Recent Charmonium Results at BESIII Experiment

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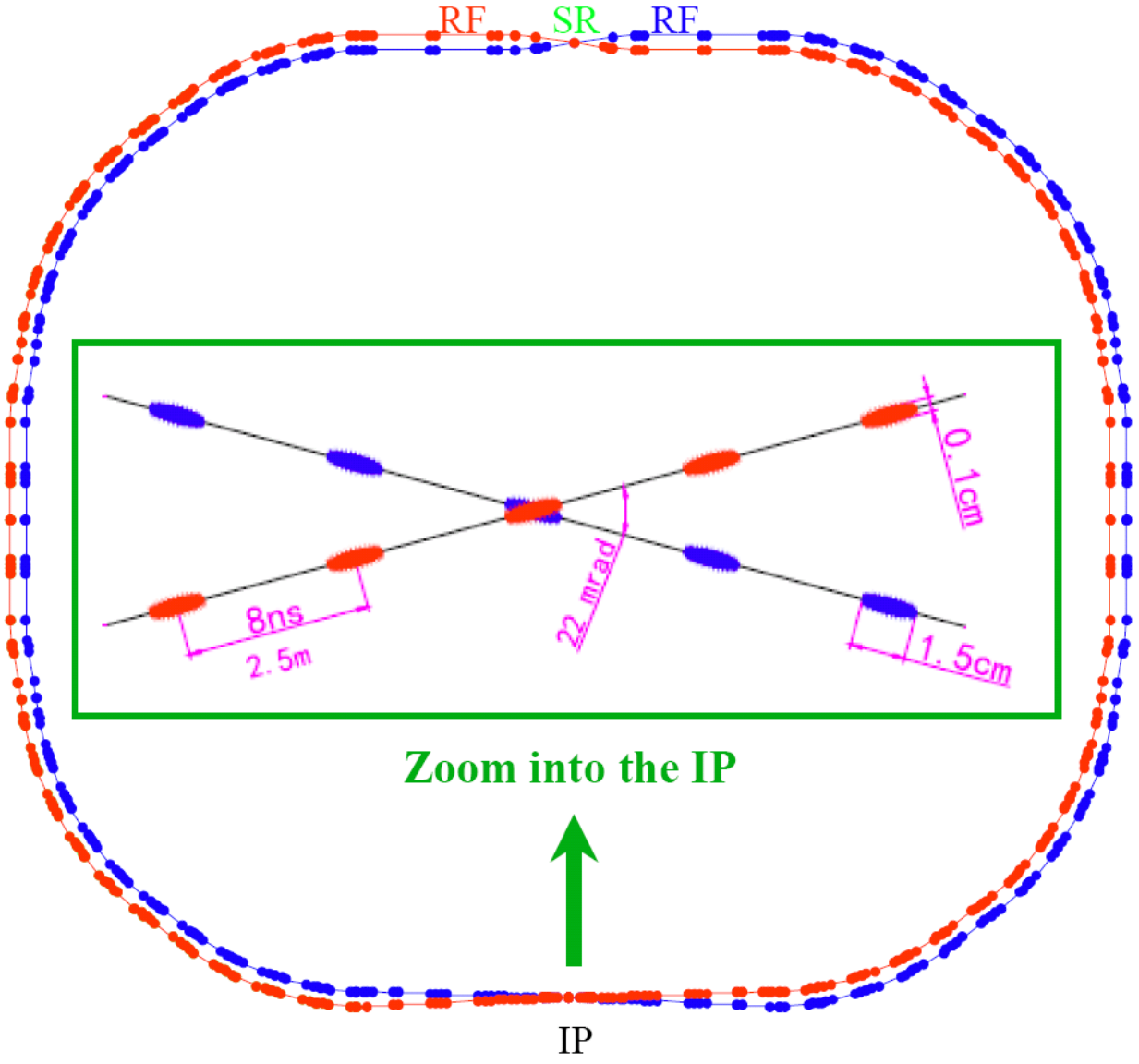
Outline

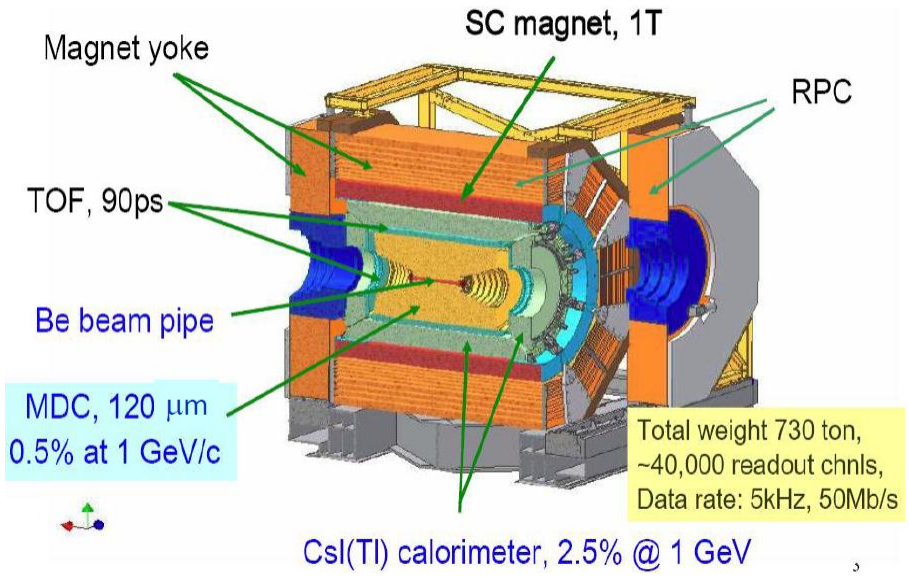
- BEPCII and BESIII
- Observation of h_c at BESIII
- Precision measurement of the η_c properties at BESIII
- The first observation of the M1 transition $\psi' \rightarrow \gamma\eta_c(2S)$
- Observation of $\chi_{cJ} \rightarrow VV$ and γV
- Evidence of $\psi' \rightarrow \gamma P (P = \pi^0, \eta, \eta')$
- Summary

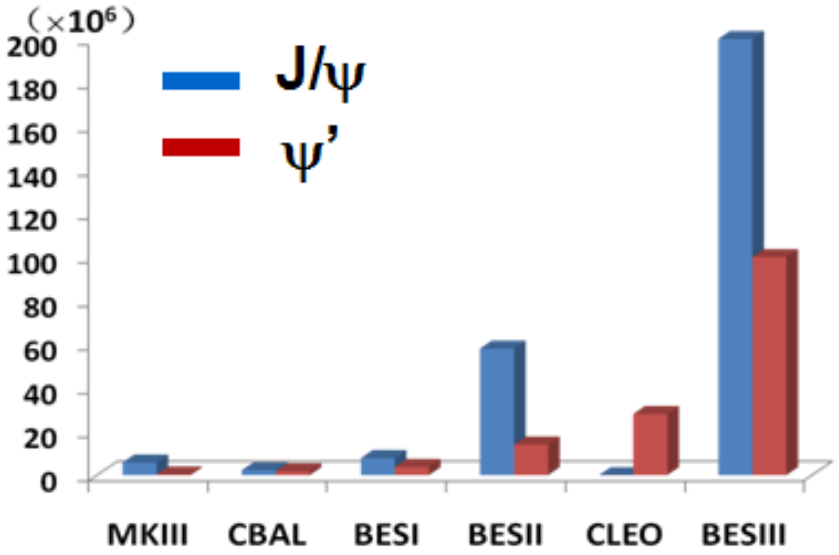
BEPCII storage rings



Beam energy:
1.0-2.3 GeV
Design Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
Circumference:
237m

BESIII





- First collisions: March 2008
- First collisions in BESIII: July 2008
- Physics in BESIII: March 2009
- Record luminosity (April 2011): $6.9 \times 10^{32} cm^{-2} s^{-1}$

So far world largest data samples:

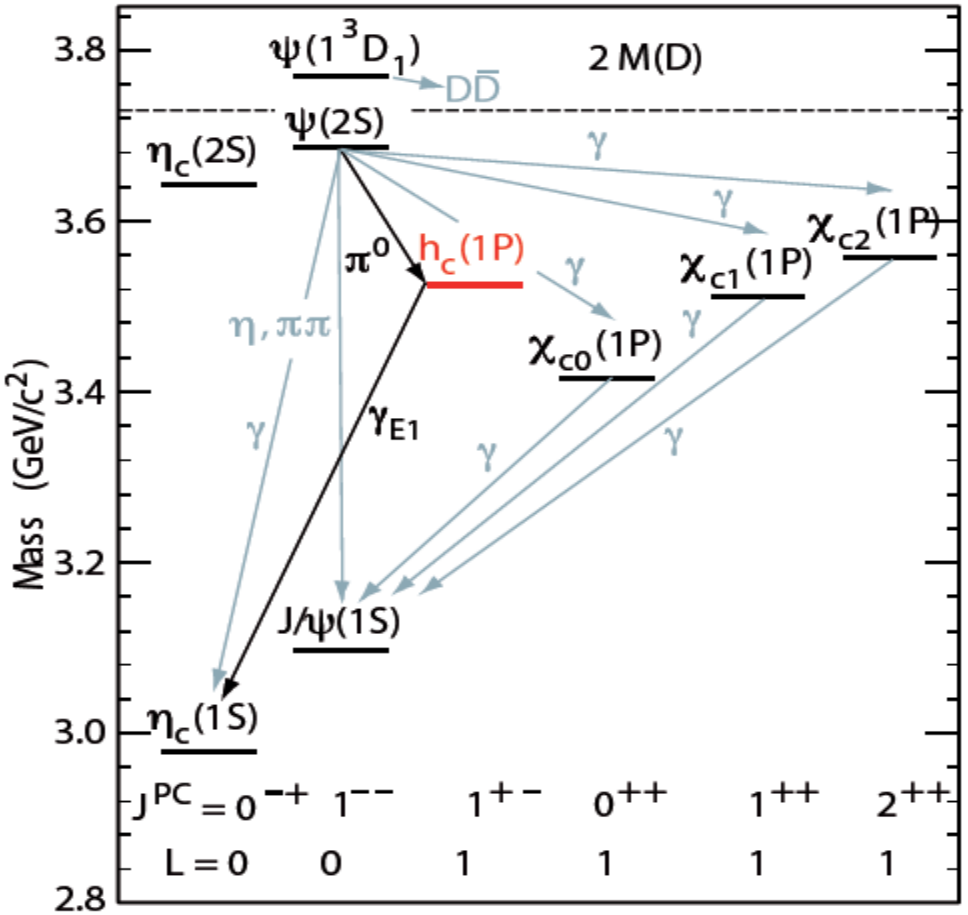
- ~225 Million J/Ψ
- ~106 Million Ψ'
- ~2.9 fb^{-1} Ψ(3770)
- ~0.5 fb^{-1} @Ψ(4010)

- BESIII will also collect:
  - more J/ψ, ψ', ψ(3770)
  - data at higher energies (for XYZ searches, R scan and Ds physics)

Observation of h_c at BESIII

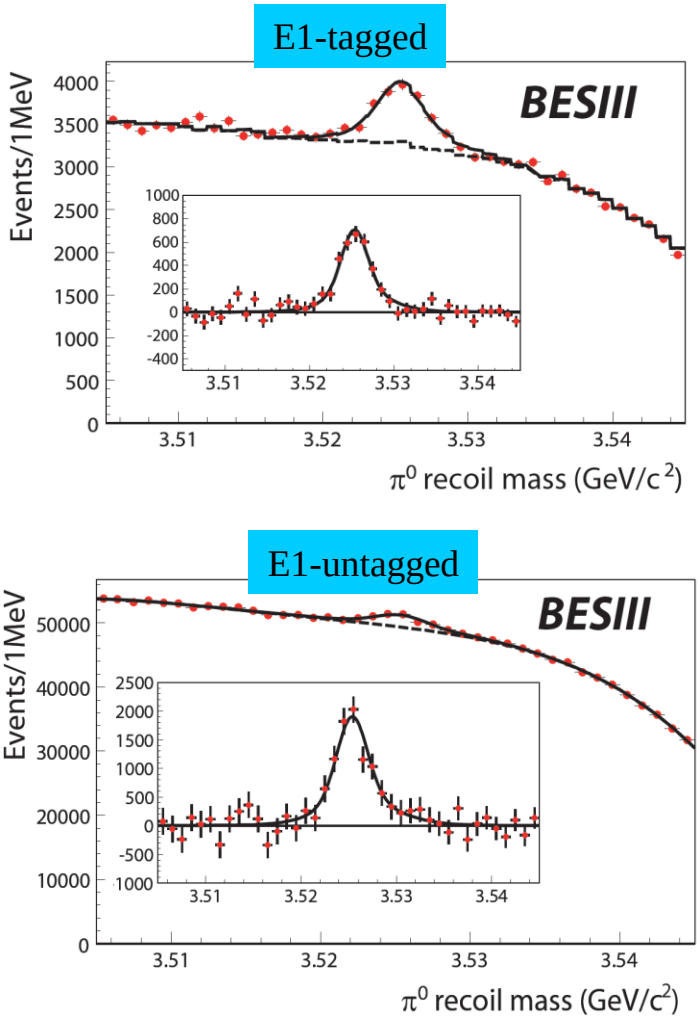
$h_c(^1P_1)$ in charmonium family

- Spin singlet P wave (S=0, L=1)
- Potential model if non-vanishing spin-spin interaction:
  $\Delta M_{hf}(1P)=M(h_c)-1/9(M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2}))\neq 0$
- E835 found evidence for h_c in $pp\rightarrow h_c\rightarrow\gamma\eta_c$
- CLEO-c observed h_c in $ee\rightarrow\psi'\rightarrow\pi^0 h_c$, $h_c\rightarrow\gamma\eta_c$
  $\Delta M_{hf}(1P)=0.08\pm0.18\pm0.12 MeV/c^2$



