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Project X Physics Study
Hadron Physics Working Group

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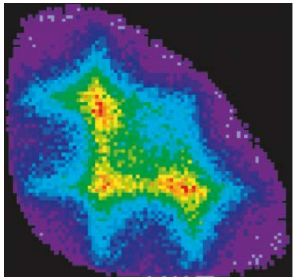
Fermilab, June 14-22, 2012



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Hadron Spectroscopy with Project X

What are our goals?

1. What is the physics case?
2. What measurements are needed to answer the questions?
3. What tools do we need?
   - What beams?
   - The detector?
4. What other facilities are available?
5. Is there an interested community?

Why is this interesting?

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22 December 2011 Last updated at 05:59 ET

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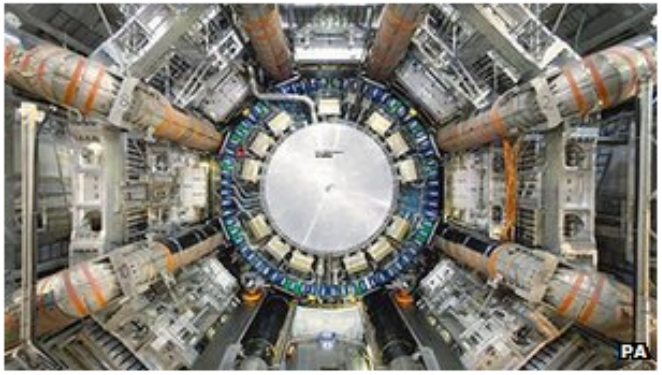
LHC reports discovery of its first new particle

By Jonathan Amos
Science correspondent, BBC News

The Large Hadron Collider (LHC) on the Franco-Swiss border has made its first clear observation of a new particle since opening in 2009.

It is called Chi_b (3P) and will help scientists understand better the forces that hold matter together.

The as-yet unpublished discovery is **reported on the Arxiv pre-print server**.



The LHC has been built to investigate the fundamental building blocks of nature

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Physicists find 'rebel' particle

By Dr David Whitehouse
BBC News Online science editor

Physicists have found a new subatomic particle, named Ds (2317). It will help them better understand the building blocks of matter.

Inside the BaBar detector

The particle consists of an unusual combination of more fundamental particles - quarks.

Two quarks form Ds (2317) and, curiously, its properties are not what theory predicted.

The announcement was made by physicist Antimo Palano to a packed auditorium at the Stanford Linear Accelerator Center (Slac) in the US.

The discovery was made by the BaBar international consortium, which operates a detector at Slac that analyses debris from subatomic particle collisions.

'Back to the drawing boards'

"Congratulations to BaBar," said Slac's director, Jonathan Dorfan.

"The existence of the particle is not a surprise, but its mass is lower than expected. This result will send theorists back to their drawing boards."

SEE ALSO:
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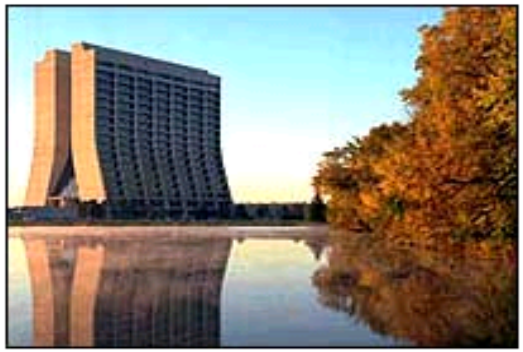
Scientists find mystery particle

By Dr David Whitehouse
BBC News Online science editor

Scientists have found a sub-atomic particle they cannot explain using current theories of energy and matter.


Fermilab confirmed the discovery

The discovery was made by researchers based at the High Energy Accelerator Research Organisation in Tsukuba.

Classified as X(3872), the particle was seen fleetingly in an atom smasher and has been dubbed the "mystery meson".

The Japanese team says understanding its existence may require a change to the Standard Model, the accepted theory of the way the Universe is constructed.

An eternity

X(3872) was found among the decay products of so-called beauty mesons - sub-atomic particles that are produced in large numbers at the Tsukuba "meson factory".

It weighs about the same as a single atom of helium and exists for only about one billionth of a trillionth of a second before it decays into other longer-lived, more familiar

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3 of top 6 most cited Babar papers on spectroscopy!

1. **The BaBar detector.**
(1450) BABAR Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Apr 2001. 119 pp.
Published in **Nucl.Instrum.Meth. A479 (2002) 1-116**
e-Print: **hep-ex/0105044**
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2. **Observation of a narrow meson decaying to $D_s^+\pi^0$ at a mass of 2.32-GeV/c^2.**
(588) BABAR Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Apr 2003. 7 pp. Note: <a href="http://www.slac.stanford.edu/slac/media-info/20030428/index
Published in **Phys.Rev.Lett. 90 (2003) 242001**
e-Print: **hep-ex/0304021**
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PDG) ; Link to pressrelease; Phys. Rev. Lett. Server; SLAC Document Server
Detailed record - Cited by 588 records

3. **Observation of CP violation in the B^0 meson system.**
(547) BABAR Collaboration (Bernard Aubert (Annecy, LAPTH) *et al.*). Jul 2001. 8 pp. Note: <a href=/slac/media-info/20010706/cpviolation.html> **Press release"
Published in **Phys.Rev.Lett. 87 (2001) 091801**
e-Print: **hep-ex/0107013**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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pressrelease; Phys. Rev. Lett. Server; SLAC Document Server
Detailed record - Cited by 547 records

4. **Measurement of the CP-violating asymmetry amplitude $\sin 2\beta$.**
(451) BABAR Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jul 2002. 7 pp.
Published in **Phys.Rev.Lett. 89 (2002) 201802**
e-Print: **hep-ex/0207042**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Abstract and Postscript and PDF from arXiv.org; Journal Server - Phys.Rev.Lett.; BaBar Publications Database; BaBar Password Protected Publicat
PDG) ; Phys. Rev. Lett. Server; SLAC Document Server
Detailed record - Cited by 451 records

5. **Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26-GeV/c^2.**
(374) BABAR Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jun 2005. 7 pp. Note: <a href=http://www.interactions.org/cms/?pid=1020846>Press Release
Published in **Phys.Rev.Lett. 95 (2005) 142001**
e-Print: **hep-ex/0506081**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Abstract and Postscript and PDF from arXiv.org; Journal Server - Phys.Rev.Lett.; BaBar Publications Database; BaBar Password Protected Publicat
pressrelease; Phys. Rev. Lett. Server; SLAC Document Server; SLAC Document Server
Detailed record - Cited by 374 records

6. **Study of the $B \to J/\psi K^- \pi^+ \pi^-$ decay and measurement of the $B \to X(3872)K^-$ branching fraction.**
(318) BABAR Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jun 2004. 7 pp.
Published in **Phys.Rev. D71 (2005) 071103**
e-Print: **hep-ex/0406022**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Abstract and Postscript and PDF from arXiv.org; Journal Server - Phys.Rev.; BaBar Publications Database; BaBar Password Protected Publicat
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Belle top 2 most cited papers on spectroscopy!

1. **Observation of a new narrow charmonium state in exclusive B+- ---> K+- pi+ pi- J / psi decays.**
(687) Belle Collaboration (K. Abe *et al.*). Aug 2003. 9 pp. Note: 9 pages, 4 figures, contributed paper to the XXI International Symposium on Lepton and Pho
CONF-0352
Published in **Phys.Rev.Lett. 91 (2003) 262001**
Contributed to 21st International Symposium on Lepton and Ph Conference: C03-08-11
e-Print: **hep-ex/0308029**
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Abstract and Postscript and PDF from arXiv.org; Journal Server - Phys.Rev.Lett.
Detailed record - Cited by 687 records

2. **Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays.**
(679) Belle Collaboration (S.K. Choi (Gyeongsang Natl. U.) *et al.*). Sep 2003. 10 pp. Note: <a href=http://www.kek.jp/press/2003/belle4e.html>Press release<
Published in **Phys.Rev.Lett. 91 (2003) 262001**
e-Print: **hep-ex/0309032**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Abstract and Postscript and PDF from arXiv.org; Journal Server - Phys.Rev.Lett.; pdgLive (measurements quoted by PDG) ; Link to pressreleas
Detailed record - Cited by 679 records

3. **Observation of large CP violation in the neutral B meson system.**
(569) Belle Collaboration (K. Abe *et al.*). Jul 2001. 12 pp.
Published in **Phys.Rev.Lett. 87 (2001) 091802**
e-Print: **hep-ex/0107061**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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Detailed record - Cited by 569 records

4. **A Measurement of the branching fraction for the inclusive B ---> X(s) gamma decays with BELLE.**
(368) Belle Collaboration (K. Abe *et al.*). Mar 2001. 13 pp.
Published in **Phys.Lett. B511 (2001) 151-158**
e-Print: **hep-ex/0103042**
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Abstract and Postscript and PDF from arXiv.org; Journal Server - Phys.Lett.; pdgLive (measurements quoted by PDG) ; Science Direct
Detailed record - Cited by 368 records

5. **An Improved measurement of mixing induced CP violation in the neutral B meson system.**
(314) Belle Collaboration (K. Abe *et al.*). Aug 2002. 10 pp.
Published in **Phys.Rev. D66 (2002) 071102**
e-Print: **hep-ex/0208025**
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What is the physics case?

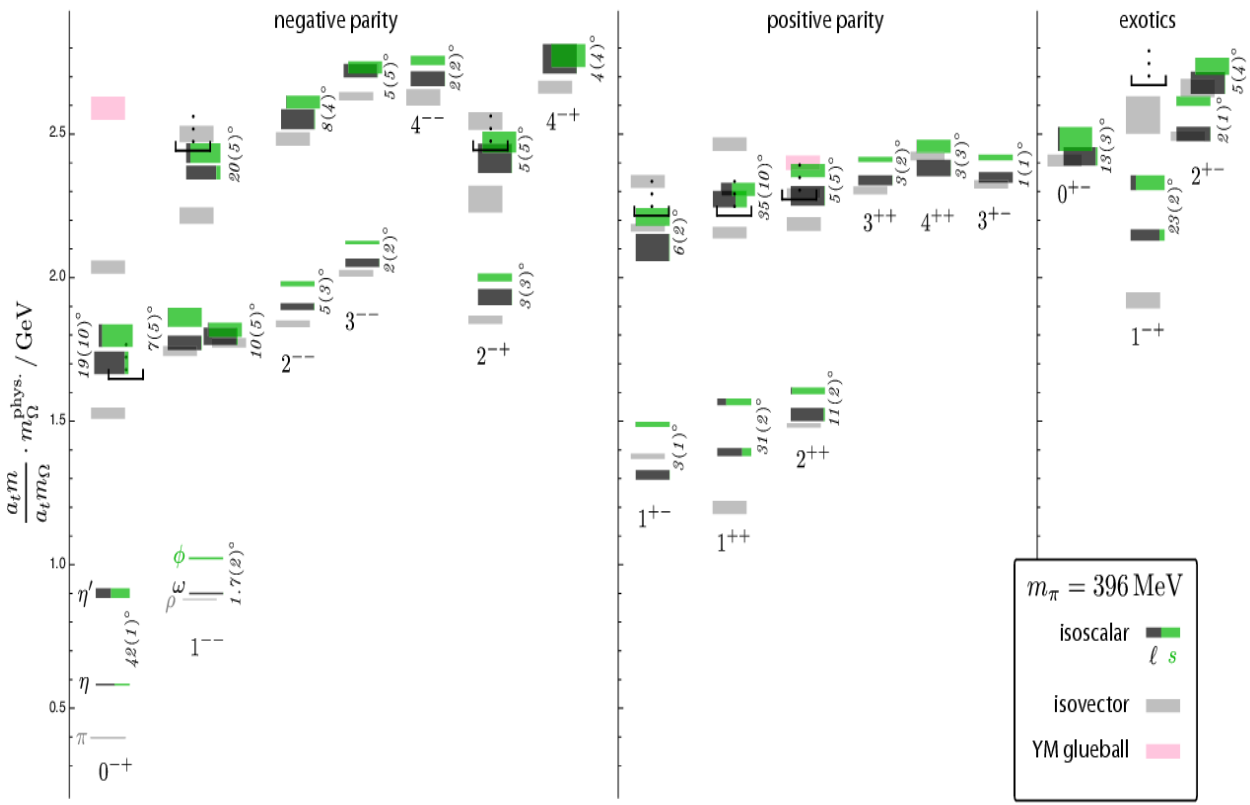
- Impressive progress in heavy quarkonium spectroscopy in recent years

- However, very little progress in light meson spectroscopy for many years

- The spectrum of light conventional mesons is still poorly understood

What is the physics case?

