Measurement of the $\Lambda_c^+ \longrightarrow pK^-\pi^+$ Decay Asymmetry at $\sqrt{s} = 4.6$GeV

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Outline

- Motivation
- Data set
- Event selection
- Background analysis
- Final selection
- Data analysis result
- Toy MC test
- Summary and outlook

Motivation

- It has long been known that hyperon nonleptonic decays have played an important role in understanding CP violation in particle physics. The observable of CP asymmetry is defined by $A_Y = \frac{\alpha_Y + \alpha_{\bar{Y}}}{\alpha_Y - \alpha_{\bar{Y}}}$. Under CP transformation, $\alpha_Y = -\alpha_{\bar{Y}}$ if CP is conserved. This also means that we study the problem of CP violation by measuring α_Y and $\alpha_{\bar{Y}}$. In the past few weeks, I have measured the value of $\alpha_{\Lambda_c^+}$ in the process of $\Lambda_c^+ \longrightarrow pK^-\pi^+$, which will be the content of my report next .

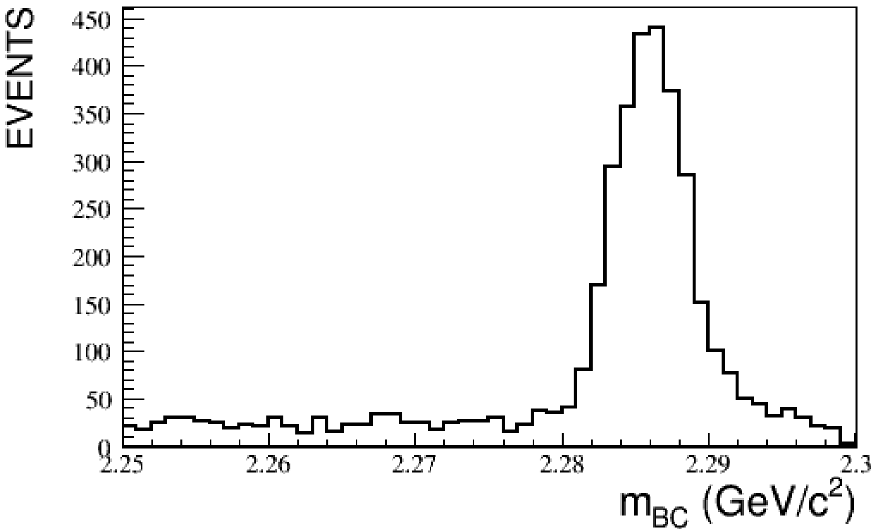
Data Set

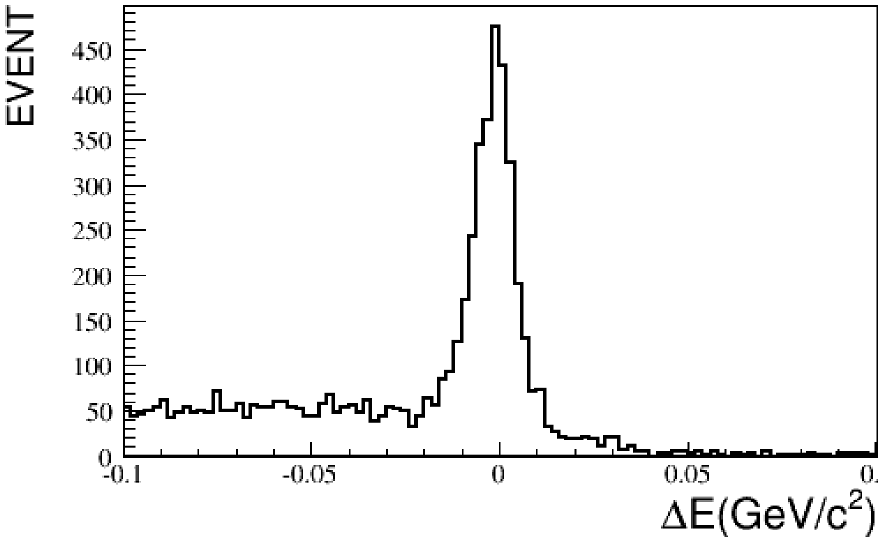
- Boss Version:
  - Analysis Environment: Boss 7.0.3;
- Data Sets:
  - 4600MeV 586.9pb-1
  - Run No. 35227~36213
- Inclusive MC:
  - 703-MC 4600MeV hadrons
- Signal MC:
  - 1M $\Lambda_c^+ \longrightarrow pK^-\pi^+$ for signal analysis
  - 1M $\overline{\Lambda}_c^- \rightarrow \bar{p}K^+\pi^-$ for charge conjugation analysis
  - (The MC events generator is KKMC)

Event Selection

- Good charged Tracks
  - $|V_z| < 10$, $|V_r| < 1$, $|\cos\theta| < 0.93$
  - $N_{good} = 3$
- Single tag:
  - $\Lambda_c^+ \longrightarrow pK^-\pi^+$, $\overline{\Lambda}_c^- \longrightarrow anything$
  - $\overline{\Lambda}_c^- \rightarrow \bar{p}K^+\pi^-$, $\Lambda_c^+ \longrightarrow anything$
- PID
  - Proton: $Prob(p) = \max\left(Prob(p), Prob(K), prob(\pi)\right)$;
  - Kaon: $Prob(K) = \max\left(Prob(p), Prob(K), prob(\pi)\right)$;
  - Pion: $Prob(\pi) = \max\left(Prob(p), Prob(K), prob(\pi)\right)$;

➢ After these selection m_{BC} and ΔE spectrum as follow.



