Measurement of $\Sigma^{+}\bar{\Sigma}^{-}$ electromagnetic form factors using initial-state-radiation technique

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Electromagnetic Form Factors

- The cross section for the process $e^+e^- \to B\overline{B}$ via one-photon exchange, where B is a spin 1/2 baryon, can be expressed in terms of the electric and magnetic FFs G_E and G_M by following formula:

$$\sigma_{B\bar{B}}(s) = \frac{4\pi\alpha^2 C\beta}{3s}\left[|G_M(s)|^2 + \frac{1}{2\tau}|G_E(s)|^2\right].$$

- s is the invariant mass of the hadronic system
- α =1/137.036 is the fine-structure constant
- $\beta = \sqrt{1-4M_B^2/s}$ is the velocity
- $\tau = s/4M_B^2$, M_B is the mass of the baryon.

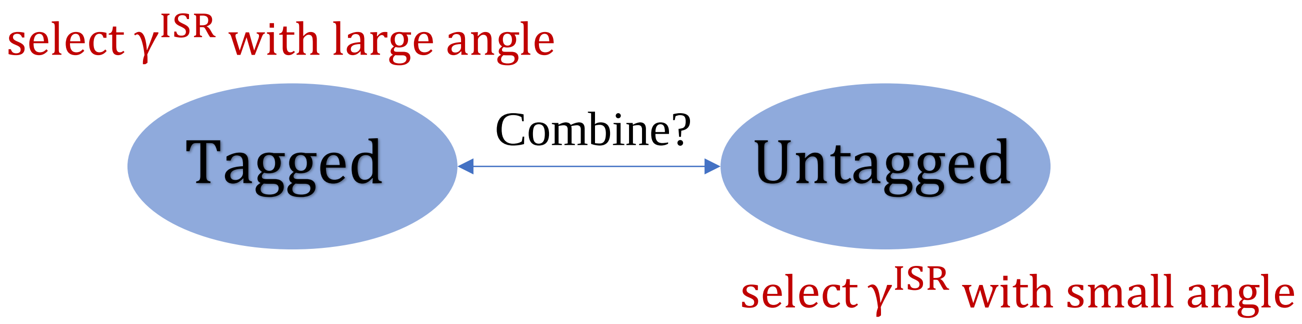
$$|G_{\mathrm{eff}}(s)| = \sqrt{\frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau + 1}}.$$

- Coulomb correction factor $C = \begin{cases} 1, for\ pairs\ of\ neutral\ baryons \\ y/(1-e^{-y}), y = \pi\alpha(1+\beta^2)/\beta, for\ pairs\ of\ charged\ baryons \end{cases}$

Analysis Strategy

$$e^+e^- \longrightarrow \gamma^{ISR}\Sigma^+\overline{\Sigma}^- \longrightarrow \gamma^{ISR}p\pi^0\overline{p}\pi^0$$

- We use two method to select the signal events:
- 1、**Tagged method:** Selecting all final particles including $\gamma^{ISR}p\pi^0\overline{p}\pi^0$. However, this method can only detect γ^{ISR} entering the EMC, and small-angle γ^{ISR} cannot be detected.
- 2、**Untagged method:** We select $p\pi^0\overline{p}\pi^0$ and miss γ^{ISR}. Since most γ^{ISR} are emitted at small angles, we can exclude a large amount of background by restricting their angles.



Data Sets

- 1、Data :

$\sqrt{s}$ $[GeV]$	Sample Type	Run number	Luminosity [pb^{-1}]	Total Luminosity
3.773	Round03 (2010)	11414-13988,14395-14604	2931.8±0.2±13.8	20247.8 pb^{-1}
	Round04 (2011)	20488-23454		
	Round15 (2022)	70522-73929	4995±19	
	Round16 (2023)	74031-78536	8157±31	
	Round17 (2024)	78615-81094	4191±16	

- 2、Monte Carlo simulations(MC) ($\sqrt{s} = 3.773$ GeV):

The signal MC:

The generator software package **ConExc** is used to simulate the signal MC samples.

Event Selection

Good charged tracks：

- $|\cos\theta| \leq 0.93$, $|V_{xy}| \leq 2cm$, $|V_z| \leq 10cm$

PID：

- p:prob(p)>prob(π)&prob(p)>prob(K)

Photon：

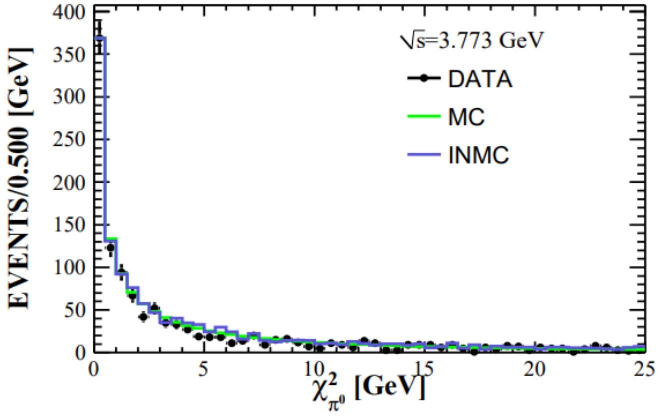
- $E_\gamma > 25MeV(|\cos\theta| \leq 0.86)$
- $E_\gamma > 50MeV(0.86 \leq |\cos\theta| \leq 0.92)$
- Time cut: $0 \leq T \leq 700ns$
- The angle of photon and proton $> 10^\circ$
- The angle of photon and anti-proton $> 20^\circ$

Other selections:

- Number of $p = 1$ and $\bar{p} = 1$
- For untagged method: $\gamma \geq 4$ and $\pi^0 \geq 2$
- For Tagged method: $\gamma \geq 5$ and $\pi^0 \geq 2$

Reconstruct π^0:

- $|M(\gamma\gamma) - M(\pi^0)| \in [-60,40]MeV$
- A kinematic fit be used, $\chi^2 < 25$



Event Selection

For Untagged Method：

- Select minimum $\Delta_m = \sqrt{\left(M_{p\pi^0} - M_{\Sigma^+}\right)^2 + \left(M_{\bar{p}\pi^0} - M_{\bar{\Sigma}^-}\right)^2}$

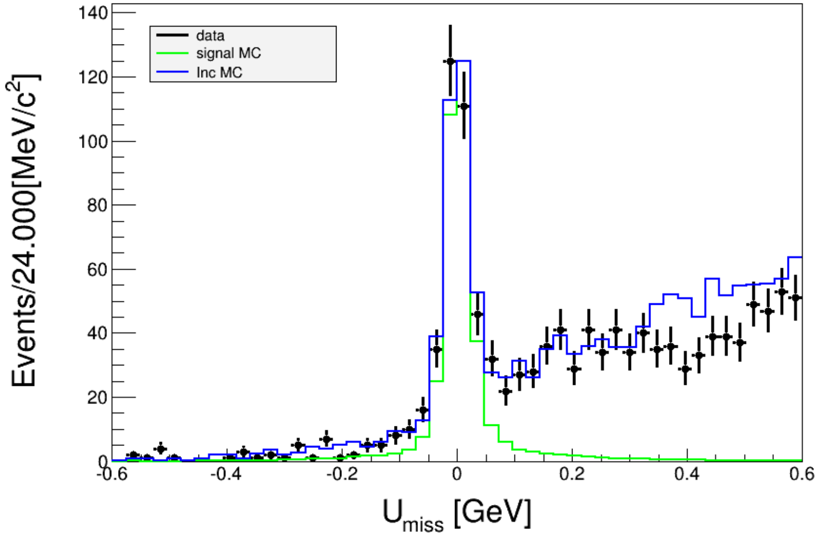
- Mass cut: $M_{\Sigma^+(\bar{\Sigma}^-)} \in [1.16, 1.21]\ [GeV]$

