Recent results of charmonium decays from BESIII

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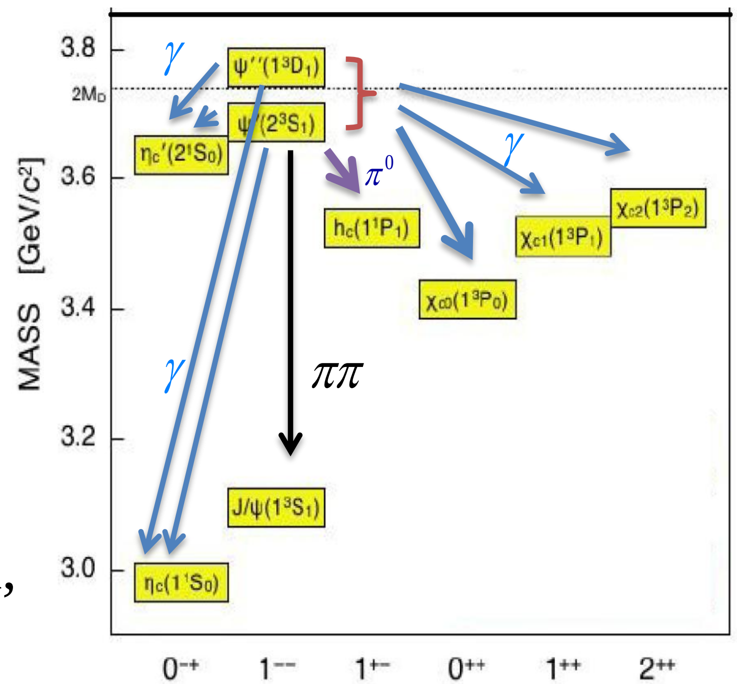
全国第十三届重味物理与CP破坏研讨会, 兰州大学，2015年22-25日

Introduction

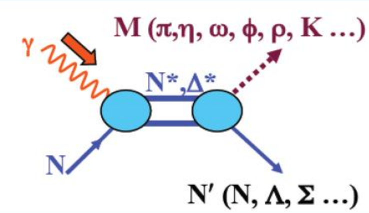
- Vector charmonium data sets

Vector charmonium	Previous data	BESIII now	Goal
J/ψ	BESII: 58 M	1.2B(20×BESII)	10 B
$\psi(3686)$	CLEO: 28 M	0.5B(20×CLEO)	3 B
$\psi(3770)$	CLEO: 0.8 fb^{-1}	2.9fb^{-1}(3.5×CLEO)	20 fb^{-1}

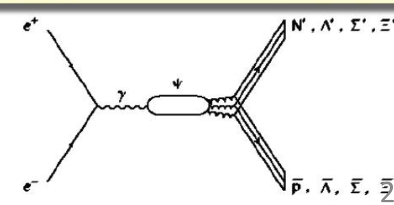
- $\eta_c, \eta_c(2S), \chi_{cJ}$ are available via γ transition, and h_c available via pion transiton.
- charmonium physics
  - $\rho\pi$ puzzle, and violation of the 12% rule
  - non-$D\bar{D}$ decays of $\psi(3770)$
  - light hadron structure and properties
- rare decays: $J/\psi \to \gamma\gamma,\ \gamma\phi,\ \phi\pi^0$



JLab, ELSA, MAMI, ESRF, Spring-8, ….



$J/\psi(\psi') \to \bar{B}BM \Rightarrow N^*, \Lambda^*, \Sigma^*, \Xi^*$



$\psi(3770) \to \gamma\eta_c,\ \gamma\eta_c(2S) \to \gamma K_S^0 K\pi$

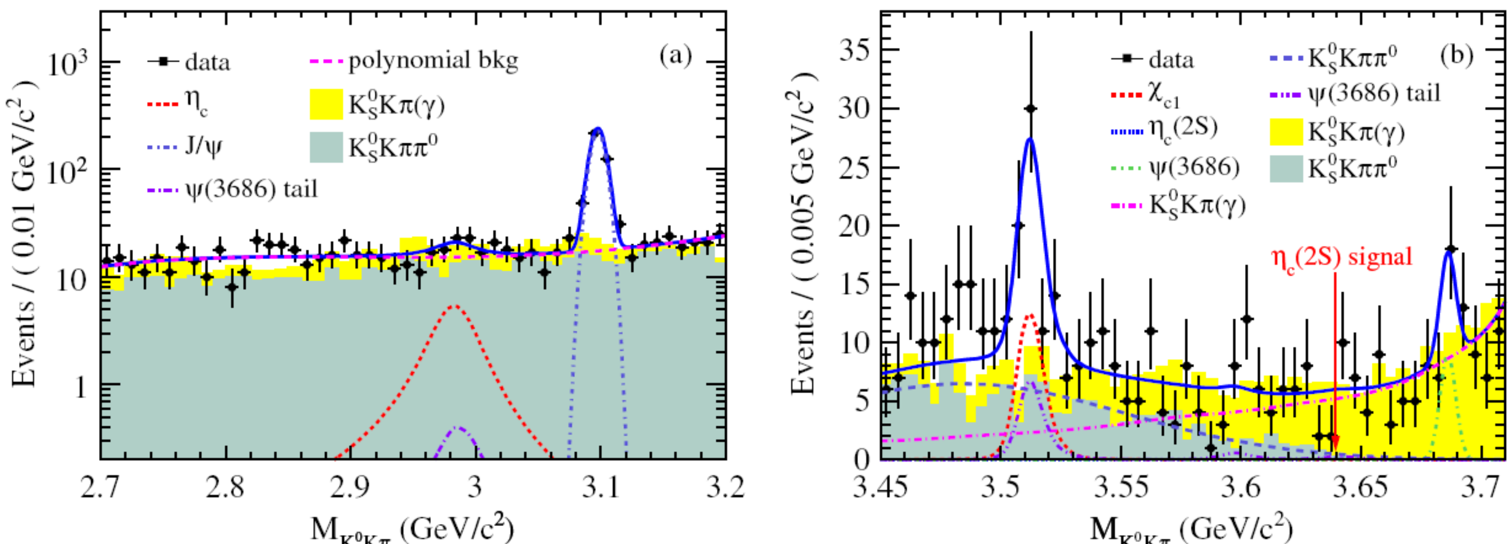
- If $\psi(3770)$ is assigned as 1^3D_1 state, the radiative transitions $\psi(3770) \to \gamma\eta_c, \gamma\eta_c(2S)$ are supposed to be highly suppressed.
- High multipoles beyond the leading one could be contributed.

$$B(\psi(3770) \to \gamma\eta_c) = 6.3^{+8.4}_{-4.4} \times 10^{-4}$$

PRD 84, 074005 (2011)

$$B(\psi(3770) \to \gamma\eta_c(2S)) = 6.7^{+7.2}_{-4.4} \times 10^{-5}$$

BESIII: the 2.92 fb^{-1} ψ'' data set



Phys. Rev. D 89, 112005

Phys. Rev. D 89, 112005

$\psi(3770) \to \gamma\eta_c,\ \gamma\eta_c(2S) \to \gamma K_S^0 K\pi$

Quantity	η_c	$\eta_c(2S)$	χ_{c1}
$N_{\rm obs}$	29.3 ± 18.2	0.4 ± 8.5	34.9 ± 9.8
$N_{\rm up}$	56.8	16.1	...
ϵ (%)	27.87	25.24	28.46
$\mathcal{B}(\psi(3770) \to \gamma X \to \gamma K_S^0 K^\pm \pi^\mp)$ $(\times 10^{-6})$	< 16	< 5.6	$8.51 \pm 2.39 \pm 1.42$
$\mathcal{B}(\psi(3770) \to \gamma X)$ $(\times 10^{-3})$	< 0.68	< 2.0	$2.33 \pm 0.65 \pm 0.43$
$\mathcal{B}_{\rm CLEO}(\psi(3770) \to \gamma X)$ $(\times 10^{-3})$	...	...	$2.9 \pm 0.5 \pm 0.4$
$\Gamma(\psi(3770) \to \gamma X)$ (keV)	< 19	< 55	...
$\Gamma_{\rm IML}$ (keV)	$17.14^{+22.93}_{-12.03}$	$1.82^{+1.95}_{-1.19}$	...
$\Gamma_{\rm LQCD}$ (keV)	10 ± 11	...	...

