
Search for $e^+e^- \rightarrow \gamma\chi_{c0,c1,c2}$ using data above e^+e^- CM energy ~ 4 GeV

Houbing Jiang , Qiyun Li , Ke Li , Zhiqing Liu , ChangZheng Yuan¹ , Xingtao Huang

Shandong university
IHEP¹

2019.3.13

◆ Motivation

- We hope use $e^+e^- \rightarrow \gamma\chi_{cj}$ to give more information about Y states ;
- Some work before this study;
(CPC 39,041001) (PhysRevD.92.012011);
- E1 radiative transitions from the higher-mass charmonium states are especially interesting. For example : we can proof if $\psi(4160)$ is 2D state

Mult.	State	Input mass (NR model)	Theor. mass		Initial meson	Multiplets	Final meson	E _{γ} (MeV)		Γ_{thy} (keV)	
			NR	GI				NR	GI	NR	GI
2D	$\psi_3(2^3D_3)$	4159	4167	4217	$\psi(4160)$	2D \rightarrow 2P	χ'_2	183.	210.	5.9	6.3
	$\psi_2(2^3D_2)$		4158	4208			χ'_1	227.	234.	168.	114.
	$\psi(2^3D_1)$		4142	4194			χ'_0	296.	269.	483.	191.
	$\eta_{c2}(2^1D_2)$		4158	4208		\rightarrow 1P	χ_2	559.	590.	0.79	0.027
							χ_1	598.	628.	14.	3.4
							χ_0	677.	707.	27.	35.
						\rightarrow 1F	$\chi_2(1^3F_2)$	128.	101.	51.	17.
Phys. Rev. D 72, 054026											

Section I $e^+e^- \rightarrow \gamma\chi_{c1,c2}$

◆ DATA Set

- **Boss version boss703**

- **DATA**

21 energy points XYZ data



- **Signal MC**

$$e^+e^- \rightarrow Y(4260) \rightarrow \gamma\chi_{c1,2}$$

$$\chi_{c1} \rightarrow \gamma J/\psi$$

$$\chi_{c2} \rightarrow \gamma J/\psi$$

P2GC1/P2GC2

AV2GV

T2GV

Named DataSet I :

C.M	$\sqrt{s}(\text{MeV})$	$L (\text{pb}^{-1})$
4009	4007.6	482.0
4180	4173.0	3189.0
4190	4189.3	521.9
4200	4199.6	523.7
4210	4209.7	511.2
4220	4218.8	508.2
4230	4226.3	1047.3
4237	4235.8	508.9
4246	4243.9	532.7
4260	4258.0	825.7
4270	4266.9	529.3
4360	4358.3	539.8
4420	4415.6	1028.9
4600	4599.5	566.9

DataSet II:

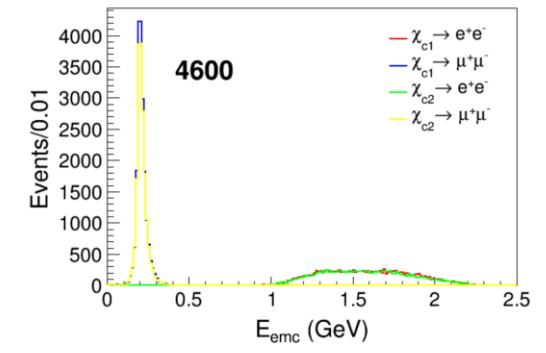
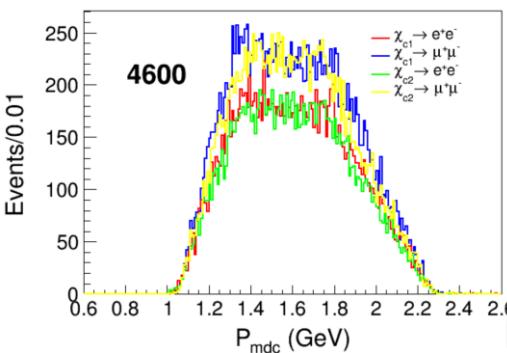
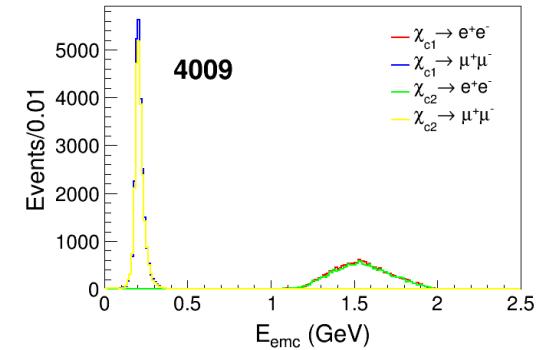
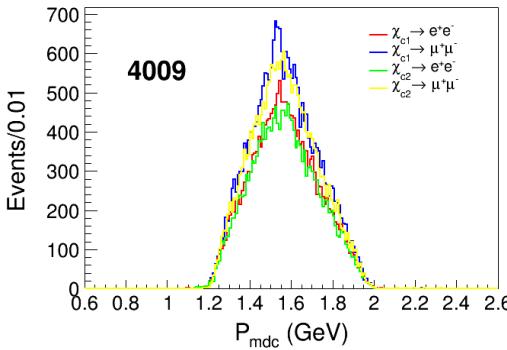
C.M	$\sqrt{s}(\text{MeV})$	$L (\text{pb}^{-1})$
4090	4085.5	52.8
4280	4277.8	174.5
4310	4307.9	45.1
4390	4387.4	55.6
4470	4467.1	111.1
4530	4427.1	112.1
4575	4574.5	48.9

◆ Event Selection

- Initial selection:

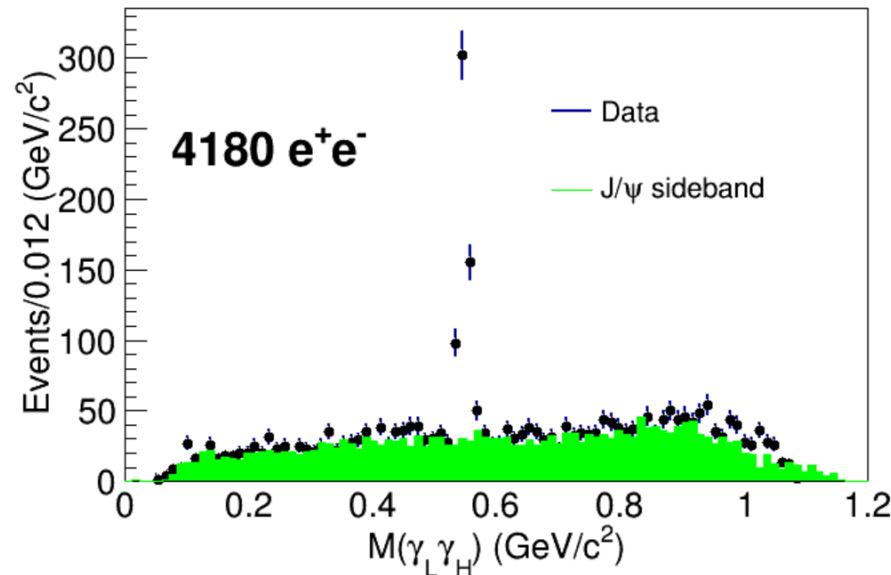
- Charged track:
N=2
- photon :
good photons ≥ 2 ;
- e , μ selection :

 $e : P_{mdc} > 1.0 \text{ && } E_{emc}(\text{deposit}) > 1.0 \text{ GeV}$
 $\mu : P_{mdc} > 1.0 \text{ && } E_{emc}(\text{deposit}) < 0.4 \text{ GeV}$
- The two photon candidates with the largest energies are retained;

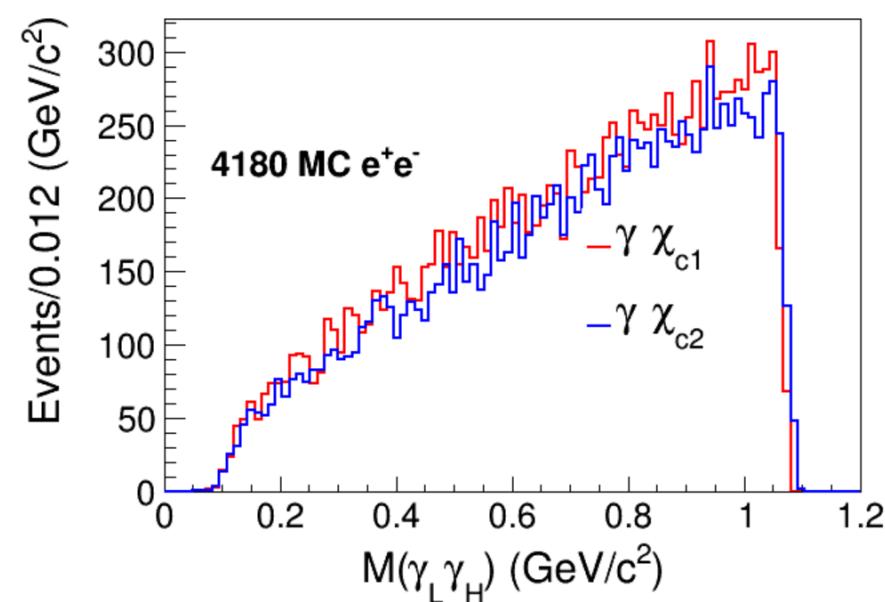


◆ Event Selection for e^+e^- channel

$M(\gamma\gamma)@4180$ DATA $M(\gamma J/\psi) > 3.3\text{GeV}$

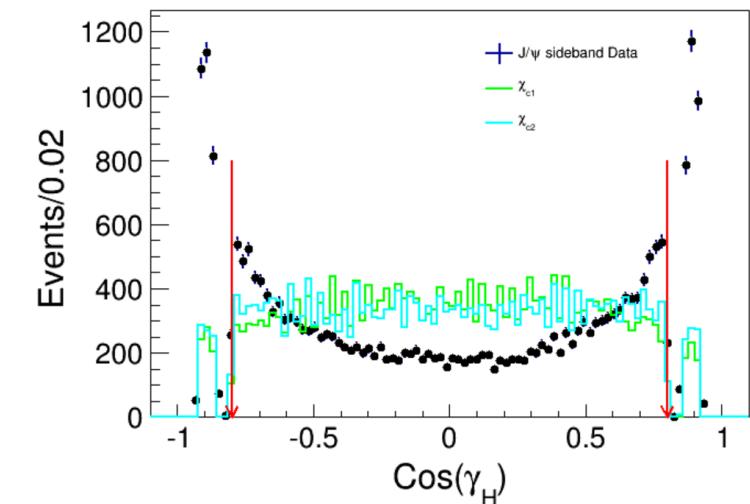
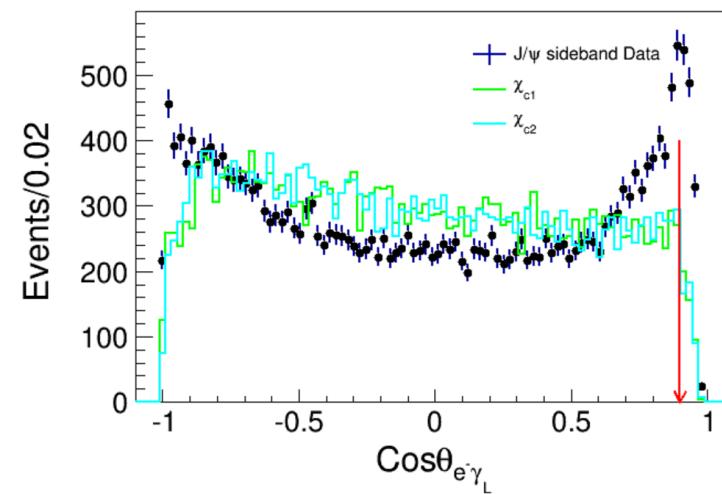
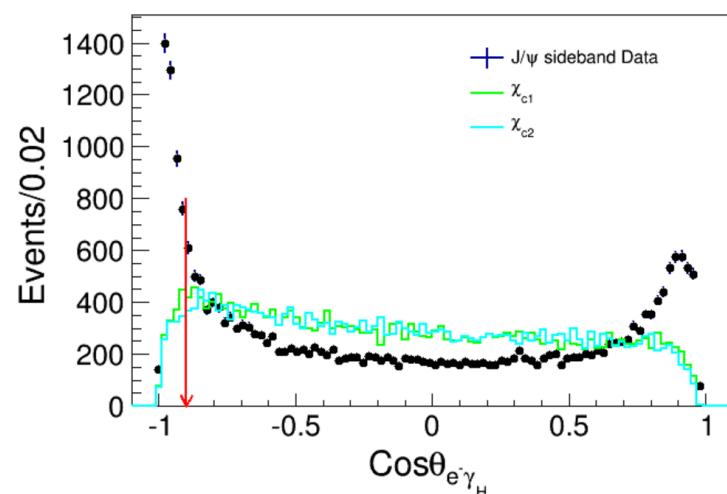
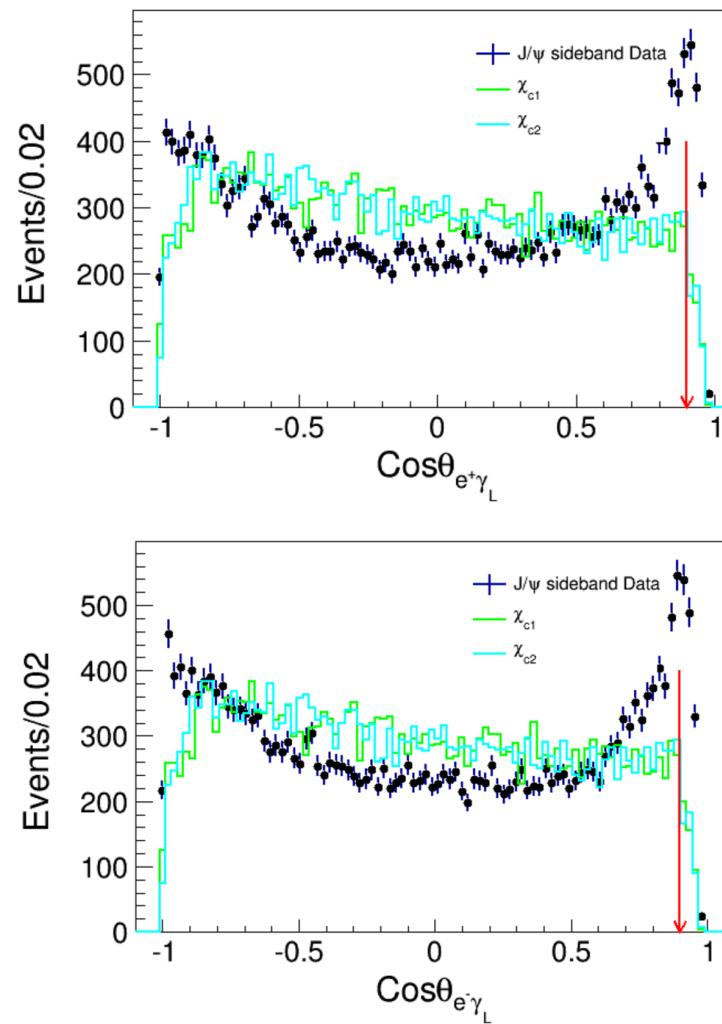
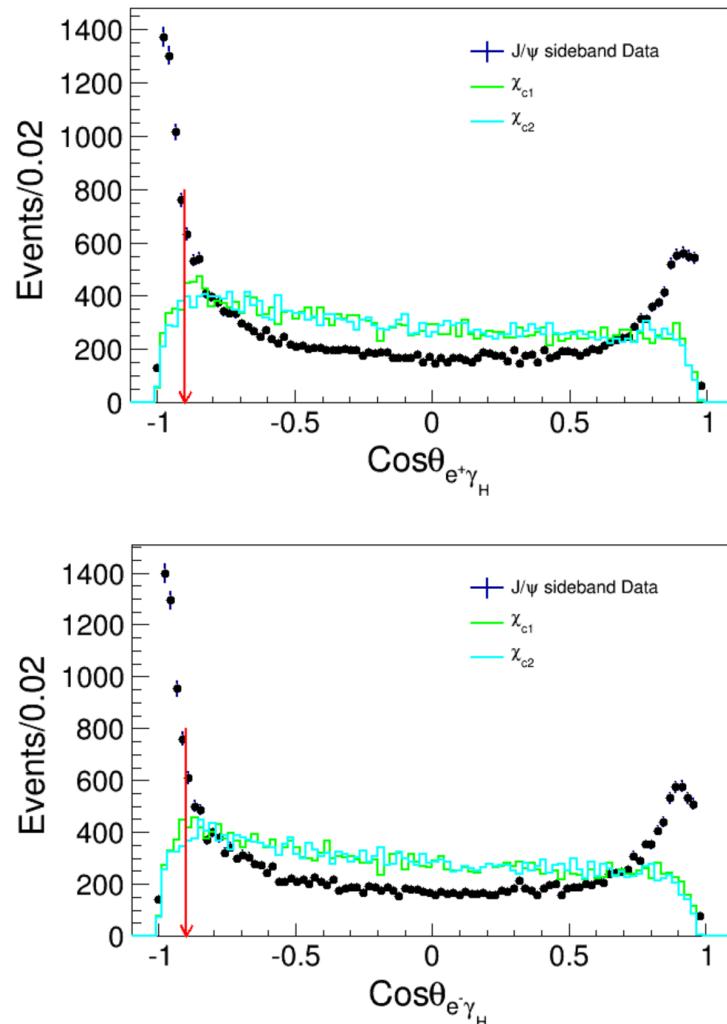


Signal MC $M(\gamma J/\psi) > 3.3\text{GeV}$



- Further selection:
 - Clearly $\eta J/\psi$ evnets, let $M(\gamma\gamma) < 0.52 \parallel M(\gamma\gamma) > 0.58 \text{ GeV};$
- After above selection, the inclusiveMC study show the dominant backgrounds come from Bhabha events.

