First measurement of $\chi_{cJ} \to \Sigma^{+}\bar{p}K_{S}^{0}$ $+c.c$(J=0, 1, 2) decays

Shan Gu[a,b] , Wencheng Yan[a], Chengping Shen[a]

[a]Beihang University

[b]Institute of High Energy Physics

Outline

- **Introduction**
- **Data Sets**
- **Event Selection**
- **Background analysis**
- **Systematic uncertainties**
- **Summary**

Introduction

- **Obtaining more experimental data on exclusive decays of χ_{cJ} state is important for a better understanding of their nature and decay mechanisms, as well as for testing QCD – based calculations.**
- **Searching for new excited baryon states is still motivated for us to enrich the relatively poor knowledge of the baryon spectrum. Search for excited baryon states via $\chi_{cJ} \to \Sigma^{+}\bar{p}K_{S}^{0}$.**
- **The world's largest statistics of $\psi(3686)$ events collected with the BESIII detector provides a unique opportunity for a detailed study of χ_{cJ} decays.**
- **This analysis report the first measurements of the branching fractions of $\chi_{cJ} \to \Sigma^{+}\bar{p}K_{S}^{0} + \mathrm{C.C.}$ decays via the E1 radiative transition $\psi(3686) \to \gamma\ \chi_{cJ}$.**

Data Sets

- **Boss Version: 664p03;**
- **Data: 447.9$\times$ 10^6(2009+2012)$\psi(3686)$;**
- **Inclusive MC: 506$\times$ 10^6 $\psi(3686)$;**
- **Exclusive MC: 2 $\times$ 10^5 events for every decay mode.**

Event topology

$$\psi(3686) \to \gamma\chi_{cJ}, \chi_{cJ} \to \Sigma^{+}\bar{p}K_S^0 + c.c$$

with $\Sigma^{+} \to p\pi^{0}$ and $K_S^0 \to \pi^{+}\pi^{-}$

- **Final states of signal: $\gamma\gamma\gamma p\bar{p}\pi^{+}\pi^{-}$.**
- **In the next slides, the charge-conjugated channel is included in default.**

Event Selection

- **Charged tracks**
  - |Rxy |<1cm and |Rz|<10cm for the free ant-proton;
  - |cosθ|<0.93;
  - 4 ≤Ngood ≤6 & ΣQ=0;
- **Neutral tracks**
  - E≥25 MeV for barrel (|cosθ|< 0.8);
  - E≥50 MeV for endcap (0.86<|cosθ|< 0.92) ;
  - θmin(γ,charge)>10°;
  - 0<TDC<14 (50ns) ;
  - Nγ≥3;
- **PID**
  - PID for proton and anti-proton;

- **K_S is reconstructed by Second VertexFit**

  $L/\sigma_L > 2$

- **4C kinematic fit**
  - With the smallest χ^2
  - Obtain $\gamma\gamma\gamma p\bar{p}\pi^+\pi^-$
- **π^0 and radiative γ_3:**

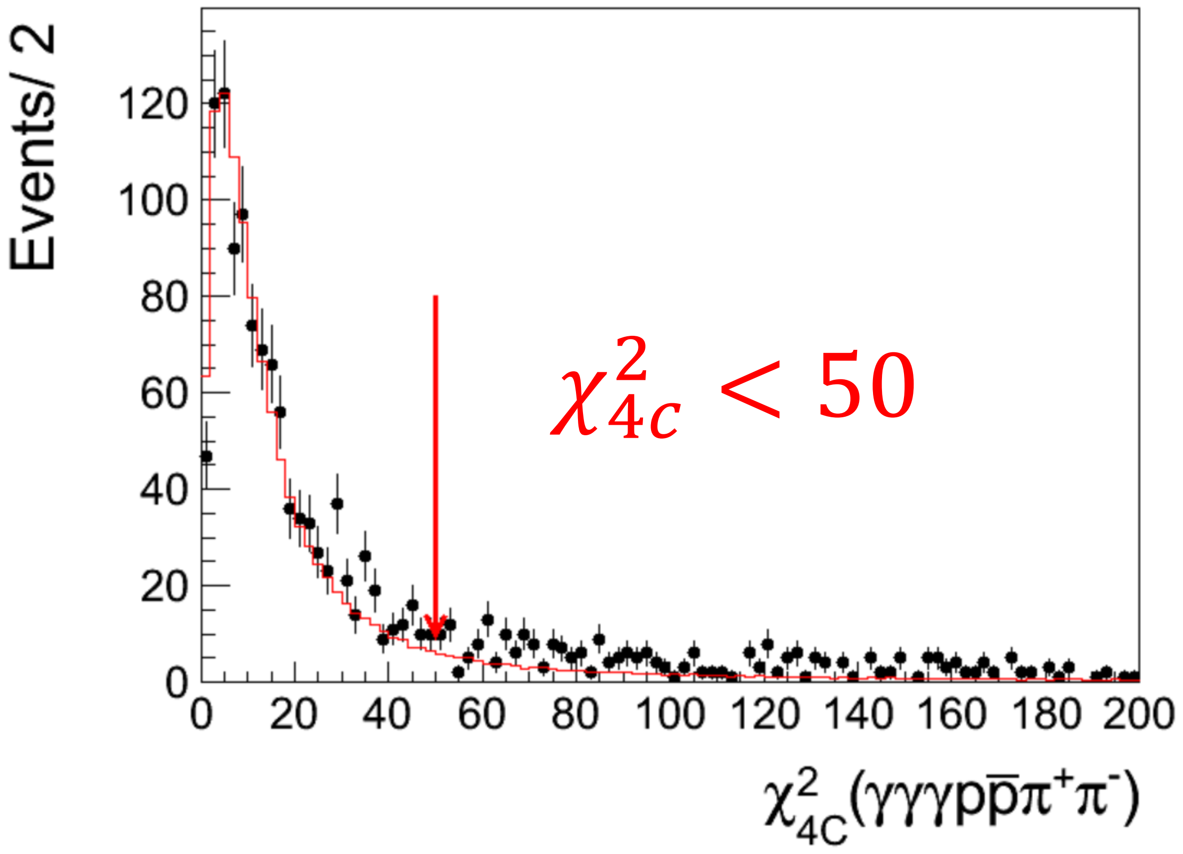
$$\chi^2 = \left(\frac{M(\gamma_1\gamma_2) - M(\pi^0)}{\sigma_{\pi^0}}\right)^2$$

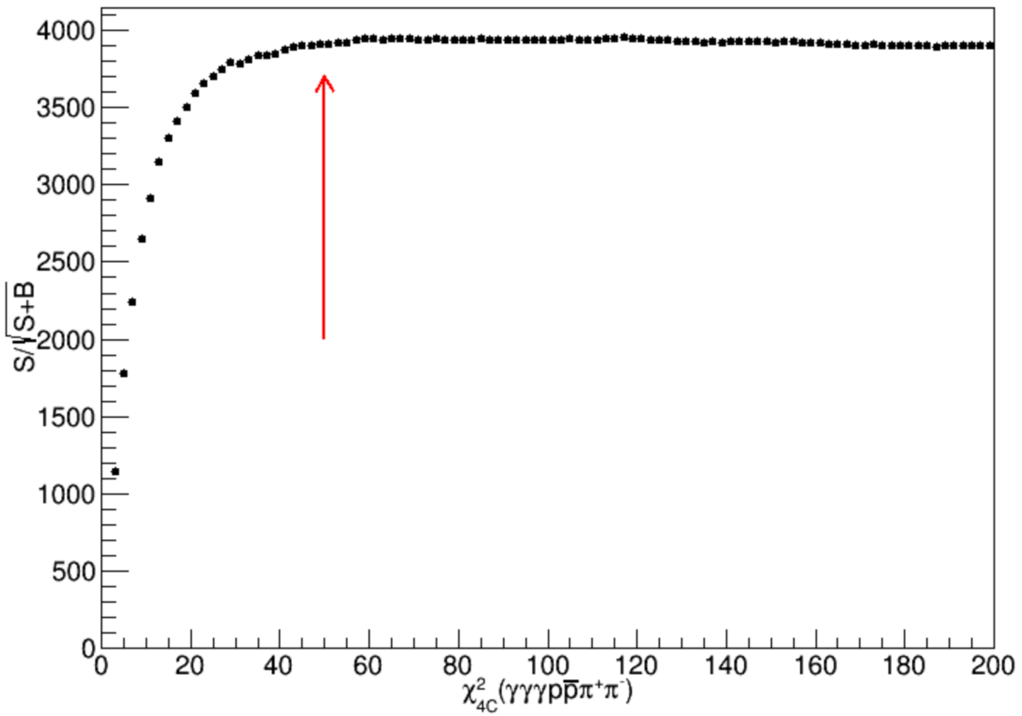
The left γ_3 is as the radiative γ from $\psi(3686)$.

- **Suppress background with $\gamma\gamma$ or $\gamma\gamma\gamma\gamma$ in final states:**

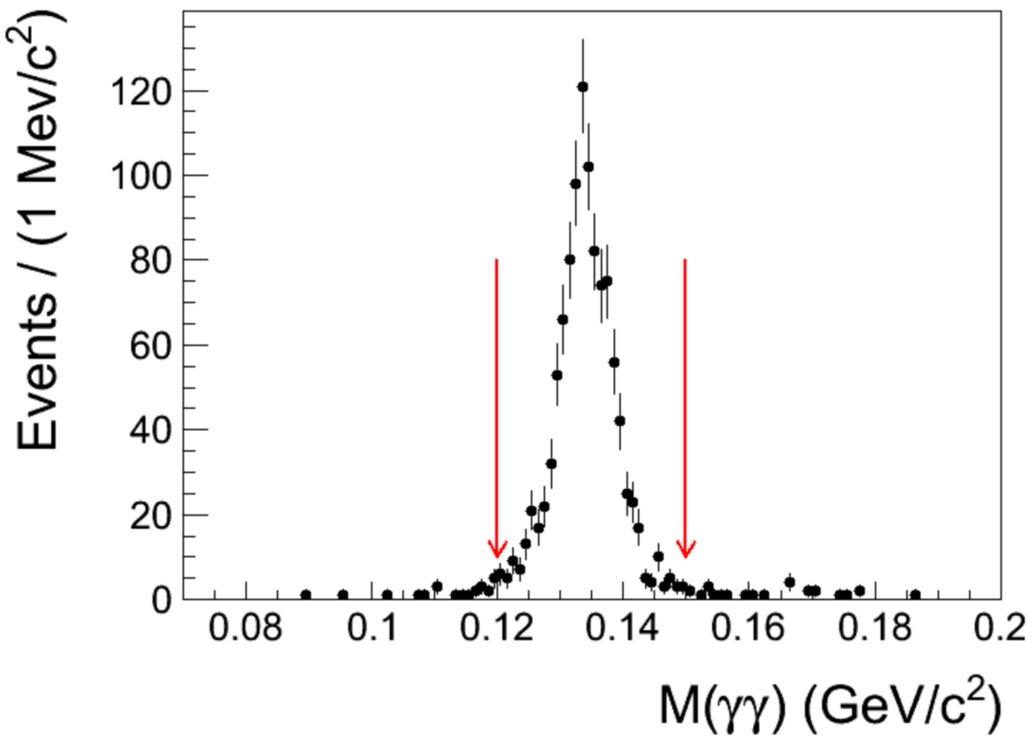
$\chi^2(\gamma\gamma\gamma\pi^+\pi^-) < \chi^2(\gamma\gamma\gamma\gamma\pi^+\pi^-)$
&& $\chi^2(\gamma\gamma\gamma\pi^+\pi^-) < \chi^2(\gamma\gamma\pi^+\pi^-)$

