The Study of $e^+e^- \to \Sigma^\circ\bar{\Sigma}^\circ$ from $\sqrt{s} = 2.396$ to 3.08 GeVat *BESIII* with R-Scan Data

Irshad Muzaffar, Dr.Xiaorong Zhou, Prof.Huang Guangshun

University of Science and Technology of China
State Key Laboratory of Particle Detection and Electronics

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Outline

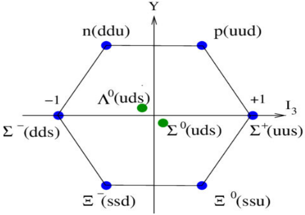
Longstanding Mystery About Nucleons :

- Nucleons continue to puzzle us. We still don't completely understand their properties such as:
  - ✓ Size
  - ✓ Spin
  - ✓ Internal Structure

What we can do it now?

- Our aim to probe the cross section near threshold of nucleon pairs experimentally.
  - ✓ By replacing one of the quark (u/d) with s-quark in the nucleon to make Hyperons.
  - ✓ Time-like EMFFs is accessible in e^+e^- collision.

Baryon Octet



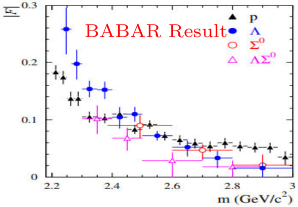
Electromagnetic Form Factors (EMFFs)

Spin 1/2 Baryons:

- **Two independent EMFFs:** $G_E(s), G_M(s)$ ($s = q^2$, four momentum transfer).
- **In one-photon exchange approximation:** ($\tau = \frac{q^2}{4m_B^2}, \beta = \sqrt{1 - \frac{4m_B^2}{q^2}}$)
  - $\frac{d\sigma^B(s)}{d\Omega} = \frac{\alpha^2 \beta C}{4s}[|G_M(s)|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E(s)|^2 \sin^2\theta]$
- **At threshold:** $\sigma_{B\bar{B}}(s) = \frac{4\pi\alpha^2 C}{3s}[1 + \frac{1}{2\tau}]|G^N_{eff}(s)| = \sigma^N_{point}(s)|G^N_{eff}(s)|^2$
- Nucleons form factors(FFs), proton FFs in particular has been studied by experiments with high precision.
- Hyperons FFs are hardly explored. The precision of hyperons FFs are quite poor and better results to be demanded in future. [**https://docbes3.ihep.ac.cn/DocDB/0007/000742/004/sigsig.pdf**]

Aim of this Analysis:

- Study of neutral channel $e^+e^- \to \Sigma^0\bar{\Sigma}^0$ and to compare our results with BABAR experiment result PRD **76**, 092006 (2007) and isospin partner Σ^+/Σ^- with BESIII.



❶ BOSS Version:

- **Analysis Environment:** BOSS 6.6.5.p01

❷ Datasets:

$\sqrt{s}$GeV	$L(pb^{-1})$	$\sqrt{s}$ GeV	$L(pb^{-1})$
2.396	66.869	2.95	15.942
2.50	1.098	2.981	16.071
2.6444	33.722	3.00	15.881
2.6444	33.722	3.02	17.290
2.90	105.253	2.9884*	65.184
2.90	105.253		

R-Scan Dataset 2015

❸ MC Sample: Generated 50k signal MC events by **ConExc** with ISR corrections at each energy point.

- **Decay Chain:**
  - ✓ $e^+e^- \to \Sigma^0\bar{\Sigma}^0$ in **PHSP**
  - ✓ $\Sigma^0 \to \gamma\Lambda(\Lambda \to p\pi^-)$ in **PHSP**
  - ✓ $\bar{\Sigma}^0 \to \gamma\bar{\Lambda}(\bar{\Lambda} \to \bar{p}\pi^+)$ in **PHSP**