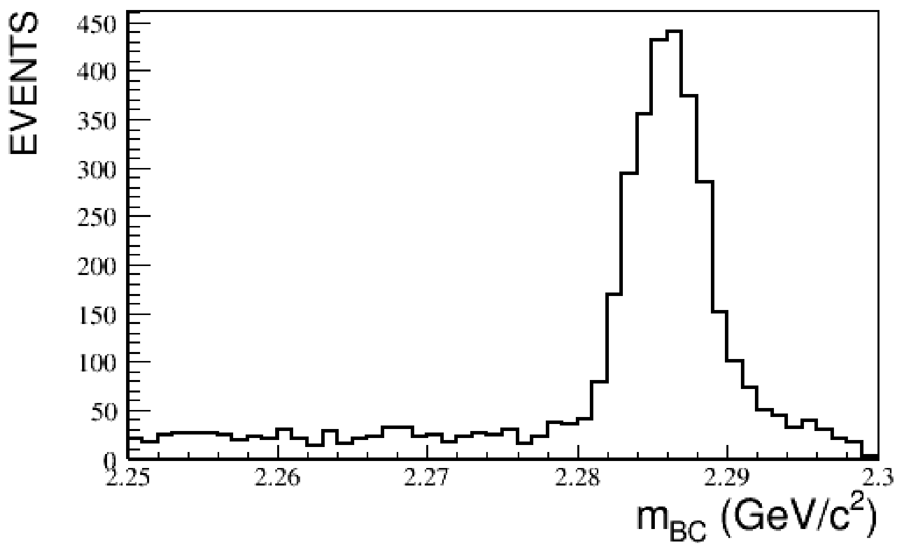


- We can see the obvious background events in above distributions.
- To select the Λ_c^+ candidate, we performed relatively loose selection criteria on the ΔE and m_{BC}.(quote from Panyue's memo)