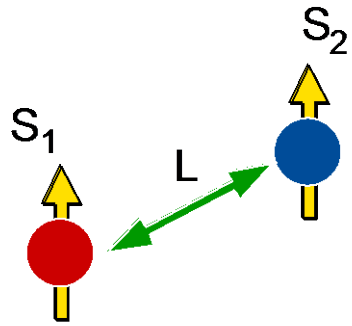
- Lattice QCD is starting to explore the spectrum of gluonic excitations



- **We need to experimentally determine the hadron spectrum and the physical states of QCD**

Conventional Mesons & Potential Models

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:

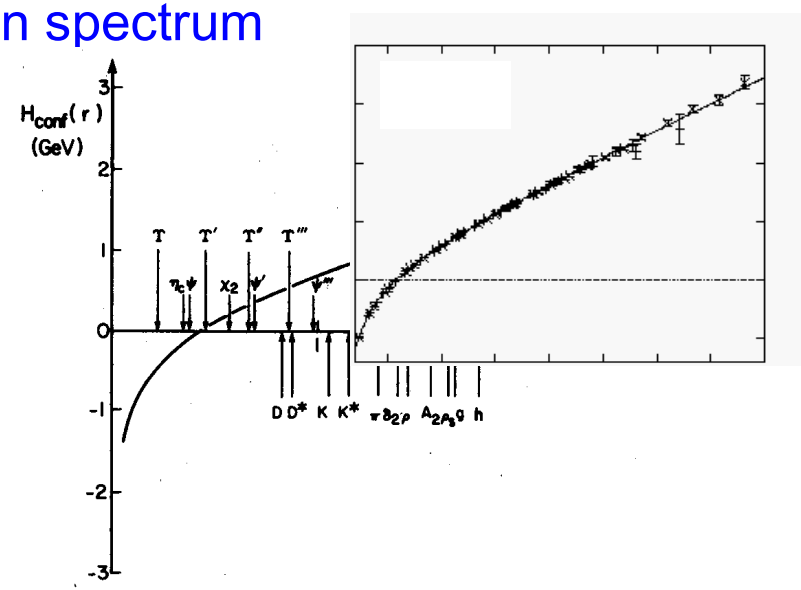
$J^{PC} = 0^{-+}\ 1^{--}\ 1^{+-}\ 0^{++}\ 1^{++}\ 2^{++} \ldots$

Not allowed: exotic combinations:

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

For given spin and orbital angular momentum configurations & radial excitations generate the meson spectrum

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$



Review: Godfrey and Napolitano, Rev. Mod. Phys. 71, 1411 (1999).

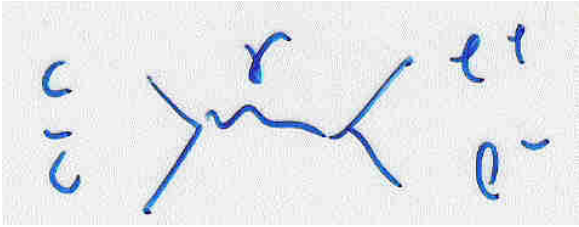
Tools to understand observed states

Models to calculate hadron properties:

- Strong OZI allowed decays
  - Well described by 3P0 decay model
- Electromagnetic transitions E1 & M1: $\Gamma[(q\bar{q})_i \to \gamma (q\bar{q})_f]$
- Electromagnetic couplings $\Gamma_{\gamma\gamma}(f_2) \cdot B(f_2 \to \pi^0\pi^0)$

$$\rho \to e^+e^-$$

$$(^3S_1 \to e^+e^-)$$



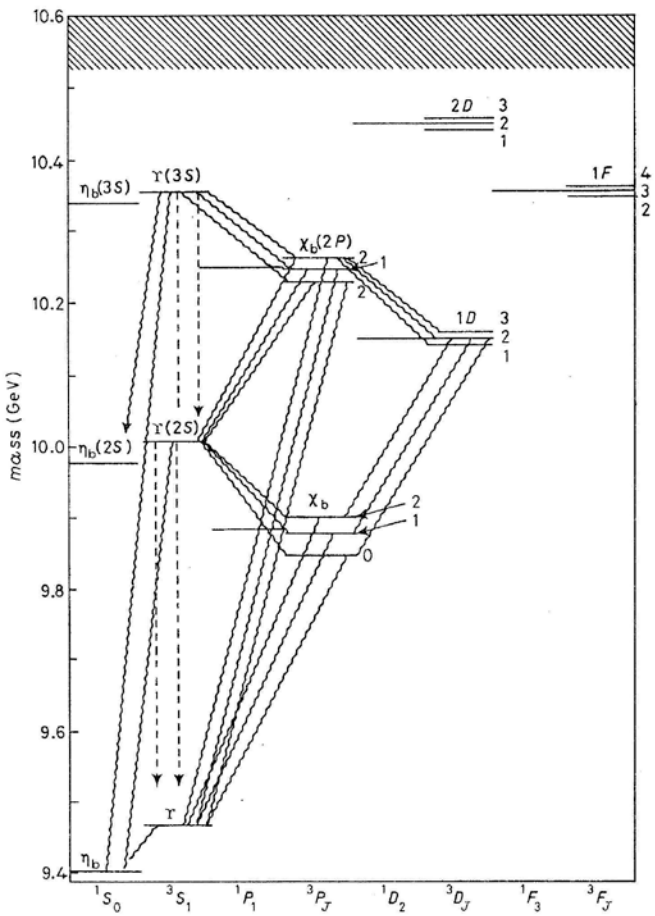
Can produce a detailed description of expected meson Properties that can be used to unravel the experimental spectrum

The Bottomonium Spectrum

PRL 94, 032001 (2005) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2005

Photon Transitions in $\Upsilon(2S)$ and $\Upsilon(3S)$ Decays

(CLEO Collaboration)



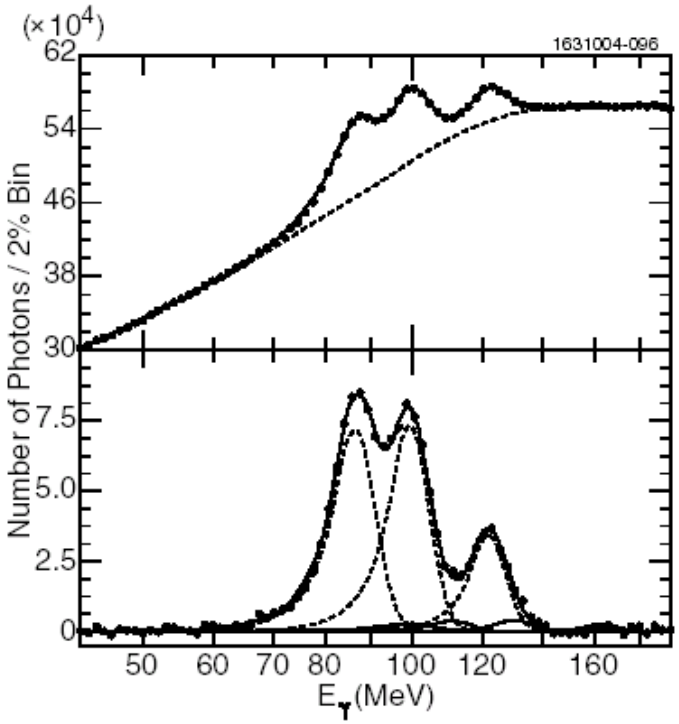
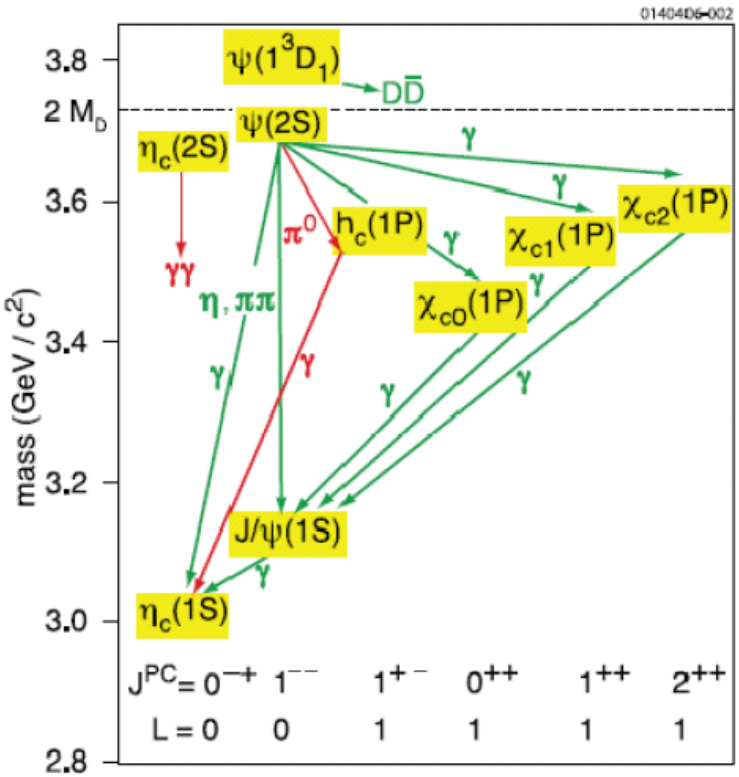


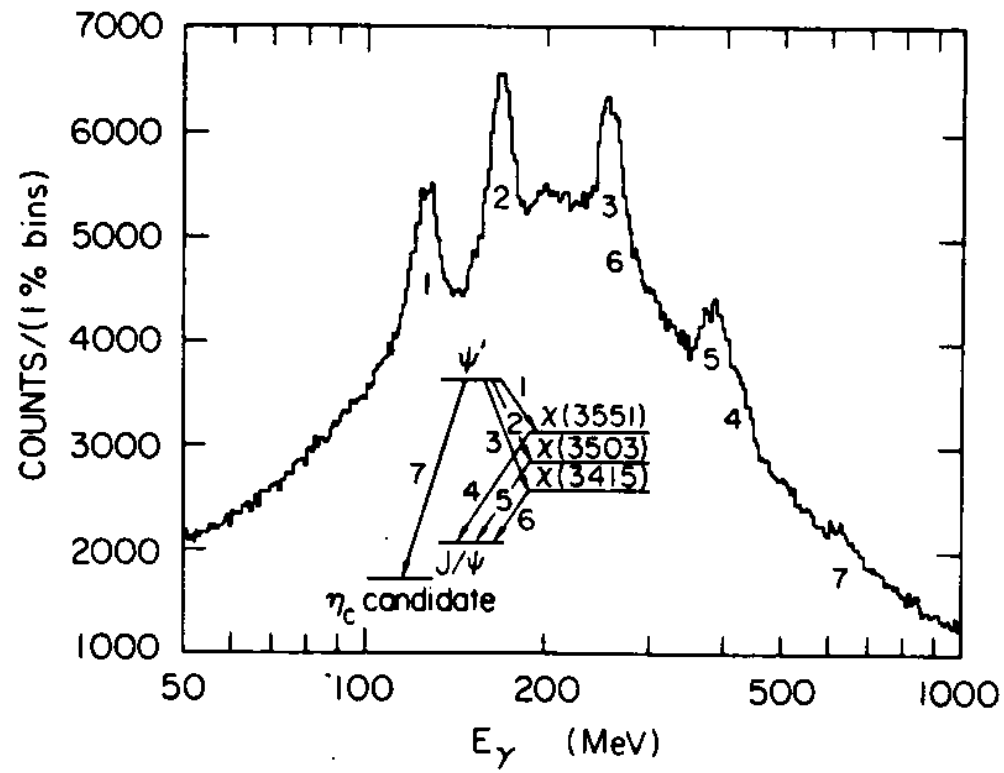
FIG. 3. Fit to the $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$ ($J = 2, 1, 0$) photon lines in the data. See caption of Fig. 2 for the description. Small solid line peaks in the bottom plot show the $\chi_{bJ}(2P) \to \gamma\Upsilon(1D)$ and $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$ contributions.

