The Analysis of $\psi(2S) \to \gamma\eta_c(2S)$, with $\eta_c(2S) \to K_s K^\pm \pi^\mp / K^+K^-\pi^0$

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Outline

Motivation

- The measurement of the mass and width of $\eta_c(2S)$ can help to understand QCD theory at this energy region.
- The first observation of the M1 transition process $\psi' \to \eta_c(2S)$ has been reported at BESIII with the 106 ψ' events taken in 2009.
- With the addition of the 2012 ψ' data, we intend to perform a more precise measurement.

BOSS Version and Data Sets

- BOSS version: 6.6.4.p03
- Data Samples: 09 ψ' data (163.49 pb^{-1}), 12 ψ' data (510.49 pb^{-1}), continuum data at 3.65 GeV (44.39 pb^{-1})
- Official Inclusive MC samples for 09/12 ψ' data are used.

Table: Exclusive MC samples used in the study of $\psi' \to \gamma K^+K^-\pi^0$

Decay Mode	Number of Events
$\psi' \to \gamma\eta_c(2S)$, $\eta_c(2S) \to K^+K^-\pi^0$	2 mil.
$\psi' \to \gamma\chi_{c1}$, $\chi_{c1} \to K^+K^-\pi^0$	1 mil.
$\psi' \to \gamma\chi_{c2}$, $\chi_{c2} \to K^+K^-\pi^0$	1 mil.
$\psi' \to K^+K^-\pi^0$	1 mil.
$\psi' \to K^+K^-\pi^0\pi^0$ (via $K_1(1270)$)	10 mil.
$\psi' \to \omega K^+K^-$, $\omega \to \gamma\pi^0$	1 mil.
$\psi' \to X + J/\psi$	1 mil.

Event Selection for $\gamma K^+K^-\pi^0$

Charged Tracks

- Exactly 2 good charged tracks, with 0 net charge.
- For each charged track: $|cos\theta < 0.93|$, $R_z < 10cm$, $R_{xy} < 1cm$

Photons

- At least 3 good photons.
- For each good photon: $0.84 < |cos\theta| < 0.92$ or $|cos\theta| < 0.8$; $E > 40MeV$; TDC in [0,14] (in the unit of 50 ns).
- The angle between the position of each photon and the closest impact position of charged tracks in EMC should be larger than 20°.

PID

- Both tracks need to be identified as kaons.

Event Selection for $\gamma K^+ K^- \pi^0$

Vertex Fit

- The two charged tracks are fitted to the IP.

5C Kinematic Fit

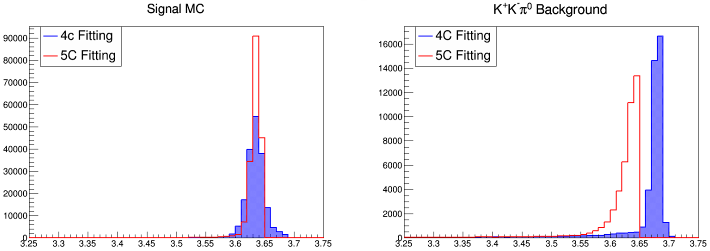
- 5 contraints: the total four-momentum, and the π^0 mass
- Iterated over all combinations of π^0 candidates and the radiative photons.
- the best combination is decided to be the one with the least χ^2_{5c}.

Representation of Mass Spectrum

Since the 5C Mass is prone to background contamination in the signal region, we use 4C kinematic fitting for the mass spectrum instead.

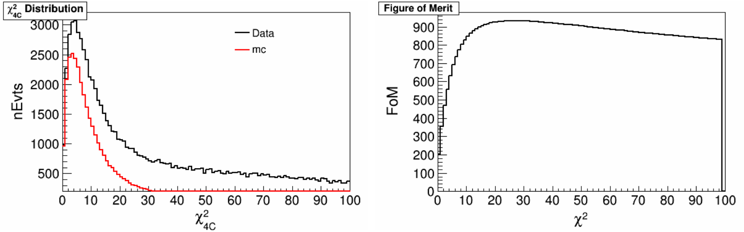
4C Kinematic Fit

- Constraints on the total four-momentum and the π^0 mass, but allow the mass of the radiative photon to be floating.
- The choices of the photons are decided by the previous 5C kinematic fit.