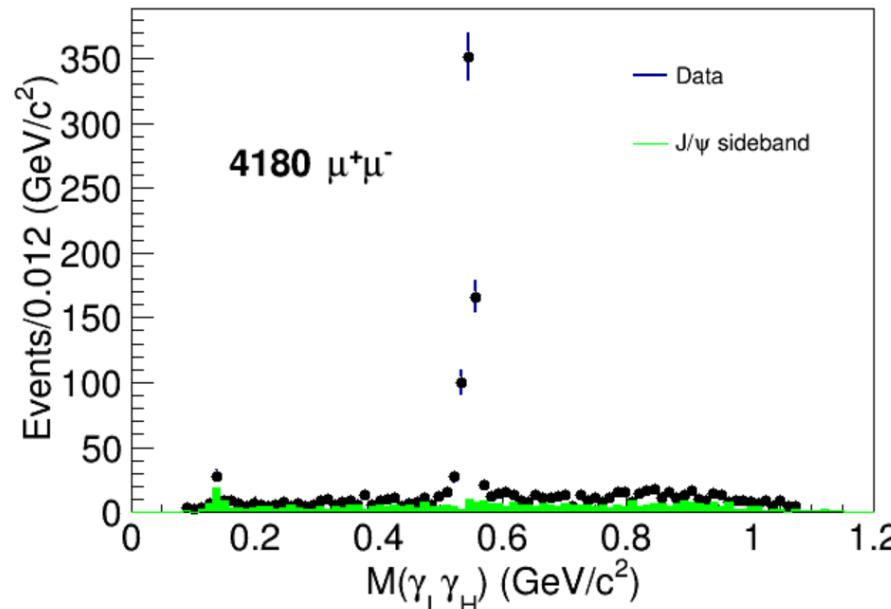
◆ Suppress Bhabha events in e^+e^- channel



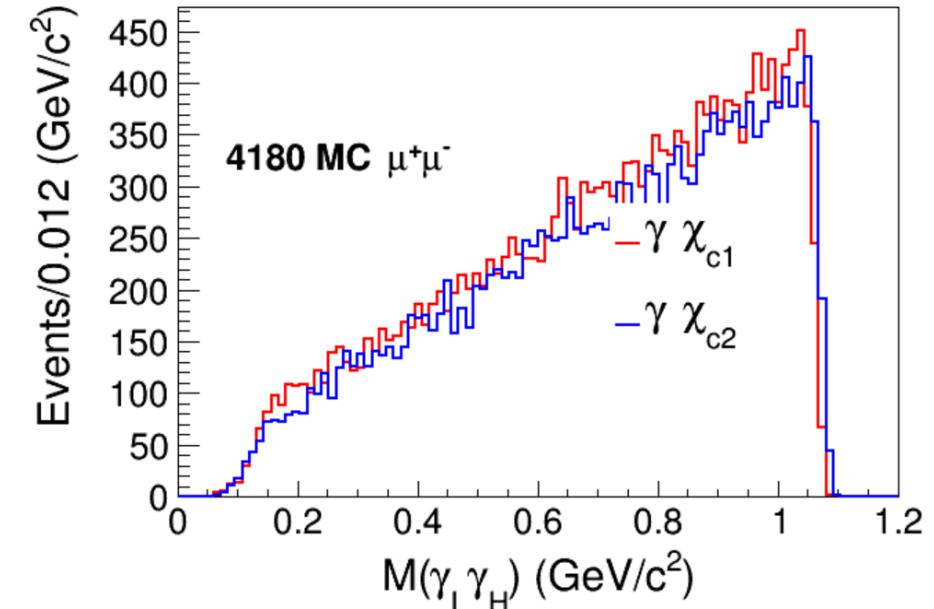
- Let $\text{Cose}^+\gamma_H > -0.9 \&\& \text{Cose}^-\gamma_H > -0.9 \&\& \text{Cose}^+\gamma_L < 0.9 \&\& \text{Cose}^-\gamma_L < 0.9$;
- $|\text{Cos } \gamma_H| < 0.8$ to remove Bhabha events;

◆ Event Selection for $\mu^+\mu^-$ channel

$M(\gamma\gamma)@4180$ DATA $M(\gamma J/\psi) > 3.3\text{GeV}$

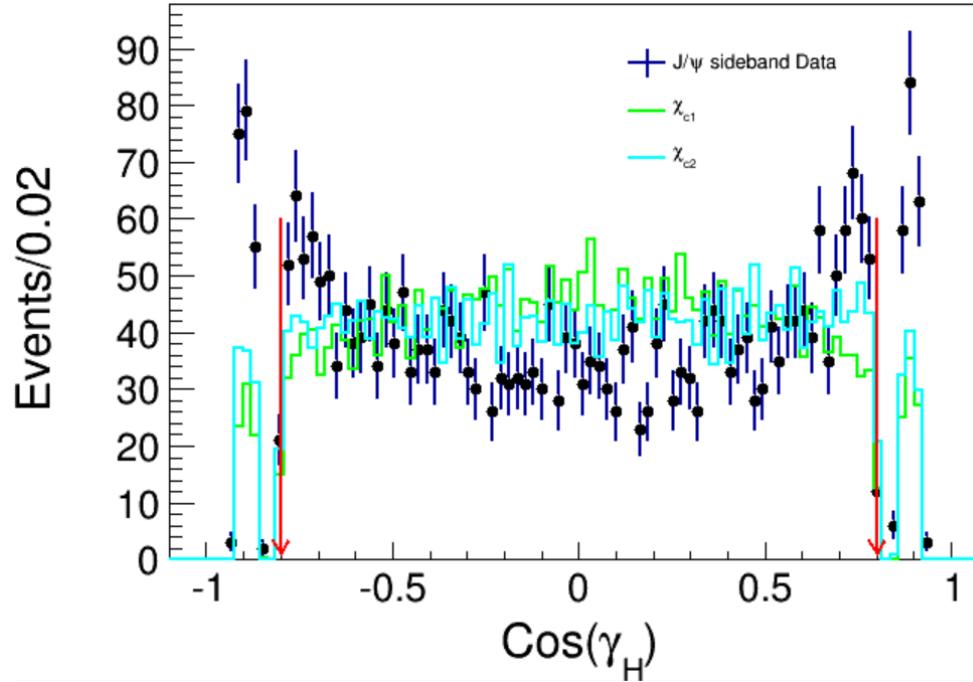


Signal MC



- Further selection:
 - Clearly $\eta J/\psi$ events, let $M(\gamma\gamma) < 0.52 \parallel M(\gamma\gamma) > 0.58\text{ GeV}$;
 - Clearly π^0 background, let $|M(\gamma\gamma) - M(\pi^0)| > 0.015\text{ GeV}$;
- After above selection, the inclusiveMC study show the dominant backgrounds come from $e^+e^- \rightarrow (n\gamma)\mu^+\mu^-$;

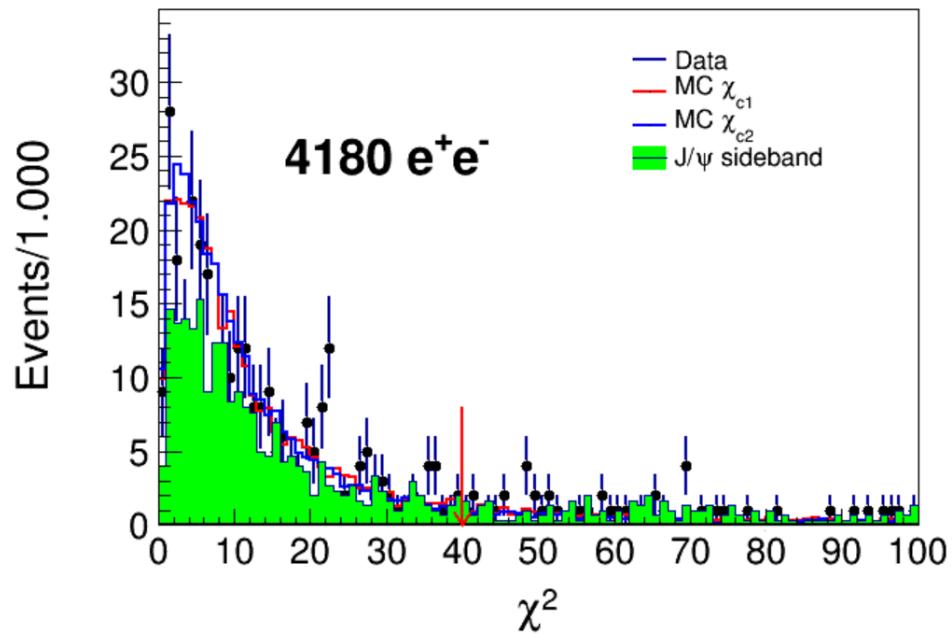
◆ Suppress dimu events in $\mu^+\mu^-$ channel



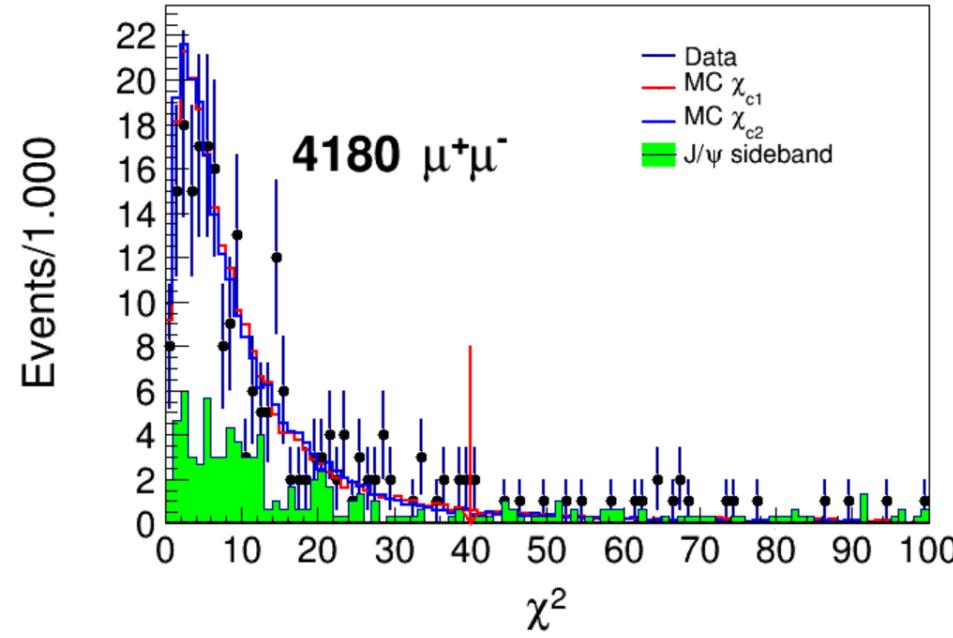
- Let $|\text{Cos } \gamma_H| < 0.8$ to suppress dimu events;

◆ Chisq4c cut

➤ In χ_{c1}, χ_{c2} region:

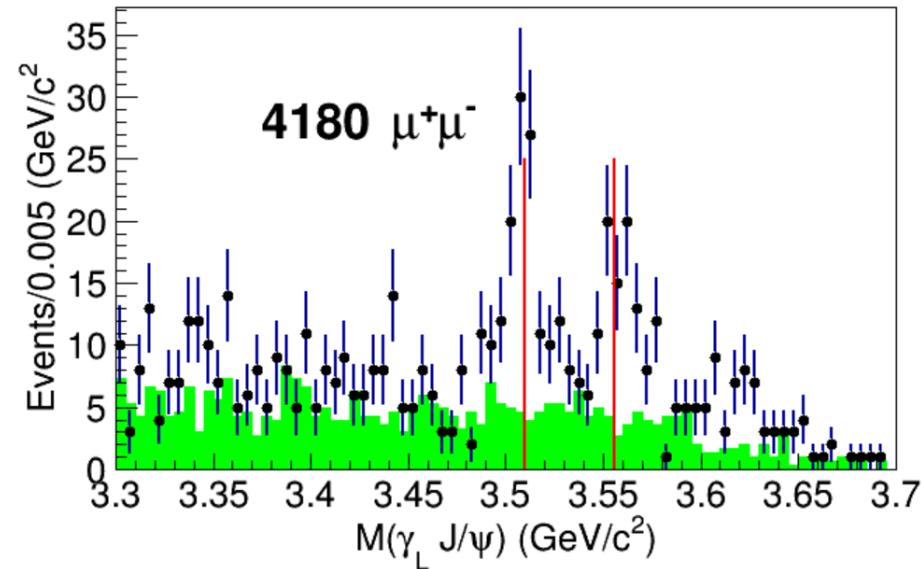
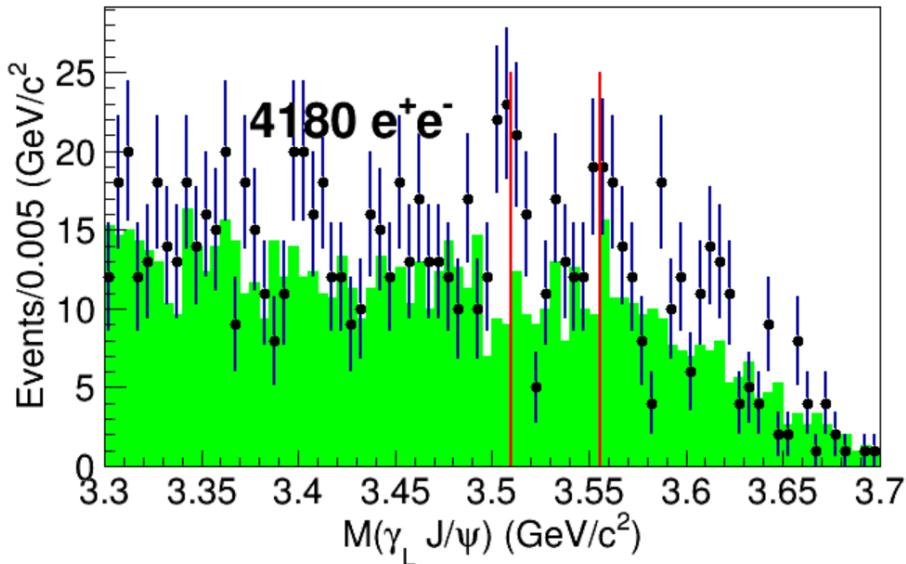


Chisq4c<40



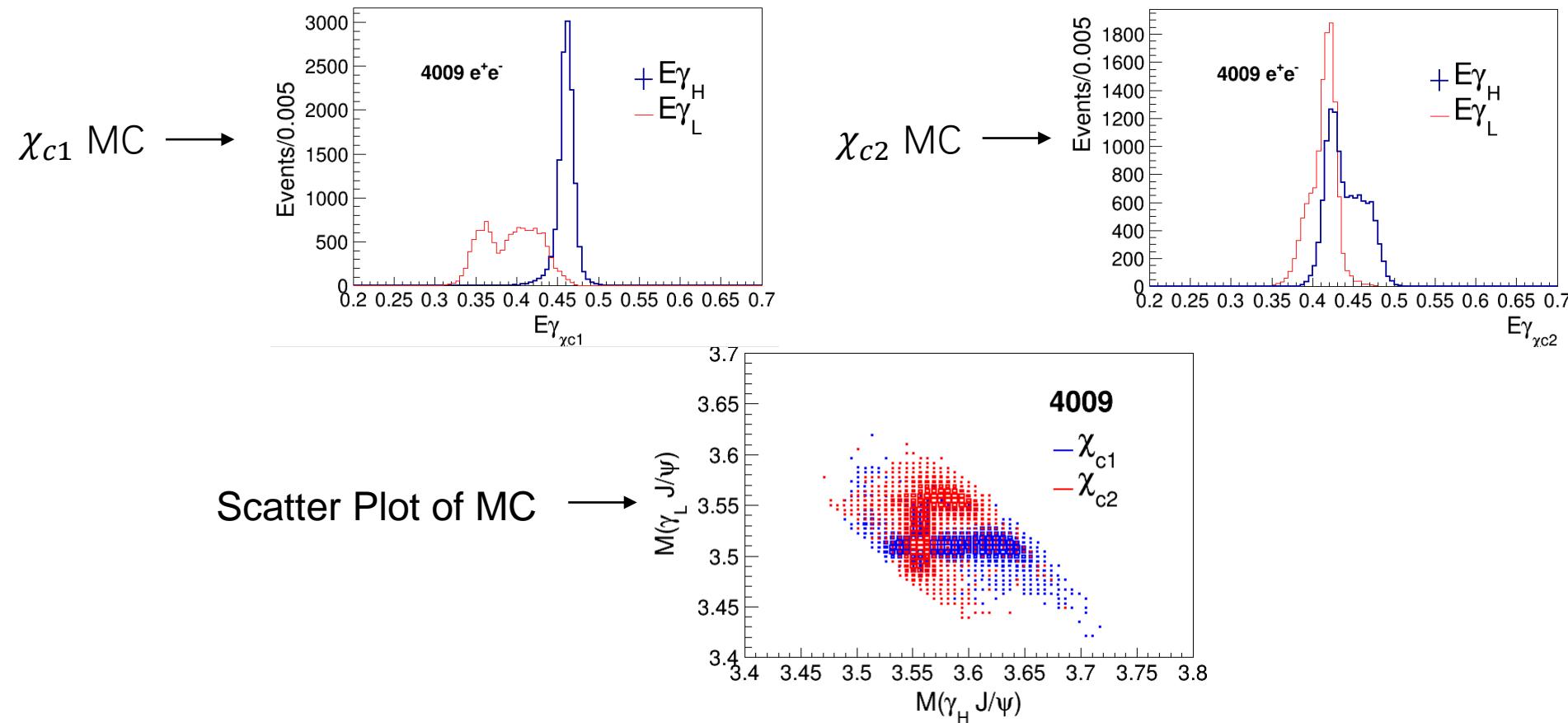
◆ $M(\gamma_L J/\psi)$ distribution@4180

➤ After above cut:



