Status and Prospects for Meson Spectroscopy: an Experimentalist's Perspective

Ryan Mitchell
Indiana University

Lattice QCD and Experiment
November 21-22, 2008

The Big Picture

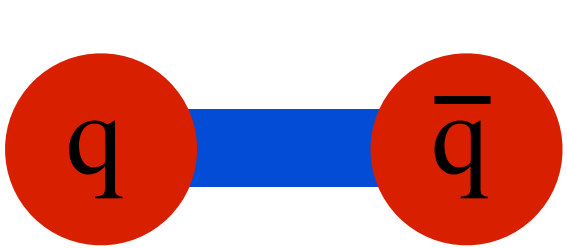
Why meson spectroscopy?

1. We want to study QCD in a "simple" environment.

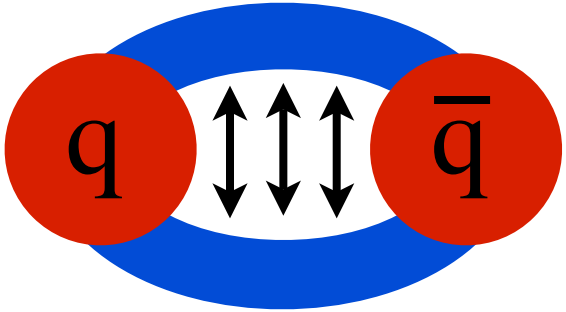
2. The meson system presents a rich spectrum of traditional states.

   ➡ *We can isolate effects due to spin-dependence, quark mass-dependence, α_S, wavefunctions, etc.*

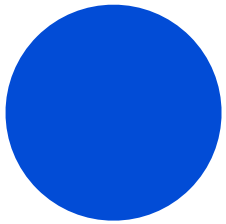
3. The meson system should also provide access to gluonic fields.



MESON



HYBRID MESON



GLUEBALL

The Role of Lattice QCD (I)

(from the perspective of an experimentalist studying meson spectroscopy)

I. Provide contact between experiment and QCD.

A. Precision tests.

- ➡ *meson masses*
- ➡ *transition rates*
- ➡ *decay constants (c.f., f_D and f_{Ds})*
- ➡ *etc.*

B. Qualitative features.

For example, **true or false**:

1. QCD predicts mesons with gluonic degrees of freedom.
2. Experiments can produce these mesons.
3. Experiments can observe these mesons.

The Role of Lattice QCD (II)

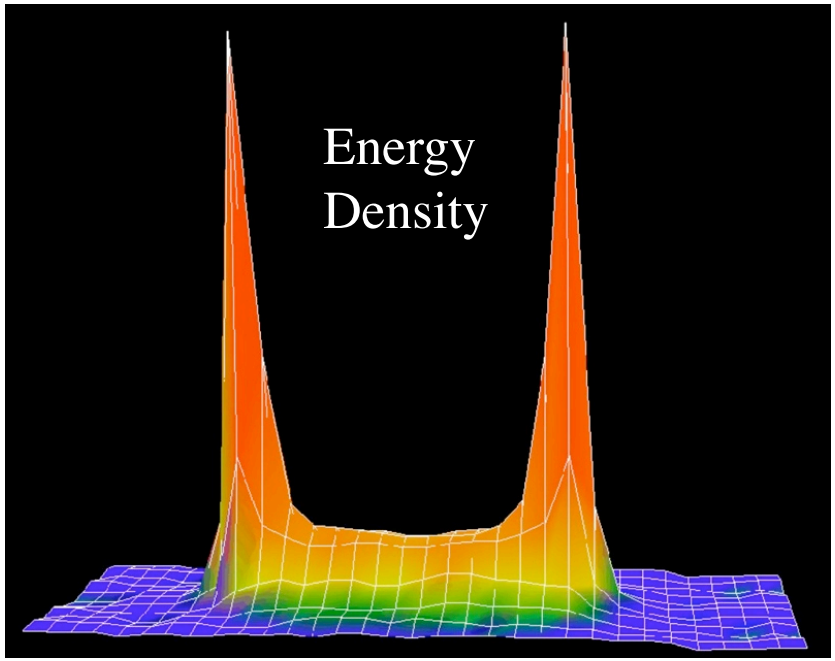
(from the perspective of an experimentalist studying meson spectroscopy)

II. Provide contact between models and QCD.

- ➡ *Lattice QCD "only gives numbers."*
- ➡ *Models are "better for our intuition."*

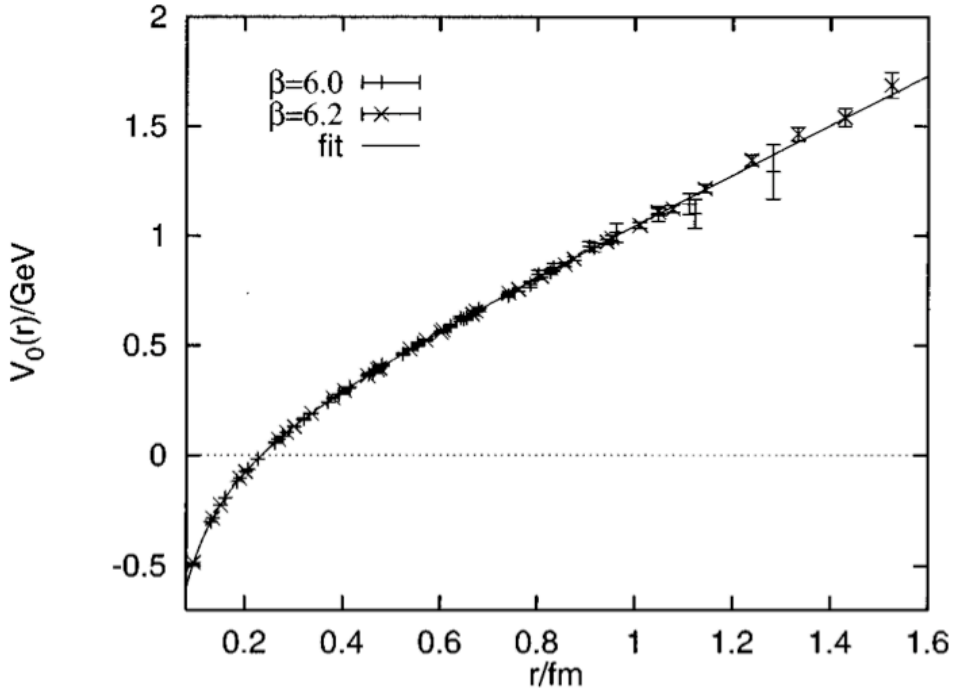
Two old calculations experimentalists still like:

Bali, Schilling, Schlichter PRD51, 5165 (1995)



QCD and the flux tube model.

Bali, Schilling, Wachter PRD56, 2566 (1997)



QCD and potential models.

Experimental Landscape

- Recent highlights of meson spectroscopy include:

  1. The discovery of the **X, Y, Z states**.
  2. High-statistics studies of $e^+e^- \rightarrow$ **light quark vectors**.
  3. Precision measurements in **charmonium**.
  4. New dialogues on **light quark hybrid mesons**.

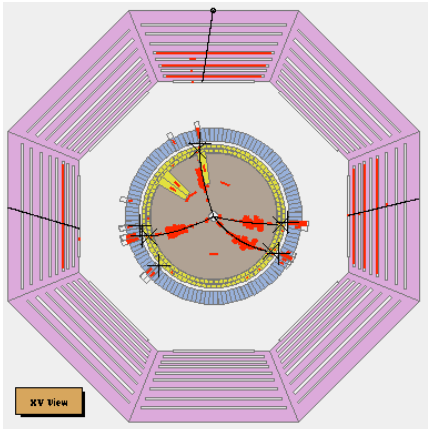
  (Also: the η_b, D_{SJ} states, D and D_S decay constants, the glueball picture)

- This is a time of transition:

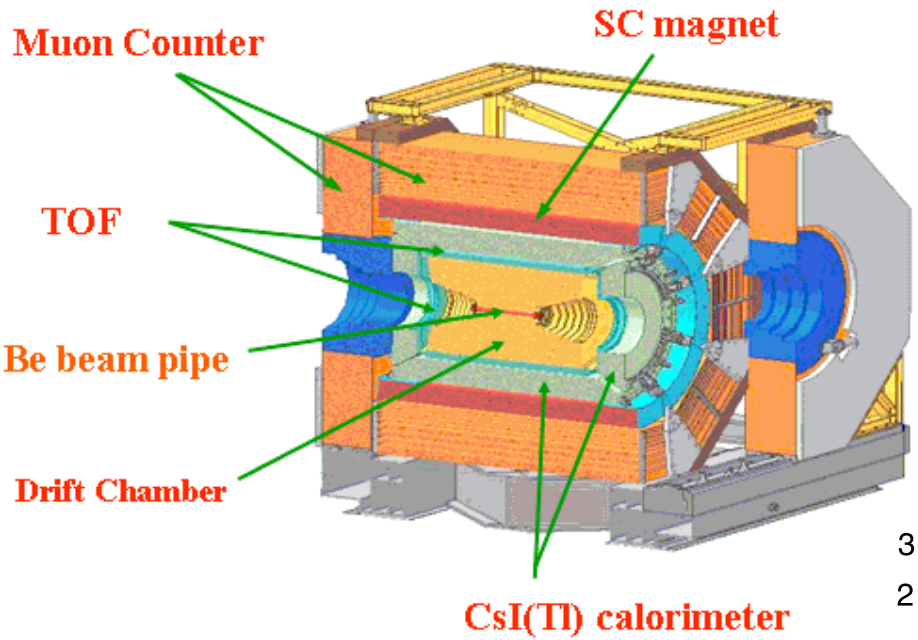
  - **BaBar** has ended; **Belle** continues
  - **CLEO-c** has ended; **BES II** has become **BES III**
  - **Zeus, H1** have ended; **PANDA** is being designed
  - **JLab** will upgrade from **6 GeV** to **12 GeV (GlueX)**
  - *(**CDF** and **D0** will end; the **LHC** will begin)*

- New facilities will carry the field into the future...

BES III *(Beijing, China)*



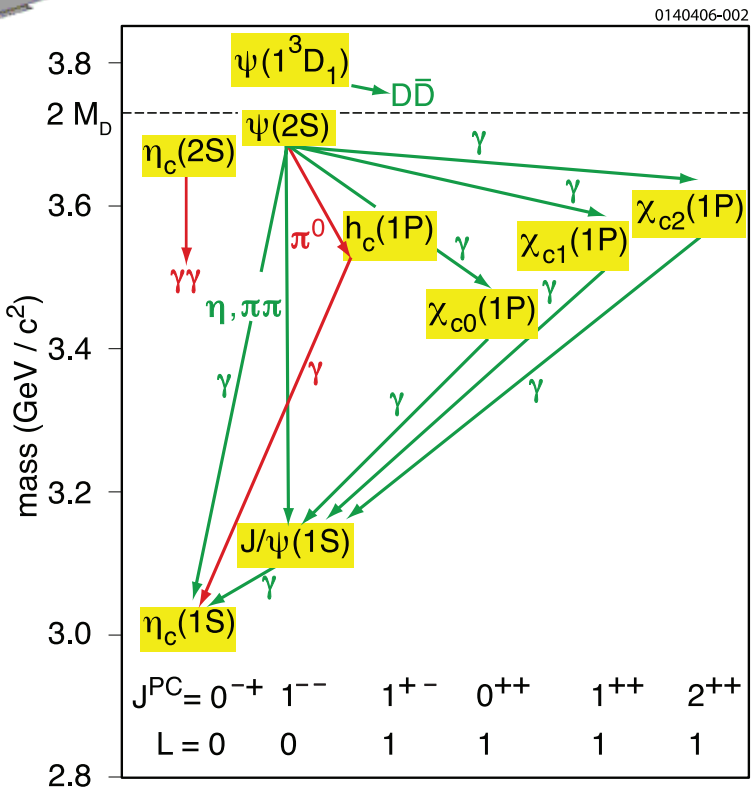
1st Hadronic Event
(7/20/08)



e^+e^- in the τ-charm region

BEPC II Luminosity:
~ 10^{33} $cm^{-2}s^{-1}$
+
New BES III Detector.