Observation of h_c at BESIII (inclusive)

BESIII Collaboration: PRL104, 132002, (2010)



- Select inclusive π^0 ($\psi' \rightarrow \pi^0 h_c$)
- Select E1-photon in $h_c \rightarrow \gamma\eta_c$ (E1 tagged) or not (E1 untagged)
- E1-tagged selection gives

  $M(h_c)=3525.40\pm0.13\pm0.18$MeV

  ($\Delta M_{hf}(1P)=0.10\pm0.13\pm0.18$MeV/$c^2$)

  $\Gamma(h_c)=0.73\pm0.45\pm0.28$MeV

  (<1.44MeV at 90% CL)

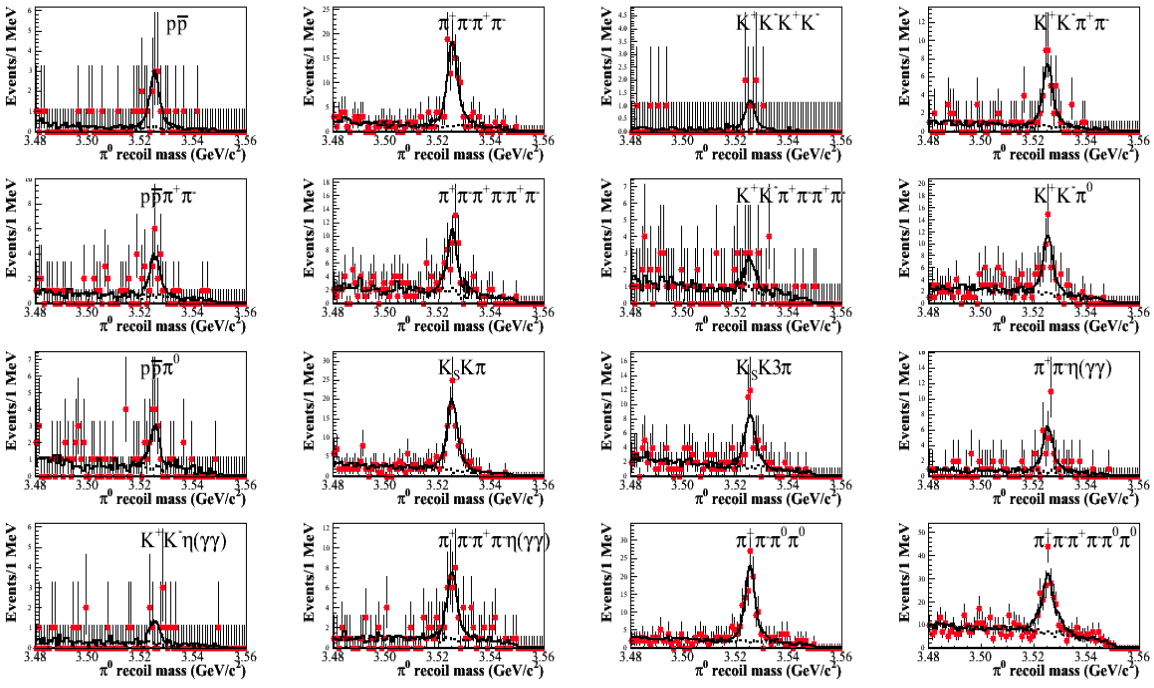
  $Br(\psi' \rightarrow \pi^0 h_c) \times Br(h_c \rightarrow \gamma\eta_c) =$

  $(4.58\pm0.40\pm0.50) \times 10^{-4}$
- E1-untagged together with tagged selection gives the first measurement

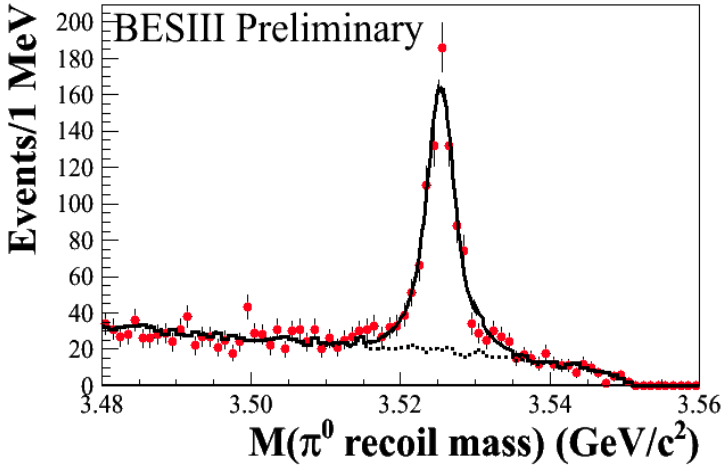
  $Br(\psi' \rightarrow \pi^0 h_c) = (8.4\pm1.3\pm1.0) \times 10^{-4}$

  $Br(h_c \rightarrow \gamma \eta_c) = (54.3\pm6.7\pm5.2)\%$

Measurements of the h_c properties at BESIII (exclusive)



Summed π^0 recoil mass



Simultaneous fit to π^0 recoiling mass

$M(h_c)$ = 3525.31±0.11±0.15 MeV

$\Gamma(h_c)$ = 0.70±0.28±0.25 MeV

N = 832±35

χ^2/d.o.f. = 32/46

BESIII preliminary

Consistent with BESIII inclusive results PRL104,132002(2010)

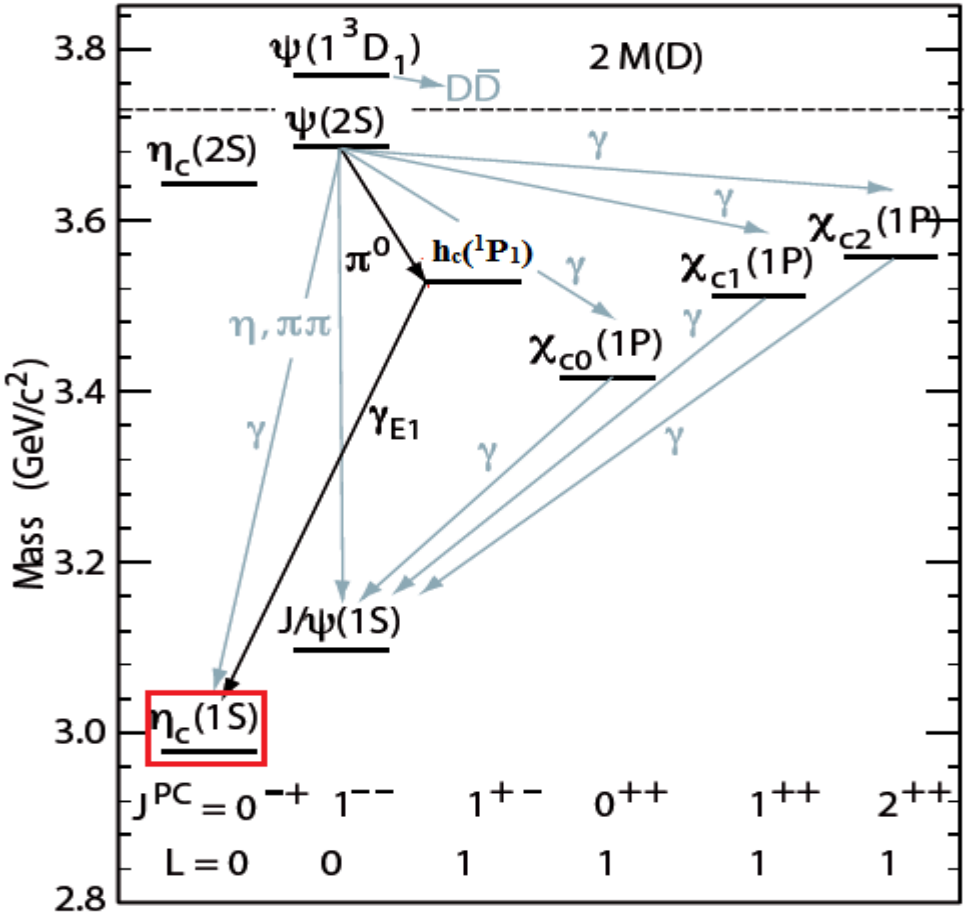
CLEOc exlusive results

$M(h_c)$=3525.21±0.27±0.14 MeV/c^2

N = 136±14

PRL101, 182003(2008)

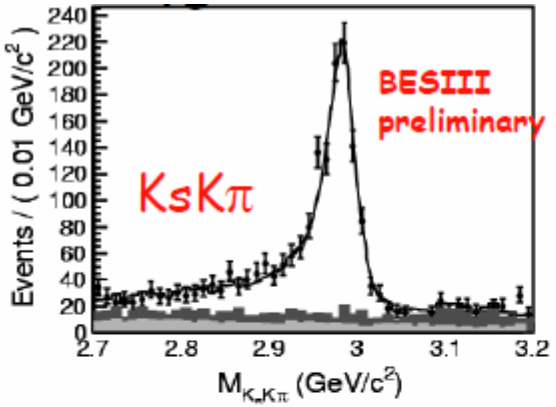
Precision measurement of the η_c properties

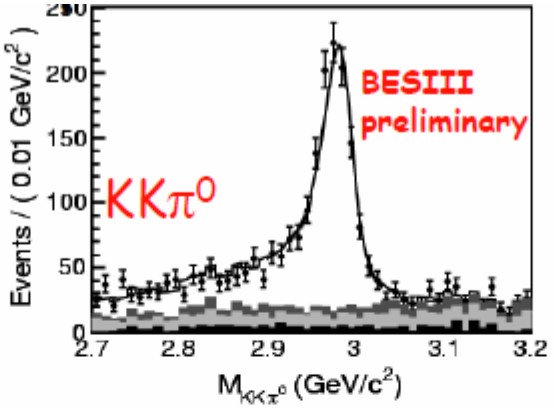


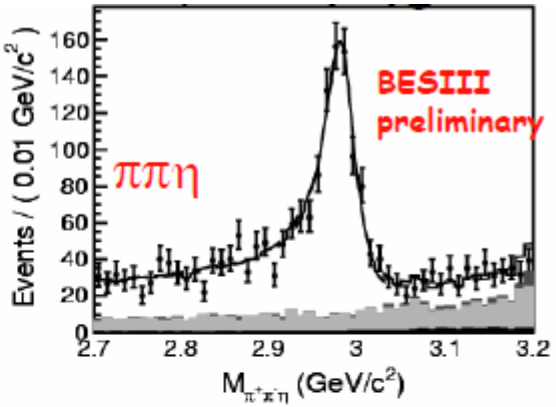
Introduction

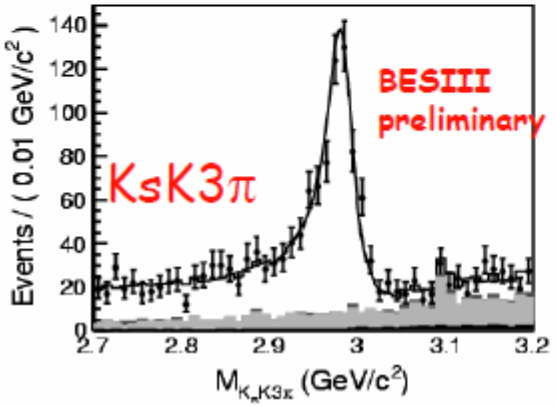
- The lowest lying S-wave spin singlet charmonium η_c was discovered in 1980 by MarkII.
- Earlier experiments using J/ψ radiative transition gives $M(\eta_c)\sim2978.0 MeV/c^2$, $\Gamma(\eta_c)\sim10 MeV$.
- Recent studies using the two-photon processes gives $M(\eta_c)=2983.1\pm1.0\ MeV/c^2$, $\Gamma(\eta_c)=31.3\pm1.9\ MeV$.
- The most recent study from CLEO-c pointed out the distortion of the η_c line shape in ψ' decays.
- Measurement of the η_c properties **at BESIII**
  - ◆Data sample: $1.06*10^8$ ψ' events, $45pb^{-1}$ continuum data at 3.65 GeV
  - ◆Decay modes (X_i): KsKπ, $K^+K^-\pi^0$, $\eta\pi^+\pi^-$, KsK3π, $K^+K^-\pi^+\pi^-\pi^0$, $3(\pi^+\pi^-)$, where Ks→$\pi^+\pi^-$, η→γγ, π^0→γγ

