Λ_c^+ DECAY PARAMETERS MEASUREMENT IN BESIII

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CONTENT

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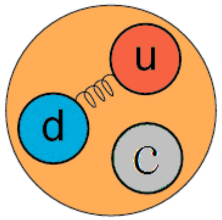
Λ_c^+: THE LIGHTEST CHARMED BARYON

Quark model picture:

A heavy quark (c) with a unexcited spin-zero diquark (u-d)

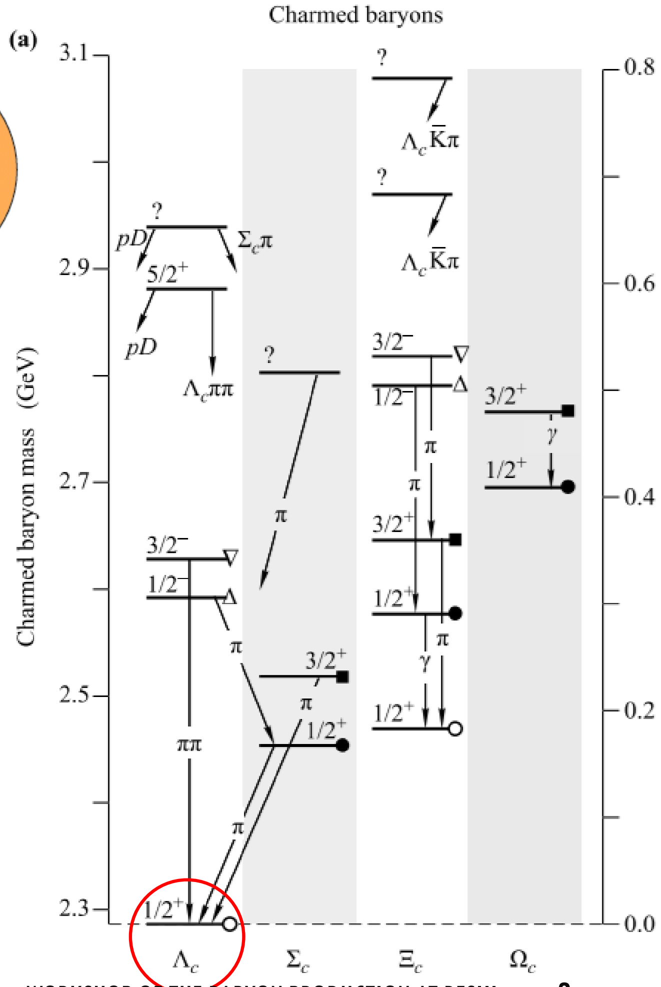


Cornerstone of charmed baryons:

Lightest charmed baryon, most of the charmed baryons will eventually decay to Λ_c^+,

Important input to Λ_b

Help to extract the b-baryon decay asymmetries.



In 2014, BESIII collected 567 pb^{-1} data above Λ_c pair threshold and run machine at 4.6 GeV with excellent performance.

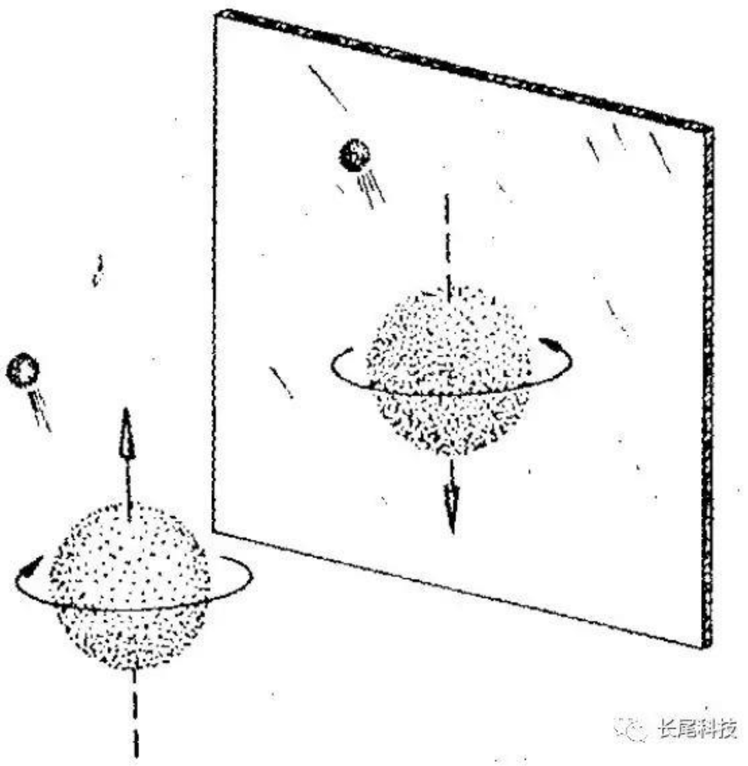
>10X More Λ_c^+ data will come soon

MOTIVATION

- **The parameter α_{BP} controls the decay asymmetry in the angular distribution:** $\frac{dN}{dcos\theta} \propto 1 + \alpha_{BP}cos\theta$

$$\alpha_{BP} = \frac{2Re(S * P)}{|S|^2 + |P|^2},$$

- **In this work , we measure α_{BP}, in a weak decay $\Lambda_c^+ \to BP, \left(B{:}\, J^P = \frac{1}{2}^+ baryon, P{:}\, 0^- \ meson\right)$**
- **The model calculations are quite uncertain**
  - Eg: The $\alpha_{\Sigma^+\pi^0}$ in the region $(-0.76 \sim 0.81)$
- **The $\alpha_{\Lambda\pi}$ and $\alpha_{\Sigma^+\pi^0}$ are measured 10 years ago, with large uncertainties:**
  - Eg: $\alpha_{\Sigma^+\pi^0}$ in PDG: -0.45 ± 0.32



THEORY PREDICTIONS

Some of the QCD-inspired charmed baryon modes are:

- The flavor symmetry model
- Factorization model
- Pole model
- Current algebra framework