- **Unprecedented Statistics:**
  - **10 billion J/ψ per year** *(BES II has 58 million)*
  - **3 billion ψ(2S) per year** *(CLEO-c has 27 million)*
- **Wide Physics Scope:**
  - charmonium
  - light quark spectroscopy
  - energy scans
  - open charm

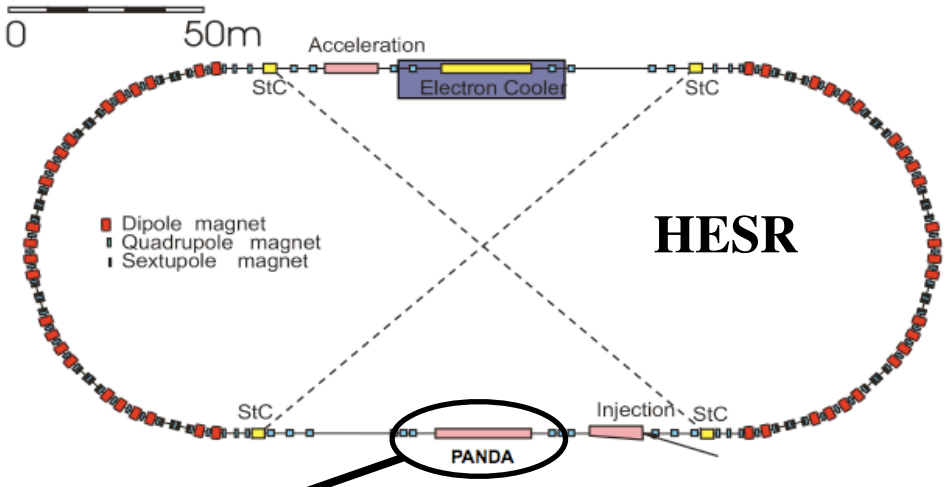


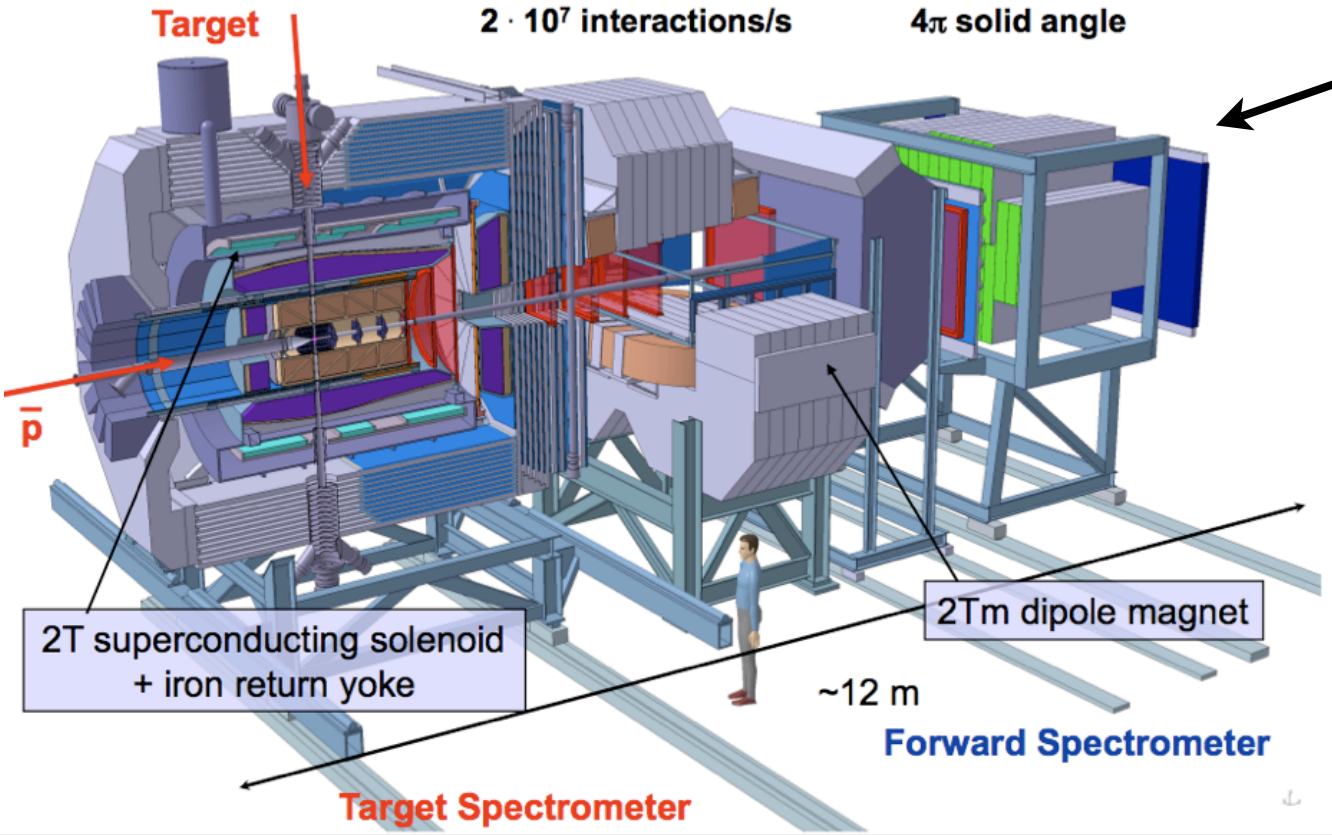
BES III physics book: arXiv:0809.1869

PANDA *(Darmstadt, Germany)*

1.5 to 15 GeV $\bar{p}$ beam on p target

- **Features:**
  - high-statistics
  - complete detector
  - precise (σ_E **~30 keV**) energy scans
    (E835 at Fermilab had $\sigma_E \sim 240$ keV)



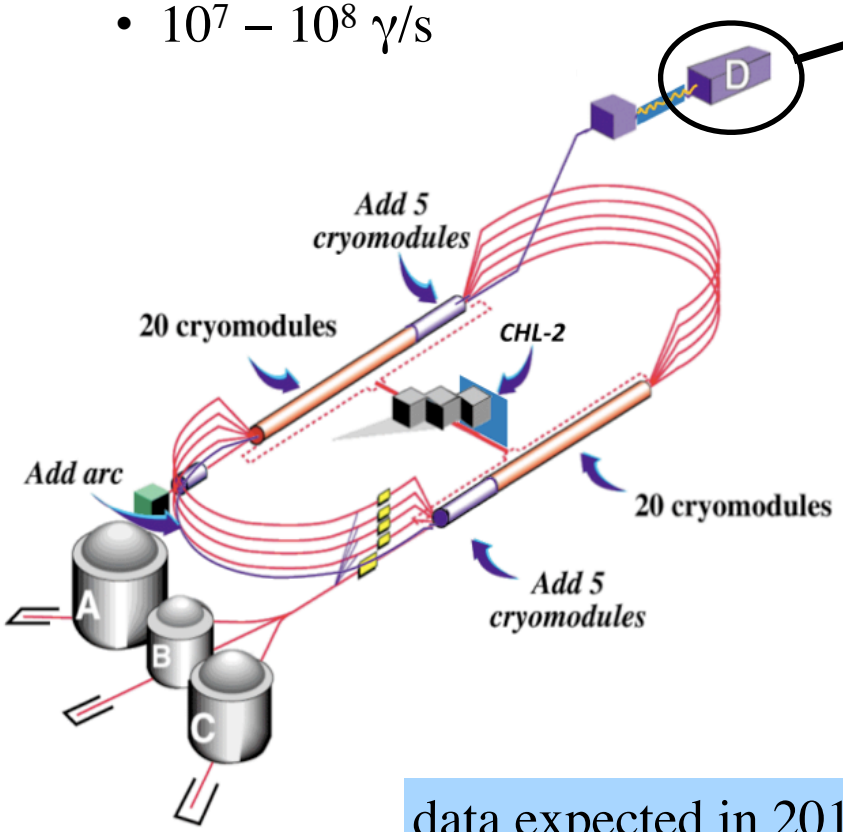


- **Physics:**
  - **Direct Production:**
    ($\bar{p}p \rightarrow X$)
    - X has non-exotic J^{PC}
    - charmonium
      (masses, widths, decays)
  - **Associated Production:**
    ($\bar{p}p \rightarrow (\pi,\eta,\omega,etc.)\ X$)
    - X has any J^{PC}
    - exotic states

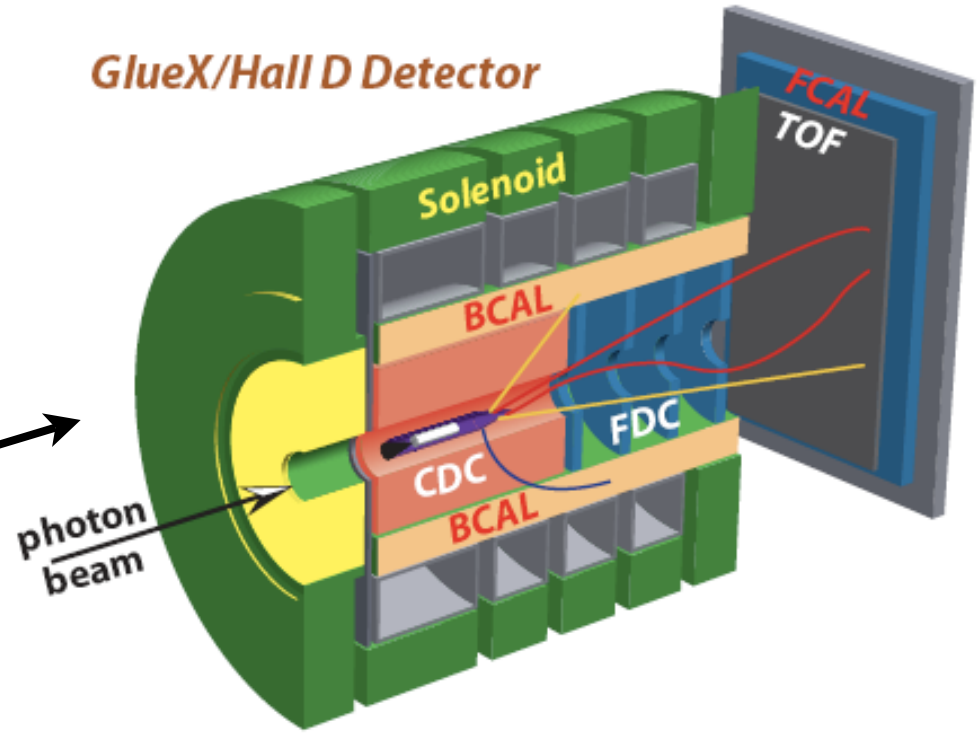
GlueX *(Newport News, USA)*

9 GeV polarized photons on p target

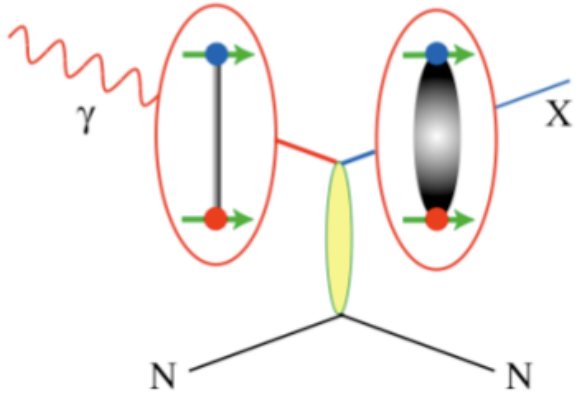
- **Features:**
  - part of the JLab 12 GeV upgrade
  - 9 GeV polarized photons from a diamond radiator
  - 10^7 – 10^8 γ/s



data expected in 2014



- **Physics:**
  - produce **hybrid mesons** with exotic J^{PC}:



Highlights of Meson Spectroscopy

1. The discovery of the **X, Y, Z states**.

2. High-statistics studies of e^+e^- → **light quark vectors**.

3. Precision measurements in **charmonium**.

4. New dialogues on **light quark hybrid mesons**.

not covered but also new and interesting:

5. the η_b discovery,

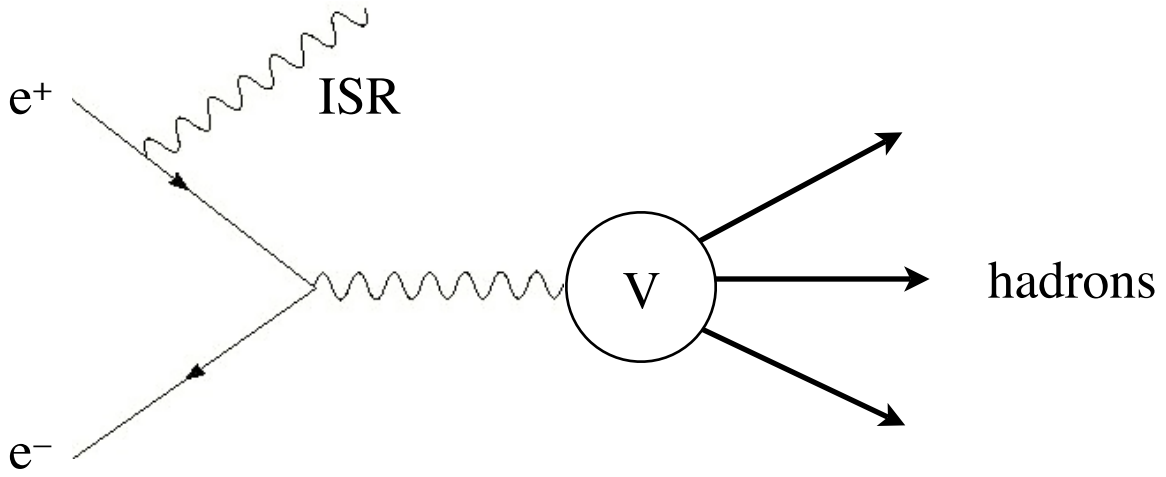
6. D_{SJ} states,

7. D and D_S decay constants,

8. the glueball picture

1/4 Discovery of the X, Y, Z States

- **The X,Y, and Z states have brought about an unexpected renaissance in meson spectroscopy.**
- Start with the **X(3872)** in B decays.
- Then the **Y(4008)**, **Y(4260)**, **Y(4350)**, **Y(4660)** in **I**nitial **S**tate **R**adiation.



