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BESIII

Study of $\Sigma^0 \to \Lambda e^+ e^-$ at BESIII

Teng Ma, He Li, Xiaorong Zhou, Haiping Peng

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

Feixiang Lu, Cong Geng

Sun Yat-sen University

Haokai Sun, Haibo Li

Institute of High Energy Physics

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Outline

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- **Introduction**
- **Analysis strategy**
- **Data set and MC samples**
- **ST analysis**
- **DT analysis**
- **Summary**

- **Standard Model**

Standard Model It is a set of theories that describe the three basic forces of strong force, weak force and electromagnetic force and the basic particles that make up all matter.

There are 61 kinds of elementary particles in the standard model, including 36 Quarks, 12 leptons, 8 gluons, 2 W and Z, gamma, Higgs(Considering color anti-particle and charge)

Introduction

- **Hyperon**

Due to the color confinement of strong forces, quarks will always appear only in combinations with zero color charge (such as mesons and baryons). These different combinations are collectively referred to as "hadrons“

There are two kinds of hadrons confirmed in the experiment: fermions composed of three quarks, namely baryons (such as protons and neutrons); And bosons composed of quark antiquark pairs, namely mesons (such as π mesons)

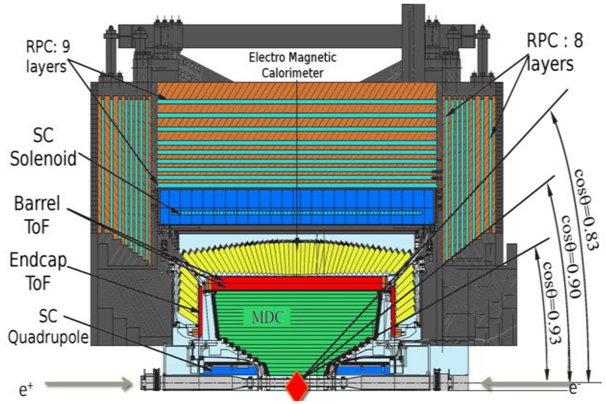
Hyperon is a baryon heavier than a nucleon, which is produced by strong interaction, and consisting of at least one strange quark. Hyperons follow Fermi-Dirac statistics. The earliest research on hyperons began in the 1950s, which is still hot till today.

- **BESIII**

BESIII at the BEPCII accelerator is a major upgrade of BESII at the BEPC for the studies of hadron physics and τ-charm physics with the highest accuracy achieved until now.

The cylindrical core of the BESIII detector consists of MDC, TOF and EMC, which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field.

This study is carried out on BESIII with Double Tag method.



Sub-system			BESIII
MDC	Single wire $\sigma_{r\phi}$ (μm)		130
	σ_p/p (1 GeV/c)		0.5%
	σ (dE/dx)		6 %
EMC	σ_E/E (1GeV)		2.5%
	Position resolution (1 GeV)		0.6 cm
TOF	σ_T (ps)	Barrel	100
		End cap	110
Muon	No. of layers (barrel/end cap)		9/8
	cut-off momentum (MeV/c)		0.4
Solenoid magnet Field (T)			1.0
$\Delta\Omega/4\pi$			93%

Background

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Σ^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\Lambda\gamma$		100 %	
Γ_2	$\Lambda\gamma\gamma$		< 3 %	90%
Γ_3	$\Lambda e^+ e^-$	[a]	5×10^{-3}	

[a] A theoretical value using QED.

- Σ^0 is a family of hyperons, consisting of quark u, d, s, $M_{\Sigma^0} = 1.192642\mathrm{GeV}/c^2$
- The existence of Σ^0 was published in 1956, which was found to decay rapidly($\tau < 10^{-20}$sec) into Λ and one γ, and Σ^0 will also perform an alternate decay $\Sigma^0 \to \Lambda e^+ e^-$. One example of such a decay was found by the Columbia bubble chamber group in 1957.

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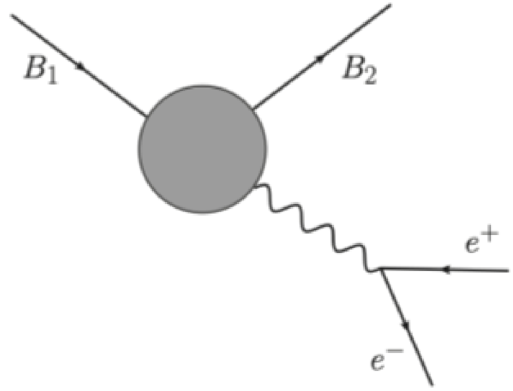
- Σ^0 is the only ground state baryon that the transition form factors are accessible at low q^2, via $\Sigma^0 \rightarrow \Lambda e^+ e^-$
- The BF of $\Sigma^0 \rightarrow \Lambda e^+ e^-$ is predicted to be 0.5%, but no experimental measurement yet
- With 10 billion J/ψ collected at BESIII, there would be millions of Σ^0 sample, enables the first measurement of $\Sigma^0 \rightarrow \Lambda e^+ e^-$