1. Many of them calculate the Λ_c^+ Br in agreement with exp result, but the decay asymmetry do not agree very well.
2. The sign of $\alpha_{\Sigma\pi}$ is not certain

$\Lambda_c^+ \to$	Predicted α_{BP}^+		PDG α_{BP}^+	This work α_{BP}^+
pK_S^0	-1.0 [12]	0.51 [11]	$\cdots$	$0.18 \pm 0.43 \pm 0.14$
	-0.49 [10]	-0.90 [10]		
	-0.49 [13]	-0.97 [14]		
	-0.66 [15]	-0.90 [17]		
	-0.99 [16]	-0.91 [18]		
$\Lambda\pi^+$	-0.70 [12]	-0.67 [11]	-0.91 ± 0.15	$-0.80 \pm 0.11 \pm 0.02$
	-0.95 [10]	-0.99 [10]		
	-0.96 [13]	-0.95 [14]		
	-0.99 [15]	-0.86 [17]		
	-0.99 [16]	-0.94 [18]		
$\Sigma^+\pi^0$	0.71 [12]	0.92 [11]	-0.45 ± 0.32	$-0.57 \pm 0.10 \pm 0.07$
	0.79 [10]	-0.49 [10]		
	0.83 [13]	0.43 [14]		
	0.39 [15]	-0.76 [17]		
	-0.31 [16]	-0.47 [18]		
$\Sigma^0\pi^+$	0.70 [12]	0.92 [11]	$\cdots$	$-0.73 \pm 0.17 \pm 0.07$
	0.78 [10]	-0.49 [10]		
	0.83 [13]	0.43 [14]		
	0.39 [15]	-0.76 [17]		
	-0.31 [16]	-0.47 [18]		

[10] Phys. Rev. D48 4188 (1993) pole model
[11] Phys. Rev. D46 270 (1992) current algebra
[12] Z. Phys. C55 659 (1992) current algebra
[13] Phys. Rev. D46 1042 (1992) pole model
[14] Phys. Rev D57 5632 (1998) factorization
[15] Phys. Rev D50 5787 (1994) pole model
[16] Eur. Phys. J. C7 217 (1999) current algebra framework
[17] Phys. Rev D50 402 (1994) pole model
[18] hel-ph/9504428 flavor symmeetry

EXPERIMENTS FOR α_{BP}^{+}

In previous experiments, **Λ_c^+ was assumed unpolarized,** and the decay asymmetry was obtained by analyzing the longitudinal polarization from the weak two-body decay of the produced baryon B:

Only $\alpha_{\Lambda\pi}$ and $\alpha_{\Sigma^+\pi^0}$ was measured:

1. $\Lambda_c^+ \to \Lambda\pi^+, \Lambda \to p\pi^-$
2. $\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma \to p\pi^0$

Using the formula:

Old formula

$$\frac{dW}{d\cos\theta} = \frac{1}{2}(1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\theta)$$

Table 2: Measurements of the decay asymmetry in different experiments.

Experiment	Date	Result	
		$\alpha_{\Lambda\pi^+}$	$\alpha_{\Sigma^+\pi^0}$
FOCUS [14]	2006	$-0.78 \pm 0.16 \pm 0.19$	
CLEO [15]	1995	$-0.94^{+0.21+0.12}_{-0.06-0.06}$	$-0.45 \pm 0.31 \pm 0.06$
ARGUS [16]	1992	-0.96 ± 0.42	
CLEO [17]	1990	$-1.0^{+0.4}_{-0.1}$	

[14]: PL B634, 165, 2006
[15]: PL B350, 256, 1995
[16]: PL B274, 239, 1992
[17]: PRL 65, 2842, 2010

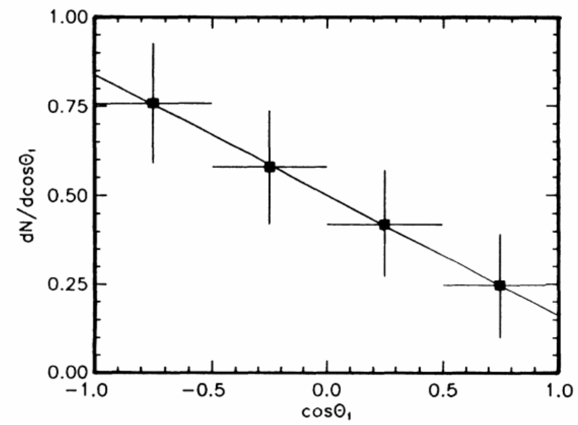


FIG. 3. The angular distribution of the decay proton ($dN/d\cos\theta_1$). The solid line is the fit to this distribution. The slope of the distribution is -0.34 ± 0.14 and represents $\alpha_\Lambda \alpha_{\Lambda_c}/2$.

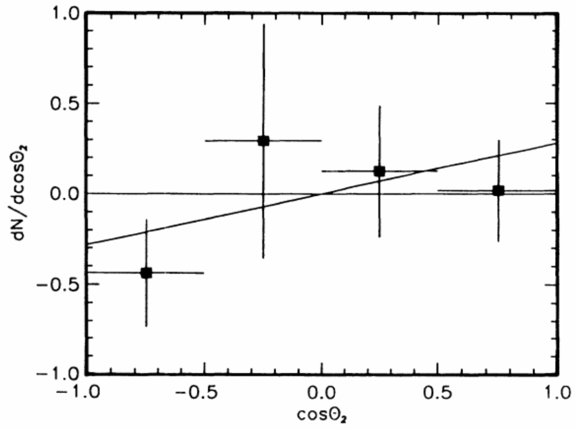


FIG. 4. The angular distribution $dN/d\cos\theta_2$. The solid line is the fit to this distribution. The slope of the distribution is $+0.24 \pm 0.24$ and represents $+P\alpha_{\Lambda_c}$.

DISADVANTAGE OF OLD WORKS

1. Need two cascade two-body decay

- Can not measure α_{pK_s} from $\Lambda_c^+ \to pK_S^0$, (large Br and low bkg level)

2. Λ_c^+ is assumed unpolarized when generated.