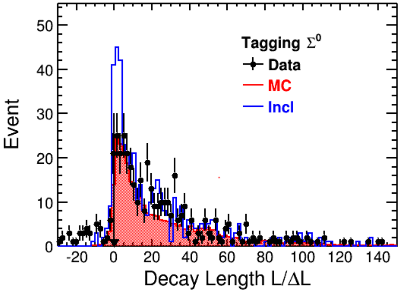
ConExc Generator:

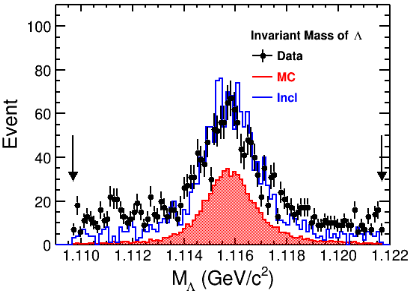
Set $\alpha = 0$, with input Xsection from BaBAR results.

1. **Good Charged Tracks:**
   - $|V_z| < 30\,\text{cm}, |V_{xy}| < 10\,cm$ and $|cos\theta| \leq 0.93$
   - $\boxed{N_{\text{Good}} > 2}$
2. **PID (dE/dX Only):**
   - **Proton:**$Prob_P > Prob_K \&\& Prob_P > Prob_\pi$
   - **Pion:**$Prob_\pi > Prob_P \&\& Prob_\pi > Prob_K$
   - $\boxed{N_p = N_\pi = 1}$
3. **Good Neutral Tracks:**
   - Minimal Energy Deposition to Suppress the Background: $\boxed{E_{barrel} > 25\text{ MeV}; E_{endcap} > 50\text{ MeV}}$
   - To Reduce the Electronic Noise: $\boxed{0 \leq T \leq 14}$
   - At least one photon track: $\boxed{N_{shower} \geq 1}$
4. **Λ Reconstruction:** Primary and Secondary vertex fit applied for Λ ($\bar{\Lambda}$).

- **Further selection for Λ candidate:**

  Decay length over its error: $L/\Delta L > 0$
  Chi-square of Second Vertex fit: $\chi^2 < 20$
  Mass Window Cut: $|M(p\pi) - M(\Lambda)_{\mathrm{PDG}}| < 6\ \mathrm{MeV}/c^2$

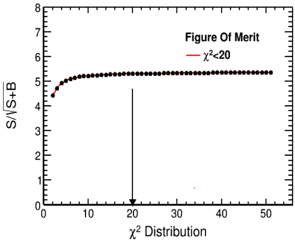


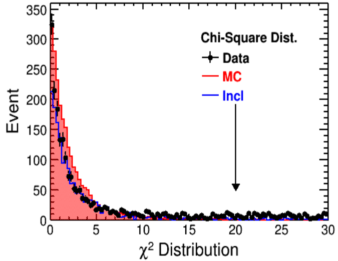


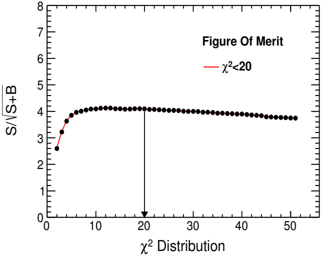
Optimized χ^2 Cut

- **Figure of Merit :**
  - To optimize the signal significance define FOM as:

$$\boxed{f(\chi^2) = \frac{S(\chi^2)}{\sqrt{S(\chi^2)+B(\chi^2)}}}$$



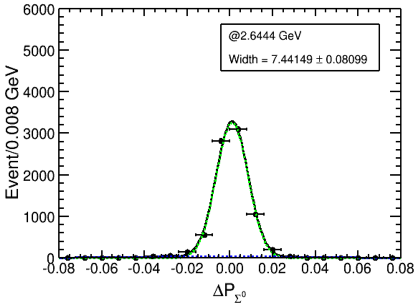


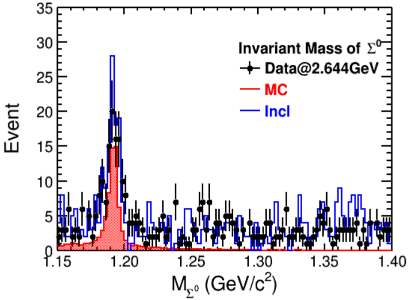


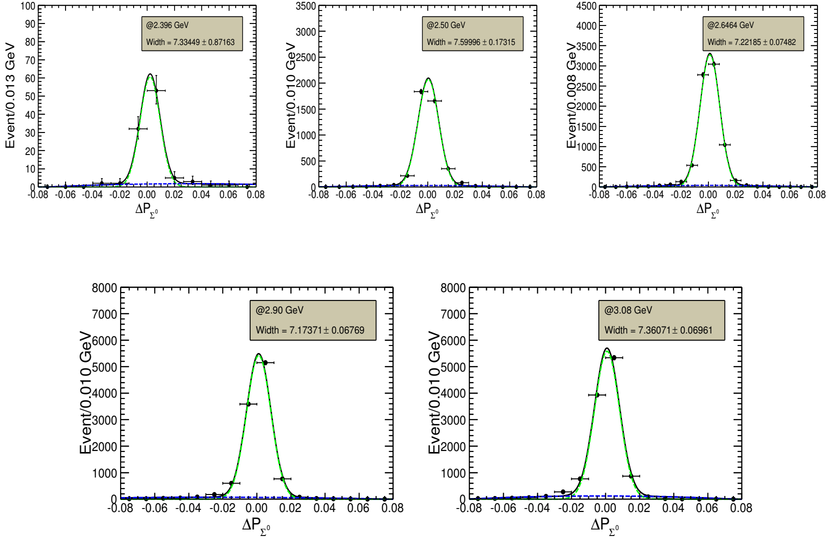
Event Selection

5. **For $\Sigma^{\circ}(\bar{\Sigma}^{\circ}) \to \gamma\Lambda$ Candidate**: Loop all the photons and select γ with minimization of Momentum as; $\Delta P \equiv |P_{\Sigma^{\circ}} - P_{\text{ave}}|$.

   - **Further Selection:** To improve the resolution of Σ°. we require minimum momentum window cut $|P_{\Sigma^{\circ}} - P_{\text{ave}}| < 3\sigma_{\text{p}}$ MeV/c and mass window cut $\Sigma^{0} \epsilon [1.15, 1.4]$ GeV/c^2.
     - $\text{P}_{\Sigma^{\circ}}$ is the reconstructed momentum of Σ°in CM frame.
     - P_{ave} is the calculated nominal momentum of Σ°in CM frame.
     - σ_p is the resolution of momentum, about 8 MeV/c at each energy point.

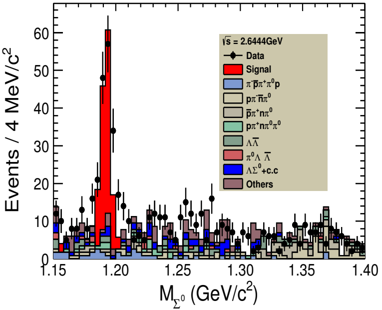





@2.396 GeV
Width = 7.33449 ± 0.87163
Event/0.013 GeV
ΔP_{Σ^0}
@2.50 GeV
Width = 7.59996 ± 0.17315
Event/0.010 GeV
ΔP_{Σ^0}
@2.6464 GeV
Width = 7.22185 ± 0.07482
Event/0.008 GeV
ΔP_{Σ^0}
@2.90 GeV
Width = 7.17371 ± 0.06769
Event/0.010 GeV
ΔP_{Σ^0}
@3.08 GeV
Width = 7.36071 ± 0.06961
Event/0.010 GeV
ΔP_{Σ^0}

