Studies of Charmonium at BESIII

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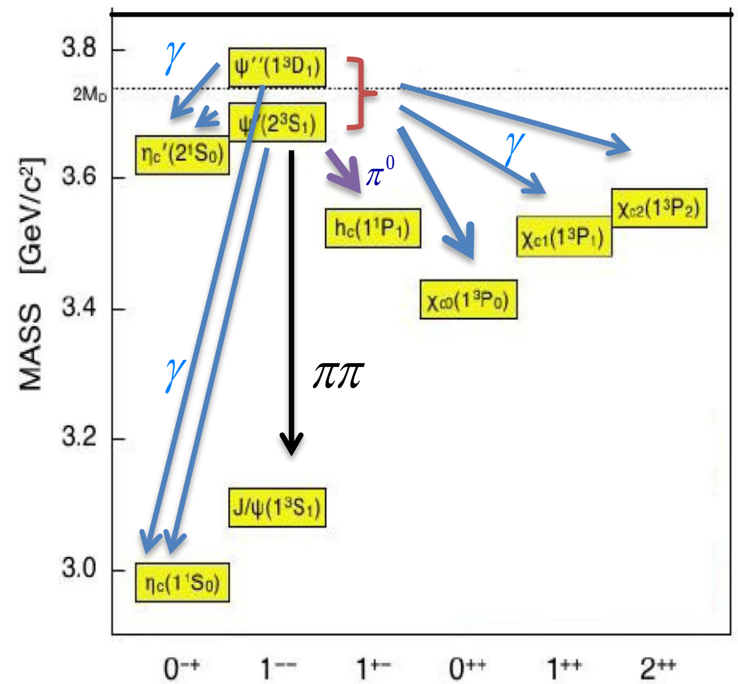
Introduction

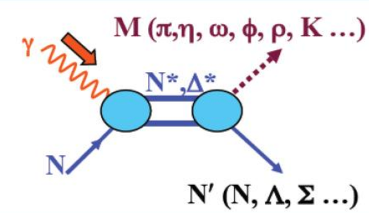
- Vector charmonium data sets

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}

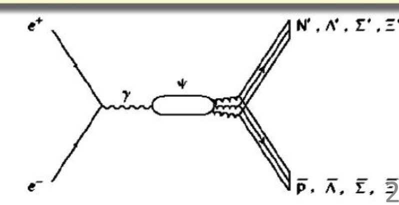
- $\eta_c, \eta_c(2S), \chi_{cJ}$ are available via γ transition, and h_c available via pion transiton.
- charmonium physics (see arXiv: 0809.1869)
  - $\rho\pi$ puzzle, and violation of the 12% rule
  - non-$D\bar{D}$ decays of $\psi(3770)$
  - light hadron structure and properties
  - ......
- rare decays: $J/\psi \to \gamma\gamma,\ \gamma\phi,\ \phi\pi^0$



JLab, ELSA, MAMI, ESRF, Spring-8, ….



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



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

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- Br($\psi(3770) \to$ non $D\bar{D}$)=(14.7$\pm$3.2)% (Phys. Lett. B641, 145 (2006)).
- 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)

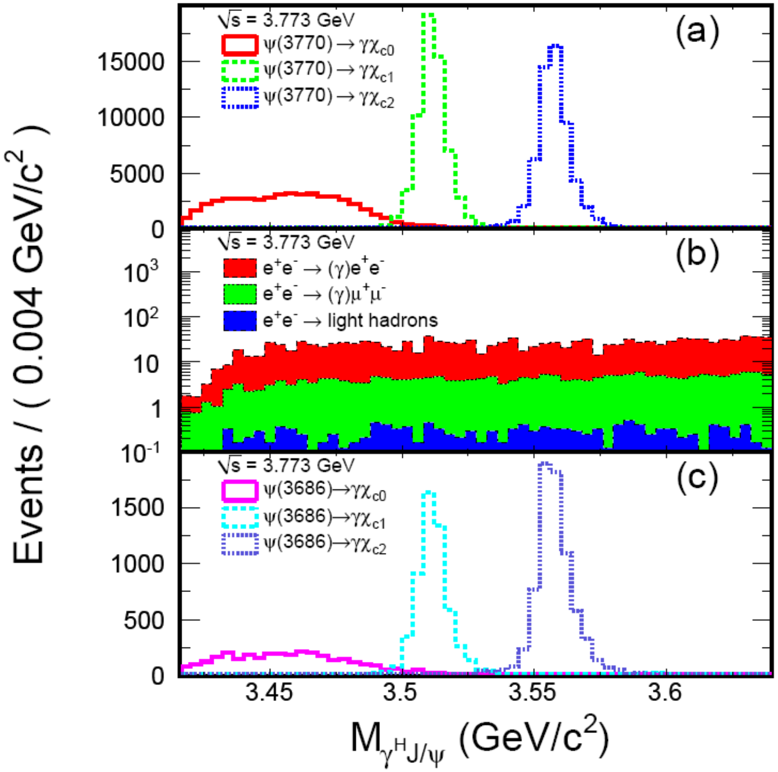
$\Gamma(\psi(3770) \to \gamma\chi_{c1})$: 59~183 KeV