The Charmonium Spectrum

VOLUME 45, NUMBER 14 PHYSICAL REVIEW LETTERS 6 OCTOBER 1980

Observation of an η_c Candidate State with Mass 2978 ± 9 MeV

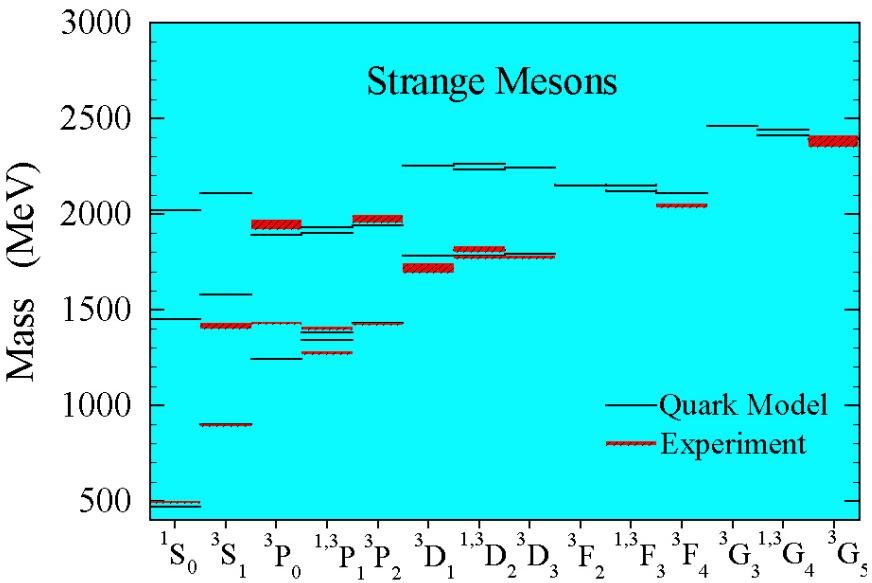


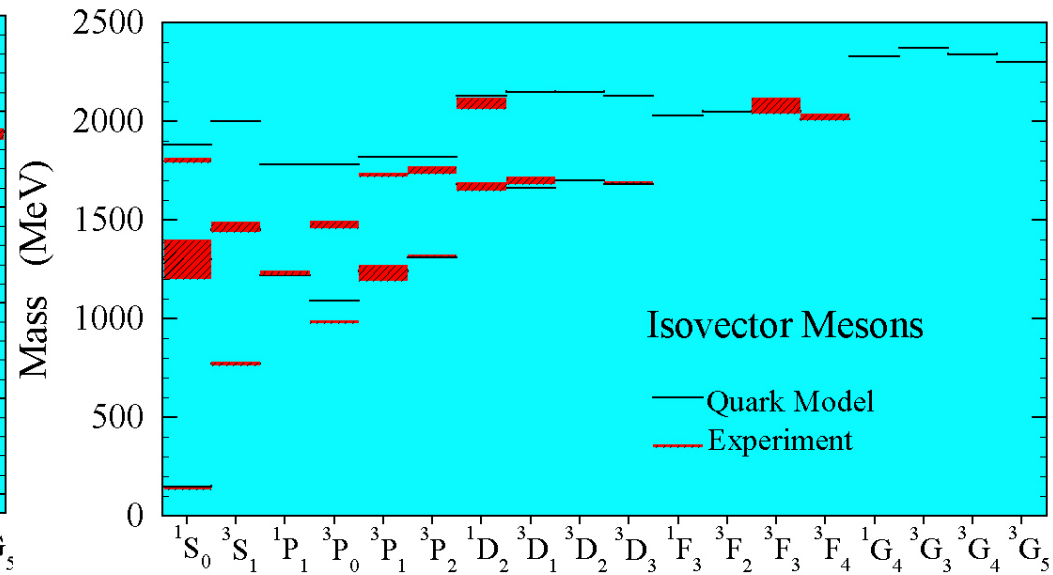


What about mesons with light quarks?

Essential features are the same, except:

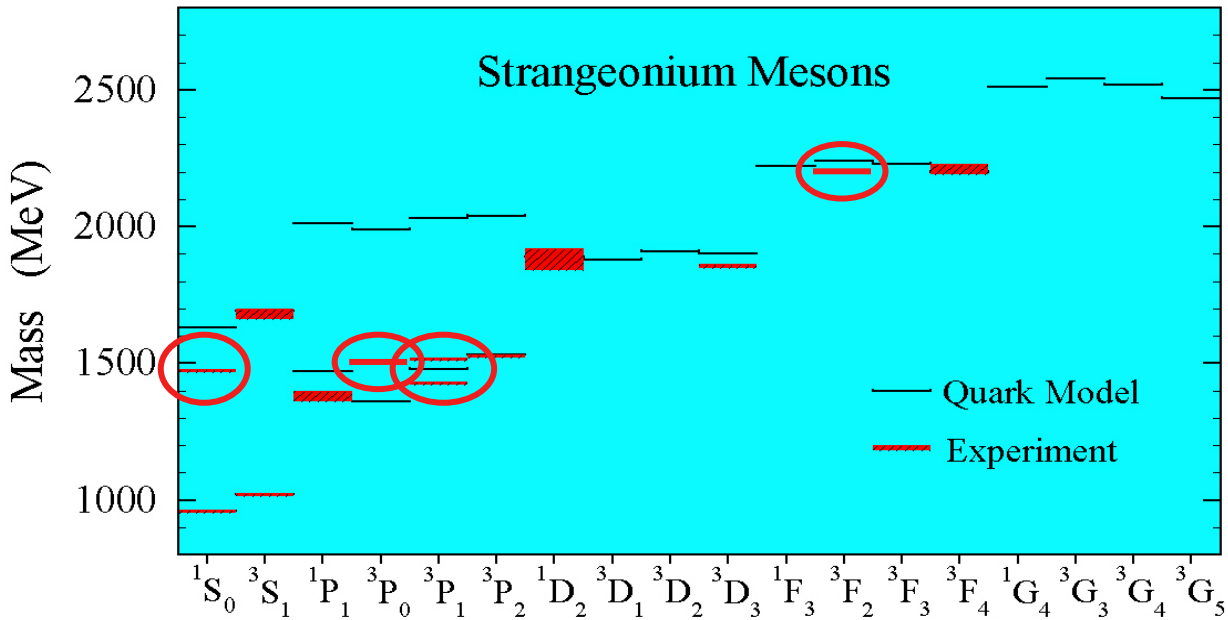
- Relative importance of relativistic effects
- Hyperfine splittings are comparable in size to orbital splittings





- Generally, good agreement for confirmed states
- But many missing states

Strangeonium Mesons



- Many missing states
- Many unconfirmed states:

  $f_1(1510)$, $h_1(1380)$, $f_2(1640)$, $\phi(2170)$, $f_4(2300)$, …
- Many unclassified states:

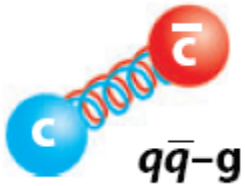
  $f_2(1950)$, $f_2(2010)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$,…
- Many puzzles:

  $\eta(1405)$, $\eta(1475)$, $f_1(1420)$, $f_1(1510)$, $f_0(1500)$ $f_0(1710)$, $f_J(2200)$,…

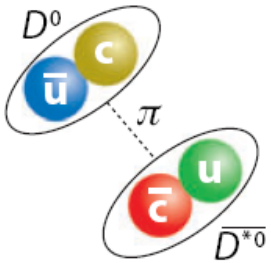
"Exotic States"

More importantly, expect hadronic matter with the glue degree of freedom manifest explicitly:

- Glueballs
- Hybrids
  - States with excited gluonic degrees of freedom
  - Distinctive decay modes
- Multiquark States
  - Molecular state
    - -loosely bound pair of mesons near threshold
    - -Exhibit large isospin violations
  - Tetraquarks
    - -tightly bound diquark-diantiquark states
    - -expect flavour multiplet of states



$q\bar{q}$–gluon hybrid

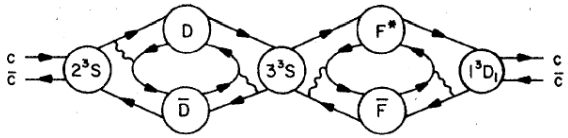


D^0–$\overline{D^{*0}}$ "molecule"

Diquark–diantiquark

Threshold-effects

- Rescattering near threshold due to interactions between two outgoing mesons
- Mass shifts due to thresholds
- Coupled channel effects mixing 2-meson states with resonances



Glueballs

Glueballs are hadrons with no valence quark content

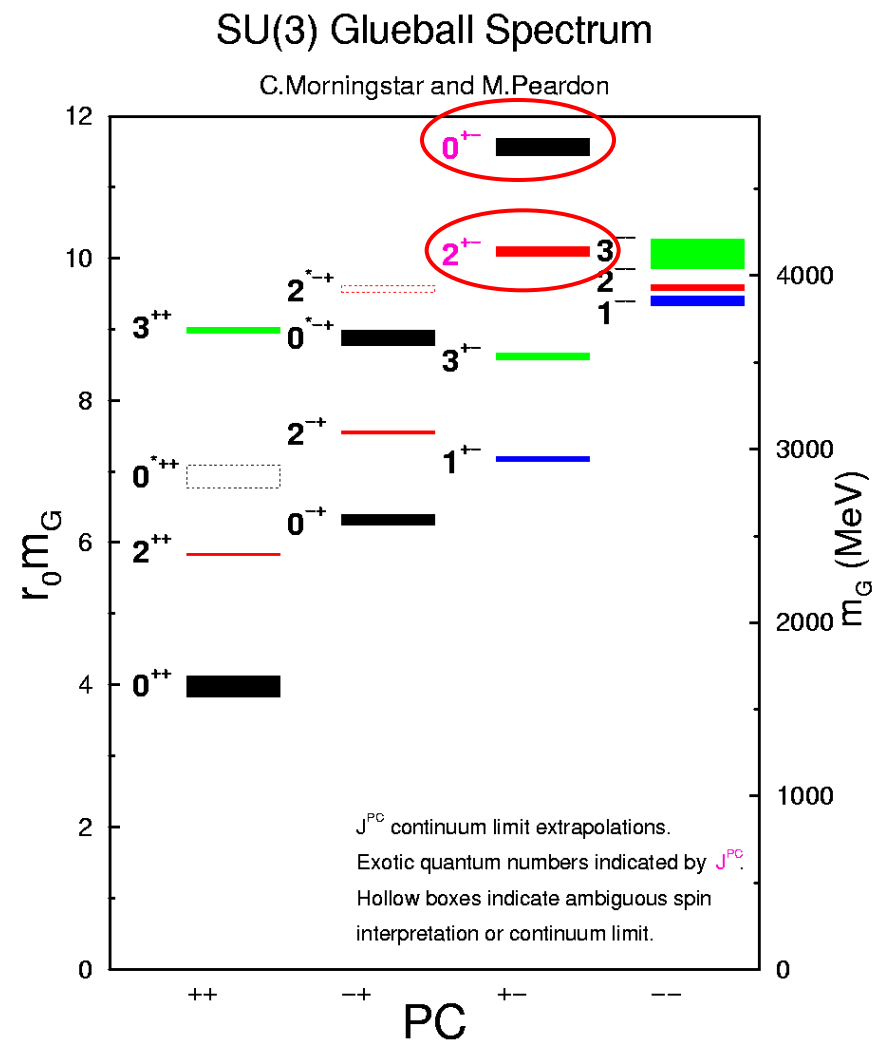
- Observation is test of QCD

Mass predictions by **Lattice QCD**

- Lowest mass glueballs have conventional quantum numbers:

$M_{0^{++}} \sim 1.6$ GeV
$M_{2^{++}} \sim 2.3$ GeV
$M_{0^{-+}} \sim 2.5$ 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

