Charmonium and light hadron spectroscopy

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Outline

- Charmonium states:

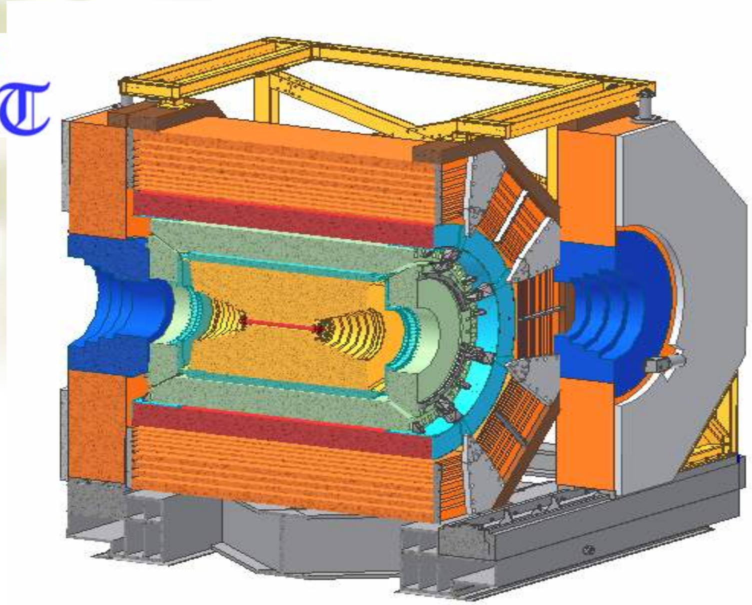
  $\Psi(4040)$, $\Psi(4160)$, η_c, $\eta_c(2S)$, $\Psi_{2,}$ X(3872)

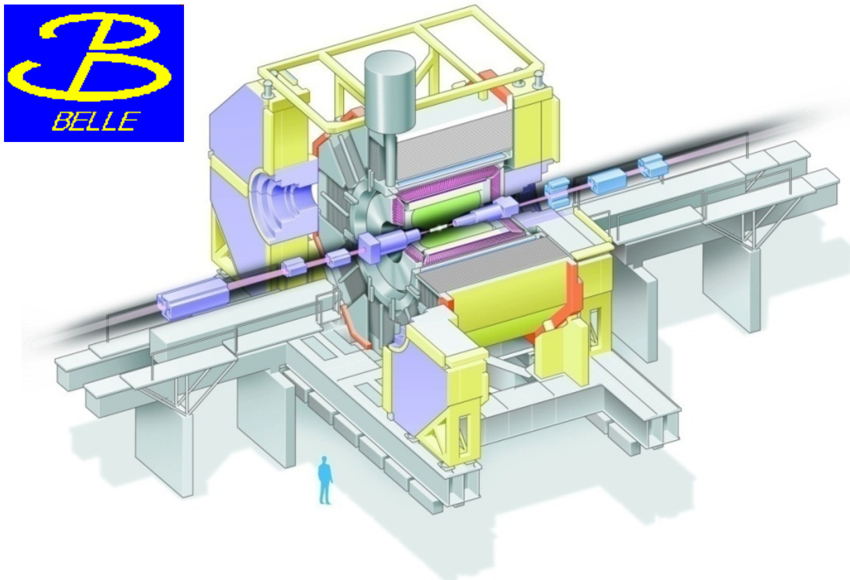
- light hadron spectroscopy

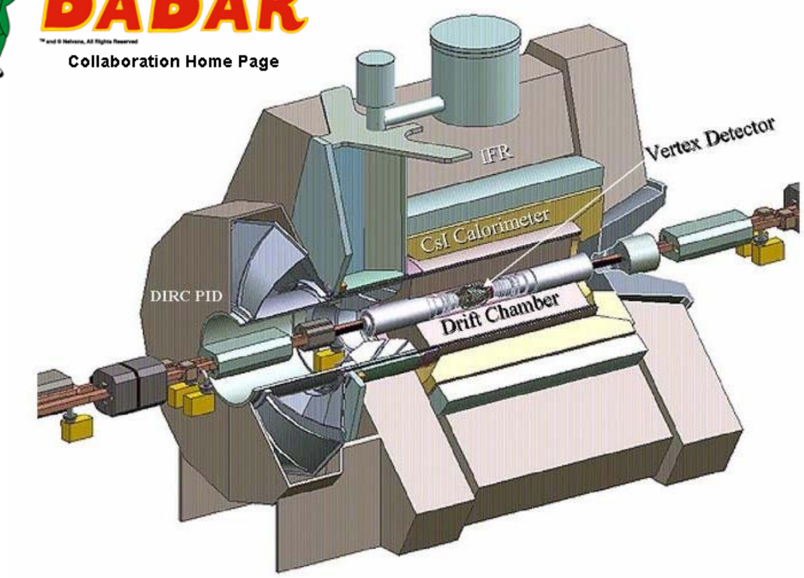
  X(1835), $\eta\eta$, $\omega\omega$, $\phi\phi$, $\omega\phi$

- Summary & Outlook

Results are from these experiments







Most of the results are from BESIII and Belle. Due to limited time, I can only cover a few topics. For more results, please refer to Belle and BESIII publication pages:

http://bes3.ihep.ac.cn/pub/physics.htm

http://belle.kek.jp/bdocs/b_journal.html

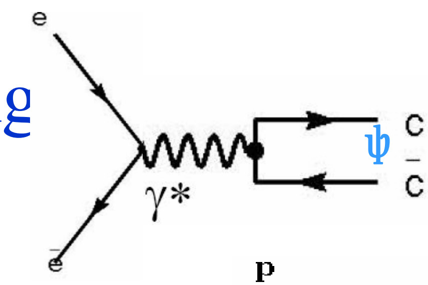
Charmonium

- Charmed-quark(c) anticharmed-quark($\bar{c}$) bound states.
- Has been a power tool for the understanding of the strong interaction
  - QCD is well tested at high energies
  - In low-energy regime, many aspects are not understood
  - Test QCD and improve out limited understanding of QCD

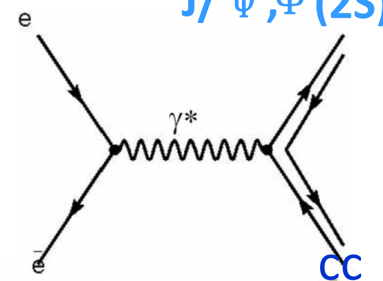
For Exotic hadrons and Quarkonium, please wait for Choi's report – next one !

Production

1. e^+e^- annihilation (including ISR/double charmonium)



ψ 1^{--}

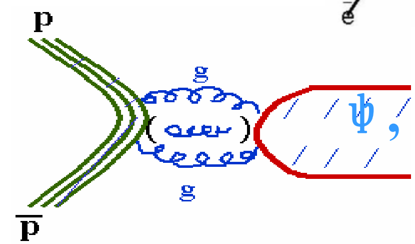


J/ψ ,Ψ(2S)

cc

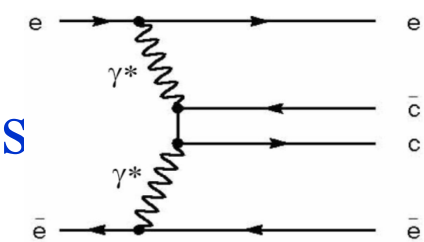
C=+

2. pp̄ annihilation



ψ , χ $_{cJ}$, η $_c$

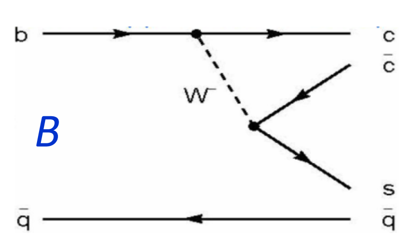
3. Two-photon process



η $_c$, η $_c$(2S)

0^{-+}, 0^{++}, 2^{++}

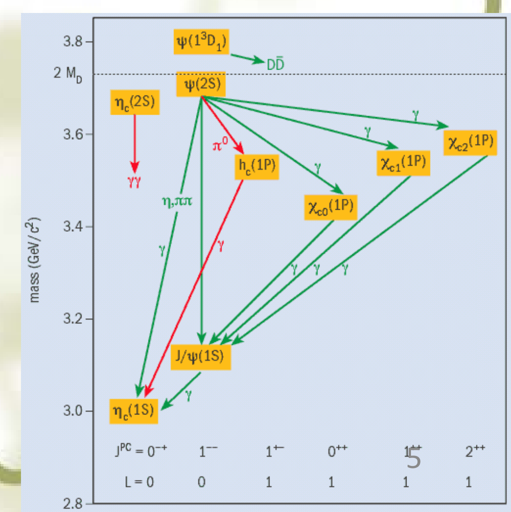
4. B decays



ψ , χ $_{cJ}$, η $_c$

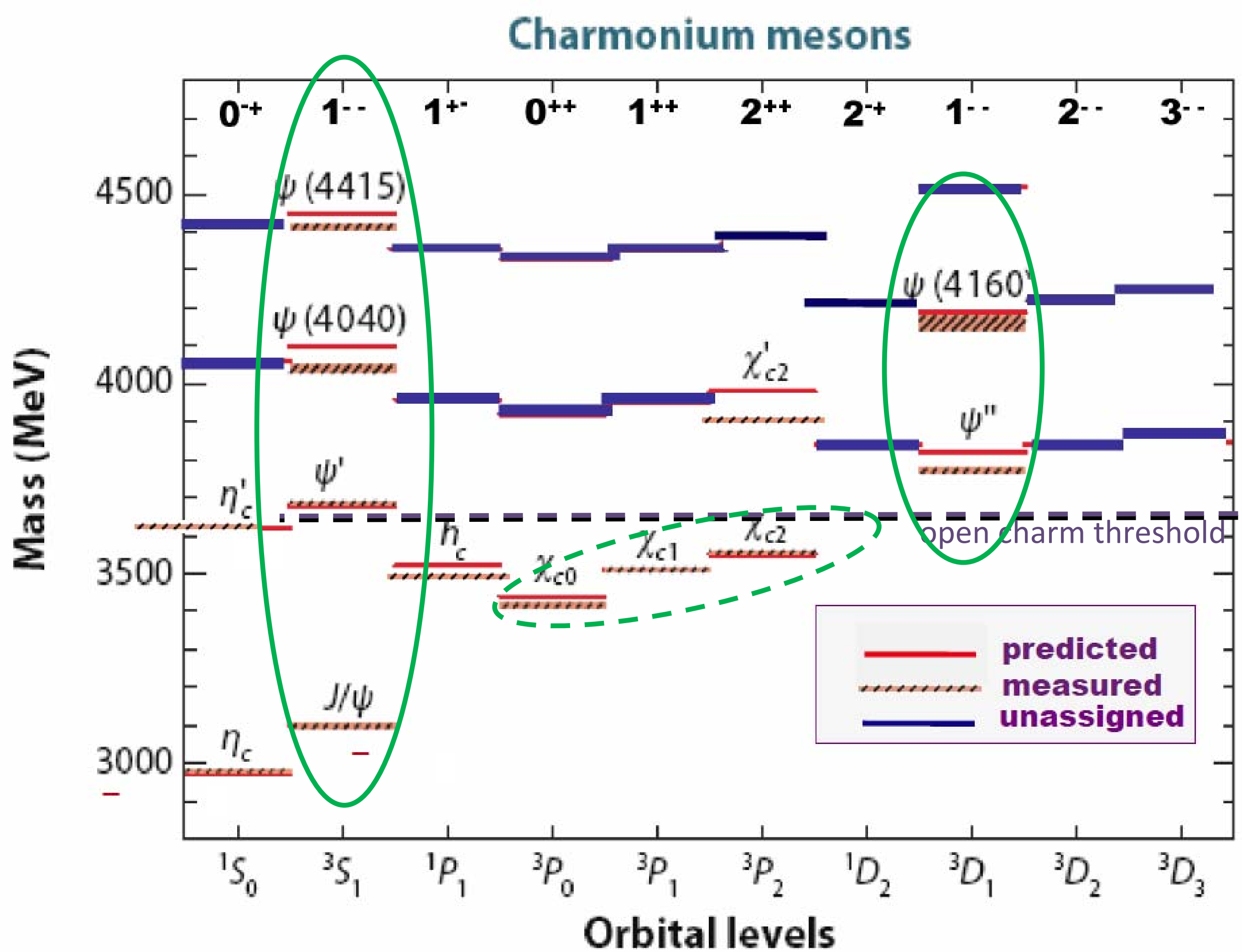
1^{--} 1^{++} or 0^{-+}

5. Through charmonium transition



1^{--} states: J/ψ, ψ', ψ'', $\psi(4040)$, $\psi(4160)$, $\psi(4415)$

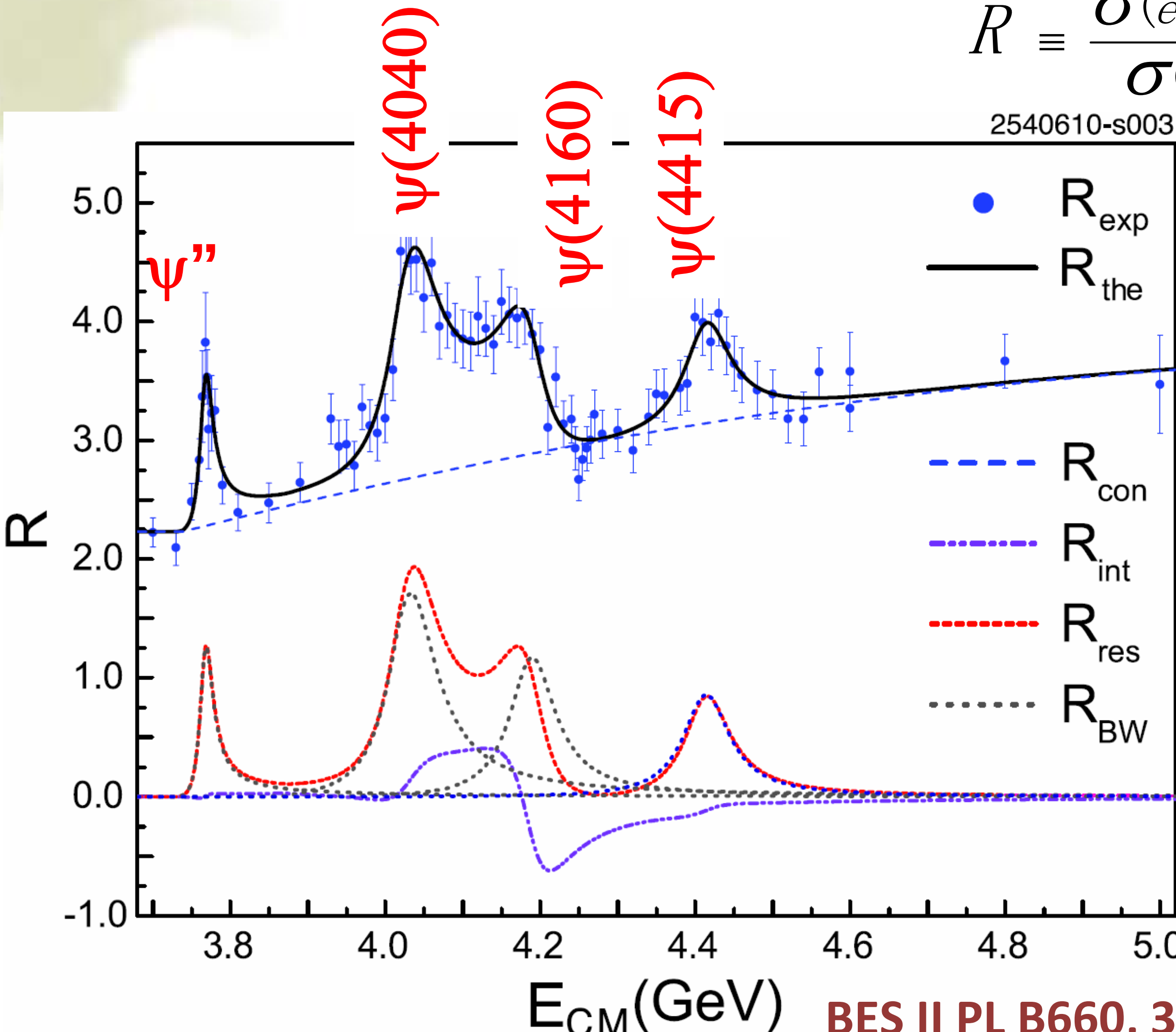
- Abundantly produced from e+e-, pp collisions
- Observed in 70's