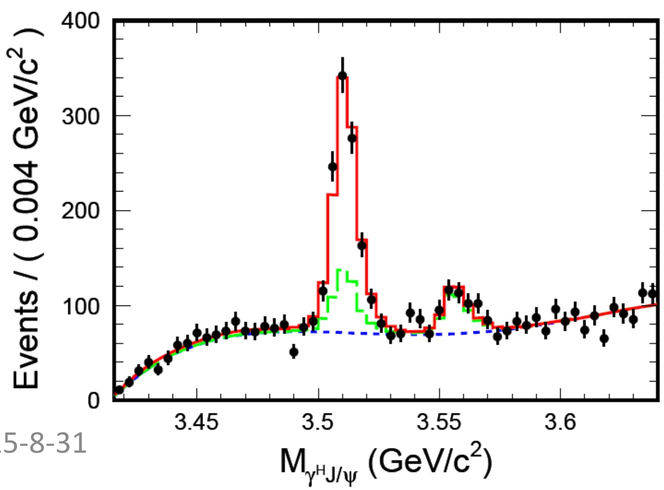
$\Gamma(\psi(3770) \to \gamma\chi_{c2})$: 3~24 KeV

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

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

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

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

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]		
$\phi = 12^\circ$ [13]	73 ± 9	24 ± 4
$\phi = (10.6 \pm 1.3)^\circ$ [32]	79 ± 6	21 ± 3
$\phi = 0^\circ$ (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

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

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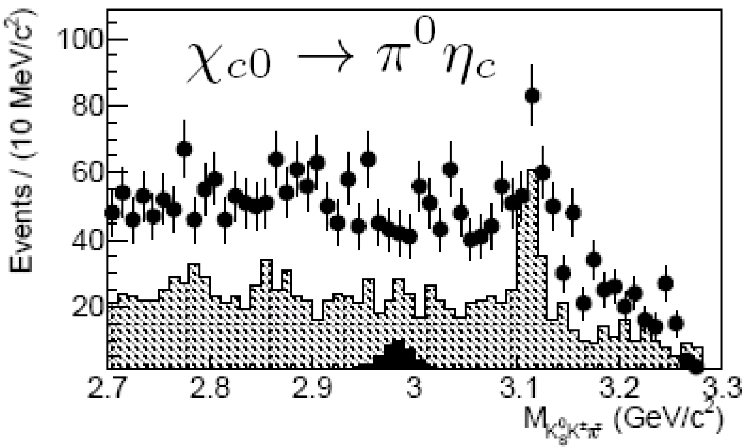
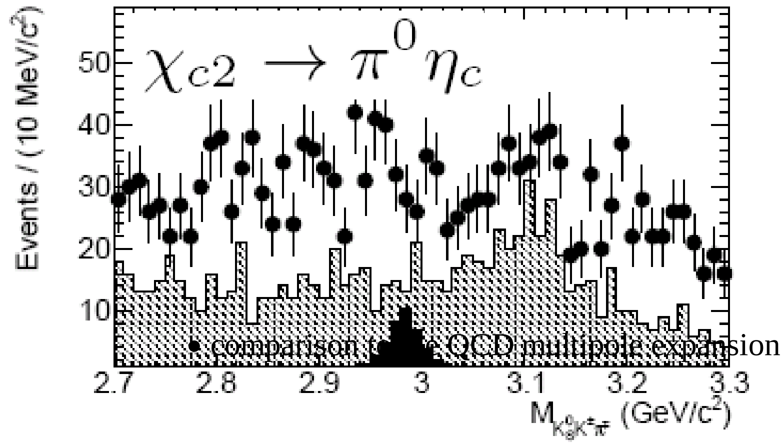
- The peack near 3.12 GeV is due to the background $\psi(2S) \to \pi^0 \pi^0 J/\psi$.
- No significant η_c signals are observed, and upper limits are set.

arXiv: 1502.02641





PRD 91, 112018 (2015)

	$\chi_{c0} \to \pi^0 \eta_c$	$\chi_{c2} \to \pi^0 \eta_c$
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

- **Comparison to the QCD multipole expansion**

  if B($\chi_{c0} \to \pi^0 \eta_c$)=0.022, then one expect the obsvered events in the 106×10^6 data sets N^{obs}=302.