Decay mode	**BF(10^{-3})**	**$N_B(10^6)$**
$J/\psi \rightarrow \Lambda\bar{\Lambda}$	1.61±0.15	16.1±1.5
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^-$	1.50±0.24	15.0±2.4
$J/\psi \rightarrow \Sigma^0\bar{\Sigma}^0$	**1.29±0.09**	**12.9±0.9**
$J/\psi \rightarrow \Xi^0\bar{\Xi}^0$	1.20±0.24	12.0±2.4
$J/\psi \rightarrow \Xi^-\bar{\Xi}^+$	0.86±0.11	8.6±1.1

Data and MC samples

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- **BOSS Version: 7.0.5**
- **Data:** 1.3 billion J/ψ data collected in 2009,2012.
- **MC sample:**
  - 1.3 billion J/ψ inclusive MC
  - DIY Signal MC (ST-MC(500k) bkg-MC(2M))

    ST : $J/\psi \to \Sigma^0\bar{\Sigma}^0,\ \bar{\Sigma}^0 \to \bar{\Lambda}\gamma,\ \bar{\Lambda} \to \bar{p}\pi^+,\ \Sigma^0 \to anything$

    bkg : $J/\psi \to \Sigma^0\bar{\Sigma}^0,\ \bar{\Sigma}^0 \to \bar{\Lambda}\gamma,\ \bar{\Lambda} \to \bar{p}\pi^+,\ \Sigma^0 \to \Lambda\gamma,\ \Lambda \to p\pi^-$
  - PHSP signal MC (DT-MC(2M))

    DT : $J/\psi \to \Sigma^0\bar{\Sigma}^0,\ \bar{\Sigma}^0 \to \bar{\Lambda}\gamma,\ \bar{\Lambda} \to \bar{p}\pi^+,\ \Sigma^0 \to \Lambda e^+e^-,\ \Lambda \to p\pi^-$

Analysis strategy

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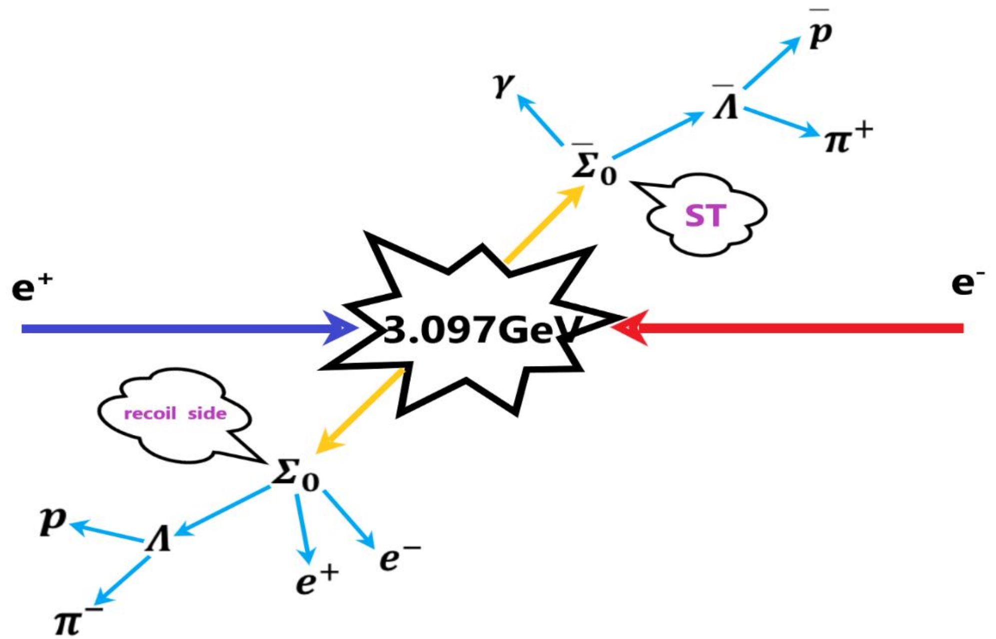
Double tag technique

- $J/\psi \to \Sigma^0\bar{\Sigma}^0$, $\bar{\Sigma}^0 \to \bar{\Lambda}\gamma$, $\Sigma^0 \to \Lambda e^+e^-$ decay.
- Single-tag(ST) $\bar{\Sigma}^0$ with $\pi^+\bar{p}\,\gamma$ and Σ^0 to anything ,
- double-tag(DT) Σ^0 with $\pi^-p\,e^+e^-$ and $\bar{\Sigma}^0$ with $\pi^+\bar{p}\,\gamma$
- N_{ST} and N_{DT} for ST and DT yield, ε_{ST} and ε_{DT} for ST and DT efficiency.