- Upper limites are set for the radiative transitions $\psi(3770) \to \gamma\eta_c, \gamma\eta_c(2S)$
- The upper limits for the $\Gamma(\psi(3770) \to \gamma\eta_c/\eta_c(2S)$) cover the theoretical predictions, but the upper limits for $\Gamma(\psi(3770) \to \gamma\eta_c(2S))$ is too high due to the large systematic uncertainties.

$\psi(3770) \to \gamma\chi_{cJ}$ with $\chi_{cJ} \to \gamma J/\psi \to \gamma l^+l^-$

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- No significant non $D\bar{D}$ exclusive decays are established. How to understand the $\psi(3770)$ decay mechanisms and properties?
- If it contains additional light quarks or gluons, it may have large branching fractios decays into ligh hadrons.
- Light hadron transition or radiative transitions, e.g. $\pi\pi J/\psi, \pi J/\psi, \eta J/\psi$, and $\gamma\chi_{cJ}$, can probe the $\psi(3770)$

PDG2014

Radiative decays

$\gamma\chi_{c2}$	$< 9 \times 10^{-4}$	CL=90%	211
$\gamma\chi_{c1}$	$(2.9 \pm 0.6) \times 10^{-3}$		253
$\gamma\chi_{c0}$	$(7.3 \pm 0.9) \times 10^{-3}$		341

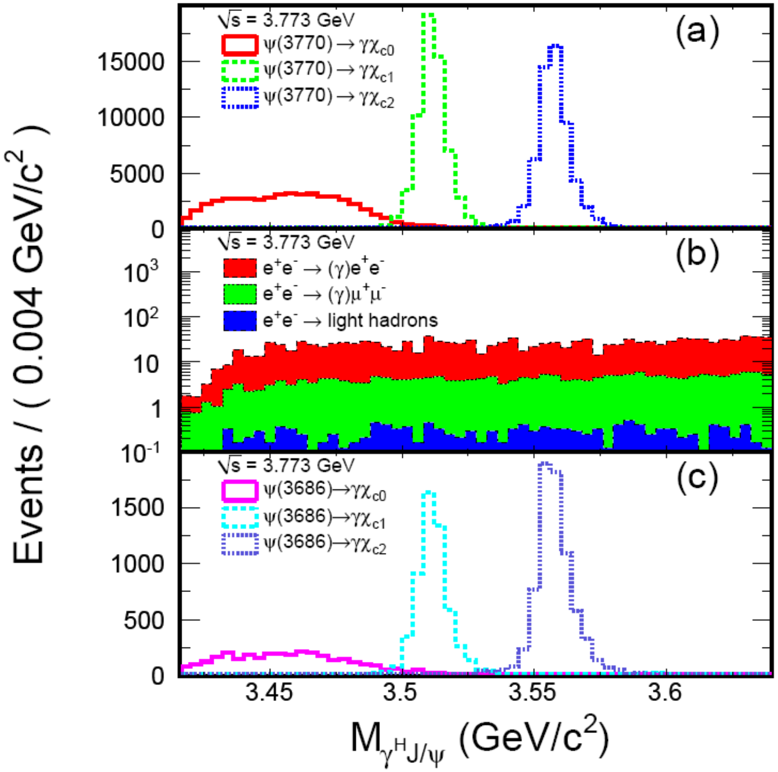
- S - D mixing model: (PRD44,3562; PRD64,094002, PRD69,094019)

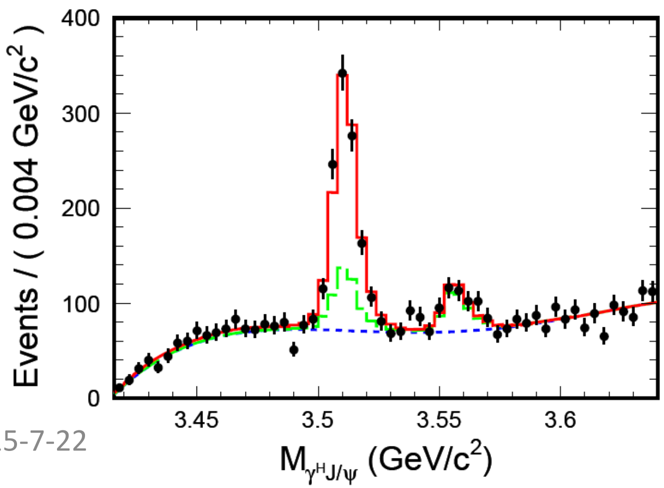
$\Gamma(\psi(3770) \to \gamma\chi_{c1})$: 59~183 KeV

$\Gamma(\psi(3770) \to \gamma\chi_{c2})$: 3~24 KeV

Large uncertainties!

$\psi(3770) \to \gamma\chi_{cJ}$ arXiv:1504.07450v01





- The analysis is based on the 2.92 fb^{-1} ψ'' data.
- The χ_{cJ} are reconstructed with the decay

$$\chi_{cJ} \to \gamma J/\psi \to \gamma l^+ l^-$$

Experiment/Theory	$\Gamma(\psi(3770) \to \gamma\chi_{cJ})$ (keV) $J=1$	$J=2$
This work	$67.5 \pm 4.1 \pm 6.7$	< 17.4
Ding-Qin-Chao [12]		
non-relativistic	95	3.6
relativistic	72	3.0
Rosner S-D mixing [13]		
$\phi = 12°$ [13]	73 ± 9	24 ± 4
$\phi = (10.6 \pm 1.3)°$ [32]	79 ± 6	21 ± 3
$\phi = 0°$ (pure 1^3D_1 state) [32]	133	4.8
Eichten-Lane-Quigg [14]		
non-relativistic	183	3.2
with coupled-channel corr.	59	3.9
Barnes-Godfrey-Swanson [15]		
non-relativistic	125	4.9
relativistic	77	3.3

$$\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (2.48 \pm 0.15 \pm 0.23) \times 10^{-3},$$

$$\mathcal{B}(\psi(3770) \to \gamma\chi_{c2}) < 0.64 \times 10^{-3}$$

Searches for isospin-violating transition $\chi_{c0,2} \to \pi^0 \eta_c$

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- In quark model, the isospin-violating is broken due to the electromagnetic interaction or the up-down quark mass difference. The expected decay rates are very small.
- However, a larger isospin decay ratio is observed in charmonium transitions, e.g. R=Br(ψ(2S) $\to \pi^0$J/ψ)/Br (ψ(2S) $\to \eta$J/ψ)=0.374$\pm$0.072, indicates the important role played by the nonperturbative effects. (PRL103,082003)
- Searches for the isospin-violating decay $\chi_{cJ} \to \pi^0 \eta_c$ gives insights in the isospin-violating mechanisms.
- QCD multipole expansion gives the relation: $Br(\chi_{c0} \to \pi^0 \eta_c) \approx Br(\chi_{c1} \to \pi^+ \pi^- \eta_c)$ (PRD86, 074033), and $Br(\chi_{c1} \to \pi^+ \pi^- \eta_c) \approx (2.22 \pm 1.24)\%$. (PRD 75, 054019)
- The analysis is based on the 106 million ψ(2S) data set at the BESIII, and the η_c is constructed with the decay $\eta_c \to K_S^0 K^\pm \pi^\mp$.

Searches for isospin-violating transition $\chi_{c0,2} \to \pi^0 \eta_c$

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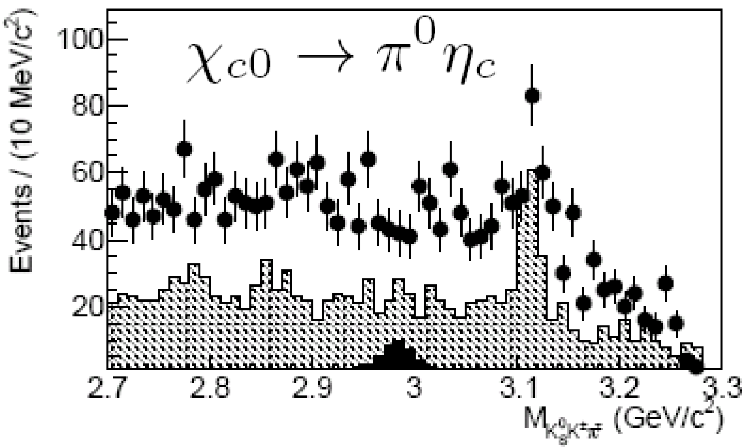
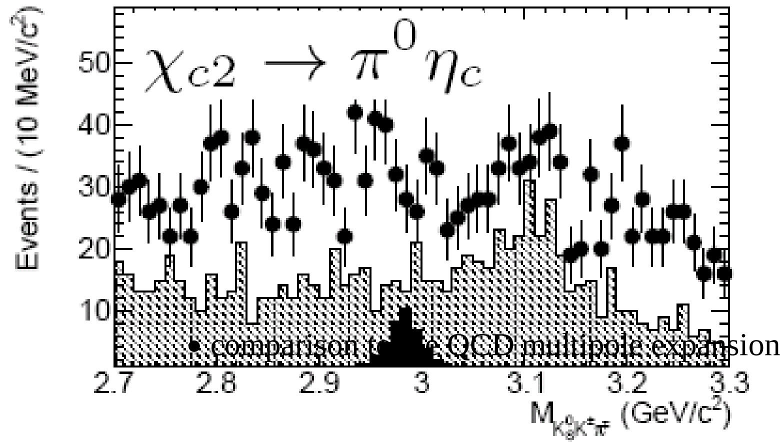
- The peack near 3.12 GeV is due to the background $\psi(2S) \to \pi^0 \pi^0 J/\psi$.
- No significant η_c signals are observed, and upper limits are set.