$J^{PC} = 1^{--}$ states produce peaks in R_{had}

Extraction of resonance parameters from R measurement

$$R \equiv \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

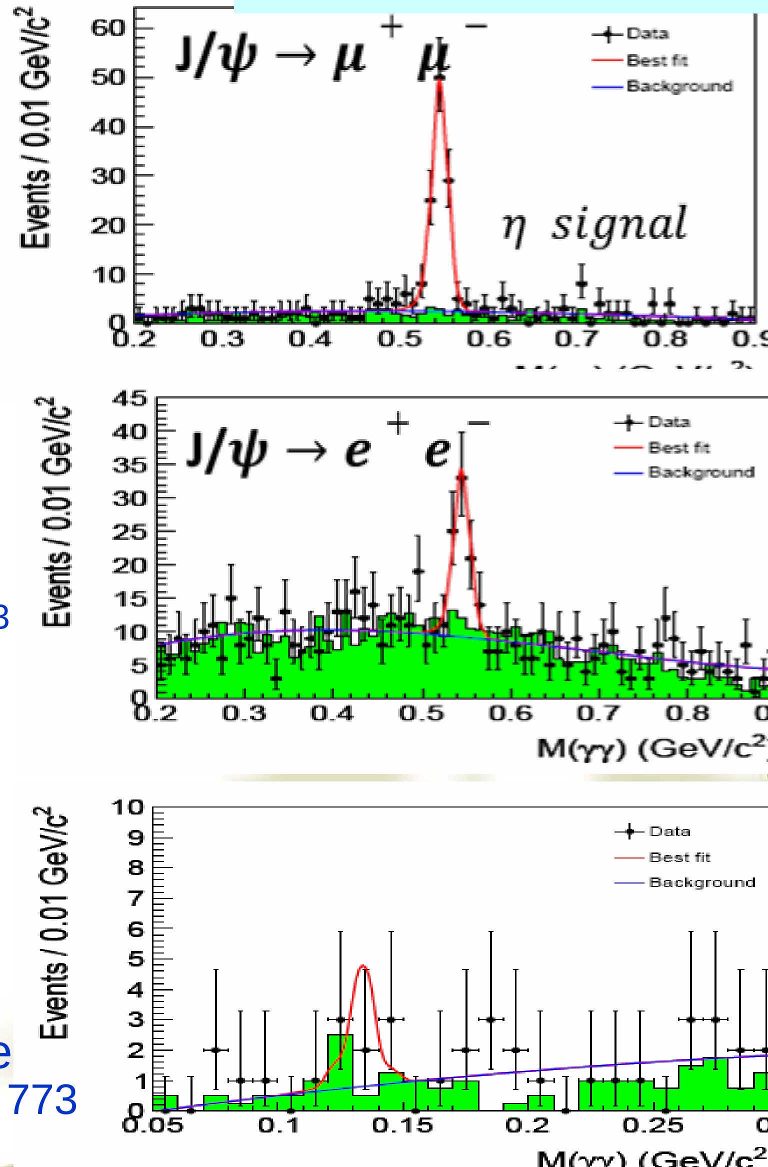


BES II PL B660, 315 (2008)

$e^+e^- \to \eta J/\psi$ @4.01GeV

PRD86, 071101(R) (2012)

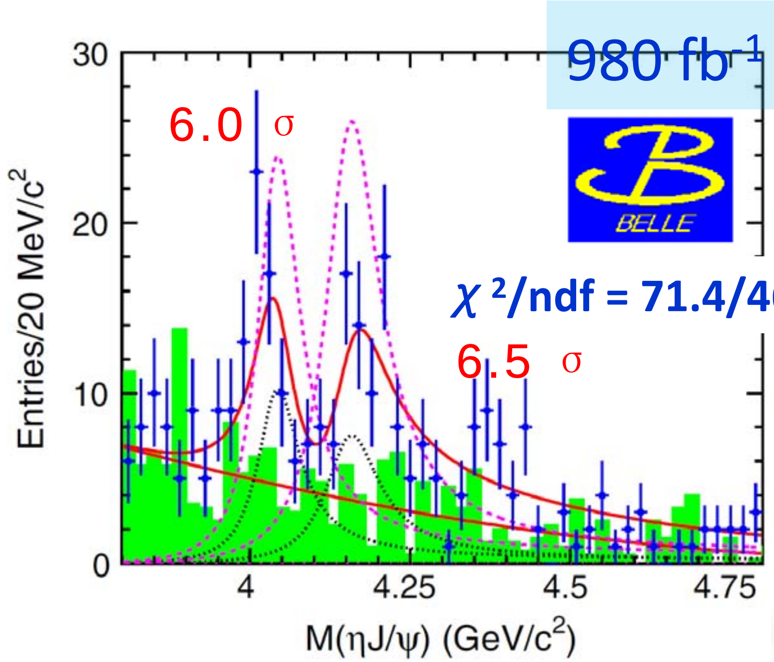
- Hadronic transition between charmonium states above open-charm threshold is not well understood
- Data sample: 478 pb^{-1} @4.01GeV
- First observation: $e^+e^- \to \eta J/\psi$ (significance > 10σ)
- Measured Born cross section: $(32.1 \pm 2.8 \pm 1.3)$ pb
- Assume $\eta J/\psi$ from $\psi(4040)$
  $Br(\psi(4040) \to \eta J/\psi) = (5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$
  $Br(\psi(4040) \to \pi^0 J/\psi) < 2.8 \times 10^{-4}$ @90% CL
- Consistent with the theoretical calculation (Q.Wang et al., arXiv:1206.4511)
- Partial width of $\psi(4040) \to \eta J/\psi$: ~400keV (> two times $\psi(4040) \to \pi\pi J/\psi$)
  - Similar to the hadronic transition of $\Upsilon(4S)$ (admixture of a four-quark state in the wave function, M. B. Voloshin, Mod. Phys. Lett. A 26, 773 (2011))



ψ(4040) and ψ(4160) decay into η J/ψ

- **BESIII can not measure the line shape of η J/Ψ. Belle did it via ISR.**

PRD 87, 051101(R) (2013)



- $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$
- J/Ψ→e^+e^- mode is not used in $\eta \to \gamma\gamma$ (high Bhabha bkg.)
- Ψ(2S) signal is a tagged signal
- $\sigma(e^+e^- \to \Psi(2S))$=13.9 ±1.4 (stat)pb and 14.0 ± 0.8 (stat) for $\eta \to \pi^+\pi^-\pi^0$ and $\gamma\gamma$, in good agreement with the theoretical value of 14.7pb.

- An unbinned maximum likelihood fit to the signal events and η and J/Ψ sidebands simultaneously
- Two coherent P-wave BWs for Ψ(4040) and Ψ(4160)

$M_{\psi(4040)}$	4039 (fixed)	
$\Gamma_{\psi(4040)}$	80 (fixed)	
$\mathcal{B}\cdot\Gamma^{\psi(4040)}_{e^+e^-}$	$4.8 \pm 0.9 \pm 1.5$	$11.2 \pm 1.3 \pm 2.1$
$M_{\psi(4160)}$	4153 (fixed)	
$\Gamma_{\psi(4160)}$	103 (fixed)	
$\mathcal{B}\cdot\Gamma^{\psi(4160)}_{e^+e^-}$	$4.0 \pm 0.8 \pm 1.4$	$13.8 \pm 1.3 \pm 2.1$
ϕ	$336 \pm 12 \pm 14$	$251 \pm 4 \pm 7$

MeV

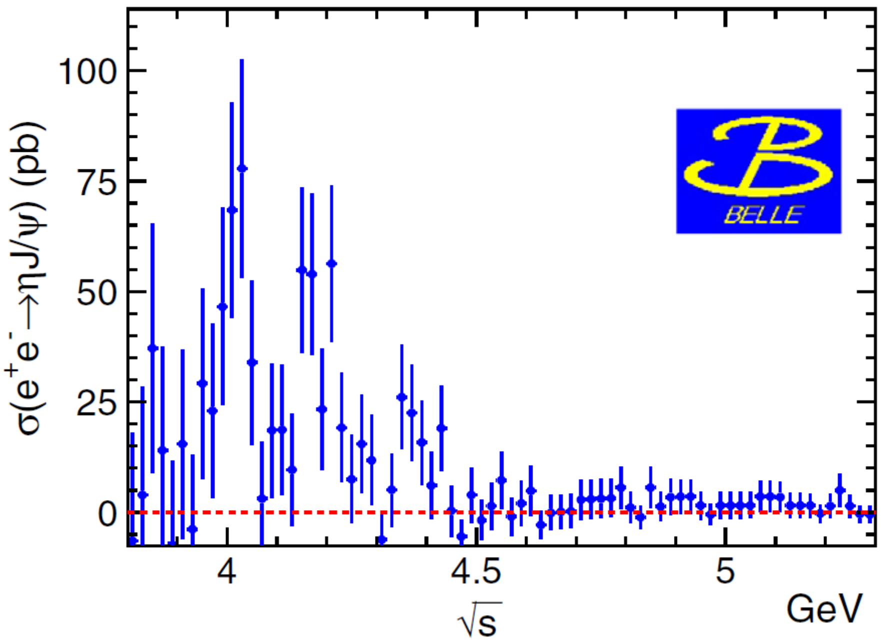
eV

transition rates to η J/Ψ are large, being of order 1 MeV/c^2

Cross section of $e^+e^- \to \eta\ J/\Psi$

- We find no evidence for the Y(4260), Y(4360), Ψ(4415) or Y(4660) in the $\eta\ J/\psi$ final states

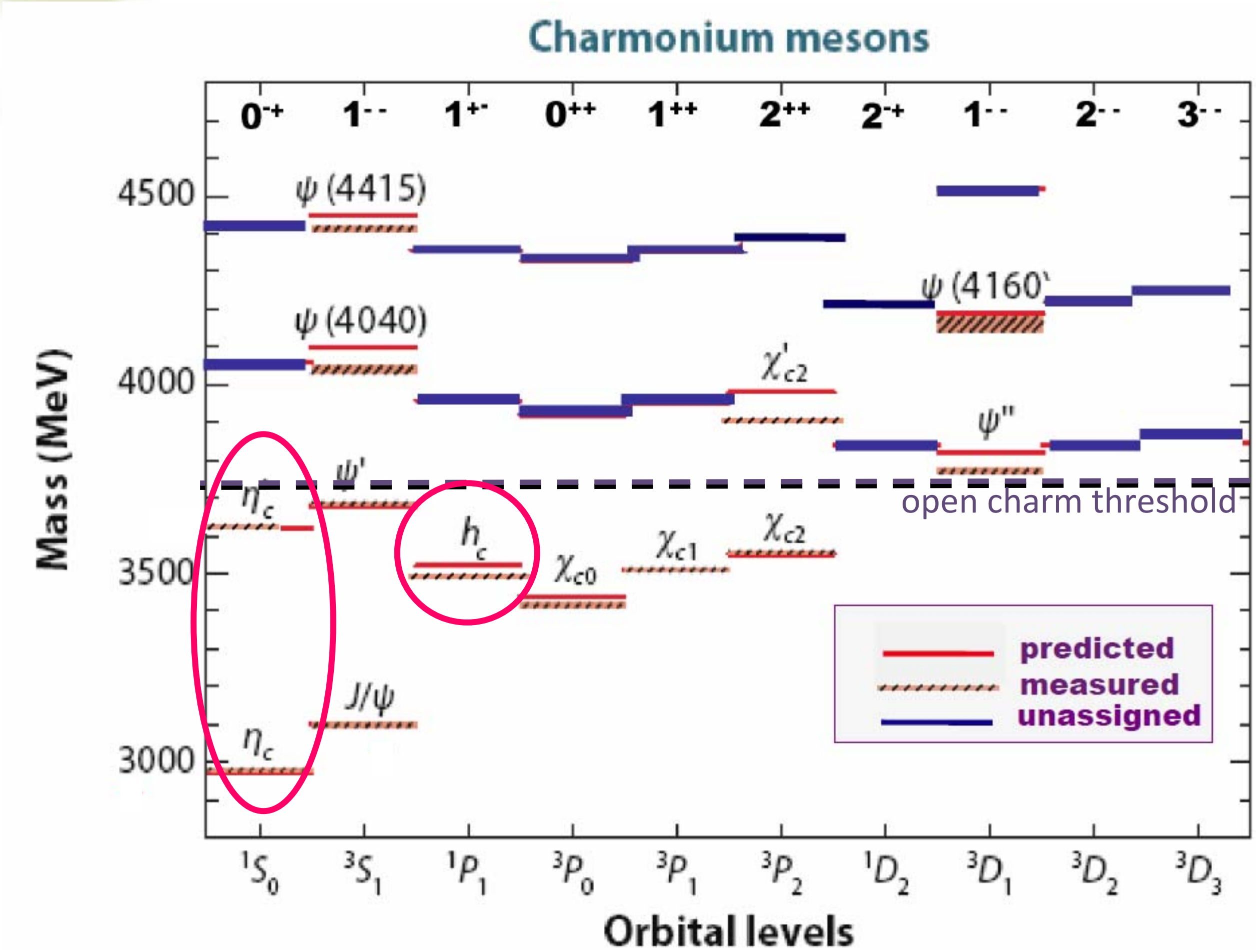
- The cross sections of $e^+e^- \to \eta\ J/\psi$ are around 70 pb and 50 pb at the Ψ(4040) and Ψ(4160) peaks, to be compared with around 20pb and 10pb measured in $e^+e^- \to \pi^+\pi^- J/\psi$



This is the first time that the $\psi(4040)$ and $\psi(4160)$ have been observed to decay to final states not involving charm meson pairs.

