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Charmonium Spectroscopy at BESIII

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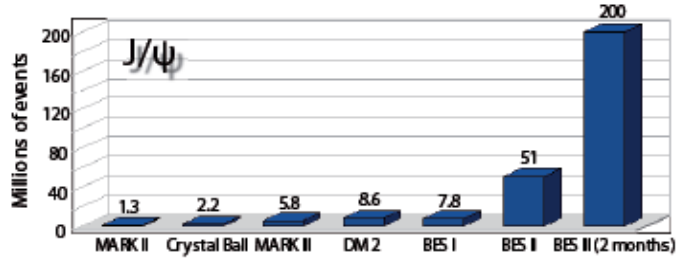
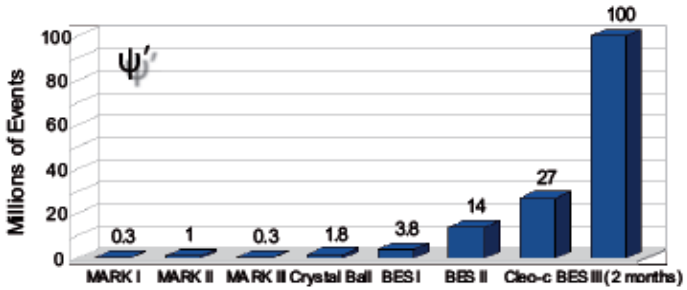
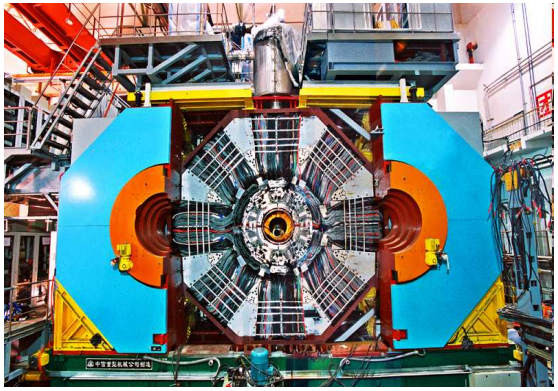
Outline

- Brief Introduction of **BEPCII & BESIII**
- Measurement of $\mathbf{h_c}$ at BESIII
- Precision measurement of the η_c properties
- The first observation of the M1 transition $\psi' \rightarrow \gamma \eta_c(2S)$
- Summary

BEPCII & BESIII







Large data samples

Updated detectors

E_{cm} = 2~4.6GeV

$L^{peak} = 10^{33}/(cm^2 \cdot s)$

BESIII is excellent!

Abundant potential physics with BESIII.

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BESIII data samples

Energy points	luminosity	Number of resonant events
J/ψ	81 pb^{-1}	225 million
ψ'	163 pb^{-1}	106 million
3.65 GeV	44 pb^{-1}	A unique facility and Open many physics opportunity!
ψ(3770)	2.9 fb^{-1}	
4.01 GeV (ψ(4040))	0.5 fb^{-1}	

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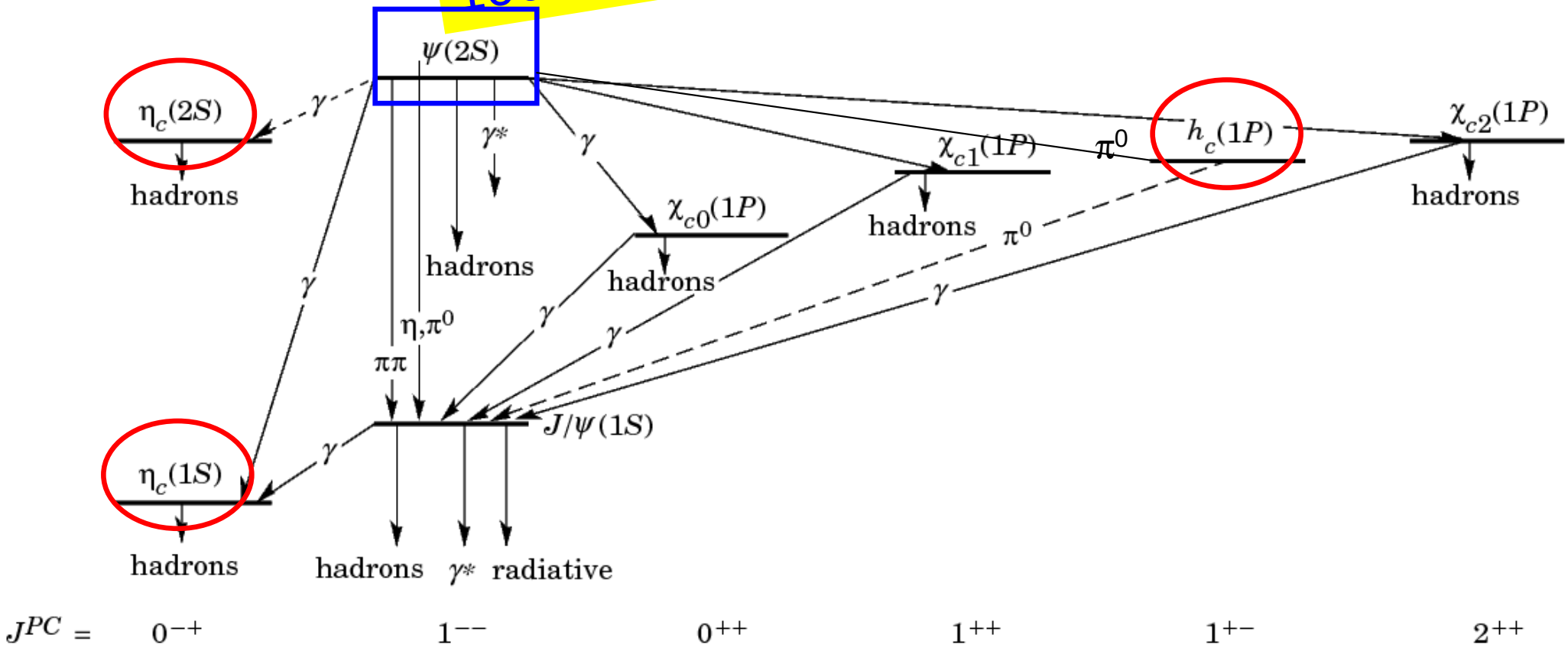
Charmonium Spectrum below open charm threshold

106M ψ(2S) at BESIII



Measurement of h_c at BESIII

$h_c(^1P_1)$ singlet 1P wave state

- Spin singlet P wave (S=0, L=1).
- **Hyperfine mass splitting is an indication of spin-spin interaction:**
  $\Delta M_{hf}(1P) = M(h_c) - 1/9(M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2}))$.
- E835 found evidence for h_c in $pp \rightarrow h_c \rightarrow \gamma\eta_c$.
- CLEO-c
- observed h_c in $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\eta_c$
  $\Delta M_{hf}(1P) = 0.08 \pm 0.18 \pm 0.12 \text{MeV}/c^2$.

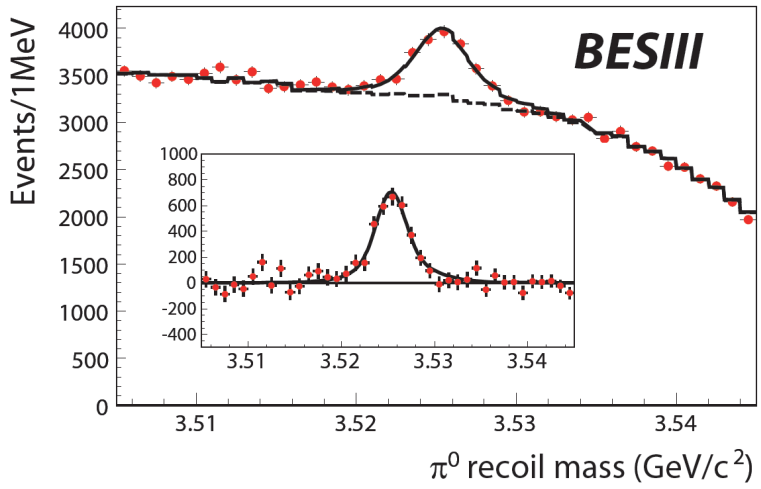
- Predicted for a long time
- Hyperfine splitting of 1P states (spin-spin)
- iso-spin forbidden transition $\psi' \rightarrow \pi^0 h_c$
- Mass and product Brs from CLEO-c [PRL101.182003(2008)]

	Inclusive	Exclusive
Counts	1146 ± 118	136 ± 14
Significance	10.0σ	13.2σ
$M(h_c)$ (MeV)	$3525.35 \pm 0.23 \pm 0.15$	$3525.21 \pm 0.27 \pm 0.14$
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^4$	$4.22 \pm 0.44 \pm 0.52$	$4.15 \pm 0.48 \pm 0.77$

