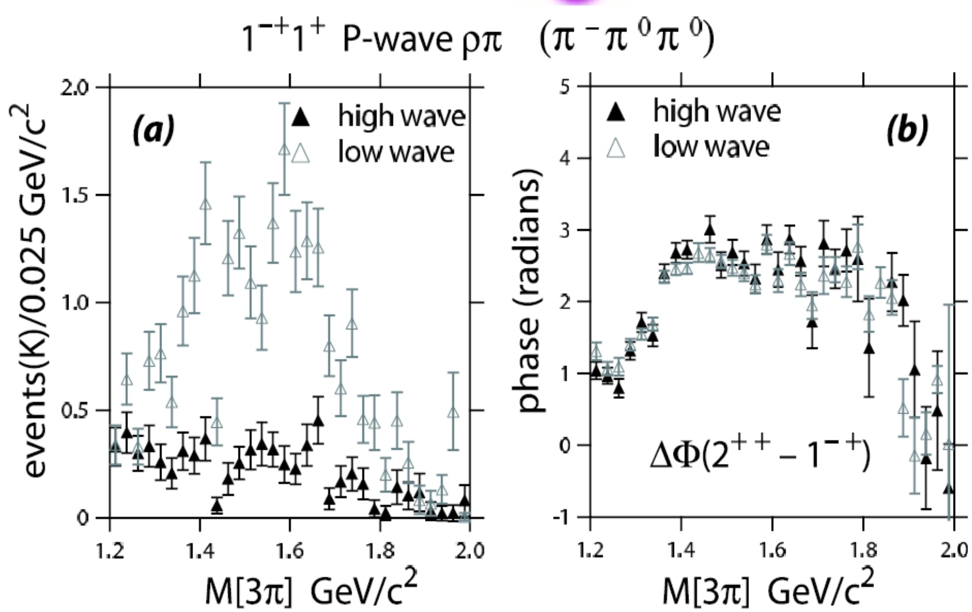
$\text{Mass} = 1.593 \pm 0.008$ GeV
$\text{Width} = 0.168 \pm 0.020$ GeV

Adams, PRL 81, (1998)



Very exciting result!

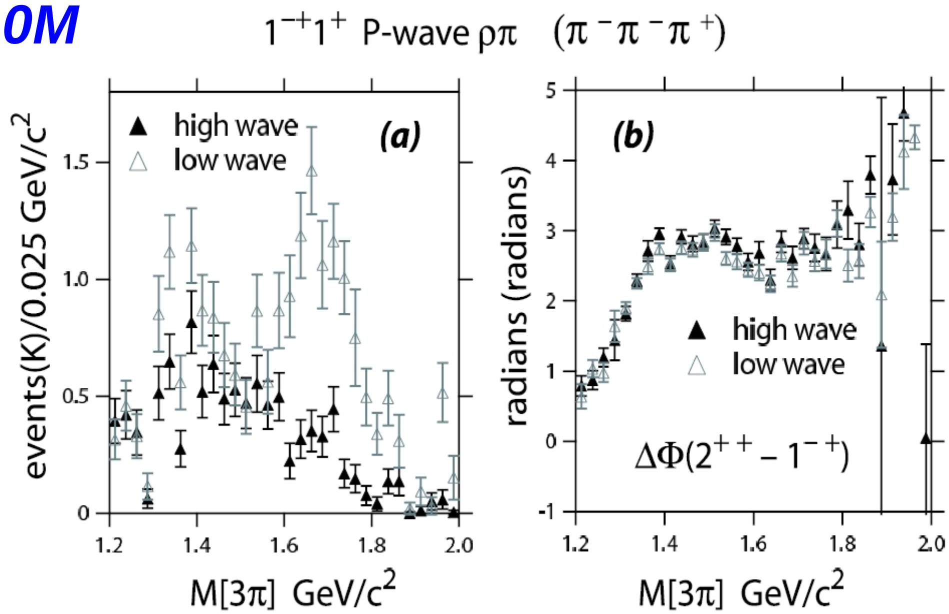
But is it now gone??



1995 run

3.0M

Dzierba, PRD 73, (2006)



π_1 (1600)

E852 Results:

- The $\pi_1(1600)$ is the dominant signal in $\eta'\pi$.