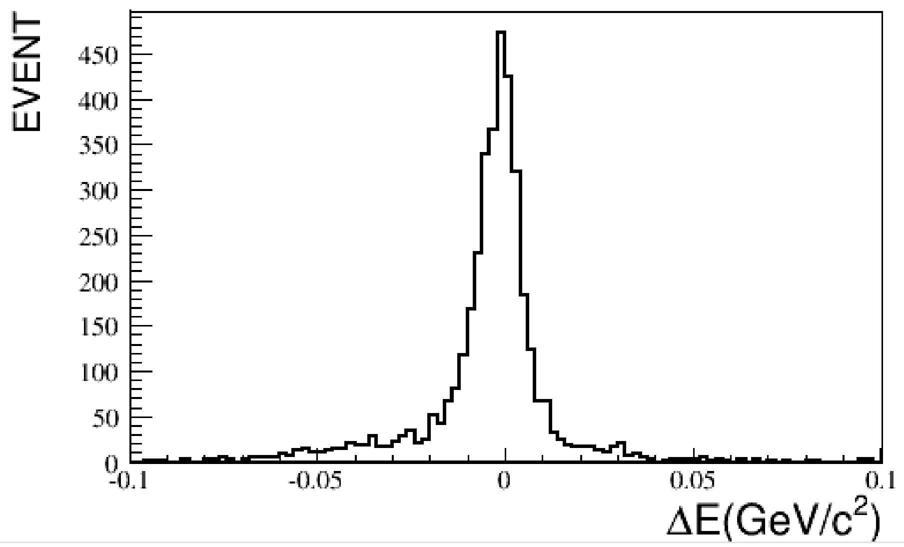
➢ Apply the cut criteria

- $m_{BC} \epsilon (2.25,2.30) GeV$
- $|\Delta E| < 0.1$GeV

➢ m_{BC} distribution



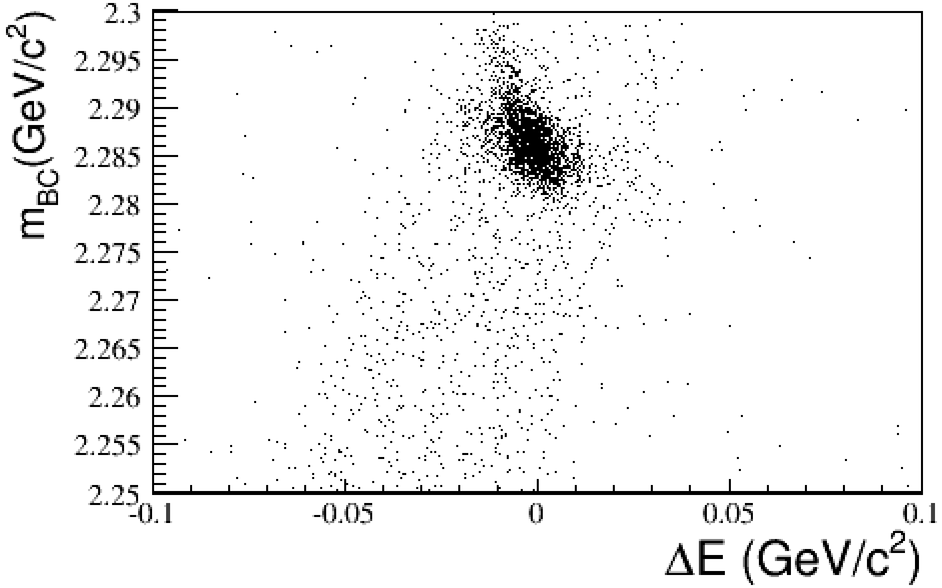
➢ ΔE distribution



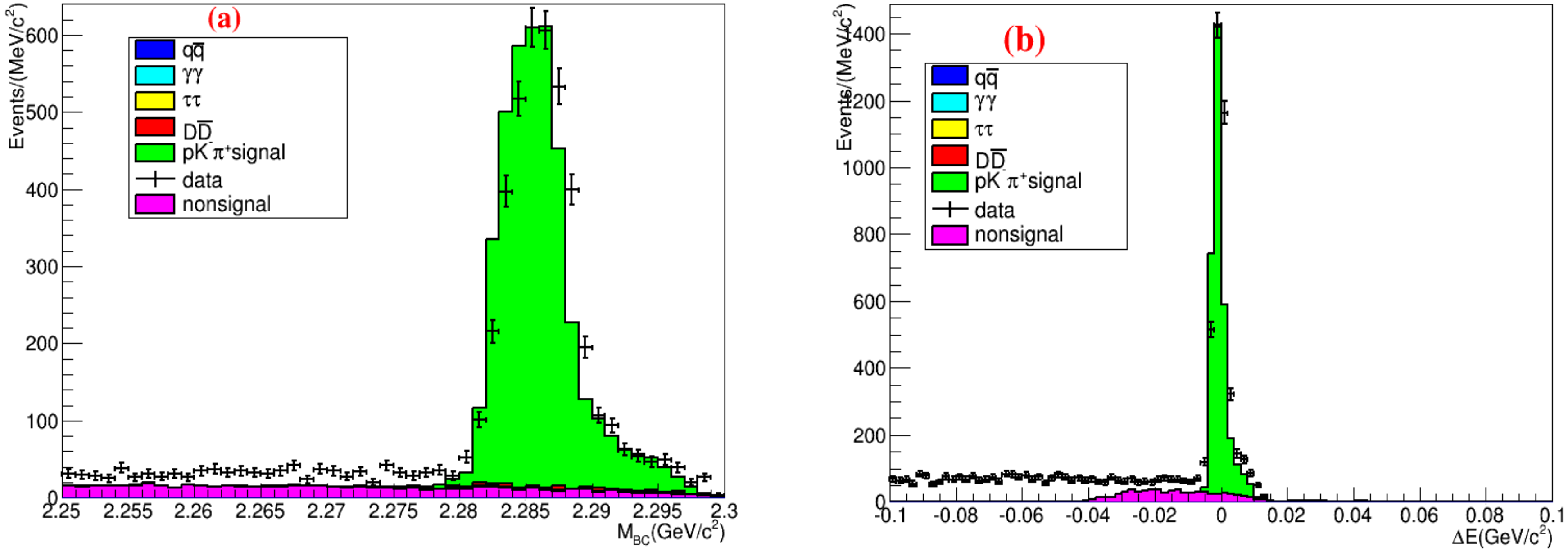
- After the previous selection , we get m_{BC} and ΔE distribution as above.
  - As we can see that there is still a lot of background events in the distribution of m_{BC}.
  - In this case , we will give specific solution in the background research below.

Background analysis

- With above selection criteria, the scatter plot of ΔE versus m_{BC} for the selected candidate are shown as follow.



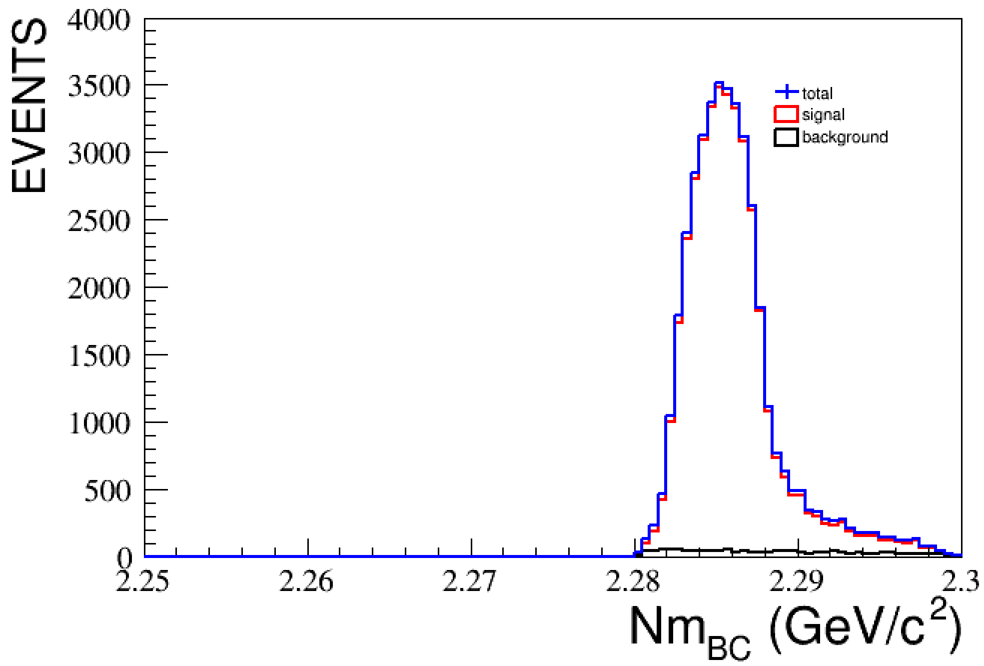
- The distribution of m_{BC} using cocktail MC samples as follow



➢Through the topology analysis, we can see primary background decay chains as follow.

