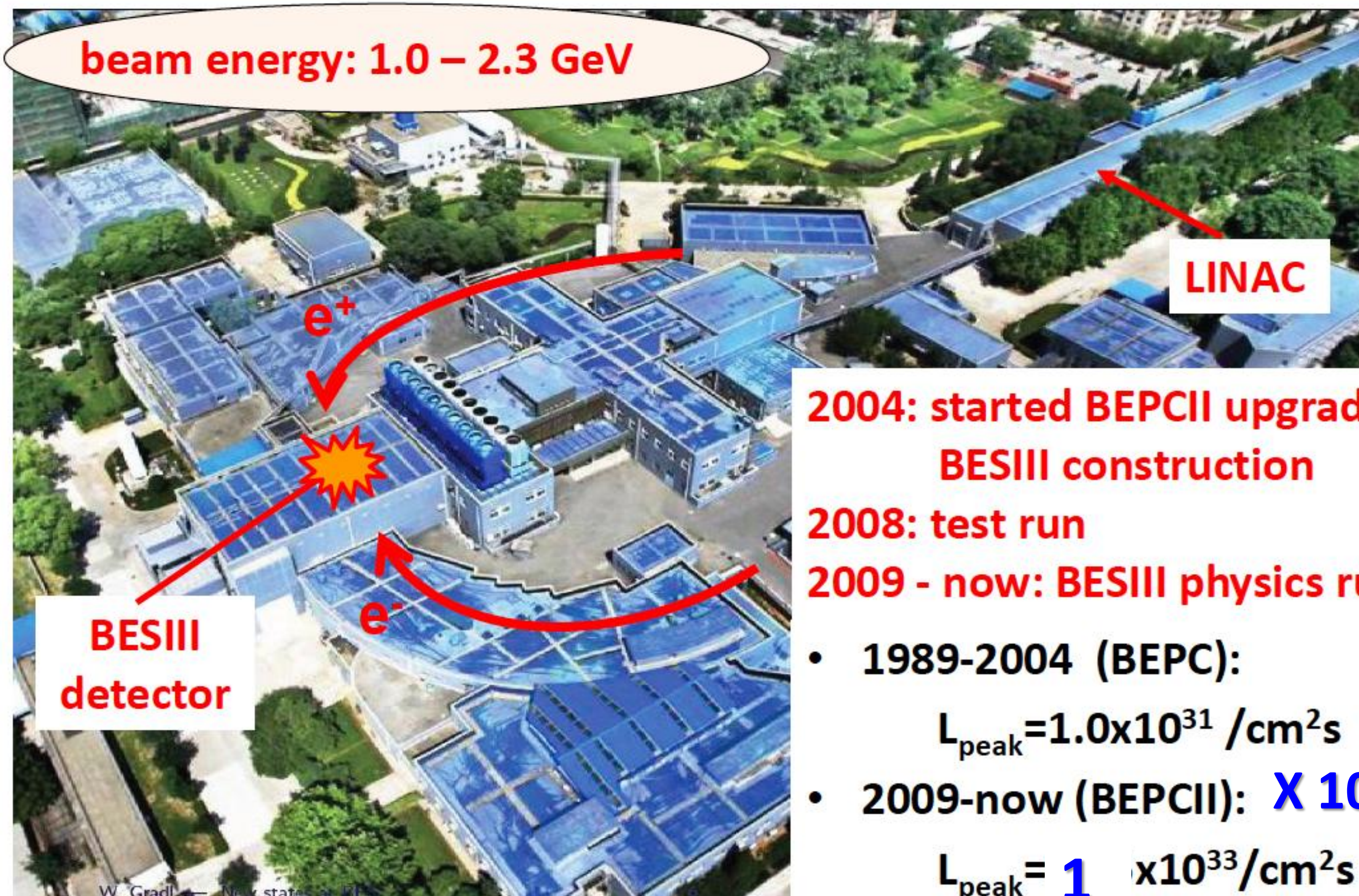
Recent results on light hadrons from BESIII

LIU Beijiang
Institute of High Energy Physics, Beijing

Outline

- Introduction
- Selected results from BESIII
  - Light meson spectroscopy
  - Light baryon spectroscopy
  - Light meson decays
- Summary

Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade, BESIII construction

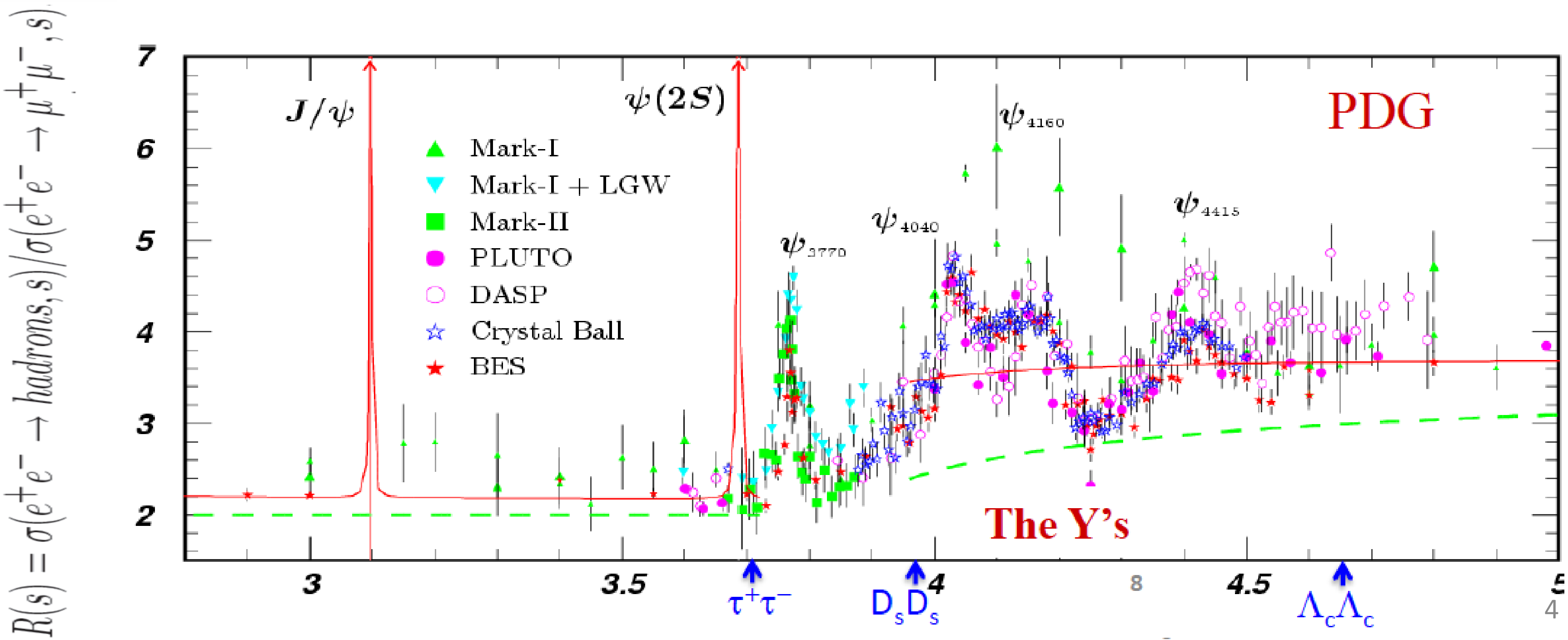
2008: test run

2009 - now: BESIII physics run

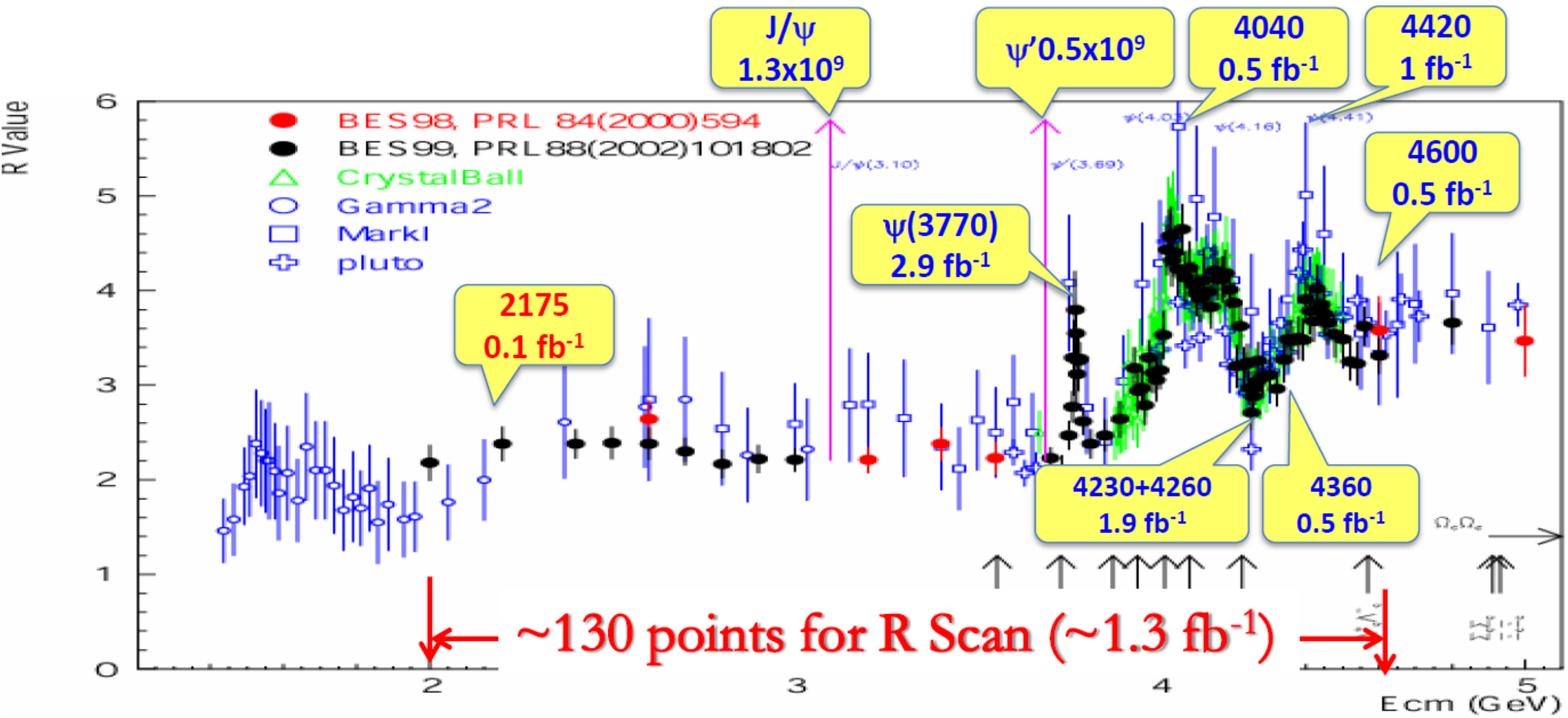
- 1989-2004 (BEPC): L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII): X 100 L_{peak}= 1 x10^{33}/cm^{2}s

Features of the BEPC Energy Region

- Rich of resonances: charmonia and charmed mesons
- Threshold characteristics (pairs of τ, D, D_s, …)
- Transition between smooth and resonances, perturbative and non-perturbative QCD
- Energy location of the gluonic excitations and multi-quark states

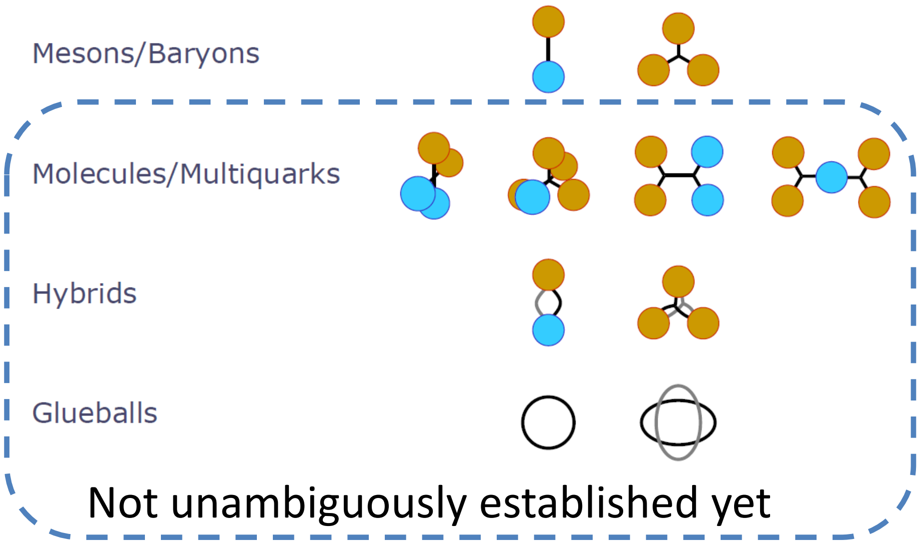


BESIII data samples



World largest J/ψ, ψ(2S), ψ(3770), Y(4260), … produced directly from e^+e^- collision

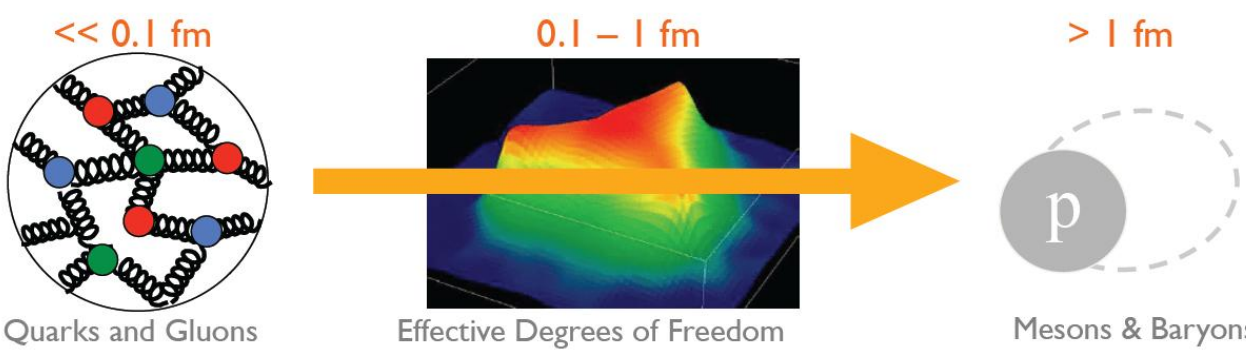
Hadron spectrum



Continuous efforts in experiment and theory

- Hadron spectroscopy is a key tool to investigate QCD

- testing QCD in the confinement regime
- providing insights into the fundamental degrees of freedom