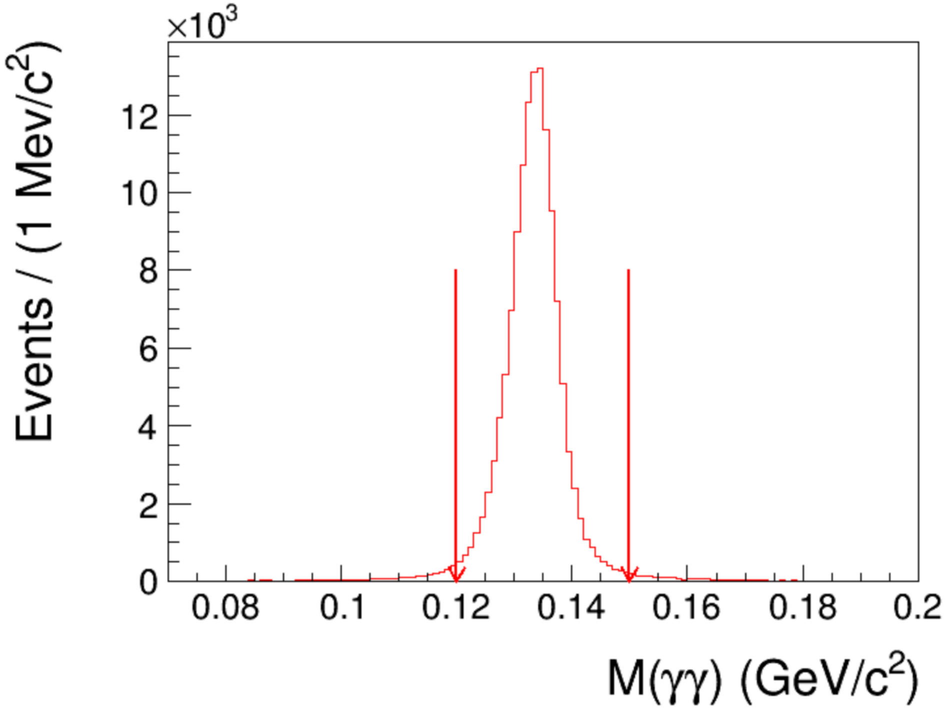
Event Selection





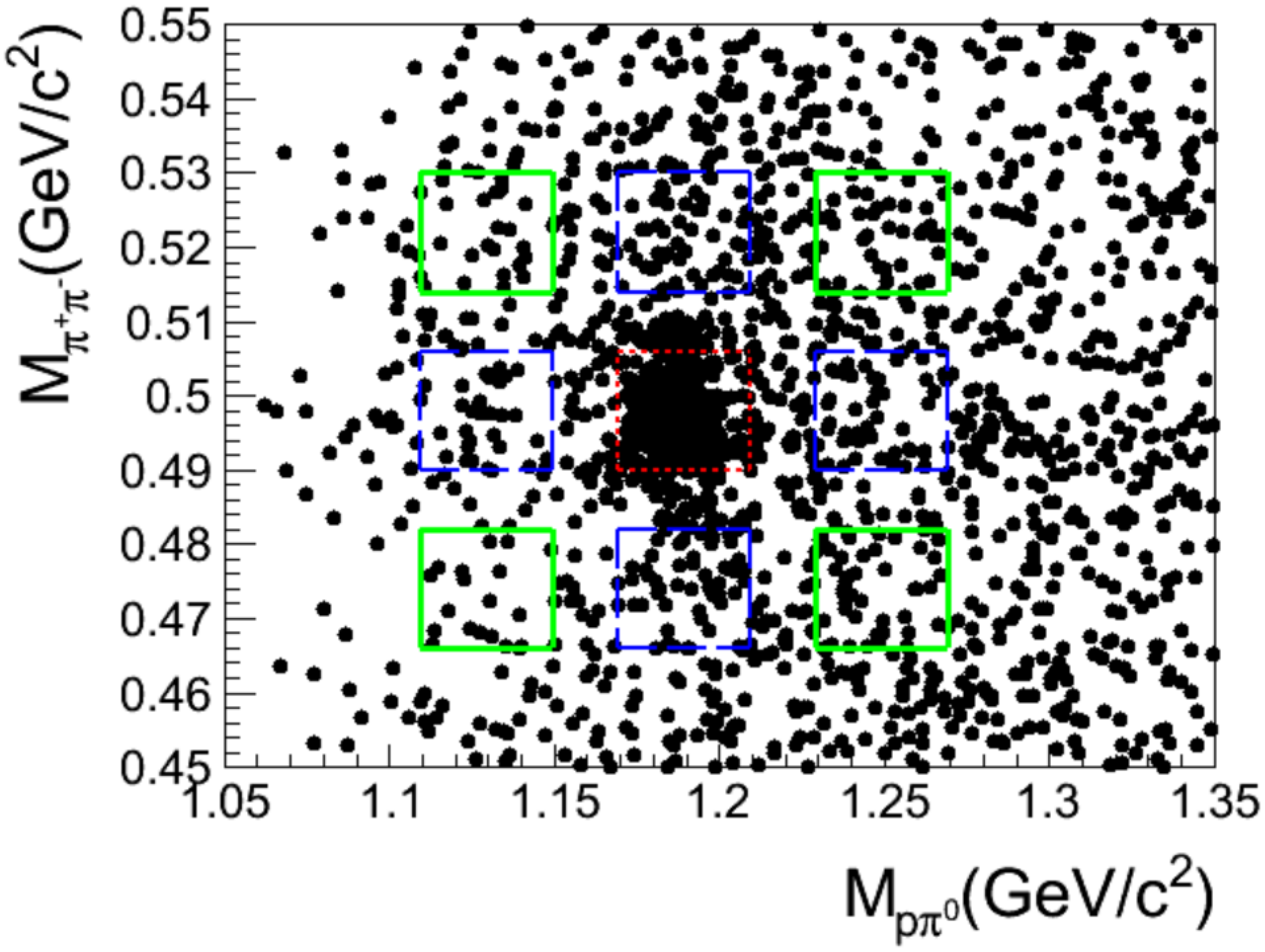
Event Selection

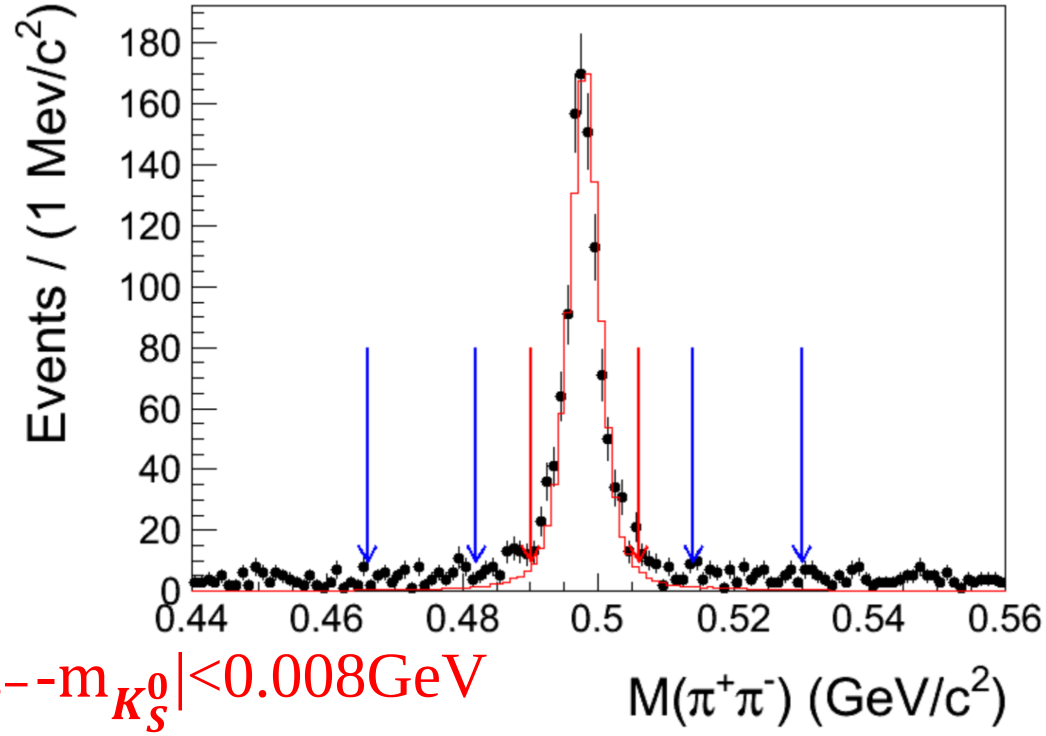




$|m_{\gamma\gamma} - m_{\pi^0}| < 0.015\text{GeV}$