Spin singlet states: η_c $\eta_c(2S)$ h_c

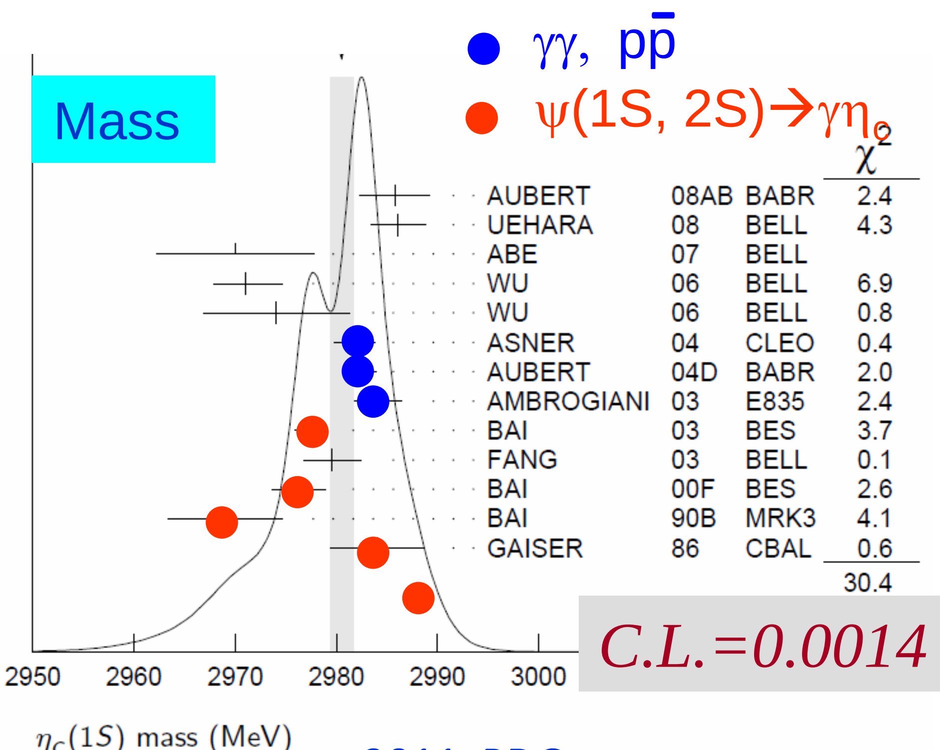
- Be produced in γ γ process, B decay, pp collision, ..
- Least-understood states below the DD threshold



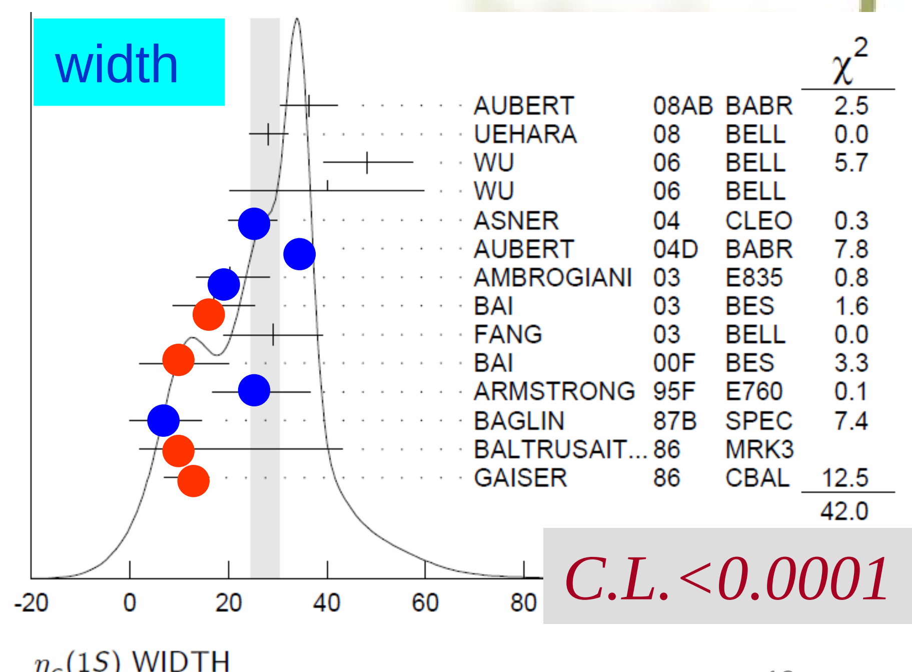
$\eta_c(1S)$

- S-wave spin-singlet ground state, first found by MarkII in 1980
  PRL 45, 1146 (1980)

- The mass & width
  J/ψ radiative transition: $M \sim 2978.0\,\mathrm{MeV}/c^2$, $\Gamma \sim 10\,\mathrm{MeV}$
  $\gamma\gamma$ process: $M = 2983.1 \pm 1.0\ \mathrm{MeV}/c^2$, $\Gamma = 31.3 \pm 1.9\ \mathrm{MeV}$

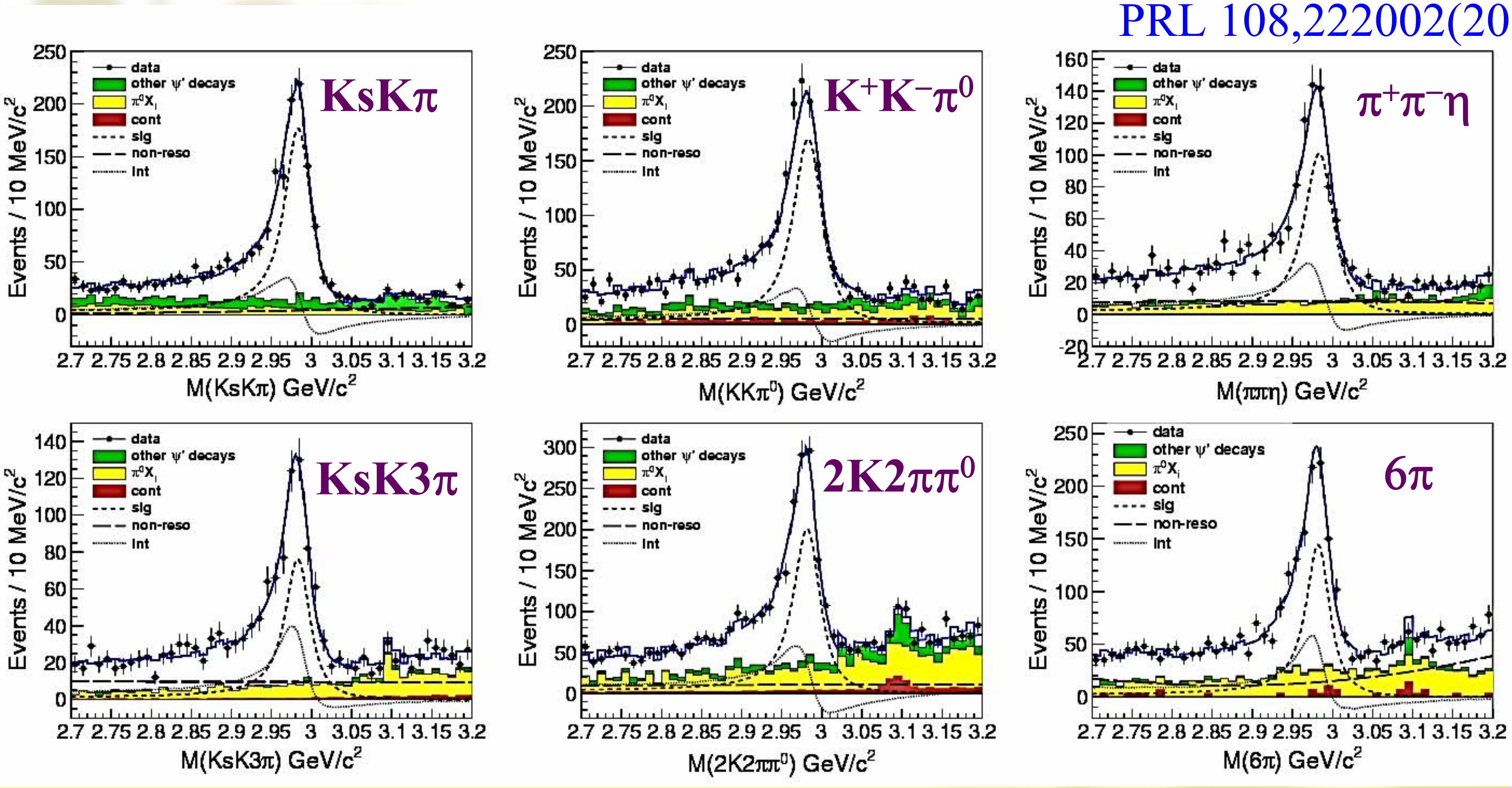


2011 PDG



Measure η_c in $\psi'\to\gamma\eta_c$

PRL 108,222002(2012)



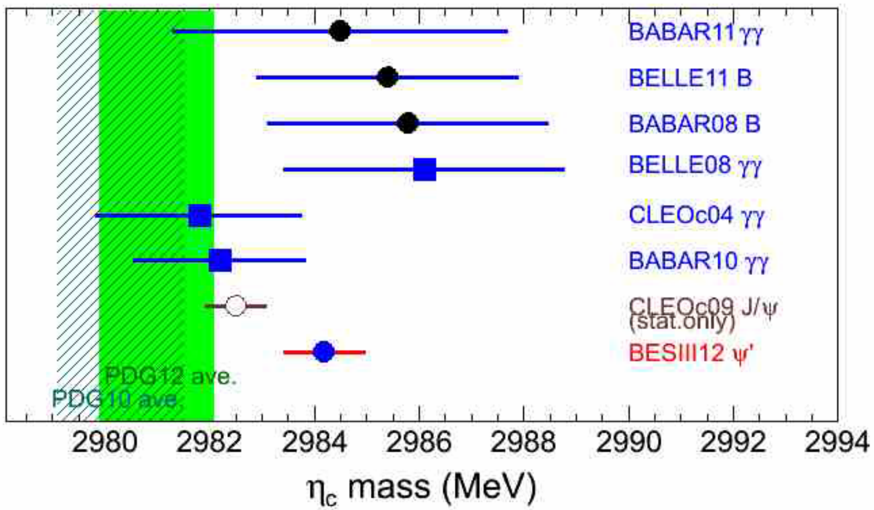
The interference between η_c and non-resonant is significant.

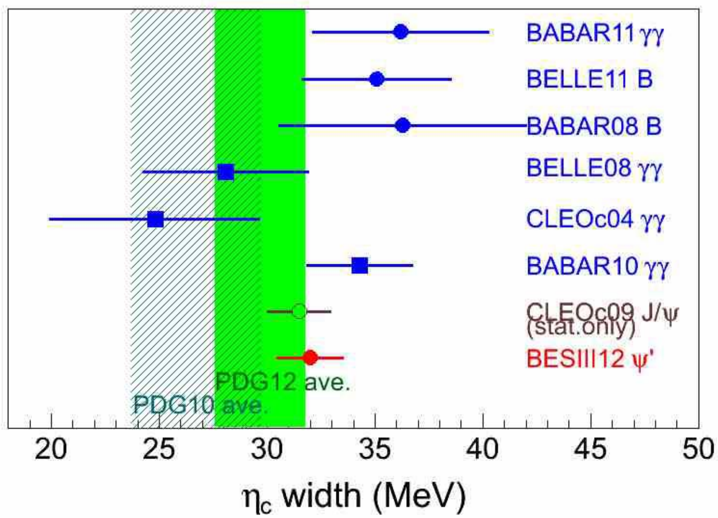
Simultaneous fit to 6 modes,

Mass = 2984.3 ± 0.6 ± 0.6 MeV/c²

Width = 32.0 ± 1.2 ± 1.0 MeV

Comparison with the η_c results

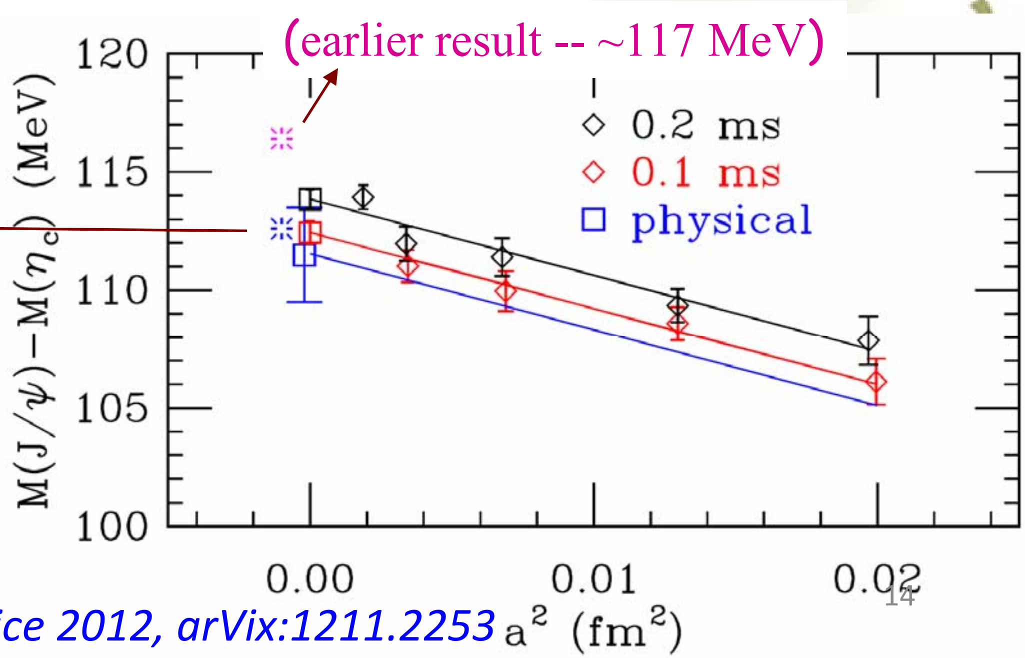




Hyperfine splitting (BESIII alone)

$\Delta M(1S) = \mathbf{112.5 \pm 0.8}$ MeV

Closer to prediction than earlier result



Lattice 2012, arVix:1211.2253

$\eta_c(2S)$

Crystal Ball's "first observation" of $\psi' \to \gamma X$ never been confirmed PRL 48 70 (1982); until Belle found it in $B \to K\eta_c(2S)$ in 2002.

Observed in different production mechanisms,

1. $B \to K\eta_c(2S)$
2. $\gamma\gamma \to \eta_c(2S) \to KK\pi$
3. double charmonium production
4. M1 transition $\psi' \to \gamma\eta_c(2S)$

   CLEO found no signals in 25M ψ'.

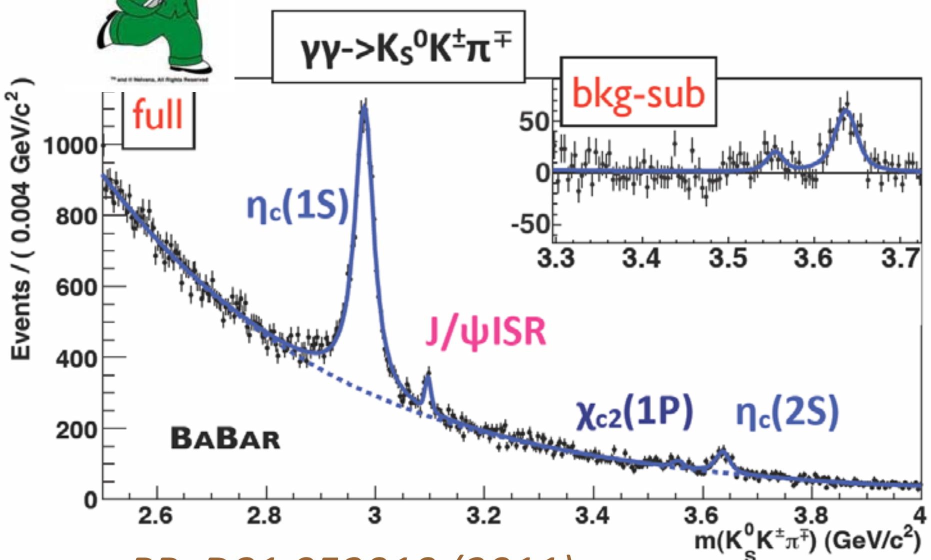
Belle: PRL 89 102001 (2002)
CLEOc: PRL 92 142001 (2004)
Belle: NPPS.184 220 (2008); PRL 98 082001(2007)
BaBar: PRL 92 142002 (2004); PR D72 031101(2005)
BaBar: PR D84 012004 (2011)

$$BF(\psi' \to \gamma\eta_c(2S)) < 7.6 \times 10^{-4}$$

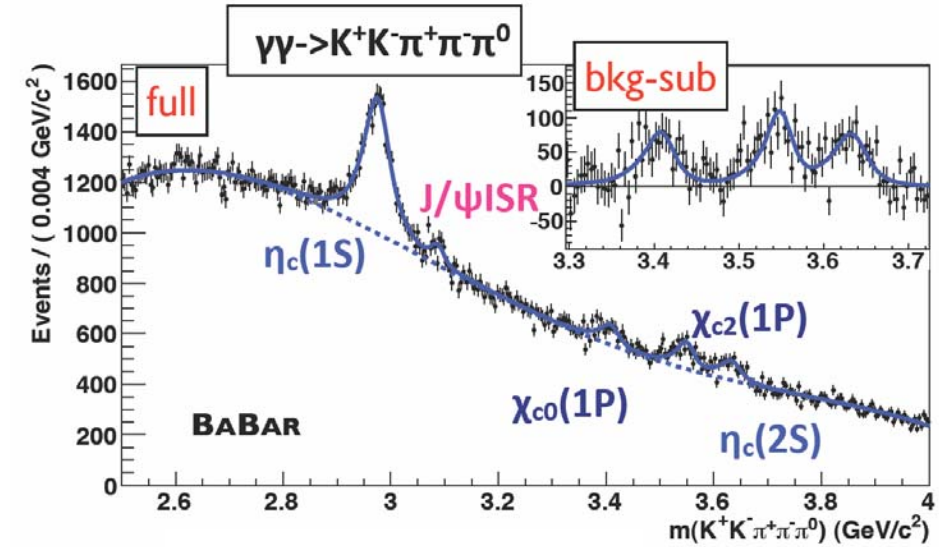
PRD 81 052002 (2010)