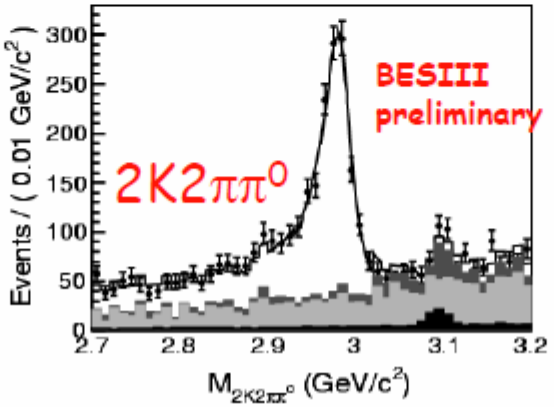
The simultaneous fit

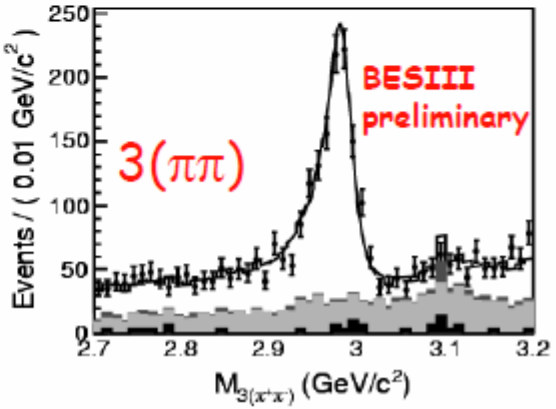












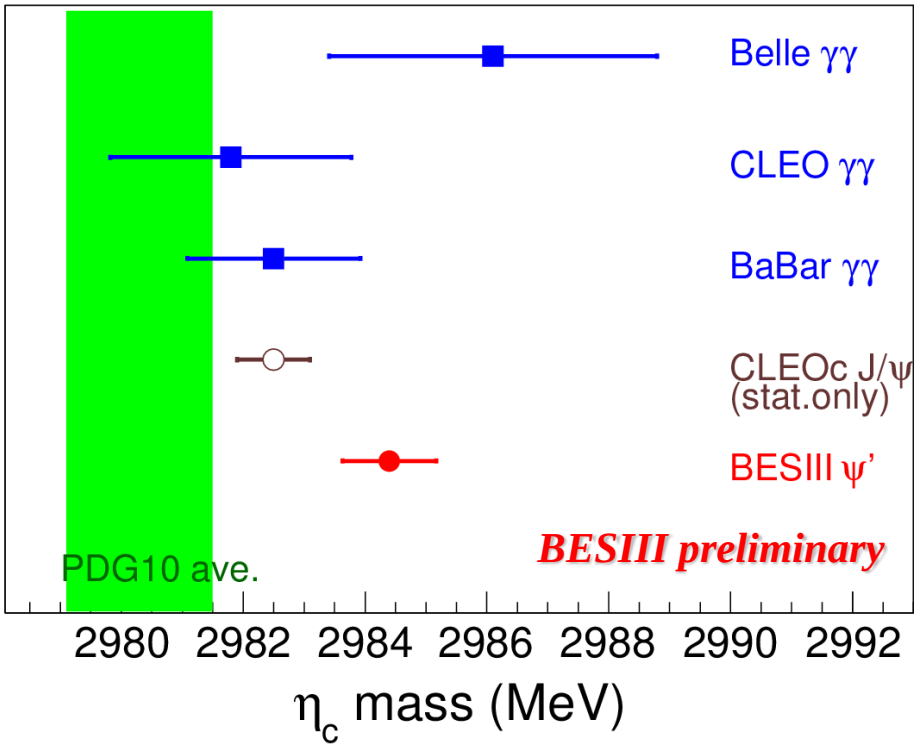
BESIII Preliminary Results

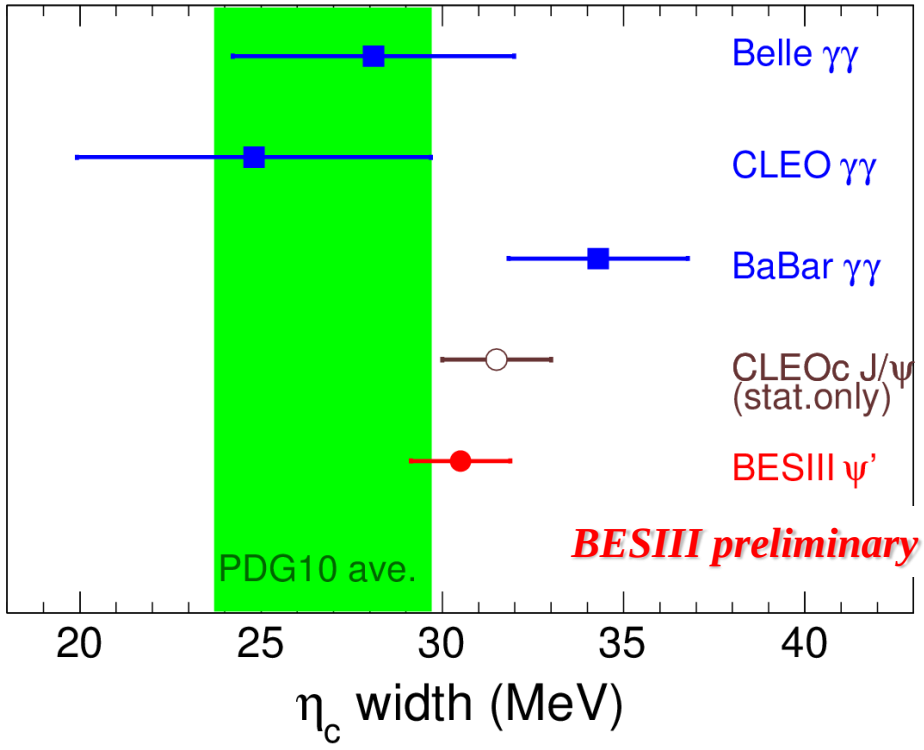
- **mass = 2984.4±0.5stat±0.6$_{sys}$ MeV/c²**
- **width = 30.5±1.0stat±0.9$_{sys}$ MeV**
- **ϕ = 2.35±0.05stat ±0.04$_{sys}$ rad**

Simultaneous fit by considering **the interference between η_c and non-η_c decays** : an universal phase for different modes is used and assume all non-η_c is 0^{-+}

Comparison of BESIII preliminary results with other measurements

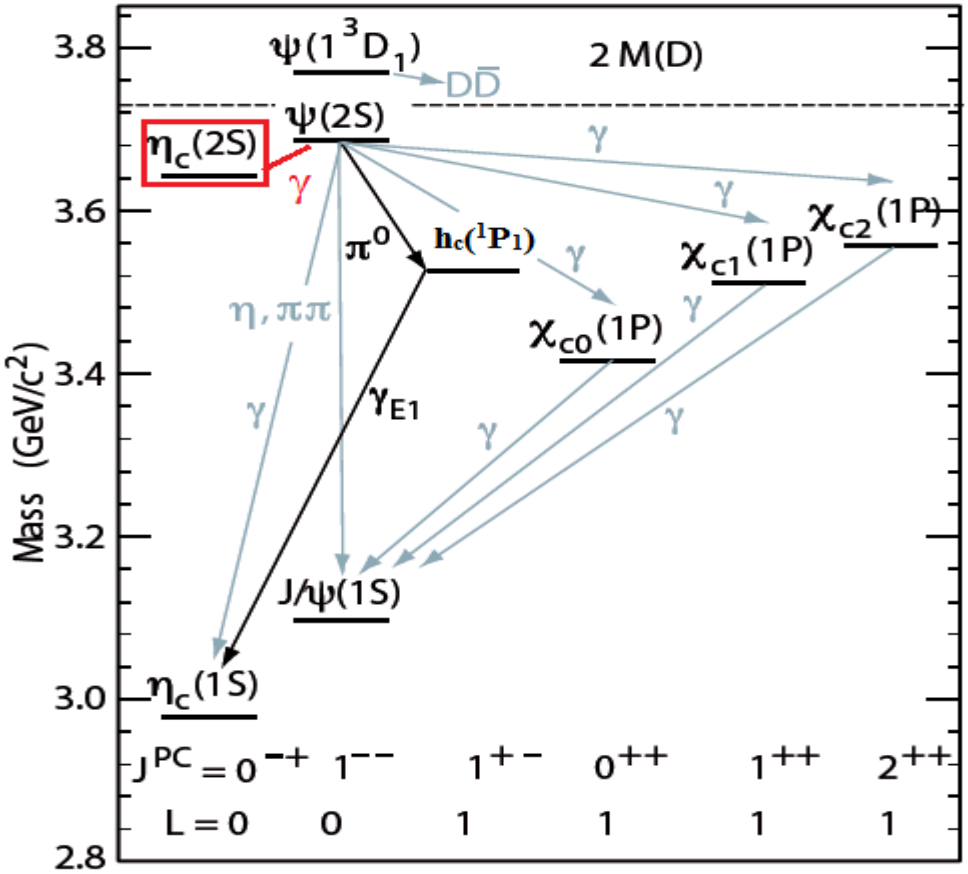
BESIII results include both stat. and syst. errors, which is the most precision measurement, the interference between ηc decay and non-resonance is important.





The world average in PDG2010 was using earlier results

The first observation of the M1 transition $\psi' \to \gamma\eta_c(2S)$



Introduction

- First "observation" by Crystal Ball in 1982 (M=3.592, B=0.2%-1.3% from $\psi' \rightarrow \gamma X$, never confirmed by other experiments.)

- Published results about $\eta_c(2S)$ observation:

Experiment	M [MeV]	Γ [MeV]	Process
Belle [1]	$3654 \pm 6 \pm 8$	—	$B^{\pm} \to K^{\pm}\, \eta_c(2S), \eta_c(2S) \to K_S K^{\pm}\pi^{\mp}$
CLEO [2]	$3642.9 \pm 3.1 \pm 1.5$	$6.3 \pm 12.4 \pm 4.0$	$\gamma\gamma \to \eta_c(2S) \to K_S K^{\pm}\pi^{\mp}$
BaBar [3]	$3630.8 \pm 3.4 \pm 1.0$	$17.0 \pm 8.3 \pm 2.5$	$\gamma\gamma \to \eta_c(2S) \to K_S K^{\pm}\pi^{\mp}$
BaBar [4]	$3645.0 + 5.5^{+4.9}_{-7.8}$	—	$e^+e^- \to J/\psi c\bar{c}$
PDG [5]	3638 ± 4	14 ± 7	—

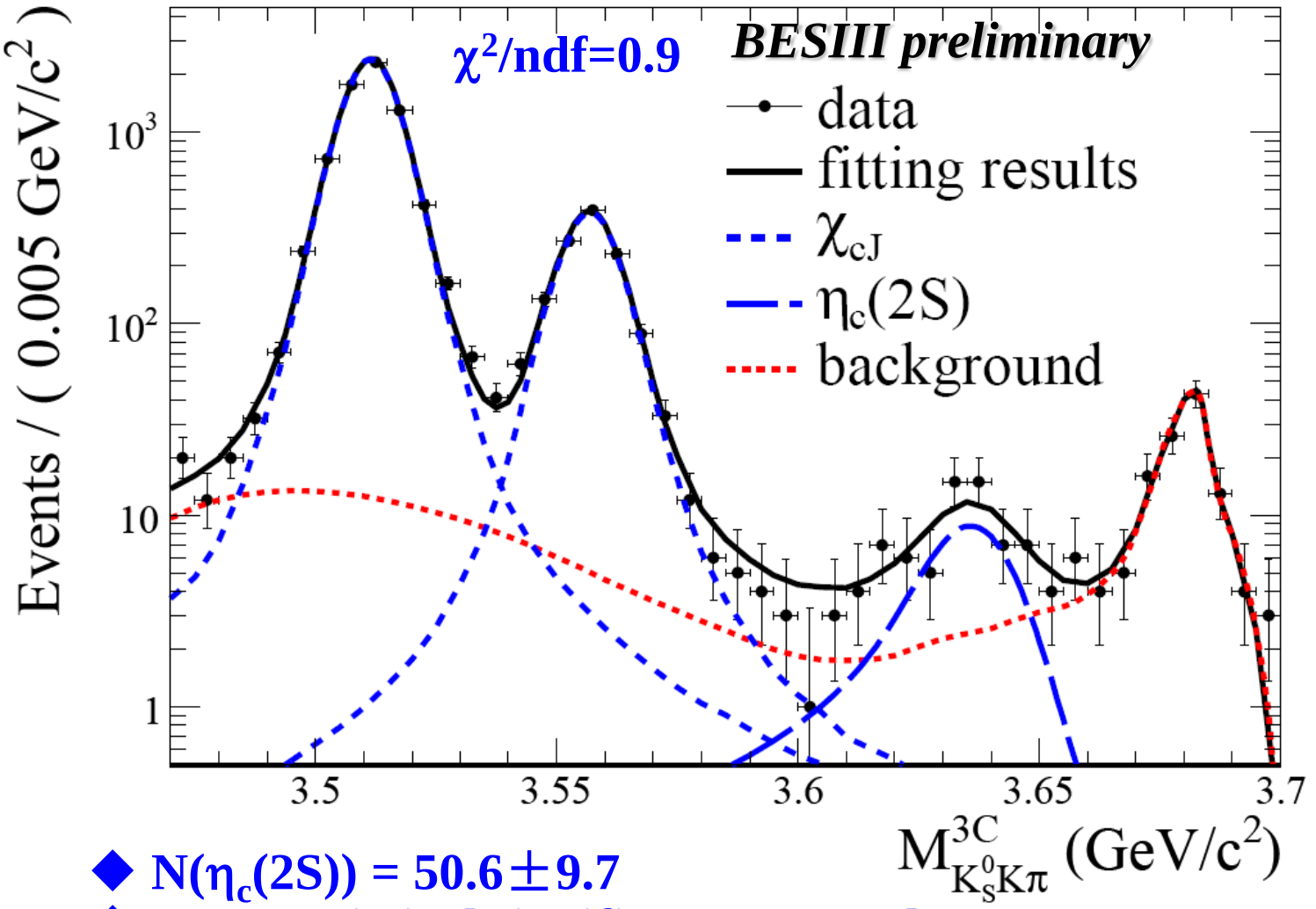
Combined with the results based on two-photon processes from BaBar and Belle reported at ICHEP 2010, the world average $\Gamma(\eta_c(2S))=12 \pm 3$ MeV

- The M1 transition $\psi' \rightarrow \gamma\eta_c(2S)$ has not been observed. (experimental challenge : search for real photons ~50MeV,)

- Better chance to observe $\eta_c(2S)$ in ψ' radiative transition with ~$1.06*10^8$ ψ' data at BESIII.

