Exotic Hadrons:
A Look at Femtoscale Matter

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Outline

- Matter at distances near 1 femtometer
- QCD, the Quark Model, and hadrons
- The role of exotic hadrons
- Examples from experiment
  - Pentaquarks
  - Glueballs
  - Exotic quantum numbers
  - Missing states
  - Molecular states
- Conclusions

Colloquium, Kent State University, 19 Feb 2004

Matter at Distances Near 1 Femtometer

Need both Quantum Mechanics and Special Relativity

Heisenberg: $\boldsymbol{\Delta x \Delta p \geq \hbar/2}$

$$\Rightarrow E \sim pc \sim (\hbar c)/x = (200\ \mathrm{MeV} \cdot \mathrm{fm})/x$$

"At distances ~ 1 fm, typical energies are ~ 200 MeV."

Einstein: $\boldsymbol{E = Mc^2}$

"At distances ~ 1 fm, new particles can be created if they have mass $M \sim 200\ MeV/c^2$."

Enter the pion (π): $\boldsymbol{M_\pi = 135\ \mathrm{MeV}/c^2}$

$\Rightarrow$ Our notion of "constituents" breaks down at 1 fm! Smash two protons together and and you *don't* get "pieces of the proton". You keep the protons, and also get π's, . . .

Quantum Chromodynamics (QCD)

The **theory of femtometer matter.**

Patterned after Quantum Electrodynamics (QED), QCD uses "quarks" and "gluons" instead of "electrons" and "photons", ***but there is one big difference:***

QCD: Color (RGB/CMY) $\Longleftrightarrow$ QED: Charge (+/−)

This leads to important new effects:

- **Gluons couple to other gluons**
- **Quark and gluons are "confined"**

$\star$ **Quarks are "asymptotically free"**

We know QCD is the right theory because ***for cases in which we can calculate the answer*****, the answer agrees with experiment.**

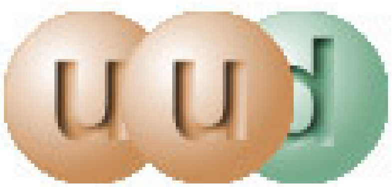
The Quark Model

The Quark Model is an approximation to QCD.
We can use it to to build "hadrons", particles of matter with sizes ~ 1 fm.

Only two kinds of hadrons exist in the Quark Model:

Baryons $\equiv |qqq\rangle$

Example: Proton



Mesons $\equiv |q\bar{q}\rangle$

Example: Pion

The quark model has been *very successful* in describing the properties of hadrons.

***However*, we know that it does not have all the degrees of freedom in QCD, so we should observe hadrons that are *not* described by the quark model.**

Exotic Hadrons

Hadrons *not* predicted by the Quark Model are "exotic".

Their existence and properties will tell us about the behavior of QCD in the confinement region.

For example: Why are exotic hadrons so rare?

Theoretical tools are available to interpret the results of searches for exotic hadrons.

- Flux tube model, bag model, ...
- Approximate analytical solutions to QCD
- Numerical QCD on a spacetime lattice

Detour: “Particles” and “Resonances”

We are discussing quantum mechanical states:
$|qqq\rangle$, $|q\bar{q}\rangle$, $|\text{other}\rangle$

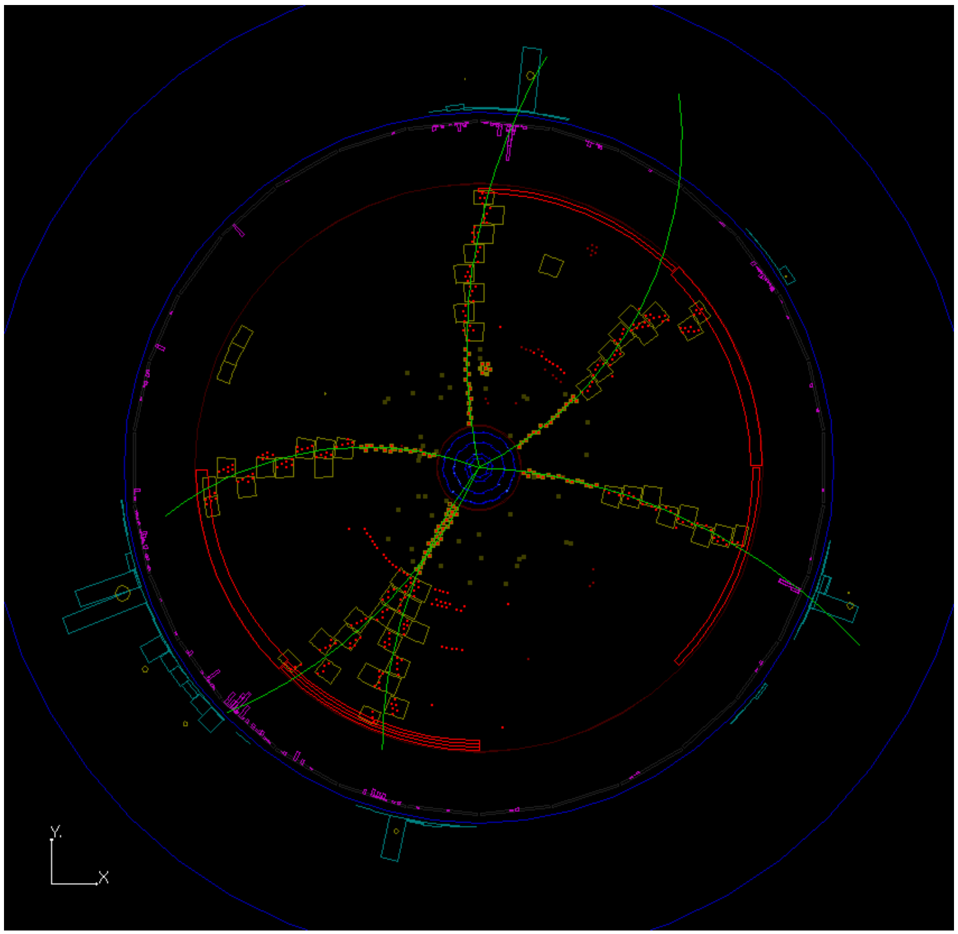
The lowest lying states are “particles”. If they decay, they do so through something other than QCD-powered interactions. Therefore they live a long time.

Exotic hadrons, if they exist, will probably be excited states. They should decay through QCD. Therefore they live a *very short* time.

Very short lived states are observed as quantum mechanical *resonances*. They can only be studied statistically, not one by one.