- We find transverse polarization in many process ($\Lambda\Lambda, \Sigma\Sigma, etc.$)

3. $\alpha_{\Sigma^0\pi^+}$ is not measured either, where $\alpha_{\Sigma^0\pi^+} \equiv \alpha_{\Sigma^+\pi^0}$ according to isospin symmetry

Old formula

$$\frac{dW}{d\cos\theta} = \frac{1}{2}(1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\theta)$$

In our Work:

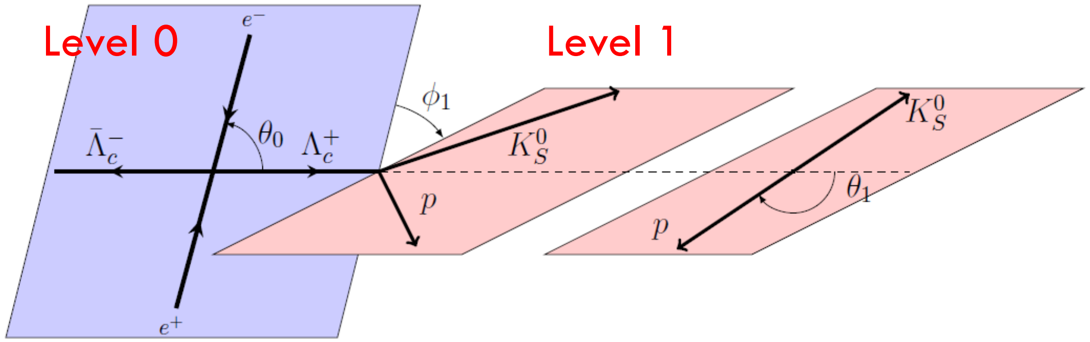
- We consider & measure the transverse polarization of Λ_c^+ baryon in unpolarized e^+e^- annihilation.
- 4 decay parameters: α_{pK_s}, $\alpha_{\Lambda\pi}$, $\alpha_{\Sigma^+\pi^0}\alpha_{\Sigma^0\pi^+}$, obtained from angular analysis, with PT as common.
- α_{pK_s} and $\alpha_{\Sigma^0\pi^+}$ are measured for the first time.

THE ANGULAR DISTRIBUTION
—1. *HELICITY FRAME AND AMPLITUDE*

For $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-, \Lambda_c^+ \to BP$, the amplitude can be constructed under the helicity basis.

- $D^J_{\{m,n\}}(\phi,\theta,\gamma) = e^{-im\phi} d^J_{m,n} e^{-in\gamma}$, is the Wigner-D function
- A, B is the amplitude related to
  - $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$
  - $\Lambda_c^+ \to BP$

Level	Decay	Angle	Amplitude
0	$e^+e^- \to \gamma^* \to \Lambda_c^+(\lambda_1)\bar{\Lambda}_c^-(\lambda_2)$	θ_0	A_{λ_1,λ_2}
1	$\Lambda_c^+ \to p(\lambda_3)K_S^0$	(θ_1,ϕ_1)	B_{λ_3}



CM frame $\quad\quad$ Λ_c^+ rest frame

$$\frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\phi_1} \propto \sum_{M,\lambda_1,\lambda_2,\lambda_3} D^{1*}_{M,\lambda_1-\lambda_2}(0,\theta_0,0) D^{1}_{M,\lambda_1'-\lambda_2}(0,\theta_0,0) A^*_{\lambda_1,\lambda_2} A_{\lambda_1',\lambda_2}$$
$$\times D^{1/2*}_{\lambda_1,\lambda_3}(\phi_1,\theta_1,0) D^{1/2}_{\lambda_1',\lambda_3}(\phi_1,\theta_1,0) |B_{\lambda_3}|^2,$$

THE ANGULAR DISTRIBUTION
–2. ANGULAR FORMULA IN $\Lambda_c^+ \to pK_S^0$

polarization

$$\frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\phi_1} \propto 1 + \alpha_0 \cos^2\theta_0 + \boxed{\mathcal{P}_T \alpha^{+}_{pK_S^0} \sin\theta_1 \sin\phi_1,}$$

$$\mathcal{P}_T = \sqrt{1-\alpha_0^2}\cos\theta_0 \sin\theta_0 \sin\Delta_0,$$

If the $sin\Delta_0 \neq 0$, we can measure $\alpha^{+}_{pK_S}$

Δ_0 is the phase angle difference between $A_{\frac{1}{2},\frac{1}{2}}$ and $A_{\frac{1}{2},-\frac{1}{2}}$

Δ_0 is also the phase angle between the electric and magnetic form factors of the Λ_c^+

THE ANGULAR DISTRIBUTION
–3. ANGULAR FORMULA IN $\Lambda_c^+ \to \Lambda\pi^+(\Sigma^+\pi^0)$

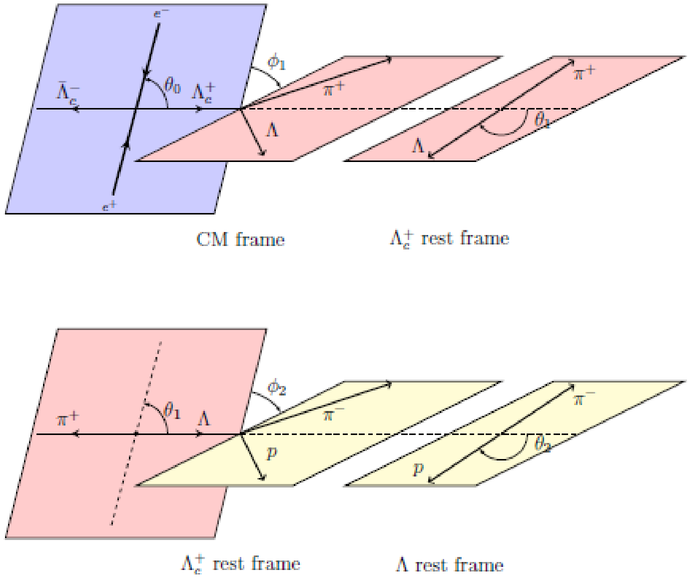


FIG. 2. Definition of the helicity frame for $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$, $\Lambda_c^+ \to \Lambda\pi^+$ and $\Lambda \to p\pi^-$