Optimization of the Kinematic Fit

As the result of the optimization, the χ^2_{4c} is required to be smaller than 30.



Main Backgrounds

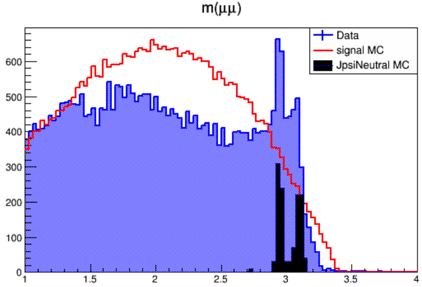
From the result of the Inclusive MC, we can expect the main backgrounds that can pass our event selection.

Main Background Components

- $J/\psi + Neutral$
- ωKK
- $KK\pi^0(\gamma_{FSR})$
- $KK\pi^0\pi^0$
- Continuum

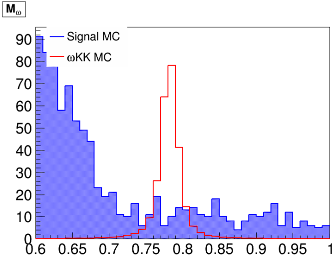
$\psi' \to Neutral + J/\psi$ Background, with $J/\psi \to \mu\mu/KK$

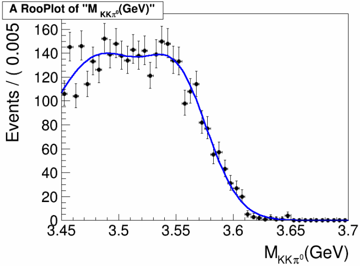
For such background, the two charged tracks should form a J/ψ. Therefore, we require that $M(\mu\mu) < 2.9$ GeV, where $M(\mu\mu)$ is calculated by assigning muon mass to the two charged tracks.



$\psi' \to \omega KK$ Background, with $\omega \to \gamma\pi^0$

To suppress this background, we veto the events with M(3γ) in the range of [0.74 GeV, 0.82 GeV].
The line shape of the remaining events is obtained by fitting the spectrum with a double Gaussian function.

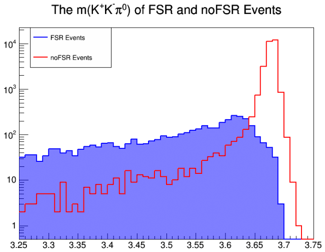


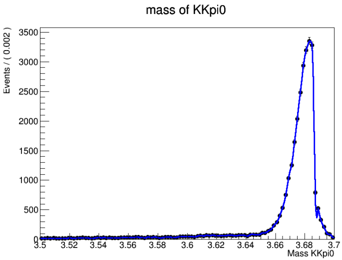


$K^+K^-\pi^0$ Background

To get the line shape of $KK\pi^0$, we reweight the number of FSR/noFSR events with a correction factor.
It's calculated from existing result:

$$f_{\gamma KK\pi^0} = 2 * f_{\gamma KK\pi\pi} - f_{\pi\pi\pi\pi} = 1.08 \pm 0.15 \qquad (1)$$





$K^+K^-\pi^0\pi^0$ Background

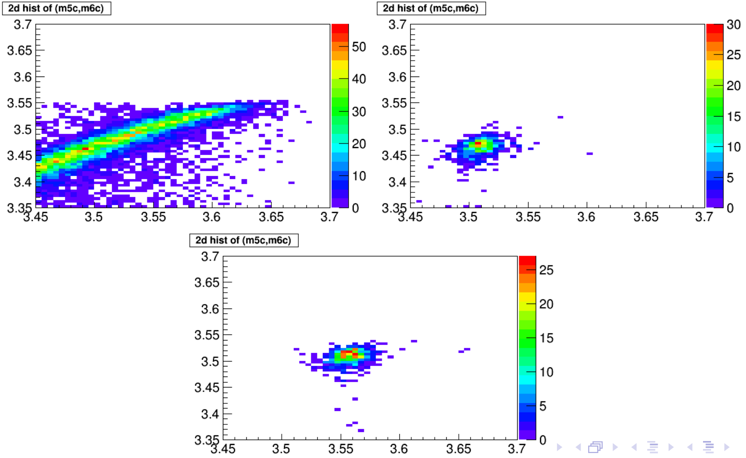
The strategy is to pick out the $KK\pi^0\pi^0$ events in data with a specifically designed event selection criterion, and reweight the spectrum according to the ratio of event selection efficiencies.