The Background Study

- **Topological Analysis**: The stack plot of the background and signal processes at $\sqrt{s} = 2.6444$ GeV compared to the data.
- **Main Background Processes**
  - $p\pi^-\bar{p}\pi^+\gamma\gamma$ $(\pi^-\bar{\Lambda}\Sigma^+, \Delta^{++}\Delta^+\pi^+)$
  - $\pi^-\bar{n}\pi^0 p$ $(\bar{\Delta}^+\pi^0 p, \bar{\Delta}^0\pi^- p)$
  - $\pi^-\bar{n}\pi^0\pi^0 p$ $(\pi^0\Sigma^+\bar{\Sigma}^-, \bar{\Delta}^+\pi^0\bar{p})$
  - $p\pi^-\bar{p}\pi^+$ $(\Lambda\bar{\Lambda}, \bar{\Delta}^{++}\pi^+ p)$
  - $\pi^-\bar{p}\pi^+ p\gamma$ $(\bar{\Lambda}\Sigma^0 + c.c)$
- No beam associated background is found at $\sqrt{s} = 2.6444$ GeV.
- All the background process distributed smoothly under Σ^0 peak.

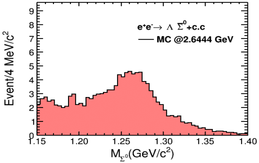


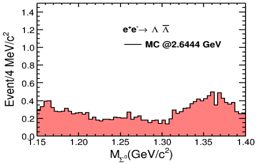
- **Main Background Process**: The main background sources come from events in the following topologies.

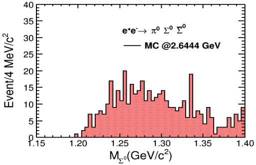
1. $e^+e^- \to \Lambda\bar{\Sigma}^0 + c.c$
2. $e^+e^- \to \Lambda\bar{\Lambda}$
3. $e^+e^- \to \pi^0\Sigma^0\bar{\Sigma}^0$

Generate Exclusive MC for Background Study

- Generate 50k MC sample decay inclusively for each decay channel to estimate the background events.
- Channel 1. Little peaking in signal region but bump in tail.
- Channel 2/3. Flat in both signal and tail region.
- **Remarks:** Peaking background have seen in channel 1.



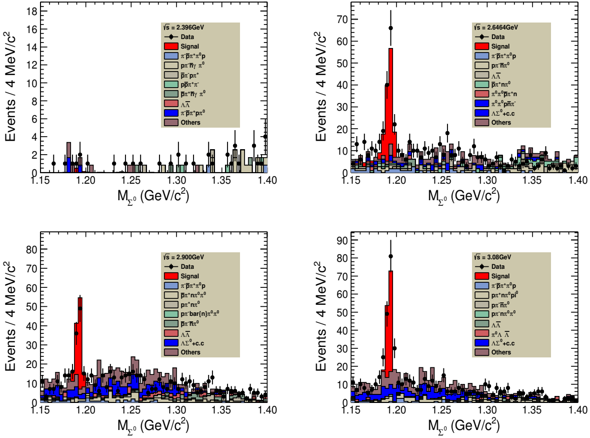




- **Scaling Background Events** : The normalized the number of survived background events in channel 1 as;
  - ✓ $N_{norm.} = \sigma_{Born} * \mathcal{L} * \epsilon$
  - ✓ $N_{norm.} = 25.7 * 33.72 * 0.145 = 125$
- **Scale Factor:**
  - ✓ $f_{S.F} = \frac{N_{Tot.gen}}{\mathcal{L} * \sigma_{Born}}$
  - ✓ $f_{S.F} = 116$

Ref :https://indico.ihep.ac.cn/event/8795/session/15/contribution/80/material/slides/0.pdf

- **Topological Analysis**:
  - At low energy, without opening threshold of baryonic process but multi-π^0 process is dominated.
  - Although background level is increasing at high c.m.energies which turns to opening more baryonic process but no peaking background observed.