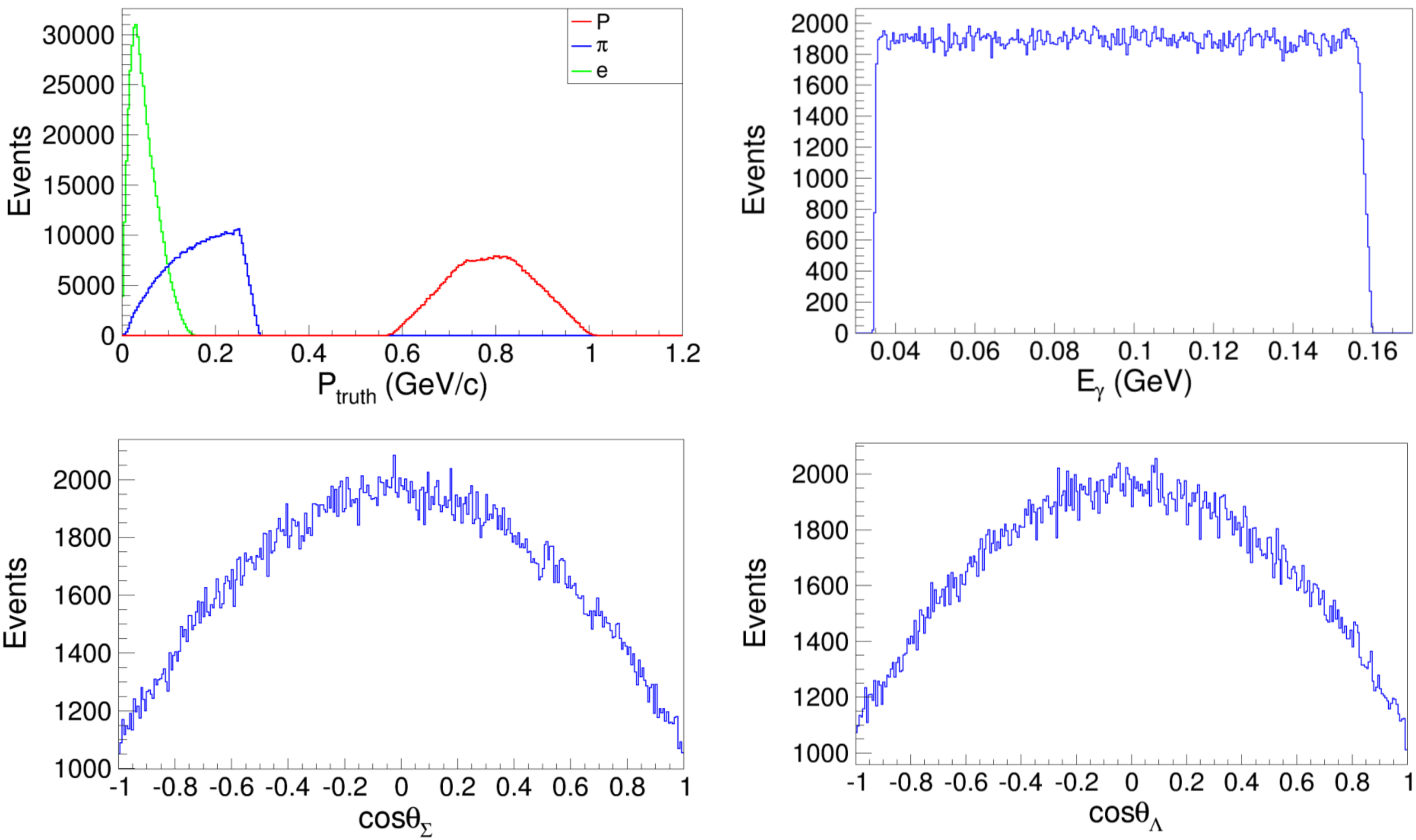


$$N_{ST} = N_{\Sigma^0\overline{\Sigma}^0} \cdot BF_{\overline{\Sigma}^0 \longrightarrow \overline{\Lambda}\gamma} \cdot BF_{\overline{\Lambda} \longrightarrow \pi^+\overline{p}} \cdot \varepsilon_{ST}$$

$$N_{DT} = N_{\Sigma^0\overline{\Sigma}^0} \cdot BF_{\overline{\Sigma}^0 \longrightarrow \overline{\Lambda}\gamma} \cdot BF_{\Sigma^0 \longrightarrow \Lambda ee} \cdot BF_{\overline{\Lambda} \longrightarrow \pi^+\overline{p}} \cdot BF_{\Lambda \to \pi^- p} \cdot \varepsilon_{DT}$$

$$\mathbf{BF_{\Sigma^0 \longrightarrow \Lambda ee} = \frac{N_{DT}/\varepsilon_{DT}}{N_{ST}/\varepsilon_{ST}} \cdot \frac{1}{BF_{\Lambda \to \pi^- p}}}$$

ST kinematics



- ST: proton and pion from lambda can be kinematically separated.

