Studies of charmonium at BESIII

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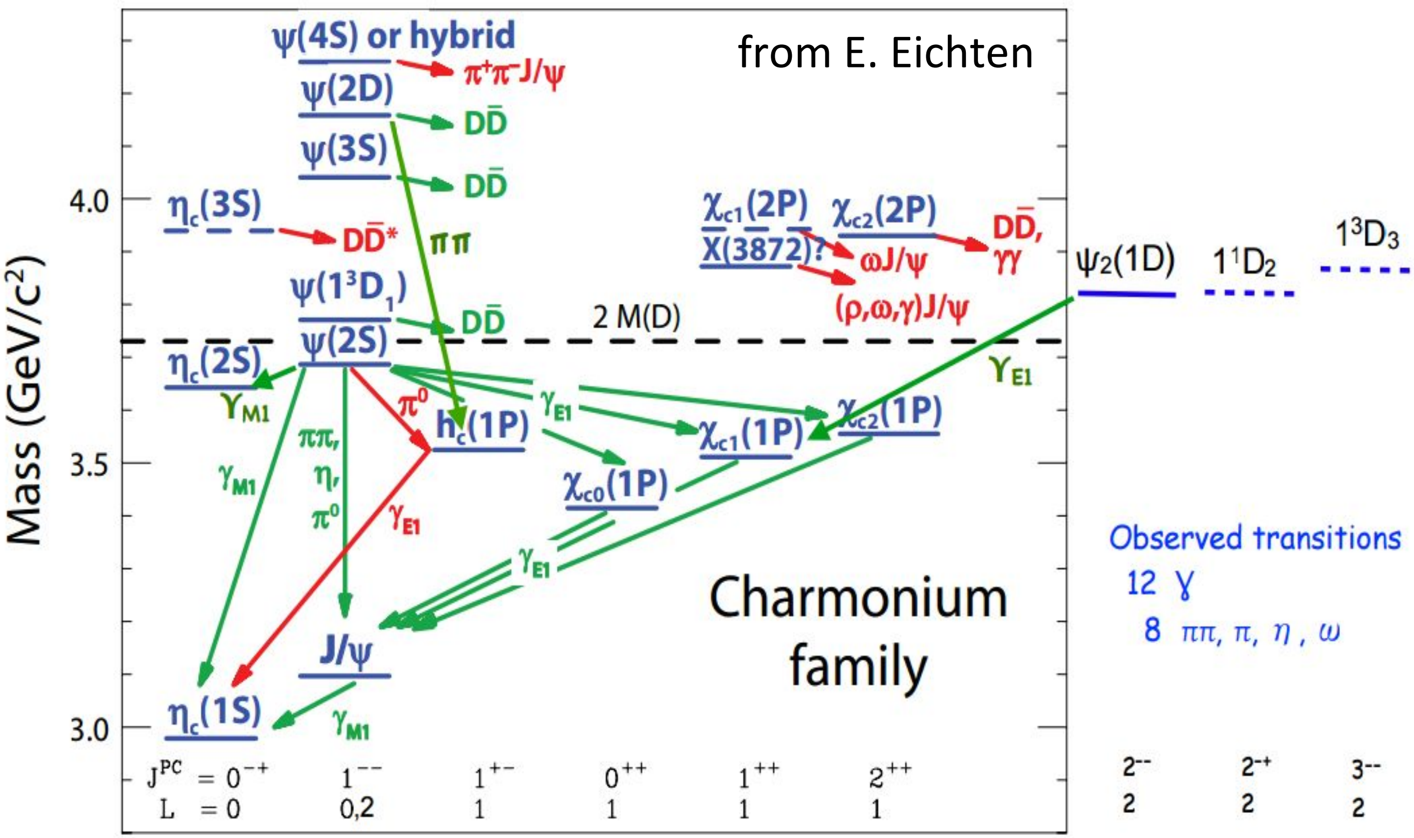
Outline

- Introduction
- Seleted latest results at BESIII:
  - **ψ(3770) radiative transitions**
    - Search for $\psi(3770)\rightarrow\gamma\eta_c$, $\gamma\eta_c(2S)\rightarrow\gamma K_S^0 K\pi$
    - Study of $\psi(3770)\rightarrow\gamma\chi_{cJ}$ with $\chi_{cJ}\rightarrow\gamma J/\psi\rightarrow\gamma l^+l^-$
  - **$\rho\pi$ puzzle and "12% rule"**
    - Branching fraction for $\psi(3686)\rightarrow\omega K^+K^-$
  - **Search for rare phenomena**
    - Search for isospin-violating transition $\chi_{c0,2}\rightarrow\pi^0\eta_c$
    - Search for C-parity violation in $J/\psi\rightarrow\gamma\gamma$, $\gamma\phi$
    - Observation of OZI-suppressed decay $J/\psi\rightarrow\pi^0\phi$
  - **Light hadron structure and properties**
    - Study of $J/\psi\rightarrow\phi\pi^0 f_0(980)$
    - Measurement of $\chi_{cJ}\rightarrow\eta' K^+K^-$
    - Study of $\chi_{cJ}\rightarrow\phi K^*(892)\bar{K}$
- Summary

Introduction

See
Dan Bennett: Hadronic Transitions above 4 GeV at BESIII
Qing Gao: Radiative Transitions above 4 GeV at BESIII
Wei Shan: Exotic Zc states at BESIII

- Potential models, and L-QCD, very successful in describing the charmonium states below open charm threshold. Above threshold, XYZ cannot be unambiguously fit into QQbar-scheme.



η_c, $\eta_c(2S)$, χ_{cJ} are available via γ transition, and h_c available via pion transiton.

Introduction

- Vector charmonium data sets at BESIII

Vector charmonium	Previous data	BESIII now
J/ψ	BESII: 58 M	1.3 B (20 $\times$ BESII)
$\psi(3686)$	CLEO: 28 M	0.5 B (20 $\times$ CLEO)
$\psi(3770)$	CLEO: 0.8 fb^{-1}	2.9 fb^{-1} (3.5 $\times$ CLEO)

Results in this presentation are based on data samples:

- **2.92 fb^{-1} $\psi(3770)$ data**
- **106 million $\psi(3686)$ data**
- **1.31 billion J/ψ data**

$\psi(3770)$ radiative transitions

- The $\psi(3770)$, lowest-mass $c\bar{c}$ state laying above the open-charm threshold, is expected to decay predominantly into $D\bar{D}$ pairs [PRD 17, 3090].

- Non-$D\bar{D}$ branching fraction measurements:
  - BES:(14.7±3.2)% [PLB 641,145]
  - CLEO: (-3.3± $1.4^{+6.6}_{-4.8}$)% [PRL 104, 159901]

suggest substantial non-$D\bar{D}$ decays!

- Observed non-$D\bar{D}$ decay modes of $\psi(3770)$: $\pi\pi J/\psi$, $\eta J/\psi$, $\gamma\chi_{c0,1}$, and $\eta\phi$. Total sum of them is less than 2% of all decays.

- Light hadron transition or radiative transitions can shed light on $\psi(3770)$.