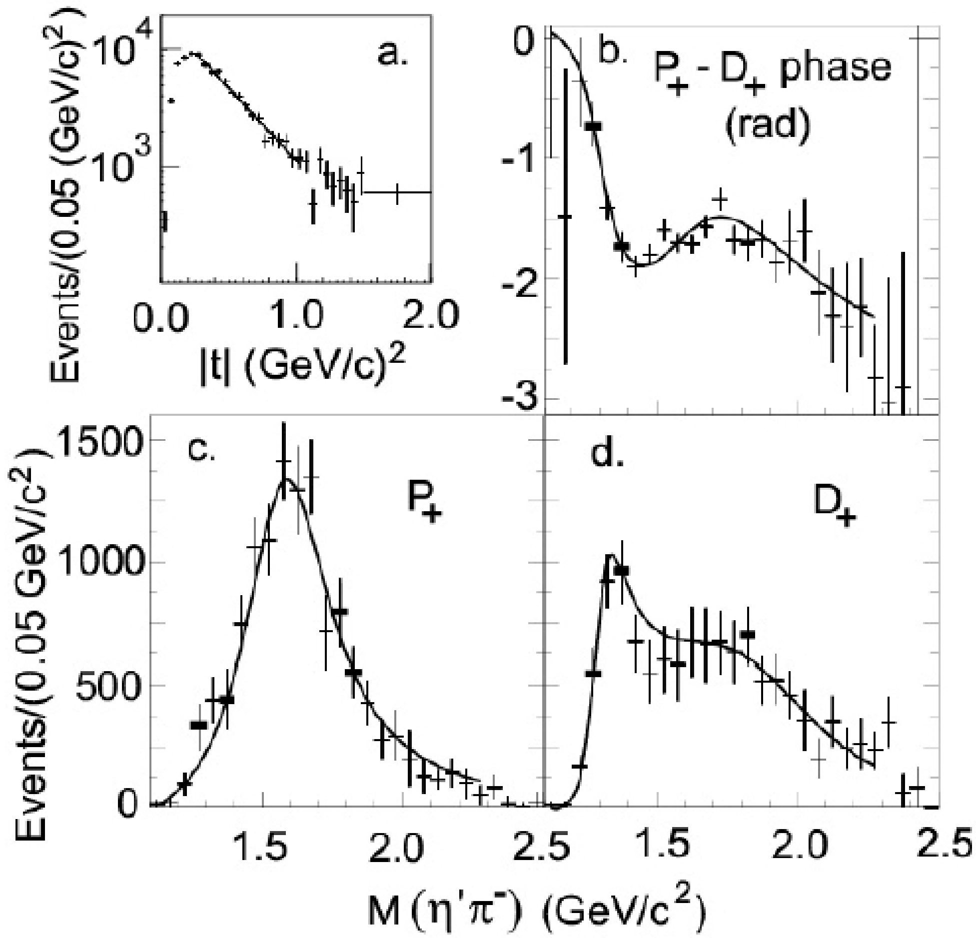
  Mass $= 1.597 \pm 0.010$ GeV
  Width $= 0.340 \pm 0.040$ GeV

  Conflict with $\rho\pi$??
  Is D−wave strength understood??

- In both $b_1\pi$ and $f_1\pi$, the $\pi_1(1600)$ is hinted at through excess intensity.

  Analyses are limited!

$\pi^- p \to \eta'\pi^- p$ at 18 GeV/c



Ivanov, PRL 86, (2001)

> Szczepaniak: Much of the $\eta'\pi$ signal is a rescattering background similar to the $\eta\pi$ final state for $\pi_1(1400)$.

EVIDENCE IS CONTROVERSIAL!

π_1 (2000)

Exotic Meson Production in the $f_1(1285)\pi^-$ System Observed in the Reaction $\pi^- p \to \eta\pi^+\pi^-\pi^- p$ at 18 GeV/c

Physics Letters B **595**, 109 (2004)

E852 Collaboration

$\pi_1(2000) \to f_1\pi$

Abstract: This Letter reports results from the partial wave analysis of the $\pi^-\pi^-\pi^+\eta$ final state in $\pi^- p$ collisions at 18 GeV/c. Strong evidence is observed for production of two mesons with exotic quantum numbers of spin, parity, and charge conjugation, $J^{PC} = 1^{-+}$ in the decay channel $f_1(1285)\pi^- \cdots$ with mass $M = 2001 \pm 30 \pm 92$ MeV/c^2 and width $\Gamma = 333 \pm 52 \pm 49$ MeV/c^2 agrees very well with predicitions from theoretical models.

Exotic Meson Decay to $\omega\pi^0\pi^-$

Phys. Rev. Lett. **94**, 032002 (2005)

