Observation of a cross-section enhancement near the mass threshold in $e^+ e^- \to \Lambda \bar{\Lambda}$

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Electromagnetic Structure of Strange Baryons

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Introduction (I)

- The electromagnetic form factors of nucleons could be used to study the inner structure of nucleon states and understand strong interactions.

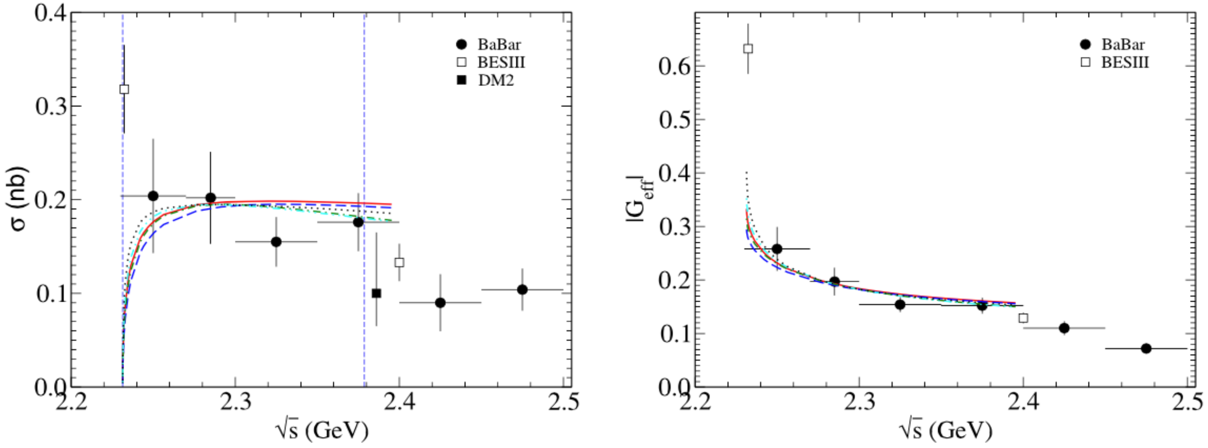
$$\sigma^B(s) = \frac{4\pi\alpha^2 C\beta}{3s}\left[|G_M(s)|^2 + \frac{2m_B^2c^4}{s}|G_E(s)|^2\right] \qquad |G| \equiv \sqrt{\frac{|G_M(s)|^2 + (2m_B^2c^4/s)|G_E(s)|^2}{1 + 2m_B^2c^4/s}}$$

- Comparing with proton anti-proton studying, only a few measurements of Lambda anti-Lambda have been published.

Introduction (II)

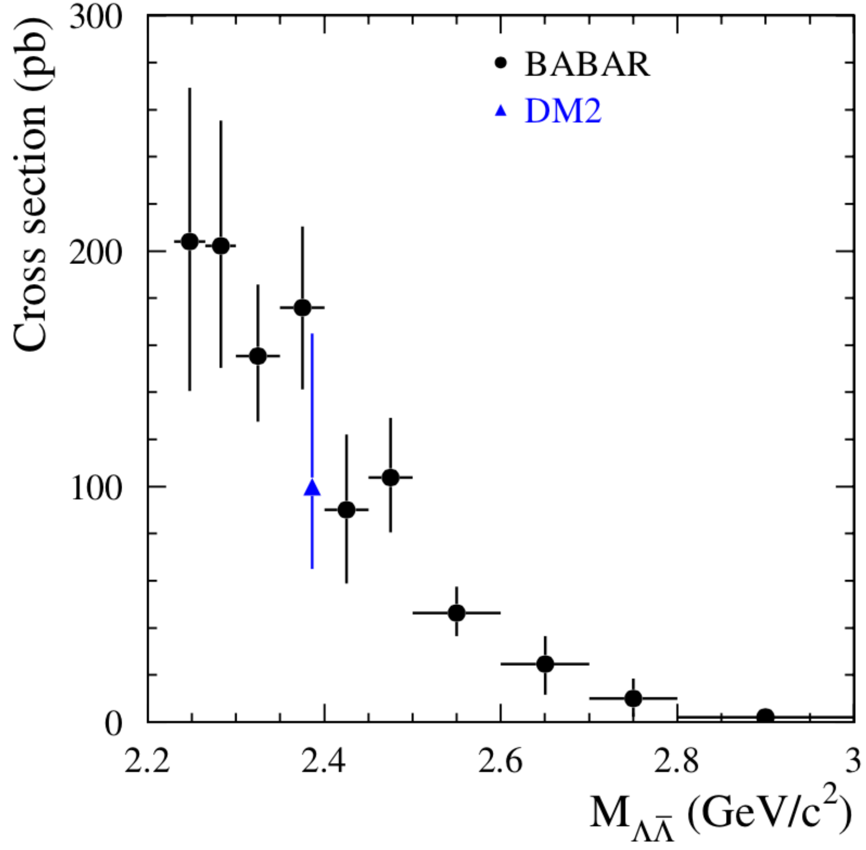
In the timelike region, based on the DM2 and BABAR experiment results, there is an enhancement near the the Lambda anti-Lambda threshold like the p pbar enhancement.

Some theoretical studies for explaining this behavior:



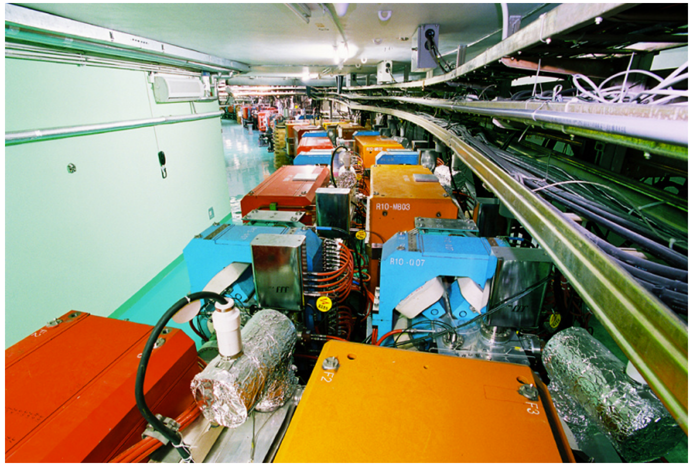
J. Haidenbauer, U.-G. Meißner / Physics Letters B 761 (2016) 456–461

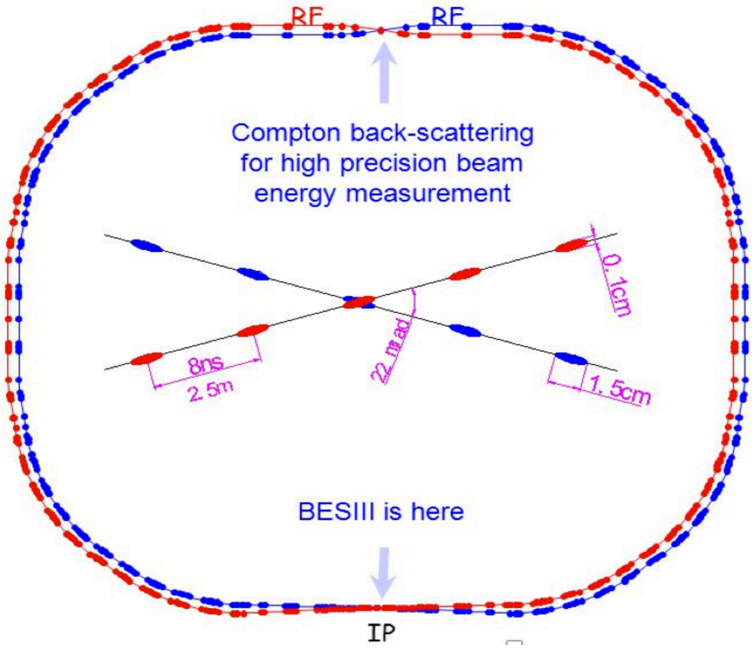
More data near the threshold are needed !

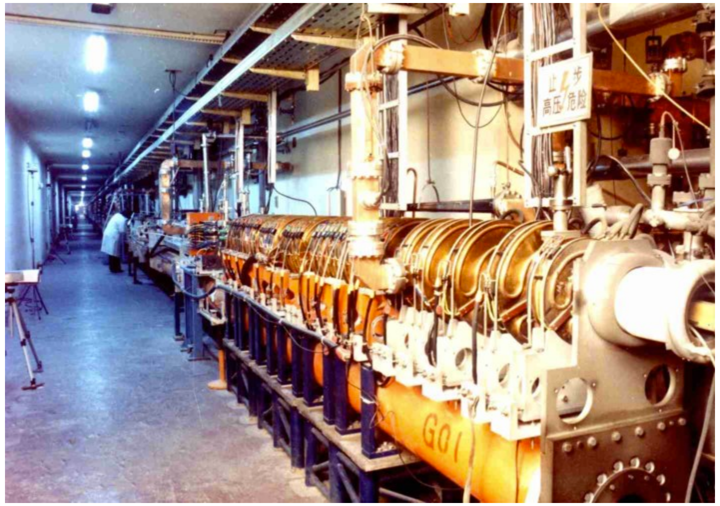


D. Bisello, et al., DM2 Collaboration, Z. Phys. C 48 (1990) 23.
B. Aubert, et al., BaBar Collaboration, Phys. Rev. D 76 (2007) 092006.

BEPCII storage rings: a τ-charm factory



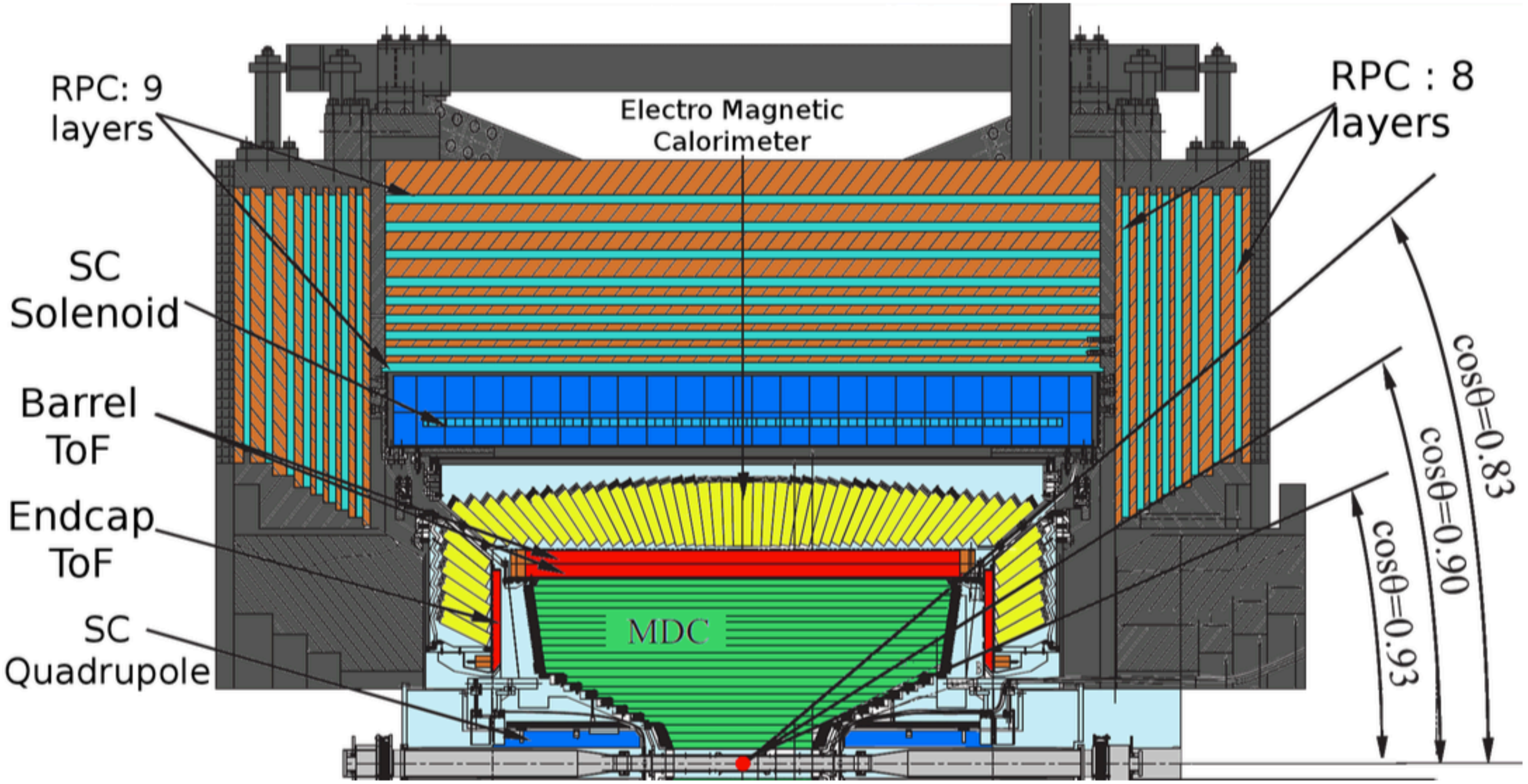




Update of BEPC (started 2004, first collisions July 2008)