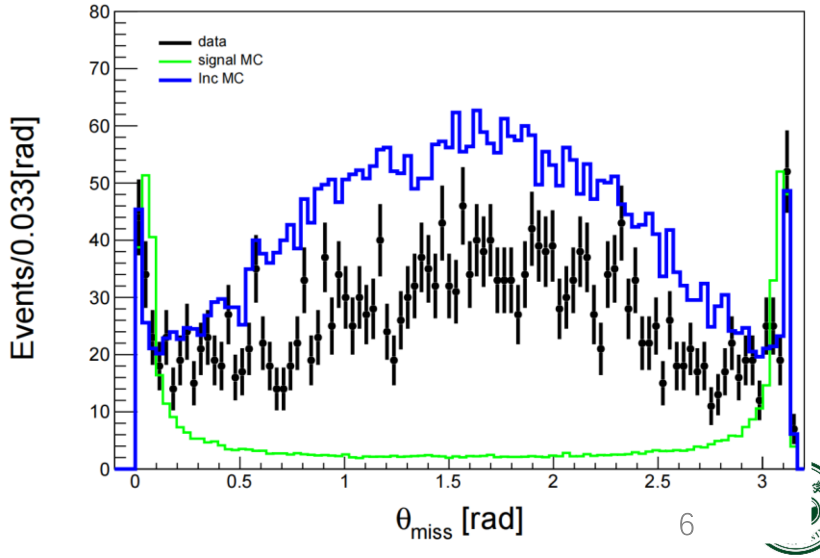
- U_{miss} cut: $-0.14 < U_{miss} < 0.06\ [GeV]$

$$U_{miss} = E^{rec}_{\Sigma^+\bar{\Sigma}^-} - P^{rec}_{\Sigma^+\bar{\Sigma}^-}$$

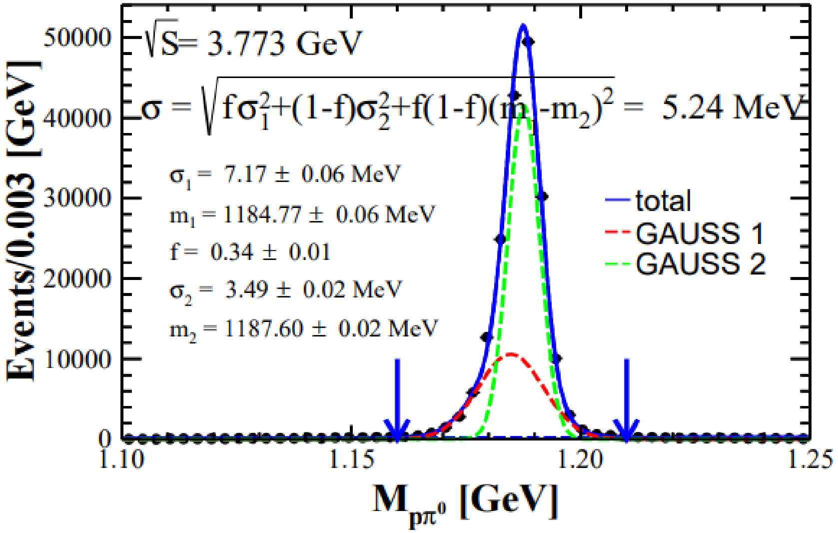
- θ_{miss} cut: $\theta_{miss} < 0.25\ or\ \theta_{miss} > 2.90\ [rads]$

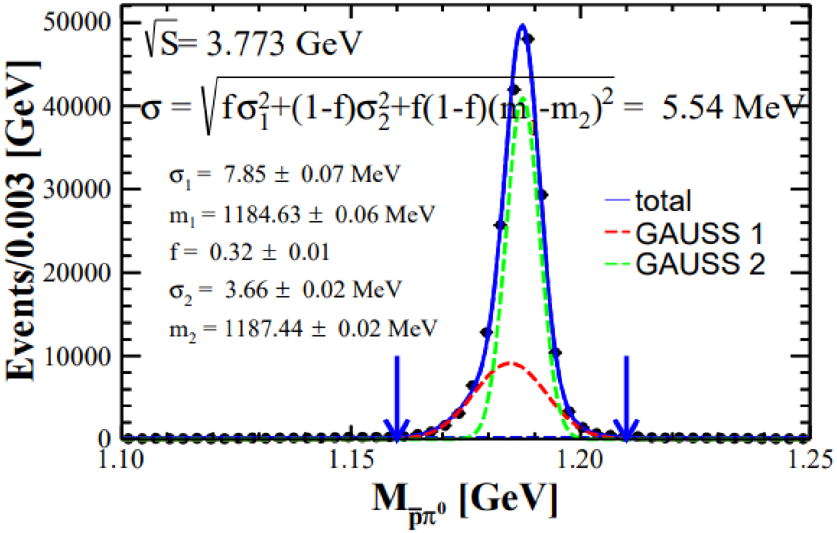
θ_{miss} means the angle between the momentum of the recoiling against the $\Sigma^+\bar{\Sigma}^-$ system and beam direction