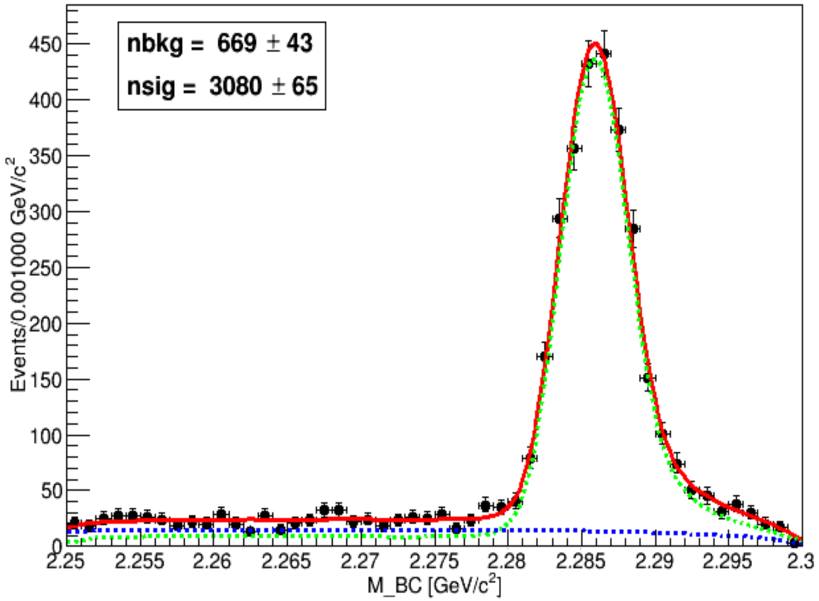
No.	decay chain	final states	iTopo	nEvt	nTot
0	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Lambda} K^- a_2^0 p$, $\bar{\Lambda} \to \bar{p}\pi^+$, $a_2^0 \to \pi^-\rho^+$, $\rho^+ \to \pi^0\pi^+$,	$\gamma^* \to \gamma\gamma\gamma p\pi^+\pi^+\pi^- K^- \bar{p}$	623	270	270
1	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Delta}^{++} K^- K^+ \Delta^{++}$, $\bar{\Delta}^{++} \to \bar{p}\pi^-$, $\Delta^{++} \to \pi^+ p$,	$\gamma^* \to \gamma p K^+\pi^+\pi^- K^- \bar{p}$	229	242	512
2	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Lambda} K^- p a_1^0$, $\bar{\Lambda} \to \bar{p}\pi^+$, $a_1^0 \to \pi^-\rho^+$, $\rho^+ \to \pi^0\pi^+$,	$\gamma^* \to \gamma\gamma\gamma p\pi^+\pi^+\pi^- K^- \bar{p}$	10	210	722
3	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Lambda} K^- p b_1^0$, $\bar{\Lambda} \to \bar{p}\pi^+$, $b_1^0 \to \pi^0\omega$, $\omega \to \pi^-\pi^0\pi^+$,	$\gamma^* \to \gamma\gamma\gamma\gamma\gamma p\pi^+\pi^+\pi^- K^- \bar{p}$	369	198	920
4	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Delta}^{++} K^-\pi^+ K^+ \Delta^+$, $\bar{\Delta}^{++} \to \bar{p}\pi^-$, $\Delta^+ \to \pi^0 p$,	$\gamma^* \to \gamma\gamma\gamma p K^+\pi^+\pi^- K^- \bar{p}$	457	196	1116
5	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Lambda} K^- p a_1^0$, $\bar{\Lambda} \to \bar{p}\pi^+$, $a_1^0 \to \rho^-\pi^+$, $\rho^- \to \pi^-\pi^0$,	$\gamma^* \to \gamma\gamma\gamma p\pi^+\pi^+\pi^- K^- \bar{p}$	96	195	1311
6	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{p} K^- f_2(1270) K^+ p$, $f_2(1270) \to \pi^-\pi^+$,	$\gamma^* \to \gamma p K^+\pi^+\pi^- K^- \bar{p}$	192	190	1501
7	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Delta}^{++} K^-\pi^0 K^+ \Delta^{++}$, $\bar{\Delta}^{++} \to \bar{p}\pi^-$, $\Delta^{++} \to \pi^+ p$,	$\gamma^* \to \gamma\gamma\gamma p K^+\pi^+\pi^- K^- \bar{p}$	619	168	1669
8	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{p} K^- K^+ p a_1^0$, $a_1^0 \to \pi^-\rho^+$, $\rho^+ \to \pi^0\pi^+$,	$\gamma^* \to \gamma\gamma\gamma p K^+\pi^+\pi^- K^- \bar{p}$	279	168	1837
9	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Lambda} K^- K^- K^+ p$, $\bar{\Lambda} \to \bar{p}\pi^+$,	$\gamma^* \to \gamma p K^+\pi^+ K^- K^- \bar{p}$	64	150	1987
10	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{p} K^-\pi^0\pi^+ K^0 p$, $K^0 \to K_S$, $K_S \to \pi^-\pi^+$,	$\gamma^* \to \gamma\gamma\gamma p\pi^+\pi^+\pi^- K^- \bar{p}$	1018	140	2127
11	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to \bar{\Lambda} K^- p b_1^0$, $\bar{\Lambda} \to \bar{n}\pi^0$, $b_1^0 \to \pi^0\omega$, $\omega \to \pi^-\pi^0\pi^+$,	$\gamma^* \to \gamma\gamma\gamma\gamma\gamma\gamma\gamma p\pi^+\pi^- K^- \bar{n}$	113	120	2247
12	$\gamma^* \to \gamma\gamma^*$, $\gamma^* \to a_1^- \bar{n} K^- K^+ p$, $a_1^- \to \pi^-\rho^0$, $\rho^0 \to \pi^-\pi^+$,	$\gamma^* \to \gamma p K^+\pi^+\pi^-\pi^- K^- \bar{n}$	400	120	2367

- ➢We can see that the number of events in each decay chain the difference is not obvious , so I fail to given a reasonable background description.
- ➢According to truth march method I get signal events and nonsignal events, and the m_{BC} distribution as follow.



- From this picture we can see the clear signal and the background shape.
  - The background shapes have no peaking in signal region.
  - We can use the sideband region background to estimate the background of the signal region.

- At this point, the signal shape is modeled by the corresponding signal MC simulation shape convoluted with a Gaussian function, the combinatorial background is modeled by an ARGUS function.
- The fitting shape of m_{BC} distribution is as follows.