Production of Glueballs

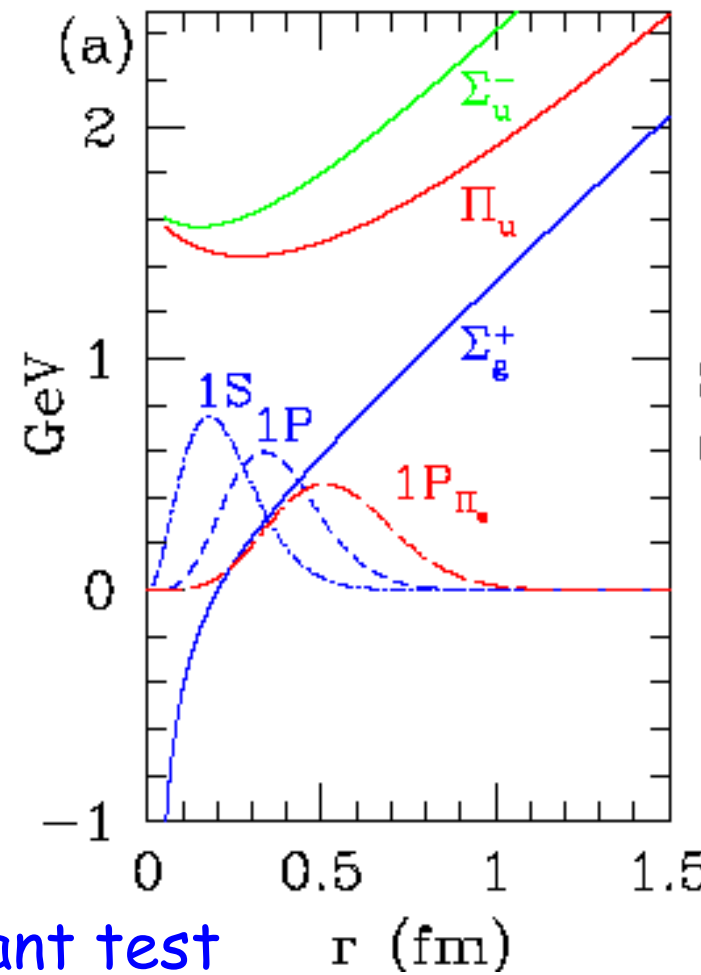
1. $J/\psi \to \gamma X$ (BES)
2. $p\bar{p}$ annihilation (GSI)
3. $pp \to p_f(G)p_s$ central production (COMPASS)

- 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 (Close & Kirk)

Hybrid Mesons

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

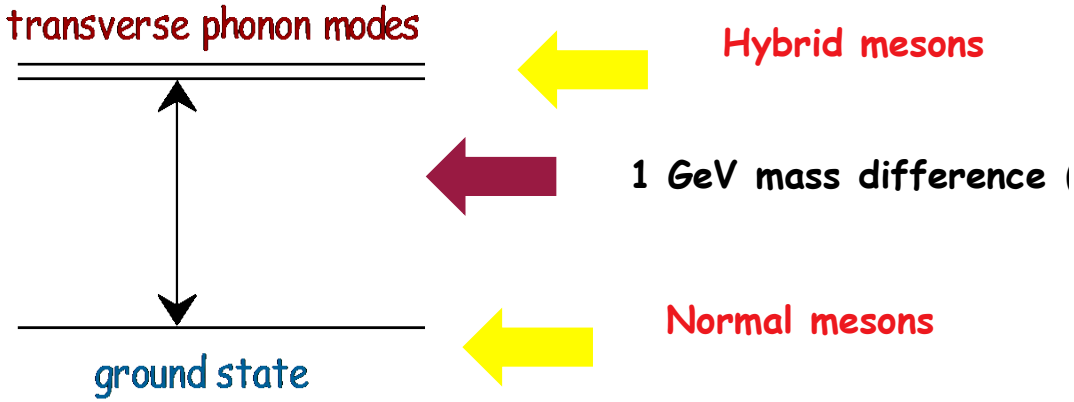
- Quarks move in adiabatic potentials
- Conventional hadrons correspond to gluon fields in ground states
- Hybrids correspond to excitations of quantum strings

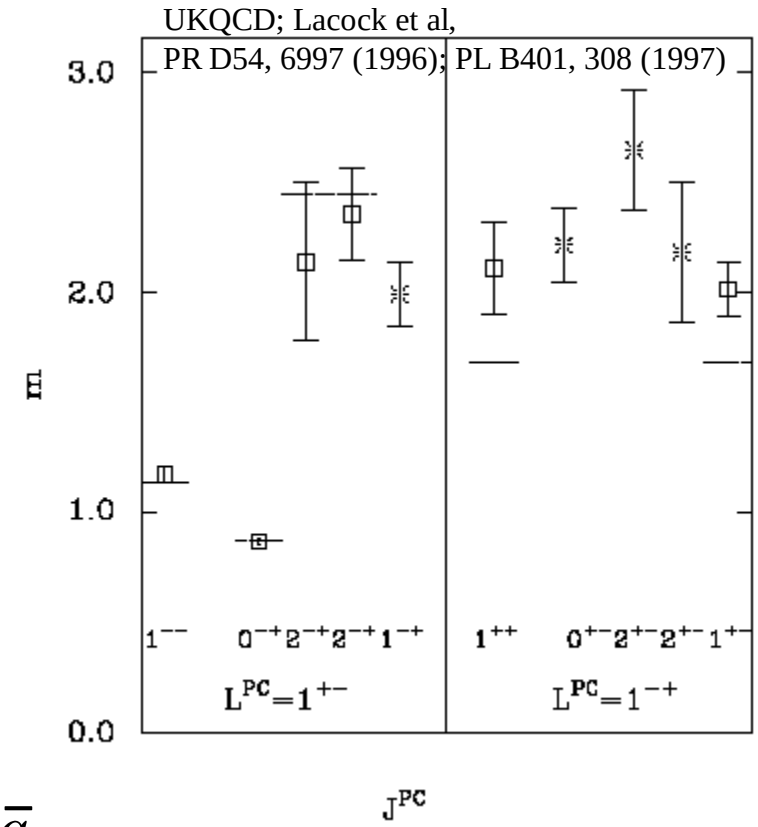


- Observing hybrids would be an important test of our understanding of QCD in the confinement regime

Hybrid Mesons

- Lowest mass hybrids corresponds to transverse excitations:





Lowest mass hybrids at ~1.9 GeV
Doubly degenerate:

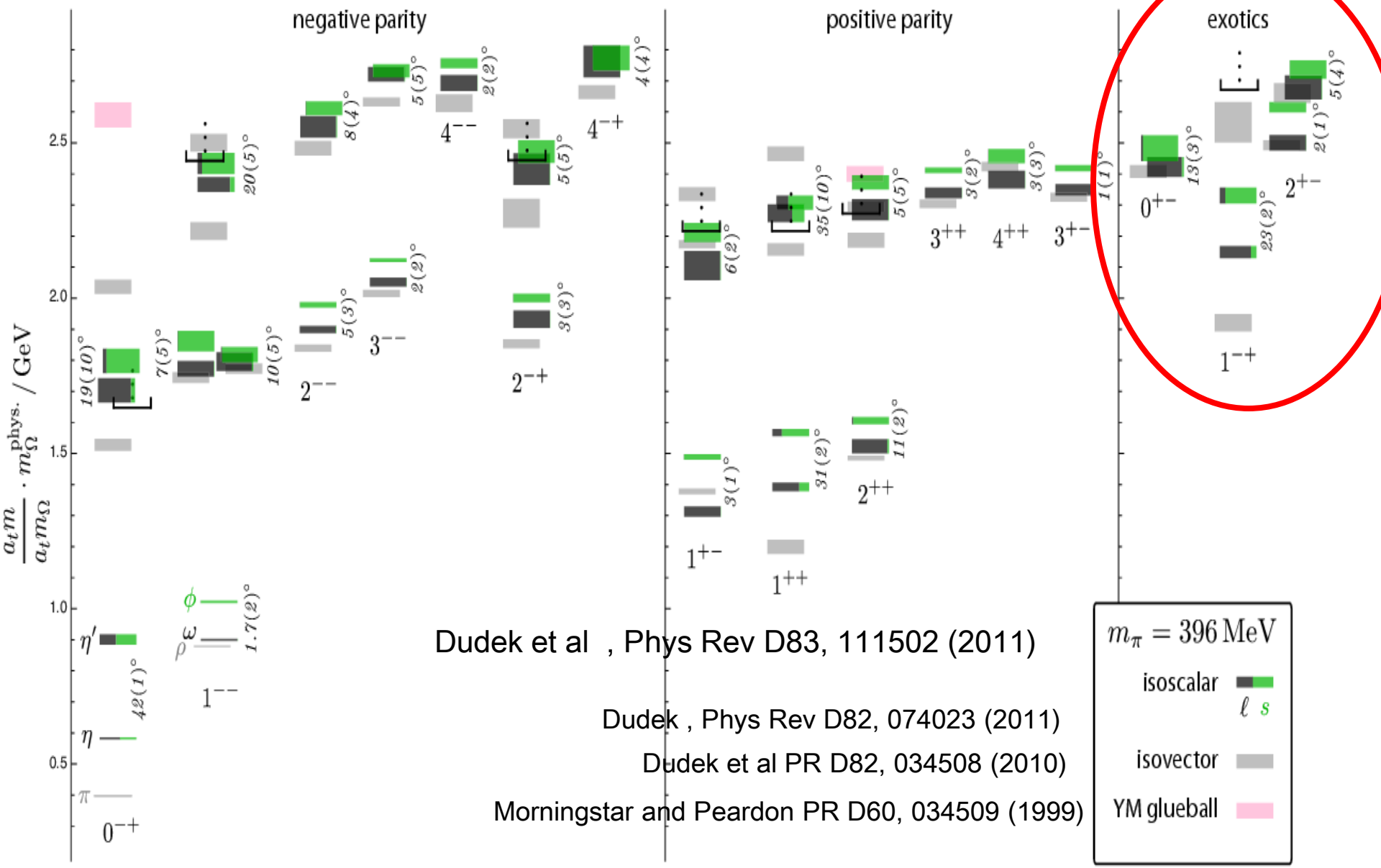
J^{PC} = 0^{+-} 0^{-+} 1^{+-} 1^{-+} 2^{+-} 2^{-+} 1^{++} 1^{--}

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

Recent lattice results



Dudek et al , Phys Rev D83, 111502 (2011)

Dudek , Phys Rev D82, 074023 (2011)

Dudek et al PR D82, 034508 (2010)

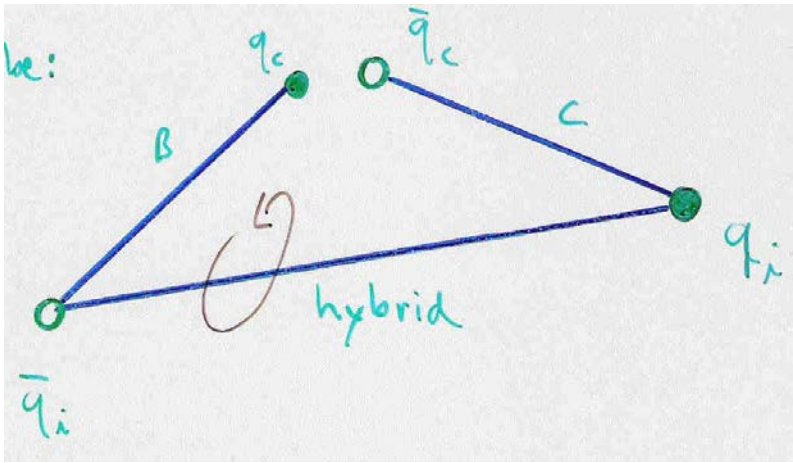
Morningstar and Peardon PR D60, 034509 (1999)

"Discovering experimental evidence for gluonic degrees of freedom in hadron spectroscopy is the most important outstanding qualitative test for QCD."