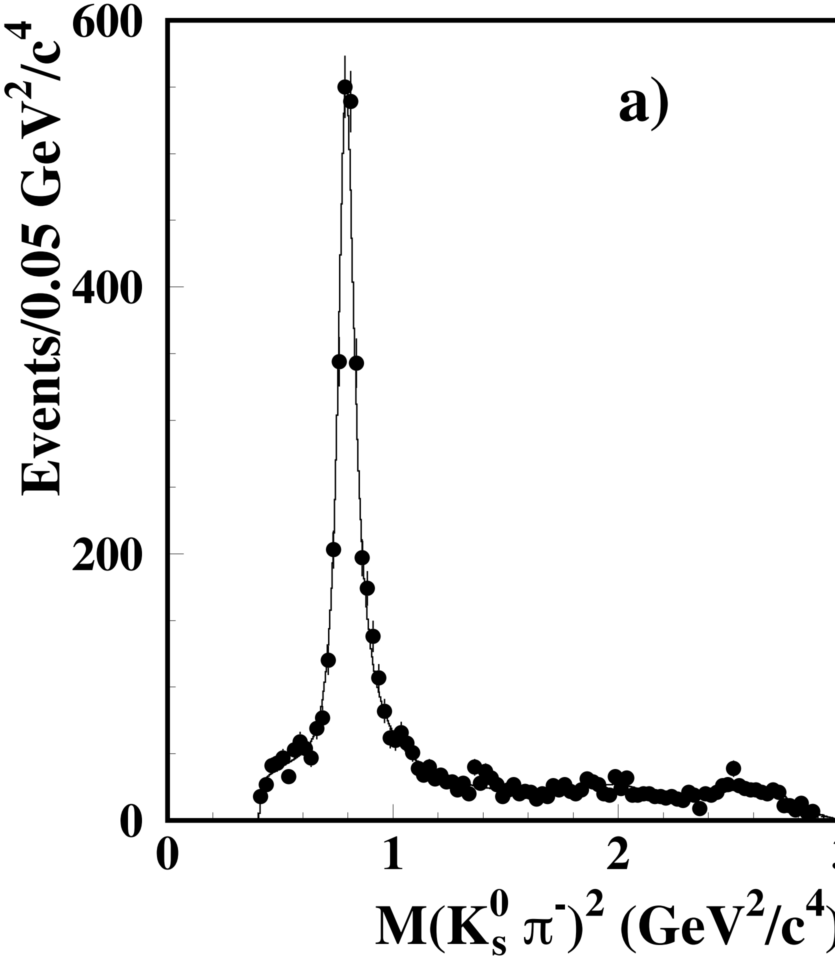
Examples

$e^+e^- \to$ Particles



One “event”

The $K^\star(892)$ Resonance



A “histogram”
of many events.

Kinds of Exotic Hadrons

A summary of exotic hadron categories,
experimental evidence for candidates,
and their potential impact on our understanding of QCD.

My own biased opinions!

	Evidence	Implication for Theory
Glueballs	$\star\star\star$	$\star\star\star$
Molecules	$\star$	$\star$
Pentaquarks	$\star\star$	$\star$
Exotic quantum numbers	$\star\star$	$\star\star\star$
Missing states	$\star\star\star$	$\star$
Dibaryons	$\times$	$\star$

Pentaquarks

"Flavor Exotics"

First consider two well known baryons:

$|uud\rangle = p$ This is the "proton"

$|uus\rangle = \Sigma^+$ This is a kind of "hyperon"

The difference is the "strange" quark:

$S(p) = 0$

$S(\Sigma^+) = -1$

Suppose we found a baryon with Strangeness $S = +1$?
This would be *exotic*!

Possible quark makeup: $|uud\bar{s}d\rangle \equiv \theta^+$

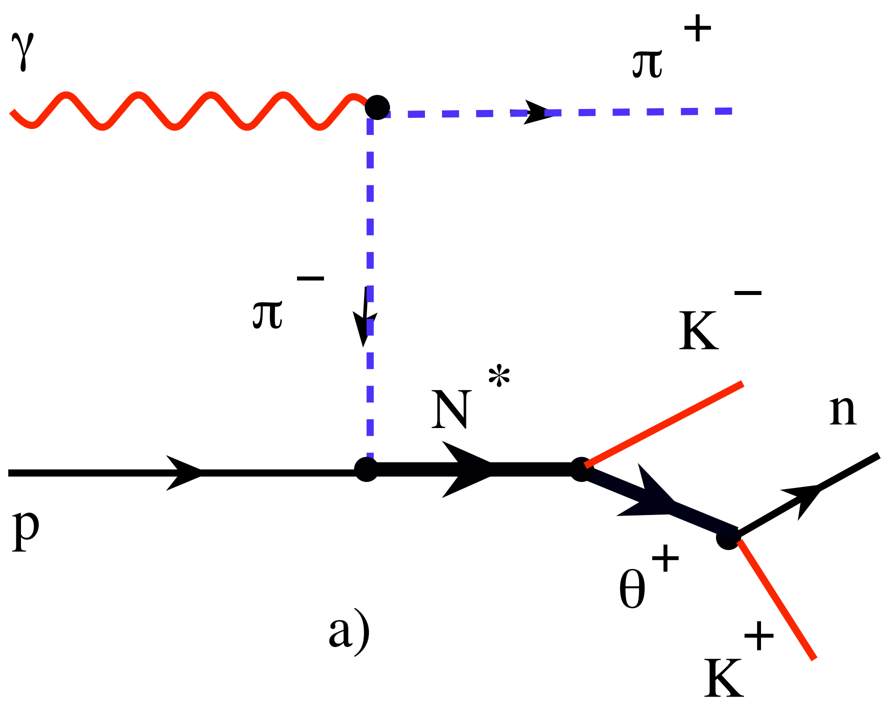
So what's the difference between this and a nK^+ or $p\bar{K}^0$ "molecule"? Hmmm...

Evidence for the Pentaquark

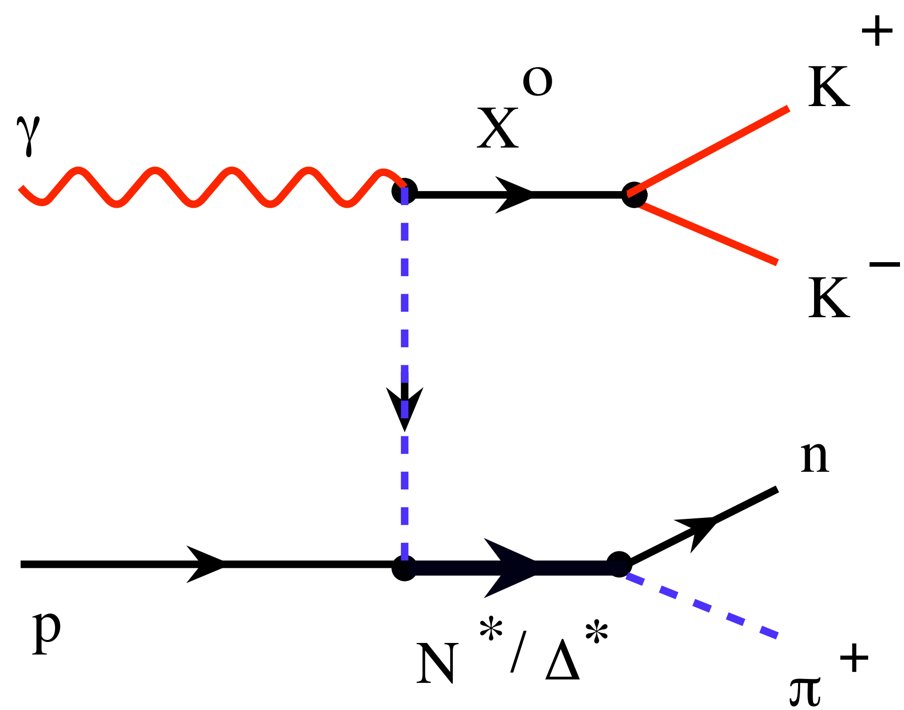
V. Kubarovsky, *et al.*, Phys. Rev. Lett. 92, 032001 (2004)

$$\gamma p \rightarrow K^- \pi^+ \theta^+ \rightarrow K^- \pi^+ n K^+$$

A possible mechanism to produce the θ^+ . . .