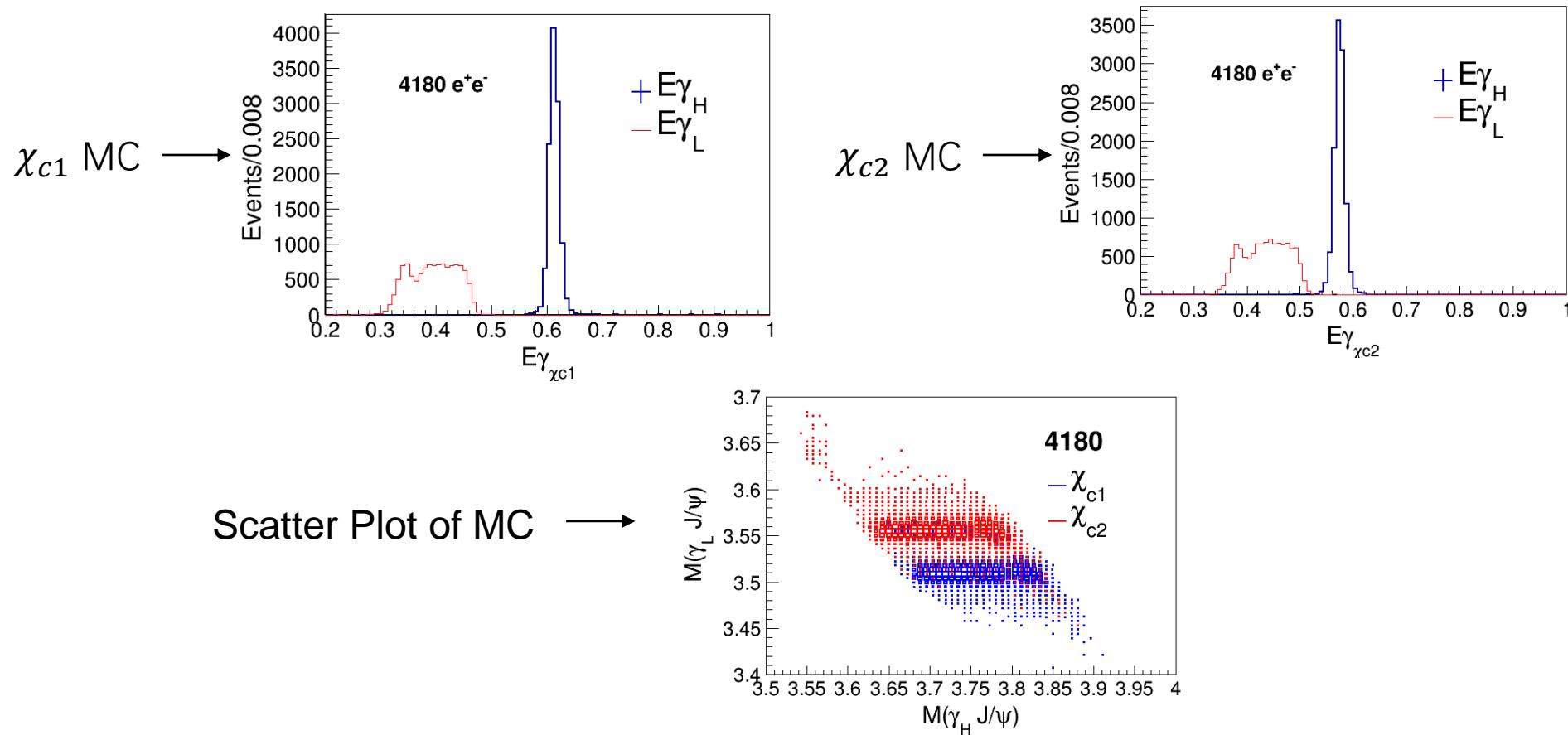
- Clearly, there are $\chi_{c1,2}$ events.

◆ Photons distribution @4009



- Obviously, some χ_{c2} decay to $\gamma_H J/\psi$ at 4009 energy point. To χ_{c1} MC, also there is an overlap between the two photons distributions .so we decide to use two photons to search signal.

◆ Photons distribution @4180



- Obviously, the distribution of two photons is essentially without overlap, and almost all $\chi_{c1,2}$ decay to low energy photon . So we use low energy photon to search signal

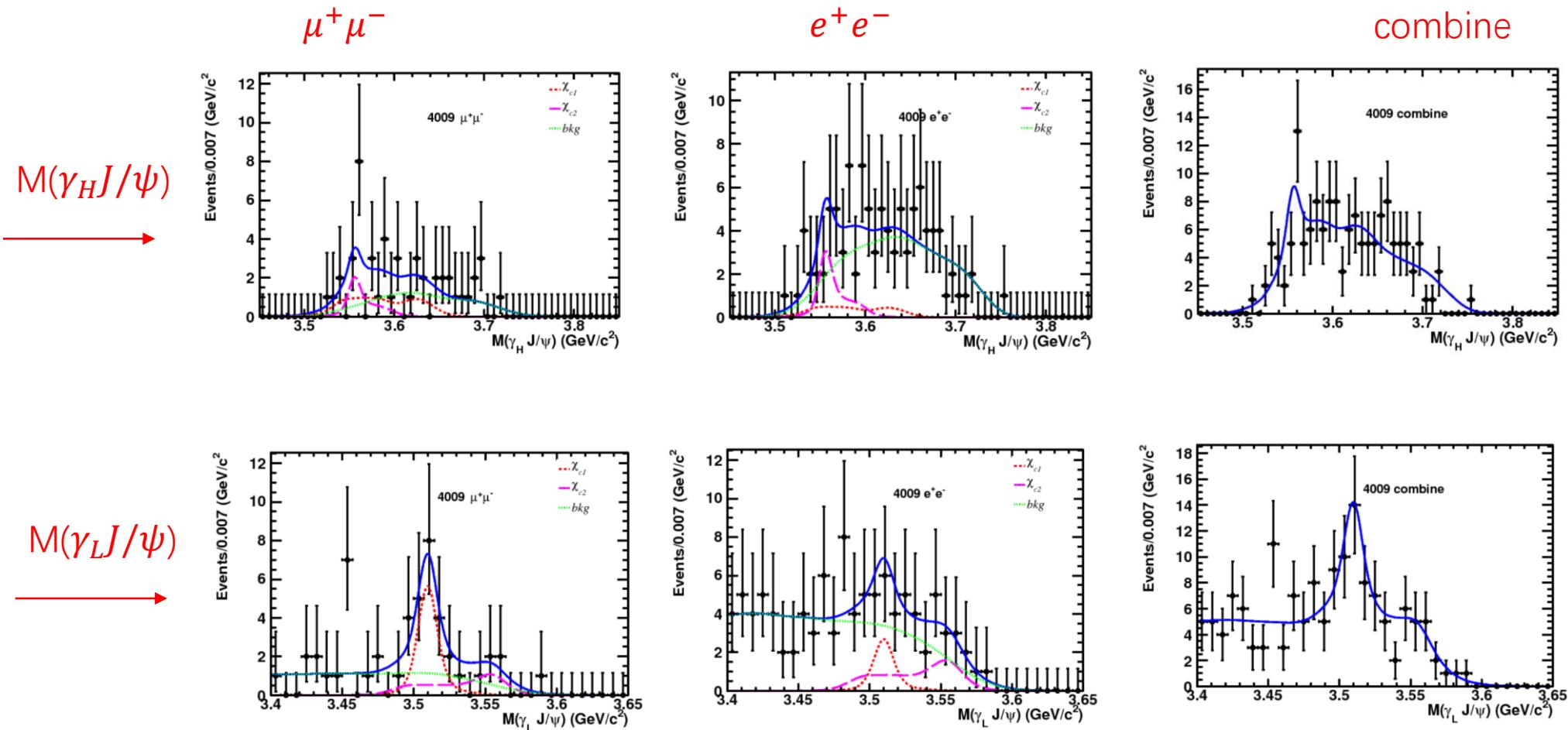
◆ Signal extraction(DataSet I)

- For dataset I, We use fit method;

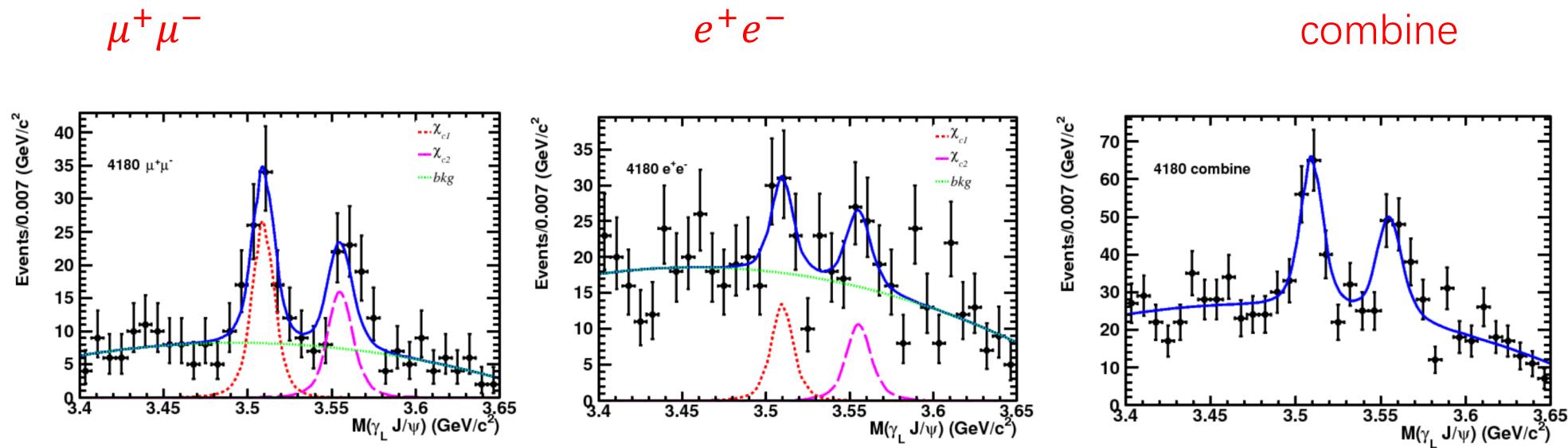
Fit Method

- As analyzed above , we use both of the two photons to search signal at 4009 (2D- Fit), and use the low energy photon to search signal at others energy points.
- Fit e^+e^- and $\mu^+\mu^-$ two channel Simultaneously.
- Fit Shape:
 - @4009
 - Signal use signal MC $M(\gamma_L J/\psi)$ and $M(\gamma_H J/\psi)$ 2-D shape ;
 - Background use dimu or bhabha MC $M(\gamma_L J/\psi)$ and $M(\gamma_H J/\psi)$ 2-D shape;
 - others
 - Signal use signal MC $M(\gamma_L J/\psi)$ fit to data
 - Background 2-order Chebychev

◆ Fit result @4009 (2-D simultaneously fit)



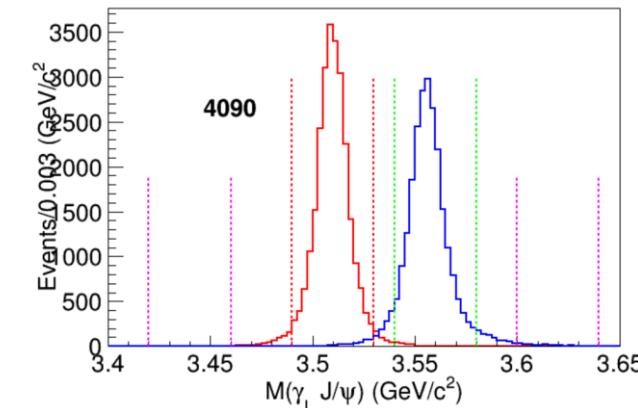
◆ Fit result @4180 (simultaneously fit)



◆ Signal extraction(DataSet II)

- Using six xyz data to fill in large gaps between some high-statistic energy points ,
For dataset II,we use count method:

- Define signal region: $\chi_{c1}(3.49,3.53)$ $\chi_{c2}(3.54,3.58)$, note the number of events as n;
- Define sideband region (3.42,3.46) (3.6,3.64), note the number of events as b;
- Statistical error:
Suppose n and b follow Poisson distribution;



C.M	N_c1	N_c2	b
4090	2	0	7
4280	10	5	20
4310	2	4	3
4390	3	3	4
4470	8	0	6
4530	2	2	3
4575	1	0	1

◆ Cross Section and lineshape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$

- Firstly, we use $\psi(4160)$ lineshape to get radiation correction factor;
- Using follow fumula measure cross section:

$$\sigma^{\text{dress}} = \frac{N^{\text{sig}}}{\mathcal{L}_{int}(1 + \delta)\epsilon\mathcal{B}}$$

- Fit to $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ cross section:
- Fit Method(likelihood Method):
Define likelihood fuction:

$$\mathcal{L} = \prod_{i=1} G(\sigma, N_{exp}) \prod_i P(N_{fit}, N_{exp})$$

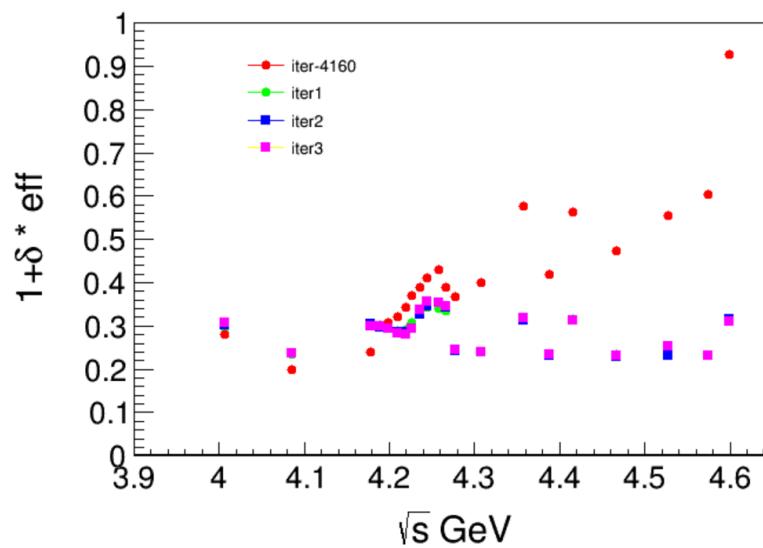
@4180 We suppose the number of events follow Gaussion distribution;
@ others We suppose the number of events follow possion distribution;

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model I)

- Fit function(two coherent Breit-Wigner functions), because of the very similar line-shape ,we give a simultaneously (decay from same resonance) fit:

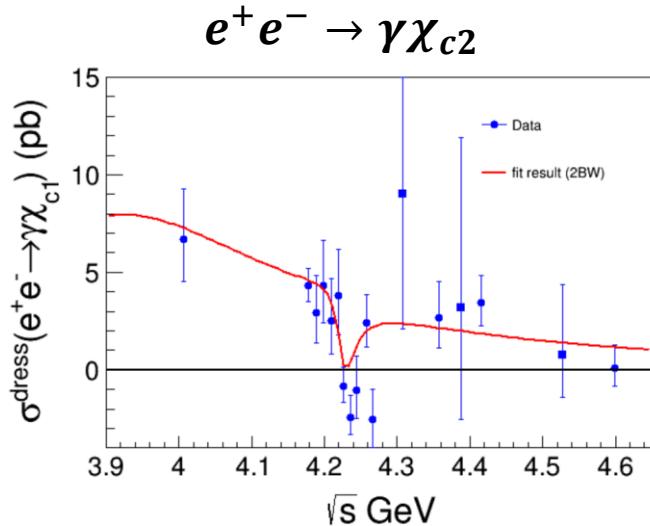
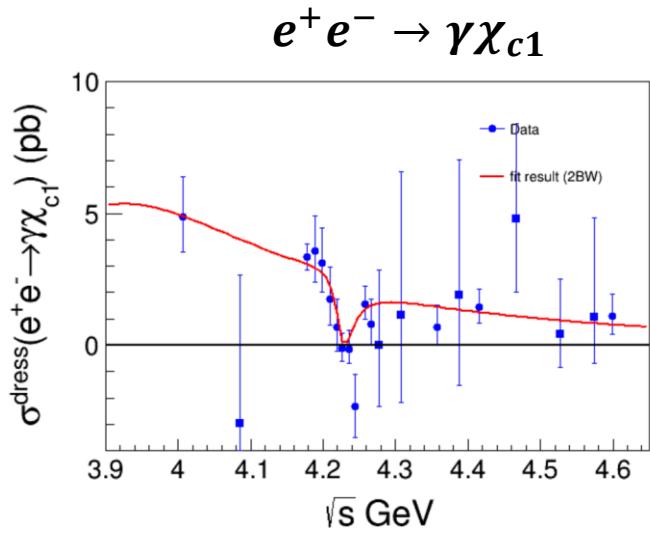
$$\sigma^{dress} = |BW1 + BW2e^{i\phi}|^2$$

- Three times iteration of the radiative correction procedure to get converge values
(For the first time , we use $\psi(4160)$ line-shape to get radiative correction factor)
 - $e^+e^- \rightarrow \gamma\chi_{c1} (1+\delta) * eff$ only $\mu^+\mu^-$



◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model I-2-BW)

➤ Fit result



➤ Parameters

Parameters	I
$M(R1)$	3866.4 ± 326.6
$\Gamma_{tot}(R1)$	523.1 ± 87.9
$\Gamma_{ee}\mathcal{B}(R1 \rightarrow \gamma\chi_{c1})$	2.8 ± 0.7
$\Gamma_{ee}\mathcal{B}(R1 \rightarrow \gamma\chi_{c2})$	4.2 ± 0.7
$M(R2)$	4225.6 ± 2.7
$\Gamma_{tot}(R2)$	28.5 ± 5.4
$\Gamma_{ee}\mathcal{B}(R2 \rightarrow \gamma\chi_{c1})$	0.094 ± 0.006
$\Gamma_{ee}\mathcal{B}(R2 \rightarrow \gamma\chi_{c2})$	0.015 ± 0.006
$\phi_1(\gamma\chi_{c1})$	79.2 ± 0.3
$\phi_2(\gamma\chi_{c2})$	343.1 ± 0.2

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model I-2-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c1}$ (Data Set I)