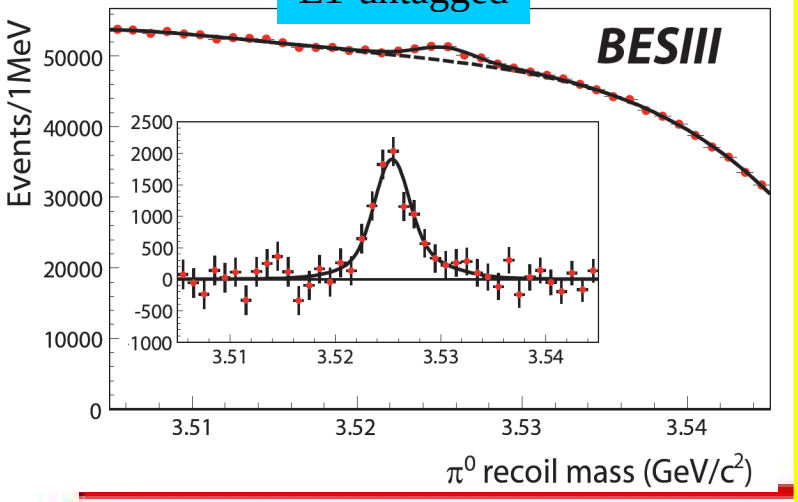
Measurement of h_c (inclusive)

BESIII Collaboration: PRL104, 132002, (2010)

E1-tagged

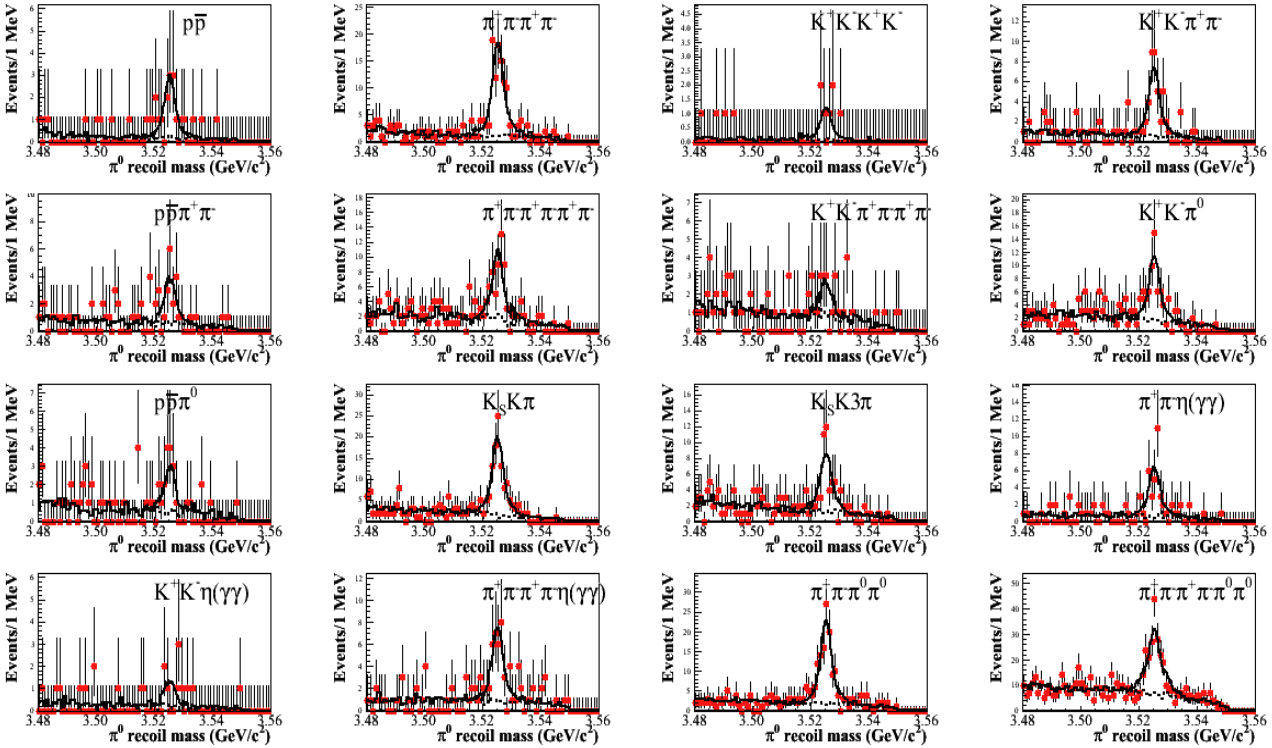


E1-untagged

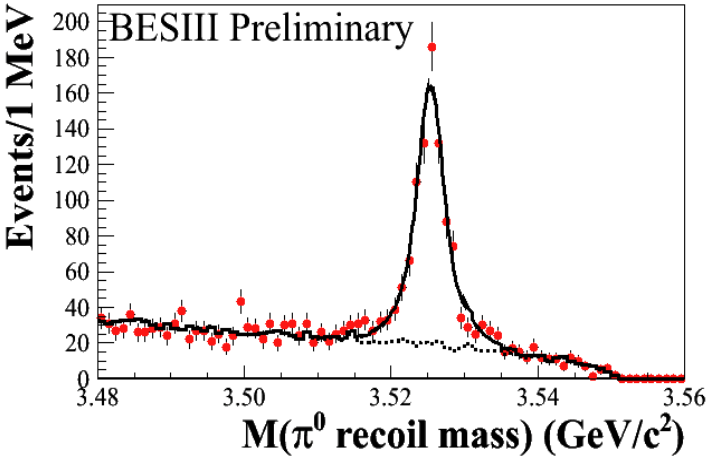


- Select inclusive π^0 in ψ' decays ($\psi' \rightarrow \pi^0 h_c$)
- Select E1-photon in $h_c \rightarrow \gamma \eta_c$ (E1 tagged) or not (E1 untagged/semi-inclusive)
- E1-tagged selection gives
  $M(h_c)=3525.40\pm0.13\pm0.18$MeV
  ($\Delta M_{hf}(1P)=0.10\pm0.13\pm0.18$MeV/$c^2$)
  $\Gamma(h_c)=0.73\pm0.45\pm0.28$MeV
  (<1.44MeV at 90% CL)
  $Br(\psi' \rightarrow \pi^0 h_c) \times Br(h_c \rightarrow \gamma \eta_c) = (4.58\pm0.40\pm0.50) \times 10^{-4}$
- **$N(h_c) = 10353\pm1097$**
- E1-untagged together with
- tagged selection gives the **first measurement**
  $Br(\psi' \rightarrow \pi^0 h_c) = (8.4\pm1.3\pm1.0) \times 10^{-4}$
  $Br(h_c \rightarrow \gamma \eta_c) = (54.3\pm6.7\pm5.2)\%$

Measurement of the h_c (exclusive)



Summed π^0 recoil mass



16 decay modes are studied:

$\psi' \to \pi^0 h_c, h_c \to \gamma\eta_c, \eta_c \to X_i$

X_i: ppbar, 4π, 4K, 2π2K, ppbarππ, 6π, 2K4π, KKπ^0, ppbarπ^0, KsKπ, KsK3π, ππη, KKη, 4πη, 2π2π^0, 4π2π^0

Simultaneous fit to π^0 recoiling mass

M(h_c) = 3525.31±0.11±0.15 MeV

Γ(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 Mass and Width

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

- The lowest lying S-wave spin singlet charmonium η_c was discovered in 1980 by MarkII.
- Earlier experiments using J/ψ radiative transition gives $M(\eta_c) \sim 2978.0 MeV/c^2$, $\Gamma(\eta_c) \sim 10 MeV$.
- Recent studies using the two-photon processes gives $M(\eta_c) = 2983.1 \pm 1.0\ MeV/c^2$, $\Gamma(\eta_c) = 31.3 \pm 1.9\ MeV$.
- 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: 106M ψ' events, 44pb^{-1} continuum data at 3.65 GeV
  - ◆Decay modes X_i: $KsK\pi$, $K^+K^-\pi^0$, $\eta\pi^+\pi^-$, $KsK3\pi$, $K^+K^-\pi^+\pi^-\pi^0$, $3(\pi^+\pi^-)$, where $Ks \rightarrow \pi^+\pi^-$, $\eta \rightarrow \gamma\gamma$, $\pi^0 \rightarrow \gamma\gamma$

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

- **$\psi' \to \pi^0 X_i$**

  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 $\psi' \to \gamma X_i$**

  exactly the same final states, can not be removed.