E852 Collaboration

$\pi_1(2000) \to b_1\pi$

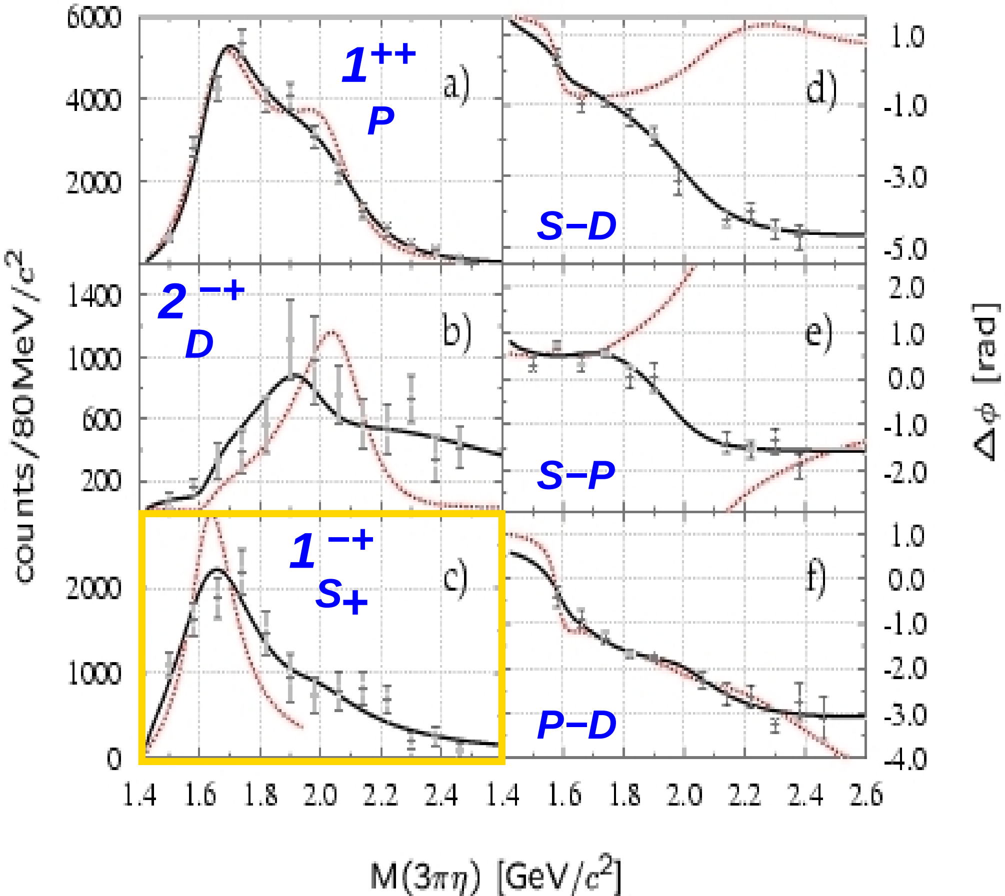
Abstract: A partial wave analysis of the mesons from the reaction $\pi^- p \to \pi^+\pi^-\pi^-\pi^0\pi^0 p$ has been performed. The data show $b_1\pi$ decay of the spin exotic states $\pi_1(1600)$ and $\pi_1(2000)$.

Encouraging! − These are more in line with what is expected from models and LQCD in terms of mass and decay modes.

. . . But the statistics are limited

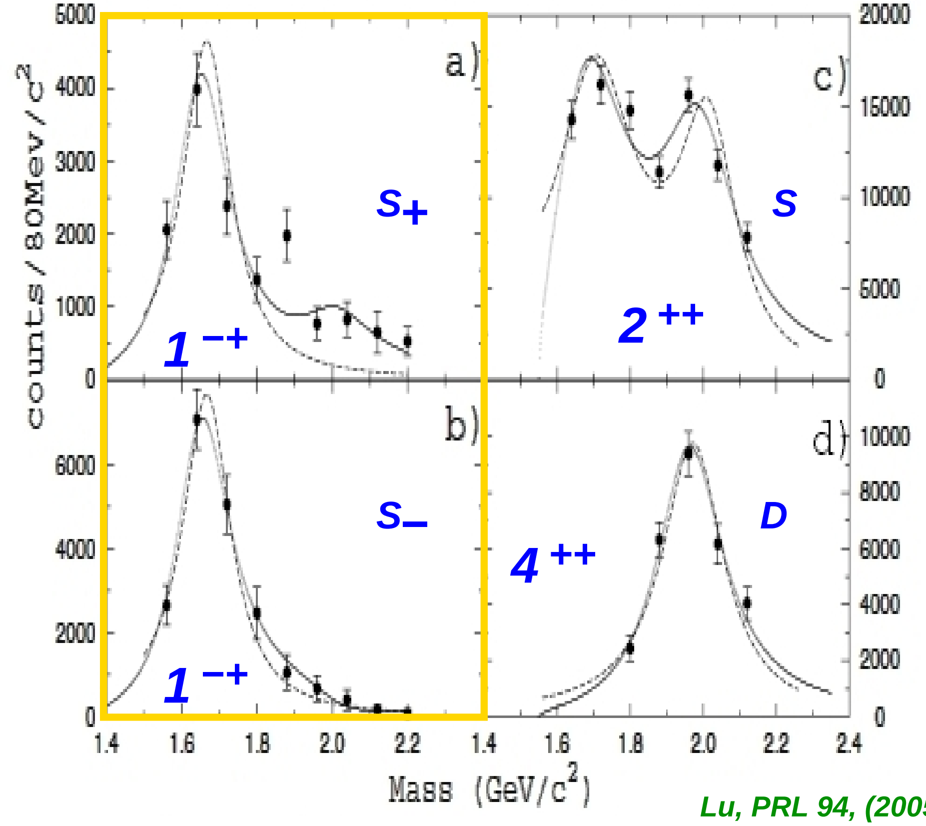
So too are the wave sets!!