Experimental challenge : search for photons of 50 MeV

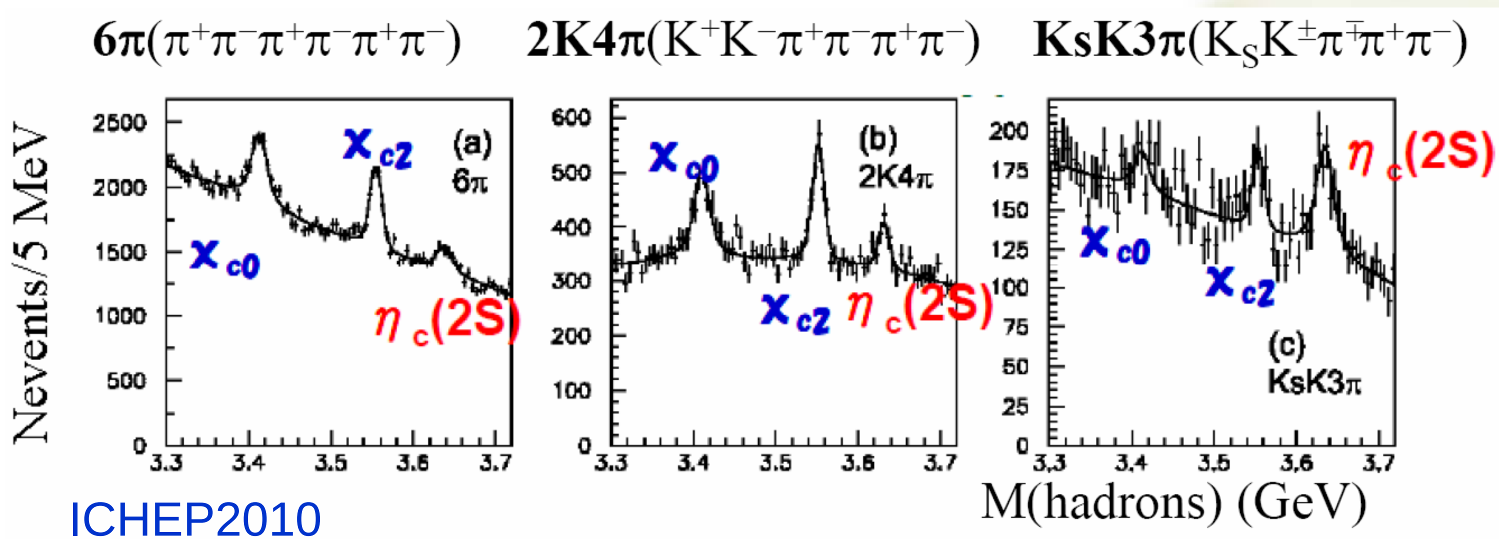
$\gamma\gamma \rightarrow \eta_c(1S/2S) \rightarrow K_sK\pi$; $KK3\pi$



PR D81 052010 (2011)



PR D84 012004 (2011)

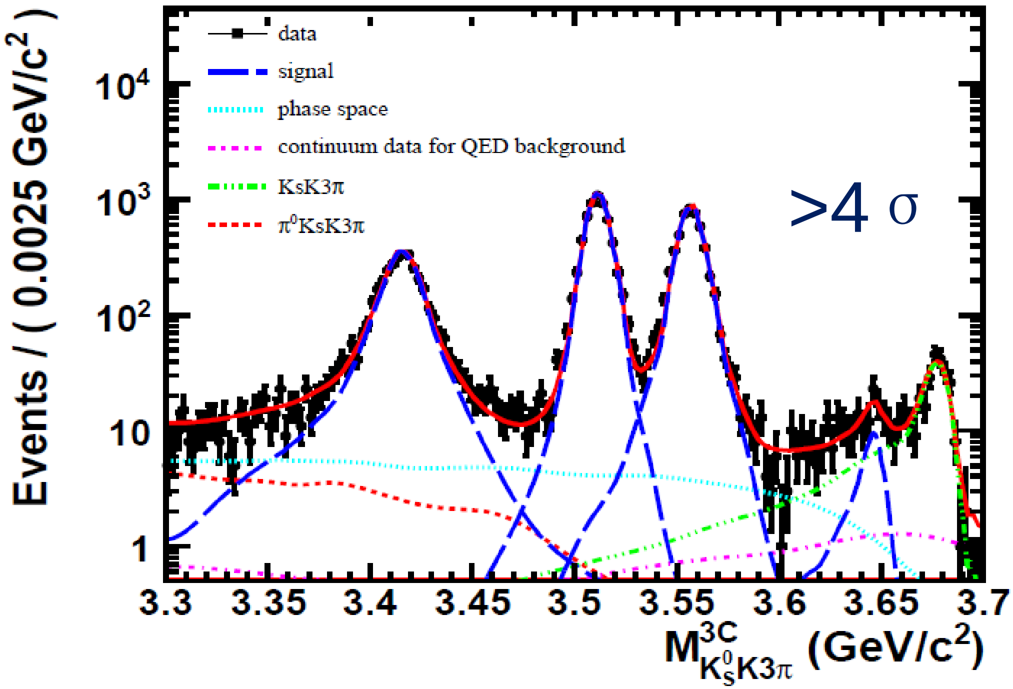


ICHEP2010

Evidence $\eta_c(2S) \to K_S K^{+-} \pi^{-+} \pi^{+}\pi^{-}$

PRD 87,052005(2013)

- For $\eta_c(2S)$, only two measured decay Brs are available: $KK\pi$ and $K^+K^- \pi^+ \pi^- \pi^0$
- $\psi' \to \gamma\eta_c(2S)$: M1 transition
- Search for more $\eta_c(2S)$ decay modes
- To measure the mass, width of $\eta_c(2S)$



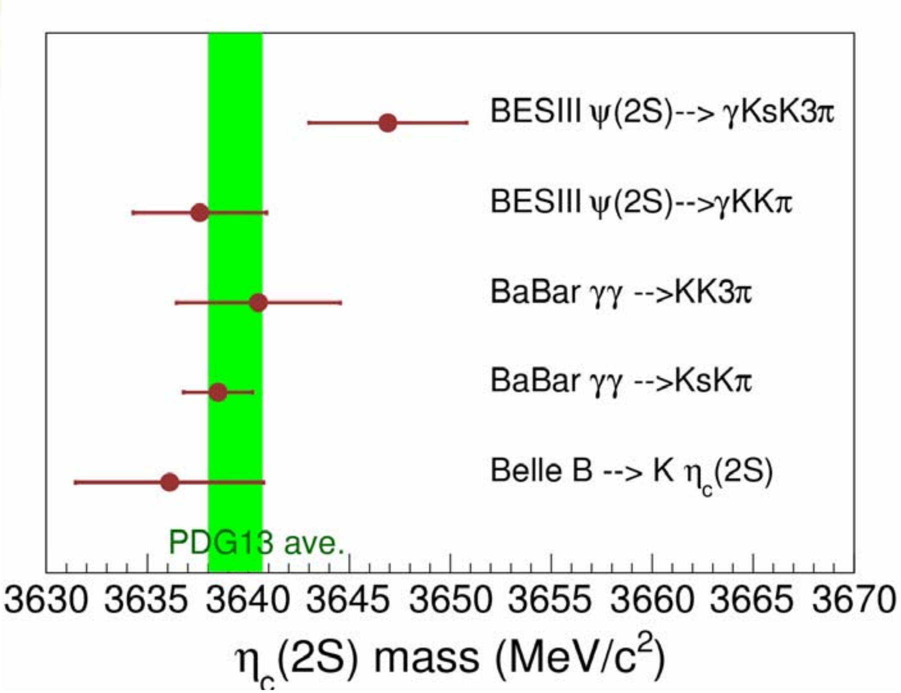
$M=3646.9\pm1.6\pm3.6$ MeV/c^2

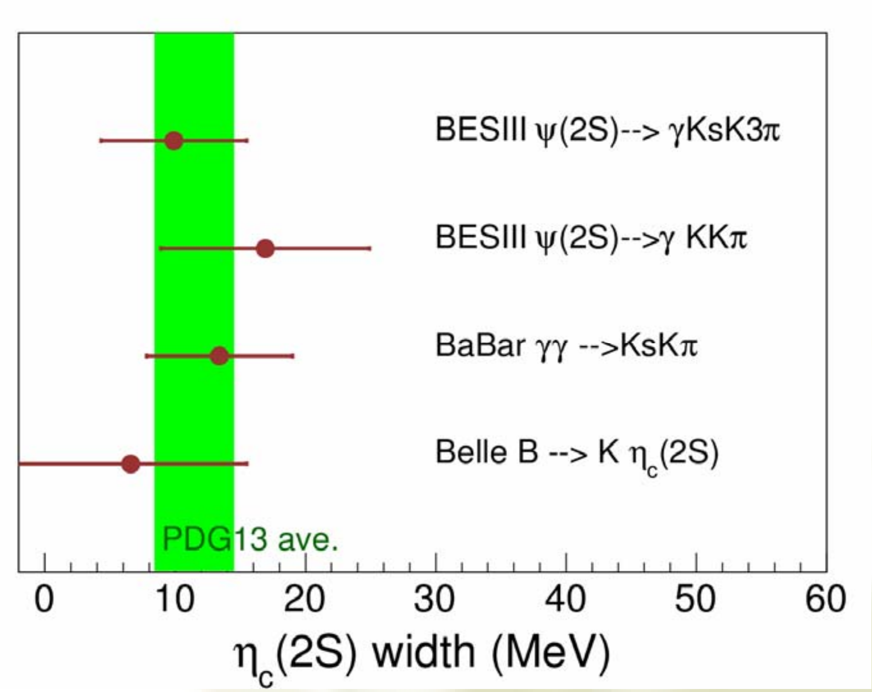
$\Gamma=9.2\pm4.8\pm2.9$ MeV

$B(\psi' \to \gamma\eta_c(2S)) \times B(K_S K^{+-} \pi^{-+} \pi^{+}\pi^{-})=(7.03\pm2.10\pm0.70)\times10^{-6}$

The measured M and Γ are consistent with values in PRL109, 042003 (2012)

Summary for $\eta_c(2S)$



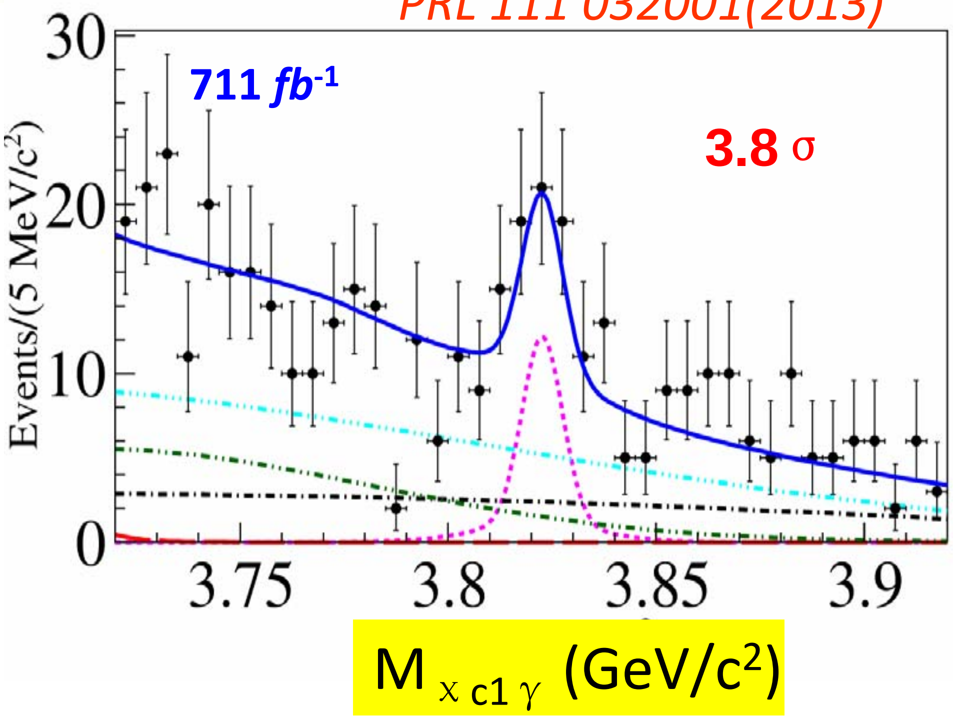


$X(3823) \rightarrow \chi_{c1}\gamma$ in $B \rightarrow \chi_{c1}\gamma K$

Simultaneous fit to $B^{\pm} \rightarrow \chi_{c1}\gamma K^{\pm}$ & $B^{0} \rightarrow \chi_{c1}\gamma K_S$

χ_{c1} reconstructed in $\gamma J/\psi$

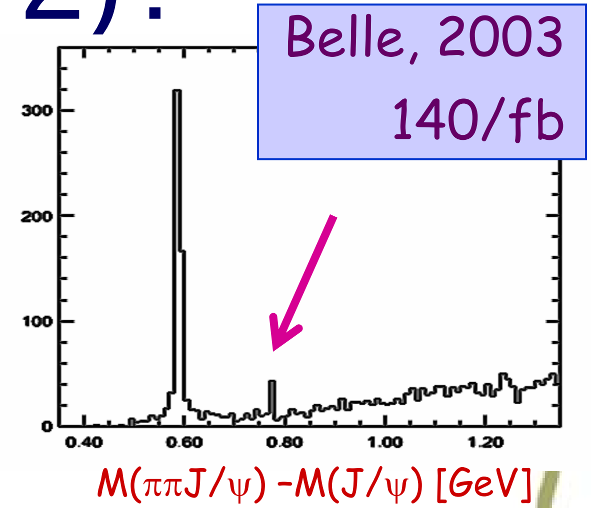
PRL 111 032001(2013)



$$M_{X(3823)} = M^{meas}_{X(3823)} - M^{meas}_{\psi'} + M^{PDG}_{\psi'}$$
$$= 3823.1 \pm 1.8 \pm 0.7\, MeV$$