ST object selection

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Charged tracks

- $|R_z| < 30cm$, $|R_{xy}| < 10cm$, because Λ has long decay length.
- The tracks have to be a valid Kalman track.
- The reconstructed polar angle should satisfy: $|\cos\theta|<0.93$.
- Protons(p > 0.5 GeV/c) and pions(p < 0.5 GeV/c) can be identified by momenta and

  Further PID for proton with dE/dx & TOF information is applied to improve purity.

  p : Prob(p)>Prob(K/π) && p>0.5GeV/c π : Prob(π)>prob(K/p/e) && p<0.5GeV/c
- $N_{good} \geq 2$
- $N_{\bar{p}} \geq 1$ && $N_{\pi^+} \geq 1$

Neutral tracks

- Opening angle between shower and the nearest charged track > 10° (> 20° for $\bar{p}$).
- Barrel: E > 25MeV, $|\cos\theta| < 0.8$.
- Endcap: E > 50MeV, $0.86 < |\cos\theta| < 0.92$.
- $N_{\mathrm{Gam}} \geq 1$

ST event selection

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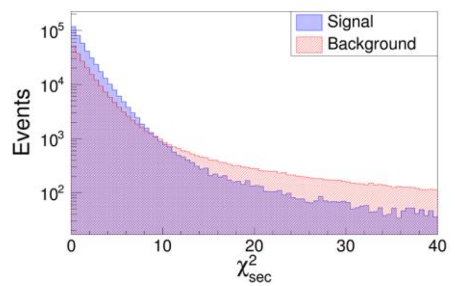
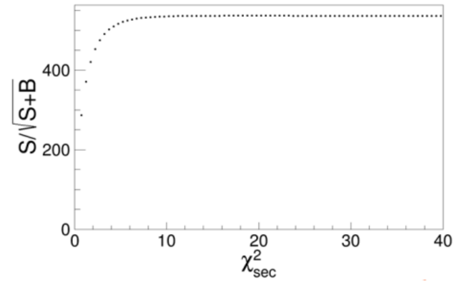
Reconstruction of $\bar{\Lambda}$

- Do the vertex fit of $\bar{\Lambda}$ by looping all $\pi^+\bar{p}$ combinations.
- The ones with minimum value of chisq is retained.
- Decay length larger than zero.
- Chisquare of the vertex fit should smaller than 20.



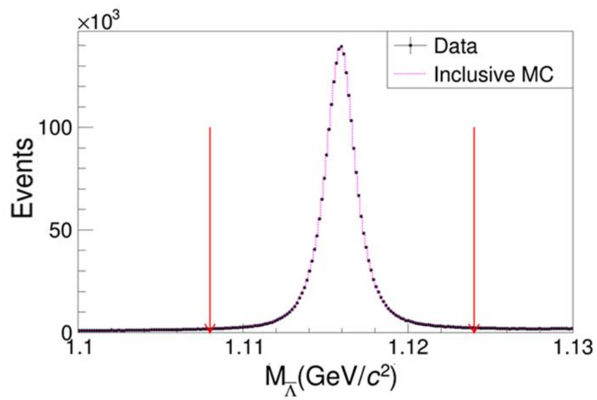


Reconstruction of $\bar{\Sigma}^0$

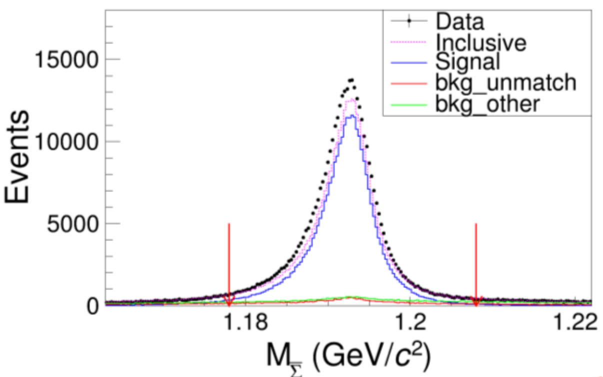
- Looping all γ candidates, and keep the ones with the minimum value of $|M(\bar{\Lambda}\gamma)-M(\bar{\Sigma}^0)|$.
- γ matching should be considered(angle_match<6°)

Further requirements

$|M(\pi^+\bar{p})-M(\bar{\Lambda})| < 0.008$ GeV/c^2(5σ)



$|M(\bar{\Lambda}\gamma)-M(\bar{\Sigma}^0)| < 0.015$ GeV/c^2(3σ)



Cutflow for ST

Selection	Efficiency
Total number	100.00%
Charged tracks selection	97.87%
PID for $\bar{p}\pi^+$	66.76%
Gamma selection	65.30%
Verfexfit for $\bar{\Lambda}$	63.99%
Selection for $\bar{\Sigma}^0$	33.55%