From V. Crede

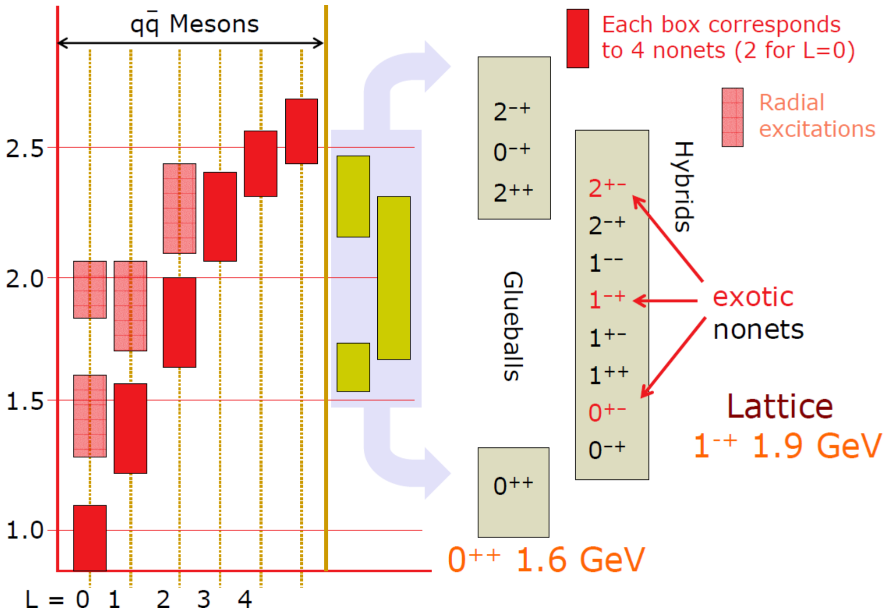
Light meson spectroscopy

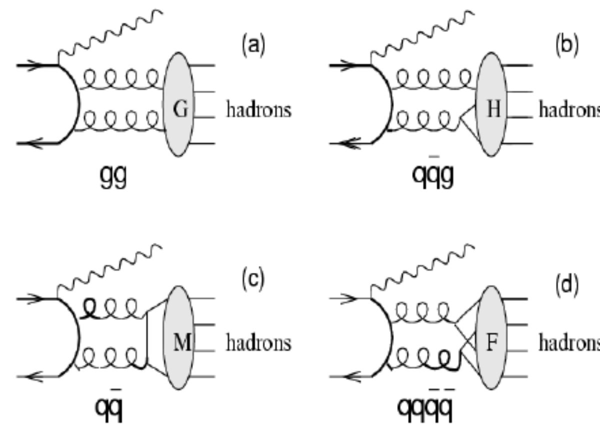
- **X(ppbar) and X(1835)**

- **$\eta(1405)$**
- **PWA of J/ψ→γ ϕϕ**
- **PWA of J/ψ→γ η η**
- **MIPWA of $J/\psi \to \gamma\pi^0\pi^0$**

- **PWA of $\chi_{c1} \to \eta\pi^+\pi^-$**

Charmonium decays provides an ideal hunting ground for light glueballs and hybrids





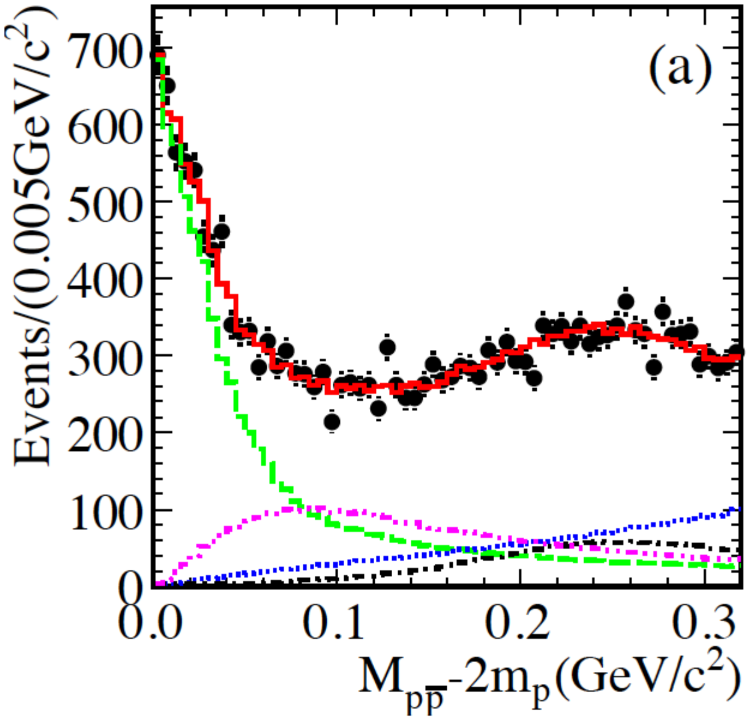
$$\Gamma(J/\psi \to \gamma G) \sim O(\alpha\alpha_s^2), \Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3),$$

$$\Gamma(J/\psi \to \gamma M) \sim O(\alpha\alpha_s^4), \Gamma(J/\psi \to \gamma F) \sim O(\alpha\alpha_s^4)$$

- **"Gluon-rich" process**
- **Clean high statistics data samples from e^+e^- production**
- **I(J^{PC}) filter in strong decays of charmonium**

PWA of $J/\psi \to \gamma p\bar{p}$

Phys. Rev. Lett. 108, 112003 (2012)



- The fit with a BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ mass threshold structure.
- It is much better than that without FSI effect ($\Delta 2\ln L = 5, 7.1\sigma$)
- Different FSI models → Model dependent uncertainty

$$R = \frac{B(\psi' \to \gamma X(p\bar{p}))}{B(J/\psi \to \gamma X(p\bar{p}))} = (5.08^{+0.71}_{-0.45}(stat)^{+0.67}_{-3.58}(syst) \pm 0.12(mod))\%$$

Spin parity, mass, width and branching ratio:

$J^{PC} = 0^{-+}, > 6.8\sigma\ better\ than\ other\ J^{PC} assignments,$

$M = 1832^{+19}_{-5}(stat)^{+18}_{-17}(sys) \pm 19(model) MeV/c^2,$

$\Gamma = 13 \pm 39(stat)^{+10}_{-13}(sys) \pm 4(model) MeV/c^2, \quad \Gamma < 76\ MeV/c^2\ (90\%\ CL),$

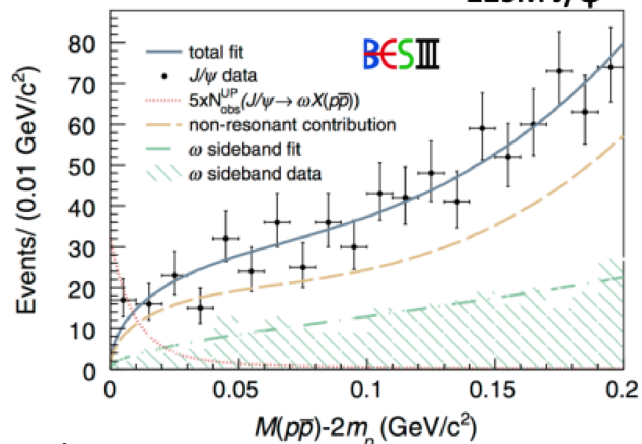
$B(J/\psi \to \gamma X) B(X \to p\bar{p}) = \left(9.0^{+0.4}_{-1.1}(stat)^{+1.5}_{-5.0}(sys) \pm 2.3(model)\right) * 10^{-5}$

In J/ψ hadronic decays

Study of $J/\psi \to \omega p\bar{p}$ and $J/\psi \to \Phi p\bar{p}$ may shed further light on the nature of $X(p\bar{p})$

BESIII, Phys. Rev. D87, 112004 (2013)

225M J/ψ

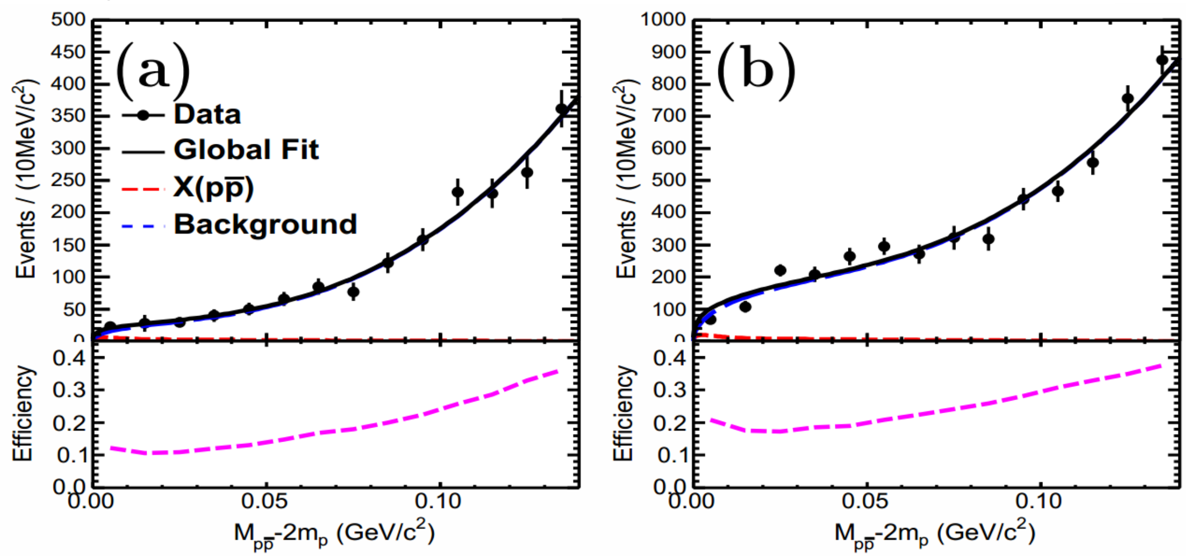


$J/\psi \to \omega p\bar{p}$

$B(J/\psi \to \omega X(p\bar{p}) \to \omega p\bar{p})$
$< 3.7\times10^{-6}$ (95% CL)

>10x suppressed compared to $J/\psi \to \gamma X(p\bar{p}) \to \gamma p\bar{p}$

BESIII Phys. Rev. D 93, 052010 (2016)



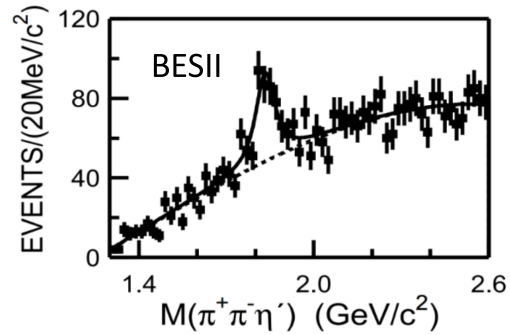
$J/\psi \to \Phi p\bar{p}$

$B(J/\psi \to \Phi X(p\bar{p}) \to \Phi p\bar{p})$
$< 2\times10^{-7}$ (90% CL)

>100x suppressed compared to $J/\psi \to \gamma X(p\bar{p}) \to \gamma p\bar{p}$

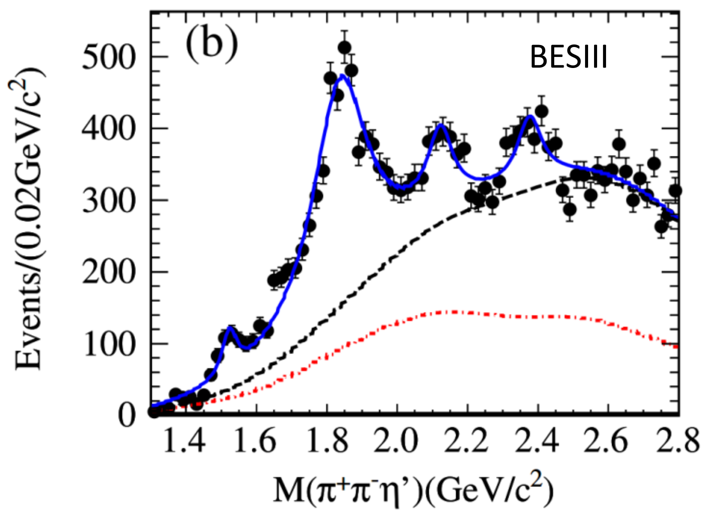
X(1835)

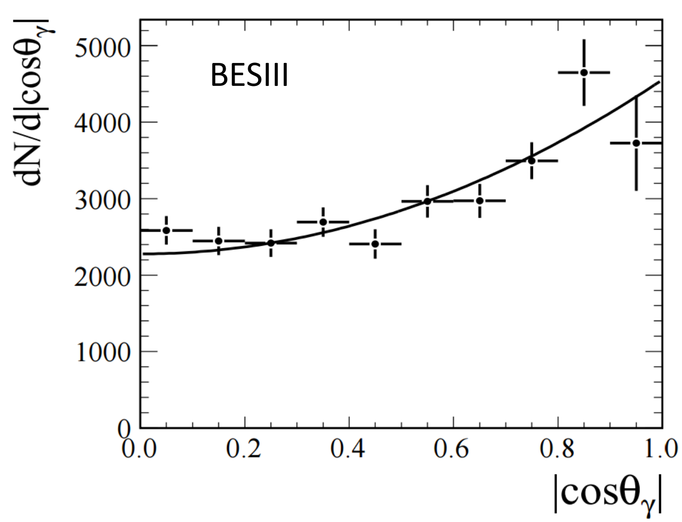
Phys. Rev. Lett. 95, 262001 (2005)



- **Discovered by BESII in J/ψ→γη′$\pi^+\pi^-$**
- **Confirmed by BESIII in J/ψ→γη′$\pi^+\pi^-$**
  - ✓ $M = 1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/c^2
  - ✓ $\Gamma = 190 \pm 9^{+38}_{-36}$ MeV/c^2
  - ✓ **Angular distribution is consistent with 0^-**

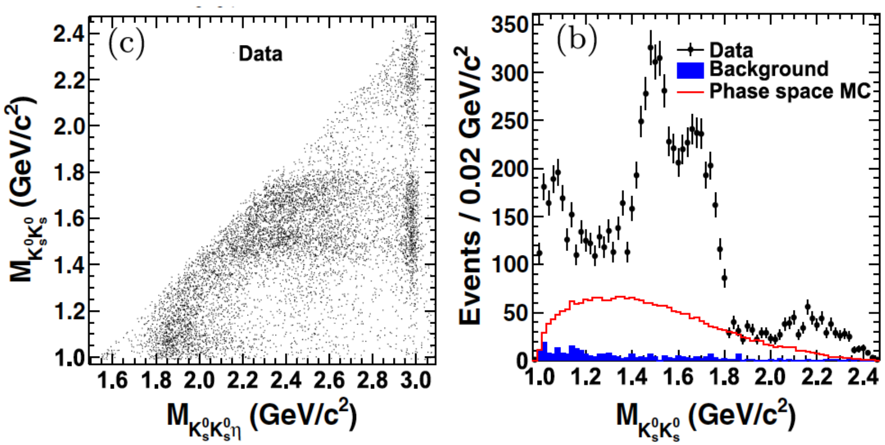
Phys. Rev. Lett. 106, 072002 (2011)