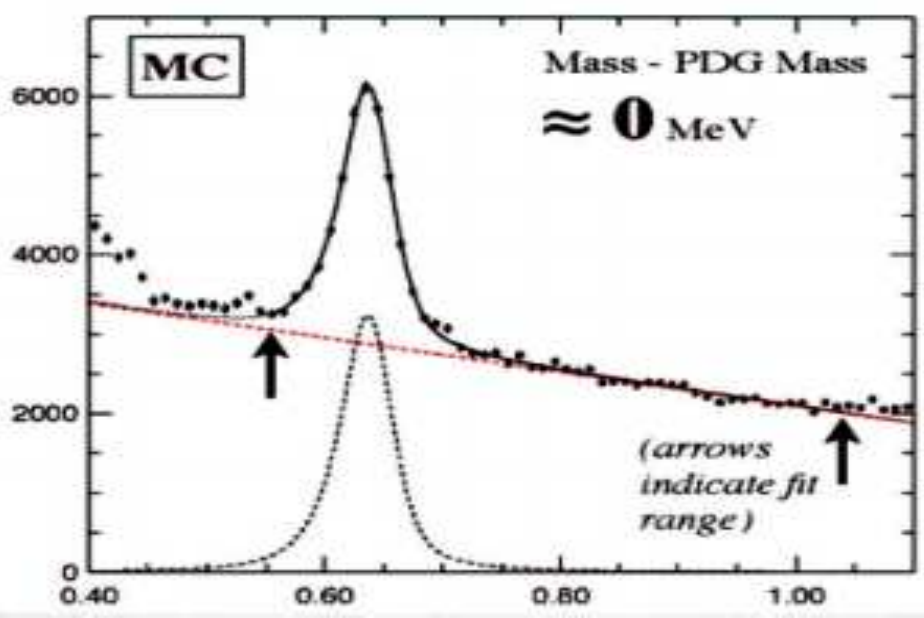
- **Rare backgrounds**

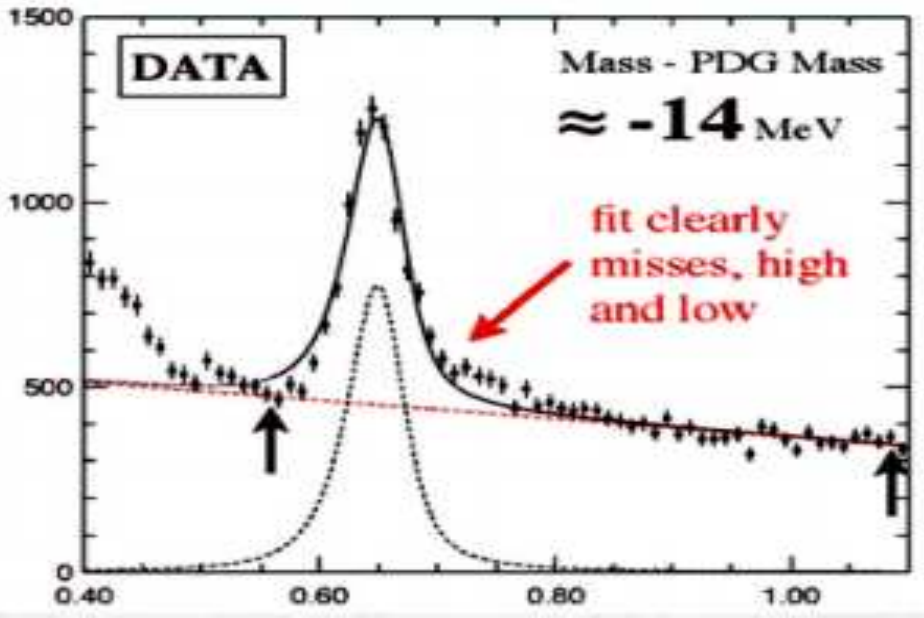
  Production rate or efficiency is very low, estimated based on the inclusive MC.

- **Continuum events**

  Estimated by using the 44pb^{-1} data taken at 3.65GeV.

η_c LineShape @CLEO-c





- CLEO-c observed an abnormal η_c line shape
- It is explained by a M1 transition factor finally in the published paper

Phys. Rev. Lett. 102, 011801 (2009)

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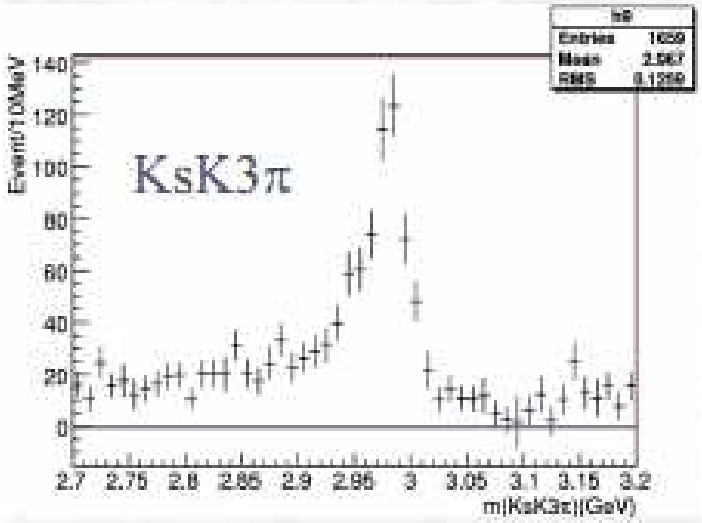
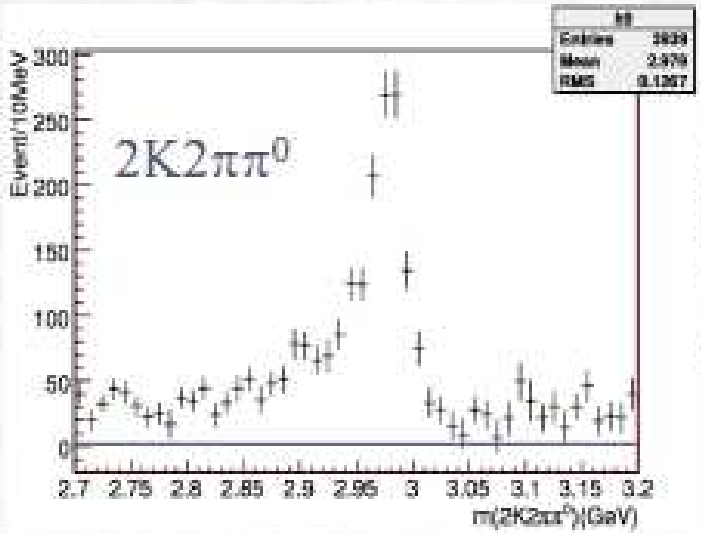
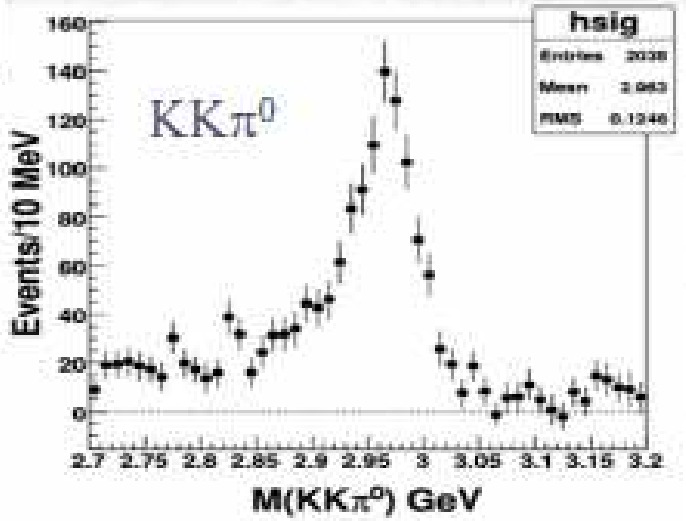
η_c LineShape @BESIII

The abnormal line shape is also observed in BESIII exclusive channels with larger statistics







- We also found only M1 factor cannot explain it
- The interference between η_c resonance and the same final states is proposed

Mass spectrum Fitting

$$PDF = \sigma \otimes (\varepsilon \cdot |e^{i\varphi} \cdot f_1 \cdot BW + \alpha \cdot BG|^2 \cdot f_2)$$