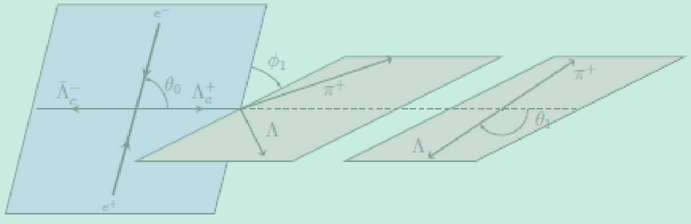
$$
\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\cos\theta_2 d\phi_1 d\phi_2} \\
&\propto 2 + 2\alpha_0\cos^2\theta_0 \\
&+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\Delta_0 \sin(2\theta_0)\sin\theta_1\cos\theta_2\sin\phi_1 \\
&+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\Delta_0 \sin(2\theta_0)\cos\theta_1\sin\theta_2\sin\phi_1 \\
&\times \sqrt{1-(\alpha_{\Lambda\pi^+}^+)^2}\cos(\Delta_1^{\Lambda\pi^+}+\phi_2) \\
&+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\Delta_0 \sin(2\theta_0)\sin\theta_2\cos\phi_1 \\
&\times \sqrt{1-(\alpha_{\Lambda\pi^+}^+)^2}\sin(\Delta_1^{\Lambda\pi^+}+\phi_2) \\
&\boxed{+ \sqrt{1-\alpha_0^2}\sin\Delta_0\sin(2\theta_0)\sin\theta_1\sin\phi_1\alpha_{\Lambda\pi^+}^+} \\
&+ 2\alpha_0\alpha_\Lambda\cos^2\theta_0\cos\theta_2\alpha_{\Lambda\pi^+}^+ \boxed{+ 2\alpha_\Lambda\cos\theta_2\alpha_{\Lambda\pi^+}^+},
\end{aligned}
$$

polarization

If we integrate other angles out: we get

$$\frac{dN}{d\cos\theta_2} \propto 1 + \alpha_{\Lambda\pi^+}^+\alpha_\Lambda\cos\theta_2.$$

THE ANGULAR DISTRIBUTION
–3. ANGULAR FORMULA IN $\Lambda_c^+ \to \Lambda\pi^+(\Sigma^+\pi^0)$



Δ_1:the phase between $B_{\frac{1}{2}}$ and $B_{-\frac{1}{2}}$,

We can obtain two Lee-Yang parameters by:

$$\beta_{BP} = \sqrt{1-(\alpha_{BP}^{+})^2}\sin\Delta_1^{BP},$$
$$\gamma_{BP} = \sqrt{1-(\alpha_{BP}^{+})^2}\cos\Delta_1^{BP}.$$

FIG. 2. Defi... $\Lambda\pi^+$ and $\Lambda \to p\pi^-$

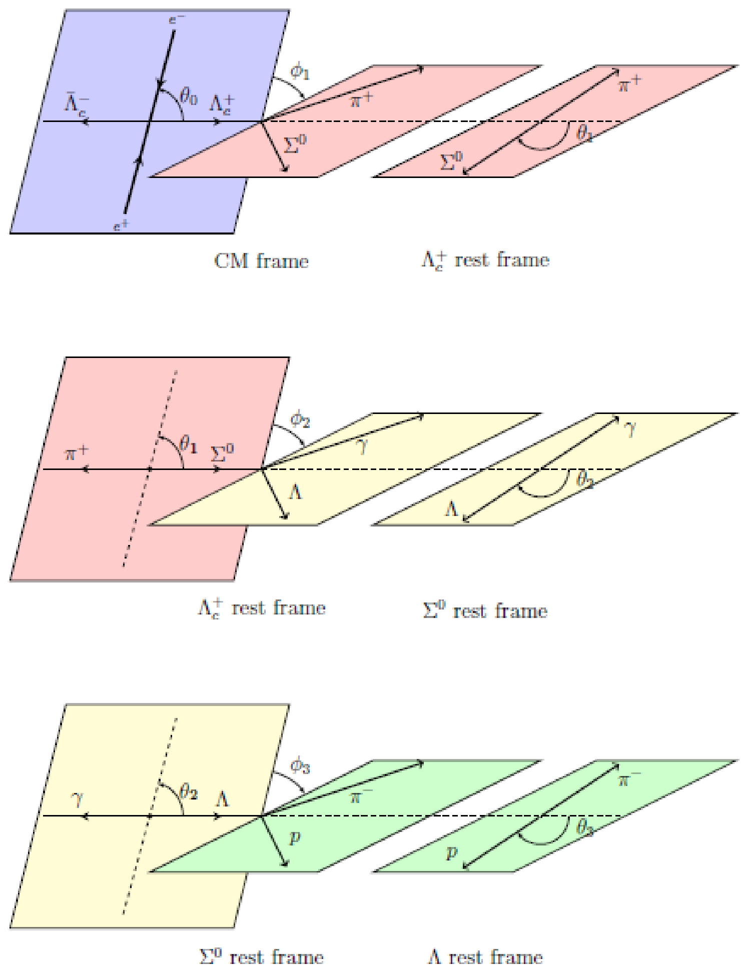
$$\frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\cos\theta_2 d\phi_1 d\phi_2}$$
$$\propto 2 + 2\alpha_0\cos^2\theta_0$$
$$+\sqrt{1-\alpha_0^2}\alpha_\Lambda\sin\Delta_0\sin(2\theta_0)\sin\theta_1\cos\theta_2\sin\phi_1$$
$$+\sqrt{1-\alpha_0^2}\alpha_\Lambda\sin\Delta_0\sin(2\theta_0)\cos\theta_1\sin\theta_2\sin\phi_1$$
$$\times\sqrt{1-(\alpha_{\Lambda\pi^+}^{+})^2}\cos(\Delta_1^{\Lambda\pi^+}+\phi_2)$$
$$+\sqrt{1-\alpha_0^2}\alpha_\Lambda\sin\Delta_0\sin(2\theta_0)\sin\theta_2\cos\phi_1$$
$$\times\sqrt{1-(\alpha_{\Lambda\pi^+}^{+})^2}\sin(\Delta_1^{\Lambda\pi^+}+\phi_2)$$
$$\boxed{+\sqrt{1-\alpha_0^2}\sin\Delta_0\sin(2\theta_0)\sin\theta_1\sin\phi_1\alpha_{\Lambda\pi^+}^{+}}$$
$$+2\alpha_0\alpha_\Lambda\cos^2\theta_0\cos\theta_2\alpha_{\Lambda\pi^+}^{+}\boxed{+2\alpha_\Lambda\cos\theta_2\alpha_{\Lambda\pi^+}^{+}},$$