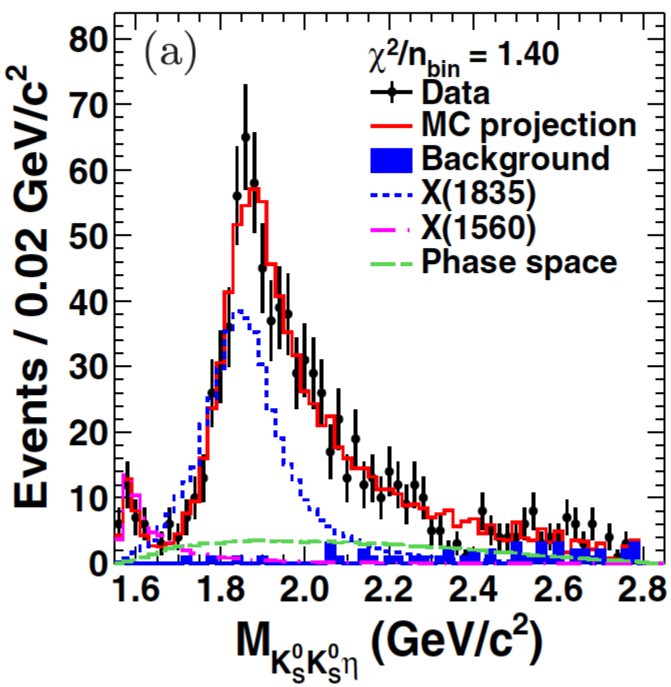


Observation and Spin-Parity Determination of the $X(1835)$ in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

Phys.Rev.Lett. 115 091803(2015)



The structure around 1.85 GeV/c² in the $K_S K_S \eta$ mass spectrum is strongly correlated to $f_0(980)$



Partial Wave Analysis for $M(K_S K_S)$<1.1 GeV/c²

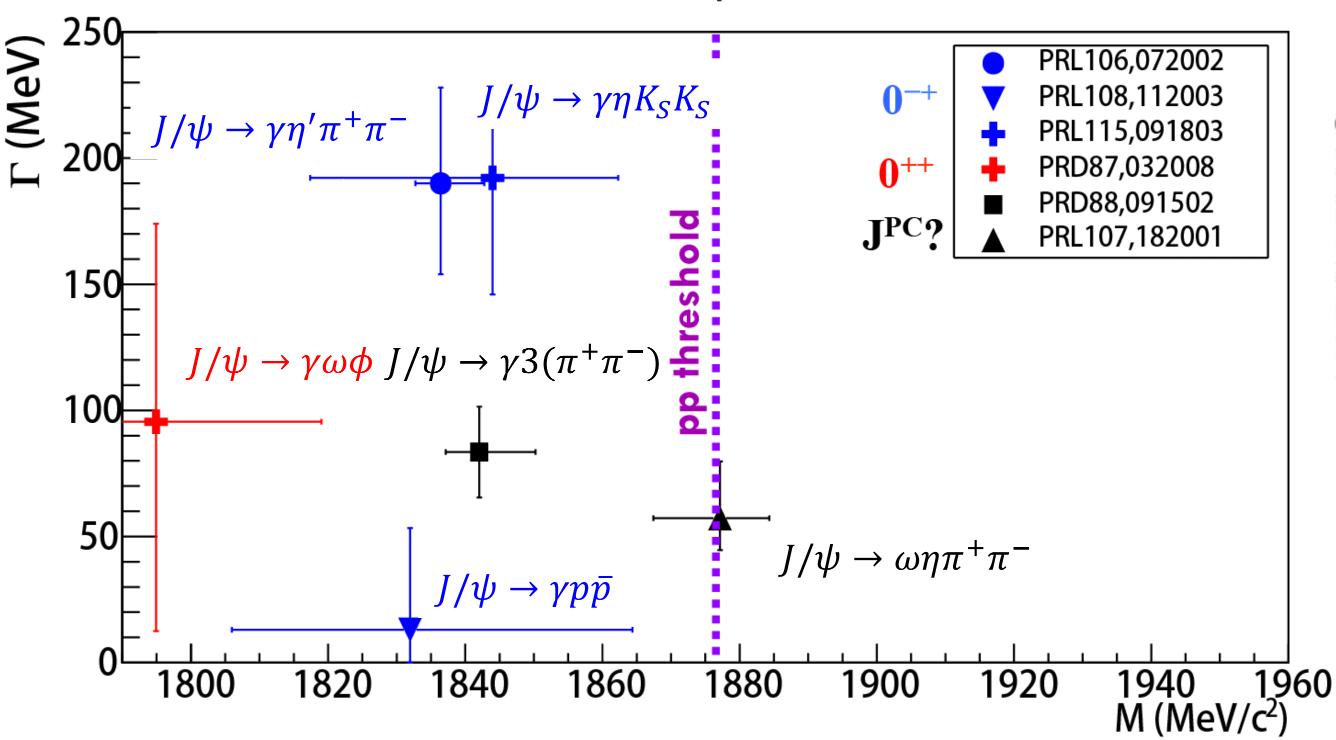
- **X(1835)→$K_S K_S \eta$ (the $K_S K_S$ system is dominantly produced through the $f_0(980)$)**

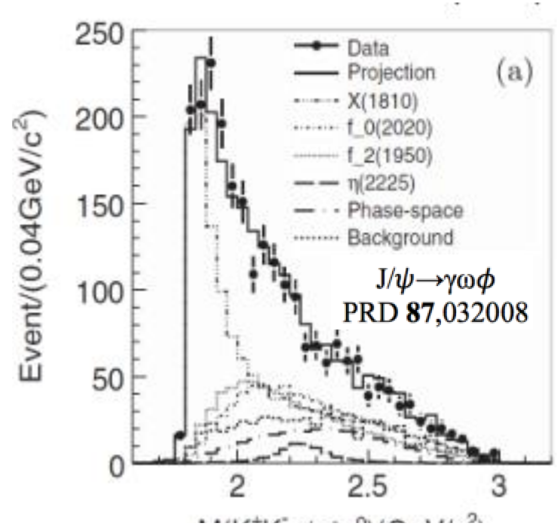
  $J^{PC}=0^{-+}$, (> 12.9 σ)

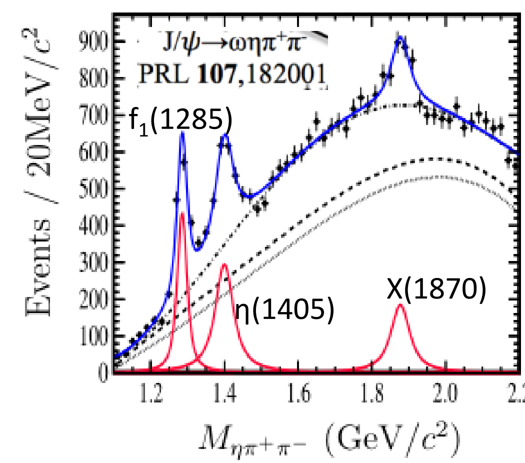
M=1844$\pm$9(stat)$^{+16}_{-25}$(syst) MeV/c², $\Gamma=192^{+20}_{-17}{}^{+62}_{-43}$ MeV,
Consistent with X(1835) observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$
$B(J/\psi\to\gamma X(1835))*B(X(1835)\to K_s K_s \eta)=(3.31^{+0.33}_{-0.30}{}^{+1.96}_{-1.29})*10^{-5}$

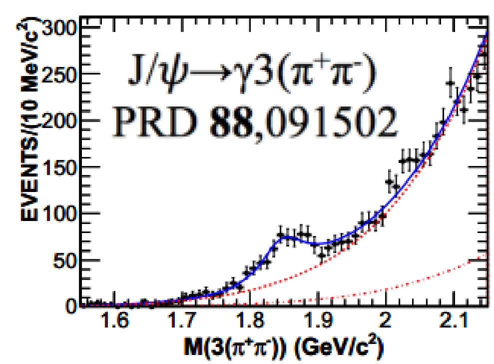
- **X(1560) → $f_0(980)\eta$: $J^{PC}=0^{-+}$, (> 8.9 σ)**

M=1565$\pm$8$^{+0}_{-63}$ MeV/c², $\Gamma=45^{+14}_{-13}{}^{+21}_{-28}$ MeV
consistent with those of $\eta(1405)$ / $\eta(1475)$ within 2.0 σ







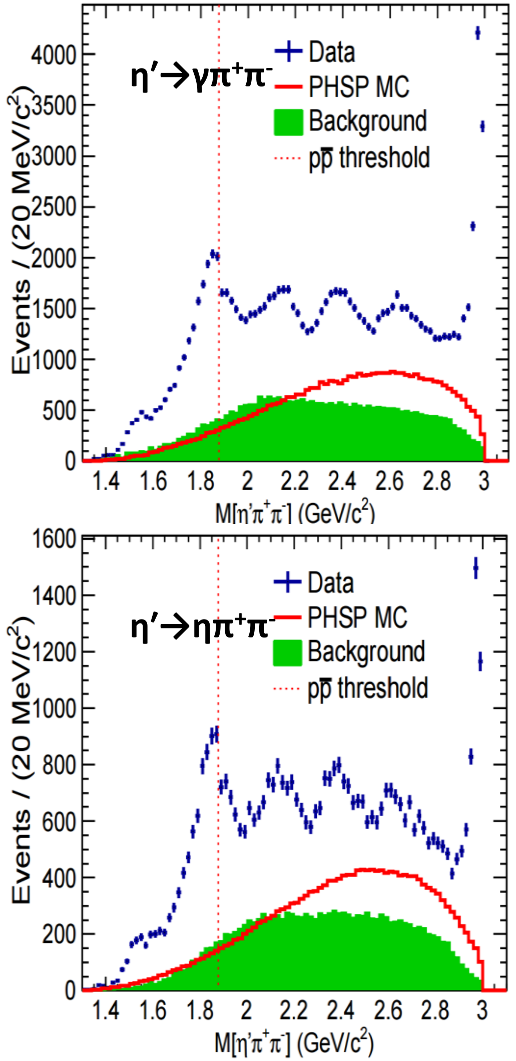


- **Any relations?**
- **What is the role of the ppbar threshold (and other thresholds)?**
- **Patterns in the production and decay modes**

New: connection is emerging

- **Use 1.09×10^{9} J/ψ events collected by BESIII in 2012**
- **Two decay modes of η′**
  - **η′→γπ⁺π⁻**
  - **η′→ηπ⁺π⁻, η→γγ**
- **Clear peaks of X(1835), X(2120), X(2370), η_c, and a structure near 2.6 GeV$/c^2$**
- **A significant distortion of the η′π⁺π⁻ line shape near the $p\bar{p}$ mass threshold**

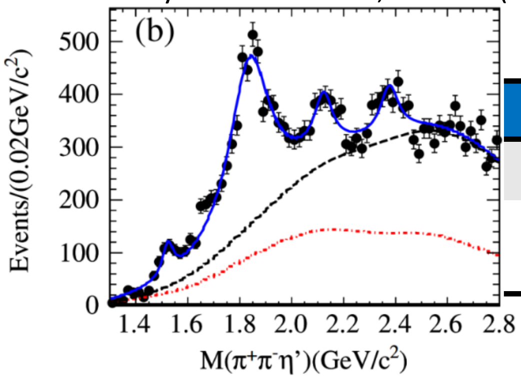
PRL 117, 042002 (2016)



Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between X(1835) and X($p\bar{p}$)

X(1835) observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$

Phys. Rev. Lett. 106, 072002 (2011)

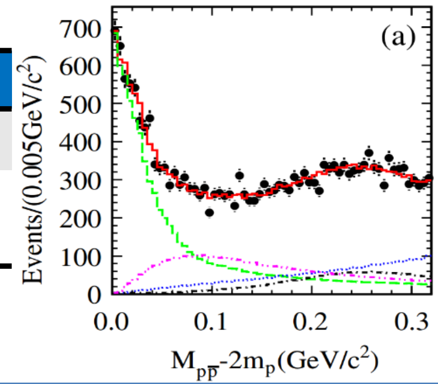


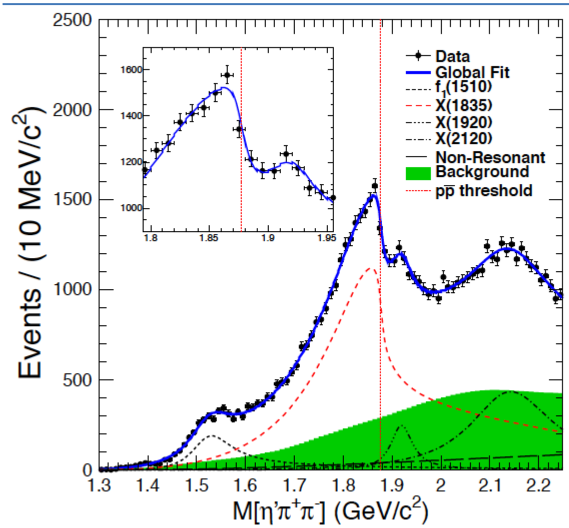
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

X($p\bar{p}$) observed in $J/\psi\to\gamma p\bar{p}$

PRL 108, 112003 (2012)
PRL 115, 091803 (2015)

X($p\bar{p}$) $J^{PC}=0^{-+}$
$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (< **76 MeV/c^2** @ 90% C.L.)



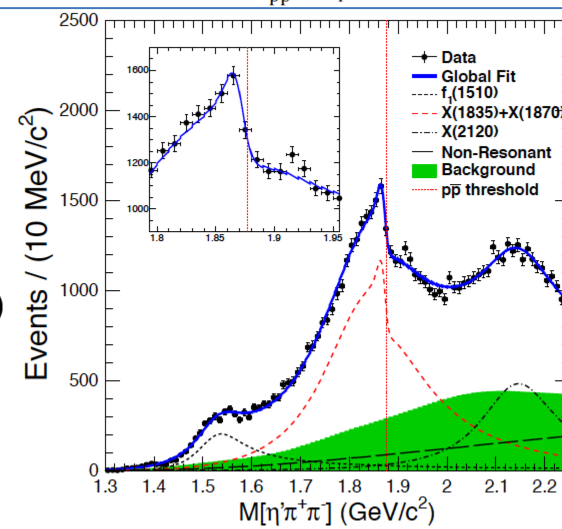


Connection is emerging

PRL 117, 042002 (2016)

Model 1:
Flatte lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at ~1920 MeV/c^2

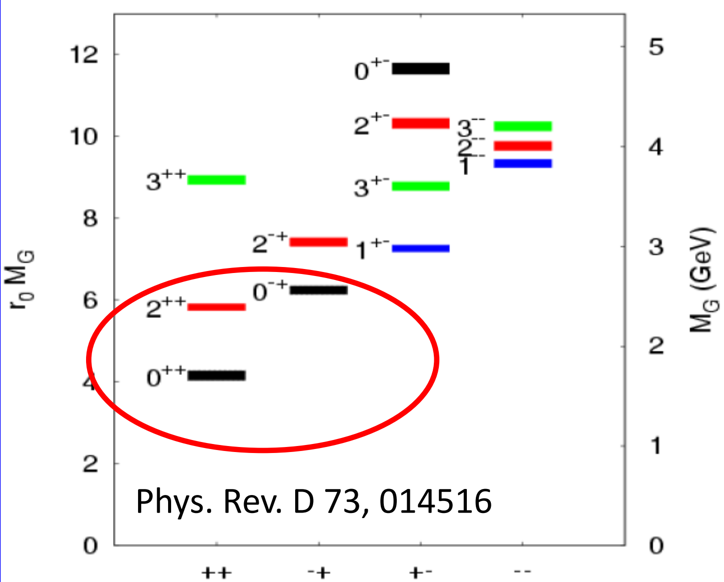
Model 2:
Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/c^2



The anomalous line shape can be modeled two models with equally good fit quality.

- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold
- Support the existence of a $p\bar{p}$ molecule-like state or bound state

Glueballs from Quenched LQCD



Phys. Rev. Lett. 110, 021601

$$\Gamma(J/\psi \to \gamma G_{0^+}) = \frac{4}{27}\alpha \frac{|p|}{M_{J/\psi}^2}|E_1(0)|^2 = 0.35(8)keV$$

$$\Gamma/\Gamma\_tot = 0.33(7)/93.2 = 3.8(9)\times 10^{-3}$$

Phys. Rev. Lett. 111, 091601

$$\Gamma(J/\psi \to \gamma G_{2^+}) = 1.01(22)keV$$

$$\Gamma(J/\psi \to \gamma G_{2^+})/\Gamma_{tot} = 1.1(2)\times 10^{-2}$$

Low lying glueballs have ordinary quantum number

0^{++}(1.5~1.7 GeV), 2^{++}(2.3~2.4 GeV),

0^{-+}(2.3~2.6 GeV)

mixing with qqbar mesons

Large Br in J/ψ radiative decays

Systematic exp. studies are required:

→Over-population

Map out the resonances

→Production patterns

$J/\psi \to \gamma/\omega/\phi$ + X

Other experiments: $\gamma\gamma$ processes from Belle2, …

→Decay patterns

"flavor blind", "chiral suppression", …

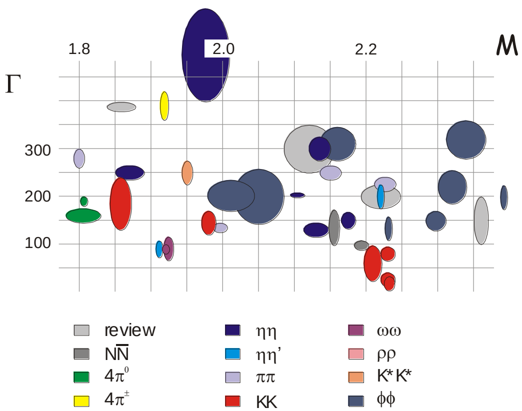
LQCD and QCD inspired models

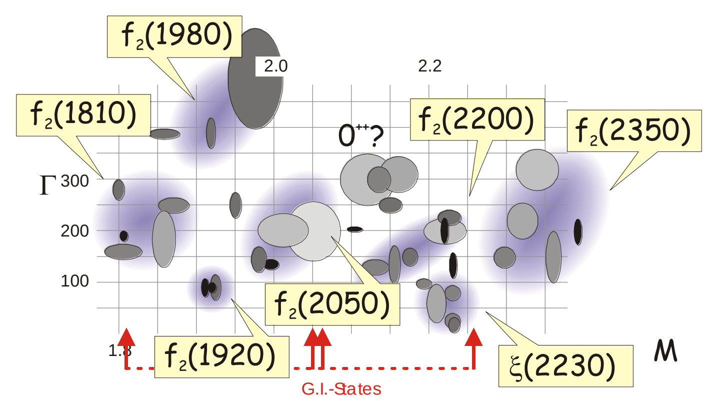
0^+ : experimental results saturated

- f_0（1710）/f_0(1790）, one or two
- Large production rate of f_0(2100) in gluon rich environment ppbar annihilations and J/psi radiative decays

$f_0(600)*$	400–1200	600–1000	$\pi\pi, \gamma\gamma$
$f_0(980)*$	980 ± 10	40–100	$\pi\pi, K\bar{K}, \gamma\gamma$
$f_0(1370)*$	1200–1500	200–500	$\pi\pi, \rho\rho, \sigma\sigma, \pi(1300)\pi, a_1\pi, \eta\eta, K\bar{K}$
$f_0(1500)*$	1507 ± 5	109 ± 7	$\pi\pi, \sigma\sigma, \rho\rho, \pi(1300)\pi, a_1\pi, \eta\eta, \eta\eta'$ $K\bar{K}, \gamma\gamma$
$f_0(1710)*$	1718 ± 6	137 ± 8	$\pi\pi, K\bar{K}, \eta\eta, \omega\omega, \gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi, \pi\pi, \rho\rho, \omega\omega, \eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi, \pi\pi, \pi\pi\pi\pi, \eta\eta, \eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi, K\bar{K}, \eta\eta$

2^+: complicated situation around 2 GeV





0^- simple in quark model （η, η’）. Very little known above 2 GeV

- η(1295) exists?
- η （1405）/ η(1475）?
- X(18xx) ?
- X(2370)

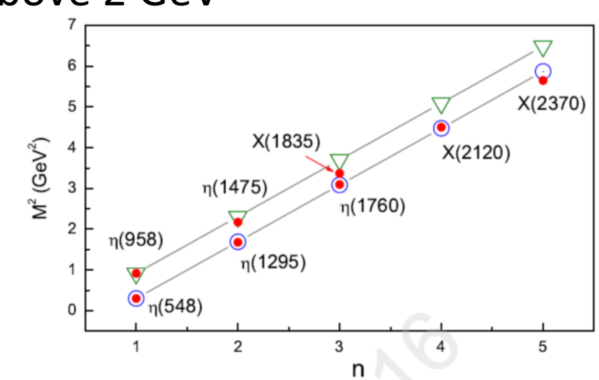


图 2，η/η′ 的 Regge trajectories [16]

Isospin-violating decay of η(1405) → $f_0(980)\pi$

PRL 108, 182001

The long standing E-ι puzzle:

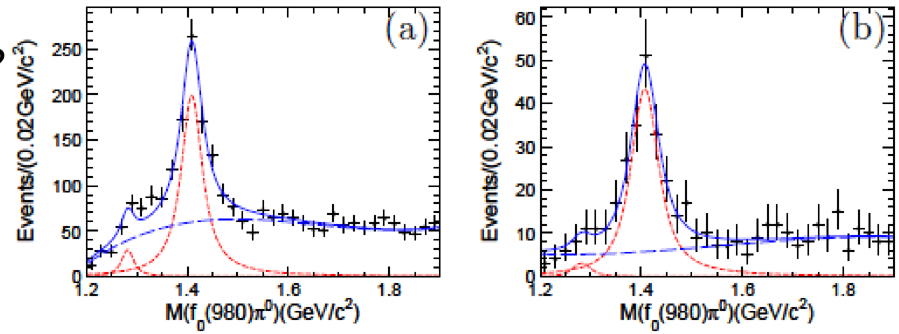
$\eta(1405)\to a_0\pi$, $\eta(1475)\to K^*\bar{K}$, overpopulation?

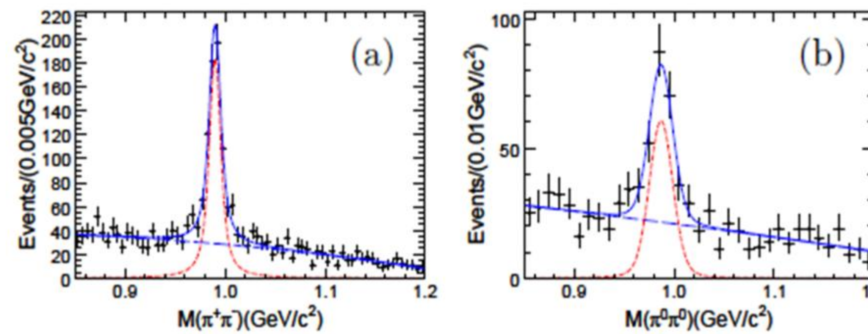
Anomalously large isospin violation:

$$\frac{Br(\eta(1405)\to f_0(980)\pi^0\to\pi^+\pi^-\pi^0)}{Br(\eta(1405)\to a_0^0(980)\pi^0\to\eta\pi^0\pi^0)}\cong(17.9\pm4.2)\%$$

Much larger than a_0-f_0 mixing (PRD 83 032003)

$$\xi_{af}=\frac{Br(\chi_{c1}\to f_0(980)\pi^0\to\pi^+\pi^-\pi^0)}{Br(\chi_{c1}\to a_0(980)\pi^0\to\eta\pi^0\pi^0)}<1\%(90\%\ C.L.)$$

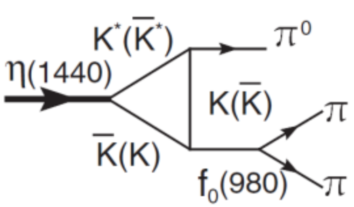




$f_0(980)$ is extremely narrow: $\Gamma\cong10$ MeV.

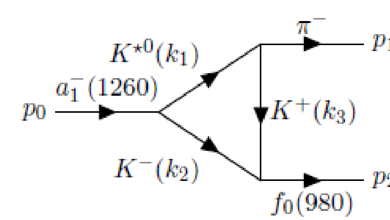
PDG: $\Gamma(f0(980))\cong 40\sim100$ MeV.

Triangle singularity is proposed (PRL 108 081803)



An important dynamical effect of threshold

$a_1(1420)$
PRD 89 054038



$J/\psi \to \omega\eta\pi^+\pi^-$

PRL 107, 182001

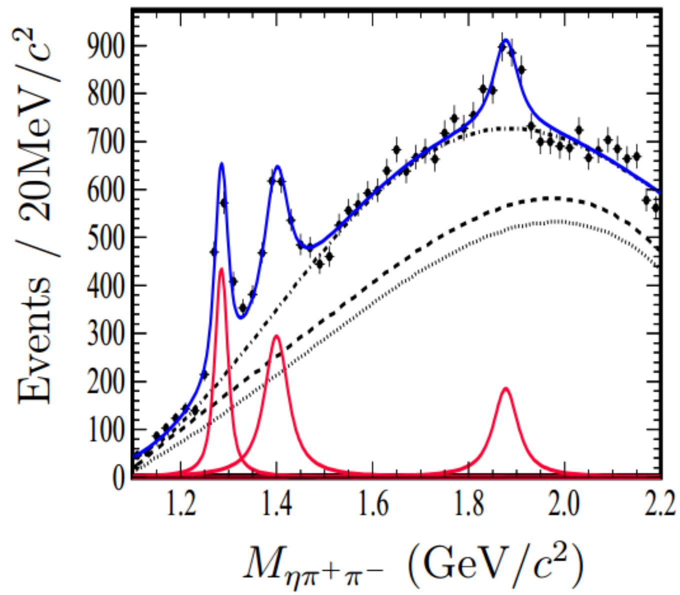


TABLE I: Summary of measurements of the mass, width and the product branching fraction of $\mathcal{B}(J/\psi \to \omega X) \times \mathcal{B}(X \to a_0^{\pm}(980)\pi^{\mp}) \times \mathcal{B}(a_0^{\pm}(980) \to \eta\pi^{\pm})$ where X represents $f_1(1285)$, $\eta(1405)$ and $X(1870)$. Here the first errors are statistical and the second ones are systematic.

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}$ (10^{-4})
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

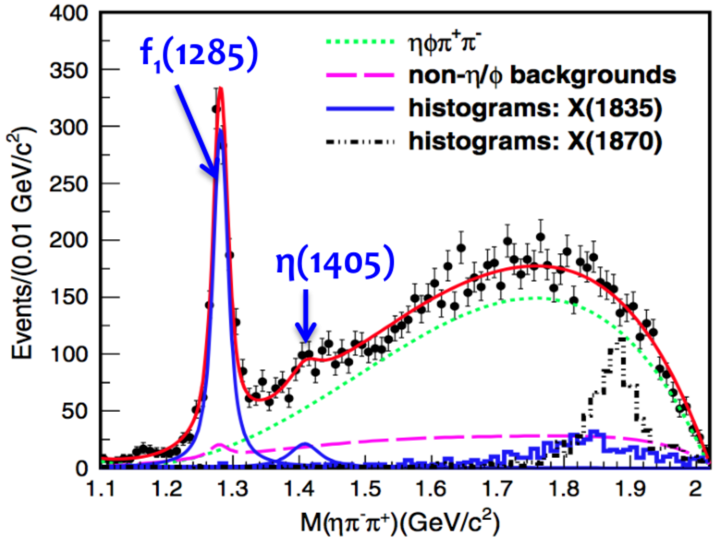
Study of $J/\psi \rightarrow \eta\phi\pi^+\pi^-$

PRD 91,052017 (2015)

- Offer a unique opportunity to investigate the properties of the $f_1(1285)$, $\eta(1295)$, and $\eta(1405)/\eta(1475)$ resonances.

- Search for the new production in different J/ψ decays for a better understand of X(1835) and X(1870):

Via the $M(\eta\pi^+\pi^-)$ spectrum recoiling against the ϕ in J/ψ decays



B= product branching fraction of $J/\psi \rightarrow \phi$ Res with Res$\rightarrow \eta\pi^+\pi^-$

Res	$N_{obs}^{(up)}$	eff. (%)	Sign.	B (up limit) [10^{-4}]
$f_1(1285)$	1154±56	22.14±0.09	…	1.20 ± 0.06 ± 0.14
$\eta(1405)$	172±50 (<345)	19.75±0.12	3.6σ	(2.01 ± 0.58 ± 0.82) ×10^{-1} (<4.45×10^{-1})
X(1835)	394±360 (<1522)	13.85±0.14	1.1σ	<2.80
X(1870)	25±73 (<330)	13.73±0.14	0.8σ	<6.13×10^{-1}

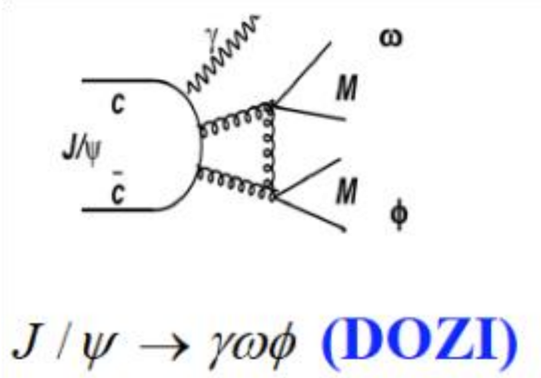
✓ $f_1(1285)$ is observed significantly:
M=1281.7±0.6 MeV, Γ=21.0±1.7 MeV
in good agreement with that of PDG.