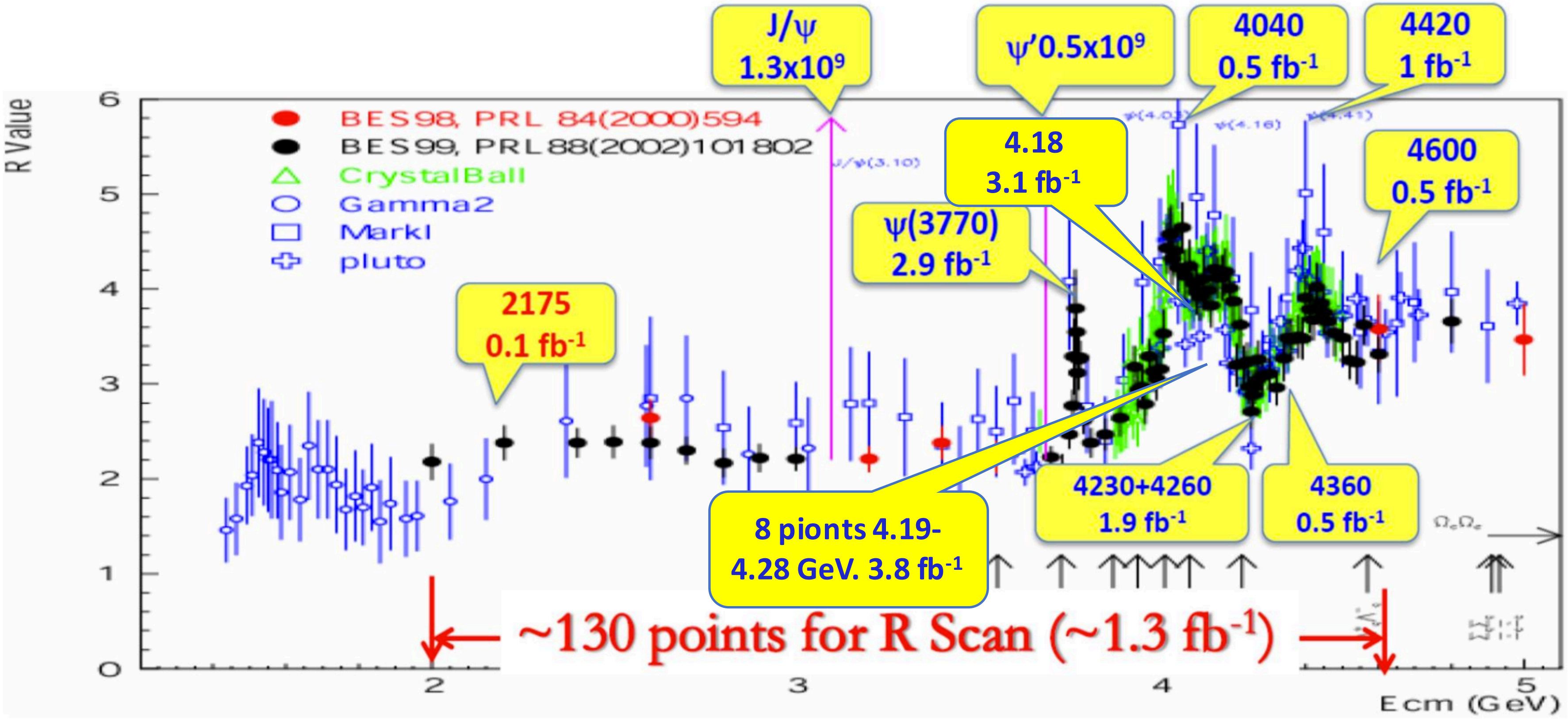
Beam energy	1 - 2.3 GeV
Optimum energy	1.89 GeV
Single beam current	0.91 A
Crossing angle	11mrad
Design luminosity	1×10^{33} cm^{-2} s^{-1}
Achieved	1×10^{33} cm^{-2} s^{-1}

BESIII detectors



- Main Drift Chamber (MDC)
  - $\sigma(p)/p$ = 0.5%
  - $\sigma_{dE/dX}$ = 5.0%
- Time-of-flight (TOF)
  - $\sigma(t)$ = 80ps (barrel)
  - $\sigma(t)$ = 70ps (endcap)
- Electro Magnetic Calorimeter (EMC)
  - $\sigma(E)/E$ = 2.5%
  - $\sigma_{z,\phi}(E)$ = 0.5 – 0.7 cm
- RPC MUON Detector
  - $\sigma(xy)$ < 2 cm

BESIII data set



- ✓ World largest data sample on J/ψ, ψ', $\psi(3770)$, Y(4260)... in e^+e^- collisions
- ✓ From light mesons spectroscopy to $\Lambda_c\Lambda_c$
- ✓ Also ISR, photon-photon physics, τ physics...

Threshold measurement in BESIII

Mode I : $\Lambda \rightarrow p\, \pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\, \pi^+$

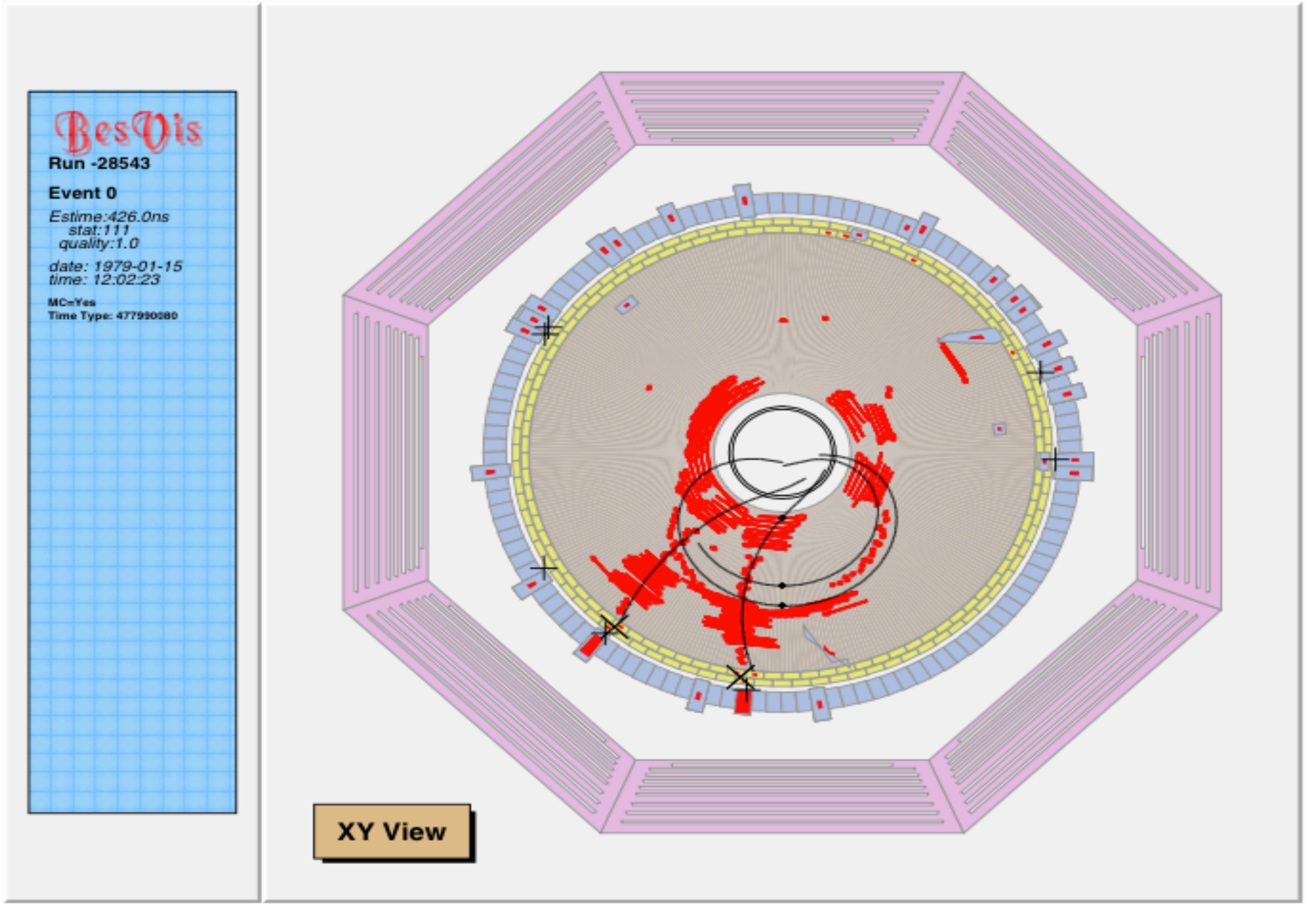
Mode II: $\bar{\Lambda} \rightarrow \bar{n}\, \pi^0$, $\Lambda \rightarrow$ Anything

$\sqrt{s}$ GeV	Lumi. (pb^{-1})
2.2324	2.63
2.40	3.42
2.80	3.75
3.08	30.73

Event Selections for Mode I

Since the final state momenta are much lower than most of BESIII analyses, we have to study the behavior of final states firstly, then decide to event criterions.