polarization

If we integrate other angles out: we get

$$\frac{dN}{d\cos\theta_2} \propto 1+\alpha_{\Lambda\pi^+}^{+}\alpha_\Lambda\cos\theta_2.$$

THE ANGULAR DISTRIBUTION
–4. ANGULAR FORMULA IN $\Lambda_c^+ \to \Sigma^0\pi^+$



$$\frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\cos\theta_2 d\cos\theta_3 d\phi_1 d\phi_2}$$
$$\begin{aligned}
&\propto 2 + 2\alpha_0\cos^2\theta_0 \\
&- \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin(2\theta_0)\sin\theta_1\cos\theta_2\cos\theta_3\sin\phi_1\sin\Delta_0 \\
&- \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin(2\theta_0)\cos\theta_1\sin\theta_2\cos\theta_3\sin\Delta_0 \\
&\times \sqrt{1-(\alpha^+_{\Sigma^0\pi^+})^2}\sin(\Delta_1^{\Sigma^0\pi^+}+\phi_2) \\
&- \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin(2\theta_0)\cos\phi_1\sin\theta_2\cos\theta_3\sin\Delta_0 \\
&\times \sqrt{1-(\alpha^+_{\Sigma^0\pi^+})^2}\sin(\Delta_1^{\Sigma^0\pi^+}-\phi_2) \\
&\boxed{+ \sqrt{1-\alpha_0^2}\sin(2\theta_0)\sin\theta_1\sin\phi_1\sin\Delta_0\alpha^+_{\Sigma^0\pi^+}} \\
&- 2\alpha_0\alpha_\Lambda\cos^2\theta_0\cos\theta_2\cos\theta_3\alpha^+_{\Sigma^0\pi^+} \\
&\boxed{- 2\alpha_\Lambda\cos\theta_2\cos\theta_3\alpha^+_{\Sigma^0\pi^+}}.
\end{aligned}$$

polarization

If we integrate other angles out: we get

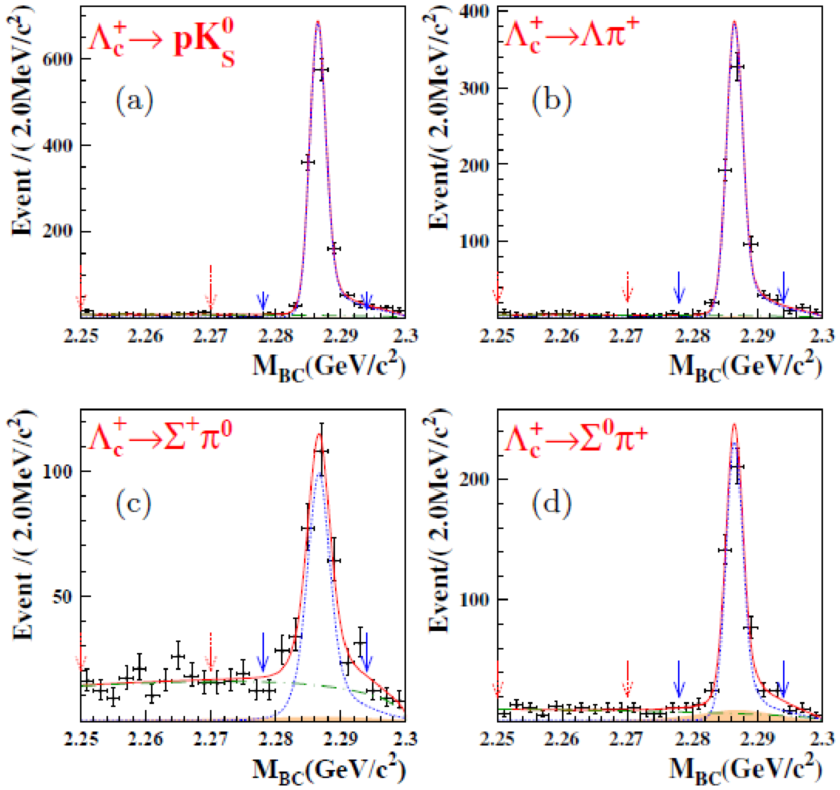
$$\frac{dN}{d\cos\theta_2 d\cos\theta_3} \propto 1 - \alpha^+_{\Sigma^0\pi^+}\alpha_\Lambda\cos\theta_2\cos\theta_3.$$

OBTAIN α_{BP}^{+} AND POLARIZATION

$$f_S(\vec{\xi}) = \frac{\epsilon(\vec{\xi})|M(\vec{\xi};\vec{\eta})|^2}{\int \epsilon(\vec{\xi})|M(\vec{\xi};\vec{\eta})|^2 \mathrm{d}\vec{\xi}},$$

$$\int \epsilon(\vec{\xi})|M(\vec{\xi};\vec{\eta})|^2 \mathrm{d}\vec{\xi} = \frac{1}{N_{\mathrm{gen}}} \sum_{k_{\mathrm{MC}}}^{N_{\mathrm{MC}}} |M(\vec{\xi}_k;\vec{\eta})|^2,$$