arXiv: 1502.02641





	$\chi_{c0} \to \pi^0 \eta_c$	$\chi_{c2} \to \pi^0 \eta_c$
N_J^{UL}	14.1	35.9
ε_J	5.8%	8.6%
δ_J	13.8%	20.2%
$B(\chi_{cJ} \to \pi^0 \eta_c)(10^{-3})$	< 1.6	< 3.2

PRD 91, 112018 (2015)

- **Comparison to the QCD multipole expansion**

  if B($\chi_{c0} \to \pi^0 \eta_c$)=0.022, then one expect

  the observed events in the 106×10^6 data sets

  N^{obs}=302.

- **The comparison indicates that the QCD multipole expansion predicts that the branching fraction is 20 times of magnitude larger than our measurement**

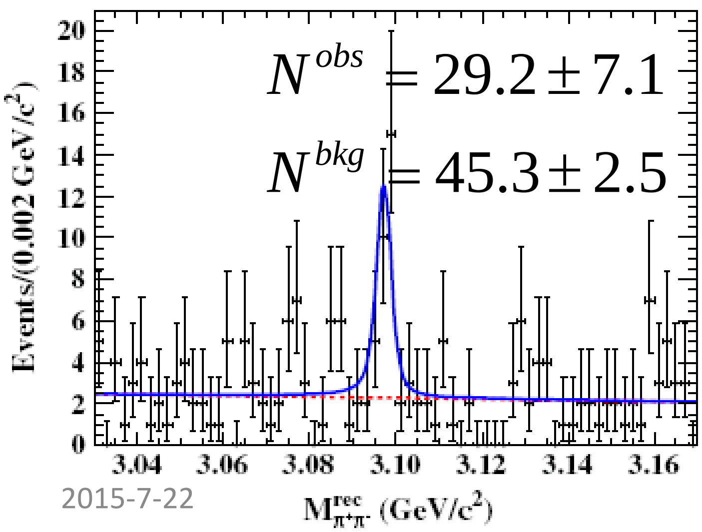
Search for $C-$violation decay $J/\psi \to \gamma\gamma, \gamma\phi$

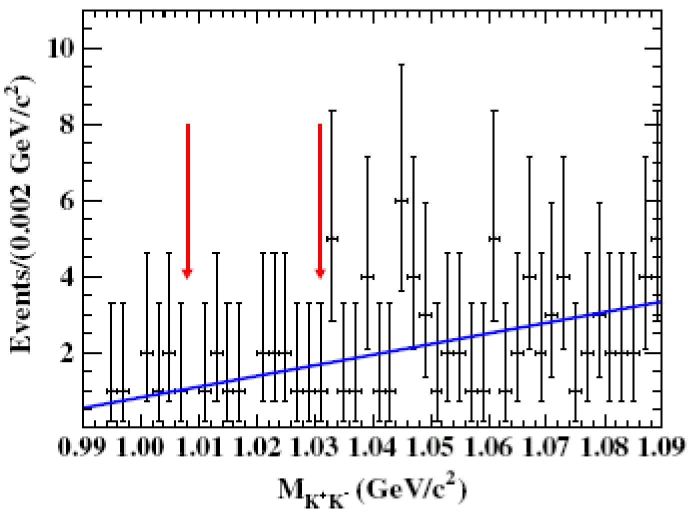
- The C-parity violation is forbidden in the electromagnetic interatction, any observation of the $J/\psi \to \gamma\gamma$ decay indicates a new physics.
- Based on the 106 million $\psi(3686)$ data set, we use the decay $\psi(2S) \to \pi^+\pi^- J/\psi$ to search for $J/\psi \to \gamma\gamma$
- Dominant backgrounds, $J/\psi \to \gamma\pi^0, \gamma\eta, \gamma\eta_c \to 3\gamma$, and $J/\psi \to 3\gamma$, are carefully studied with MC simulation.

PRD 90, 092002

No *C*-violation decays were observed!

	$\gamma\gamma$	$\gamma\phi$
$\mathcal{B}(J/\psi \to)$ (this work)	$< 2.7 \times 10^{-7}$	$< 1.4 \times 10^{-6}$
$\mathcal{B}(J/\psi \to)$ (PDG [1])	$< 50 \times 10^{-7}$	–

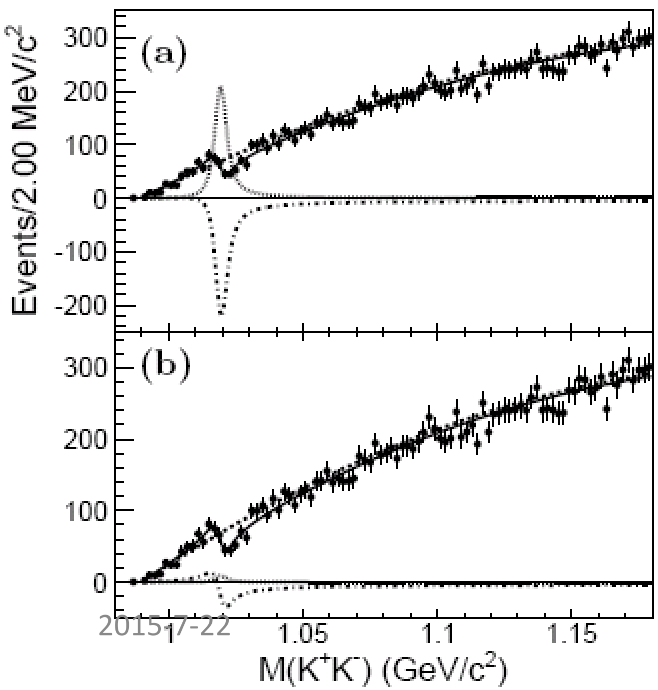




Search for OZI-suppressed decay $J/\psi \to \pi^0\phi$

BESIII

- The decay $J/\psi \to \phi\pi^0$ is highly suppressed dut to double OZI rule.
- The observation is helpful to understand the $\omega-\phi$ mixing and SU(3) flavor symmetry breaking.
- The analysis is based on the 1.31 billion J/ψ data sample, and the π^0 candidates are reconstructed with two photons
- The structure at the ϕ mass region is assumed due to the interference between the $J/\psi \to \phi\pi^0$ and $K^+K^-\pi^0$ decays.