σ : resolution,

φ : interference phase angle

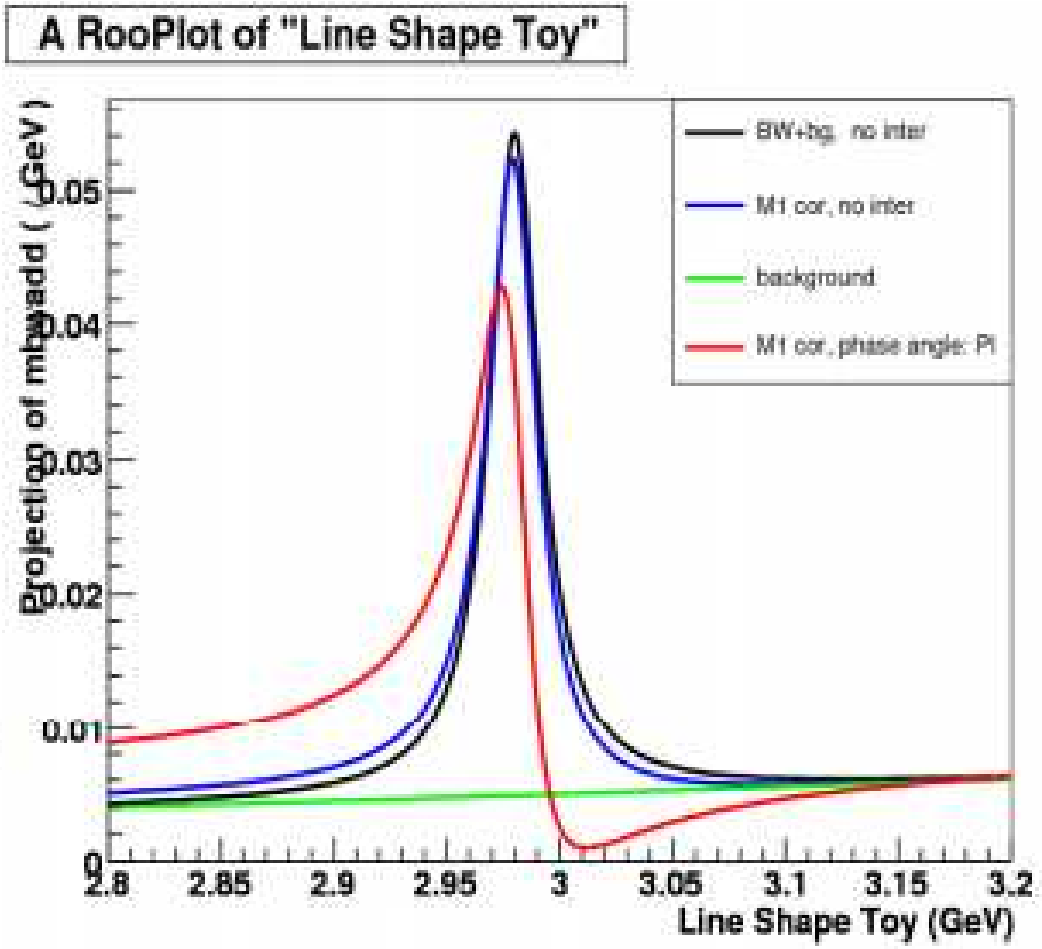
ε : efficiency

α : fraction

f_1 f_2 : M1 transition factor

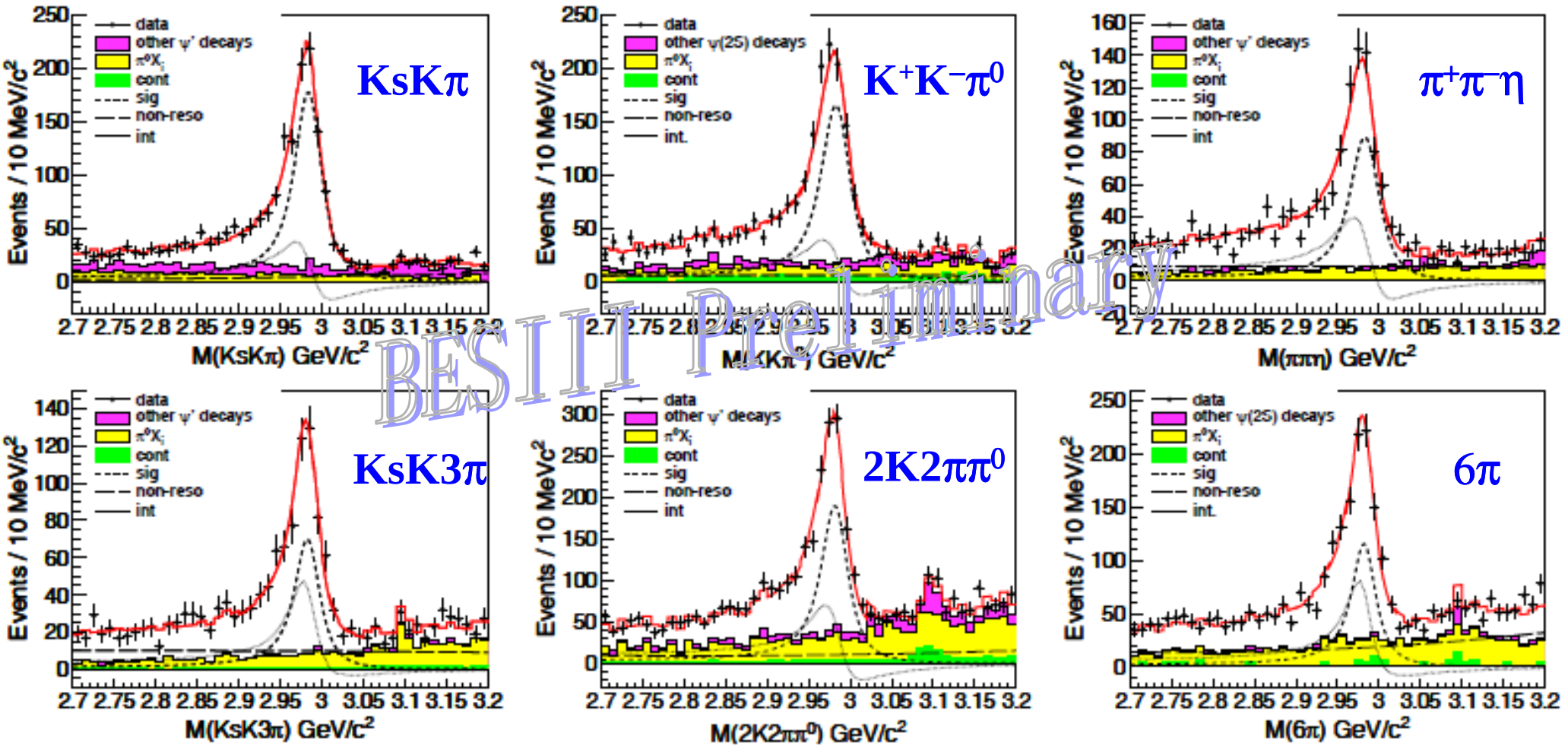
($E_\gamma^4 \cdot E_\gamma^3 = E_\gamma^7$ for $\psi' \rightarrow \gamma\eta_c$)

BG: background with the same final states



The simultaneous Fit

The η_c **mass**, **width** and interference phase ϕ are constrained to be the same.



Simultaneous fit with modified Breit-Wigner (hindered M1) with considering **interference** between η_c and non-η_c decays

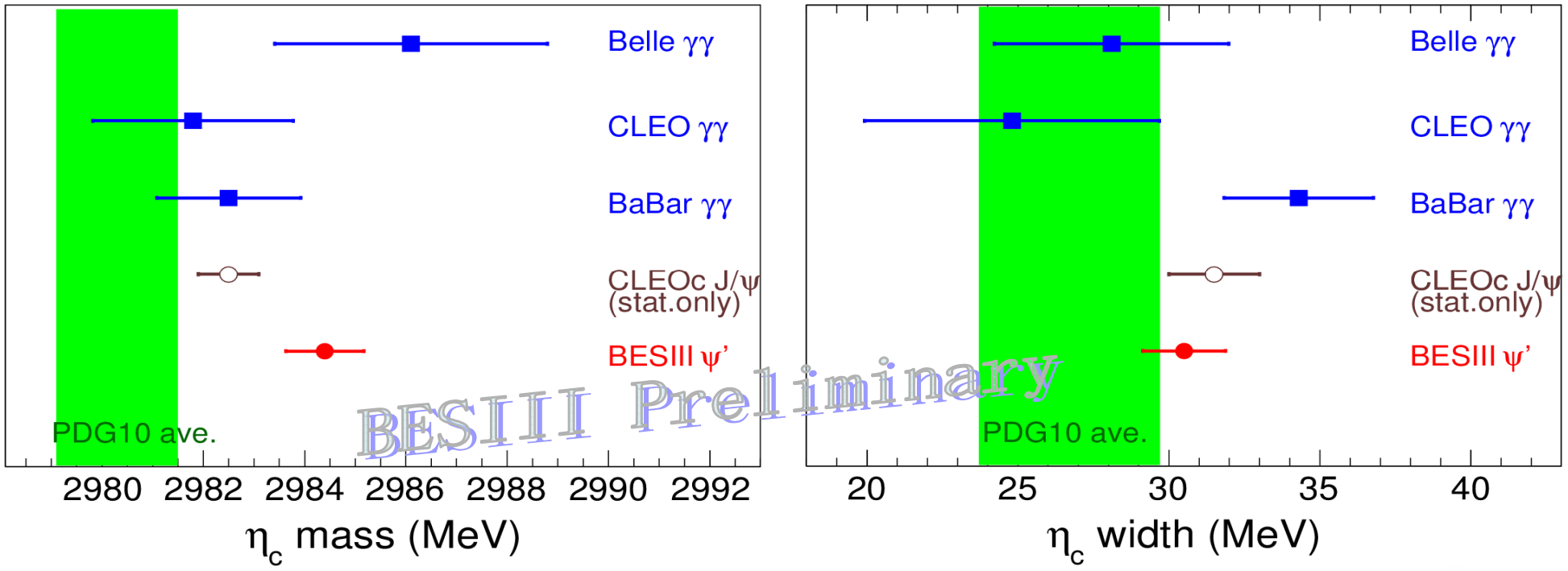
Mass and Width of η_c

BESIII preliminary

- mass = $2984.4 \pm 0.5_{stat} \pm 0.6_{syst}$ MeV/c^2
- width = $30.5 \pm 1.0_{stat} \pm 0.9_{syst}$ MeV

Interference is necessary!