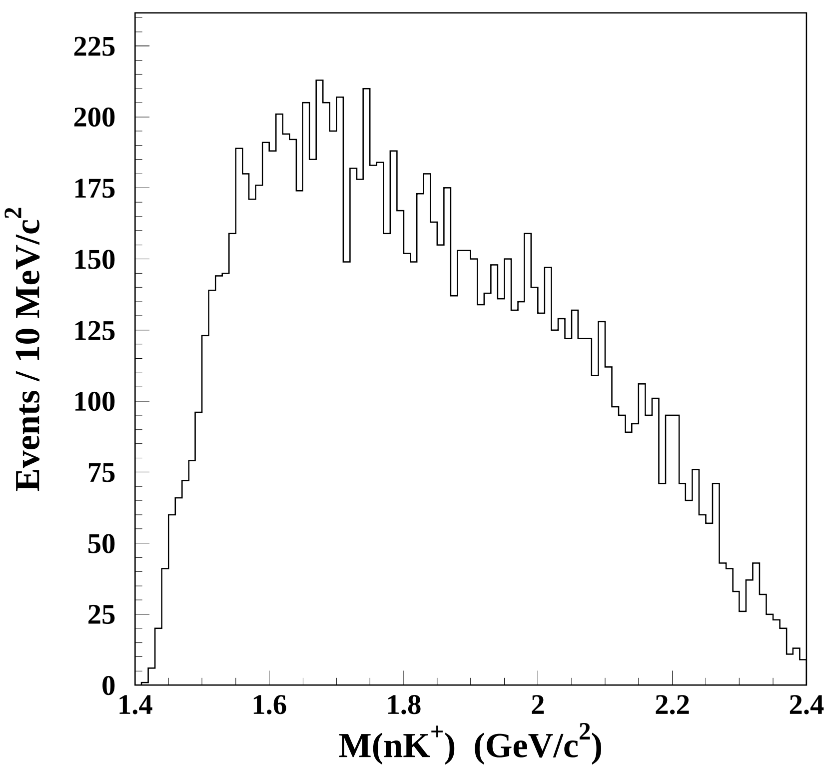
Important backgrounds, for example . . .



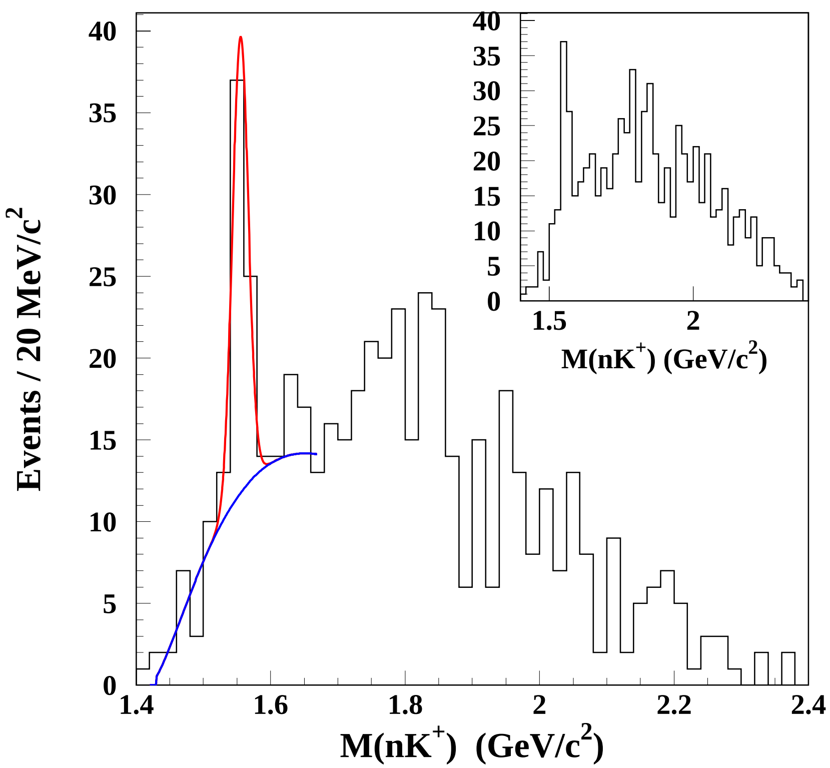
Results from the experiment

Histogram the "invariant mass" of the nK^+ combination. Make various cuts to enhance the signal relative to the background.

All events...



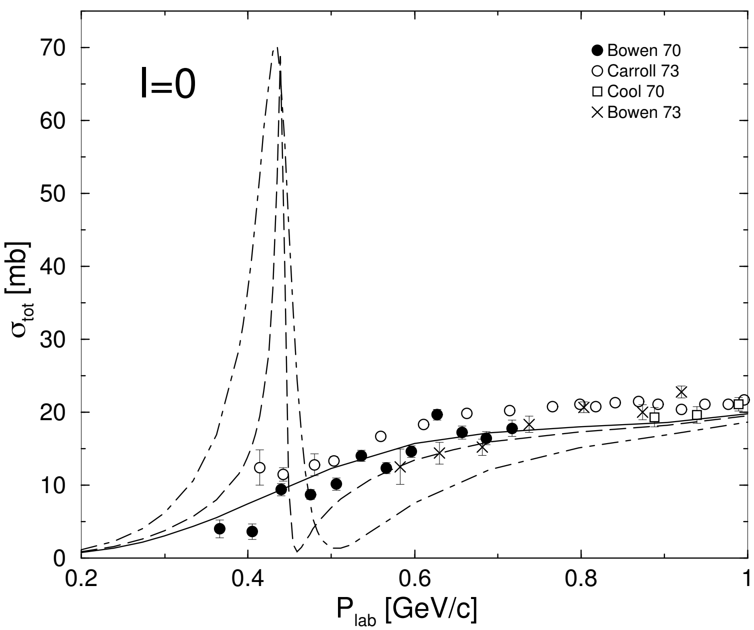
Selected events...



Evidence *against* the Pentaquark

There is still some (healthy) skepticism in the community. This will take some time to sort itself out.

One problem:
There is no evidence of the θ^+ in K^+n elastic scattering.



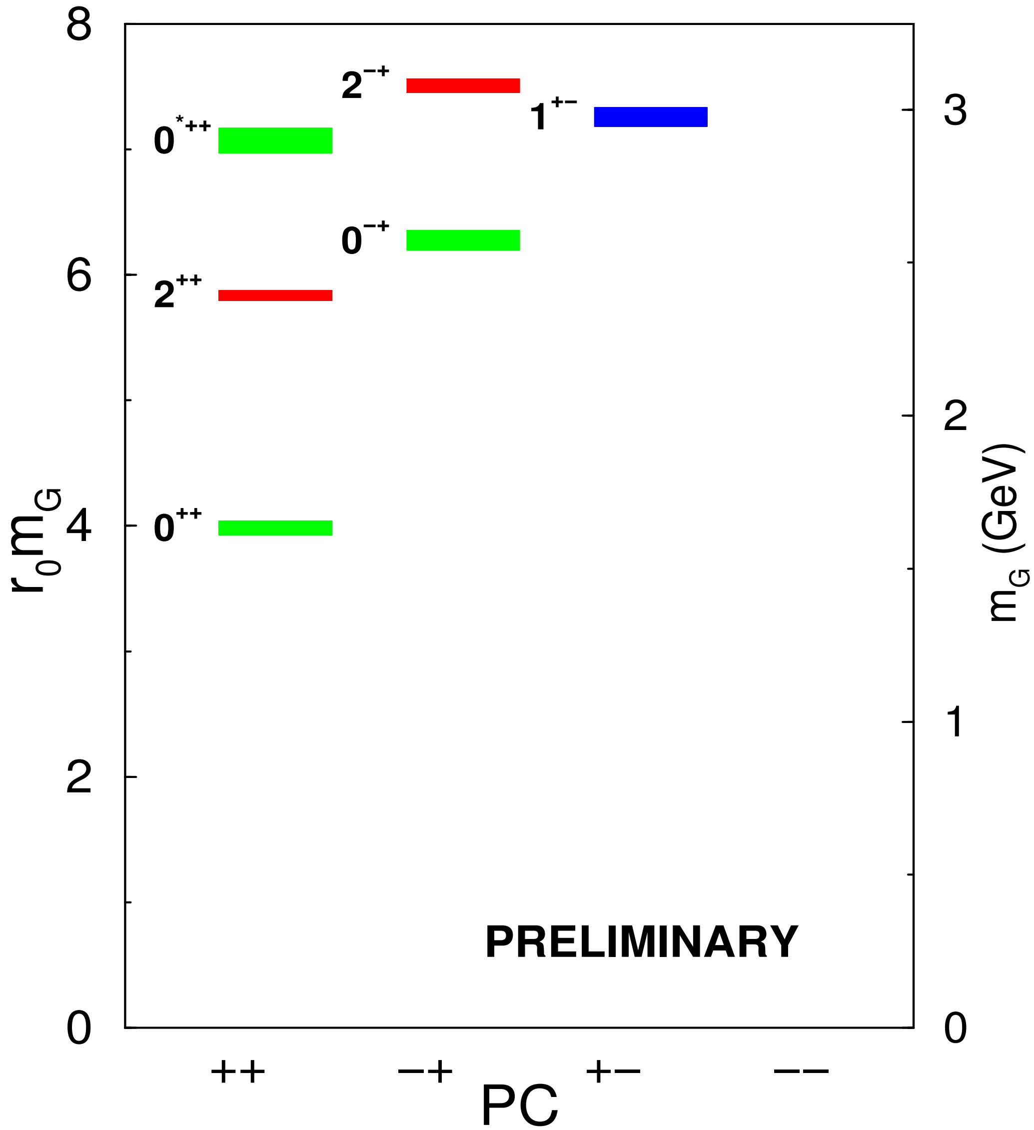
J. Haidenbauer and G. Krein, "Influence of a $Z^+(1540)$ resonance on K^+N scattering," Phys. Rev. C 68, 052201 (2003)