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

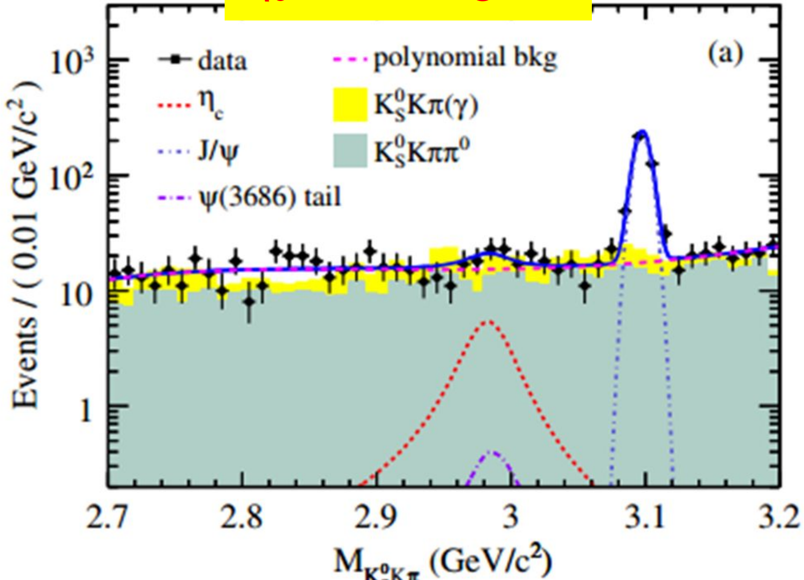
PRD 89, 112005 (2014)

- If $\psi(3770)$ is a pure D-wave state, the radiative transitions $\psi(3770)\to\gamma\eta_c(\eta_c(2S))$ are supposed to be highly suppressed. However, due to the nonvanishing photon energy, higher multipoles beyond the leading one could contribute.

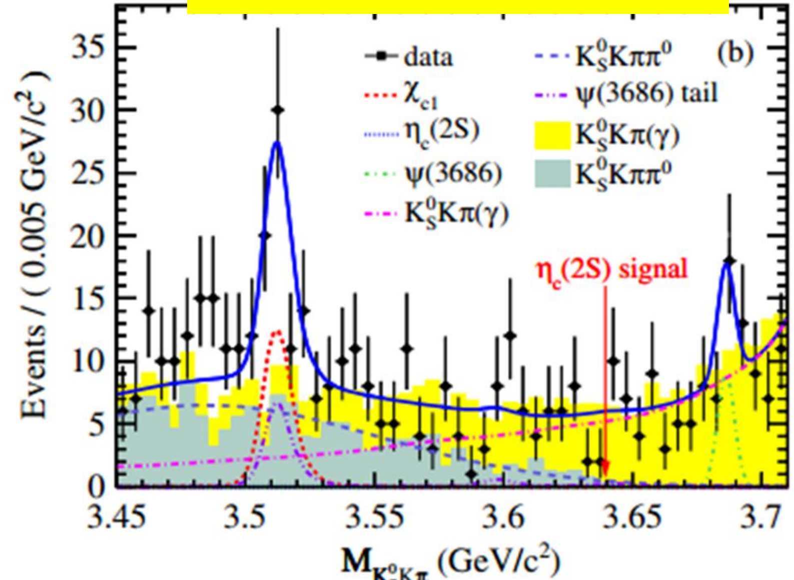
- IML transition model predictions [PRD 84, 074005]:

$$\mathcal{B}(\psi(3770)\to\gamma\eta_c) = 6.3^{+8.4}_{-4.4}\times 10^{-4}$$
$$\mathcal{B}\big(\psi(3770)\to\gamma\eta_c(2S)\big) = 6.7^{+7.2}_{-4.4}\times 10^{-5}$$

η_c mass region



χ_{c1}-$\eta_c(2S)$ mass region



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

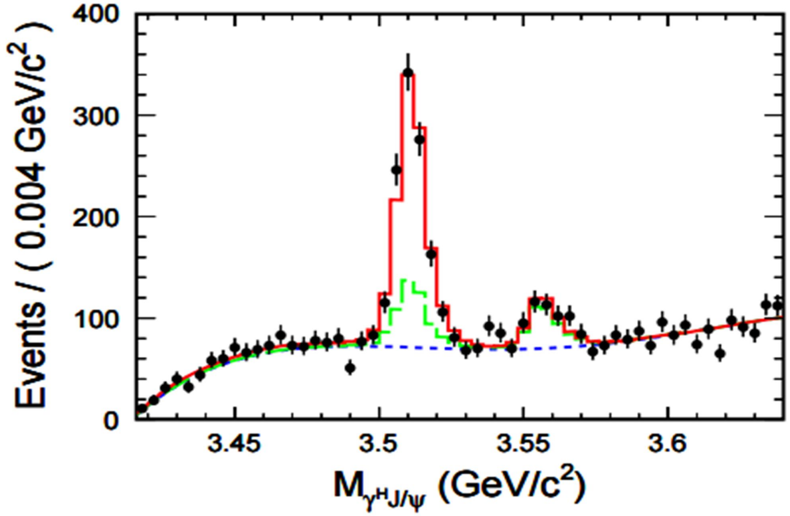
PRD 89, 112005 (2014)

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	...	...

- **No significant η_c and $\eta_c(2S)$ signals are observed.** Upper limits on $B(\psi(3770)\to\gamma\eta_c\ (\eta_c(2S)))$ are set.
- The upper limit for $\Gamma(\psi(3770)\to\gamma\eta_c)$ is within the error of the theoretical predictions (IML, LQCD), but $\Gamma(\psi(3770)\to\gamma\eta_c(2S))$ is larger than the prediction (IML) and limited by large systematic uncertainties.

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

PRD 91, 092009 (2015)



- S-D mixing model predictions

  [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

- Measured branching fractions:
  - $B(\psi(3770)\to\gamma\chi_{c1})=(2.48\pm0.15\pm0.23)\times10^{-3}$, is consistent with CLEO-c but with improved precision.
  - $B(\psi(3770)\to\gamma\chi_{c2})<0.64\times10^{-3}$

Experiment/theory	$\Gamma(\psi(3770)\to\gamma\chi_{cJ})$ (keV)	
	$J=1$	$J=2$
This work	$67.5\pm4.1\pm6.7$	<17.4
Ding-Qin-Chao		
Nonrelativistic	95	3.6
Relativistic	72	3.0
Rosner S-D mixing		
$\phi=12^\circ$	73 ± 9	24 ± 4
$\phi=(10.6\pm1.3)^\circ$	79 ± 6	21 ± 3
$\phi=0^\circ$ (pure 1^3D_1 state)	133	4.8
Eichten-Lane-Quigg		
Nonrelativistic	183	3.2
With coupled-channel corr.	59	3.9
Barnes-Godfrey-Swanson		
Nonrelativistic	125	4.9
Relativistic	77	3.3

ρπ puzzle and "12% rule"

- Perturbative QCD provides the relation:

$$Q_h = \frac{\mathcal{B}_{\psi(3686)\to h}}{\mathcal{B}_{J/\psi\to h}} \approx \frac{\mathcal{B}_{\psi(3686)\to e^+e^-}}{\mathcal{B}_{J/\psi\to e^+e^-}} = 12.7\%$$