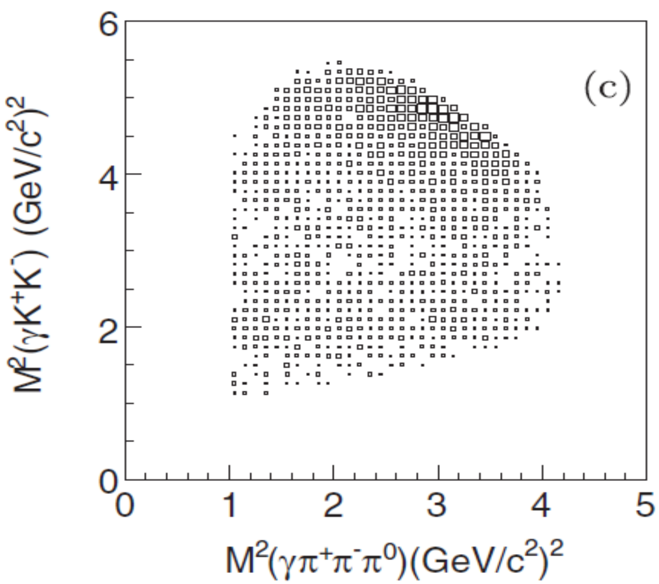
✓ A small structure around 1.4 GeV seems to be present (3.6σ for $\eta(1405)$):
It imply the u-d account for more of the quark content in the $\eta(1405)$ than s quark.

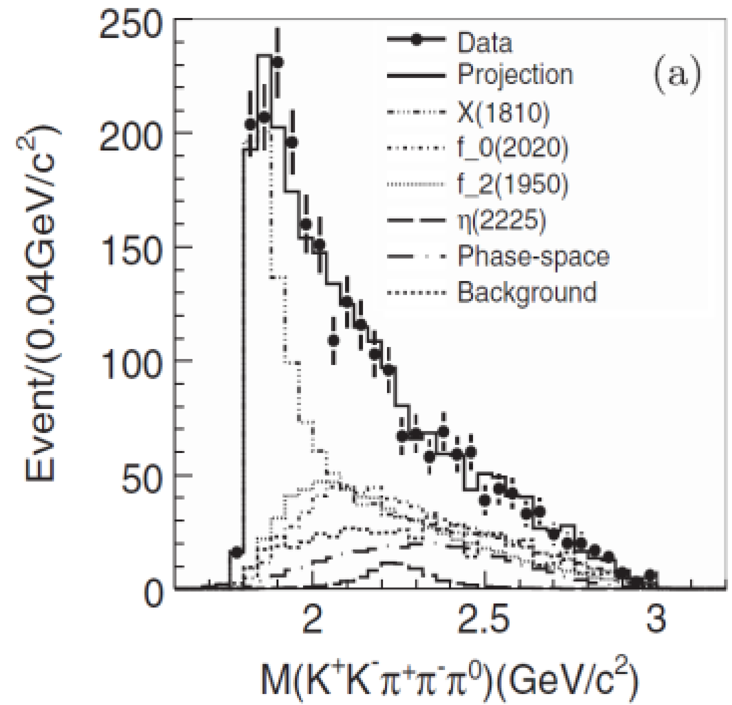
✓ No evidence of X(1835) and X(1870), upper limits at 90% C.L. are set.

PWA of $J/\psi \to \gamma\omega\phi$

PRD 87, 032008(2013)







- Confirmed the enhancement observed at BESII

$M = 1795 \pm 7^{+13}_{-5} \pm 19$(model) MeV/c^2,

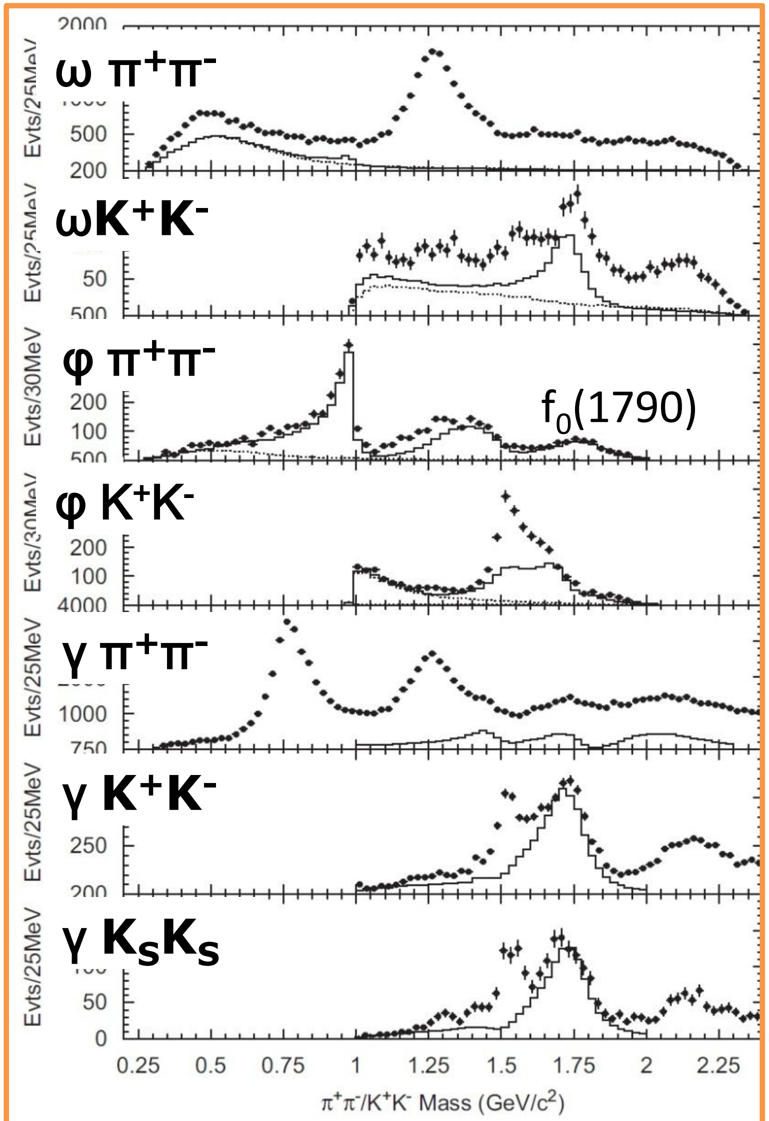
$\Gamma = 95 \pm 10^{+21}_{-34} \pm 75$(model) MeV

Spin-parity is determined to be 0^+

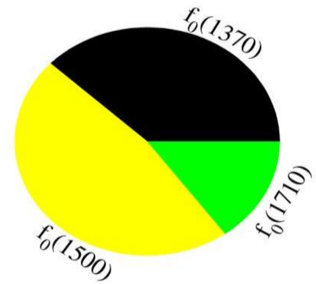
- the same as $f_0(1710)/f_0(1790)$, or a new state ?

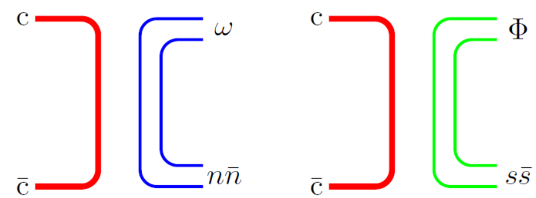
0^{++}

the most complex and controversial



@BES2





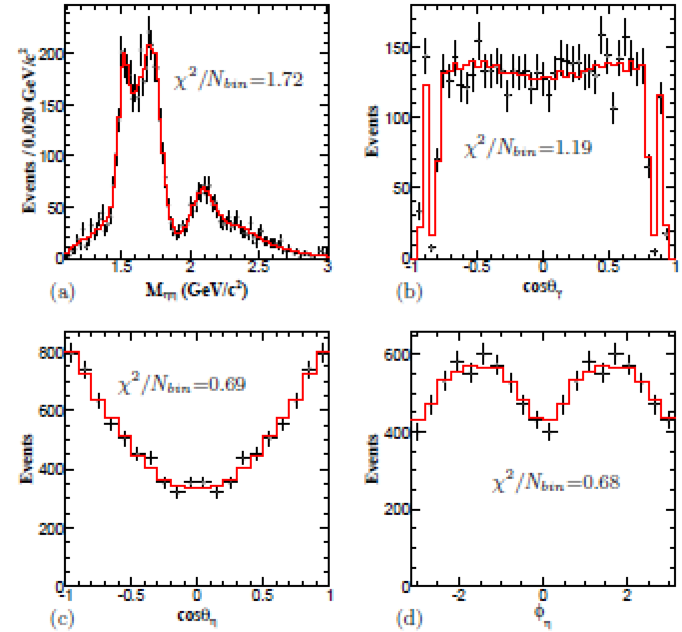
ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

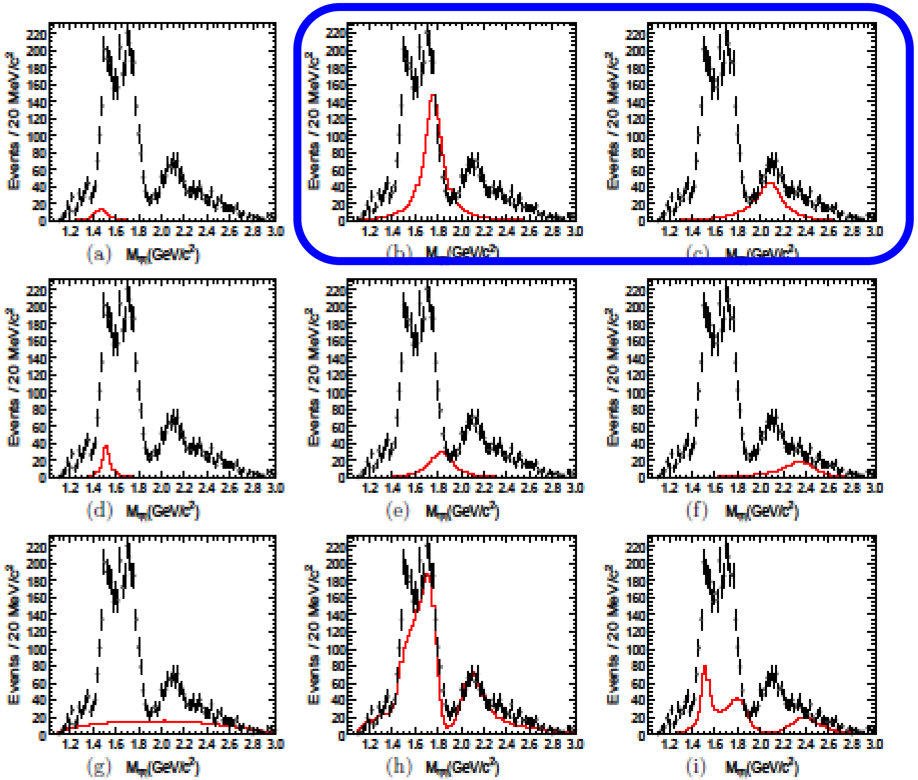
ϕK^+K^- ➜ No peak around 1700 MeV/c^2

PWA of $J/\psi \rightarrow \gamma\eta\eta$

(Phys. Rev. D87 092009 (2013))

Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40}) \times 10^{-5}$	$8.2\ \sigma$
$f_0(1710)$	$1759\pm6^{+14}_{-25}$	$172\pm10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	$25.0\ \sigma$
$f_0(2100)$	$2081\pm13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	$13.9\ \sigma$
$f'_2(1525)$	$1513\pm5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	$11.0\ \sigma$
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35}) \times 10^{-5}$	$6.4\ \sigma$
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	$7.6\ \sigma$

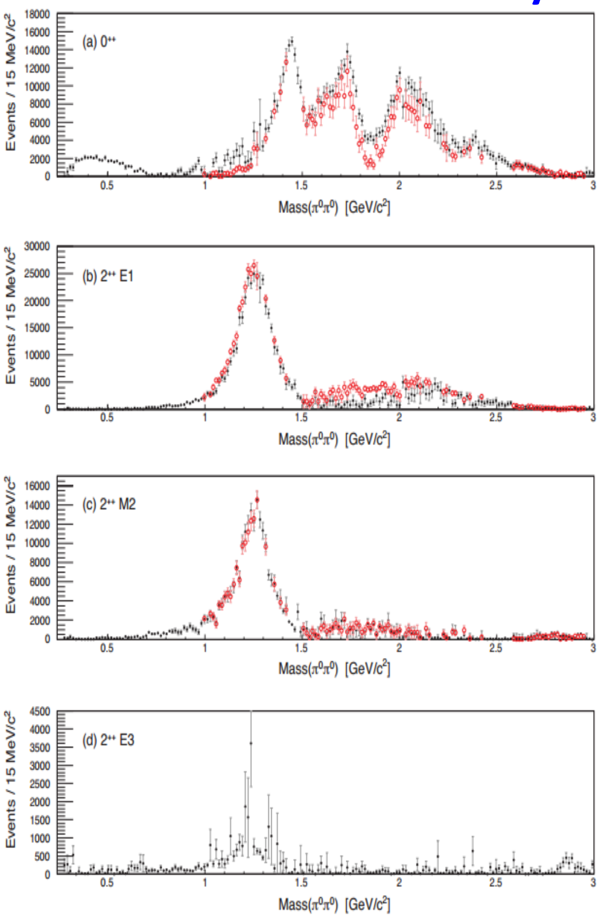




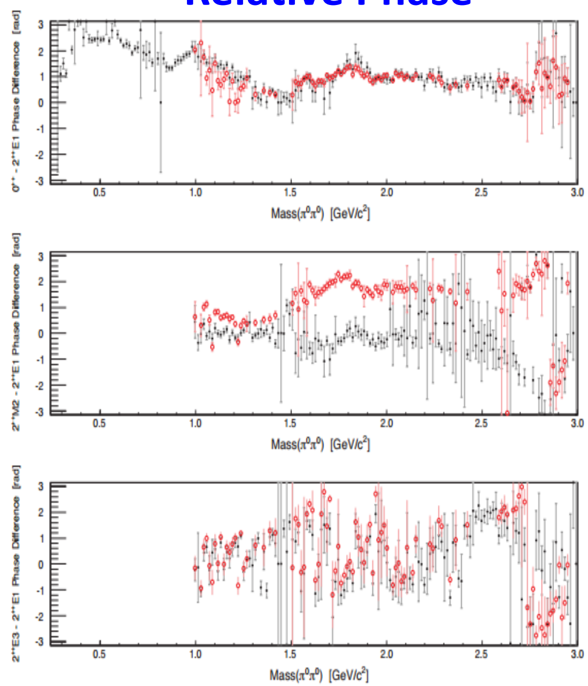
- **Br of $f_0(1710)$ and $f_0(2100)$ are ~10x larger than that of $f_0(1500)$**
  - **Possible large overlap with LQCD predictions of 0+ Glueball: PRL 110 021601 (2013)**
- **Strong production of $f_2(2340)$**