Phys.Rev. D91 ,11, 112001 (2015)

- **Two solutions are obtained.**

Solution	$N^{\rm sig}$	δ	$2\Delta\log\mathcal{L}/N_f$	Z
I	838.5 ± 45.8	$-95.9^\circ \pm 1.5^\circ$	$45.8/2$	6.4σ
II	35.3 ± 9.3	$-152.1^\circ \pm 7.7^\circ$	$45.8/2$	6.4σ

Branching fraction:

I: $[2.94 \pm 0.16(\text{stat.}) \pm 0.16(\text{syst.})] \times 10^{-6}$

II: $[1.24 \pm 0.33(\text{stat.}) \pm 0.30(\text{syst.})] \times 10^{-7}$

Search for OZI-suppressed decay $J/\psi \to \pi^0\phi$

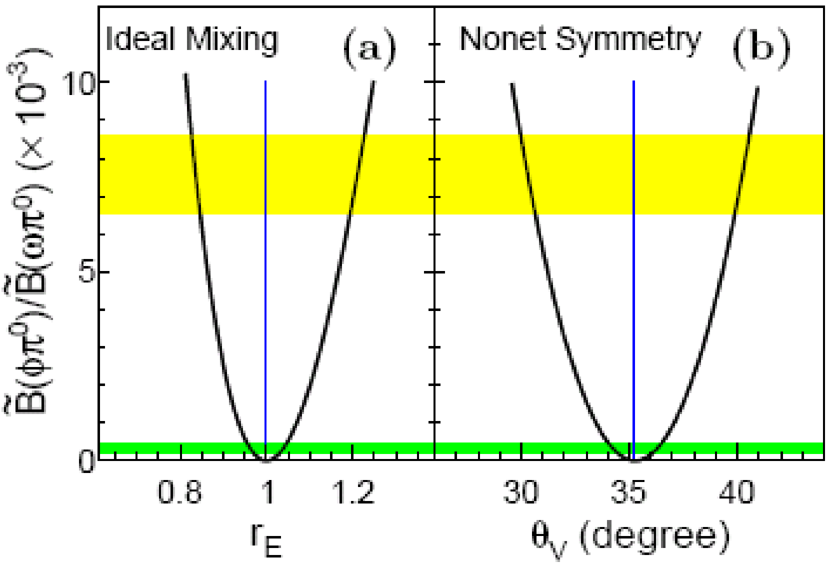
- Nonet symmetry broken

PRD32,2961

$$\frac{B(\phi\pi^0)}{B(\omega\pi^0)} = \left(\frac{p_\phi}{p_\omega}\right)^3 \frac{(r_E \tan\theta_V - 1/\sqrt{2})^2}{(r_E + \tan\theta_V/\sqrt{2})^2}$$

$r_E = 1$ (nonet symmetry)

$\theta_V = arc\tan(1/\sqrt{2})$ (ideal $\omega-\phi$ mixing)



ideal mixing: $r_E - 1 = (21.0 \pm 1.6)\%$ or $(-16.4 \pm 1.0)\%$ (solution I)

$(3.9 \pm 0.8)\%$ or $(-3.7 \pm 0.7)\%$ (solution II)

Nonet symmetry: $\phi_V = |\theta_V - \theta_V^{ideal}| = 4.97^\circ \pm 0.33^\circ$ (solution I)

$= 1.03^\circ \pm 0.19^\circ$ (solution II)

quardratic mass formula: $\phi_V = 3.84^\circ$ (PDG)

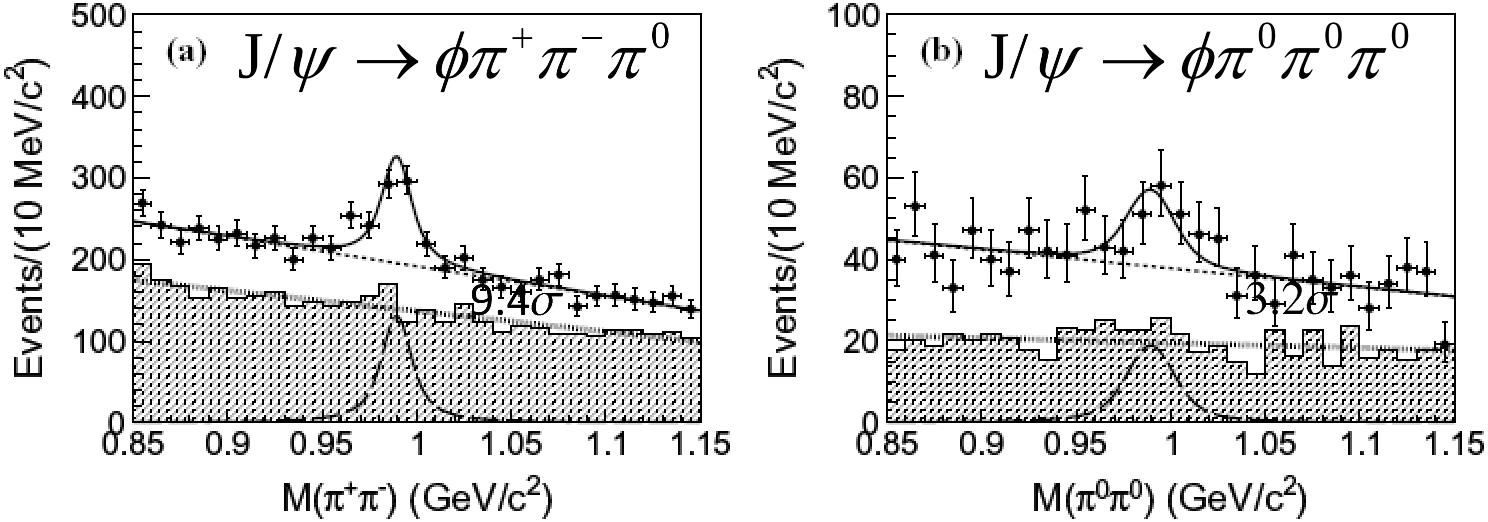
fit to radiative transition: $3.34^\circ \pm 0.09^\circ$ (J. High Energy Phys. 0907,105)

Nonet asymmetry indication!

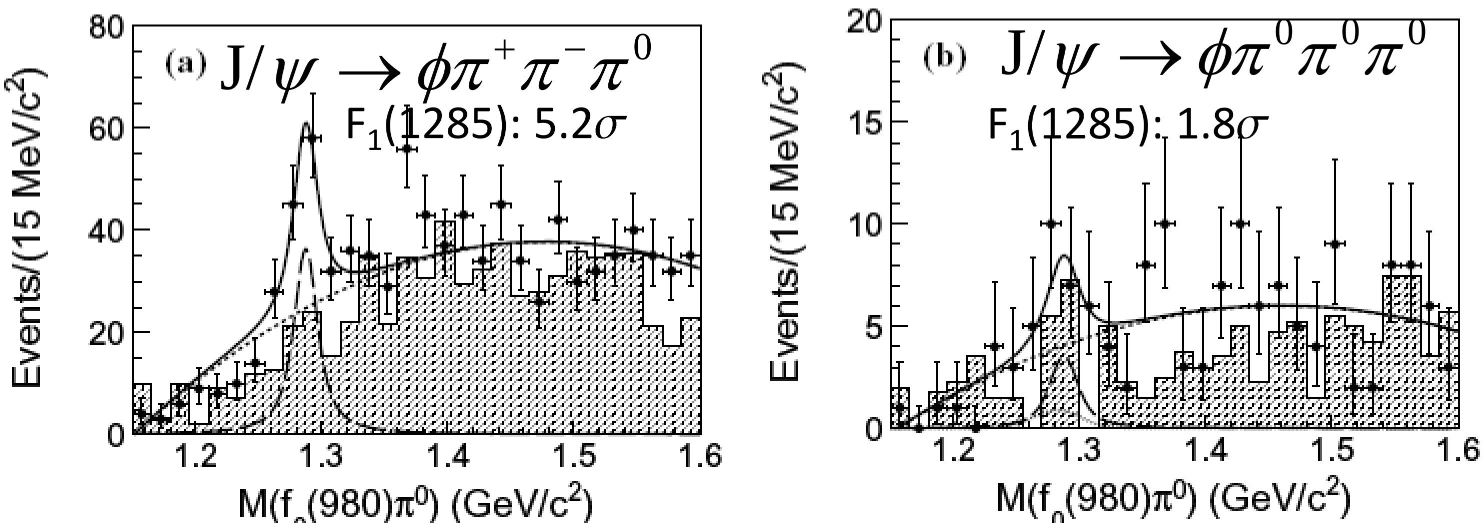
Observation of the isospin-violating decay $J/\psi \to \phi\pi^0 f_0(980)$

- The nature of $f_0(980)$ is a long-standing puzzle.
- It has been interpreted as a $q\bar{q}$ state, a $K\bar{K}$ molecule, a glueball, and a four-quark state.
- Average values of $f_0(980)$ resonance parameters: M=980 ± 20 MeV, Γ=40 to 100 MeV.
- In $J/\psi \to \gamma\eta(1405) \to \gamma\pi^0 f_0(980)$, measured Γ=9.5 ± 1.1 MeV (PRL. 108,182001)
- Not $a_0 - f_0(980)$ mixing mechanism, it was identified as a triangle singularity mechanism (PRL108,081803)
- What about $f_0(980)$ in the decay $J/\psi \to \phi\pi^0 f_0(980)$