("12% rule")

Severe violation is found in ρπ channel and others, i.e. ρπ puzzle

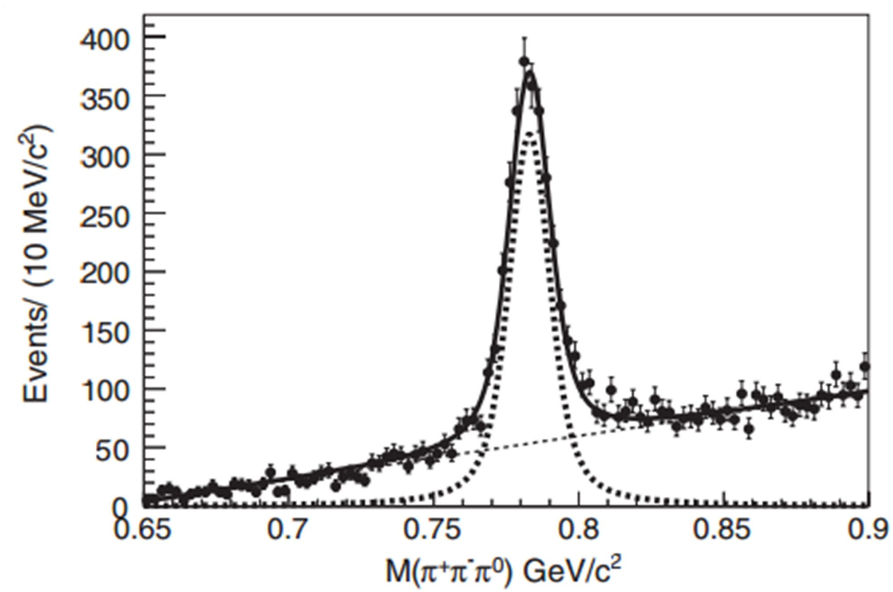
- Various possible mechanisms for ρπ puzzle have been proposed [Int. J. Mod. Phys. A 24, 499], but none provides an universally satisfactory explanation at present.

- More measurements of different J/ψ and ψ(3686) decay modes at higher level precision are helpful to understand the puzzle.

Branching fraction for $\psi(3686)\to\omega K^+K^-$

PRD 89, 112006 (2014)

- Most precise measurement of $B(\psi(3686)\to\omega K^+K^-) = (1.56\pm0.04\pm0.11)\times10^{-4}$
- $Q = \frac{B(\psi(3686)\to\omega K^+K^-)}{B(J/\psi\to\omega K^+K^-)} \approx$ $(18.4\pm3.7)\%$, smaller than previous result $(21.8\pm5.0)\%$.
- A measurement of $B(J/\psi\to\omega K^+K^-)$ with higher precision is needed to establish a significant deviation from 12% rule.



Branching fraction	Source
$(1.56\pm0.04\pm0.11)\times10^{-4}$	this analysis
$(2.38\pm0.37\pm0.29)\times10^{-4}$	BESII [20]
$(1.9\pm0.3\pm0.3)\times10^{-4}$	CLEO [21]
$(1.5\pm0.3\pm0.2)\times10^{-4}$	BES [22]
$(1.85\pm0.25)\times10^{-4}$	PDG [5]

Search for rare phenomena

- Using high statistics charmonium decays:
  - Search for isospin-violating transition $\chi_{c0,2} \to \pi^0 \eta_c$
  - Search for C-parity violation in $J/\psi \to \gamma\gamma$, $\gamma\phi$
  - Observation of OZI-suppressed decay $J/\psi \to \pi^0 \phi$

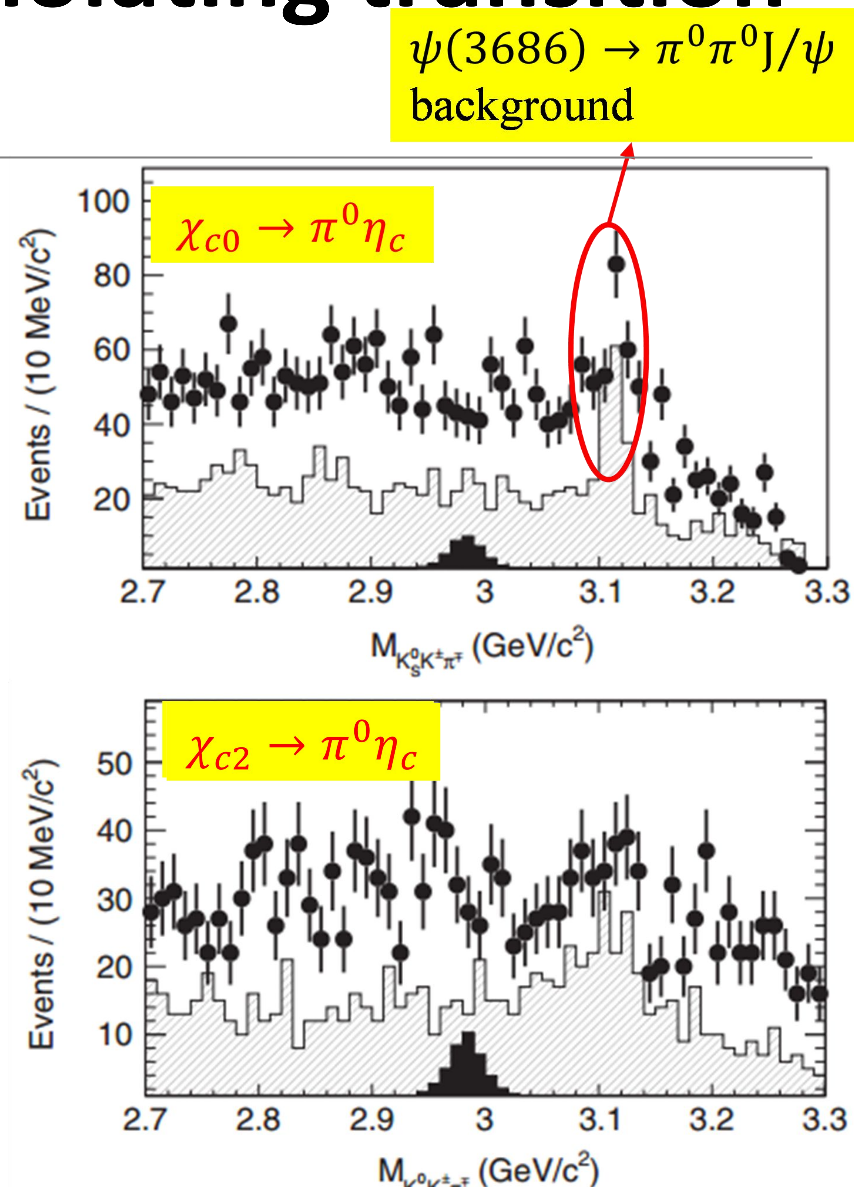
Search for isospin-violating transition $\chi_{c0,2} \to \pi^0 \eta_c$