Event Selection for $KK\pi^0\pi^0$ in data

- 2 charged tracks, 0 net charge. At least 4 good photons.
- Both charged tracks need to be identified as kaons.
- Iterate 6C kinematic fit: total four-momentum, masses of both π^0

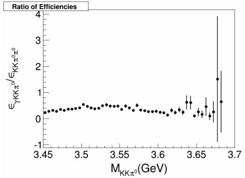
$K^+K^-\pi^0\pi^0$ Background - Mass Shift

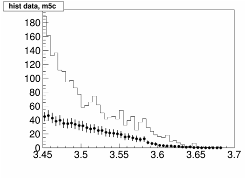
The two event selection procedures use different kinematic fits, so their $m(KK\pi^0)$ are of different definitions. We obtained the matrix of mass transformation with 10 mil. MC events.

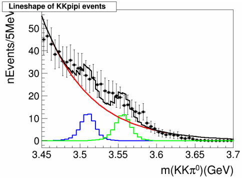


$K^+K^-\pi^0\pi^0$ Background

After mass shifting, we reweight the spectrum according to the ratio of selection efficiency of $\gamma K^+K^-\pi^0$ and $K^+K^-\pi^0\pi^0$.
The resulting spectrum is fitted to get the line shape of $K^+K^-\pi^0\pi^0$.
Gaussian function is used for $K^+K^-\pi^0\pi^0$ component, and MC shapes are used for the $\gamma\chi_{cj}$ backgrounds.





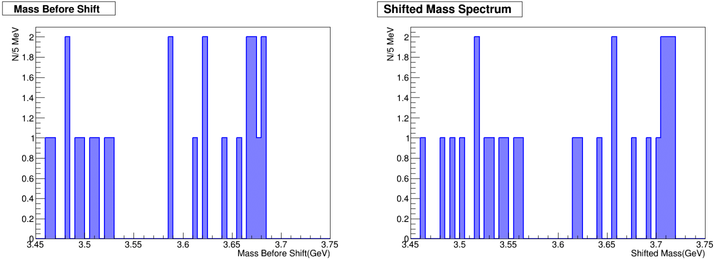


Continuum Background

The background from continuum processes are estimated with off-resonance data at 3.65 GeV.

The scaling factor: $f = \frac{L_{\psi'}}{L_{off-res}} * \frac{E^2_{off-res}}{E^2_{\psi'}}$

Mass shift: $m \to a * (m - m_0) + m_0$, with $m_0 = 1.122$ GeV and $a = 1.014$



BOSS Version and Data Sets

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- Official Inclusive MC samples for 09/12 ψ' data are used.

Table: The exclusive MC samples

Decay Mode	Number of Events
$\psi' \to \gamma\eta_c(2S), \eta_c(2S) \to K_s^0 K^\pm \pi^\mp$	2 mil.
$\psi' \to \gamma\chi_{c1}, \chi_{c1} \to K_s^0 K^\pm \pi^\mp$	1 mil.
$\psi' \to \gamma\chi_{c2}, \chi_{c2} \to K_s^0 K^\pm \pi^\mp$	1 mil.
$\psi' \to \gamma\chi_{cj}, \chi_{cj} \to K_s^0 K_s^0$	1 mil.
$\psi' \to K_s^0 K^\pm \pi^\mp$	1 mil.
$\psi' \to \pi^0 K_s^0 K^\pm \pi^\mp$ (via $K_1(1270)$)	10 mil.
$\psi' \to X + J/\psi$	1 mil.