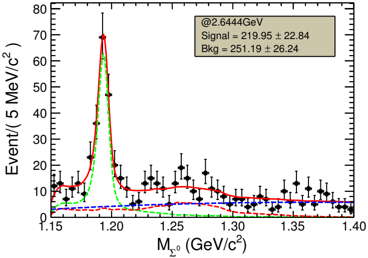


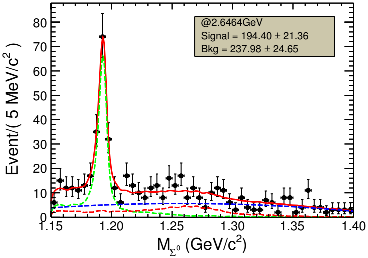
Cross Section Measurement

- The cross section is determined by:

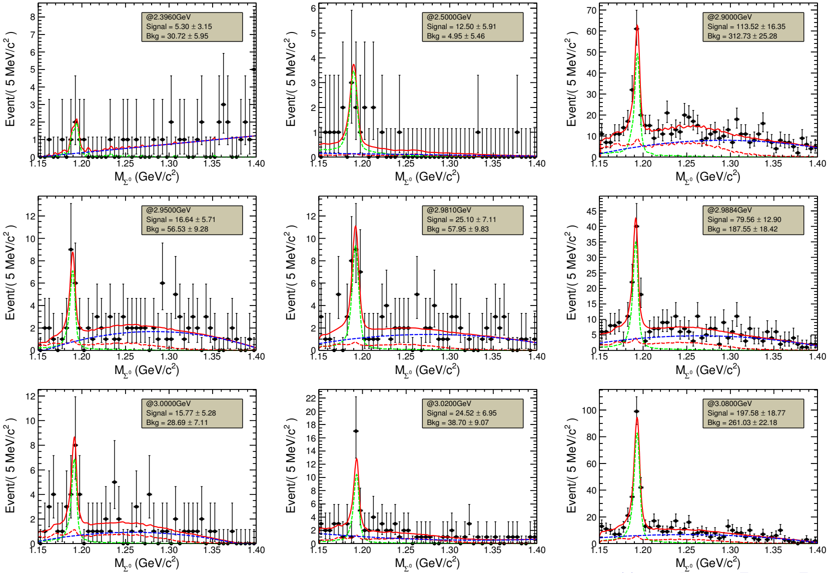
$$\sigma^B(e^+e^- \to \Sigma^0\bar{\Sigma}^0) = \frac{N^{sig}}{\mathcal{L}_{int} \cdot (1+\delta) \cdot \varepsilon} \tag{1}$$

- Unbinned maximum likelihood fit is performed to $\Sigma^0(\bar{\Sigma}^0)$ mass reconstruction.
- Number of signal events in data is fitted by the following PDF:
  - **Total Fit (Red) = MC shape $\otimes$ Gaussian (Signal)+ Bkg (2^{nd} Poly.)+ Bkg shape (Fixed)**





Fit Result



@2.3960GeV
Signal = 5.30 ± 3.15
Bkg = 30.72 ± 5.95
@2.5000GeV
Signal = 12.50 ± 5.91
Bkg = 4.95 ± 5.46
@2.9000GeV
Signal = 113.52 ± 16.35
Bkg = 312.73 ± 25.28
@2.9500GeV
Signal = 16.64 ± 5.71
Bkg = 56.53 ± 9.28
@2.9810GeV
Signal = 25.10 ± 7.11
Bkg = 57.95 ± 9.83
@2.9884GeV
Signal = 79.56 ± 12.90
Bkg = 187.55 ± 18.42
@3.0000GeV
Signal = 15.77 ± 5.28
Bkg = 28.69 ± 7.11
@3.0200GeV
Signal = 24.52 ± 6.95
Bkg = 38.70 ± 9.07
@3.0800GeV
Signal = 197.58 ± 18.77
Bkg = 261.03 ± 22.18
Event/(5 MeV/c^2)
M_{Σ^0} (GeV/c^2)

- **Effective FFs:**

$$|G| = \sqrt{\frac{\sigma^{Born}}{86.854\ C.\frac{\beta}{s}(1+\frac{2m^2}{s})}} \tag{2}$$

where σ^{Born} in nb, and m, $\sqrt{s}$ are in GeV.

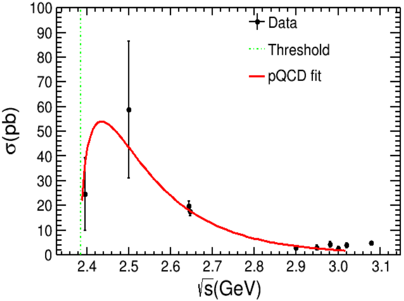
Table 1.Summarize the cross sections and parameters related to each energy point, where the first uncertainty is statistical and second is systematic. The last column shows the significance of the signal at each energy points.