The world average in PDG2010 was using earlier results.



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

$\eta_c(2S)$ (never confirmed in M1 transition)

- First "observation" by Crystal Ball in 1982 (M=3.592, Br=0.2%-1.3% from $\psi' \rightarrow \gamma X$, never confirmed by other experiments.)
- **experimental challenge : search for real photons ~50MeV**
- 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.

- Decay mode studied: $\psi' \rightarrow \gamma\eta_c(2S) \rightarrow \gamma K_S K\pi$ ($K^+K^-p^0$ etc. in progress). Better chance with ~106M y' data at BESIII.

Mass fitting

- $\eta_c(2S)$ 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

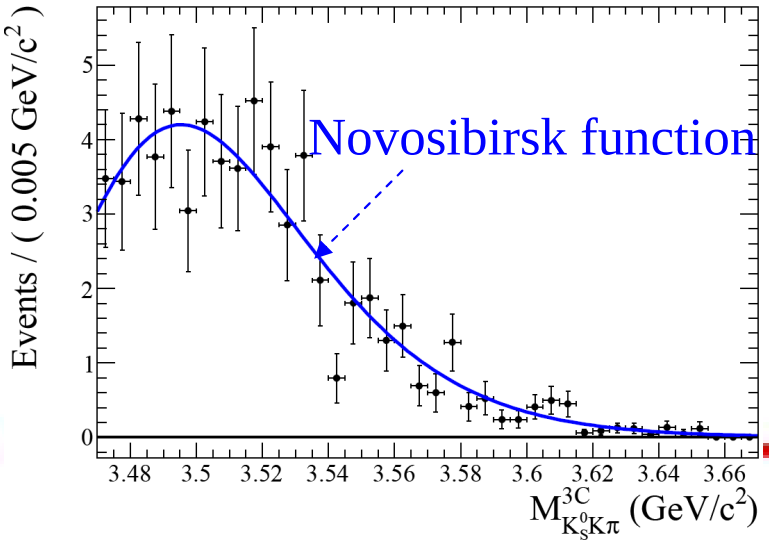
$$\frac{E_0^2}{E_\gamma E_0 + (E_\gamma - E_0)^2}$$

For convergence

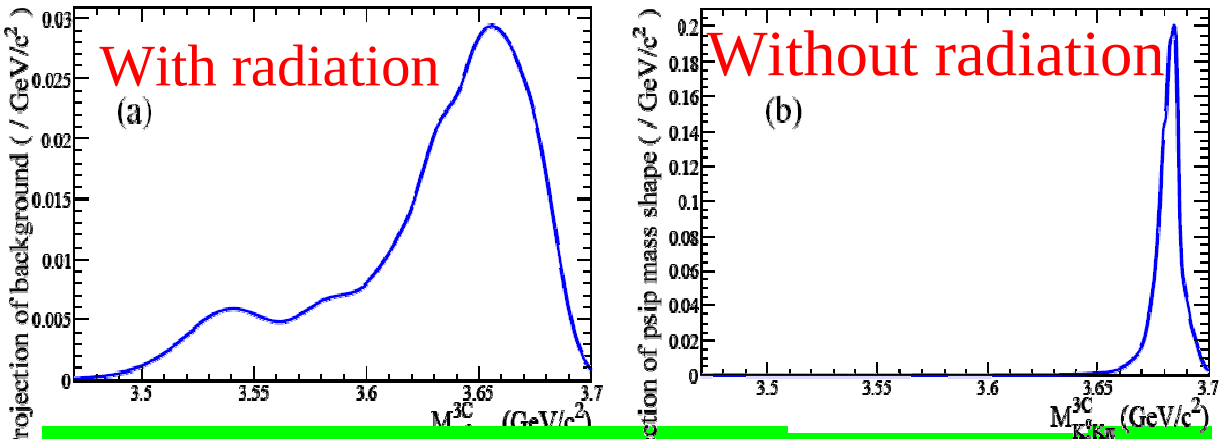
Fixed to the linear Extrapolation from $\sigma(\chi_{cJ})$

- χ_{cJ}: MC shape ⊗ a Gaussian
- BG from $\pi^0 K_S K\pi$:

Measurement + scaling with MC simulation

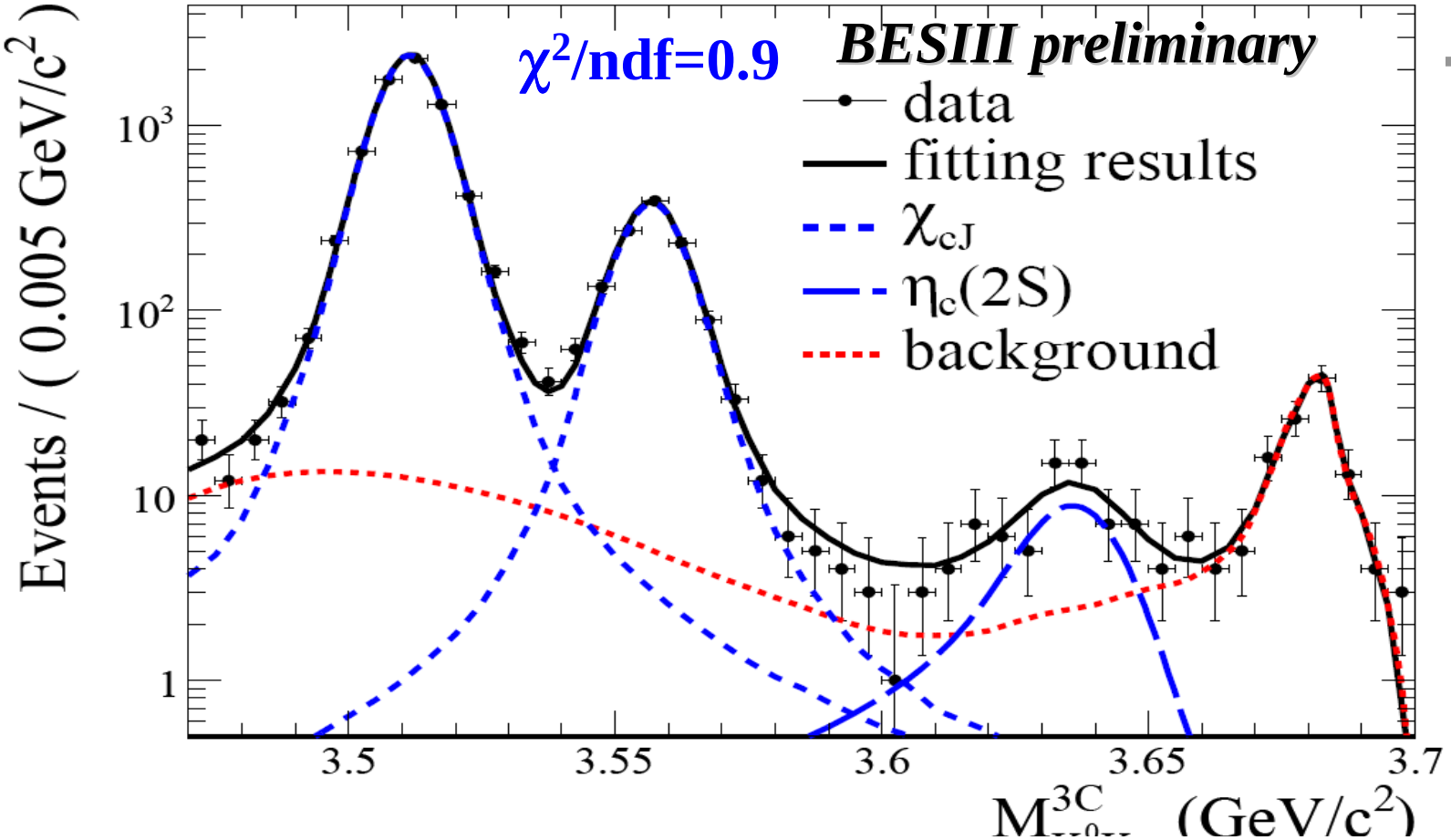


- BG from $\psi' \rightarrow K_S K\pi(\gamma_{FSR})$ & continuum ($K_S K\pi(\gamma_{ISR})$):



Ratio of the two is fixed in the final mass fitting

Mass spectrum Fitting



- $N(\eta_c(2S)) = 50.6 \pm 9.7$.
- Pure statistical significance more than 6σ.
- Significance with systematic variations is still more 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: $< 7.6 \times 10^{-4}$ (@90% CL) (PRD81,052002(2010))
Potential model: $(0.1–6.2) \times 10^{-4}$ (PRL89,162002(2002))

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Future Plan @BESIII

~0.5 fb^{-1} at $\psi(4040)$ taken already

-Search for XYZ states

-Hadronic transitions of $\psi(4040)$

-Radiative transitions of $\psi(4040)$

~0.7 B-1.0 B $\psi(2S)$ events are expected in 2012

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 distorted **η_c line shape** could be described successfully by including an interfering non-resonant amplitude.
- Searching for $\eta_c(2S)$ in the M1 transition **$\psi' \to \gamma \eta_c(2S)$.**
- More results will come out soon at BESIII.