\sqrt{s}	L(pb-1)	ϵ_{ee}	ϵ_{uu}	$1+\delta$	$\sigma^{dress}(ee)$	$\sigma^{dress}(\mu\mu)$	Sig
4.0076	482.0	0.196	0.325	0.943	$4.2^{+3.0}_{-2.5}$	$5.1^{+1.8}_{-1.6}$	4.1σ
4.1783	3194.5	0.184	0.308	0.972	$2.9^{+1.1}_{-1.0}$	$3.5^{+0.6}_{-0.6}$	7.6σ
4.1888	522.5	0.188	0.319	0.941	$0.5^{+2.6}_{-2.2}$	$4.7^{+1.6}_{-1.4}$	3.9σ
4.1989	524.6	0.196	0.329	0.898	$1.3^{+2.3}_{-1.9}$	$1.7^{+1.3}_{-1.1}$	3.1σ
4.2092	518.1	0.201	0.338	0.839	$1.8^{+2.9}_{-2.5}$	$1.7^{+1.4}_{-1.1}$	-
4.2187	514.3	0.213	0.356	0.789	$-2.1^{+2.5}_{-2.1}$	$1.3^{+1.2}_{-1.0}$	-
4226.3	1047.3	0.212	0.360	0.819	$-1.7^{+1.4}_{-1.2}$	$0.2^{+0.6}_{-0.5}$	-
4.2357	530.6	0.204	0.347	0.970	$-0.4^{+2.0}_{-1.7}$	$-0.1^{+0.7}_{-0.6}$	-
4.2438	537.4	0.188	0.316	1.127	$2.4^{+2.2}_{-1.9}$	$-4.6^{+1.5}_{-1.4}$	-
4.258	825.7	0.164	0.275	1.291	$3.9^{+1.9}_{-1.7}$	$1.3^{+0.7}_{-0.6}$	-
4.2668	529.3	0.152	0.258	1.336	$1.0^{+1.9}_{-1.5}$	$0.7^{+1.1}_{-0.9}$	-
4.3583	539.8	0.133	0.231	1.379	$-0.2^{+2.1}_{-1.8}$	$0.8^{+0.9}_{-0.7}$	-
4.4156	1028.9	0.129	0.223	1.400	$-0.3^{+1.3}_{-1.1}$	$2.1^{+0.8}_{-0.7}$	-
4.5995	566.9	0.114	0.204	1.520	$-0.1^{+2.0}_{-1.6}$	$1.4^{+0.9}_{-0.7}$	-

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model I-2-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c1}$ (Data Set II)

\sqrt{s}	L(pb-1)	ϵ	1+ δ	σ^{dress}
4.0855	52.8	0.238	0.990	$-3.0^{+5.6}_{-3.8}$
4.2778	174.5	0.180	1.356	$0^{+2.9}_{-2.3}$
4.3079	45.1	0.174	1.369	$1.1^{+5.4}_{-3.2}$
4.3874	55.6	0.170	1.384	$1.9^{+5.2}_{-3.4}$
4.4671	111.1	0.163	1.428	$4.8^{+3.6}_{-2.8}$
4.4271	112.1	0.155	1.470	$0.5^{+2.3}_{-1.4}$
4.5745	48.9	0.154	1.503	$1.1^{+3.8}_{-1.8}$

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model I-2-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c2}$ (Data Set I)

\sqrt{s}	L(pb-1)	ϵ_{ee}	ϵ_{uu}	$1+\delta$	$\sigma^{dress}(ee)$	$\sigma^{dress}(\mu\mu)$	Sig
4.0076	482.0	0.182	0.297	0.959	13.1$^{+6.1}_{-5.3}$	5.3$^{+2.8}_{-2.4}$	3.2σ
4.1783	3194.5	0.139	0.225	1.292	4.7$^{+1.9}_{-1.8}$	4.2$^{+1.0}_{-0.9}$	5.4σ
4.1888	522.5	0.130	0.218	1.357	3.7$^{+4.7}_{-4.1}$	2.8$^{+2.0}_{-1.7}$	-
4.1989	524.6	0.128	0.216	1.337	9.4$^{+5.4}_{-4.7}$	3.2$^{+2.6}_{-2.1}$	-
4.2092	518.1	0.148	0.249	1.069	9.7$^{+6.5}_{-5.8}$	1.7$^{+2.3}_{-1.8}$	-
4.2187	514.3	0.182	0.313	0.811	-0.8$^{+5.8}_{-5.1}$	4.7$^{+3.6}_{-2.1}$	-
4226.3	1047.3	0.202	0.338	0.749	-1.3$^{+2.9}_{-2.6}$	-0.8$^{+1.1}_{-0.9}$	-
4.2357	530.6	0.202	0.337	0.809	5.7$^{+2.9}_{-2.1}$	-1.8$^{+1.2}_{-1.1}$	-
4.2438	537.4	0.195	0.331	0.877	4.6$^{+4.2}_{-2.6}$	-2.2$^{+1.9}_{-1.6}$	-
4.258	825.7	0.186	0.316	0.964	2.5$^{+3.4}_{-3.0}$	2.4$^{+1.6}_{-1.4}$	-
4.2668	529.3	0.177	0.299	1.001	5.0$^{+4.4}_{-3.8}$	-3.8$^{+1.7}_{-1.6}$	-
4.3583	539.8	0.149	0.251	1.167	1.9$^{+4.6}_{-4.0}$	2.8$^{+2.1}_{-1.7}$	-
4.4156	1028.9	0.138	0.236	1.231	1.3$^{+3.0}_{-2.6}$	4.0$^{+1.5}_{-1.3}$	3.1σ
4.5995	566.9	0.117	0.208	1.380	-3.6$^{+3.1}_{-2.5}$	0.7$^{+1.3}_{-0.9}$	-

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model I-2-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c2}$ (Data Set II)

\sqrt{s}	L(pb-1)	ϵ	$1+\delta$	σ^{dress}
4.0855	52.8	0.205	1.037	-18.1^{+9.2}_{-6.3}
4.2778	174.5	0.213	1.038	-4.3^{+3.8}_{-3.0}
4.3079	45.1	0.196	1.099	9.0^{+10.2}_{-6.9}
4.3874	55.6	0.178	1.189	3.2^{+8.7}_{-5.7}
4.4671	111.1	0.166	1.273	-6.6^{+3.5}_{-2.3}
4.4271	112.1	0.157	1.321	0.8^{+4.0}_{-2.4}
4.5745	48.9	0.152	1.361	-5.7^{+4.6}_{-1.6}

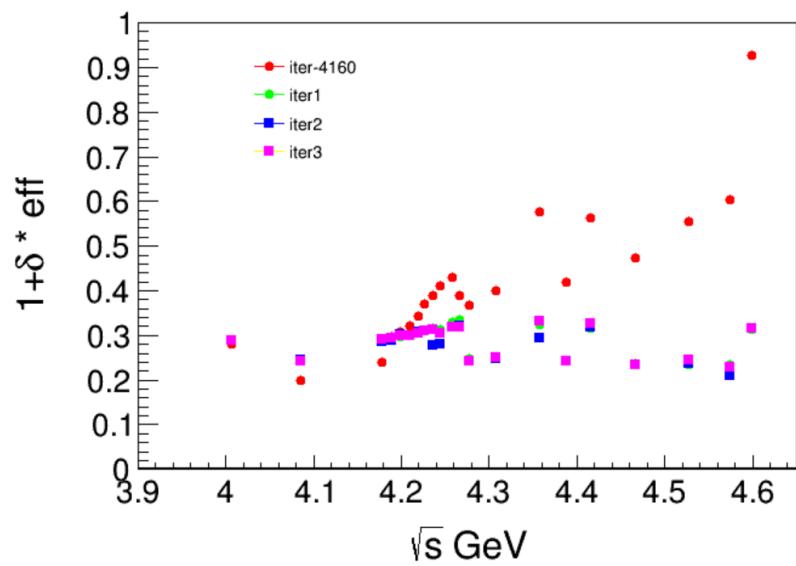
◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model II-3BW)

- Fit function: Suppose the line shape determined by $\psi(4040)$ and $\psi(4160)$ in $4\sim4.18\text{GeV}$, we use(simultaneously fit):

$$\sigma^{dress} = |BW(\psi(4040)) + BW(\psi(4160))e^{i\phi_1} + BW(R1)e^{i\phi_2}|^2;$$

- Fix $\psi(4040)$ and $\psi(4160)$ mass and width (PDG values);
- Three times iteration of the radiative correction procedure to get converge values (For the first time , we use $\psi(4160)$ line-shape to get radiative correction factor)

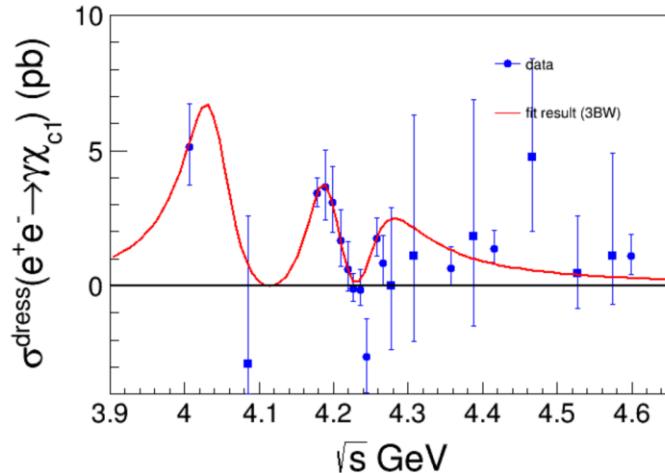
- $e^+e^- \rightarrow \gamma\chi_{c1}$ $(1+\delta) * eff$ only mu mu



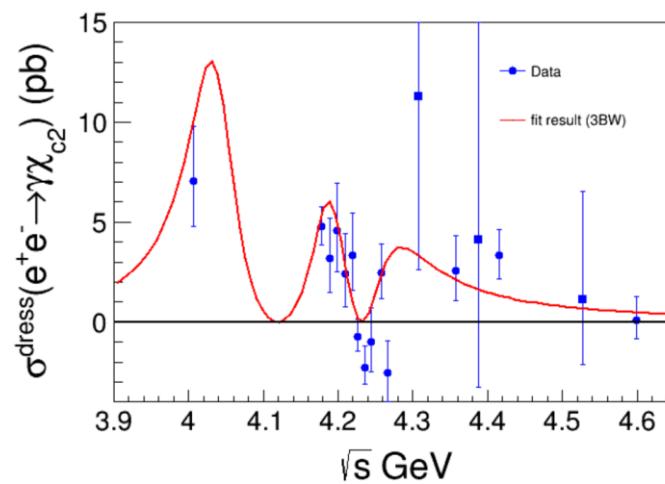
◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$

➤ Fitting result :

$e^+e^- \rightarrow \gamma\chi_{c1}$



$e^+e^- \rightarrow \gamma\chi_{c2}$



➤ Parameters:

Parameters	I
$M(\psi(4040))$	$4039(\text{fixed})$
$\Gamma_{tot}(\psi(4040))$	$80(\text{fixed})$
$\Gamma_{ee}\mathcal{B}(\psi(4040) \rightarrow \gamma\chi_{c1})$	0.8 ± 0.3
$\Gamma_{ee}\mathcal{B}(\psi(4040) \rightarrow \gamma\chi_{c2})$	1.6 ± 0.4
$M(\psi(4160))$	$4191(\text{fixed})$
$\Gamma_{tot}(\psi(4160))$	$70(\text{fixed})$
$\Gamma_{ee}\mathcal{B}(\psi(4160) \rightarrow \gamma\chi_{c1})$	1.0 ± 0.3
$\Gamma_{ee}\mathcal{B}(\psi(4160) \rightarrow \gamma\chi_{c2})$	1.8 ± 0.6
$M(R2)$	4244.8 ± 6.3
$\Gamma_{tot}(R2)$	83.2 ± 14.8
$\Gamma_{ee}\mathcal{B}(R2 \rightarrow \gamma\chi_{c1})$	0.8 ± 0.2
$\Gamma_{ee}\mathcal{B}(R2 \rightarrow \gamma\chi_{c2})$	1.5 ± 0.8

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model II-3-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c1}$ (Data Set I)

\sqrt{s}	L(pb-1)	ϵ_{ee}	ϵ_{uu}	$1+\delta$	$\sigma^{dress}(ee)$	$\sigma^{dress}(\mu\mu)$
4.0076	482.0	0.233	0.378	0.763	4.3^{+3.1}_{-2.7}	5.4^{+1.9}_{-1.7}
4.1783	3194.5	0.220	0.375	0.778	3.1^{+1.1}_{-1.0}	3.5^{+0.6}_{-0.6}
4.1888	522.5	0.222	0.374	0.783	0.5^{+2.6}_{-2.3}	4.8^{+1.6}_{-1.4}
4.1989	524.6	0.220	0.375	0.802	1.3^{+2.3}_{-1.9}	3.9^{+1.6}_{-1.4}
4.2092	518.1	0.216	0.363	0.825	1.7^{+2.7}_{-2.4}	1.6^{+1.3}_{-1.0}
4.2187	514.3	0.215	0.362	0.844	-2.0^{+2.3}_{-2.0}	1.2^{+1.1}_{-0.9}
4226.3	1047.3	0.214	0.363	0.853	-1.6^{+1.3}_{-1.1}	0.2^{+0.6}_{-0.5}
4.2357	530.6	0.213	0.363	0.863	-0.5^{+2.2}_{-1.8}	-0.1^{+0.8}_{-0.6}
4.2438	537.4	0.214	0.349	0.875	2.7^{+2.5}_{-2.2}	-5.4^{+1.7}_{-1.8}
4.258	825.7	0.207	0.347	0.917	4.3^{+2.2}_{-1.9}	1.4^{+0.8}_{-0.7}
4.2668	529.3	0.198	0.334	0.957	1.0^{+2.0}_{-1.6}	0.8^{+1.2}_{-1.0}
4.3583	539.8	0.122	0.210	1.577	-0.2^{+2.0}_{-1.6}	0.8^{+0.8}_{-0.7}
4.4156	1028.9	0.095	0.164	1.985	-0.3^{+1.3}_{-1.1}	2.0^{+0.8}_{-0.7}
4.5995	566.9	0.054	0.097	3.244	-0.1^{+2.0}_{-1.6}	1.3^{+0.9}_{-0.7}

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model II-3-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c1}$ (Data Set II)

\sqrt{s}	L(pb-1)	ϵ	$1+\delta$	σ^{dress}
4.0855	52.8	0.264	0.901	$-2.9^{+5.5}_{-3.7}$
4.2778	174.5	0.237	1.049	$0^{+2.9}_{-2.3}$
4.3079	45.1	0.205	1.289	$1.1^{+5.2}_{-3.2}$
4.3874	55.6	0.135	2.004	$1.8^{+5.0}_{-3.3}$
4.4671	111.1	0.099	2.712	$4.8^{+3.6}_{-2.7}$
4.4271	112.1	0.089	3.240	$0.4^{+2.1}_{-1.3}$
4.5745	48.9	0.075	3.657	$1.1^{+3.8}_{-1.8}$

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model II-3-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c2}$ (Data Set I)

\sqrt{s}	L(pb-1)	ϵ_{ee}	ϵ_{uu}	$1+\delta$	$\sigma^{dress}(ee)$	$\sigma^{dress}(\mu\mu)$
4.0076	482.0	0.222	0.357	0.760	13.6^{+6.3}_{-5.5}	5.6^{+3.0}_{-2.5}
4.1783	3194.5	0.208	0.339	0.779	5.2^{+2.1}_{-2.0}	4.7^{+1.1}_{-1.0}
4.1888	522.5	0.206	0.350	0.780	4.0^{+5.2}_{-4.5}	3.1^{+2.2}_{-1.8}
4.1989	524.6	0.209	0.349	0.797	9.7^{+5.6}_{-4.9}	3.4^{+2.7}_{-2.2}
4.2092	518.1	0.204	0.338	0.818	9.2^{+6.2}_{-5.5}	1.7^{+2.2}_{-1.7}
4.2187	514.3	0.201	0.337	0.838	-0.7^{+5.1}_{-4.5}	4.2^{+2.4}_{-2.0}
4226.3	1047.3	0.205	0.343	0.851	-1.1^{+2.5}_{-2.2}	-0.7^{+0.9}_{-0.7}
4.2357	530.6	0.203	0.335	0.864	5.3^{+2.6}_{-2.0}	-1.7^{+1.2}_{-0.9}
4.2438	537.4	0.197	0.332	0.880	4.5^{+4.2}_{-3.6}	-2.1^{+1.9}_{-1.6}
4.258	825.7	0.189	0.323	0.932	2.6^{+3.5}_{-3.1}	2.4^{+1.6}_{-1.4}
4.2668	529.3	0.186	0.315	0.979	4.9^{+4.3}_{-3.7}	-3.7^{+1.6}_{-1.5}
4.3583	539.8	0.104	0.179	1.739	1.9^{+4.4}_{-3.8}	2.6^{+1.9}_{-1.6}
4.4156	1028.9	0.075	0.135	2.263	1.3^{+3.0}_{-2.6}	3.8^{+1.5}_{-1.3}
4.5995	566.9	0.043	0.075	3.882	-3.5^{+3.1}_{-2.5}	0.7^{+1.3}_{-1.0}

◆ The line shape of $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ (Model II-3-BW)

➤ Cross section $e^+e^- \rightarrow \gamma\chi_{c2}$ (Data Set II)

\sqrt{s}	L(pb-1)	ϵ	$1+\delta$	σ^{dress}
4.0855	52.8	0.205	1.037	-18.1^{+9.2}_{-6.3}
4.2778	174.5	0.213	1.038	-4.3^{+3.8}_{-3.0}
4.3079	45.1	0.196	1.099	9.0^{+10.2}_{-6.9}
4.3874	55.6	0.178	1.189	3.2^{+8.7}_{-5.7}
4.4671	111.1	0.166	1.273	-6.6^{+3.5}_{-2.3}
4.4271	112.1	0.157	1.321	0.8^{+4.0}_{-2.4}
4.5745	48.9	0.152	1.361	-5.7^{+4.6}_{-1.6}

◆ Compare these two fit methods

- $-\log(L)$:

2-BW $-\log(L)=165.5$

3-BW $-\log(L)=173.8$

Can't distinguish these two methods;

- For Resonance: Consistent with each other , Also consistent with $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ channel;