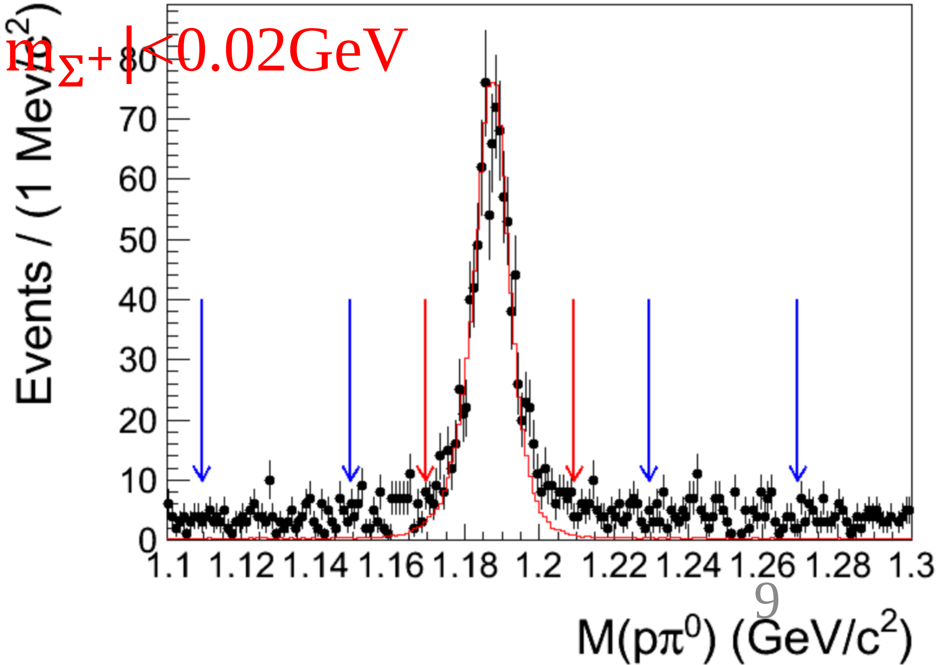
Event Selection



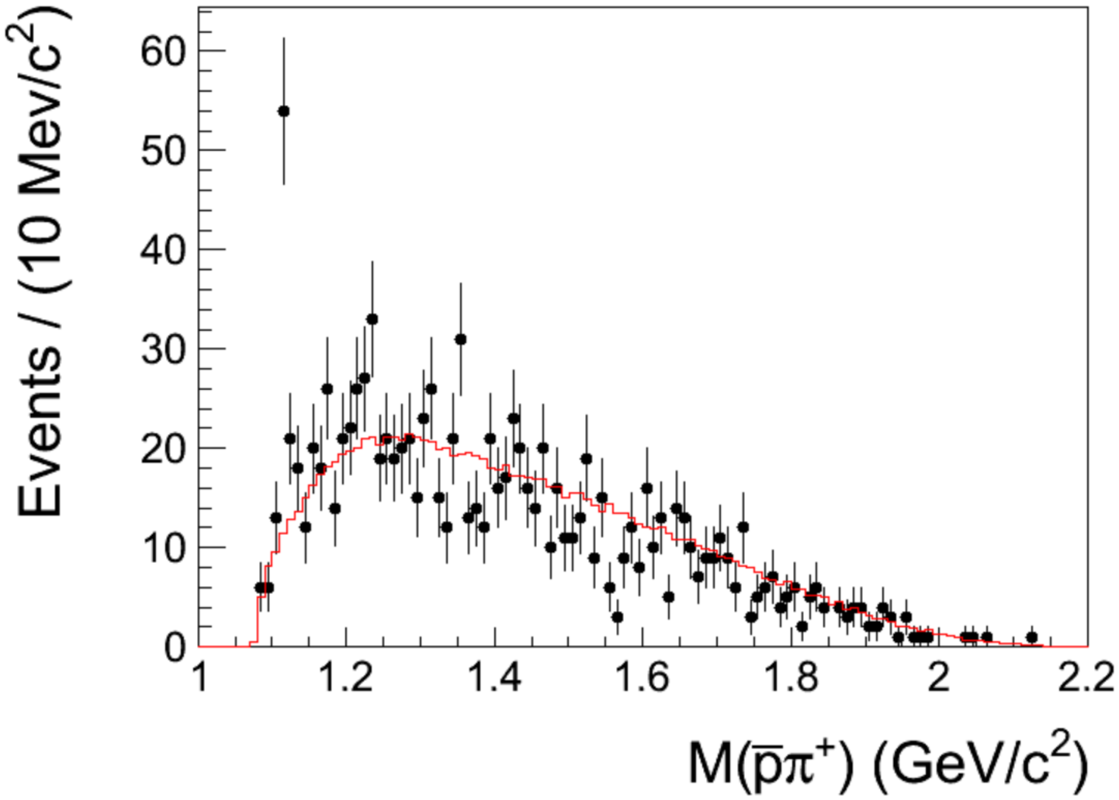


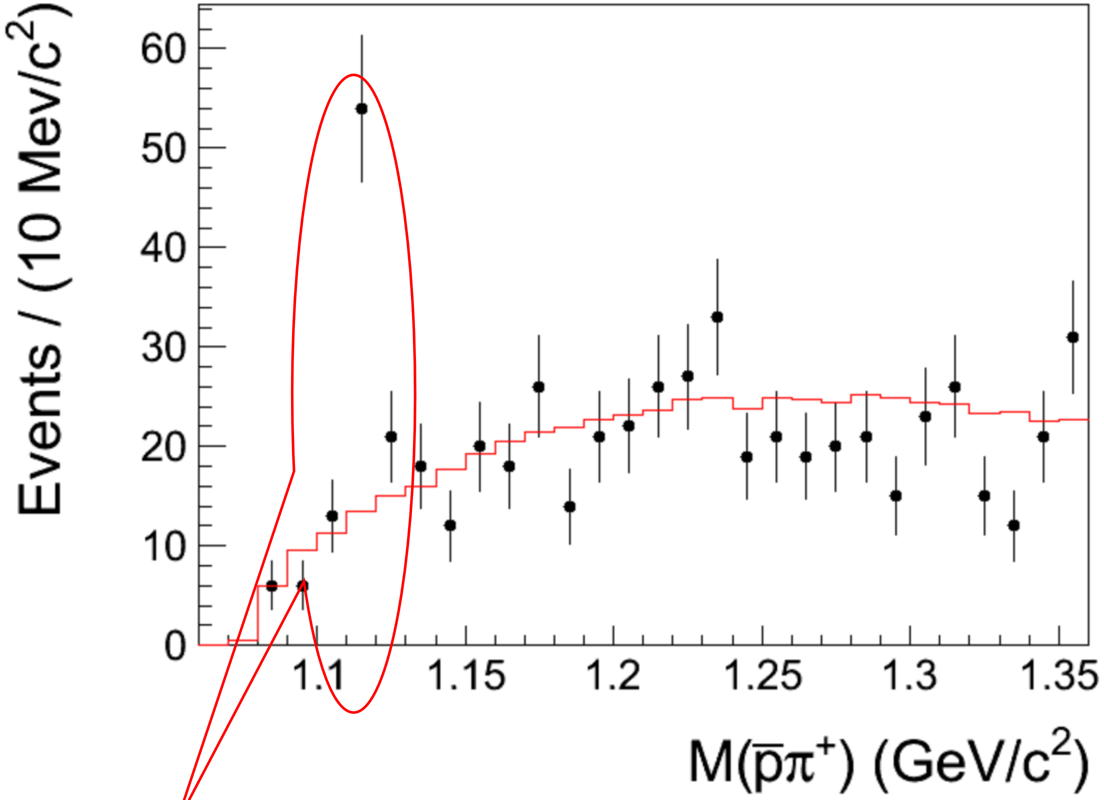
$|m_{\pi^+\pi^-} - m_{K_S^0}| < 0.008\text{GeV}$