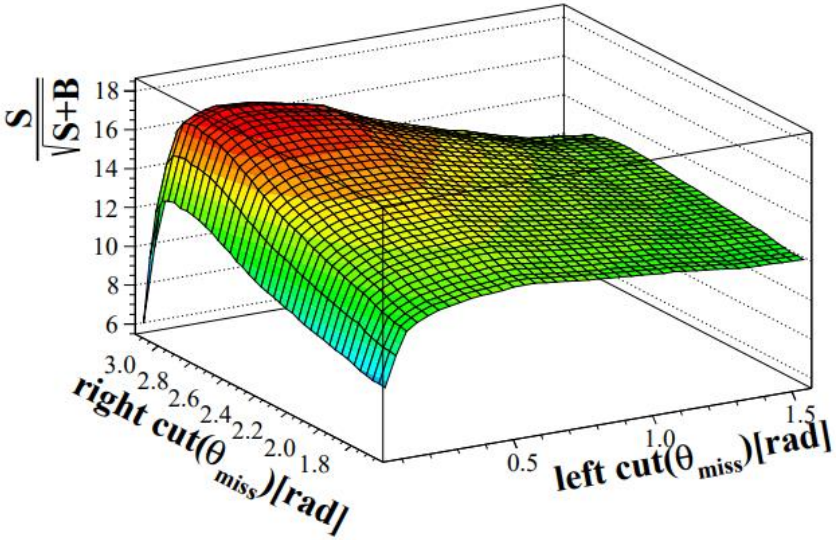


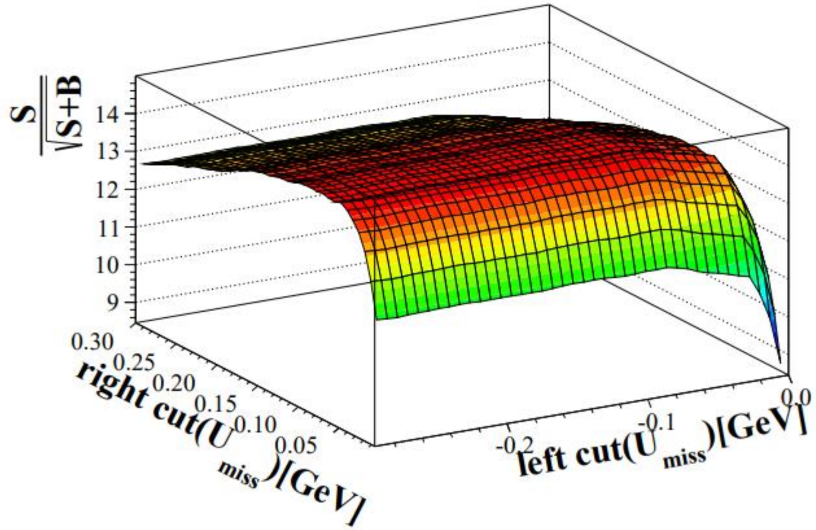


Study of Event Selection





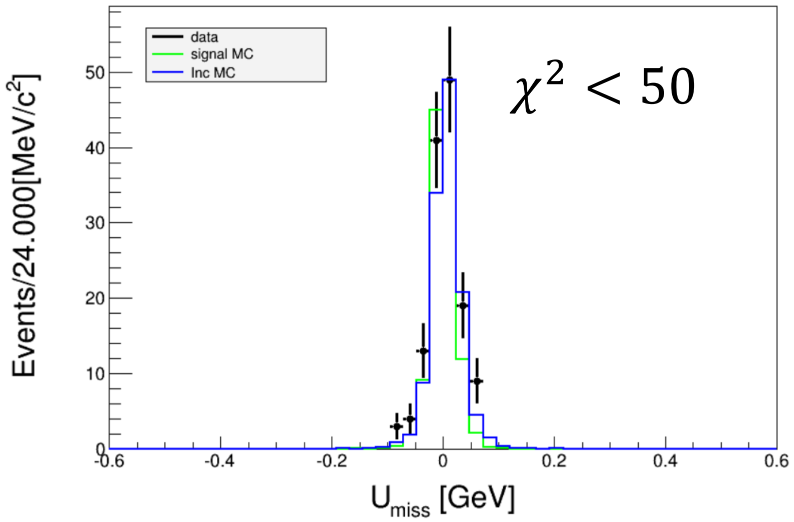


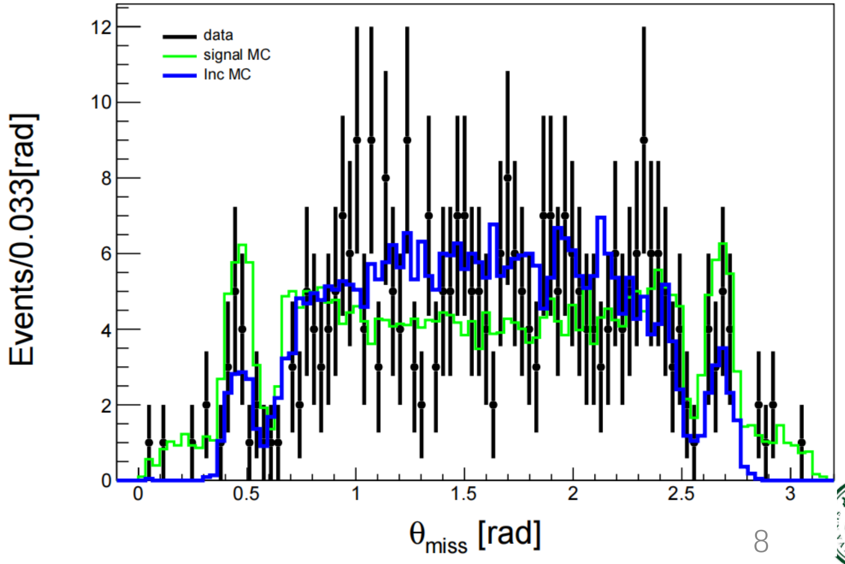


Event Selection

For Tagged Method：

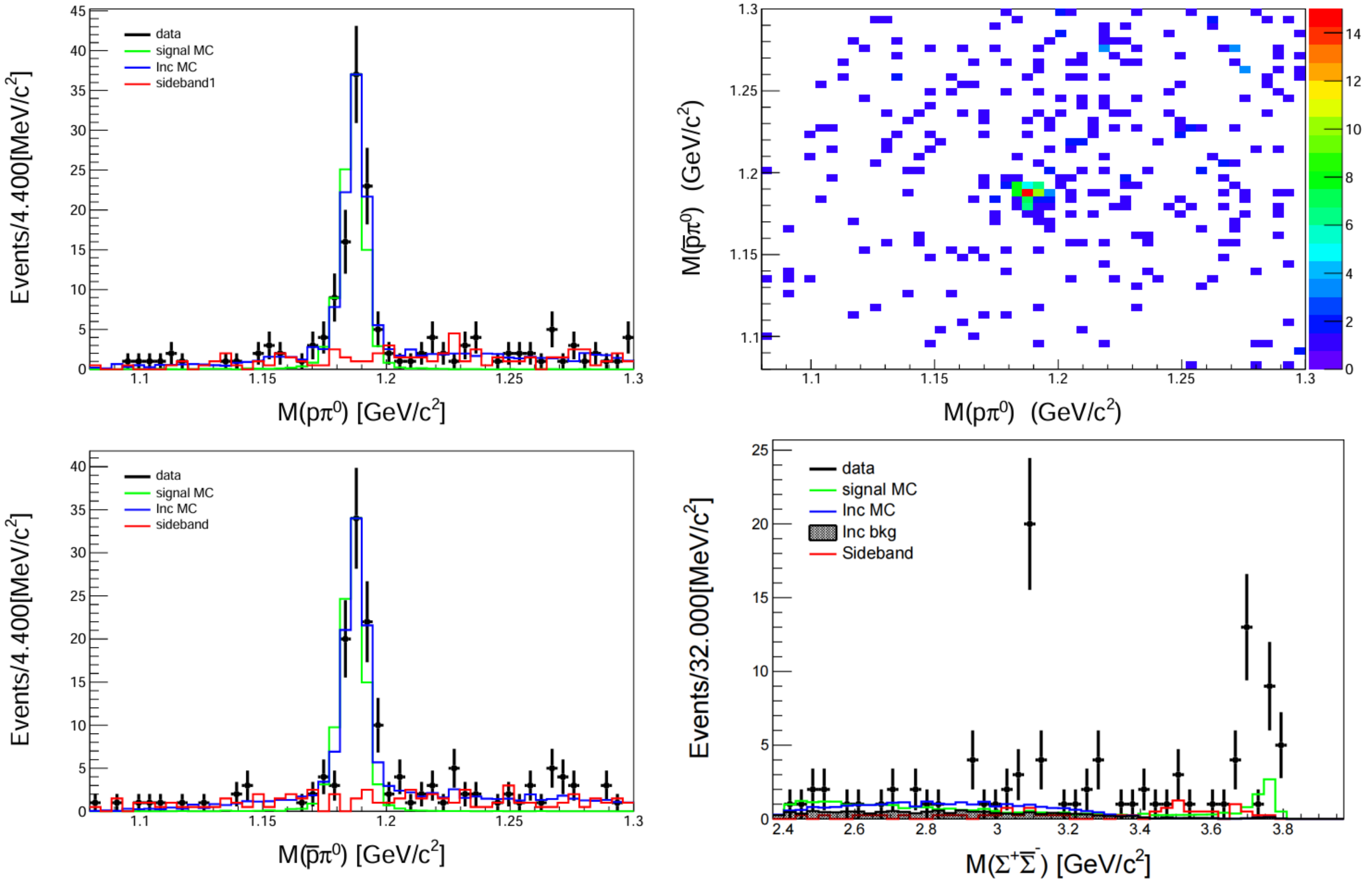
- Select minimum $\Delta_m = \sqrt{(M_{p\pi^0} - M_{\Sigma^+})^2 + (M_{\bar{p}\pi^0} - M_{\bar{\Sigma}^-})^2}$
- A kinematic fit is used, there are $5\gamma,\ 1p\ and\ 1\ \bar{p}$. And we require $\chi^2 < 50$.
- A kinematic fit of background is used $(6\gamma, 1p, 1\bar{p})$. If $\chi^2_{BG} < \chi^2_{sig}$, then we exclude this event. (exclude $\pi^0\Sigma^+\bar{\Sigma}^-$)
- θ_{miss} cut: $0.25 < \theta_{miss} < 2.90\ [rads]$
- U_{miss} cut: $-0.06 < U_{miss} < 0.06\ [GeV]$
- Mass cut: $M_{\Sigma^+(\bar{\Sigma}^-)} \in [1.16, 1.21]\ [GeV]$