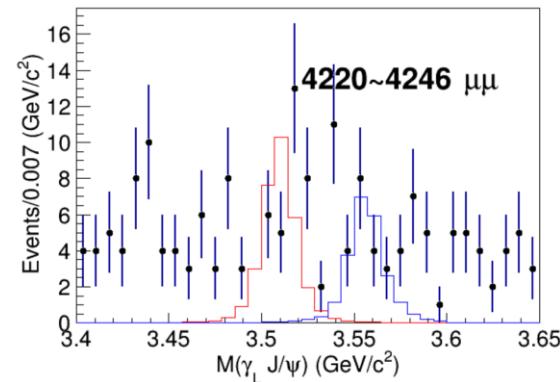
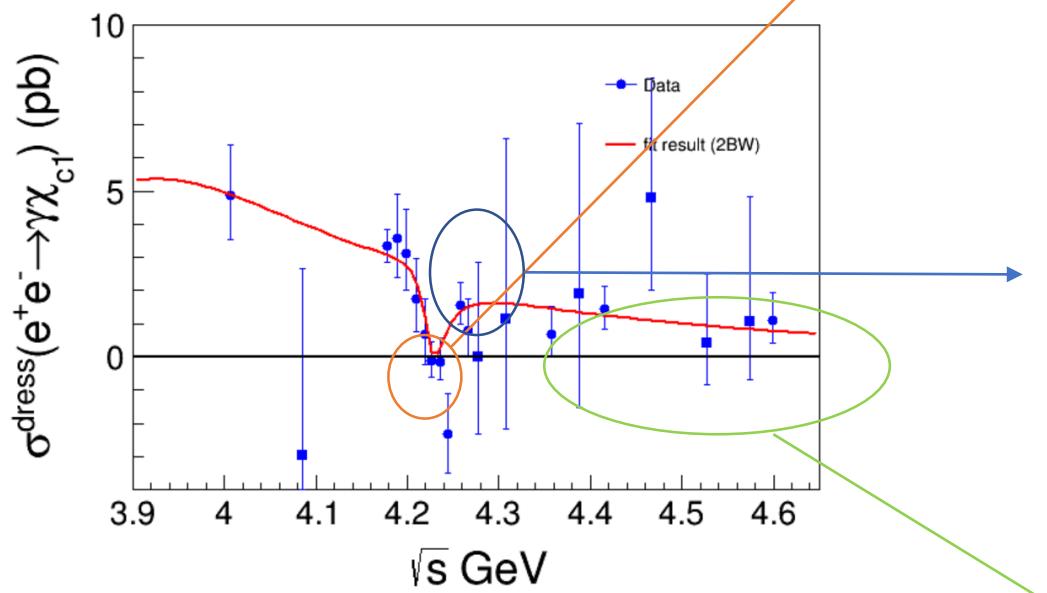
2-BW

Parameters (MeV)	$e^+ e^- \rightarrow \gamma \chi_{c1,2}$
M(R2)	4225.6 ± 2.6
$\Gamma(R2)$	28.5 ± 5.4

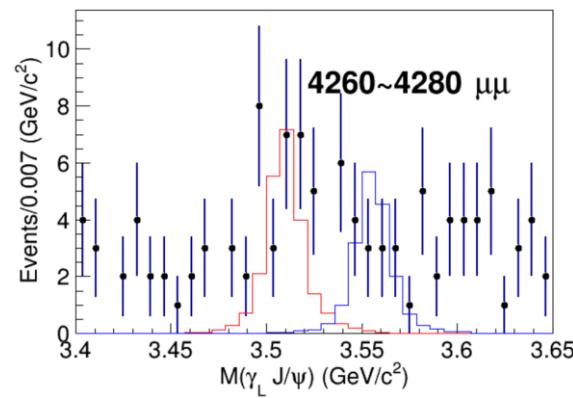
3-BW

Parameters(MeV)	$e^+ e^- \rightarrow \gamma \chi_{c1,2}$
M(R1)	4247.2 ± 6.2
$\Gamma(R1)$	82.5 ± 14.1

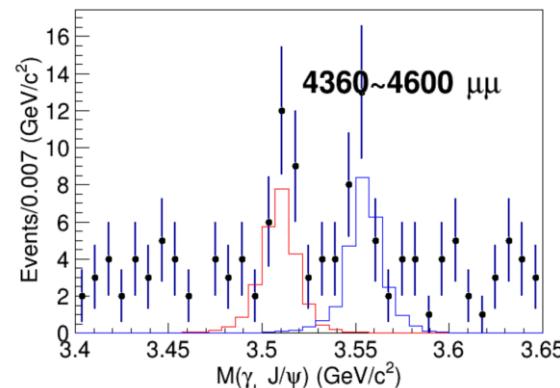
◆ Confirm the dip around 4.23GeV



$\mathcal{L} \sim 2683.2$



$\mathcal{L} \sim 1533.6$



$\mathcal{L} \sim 2221.5$

◆ Systematic uncertainty (Cross Section)

- The luminosity : measured using Bhabha events, with uncertainty 1.0%;
- Tracking efficiency : 1% is assigned to each track, 2% in total ;
- branching ratios : 0.6% for each channel $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$;
- branching ratios : 3.5% for $\chi_{c1} \rightarrow \gamma J/\psi$, 3.6% for $\chi_{c2} \rightarrow \gamma J/\psi$;
- Photon efficiency: each 1%, total 2%;
- Fit to $M(\gamma_L J/\psi)$:
 - Change background shape 2nd —> 3rd ;
 - Fit Range-----> (3.4,3.65) -> (3.45,3.7)

$\chi_{c1} \sim \mathbf{4.8\%}$ $\chi_{c2} \sim \mathbf{7.2\%}$
- Kinematic fit:

The difference efficiency between before and after pull correction;
 $\chi_{c1} \sim \mathbf{2.4\%}$, $\chi_{c2} \sim \mathbf{2.3\%}$

Use 4180

◆ Systematic uncertainty (Cross Section)

- Radiative correction: Take the difference $\varepsilon * (1 + \delta)$ between two fit models as systematic uncertainty;
 $\chi_{c1} \sim 2.7\% \quad \chi_{c2} \sim 1\% \quad @4180$
- Total systematic uncertainty : $e^+e^- \rightarrow \gamma\chi_{c1} \sim 7.5\% ;$
 $e^+e^- \rightarrow \gamma\chi_{c2} \sim 8.9\%;$

◆ Systematic uncertainty (Resonance Y(4220))

- The CMS energies of all dataset: 1MeV for mass mesurement;
- The difference of Two models(width and mass);

Parameters(MeV)	$e^+e^- \rightarrow \gamma\chi_{c1,2}$
M(Y(4220))	$4225.6 \pm 2.7 \pm 20.2$
$\Gamma_{tot}(Y(4220))$	$28.5 \pm 5.4 \pm 54.7$

◆ Upper Limit for (significance <3 σ)

- To evaluate the upper limits of cross section at 90% C.L. :
Define likelihood function:

$$\mathcal{L}(N_0) = \int G(N_0, N_0\sigma) * \mathcal{L}(N) dN$$

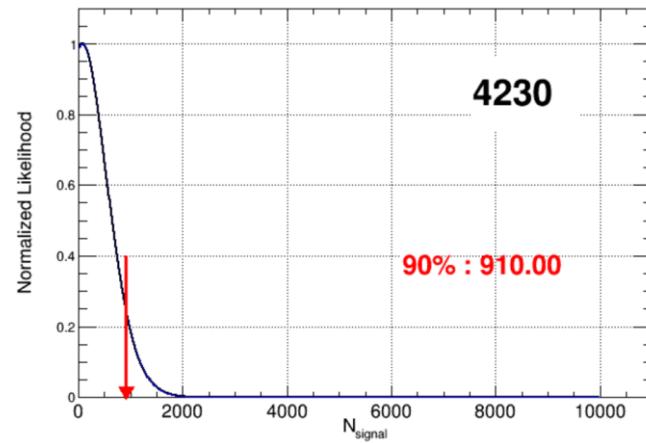
- N_0 is the fixed number of signal events;
- $G(N_0, N_0\sigma)$ is Gauss function, σ is systematic uncertainty ;
- The upper limit on the cross section is calculated with following formula:

$$\sigma_{born}^{up} = \frac{N^{up}}{\mathcal{L} \cdot \mathcal{B} \cdot \epsilon \cdot (1 + \delta) \cdot (1 + \delta^{VP})}$$

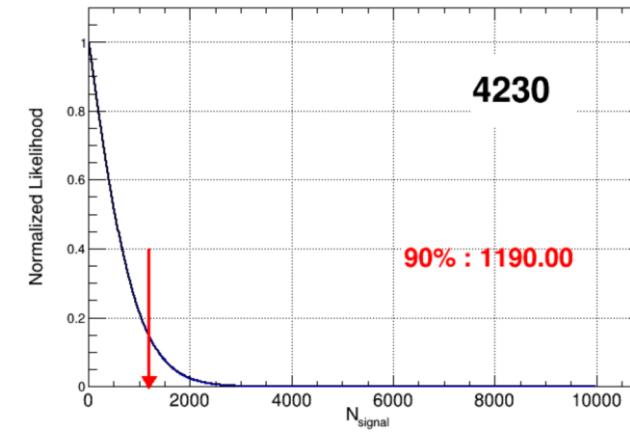
◆ Upper Limit @4230

- After consider to system uncertainty, we give the number of signal upper limit at 90% confidence level:
- Total systematic uncertainty : $e^+e^- \rightarrow \gamma\chi_{c1} \sim 8.5\%$;
 $e^+e^- \rightarrow \gamma\chi_{c2} \sim 15.8\%$;

$e^+e^- \rightarrow \gamma\chi_{c1}$



$e^+e^- \rightarrow \gamma\chi_{c2}$



$$\sigma_{born}^{up} < 0.8 \text{ pb}$$

$$\sigma_{born}^{up} < 1.4 \text{ pb}$$

◆ Upper Limit (For $<3\sigma$)

- After consider to system uncertainty, we give the number of signal upper limit at 90% confidence level:

$$e^+ e^- \rightarrow \gamma \chi_{c1}$$

C.M	Sys error(%)	Upper Limit(pb)
4210	8.6	2.8
4220	10.8	1.8
4230	8.5	0.8
4237	10.3	1.3
4246	18.2	0.9
4260	13.5	2.2
4270	10.7	2.4
4360	8.1	1.6
4420	8.1	2.0
4600	7.3	2.24

$$e^+ e^- \rightarrow \gamma \chi_{c2}$$

C.M	Sys error(%)	Upper Limit(pb)
4190	12.1	4.1
4200	9.7	5.7
4210	9.6	5.1
4220	13.5	6.3
4230	15.8	1.4
4237	11.9	1.4
4246	8.8	4.0
4260	8.9	3.1
4270	9.4	2.1
4360	10.8	4.7
4600	9.0	1.9

Section II $e^+e^- \rightarrow \gamma\chi_{c0}$

◆ DATA Set

- Boss version boss703
- DATA

XYZ data

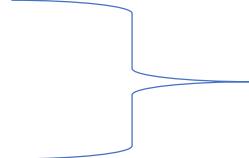
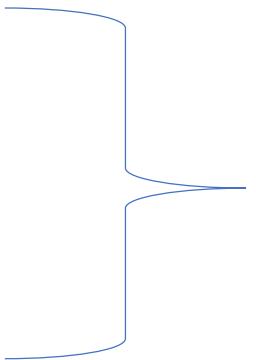


DataSet :

C.M	$\sqrt{s}(\text{MeV})$	$L (\text{pb}^{-1})$
4009	4007.6	482.0
4180	4173.0	3189.0
4190	4189.3	521.9
4200	4199.6	523.7
4210	4209.7	511.2
4220	4218.8	508.2
4230	4226.3	1047.3
4237	4235.8	508.9
4246	4243.9	532.7
4260	4258.0	825.7
4270	4266.9	529.3
4360	4358.3	539.8
4420	4415.6	1028.9
4600	4599.5	566.9

◆ MC Samples for $\chi_{c0} \rightarrow K^+K^- \pi^+\pi^- / \pi^+\pi^- \pi^+\pi^-$

- In PDG, χ_{c0} can mainly decay to $K^+K^- \pi^+\pi^- \pi^+\pi^- \pi^+\pi^-$ through the following channel:

Γ_1	$2(\pi^+\pi^-)$	$(2.34 \pm 0.18) \%$		$\pi^+\pi^- \pi^+\pi^-$
Γ_2	$\rho^0\pi^+\pi^-$	$(9.1 \pm 2.9) \times 10^{-3}$		
Γ_3	$\rho^0\rho^0$			
Γ_4	$f_0(980)f_0(980)$	$(6.6 \pm 2.1) \times 10^{-4}$		
Γ_8	$\pi^+\pi^- K^+K^-$	$(1.81 \pm 0.14) \%$		$K^+K^- \pi^+\pi^-$
Γ_9	$K_0^*(1430)^0 \bar{K}_0^*(1430)^0 \rightarrow \pi^+\pi^- K^+K^-$	$(9.8 \pm 4.0) \times 10^{-4}$		
Γ_{10}	$K_0^*(1430)^0 \bar{K}_2^*(1430)^0 + \text{c.c.} \rightarrow \pi^+\pi^- K^+K^-$	$(8.0 \pm 2.0) \times 10^{-4}$		
Γ_{11}	$K_1(1270)^+ K^- + \text{c.c.} \rightarrow \pi^+\pi^- K^+K^-$	$(6.3 \pm 1.9) \times 10^{-3}$		
Γ_{12}	$K_1(1400)^+ K^- + \text{c.c.} \rightarrow \pi^+\pi^- K^+K^-$	$< 2.7 \times 10^{-3}$		$\text{CL}=90\%$
Γ_{14}	$f_0(980)f_0(2200)$	$(7.9 \pm 2.0) \times 10^{-4}$		
Γ_{17}	$f_0(1370)f_0(1710)$	$(6.7 \pm 3.5) \times 10^{-4}$		
Γ_{30}	$K^+\bar{K}^*(892)^0 \pi^- + \text{c.c.}$	$(7.5 \pm 1.6) \times 10^{-3}$		
Γ_{31}	$K^*(892)^0 \bar{K}^*(892)^0$	$(1.7 \pm 0.6) \times 10^{-3}$		

◆ MC Samples for $\chi_{c0} \rightarrow K^+K^- \pi^+\pi^- / \pi^+\pi^- \pi^+\pi^-$

- **Signal MC**

$$e^+e^- \rightarrow Y(4260) \rightarrow \gamma\chi_{c0}$$



P2GC0

➤ $\pi^+\pi^- \pi^+\pi^-$

1. $\chi_{c0} \rightarrow \pi^+\pi^- \pi^+\pi^-$; PHSP

2. $\chi_{c0} \rightarrow \rho^0\pi^+\pi^-$;

3. $\chi_{c0} \rightarrow f_0(980)f_0(980)$;

➤ $K^+K^- \pi^+\pi^-$

1. $\chi_{c0} \rightarrow K^+K^-\pi^+\pi^-$; PHSP

2. $\chi_{c0} \rightarrow \overline{K}_0^*(1430)^0 K_0^*(1430)^0$;

3. $\chi_{c0} \rightarrow \overline{K}_0^*(1430)^0 K_2^*(1430)^0 + \text{c.c.}$;

4. $\chi_{c0} \rightarrow K_1(1270)^+ + \text{c.c.}$;

5. $\chi_{c0} \rightarrow K_1(1400)^+ + \text{c.c.}$;

6. $\chi_{c0} \rightarrow f_0(980)f_0(2200)$;

7. $\chi_{c0} \rightarrow f_0(1370)f_0(1710)$;

8. $\chi_{c0} \rightarrow \overline{K}^*(892)^0 \pi^- K^+ + \text{c.c.}$;

9. $\chi_{c0} \rightarrow \overline{K}^*(892)^0 K^* (892)^0$;

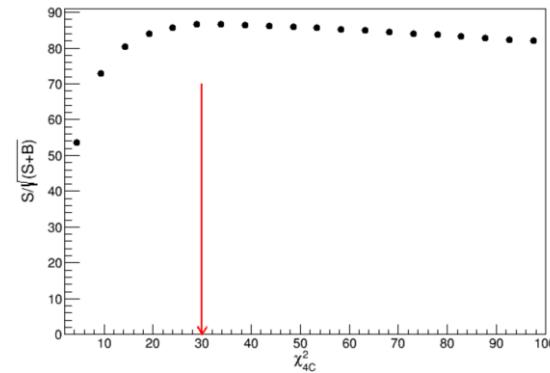
◆ Event Selection

- Initial selection:
 - Charged tracks: N=4
 - photon : good photon ≥ 1
 - PID:
 - K: Prob(K)>Prob(π), Prob(K)>0.001
 - π : Prob(π)>Prob(K), Prob(π)>0.001
- Retain the photon with the large energy
- 4C Kinematic fit:

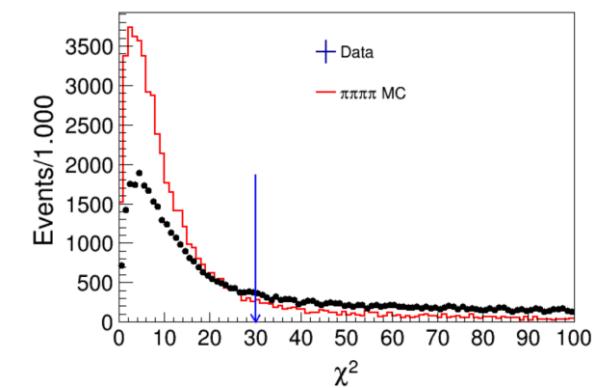
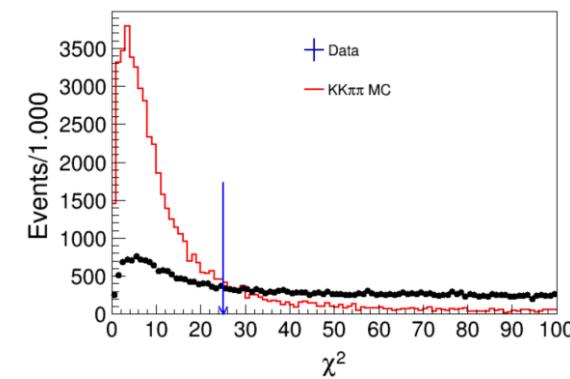
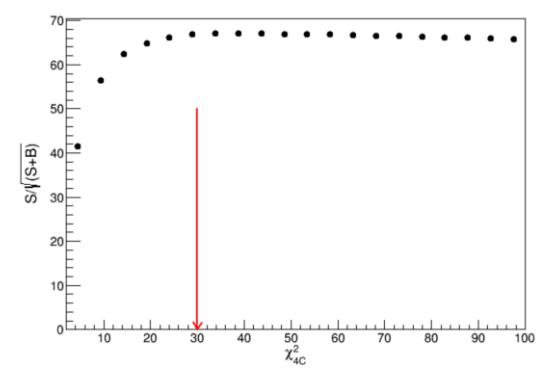
$$\chi^2 < 30 \quad \chi_{c0} \rightarrow K^+K^- \pi^+\pi^-$$