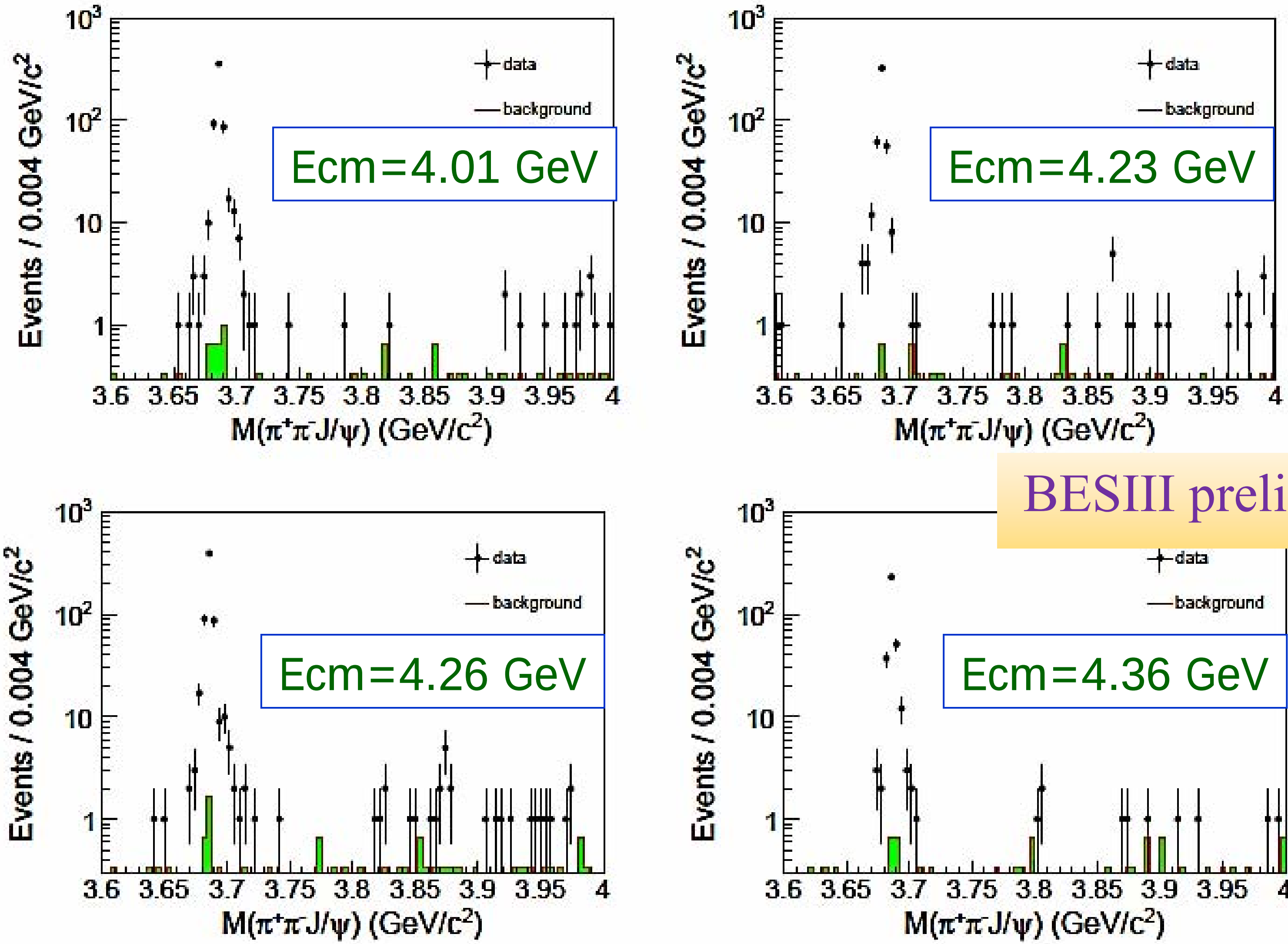
The measured mass and other properties are consistent with the missing $\psi_2(1\,^3D_2)$ state

What is the X(3872)?



- Mass: Very close to $\bar{D}^0 D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$ [LHCb]
- Production
  - in $\bar{p}p$/pp collison – rate similar to charmonia
  - In B decays – KX similar to $\bar{c}c$, K*X smaller than $\bar{c}c$
  - Y(4260)→γ+X(3872) [BESIII, see next slides]
- Nature (very likely exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron?)?
  - Mixture of excited χ_{c1} and $\bar{D}^0 D^{*0}$ bound state?
  - Many other possibilities (if it is not χ'_{c1}, where is χ'_{c1}?)

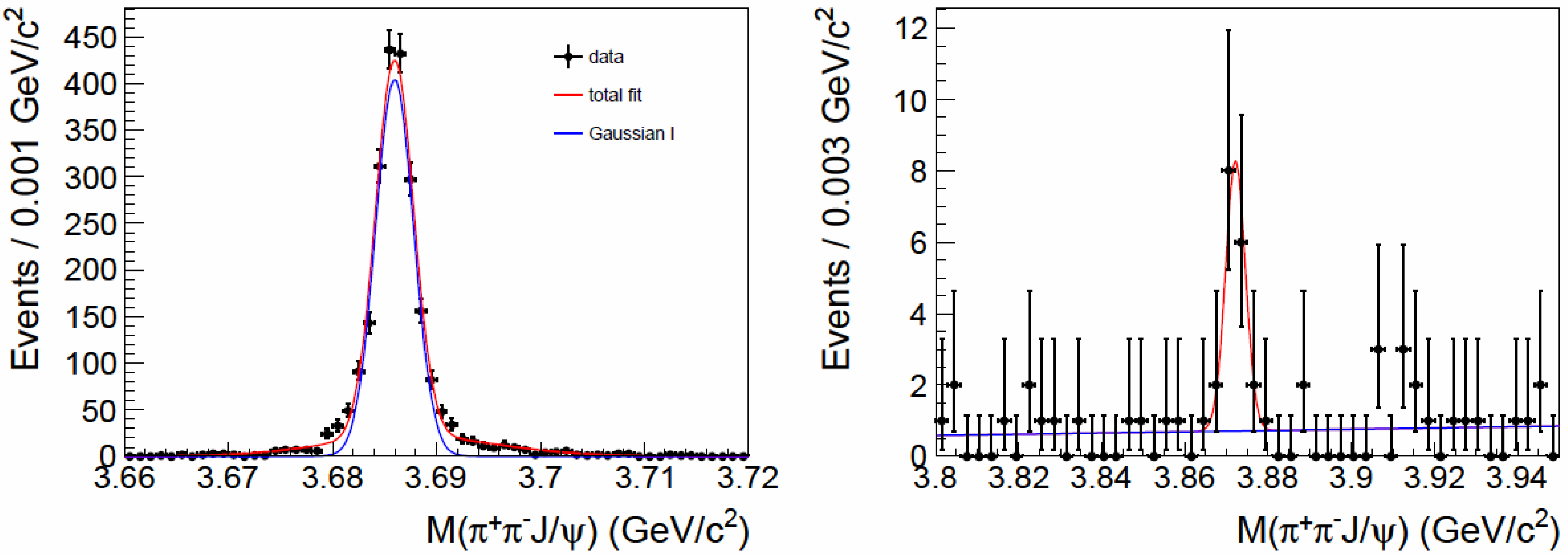
Observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$



BESIII preliminary

Clear ISR ψ' signal for data validation
X(3872) signal at around 4.23-4.26 GeV

Observation of $e^+e^- \to \gamma X(3872)$



ISR ψ' signal is used for rate, mass, and mass resolution calibration.

$N(\psi')=1242$; Mass=3685.96±0.05 MeV; $\sigma_M=1.84 \pm 0.06$ MeV

BESIII preliminary

N(X(3872))=15.0±3.9 **5.3σ**

M(X(3872)) = 3872.1±0.8±0.3 MeV [PDG: 3871.68 ±0.17 MeV]

Observation of $e^+e^- \to \gamma X(3872)$

$\sqrt{s}$ (GeV)	$\sigma^B[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (pb)
4.009	< 0.13 at 90% C.L.
4.230	$0.32 \pm 0.15 \pm 0.02$
4.260	$0.35 \pm 0.12 \pm 0.02$
4.360	< 0.39 at 90% C.L.

It seems X(3872) is from Y(4260) decays. At 4.26 GeV,
$\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb,

$$\frac{\sigma[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (5.6 \pm 2.0) \times 10^{-3}$$

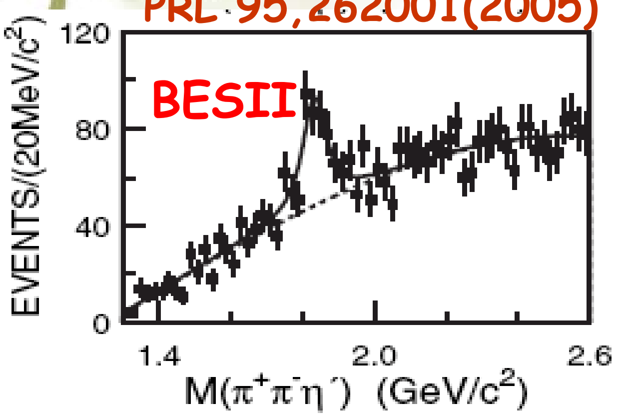
If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, (>2.6% in PDG)
$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 11.2\%$ Large transition ratio !

BESIII preliminary

light hadron spectroscopy

Confirmation of X(1835) and two new structures

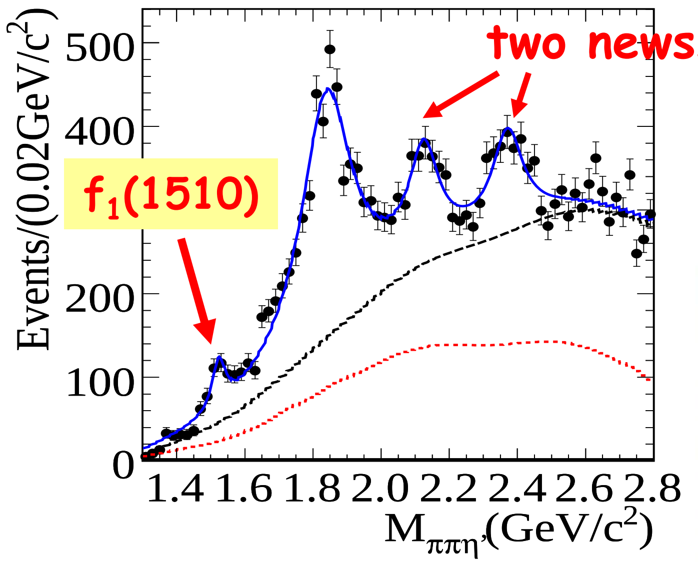
PRL 95,262001(2005)



$J/\psi \rightarrow \gamma\,(\eta'\pi^+\pi^-)$

BESIII: 225M J/ψ events, new structures!

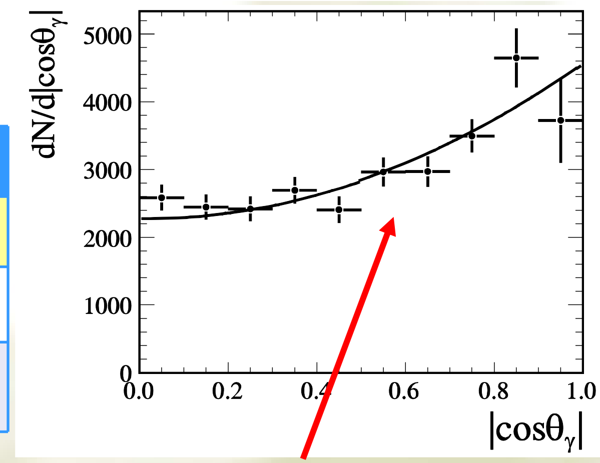
PRL 106, 072002(2011)



$BESII\ result(\text{Stat. sig.} \sim 7.7\sigma):$

$M = 1833.7 \pm 6.1(stat) \pm 2.7(syst)MeV$

$\Gamma = 67.7 \pm 20.3(\text{stat}) \pm 7.7(\text{syst})\text{MeV}$



BESIII fit results:

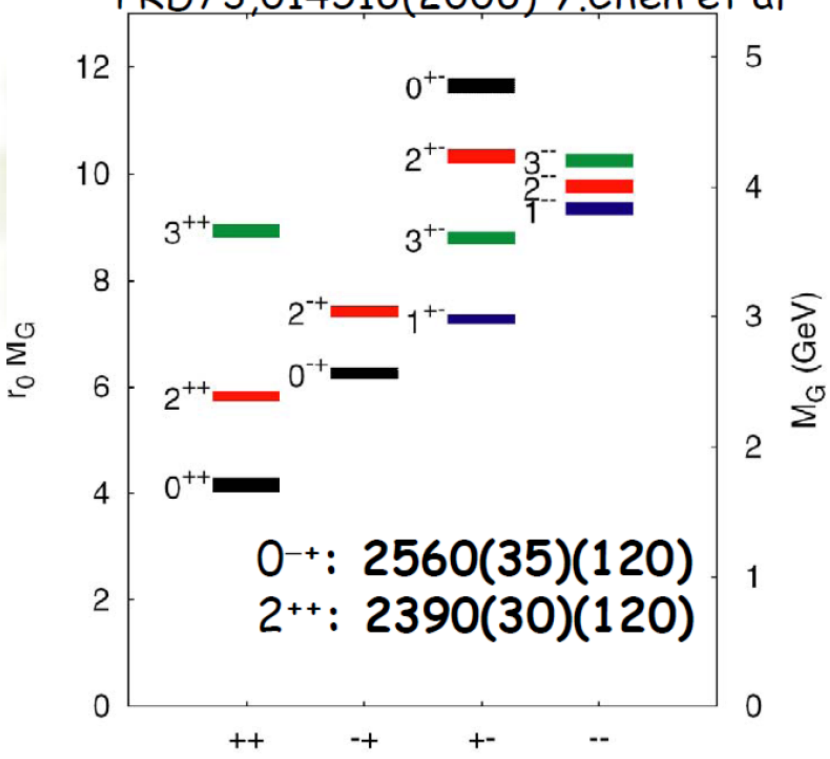
Resonance	M(MeV/c²)	Γ(MeV/c²)	Stat.Sig.
X(1835)	$1836.5 \pm 3.0^{+5.6}_{-2.1}$	$190.1 \pm 9.0^{+38}_{-36}$	>20 σ
X(2120)	$2122.4 \pm 6.7^{+4.7}_{-2.7}$	$83 \pm 16^{+31}_{-11}$	7.2 σ
X(2370)	$2376.3 \pm 8.7^{+3.2}_{-4.3}$	$83 \pm 17^{+44}_{-6}$	6.4 σ

X(1835) favors 0^{-+}

An amplitude analysis could help with interpretation for the additional new structures!

Possible theoretical explanation

PRD73,014516(2006) Y.Chen et al



✓It is the first time resonant structures are observed in the 2.3 GeV/c2 region, it is interesting since:

LQCD predicts that the lowest lying pseudoscalar glueball: around 2.3 GeV/c^2.

$J/\psi \to \gamma\pi\pi\eta'$ decay is a good channel for finding 0^{-+} glueballs.

✓Nature of X(2120)/X(2370)
pseudoscalar glueball ?
η/η' excited states?

Finally we need a full amplitude analysis to determine the property for the new structures, but there were many predictions which make the observation more interesting!