Tagged Result

2010-11 3773 data



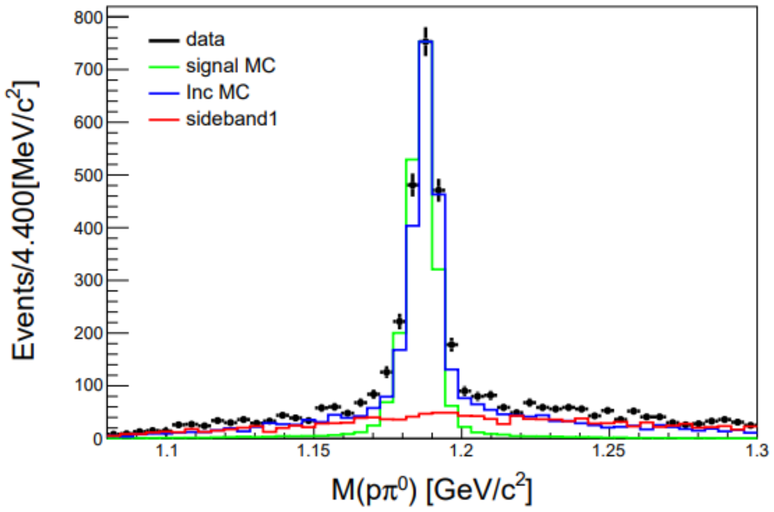
Sideband Region:

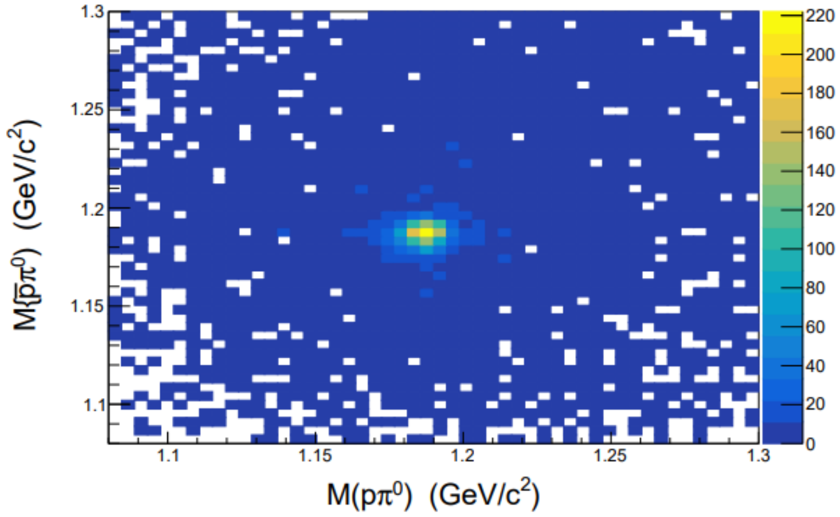
- BKG1: $1.10 \le M_{\Sigma^+} \le 1.15$ GeV and $1.22 \le M_{\bar{\Sigma}^-} \le 1.27$ GeV,
- BKG2: $1.22 \le M_{\Sigma^+} \le 1.27$ GeV and $1.22 \le M_{\bar{\Sigma}^-} \le 1.27$ GeV,
- BKG3: $1.10 \le M_{\Sigma^+} \le 1.15$ GeV and $1.10 \le M_{\bar{\Sigma}^-} \le 1.15$ GeV,
- BKG4: $1.22 \le M_{\Sigma^+} \le 1.27$ GeV and $1.10 \le M_{\bar{\Sigma}^-} \le 1.15$ GeV.

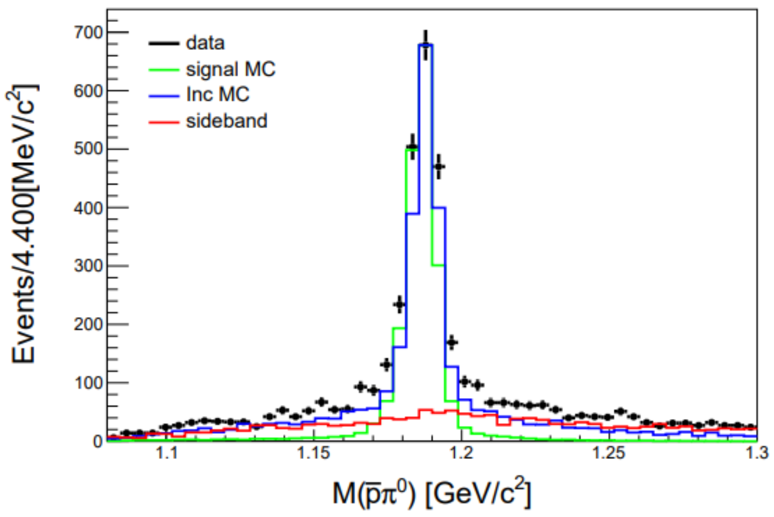
For the **tagged method**, the main background are $\pi^0\Sigma\Sigma$ from IncMC topology. The sideband method is used to estimate other background. Considering the low efficiency and high background, we have abandoned this method.