$\pi_1(2000) \rightarrow f_1\pi$

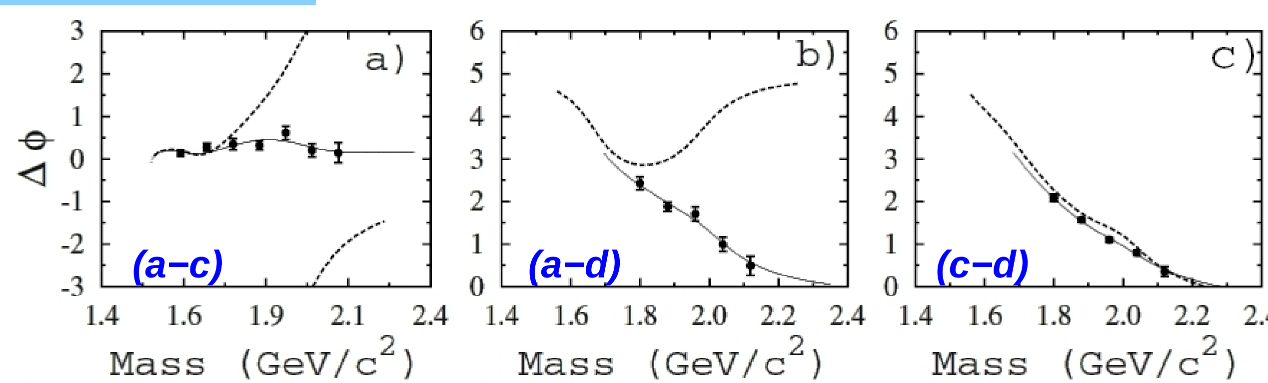


Kuhn, PLB 595, (2004)

$\pi_1(2000) \rightarrow b_1\pi$



Lu, PRL 94, (2005)



Status:
Far from clear

Why are Exotic Hybrids Hard to Find?

- Hybrids couple to high multiplicity final states.
  - *Coupling of hybrids to two−body final states is almost non−existent.*
- Require detailed knowledge of full meson spectrum.
  - *Understanding of multiple decay modes required.*
- States are expected to have fairly broad widths. *(100−400 MeV)*
  - *Difficult to cleanly isolate.*
  - *Traditional "bump hunting" is not an option.*
- Sophisticated analysis tools are required.
  - *Plagued by model dependence, ambiguities & interpretation dependence.*

    (isobar model, wave sets, leakage)
- Important experimental requirements.
  - *Large acceptance detector with well−understood response essential.*

Detailed spectroscopy is the answer.

Designing the Next Generation Experiment

WHAT IS NEEDED?

- PWA requires that the entire event be identified − all particles detected, measured, and identified.

  The detector should be hermetic for neutral and charged particles, with excellent resolution and particle ID capability.

- The beam energy should be sufficiently high to produce mesons in the desired mass range with excellent acceptance.

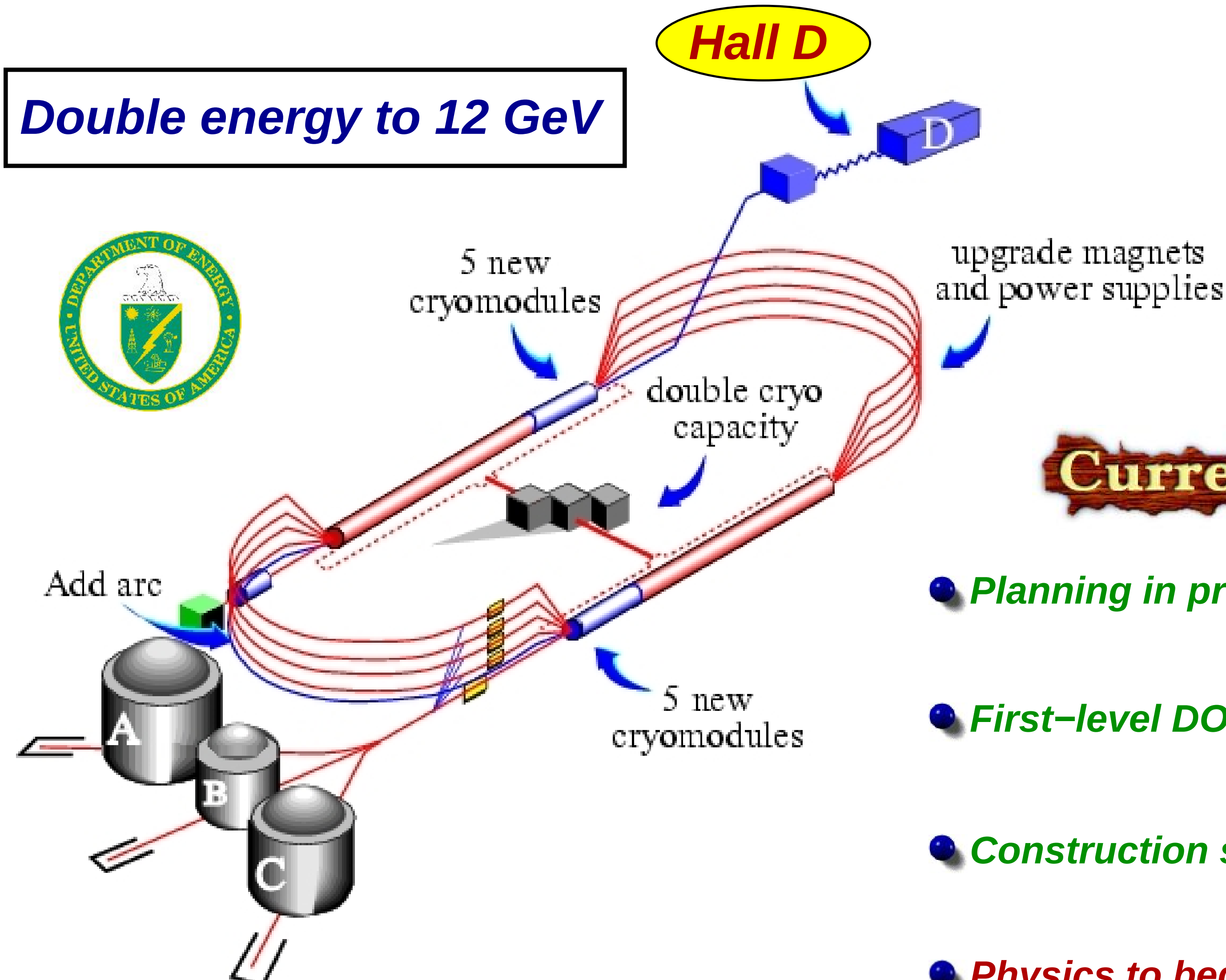
  Too high an energy will introduce backgrounds, reduce cross sections of interest, and make it difficult to achieve goals.