Acknowledgment

International Workshop on
Heavy Quarkonium 2011
GSI, Darmstadt, Germany

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Backups

Mass spectrum fitting

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

- **S**: signal function (BW with mass width floated)
- **Non**: non-resonant γX_i PDF (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

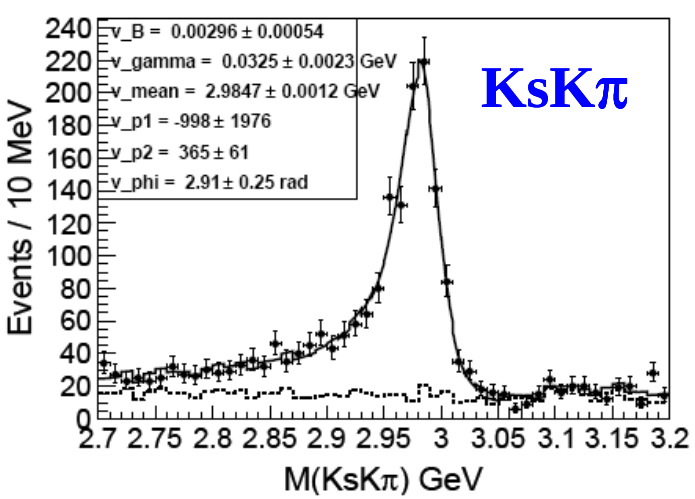
Fit results for individual modes:

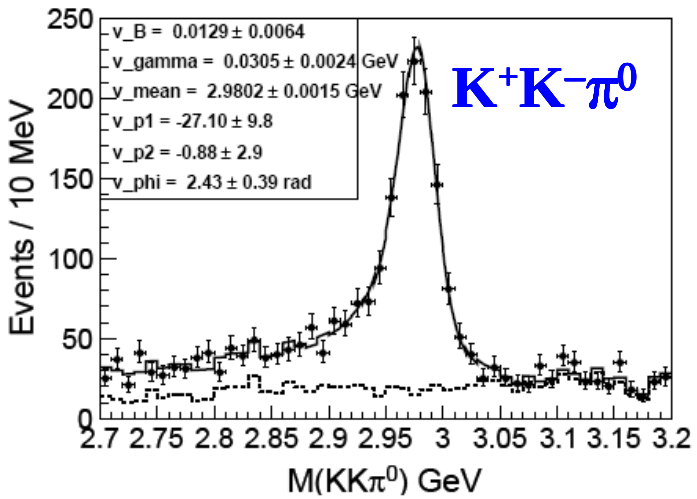
Interference

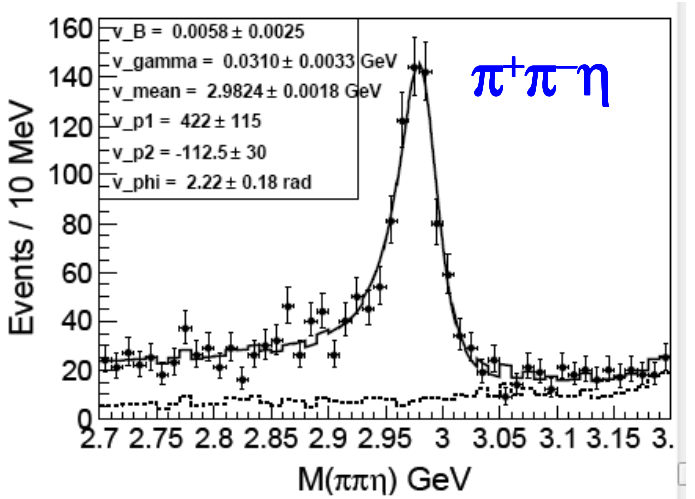
mode (i)	signal yield	ε (%)	mass (MeV/c^2)	width(MeV)	ϕ_i	$\chi^2/d.o.f$	significance
$K_S K^+\pi^-$	880.4	35.0	2984.7 ± 1.2	32.5 ± 2.3	2.9 ± 0.3	1.1	6.4
$K^+K^-\pi^0$	948.4	25.0	2980.3 ± 1.5	30.5 ± 2.4	2.4 ± 0.4	0.9	3.4
$\eta\pi^+\pi^-$	573.4	25.0	2982.4 ± 1.8	31.0 ± 3.3	2.2 ± 0.2	1.2	3.8
$K_S K^+\pi^+\pi^-\pi^-$	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%	-	-