Event Selection for $\gamma K^0_s K^\pm\pi^\mp$

Charged Tracks

- Exactly 4 good charged tracks, with 0 net charge.
- For each charged track: $|cos\theta < 0.93|$, $R_z < 10cm$, $R_{xy} < 1cm$

Photons

- At least 1 good photon.
- For each good photon: $0.84 < |cos\theta| < 0.92$ or $|cos\theta| < 0.8$; $E > 40MeV$; TDC in [0,14] (in the unit of 50 ns).
- The angle between the position of each photon and the closest impact position of charged tracks in EMC should be larger than 20°.

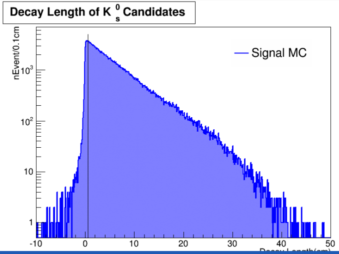
PID

- The χ^2 of K and π hypothesis for each track is saved.

Event Selection for $\gamma K_s^0 K^\pm \pi^\mp$

K_s Reconstruction

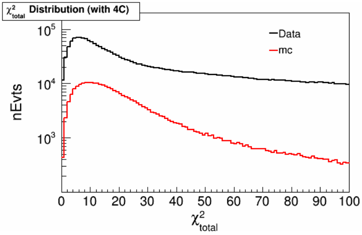
- Iterate secondary vertex fit over each pair of oppositely charged tracks, assume the tracks to be $\pi^+\pi^-$.
- Get the best combination with the minimal χ^2_{svtx}.
- $m(\pi^+\pi^-)$ should be less than 15 MeV away from K_s mass.
- Decay length must be larger than 0.5 cm.
- The other two tracks must fail to make a second K_s.

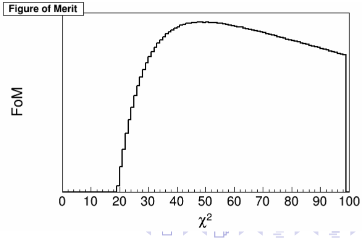


Event Selection for $\gamma K_s^0 K^\pm \pi^\mp$

Kinematic Fit

- 4 Constraints: total four-momentum.
- Iterate the fit over all photon candidates and the two assumptions of the event beingeither $\gamma K_s K^+\pi^-$ or $\gamma K_s K^-\pi^+$
- The best combination is the one with the minimal $\chi^2_{comb} = \chi^2_{4c} + \chi^2_K + \chi^2_\pi$
- We require that $(\chi^2_{4C} + \chi^2_K + \chi^2_\pi + \chi^2_{vtx} + \chi^2_{svtx}) < 50$



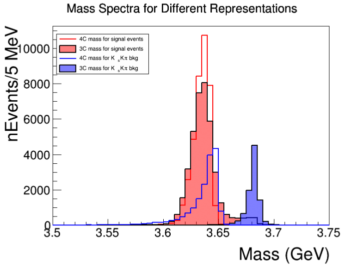


Representation of Mass Spectrum

Since the 4C Mass is prone to background contamination in the signal region, we use 3C kinematic fitting for the mass spectrum instead.

3C Kinematic Fit

- Constraints on the total four-momentum, but allow the mass of the radiative photon to be floating.
- The choices of the photon and the $K\pi$ hypothesis are decided by the previous 4C kinematic fit.



Main Backgrounds

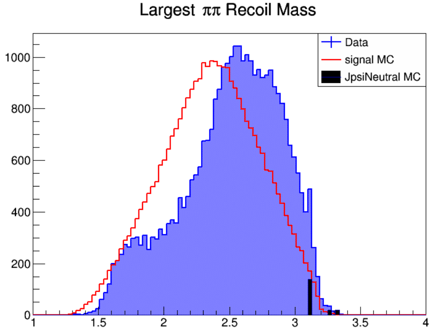
From the result of the Inclusive MC, we can expect the main backgrounds that can pass our event selection.