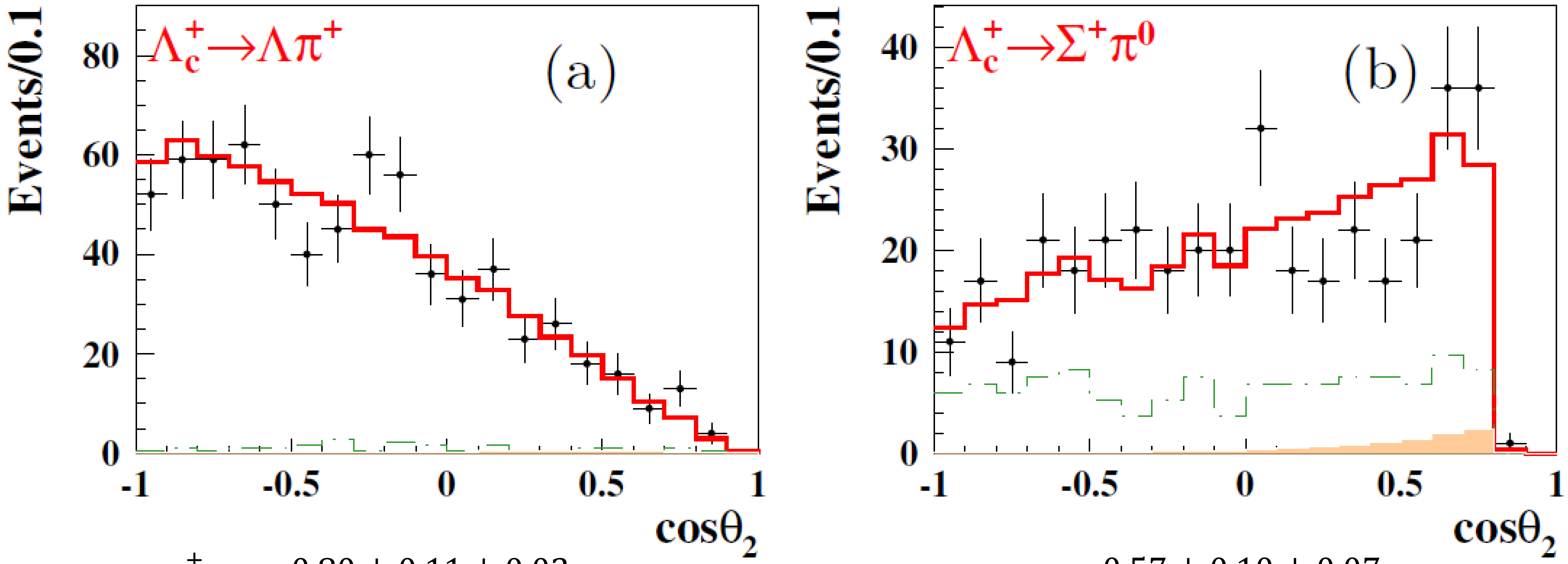
- ✓Parameters are obtained from simultaneous fit:
- ✓Both Λ_c^+ and $\overline{\Lambda}_c^-$ used, the relation $\alpha_{BP}^{+} = \alpha_{BP}^{-}$ is put in the fit.
- ✓The MINUIT package in CERN library with Log-Likelihood method is used to yield the fitting parameters.
- ✓Combinatorial bkg events are estimated by M_{BC} sidebands
- ✓(Peaking) bkg events are estimated by MC.



RESULT

1. $\alpha_{\Lambda\pi}$ & $\alpha_{\Sigma^+\pi^0}$

$$\frac{dN}{d\cos\theta_2} \propto 1 + \alpha^+_{\Lambda\pi^+(\Sigma^+\pi^0)}\alpha_{\Lambda(\Sigma^+)}\cos\theta_2.$$



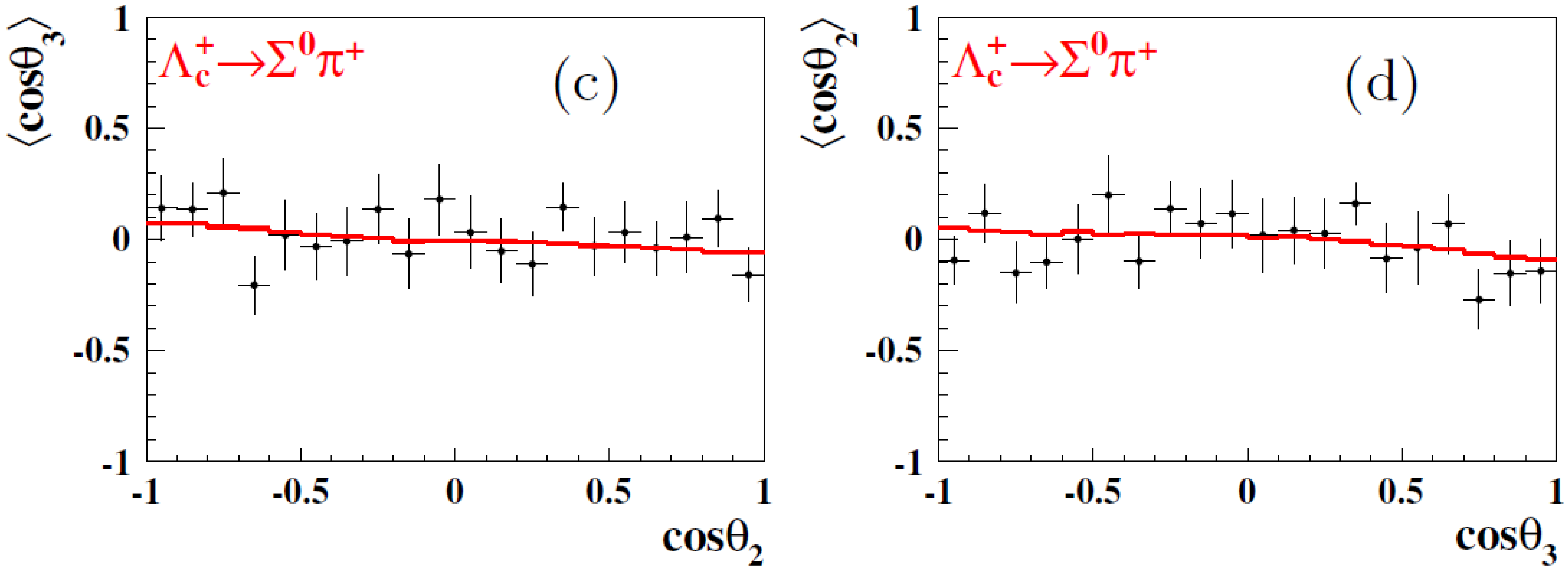
$\alpha^+_{\Lambda\pi} = -0.80 \pm 0.11 \pm 0.02$ $\qquad$ $\alpha_{\Sigma^+\pi^0} = -0.57 \pm 0.10 \pm 0.07$