$$\chi^2 < 30 \quad \chi_{c0} \rightarrow \pi^+\pi^- \pi^+\pi^-$$

$$\chi_{c0} \rightarrow K^+K^- \pi^+\pi^-$$

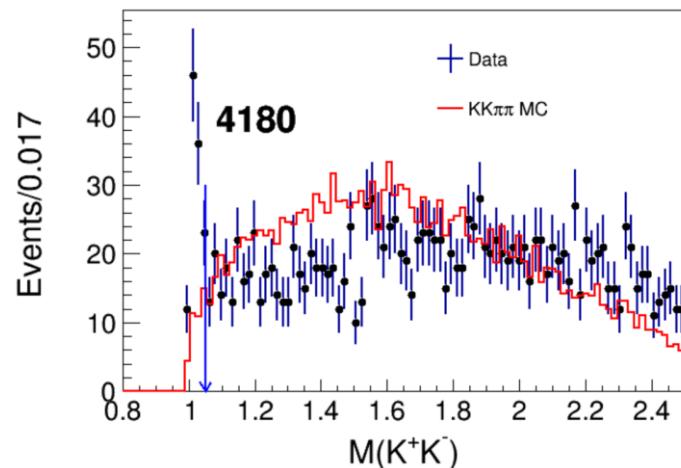


$$\chi_{c0} \rightarrow \pi^+\pi^- \pi^+\pi^-$$



◆ Background study in $K^+K^- \pi^+\pi^-$ mode

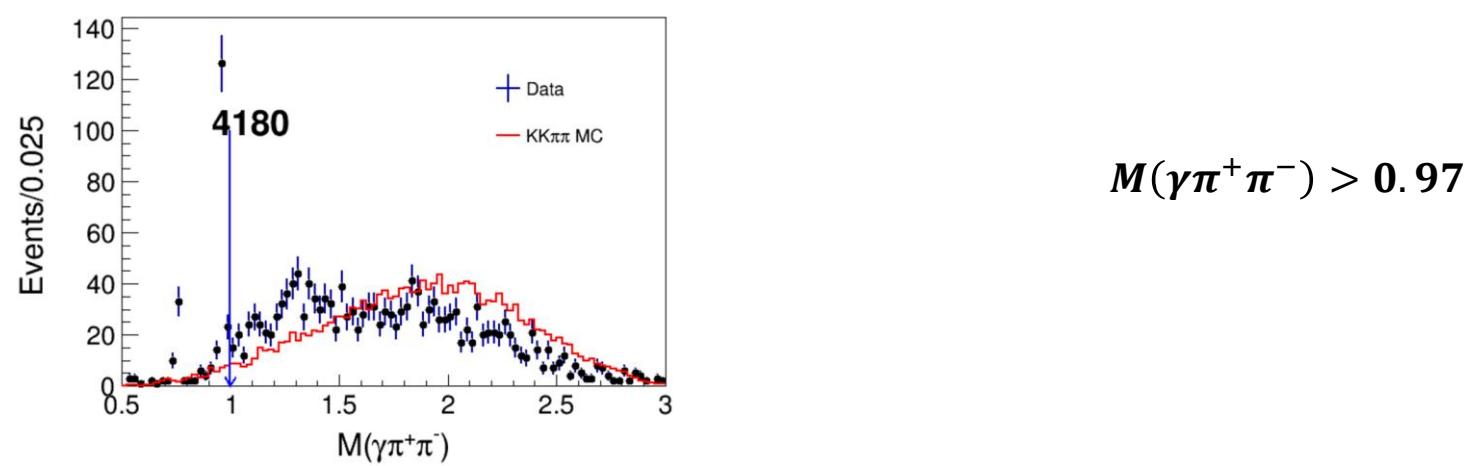
- background events mainly come from:
 1. $e^+e^- \rightarrow (n)\gamma_{ISR} K^+K^- \pi^+\pi^-;$
 2. $e^+e^- \rightarrow \gamma_{ISR} K^*\bar{K}^*$;
 3. $e^+e^- \rightarrow (n)\gamma_{ISR} K^- \pi^- K^* + c.c.;$
 4. include $\phi \rightarrow K^+K^-$ background;
 5. include $\eta' \rightarrow \gamma\rho_0 (\rho_0 \rightarrow \pi^+\pi^-)$ background;
 6. include $\rho_0 \rightarrow \pi^+\pi^-$ background;
- For $\phi \rightarrow K^+K^-$ background in $M(K^+K^- \pi^+\pi^-) \in [3.2,3.6]$:



- $M(K^+K^-) > 1.05 \text{ GeV}$

◆ Background study in $K^+K^-\pi^+\pi^-$ mode

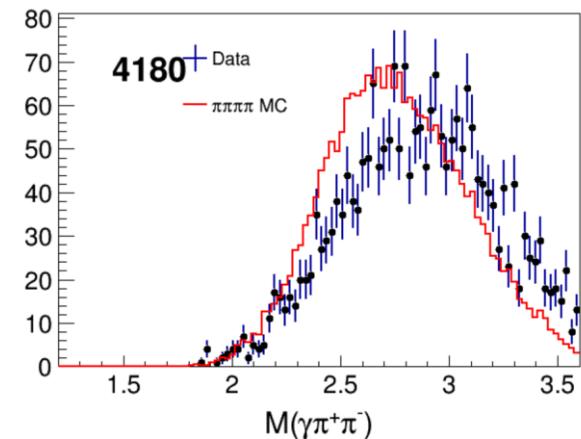
- background events mainly come from:
 1. $e^+e^- \rightarrow (n)\gamma_{ISR} K^+K^-\pi^+\pi^-;$
 2. $e^+e^- \rightarrow \gamma_{ISR} K^*\bar{K}^*$;
 3. $e^+e^- \rightarrow (n)\gamma_{ISR} K^-\pi^-K^* + c.c.;$
 4. include $\phi \rightarrow K^+K^-$ background;
 5. include $\eta' \rightarrow \gamma\rho_0 (\rho_0 \rightarrow \pi^+\pi^-)$ background;
 6. include $\rho_0 \rightarrow \pi^+\pi^-$ background;
- η' background in $M(K^+K^-\pi^+\pi^-) \in [3.2,3.6]$:



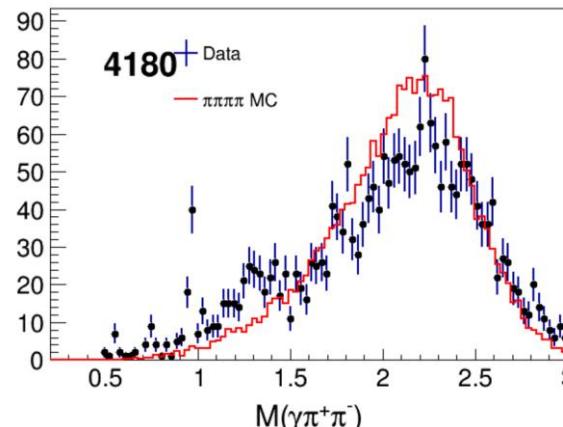
◆ Background study in $\pi^+\pi^- \pi^+\pi^-$ mode

- background events mainly come from:
 - $e^+e^- \rightarrow (n)\gamma_{ISR}\pi^+\pi^-\pi^+\pi^-$;
 - $e^+e^- \rightarrow (n)\gamma_{ISR}\pi^+\pi^-\pi^+\pi^-$;
 - include $\rho_0 \rightarrow \pi^+\pi^-$ background;
 - include $\eta' \rightarrow \gamma\pi^+\pi^-$ background;
- All combinations of $\gamma\pi^+\pi^-$ pairs in $M(\pi^+\pi^- \pi^+\pi^-) \in [3.2, 3.6]$

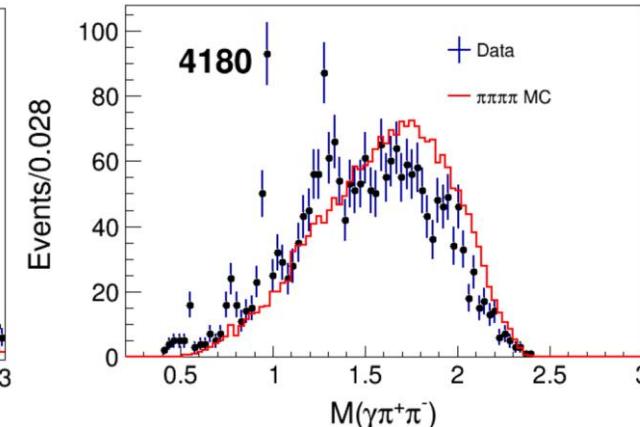
• $M(\gamma\pi^+\pi^- \text{hh})$



• $M(\gamma\pi^+\pi^- \text{lh})$



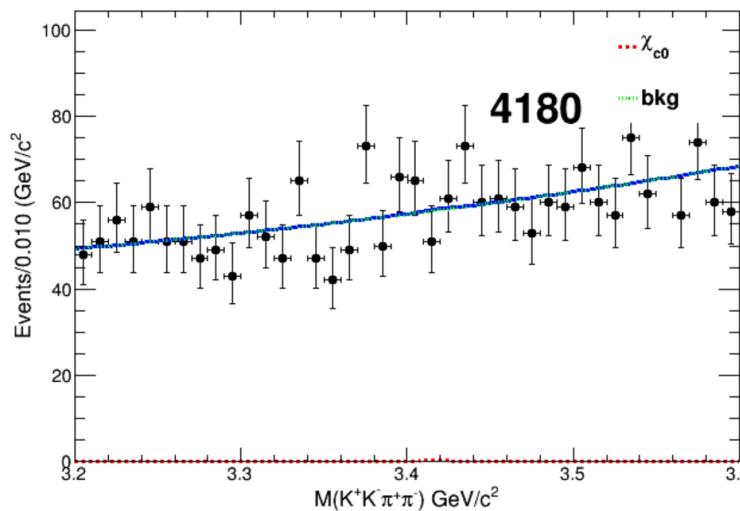
• $M(\gamma\pi^+\pi^- \text{ll})$



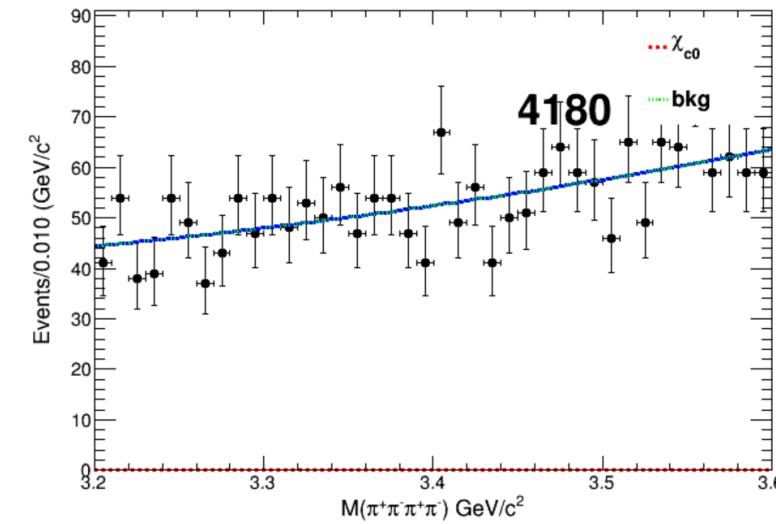
$|M(\gamma\pi^+\pi^-) - M(\eta')| > 0.01 \text{GeV}$

◆ Fit to $M(\pi^+\pi^- \pi^+\pi^-)$ and $M(k^+k^- \pi^+\pi^-)$

- Fit Method: Fit two channel simultaneously;
- MC shape + 2nd polynomial;



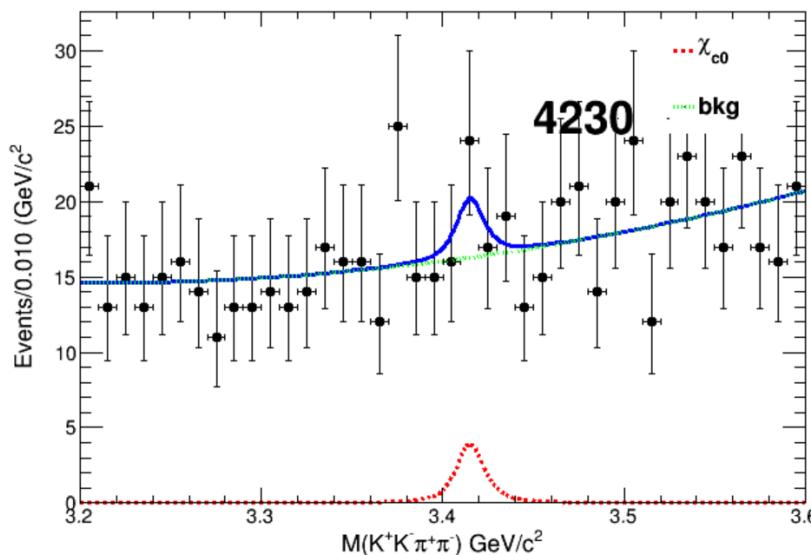
$$\chi_{c0} \rightarrow K^+K^-\pi^+\pi^-$$



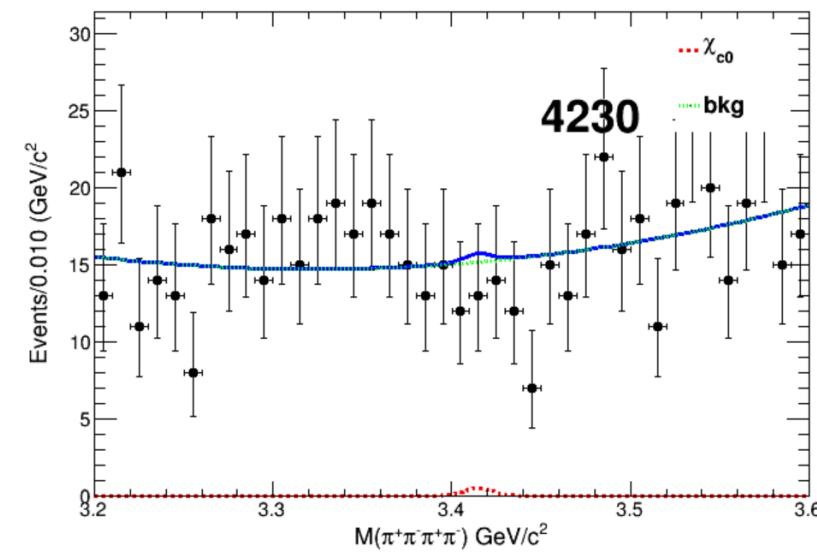
$$\chi_{c0} \rightarrow \pi^+\pi^-\pi^+\pi^-$$

◆ Fit to $M(\pi^+\pi^- \pi^+\pi^-)$ and $M(k^+k^- \pi^+\pi^-)$

- Fit Method: Fit two channel simultaneously;
- MC shape + 2nd polynomial;



$$\chi_{c0} \rightarrow K^+K^-\pi^+\pi^-$$



$$\chi_{c0} \rightarrow \pi^+\pi^-\pi^+\pi^-$$

◆ Systematic uncertainty

- The luminosity : measured using Bhabha events, with uncertainty 1.0%;
- Tracking efficiency : 1% is assigned to each track, 4% in total ;
- branching ratios : 8% for $\chi_{c0} \rightarrow k^+k^- \pi^+\pi^-$, 8% for $\chi_{c0} \rightarrow \pi^+\pi^- \pi^+\pi^-$;
- PID: ,1.0% per kaon or pion $\sim 4\%$;
- Kinematic fit:
The difference efficiency between before and after pull correction;
 $\chi_{c0} \rightarrow k^+k^- \pi^+\pi^- \sim 6\%$, $\chi_{c0} \rightarrow \pi^+\pi^- \pi^+\pi^- \sim 2\%$;
- Radiative correction:use $e^+e^- \rightarrow \gamma\chi_{c1}$ line shape, take the difference $\varepsilon * (1 + \delta)$ between 2-bw and 3-bw model as systematic uncertainty; $\sim 2.7\% \sim 1\%$
- @4180 Total systematic uncertainty : $\chi_{c0} \rightarrow k^+k^- \pi^+\pi^- \sim 11.8\%$;
 $\chi_{c0} \rightarrow \pi^+\pi^- \pi^+\pi^- \sim 10.9\%$;

Use 4180

◆ Upper Limit

- To evaluate the upper limits of cross section at 90% C.L. :
Define likelihood fuction:

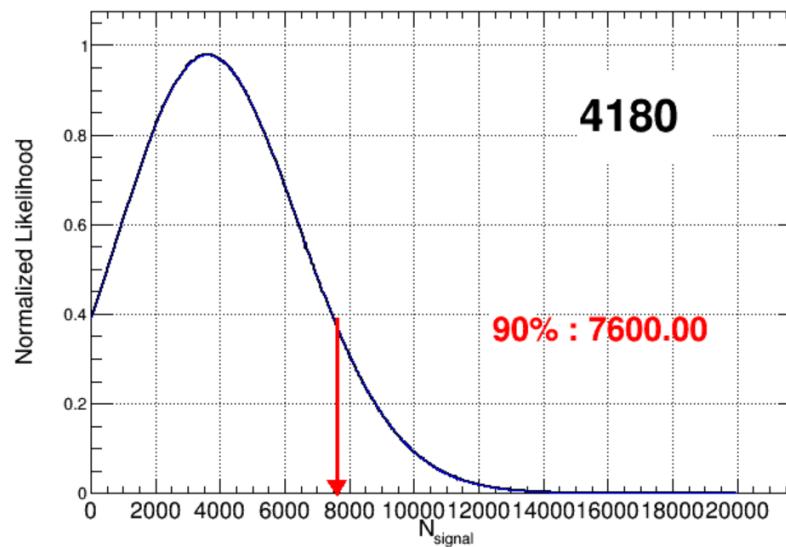
$$\mathcal{L}(N_0) = \int G(N_0, N_0\sigma) * \mathcal{L}(N) dN$$

- N_0 is the fixed number of signal events;
- $G(N_0, N_0\sigma)$ is Gauss function, σ is systematic uncertainty ;
- The upper limit on the cross section is calculated with following formula:

$$\sigma_{born}^{up} = \frac{N^{up}}{\mathcal{L} \cdot \mathcal{B} \cdot \epsilon \cdot (1 + \delta) \cdot (1 + \delta^{VP})}$$

Upper limit @4180

- Suppose $e^+e^- \rightarrow \gamma\chi_{c0}$ follow $e^+e^- \rightarrow \gamma\chi_{c1}'$ line shape (P19), we generate signal MC samples ;
- Similarly, After consider to systematic uncertainty,we give the number of signal upper limit at 90% confidence level:



- $\sigma_{\text{born}}^{up} < 2.4 \text{ pb}$;

◆ Summary

- Using data above e^+e^- CM energy ~ 4 GeV, we observed $e^+e^- \rightarrow \gamma\chi_{c1,c2}$ at 4180, evidence for $e^+e^- \rightarrow \gamma\chi_{c1}$ at 4009@4190@4200, evidence for $e^+e^- \rightarrow \gamma\chi_{c2}$ at 4009@4420;
- Branch ratio(4180) about $\mathcal{B}(e^+e^- \rightarrow \gamma\chi_{c1}/ e^+e^- \rightarrow \gamma\chi_{c2}) \approx 0.767^{+0.258}_{-0.242}$, there is a big difference from theoretical prediction about $\psi(4160)$ E1 radiative transitions ;
- Both $e^+e^- \rightarrow \gamma\chi_{c1}$ and $e^+e^- \rightarrow \gamma\chi_{c2}$ show there are a dip around 4230, which might be due to the interference of the $\Upsilon(4220)$ resonance;
- Using $\chi_{c0} \rightarrow K^+K^- \pi^+\pi^- / \pi^+\pi^- \pi^+\pi^-$, we don't observe $e^+e^- \rightarrow \gamma\chi_{c0}$ signal, upper limit of born cross sections are given;

Thanks!