Main Background Components

- $J/\psi + Neutral$
- $K_s^0 K^\pm \pi^\mp (\gamma_{FSR})$
- $\pi^0 K_s^0 K^\pm \pi^\mp$
- Continuum

Background from $\psi' \to X + J/\psi$

To get rid of such background, we assume all tracks to be pions and compute the recoil masses of $\pi^+\pi^-$, and veto the events with the largest recoil mass being above 3.05 GeV.

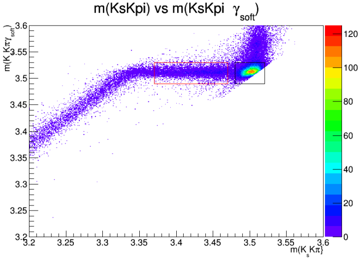


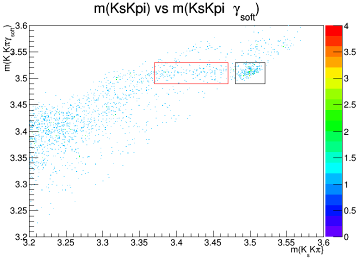
Background from $K_s^0 K^\pm \pi^\mp (\gamma_{FSR})$

Reweight the ratio of FSR/noFSR events with a factor f_{data}, which describes the difference of MC and data samples.

r_{data} is obtained by analyzing $\psi' \to \gamma\chi_{c1}$, $\chi_{c1} \to K_s^0 K^\pm \pi^\mp (\gamma_{FSR})$

- Similar event selection, but with one more photon decaying from χ_{cj}.
- π^0 mass veto in the range of [0.10 GeV, 0.155 GeV]





Background from $K_s^0 K^\pm \pi^\mp (\gamma_{FSR})$

For MC sample:

$$R_{FSR,mc} = \frac{N_{FSR}}{N_{noFSR}}, \tag{2}$$

while for the data sample:

$$R_{FSR,data} = \frac{N_{FSR}^{obs} - N_{FSR}^{bkg}}{N_{noFSR}^{obs} - N_{noFSR}^{bkg}}, \tag{3}$$

where the N_{FSR}^{bkg} and N_{noFSR}^{bkg} are estimated by the inclusive MC sample.

The result is $f_{data} = \frac{R_{FSR,data}}{R_{FSR,mc}} = 1.58 \pm 0.37$

$\pi^0 K_s^0 K^\pm \pi^\mp$ Background

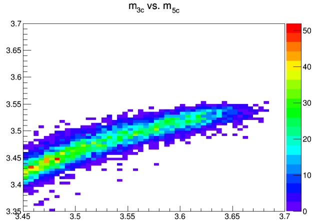
The strategy is to pick out the $\pi^0 K_s^0 K^\pm \pi^\mp$ events in data with a specifically designed event selection criterion, and reweight the spectrum according to the ratio of event selection efficiencies.

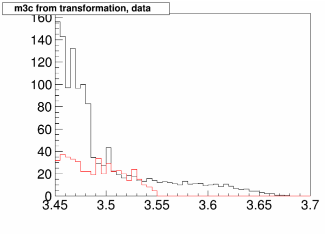
Event Selection for $\pi^0 K_s^0 K^\pm \pi^\mp$ in data

- 4 charged tracks, 0 net charge. At least 2 good photons. Exactly 1 Ks.
- Iterate 5C kinematic fit: total four-momentum, masses of π^0
- $\chi^2_{5c} < 15$ is required.

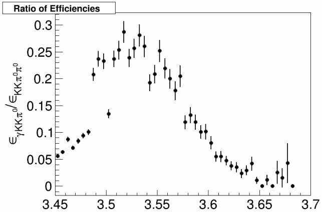
$\pi^0 K_s^0 K^\pm \pi^\mp$ Background

The m_{5C} spectrum needs to use a transformation to offset the mass shift introduced by different kinematic fits.