- Searches for the isospin-violating decay $\chi_{cJ} \to \pi^0 \eta_c$ give insights to the isospin violating mechanism.
- No statistically significant signal is observed. First report of upper limits:

$$\mathcal{B}(\chi_{c0} \to \pi^0 \eta_c) < 1.6 \times 10^{-3},$$
$$\mathcal{B}(\chi_{c2} \to \pi^0 \eta_c) < 3.2 \times 10^{-3}$$

- Measured $B(\chi_{c0} \to \pi^0 \eta_c)$ is consistent with leading-order QCD expansion prediction [PRD86, 074033]:

$$\mathcal{B}(\chi_{c0} \to \pi^0 \eta_c) \approx \mathcal{B}(\chi_{c1} \to \pi^+ \pi^- \eta_c)$$



PRD 91, 112018 (2015)

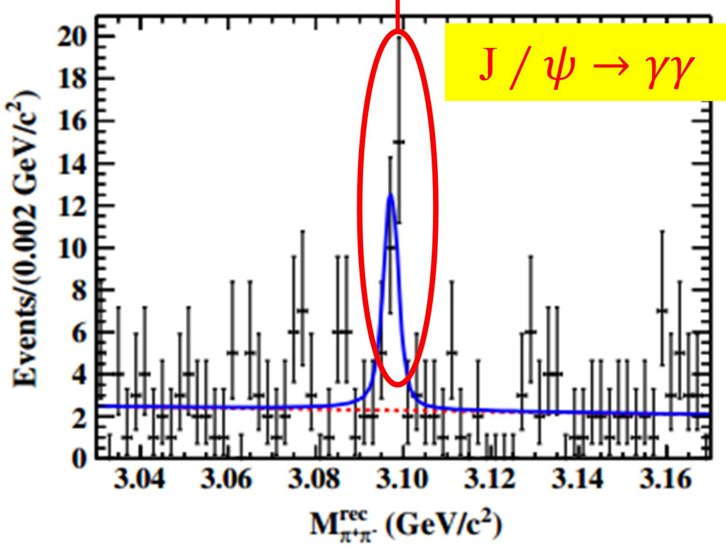
Search for C-parity violation in $J/\psi \to \gamma\gamma$, $\gamma\phi$

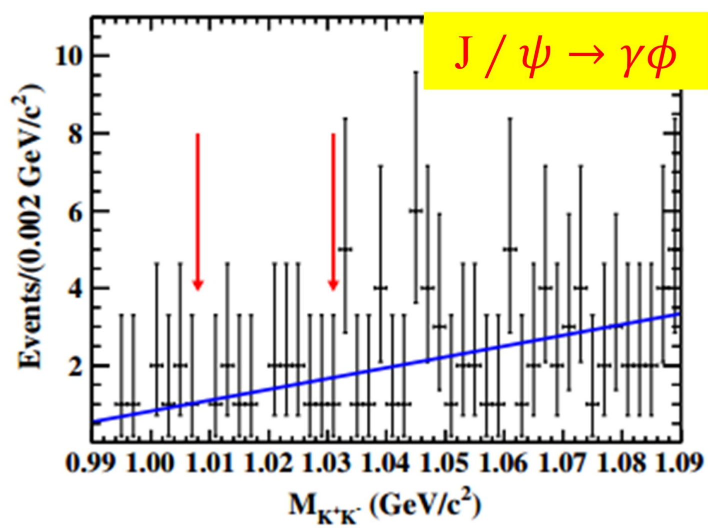
PRD 90, 092002 (2014)

- Evidence for them in the EM sector would indicate physics beyond the SM.
- $J/\psi \to \gamma\gamma$, $\gamma\phi$ decays are searched for via $\psi(3686) \to \pi^+\pi^- J/\psi$.
- No C violation decays were observed!

Peaking backgrounds from $J/\psi \to \gamma\pi^0, \gamma\eta, \gamma\eta_c \to 3\gamma$, and $J/\psi \to 3\gamma$

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

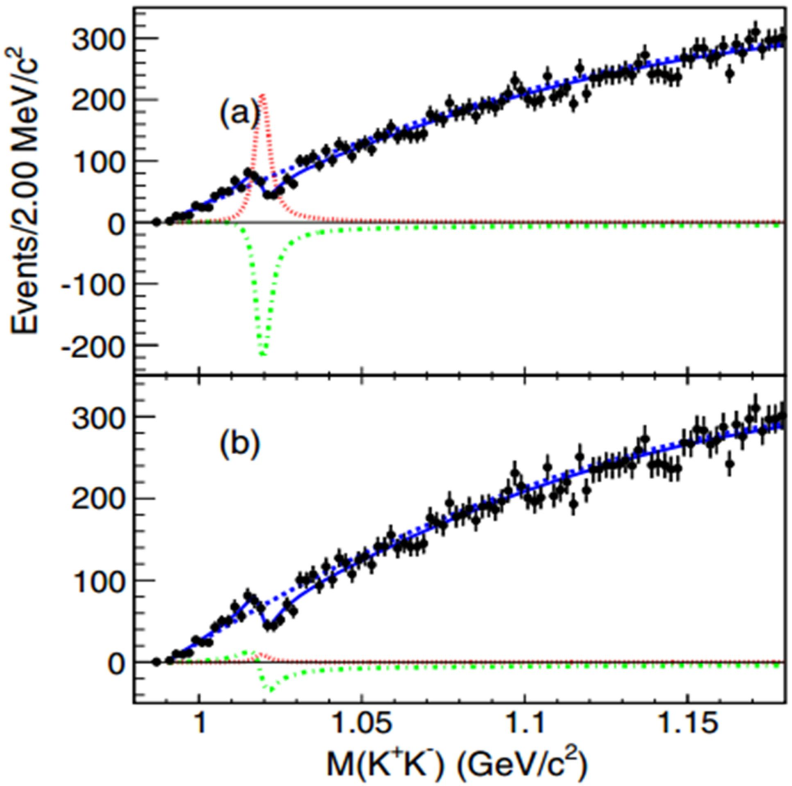




Observation of OZI-suppressed decay $J/\psi \rightarrow \pi^0 \phi$

PRD 91,112001 (2015)

- First evidence for a DOZI suppressed electromagnetic J/ψ decay.
- The structure at the ϕ mass region is attributed to the interference between the $J/\psi \rightarrow \pi^0 \phi$ and $J/\psi \rightarrow \pi^0 K^+ K^-$ decays.