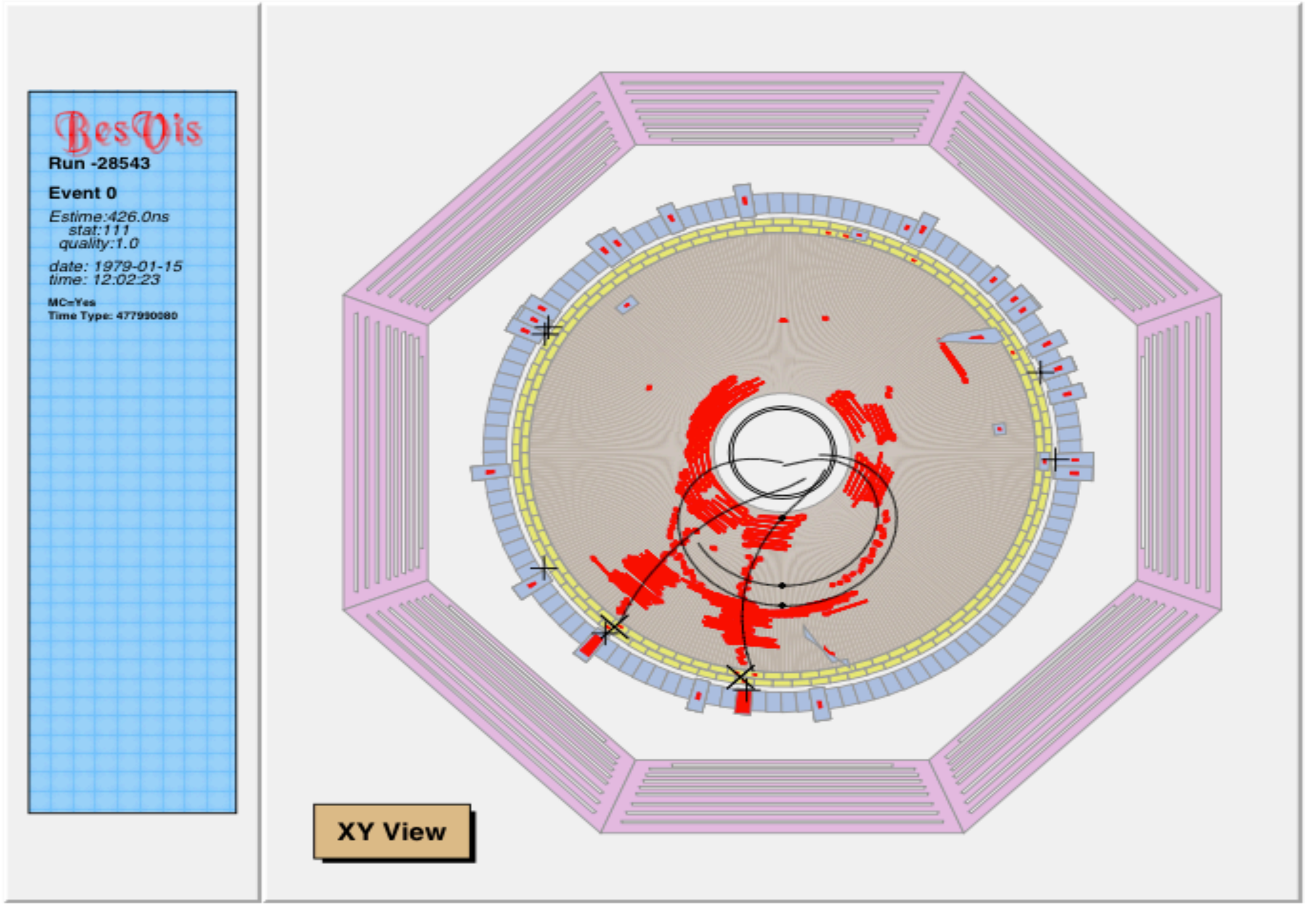
In this plot, we observe two tracks take circles which are low momentum pions. The other two tracks are not proton and antiproton, because the momentum of these tracks are much larger than we expected.



Event Selections for Mode I

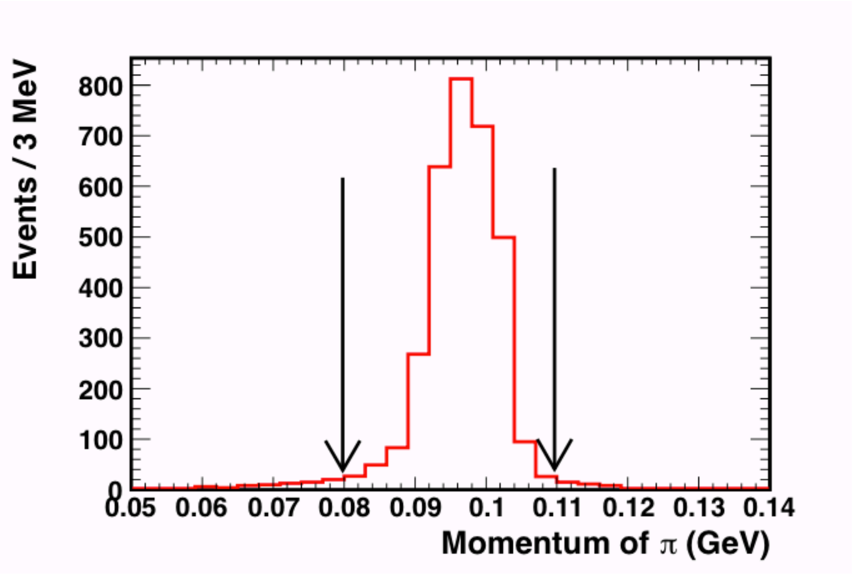
- The large energy loss for the low momentum proton makes it difficult to observe the track of proton in MDC. For the anti-proton, the cross section of interaction with materials of detectors is large at low momentum range. As a consequence, the anti-proton will annihilate with a nucleon in the detector material and produce secondary particles. It is therefore impossible to directly observe the anti-proton signal.

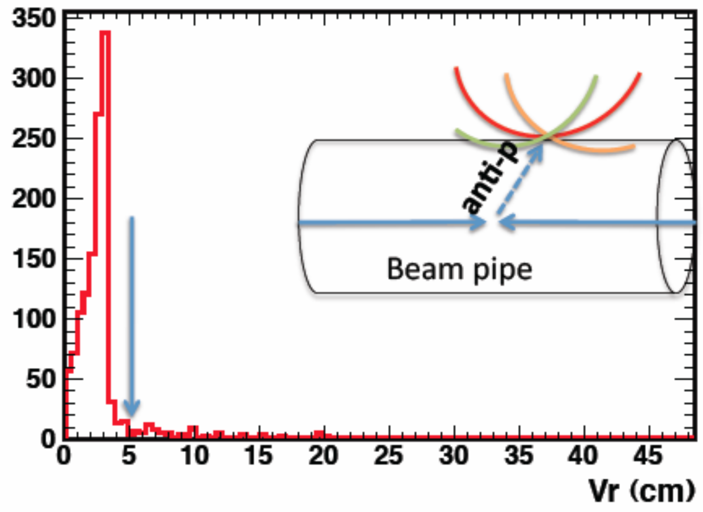
- Based on the above reasons, the analysis is focused on searching for two low momentum pions and a possible antiproton signal.



Final Event Selections

- 2 good charged tracks with low momentum([0.08, 0.11]GeV) and net charged = 0;
- PID: $N_{\pi+} = N_{\pi-} = 1$;
- "V_r" < 5 cm for other tracks. (V_r: the largest one in the V_{xy} of other charged tracks, in the plane perpendicular to the beam V_{xy})



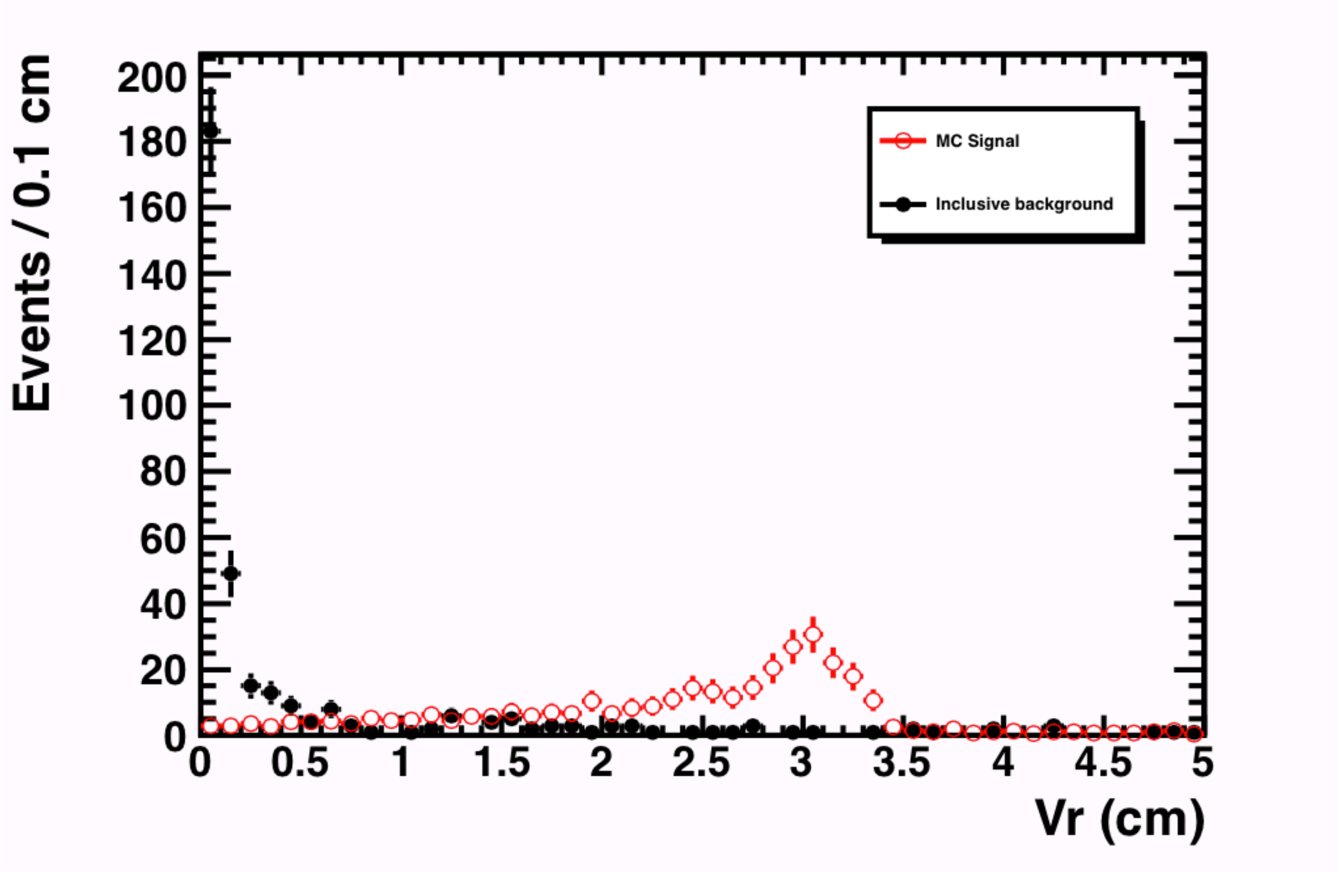


Background analysis (I)

The 1.47 pb $^{-1}$ inclusive MC samples generated at $\sqrt{s}$ = 2.2324 GeV are used to estimate the remaining backgrounds after the final event selection. The normalized numbers of events from background MC samples are listed in the following table.