Model Independent PWA of $J/\psi \to \gamma\pi^0\pi^0$

Extracted Intensity



Relative Phase



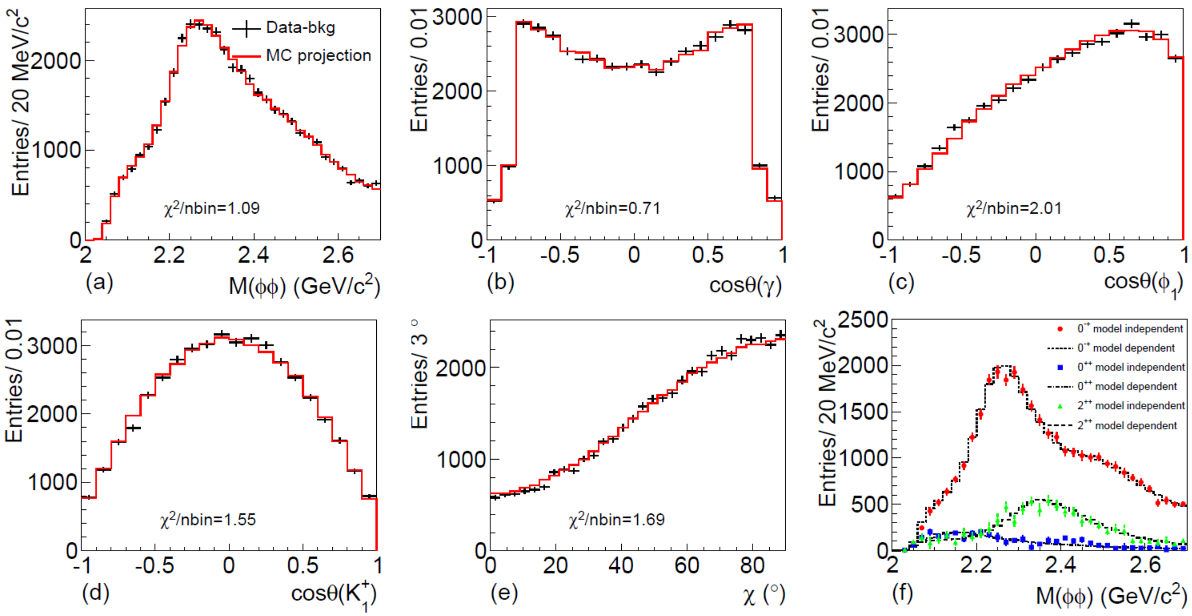
- Solution 1
- Solution 2

Phys. Rev. D 92, 052003 (2015)

- ✓ Extract amplitudes in each $M(\pi^0\pi^0)$ mass bin
- ✓ Significant features of the scalar spectrum includes structures near 1.5, 1.7 and 2.0 GeV/c^2
- ✓ Multi-solution problem in MIPWA is usually unavoidable.
- ✓ Model Dependent PWA of global PWA fit is still needed to extract resonance parameters

Partial Wave Analysis of J/ψ→γφφ [PR D93 112011]

Besides η(2225) , very little was known in the sector of pseudoscalar above 2 GeV. The new experimental results are helpful for mapping out the pseudoscalar excitations and searching for 0^{-+} glueball



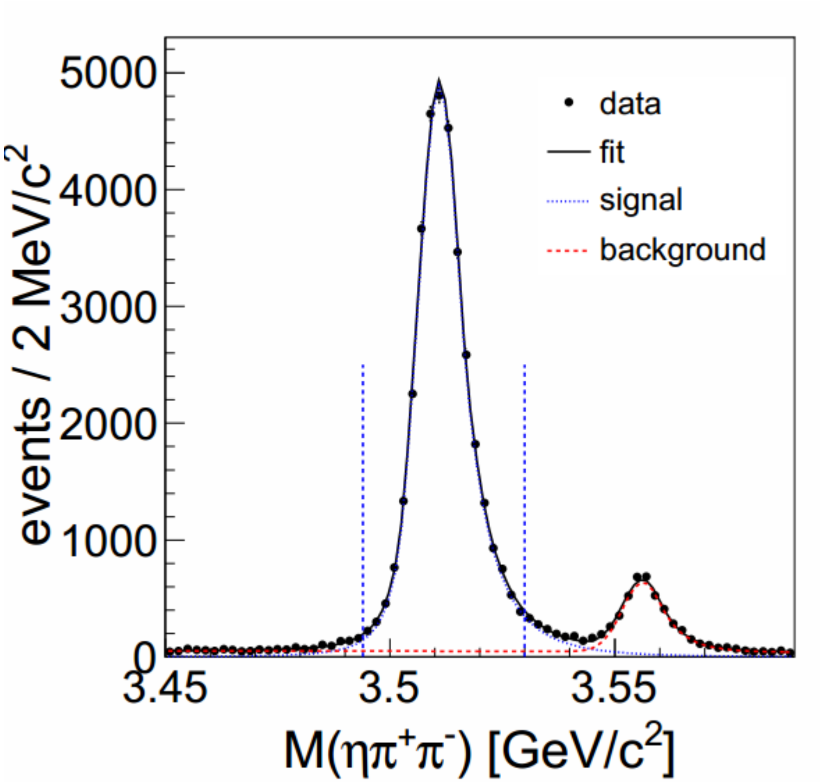
Resonance	M(MeV/c^2)	Γ(MeV/c^2)	B.F.(×10^{-4})	Sig.
η(2225)	2216^{+4+18}_{-5-11}	185^{+12+44}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28.1σ
η(2100)	2050^{+30+77}_{-24-26}	$250^{+36+187}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	21.5σ
X(2500)	2470^{+15+63}_{-19-23}	230^{+64+53}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2102	211	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24.2σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.07^{+0.72}_{-0.69})$	10.7σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

- **Dominant contribution from pseudoscalars**
    - **η(2225) is confirmed;**
    - **η(2100) and X(2500) are observed with large significance.**
- **The three tensors $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$ stated in $\pi^- p$ reactions are also observed with a strong production of $f_2(2340)$.**
- **Model-dependent PWA results are well consistent with the results from MIPWA**

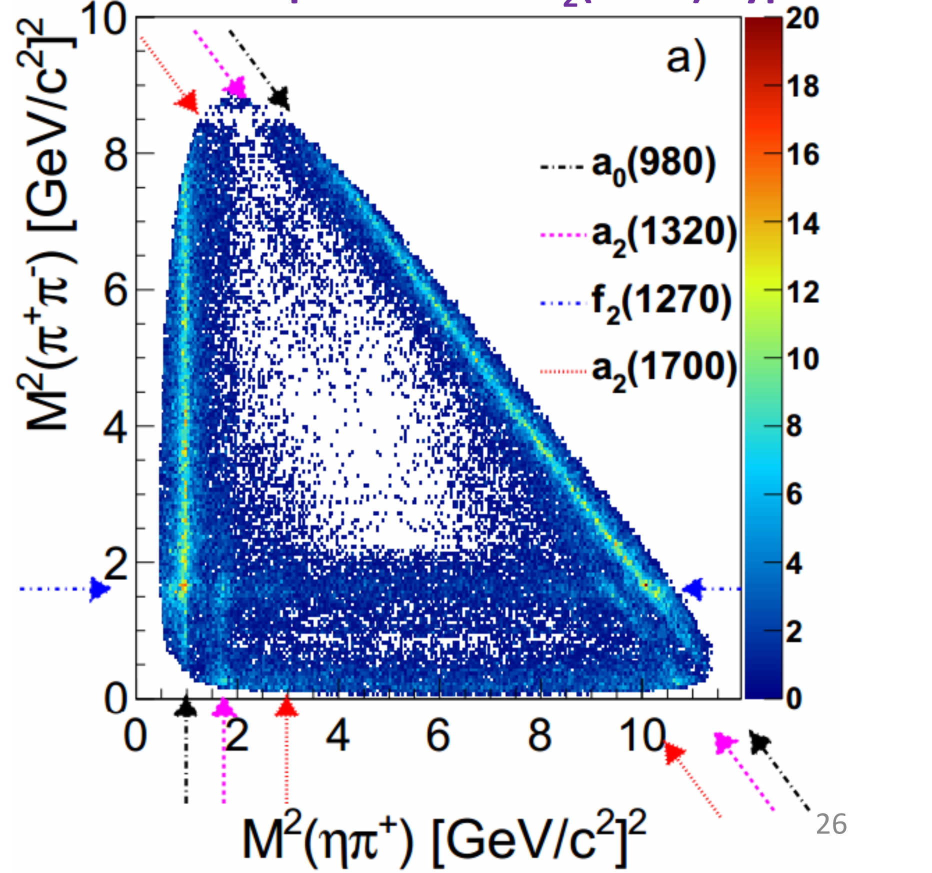
Amplitude analysis of $\chi_{c1} \to \eta\pi^+\pi^-$

arXiv:1610.02479

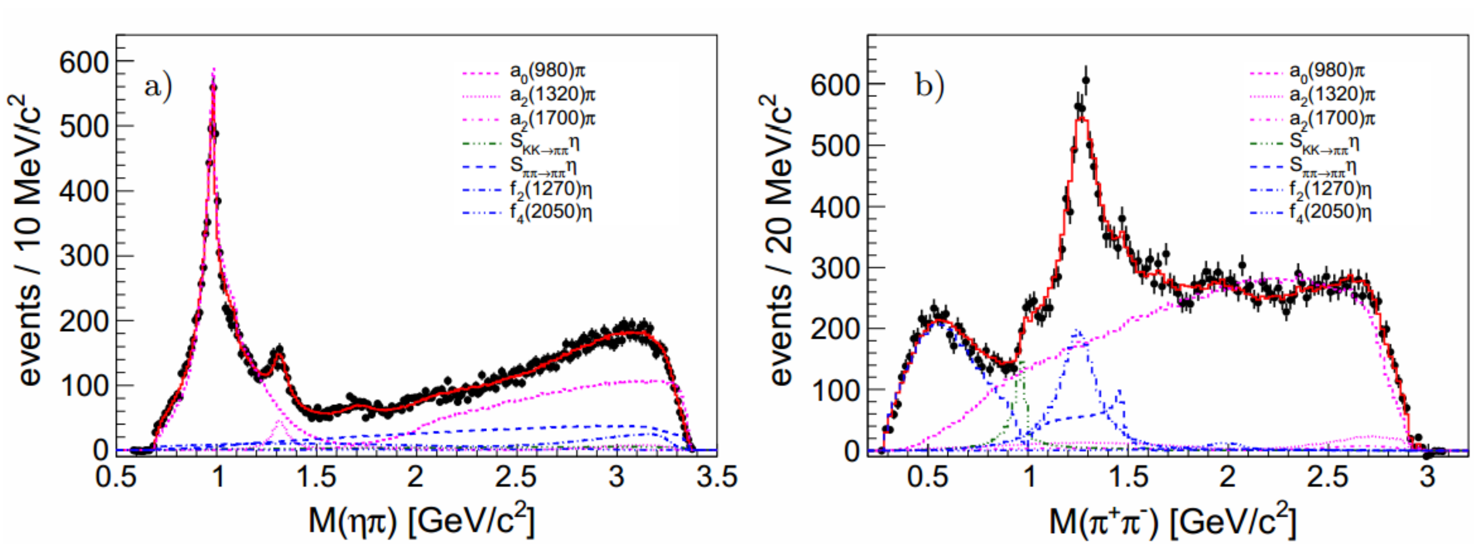
- **χ_{c1} provides another suitable environment to look for 1^{-+}**
  - **$\pi_1(1600)$ studied in χ_{c1} decays by CLEO-c**
  - **only $\pi_1(1400)$ has been reported decays to $\eta\pi$**
- **Properties of a_0 and a_2 still need further studies**



compatible with $a_2(1700)$ hypothesis

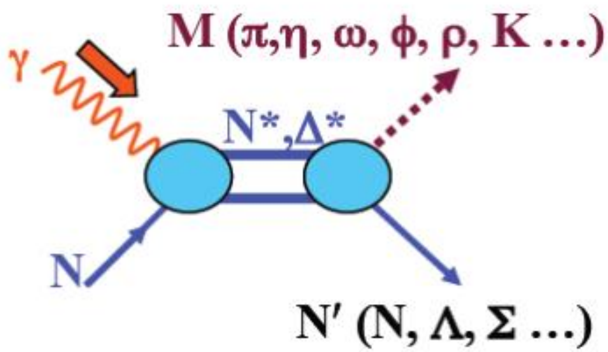


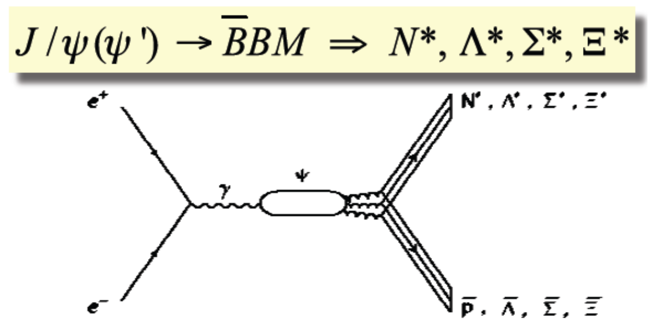
Decay	$\mathcal{F}$ [%]	Significance [σ]	$\mathcal{B}(\chi_{c1} \to \eta\pi^+\pi^-)$ [10^{-3}]
$\eta\pi^+\pi^-$	-	-	$4.67 \pm 0.03 \pm 0.23 \pm 0.16$
$a_0(980)^+\pi^-$	$72.8 \pm 0.6 \pm 2.3$	> 100	$3.40 \pm 0.03 \pm 0.19 \pm 0.11$
$a_2(1320)^+\pi^-$	$3.8 \pm 0.2 \pm 0.3$	32	$0.18 \pm 0.01 \pm 0.02 \pm 0.01$
$a_2(1700)^+\pi^-$	$1.0 \pm 0.1 \pm 0.1$	20	$0.047 \pm 0.004 \pm 0.006 \pm 0.002$
$S_{K\bar{K}}\eta$	$2.5 \pm 0.2 \pm 0.3$	22	$0.119 \pm 0.007 \pm 0.015 \pm 0.004$
$S_{\pi\pi}\eta$	$16.4 \pm 0.5 \pm 0.7$	> 100	$0.76 \pm 0.02 \pm 0.05 \pm 0.03$
$(\pi^+\pi^-)_S\eta$	$17.8 \pm 0.5 \pm 0.6$	-	$0.83 \pm 0.02 \pm 0.05 \pm 0.03$
$f_2(1270)\eta$	$7.8 \pm 0.3 \pm 1.1$	> 100	$0.36 \pm 0.01 \pm 0.06 \pm 0.01$
$f_4(2050)\eta$	$0.6 \pm 0.1 \pm 0.2$	9.8	$0.026 \pm 0.004 \pm 0.008 \pm 0.001$
Exotic candidates			U.L. [90% C.L.]
$\pi_1(1400)^+\pi^-$	0.58 ± 0.20	3.5	< 0.046
$\pi_1(1600)^+\pi^-$	0.11 ± 0.10	1.3	< 0.015
$\pi_1(2015)^+\pi^-$	0.06 ± 0.03	2.6	< 0.008