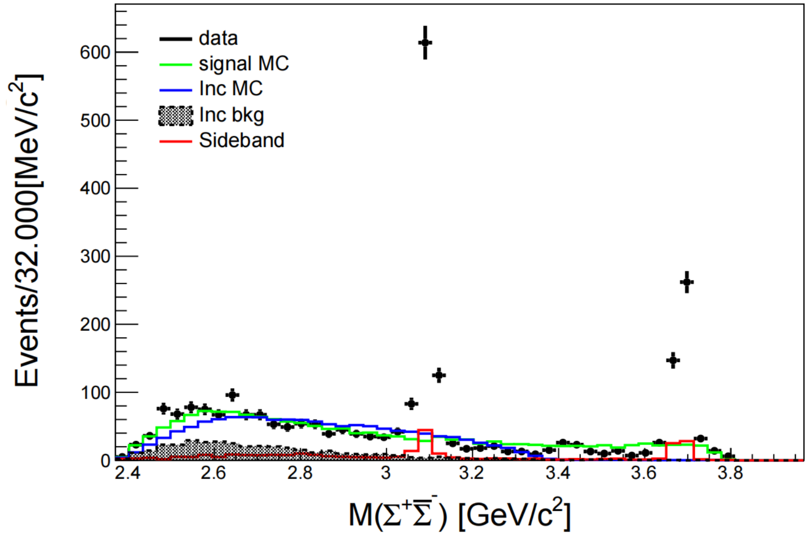
Untagged Results

Whole 3773 data









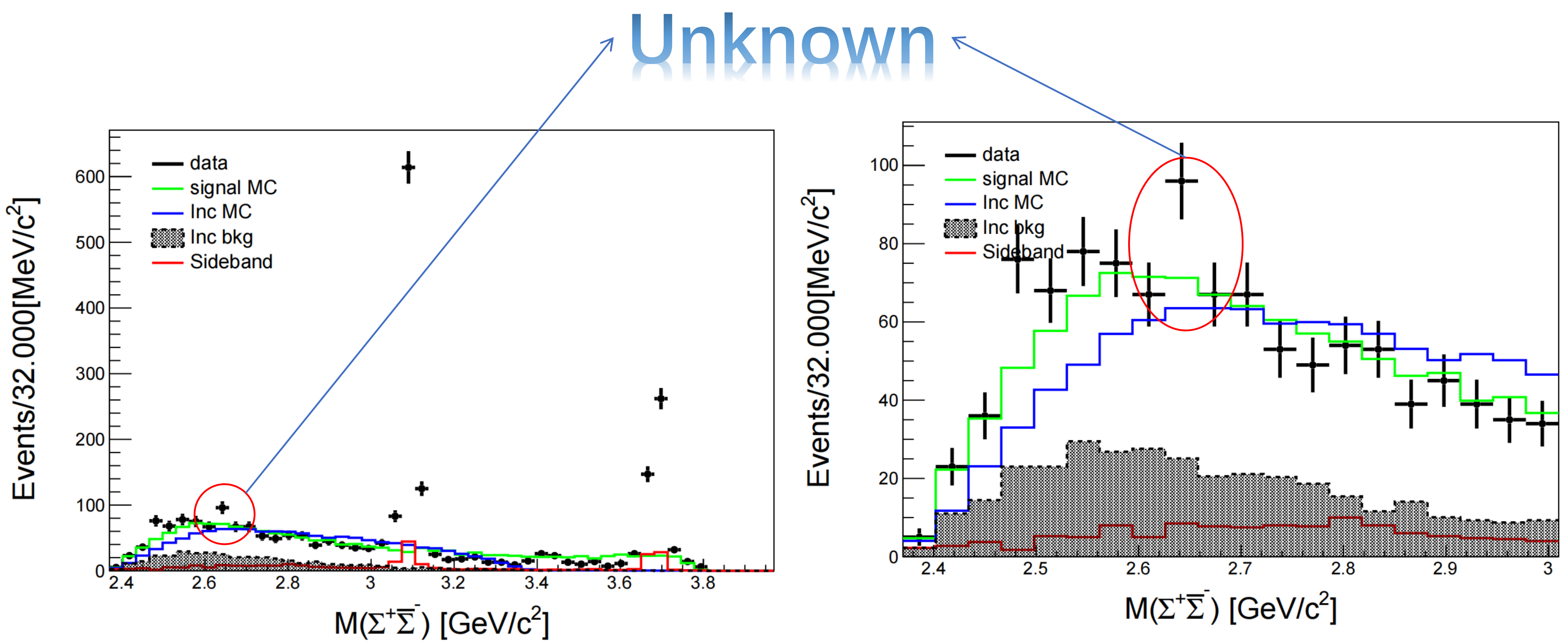
Sideband Region:

- BKG1: $1.10 \leq M_{\Sigma^+} \leq 1.15$ GeV and $1.22 \leq M_{\bar{\Sigma}^-} \leq 1.27$ GeV,
- BKG2: $1.22 \leq M_{\Sigma^+} \leq 1.27$ GeV and $1.22 \leq M_{\bar{\Sigma}^-} \leq 1.27$ GeV,
- BKG3: $1.10 \leq M_{\Sigma^+} \leq 1.15$ GeV and $1.10 \leq M_{\bar{\Sigma}^-} \leq 1.15$ GeV,
- BKG4: $1.22 \leq M_{\Sigma^+} \leq 1.27$ GeV and $1.10 \leq M_{\bar{\Sigma}^-} \leq 1.15$ GeV.

For the **untagged method**, the background is cleaner. We should estimate its background. There are two methods:

1. Estimate using IncMC;
2. Estimate using sideband + π^0 $\Sigma\Sigma$

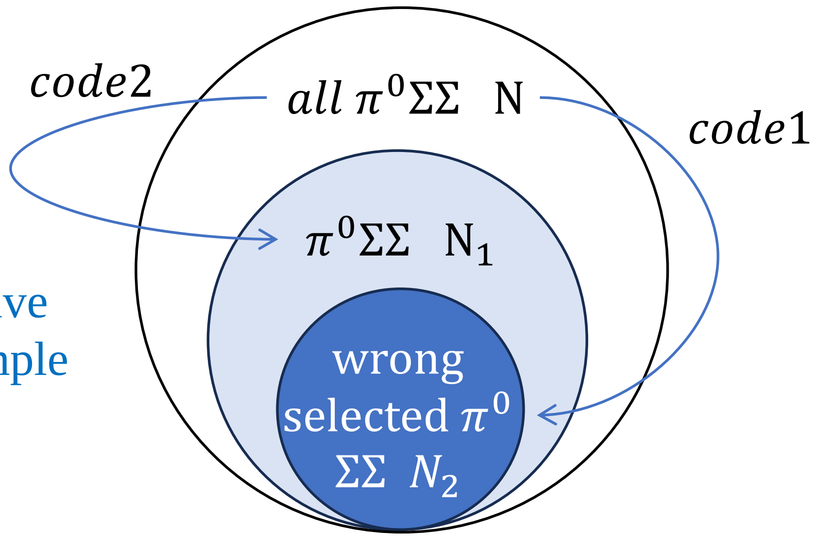
Untagged Result

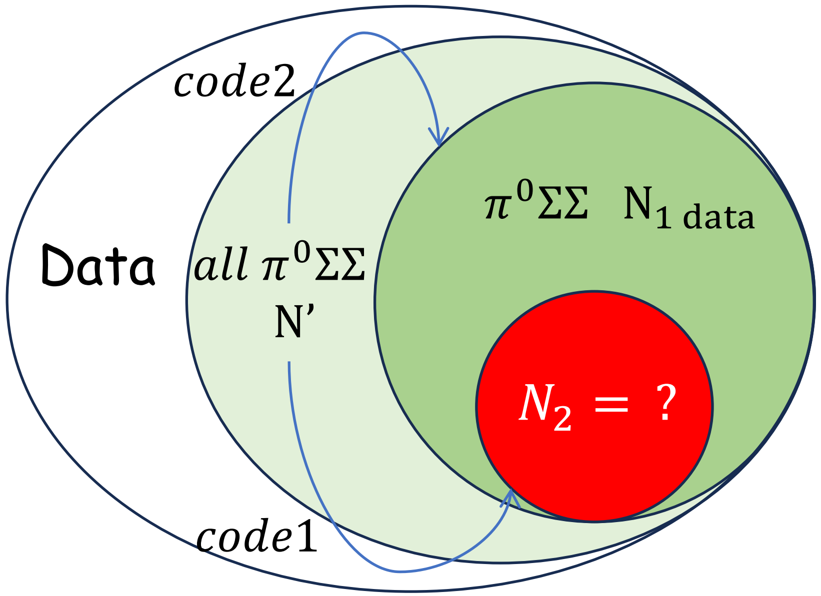


$\pi^0\Sigma\Sigma$ BG Estimate

We use another code to select $\boldsymbol{\pi^0}\boldsymbol{\Sigma\Sigma}$ code1: select $\boldsymbol{\gamma\Sigma\Sigma}$(signal). code2: select $\boldsymbol{\pi^0}\boldsymbol{\Sigma\Sigma}$(bkg)

Exclusive MC Sample





Code2 Event Selection:

a The same as untagged method, select $p\,\pi^0\,\bar{p}\,\pi^0$ tracks first.

b Limit $U_{miss} < -0.14\ or\ U_{miss} > 0.06$ to exclude $\boldsymbol{\gamma\Sigma\Sigma}$ signal.

c Loop all π^0 and make kmfit, select the minimum χ^2 event.