$|m_{p\pi^0} - m_{\Sigma^+}| < 0.02\text{GeV}$



Event Selection

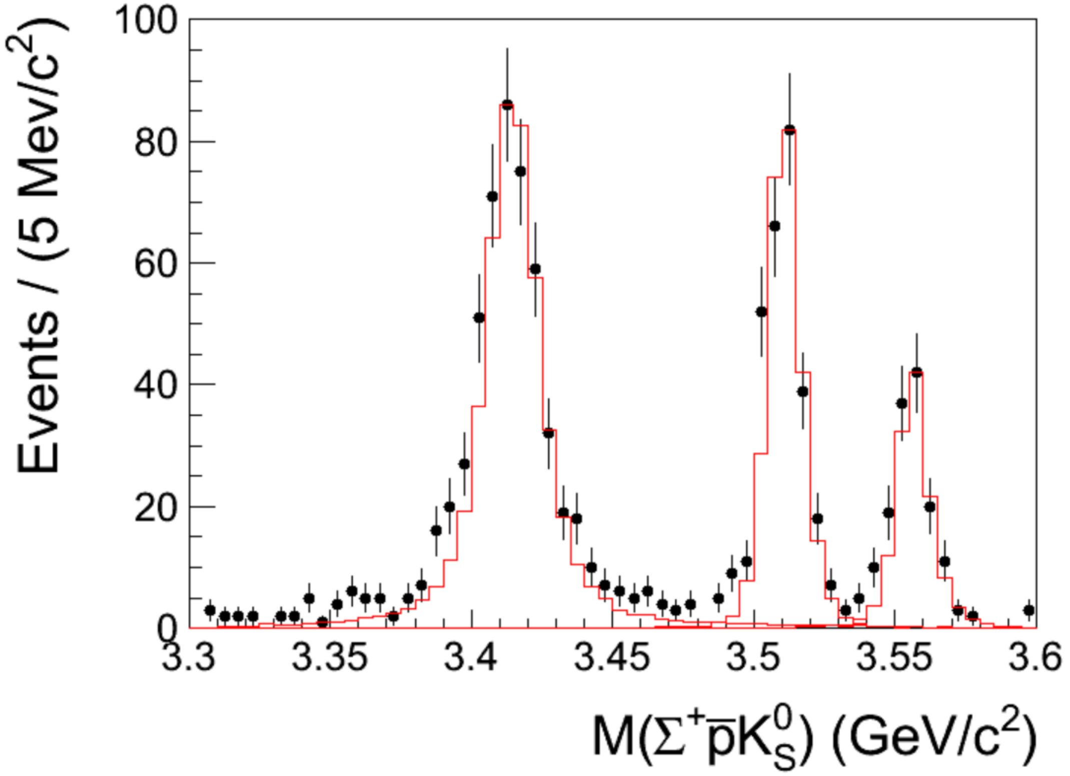




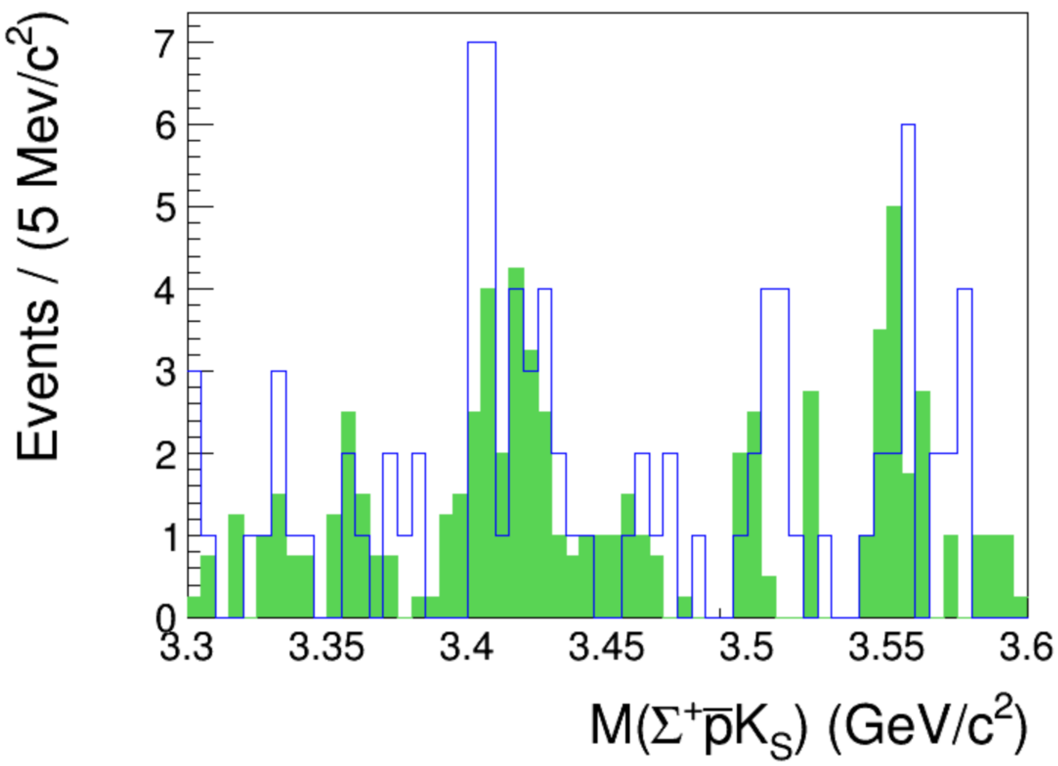
Veto Λ : $\left|m_{\bar{p}\pi^+} - m_\Lambda\right| > 0.006\text{GeV}$

to suppress the backgrounds from $\psi' \to \gamma\chi_{cJ}, \chi_{cJ} \to \Sigma^+\bar{\Lambda}\pi^-, \Sigma^+ \to p\pi^0, \bar{\Lambda} \to \bar{p}\pi^+$. The cut efficiency is 98.8% .

$\Sigma^+\bar{p}K_S^0$ mass



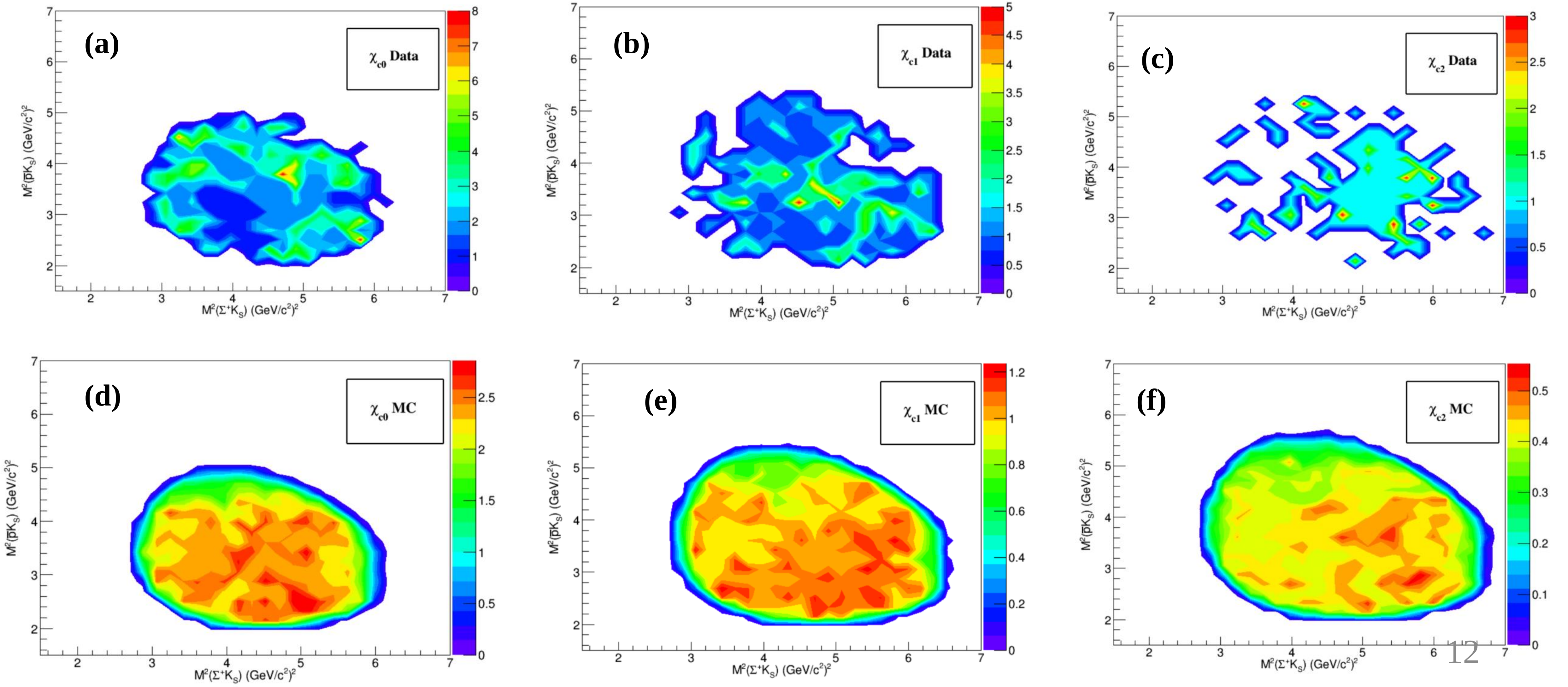
(a)Dots with error bars are data, the solid line histogram is the χ_{cJ} line shape from the signal MC simulation.



(b) The solid line is the background estimated from inclusive MC sample, and the green-shaded histograms are the 2-D sideband events of K_S^0 and Σ^+ invariant mass from inclusive MC sample.

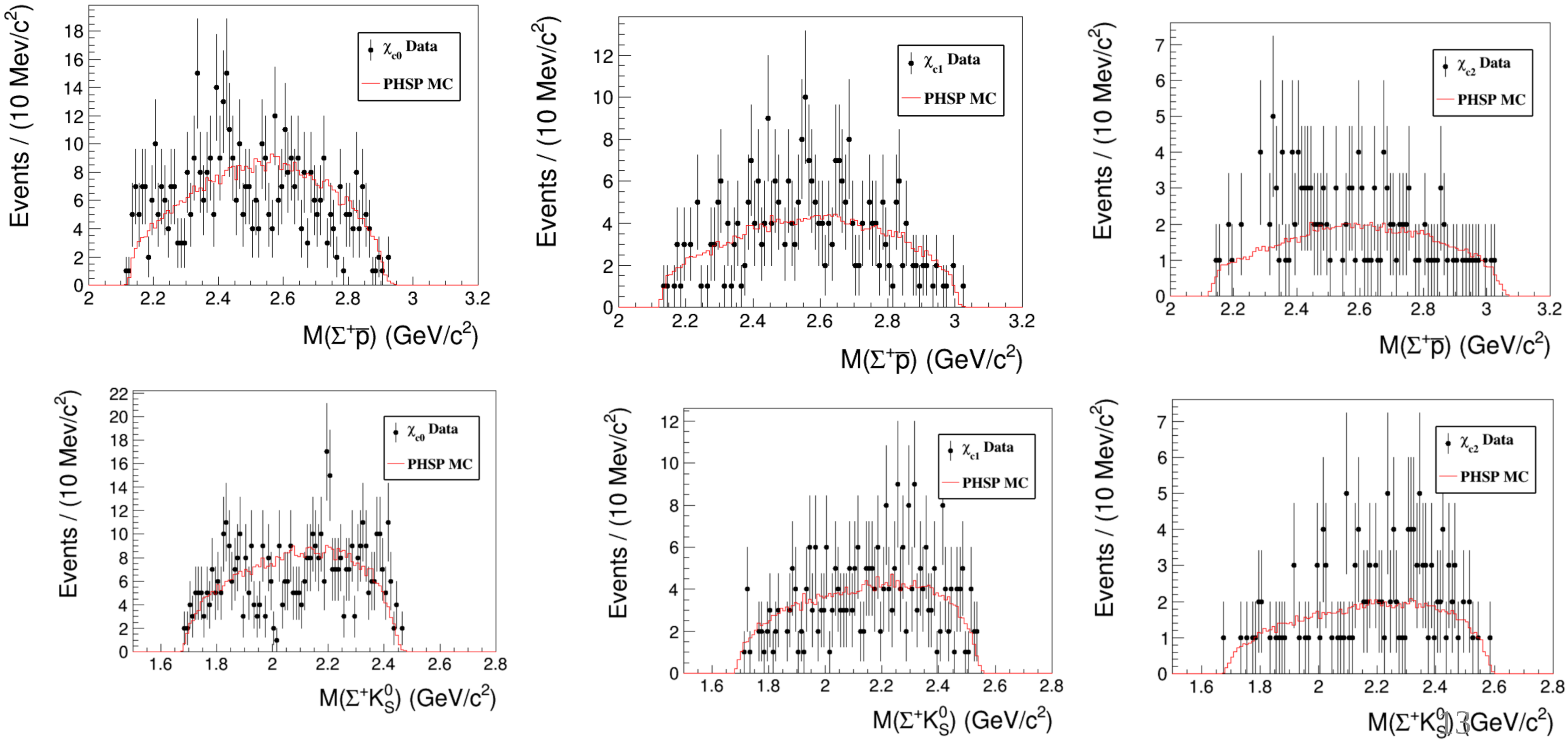
Distributions

$\chi_{c0,1,2}$ regions are defined as [3.36, 3.46] , [3.48, 3.54] and [3.54, 3.58] GeV/c ^{2} .