Hybrid Decays

Flux Tube Model:

Expect stronger coupling to one s-wave and one p-wave final state meson



Turns out to be a more general selection rule:

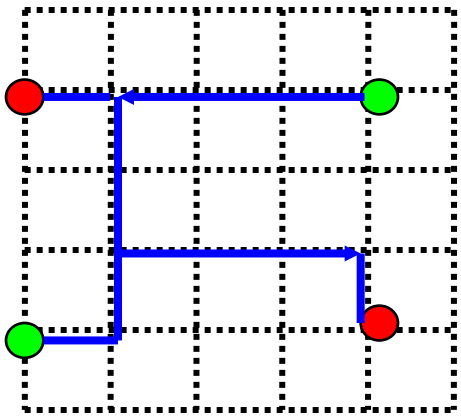
To preserve symmetries of quark and colour fields the hybrid must decay to meson in a P-wave

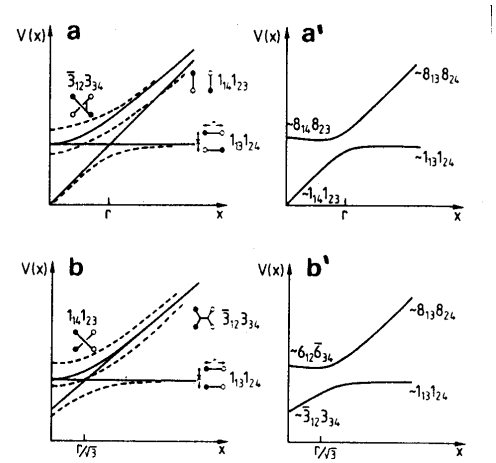
e.g. cannot transfer angular momentum as relative angular momentum but appears as internal angular momentum

This appears to be a universal selection rule

For 1^{-+} exotic expect $\hat{\rho} \rightarrow b_1\pi,\ f_1\pi$ modes to dominate

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

Much interesting physics:

- Meson-meson potentials in scattering
- Higher Fock space components which shift $q\bar{q}$ masses

Distinguishing states

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

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

$\pi(1800)$

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 Swanson and Szczepaniak [PR D56, 5692] predict small $\rho\omega$ partial width)

ρ' and ω' (1^{--})

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

Expect mixing: $|V\rangle = \alpha|2^3S_1\rangle + \beta|1^3D_1\rangle + \gamma|V_H\rangle$

	$\pi\pi$	$\omega\pi$	$\rho\eta$	$\rho\rho$	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	≈ 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	≈ 20

$\omega(1420) \to \pi b_1$ and $\omega(1600) \to \pi b_1$ are observed to be small so both unlikely to be pure 1^3D_1 state implying ω_H admixture

Y(2175)

Ding & Yan, Phys Lett B657 (2007)

Observed by BaBar: $Y(2175) \to \phi f_0(980)$ PR D74, 091103 (2006)

in ISR process: $e^+e^- \to \gamma_{ISR} \to \phi f_0(980) \to (K^+K^-) + (\pi^+\pi^-)$

& by BES in: $J/\psi \to \phi f_0 \eta$ PRL 100, 102003 (2008)

Seen in ISR so 1^- and I=0, most likely $s\bar{s}$

Use decays to discriminate between possibilities

$Y(2175)$ as $2\,^3D_1 s\bar{s}$ quarkonium			$Y(2175)$ as $s\bar{s}g$ hybrid [2]	$Y(2175)$ as $3\,^3S_1$ $s\bar{s}$ quarkonium [6]
Decay modes	Γ_{LJ} in $^3P_0$ model	Γ_{LJ} in flux tube model	In flux tube model	In $^3P_0$ model
KK	$\Gamma_{P0} = 9.8$	$\Gamma_{P0} = 23.1$	0	0
K^*K	$\Gamma_{P1} = 1.3$	$\Gamma_{P0} = 11.7$	3.7	20
$\phi\eta$	$\Gamma_{P1} = 0$	$\Gamma_{P1} = 0$	1.2	21
$\phi\eta'$	$\Gamma_{P1} = 2.9$	$\Gamma_{P1} = 2.8$	0.4	11
K^*K^*	$\Gamma_{P0} = 0.76$	$\Gamma_{P0} = 0$	0	102
	$\Gamma_{P1} = 0^*$	$\Gamma_{P1} = 0^*$		
	$\Gamma_{P2} = 0.15$	$\Gamma_{P2} = 0$		
	$\Gamma_{F2} = 17.2$	$\Gamma_{F2} = 23.5$		
$K(1460)K$	$\Gamma_{P0} = 58.3$	$\Gamma_{P0} = 50.2$	0	29
$K^*(1410)K$	$\Gamma_{P1} = 31.9$	$\Gamma_{P1} = 26.0$	23	93
$h_1(1380)\eta$	$\Gamma_{S1} = 3.6$	$\Gamma_{S1} = 3.5$	0	8
$K_1(1270)K$	$\Gamma_{S1} = 2.3$	$\Gamma_{S1} = 20.5$	35.3	58
	$\Gamma_{D1} = 19.6$	$\Gamma_{D1} = 25.9$		
$K_1(1400)K$	$\Gamma_{S1} = 3.0$	$\Gamma_{S1} = 0.8$	70.1	26
	$\Gamma_{D1} = 5.6$	$\Gamma_{D1} = 8.6$		
$K_2(1430)K$	$\Gamma_{D2} = 10.8$	$\Gamma_{D2} = 15.3$	15.0	9
Γ_{tot}	167.21	211.9	148.7	378

$f_0(1500)$ and $f_0(1710)$

Glueball:

$B(\underline{1})/p.s.\ \ (\pi\pi{:}KK{:}\eta\eta{:}\eta\eta'{:}\eta'\eta') = 3{:}4{:}1{:}0{:}1.$

	$f_0(1500)$	
Mode	Γ_i(MeV)	Amps.
KK	214	${}^1S_0 = +0.28$
KK^*		
$\eta\eta$	66	${}^1S_0 = -0.33$
$\eta\eta'$		
(no ππ)		
	$\Gamma_{thy} = 279$ MeV see text	

State	Experiment	$\pi\pi$	KK	$\eta\eta$	$\eta\eta'$	4π
$f_0(1500)$	WA102	1	0.33 ± 0.07	0.18 ± 0.003	0.096 ± 0.026	1.36 ± 0.15
	CBar	1	0.184 ± 0.025	0.08 ± 0.04	0.065 ± 0.008	1.62 ± 0.18
$f_0(1710)$	WA102	1	5.0 ± 0.7	2.4 ± 0.6	< 0.18	< 5.4

Implies states are mixtures but other input like radiative transitions and 2γ decays could help sort this out

Baryons

- Could use better KN data to produce Σ and Λ 's
- Never really cleaned up because of low intensity
- Will need high statistics $K^- p \rightarrow \Xi^- K^+$

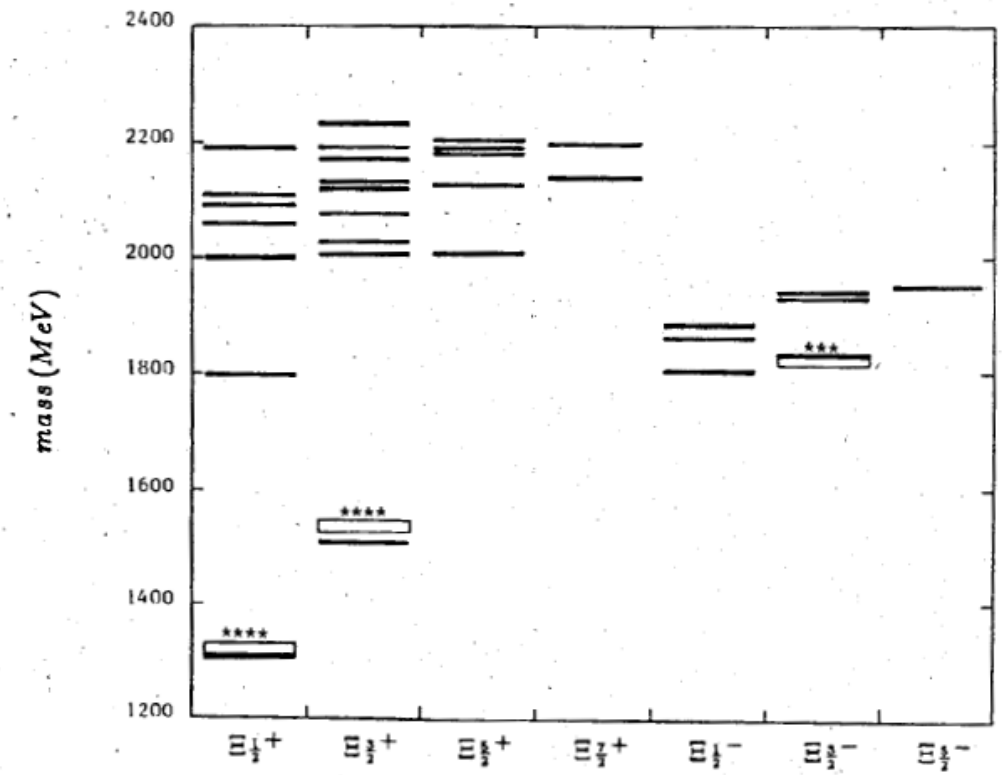


FIG. 8. The Ξ baryons up to $N=2$: we have

How do we answer these questions?

To disentangle the final possibilities need to

- Determine J^{PC}
- measure the BR's to many final states

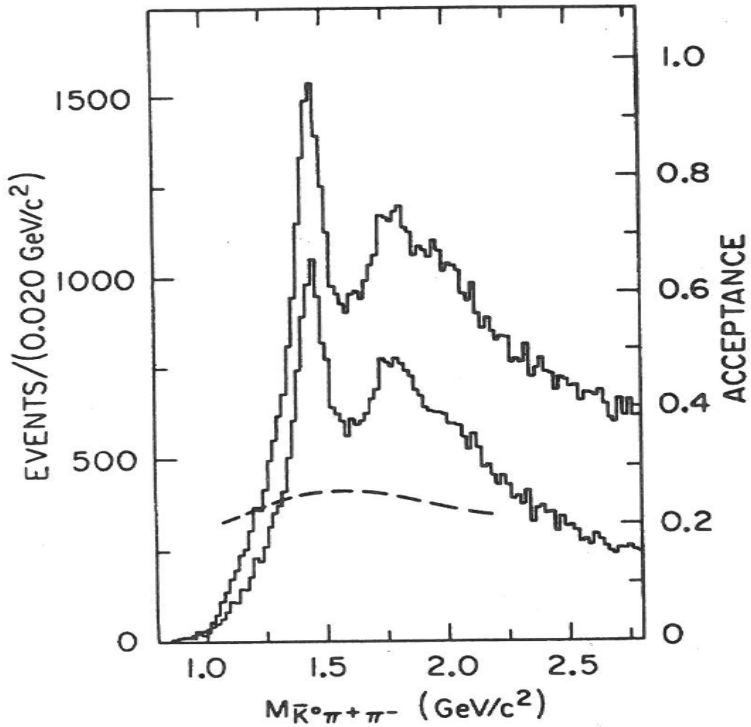
To accomplish this need:

More sophisticated analysis with:

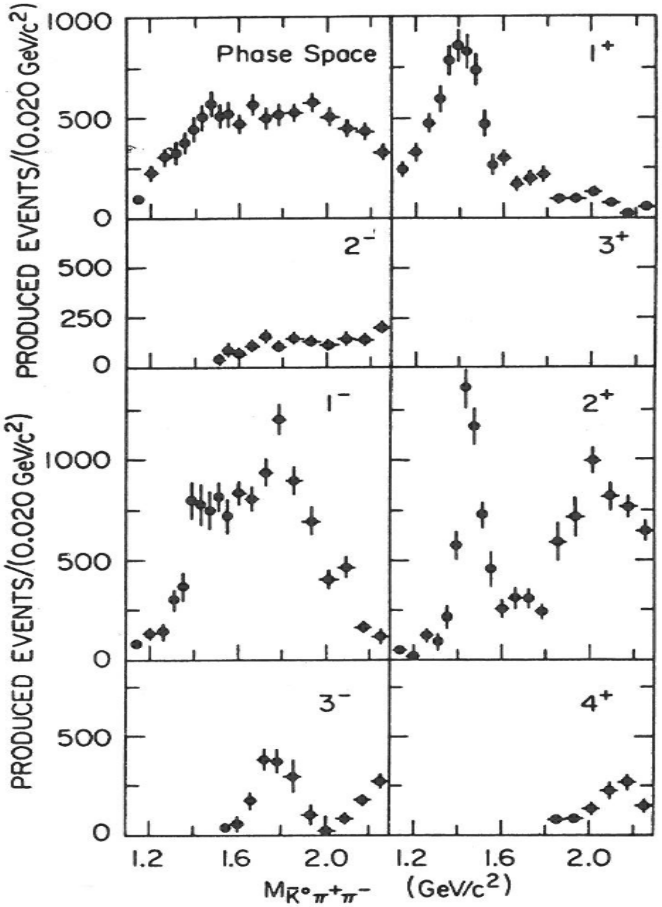
- Wide range of data
- High intensity beams
- Advanced detectors

How do we answer these questions?