Final states	Luminosity (pb^1)	Events generated	Events survived	Normalized number
e^+e^-	1.47	2.14M	2	3.6
$\mu^+\mu^-$	1.47	26.7k	1	1.8
$\gamma\gamma$	1.47	103k	0	0
e^+e^-X	1.47	24k	22	39.4
$q\bar{q}$	1.47	53.5k	339	606.7

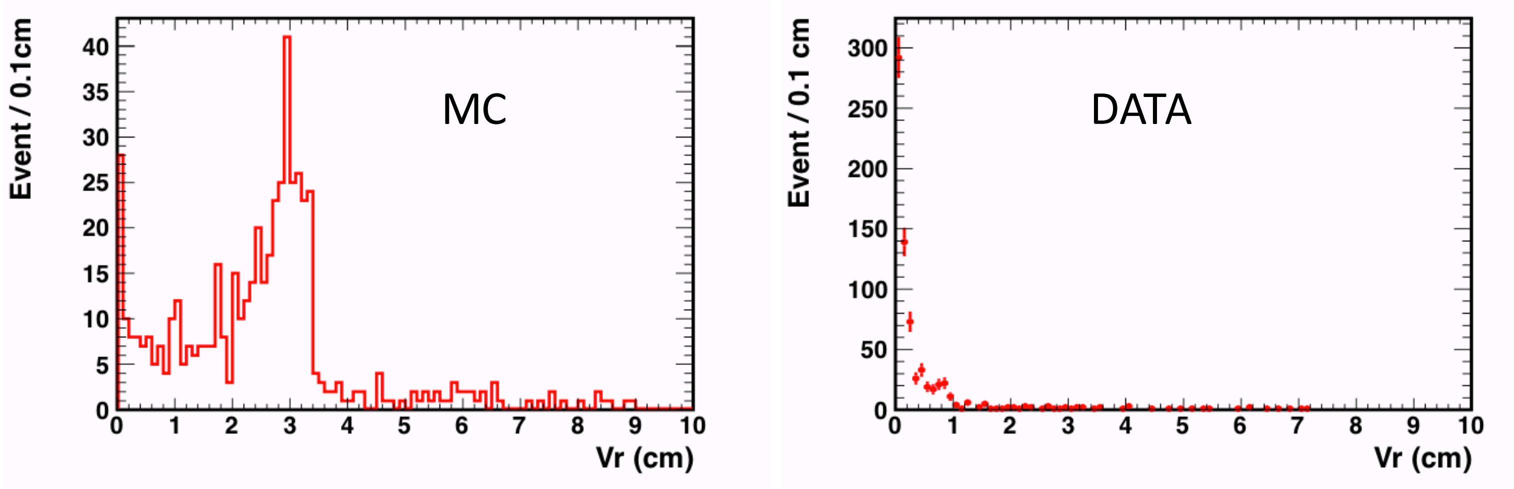
Background analysis (II)



There is no peaking background events.

Background analysis (III)

- By checking the momentum distribution of pions for the process of $e^+ e^- \rightarrow \pi^+ \pi^- p \bar{p}$, the range is from 0.0 to 0.16 GeV/*c*. If we study the pion momentum range ([0.0 - 0.07] GeV/*c* and [0.12 - 0.16] GeV/*c*) which is out of the pion momentum range [0.08, 0.11] of $e^+ e^- \rightarrow \Lambda \bar{\Lambda}$ process, the enhancements around 3 cm could still be observed in the MC.
- But there is no such enhancements in the experimental data. According to the above checks, the process of $e^+ e^- \rightarrow \pi^+ \pi^- p \bar{p}$ is insignificant, and can be neglected when calculating the cross section of $e^+ e^- \rightarrow \Lambda \bar{\Lambda}$.

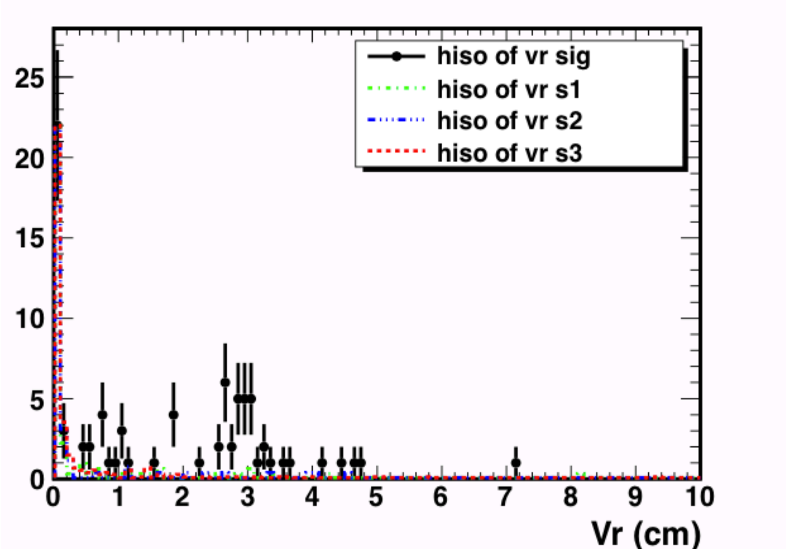


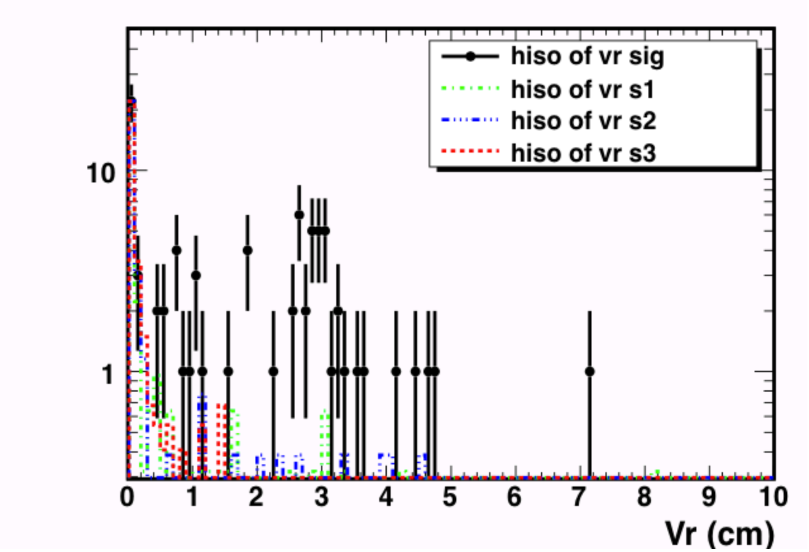
Fitting Vr distributions

✓Signal shape: MC signal shape

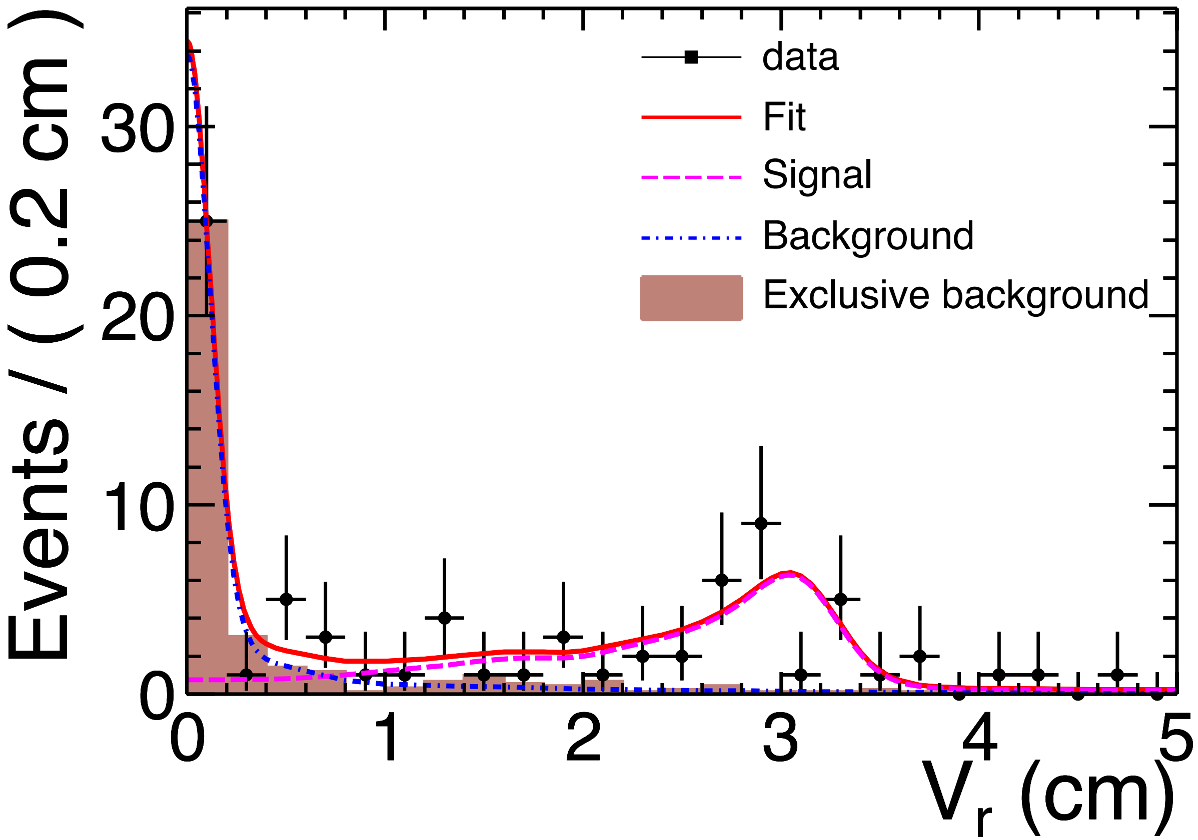
✓Background shape: described by the shape in the sideband regions.

1. Sideband region 1: $p_{\pi+} \in [0.08, 0.11]$ GeV/c and $p_{\pi-} \in [0.15, 0.18]$ GeV/c;
2. Sideband region 2: $p_{\pi+} \in [0.15, 0.18]$ GeV/c and $p_{\pi-} \in [0.08, 0.11]$ GeV/c;
3. Sideband region 3: $p_{\pi+} \in [0.15, 0.18]$ GeV/c and $p_{\pi-} \in [0.15, 0.18]$ GeV/c.





Fitting Vr distributions



The fitted Vr distribution for charged channel where an un-binned likelihood method is used.
The fit yields N = 43 ± 7. The efficiency is 20.05 % from MC simulation after applying all the selections.

Cross section calculation

$$\sigma^B = \frac{N_{obs}}{\mathcal{L}_{int}(1+\delta)\epsilon\mathcal{B}} \quad = \quad 312 \pm 51 \text{ pb}$$

where N_{obs} is the number of observed events, L_{int} is integrate luminosity, ε is selection efficiency, B are the branching ratios of $\Lambda \to \pi^- p$ and $\bar{\Lambda} \to \pi^+ \bar{p}$, (1 + δ) is the radiative correction factor.

The radiative correction factor is evaluated considering beam energy spread and ISR, which cause an efficiency loss bringing the effective total energy below the threshold. The total c.m. energy spread at the J/ψ peak has been recently measured to be 0.92 MeV, has previously been found to be 1.3 MeV at the ψ′ peak. The energy spread Δ*E* is expected to be proportional to E^2

Then energy spread Δ*E* at 2.2324 GeV can be calculated:

$$\Delta E(2.2324) = \Delta E(3.097) \times \frac{2.2324^2}{3.097^2} = 0.48\ MeV$$

Event Selection for Mode II

$\bar{\Lambda} \to \bar{n}\, \pi^0$, $\Lambda \to$ Anything

- To improve the detect efficiency, we only reconstruct the $\bar{\Lambda}$ signal by tagging $\bar{n}$ and π^0 .
  - ✓ At most one good charged track and at least three neutral candidates;
  - ✓ The most energetic shower is assumed to be a $\bar{n}$ and others to be photons;
  - ✓ A π^0 candidate is identified by a one-constrained kinematic fit on π^0 mass applied to each photon pair;
  - ✓ if more than one π^0 candidate, the one with the smallest χ^2_{1C} value is taken as the π^0 candidate;
  - ✓ The angle between the directions of $\bar{n}$ and π^0 is required to be larger than 140 degree.