- **Clear evidence for $a_2(1700)$ in χ_{c1} decays.**
- **First measurement of $g'_{\eta'\pi} \neq 0$ using $a_0(980) \to \eta\pi$ line shape.**
- **Measured upper limits for $\pi_1(1^{-+})$ in 1.4 - 2.0 GeV/c^2 region.**

Light Baryon spectroscopy



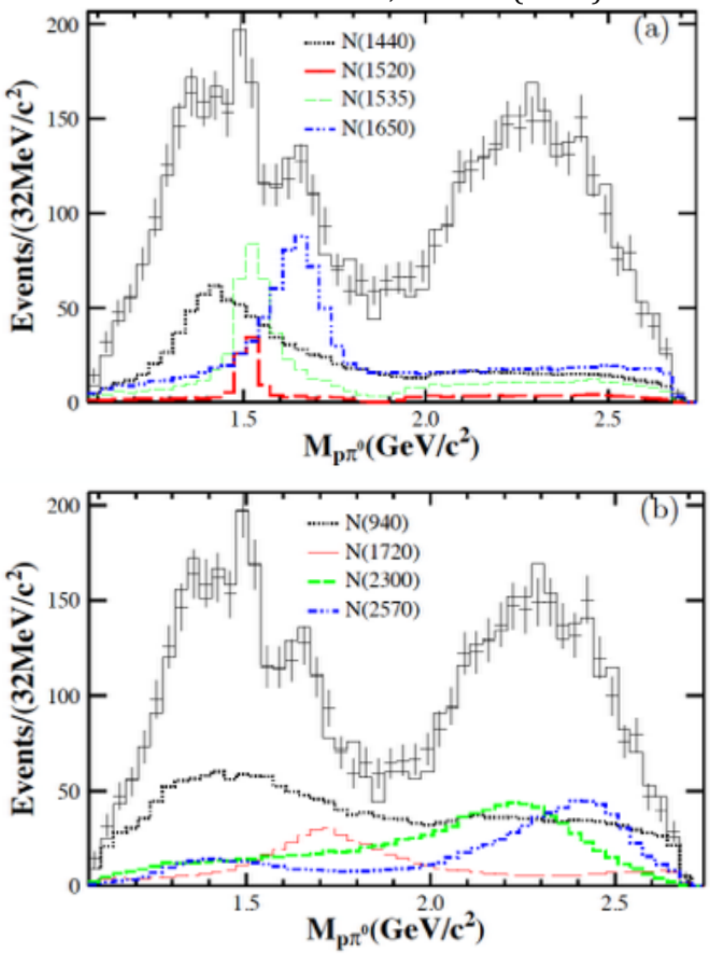


Charmonium decays can provide novel insights into baryons and complementary information to other experiments

- ✓ Missing N* with small couplings to πN & γN , but large coupling to gggN : $\psi \to N\bar{N}\pi/\eta/\eta'/\omega/\phi, \bar{p}\Sigma\pi, \bar{p}\Lambda K$ …
- ✓ Not only N*, but also Λ^*, Σ^*, Ξ^*
- ✓ Gluon-rich environment: a favorable place for producing hybrid (qqqg) baryons
- ✓ High statistics of charmonium @ BES III

Observation of two new N* resonances in $\psi(3686) \rightarrow p\bar{p}\pi^0$

BESIII: PRL 110, 022001 (2013)



- In photon or meson beam studies, isospin 1/2 and 3/2 resonances are excited, complicating the analysis
- Δ resonances suppressed in charmonium decays to $p\bar{p}\pi^0$, giving a cleaner spectrum
  - Thought to be dominated by two body decays involving N* intermediate states
  - Also consider $p\bar{p}$ resonances ($\psi(3686) \rightarrow R\pi^0$)
- Seven N* states observed in partial wave analysis
  - Two new resonances, N(2300) with $J^P = 1/2^+$ and N(2570) with $J^P = 5/2^-$
  - Other five consistent with previous results

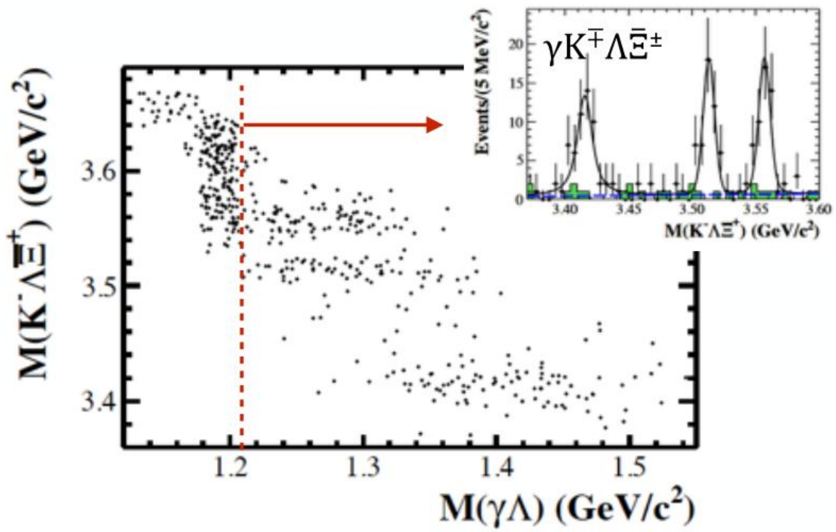
Resonance	M(MeV/c^2)	Γ(MeV/c^2)	ΔS	ΔN_{dof}	Sig.
$N(1440)$	1390^{+11+21}_{-21-30}	$340^{+46+70}_{-40-156}$	72.5	4	11.5σ
$N(1520)$	1510^{+3+11}_{-7-9}	115^{+20+0}_{-15-40}	19.8	6	5.0σ
$N(1535)$	1535^{+9+15}_{-8-22}	120^{+20+0}_{-20-42}	49.4	4	9.3σ
$N(1650)$	1650^{+5+11}_{-5-30}	150^{+21+14}_{-22-50}	82.1	4	12.2σ
$N(1720)$	1700^{+30+32}_{-28-35}	$450^{+109+149}_{-94-44}$	55.6	6	9.6σ
N(2300)	$\mathbf{2300^{+40+109}_{-30-0}}$	$\mathbf{340^{+30+110}_{-30-58}}$	**120.7**	**4**	$\mathbf{15.0\sigma}$
N(2570)	$\mathbf{2570^{+19+34}_{-10-10}}$	$\mathbf{250^{+14+69}_{-24-21}}$	**78.9**	**6**	$\mathbf{11.7\sigma}$

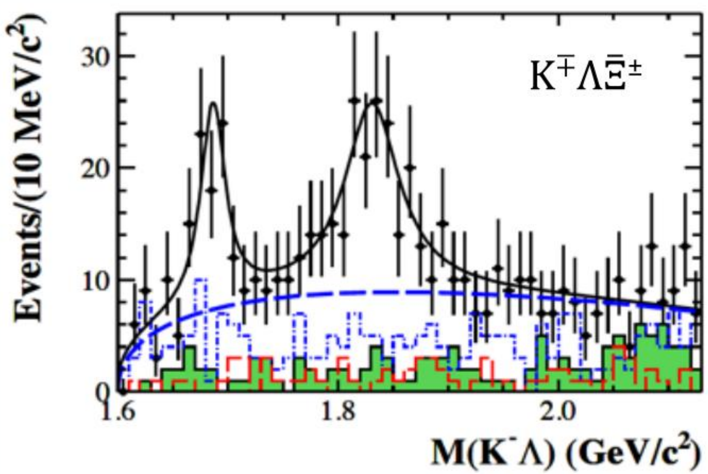
Measurements of $\psi(3686) \to (\gamma)K^{\mp}\Lambda\bar{\Xi}^{\pm}$

BESIII: PRD 91, 092006 (2015)

- $\psi(3686) \to (\gamma)K^{\mp}\Lambda\bar{\Xi}^{\pm}$; $\Lambda \to p\pi$, $\bar{\Xi} \to \Lambda\pi$; $\Lambda \to p\pi$

Decay	Branching fraction
$\psi(3686) \to K^-\Lambda\bar{\Xi}^+$	$(3.86 \pm 0.27 \pm 0.32) \times 10^{-5}$
$\psi(3686) \to \Xi(1690)^-\bar{\Xi}^+,\ \Xi(1690)^- \to K^-\Lambda$	$(5.21 \pm 1.48 \pm 0.57) \times 10^{-6}$
$\psi(3686) \to \Xi(1820)^-\bar{\Xi}^+,\ \Xi(1820)^- \to K^-\Lambda$	$(12.03 \pm 2.94 \pm 1.22) \times 10^{-6}$
$\psi(3686) \to K^-\Sigma^0\bar{\Xi}^+$	$(3.67 \pm 0.33 \pm 0.28) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c0},\ \chi_{c0} \to K^-\Lambda\bar{\Xi}^+$	$(1.90 \pm 0.30 \pm 0.16) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c1},\ \chi_{c1} \to K^-\Lambda\bar{\Xi}^+$	$(1.32 \pm 0.20 \pm 0.12) \times 10^{-5}$
$\psi(3686) \to \gamma\chi_{c2},\ \chi_{c2} \to K^-\Lambda\bar{\Xi}^+$	$(1.68 \pm 0.26 \pm 0.15) \times 10^{-5}$
$\chi_{c0} \to K^-\Lambda\bar{\Xi}^+$	$(1.96 \pm 0.31 \pm 0.16) \times 10^{-4}$
$\chi_{c1} \to K^-\Lambda\bar{\Xi}^+$	$(1.43 \pm 0.22 \pm 0.12) \times 10^{-4}$
$\chi_{c2} \to K^-\Lambda\bar{\Xi}^+$	$(1.93 \pm 0.30 \pm 0.15) \times 10^{-4}$

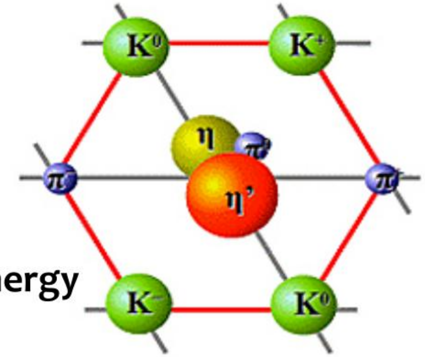




- Observe two hyperons, Ξ(1690) and Ξ(1820) in M(KΛ)
  - Both are well established states
  - Resonance parameters consistent with the PDG

	$\Xi(1690)^-$	$\Xi(1820)^-$
M(MeV/c^2)	1687.7±3.8±1.0	1826.7±5.5±1.6
Γ(MeV)	27.1±10.0±2.7	54.4±15.7±4.2
Event yields	74.4±21.2	136.2±33.4
Significance(σ)	4.9	6.2
Efficiency(%)	32.8	26.1
$\mathcal{B}$ (10^{-6})	5.21±1.48±0.57	12.03±2.94±1.22
M_{PDG}(MeV/c^2)	1690±10	1823±5
Γ_{PDG}(MeV)	<30	24^{+15}_{-10}

Light meson decays



- **Listed in many facilities' physics program:**
  (VES, Gams (-4π), CLEO, CLAS, Crystal Ball at MAINZ, WASA-at-COSY, KLOE-2, GlueX, BESIII)

- **Unique place to test fundamental symmetries in QCD at low energy**

- **Probe physics beyond the Standard Model (SM):**

$\eta/\eta' \to 2\gamma$	chiral anomaly
$\eta/\eta' \to \pi^+\pi^-\pi^0$	quark masses
$\eta' \to \gamma\pi^+\pi^-$	box anomaly
$\eta/\eta' \to \pi\pi$	CP violation
$\eta/\eta' \to \mu^+\mu^-\pi^0, e^+e^-\pi^0$	C violation
$\eta/\eta' \to \mu e$	LF violation

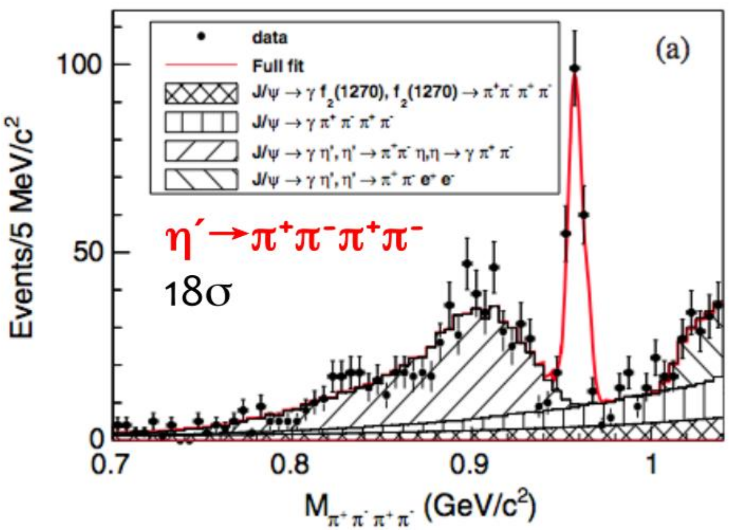
……

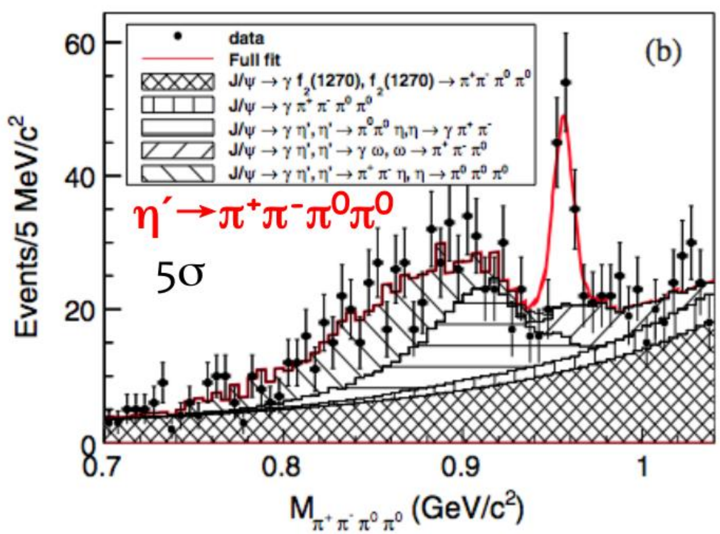
- **η and η' events at BESIII**
  - $B(J/\psi \to \gamma\eta) \sim 1.10\times10^{-3} \to 1.44\times10^{6}$ η events;
  - $B(J/\psi \to \gamma\eta') \sim 5.15\times10^{-3} \to 6.74\times10^{6}$ η' events;