- Decay mode studied: $\psi' \rightarrow \gamma\eta_c(2S) \rightarrow \gamma K_S K \pi$ ($K^+K^-\pi^0$ etc. in progress)

Mass fitting (conti.)



- $N(\eta_c(2S)) = 50.6 \pm 9.7$
- Pure statistical significance more than 6σ
- Significance with systematic variations not less than 5σ

Preliminary measurements from $\psi' \to \gamma\eta_c(2S) \to \gamma K_S K\pi$

$$M(\eta_c(2S)) = 3638.5 \pm 2.3_{stat} \pm 1.0_{sys}\ (MeV/c^2)$$

$$Br(\psi' \to \gamma\eta_c(2S) \to \gamma K_S K\pi) = (2.98 \pm 0.57_{stat} \pm 0.48_{sys}) \times 10^{-6}$$

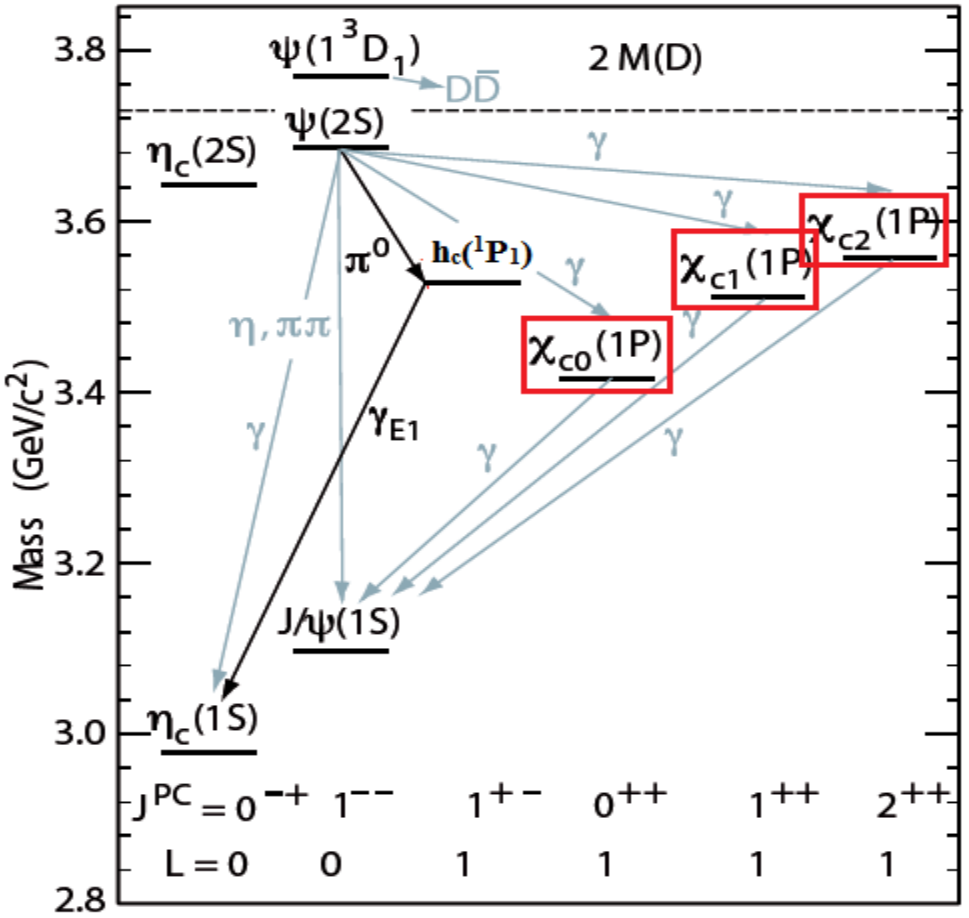
$Br(\eta_c(2S) \to K\bar{K}\pi) = (1.9 \pm 0.4 \pm 1.1)\%$ from BaBar

$$Br(\psi' \to \gamma\eta_c(2S)) = (4.7 \pm 0.9_{stat} \pm 3.0_{sys}) \times 10^{-4}$$

CLEO-c: $<7.6\times10^{-4}$ (PRD81,052002(2010))

Potential model: $(0.1\text{–}6.2)\times10^{-4}$ (PRL89,162002(2002))

χ_{c1} decays into Vector Meson pairs ($\phi\phi$, $\omega\omega$, $\omega\phi$)

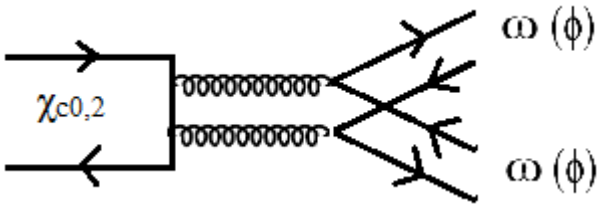


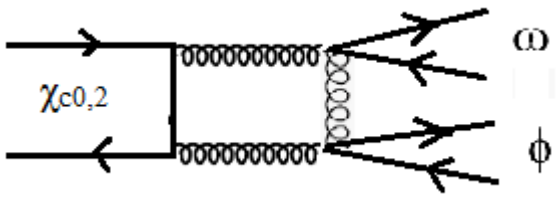
Introduction

- $e^+e^- \to \psi' \to \gamma\chi_{cJ}$ is the clean mode for the study of χ_{cJ}
- Previous measurements from BESII. Only χ_{c0} and χ_{c2} decays into $\phi\phi$ and $\omega\omega$ are observed

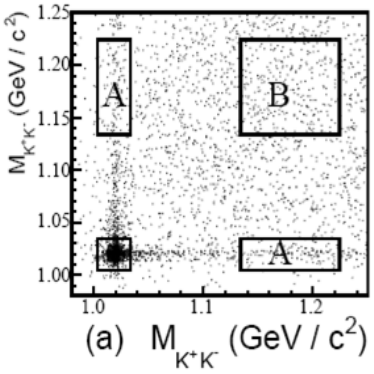
BR(10^{-3})	**χ_{c0}**	**χ_{c2}**	
$\to\phi\phi$	$0.94 \pm 0.21 \pm 0.13$	$1.70 \pm 0.30 \pm 0.25$	**BESII, PLB 642, 197 (2006)**
$\to\omega\omega$	$2.29 \pm 0.58 \pm 0.41$	$1.77 \pm 0.47 \pm 0.36$	**BESII, PLB 630, 7 (2005)**

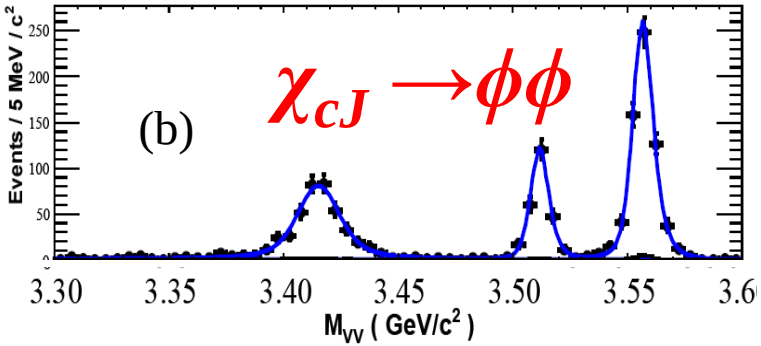
- χ_{c1} violate the helicity selection rule (HSR) and expected to be suppressed
- Recently, long-distance effects in χ_{c1} have been proposed to account for the HSR violation
- Decays $\chi_{cJ} \to \omega\phi$ are doubly OZI suppressed and have yet to be observed





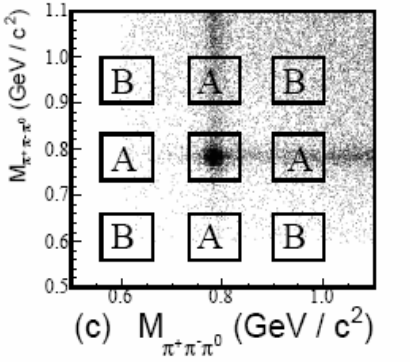
Study of $\chi_{cJ} \to \phi\phi, \omega\omega, \omega\phi$

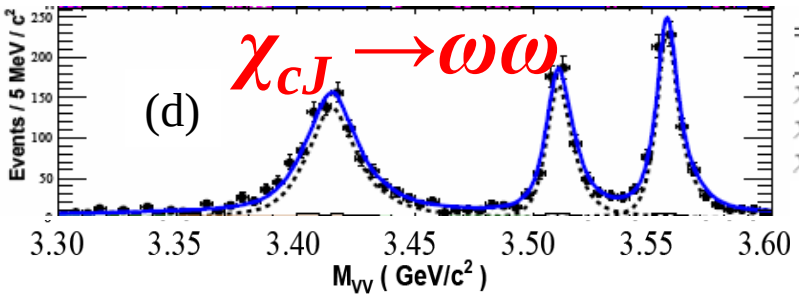




Channel	$\mathcal{B}(\times 10^{-4})$	PDG$(\times 10^{-4})$
$\chi_{c0} \to \phi\phi$	$7.8 \pm 0.4 \pm 0.8$	9.2 ± 1.9
$\chi_{c1} \to \phi\phi$	$4.1 \pm 0.3 \pm 0.4$	—
$\chi_{c2} \to \phi\phi$	$10.7 \pm 0.4 \pm 1.1$	14.8 ± 2.8

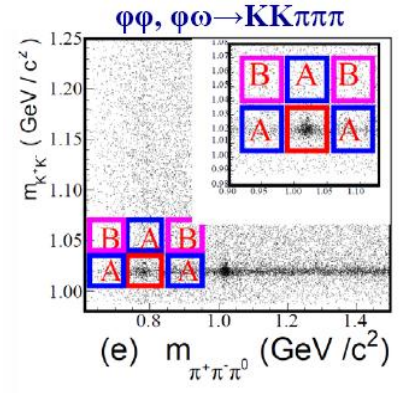
First observation

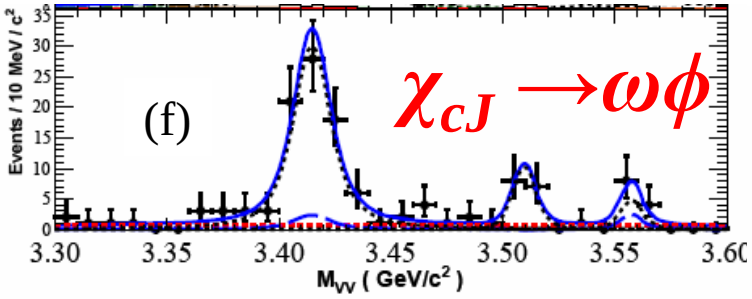




Channel	$\mathcal{B}(\times 10^{-4})$	PDG$(\times 10^{-4})$
$\chi_{c0} \to \omega\omega$	$9.5 \pm 0.3 \pm 1.1$	22 ± 7.0
$\chi_{c1} \to \omega\omega$	$6.0 \pm 0.3 \pm 0.7$	—
$\chi_{c2} \to \omega\omega$	$8.9 \pm 0.3 \pm 1.1$	19.0 ± 6.0

First observation





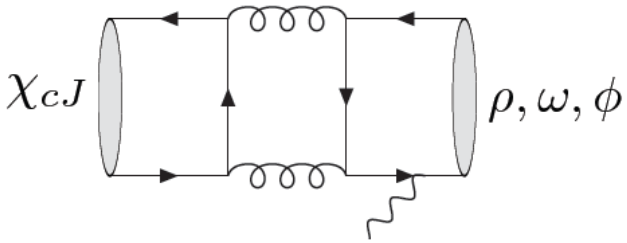
Channel	$\mathcal{B}(\times 10^{-4})$	PDG$(\times 10^{-4})$
$\chi_{c0} \to \omega\phi$	$1.2 \pm 0.1 \pm 0.2$	—
$\chi_{c1} \to \omega\phi$	$0.22 \pm 0.06 \pm 0.02$	—
$\chi_{c2} \to \omega\phi$	< 0.2	—