- PWA also requires high statistics and linearly polarized photons.

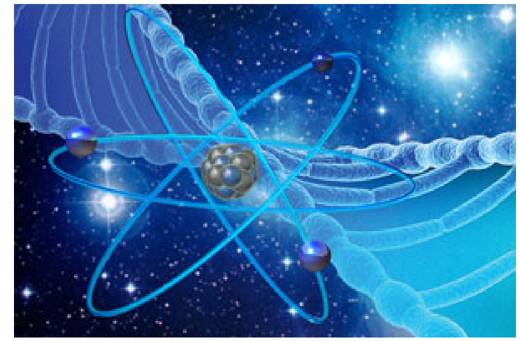
  Require sensitivity to sub−nanobarn production cross sections.

Jefferson Laboratory Upgrade

Double energy to 12 GeV



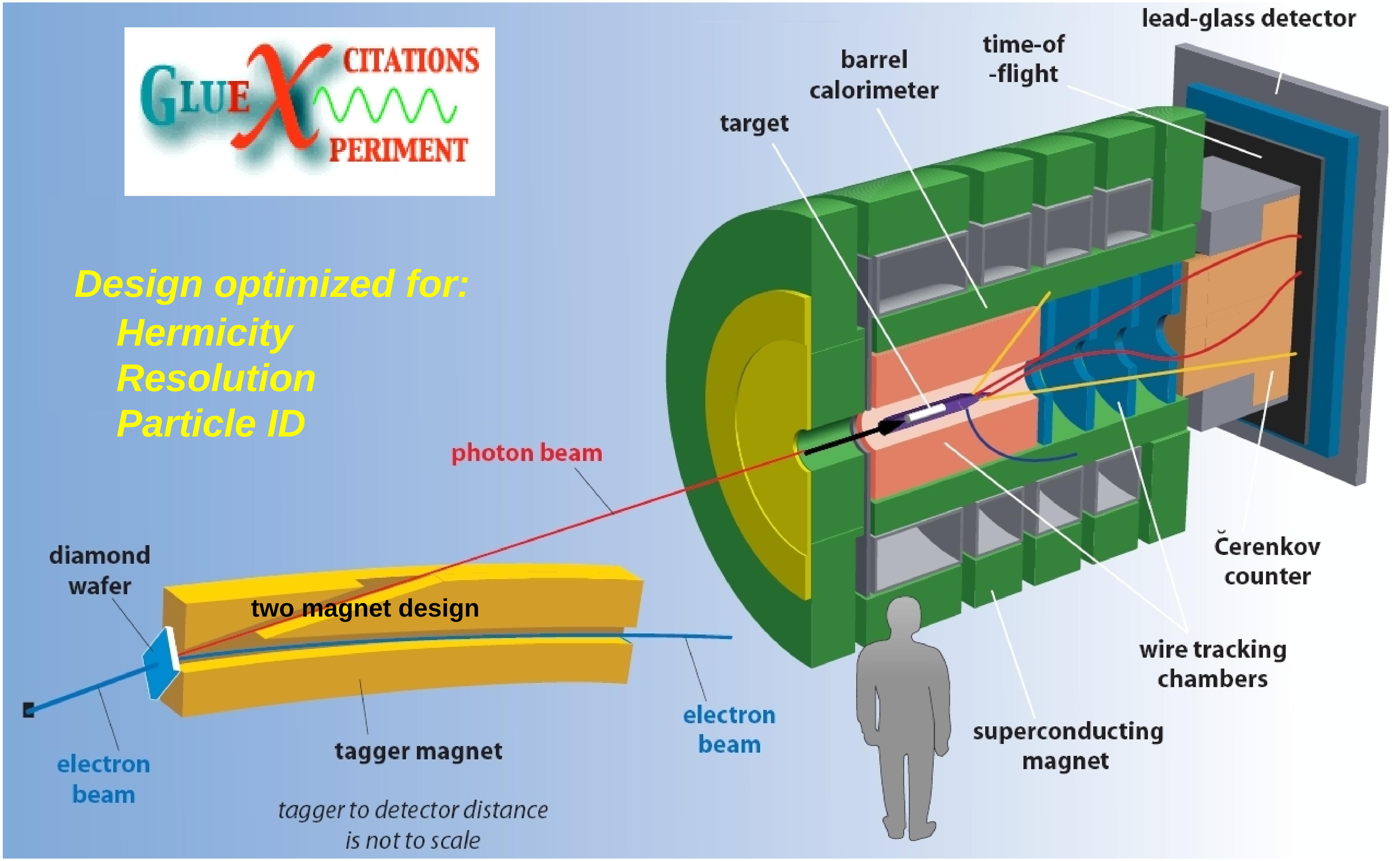
Enhance equipment in existing Halls



Current status:

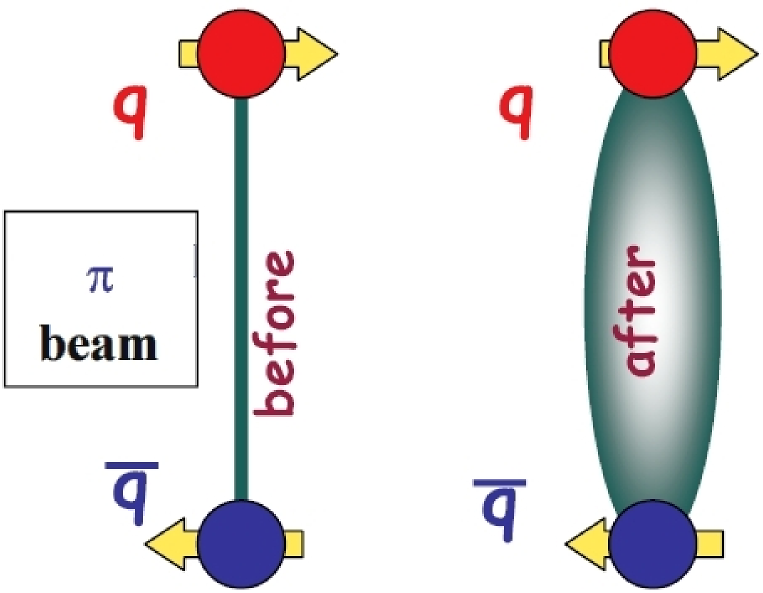
- *Planning in progress for 10+ years.*
- *First−level DOE approval in April 2004.*
- *Construction set to begin this year.*
- *Physics to begin 2012−2013.*

GlueX Detector in Hall D