Event Selections for Model II

- After the above criterions, most of background events from QED processes have been removed.

- Inclusive hadronic final states with multiple π^0s and the beam-associated background events are the dominant background sources.
  - ✓ Hadronic final state: MC background channels study, be normalized according to the cross sections and luminosities.

  - ✓ Beam associated background: A delicated data sample collected with BESIII with non-colliding beams.

Comparison between Data and MC

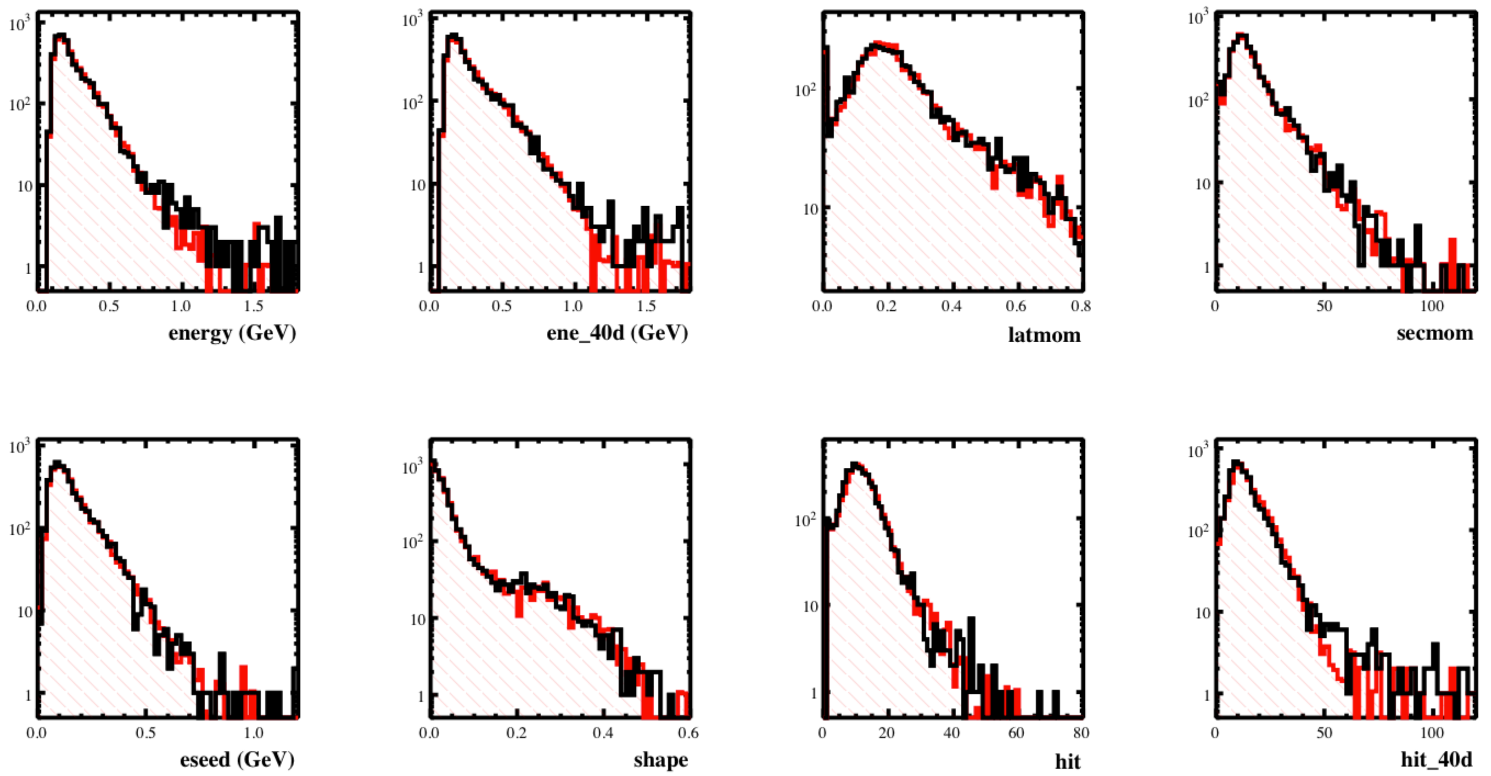


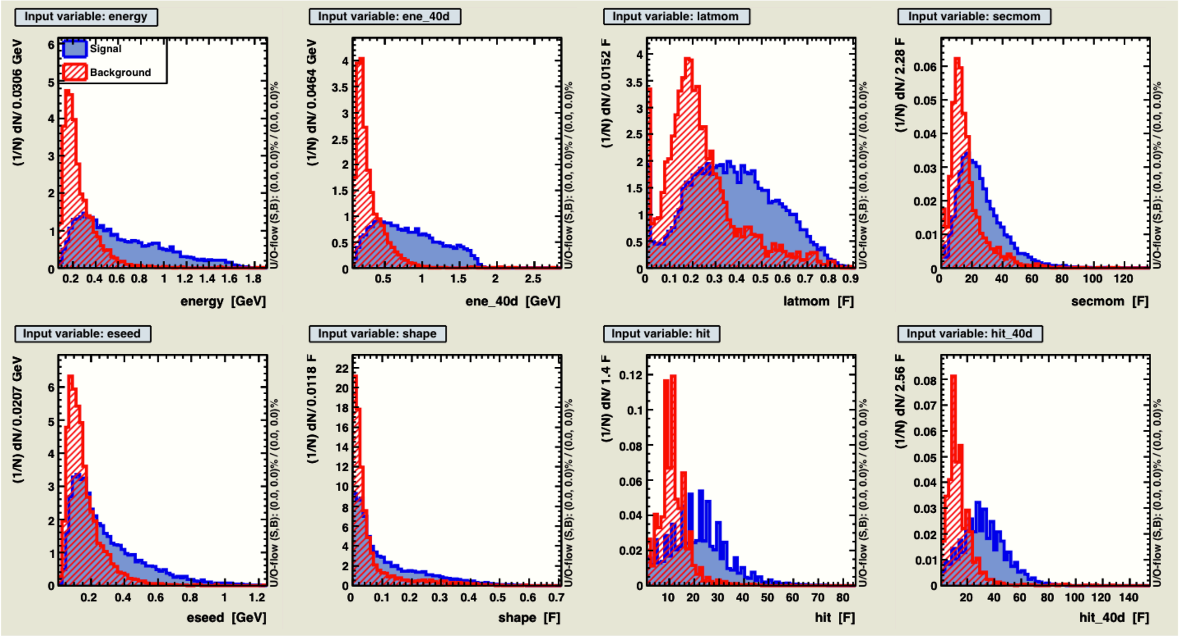
TABLE I. The variables used in the BDT classifier, ranked by the importance.

Rank	Variable	Importance
1	Energy deposition within 40° cone	2.4×10^{-1}
2	Deposited energy	2.0×10^{-1}
3	Deposit of energy seed	1.3×10^{-1}
4	Number of hits within 40° cone	1.1×10^{-1}
5	Number of hits	1.0×10^{-1}
6	Lateral moment	9.3×10^{-2}
7	Second moment	7.6×10^{-2}
8	Deposition shape [30]	5.4×10^{-2}

Good agreement between data and MC, and these 8 variables will be used to separate signal and background.

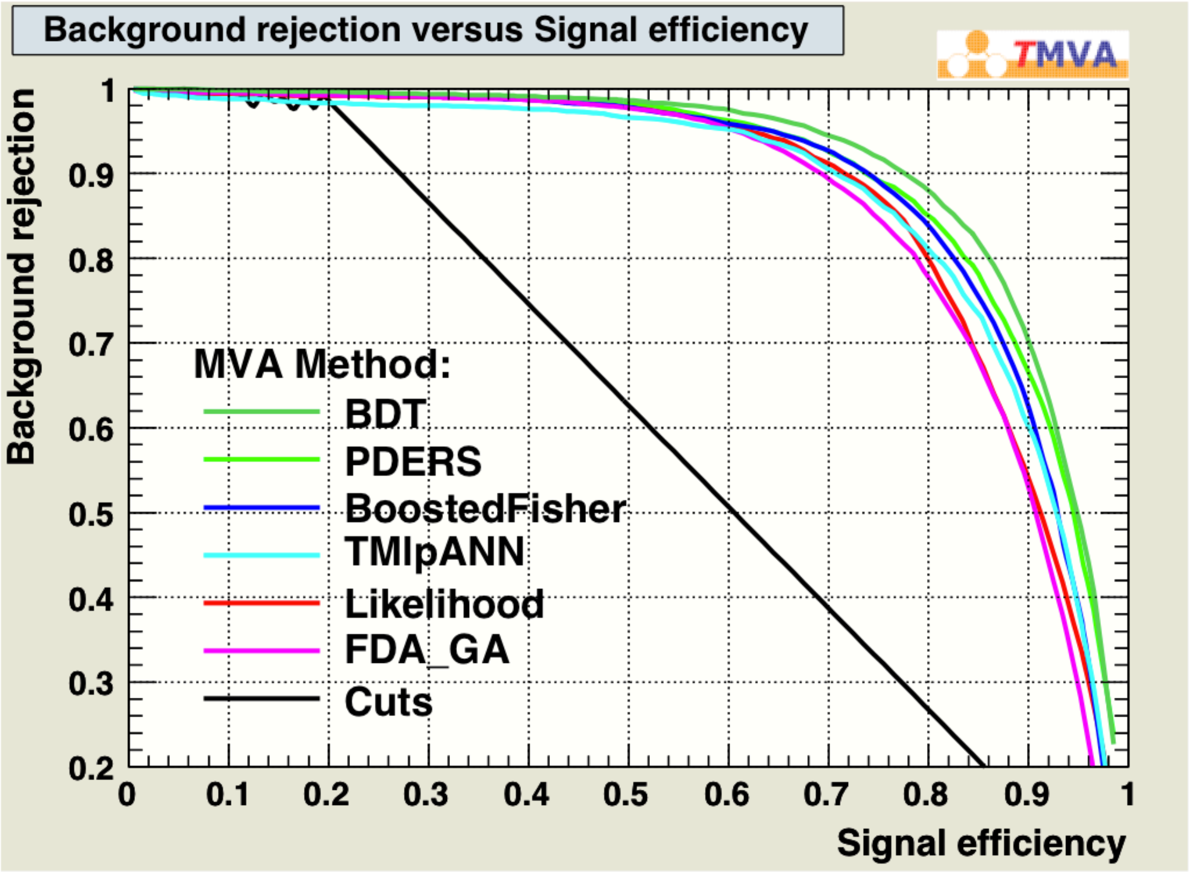
Multiple Variable Analysis

- The multiple variable analysis method is used to classify signal and background.



Comparison of input variables between signal and background.
Blue: Signal, Red: Background.