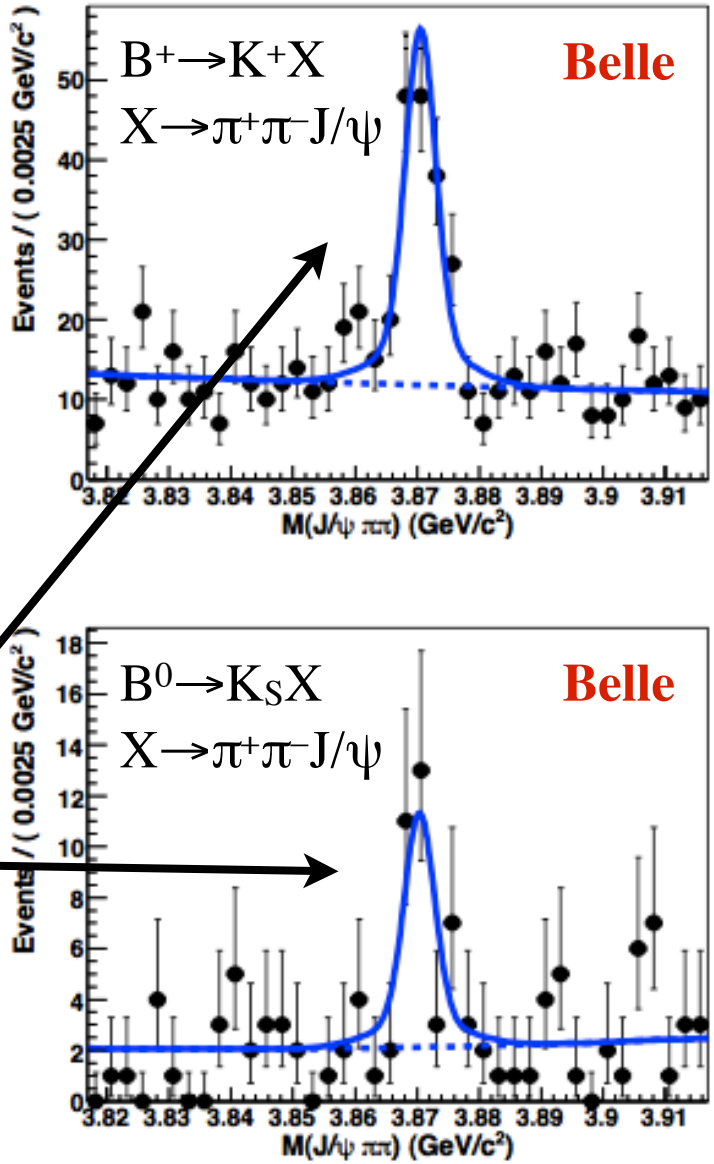
- The discoveries have extended beyond the charmonium region into bottomonium (the **Y(10890)**) and strangeonium (the **Y(2175)**).
- It is difficult to fit these new states into the traditional charmonium (or bottomonium or strangeonium) spectra. ⇒ **Molecules?** ⇒ **Tetraquarks?** ⇒ **Hybrid Mesons?**

1/4 Discovery of the X, Y, Z States

X(3872)

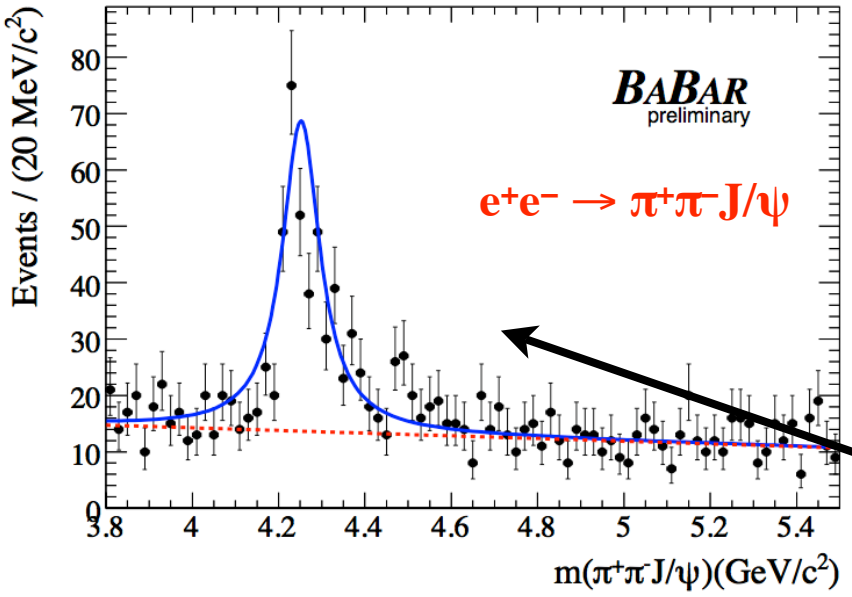
- Discovered by **Belle** in $B^+ \to K^+X$; $X \to \pi^+\pi^- J/\psi$ (**PRL 91, 262001 (2003):** *2nd most cited Belle paper(!)*).
- Confirmed by **BaBar**, **CDF**, and **D0**.
- The mass (3872.2 ± 0.8 MeV/c^2) is very close to $M(D^0) + M(D^{0*})$. Width is ~3 MeV/c^2.
  - ➡ ***Possible D^0D^{0*} molecule? Tetraquark?***
- **CDF** angular analysis concludes it has $J^{PC} = 1^{++}$ or 2^{-+} (**PRL 98, 132002 (2007)**).
- **Belle** and **BaBar** both see **X(3872)** $\to D^0D^{0*}$.
- **Belle** now observes **X(3872)** in both $B^+ \to K^+X$ and $B^0 \to K^0X$ with about equal strengths.
- **BaBar** has observed **X(3872)** $\to \gamma\psi(2S)$ and $\gamma J/\psi$, with $B(\gamma\psi(2S))/B(\gamma J/\psi) \sim 3$.

arXiv:0809.1224

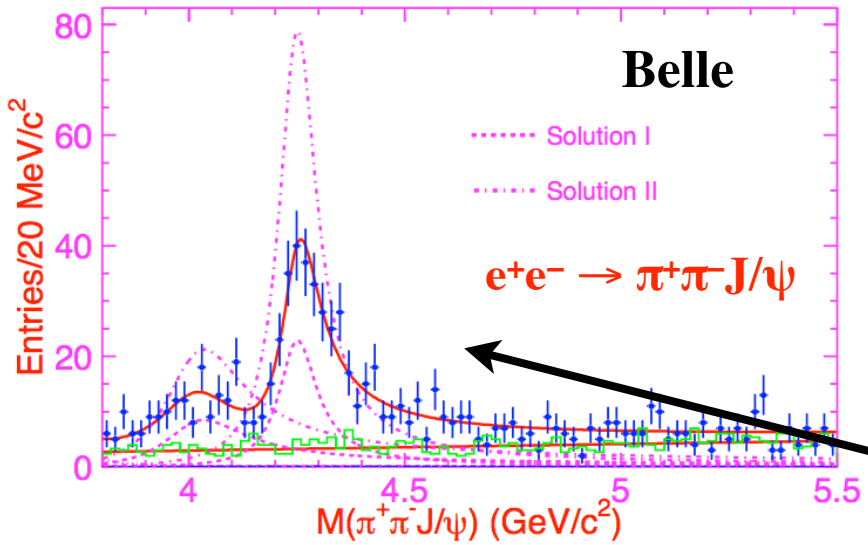


1/4 Discovery of the X, Y, Z States

arXiv:0808.1543



PRL99, 182004 (2007)



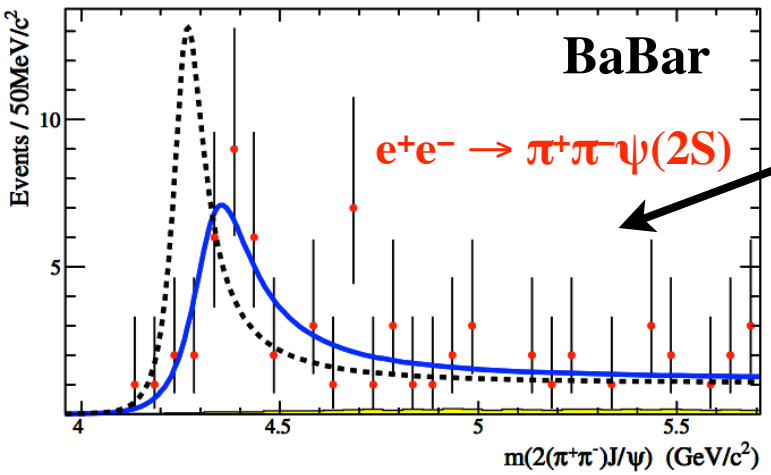
Y(4260)

- Discovered by **BaBar** in ISR $e^+e^- \to \pi^+\pi^- J/\psi$ **(PRL 95, 142001 (2005))**.
- ISR gives $J^{PC} = 1^{--}$.
- Confirmed by **CLEO** and **Belle**.
- Latest **BaBar** results:
  - ➡ $M = 4252 \pm 6\ ^{+2}_{-3}$ MeV/c^2.
- No expected 1^{--} charmonium states in this region. Models predict hybrids between 4200 and 5000 MeV/c^2.
  - ➡ ***Possible charmonium hybrid meson?***
- **CLEO** finds $\pi^0\pi^0 J/\psi$ / $\pi^+\pi^- J/\psi$ consistent with an isoscalar.
- **Belle** observes **Y(4008)**, not confirmed by **BaBar**.

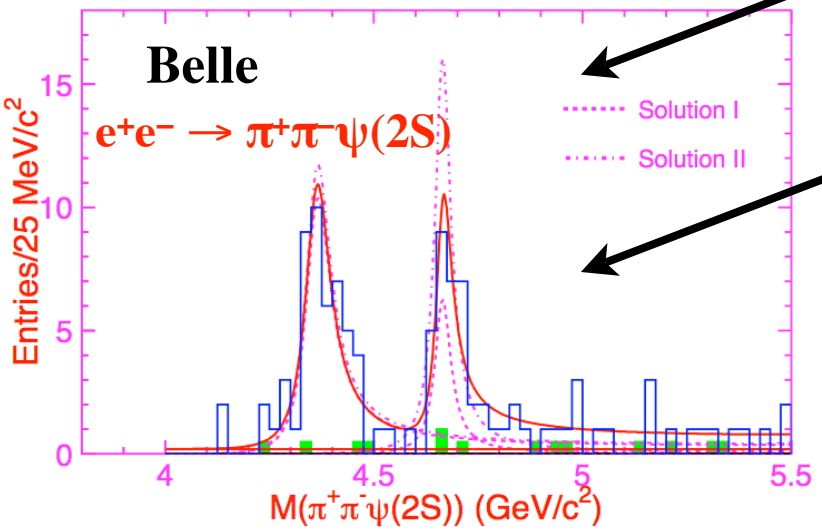
1/4 Discovery of the X, Y, Z States

Y(4350)?, Y(4660)?

PRL98, 212001 (2007)



PRL99, 142002 (2007)



- **Y(4350)** discovered by **BaBar** in $e^+e^- \to \pi^+\pi^-\psi(2S)$.
  - $M = 4324 \pm 24$ MeV/c^2, $\Gamma = 172 \pm 33$ MeV/c^2
- **Y(4350)** must be 1^{--}, but not consistent with **Y(4260)**. Also not consistent with any expected charmonium.
  - ***What is the Y(4350)??***
- **Y(4350)** confirmed by **Belle**.
  - $M = 4361 \pm 9 \pm 9$ MeV/c^2, $\Gamma = 74 \pm 15 \pm 10$ MeV/c^2
- But **Belle** also observes **Y(4660)**.
  - $M = 4664 \pm 11 \pm 15$ MeV/c^2, $\Gamma = 58 \pm 15 \pm 3$ MeV/c^2
- **Y(4660)** is also inconsistent with any expected charmonium states.