Doubly OZI suppressed $\chi_{cJ} \to$ $\omega\phi$ are observed for the first time

χ_{cJ} radiative decays into a Vector Meson

Introduction

- $\psi \to \gamma X \to \gamma\gamma V$ (V is ρ, ω and ϕ) provide information on the flavor content of the C-even resonance X
- $\chi_{cJ} \to \gamma V$

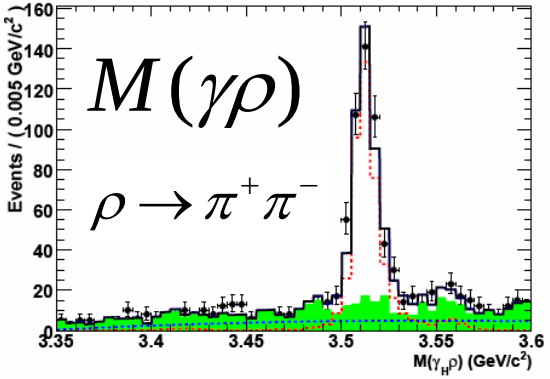


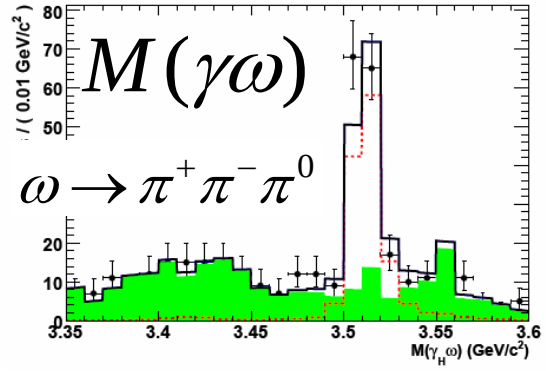
- Recent pQCD calculation includes nonperturbative QCD hadronic loop contribution to account for the discrepancy between experimental results and former theoretical predications (pQCD, NRQCD, NRQCD+QED)

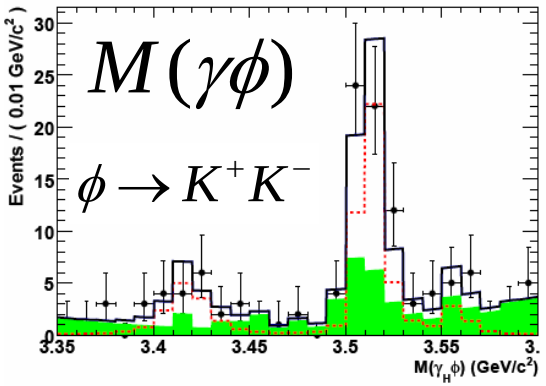
Mode	CLEO[1]	pQCD[2]	QCD[3]	QCD+QED[3]
$\chi_{c0} \to \gamma\rho^0$	< 9.6	1.2	3.2	2.0
$\chi_{c1} \to \gamma\rho^0$	$243 \pm 19 \pm 22$	14	41	42
$\chi_{c2} \to \gamma\rho^0$	< 50	4.4	13	38
$\chi_{c0} \to \gamma\omega$	< 8.8	0.13	0.35	0.22
$\chi_{c1} \to \gamma\omega$	$83 \pm 15 \pm 12$	1.6	4.6	4.7
$\chi_{c2} \to \gamma\omega$	< 7.0	0.5	1.5	4.2
$\chi_{c0} \to \gamma\phi$	< 6.4	0.46	1.3	0.03
$\chi_{c1} \to \gamma\phi$	< 26	3.6	11	11
$\chi_{c2} \to \gamma\phi$	< 13	1.1	3.3	6.5

Analysis Results

BESIII Collaboration: **Phys. Rev. D 83, 112005 (2011)**







Br. are in unit of 10^{-6}.

Mode	BESIII	CLEO	pQCD
$\chi_{c0} \to \gamma\rho^0$	< 10.5	< 9.6	1.2
$\chi_{c1} \to \gamma\rho^0$	$228 \pm 13 \pm 22$	$243 \pm 19 \pm 22$	14
$\chi_{c2} \to \gamma\rho^0$	< 20.8	< 50	4.4
$\chi_{c0} \to \gamma\omega$	< 12.9	< 8.8	0.13
$\chi_{c1} \to \gamma\omega$	$69.7 \pm 7.2 \pm 6.6$	$83 \pm 15 \pm 12$	1.6
$\chi_{c2} \to \gamma\omega$	< 6.1	< 7.0	0.5
$\chi_{c0} \to \gamma\phi$	< 16.2	< 6.4	0.46
$\chi_{c1} \to \gamma\phi$	$25.8 \pm 5.2 \pm 2.3$	< 26	3.6
$\chi_{c2} \to \gamma\phi$	< 8.1	< 13	1.1

consistent

new

pQCD predictions too lower than experimental measurements.

See an non-pQCD explanation "hadronic loop correction", D.Y Chen et al. arXiv:1005.0066v2[hep-ph]

CLEOc: PRL 101, 151801 (2008)
pQCD: Y.J. Gao et al., hep-ph/0701009

Helicity Angle

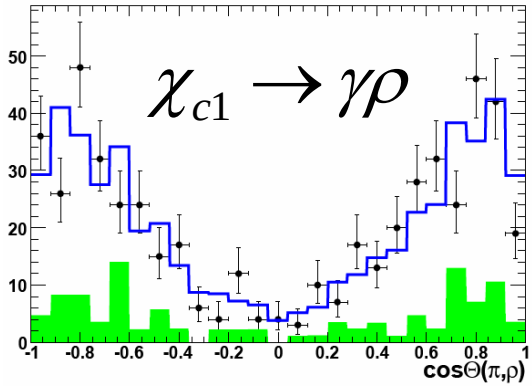
L: Longitudinal polarization, T: Transverse polarization,

θ: Helicity angle

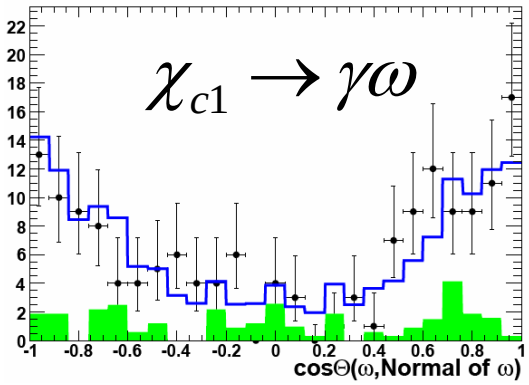
$$\frac{d\Gamma}{\Gamma d\cos\theta} \propto (1-f_T)\cos^2\theta + \frac{1}{2} f_T \sin^2\theta \qquad f_T = \frac{|A_T|^2}{|A_T|^2 + |A_L|^2}$$

- Longitudinal polarization dominates in the $\chi_{c1} \to \gamma V$

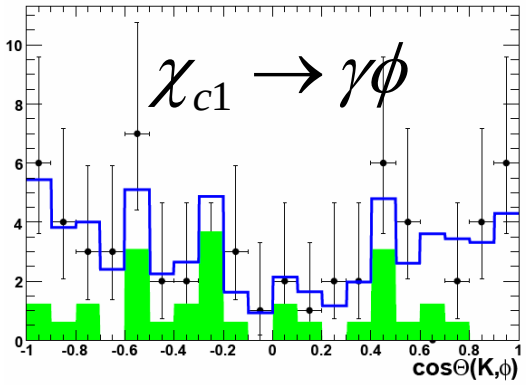
  ⇨ As expected in axial-vector particle radiative decaying to a vector.



$f_T = 0.158 \pm 0.034^{+0.015}_{-0.014}$



$f_T = 0.247^{+0.090+0.044}_{-0.087-0.026}$



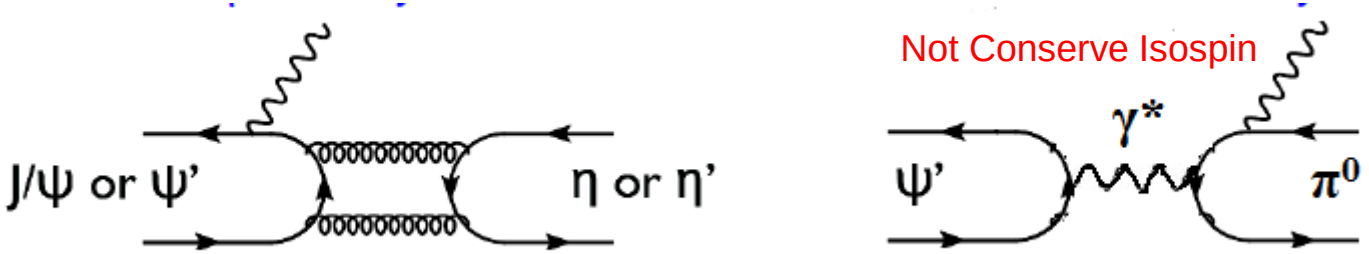
$f_T = 0.29^{+0.13+0.10}_{-0.12-0.09}$

Evidence for ψ' decays into $\gamma\pi^0$ and $\gamma\eta$

Introduction

- Important tests for various phenomenological mechanisms:

Vector meson Dominance Model (VDM); Two-gluon couplings to $q\bar{q}$ states; Mixing of η_c-$\eta^{(\prime)}$; Final-state radiation by light quarks.



- $R_{J/\psi} = B(J/\psi \to \gamma\eta)/ B(J/\psi \to \gamma\eta')$ predicted by 1st order perturbation theory. $R_{\psi'} = B(\psi' \to \gamma\eta)/ B(\psi' \to \gamma\eta') \approx R_{J/\psi}$ was expected.
- **Recently, CLEOc reported on J/ψ, ψ', $\psi'' \to \gamma P$:**
  - **Found no evidence for $\psi' \to \gamma\pi^0$ or $\gamma\eta$**
  - **Determine $B(\psi' \to \gamma\pi^0) < 5 \times 10^{-6}$**
  - **Obtain $R_{\psi'} < 1.8\%$ at 90% CL and $R_{J/\psi} = (21.1 \pm 0.9)\%$**

CLEOc, PRD 79, 111101 (2009)

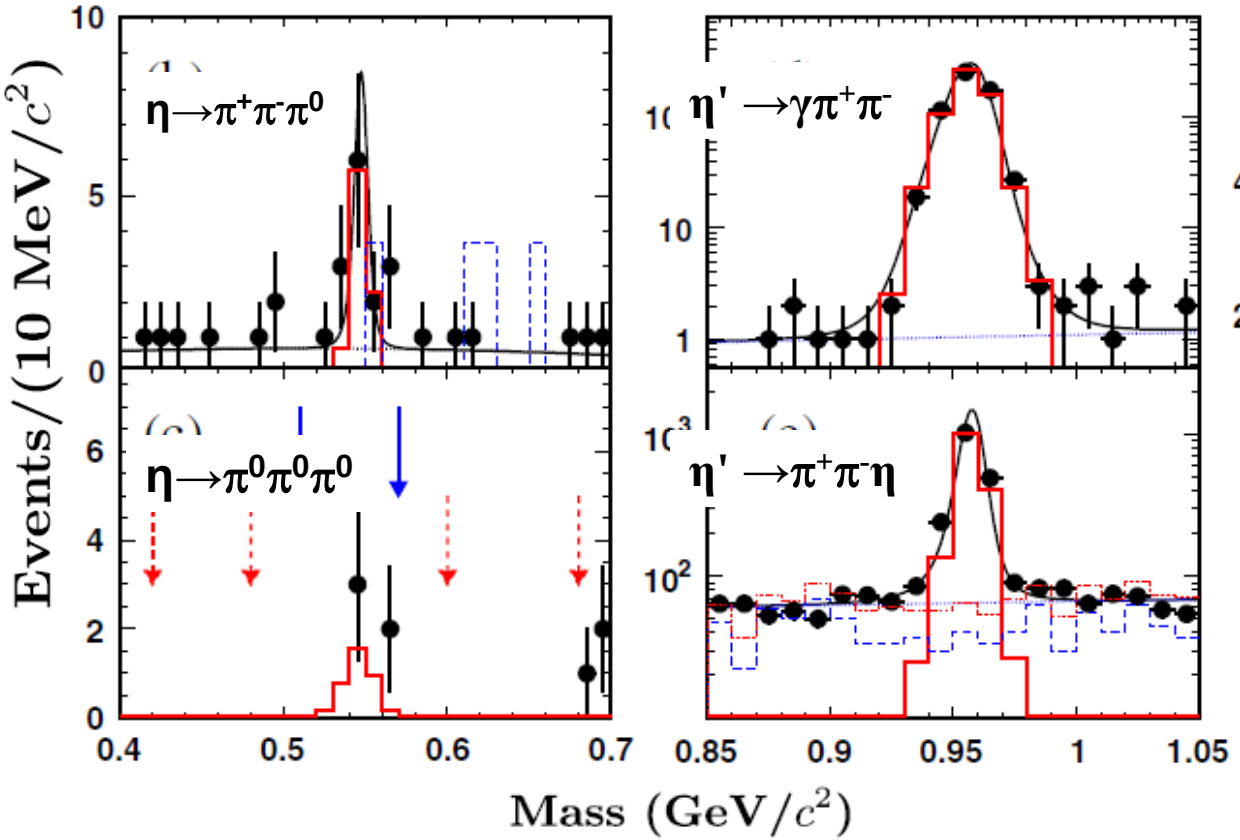
$R_{\psi'} << R_{J/\psi}$ poses a significant challenge to theory.