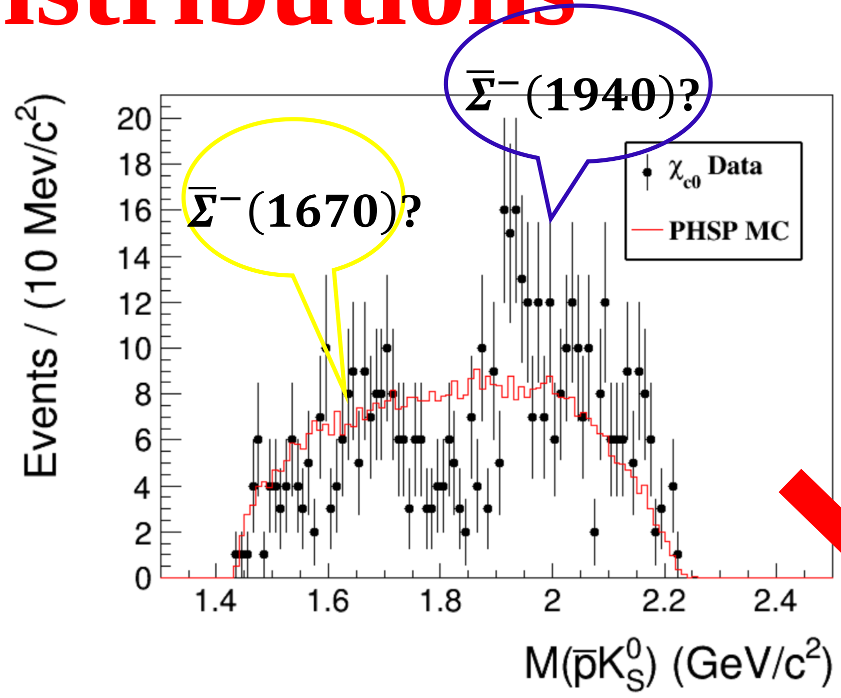


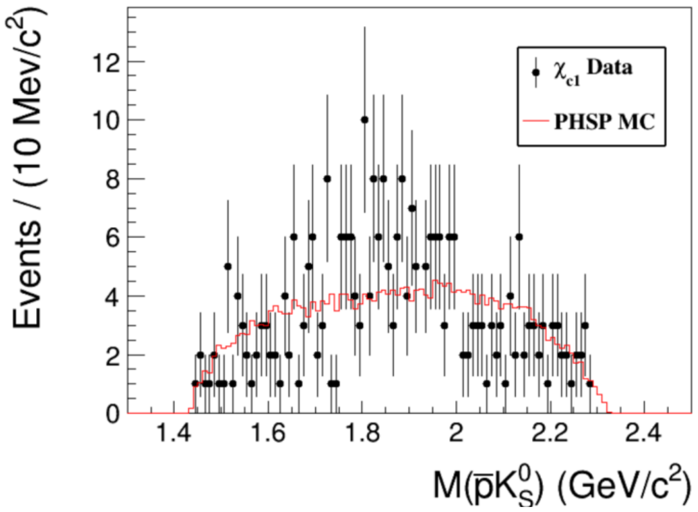
Distributions

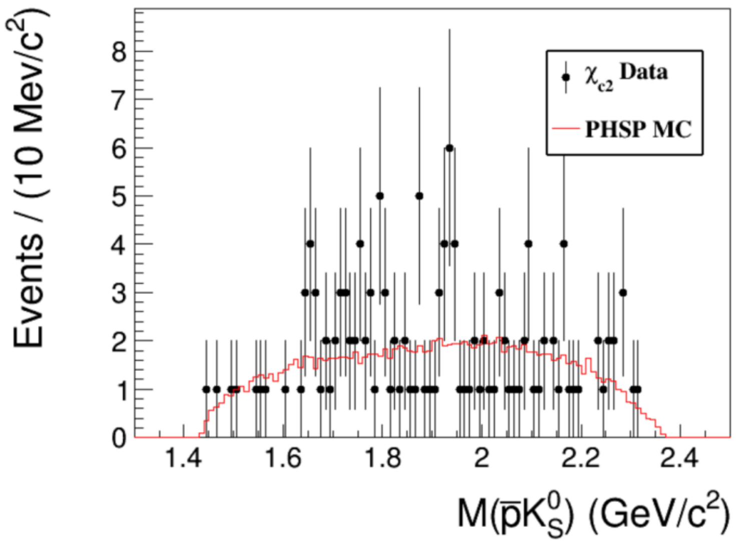
No clear structure can be seen from them.

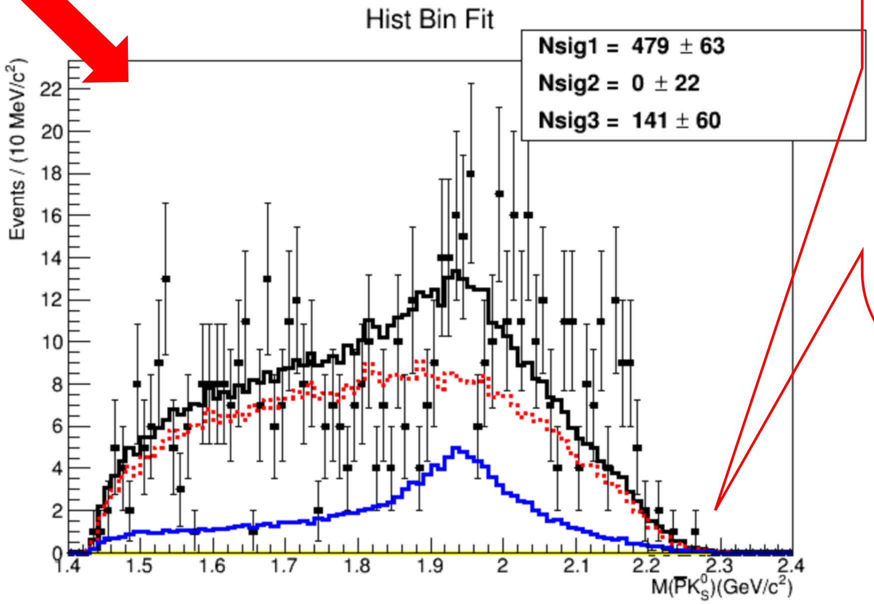


Distributions







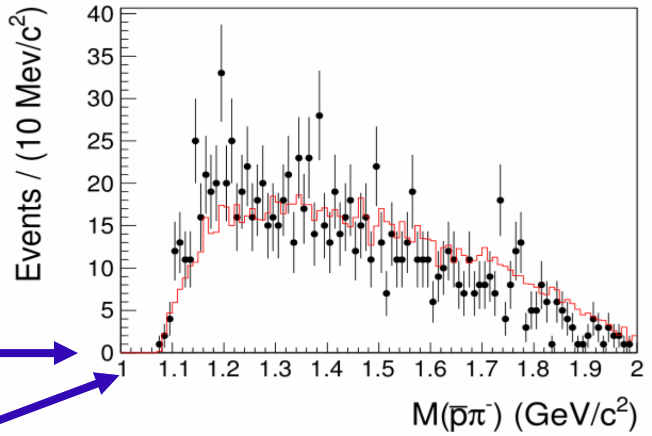


Use $\chi_{c0} \to \Sigma^+\bar{\Sigma}^-(1940)$, $\chi_{c0} \to \Sigma^+\bar{\Sigma}^-(1670)$ MC and the Phase Space MC to fit it.

$\bar{\Sigma}^-(1940)$:
M = 1940 MeV,
Γ= 150 MeV,
$I(J^P) = 1(3/2^-)$).
Significance: 2.3σ