PRD82,074026,2010
J.F. Liu, G.J. Ding and M.L.Yan
PRD**83:114007,2011**
(J.S. Yu, Z.-F. Sun, X. Liu, Q. zhao),
and more…

η_c, η(1760) and X(1835) in $\gamma\gamma \to \eta' \pi^+ \pi^-$

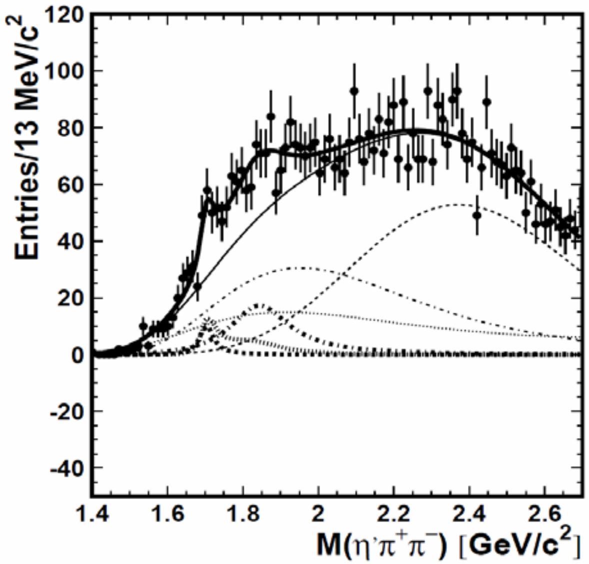
BELLE

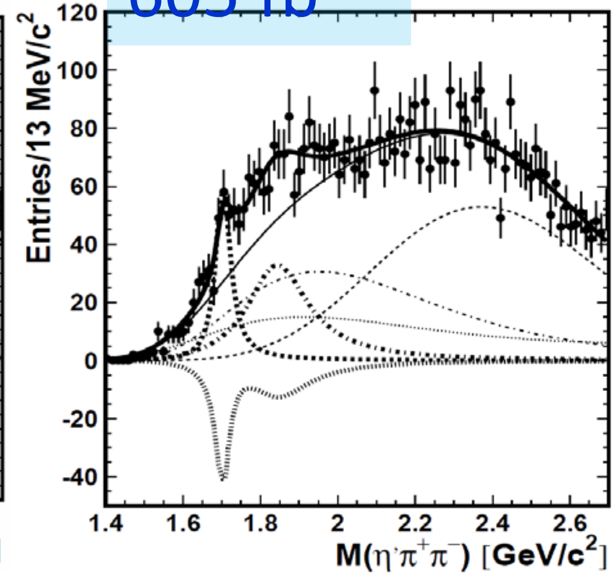
PRD 86, 052002 (2012)

605 fb^{-1}

Search for X(1835) in Belle experiment in two-photon process !

- ▼ X(1835) and η(1760) with interference (assuming $J^{PC}=0^{-+}$)
- ▼ No interference between resonant and non-resonant
- ▼ Two solutions (see Table)





No significant X(1835) signal --- 2.8 σ !

- ★ thin solid line: total bkg
- ★ thick dashed (dot-dashed, dotted) lines: the η(1760) (X(1835), the interference term)
- ★ thin dashed, dot-dashed and dotted lines: non-resonant, η'-sidebands and $\eta' \pi^+ \pi^-$X bkg components

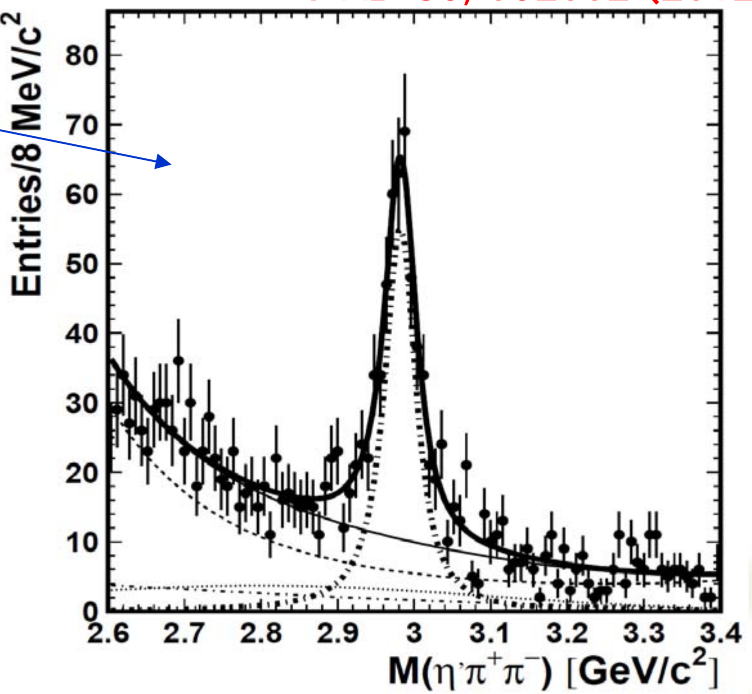
Parameter	One resonance	Two interfering resonances	
		Solution I	Solution II
		$X(1835)$	
M, MeV/c^2		1836.5 (fixed)	
Γ, MeV/c^2		190 (fixed)	
Y		$332^{+140}_{-122} \pm 73$	$632^{+224}_{-231} \pm 139$
Y_{90}		$<$ 650	$<$ 1490
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/$c^2$		$18.2^{+7.7}_{-6.7} \pm 4.0$	$35^{+12}_{-13} \pm 8$
$(\Gamma_{\gamma\gamma}\mathcal{B})_{90}$ eV/c^2		$<$ 35.6	$<$ 83
S, σ		2.8	
		$\eta(1760)$	
M, MeV/c^2	$1768^{+24}_{-25} \pm 10$	$1703^{+12}_{-11} \pm 1.8$	
Γ, MeV/c^2	$224^{+62}_{-56} \pm 25$	$42^{+36}_{-22} \pm 15$	
Y	$465^{+131}_{-124} \pm 60$	$52^{+35}_{-20} \pm 15$	$315^{+223}_{-165} \pm 88$
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV/$c^2$	$28.2^{+7.9}_{-7.5} \pm 3.7$	$3.0^{+2.0}_{-1.2} \pm 0.8$	$18^{+13}_{-10} \pm 5$
S, σ	4.7	4.1	
ϕ		$(287^{+42}_{-51})^\circ$	$(139^{+19}_{-9})^\circ$

◆ The fit with only η(1760) signal is also tried

$M(\eta'\pi^+\pi^-)$ in η_c mass region

- **Assuming no interference between η_c and background**

PRD 86, 052002 (2012)



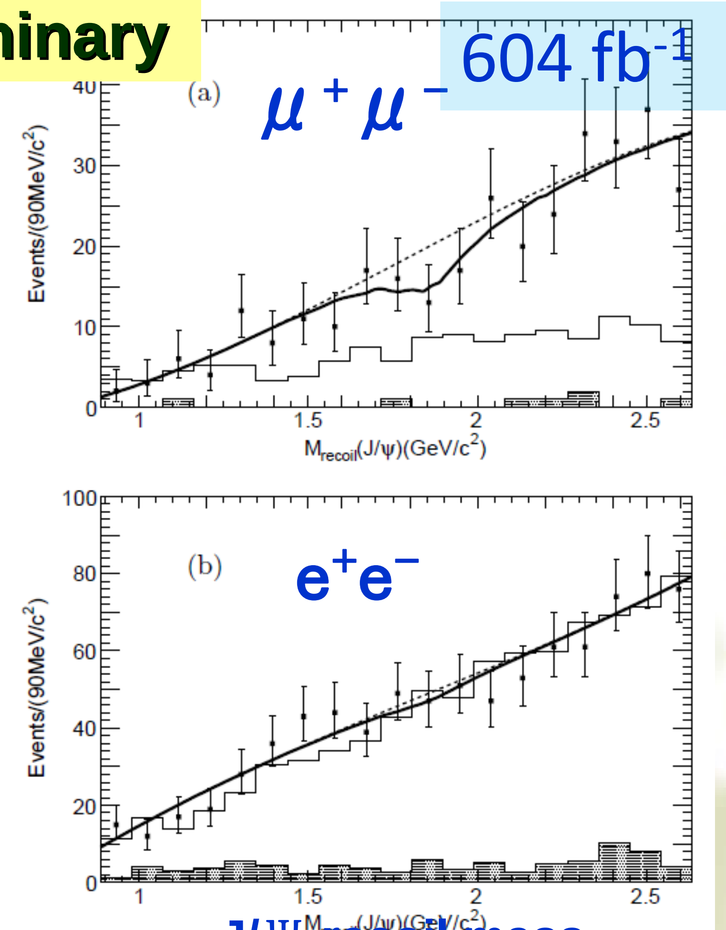
★ The fit with interference was also tried. The results of mass and width of η_c are almost the same. The differences are taken as sys error.

Parameters	This work	PDG
Y	$486^{+40}_{-39} \pm 53$	
M, MeV$/c^2$	$2982.7 \pm 1.8 \pm 2.2$	2980.3 ± 1.2
Γ, MeV$/c^2$	$37.8^{+5.8}_{-5.3} \pm 2.8$	26.7 ± 3
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV$/c^2$	$50.5^{+4.2}_{-4.1} \pm 5.6$	194 ± 97
$\mathcal{B}$, %	0.87 ± 0.20	2.7 ± 1.1

Search for $e^+e^- \to J/\Psi + X(1835)$ at 10.6 GeV

- **Search for X(1835) in Belle experiment in e^+e^- continuum process !**
- **C-even glueballs can be studied in $e^+e^- \to \gamma^* \to H+G_J$, H denotes a ccbar quark pair or charmonium state**

Preliminary



J/Ψ recoil mass

- **Signal pdf is from MC with mass and width fixed to the values from BESIII [PRL 106, 072002, 2012]**
- **90% C.L. upper limit on the σ (e+e-**
- **$\to J/\Psi$ X(1835))Br(X(1835) $\to$>2**
- **charged tracks)<1.3 fb**

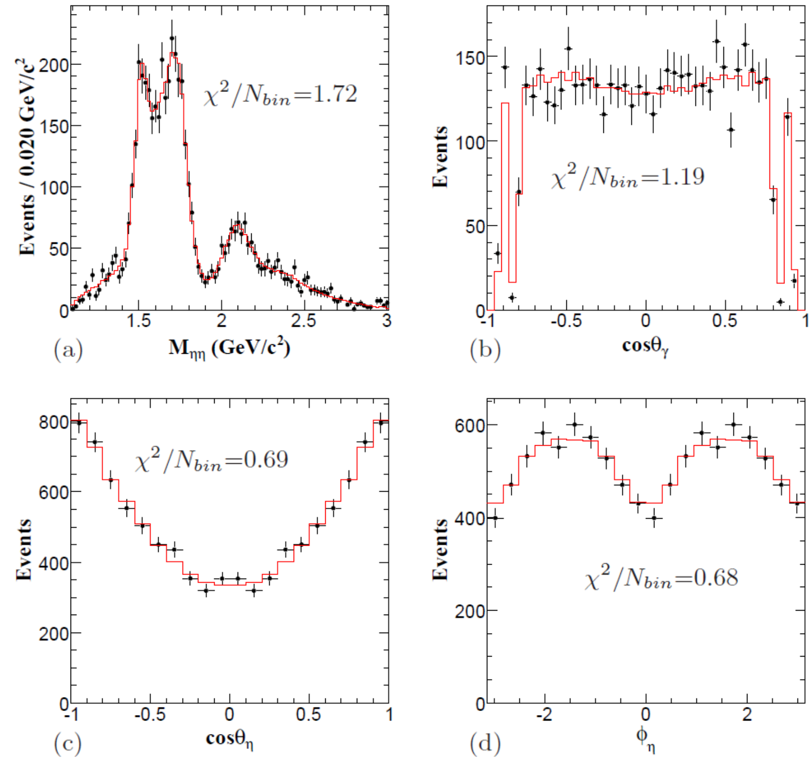
Mode	N_{signal}	$N_{\mathrm{backgroud}}$
$M_{\mathrm{recoil}}(J/\psi \to \mu^+\mu^-)$	-20.0 ± 20.0	340.0 ± 18.0
$M_{\mathrm{recoil}}(J/\psi \to e^+e^-)$	-7.5 ± 7.6	859.5 ± 29.2

open histogram: J/Ψ sidebands
shaded histogram: charmed + uds background

PWA of J/ψ → γηη

PRD 87,092002(2013)

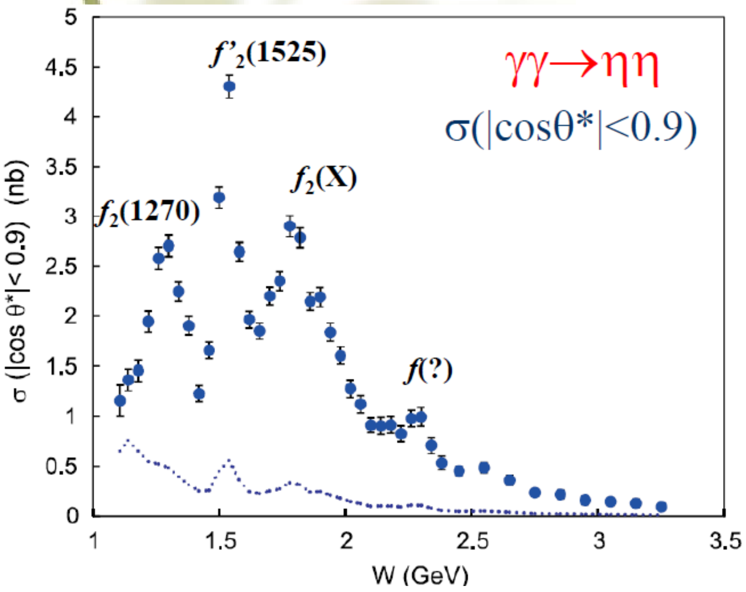
- Search for glueballs, hybrids and multi-quarks
- LQCD: the lowest mass glueball with 0^{++} is in the mass region from 1.5-1.7 GeV
- The mixing with q $\underline{q}$ nonet mesons makes the identification of the glueballs difficult
- Radiative J/ψ decay is a gluon-rich process
- J/ψ radiative decay to two pseudoscalar mesons offers a very clean laboratory to search for scalar and tensor glueballs



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 σ
$f_0(1710)$	$1759\pm6^{+14}_{-25}$	$172\pm10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	25.0 σ
$f_0(2100)$	$2081\pm13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28}) \times 10^{-4}$	13.9 σ
$f_2'(1525)$	$1513\pm5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30}) \times 10^{-5}$	11.0 σ
$f_2(1810)$	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 σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$	7.6 σ

$\gamma\gamma \to \eta\eta$

PRD 82, 114031 (2010)



Fits for low-mass resonances with partial-wave decomposition

Parameter	Fit (1.1-1.64GeV)	Unit
Mass $f_0(Y)$	$1262\ ^{+51}_{-78}\ ^{+82}_{-103}$	MeV/c²
Width	$484\ ^{+246}_{-170}\ ^{+246}_{-263}$	MeV
$\Gamma_{\gamma\gamma}$ B(ηη)	$121\ ^{+133}_{-53}\ ^{+169}_{-106}$	eV
$\Gamma_{\gamma\gamma}$ B(ηη) $f_2(1270)$	$11.5\ ^{+1.8}_{-2.0}\ ^{+4.5}_{-3.7}$	eV
χ^2 (ndf)	137.1 (119)	

Parameter	Fit (1.1-2.0GeV)	Unit
Mass	$1737 \pm 9\ ^{+198}_{-65}$	MeV/c²
Width $f_2(X)$	$228\ ^{+21}_{-20}\ ^{+234}_{-153}$	MeV
$\Gamma_{\gamma\gamma}$ B(ηη)	$5.2\ ^{+0.9}_{-0.8}\ ^{+37.3}_{-4.5}$	eV
χ^2 (ndf)	311.4(204)	

Confirmation of $f'_2(1525)$ amplitude

Parameter	Fit (1.1-1.64GeV)	Unit	χ^2 (ndf)
$\Gamma_{\gamma\gamma}$ B(ηη)	$f'_2(1525)$		
Sol. A	$23.1\ ^{+2.6}_{-2.8}$	eV	136.4 (119)
Sol. B	$8.0\ ^{+2.0}_{-1.5}$	eV	137.2 (119)
Sol. C	$5.0\ ^{+5.8}_{-5.0}$	eV	138.6 (119)

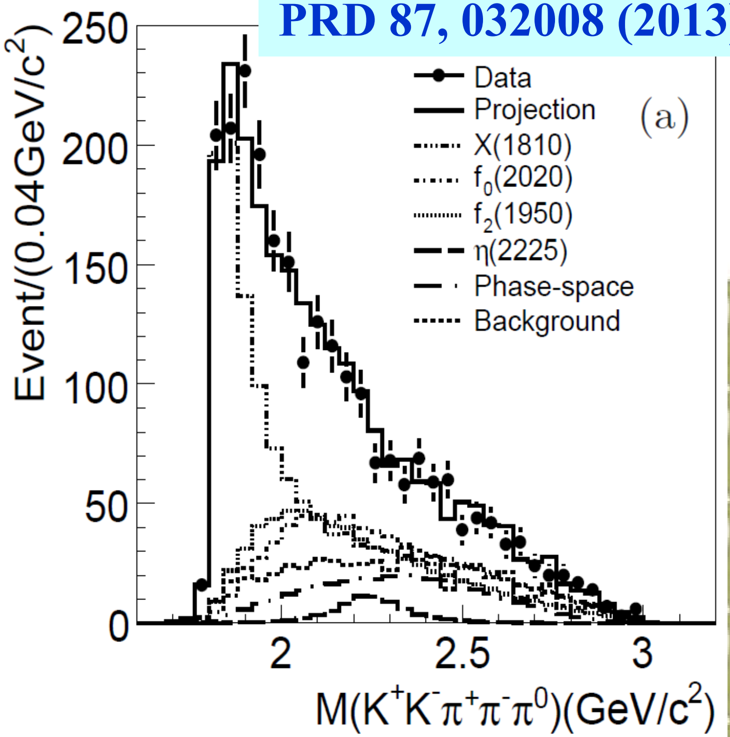
Structures are very complicated !