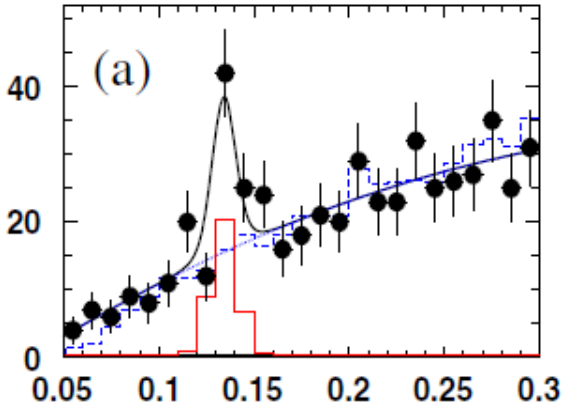
$\psi' \to \gamma P$ ($P=\pi^0, \eta$ and η') at BESIII

$\psi' \to \gamma\eta$
$\eta \to \pi^+\pi^-\pi^0$, $\pi^0\pi^0\pi^0$
(First observation)

$\psi' \to \gamma\eta'$
$\eta' \to \gamma\pi^+\pi^-$,
$\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$

$\psi' \to \gamma\pi^0(\pi^0 \to \gamma\gamma)$
(First observation)





$\psi' \to \gamma P$ ($P=\pi^0, \eta$ and η') at BESIII

Phys. Rev. Lett 105, 261801 (2010)

Mode	BESIII	Combined BESIII	PDG
$\psi' \to \gamma\pi^0$	$1.58 \pm 0.40 \pm 0.13$	$1.58 \pm 0.40 \pm 0.13$	≤ 5
$\psi' \to \gamma\eta(\pi^+\pi^-\pi^0)$	$1.78 \pm 0.72 \pm 0.17$	$1.38 \pm 0.48 \pm 0.09$	≤ 2
$\to \gamma\eta(\pi^0\pi^0\pi^0)$	$1.07 \pm 0.65 \pm 0.08$		
$\psi' \to \gamma\eta'(\pi^+\pi^-\eta)$	$120 \pm 5 \pm 8$	$126 \pm 3 \pm 8$	121 ± 8
$\to \gamma\eta'(\pi^+\pi^-\gamma)$	$129 \pm 3 \pm 8$		

(x 10^{-6})

- **Measured branching ratios of $\psi' \to \gamma\eta$ and $\psi' \to \gamma\pi^0$ for the first time**
- **The first measurement of**

$$R_{\psi'} = (1.10 \pm 0.38 \pm 0.07)\%$$

- **Confirmed $R_{\psi'} << R_{J/\psi}$**

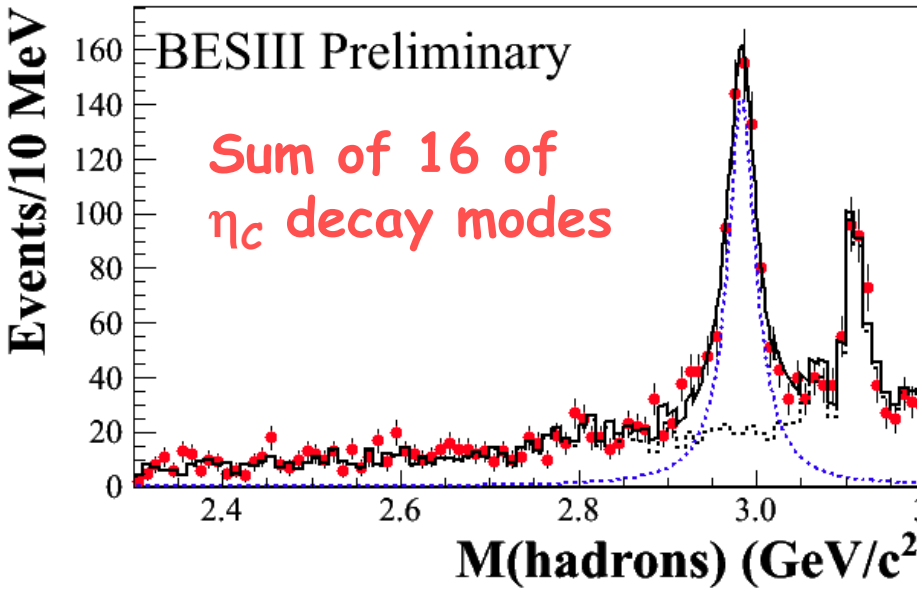
Theoretical explanation: Q. Zhao, Phys. Lett. B697, 52 (2011)

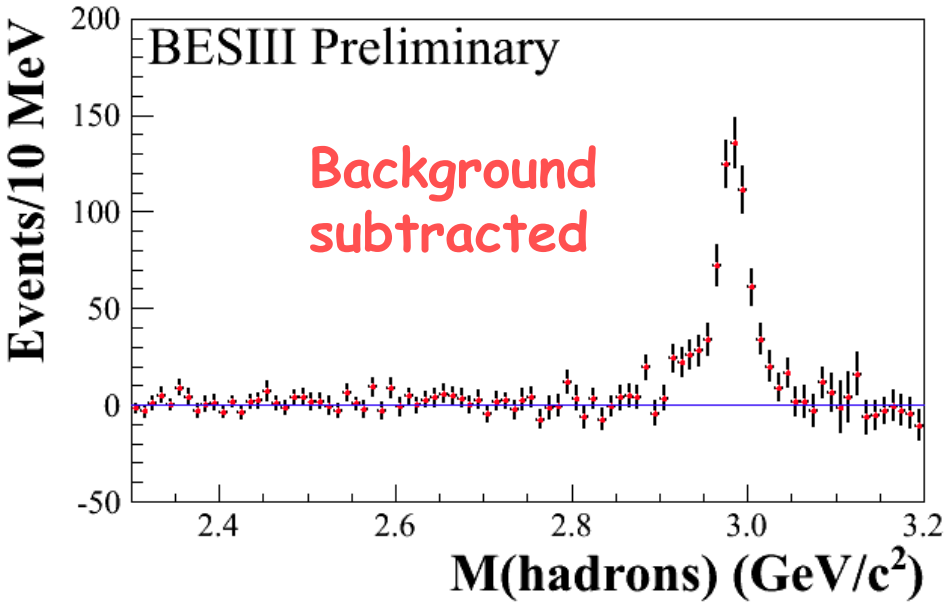
Summary

- High luminosity by BEPCII and the good performance of BESIII give us better chance to study the chamonium spectroscopy.
- Study of h_c at BESIII (inclusive & exclusive) gives the measurements of mass, width of h_c as well as Br($\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$).
- Precise measurement of the properties of η_c done at BESIII. The observed distortion η_c line shape described successfully by a interference model.
- The first observation of the M1 transition $\psi' \to \gamma\eta_c(2S)$.
- Observation of $\chi_{cJ} \to VV$, γV and $\psi' \to \gamma P$(P= π^0, η, η')

Backup

η_c lineshape from $\psi' \to \pi^0 h_c$, $h_c \to \gamma\eta_c$

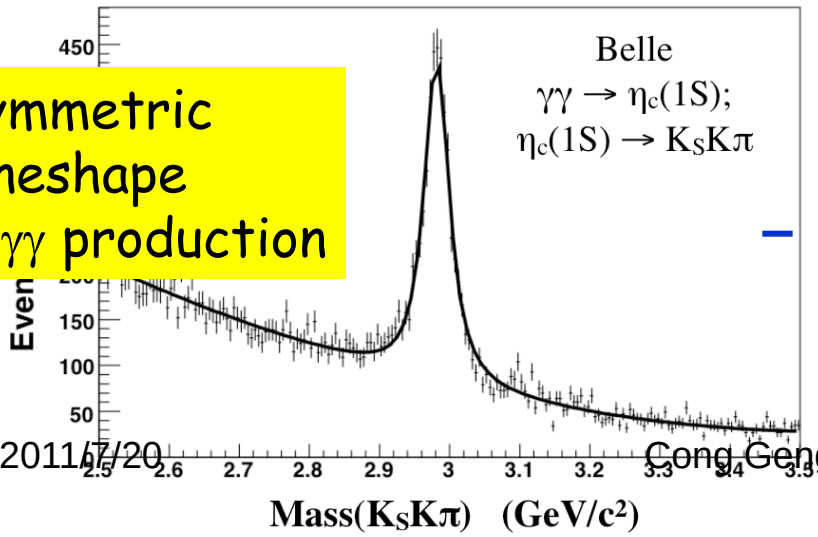


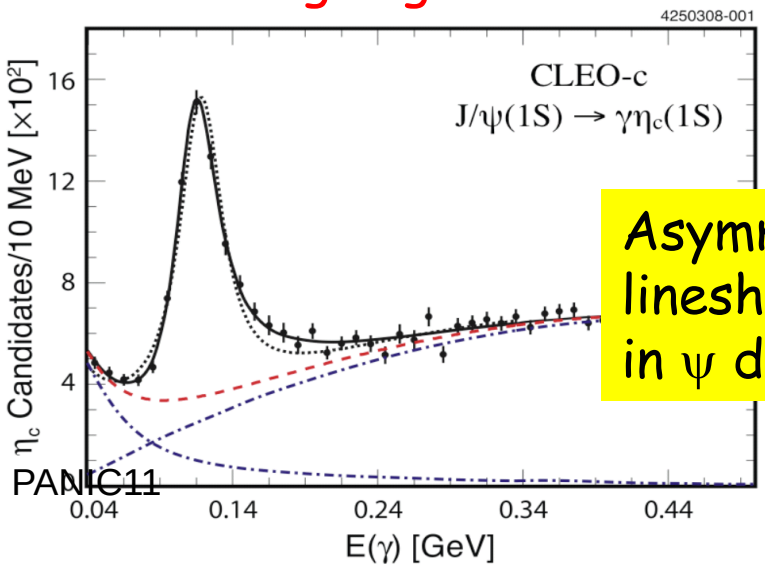


The η_C lineshape is not distorted in the $h_C \to \gamma\eta_C$

Detail analysis of η_c parameters is ongoing!

Symmetric lineshape in $\gamma\gamma$ production





Asymmetric lineshape in ψ decay

Backgrounds for $\psi' \rightarrow \gamma\eta_c \rightarrow \gamma X_i$

- $\psi' \rightarrow \pi^0 X_i$

  With the optimized selection, the mass spectra for $\pi^0 X_i$ events are measured in data and scaled according to the full simulation to estimate the contribution in $\gamma\eta_c$ candidates.

- Non-resonant contribution $\psi' \rightarrow \gamma X_i$

  the same final states, can not be removed

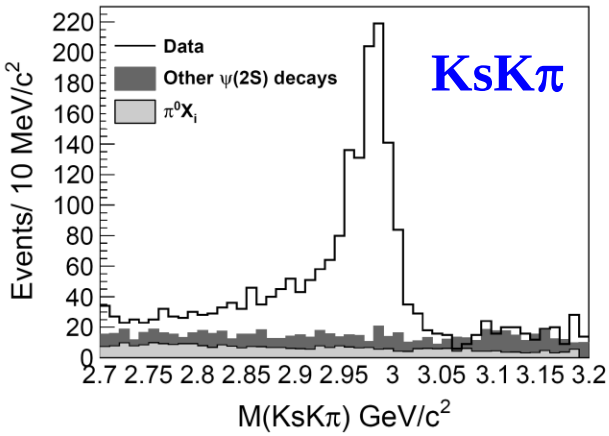
- Rare backgrounds

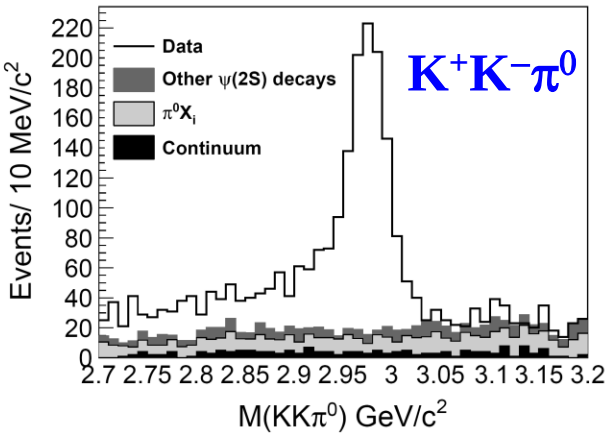
  Production rate or efficiency is very low, estimated according to the inclusive MC sample