Background analysis

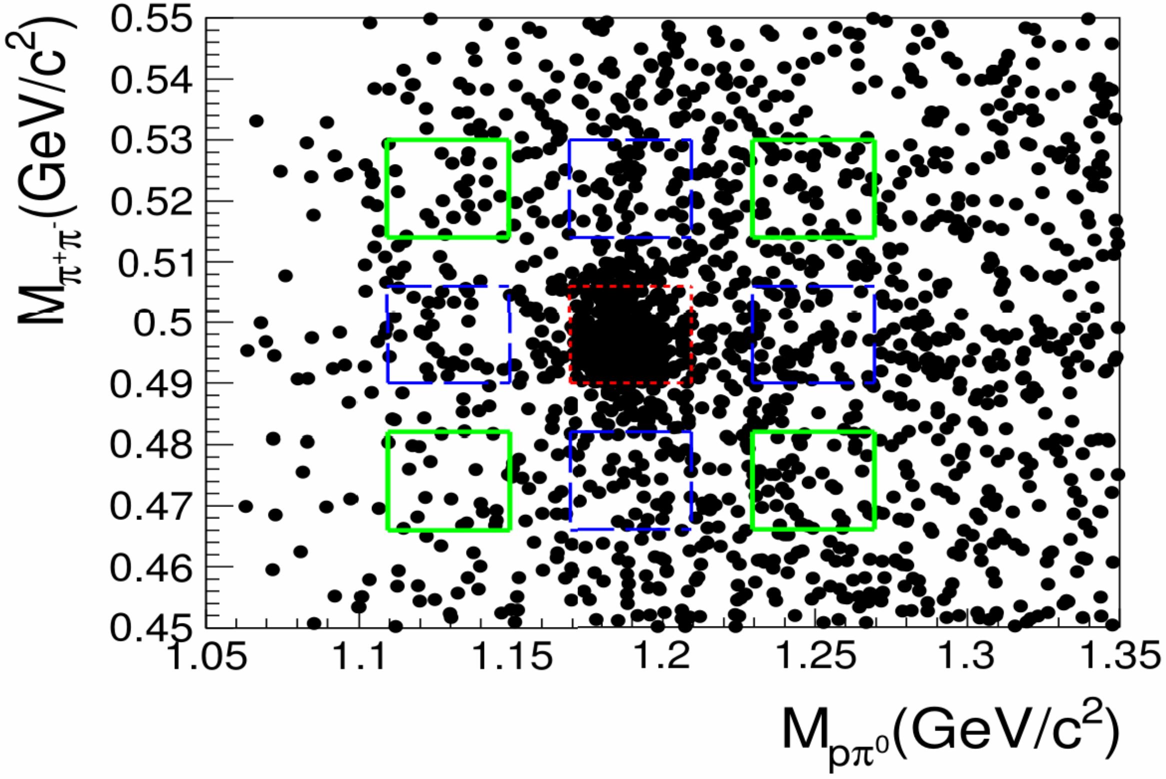
No.	decay chain	final states	iTopology	nEvt
6	$\psi' \to \gamma\chi_{c1}, \chi_{c1} \to \Delta^+\pi^+\bar{\Delta}^{--}, \Delta^+ \to p\pi^0, \bar{\Delta}^{--} \to \bar{p}\pi^-$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	3	4
7	$\psi' \to \bar{p}\Sigma^+K^*, \Sigma^+ \to p\pi^0, K^* \to K^0\pi^0, K_S \to \pi^+\pi^-$	$\pi^-\bar{p}\pi^0\pi^0\pi^+p$	22	4
8	$\psi' \to \gamma\chi_{c2}, \chi_{c2} \to \Delta^{++}\pi^-\bar{\Delta}^-, \Delta^{++} \to p\pi^+, \bar{\Delta}^- \to \bar{p}\pi^0$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	12	4
9	$\psi' \to J/\psi\pi^0\pi^0, J/\psi \to p\bar{p}\pi^+\pi^-$	$\pi^-\bar{p}\pi^0\pi^0\pi^+p$	10	3
10	$\psi' \to J/\psi\pi^0\pi^0, J/\psi \to \Delta^{++}\bar{p}\pi^-, \Delta^{++} \to p\pi^+$	$\pi^-\bar{p}\pi^0\pi^0\pi^+p$	1	3
11	$\psi' \to \bar{K}^*p\bar{\Sigma}^-, \bar{K}^* \to \bar{K}^0\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0, K_S \to \pi^+\pi^-$	$\pi^-\bar{p}\pi^0\pi^0\pi^+p$	47	3
12	$\psi' \to \gamma\chi_{c0}, \chi_{c0} \to \bar{\Delta}^{--}\pi^0\Delta^{++}, \bar{\Delta}^{--} \to \bar{p}\pi^-, \Delta^{++} \to p\pi^+$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	14	2
13	$\psi' \to \gamma\chi_{c0}, \chi_{c0} \to \Delta^+\pi^-\bar{\Delta}^0, \Delta^+ \to p\pi^0, \bar{\Delta}^0 \to \bar{p}\pi^+$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	20	2
14	$\psi' \to \gamma\chi_{c2}, \chi_{c2} \to \omega p\bar{p}, \omega \to \pi^-\pi^+\pi^0$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	5	2
15	$\psi' \to \gamma\chi_{c0}, \chi_{c0} \to \bar{\Delta}^{--}p\rho^+, \bar{\Delta}^{--} \to \bar{p}\pi^-, \rho^+ \to \pi^+\pi^0$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	23	2
16	$\psi' \to \gamma\chi_{c1}, \chi_{c1} \to \pi^0\Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \bar{p}\pi^-$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	9	2
17	$\psi' \to \gamma\chi_{c1}, \chi_{c1} \to \Sigma^+\pi^-\bar{\Lambda}, \Sigma^+ \to p\pi^0, \bar{\Lambda} \to \bar{p}\pi^+$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	25	2
18	$\psi' \to \gamma\chi_{c2}, \chi_{c2} \to \pi^0\Delta^{++}\bar{\Delta}^{--}, \Delta^{++} \to p\pi^+, \bar{\Delta}^{--} \to \bar{p}\pi^-$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	26	2
19	$\psi' \to \gamma\chi_{c1}, \chi_{c1} \to \bar{\Delta}^-\pi^+\Delta^0, \bar{\Delta}^- \to \bar{p}\pi^0, \Delta^0 \to p\pi^-$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	27	2
20	$\psi' \to \gamma\chi_{c0}, \chi_{c0} \to \pi^+\Lambda\bar{\Sigma}^-, \Lambda \to p\pi^-, \bar{\Sigma}^- \to \bar{p}\pi^0$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	28	2
21	$\psi' \to \gamma\chi_{c0}, \chi_{c0} \to \pi^+\Delta^0\bar{\Delta}^-, \Delta^0 \to p\pi^-, \bar{\Delta}^- \to \bar{p}\pi^0$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	29	2
22	$\psi' \to \gamma\chi_{c0}, \chi_{c0} \to \pi^-\rho^+\bar{p}p, \rho^+ \to \pi^+\pi^0$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	30	2
23	$\psi' \to \gamma\chi_{c0}, \chi_{c0} \to \Delta^{++}\pi^-\bar{\Delta}^-, \Delta^{++} \to p\pi^+, \bar{\Delta}^- \to \bar{p}\pi^0$	$\pi^-\bar{p}\pi^0\pi^+\gamma p$	31	2



no clear $\bar{\Delta}^{--}$ peak

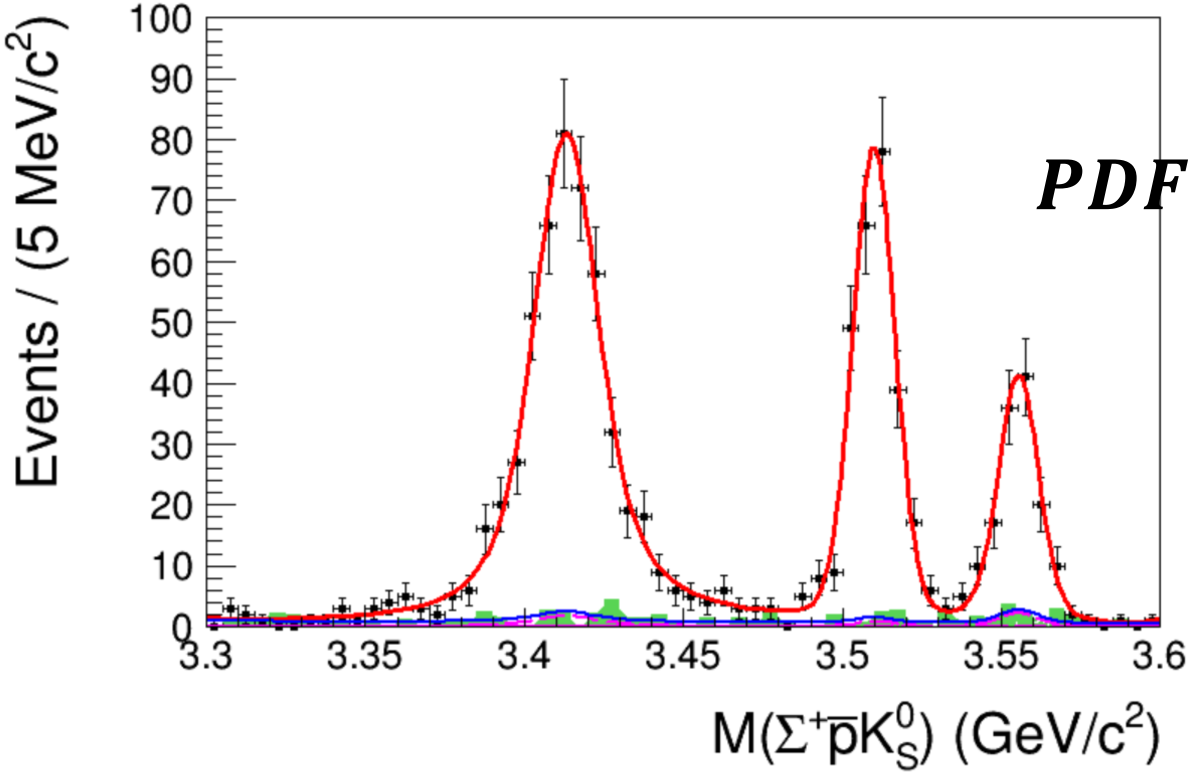
Background from $\Delta^+ \to p\pi^0$ are estimated by K_S^0 and Σ^+ 2-D sideband

Background analysis



$$Nbkg=\frac{1}{2}Nblue-\frac{1}{4}Ngreen$$

Unbinned simultaneous fit to $M(\Sigma^+\overline{p}K_S^0)$



$$PDF = (\mathrm{BW(m)} \times E_\gamma^3 \times D(E_\gamma)) \otimes \mathrm{Gaussion}$$

$$E_\gamma = \frac{M^2_{\psi(3686)} - m^2}{2M_{\psi(3686)}}$$

$$D(E_\gamma) = e^{-\frac{E_\gamma^2}{8\beta^2}}$$ [1]

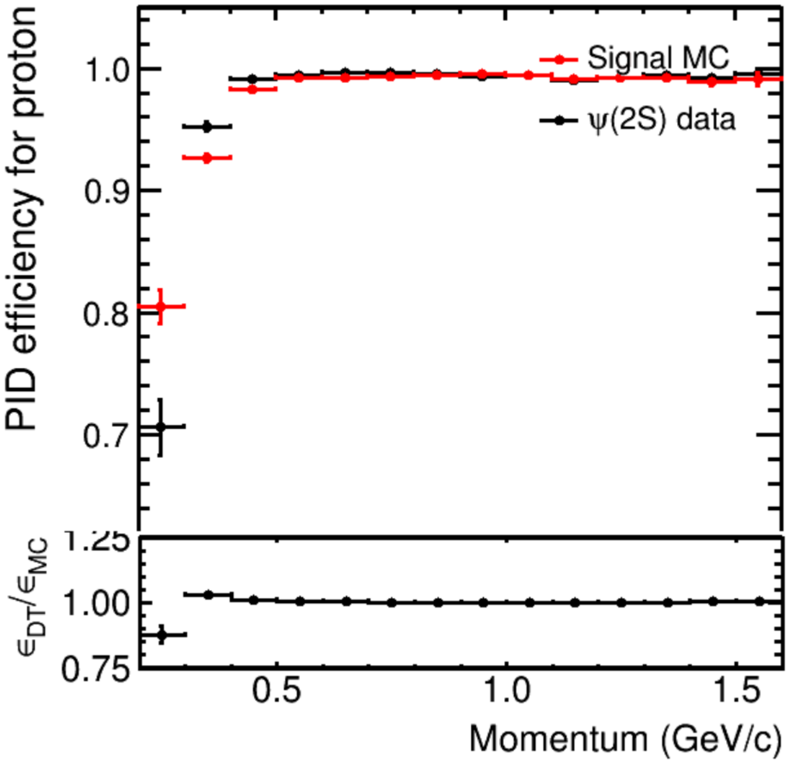
[1] R. E. Mitchell et al. (CLEO Collaboration), Phys. Rev. Lett. 102, 011801 (2009)

Dots with error bars are data, the red solid curve shows the result of fit, the green-shaded histograms are the events from 2-D sideband regions, the blue solid line is total background components of the fit, and the violet long dashed curve is the fit of the 2-D sideband events.

In the simultaneous fit, the shape of χ_{cJ} are the same between data and 2-D sideband events.