GlueX will exceed existing photoproduction data in its first year by several orders of magnitude.

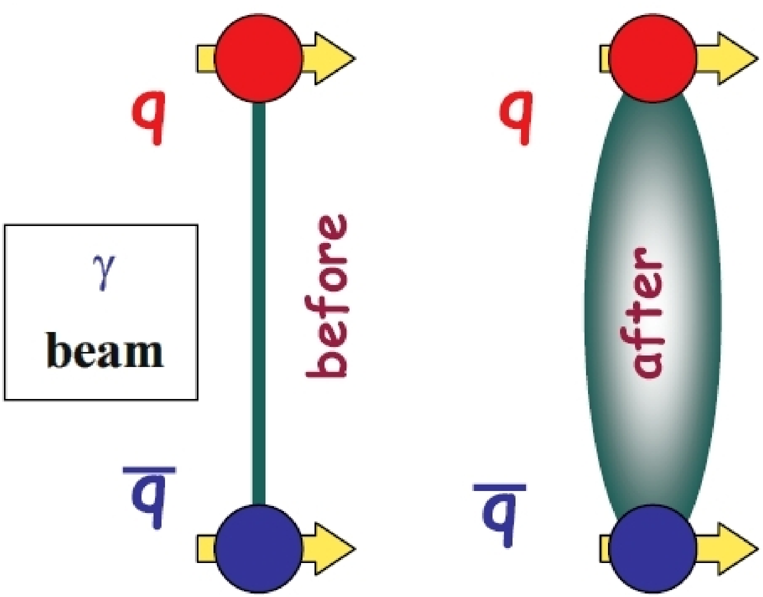
Photoproduction Experiment



Quark spins anti-aligned

A pion or kaon beam,
when scattering occurs,
can have its flux tube excited

Much data in hand but little
evidence for gluonic excitations
(and not expected)

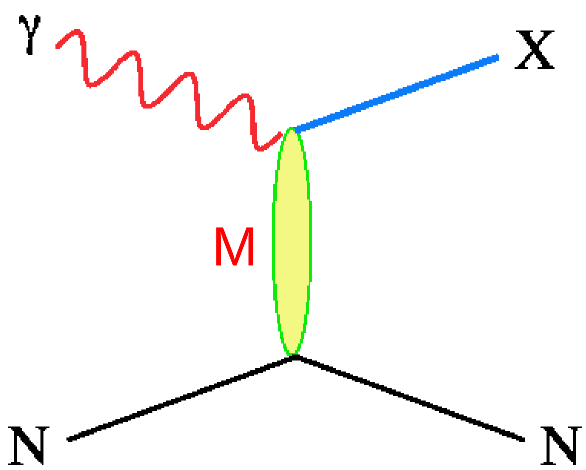


Quark spins aligned

Almost no data in hand
in the mass region
where we expect to find exotic hybrids
when flux tube is excited

CROSS SECTIONS SHOULD BE SIZEABLE!