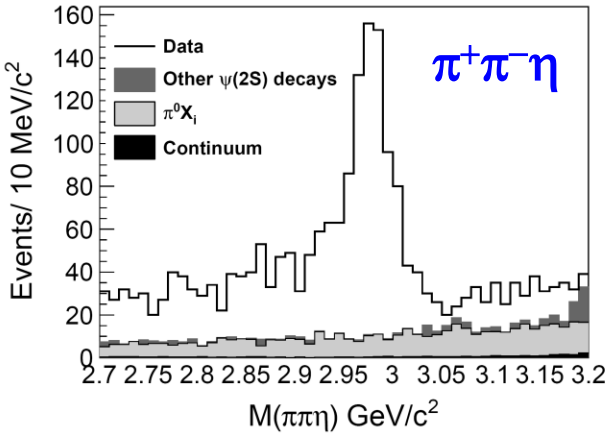
- Continuum events

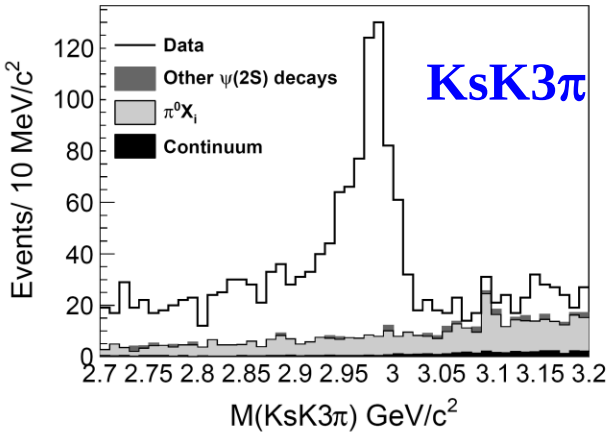
  Estimated by using the 45pb^{-1} data taken at 3.65GeV

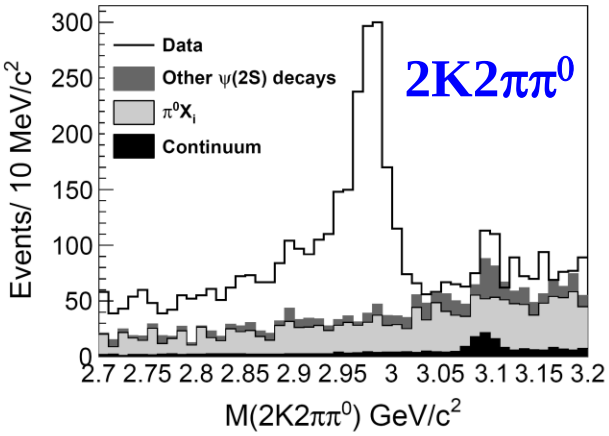
Backgrounds for $\psi' \rightarrow \gamma\eta_c \rightarrow \gamma X_i$ (conti.)

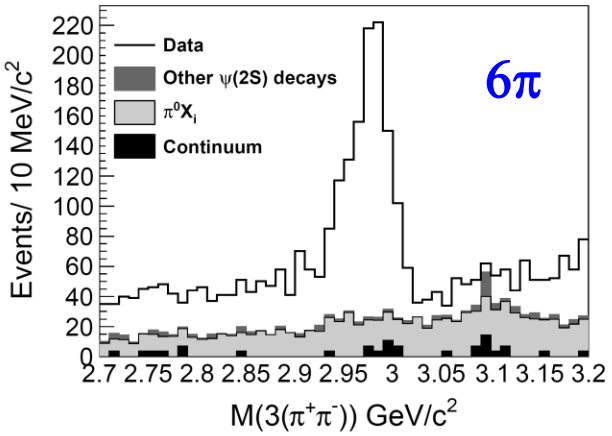












Mass spectrum fitting

$$\sigma \bigotimes (\epsilon |e^{i\phi} f_1 \mathcal{S} + \alpha Non|^2 f_2) + BKG$$

- **S**: signal function (BW with mass width floated)
- **Non**: PDF for the non-resonant γX_i (all assumed to 0^{-+})
- **BKG**: the sum of other backgrounds $\pi^0 X_i$ + other rare ψ' decays + continuum, fixed in the fitting
- ϕ: interference phase between η_c decay and non-resonant contribution

Fit results for individual modes:

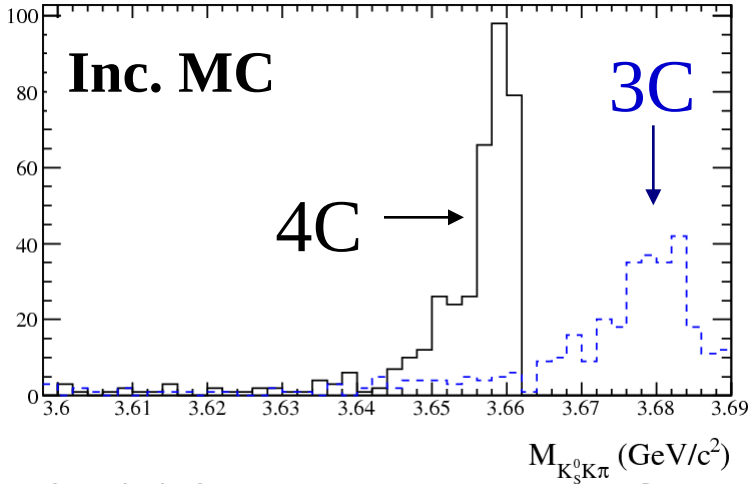
Interference

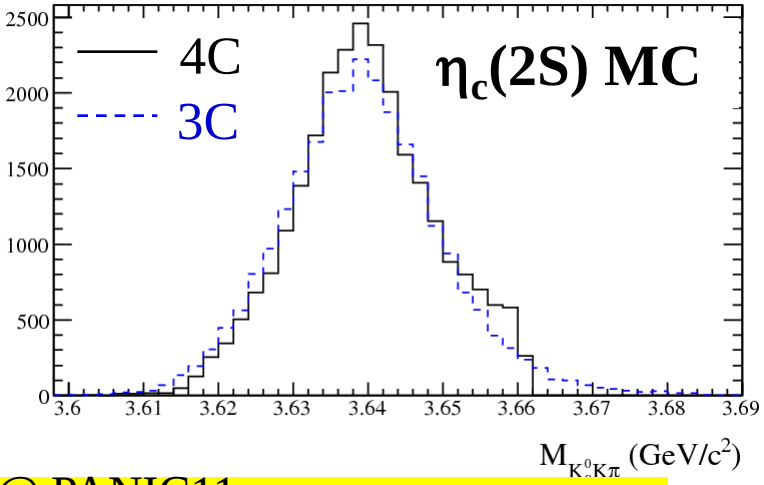
mode (i)	signal yield	ε (%)	mass (MeV/c^2)	width(MeV)	ϕ_i	$\chi^2/d.o.f$	significance
$K_S K^+\pi^-$	880.4	35.0	2984.7 ± 1.2	32.5 ± 2.3	2.9 ± 0.3	1.1	6.4
$K^+K^-\pi^0$	948.4	25.0	2980.3 ± 1.5	30.5 ± 2.4	2.4 ± 0.4	0.9	3.4
$\eta\pi^+\pi^-$	573.4	25.0	2982.4 ± 1.8	31.0 ± 3.3	2.2 ± 0.2	1.2	3.8
$K_S K^+\pi^+\pi^-\pi^-$	432.3	11.0	2986.9 ± 2.1	34.1 ± 3.3	2.3 ± 0.2	0.7	4.4
$K^+K^-\pi^+\pi^-\pi^0$	1033.6	11.0	2985.4 ± 1.3	29.1 ± 2.8	2.6 ± 0.2	1.2	7.0
$3(\pi^+\pi^-)$	664.4	17.0	2986.8 ± 1.3	33.7 ± 3.1	2.5 ± 0.1	1.1	7.0
combined	4532.5	-	2984.5 ± 0.6	31.7 ± 1.1	2.5 ± 0.1	-	-
C.L.	-	-	1.1%	89%	28%	-	-

Constant fitting gives χ^2/ndf=5.142/5

Mass spectrum representation for $\psi' \rightarrow \gamma\eta_c(2S)$

- The 4C kinematic fitting used to select the $\gamma K_S K\pi$ candidates ($\chi^2_{4C}<50$)
- Still some $K_S K\pi$ BG events contribute the $\gamma K_S K\pi$ candidates with a fake photon.
- The invariant mass from 4C-kinematic fits make the BG $\psi' \rightarrow K_S K\pi$ contaminates the $\eta_c(2S)$ mass region (3.6~3.66GeV).
- The mass from 3C-kinematic fits (the measured energy of the photon is free) is little biased by the fake photon.
- Difference small between 4C and 3C for signal events





So the 3C fit mass used to determine the yields and parameters

Mass fitting for $\psi' \rightarrow \gamma\eta_c(2S)$

- $\eta_c(2S)$ signal:

$\Gamma(\eta_c(2S))$ fixed to 12MeV (world average)

$$(E_\gamma^3 \times BW(m) \times damping(E_\gamma)) \otimes Gauss(0,\sigma)$$

M1 transition

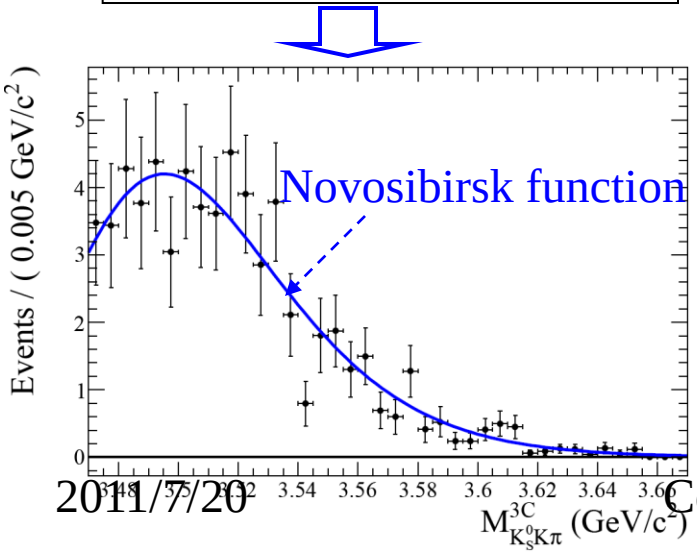
$$\frac{E_0^2}{E_\gamma E_0 + (E_\gamma - E_0)^2}$$

Fixed to the linear Extrapolation from $\sigma(\chi_{cJ})$

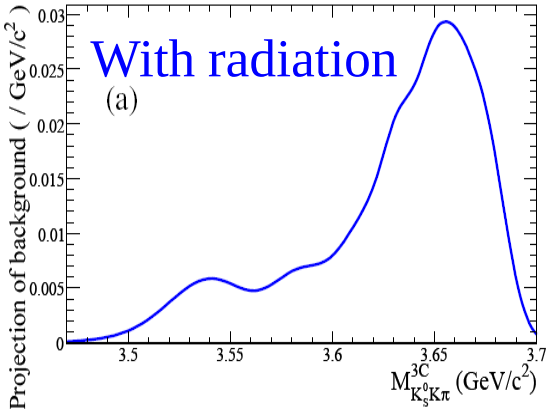
- χ_{cJ}: MC shape ⊗ a Gaussian

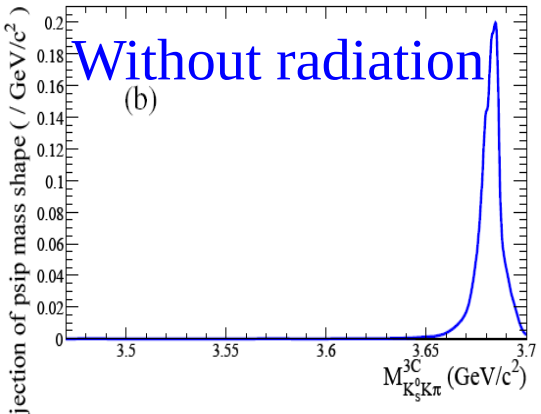
- BG from π^0KsKπ:

Measurement + scaling with MC simulation



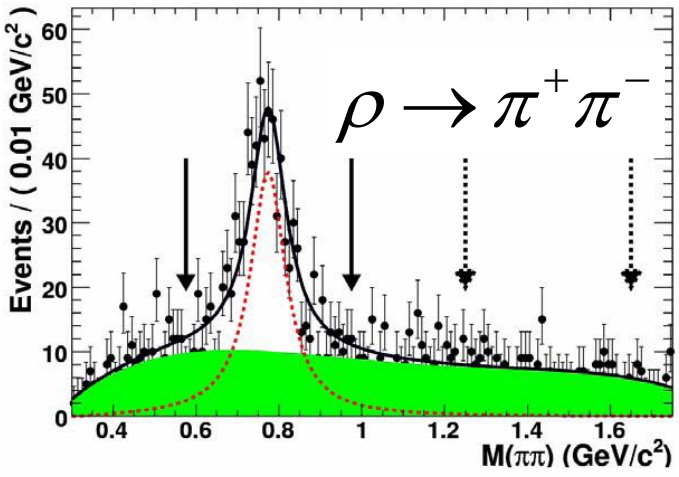
- BG from $\psi' \rightarrow$KsK$\pi(\gamma_{FSR})$ & continuum (KsK$\pi(\gamma$ISR)):