$\Rightarrow$ The resonance would have to be *very* narrow.

Glueballs

Morningstar & Peardon

arXiv:nucl-th/0309068



Hadrons with *no quarks*! Total breakdown of the quark model.

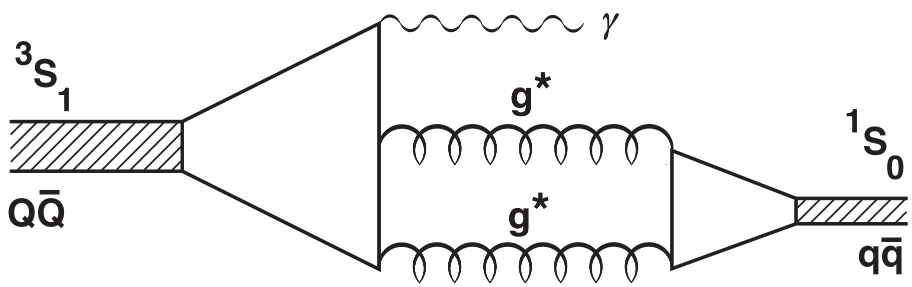
But how do you know it's a glueball?

Answer: Overpopulation and the dynamics of its production and decay.

Caveat: States will mix!

A Sticky Situation: $J/\psi \to \gamma X$

Prediction for $J/\psi \to \gamma gg$
$\Rightarrow$ Expect to observe
$J/\psi \to \gamma$ Glueball

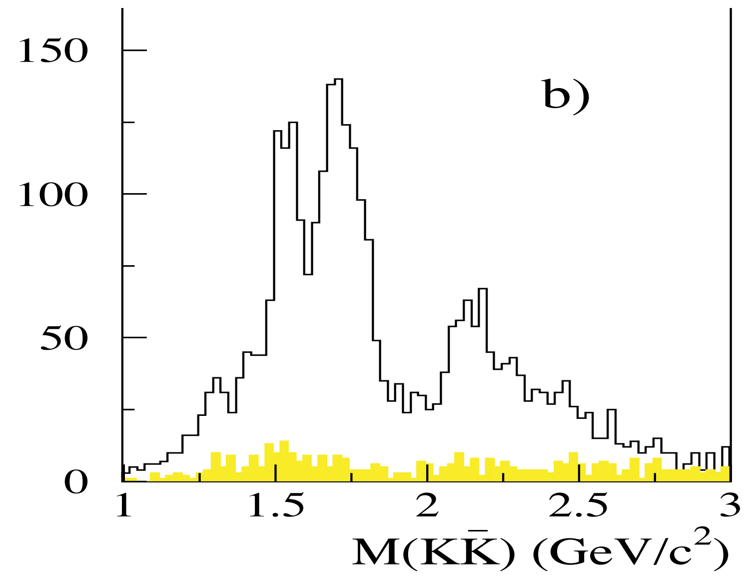


Next you need to decide how the glueball might decay.
It is best to consider specific glueball quantum numbers.

Good example:
$J/\psi \to \gamma K^+K^-$ or $J/\psi \to \gamma K^0\bar{K}^0$

There are many "resonances"!

This data from BES collaboration.



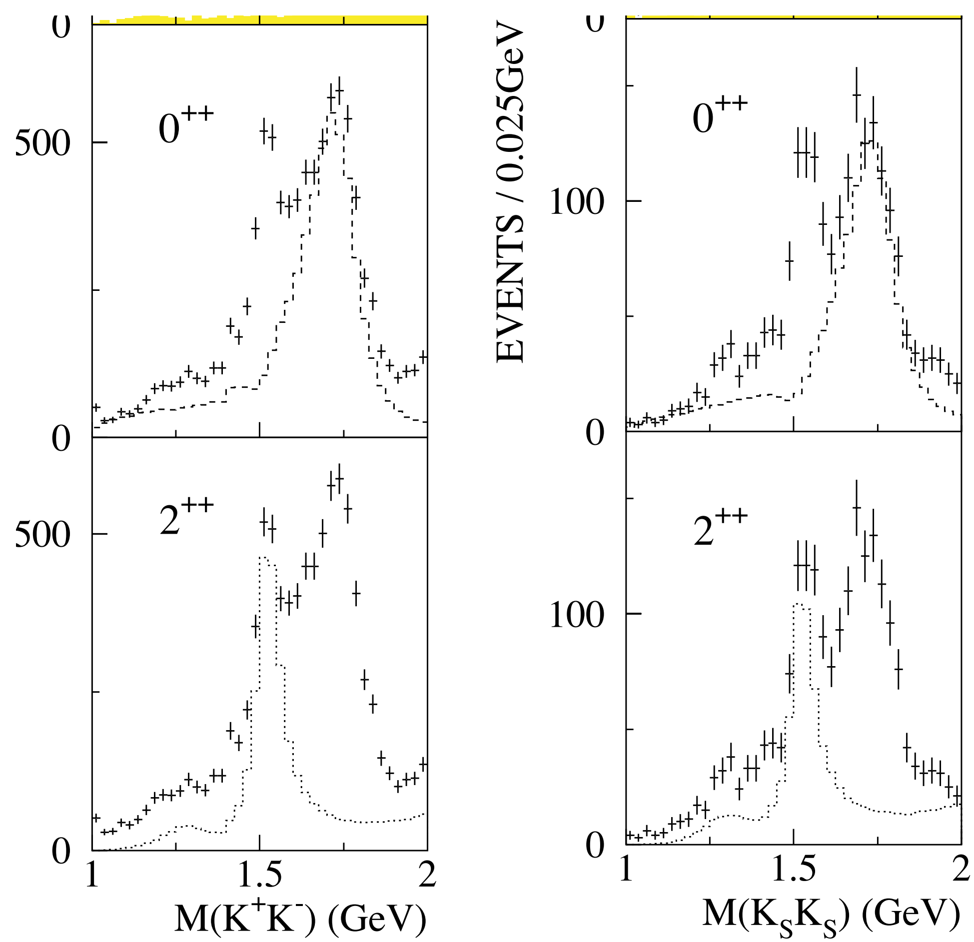
Unraveling the Bumps: Partial Wave Analysis

- **What are the quantum numbers of the "bumps"?**
- **Are they really "resonances"?**
- **Are they consistent with our picture of glueballs?**

"Partial Wave Analysis"

Use angular distributions of decays to decompose event sample into separate quantum numbers.