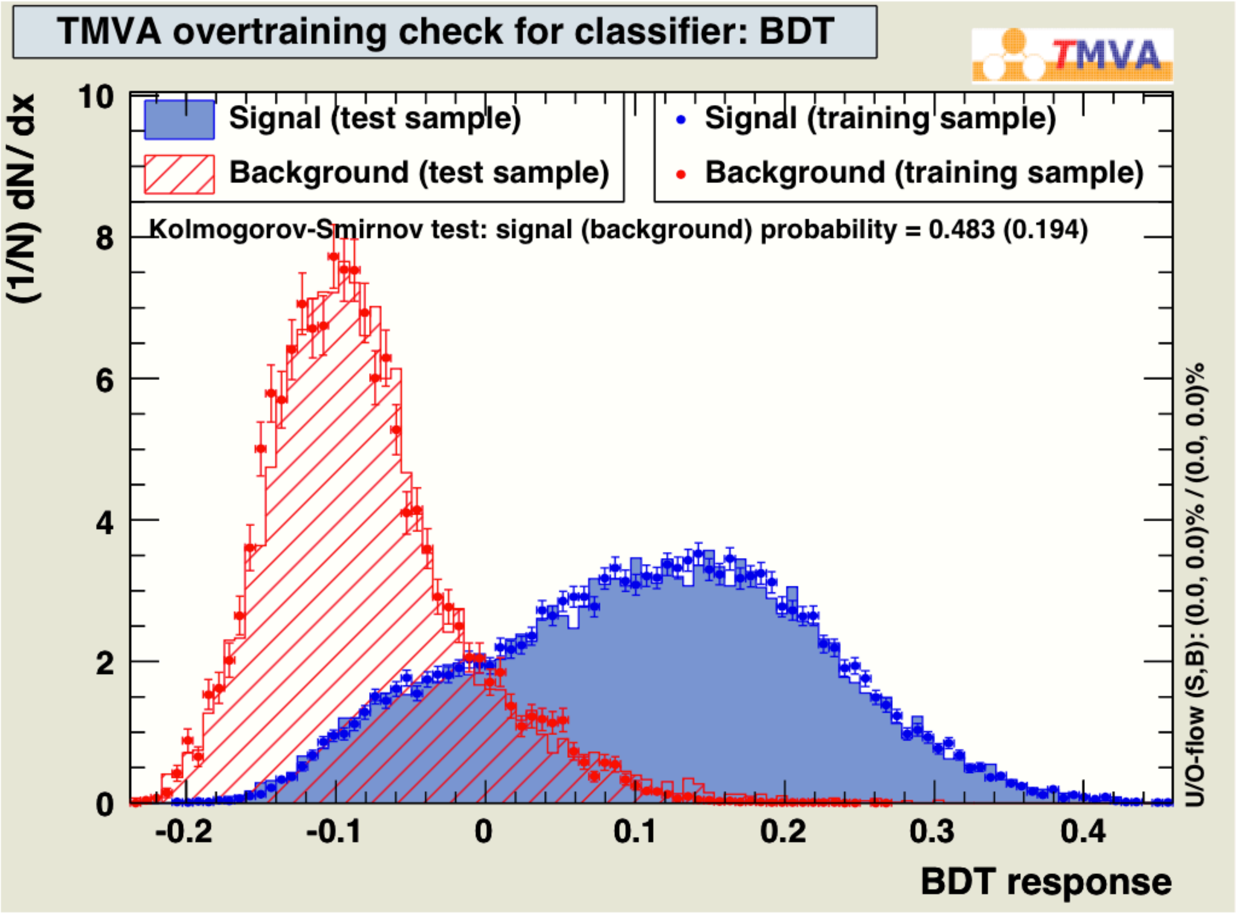
Multiple Variable Analysis



The result for various MVA methods, where the BDT classifier gives best performance.

Multiple Variable Analysis

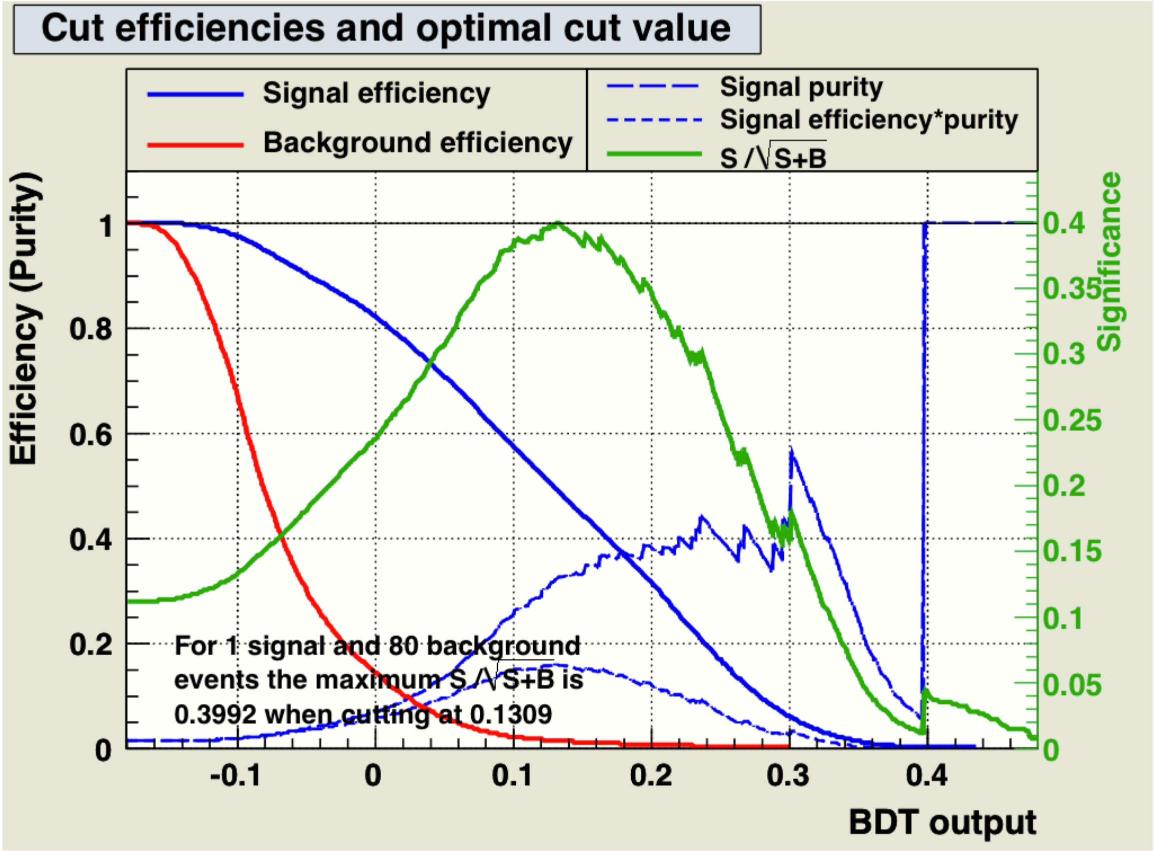
To study whether the sample is over-trained, distributions of the classifiers between test and training samples are compared for the BDT classifier.. From the Kolmogorov-Smirnov test, the probability of signal and background are both larger than 0.05 for BDT classifier, therefore, we can conclude that the training sample is not over-trained.



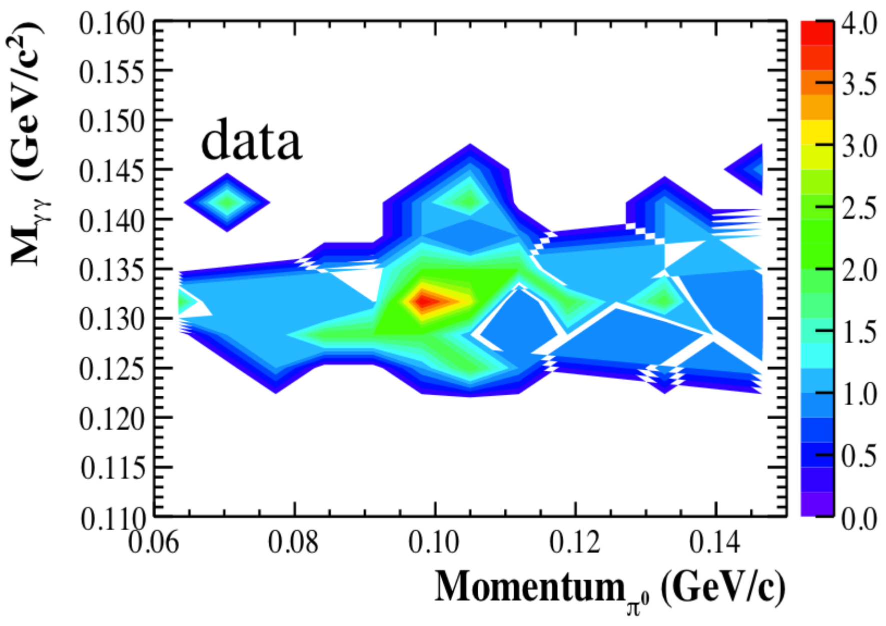
Multiple Variable Analysis

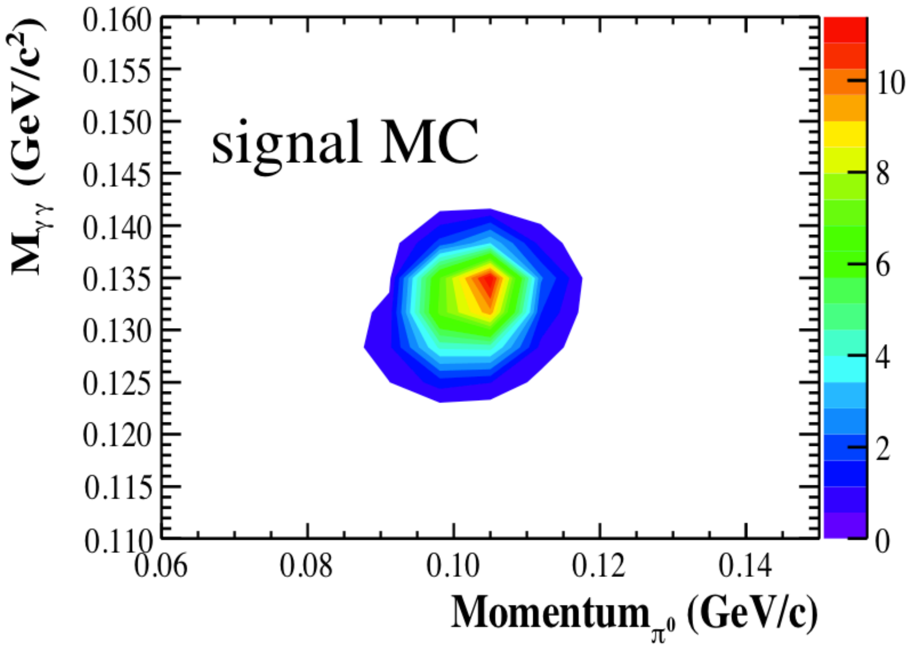
After the MAV study, assuming the cross section of $e^+ e^- \to \Lambda \bar{\Lambda}$ is 300 pb, there are 57 events in data and the signal to background ratio is 1:80. The optimal classifier cut value is determined for signal to background ratio 1:80 for BDT classifier.

The optimal cut is ”mva”>0.1309 for BDT classifier.