Systematic uncertainties

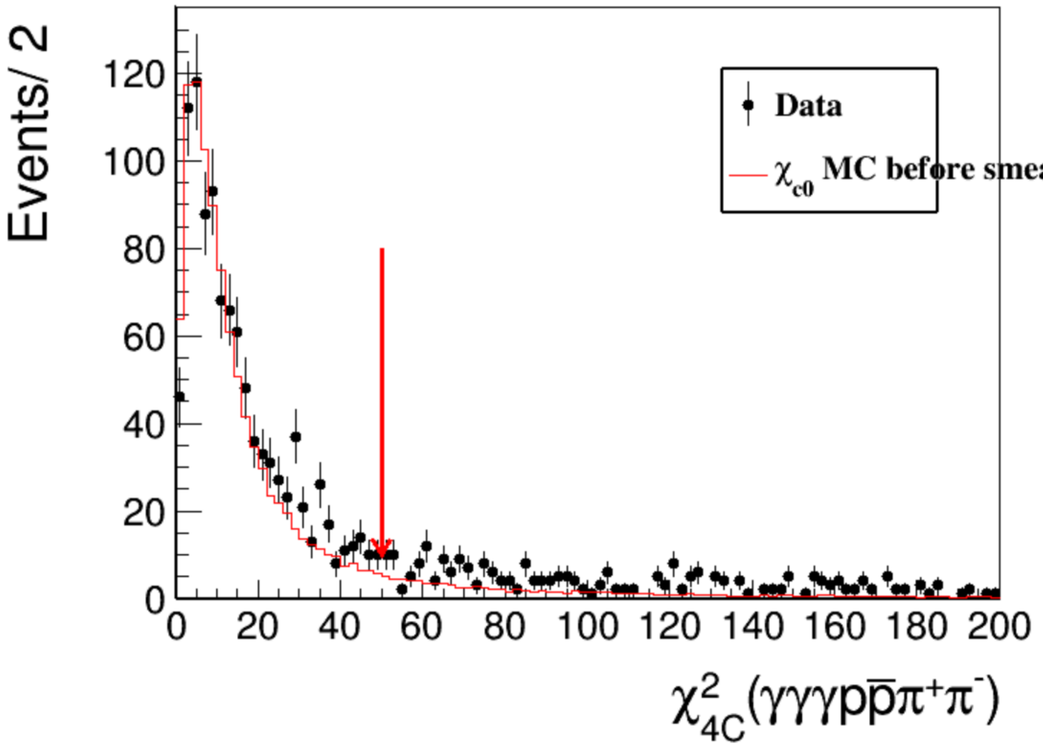
Particle identification and tracking of P($\bar{P}$) **using the control sample ψ(3686) (J/ψ)→$\bar{P}P\pi^+\pi^-$**

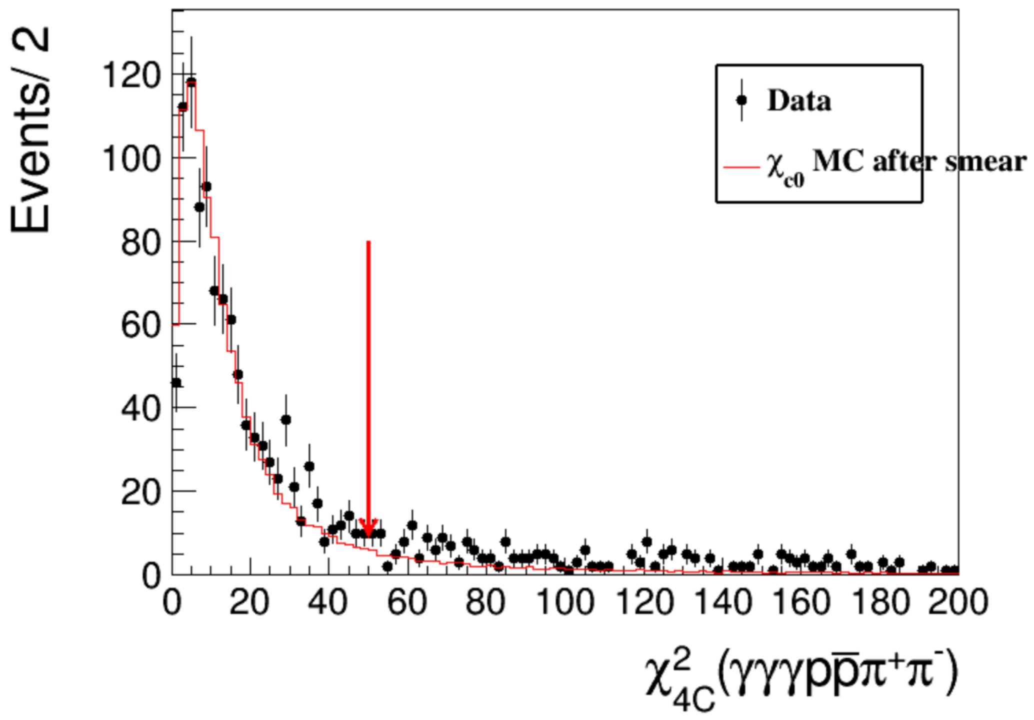


$\epsilon^{p-trackandpid}(MC)$	(0.2,0.3)	(0.3,0.4)	(0.4,0.5)	(0.5,0.6)	(0.6,0.7)	(0.7,0.8)
(-0.93,-0.8)	103.46 ± 0.48	101.25 ± 0.31	100.66 ± 0.38	102.40 ± 0.99	1 ± 0	1 ± 0
(-0.8,-0.6)	100.35 ± 0.32	100.33 ± 0.15	100.11 ± 0.15	100.49 ± 0.15	100.13 ± 0.22	100.03 ± 0.41
(-0.6,-0.4)	99.08 ± 0.53	100.02 ± 0.19	99.79 ± 0.14	100.03 ± 0.13	100.20 ± 0.14	100.08 ± 0.13
(-0.4,-0.2)	96.73 ± 0.86	99.68 ± 0.21	99.73 ± 0.14	99.71 ± 0.12	100.23 ± 0.13	100.14 ± 0.14
(-0.2,0)	87.62 ± 1.13	97.93 ± 0.28	99.14 ± 0.18	99.47 ± 0.15	99.76 ± 0.14	99.80 ± 0.14
(0,0.2)	85.33 ± 1.09	98.81 ± 0.26	99.55 ± 0.17	99.63 ± 0.13	99.84 ± 0.13	99.76 ± 0.14
(0.2,0.4)	98.07 ± 0.86	99.90 ± 0.21	100.04 ± 0.16	99.85 ± 0.12	100.04 ± 0.13	99.85 ± 0.13
(0.4,0.6)	98.41 ± 0.51	100.17 ± 0.18	99.88 ± 0.14	100.09 ± 0.14	100.14 ± 0.14	99.77 ± 0.17
(0.6,0.8)	100.71 ± 0.33	100.20 ± 0.15	100.59 ± 0.15	100.01 ± 0.16	99.81 ± 0.22	99.80 ± 0.30
(0.8,0.93)	102.46 ± 0.44	100.73 ± 0.30	100.56 ± 0.37	99.91 ± 0.71	1 ± 0	1 ± 0

Systematic uncertainties

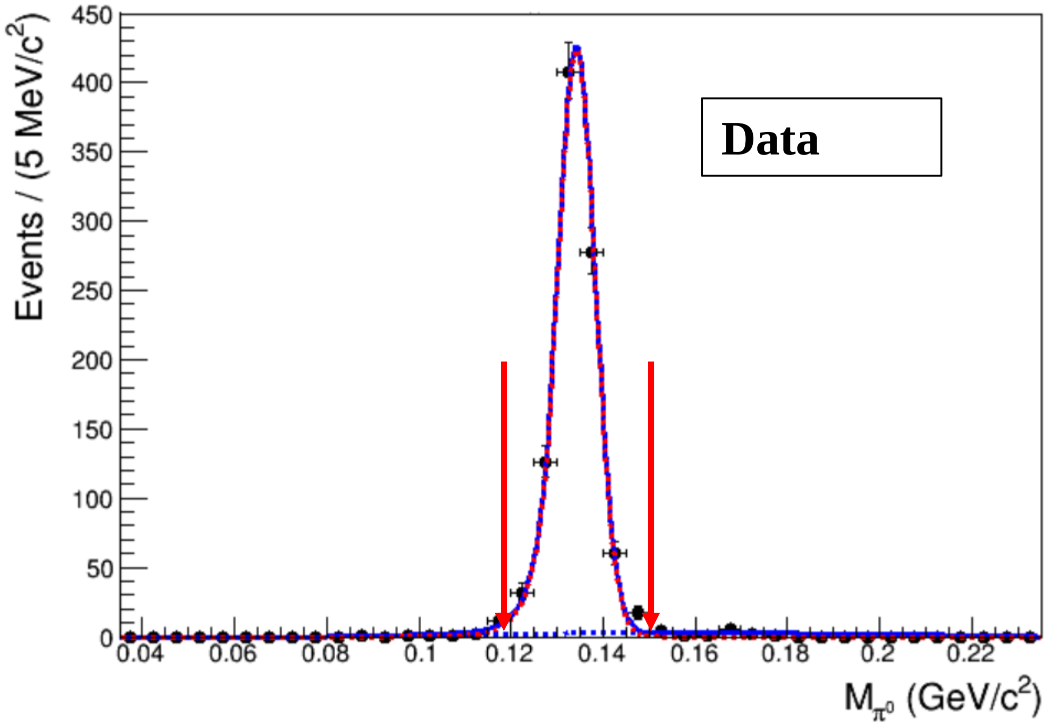
4C kinematic fit-take χ_{c0} as example.