➡ ***What is the Y(4660)??***

1/4 Discovery of the X, Y, Z States

$\Upsilon_b(10890)$?

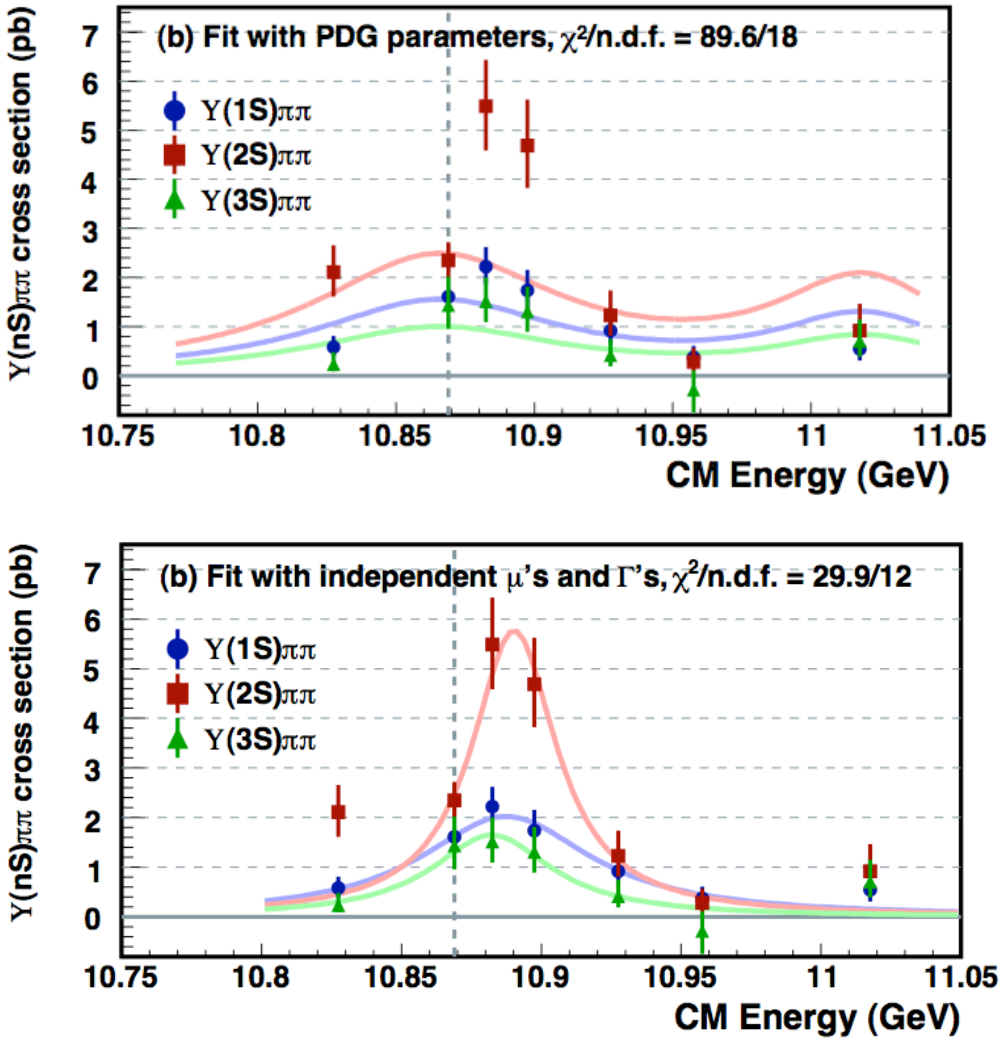
- **Belle** performed a scan in 2005 around the Υ**(5S)**/Υ**(10860)** peak to maximize B_S production.
- Anomalously large rates to $\pi^+\pi^-\Upsilon$**(nS)** were observed, more than 100 times what one would expect from Υ**(4S)**.
- This is similar to the charmonium system if you compare **Y(4260)** with ψ**(nS)** or ψ**(3770)**.
- Perform another scan (12/07) and see if the $\pi^+\pi^-\Upsilon$**(nS)** cross sections look like Υ**(5S)**?

  NO.

  ➡ M = 10889.6 ± 1.8 ± 1.5 MeV/c2

  ➡ Γ = 54 +8.5–7.2 ± 2.5 MeV/c2
- ***Is this a bottomonium version of Y(4260)?***

arXiv:0810.3829

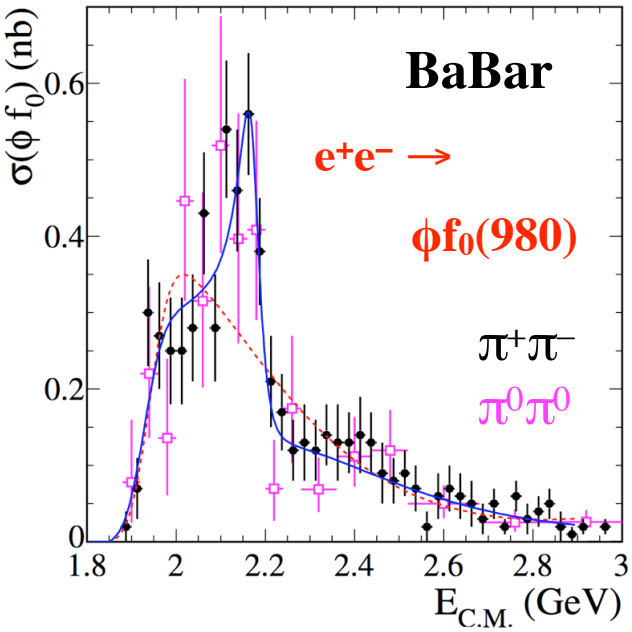


1/4 Discovery of the X, Y, Z States

$Y_s(2175)$?

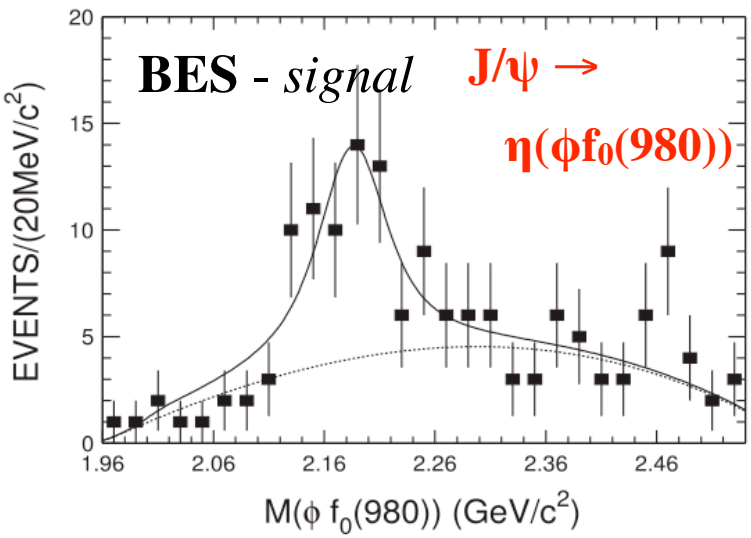
- ***Is there also a strangeonium analogue of the Y(4260)?***
- **BaBar** looked at $e^+e^- \to \phi f_0(980)$ using ISR, where $\phi \to K^+K^-$ and $f_0(980) \to \pi^+\pi^-$ or $\pi^0\pi^0$.
  - ➡ **peak at 2175:**
    - ➡ $M = 2175 \pm 10 \pm 15$ MeV/c^2
    - ➡ $\Gamma = 58 \pm 16 \pm 20$ MeV/c^2

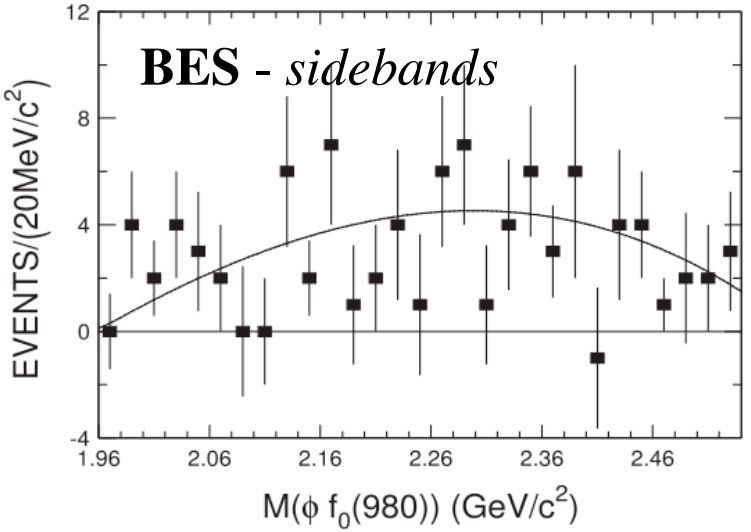
PRD 74, 091103 (2006)



- **BES** also sees this state in $J/\psi \to \eta\phi f_0(980)$
  - ➡ $M = 2175 \pm 10 \pm 15$ MeV/c^2
  - ➡ $\Gamma = 58 \pm 16 \pm 20$ MeV/c^2
- **Belle** also confirms. **(arXiv:0808.0006)**

PRL 100, 102003 (2008)





1/4 Discovery of the X, Y, Z States

- **The Future?**

  ➡ Keep looking for new decay modes of the **X, Y, Z** to help elucidate their nature.

  ➡ **Belle** continues running in the Υ region (ISR, B decays).

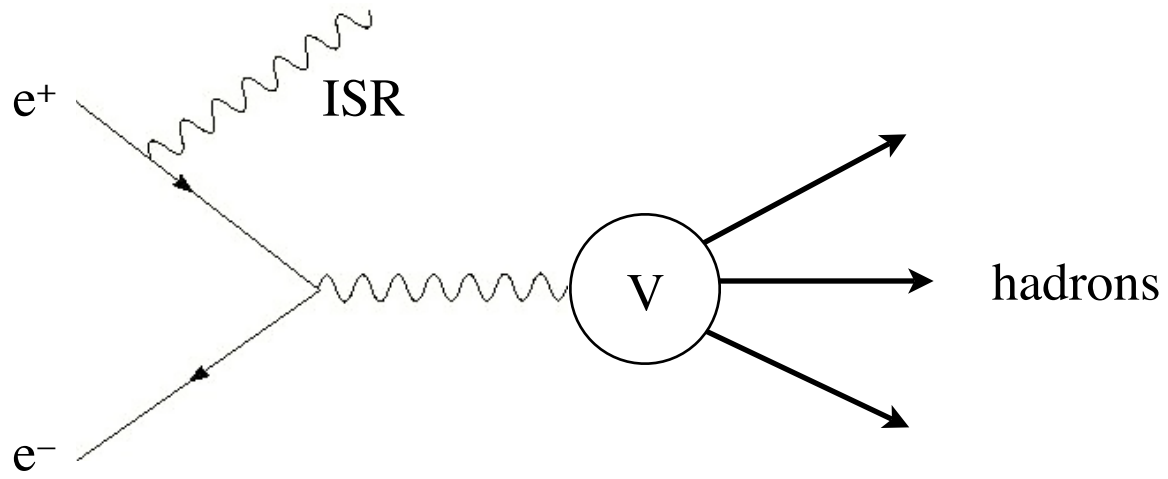
  ➡ **BES III** has the capability to do energy scans in the ψ region.

  ➡ **PANDA** will be well-suited to study any X, Y, Z coupling to pp.

  ➡ **GlueX** could offer insight into the $Y_s(2175)$.

2/4 Light Quark Vectors

- **BaBar** has been using **Initial State Radiation (ISR)** to study $e^+ e^- \rightarrow V$



- One motivation is to provide input for the hadronic contributions to the calculation of $(g\text{-}2)_\mu$.
  - ➡ *Measure R exclusively (!).*

- But **meson spectroscopy** also benefits (e.g., the Y(2175)).