PDG: Product of $\Gamma_{\gamma\gamma}$ and B(ηη)
$f_2(1270)$: 12.1 ± 2.8 eV : consistent
$f'_2(1525)$: 8.3 ± 2.1eV :

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

- X(1810) was observed in $J/\psi \to \gamma \omega \phi$ by BESII [PRL96,162002]
- PWA: 0^{++} favors 0^{-+} or 2^{++} (>10 σ)
- $J/\psi \to \gamma \omega \phi$ is a doubly OZI suppressed process
- Possible interpretations: a tetraquark state, a hybrid, or a glueball state, a dynamical effect arising from intermediate meson rescattering, or a threshold cusp of an attracting resonance.

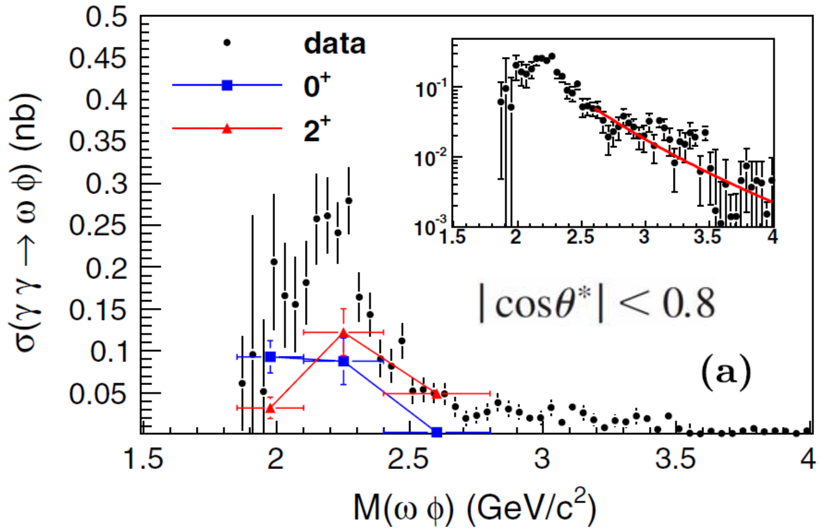
PRD 87, 032008 (2013)



Resonance	J^{PC}	$M(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV}/c^2)$	Events	$\Delta\mathcal{S}$	Δndf	Significance
$X(1810)$	0^{++}	1795 ± 7	95 ± 10	1319 ± 52	783	4	$> 30\sigma$
$f_2(1950)$	2^{++}	1944	472	665 ± 40	211	2	20.4σ
$f_0(2020)$	0^{++}	1992	442	715 ± 45	100	2	13.9σ
$\eta(2225)$	0^{-+}	2226	185	70 ± 30	23	2	6.4σ
phase space	0^{-+}	—	—	319 ± 24	45	2	9.1σ

$\gamma\gamma \to \omega\omega, \phi\phi, \omega\phi$

PRL 108, 232001 (2012)



In order to search for possible structures in low mass region, we did $\gamma\gamma \to VV$

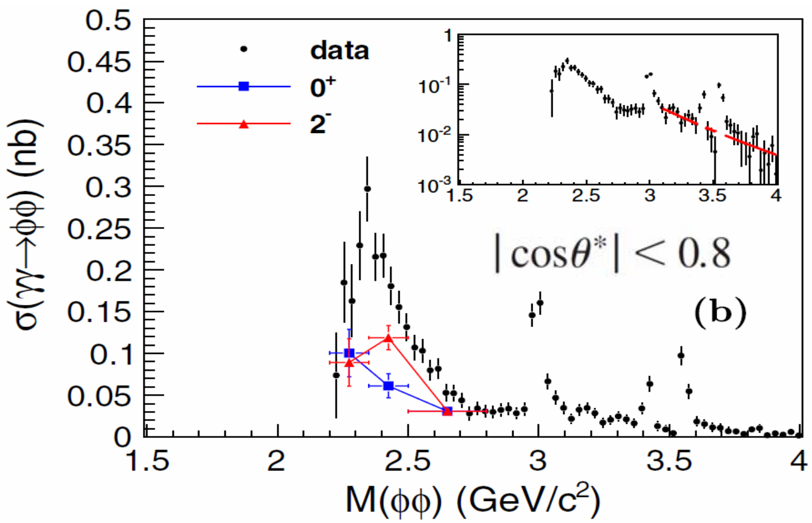
$$\sigma_{\gamma\gamma\to VV}(W_{\gamma\gamma}) = \frac{\Delta n}{\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}\epsilon(W_{\gamma\gamma})\Delta W_{\gamma\gamma}}$$

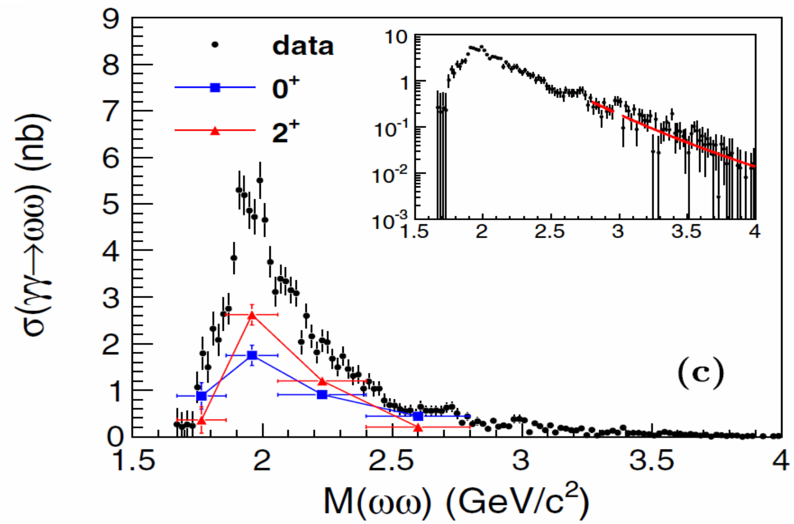
$\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}$: the differential luminosity

ϵ: efficiency

$\Delta W_{\gamma\gamma}$: bin width

Δn: the number of events in the $\Delta W_{\gamma\gamma}$ bin.



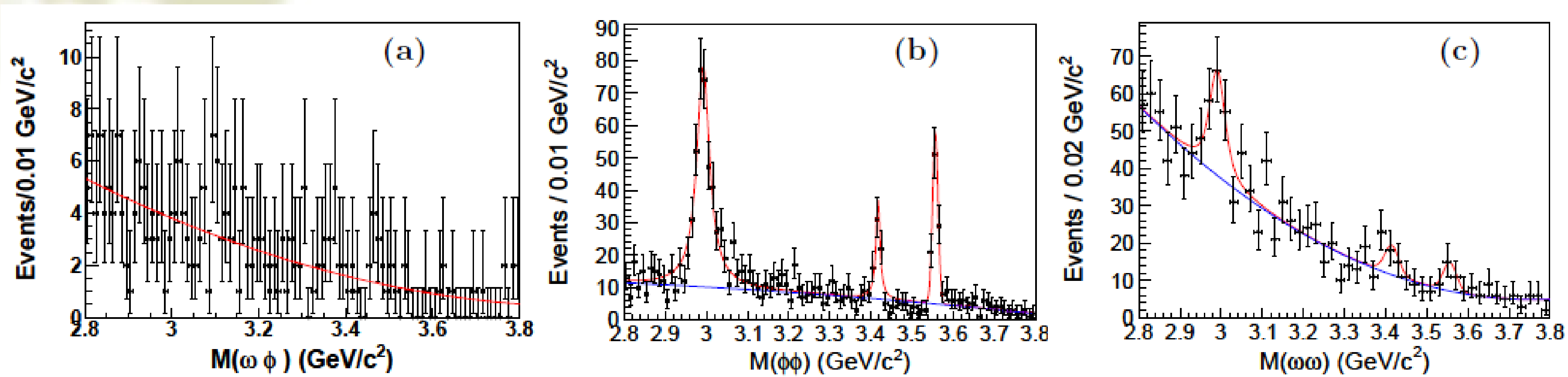


there are at least two different J^P components (J=0 and J=2)

$\Gamma_{\gamma\gamma}\mathcal{B}(X \to VV)$ (eV) for η_c, χ_{c0} and χ_{c2}:

Fits: three incoherent BW $\otimes$ double Gaussian + 2nd order Chebychev polynomial

PRL 108, 232001 (2012)



Results for $\Gamma_{\gamma\gamma}\mathcal{B}(X \to VV)$ (eV) for η_c, χ_{c0} and χ_{c2}. The upper limits are obtained at the 90% confidence level.

Mode	$\omega\phi$	$\phi\phi$	$\omega\omega$
η_c	< 0.49	$7.75 \pm 0.66 \pm 0.62$	$8.67 \pm 2.86 \pm 0.96$
χ_{c0}	< 0.34	$1.72 \pm 0.33 \pm 0.14$	< 3.9
χ_{c2}	< 0.04	$0.62 \pm 0.07 \pm 0.05$	< 0.64

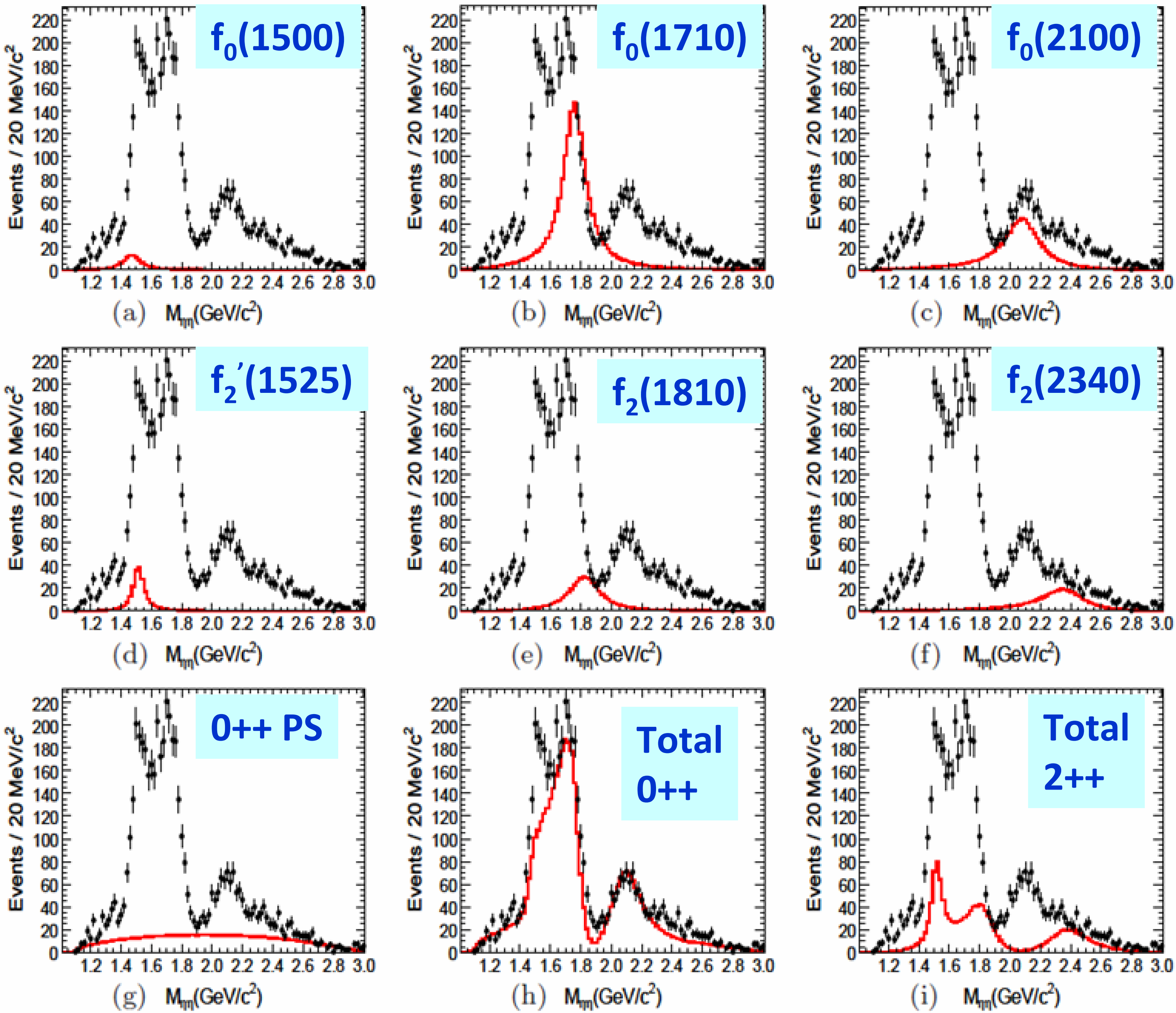
The measurements of $\Gamma_{\gamma\gamma}\mathcal{B}(X \to \phi\phi)$ are consistent with results [Eur. Phys. J. C **53**, 1 (2008)] with improved precision.