- **Results of η/η' presented in this talk are based on all the data sample of J/ψ events.**

Observation of $\eta' \to \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-\pi^0\pi^0$

PRL 112, 251801(2014)





Upper limits @90% C.L. by CLEO (PRL102, 061801(2009)):

$B(\eta' \to \pi^+\pi^-\pi^+\pi^-) < 2.4 \times 10^{-4}$

$B(\eta' \to \pi^+\pi^-\pi^0\pi^0) < 2.6 \times 10^{-3}$

Prediction by ChPT and VMD (PRD85, 014014(2012)):

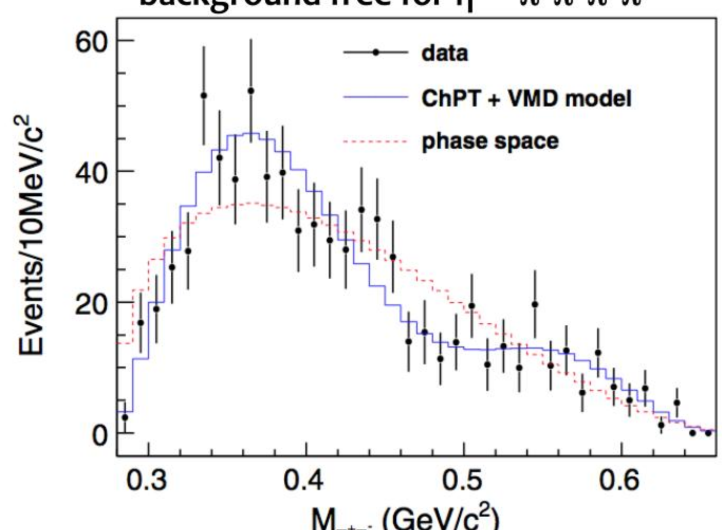
$B(\eta' \to \pi^+\pi^-\pi^+\pi^-) = (1.0 \pm 0.3) \times 10^{-4}$

$B(\eta' \to \pi^+\pi^-\pi^0\pi^0) = (2.4 \pm 0.7) \times 10^{-4}$

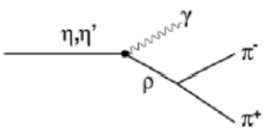
$B(\eta' \to \pi^+\pi^-\pi^+\pi^-) = [8.53 \pm 0.69 \pm 0.64] \times 10^{-5}$

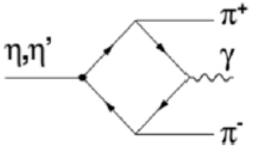
$B(\eta' \to \pi^+\pi^-\pi^0\pi^0) = [1.82 \pm 0.35 \pm 0.18] \times 10^{-4}$

background free for $\eta' \to \pi^+\pi^-\pi^+\pi^-$

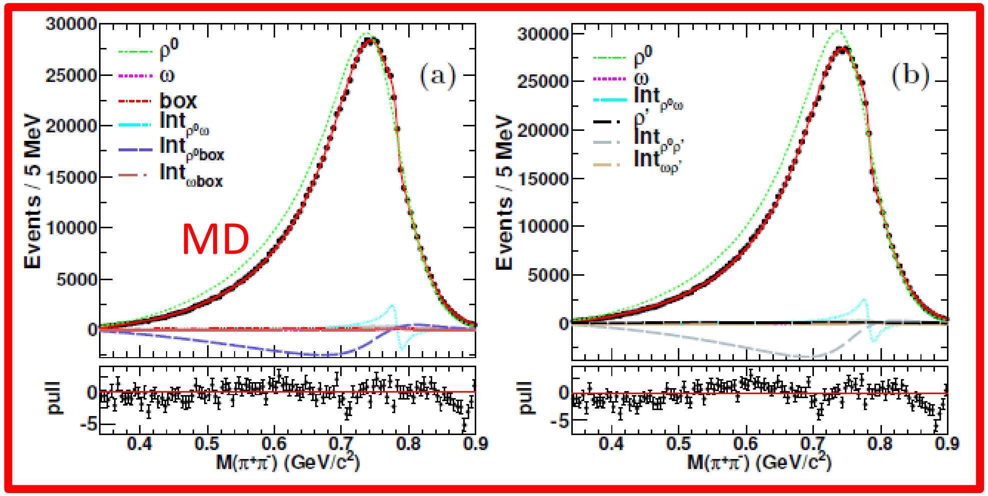


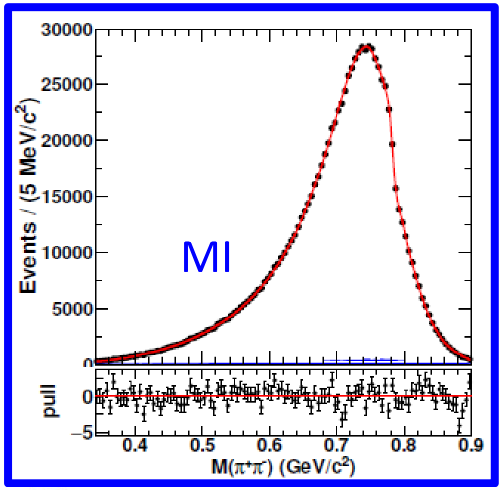
$\eta' \to \gamma\pi^+\pi^-$ decay dynamics





- High term of WZW χPT → box anomaly
- Studied by many experiments (CB, L3, …)
- No consistent picture due to limited statistics
  - rho mass shift?
  - Box anomaly?





$$\frac{d\Gamma}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2\Gamma_0(s_{\pi\pi})$$

* Physics Letters B 707 (2012) 184-190

$$P(s) = 1 + \kappa \cdot s + \lambda \cdot s^2 + \xi \cdot BW_\omega + \mathcal{O}(s^4)$$

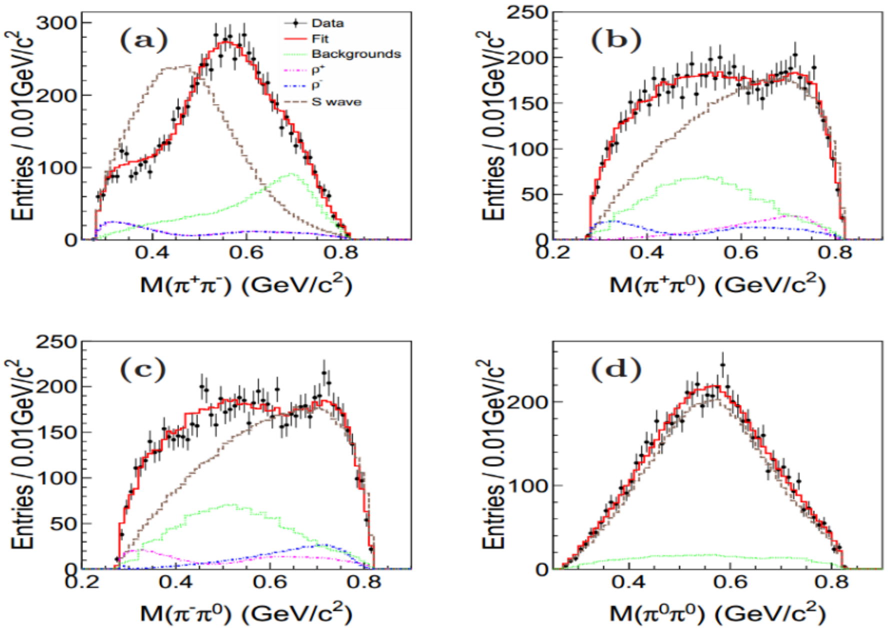
For the first time, ω contribution is observed

Model dependent fit: the box diagram or ρ(1450) is required

Model independent fit: ω contribution and non-linear term is required

Amplitude analysis of the decays $\eta' \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^0\pi^0\pi^0$

arXiv:1606.03847



Decay Mode	Yield	ε (%)	$\mathcal{B}$ ($\times 10^{-4}$)
$\pi^+\pi^-\pi^0$	6067 ± 91	25.3	$35.91 \pm 0.54 \pm 1.74$
$\pi^0\pi^0\pi^0$	2015 ± 47	8.8	$35.22 \pm 0.82 \pm 2.60$
$\rho^+\pi^-$	616 ± 49	24.8	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$\rho^-\pi^+$	615 ± 49	24.7	$3.72 \pm 0.30 \pm 0.63 \pm 0.92$
$(\pi^+\pi^-\pi^0)_S$	6580 ± 134	26.2	$37.63 \pm 0.77 \pm 2.22 \pm 4.48$

Significant P-wave contribution from $\eta' \to \rho^\pm\pi^\mp$ is observed for the first time in $\eta' \to \pi^+\pi^-\pi^0$

$$775.49(\text{fixed}) - i(68.5 \pm 0.2)\ \text{MeV}$$

In addition to the non-resonant S-wave component, a contribution from the σ meson is also essential.

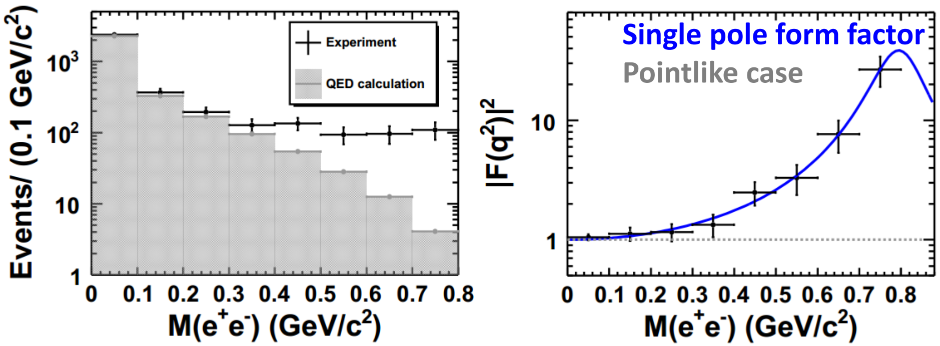
$$(512 \pm 15) - i(188 \pm 12)\ \text{MeV}$$

See also "Matrix element for $\eta \to \pi^+\pi^-\pi^0, \eta/\eta' \to \pi^0\pi^0\pi^0$"
BESIII PRD 92 012024(2015)

Observation of $\eta' \to V e^+ e^-$

$\eta' \to \gamma e^+ e^-$

Phys.Rev. D92, 012001 (2015)



$$|F(q^2)|^2 = \frac{\Lambda^2(\Lambda^2 + \gamma^2)}{(\Lambda^2 - q^2)^2 + \Lambda^2\gamma^2}$$

$$b = \left.\frac{dF}{dq^2}\right|_{q^2=0} = \Lambda^{-2}$$

$\Lambda = (0.79 \pm 0.04 \pm 0.02)$ GeV/c^2

$\gamma = (0.13 \pm 0.06 \pm 0.03)$ GeV/c^2

$b = (1.60 \pm 0.17 \pm 0.08)$ GeV^{-2}

- **In agreement with the result of $\eta' \to \gamma\mu^+\mu^-$ from CELLO:**
  $b = (1.7 \pm 0.4)$ GeV^{-2}

- **Theoretical predictions:**
  $b = 1.45$ GeV^{-2} VMD model
  $b = 1.60$ GeV^{-2} ChPT
  $b = 1.53^{+0.15}_{-0.08}$ GeV^{-2} Dispersion

$\eta' \to \omega e^+ e^-$

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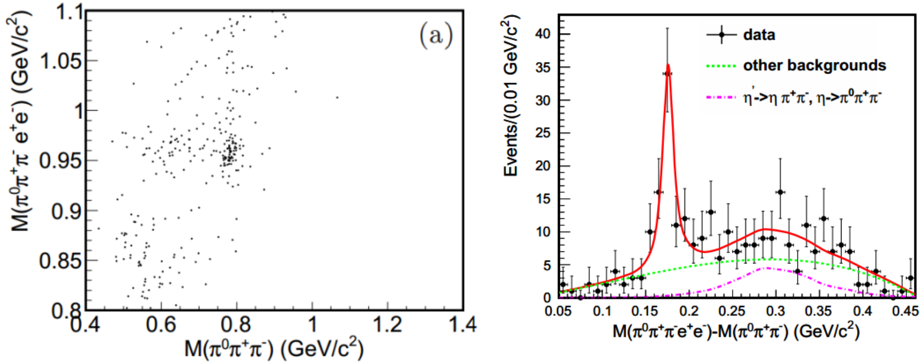

- Theoretical predictions from VMD*:
  $B(\eta' \to \omega e^+e^-) \sim 2.0\times10^{-4}$

  * PRC 61, 035206 (2000); EPJ A48, 190 (2012)

- **First measurement of $\eta' \to \omega e^+e^-$: 8σ**

$B(\eta' \to \gamma\omega) = (2.55 \pm 0.03 \pm 0.16)\times10^{-2}$ **Good agreement with PDG**

$B(\eta' \to \omega e^+e^-) = (1.97 \pm 0.34 \pm 0.17)\times10^{-4}$ **Consist with prediction**

$\frac{\mathcal{B}(\eta' \to \omega e^+ e^-)}{\mathcal{B}(\eta' \to \omega\gamma)} = (7.71 \pm 1.34 \pm 0.54)\times10^{-3}$

Prospects of hadron spectroscopy at BESIII

- **BESIII collected world's largest samples of J/ψ, ψ(2S), ψ(3770), Y(4260), … from e^+e^- production.**
- **It will continue to run for a few years.**

	BESIII	Goal
J/ψ	$1.3*10^9$ 21x BESII	$10*10^9$
ψ'	$0.6*10^9$ 24x CLEO-c	$3*10^9$
$\psi(3770)$	2.9 fb^{-1} 21x CLEO-c	20 fb^{-1}
Above open charm threshold	0.5 fb^{-1}@ψ(4040), 1.9 fb^{-1} @~4260, 0.5 fb^{-1}@4360, 1.0 fb^{-1} @4420, 0.5 fb^{-1} @4600	5-10 fb^{-1}
R scan and tau	3.8-4.6 GeV at 105 energy points 2.0-3.1 GeV at 20 energy points	
Y(2175)	100 pb^{-1} (2015)	
ψ(4170)	3 fb^{-1} (2016)	

Opportunities for hadron spectroscopy of both light quarks and heavy quarks.

Thank you