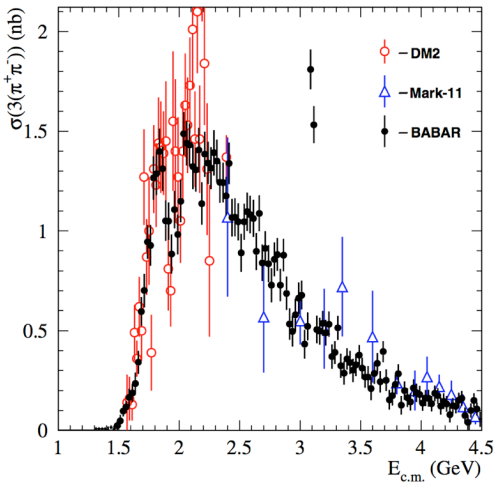
2/4 Light Quark Vectors

A Collection of BaBar $e^+e^- \to V$ Cross Sections

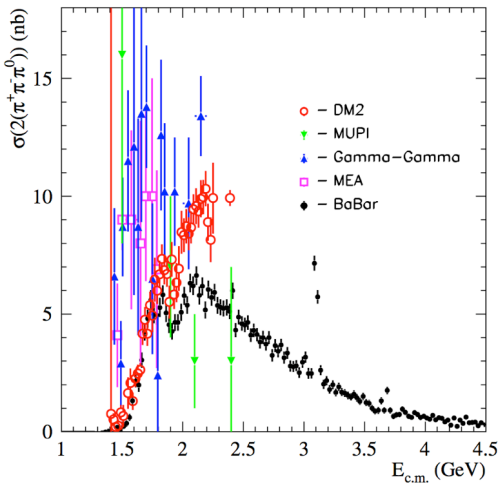
- **BaBar ISR**
- **Older Experiments**

PRD70,072004(2004)
PRD73,052003(2006)
PRD76,012008(2007)
PRD76,092005(2007)
PRD77,092002(2008)

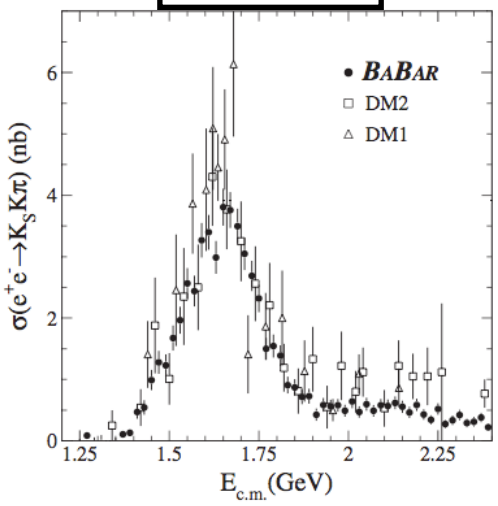
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$



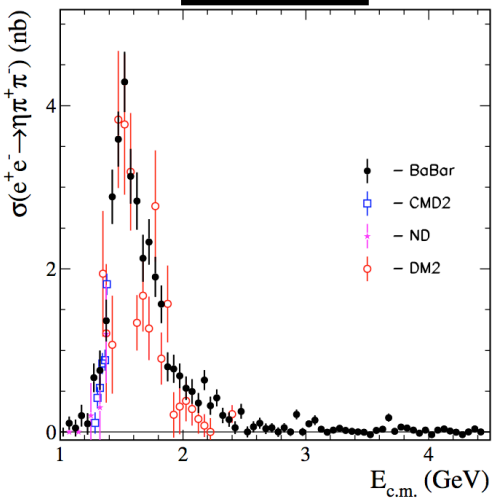
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$



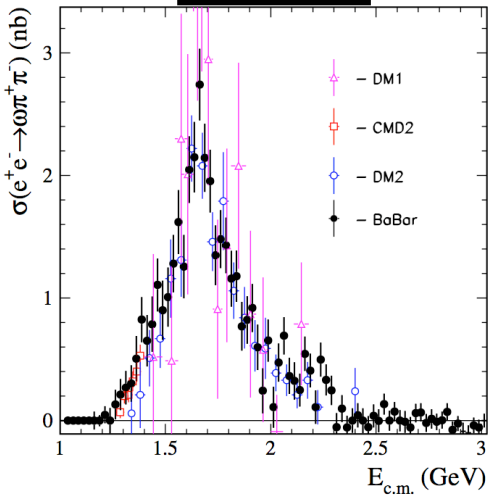
$K_S K^+\pi^-$



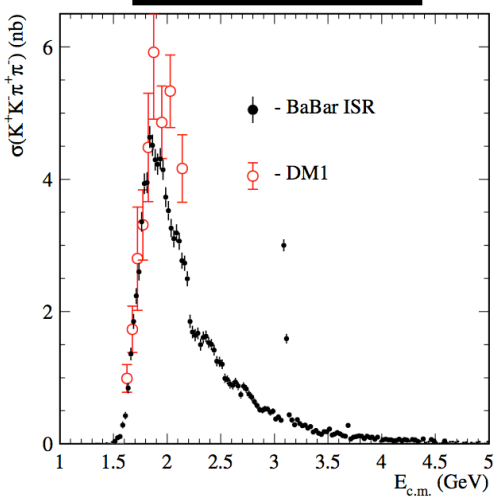
$\eta\pi^+\pi^-$



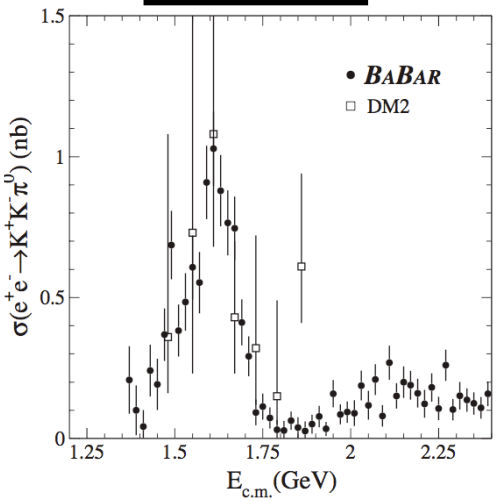
$\omega\pi^+\pi^-$



$K^+K^-\pi^+\pi^-$



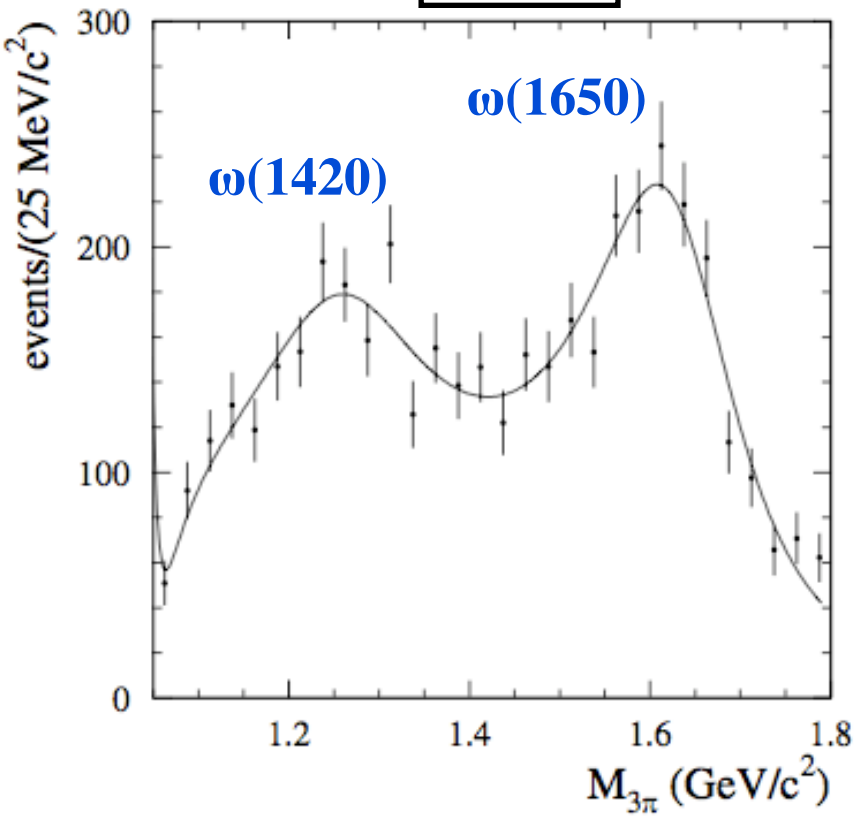
$K^+K^-\pi^0$



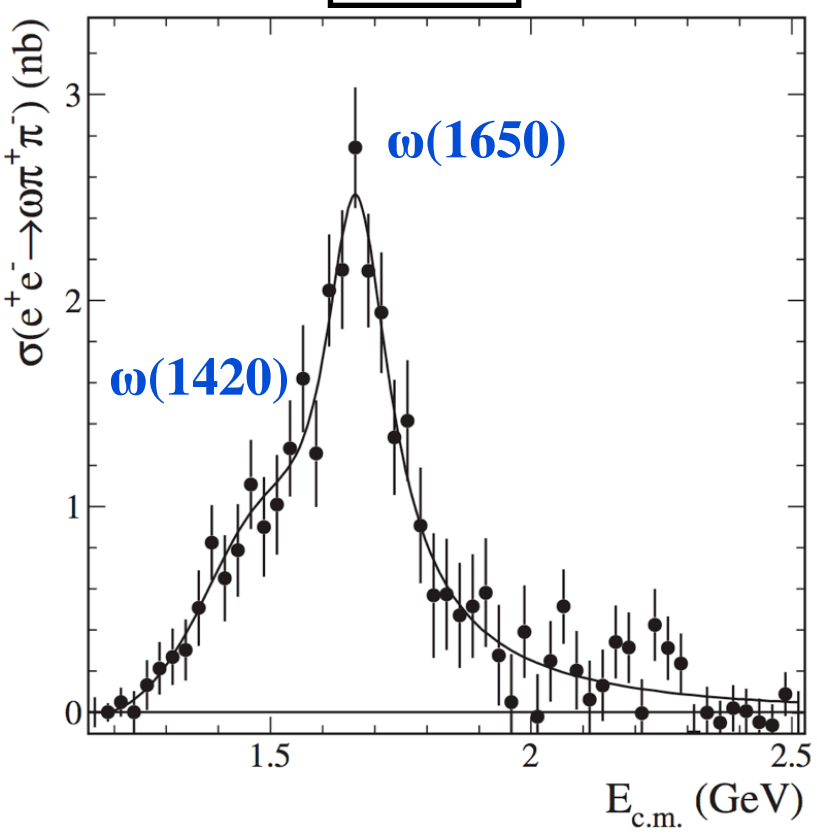
2/4 Light Quark Vectors

Use $e^+e^- \rightarrow V$ to extract properties of vector excitations.

$\pi^+ \pi^+ \pi^0$



$\omega \pi^+ \pi^-$



M(ω(1420)) = 1350 ± 20 ± 20 MeV/c²

M(ω(1650)) = 1660 ± 10 ± 2 MeV/c²

M(ω(1420)) = 1380 ± 20 ± 70 MeV/c²

M(ω(1650)) = 1667 ± 13 ± 6 MeV/c²

Light Quark Vectors

- Also results on:
  - $\phi(1680)$
  - $\varrho(1450)$
  - $\varrho(1700)$
  - the dip in 6π
  - substructure analyses

- **BaBar** continues to analyze more final states.

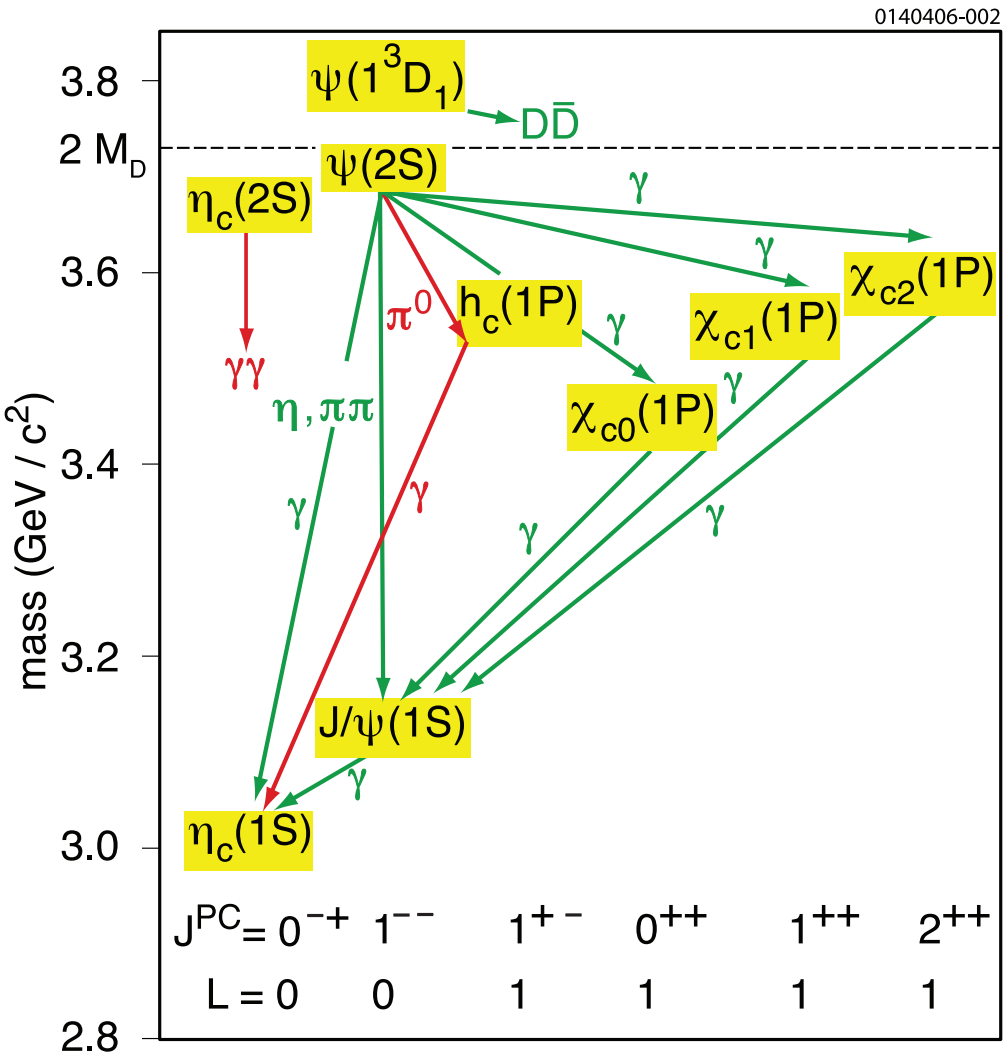
- Vectors will also be produced in **GlueX**.