From the LASS collaboration at SLAC (PWA/Isobar analysis)

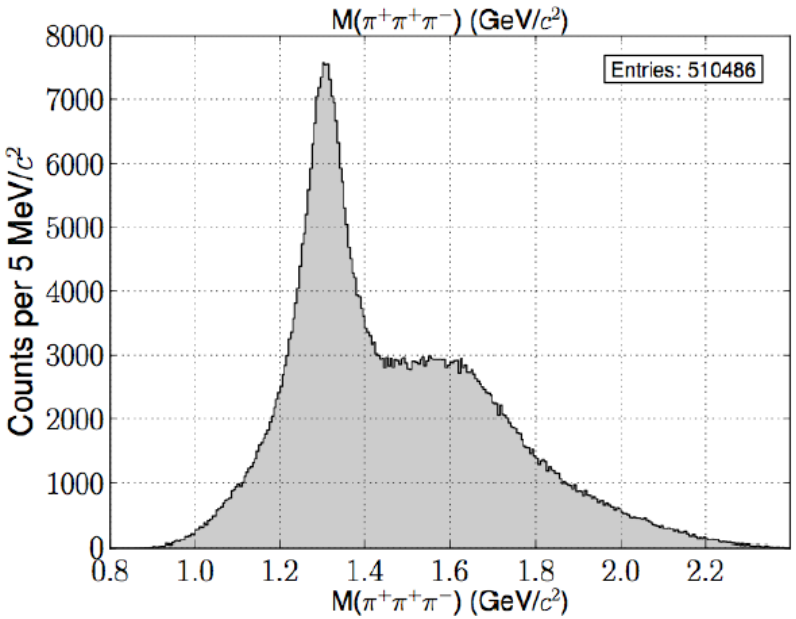


(a)

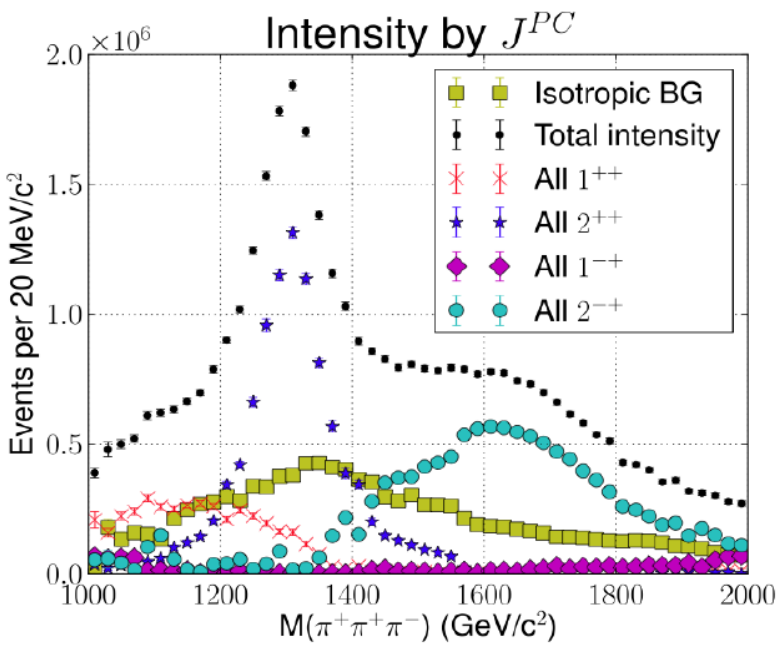


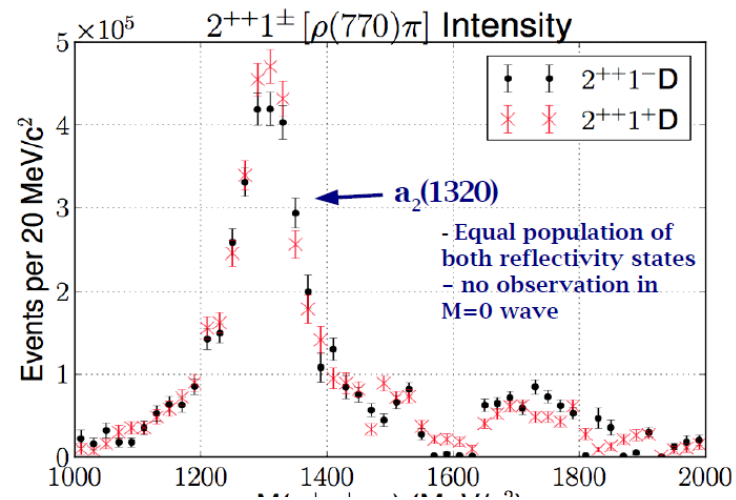
From LASS: D. Aston et al Nucl. Phys B292, 693 (1987); Phys Lett 180B, 308 (1986); Phys Lett 201B, 169 (1988)

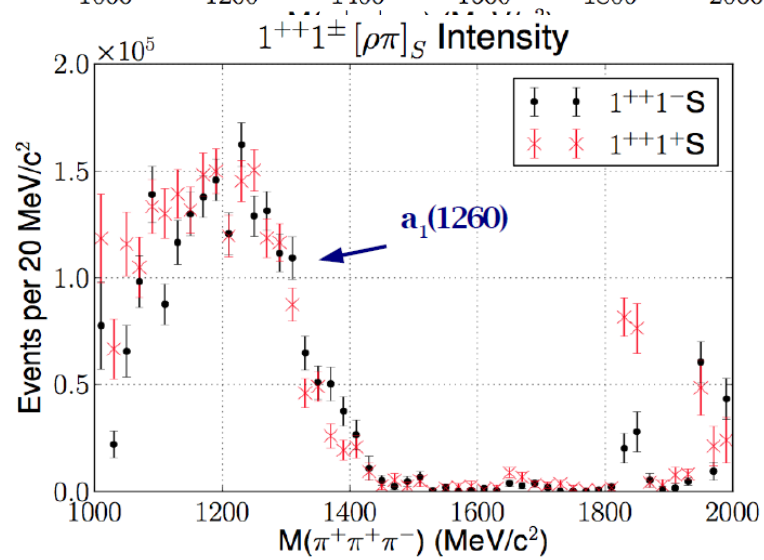
CLAS g12 Analysis of $\gamma p \rightarrow n\, \pi^+\pi^+\pi^-$



Paul Eugenio CIPANP 2012







To do this need:

More sophisticated analysis with:

- Wide range of data
- High intensity beams
- Advanced detectors

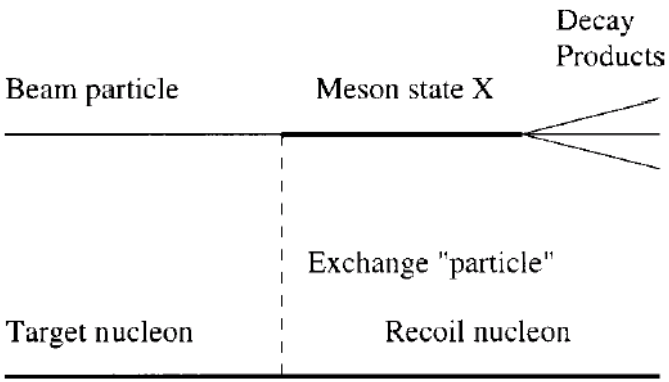
What beams?

- $\pi^{+/-}$
- K
- pbar
- γ

What beam energies:

20-30 GeV?

π or K's: 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

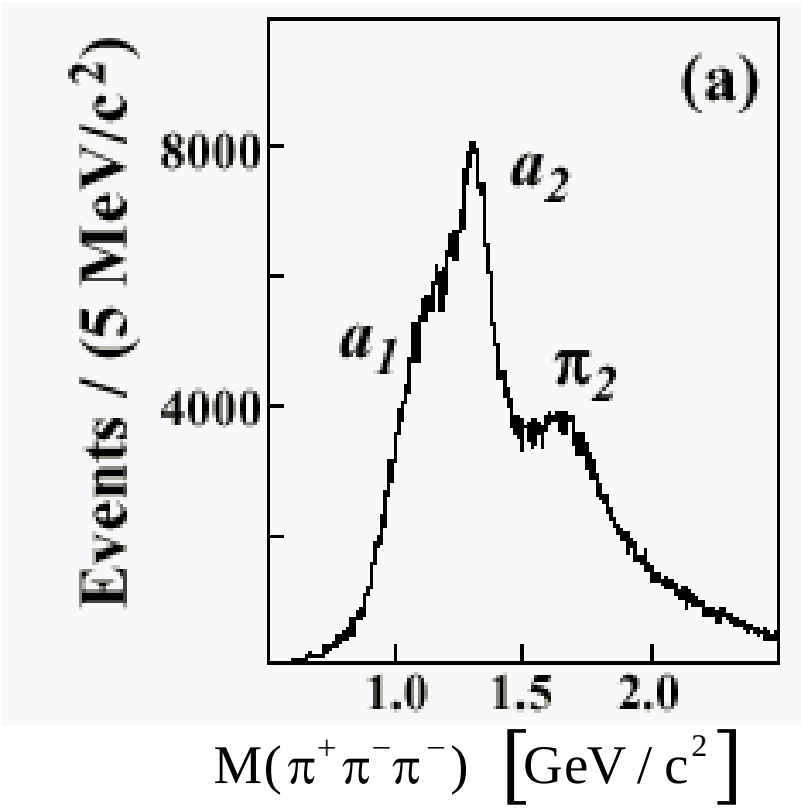
Evidence for $\hat{\rho}(1600)$

Serpukhov: $\pi^- N \rightarrow (\pi^+\pi^-\pi^-)N$ 40 GeV / c π beam in $\rho^0\pi^-$, $\pi\eta$ and πb_1

BNL E852: $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$ at 18 GeV / c π beam signal in $\pi f_1(1285)$

Eg: E852 Results: $\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$ At 18 GeV/c