You need lots of events to do this well!



Glueballs: Status and Prospects

**There is solid evidence for an "extra" 0^{++} meson.
There is controversy over which is "mostly" glueball.**

CLEO-c will gather *one billion* J/ψ decays. This will allow very precise partial wave decompositions.

**Excellent prospect to unravel the mixing problem:
Radiative decay of glueball candidates.**

Radiative Decay Widths in keV							Γ_{Tot}
	$f_0 \to \gamma\rho(770)$			$f_0 \to \gamma\phi(1020)$			MeV
State	L	M	H	L	M	H	
$f_0(1370)$	443	1121	1540	8	9	32	$\sim$300
$f_0(1500)$	2519	1458	476	9	60	454	109
$f_0(1710)$	42	94	705	800	718	78	125

Mesons with Exotic Quantum Numbers

The Quark Model builds mesons from $q\bar{q}$ pairs:

$$|\text{meson with spin } j\rangle = |q_1\bar{q}_2; \ell s\rangle$$

where $|\ell - s| \leq j \leq \ell + s$ and $s = 0, 1$.

For "self conjugate" states (i.e. particle=*anti*-particle) only some combinations of quantum numbers are possible:

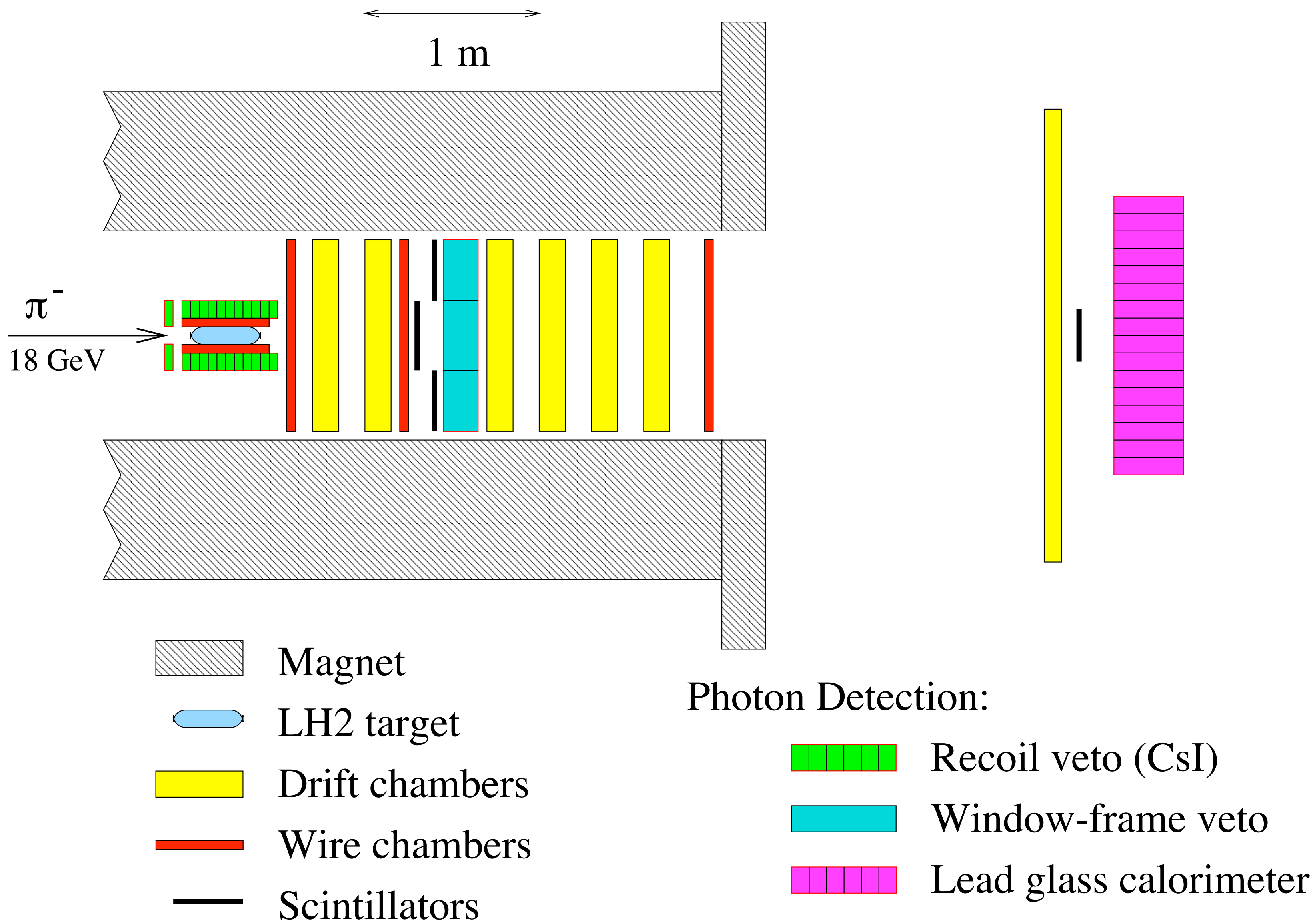
$$J^{PC} = 0^{++}, 0^{-+}, 1^{++}, 1^{+-}, 1^{--}, 2^{++}, \ldots$$

A state with forbidden quantum numbers ($J^{PC} = 1^{-+}$ for example) cannot be accommodated by the quark model. It would be "manifestly exotic".