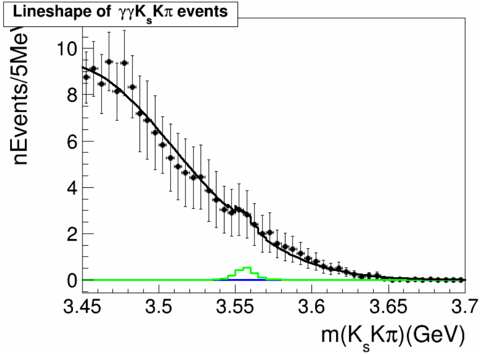


Next. the spectrum is scaled by the ratio of selection efficiencies



$\pi^0 K_s^0 K^\pm \pi^\mp$ Background

The line shape of $\pi^0 K_s^0 K^\pm \pi^\mp$ is fitted with a Gaussian function, with the $\gamma\chi_{cj}$ backgrounds fitted with MC shapes.

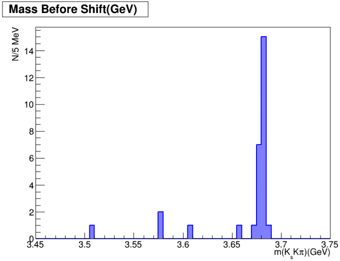


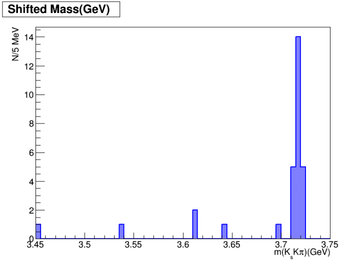
Continuum Background

The background from continuum processes are estimated with off-resonance data at 3.65 GeV.

The scaling factor: $f = \frac{L_{\psi'}}{L_{off-res}} * \frac{E^2_{off-res}}{E^2_{\psi'}}$

Mass shift: $m \to a*(m-m_0)+m_0$, with $m_0 = 1.131$ GeV and $a = 1.014$





Fitting of the Mass Spectra

A simultaneous fit is performed over the two mass spectra, with a same line shape for the $\gamma\eta_c(2S)$ component.

Signal line shape

$$(E_\gamma^3 \times BW(m) \times DMP(E_\gamma)) \otimes Gauss(0,\sigma) \tag{4}$$

- m is the invariant mass of $K^+K^-\pi^0$, $BW(m)$ is the Breit-Wigner function
- $E_\gamma = \frac{m_{\psi'}^2 - m^2}{2m_{\psi'}}$ is the energy of the transition photon in the rest frame of ψ',
- $DMP(E_\gamma)$ is the damping function that suppress the diverging tail raised by the term of E_γ^3,
- $Gauss(0,\sigma)$ is the Gaussian function which describes the detector resolution.

Damping Function

The possible form of the damping function is somewhat arbitrary, and one suitable function used by KEDR for a similar process is

$$DMP(E_\gamma) = \frac{E_0^2}{E_\gamma E_0 + (E_\gamma - E_0)^2}, \tag{5}$$

where $E_0 = \frac{m_{\psi'}^2 - m_{\eta_c(2S)^2}}{2m_{\psi'}}$ is the peaking energy of the transition photon. Alternatively, the CLEO experiment developed a damping function with the inspiration of the overlap of the wave functions, the shape of which being

$$DMP(E_\gamma) = exp(-E_\gamma^2/8\beta^2), \tag{6}$$

with $\beta = (65.0 \pm 2.5) MeV$ from CLEO's fitting result.
We use the CLEO damping function for our fitting.

Fitting of the Mass Spectra

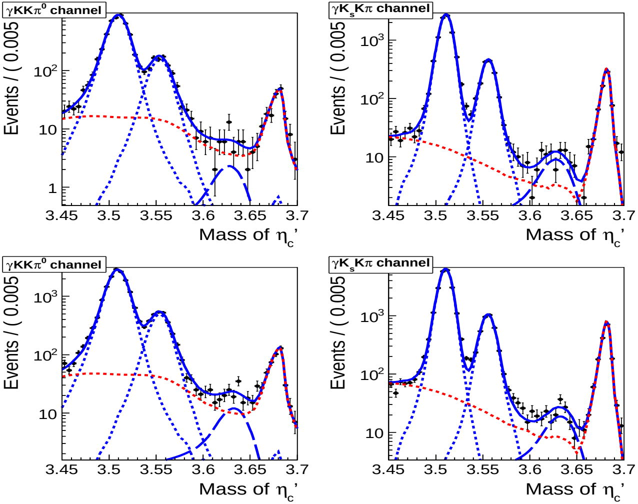
Other components in $m(K^+K^-\pi^0)$ Spectrum