ST Recoil study

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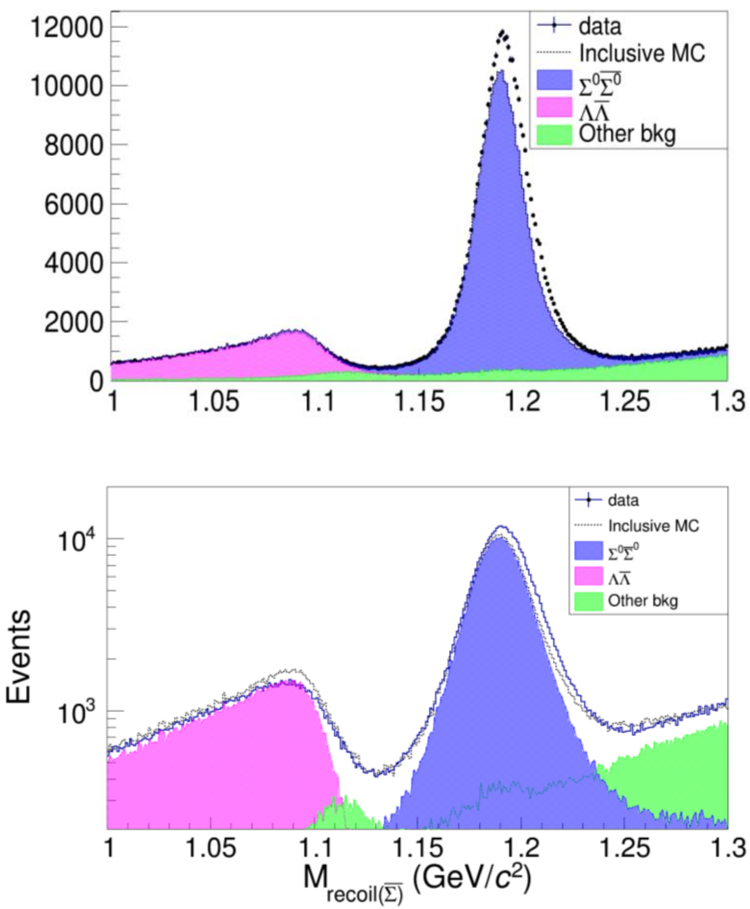
- 1.3 billion inclusive MC to estimate combinatorial backgrounds.
- No peaking background under signal peak.

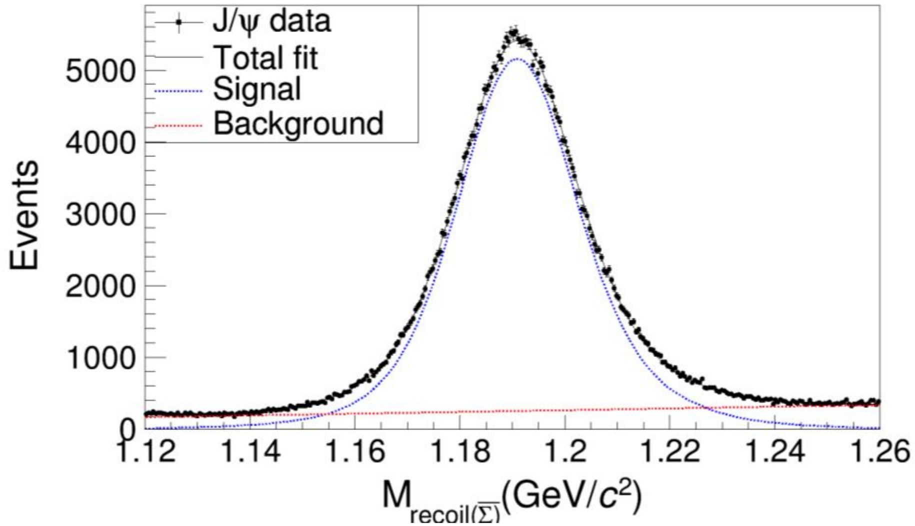


Topology result from inclusive MC

Table 1: Decay trees and their respective initial-final states.