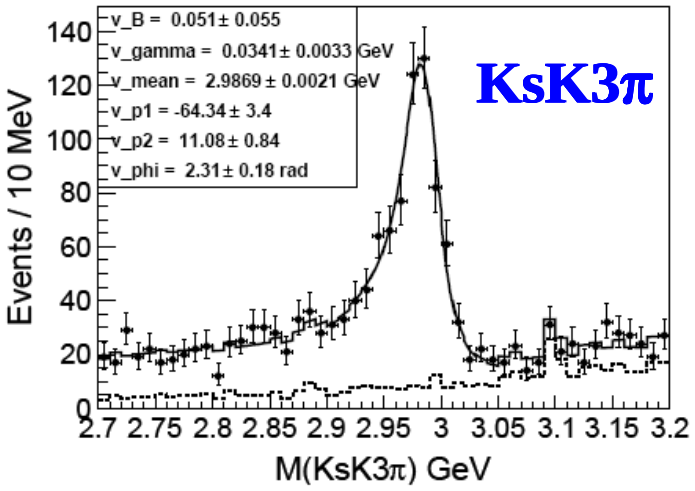
Constant fitting gives χ^2/ndf=5.142/5

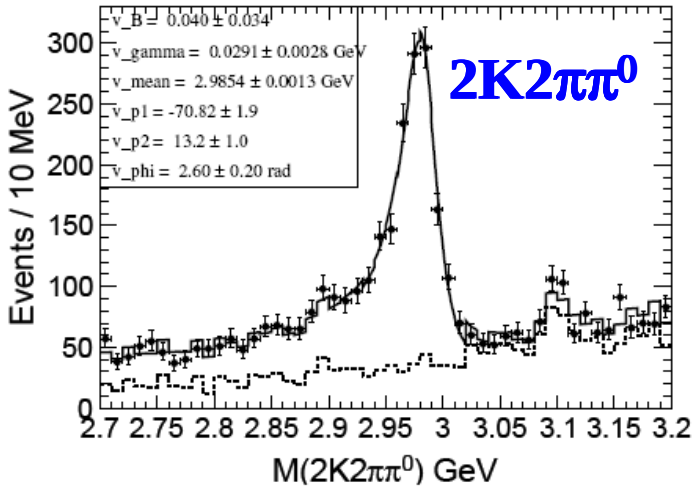
Results of the fits for different modes

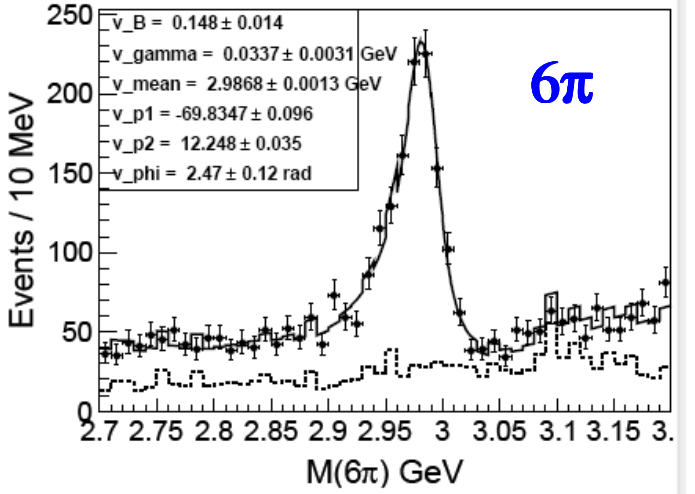




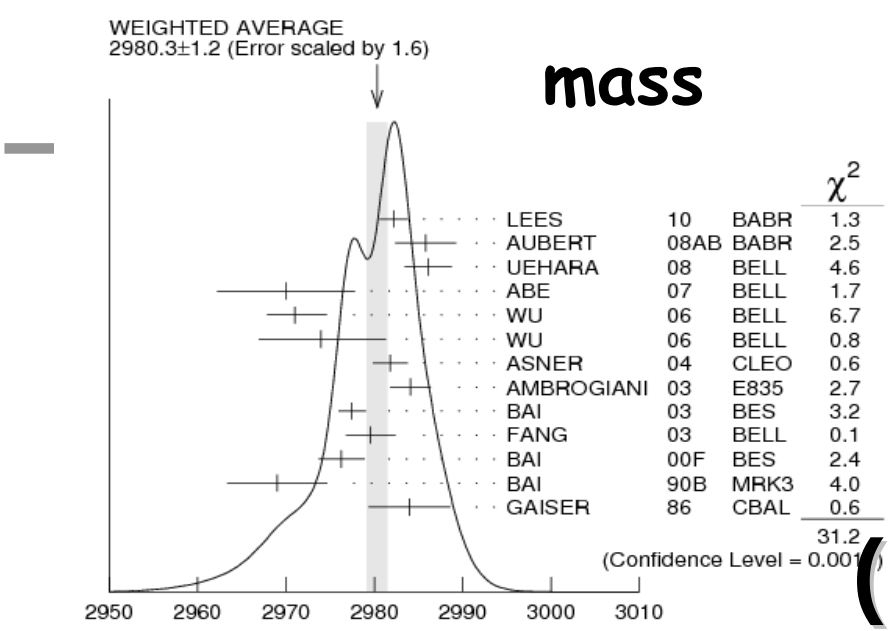


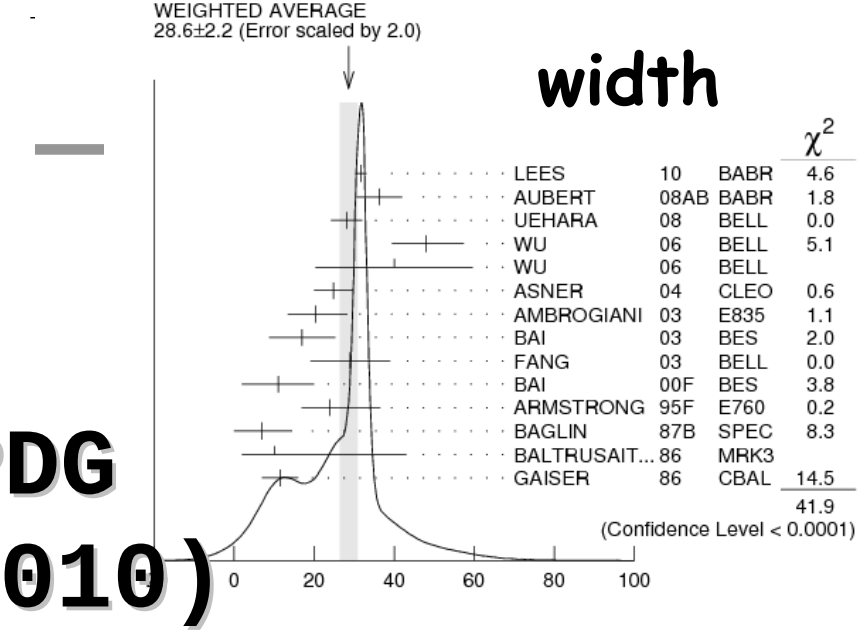




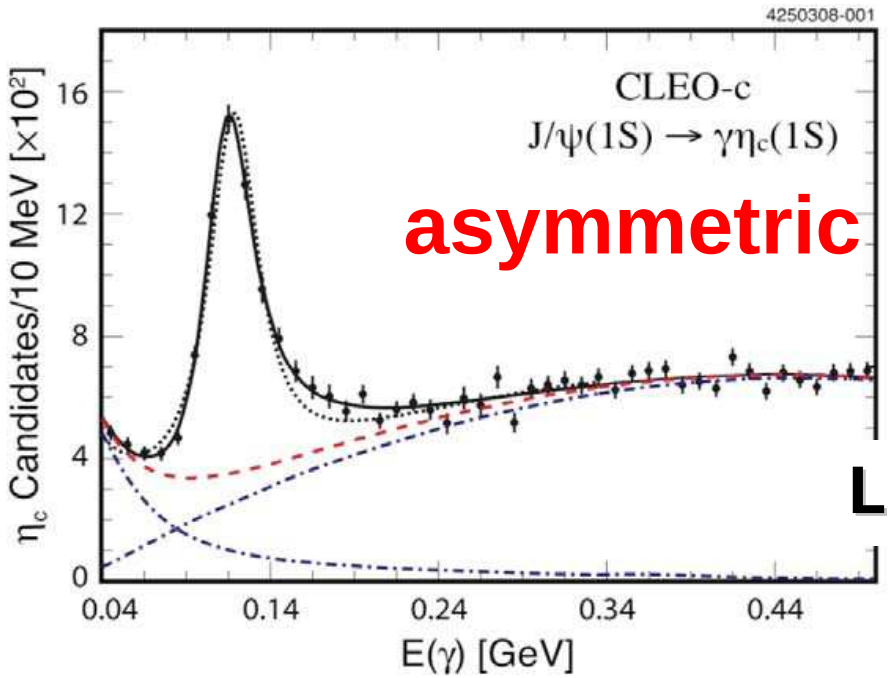


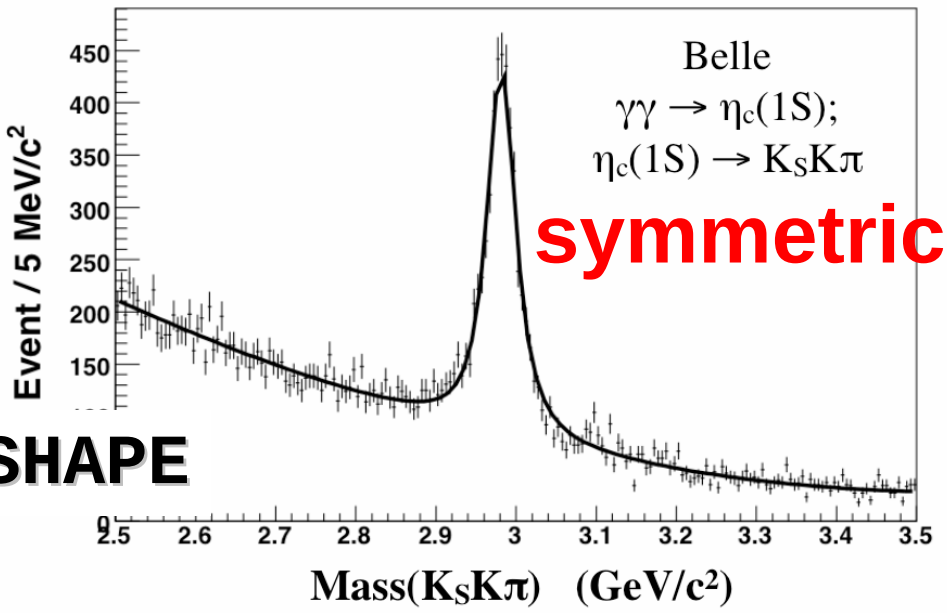
η_c, the lightest charmonium state





PDG (2010)

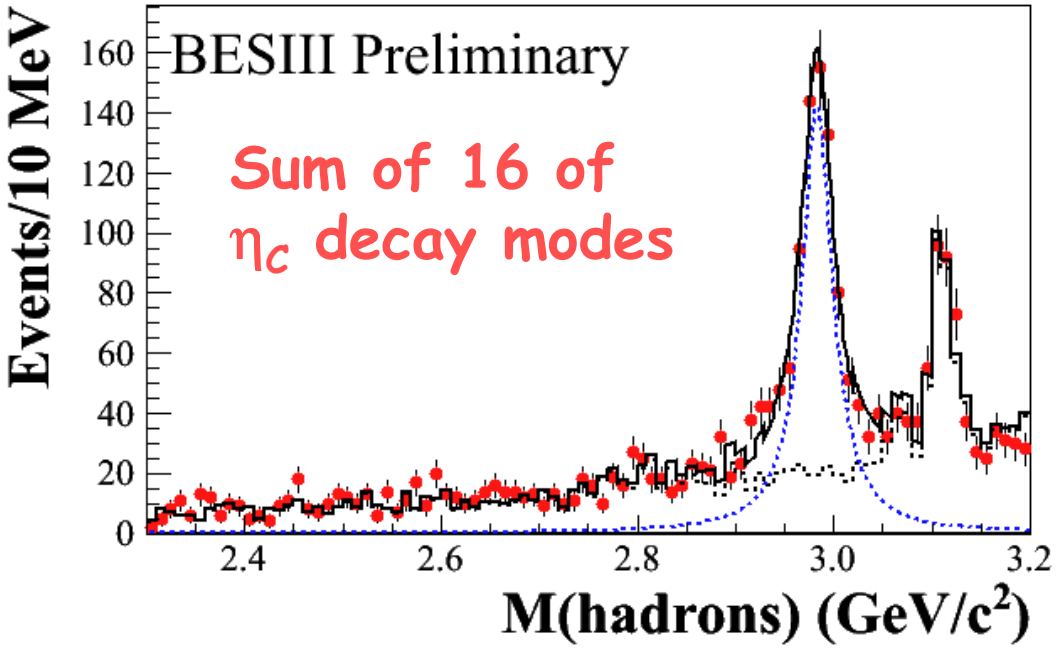


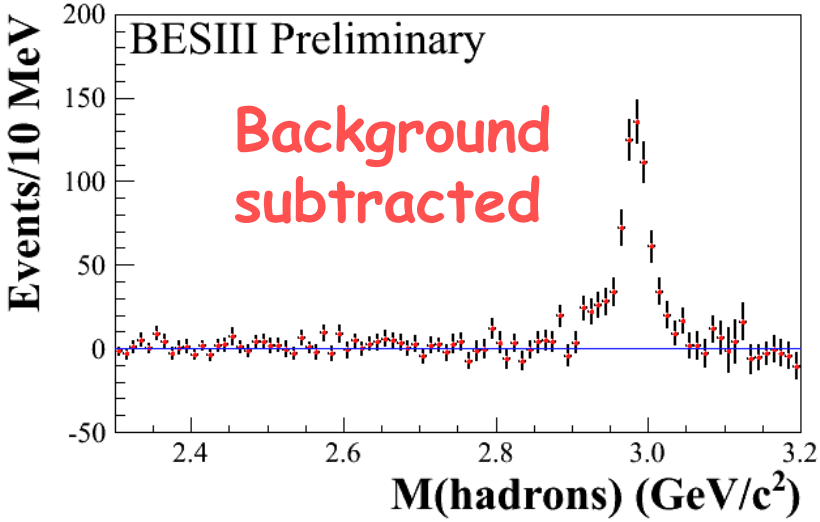


LINESHAPE

(IHEP)