Two possible solutions:

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

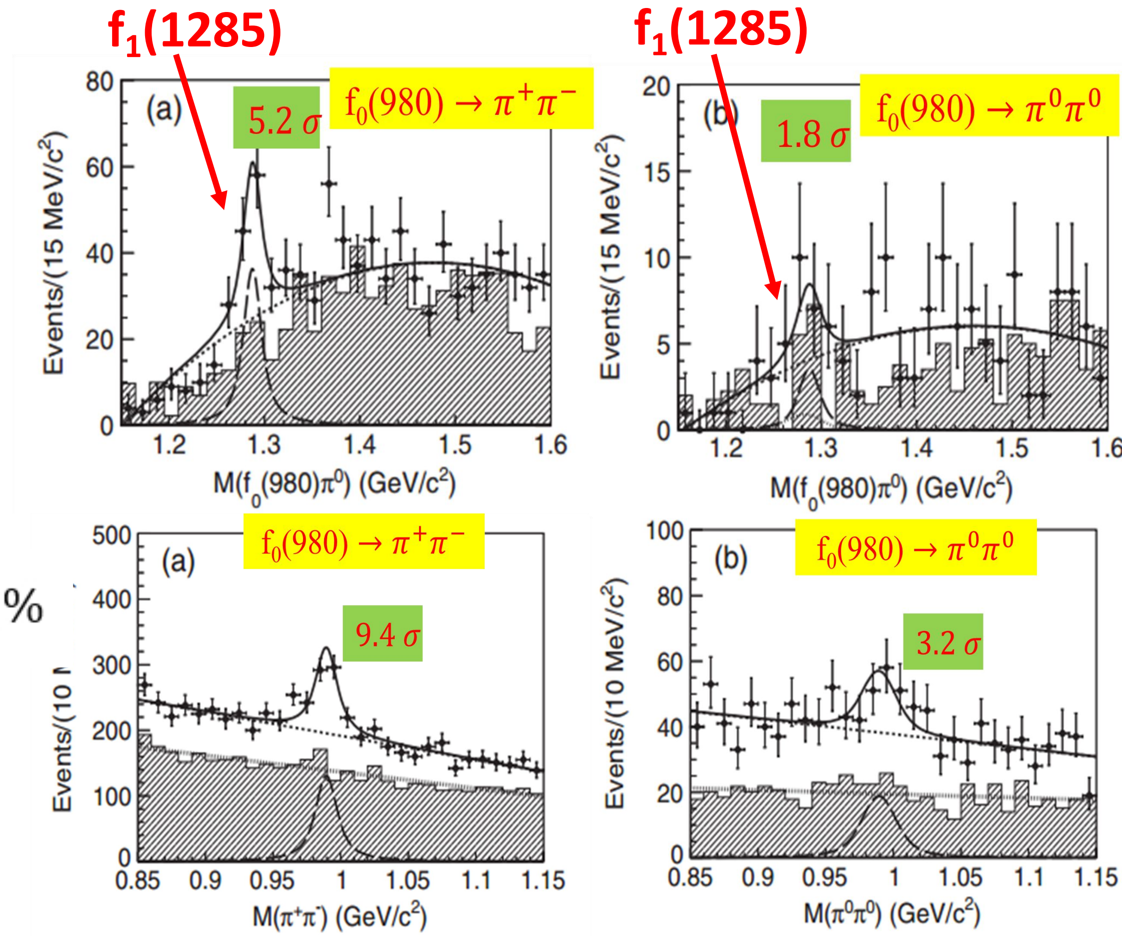
Light hadron structure and properties

- The decays of charmonium offer a good laboratory for studying light hadron properties. In this presentation:
  - Study of $J/\psi \to \phi \pi^0 f_0(980)$
  - Measurement of $\chi_{cJ} \to \eta' K^+ K^-$
  - Study of $\chi_{cJ} \to \phi K^*(892)\bar{K}$

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

PRD 92,012007 (2015)

- Long standing puzzle of $f_0(980)$: $q\bar{q}$, $K\bar{K}$ molecule, four-quark state?
- In isospin-violating decay $J/\psi \to \gamma\eta(1405) \to \gamma\pi^0 f_0(980)$
  [PRL 108,182001]
  - **large isospin violation**
    $\frac{\mathcal{B}(\eta(1405)\to\pi^0 f_0(980))}{\mathcal{B}(\eta(1405)\to\pi^0 a_0(980))}=(17.9 \pm 4.2)\%$
  - **very narrow $f_0(980)$:**
    $\Gamma \approx 10$ MeV (PDG: 40-100MeV)



$M(f_0(980))$=989.4±1.3 MeV,

$\Gamma(f_0(980))$=15.3±4.7 MeV **(consistent with $J/\psi \to \gamma\eta(1405) \to \gamma\pi^0 f_0(980)$)**

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

PRD 92,012007 (2015)

Decay mode	Branching fractions
$J/\psi \to \phi\pi^0 f_0, f_0 \to \pi^+\pi^-$	$(4.50 \pm 0.80 \pm 0.61) \times 10^{-6}$
$J/\psi \to \phi\pi^0 f_0, f_0 \to \pi^0\pi^0$	$(1.67 \pm 0.50 \pm 0.24) \times 10^{-6}$
$J/\psi \to \phi f_1, f_1 \to \pi^0 f_0 \to \pi^0\pi^+\pi^-$	$(9.36 \pm 2.31 \pm 1.54) \times 10^{-7}$
$J/\psi \to \phi f_1, f_1 \to \pi^0 f_0 \to \pi^0\pi^0\pi^0$	$(2.08 \pm 1.63 \pm 1.47) \times 10^{-7}$

- First observation of $J/\psi \to \phi\pi^0 f_0(980)$
- Evidence of axial-vector meson $f_1(1285) \to \pi^0 f_0(980)$
- $\frac{\mathcal{B}(f_1(1285)\to\pi^0 f_0(980))}{\mathcal{B}(f_1(1285)\to\pi^0 a_0(980))}$=$(3.6 \pm 1.4)\%$,
  - consistent with triangle singularity predition (≈1%)[EPJA 51, 48]
  - 1/5 of $\frac{\mathcal{B}(\eta(1405)\to\pi^0 f_0(980))}{\mathcal{B}(\eta(1405)\to\pi^0 a_0(980))}$

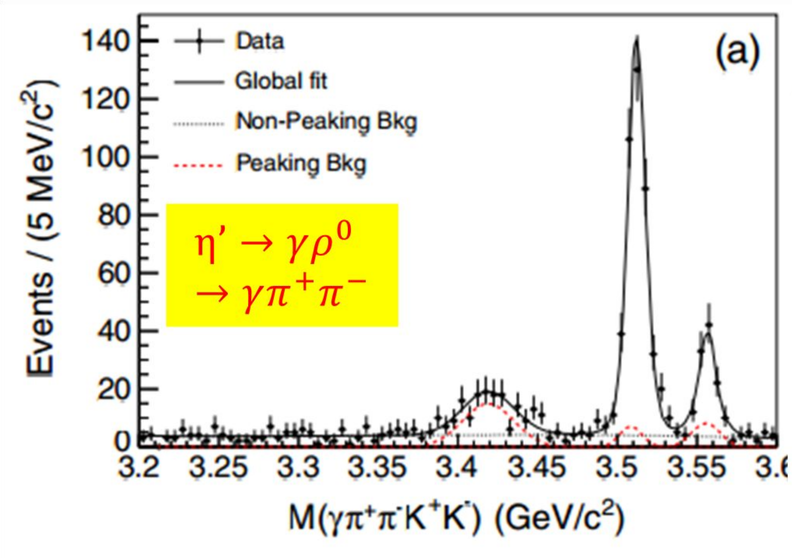
The nature of the resonances a_0 and f_0 as dynamically generated makes isospin breaking strength strongly process-dependent [EPJA 51, 48].