rowNo	decay tree (decay initial-final states)	iDcyTr	iDcyIFSts	nEtr	nCEtr
1	$J/\psi \to \Sigma^0\bar{\Sigma}^0, \Sigma^0 \to \Lambda\gamma, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^+\pi^- p\bar{p}\gamma\gamma$)	2	2	242579	242579
2	$J/\psi \to \Sigma^0\bar{\Sigma}^0, \Sigma^0 \to \Lambda\gamma, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \Lambda \to \pi^0 n, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^0\pi^+ n\bar{p}\gamma\gamma$)	0	0	136219	378798
3	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to \pi^0 n, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^0\pi^+ n\bar{p}$)	1	1	102329	481127
4	$J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^+\pi^- p\bar{p}$)	3	3	94243	575370
5	$J/\psi \to \Lambda\bar{\Lambda}\gamma, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^+\pi^- p\bar{p}\gamma$)	14	6	22591	597961
6	$J/\psi \to \Lambda\bar{\Lambda}\gamma, \Lambda \to \pi^0 n, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^0\pi^+ n\bar{p}\gamma$)	21	8	15920	613881
7	$J/\psi \to \pi^+\pi^- p\bar{p}$ ($J/\psi \dashrightarrow \pi^+\pi^- p\bar{p}$)	26	3	4018	617899
8	$J/\psi \to \Sigma^0\bar{\Sigma}^{*0}, \Sigma^0 \to \Lambda\gamma, \bar{\Sigma}^{*0} \to \pi^0\bar{\Lambda}, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^0\pi^+\pi^- p\bar{p}\gamma$)	24	13	3891	621790
9	$J/\psi \to \pi^-\bar{\Lambda}\Sigma^+, \bar{\Lambda} \to \pi^+\bar{p}, \Sigma^+ \to \pi^0 p$ ($J/\psi \dashrightarrow \pi^0\pi^+\pi^- p\bar{p}$)	4	4	3444	625234
10	$J/\psi \to \Sigma^-\bar{\Sigma}^{*+}, \Sigma^- \to \pi^- n, \bar{\Sigma}^{*+} \to \pi^+\bar{\Lambda}, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^+\pi^+\pi^- n\bar{p}$)	5	5	3400	628634
11	$J/\psi \to \bar{\Xi}^+\Xi^-, \bar{\Xi}^+ \to \pi^+\bar{\Lambda}, \Xi^- \to \pi^-\Lambda, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to \pi^- p$ ($J/\psi \dashrightarrow \pi^+\pi^+\pi^-\pi^- p\bar{p}$)	10	9	3111	631745
12	$J/\psi \to \Lambda\bar{\Sigma}^0, \Lambda \to \pi^- p, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^+\pi^- p\bar{p}\gamma$)	6	6	3097	634842
13	$J/\psi \to \bar{\Lambda}\Sigma^{*0}, \bar{\Lambda} \to \pi^+\bar{p}, \Sigma^{*0} \to \pi^0\Lambda, \Lambda \to \pi^- p$ ($J/\psi \dashrightarrow \pi^0\pi^+\pi^- p\bar{p}$)	36	4	2926	637768
14	$J/\psi \to \pi^+\pi^-\Lambda\bar{\Lambda}, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^+\pi^+\pi^-\pi^- p\bar{p}$)	29	9	2722	640490
15	$J/\psi \to \Sigma^+\bar{\Sigma}^{*-}, \Sigma^+ \to \pi^0 p, \bar{\Sigma}^{*-} \to \pi^-\bar{\Lambda}, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^0\pi^+\pi^- p\bar{p}$)	53	4	2583	643073
16	$J/\psi \to K^- p\bar{\Lambda}, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^+ K^- p\bar{p}$)	41	18	2534	645607
17	$J/\psi \to \Xi^0\bar{\Xi}^0, \Xi^0 \to \pi^0\Lambda, \bar{\Xi}^0 \to \pi^0\bar{\Lambda}, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ ($J/\psi \dashrightarrow \pi^0\pi^0\pi^+\pi^- p\bar{p}$)	8	7	2505	648112

ST yield



ST $\bar{\Sigma}^0$ recoil mass distribution was used to extract signal yields

- **Signal PDF:** MC shape convoluting a Gaussian function.
- **BKG PDF:** 1st order Chebyshev polynomial function.
- **Efficiency:** DIY MC samples of $J/\psi \to \Sigma^0\bar{\Sigma}^0$, $\bar{\Sigma}^0 \to \bar{\Lambda}\gamma$, $\Sigma^0 \to$ anything.

Channels of signals	ST Yields	Efficiency
$J/\psi \to \Sigma^0\bar{\Sigma}^0$, $\bar{\Sigma}^0 \to \bar{\Lambda}\gamma$, $\Sigma^0 \to$ anything	351852 ± 698	33.552%

$Br(J/\psi \to \Sigma^0\bar{\Sigma}^0)$

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$$N_{ST} = N_{J/\psi} \cdot BF_{J/\psi \to \Sigma^0\bar{\Sigma}^0} \cdot BF_{\bar{\Sigma}^0 \longrightarrow \bar{\Lambda}\gamma} \cdot BF_{\bar{\Lambda} \longrightarrow \pi^+\bar{p}} \cdot \varepsilon_{ST}$$

$\varepsilon_{ST} = \mathbf{33.552\%}$ $N_{ST} = \mathbf{351852 \pm 698}$ $N_{J/\psi} = \mathbf{1.311 \times 10^9}$

$BF_{\bar{\Sigma}^0 \longrightarrow \bar{\Lambda}\gamma} = \mathbf{100\%}$ $BF_{\bar{\Lambda} \longrightarrow \pi^+\bar{p}} = \mathbf{63.9\%}$