RESULT

2. $\alpha_{\Sigma^0\pi^+}$

$$\frac{dN}{d\cos\theta_2 d\cos\theta_3} \propto 1 - \alpha^+_{\Sigma^0\pi^+}\alpha_\Lambda \cos\theta_2 \cos\theta_3 .$$

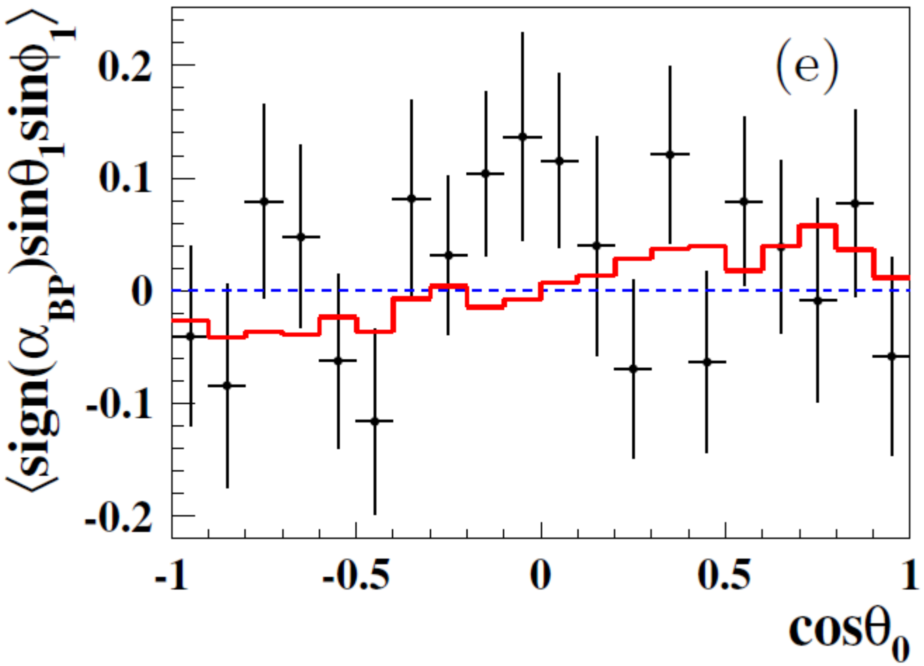
$$\langle \cos\theta_i \rangle = -\frac{1}{6}\alpha^+_{\Sigma^0\pi^+}\alpha_\Lambda \cos\theta_j ,$$



$$\alpha_{\Sigma^0\pi^+} = -0.73 \pm 0.17 \pm 0.07$$

RESULT
3. POLARIZATION

$$< \sin\theta_1 \sin\phi_1 > \propto P_T(\cos\theta_0)/(1+\alpha_0\cos^2\theta_0)$$



Nature Phy. 15 631 (2019)

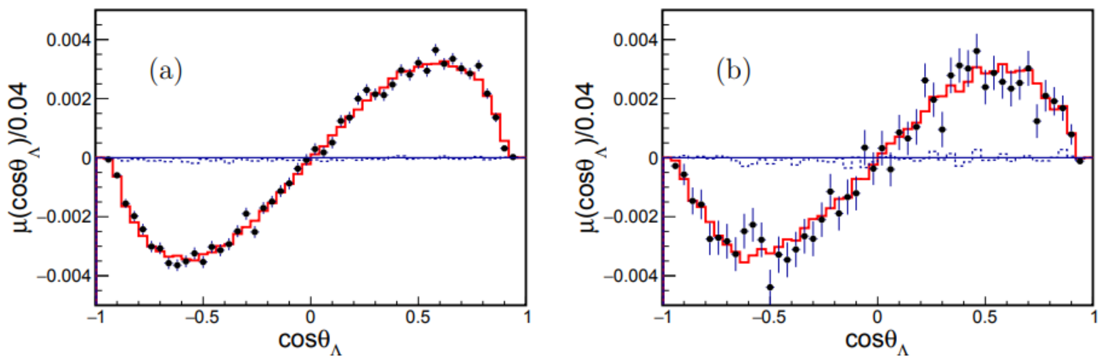


FIG. 2. Moments $\mu(\cos\theta_\Lambda)$ for acceptance uncorrected data as a function of $\cos\theta_\Lambda$ for (a) $p\pi^-\bar{p}\pi^+$ and (b) $p\pi^-\bar{n}\pi^0$ data sets. The points with error bars are the data, and the solid-line histogram is the global fit result. The dashed histogram shows the no polarization scenario ($\mathcal{W}(\boldsymbol{\xi}; 0, 0, 0, 0) \equiv 1$).

$$sin\Delta_0 = -0.28 \pm 0.13 \pm 0.03$$

$$\Delta\Phi = 42.4 \pm 0.6 \pm 0.5(rad)$$

- The transverse polarization is first studied and found to be non-zero with 2.1σ
- Expect more data

- With a large data sample, the PT of $J/\psi \to \Lambda\bar{\Lambda}$ is quite accurate.