Summary & Outlook

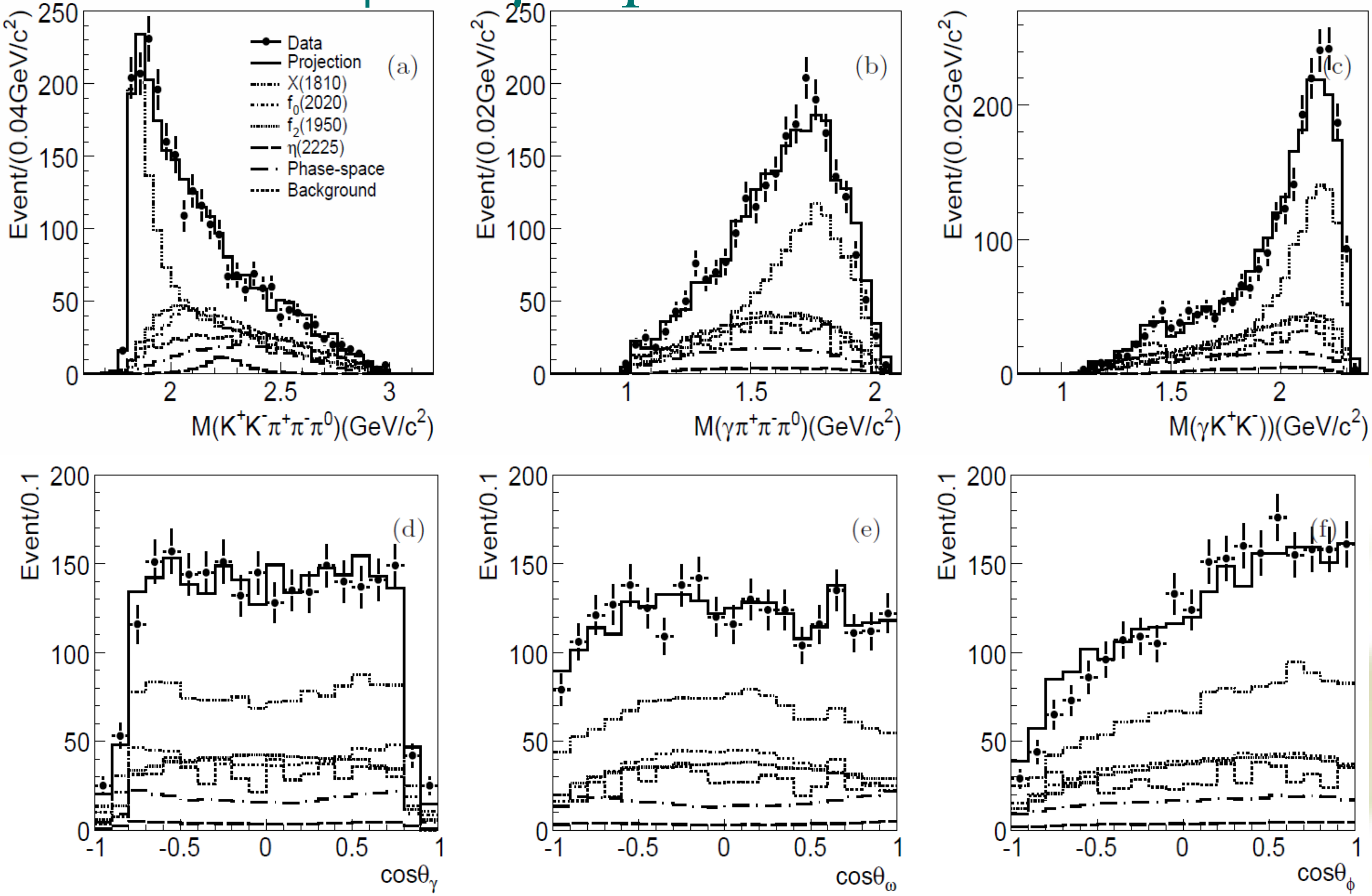
- Charmonium states provide a platform to study non-perturbative mechanism.
- Below the open-charm threshold: Spin-singlet states η_c , h_c , $\eta_c(2S)$ have been measured
- Lots of discoveries, expected and unexpected
  - Xc_{c2}' is assigned; X(3823) is consistent with $y_2(1\ ^3D_2)$
  - Are the X/Y states really new? Or the missing charmonium states X_{c1}'? What's their nature?
- Future potential model, Lattice QCD, sum rules, novel method
- BESIII and future experiments, Panda, Belle II, have chance to establish not-yet-observed states.

- Many interesting states are observed:
  X(1835)(0^{-+}), X($\omega\ \phi$)(0^{++}), …
- Some of them may be exotic states candidates.
- Where is lowest scalar/ pseudo-scalar glueball(f_0(1500), f_0(1710), x($\omega\ \phi$)?...)
- Troubled by the possible mixing between glueball and $q\underline{q}$, it's hard to distinguish an exotic state from normal states.
- Amplitude analysis is needed to determine the property of these states.

Thanks!

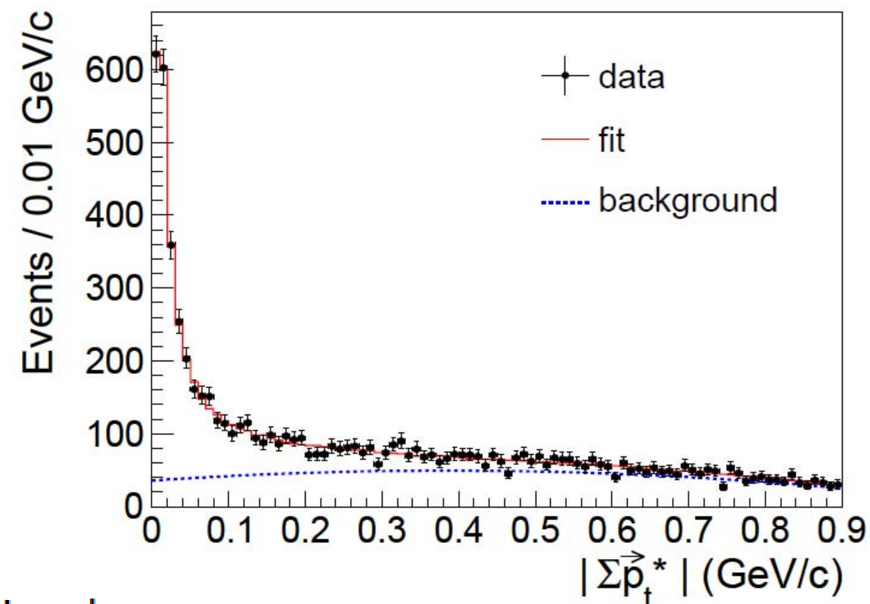

f0(1500)
f0(1710)
f0(2100)
f2'(1525)
f2(1810)
f2(2340)
0++ PS
Total 0++
Total 2++
Events / 20 MeV/c2
Mηη(GeV/c2)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)

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

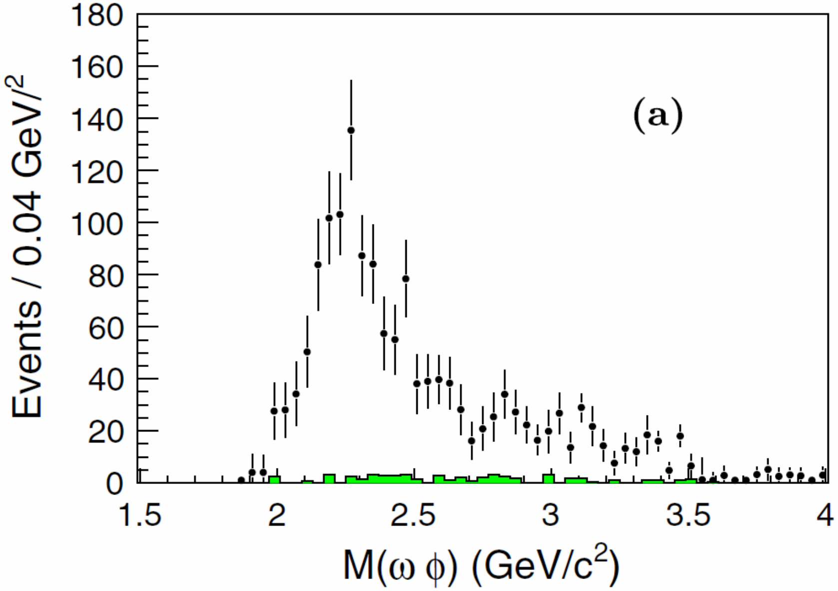


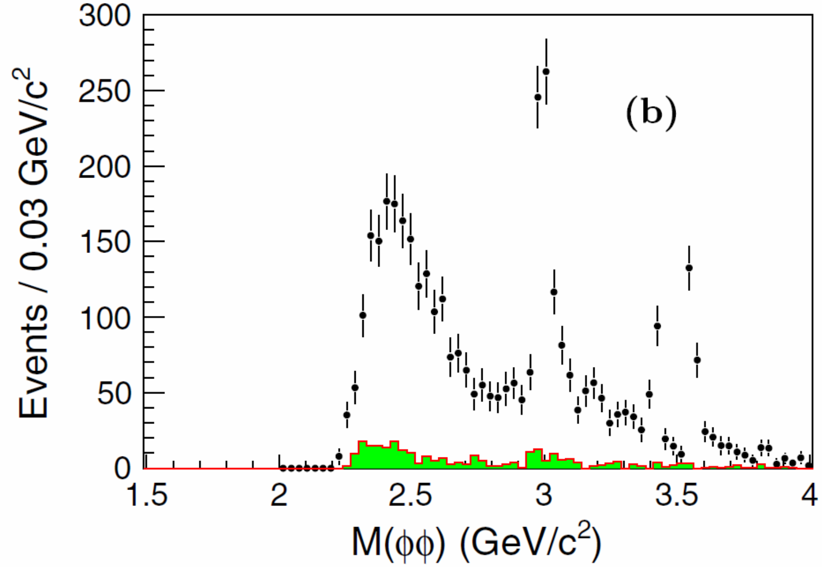
VV ($V = \omega$ or ϕ) invariant mass distributions:

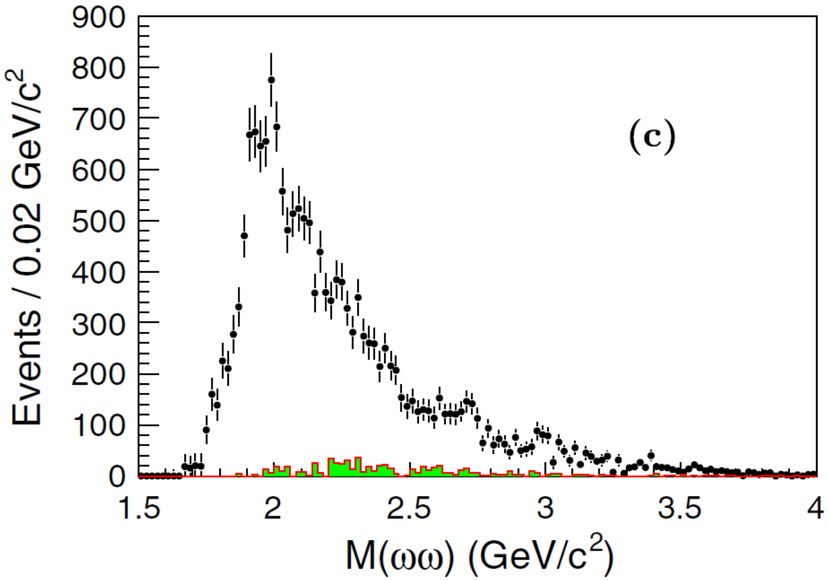
$|\sum \vec{P}_t^*|$: the magnitude of the vector sum of the final particles' transverse momenta in the e^+e^- C.M. frame.



N(VV) in each VV mass bin is obatined by fitting the $|\sum \vec{P}_t^*|$ distribution.
Signal pdf: MC simulation
Background pdf: 2nd Cheby. poly.







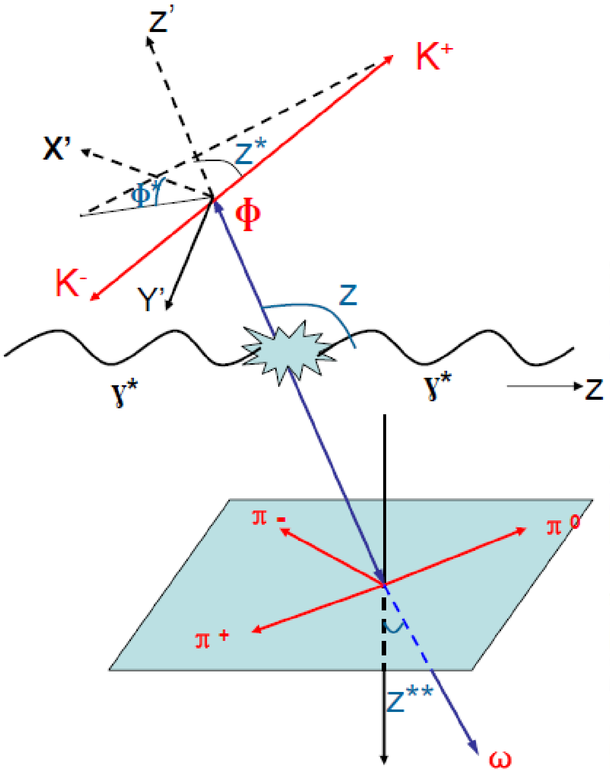
The shaded histograms are from the corresponding normalized sidebands

There are some obvious structures in the low VV invariant mass region. We did spin-parity analysis.

Spin-parity analysis:

For $\gamma\gamma \to VV$, five angles are kinematically independent: z, z^*, z^{**}, ϕ^*, and ϕ^{**}.
Using $\omega\phi$ as an example:

- z: cosine of the scattering polar angle of ϕ in the $\gamma\gamma$ C.M. system;
- z^* and ϕ^*: the cosine of the helicity angle of K^+ in the ϕ decays and the azimuthal angle defined in the ϕ rest frame with respect to the $\gamma\gamma \to \omega\phi$ scattering plane;
- z^{**} and ϕ^{**}: the cosine of the helicity angle of normal direction to the decay plane of the $\omega \to \pi^+\pi^-\pi^0$ and the azimuthal angle defined in the ω rest frame.



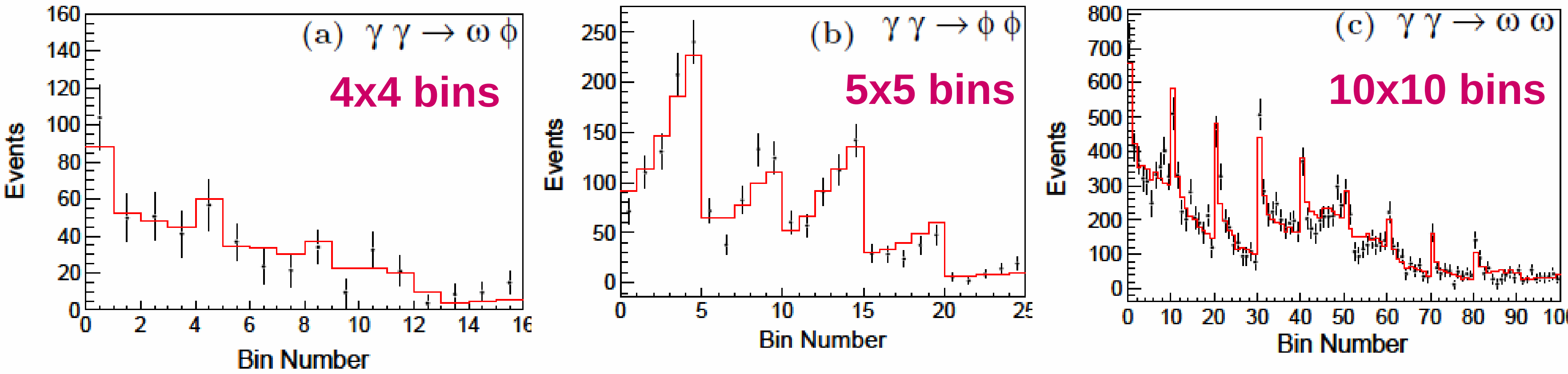
transversity angle (ϕ_T): $\phi_T = |\phi^* + \phi^{**}|/2\pi$
polar-angle product (Π_θ): $\Pi_\theta = [1-(z^*)^2][1-(z^{**})^2]$

N_{event} is obtained by fitting the $|\sum \vec{P}_t^*|$ distribution in each ϕ_T and Π_θ bin in the 2D space.

The number of event projections in the 2D space of the transversity angle and polar-angle product

M(VV)<2.8 GeV/c^2

Histograms: the best fits with different J^P components



- for $\omega\phi$: a mixture of 0^+ (S-wave) and2^+ (S-wave) describes data with $\chi^2/ndf = 0.9$ (ndf is the number of degrees of freedom)
- for $\phi\phi$: a mixture of 0^+ (S-wave) and 2^- (P-wave) describes data with $\chi^2/ndf = 1.3$
- for $\omega\omega$: a mixture of 0^+ (S-wave) and 2^+ (S-wave) describes data with $\chi^2/ndf = 1.3$