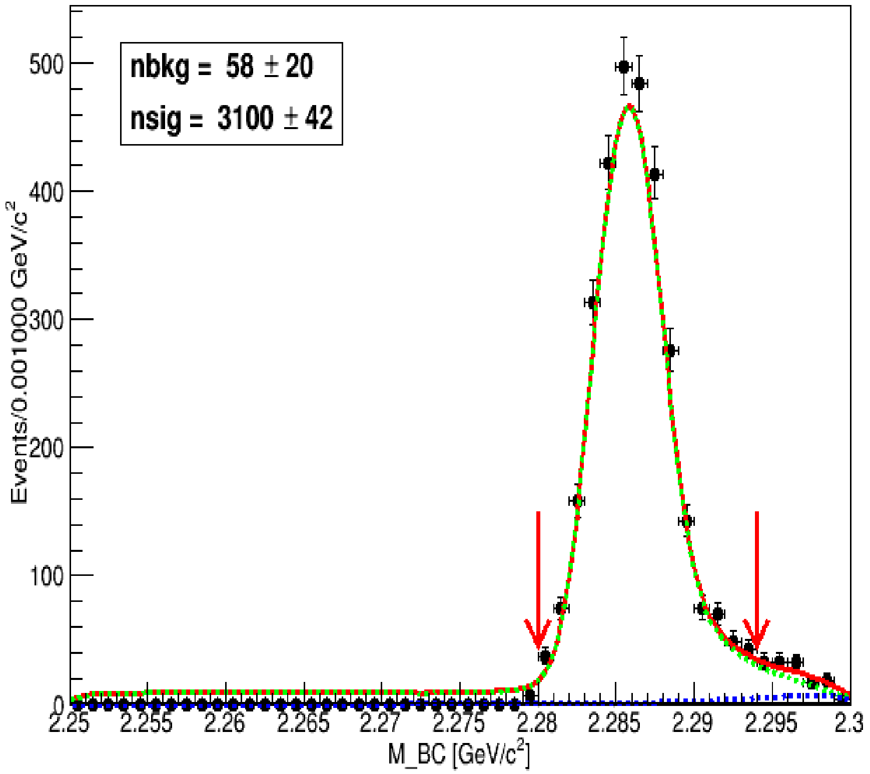


- Where the black error bar representative data sample
- The blue dashed represents the shape of the background

➢We subtracted the background by tightening the cut condition

➢Add the following cut conditions, respectively. The fitting shape of m_{BC} distribution is change to below.

- 4C kmfit
- $|\Delta E| < 0.02$GeV

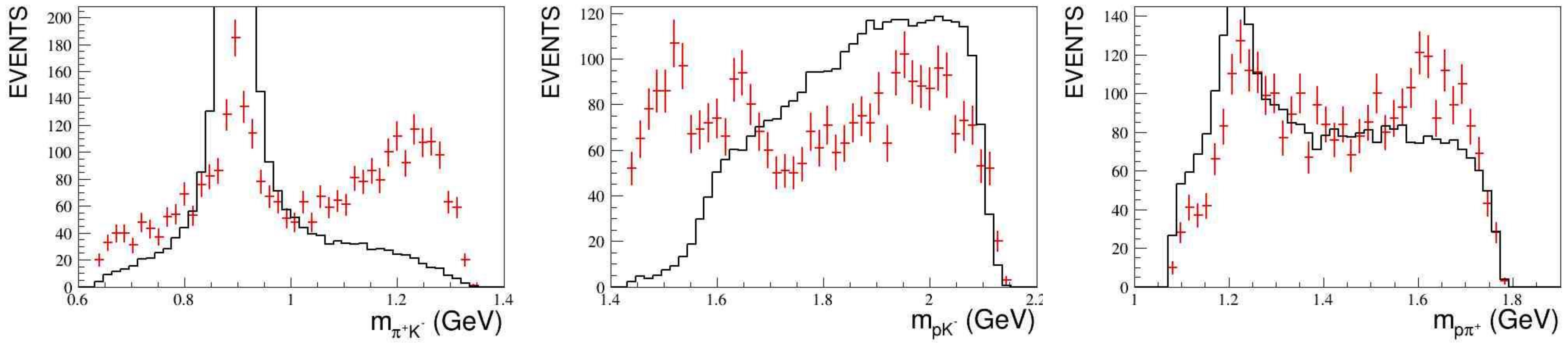


Final selection

- After all selection
- The number of events is shown in the table below.

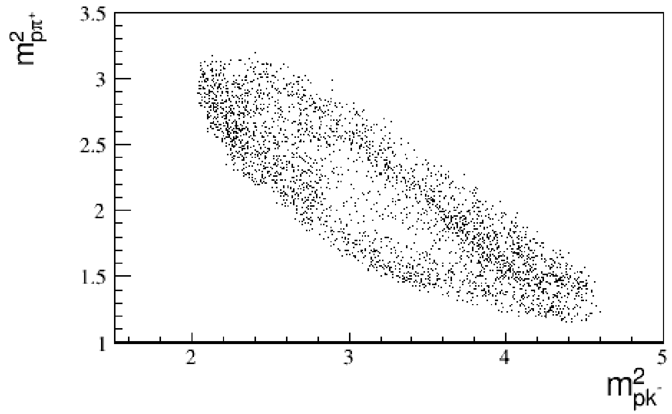
	data	MC
$\Lambda_c^+ \longrightarrow pK^-\pi^+$	3195	545523
$\overline{\Lambda}_c^- \rightarrow \bar{p}K^+\pi^-$	3416	548013

- The invariant mass distribution as follow.

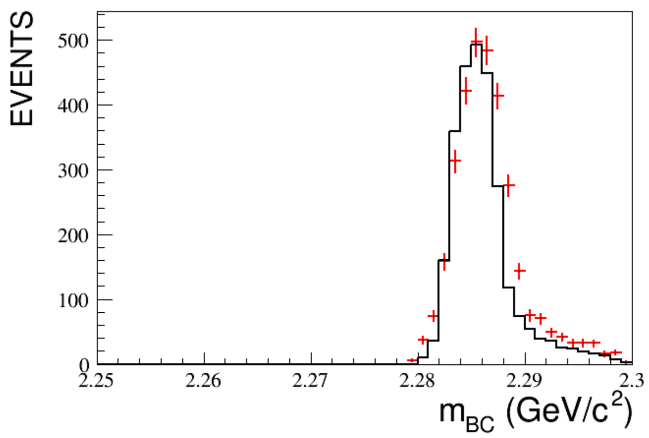


- Where the red error bar representative data sample， the black line representative inclusive MC sample.