- χ_{cj}: MC shape convolved with a Gaussian resolution function.
- ωKK background: double Gaussian function obtained previously
- $K^+K^-\pi^0$ background: MC shape with the ratio of FSR events reweighted
- $K^+K^-\pi^0\pi^0$ background: Gaussian function obtained previously

Other components in $m(K_s^0K^\pm\pi^\mp)$ Spectrum

- χ_{cj}: MC shape convolved with a Gaussian resolution function.
- $K_s^0K^\pm\pi^\mp$ background: MC shape with the ratio of FSR events reweighted
- $\pi^0K_s^0K^\pm\pi^\mp$ background: Gaussian function obtained previously

Fitted Spectra of 2009 (up) and 2012 Data (bottom)



Fitted Parameters

Table: The number of events in the fitting result.

	Component	09 data	12 data
$\gamma K^+K^-\pi^0$	$\eta_c(2S)$	46	192
	χ_{cj}	5549	17542
	backgrounds	504	1594
$\gamma K_s^0 K^\pm \pi^\mp$	$\eta_c(2S)$	85	186
	χ_{cj}	10371	24597
	backgrounds	1046	2860

Table: The fitted mass of the $\eta_c(2S)$.

Sample	Mass(MeV)
09 data	3634.1 ± 2.2
12 data	3638.5 ± 1.5

Subtraction of Continuum Background

It is assumed that the number of events from continuum processes being absorbed into each component in the fitting is proportional to the size of that component.
Calculating with the assumption, we can get the number of signal events after subtracting the continuum background.

Table: The number of signal events after the subtraction of continuum background, with only statistical uncertainties.

	continuum background	signal events after subtractio
$\gamma K^+K^-\pi^0$, 09data	6.0 ± 3.5	40 ± 8
$\gamma K_s^0 K^\pm \pi^\mp$, 09data	8.6 ± 5.0	76 ± 10
$\gamma K^+K^-\pi^0$, 12data	20.5 ± 11.8	172 ± 18
$\gamma K_s^0 K^\pm \pi^\mp$, 12data	25.7 ± 14.9	160 ± 20

Efficiencies of Event Selection for $\gamma K^+K^-\pi^0$

Table: The cut flow of the event selection for $\psi' \to \gamma\eta_c(2S)$, $\eta_c(2S) \to K^+K^-\pi^0$.

Requirement	09 Eff. (%)	12 Eff. (%)
preliminary selection	31.39	31.02
χ^2 of kinematic fitting	20.89	20.61
π^0 mass requirement	20.67	20.41
veto $J/\psi + X$	19.21	18.95
Veto ωK^+K^- background	19.19	18.94
$m(K^+K^-\pi^0)$ in fitting range	18.47	18.21
Overall	18.47	18.21

Efficiencies of Event Selection for $\gamma K_s^0 K^\pm \pi^\mp$

Table: The cut flow of the event selection for $\psi' \to \gamma\eta_c(2S)$, $\eta_c(2S) \to K_s^0 K^\pm \pi^\mp$.

Requirement	09 Eff.(%)	12 Eff.(%)
preliminary selection	33.26	31.39
veto $\gamma K_s^0 K_s^0$	31.60	29.81
decay length > 0.5 cm	31.60	29.81
K_s^0 mass requirement	23.75	22.55
$chi^2_{comb} < 30$	17.81	16.86
veto $X + J/\psi$	17.36	16.44
$m(K_s^0 K^\pm \pi^\mp)$ in fitting range	17.36	16.44
Overall	17.36	16.44