Linear Polarization



$$N : J^P = 0^+, 1^-, 2^+$$
$$U : J^P = 0^-, 1^+, 2^-$$

- **Diffractive production:**

  Takes place via natural (N) parity exchange

- **Exotic production:**

  Takes place via unnatural (U) parity exchange

- **Unpolarized or circularly polarized photons cannot distinguish between N and U.**

  With linear polarization one can distinguish by selection based on the angle the polarization vector makes with the production plane.

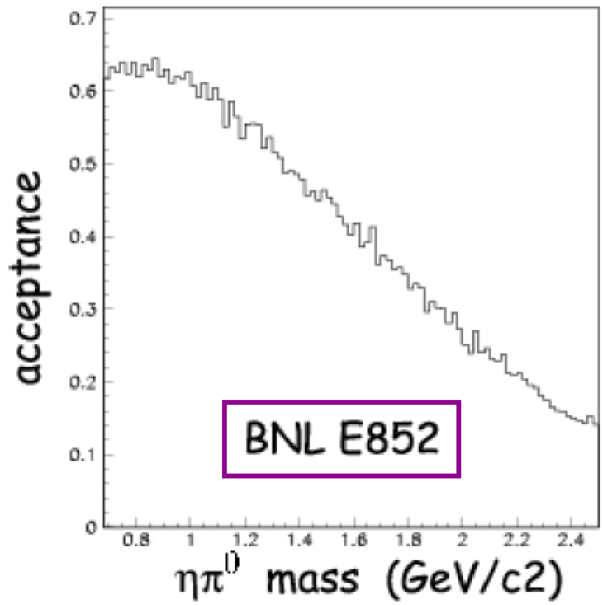
  This angle is related to the naturality of the exchanged meson M.

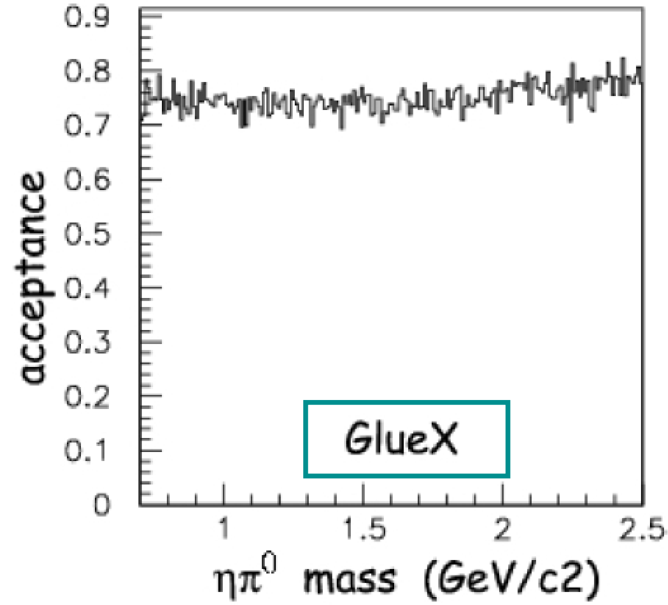
THIS CAPABILITY WILL BE ESSENTIAL IN ISOLATING THE EXOTIC WAVES!

Acceptance of GlueX

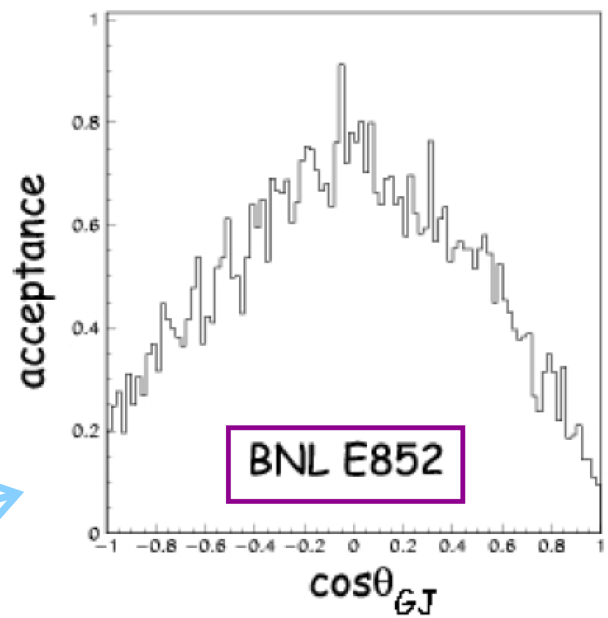
$\pi^- p \rightarrow X n \rightarrow \eta\pi^0 n$