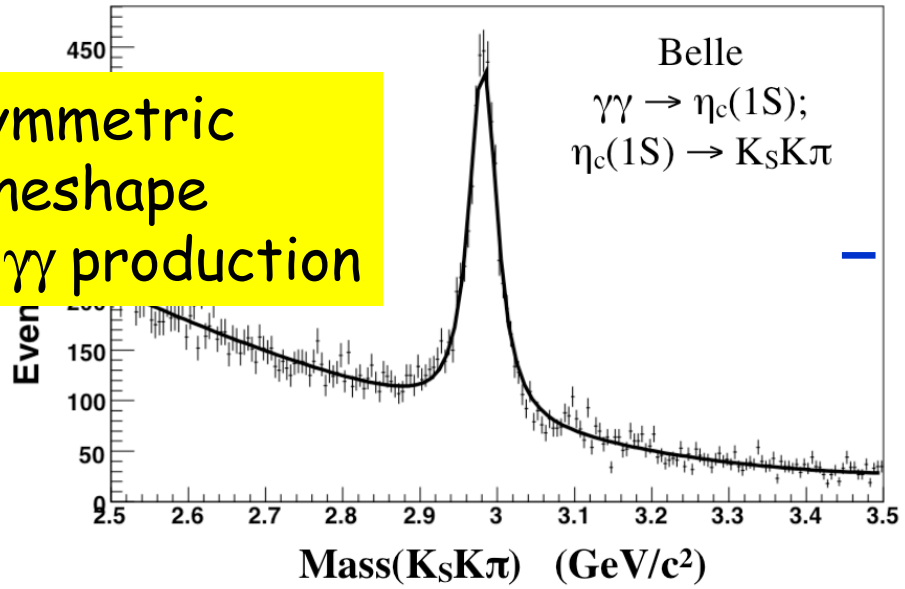
η_c lineshape from $\psi' \to \pi^0 h_c$, $h_c \to \gamma \eta_c$

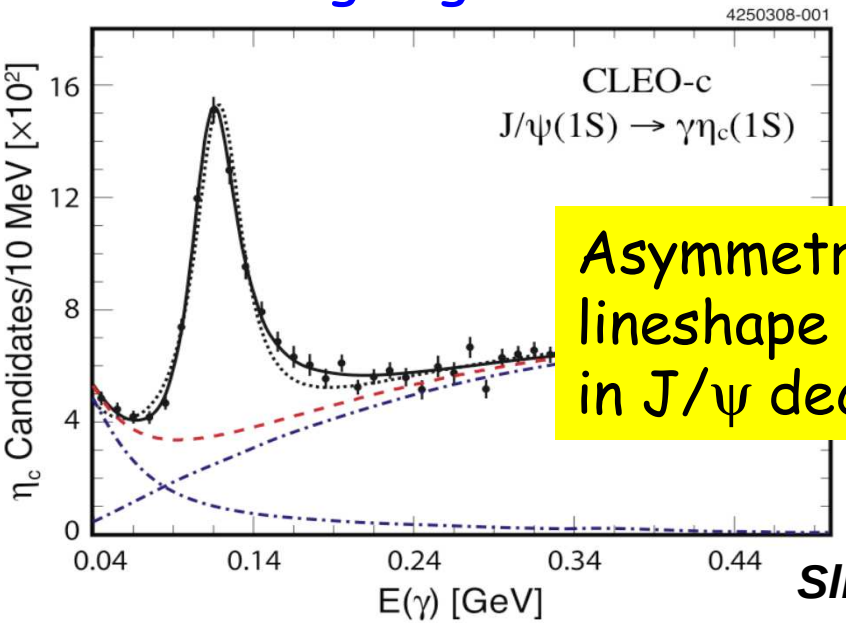




The η_c lineshape is not distorted in the $h_c \to \gamma \eta_c$
Detail analysis of η_c parameters is ongoing!

Symmetric lineshape in $\gamma\gamma$ production

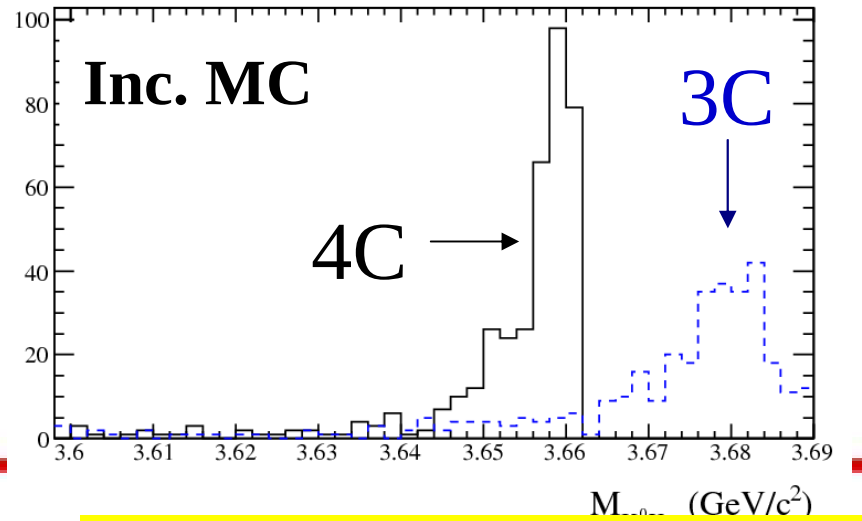


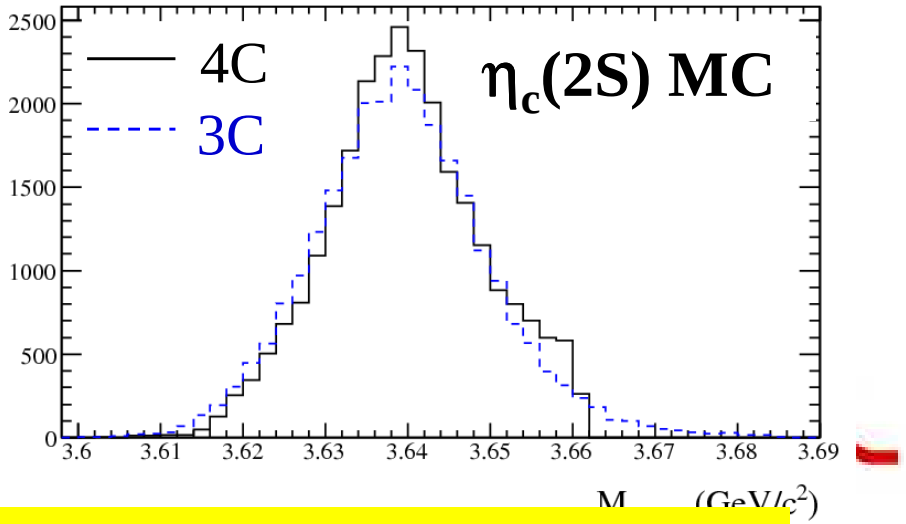


Asymmetric lineshape in J/ψ decay

Mass spectrum representation

- The 4C kinematic fitting used to select the γKsKπ candidates (χ^2_{4C}<50)
- Still some KsKπ BG events contribute the γKsKπ candidates with a fake photon.
- The invariant mass from 4C-kinematic fits make the BG ψ'→KsKπ contaminates the η_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

More consistency checks

- Difference between the BG estimation and mass fitting DN=12 ± 14
- Branching ratios for $\psi' \rightarrow \gamma\chi_{cJ} \rightarrow \gamma K_S K\pi$

From this analysis (stat. err. only)

	N_{obs}	ϵ	$\mathcal{B}(\psi' \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow K_S^0 K^{\pm}\pi^{\mp})$	$\mathcal{B}$ from PDG
χ_{c1}	7065 ± 88	27.2%	$(3.54 \pm 0.15) \times 10^{-4}$	$(3.39 \pm 0.34) \times 10^{-4}$
χ_{c2}	1204 ± 37	26.0%	$(6.31 \pm 0.30) \times 10^{-5}$	$(5.81 \pm 0.91) \times 10^{-5}$

- The distributions of the selected photons

$M_{KsKp} \in (3.6, 3.66)$ GeV/c^2 :