Back Up

◆ MC for $\chi_{c0} \rightarrow K^+K^- \pi^+\pi^- / \pi^+\pi^- \pi^+\pi^-$

- Decay card:

$\pi^+\pi^- \pi^+\pi^-$

```

Decay psi(4260)
1.00 gamma chi_c0          P2GC0;
Enddecay
#
Decay chi_c0
0.01364 pi+ pi- pi+ pi- PHSP;
0.0091 rho0 pi+ pi-      PHSP;
0.00066 f_0   f_0         PHSP;
Enddecay
#
#
Decay rho0
1.000 pi+   pi-          VSS;
Enddecay

Decay f_0
1.000 pi+   pi-          PHSP;
Enddecay

End

```

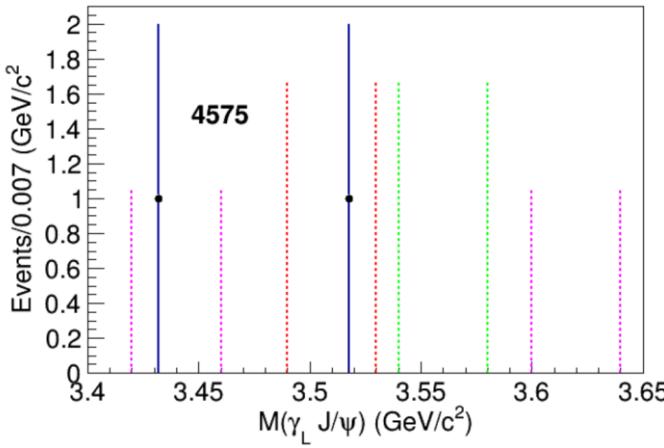
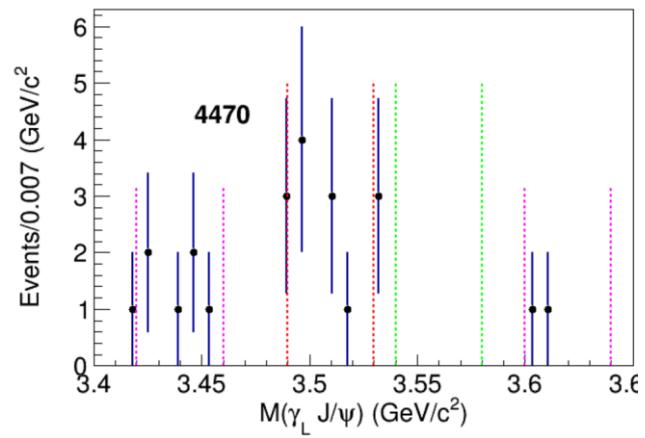
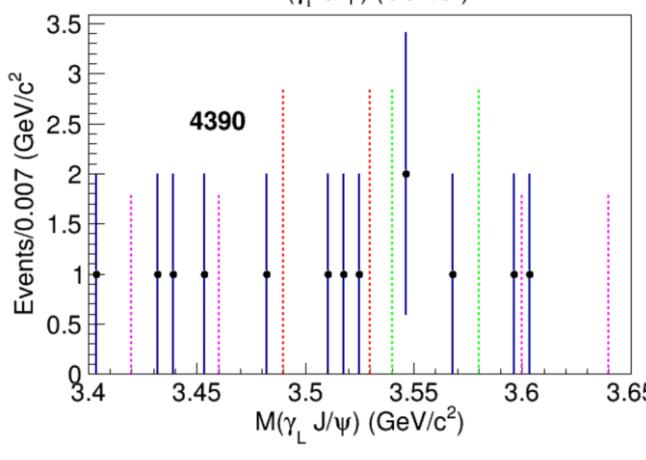
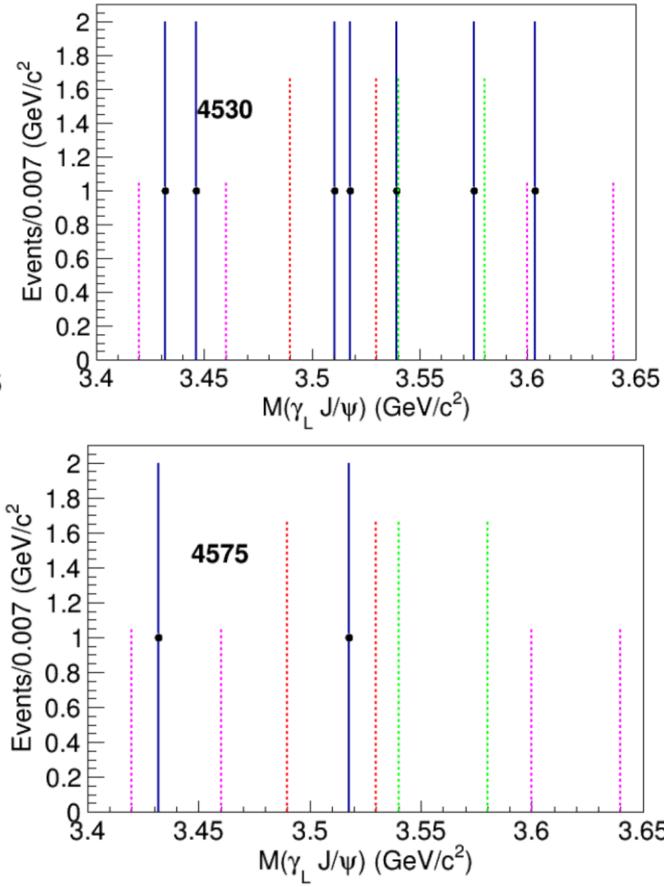
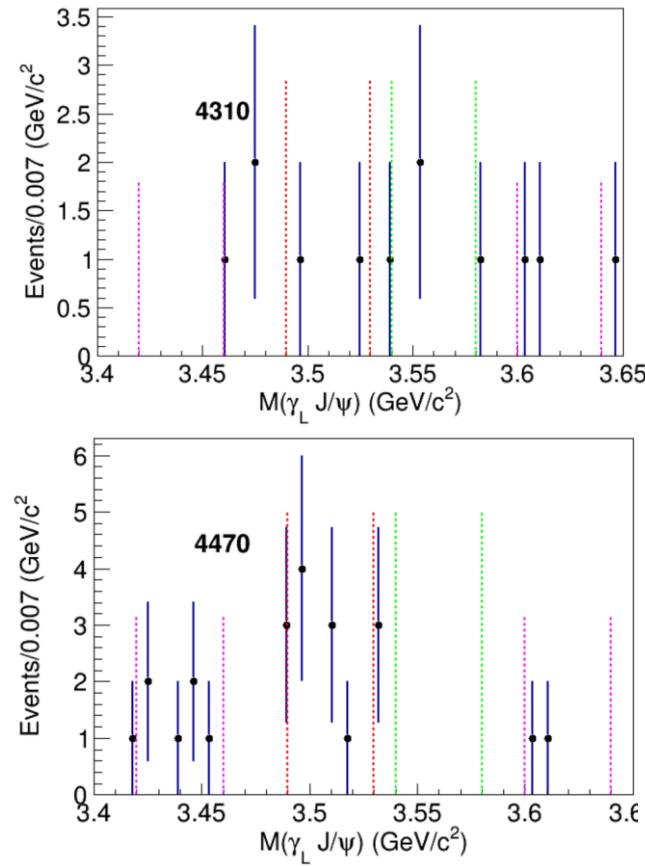
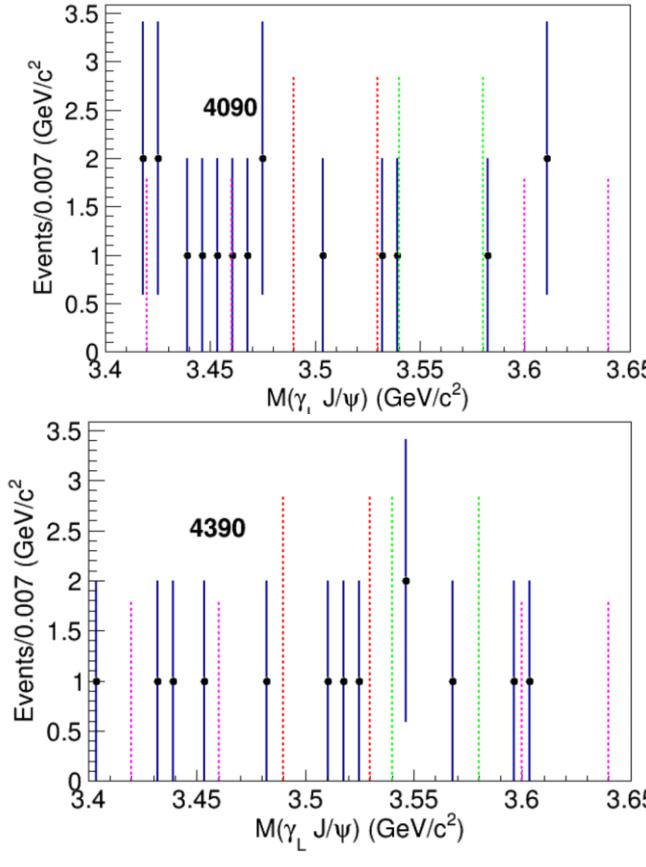
$K^+K^- \pi^+\pi^-$

```

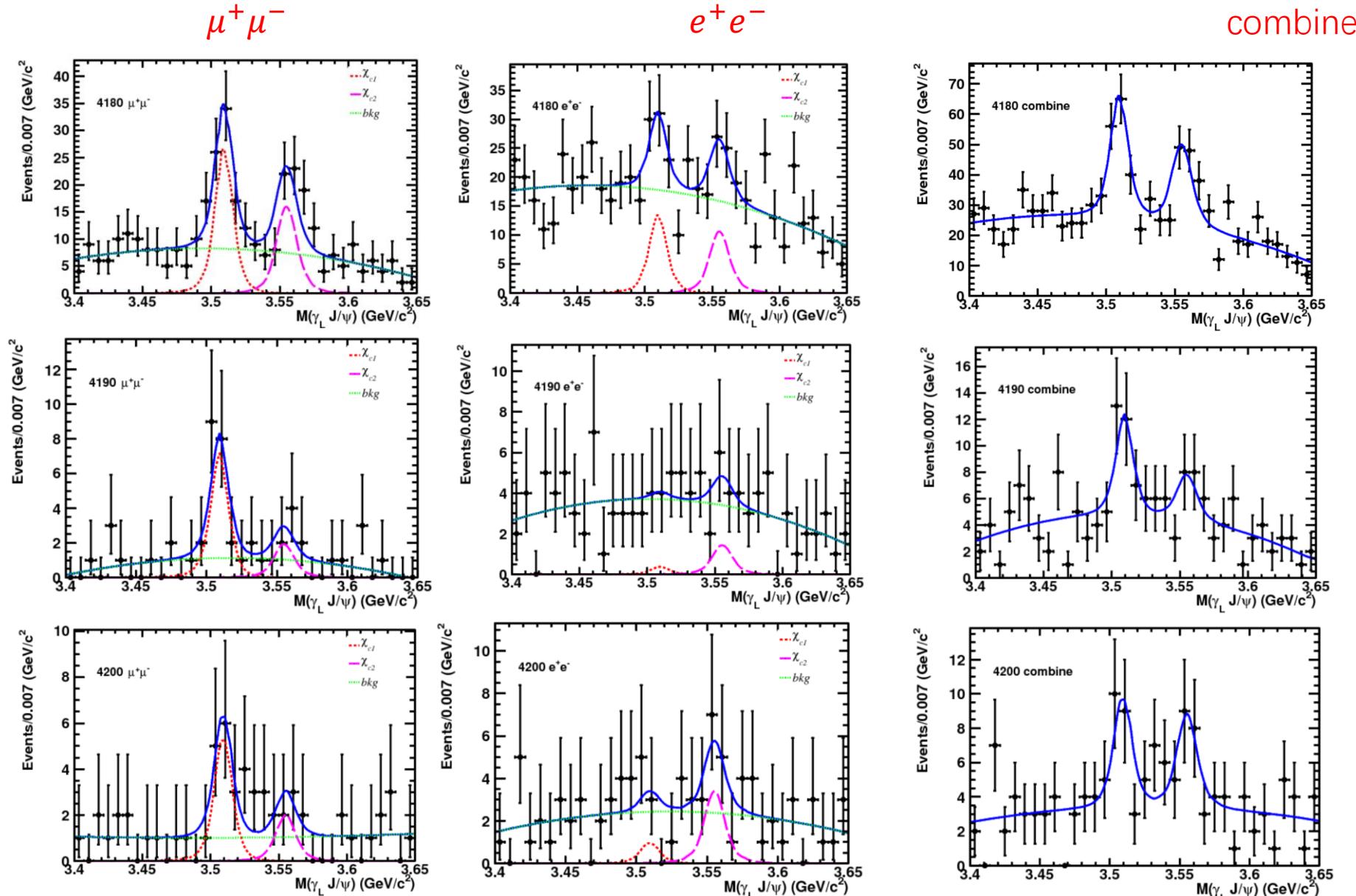
Decay psi(4260)
1.00 gamma chi_c0          P2GC0;
Enddecay
#
Decay chi_c0
0.00098 K_0*0  anti-K_0*0    PHSP;
0.0004  K_0*0   anti-K_2*0    PHSP;
0.0004  anti-K_0*0  K_2*0    PHSP;
0.00315 K_1+   K-           PHSP;
0.00315 K_1-   K+           PHSP;
0.01   K+   K-   pi+   pi-  PHSP;
0.0017  K*0   anti-K*0     PHSP;
0.00375 K+   anti-K*0  pi-  PHSP;
0.00375 K-   K*0   pi+  PHSP;
Enddecay