Observation of $J/\psi \to \phi\pi^0 f_0(980)$



PRD92,012007

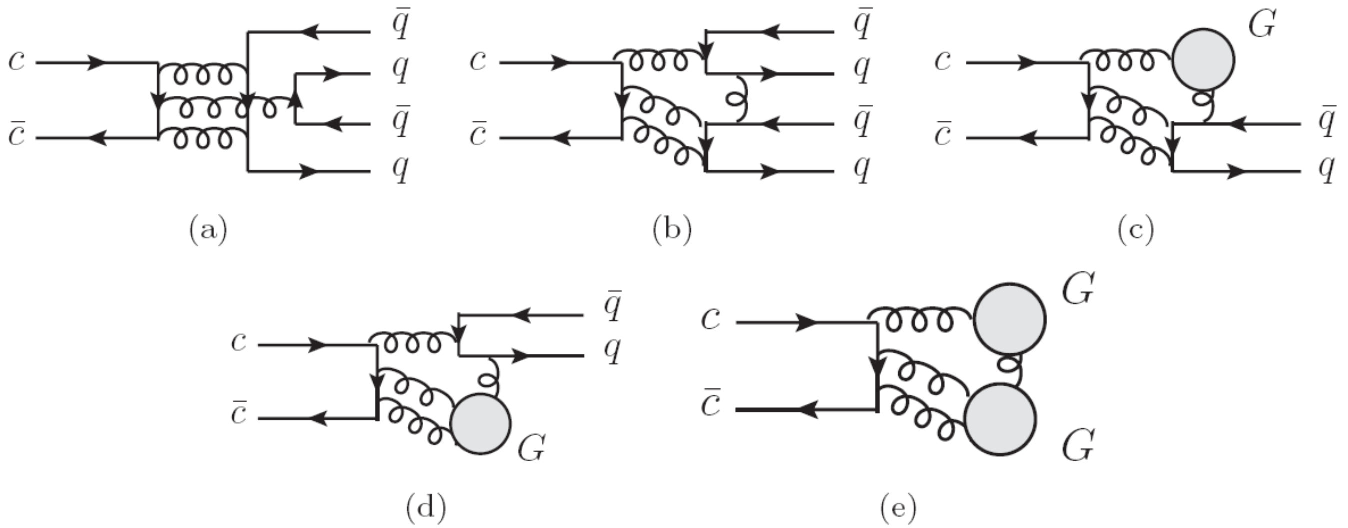


- A simultaneous fit gave M=989.4±1.3MeV, Γ=15.3 ± 4.7 MeV.
- Measured mass and width consistent with those measured in $J/\psi \rightarrow \gamma\pi^0 f_0(980)$.
- $\mathcal{B}(f_1 \to \pi^0 f_0 \to \pi^0\pi^+\pi^-)/\mathcal{B}(f_1 \to \pi^0 a_0^0 \to \pi^0\pi^0\eta) = (3.6 \pm 1.4)\%$
- $\mathcal{B}(\eta(1405) \to \pi^0 f_0 \to \pi^0\pi^+\pi^-)/\mathcal{B}(\eta(1405) \to \pi^0 a_0^0 \to \pi^0\pi^0\eta) = (17.9 \pm 4.2)\%$

- This analysis supports the argument that the nature of the resonances a_0 and f_0 as dynamically generated makes the amount of isospin breaking strongly dependent on the physical process.

$\chi_{cJ} \to \eta' K^+ K^-$

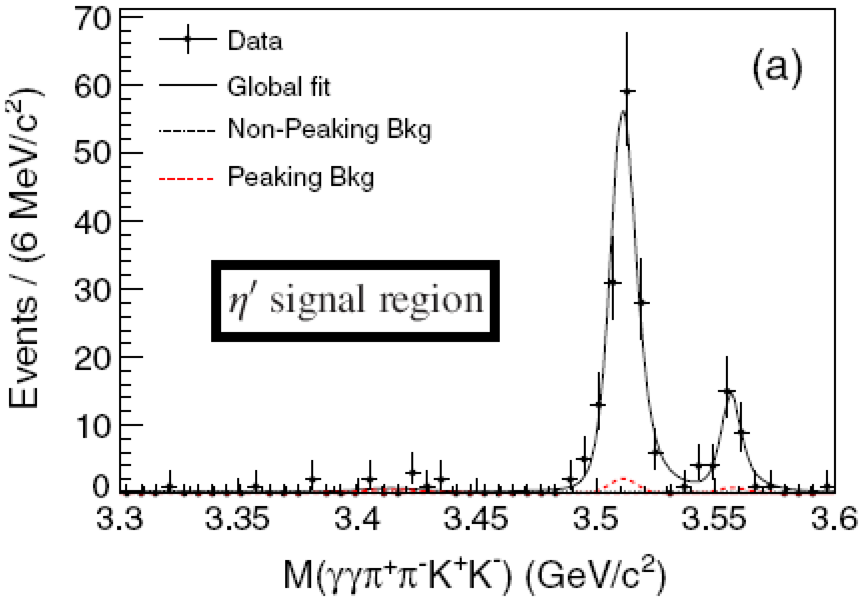
- Compared to J/ψ and $\psi(3686)$ decays, relatively little is known about χ_{cJ} decays.
- Look for scalar states, e.g. f_0(1370), f_0(1500), and so on, and test the glueball-qqbar mixing relations (Int.J.Mod.Phys.27,1250135).

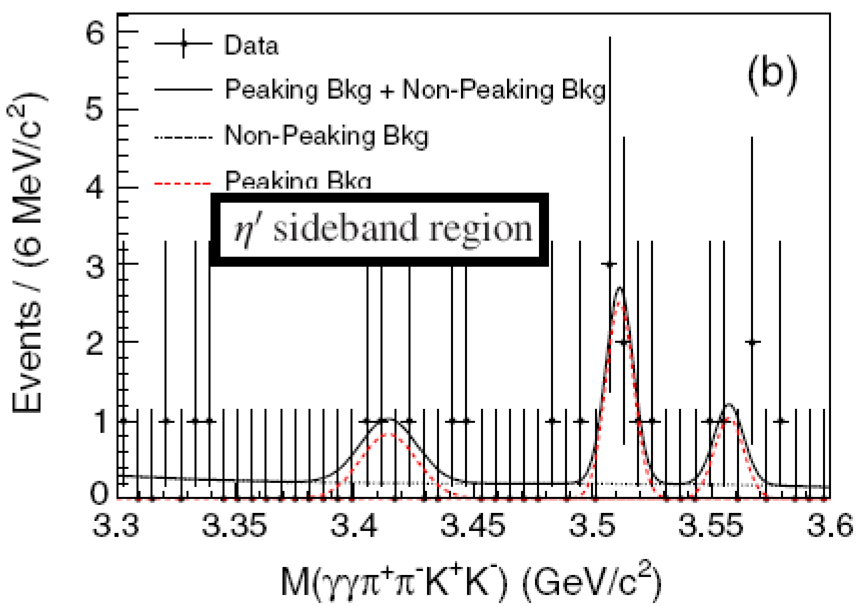


The schematic Feynman diagrams of $\chi_{c1} \to PS$ via three-gluon annihilations.