➢The dalitz plot of data sample as follow



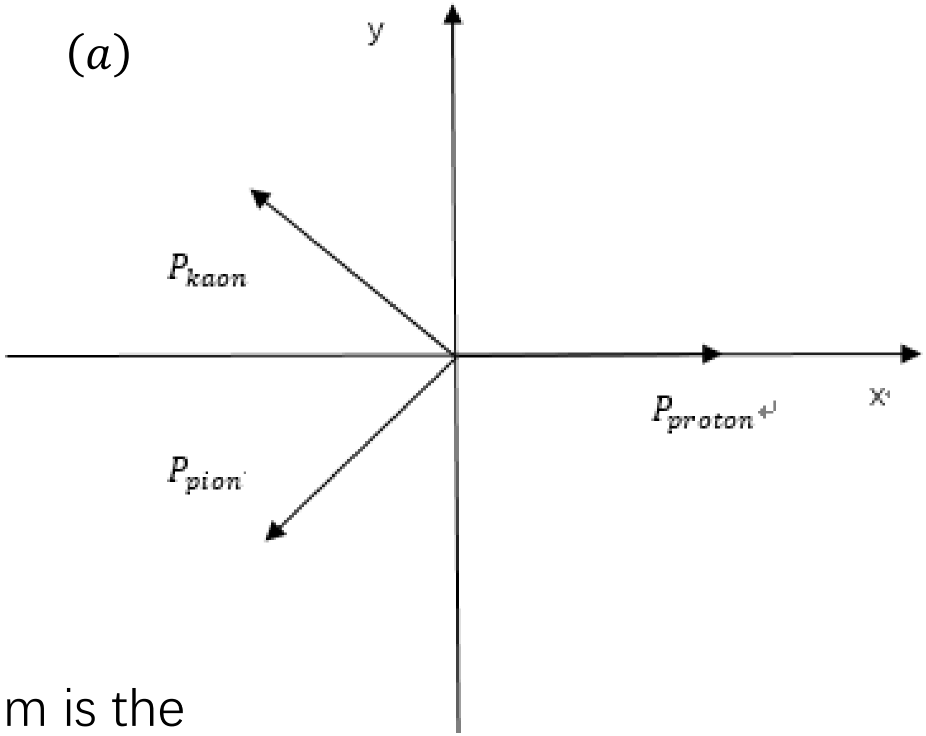
➢ And the beam-constrained mass mBC spectrum like this .



Data analysis result

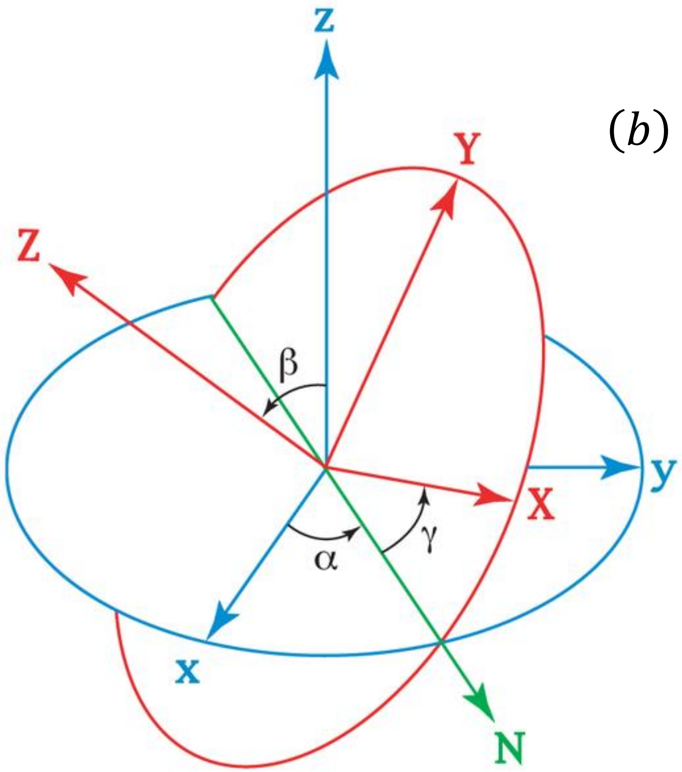
- Unbinned Likelihood Method
  - $p.d.f(\xi,\eta) = \frac{\omega(\xi,\eta)}{\int d\xi\omega(\xi,\eta)\varepsilon(\xi)}$
  - $-ln\mathcal{L} = -\sum_{i=1}^{N} ln\frac{\omega(\xi_i,\eta)}{\sigma}$
  - We can minimize the Log equation $-ln\mathcal{L} = -\sum_{i=1}^{N} ln\frac{\omega(\xi_i,\eta)}{\sigma}$ and obtain the decay asymmetry parameter.
- Three body decay amplitude formula
  - $w(\xi) = 4\pi\left(1+\eta cos^2\theta + \alpha_{L_c}\sqrt{1-\eta^2}\sin(\Delta\phi)\left(\frac{1}{2}sin(2\theta)sin\alpha sin\beta\right)\right)$
  - Where η is the angular distribution parameter of $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$, $\Delta\phi$ is the difference of phase angle for the helicity amplitude , θ is the polar angle of Λ_c^+ which generate in $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ decay process.
- We can determine α and β value by obtaining the angular distribution information of the decay process.

- Where the final state particle momentum direction in Λ_c^+ centre of mass system as follow



- We provide the direction of proton momentum is the direction of the X-axis
- Where the Euler angle α and β as follow

- The blue coordinate system corresponds to the center mass system for the $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$ process , and the red frame corresponds to the center mass system for Λ_c^+.



➢MINUIT fit method

- Three-body decay
- $w(\theta) = 4\pi\left(1 + \eta cos^2\theta + \alpha_{L_c}\sqrt{1-\eta^2}\sin(\Delta\phi)\left(\frac{1}{2}sin(2\theta)sin\alpha sin\beta\right)\right)$
- We use the maximum likelihood method to fit the values of α_{L_c} and η .
- Meanwhile , because I can't get all three parameters at the same time so I define the alphaLc=$\alpha_{Lc}\sin(\Delta\phi)$.