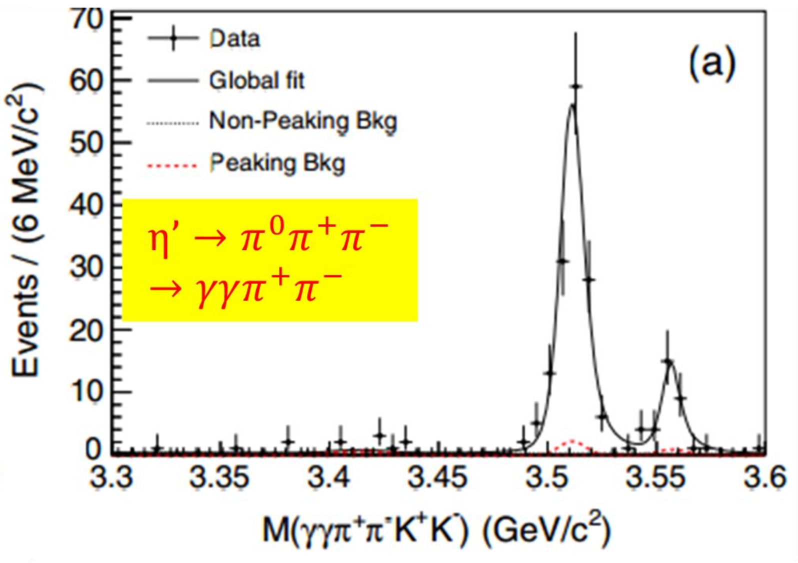
Measurement of $\chi_{cJ} \to \eta' K^+K^-$

PRD 89,074030 (2014)

Mode I: $\eta' \to \gamma\rho^0 \to \gamma\pi^+\pi^-$
Mode II: $\eta' \to \pi^0\pi^+\pi^- \to \gamma\gamma\pi^+\pi^-$

- $K_0^*(1430)$ has been observed in $K_0^*(1430) \to K\pi$ only, but it is also expected to couple to $\eta' K$ [PRD 78, 052001, PLB 632, 471]
- Abundant structures are observed in the $M(K^+K^-)$ and $M(\eta' K^\pm)$
- PWA is performed to disentangle the structures and determine the detection efficiency.

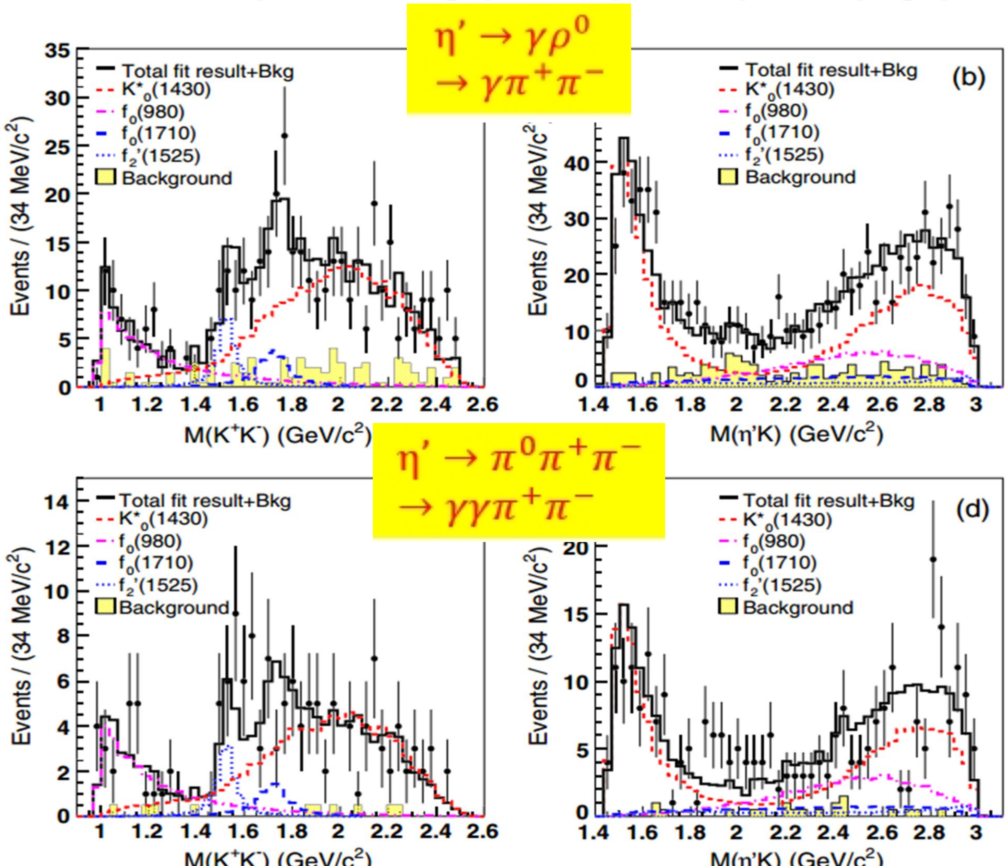




Measurement of $\chi_{cJ} \rightarrow \eta' K^+ K^-$

PRD 89,074030 (2014)

- First observation of $K_0^*(1430) \rightarrow \eta' K^\pm$
- First measurements of
  - $\mathcal{B}(\chi_{c1} \rightarrow X\eta') \cdot \mathcal{B}(X \rightarrow K^+K^-)$ (X=$f_0(980)$, $f_0(1710)$ and $f_2'(1525)$)
  - $\mathcal{B}(\chi_{c1} \rightarrow K_0^*(1430)^\pm K^\mp) \cdot \mathcal{B}(K_0^*(1430)^\pm \rightarrow \eta' K^\pm)$