$\pi^0\Sigma\Sigma$ BG Estimate

code1: select $\gamma\Sigma\Sigma$(signal). code2: select $\pi^0\Sigma\Sigma$(bkg)

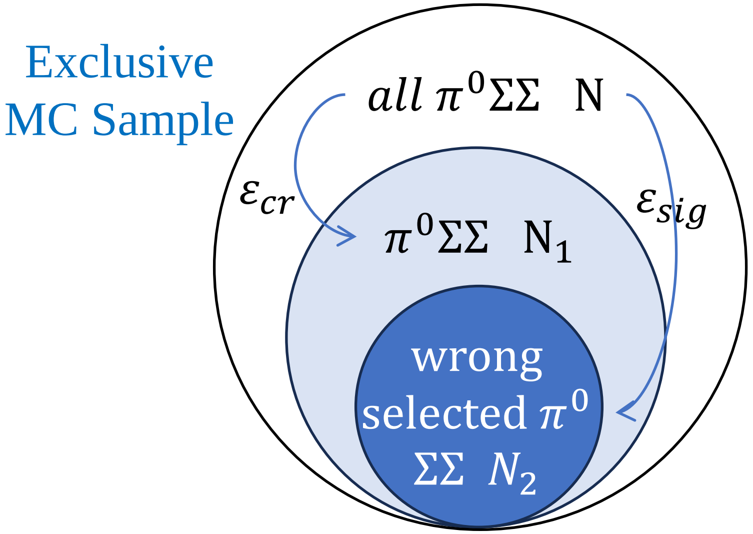
In Exclusive MC:

1、ε_{sig}^{i} means the number of bkg($\pi^0\Sigma\Sigma$) events N_i misidentified as signal($\gamma\Sigma\Sigma$) ratio --> Code1

$$\varepsilon_{sig}^{i} = N_2^i / N^i$$

2、ε_{cr}^{i} means the efficiency of bkg($\pi^0\Sigma\Sigma$) selection --> Code2

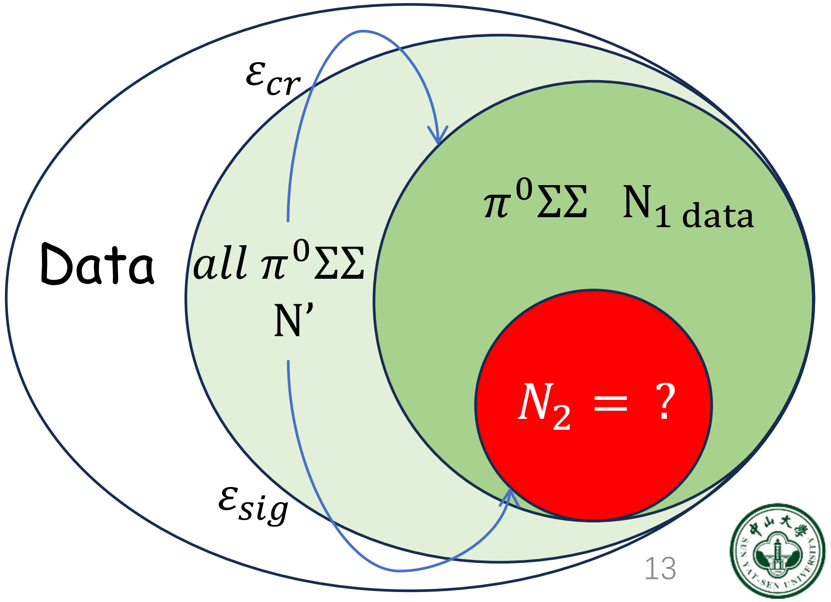
$$\varepsilon_{cr}^{i} = N_1^i / N^i$$



In Data:

3、We can estimate the number of $\pi^0\Sigma\Sigma$ misidentified as signal($\gamma\Sigma\Sigma$) number:

$$N_{2\ data} = N' \cdot \varepsilon_{sig}^{i} = N_{1\ data}^{i} / \varepsilon_{cr}^{i} \cdot \varepsilon_{sig}^{i} = R N_{1\ data}^{i} \quad \left(R = \frac{\varepsilon_{sig}^{i}}{\varepsilon_{cr}^{i}}\right)$$



Calculation the Cross Section

Cross Section： $\sigma_{\Sigma^+\bar{\Sigma}^-}(M_{\Sigma^+\bar{\Sigma}^-}) = \frac{(dN_{sig}/dM_{\Sigma^+\bar{\Sigma}^-})}{\varepsilon \cdot \mathcal{B}(\Sigma^+ \to p\pi^0)\mathcal{B}(\bar{\Sigma}^- \to \bar{p}\pi^0)\mathcal{B}^2(\pi^0 \to \gamma\gamma) \cdot (d\mathcal{L}_{int}/dM_{\Sigma^+\bar{\Sigma}^-})}.$

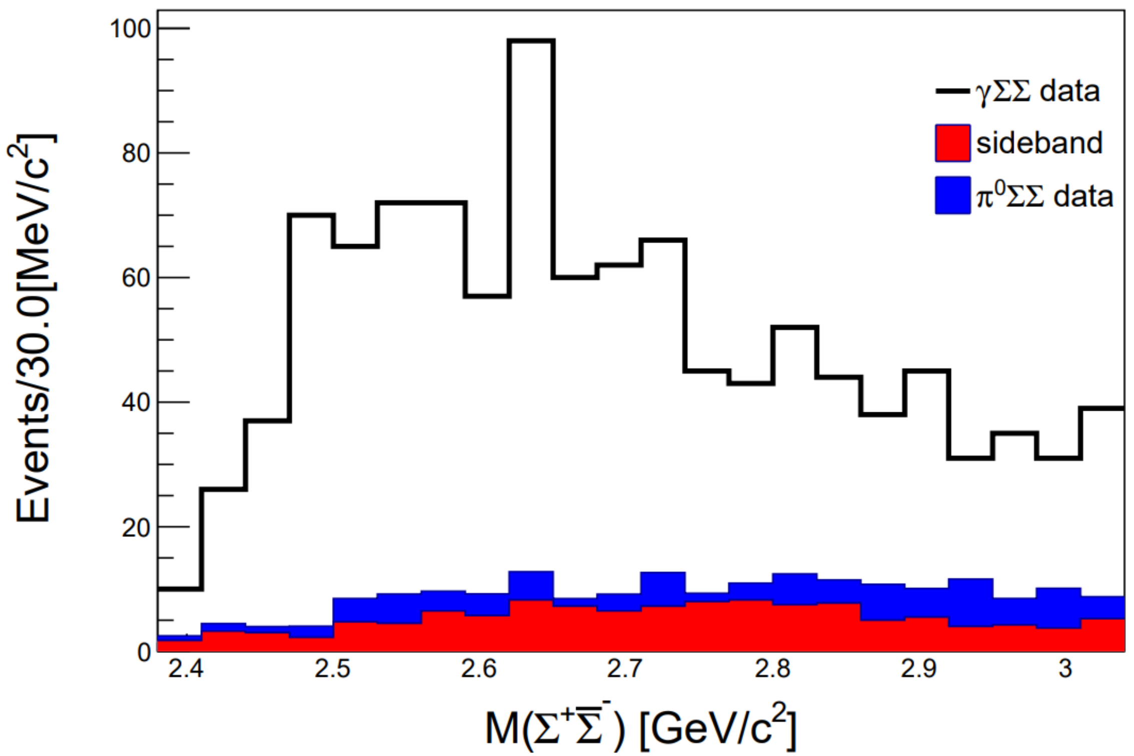
Here, $d\mathcal{L}_{int}/dM_{\Sigma^+\bar{\Sigma}^-} = W(s,x)\cdot\mathcal{L}_{int}$ $\quad W(s,x) = \frac{\alpha}{\pi x}\left[\ln\left(\frac{s}{M_e^2}\right) - 1\right]\cdot(2 - 2x + x^2)\,, x = 1 - \frac{M^2_{\Sigma^+\bar{\Sigma}^-}}{s}$