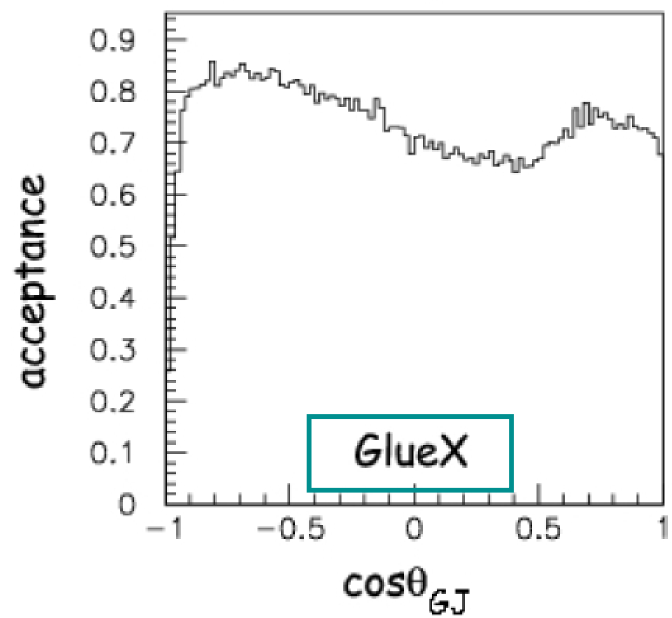
$\gamma p \rightarrow X p \rightarrow \eta\pi^0 p$





CM frame for X





Exotic Hybrid Spectroscopy

- GlueX seeks to map nonets of exotics (not just find one state) and to determine branching ratios.

  Exotic hybrids will be the initial focus − these states cannot mix with conventional mesons.

Exotic meson width and decay predictions

Particle	J^{PC}	Total Width (MeV/c^2) [8]	[9]	Most Likely Decays
π_1	1^{-+}	81 − 168	117	$b_1\pi$, $\rho\pi$, $\eta(1295)\pi$
η_1	1^{-+}	59 − 158	107	$a_1\pi$, $\pi(1300)\pi$
η_1'	1^{-+}	95 − 216	172	$K_1(1400)K$, $K_1(1270)K$, K^*K
b_0	0^{+-}	247 − 429	665	$\pi(1300)\pi$, $h_1\pi$
h_0	0^{+-}	59 − 262	94	$b_1\pi$
h_0'	0^{+-}	259 − 490	426	$K(1460)K$, $K_1(1270)K$
b_2	2^{+-}	5 − 11	248	$a_2\pi$, $a_1\pi$, $h_1\pi$
h_2	2^{+-}	4 − 12	166	$b_1\pi$, $\rho\pi$
h_2'	2^{+-}	5 − 18	79	$K_1(1400)K$, $K_1(1270)K$, $K_2^*(1430)K$

- Non−exotic hybrids will be mapped out as well, and this requires detailed understanding of the conventional meson spectrum.

What Else is Out There?

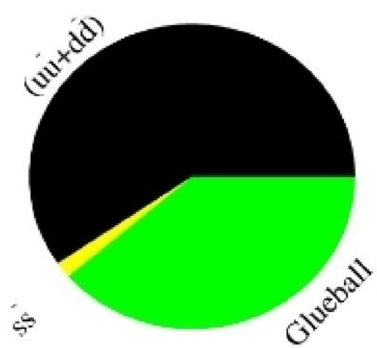
- Experiments have focussed on the search for the lightest exotics predicted by LQCD. All of the rich structure predicted for the 1^{-+} mesons is also expected for the 2^{+-} and 0^{+-} mesons too.

- The discussion here has focussed on light quark exotic mesons, there is alot of work also being focussed currently on the spectroscopy of heavy quark mesons.

- LQCD predicts states composed purely of gluons (aka "glueballs"). The mass predictions for glueballs are in the range from 2 to 4 GeV.

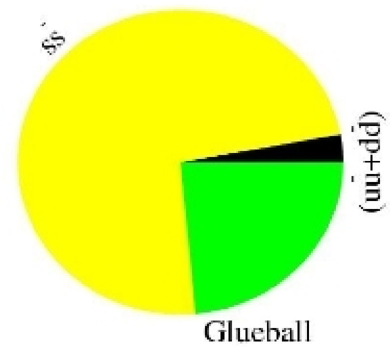
glueballs are expected to mix with ordinary mesons!

$f_o(1370)$



$f_o(1500)$

$f_o(1700)$



Summary & Conclusions

- Understanding confinement requires an understanding of the glue that binds quarks. Exotic hybrid mesons are perhaps the most promising subject for studying the nature of the glue.

- Despite tantalizing hints, the existence of low−lying exotic mesons is controversial and open to a lot of discussion. Experiments suffer from low statistics and conflicting results. Analysis suffers from ambiguities.

- GlueX at the energy−upgraded Jefferson Laboratory will provide photon beams of the necessary flux and polarization, along with an optimized state−of−the−art detector for this physics.

Detailed spectroscopy is the next step to hopefully add some clarity and to provide more definitive answers!