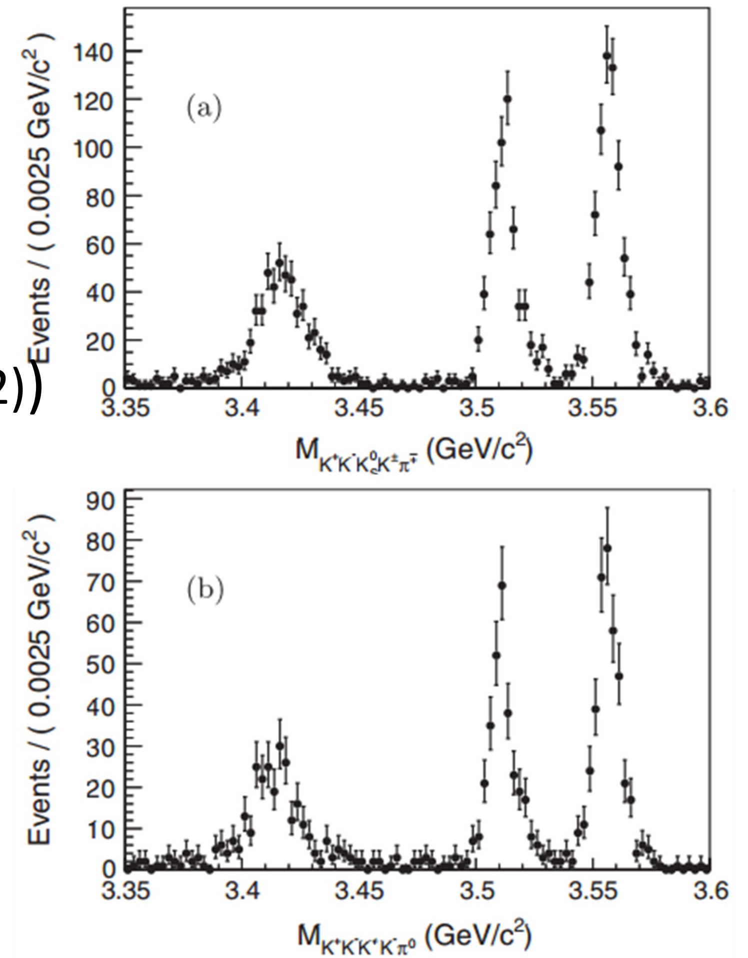


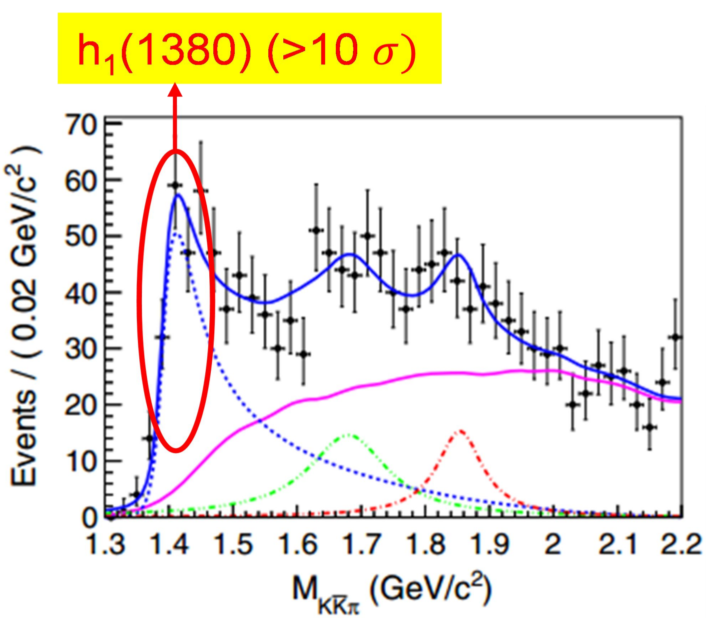
ocess		$\mathcal{B}(\times 10^{-4})$
	$\eta' \rightarrow \gamma\rho^0$	$9.09 \pm 0.54 \pm 0.86$
$\chi_{c1} \rightarrow \eta' K^+K^-)$	$\eta' \rightarrow \eta\pi^+\pi^-$	$8.33 \pm 0.77 \pm 0.77$
	average	8.75 ± 0.87
	$\eta' \rightarrow \gamma\rho^0$	$1.84 \pm 0.31 \pm 0.33$
$\chi_{c2} \rightarrow \eta' K^+K^-)$	$\eta' \rightarrow \eta\pi^+\pi^-$	$2.05 \pm 0.41 \pm 0.25$
	average	1.94 ± 0.34
$\rightarrow K_0^*(1430)^\pm K^\mp$, $K_0^*(1430)^\pm \rightarrow \eta' K^\pm$		$6.41 \pm 0.57^{+2.09}_{-2.71}$
$\rightarrow \eta' f_0(980)$, $f_0(980) \rightarrow K^+K^-$		$1.65 \pm 0.47^{+1.32}_{-0.56}$
$\rightarrow \eta' f_0(1710)$, $f_0(1710) \rightarrow K^+K^-$		$0.71 \pm 0.22^{+0.68}_{-0.48}$
$\rightarrow \eta' f_2'(1525)$, $f_2'(1525) \rightarrow K^+K^-$		$0.92 \pm 0.23^{+0.55}_{-0.51}$

Study of $\chi_{cJ}\to\phi K^*(892)\bar{K}$

PRD 91, 112008 (2015)

- First measurement of the decay $\chi_{cJ}\to\phi K^*(892)\bar{K}$ (neutral and charged $K^*(892)$)
- $\mathcal{B}(\chi_{cJ}\to\phi K^*(892)^{\pm}K^{\mp})$ is consistent with $\mathcal{B}(\chi_{cJ}\to\phi K^*(892)^0\bar{K}^0)$
- First observation $h_1(1380)\to K^*(892)\bar{K}$





Decay Modes		$\phi K_s K^{\pm}\pi^{\mp}$ $(\times 10^{-3})$	$\phi K^+K^-\pi^0$ $(\times 10^{-3})$
χ_{c0}	$\phi K^*(892)^{\pm}K^{\mp}$	$1.65\pm0.21(\text{stat})\pm0.22(\text{sys})$	$1.90\pm0.14(\text{stat})\pm0.32(\text{sys})$
	$\phi K^*(892)^0\bar{K}^0$ + c.c.	$2.03\pm0.21(\text{stat})\pm0.28(\text{sys})$	...
χ_{c1}	$\phi K^*(892)^{\pm}K^{\mp}$	$1.76\pm0.21(\text{stat})\pm0.26(\text{sys})$	$1.62\pm0.12(\text{stat})\pm0.28(\text{sys})$
	$\phi K^*(892)^0\bar{K}^0$ + c.c	$1.51\pm0.19(\text{stat})\pm0.22(\text{sys})$	...
χ_{c2}	$\phi K^*(892)^{\pm}K^{\mp}$	$2.56\pm0.23(\text{stat})\pm0.35(\text{sys})$	$2.74\pm0.16(\text{stat})\pm0.44(\text{sys})$
	$\phi K^*(892)^0\bar{K}^0$ + c.c.	$2.27\pm0.22(\text{stat})\pm0.32(\text{sys})$	...