- Looking for $K^*_0(1430) \to \eta' K$

PRD 89, 074030



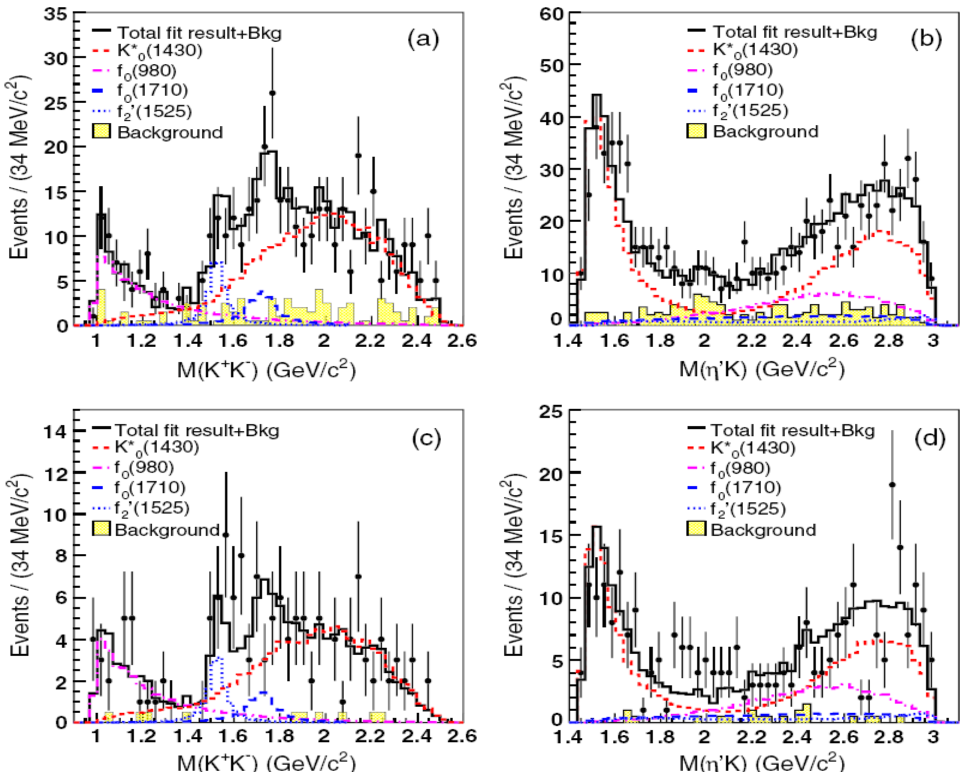


- **Use 106 million $\psi(3686)$ decays**
- η' is reconstructed with decays

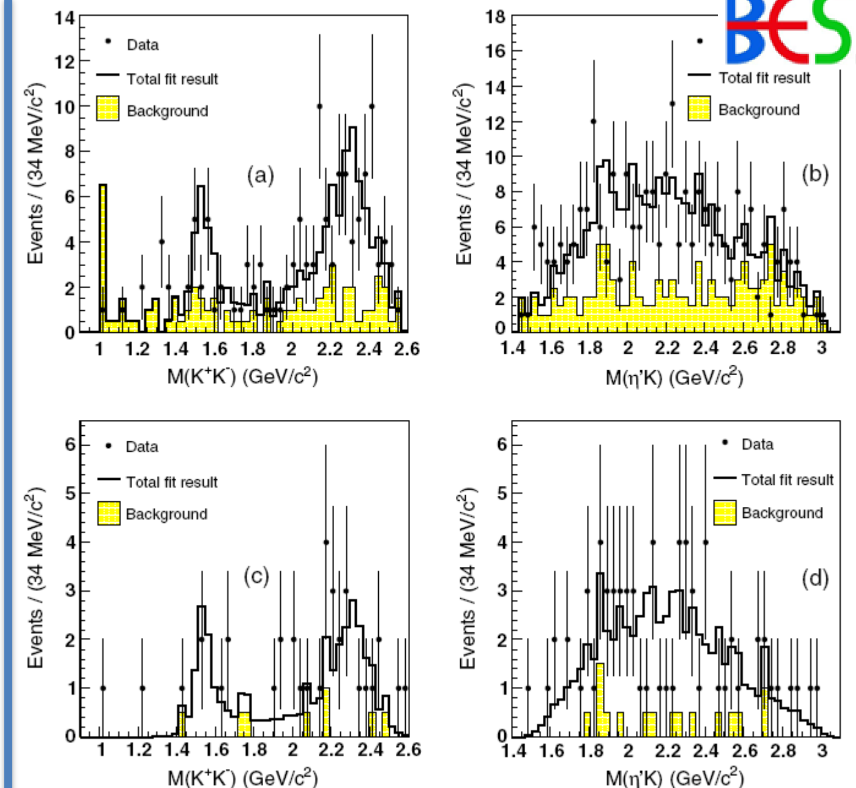
$$\eta' \to \gamma\rho^0 \to \gamma\pi^+\pi^- \quad \text{(mode I)}$$

$$\eta' \to \eta\pi^+\pi^- \to \gamma\gamma\pi^+\pi^- \quad \text{(mode II)}$$

Process	$\mathcal{B}(\times 10^{-4})$
$\mathcal{B}(\chi_{c1} \to \eta' K^+ K^-)$	8.75 ± 0.87
$\mathcal{B}(\chi_{c2} \to \eta' K^+ K^-)$	1.94 ± 0.34



$\chi_{c1} \rightarrow \eta' K^+ K^-$



$\chi_{c2} \rightarrow \eta' K^+ K^-$

where (a) (b) for mode I, and (c) (d) for mode II

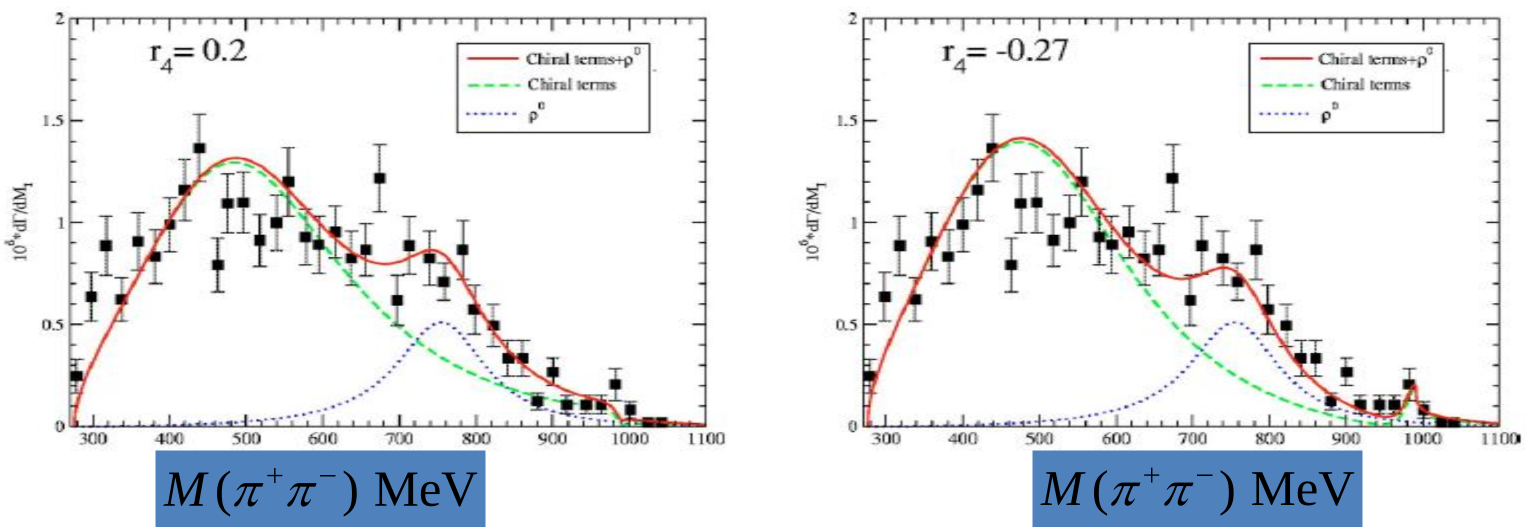
PRD 89, 074030

Process	$\mathcal{B}(\times 10^{-4})$
$\chi_{c1} \rightarrow K_0^*(1430)^{\pm} K^{\mp},\ K_0^*(1430)^{\pm} \rightarrow \eta' K^{\pm}$	$6.41 \pm 0.57^{+2.09}_{-2.71}$
$\chi_{c1} \rightarrow \eta' f_0(980),\ f_0(980) \rightarrow K^+ K^-$	$1.65 \pm 0.47^{+1.32}_{-0.56}$
$\chi_{c1} \rightarrow \eta' f_0(1710),\ f_0(1710) \rightarrow K^+ K^-$	$0.71 \pm 0.22^{+0.68}_{-0.48}$
$\chi_{c1} \rightarrow \eta' f_2'(1525),\ f_2'(1525) \rightarrow K^+ K^-$	$0.92 \pm 0.23^{+0.55}_{-0.51}$