➢Likelihood estimation

- The joint probability density for the observed N event in a data sample is defined as $\mathcal{L} = \prod_{i=1}^{N} P(x_i)$,
- The normalized $P(x_i)$ is calculated from the differential cross section
- $P(x_i) = \frac{(d\sigma/d\phi)_i}{\sigma_{MC}}$,
- Where $d\phi$ is the standard 3-body phase space ; the normalization factor σ_{MC} is calculated from a MC sample with N_{MC} accepted events , which are generated with a phase space model. The response of the detector to the final-state particles is simulated using GEANT4 . The e^+e^- annihilation and the subsequent decay of $\Lambda_c^+\overline{\Lambda}_c^-$ are simulated by the KKMC generator, taking into consideration the spread of the beam energy and the effect of initial-state radiation (ISR).

- PHSP (phase Space) signal MC , while works as efficiency MC sample and is used to perform the maximum likelihood fit to the data , the fit result as follow

```
external parameters:
# ext. ||    Name     ||   type   ||      Value       ||  Error +/-

   0    ||         eta ||  free    ||    -0.2443718559321 ||0.04820830886996
   1    ||    alphaLc ||  free    ||   0.009049095778473 ||0.08385436556541
```

➢ Here we cite wangbinlong's measurement results of the $\Delta\phi$, that is $\Delta\phi = -0.28 \pm 0.14$

- So we can get specific asymmetry parameter results in $\Lambda_c^+ \longrightarrow pK^-\pi^+$ process by using the maximum likelihood fit method and the mathematica calculate method .

```
external parameters:
# ext. ||    Name     ||   type   ||      Value       ||  Error +/-

   0    ||         eta ||  free    ||    -0.2350420396964 ||0.04867730845362
   1    ||    alphaLc ||  free    ||    -0.0914786786611 ||0.304159393407
   2    ||       delta ||  fixed   ||               -0.28 ||
```

- So this is what we get for asymmetry parameter center value results by mathematica calculate method .

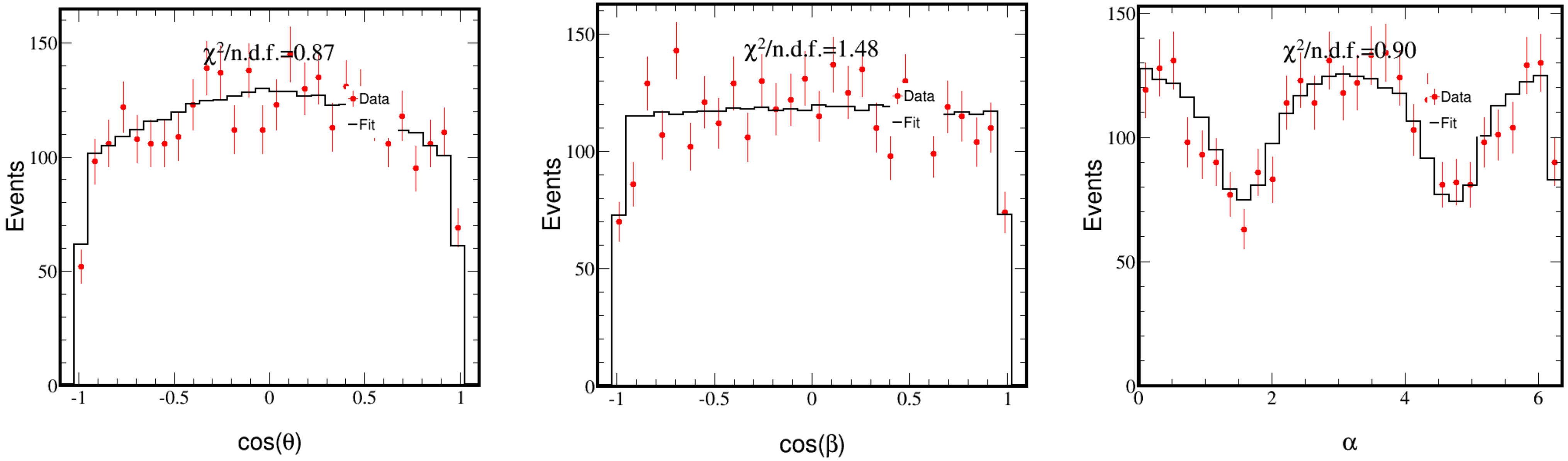
```
In[30]:= A = -0.0253; Δ = -0.28; α = A/Sin[Δ]

Out[30]= 0.0915487
```

- The uncertainty is calculated from Error transfer method .

```
In[32]:= b = Sqrt[(1/-0.28)^2*(0.083)^2 + (-0.0368/-0.28^2)^2*(0.14)^2]

Out[32]= 0.303625
```

- Asymmetry parameter results determined by computing the decay parameter to be -0.0915487 ± 0.303383

➢ Next we show the output check through the following three angular distribution information.



- The red error bars are data, black lines are the fit shape .
- The same way to do $\overline{\Lambda}_c^- \longrightarrow \bar{p}K^+\pi^-$ we get the following result .
  - The fit result as follow

```
external parameters:
# ext. ||    Name     ||   type   ||      Value       ||  Error +/-

   0   ||        eta ||  free    ||   -0.1413278557165 ||0.05171288629871
   1   ||   alphaLc ||  free    ||    0.1330758158956 ||0.3008703657499
   2   ||     delta ||  fixed   ||              -0.28 ||
```

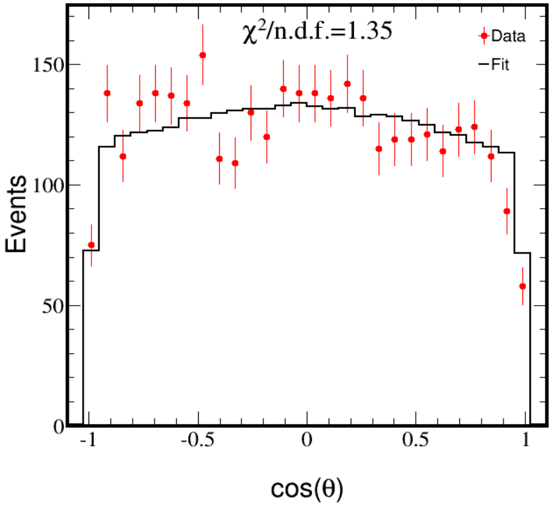
- The mathematica calculate asymmetry parameter center value result