Brookhaven National Lab Experiment E852

A Search for Mesons with Unusual Quantum Numbers

http://www.phy.bnl.gov/~e852/publications.html

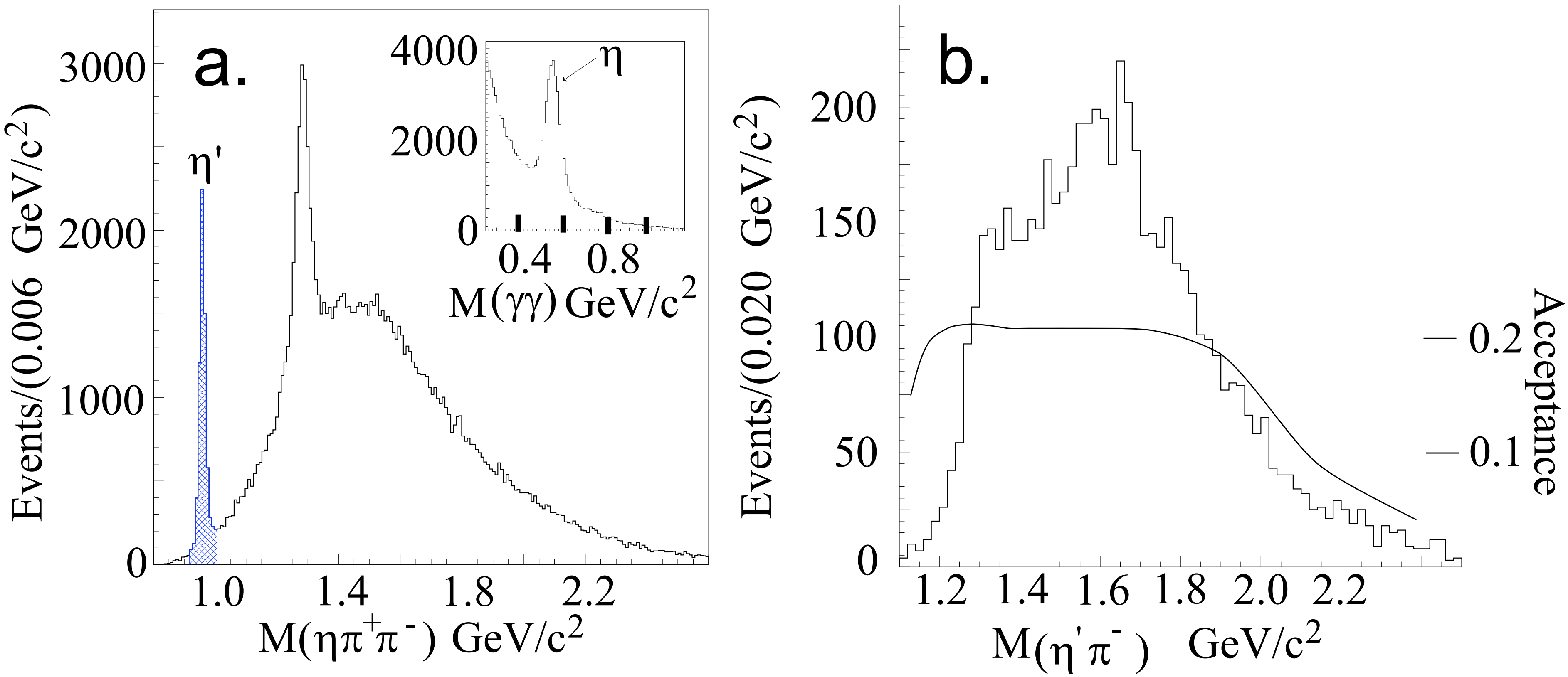


Example: $J^{PC} = 1^{-+}$ Meson Decaying to $\eta'\pi^-$

E. I. Ivanov *et al.* Phys. Rev. Lett. 86, 3977 (2001)

$$\pi^- p \rightarrow \eta' \pi^- p \rightarrow \eta \pi^+ \pi^- \pi^- p \rightarrow \gamma\gamma \pi^+ \pi^- \pi^- p$$

$\Rightarrow$ **Need to detect many particles including photons.**



Results of Partial Wave Analysis

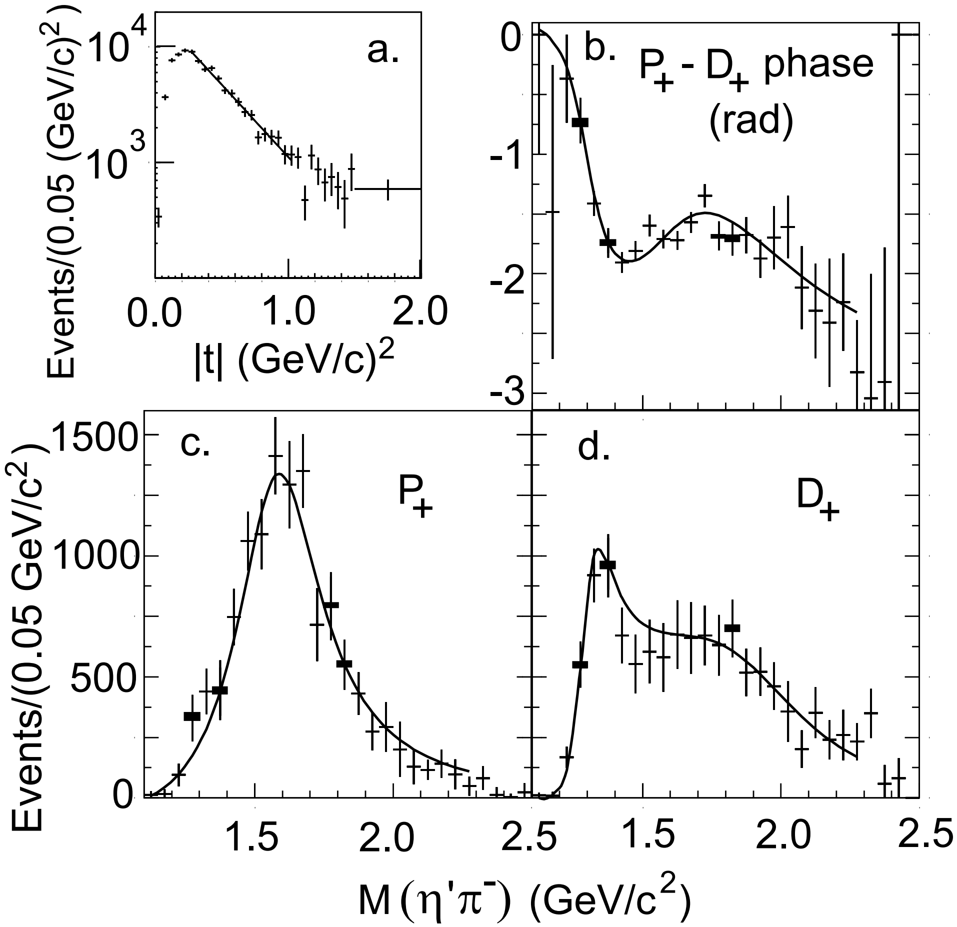
In principle, this case is "easy":
Any odd L for $(\eta'\pi)_L$ is manifestly exotic.

Spectrum is dominated by D $(L = 2)$ and P $(L = 1)$.

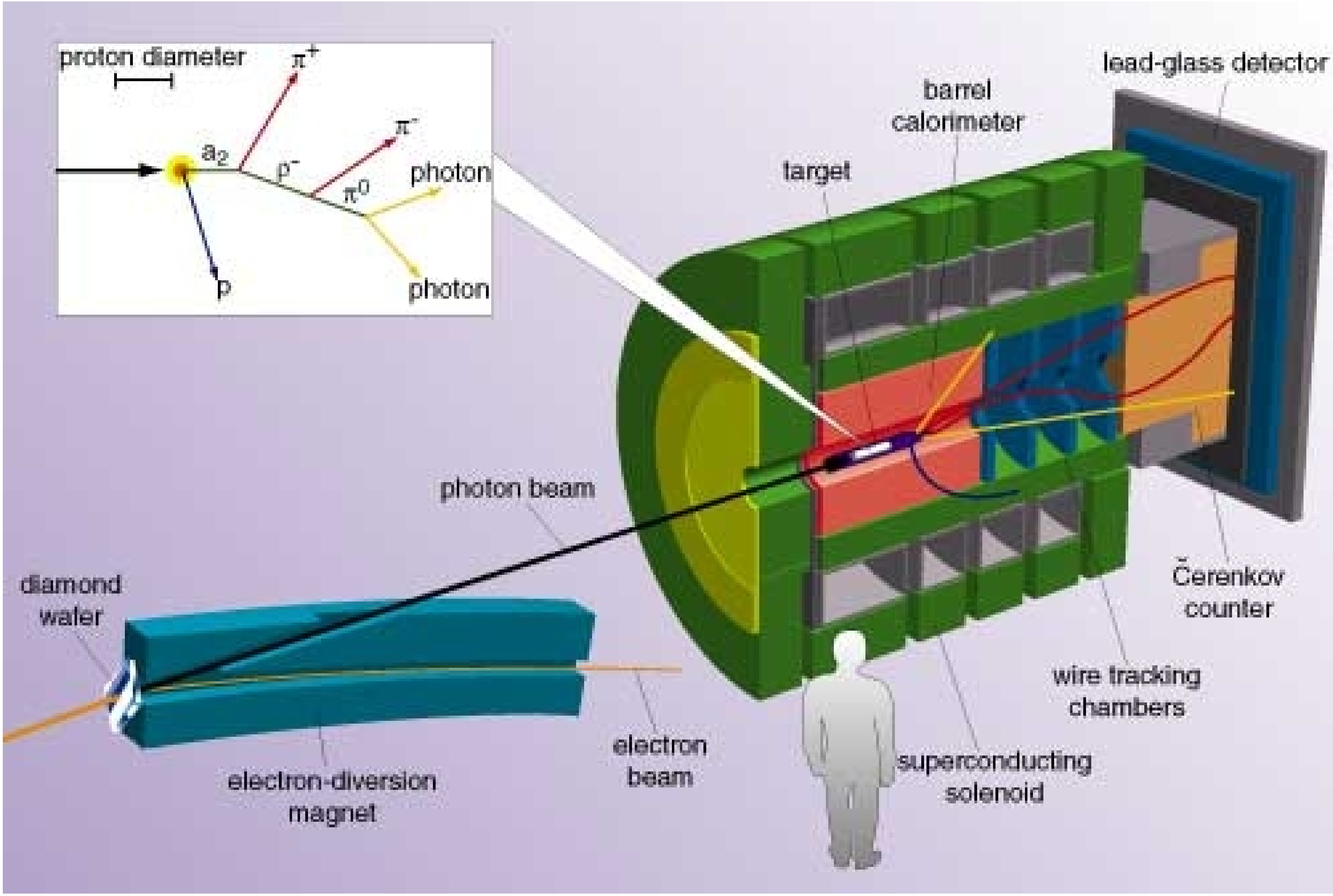
The phase variation is characteristic of "resonances".