$BF_{J/\psi \to \Sigma^0\bar{\Sigma}^0} = \mathbf{(1.252 \pm 0.002) x 10^{-3}}$

$BF_{J/\psi \to \Sigma^0\bar{\Sigma}^0}$ (PDG) $= \mathbf{(1.172 \pm 0.032) x 10^{-3}}$

$BF_{J/\psi \to \Sigma^0\bar{\Sigma}^0}$ (BESIII) $= \mathbf{(1.29 \pm 0.09) x 10^{-3}}$

DT object selection

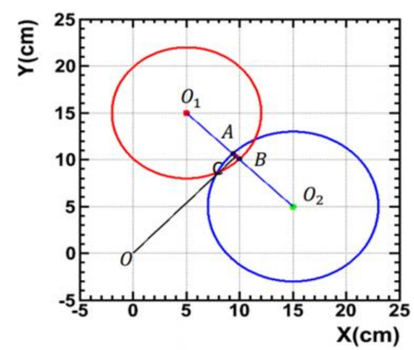
Charged tracks

- These jobs are based on Single tag.
- $|R_z| < 30cm$, $|R_{xy}| < 10cm$, because Λ has long decay length.
- The tracks have to be a valid Kalman track.
- The reconstructed polar angle should satisfy: |cosθ|<0.93.
- PID for $p\pi^-$ has been finished in pπ identification in Single tag.
- $N_{good} \geq 6$
- $N_p \geq 1$ && $N_{\pi^-} \geq 1$
- The reconstruction of Λ is the same as $\bar{\Lambda}$
- PID for e^+e^- is independent from PID for pπ , Besides $p\bar{p}\pi^+\pi^-$, all tracks left are looped for eePID, ee are indentified by prob_e/(prob_e+prob_π+prob_K+prob_p) > 0.8, and select $N_{e^+} \geq 1$ $N_{e^-} \geq 1$

Kinematic Fit

Futher Selection

- Loop all e^+e^- with $\gamma, \Lambda, \overline{\Lambda}$ to do 4C kinematic Fit , find the successfully fit ones with the minimum value of χ^2_{kmf}, and make sure $|M(\overline{\Lambda}\gamma)\text{-}M(\overline{\Sigma}^0)|<3\sigma$
- However, gamma conversion($\gamma \rightarrow e^+e^-$) should also be taken into consideration
- $!(R_{xy} > 2 \ \&\& \ cos\theta_{eg} > 0.8 \ \&\& \ |\Delta_{xy}| < 0.5)$ (https://indico.ihep.ac.cn/event/13532/contribution/27/material/slides/0.pdf)
- R_{xy} : x-y plane distance from ee vertex point to (0,0,0)
- θ_{eg}: the angle between the vector of reconstructed γ and the direction from IP to reconstructed conversion point.
- $|\Delta_{xy}|$ has been shown in the picture



The two circles are the electron pair tracks. O_1 and O_2 are center of the tracks.

Δ_{xy}: the distance between point A and B.

Efficiency for BKG

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- From the decay modes of Σ^0 , we can know the importance of reducing the bkg in the data , the dominant bkg comes from $\Sigma^0\bar{\Sigma}^0 \to \Lambda\bar{\Lambda}\gamma\gamma$
- $N_{sig} = N_{J/\psi} * Br_{\Sigma^0\bar{\Sigma}^0} * Br_{\Sigma^0\to\Lambda ee} * Br_{\bar{\Sigma}^0\to\bar{\Lambda}\gamma} * Br_{\Lambda\to p\pi^-} * Br_{\bar{\Lambda}\to\bar{p}\pi^+} * \varepsilon_{sig}$
- $N_{bkg} = N_{J/\psi} * Br_{\Sigma^0\bar{\Sigma}^0} * Br_{\Sigma^0\to\Lambda\gamma} * Br_{\bar{\Sigma}^0\to\bar{\Lambda}\gamma} * Br_{\Lambda\to p\pi^-} * Br_{\bar{\Lambda}\to\bar{p}\pi^+} * \varepsilon_{bkg}$
- So reducing the bkg means increasing $\frac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$, after the selection all above , $\frac{\varepsilon_{sig}}{\varepsilon_{bkg}}$ can be increased to about 500, which means we've still got many events of background in data.