$\sqrt{s}$(GeV)	$\mathcal{L}(pb^{-1})$	$\varepsilon(\%)$	$1+\delta$	$N_{sig.}$	$\sigma(pb)$	$G_{eff}(\times 10^{-2})$	Significance
2.3960	66.869	0.43	0.75	5.29±3.16	24.6±14.6± 8.86	10.7±3.17±1.92	2.2σ
2.5000	1.098	20.6	0.94	12.5±5.91	58.8± 27.8± 8.41	9.86±2.33±0.71	3.1σ
2.6444	33.722	29.9	1.10	220±23	19.8± 2.06 ± 1.90	5.12±0.27 ±0.25	12.4σ
2.6464	34.003	29.4	1.10	194±21	17.7± 1.94 ±1.81	4.84±0.27 ±0.25	11.9σ
2.9000	104.253	25.4	1.44	114±16	2.96± 0.43 ± 0.31	1.94±0.14 ±0.10	9.4σ
2.9500	15.942	23.8	1.53	16.6±5.71	2.86± 0.98	1.92±0.33	-
2.9810	16.071	22.7	1.60	25.1±7.11	4.29± 1.22	2.35±0.34	-
3.0000	15.881	22.7	1.65	15.8±5.28	2.65± 0.89	1.85±0.31	-
3.0200	17.290	21.8	1.69	24.5±6.95	3.85± 1.09	2.24±0.32	-
2.9884* [1]	65.184	22.8	1.62	79.9±12.9	3.31± 0.54± 0.31	2.07±0.17±0.10	9.0σ
3.0800	126.185	18.6	1.79	198±19	4.71± 0.45±0.43	2.50±0.12 ±0.11	15.6σ

[1] Energy point 2.9884 GeV is a combined dataset from 2.95, 2.981, 3.00, 3.02 GeV.

- **To Fit the Line-Shape**:
  - A perturbative QCD driven energy function is applied to the measured Born cross-section for **C=1** as;

$$\boldsymbol{\sigma} = \frac{c_0 \,.\beta \,.C}{(\sqrt{s}-c_1)^{10}}$$



Fitting result of line-shape $e^+e^- \to \Sigma^\circ\bar{\Sigma}^\circ$

Systematic Uncertainty

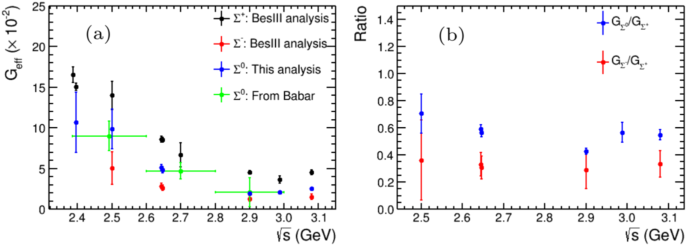
- **Luminosity:** The Integrated luminosity is measured to be 1.0% with Bhabha process.
- **Reconstruction Λ:** Including the tracking and PID efficiency of final states, vertex fit of Λ (**see in Ref.** PRD **97**, 032013 (2018))
- **Photon Rec.** The uncertainty due to photon detection and conversion is 1.0%.
- **Momentum Window Cut:** By varying the momentum 3σ to 4σ.
- **Signal Shape:** By changing the resolution of Gaussian with few MeV.
- **Background Shape:** By changing the order of polynomial from 2^{nd} to 3^{rd}.
- **Fitting Range:** By varying the fitting range of M_{Σ^0} by ± 5 MeV/c^2.
- **Fix Background Shape :** By varying the cross section within the uncertainty to renormalized the number of events.
- **Angular Distribution:** By considering two extreme cases for $\alpha = 1$ and $\alpha = -1$.
- **ISR Factor:** The difference between last two iteration

Systematic uncertainty @2.644 GeV(in%).