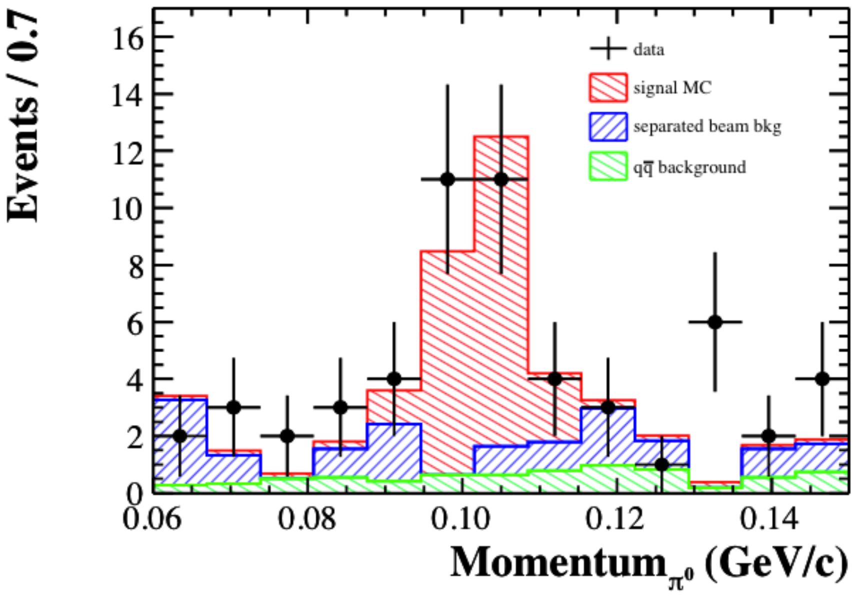
π^0 spectrum

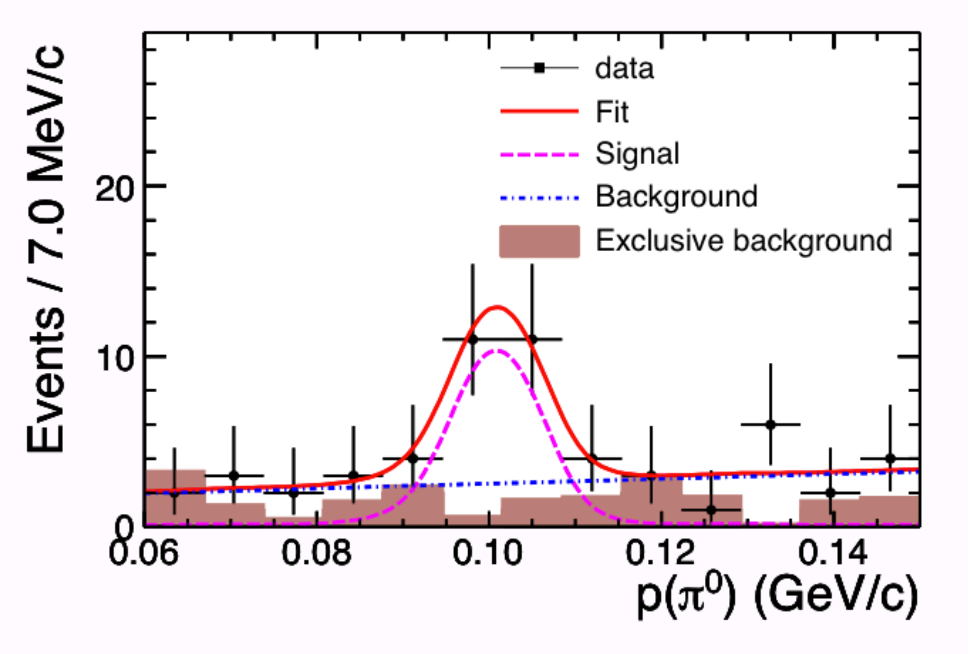




Signals are centered in the [0.08, 0.12] GeV region in X-axis which corresponds to π^0 momentum, while in the data, concentration appears in the same region. It indicates the existence of a $\Lambda\,\bar{\Lambda}$ signal in the data.

π^0 spectrum





The signal yields in data is obtained by fitting momentum distribution of π^0 with the un-binned method, where the signal is described by MC shape convoluted with a gaussian function, and background is described by the shape of separated beam and hadronic final state processes.

Cross section calculation

Cross section for $e^+e^- \to \Lambda\bar{\Lambda}$ is calculated to be:

$$\sigma = \frac{N_{sig}}{\varepsilon \times (1+\delta) \times L \times Br(\bar{\Lambda} \to \bar{n}\pi^0) \times Br(\pi^0 \to \gamma\gamma)}$$

$$= \frac{22 \pm 6}{13.0\% \times 61.5\% \times 1.04 \times 2.63 \times 35.8\% \times 98.8\%} = 288 \pm 96\ pb$$

Charged channel 312 ± 51 pb

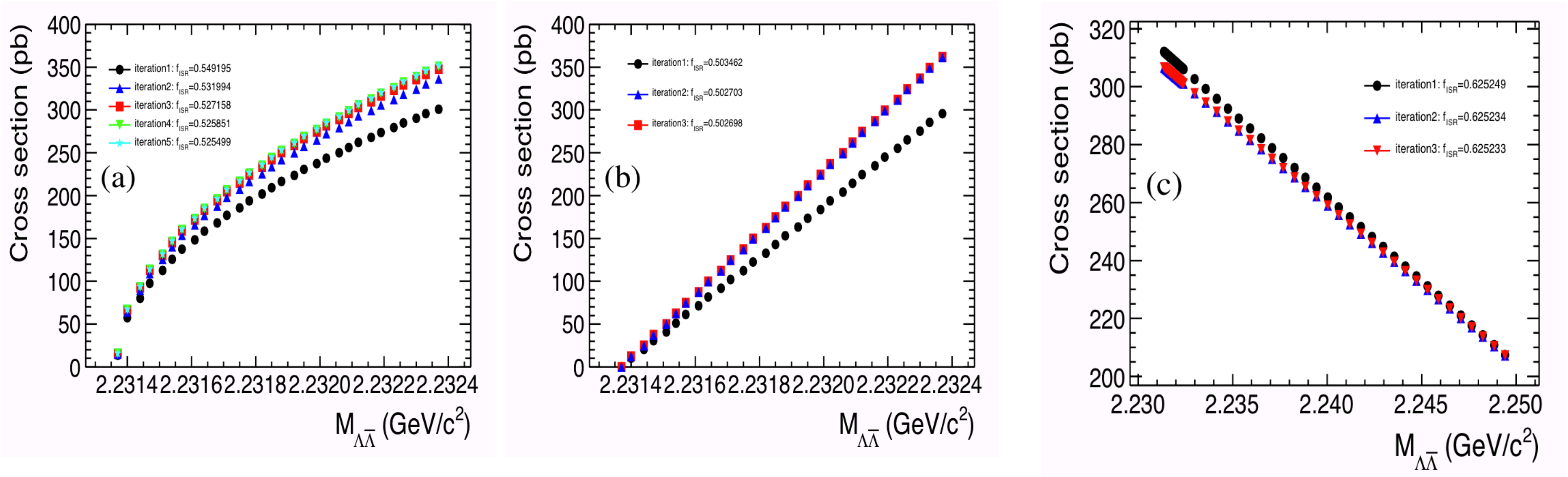
Systematic Uncertainties for two modes

Source	Uncertainty (%)
pion track efficiency	12.3
pion PID efficiency	1.0
anti-proton selection	0.3
Background line shape	4.6
ISR correction factor	$^{+18.5}_{-3.6}$
Energy spread	2.0
Energy shift	3.9
Luminosity	1.0
total	$^{+23.2}_{-14.4}$

Systematic source	Uncertainty
$\bar{n}$ selection	2.2%
π^0 selection	2.1%
χ^2_{1C} cut	0.9%
MVA classifier cut	4.8%
Fitting range	3.9%
Background shape	8.8%
ISR correction factor	$^{+18.5}_{-3.6}\%$
Energy spread	2.0%
Energy scale	3.9%
Trigger efficiency	1.0%
Luminosity	1.0%
sum	$^{+22.1}_{-12.6}\%$

ISR correction factor

- In our nominal result, the lineshape from threshold to 2.2324 GeV is input by a flat linear distribution. Here, we test the different line- shape from threshold toward 2.2324 GeV from three situations: in phase space, interpolation from 0 at threshold, interpolation according to cross section at 2.25 GeV.



Energy Spread

- The uncertainty of energy spread: In another $\psi(3686)$ scan, the BEPCII energy spread is 1.6 MeV, instead of 1.3 MeV. Here, if we use 1.6 MeV to do E^2 extrapolation, the energy spread at 2.2324 GeV would be 0.59 MeV, and the corresponding correction factor is 0.603. The systematic error on cross section measurement is 2.0%.

Energy scale

- The uncertainty of energy measurement: In the reconstruction of $e^{+} e^{-} \rightarrow \mathrm{p}\bar{p}$, we fit the invariant mass of $\mathrm{p}\bar{p}$ by a single gaussian.

- The mean value of the center-of-mass is measured to be 2232.9 ± 0.2 MeV, which 0.5 MeV difference from the required energy, 2232.4 MeV.

- Therefore, we take 0.5 MeV as the uncertainty of energy scale. The ISR and energy spread correction factor at 2232.9 MeV is 0.639, which brings 3.9% uncertainty.

Combined results

The weighted least squares method is used to calculate the combined cross section.

$$x = \frac{x_1\sigma_2^2 + x_2\sigma_1^2}{\sigma_1^2 + \sigma_2^2 + (x_1 - x_2)^2\epsilon_f^2}$$

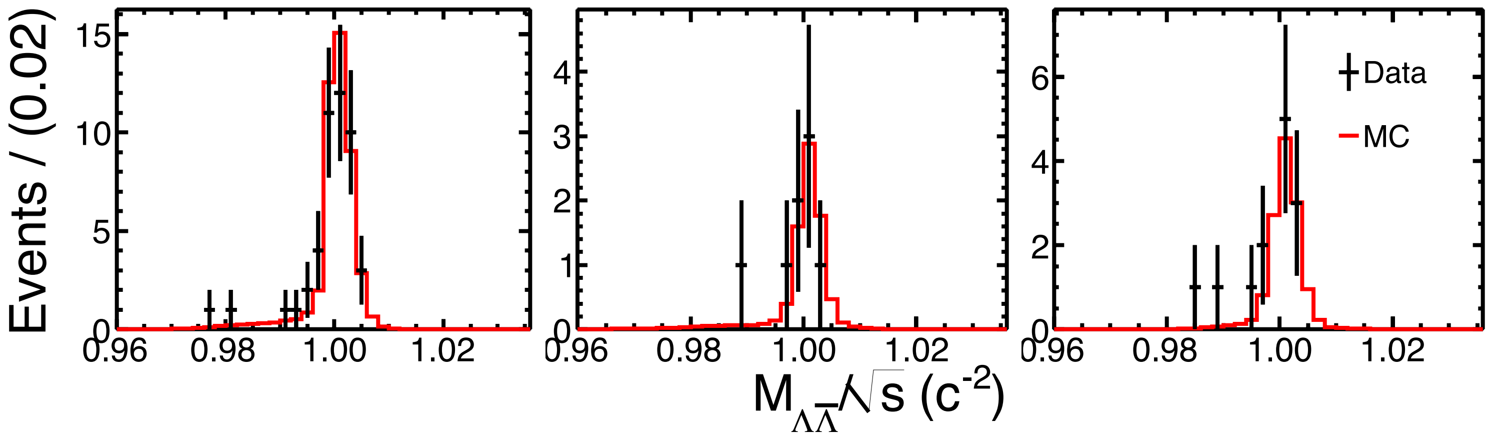
$$\sigma^2(x) = \frac{\sigma_1^2\sigma_2^2 + (x_1^2\sigma_2^2 + x_2^2\sigma_1^2)\epsilon_f^2}{\sigma_1^2 + \sigma_2^2 + (x_1 - x_2)^2\epsilon_f^2}$$

where σ_i is the independent error in the measurement mode i, including statistic error and independent systematic errors, and ε_f is the common relative systematic error between the two measurements.