3/4 High-Statistics Charmonium

- The **charmonium system** provides a laboratory for the study of the strong force.

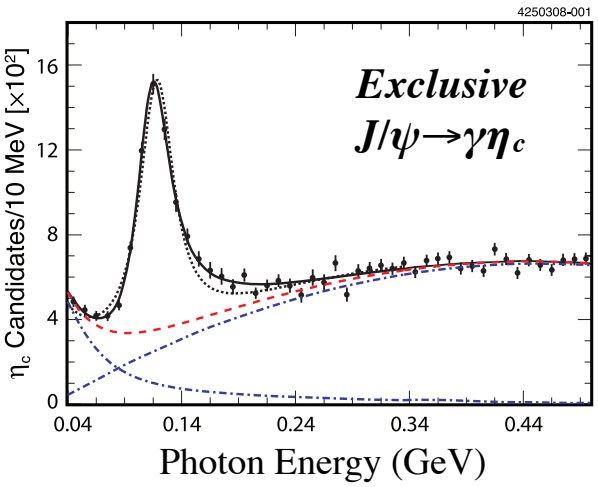
- The experimental situation:
  - Many new results from **CLEO**'s total sample of 27M ψ(2S).
  - **Belle** has new γγ results and **BaBar** has new B decays to charmonium results.
  - We are about to enter a new **BES III** era.

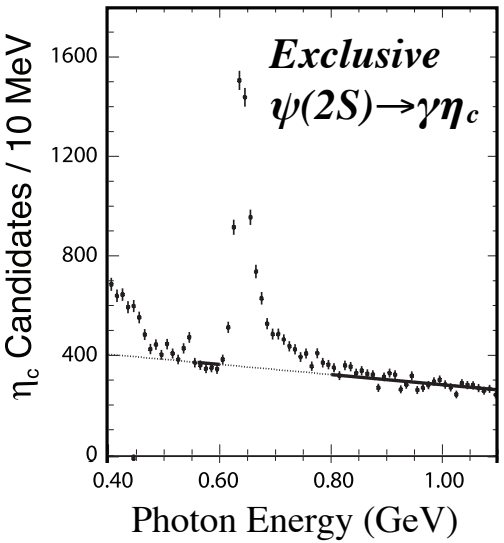
- Recent results in charmonium include:
  - M1 radiative transitions:
    ψ(1S,2S)→γη$_c$(1S) and η$_c$(1S) mass
  - h$_c$ mass
  - J/ψ→γγγ
  - χ$_{cJ}$ decays:
    → γ(ϱ,ω,ϕ), two bodies, γγ, etc.
  - η$_c$(2S) properties
  - etc. etc.



3/4 J/ψ, ψ(2S) → γηc(1S) (CLEO)

CLEO: 24.5M ψ(2S) arXiv:0805.0252[hep-ex] (submitted to PRL)



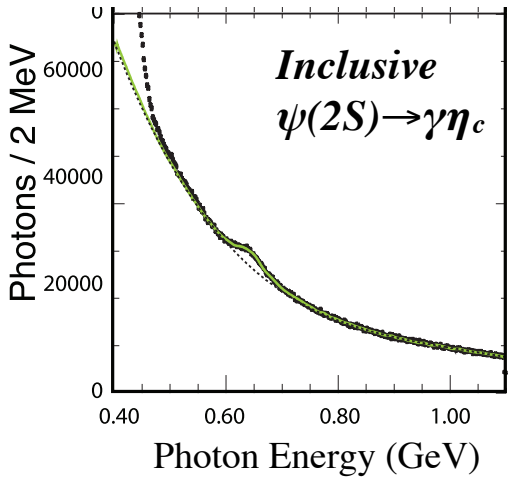


Three Measurements of M1 Transitions:

A. **$B(\psi(2S)\to\gamma\eta_c) = (4.32\pm0.16\pm0.60)\times10^{-3}$** *from inclusive η_c decays.*

B. **$B(J/\psi\to\gamma\eta_c)$ / $B(\psi(2S)\to\gamma\eta_c)$** *using exclusive η_c decays.*

C. **$B(J/\psi\to\gamma\eta_c) = (1.98\pm0.09\pm0.30)\%$** *taking A×B.*



$\times$ $=$ $B(J/\psi\to\gamma\eta_c)$

- One "surprise" was the non-trivial line-shape of the η_c.
- Recent Lattice QCD Results **(Dudek et al, PRD73,07450(2006))** predict $\Gamma_{\gamma\eta c}$ = (2.0±0.1±0.4) keV

$\Rightarrow$ **$B(J/\psi\to\gamma\eta_c) = (2.1\pm0.1\pm0.4)\%$**

The experimental value of $B(J/\psi\to\gamma\eta_c)$ is now in line with theoretical expectations.

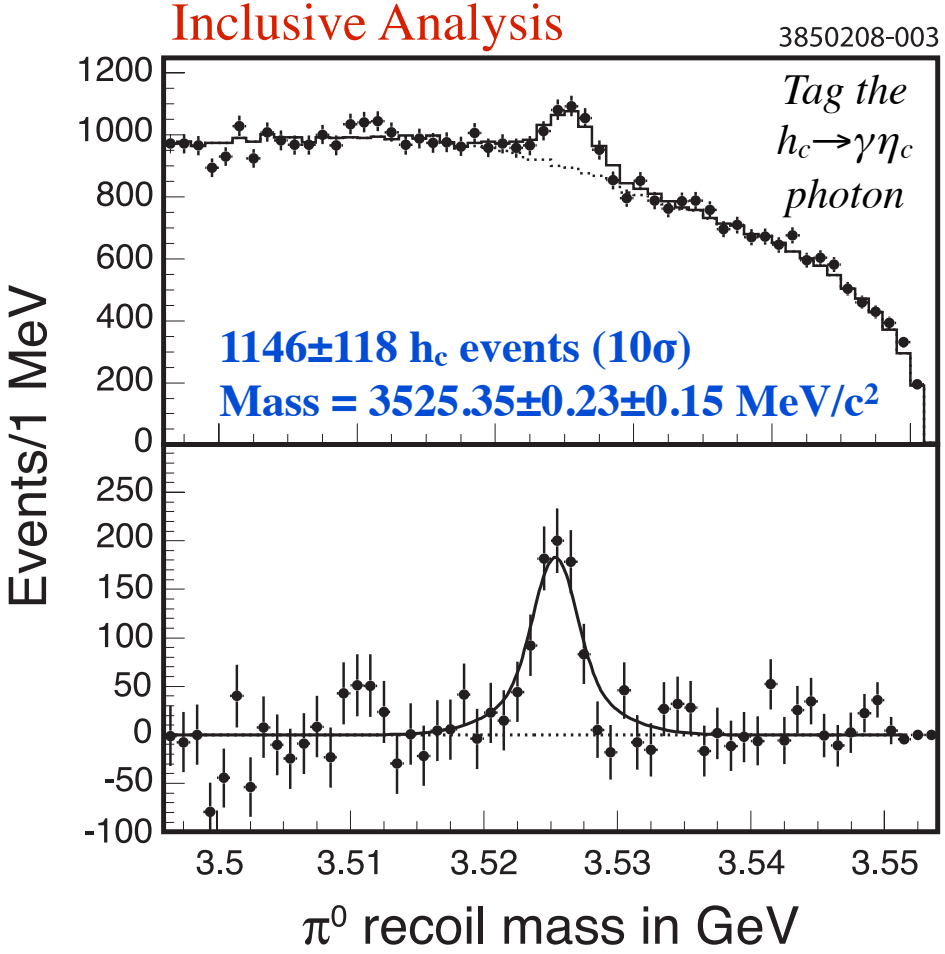
3/4 The $h_c(1P)$ Mass (CLEO)

CLEO 24.5M ψ(2S) arXiv:0805.4599 [hep-ex] (accepted by PRL)

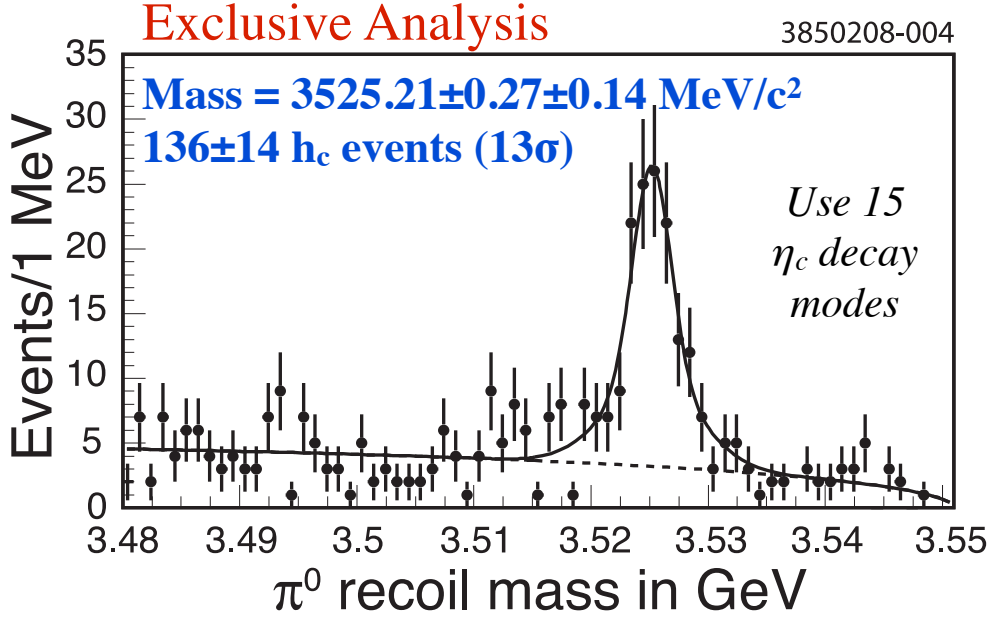
$$\psi(2S) \rightarrow \pi^0 h_c(1P);\ h_c(1P) \rightarrow \gamma\eta_c$$

(factor of 9 more data than previous measurement)