$J/\psi \to p\bar{p}a_0(980)$

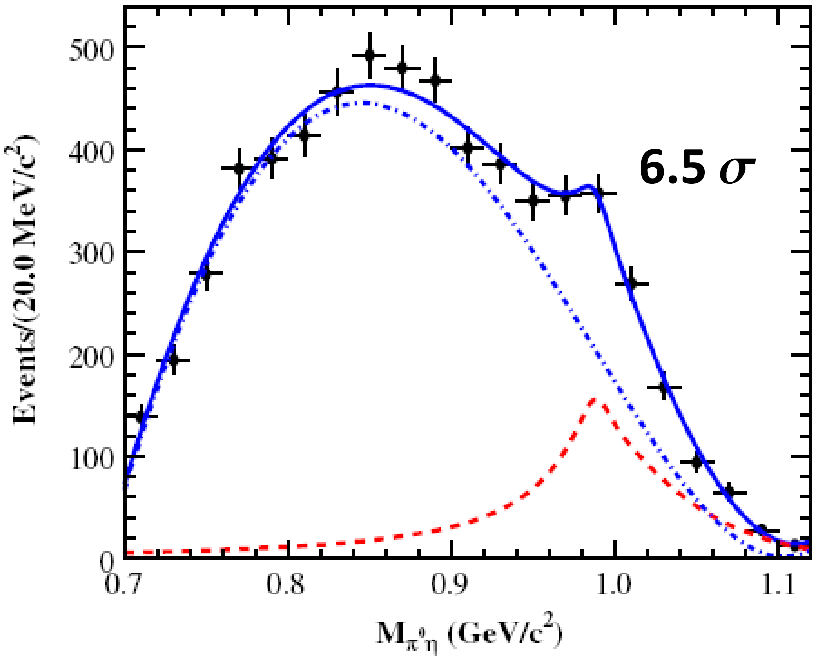
- The nature of a_0(980) and f_0(980) is a long-standing problem of physics
- The measurement of J/ψ→p$\bar{\text{p}}$$a_0$ (980) will provide an additional constraint to any model describing a_0(980) formation and decays.
- χPT provides a description of J/ψ →N$\bar{\text{N}}$MM process, yet to be test experimentally.

PRC **69**, 015201



- **225 million J/ψ decays**

PRD 90, 052009



$$J/\psi \to p\bar{p}a_0(980),$$

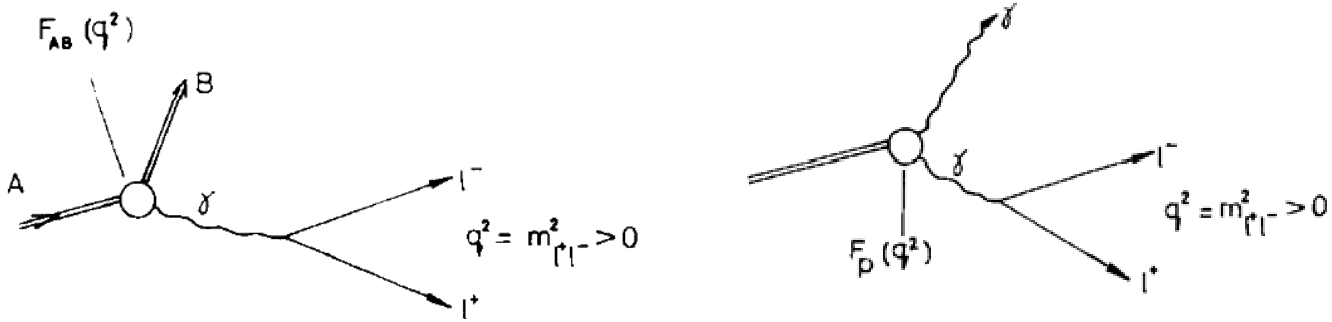
$$a_0(980) \to \pi^0\eta$$

is observed for the first time.

- $Br(\mathrm{J}/\psi \to p\bar{p}a_0(980) \to p\bar{p}\pi^0\eta) = (6.8 \pm 1.2 \pm 1.3) \times 10^{-5}$.
- Interference with N^* states is not taken into account.
- Comparison with $Br(\mathrm{J}/\psi \to p\bar{p}\pi^+\pi^-)$ from the PDG shows preference r_4=0.2 in ChPT .

$J/\psi \to Pe^+e^- \quad (P = \eta'/\eta/\pi^0)$

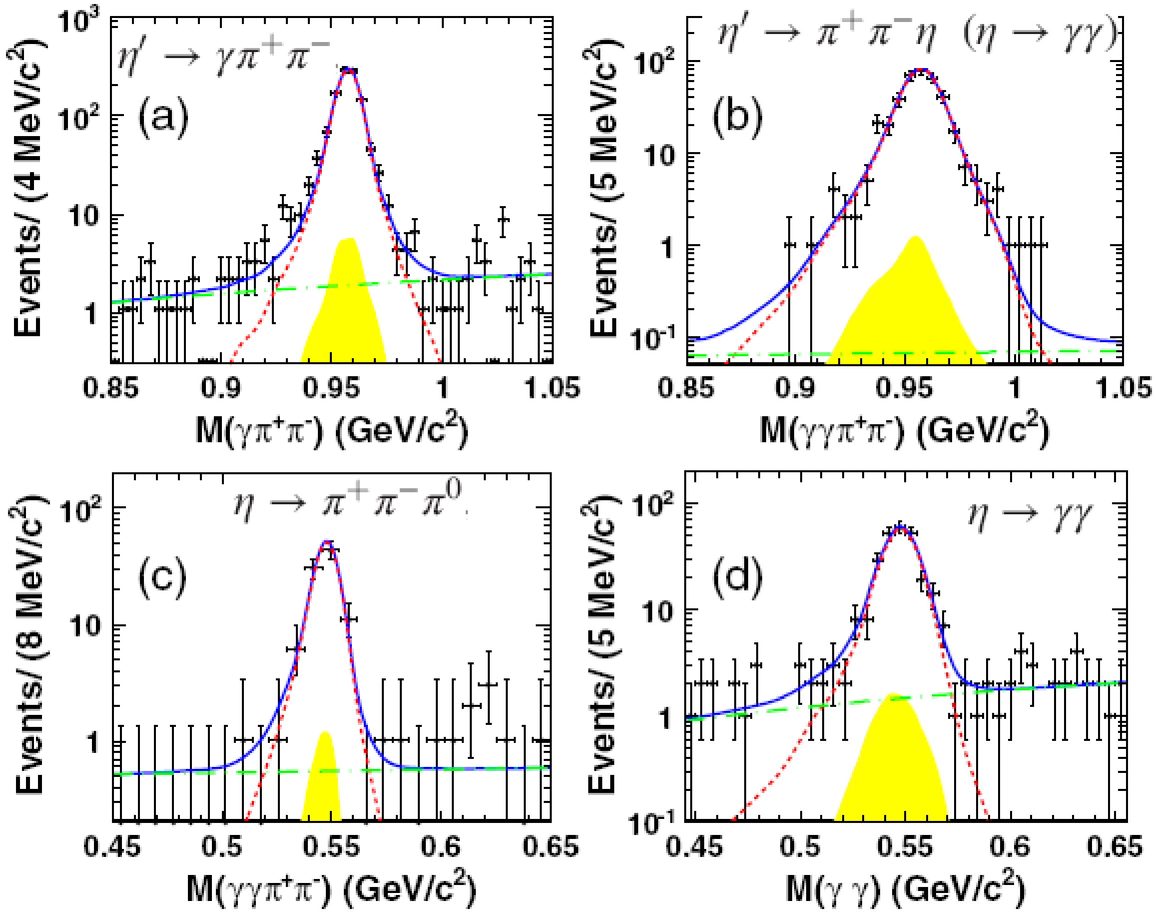
- Electromagnetic decays are suggested as an important probe to reveal the structure of hadrons.

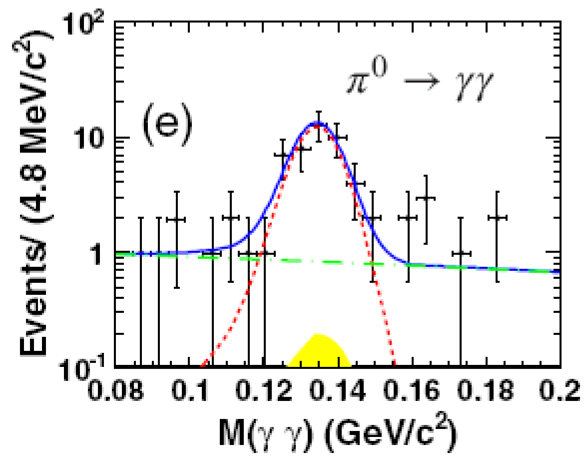


$$\frac{d\Gamma(V \to Pe^+e^-)}{dq^2\Gamma(V \to P\gamma)} = |F_{VP}(q^2)|^2 \times [\mathrm{QED}(q^2)], \quad |F_{VP}(q^2)| = \frac{1}{(1 - q^2/\Lambda^2)}$$

Pointlike QED part

- Measurements of EM decays for ρ, ω, ϕ mesons have been performed at CMD2, CLOE and so on.
- The branching fractions and form factors for $\phi \to \eta e^+e^-$, $\omega \to \pi^0 e^+e^-$ are consistent with VMD model prediction, but for decay $\omega \to \pi^0 \mu^+\mu^-$, measured Λ^{-2} significantly deviates from VDM.