- **This measurement is not contradictory to another prediction (a few $\times 10^{-4}$) (PRD, 86, 074033) with the QCD multipole expansion.**

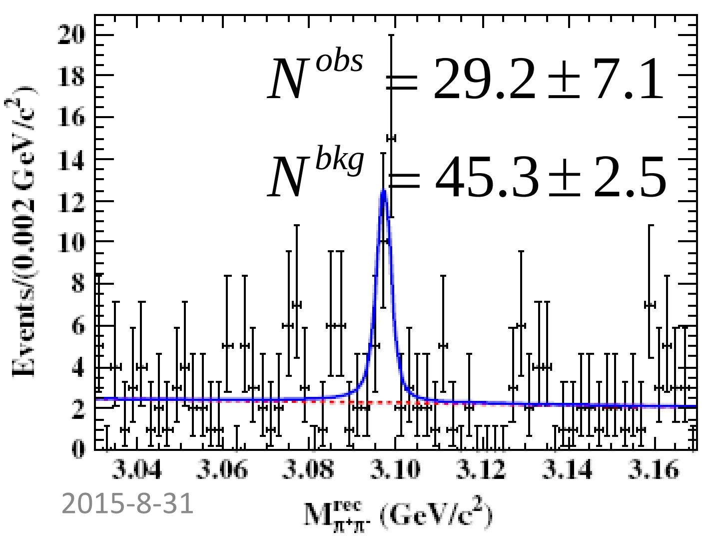
Search for C – violation decay $J/\psi \to \gamma\gamma, \gamma\phi$

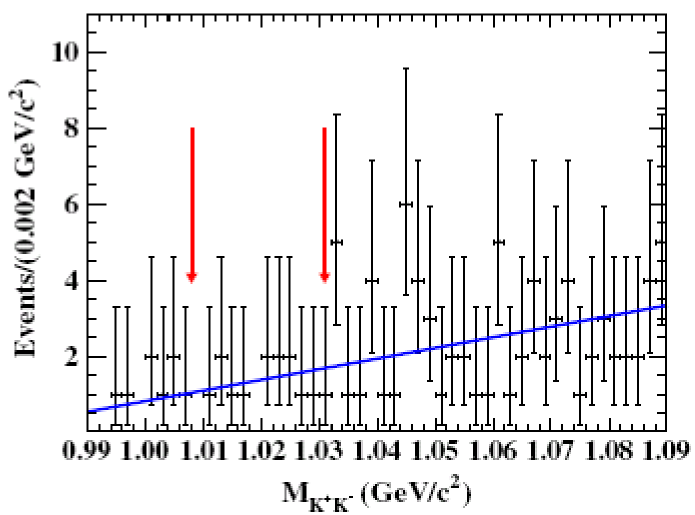
- The C-parity violation is forbidden in the electromagnetic interatction, any observation of the $J/\psi \to \gamma\gamma$ decay indicates a new physics.
- Based on the 106 million $\psi(3686)$ data set, we use the decay $\psi(2S) \to \pi^+\pi^- J/\psi$ to search for $J/\psi \to \gamma\gamma,\ \gamma\phi$.
- 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!

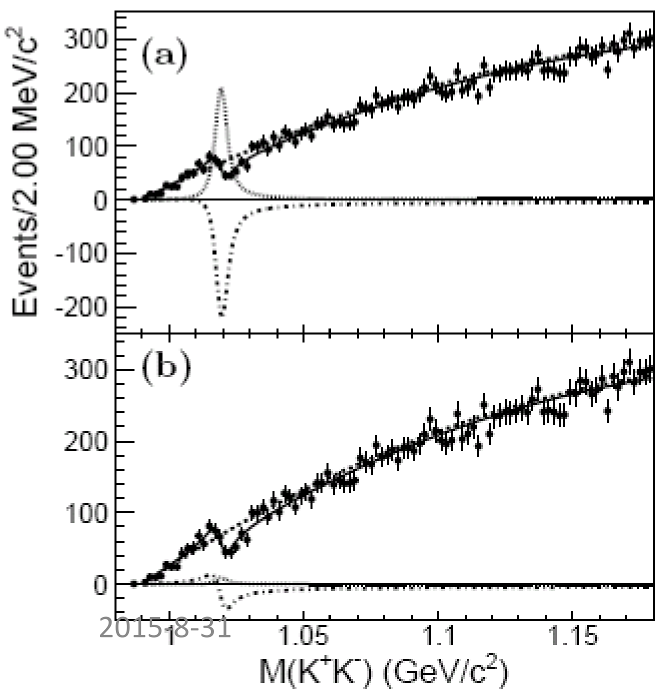
	$\gamma\gamma$	$\gamma\phi$
$\mathcal{B}(J/\psi \to)$ (this work)	$< 2.7 \times 10^{-7}$	$< 1.4 \times 10^{-6}$
$\mathcal{B}(J/\psi \to)$ (PDG [1])	$< 50 \times 10^{-7}$	–