Inclusive Analysis



Exclusive Analysis



Combined Mass = 3525.28±0.19±0.12 MeV/c²

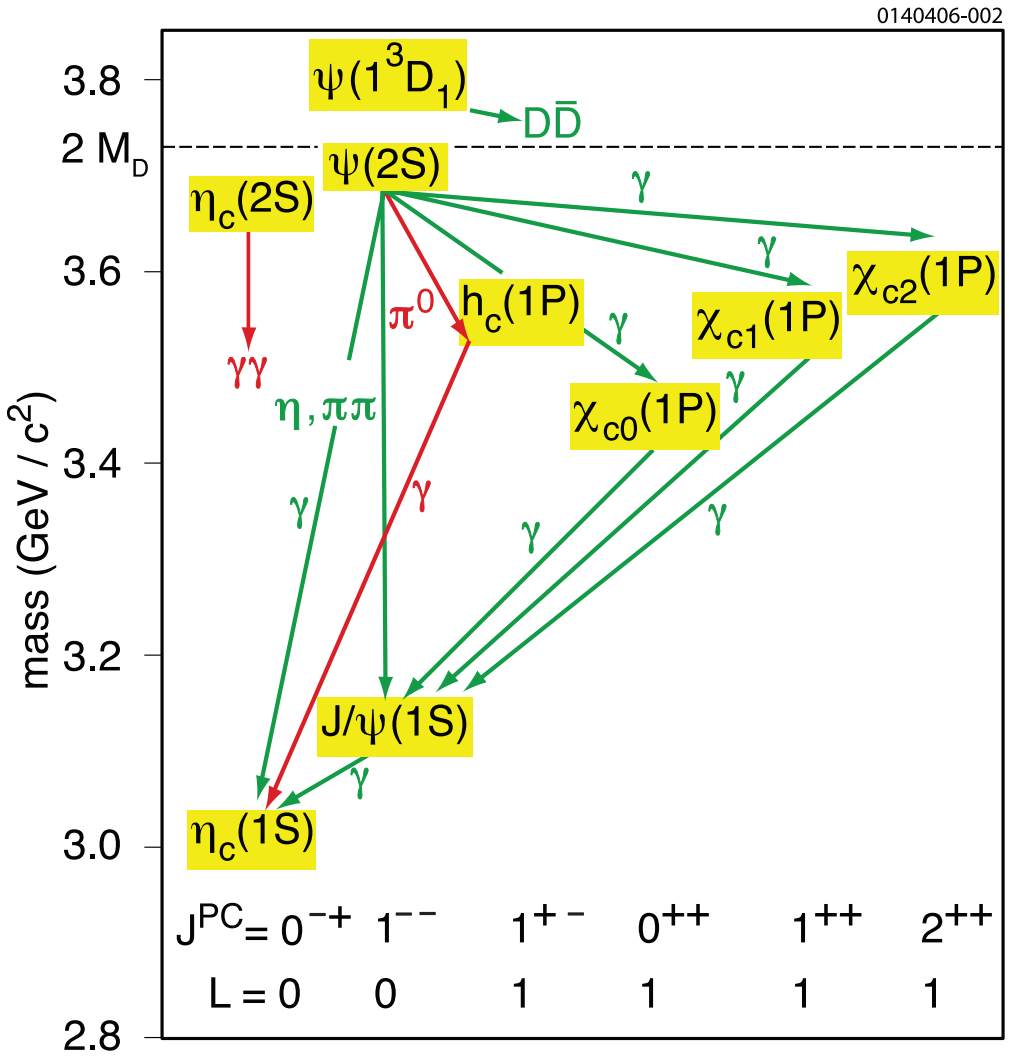
Compare to:

$\langle M(\chi_{cJ}(1P))\rangle = (3525.30 \pm 0.11)$ MeV/c² (PDG)

⇒ ***Hyperfine splitting of 1P states is small (or 0)***.

3/4 High-Statistics Charmonium

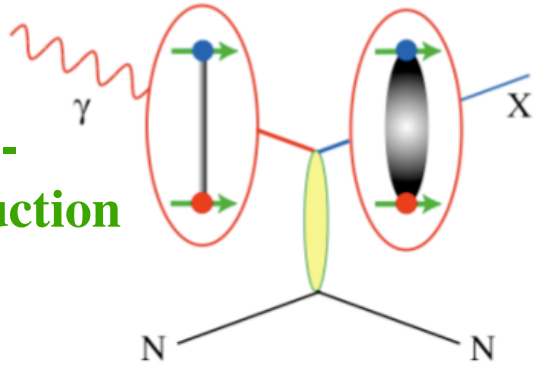
- This work will continue at **BES III**.
- Also expect precision studies from **PANDA**, **Belle**, and the **LHC (?)**.
- Charmonium decays also offer opportunities to do light quark specroscopy.
  - ➡ *Pick your quantum numbers.*



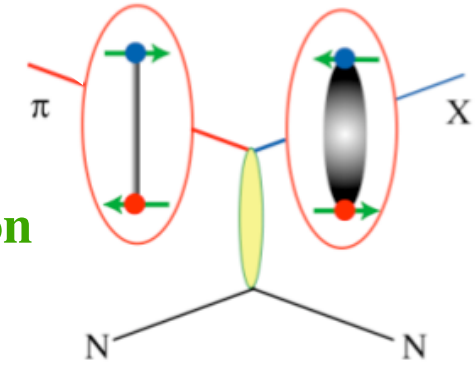
4/4 Light Quark Hybrid Mesons

- The observation of a meson with **exotic J^{PC}** would be a **"smoking gun"** for a meson beyond the quark model.
- The lightest exotic hybrid meson is *expected* to...
  - ... have $J^{PC} = 1^{-+}$ (called π_1)
  - ... decay through an S-wave to final states like $b_1\pi$ and $f_1\pi$
  - ... be produced most readily in photoproduction

photo-production



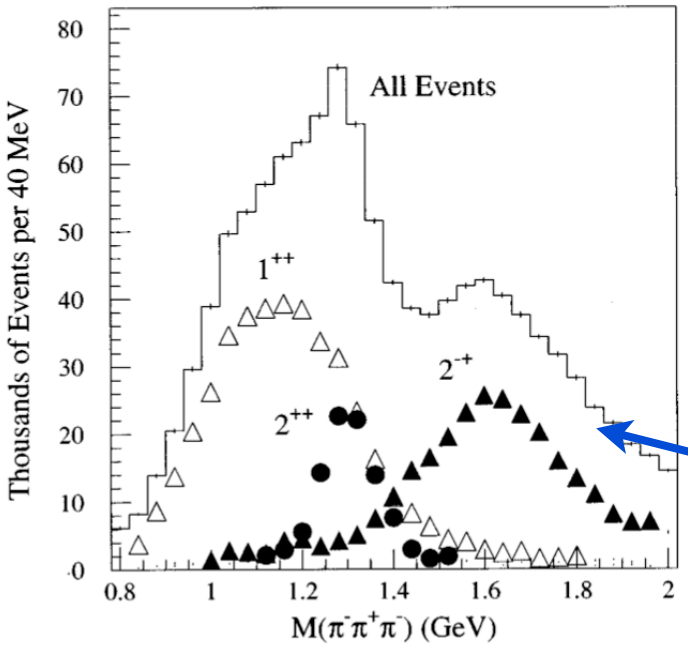
pion-production



- Most data to date has come from experiments with pion beams. *(For example, E852 at Brookhaven used $\pi^- p \rightarrow Xp$ at 18 GeV/c.)*
- One hybrid candidate that has received a lot of attention is the **$\pi_1(1600) \rightarrow \varrho\pi$...**

4/4 Light Quark Hybrid Mesons

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



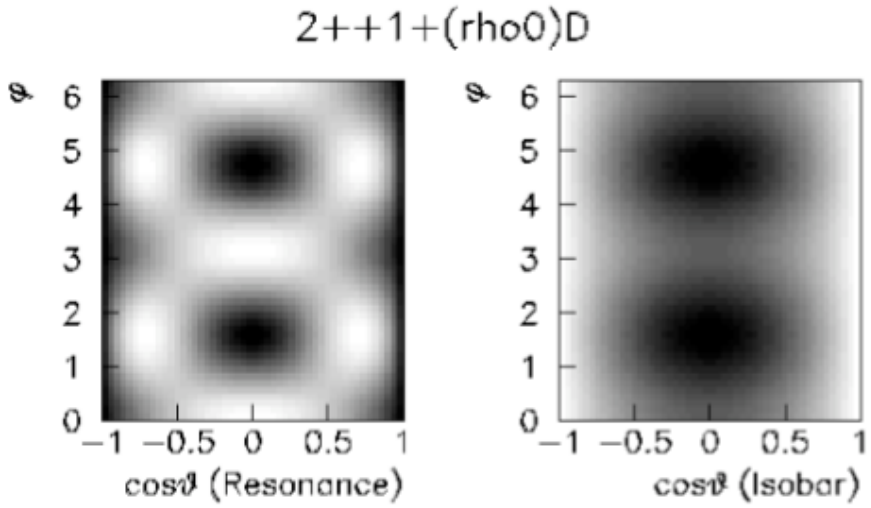
Partial Wave Analysis Method:

➡ In every bin of 3π mass, fit for the (complex) sizes of different J^{PC} amplitudes using all available event kinematics.

Dominant resonances are remarkably stable.

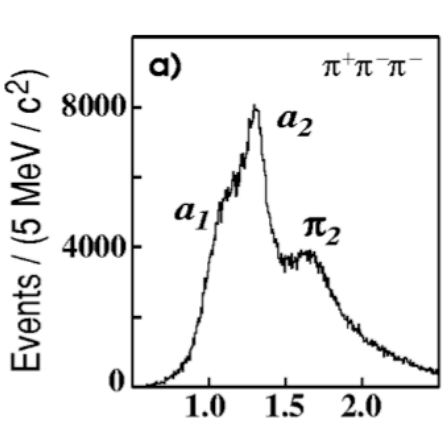
$$I(\Omega) = \sum_{\alpha} \left| \sum_{\beta} V_{\alpha,\beta} A_{\alpha,\beta}(\Omega) \right|^2$$

A(Ω) = Resonance Angles
× Isobar Angles
× Isobar Breit Wigner

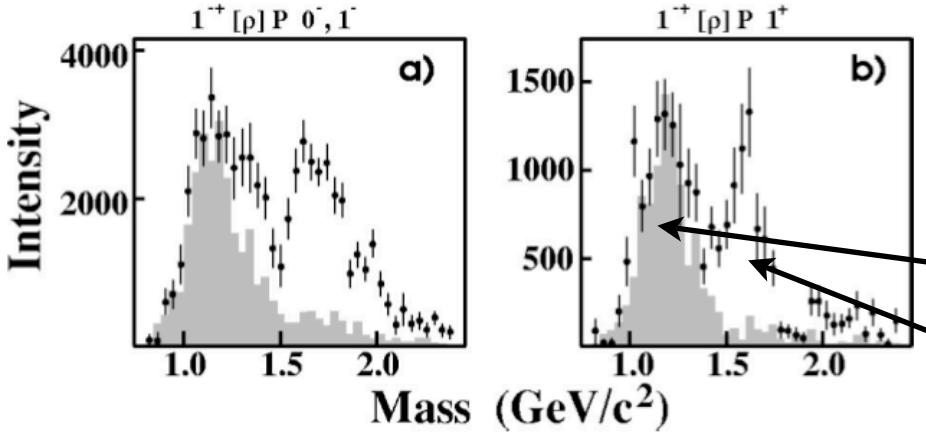


4/4 Light Quark Hybrid Mesons

TOTAL



EXOTIC WAVE



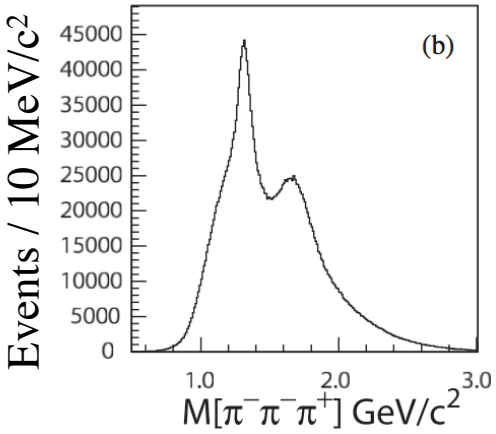
E852 1994 data
(PRD65,072001(2002))

250k $\pi^+\pi^-\pi^-$

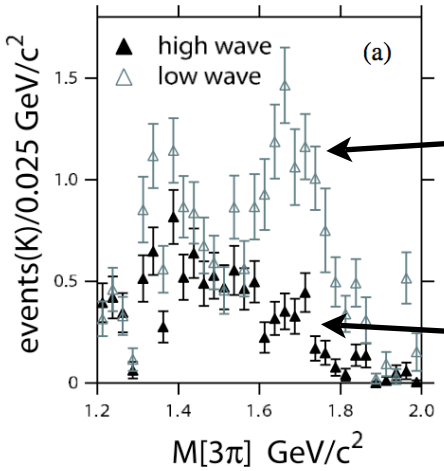
"leakage" from a_1

$\pi_1(1600)$ candidate

TOTAL



EXOTIC WAVE



original set of amplitudes

including additional $\pi_2(1670)$ amplitudes

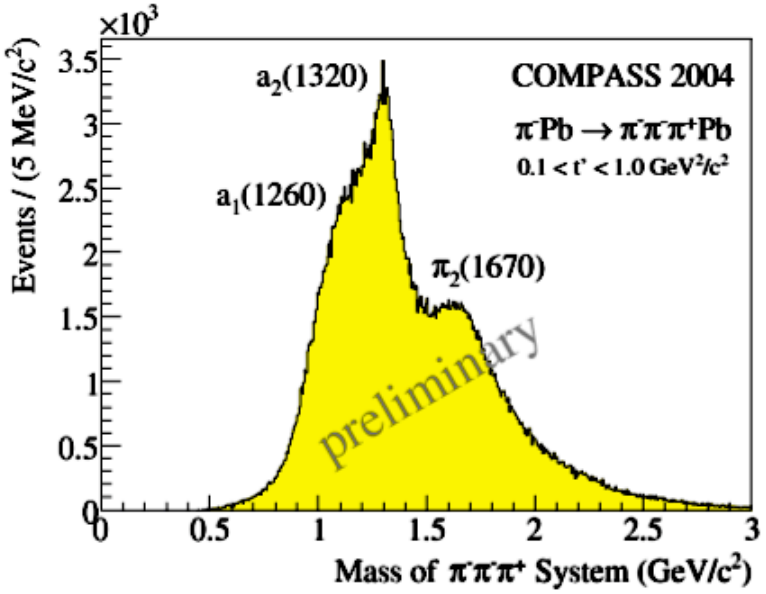
E852 1995 data
(PRD73,072001(2006))