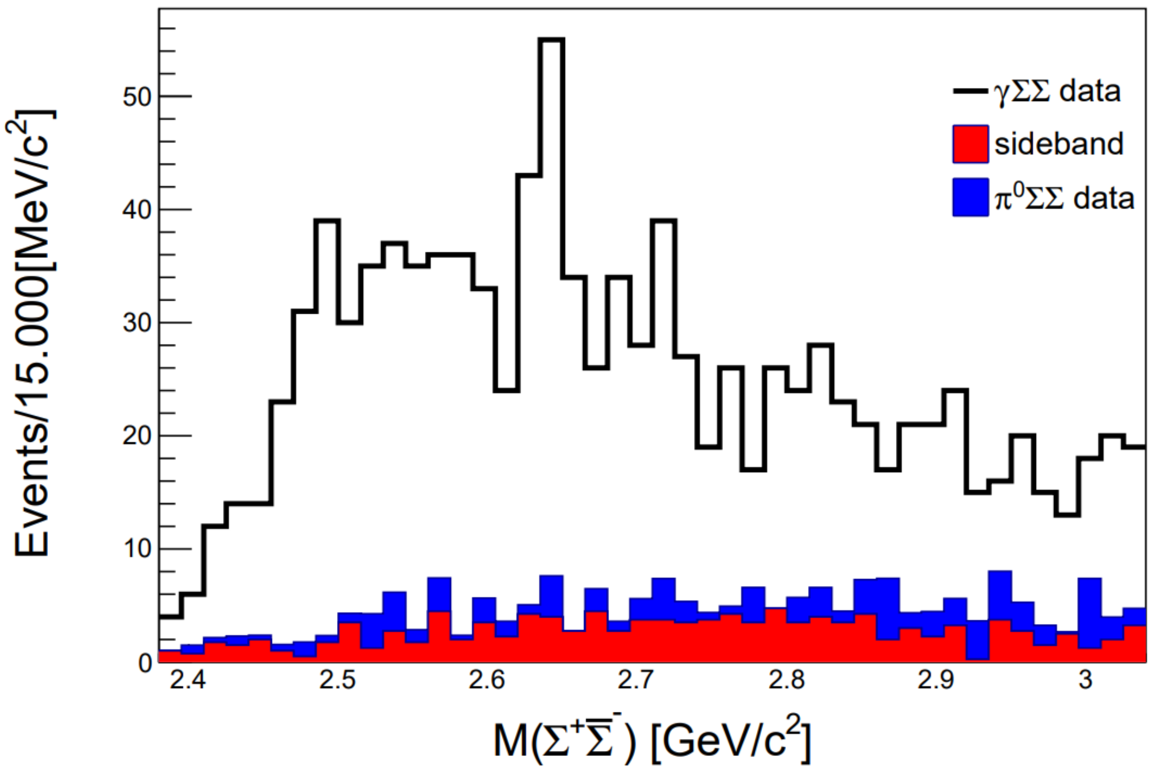
If higher-order terms are considered (to more accurately describe the ISR process), then $W(s,x)$:

$$W(s,x) = kx^{k-1}\left[1 + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right) + \frac{3}{4}k + k^2\left(\frac{37}{96} - \frac{\pi^2}{12} - \frac{1}{72}\ln\frac{s}{m_e^2}\right)\right] - k\left(1 - \frac{1}{2}x\right)$$
$$+\frac{1}{8}k^2\left[4(2-x)\ln\frac{1}{x} - \frac{1+3(1-x)^2}{x}\ln(1-x) - 6 + x\right], k = \frac{2\alpha}{\pi}\left[\ln\frac{s}{m_e^2} - 1\right],$$

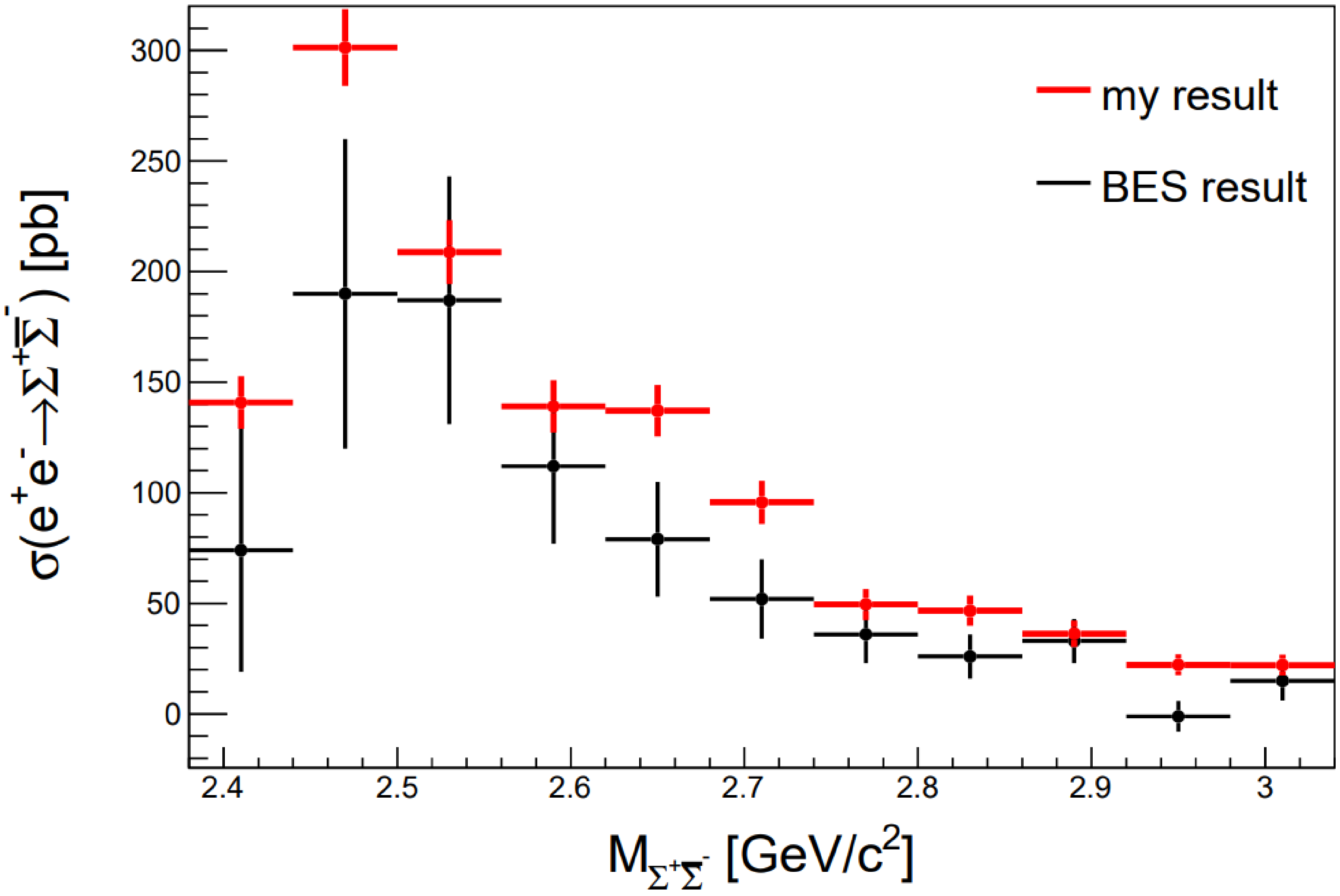
From this, we can calculate the production cross section of ΣΣ in each bin.