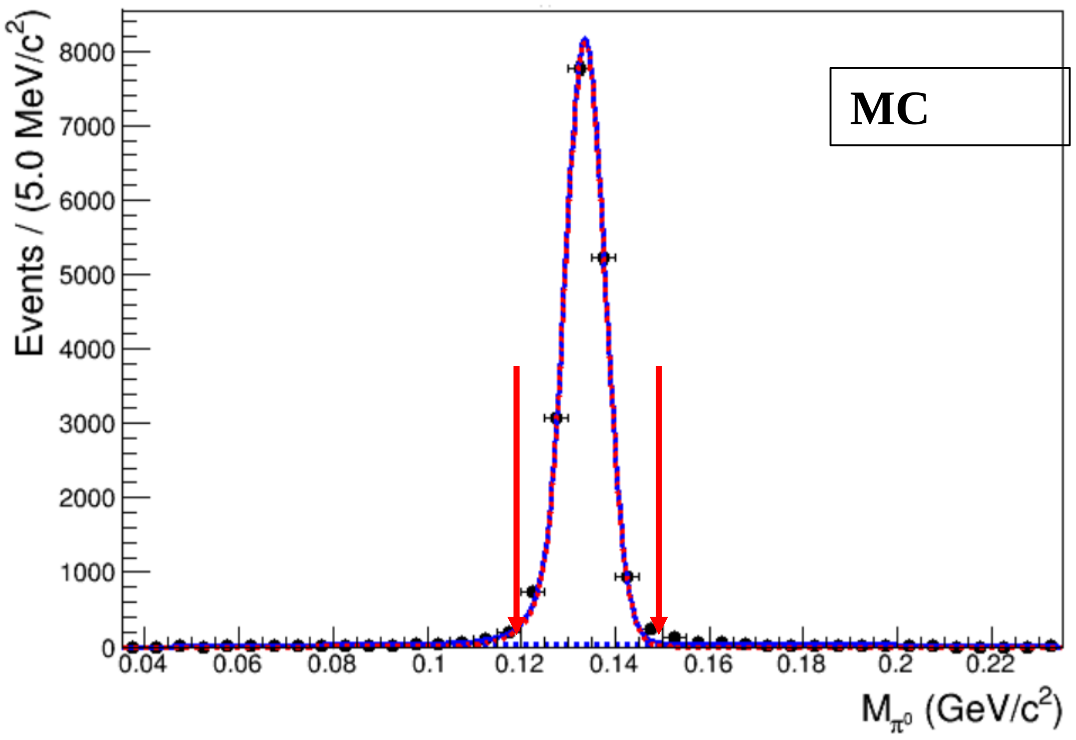




Systematic uncertainties

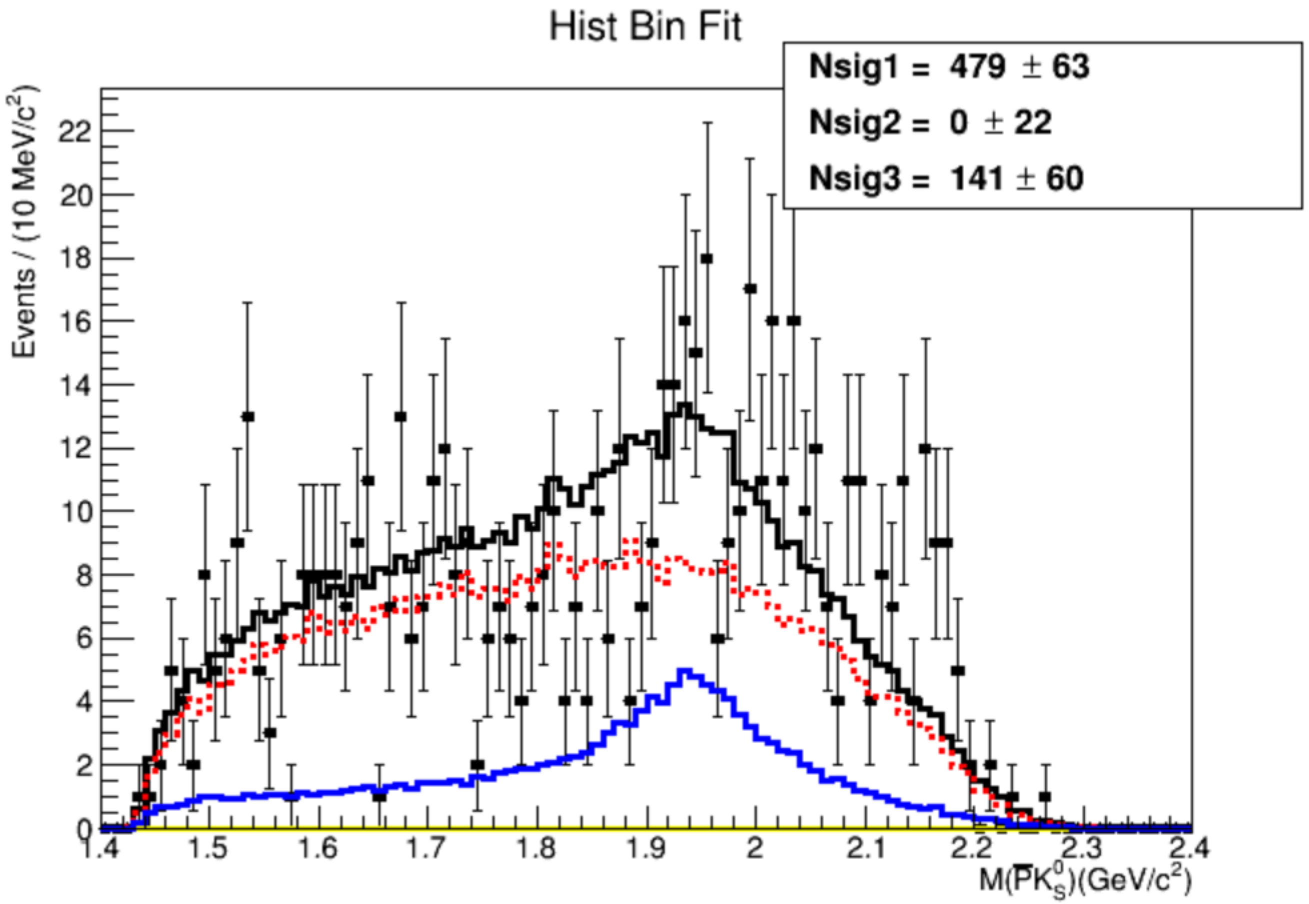
π^0, K_S^0 and Σ^+ mass window-take π^0 as example





Systematic uncertainties

$\bar{\Sigma}^-(1940)$ structure



Systematic uncertainties

$$D(E_\gamma) = \frac{E_0^2}{E_0 E_\gamma + (E_0 - E_\gamma)^2}$$ [2]

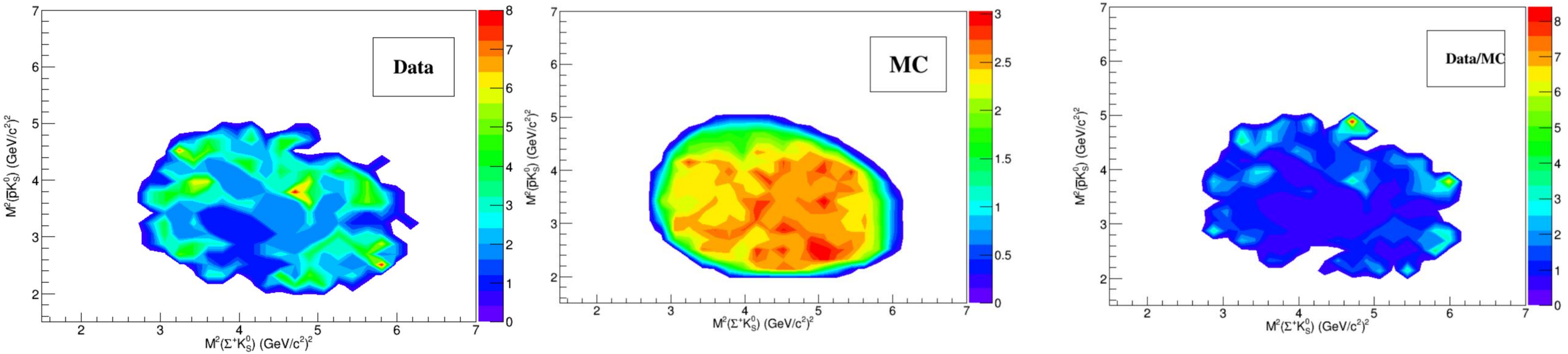
[2]V. V. Anashin et al. (KEDR Collaboration), Int. J. Mod. Phys. Conf. Ser. 02, 188 (2011)

Summary of systematic uncertainty sources and their contributions (in %).

Source	$\mathcal{B}(\chi_{c0})$	$\mathcal{B}(\chi_{c1})$	$\mathcal{B}(\chi_{c2})$
pion tracking	2.0	2.0	2.0
Photon detection	3.0	3.0	3.0
P($\bar{P}$)Particle ID and tracking	0.8	0.7	0.6
4C kinematic fit	0.4	0.3	0.3
π^0 mass window	0.3	0.3	0.3
K_S^0 mass window	0.3	0.3	0.3
Σ^+ mass window	0.1	0.1	0.1
$\bar{\Sigma}^-(1940)$ structure	0.1	...	...
Signal line shape	1.2	2.3	0.3
change β	0.2	0.4	0.8
Fit range	0.8	0.8	2.0
2D-sideband	0.4	0.1	0.8
Remaining background shape	3.1	0.7	1.5
Intermediate decay	0.4	0.4	0.4
Number of $\psi(3686)$	0.6	0.6	0.6
Total	5.1	4.6	4.7

Weighted Efficiency

Take χ_{c0} as an example



channel	Before weight	After weight
χ_{c0}	9.57%	9.47%
χ_{c1}	11.23%	10.85%
χ_{c2}	10.58%	10.05%

Calculation

The branching fractions for $\chi_{cJ} \to \Sigma^+ \bar{p} K_S^0 + c.c$ are calculated by

$$\mathcal{B}(\chi_{cJ}) = \frac{N_{obs}^{\chi_{cJ}}}{N_{\psi(3686)} \times \epsilon \times \mathcal{B}(\psi(3686) \to \gamma\chi_{cJ}) \times \mathcal{B}(\Sigma^+ \to p\pi^0) \times \mathcal{B}(K_S^0 \to \pi^+\pi^-) \times \mathcal{B}(\pi^0 \to \gamma\gamma)},$$

where $N_{\psi(3686)}$ is the total number of $\psi(3686)$ events, ϵ is the corresponding detection efficiency which is obtained by weighting the signal MC to data, $\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ})$, $\mathcal{B}(\Sigma^+ \to p\pi^0)$, $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$, and $\mathcal{B}(\pi^0 \to \gamma\gamma)$ are the branching fractions of $\psi(3686) \to \gamma\chi_{cJ}$, $\Sigma^+ \to p\pi^0$, $K_S^0 \to \pi^+\pi^-$, and $\pi^0 \to \gamma\gamma$ [2],

Summary

- $\chi_{cJ} \to \Sigma^+\bar{p}K_S^0 + c.c$ is performed for the first time, the branching fractions of them are

channel	Efficiency	Nsignal	Branching Fraction($\chi_{cJ} \to \Sigma^+\bar{p}K_S + c.c$) (*10^{-4})
χ_{c0}	9.47%	509 ± 26	$3.43 \pm 0.18 \pm 0.17$
χ_{c1}	10.85%	260 ± 17	$1.59 \pm 0.10 \pm 0.07$
χ_{c2}	10.05%	132 ± 13	$0.913 \pm 0.090 \pm 0.043$

- We can not draw the conclusion there are any intermediate states existing in these decays.

Thank you !!!