$$305 \pm 45^{+66}_{-36}\ \text{pb}$$

Other energy points

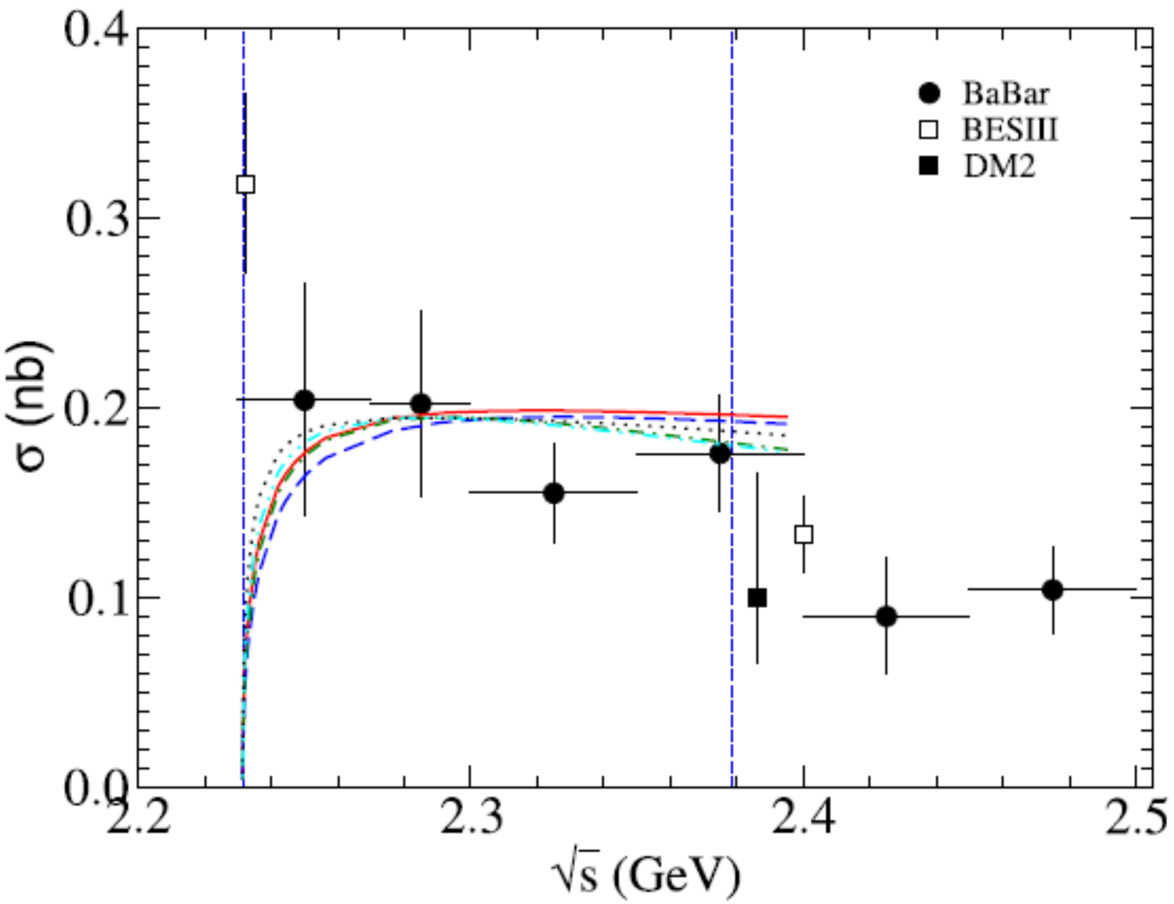
Measurements @ 2.4, 2.8 and 3.08 GeV



$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ ($\rm pb^{-1}$)	$N_{\rm obs}$	$\epsilon(1+\delta)$ (%)	$\sigma^{\rm B}$ (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2.2324_1	2.63	43 ± 7	12.9	$312 \pm 51^{+72}_{-45}$	
2.2324_2	2.63	22 ± 6	8.25	$288 \pm 96^{+64}_{-36}$	
2.2324_c				$305 \pm 45^{+66}_{-36}$	$61.9 \pm 4.6^{+18.1}_{-9.0}$
2.400	3.42	45 ± 7	25.3	$128 \pm 19 \pm 18$	$12.7 \pm 0.9 \pm 0.9$
2.800	3.75	8 ± 3	36.1	$14.8 \pm 5.2 \pm 1.9$	$4.10 \pm 0.72 \pm 0.26$
3.080	30.73	13 ± 4	24.5	$4.2 \pm 1.2 \pm 0.5$	$2.29 \pm 0.33 \pm 0.14$

Present data on $e^+ e^- \rightarrow \Lambda \bar{\Lambda}$

- BESIII results (**Phys. Rev. D 97, 032013)**
- Neutral Baryon: no Coulomb, but still step at thr !

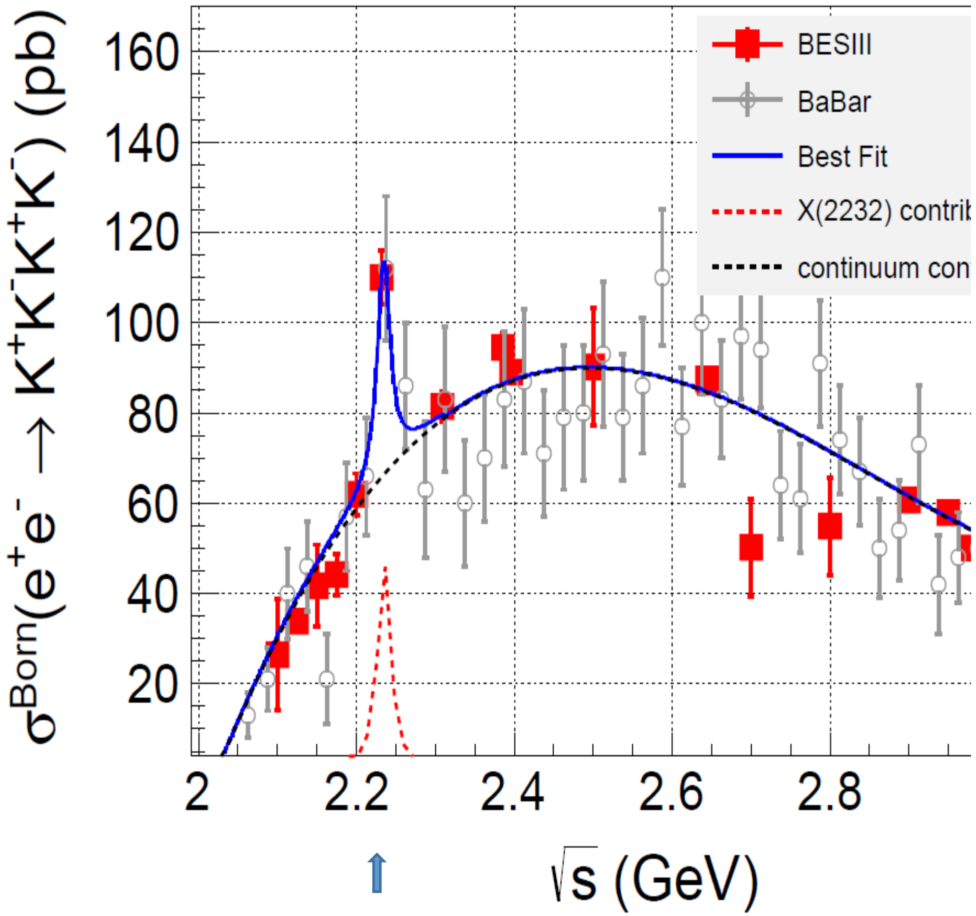


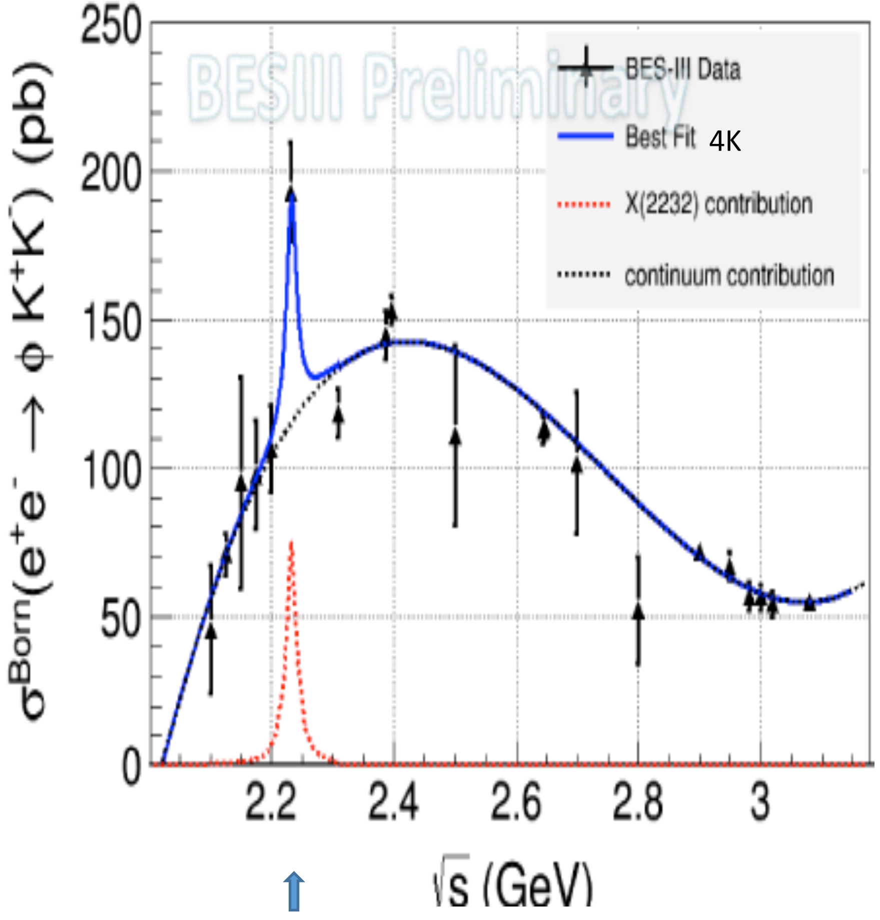
FSI fit to $e^+ e^- \to \Lambda \bar{\Lambda}$

- J.Haidenbauer and U.G. Meissner [Phys.Lett B761 (2016)] FSI model fit BaBar, (even if the first point energy error is suspicious, it should already show a trend to zero), but not BESIII data.
- *"BESIII data suggest a very different trend for the energy dependence . Specifically, a large finite value for the cross section practically at the threshold is suggested. This cannot be reproduced by our model because of the phase-space β.*
- *There is no Coulomb interaction here that would change the threshold behavior*
- *The only possibility could be a very narrow resonance sitting more or less directly at the threshold, which would then allow to overrule the behavior from the phase space alone."*

An anomaly related to $e^+ e^- \to \Lambda \bar{\Lambda}$ thr ?

○ $e^+e^- \to K^+K^- K^+K^-, \phi K^+K^-$ $M = 2232 \pm 3.5$ MeV , $\Gamma = 7.5(+13.5)$ MeV
(A hint for such a resonance, more data needed)





$e^+ e^- \to \Lambda \Lambda_{bar}$ **threshold** $e^+ e^- \to \Lambda \Lambda_{bar}$ **threshold**

Summary

- In the two decay modes, we both observed $\Lambda\,\bar{\Lambda}$ enhancement near the threshold.
- FSI effect is not enough to explain this large cross section near the threshold.
- e^+e^- -> K^+K^- K^+K^-, ϕ K^+K^- show a hint for narrow resonance near the threshold both in BESIII and BABAR data.
- More data are needed.