```

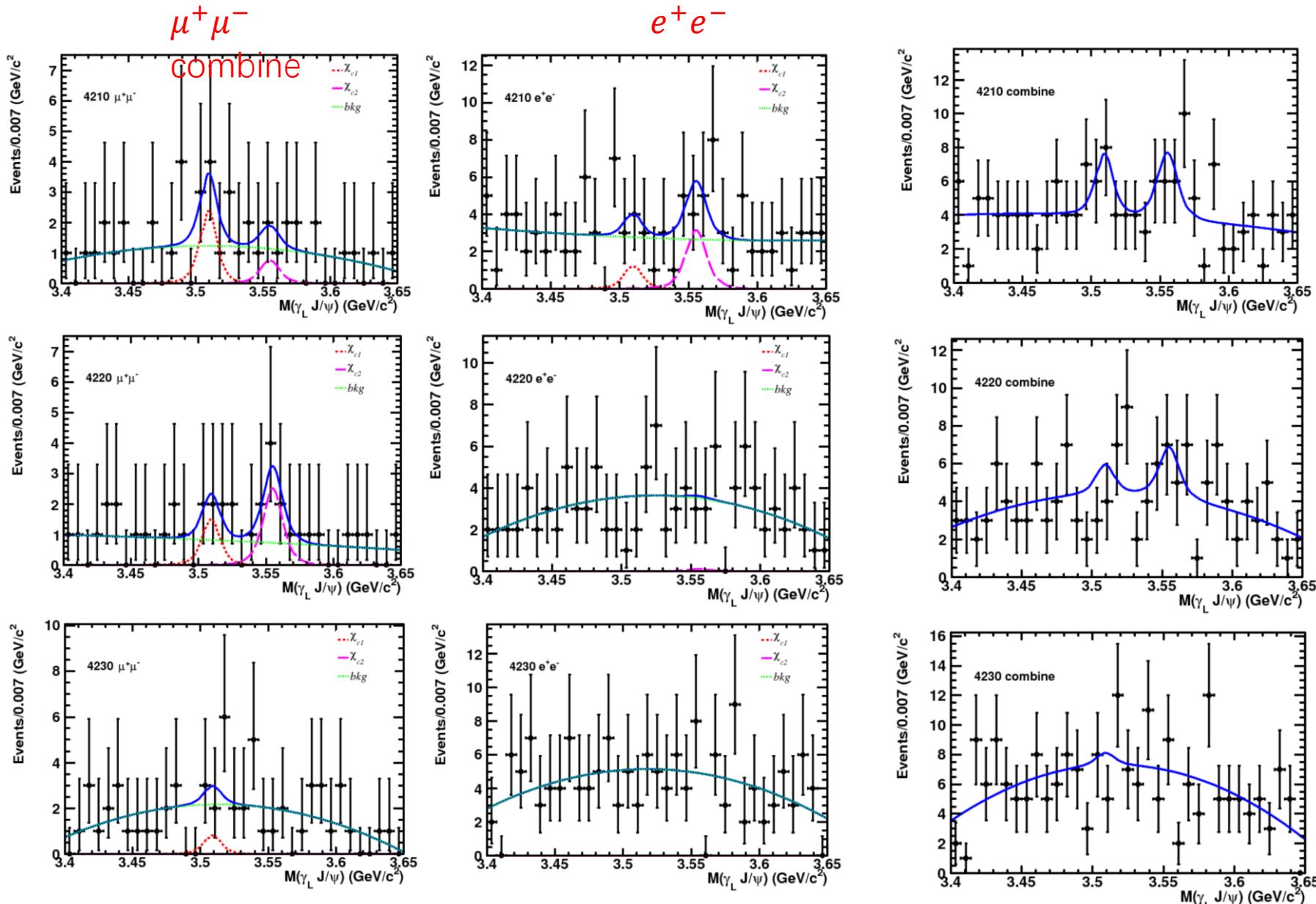
Scan data



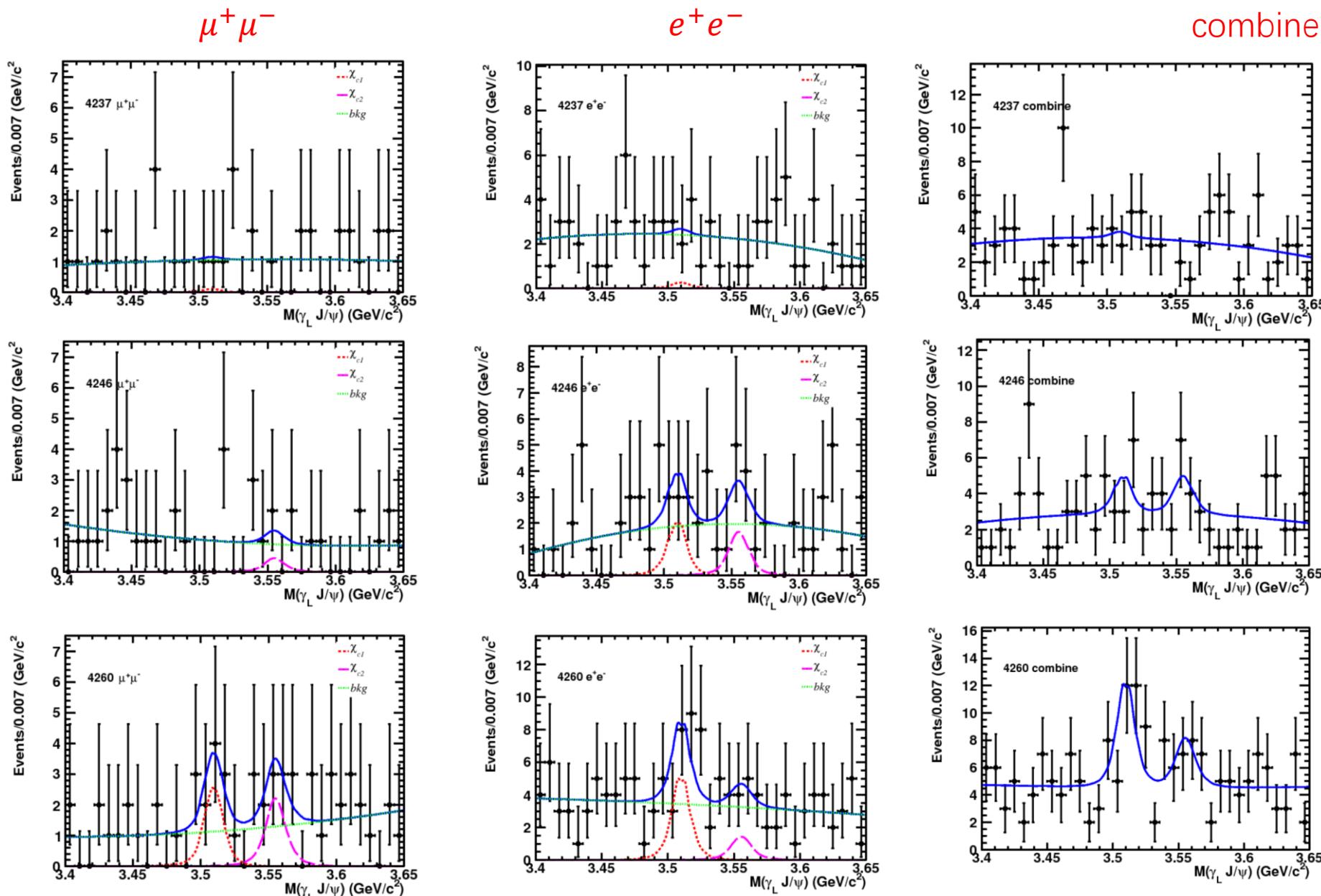
Fit result @4180&4190&4200



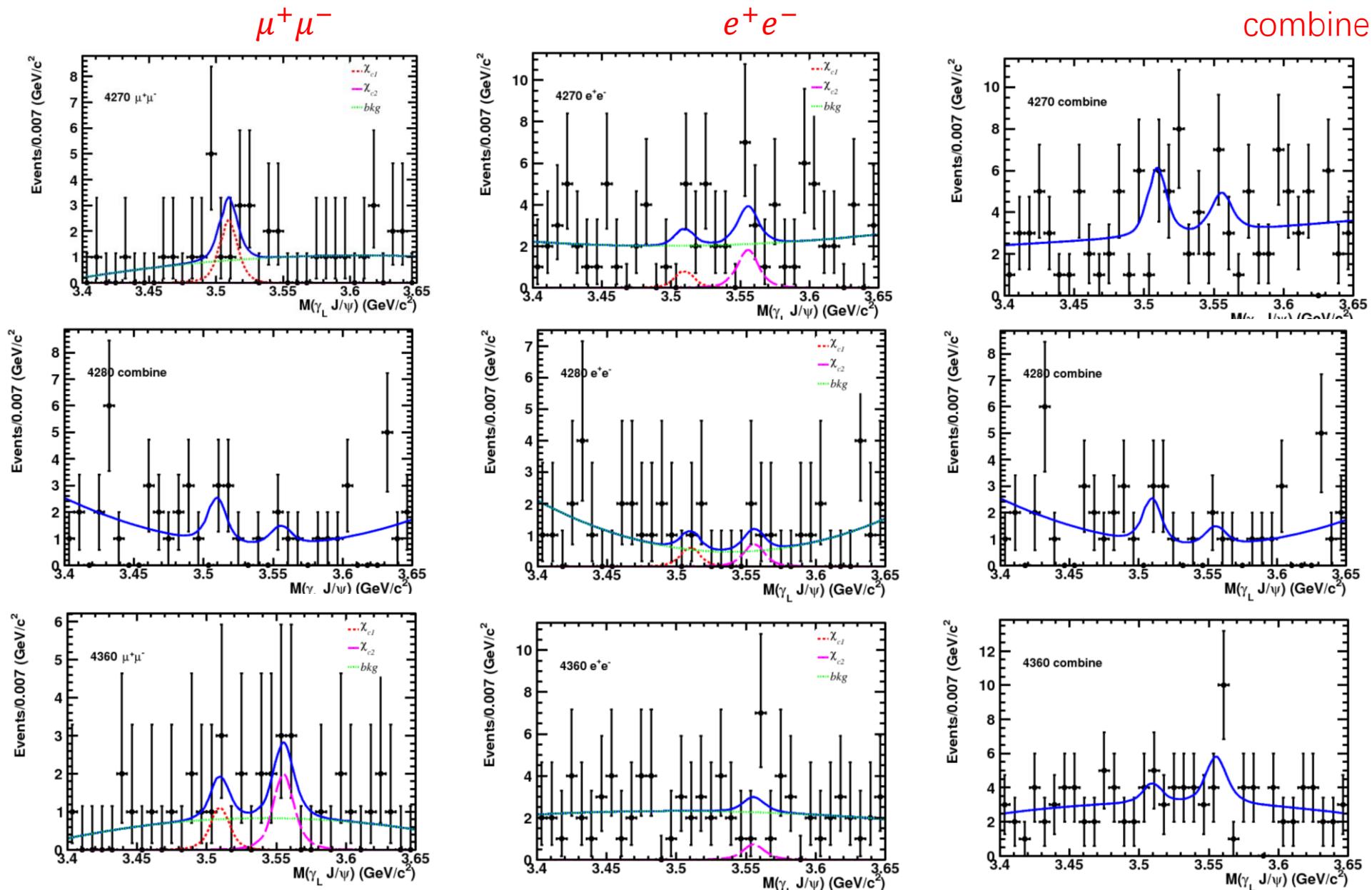
Fit result @4210&4220&4230



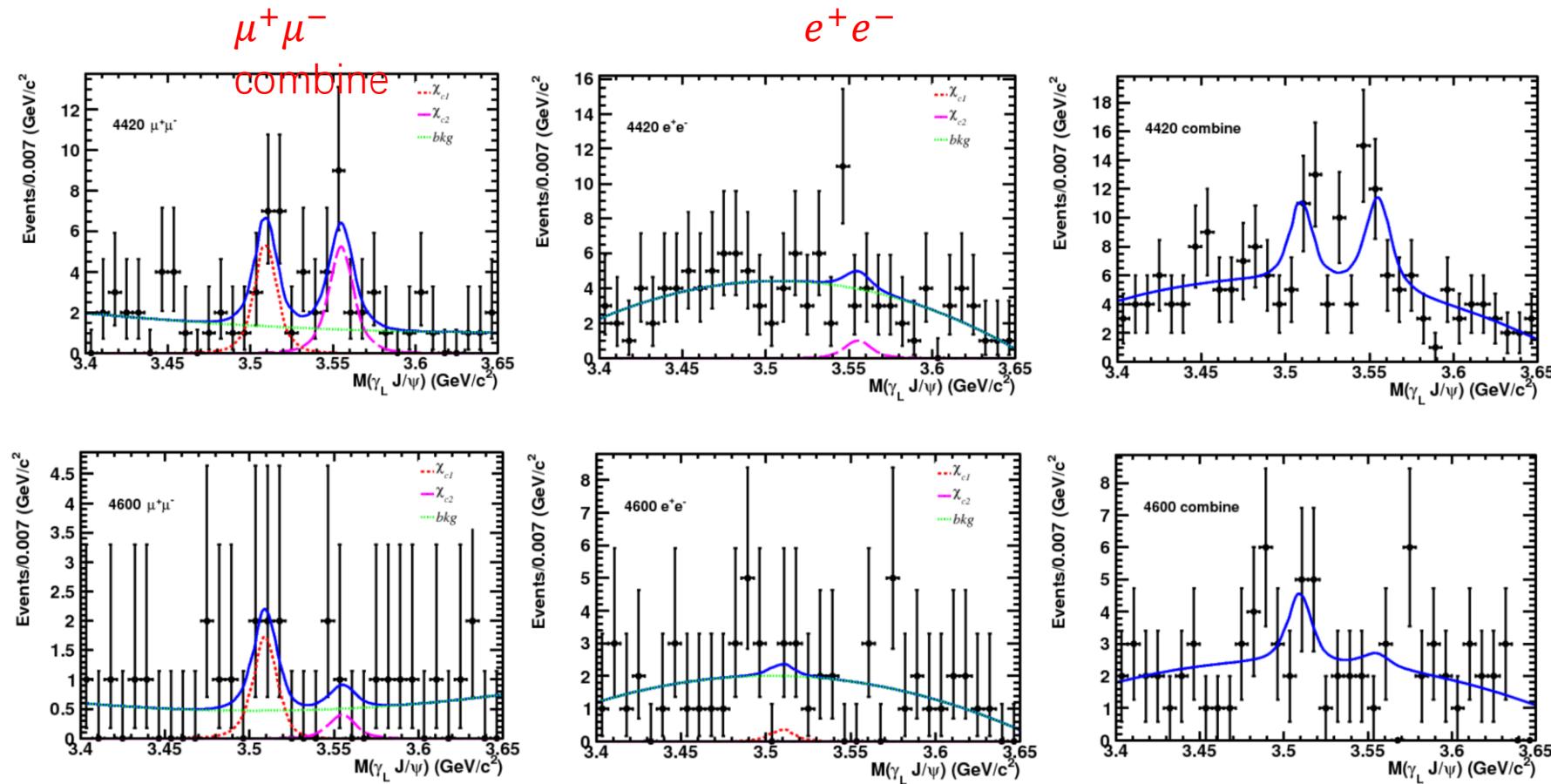
Fit result @4237&4246&4260



Fit result @4270&4280&4360

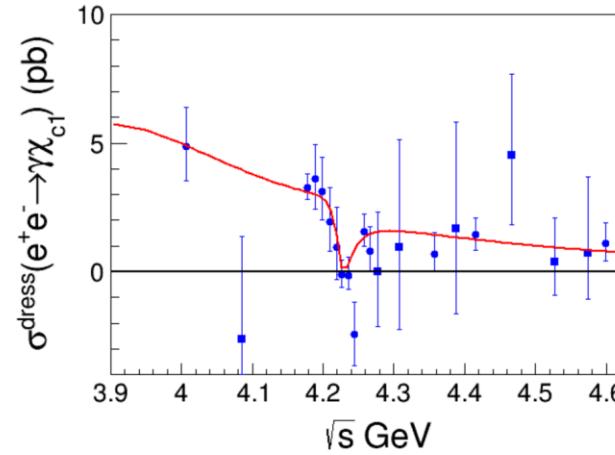
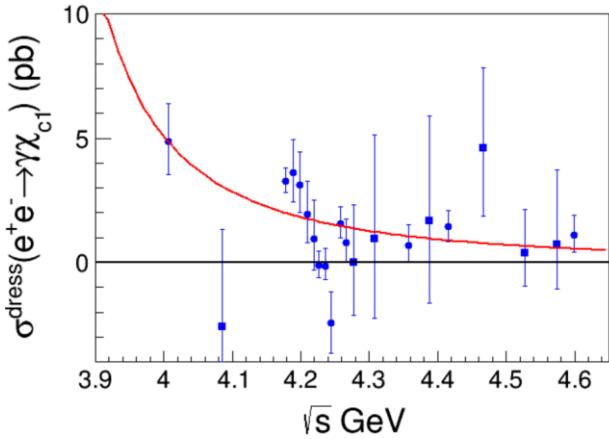


Fit result @4420&4600



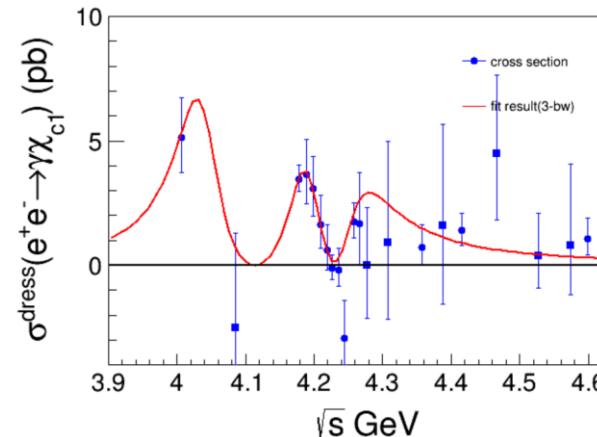
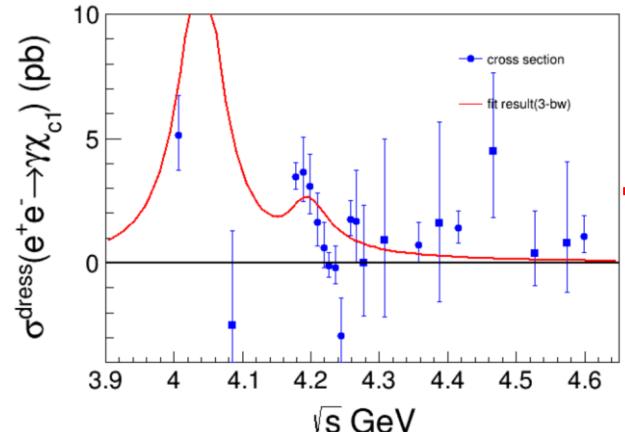
Significance test

- $e^+e^- \rightarrow \gamma\chi_{c1}$



$\Delta - \log(L) = 46.906$
 Ndf=5
 Sig>10

- $e^+e^- \rightarrow \gamma\chi_{c1}$



$\Delta - \log(L) = 85.116$
 Ndf=6
 Sig>10

◆ Compare these two fit methods

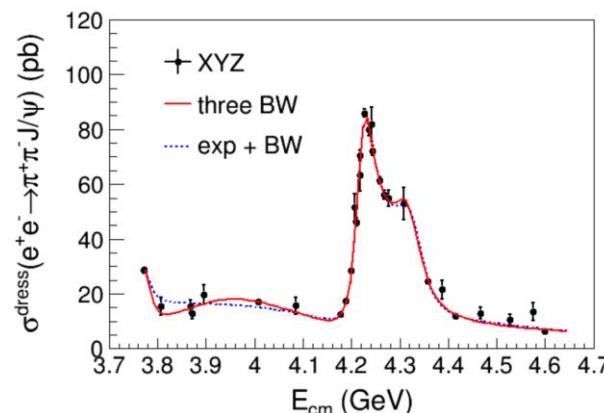
- $-\log(L)$:
2-BW $-\log(L) = 165.5$ 3-BW $-\log(L) = 173.8$

Can't distinguish these two methods;

- For Resonance: Consistent with each other , Also consistent with $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ channel;

Parameters (MeV)	$e^+e^- \rightarrow \gamma\chi_{c1,2}$
M(R2)	4225.6 \pm 2.6
Γ (R2)	28.5 \pm 5.4

Parameters(MeV)	$e^+e^- \rightarrow \gamma\chi_{c1,2}$
M(R1)	4247.2 \pm 6.2
Γ (R1)	82.5 \pm 14.1



Parameters	Values(MeV)
$M(R1)$	4220.9 ± 1.0
$\Gamma(R1)$	$47.4^{+2.2}_{-2.1}$

$$e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$$

◆ MC for $\chi_{c0} \rightarrow K^+K^- \pi^+\pi^- / \pi^+\pi^- \pi^+\pi^-$

- Decay card:

$\pi^+\pi^- \pi^+\pi^-$

```

Decay psi(4260)
1.00 gamma chi_c0          P2GC0;
Enddecay
#
Decay chi_c0
0.01364 pi+ pi- pi+ pi- PHSP;
0.0091 rho0 pi+ pi-      PHSP;
0.00066 f_0 f_0           PHSP;
Enddecay
#
#
Decay rho0
1.000 pi+ pi-            VSS;
Enddecay

Decay f_0
1.000 pi+ pi-            PHSP;
Enddecay

End

```

$K^+K^- \pi^+\pi^-$

```

Decay psi(4260)
1.00 gamma chi_c0          P2GC0;
Enddecay
#
Decay chi_c0
0.00098 K_0*0 anti-K_0*0   PHSP;
0.0004 K_0*0 anti-K_2*0   PHSP;
0.0004 anti-K_0*0 K_2*0   PHSP;
0.00315 K_1+ K-           PHSP;
0.00315 K_1- K+           PHSP;
0.01 K+ K- pi+ pi-       PHSP;
0.0017 K*0 anti-K*0       PHSP;
0.00375 K+ anti-K*0 pi-   PHSP;
0.00375 K- K*0 pi+       PHSP;
Enddecay

```