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

- 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	$-95.9° \pm 1.5°$	$45.8/2$	6.4σ
II	35.3 ± 9.3	$-152.1° \pm 7.7°$	$45.8/2$	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 $J/\psi \to \pi^0\phi$

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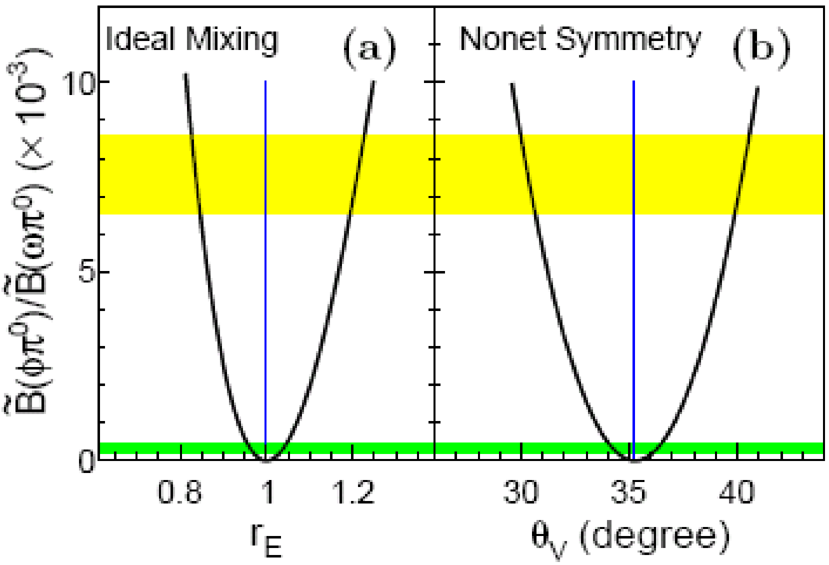
- Nonet symmetry broken

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)



assume 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)

assume 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)

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

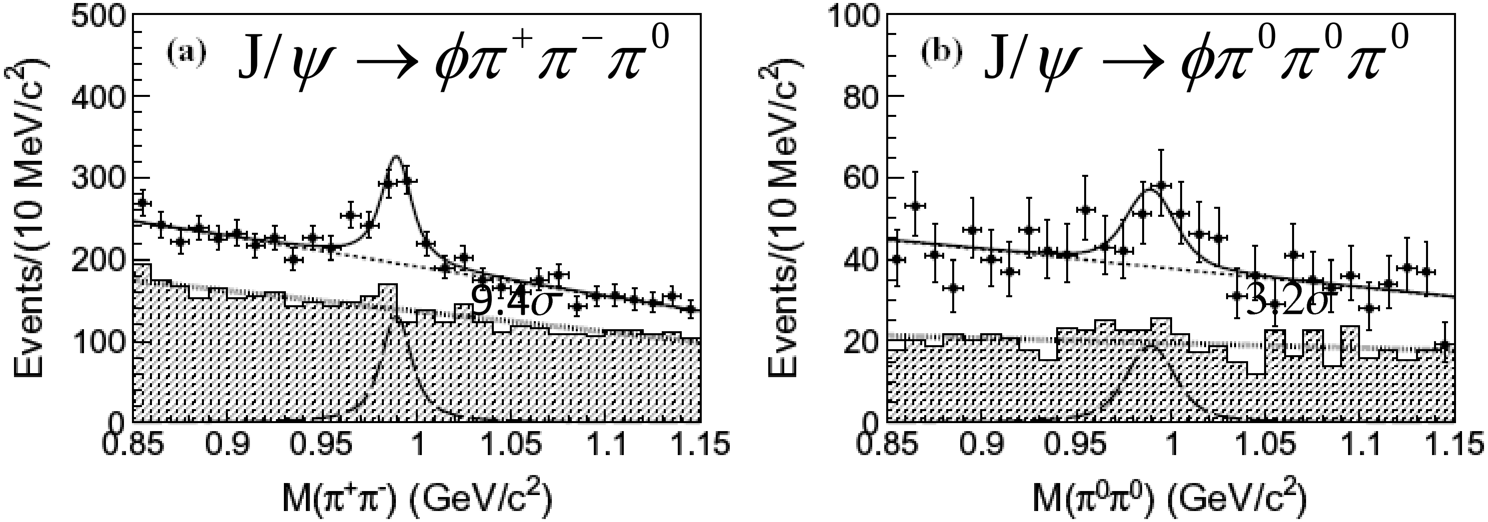
fit to radiative transition: $3.34^\circ \pm 0.09^\circ$ (J. High Energy Phys. 0907,105)