Source	**Value**
Luminosity	1.0
Reconstruction of Λ	3.4
Photon Reconstruction.	1.0
Momentum Window Cut	2.0
Signal Shape	0.5
Background Shape	1.0
Fitting Range	3.0
Fix Background Shape	0.5
Angular Distribution	1.1
ISR Factor	1.0
Total	**5.5**

Results and Discussion

- **Charge of Valence Quark**:
  - As charge of valence quark $\sum_{i=1}^{3} Q_i^2$ to be $1 : 0.66 : 0.33$



(a) Comparison of the EFFS for Σ isospin partner and (b) Ratio of EFFs.

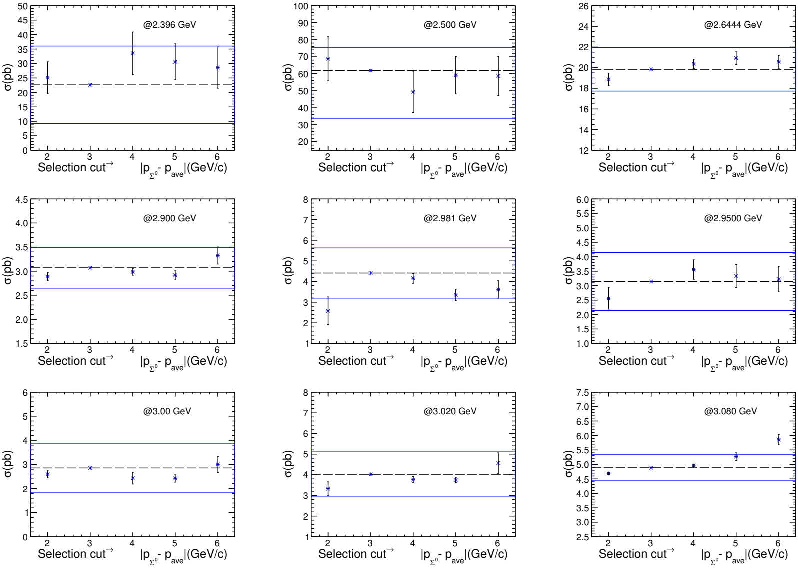
- **Remarks**: It is found that the fraction of the effective FFs of BesIII results is consistent with the charge of valence quark.

Summary

- We studied the process of $e^+e^- \to \Sigma^0\bar{\Sigma}^0$ and measured the born cross section in a wide range of $\sqrt{s}$. The precision is significantly improved.
- A pQCD based function is applied to fit the line-shape from $\sqrt{s}$ =2.396 to 3.02 GeVwith the fit quality is $\chi_2/n.o.d.f = 11.03/7.0$ which is consistent with pQCD prediction.
- By comparing the EFFS of Σ iso-spin states with BESIII results, it is found that they are proportional to the total charge square of its valence quark. However. due to the large uncertainty, it is not finally determined yet.
- With more datasets needed in future, expected to more precise results at BESIII and to the determination of G_E and G_M.
- Memo is being prepared.

Back up

Systematical Test for Momentum Window Cut



Systematic uncertainties of the Born cross section measurements (in%).

Source	2.396	2.500	2.6444	2.6464	2.900	2.9884	3.08
Luminosity	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Reconstruction of Λ	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Photon Rec.	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Momentum Cut	31	3.6	2.0	3.4	3.4	2.2	0.6
Signal Shape	3.3	2.2	0.5	1.1	0.7	0.6	0.6
Background Shape	12	9.9	1.0	0.6	1.0	1.5	0.2
Fitting Range	3.7	2.9	3.0	2.8	3.1	1.2	1.7
Angular Distribution	7.9	1.8	1.1	1.9	2.5	1.4	1.6
Fix Background Shape	-	0.2	0.5	0.6	0.7	1.7	0.6
ISR Factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total	35.0	11.9	5.5	6.3	6.6	5.3	4.6

The total systematic uncertainties of the Born cross section is obtained the individual contributions in quadrature.