DT Cutflow

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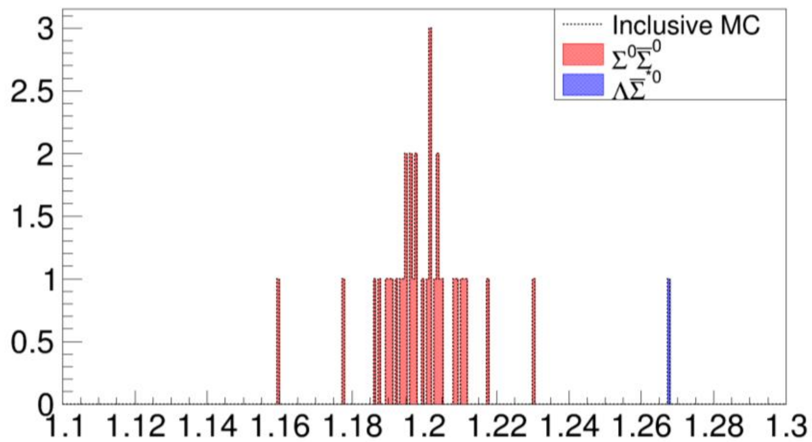
Selection:	DT Efficiency	Bkg Efficiency
Total number	100.00%	100.00%
Charged tracks selection(>6)	5.69%	0.59%
PID for $p\pi^-$	4.85%	0.52%
Verfexfit for Λ	3.94%	0.41%
PID for e^+e^-	2.00%(30,10) 1.06%(10,1) 1.06%(10,1), no TOF	0.0573%(30,10) 0.0193%(10,1) 0.0193%(10,1), no TOF
Selection for DT	0.954%(30,10) 0.665%(10,1) 0.665%(10,1), no TOF	0.0063%(30,10) 0.0018%(10,1) 0.0018%(10,1), no TOF

Inclusive MC



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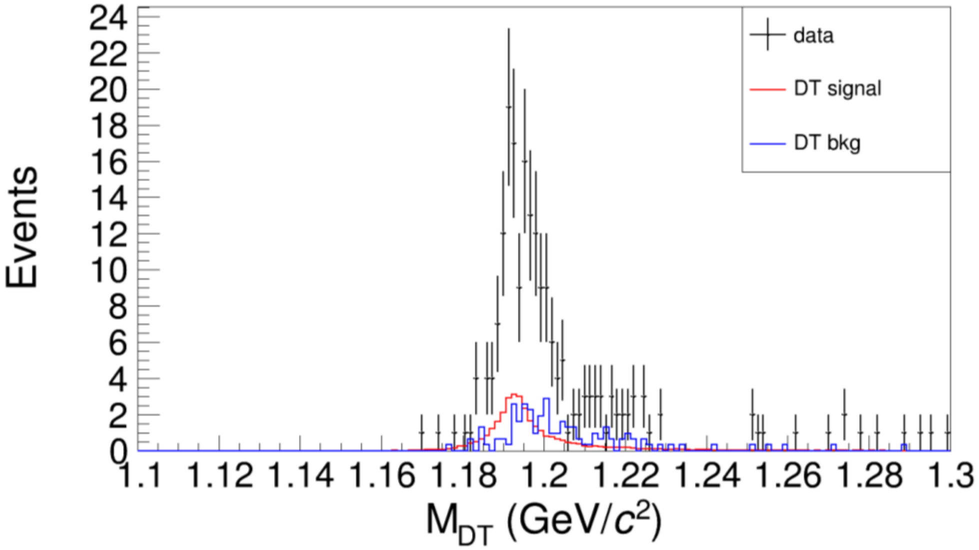
1	$J/\psi \to \Sigma^0\bar{\Sigma}^0, \Sigma^0 \to \Lambda\gamma, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ $(J/\psi \dashrightarrow \pi^+\pi^- p\bar{p}\gamma\gamma)$	0	0	34	34
2	$J/\psi \to \Lambda\bar{\Sigma}^{*0}, \Lambda \to \pi^- p, \bar{\Sigma}^{*0} \to \pi^0\bar{\Lambda}, \pi^0 \to e^+e^-\gamma^F, \bar{\Lambda} \to \pi^+\bar{p}$ $(J/\psi \dashrightarrow e^+e^-\pi^+\pi^- p\bar{p}\gamma^F)$	1	1	1	35

- After topology, almost only $\Sigma^0 \to \Lambda\gamma$ process survives from 1.3 billion inclusive MC
- As calculated, $N_{\Sigma^0\to\Lambda\gamma\ in\ data} = N_{J/\psi} \times Br_{J/\psi\to\Sigma^0\bar{\Sigma}^0} \times Br^2_{\Sigma^0\to\Lambda\gamma} \times Br^2_{\Lambda\to p\pi^-} \times \varepsilon_{bkg}$ =35, which is consistent with that inclusive MC

Data for DT



- After selection, there are 205 data survived, where signal process and background process are scaled according to their BFs in PDG
- The data can not be well described by the two parts currently.

Summary

- Process $\Sigma^0 \to \Lambda e^+ e^-$ is studied with double-tag method using 1.3 billion data at BESIII
- The dominant background comes from $\Sigma^0 \to \Lambda\gamma$
- Using the predicted BF from Dalitz decay, the MC cannot describe data well

- Next to do
  - Update the MC generator for signal process
  - Optimize the selection criteria
  - Analysis 10 billion inclusive MC

Thank you