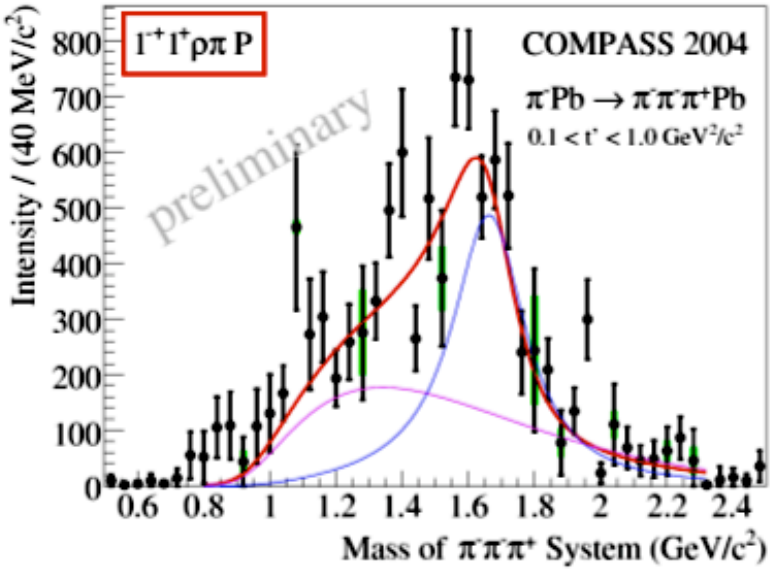
2.6M $\pi^+\pi^-\pi^-$
3.0M $\pi^-\pi^0\pi^0$

(gives a consistent picture)

The exotic wave is sensitive to the number of amplitudes in the fit…

4/4 Light Quark Hybrid Mesons



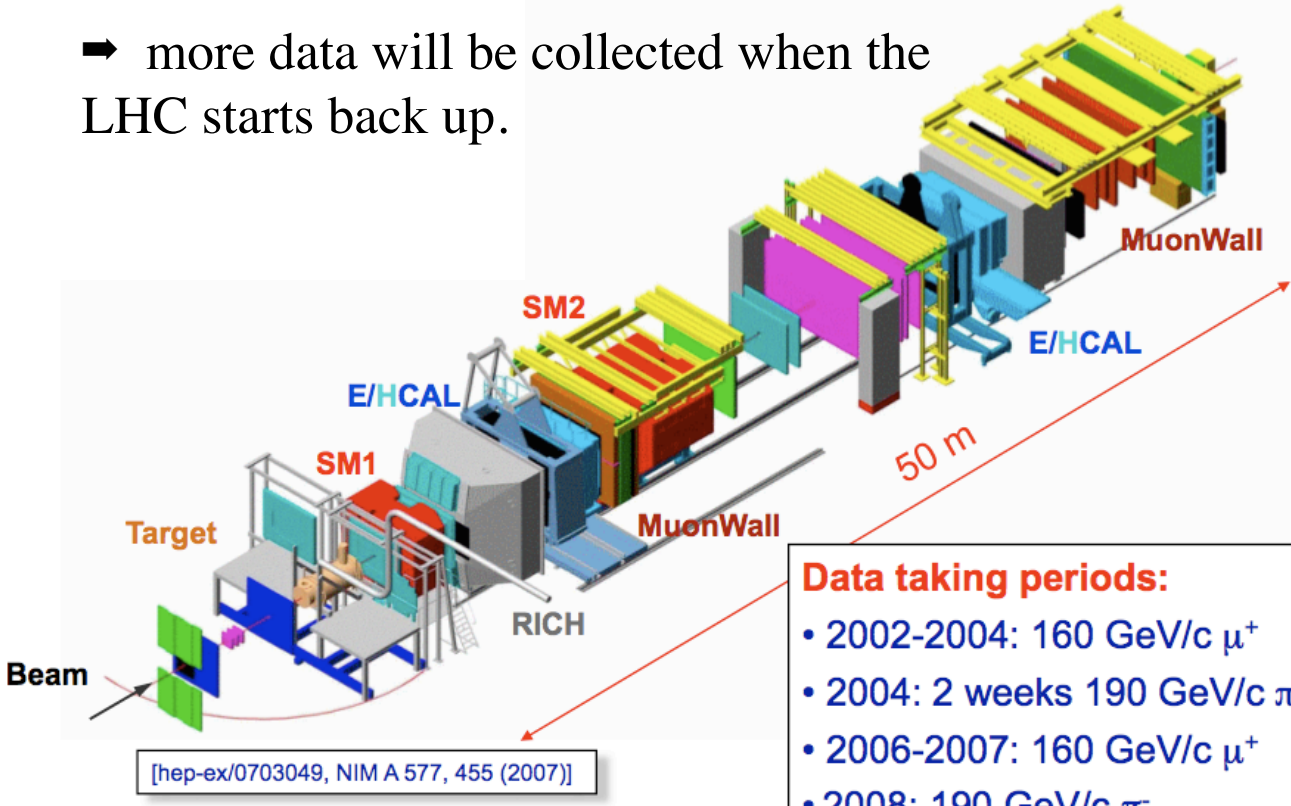


COMPASS at CERN

➡ 450k events of π^-Pb → $\pi^+\pi^-\pi^-$Pb at 190 GeV/c collected in 3 days (!) in 2004.

➡ qualitative features of the exotic wave are reproducible but the interpretation is still unclear.

➡ more data will be collected when the LHC starts back up.

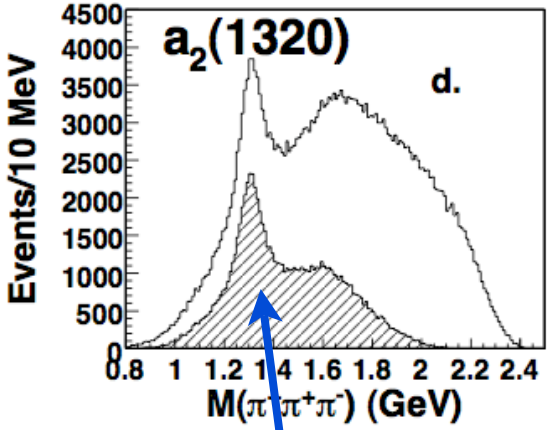


Data taking periods:
- 2002-2004: 160 GeV/c μ^+
- 2004: 2 weeks 190 GeV/c π^-
- 2006-2007: 160 GeV/c μ^+
- 2008: 190 GeV/c π^-

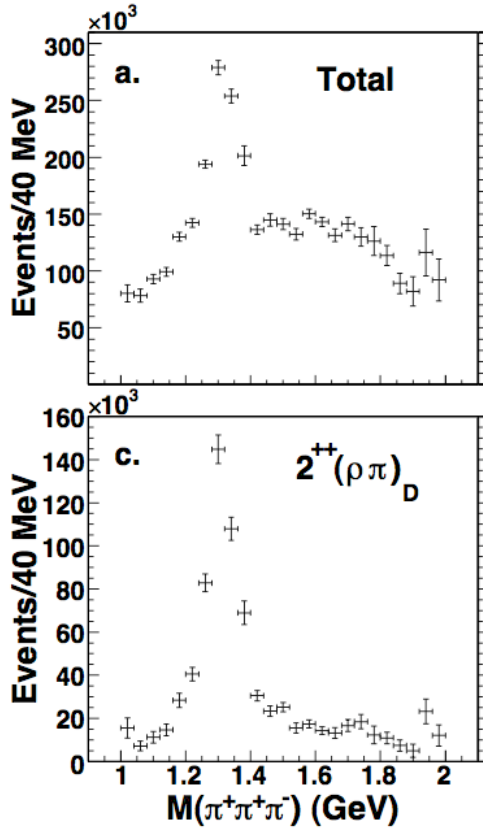
4/4 Light Quark Hybrid Mesons

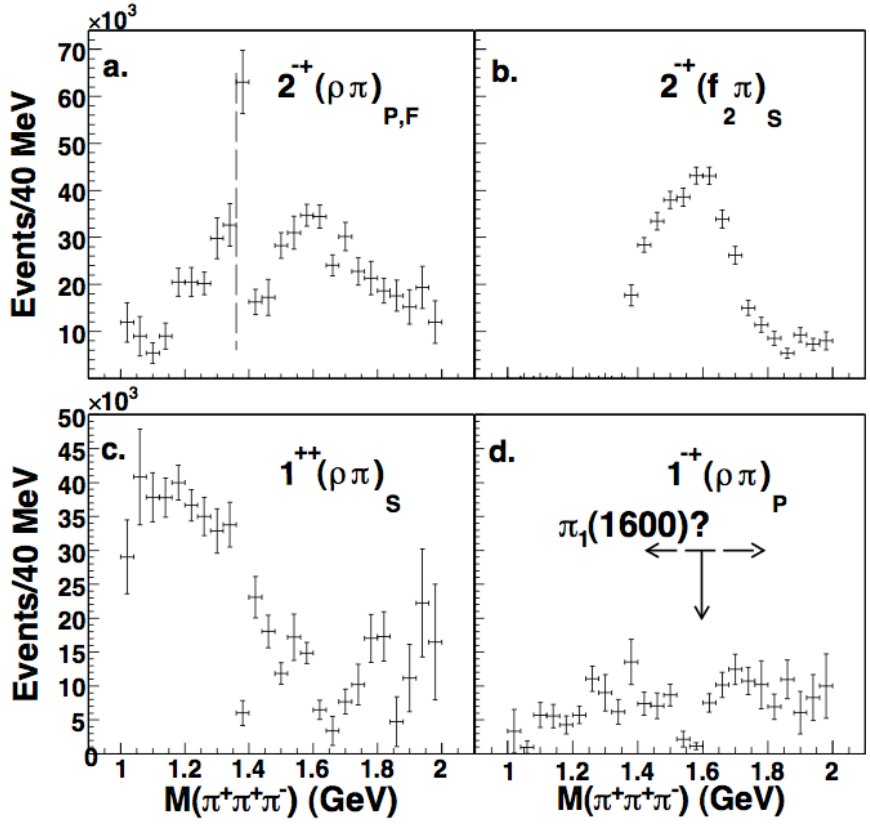
New Preliminary Results from CLAS (arXiv:0805.4438)

$\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$ at ~5 GeV



Raw 3π mass after selection





$\sigma(\gamma p \rightarrow \pi_1(1600)n;\ \pi_1(1600) \rightarrow \varrho\pi)\ /\ \sigma(\gamma p \rightarrow a_2(1320)n;\ a_2(1320) \rightarrow \varrho\pi) < 2\%.$

But the 1^{-+} hybrid meson is supposed to be enhanced in photoproduction...

4/4 Light Quark Hybrid Mesons

- The status of the **$\pi_1(1600) \rightarrow \varrho\pi$** remains in flux:
  - **COMPASS** is picking up the thread in pion production where E852 left off.
  - **CLAS** is giving us a first glance at photoproduction.
- New voices are joining in the dialogue:
  - Is the **Y(2170)** a viable (non-exotic J^{PC}) light quark hybrid candidate?
- We can look forward to:
  - Searches for hybrid production in charmonium decays from **BES III**.
  - Possible associated production ($pp \rightarrow (\pi,\eta,\omega,\text{etc.})X$) of hybrid mesons at **PANDA**?
  - High-energy and polarized photoproduction at **GlueX**.

Summary

- **The field of meson spectroscopy is vibrant.**
- Recent highlights include:
  1. The discovery of the **X, Y, Z states**.
  2. High-statistics studies of $e^+e^- \rightarrow$ **light quark vectors**.
  3. Precision measurements in **charmonium**.
  4. New dialogues on **light quark hybrid mesons**.

not covered but also new and interesting:

5. the η_b discovery,

6. D_{SJ} states,

7. D and D_S decay constants,

8. the glueball picture

- Interactions with **lattice QCD** are important for precision tests, but also for our qualitative understanding of mesons and in the justification of models.
- The future is with, among others, **BES III**, **PANDA**, and **GlueX**.