BG estimate


γΣΣ data
sideband
π0ΣΣ data
Events/30.0[MeV/c2]
M(Σ+Σ-) [GeV/c2]


γΣΣ data
sideband
π0ΣΣ data
Events/15.000[MeV/c2]
M(Σ+Σ-) [GeV/c2]

Compare


my result
BES result
$\sigma(e^+e^-\to\Sigma^+\overline{\Sigma}^-)$ [pb]
$M_{\Sigma^+\overline{\Sigma}^-}$ [GeV/c^2]
300
250
200
150
100
50
0
2.4
2.5
2.6
2.7
2.8
2.9
3

- **Compare1**

MSigmaSigma	N1(Origin)	N2(sideband)	Nbkg(pi0SigmaSigma)	Nsig	ε	Leff	σ[pb]	Geff [10-2]
Bin0	36	5	2.14	28.86	2.42%	32.61	140.79	15.77
Bin1	107	5.25	2.70	99.05	3.61%	35.04	301.32	23.08
Bin2	137	9.25	8.45	119.30	5.83%	37.74	208.75	19.21
Bin3	129	12.25	6.63	110.12	7.48%	40.75	139.10	15.68
Bin4	158	15.5	5.81	136.69	8.70%	44.13	137.09	15.57
Bin5	128	13.75	7.83	106.42	8.93%	47.93	95.71	13.01
Bin6	88	16.25	3.85	67.90	10.10%	52.24	49.53	9.36
Bin7	96	15.25	8.56	72.19	10.42%	57.15	46.67	9.08
Bin8	83	10.5	10.75	61.75	10.44%	62.78	36.29	8.01
Bin9	66	8.25	11.73	46.02	11.52%	69.30	22.20	6.26
Bin10	70	9	10.34	50.66	11.50%	76.89	22.06	6.24

$M_{\Sigma^+\bar{\Sigma}^-}$[GeV]	N_1	N_2	$N_{bkg}(\varepsilon_{bkg}[\%], N_{\pi^0\Sigma^+\bar{\Sigma}^-}, \varepsilon_{\pi^0\Sigma^+\bar{\Sigma}^-}[\%])$	N_{sig}	$\varepsilon[\%]$	$\mathcal{L}_{\mathrm{eff}}[\mathrm{pb}^{-1}]$	$\sigma_{\Sigma^+\bar{\Sigma}^-}$[pb]	$\lvert G_{\mathrm{eff}}\rvert \times 10^{-2}$
Bin_0	2.00±1.41	0.25±0.25	0.06 (0.09,5.25,7.39)	1.69±1.52	1.50	4.82	90.00±80.95	15.59±7.01
Bin_1	10.00±3.16	0.50±0.35	0.10 (0.15,4.50,6.56)	9.40±3.26	2.88	5.07	247.87±85.96	20.82±3.61
Bin_2	18.00±4.24	1.50±0.61	0.16 (0.17,6.00,6.46)	16.34±4.43	4.63	5.47	248.41±67.35	19.21±2.60
Bin_3	10.00±3.16	2.50±0.79	0.22 (0.21,7.00,6.69)	7.28±3.57	6.20	5.90	76.63±37.58	10.23±2.51
Bin_4	15.00±3.87	1.25±0.56	0.46 (0.27,12.00,7.02)	13.29±4.09	7.17	6.39	111.68±34.37	12.06±1.86
Bin_5	8.00±2.83	1.00±0.50	0.25 (0.31,5.75,7.20)	6.75±3.04	7.88	6.94	47.52±21.40	7.77±1.75
Bin_6	3.00±1.73	1.25±0.56	0.01 (0.33,0.25,7.57)	1.74±2.06	8.41	7.56	10.54±12.47	3.64±2.15
Bin_7	7.00±2.65	1.50±0.61	0.20 (0.36,4.25,7.65)	5.30±2.95	8.86	8.28	27.82±15.48	5.91±1.65
Bin_8	11.00±3.32	0.75±0.43	0.27 (0.36,5.50,7.31)	9.98±3.47	9.20	9.09	45.95±15.98	7.62±1.33
Bin_9	5.00±2.24	4.75±1.09	0.24 (0.40,4.50,7.49)	0.01±3.16	9.46	10.03	0.04±12.82	0.23±36.25
Bin_{10}	7.00±2.65	2.25±0.75	0.24 (0.33,5.25,7.35)	4.51±3.08	9.68	11.14	16.10±11.00	4.57±1.56

- **Compare2**

MSigmaSigma	N1(Origin)	N2(sideband)	Nbkg(pi0SigmaSigma)	Nsig	ε	Leff	σ[pb]	Geff [10-2]
Bin0	36	5	2.14	28.86	2.42%	32.61	140.79	15.77
Bin1	107	5.25	2.70	99.05	3.61%	35.04	301.32	23.08
Bin2	137	9.25	8.45	119.30	5.83%	37.74	208.75	19.21
Bin3	129	12.25	6.63	110.12	7.48%	40.75	139.10	15.68
Bin4	158	15.5	5.81	136.69	8.70%	44.13	137.09	15.57
Bin5	128	13.75	7.83	106.42	8.93%	47.93	95.71	13.01
Bin6	88	16.25	3.85	67.90	10.10%	52.24	49.53	9.36
Bin7	96	15.25	8.56	72.19	10.42%	57.15	46.67	9.08
Bin8	83	10.5	10.75	61.75	10.44%	62.78	36.29	8.01
Bin9	66	8.25	11.73	46.02	11.52%	69.30	22.20	6.26
Bin10	70	9	10.34	50.66	11.50%	76.89	22.06	6.24

$M_{\Sigma^+\bar{\Sigma}^-}$ [GeV/c^2]	N^{sig}	$\bar{\varepsilon}$[%]	$\mathcal{L}_{\text{eff}}$[pb^{-1}]	$\sigma_{\Sigma^+\bar{\Sigma}^-}$ [pb]	$\lvert G_{\text{eff}}\rvert(\times 10^{-2})$
2.379-2.44	$2.7^{+1.8}_{-1.9}(<6.8)$	0.91	15.13	$74^{+50}_{-52}\pm5(<190)$	$14.1^{+4.8}_{-5.0}\pm0.5(<22.7)$
2.44-2.50	16 ± 4	2.07	15.77	$190\pm50\pm20$	$18.2\pm2.4\pm1.0$
2.50-2.56	30 ± 6	3.69	16.82	$187\pm37\pm19$	$16.6\pm1.7\pm0.8$
2.56-2.62	28 ± 6	5.33	17.96	$112\pm24\pm11$	$12.3\pm1.3\pm0.6$
2.62-2.68	26 ± 6	6.49	19.22	$79\pm18\pm8$	$10.2\pm1.2\pm0.5$
2.68-2.74	20 ± 5	7.24	20.62	$52\pm14\pm4$	$8.1\pm1.1\pm0.3$
2.74-2.80	16 ± 5	7.85	22.16	$36\pm10\pm3$	$6.7\pm1.0\pm0.3$
2.80-2.86	13 ± 4	8.19	23.90	$26\pm8\pm2$	$5.5\pm0.9\pm0.2$
2.86-2.92	19 ± 5	8.62	25.83	$33\pm8\pm2$	$6.5\pm0.8\pm0.2$
2.92-2.98	$-0.7^{+4.5}_{-4.6}(<7.7)$	8.96	28.01	$-1.1^{+6.8}_{-7.1}\pm0.1(<11.7)$	$-1.2^{+3.6}_{-3.8}\pm0.1(<3.9)$
2.98-3.04	11 ± 6	9.23	30.50	$15\pm8\pm1$	$4.4\pm1.1\pm0.1$

Thank you!

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