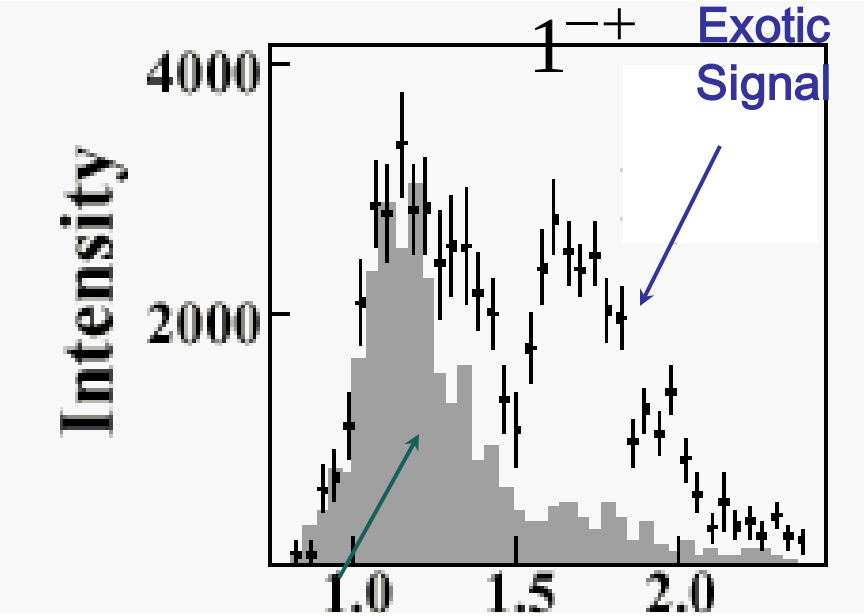
Advantage is high statistics

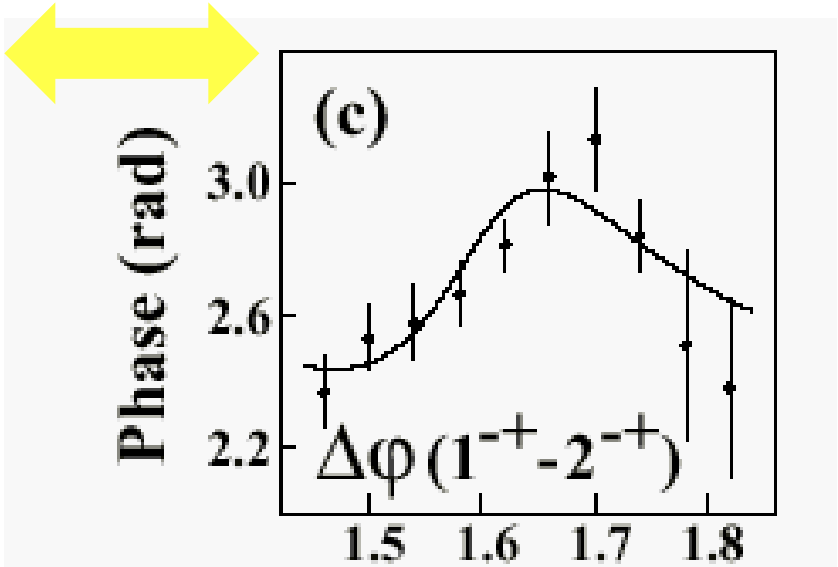


to partial wave analysis

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

pbar-p

- Democratic in producing J^{PC}:
  - Produce non-exotic J^{PC} in direct s-channel annihilation

$$\bar{p}p \to c\bar{c} \to hadrons$$

  - Can produce $c\underline{c}$ sector J^{PC}-exotics (presumably hybrids) using associated production

$$\bar{p}p \to \text{light meson} + c\bar{c}\ (\text{exotic})$$

- High statistics
- Can do PWA to measure quantum numbers?

- **Crucial question:** just how large are these cross sections?
- Very little relevant data exists. There is some data on the hopefully similar associated charmonium production reaction

  p$\underline{\text{p}}$ –> J/ψ π^0 from E760/835 at Fermilab.

Photoproduction

- The photon has significant $s\bar{s}$ content

- Therefore can finally study strangeonium in detail
  - Fill in missing states
  - Resolve these puzzles

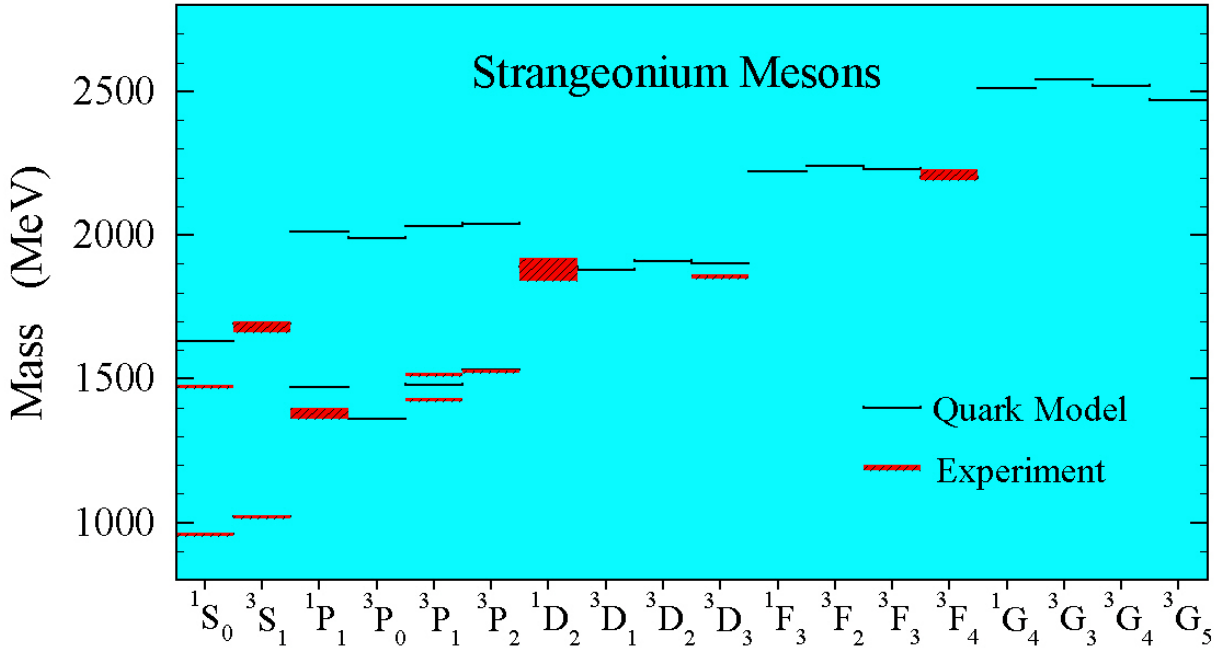
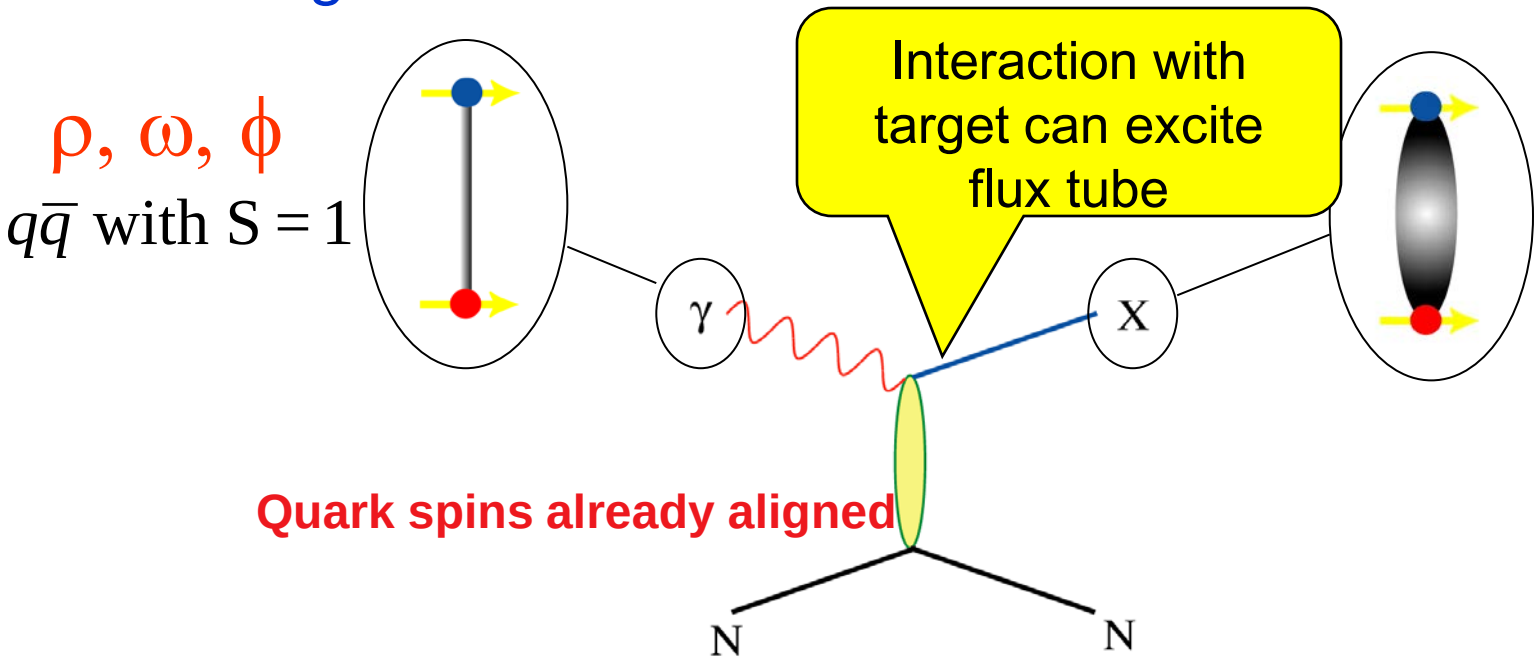


Photo-production (of hybrids by GlueX)

Qualitative alternative to hadronic peripheral production

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



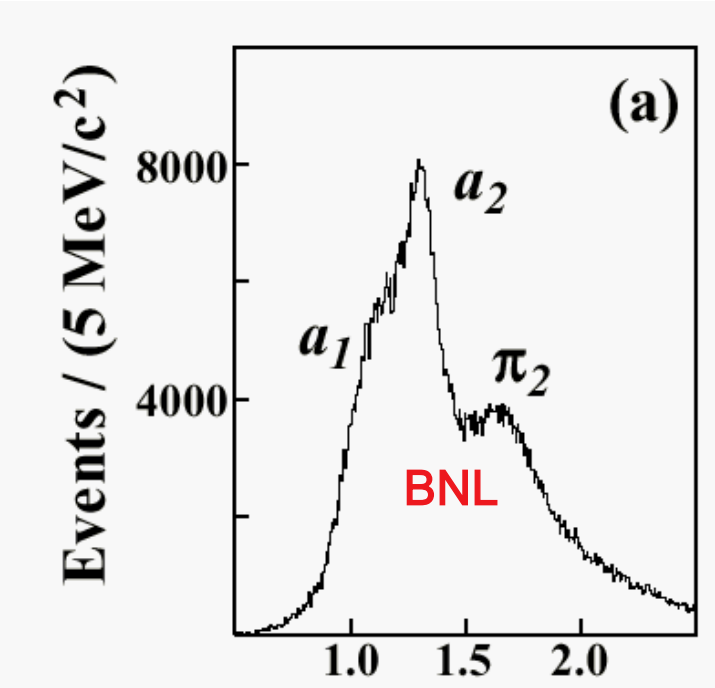
- Production of exotic hybrids is favoured: $J^{PC}=0^{+-}, 1^{-+}, 2^{+-}$
- Almost no data is available