Summary

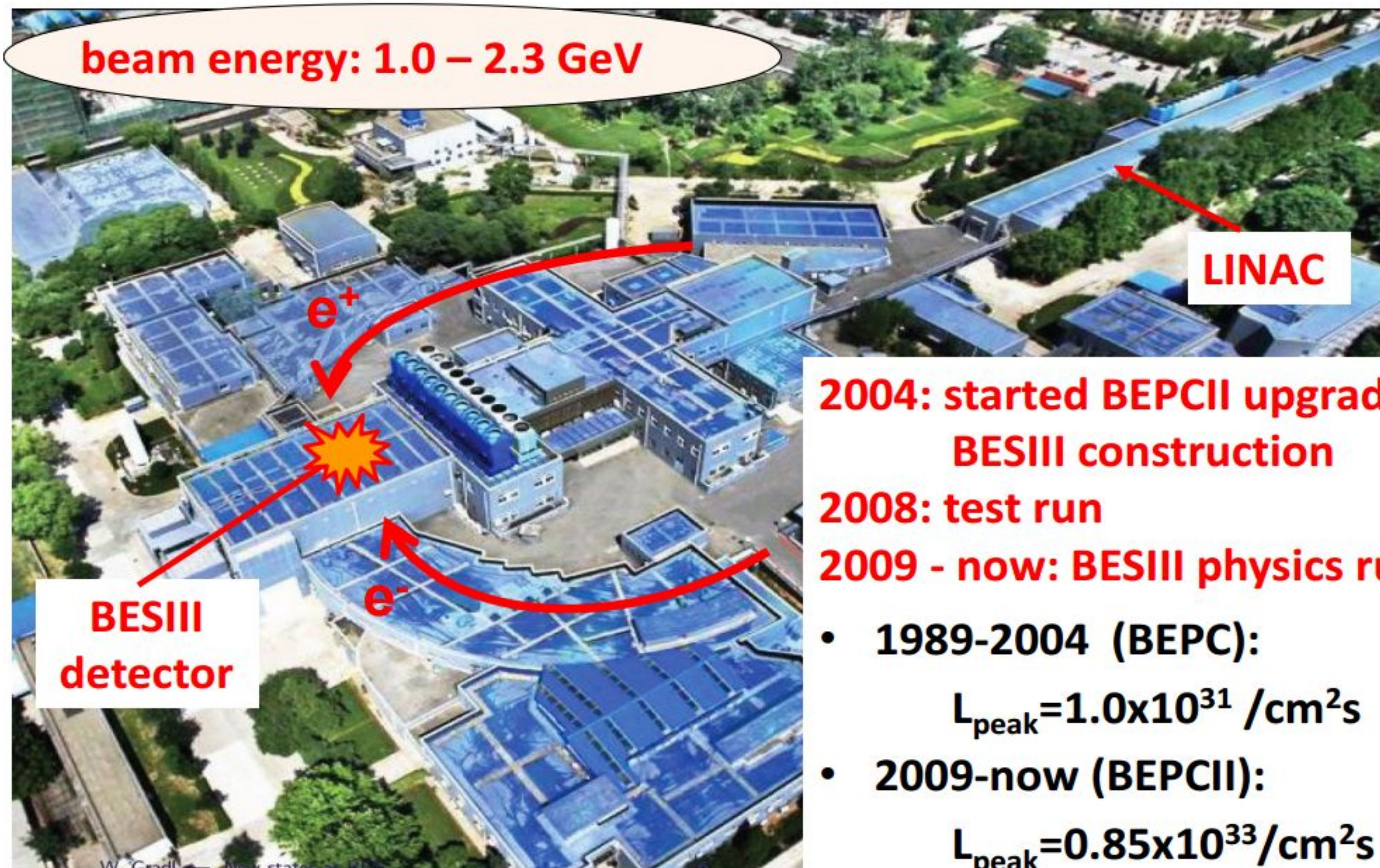
- By using BESIII data samples collected at J/ψ , $\psi(3686)$ and $\psi(3770)$ peak:
  - **Measurements of $\psi(3770)$ radiative transitions:**
    - $B(\psi(3770)\to\gamma\chi_{c1})$
    - Upper limits of $B(\psi(3770)\to\gamma\eta_c$ $(\eta_c(2S))$ and $B(\psi(3770)\to\gamma\chi_{c2})$
  - **Rare phenomena in charmonium decays:**
    - No isospin-violating decay $\chi_{c0,2}\to\pi^0\eta_c$ is observed
    - No C-violation decay $J/\psi\to\gamma\gamma$, $\gamma\phi$ is observed
    - Observation of DOZI suppressed decay $J/\psi\to\pi^0\phi$
  - **Studies of light hadrons:**
    - Study of $f_0(980)$ in $J/\psi\to\phi\pi^0 f_0(980)$
    - Observation of $K_0^*(1430)\to\eta' K^\pm$, $h_1(1380)\to K^*(892)\bar{K}$
    - Measurement of $\chi_{cJ}\to\phi K^*(892)\bar{K}$

A lot more interesting results from charmonium decays at BESIII in the future are expected!

Thank you for your attention

backup

Beijing Electron Positron Collider (BEPC)

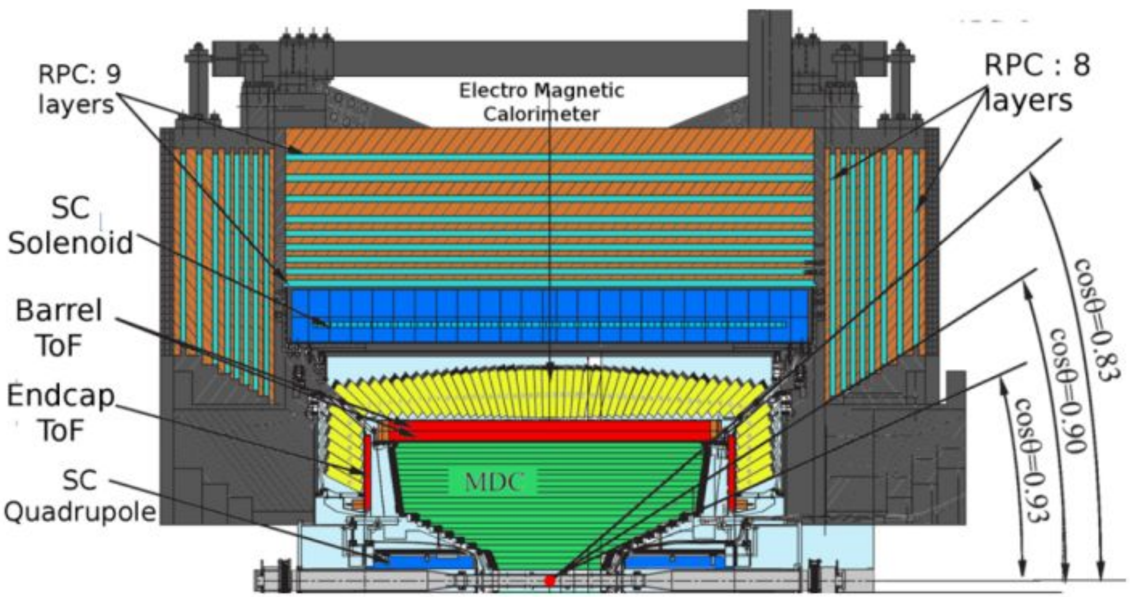


2004: started BEPCII upgrade,
BESIII construction
2008: test run
2009 - now: BESIII physics run

- **1989-2004 (BEPC):**
  $L_{peak}=1.0\times10^{31}\ /cm^2s$
- **2009-now (BEPCII):**
  $L_{peak}=0.85\times10^{33}/cm^2s$

BESIII detector

Nucl. Instr. Meth. A614, 345 (2010)



Excellent performance detector

Sub-system			BESIII
MDC	Single wire $\sigma_{r\phi}$ (μm)		130
	σ_p/p (1 GeV/c)		0.5%
	σ (dE/dx)		6 %
EMC	σ_E/E (1GeV)		2.5%
	Position resolution (1 GeV)		0.6 cm
TOF	σ_T (ps)	Barrel	100
		End cap	110
Muon	No. of layers (barrel/end cap)		9/8
	cut-off momentum (MeV/c)		0.4
Solenoid magnet Field (T)			1.0
$\Delta\Omega/4\pi$			93%

Physics goals cover a diverse range:

- **Charmonium(like) physics**: XYZ, spectroscopy, transition and decays
- **Open Charm physics**: D_0-$\bar{D}_0$ mixing and C-P violation, (semi)leptonic+hadronic decays, …
- **Light hadron**: meson & baryon spectroscopy, glueballs and hybrids, e.m. form factors, …
- **τ physics**: precise R measurement, ..
- and many more