Nonet asymmetry indication!

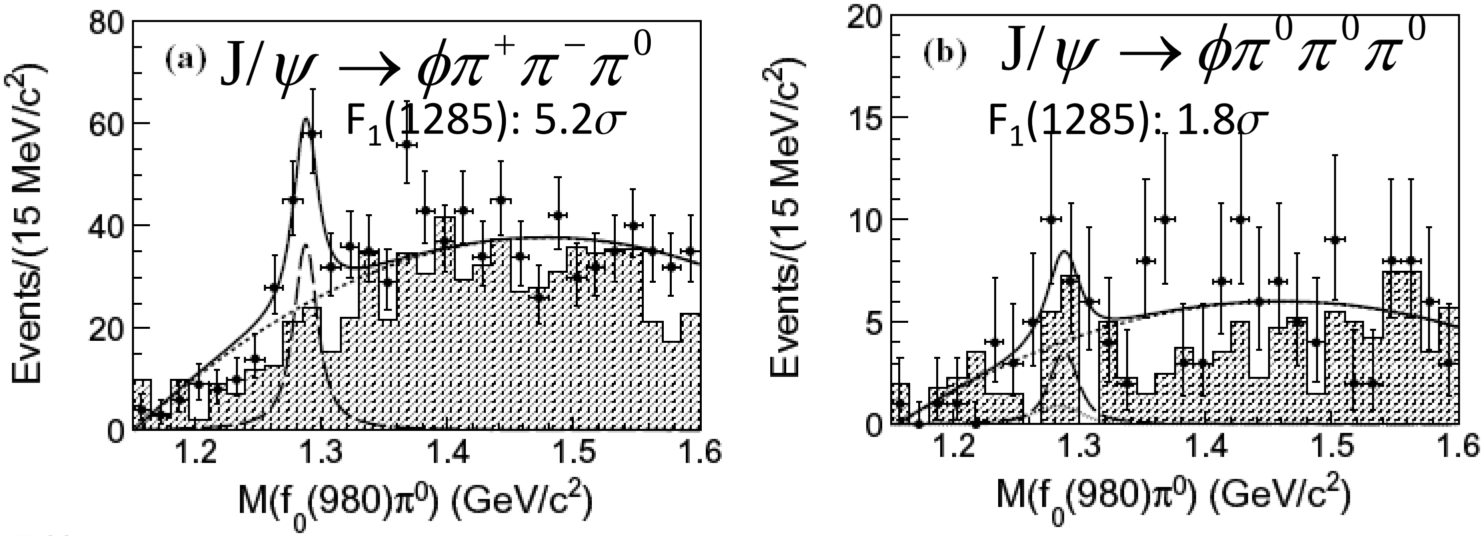
Observation of the isospin-violating decay $J/\psi \to \phi\pi^0 f_0(980)$

- 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 $\pm$ 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 $\pm$ 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 $J/\psi \to \gamma\pi^0 f_0(980)$.

- $\mathcal{B}(f_1 \to \pi^0 f_0 \to \pi^0\pi^+\pi^-)/\mathcal{B}(f_1 \to \pi^0 a_0^0 \to \pi^0\pi^0\eta)$ = $(3.6 \pm 1.4)\%$

- $\mathcal{B}(\eta(1405) \to \pi^0 f_0 \to \pi^0\pi^+\pi^-)/\mathcal{B}(\eta(1405) \to \pi^0 a_0^0 \to \pi^0\pi^0\eta) = (17.9\pm4.2)\%$

- 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.

Summary

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

- The measurement of $Br(\psi(3770) \to \gamma\chi_{c1})$ is improved.
- No significant signals for the isospin-violating transition $\chi_{c0/2} \to \pi^0\eta_c$ and C-violation $J/\psi \to \gamma\gamma, \gamma\phi$ 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.

These measurements provide more information on the charmonium structure, and the isospin and C-parity violation in the charmonium decays.