Compare π□p and γ□p Data

Compare statistics and shapes

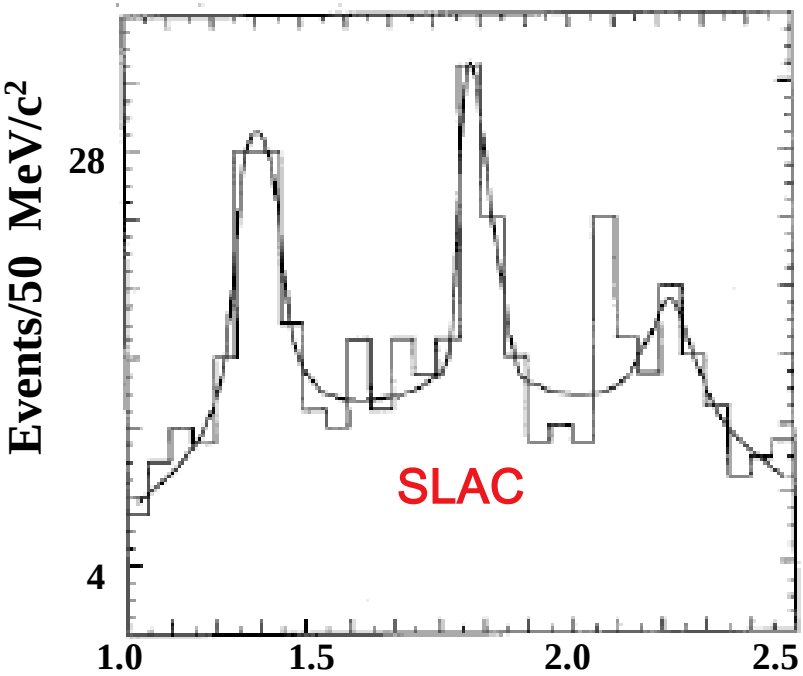
$$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$$

ca. 1998 @ 18 GeV



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

ca. 1993 @ 19 GeV

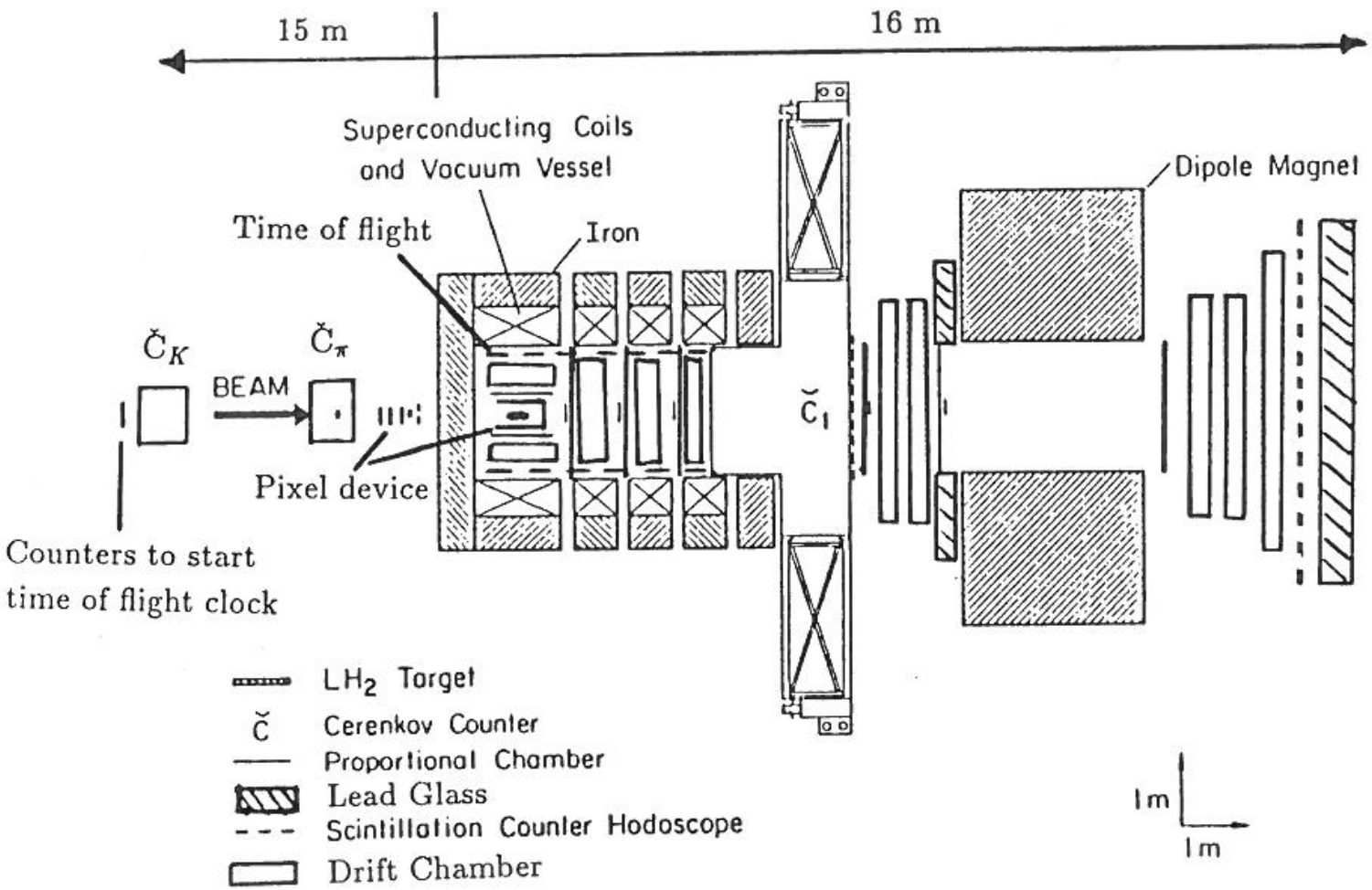


$$M(3\pi) \quad \left[\mathrm{GeV}/c^2\right]$$

Requirements:

- 10 – 20 GeV K beam
- 5 x 10^9 events recorded
- Good uniform 4π acceptance is crucial
- Time of flight for particle identification
- High resolution vertex detection to separate secondary from primary vertices
- Photon detection to see π^0 's
- Computing

The Detector?



GlueX Detector

Indiana U Responsibilities

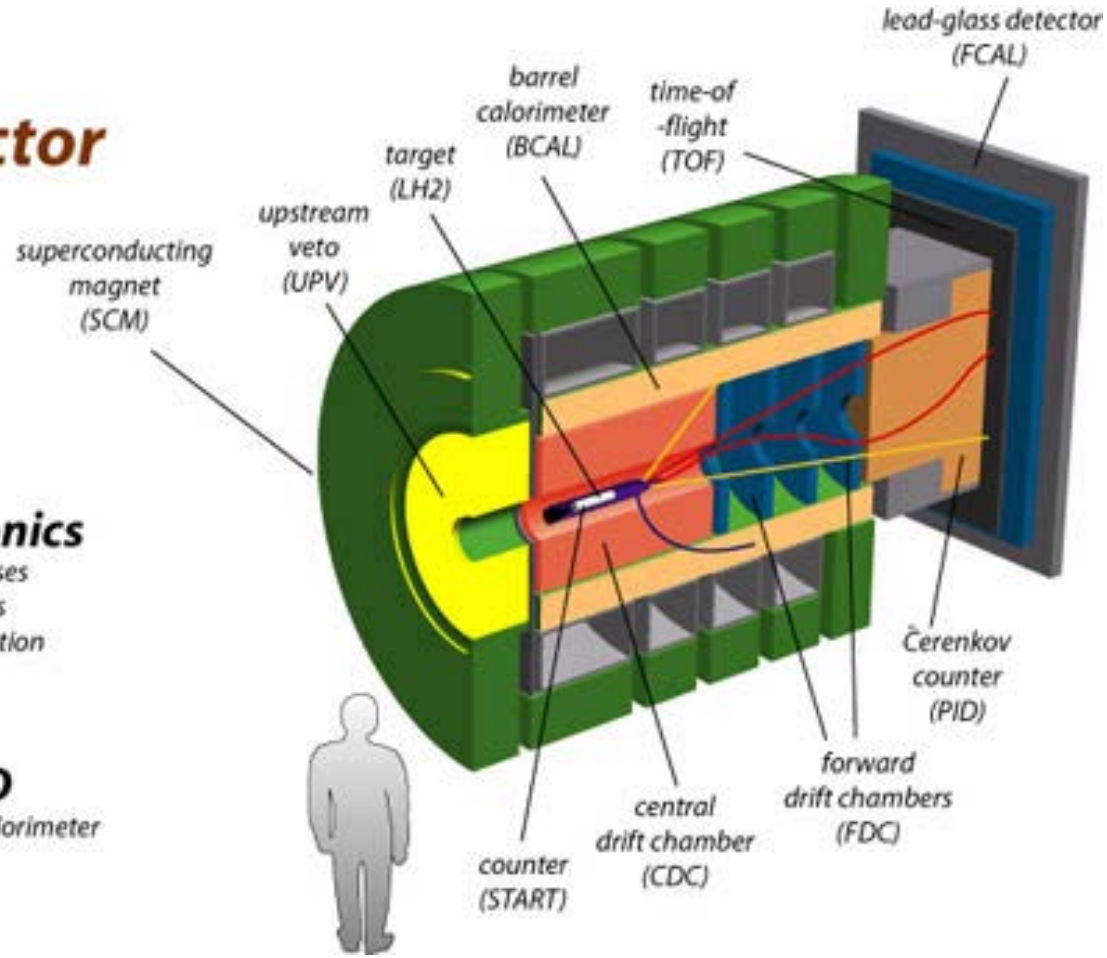
Solenoid
Refurbishment
at the Indiana University Cyclotron Facility

Electronics
PMT Bases
FADC's
Coordination

TOF
Time-of-Flight

LGD
Lead Glass Calorimeter

in collaboration with IHEP - Russia



What other facilities will there be?

BESIII	$J/\psi \to \gamma X$
PANDA	$p\bar{p}$ annihilation
COMPASS	peripheral production
GlueX	photoproduction
JPARC?	

Summary

- The goal is to understand QCD

- In the last decade there has been much theoretical progress especially in lattice QCD.

- Need comparable experimental results, especially on gluonic excitations, to understand the nature of confinement in QCD.
- Need to improve our understanding of conventional mesons
    - Find missing states
    - Resolve puzzles

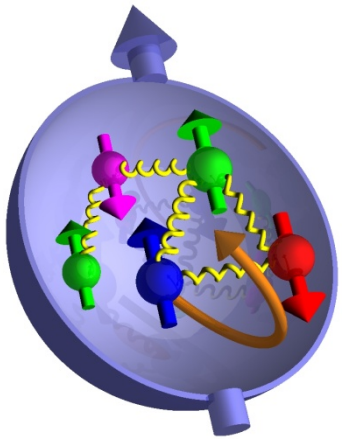
- Unambiguous confirmation of states with explicit gluonic degrees of freedom would be an important test of QCD

- Need high statistics and good detector acceptance with high rate capabilities

What questions do we need to answer?

1. **Is there a compelling the physics case?**
2. Define the measurements needed to answer the questions
3. Decide on the tools needed to make these measurements:
   - **The beams**
   - The detector
4. What other facilities are available?
5. **Is there an interested community?**

Hadron Structure with Project X:



From Paul Reimer Friday June 15:

- **Hadron Structure from Neutrino Induced Interactior**
- **Hadron Structure from Proton Induced Interactions**

EMC Effect

MINERνA

- The EMC effect
- How is the proton's structure modified when the proton is placed in a nucleus?
- Directly addressed by nuclear target data in MINERνA

MINERνA Targets						
C	Fe	Pb	He	Water	LD_2	LH_2
				H_2O	Future??	

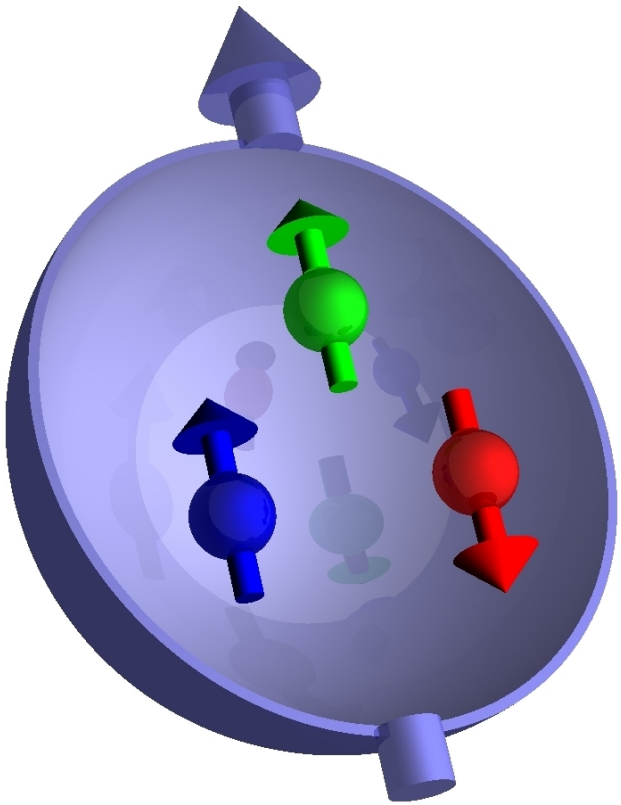
- Deep Virtual Compton Scattering (DVCS) to measure Generalized Parton Distributions (GPDs)

QCD and the spin puzzle

- How does the spin of the proton formed from it's constituents?

$$S_1 = \frac{1}{2} \quad = \quad \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

- Could the Glue carry the Spin?
  - Still large uncertainty and limited coverage in x_{Bj}



Project X Physics Study
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Please contact us if you are interested