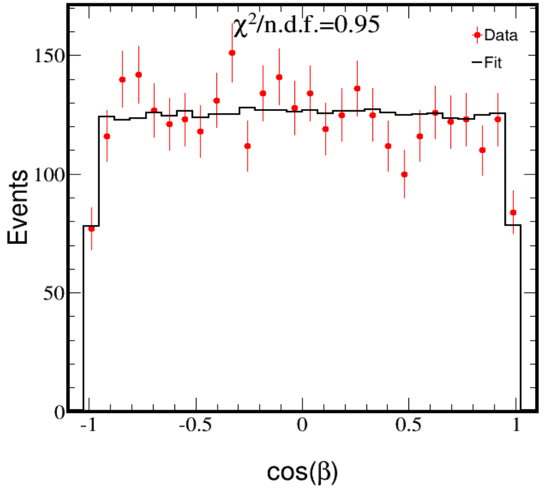
```
In[31]:= A = -0.0368; Δ = -0.28; α = A / Sin[Δ]

Out[31]= 0.133162
```

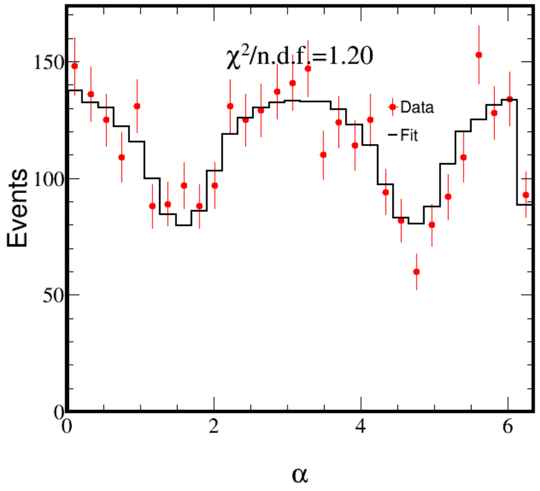
- The uncertainty is calculated from Error transfer

```
In[32]:= b = Sqrt[(1/-0.28)^2*(0.083)^2+(-0.0368/-0.28^2)^2*(0.14)^2]
         平方根

Out[32]= 0.303625
```

- So the result is 0.133162 ± 0.303625 .

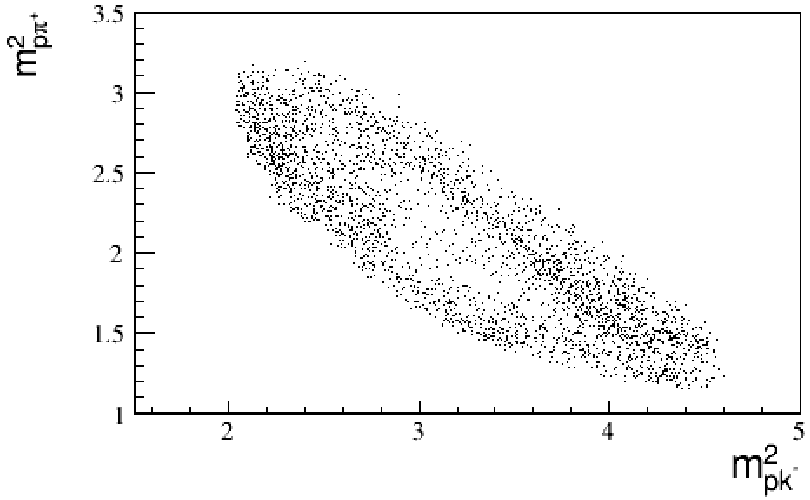






Toy MC test

- We use the massH2 method to regenerate the toy MC sample of .
  - The data sample dalitz plot is used as follows:



- The e^+e^- annihilation is simulated by the KKMC generator, taking into consideration the spread of the beam energy and the effect of initial-state radiation (ISR). The subsequent decay of $\Lambda_c^+\overline{\Lambda}_c^-$ are generated using massH2 model .

- Use the same method to get the value of asymmetry parameter in $\Lambda_c^+ \longrightarrow pK^-\pi^+$ process ,the fit result as follow

```
external parameters:
# ext. ||    Name     ||   type   ||      Value      ||  Error +/-

   0   ||         eta ||  free    ||    -0.2387238192072 ||0.0484946422849
   1   ||     alphaLc ||  free    ||    -0.0345800996708 ||0.3038653606774
   2   ||       delta ||  fixed   ||               -0.28 ||
```

- And the Mathematica result is -0.0327± 0.2999 .
- By the same method we can get the value of asymmetry parameter in the process $\overline{\Lambda}_c^- \longrightarrow \bar{p}K^+\pi^-$ of and we won't go into the details of the operation.

```
external parameters:
# ext. ||    Name     ||   type   ||      Value      ||  Error +/-

   0   ||         eta ||  free    ||    -0.1423911816089 ||0.05166380460614
   1   ||     alphaLc ||  free    ||     0.1555164210295 ||0.3007805143053
   2   ||       delta ||  fixed   ||               -0.28 ||
```

Summary and outlook

- We know that when CP conserves the asymmetry parameter of $\Lambda_c^+ \longrightarrow pK^-\pi^+$ process and its asymmetry parameter in charge conjugated engineering are the inverse of each other.
- Through our previous measurement and calculation, the asymmetry parameter value in different processes can be obtained as shown in the following table

	α
$\Lambda_c^+ \longrightarrow pK^-\pi^+$	-0.0327$\pm$ 0.2999
$\overline{\Lambda}_c^- \longrightarrow \bar{p}K^+\pi^-$	0.1555 $\pm$ 0.3008

  - It can be seen from the above table that there is CP violation in the process of Λ_c decay to $proton\ , kaon\ and\ pion$, and the determination of CP violation parameters will become the direction of our next work .

- Finish my master's thesis.

Thank you !