The P wave has exotic quantum numbers.

$\Rightarrow$ Exotic meson candidate!



The Future: GLUEX at Jefferson Laboratory



Missing States

So far, we have looked at states that may *exist*, but are *not* predicted by the quark model.

Are there any states that *are* predicted by the quark model, but have not been observed?

Yes! **There are some glaring examples:**

Mesons: All of the $^3D_2$ are missing! (ρ_2, ω_2, ϕ_2, . . .)

Baryons: This "missing baryons" problem has been around since the 1960's!

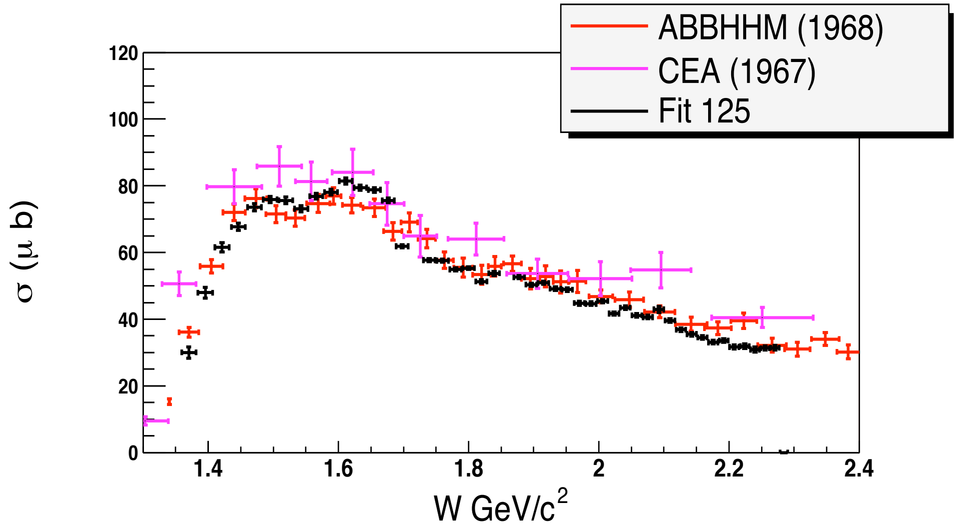
The N and Δ Baryons from the PDG

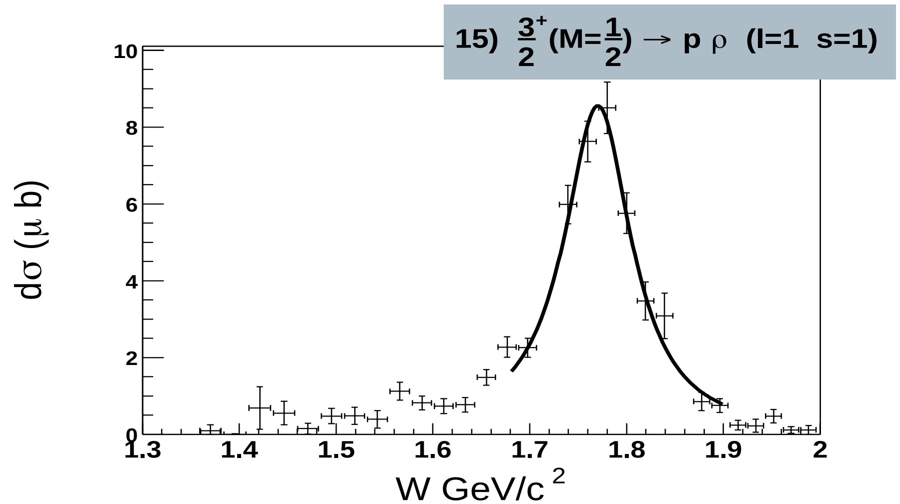
$L_{2I,2J}(Mass)$	Multiplet	Status	$L_{2I,2J}$(Mass)	Multiplet	Status
$P_{11}(938)$	$(56,0^+)$	****	$P_{33}(1232)$	$(56,0^+)$	****
$S_{11}(1535)$	$(70,1^-)$	****	$S_{31}(1620)$	$(70,1^-)$	****
$S_{11}(1650)$	$(70,1^-)$	****			
$D_{13}(1520)$	$(70,1^-)$	****	$D_{33}(1700)$	$(70,1^-)$	****
$D_{13}(1700)$	$(70,1^-)$	***			
$D_{15}(1675)$	$(70,1^-)$	****			
$P_{11}(1440)$	$(56,0^+)$	****	$P_{31}(1875)$	$(56,2^+)$	****
$P_{11}(1710)$	$(70,0^+)$	***	$P_{31}(1835)$	$(70,0^+)$	
$P_{11}(1880)$	$(70,2^+)$				
$P_{11}(1975)$	$(20,1^+)$				
$P_{13}(1720)$	$(56,2^+)$	****	$P_{33}(1600)$	$(56,0^+)$	***
$P_{13}(1870)$	$(70,0^+)$	*	$P_{33}(1980)$	$(56,2^+)$	***
$P_{13}(1910)$	$(70,2^+)$		$P_{33}(1985)$	$(70,2^+)$	
$P_{13}(1950)$	$(70,2^+)$				
$P_{13}(2030)$	$(20,1^+)$				
$F_{15}(1680)$	$(56,2^+)$	****	$F_{35}(1905)$	$(56,0^+)$	****
$F_{15}(2000)$	$(70,2^+)$	**	$F_{35}(2000)$	$(70,2^+)$	**
$F_{15}(1995)$	$(70,2^+)$				
$F_{17}(1990)$	$(70,2^+)$	**	$F_{37}(1950)$	$(56,2^+)$	****