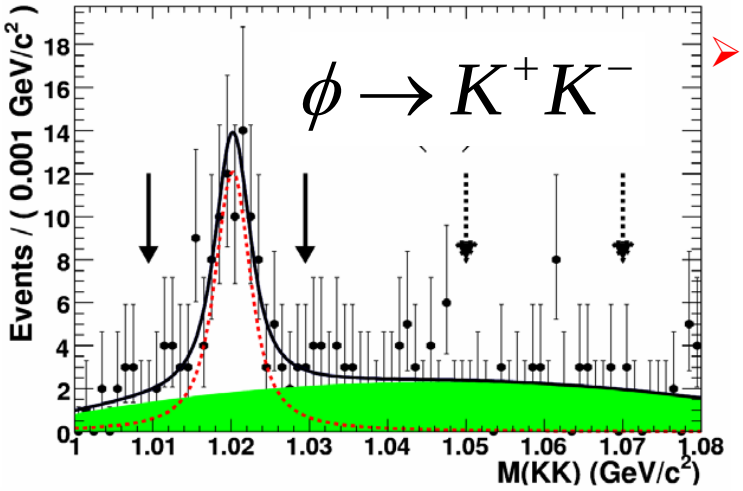




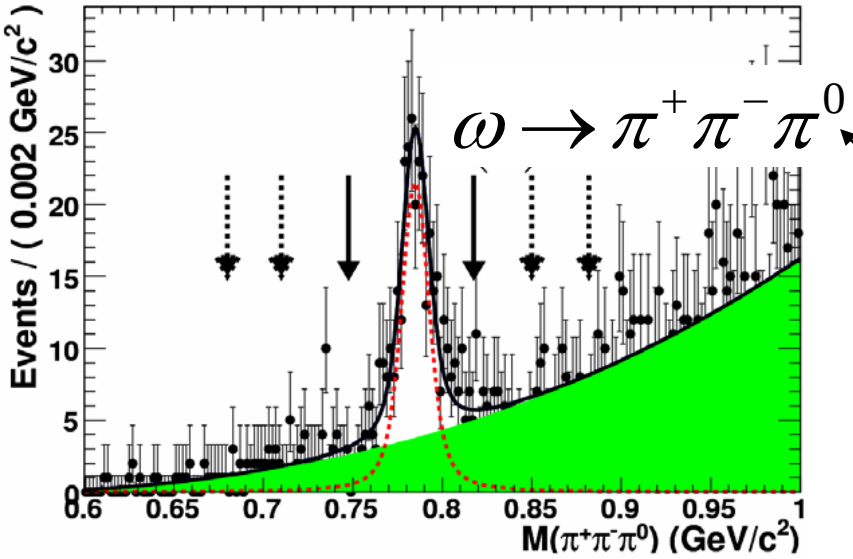
Ratio of the two is fixed in the final mass fitting

ρ, ω and ϕ Reconstruction





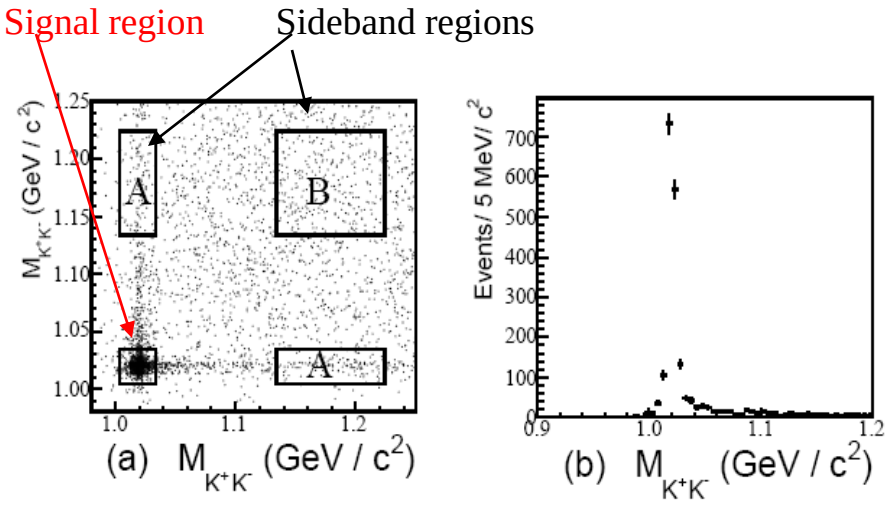
- Applying 4C kinematic fit to $\gamma\gamma\pi^+\pi^-$ or $\gamma\gamma K^+K^-$.



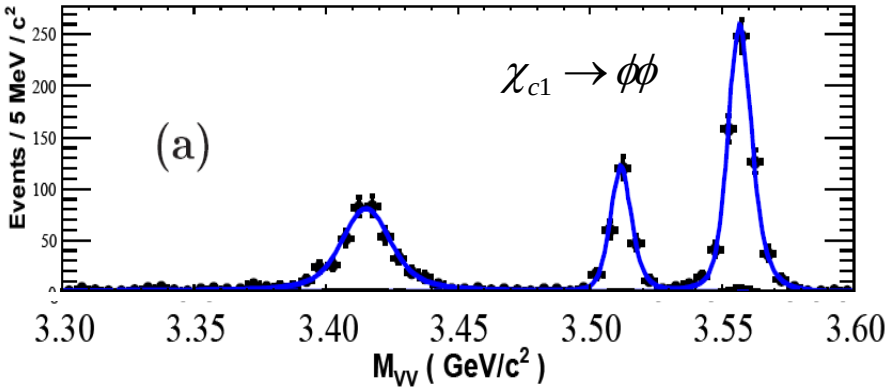
- Using 5C(energy-momentum+π^0 mass) kinematic fit for $4\gamma\pi^+\pi^-$ candidates.
- π^0 reconstruction:

$$\left(\frac{M_{\gamma_1\gamma_2} - M_{\pi^0}}{\sigma_{\pi^0}}\right)^2 + \left(\frac{M_{\pi^+\pi^-\gamma_1\gamma_2} - M_{\omega}}{\sigma_{\omega}}\right)^2$$

Study of $\chi_{cJ} \to \phi\phi$ ($\phi \to K^+K^-$)



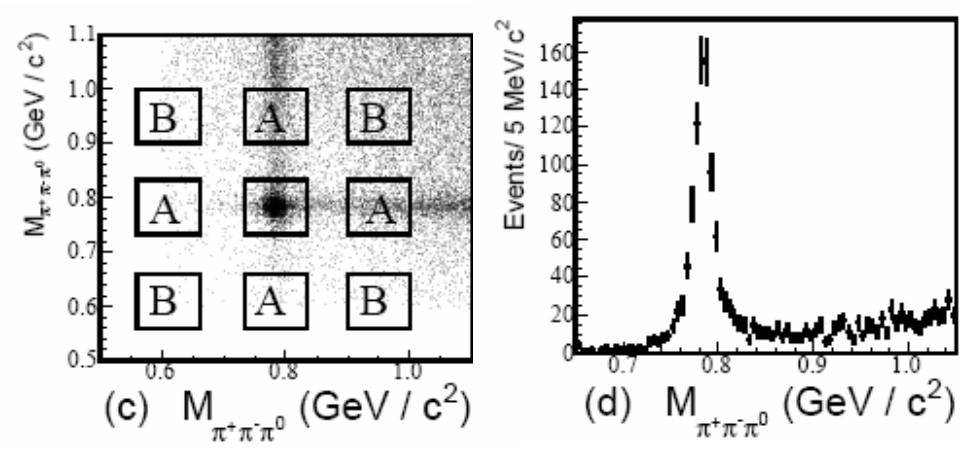
- Using kinematic fit to select $\gamma 2(K^+K^-)$ candidates
- KK pairs reconstruction by minimizing :
  $[M_1(K^+K^-)-M_\phi]^2 + [M_2(K^+K^-)-M_\phi]^2$



Channel	$\mathcal{B}(\times 10^{-4})$	PDG$(\times 10^{-4})$
$\chi_{c0} \to \phi\phi$	$7.8 \pm 0.4 \pm 0.8$	9.2 ± 1.9
$\chi_{c1} \to \phi\phi$	$4.1 \pm 0.3 \pm 0.4$	—
$\chi_{c2} \to \phi\phi$	$10.7 \pm 0.4 \pm 1.1$	14.8 ± 2.8

First observation

Study of $\chi_{cJ} \to \omega\omega$ ($\omega \to \pi^+\pi^-\pi^0$)



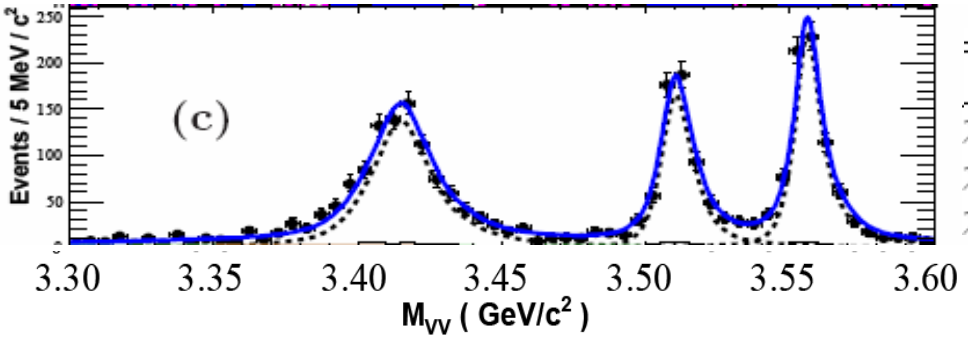
- Using kinematic fit to select $5\gamma 2(\pi^+\pi^-)$ candidates
- Two π^0 pair reconstruction: minimizing

$$\sum (M_{\gamma\gamma} - M_{\pi^0})^2$$

by looping over 5γ

- ω reconstruction: minimizing

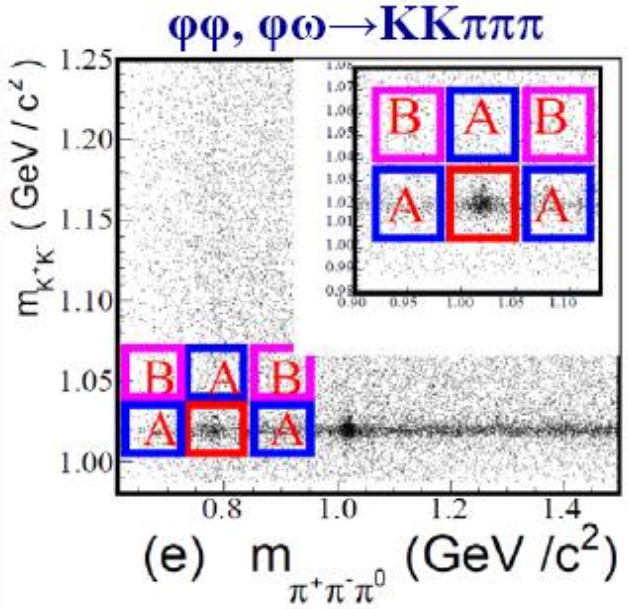
$$\sum (M_{\pi^+\pi^-\pi^0} - M_{\omega})^2$$

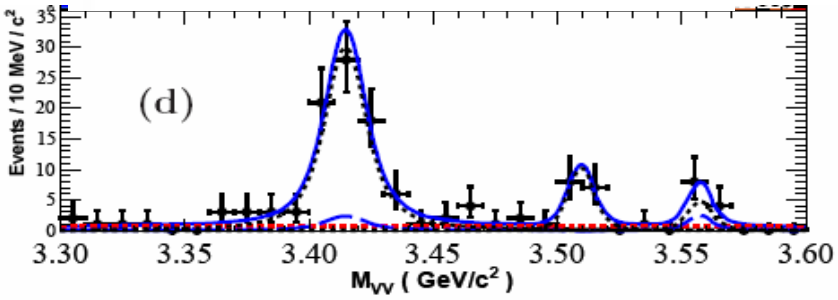


Channel	$\mathcal{B}(\times 10^{-4})$	PDG$(\times 10^{-4})$
$\chi_{c0} \to \omega\omega$	$9.5 \pm 0.3 \pm 1.1$	22 ± 7.0
$\chi_{c1} \to \omega\omega$	$6.0 \pm 0.2 \pm 0.7$	—
$\chi_{c2} \to \omega\omega$	$8.9 \pm 0.3 \pm 1.1$	19.0 ± 6.0

First observation

Study of $\chi_{cJ} \to \omega\phi \to \pi^+\pi^-\pi^0K^+K^-$





- Two tracks are identified as K^+K^-
- Using kinematic fit to select $3\gamma 2K2\pi$ candidates
- $\pi^0\omega$ are reconstructed by minimizing

$$(M_{\gamma\gamma} - M_{\pi^0})^2 + (M_{\gamma\gamma\pi^+\pi^-} - M_{\omega})^2$$

Channel	$\mathcal{B}(\times 10^{-4})$	PDG$(\times 10^{-4})$
$\chi_{c0} \to \omega\phi$	$1.2 \pm 0.1 \pm 0.2$	—
$\chi_{c1} \to \omega\phi$	$0.22 \pm 0.06 \pm 0.02$	—
$\chi_{c2} \to \omega\phi$	< 0.2	—

Doubly OZI suppressed χ_{cJ} → $\omega\phi$ are observed for the first time