PRD 89, 092008

BESIII

- **Using 225 million J/ψ decays**
- **γ-conversion backgrounds from J/ψ→Pγ are subtracted.**
- **Backgrounds from J/ψ→Pϕ/ω are subtracted.**
- **Non-peaking backgrounds are carefully checked with MC simulation.**

Signal yield and peaking BG.

Modes	N_S	N_B	ϵ
$J/\psi \to \eta' e^+e^-(\eta' \to \gamma\pi^+\pi^-)$	983.3 ± 33.0	27.4 ± 1.0	24.8%
$J/\psi \to \eta' e^+e^-(\eta' \to \pi^+\pi^-\eta)$	373.0 ± 19.9	8.5 ± 0.3	17.6%
$J/\psi \to \eta e^+e^-(\eta \to \pi^+\pi^-\pi^0)$	84.2 ± 9.6	5.3 ± 0.3	14.9%
$J/\psi \to \eta e^+e^-(\eta \to \gamma\gamma)$	235.5 ± 16.4	8.7 ± 0.3	22.7%
$J/\psi \to \pi^0 e^+e^-(\pi^0 \to \gamma\gamma)$	39.4 ± 6.9	1.1 ± 0.1	23.4%

PRD 89, 092008

Mode	Branching fraction	Combined result	Theoretical prediction
$J/\psi \to \eta' e^+ e^- (\eta' \to \gamma\pi^+\pi^-)$	$(6.01 \pm 0.20 \pm 0.34) \times 10^{-5}$		
$J/\psi \to \eta' e^+ e^- (\eta' \to \pi^+\pi^-\eta)$	$(5.51 \pm 0.29 \pm 0.32) \times 10^{-5}$	$(5.81 \pm 0.16 \pm 0.31) \times 10^{-5}$	$(5.66 \pm 0.16) \times 10^{-5}$
$J/\psi \to \eta e^+ e^- (\eta \to \pi^+\pi^-\pi^0)$	$(1.12 \pm 0.13 \pm 0.06) \times 10^{-5}$		
$J/\psi \to \eta e^+ e^- (\eta \to \gamma\gamma)$	$(1.17 \pm 0.08 \pm 0.06) \times 10^{-5}$	$(1.16 \pm 0.07 \pm 0.06) \times 10^{-5}$	$(1.21 \pm 0.04) \times 10^{-5}$
$J/\psi \to \pi^0 e^+ e^- (\pi^0 \to \gamma\gamma)$	$(7.56 \pm 1.32 \pm 0.50) \times 10^{-7}$	$(7.56 \pm 1.32 \pm 0.50) \times 10^{-7}$	$(3.89^{+0.37}_{-0.33}) \times 10^{-7}$

- Measured branching fraction for $J/\psi \to \eta' e^+e^-$, ηe^+e^- are consistent with the VMD predictions.
- But for $J/\psi \to \pi^0 e^+e^-$, there is about 2.5 standard deviation from the VMD prediction.
- Further improvement of the theoretical calculation are needed.

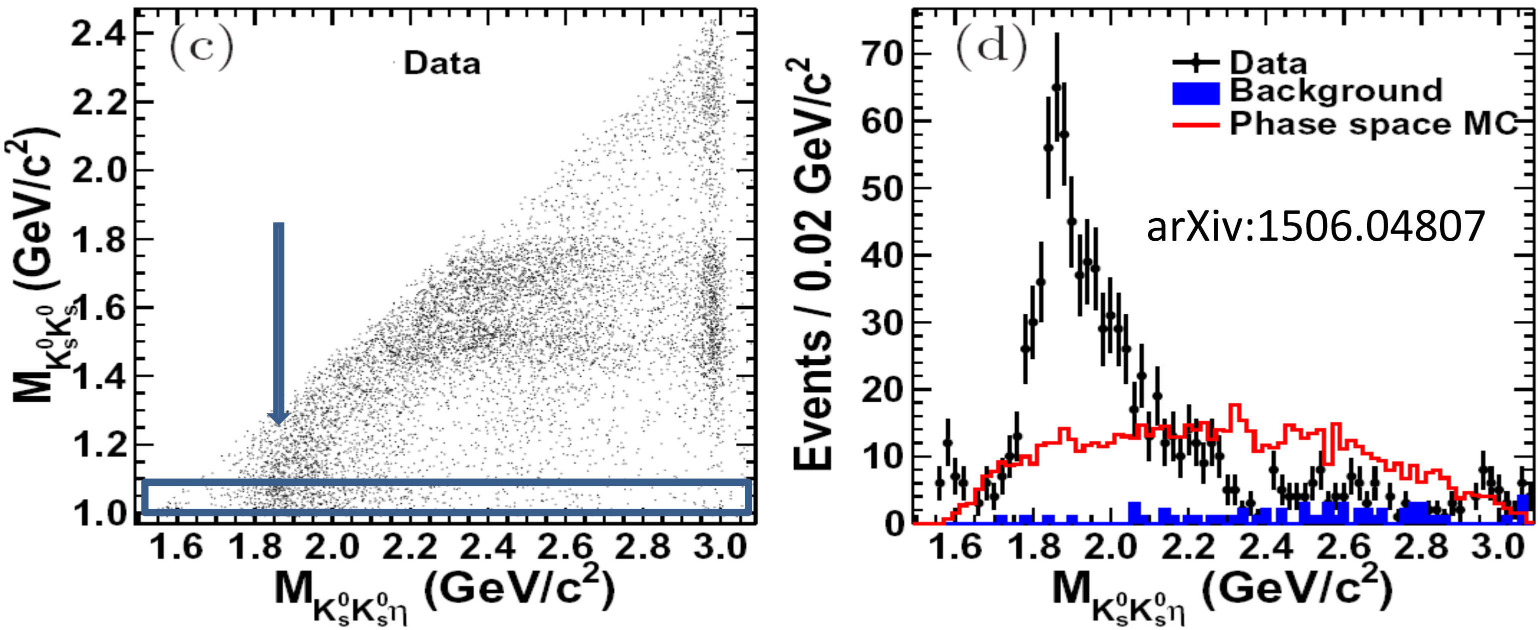
Observation and Spin-Parity Determination of the X(1835) in $J/\psi \to \gamma K_S^0 K_S^0 \eta$

- The search for unconventional states is one of the main interests in experimental particle physics.
- The X(1835) was observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$ (PRL95, 262001)

- Possible interpretations include a ppbar bound state (EPJC 53, 413), a second radial excitation of the h′ (PRD73, 014023), and a pseudo-scalar glueball (PRD74, 034019).

- In addition, $p\bar{p}$ threshold enhancement observed in $J/\psi \to \gamma p\bar{p}$ (CPC34, 421) was determined to be state with $J^{PC}=0^{-+}$, its mass and width consistent with $X(1835)$.

Observation of X(1835) in $J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$



- The data is described with $X(1835) \rightarrow f_0(980)\eta$, $X(1560) \rightarrow f_0(980)\eta$, and direct 3-body decay.
- Data favors for 0^{-+} hypothesis for X(1835) and X(1560) .
- Mass and width are measured:

$X(1835)$: $M=1844 \pm 9(stat)^{+16}_{-25}(syst)$ MeV, $\Gamma=192^{+20}_{-17}(stat)^{+62}_{-43}(syst)$MeV

Summary

By using BESIII data sets taken at J/ψ, $\psi(3686)$ and $\psi(3770)$ peak, we search for the radiative and rare decays:

- No significant decays of $\psi(3773) \to \gamma\eta_c, \gamma\eta_c(2S)$ are observed.
- The measurement of $Br(\psi(3770) \to \gamma\chi_{c1})$ is improved.
- No significant decays for the isospin-violating transition $\chi_{c0/2} \to \pi^0\eta_c$ are observed.
- The double OZI suppressed decay $J/\psi \to \pi^0\phi$, and isospin violation decay $J/\psi \to \phi\pi^0 f_0(980)$ observed.
- The X(1835) identified with 0^{-+} observed in $J/\psi \to \gamma K_S^0 K_S^0 \eta$.

A more interesting light hadron decays of charmonium will come soon!