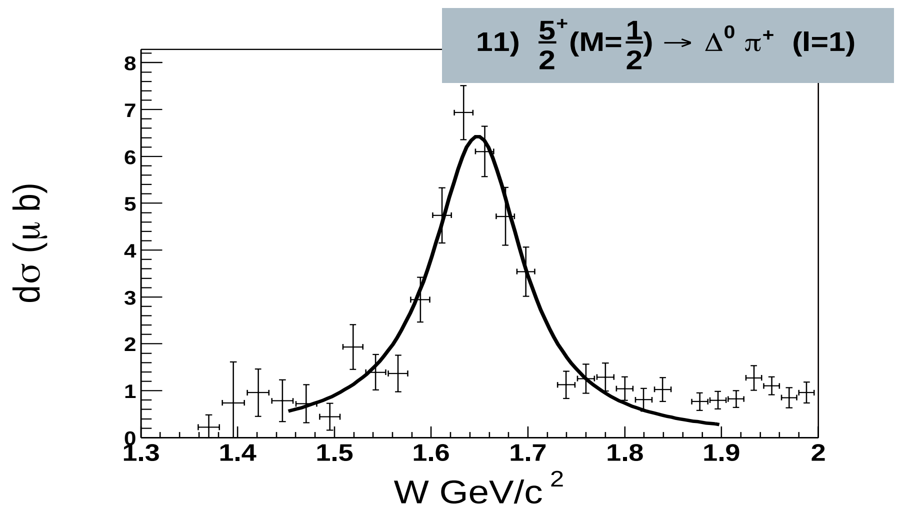
A Search for Missing Baryon States at Jefferson Laboratory

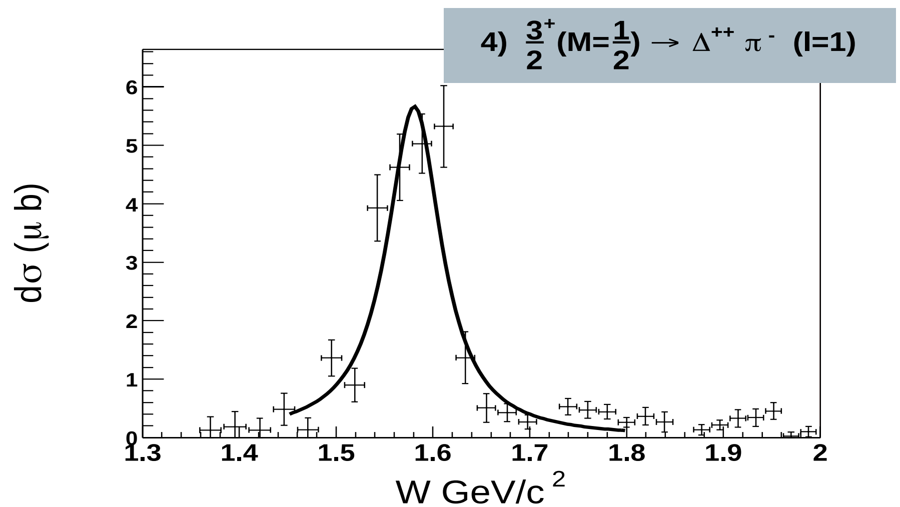
M. Bellis PhD Thesis (RPI)

$\gamma p \rightarrow$ Baryon State $\rightarrow p\pi^+\pi$









Molecules

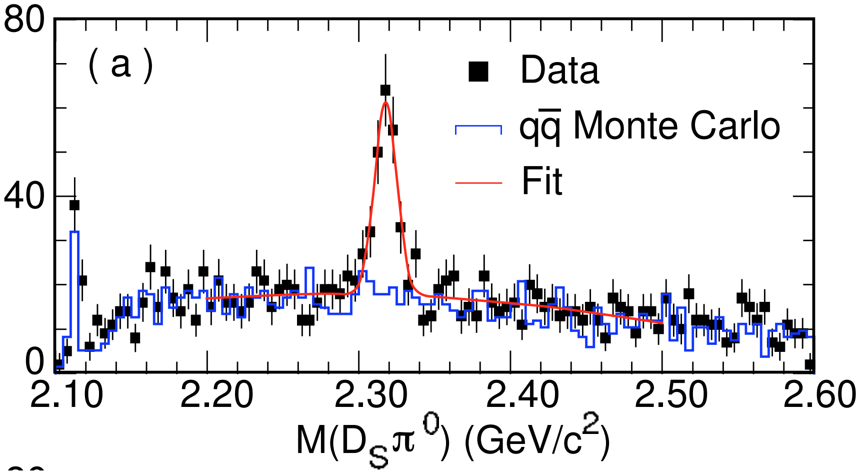
Nobody ever looks for them, but sometimes they just show up.

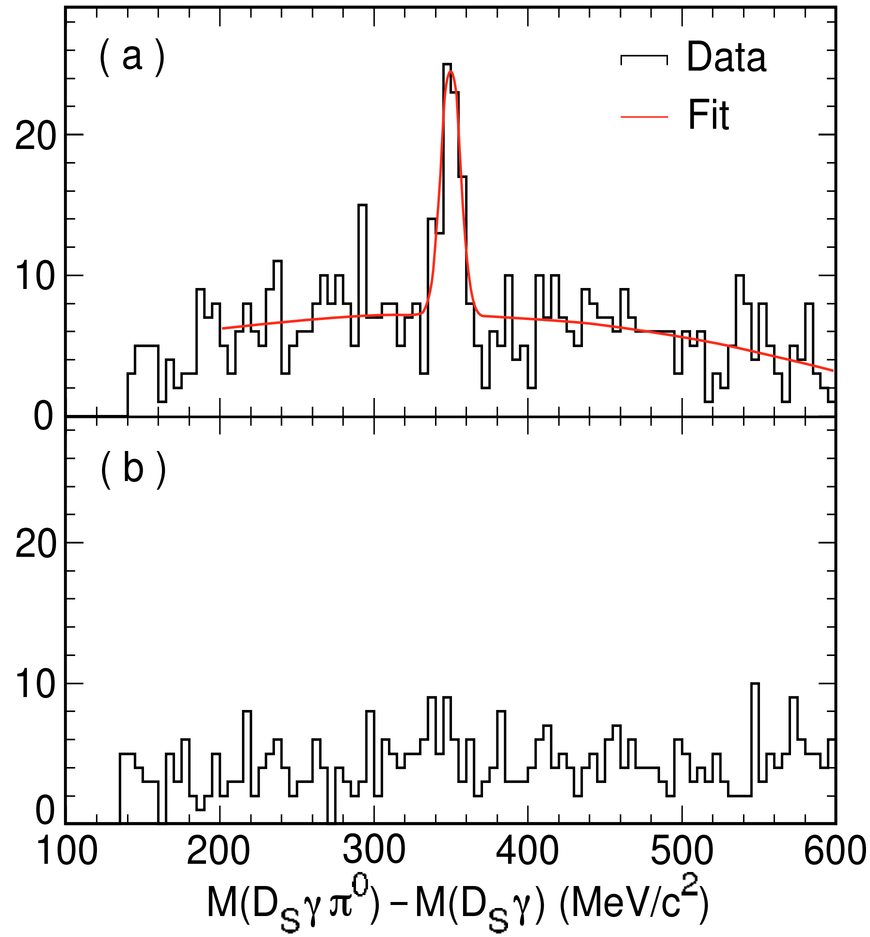
Nobody is sure how to even define them, but some people know them when they see them.

Old examples: The $a_0(980)$ (δ) and $f_0(980)$ (S) mesons.
Are these $K\bar{K}$ molecules?

Latest candidates: The $D_{sJ}(2317)$ and $D_{sJ}(2463)$
Are these DK and $D^{\star}K$ molecules?

Results from CLEO at Cornell





Conclusions

The Quark Model is a powerful tool. We should continue to teach it and learn from it.

The Quark Model works better than it should.

However, the Quark Model is a *model*. The *theory* is QCD. An important goal of nuclear and particle physics is to understand how these fit together.

***Exotic Hadrons* are a good jumping-off point. There is good evidence that some exist. Their existence needs to be more firmly established, and calculations need to bridge the gap.**

Thank You!