SYSTEMATIC UNCERTAINTY

Source	α_A^+	α_B^+	α_C^+	α_D^+	$\sin\Delta_0$	Δ_1^B	Δ_1^C	Δ_1^D
Reconstruction	0.00	0.00	0.00	0.01	0.00	0.8	0.0	0.0
$\pi^0\pi^0$ veto	0.01	0.00	0.01	0.00	0.00	0.0	0.2	0.0
ΔE signal region	0.07	0.01	0.02	0.05	0.02	0.3	0.1	0.1
M_{BC} signal region	0.12	0.01	0.05	0.02	0.02	0.5	0.4	0.1
Bkg subtraction	0.03	0.01	0.05	0.04	0.02	0.3	0.3	0.0
Total	0.14	0.02	0.07	0.07	0.03	1.0	0.6	0.2

The systematic uncertainties arise from:

1. The reconstruction of final tracks.
2. $K_S^0 \to \pi^0\pi^0$ veto
3. ΔE requirement
4. Background subtraction.

The statistic uncertainties dominate.

SUMMARY

$\Lambda_c^+ \to$	Predicted α_{BP}^+		PDG α_{BP}^+	This work α_{BP}^+	β_{BP}	γ_{BP}	Δ_1^{BP}(rad)
pK_S^0	-1.0 [12]	0.51 [11]	...	$0.18 \pm 0.43 \pm 0.14$	...	...	...
	-0.49 [10]	-0.90 [10]					
	-0.49 [13]	-0.97 [14]					
	-0.66 [15]	-0.90 [17]					
	-0.99 [16]	-0.91 [18]					
$\Lambda\pi^+$	-0.70 [12]	-0.67 [11]	-0.91 ± 0.15	$-0.80 \pm 0.11 \pm 0.02$	$0.06^{+0.58+0.05}_{-0.47-0.06}$	$-0.60^{+0.96+0.17}_{-0.05-0.03}$	$3.0 \pm 2.4 \pm 1.0$
	-0.95 [10]	-0.99 [10]					
	-0.96 [13]	-0.95 [14]					
	-0.99 [15]	-0.86 [17]					
	-0.99 [16]	-0.94 [18]					
$\Sigma^+\pi^0$	~~0.71~~ [12]	~~0.92~~ [11]	-0.45 ± 0.32	$-0.57 \pm 0.10 \pm 0.07$	$-0.66^{+0.46+0.22}_{-0.25-0.02}$	$-0.48^{+0.45+0.21}_{-0.42-0.04}$	$4.1 \pm 1.1 \pm 0.6$
	~~0.79~~ [10]	-0.49 [10]					
	~~0.83~~ [13]	~~0.43~~ [14]					
	~~0.39~~ [15]	-0.76 [17]					
	-0.31 [16]	-0.47 [18]					
$\Sigma^0\pi^+$	~~0.70~~ [12]	~~0.92~~ [11]	...	$-0.73 \pm 0.17 \pm 0.07$	$0.48^{+0.35+0.07}_{-0.57-0.13}$	$0.49^{+0.35+0.07}_{-0.56-0.12}$	$0.8 \pm 1.2 \pm 0.2$
	~~0.78~~ [10]	-0.49 [10]					
	~~0.83~~ [13]	~~0.43~~ [14]					
	~~0.39~~ [15]	-0.76 [17]					
	-0.31 [16]	-0.47 [18]					

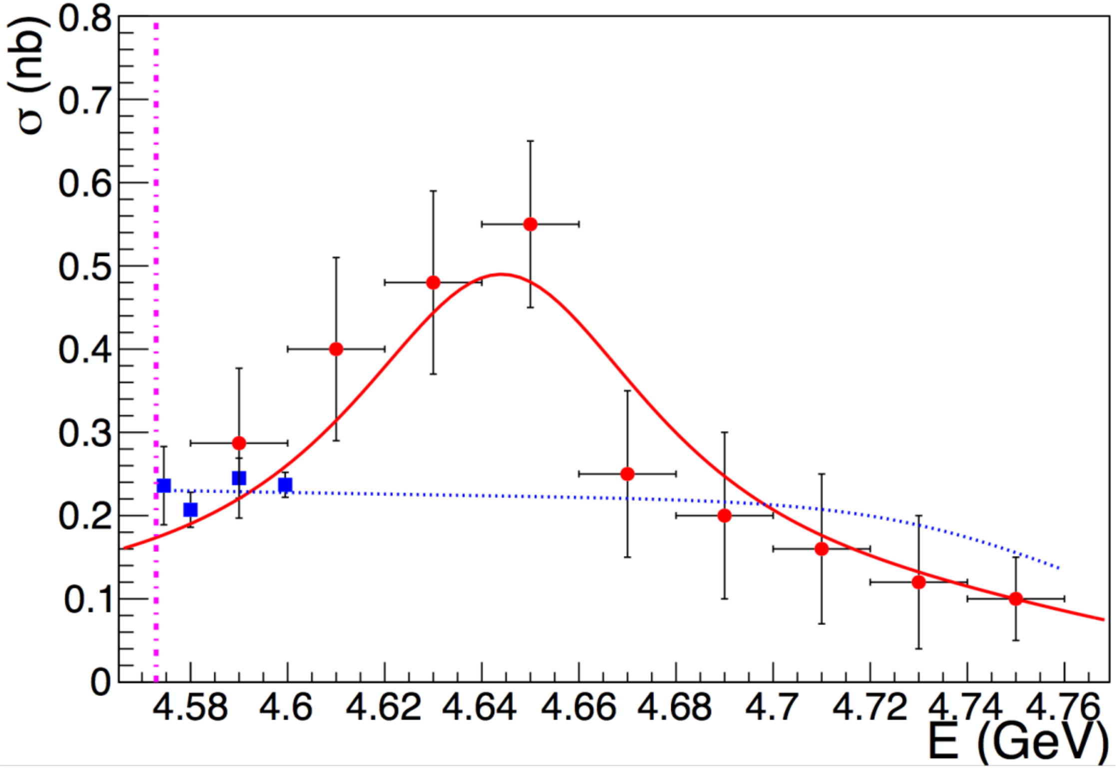
$sin\Delta_0 = -0.28 \pm 0.13 \pm 0.03$

- The transverse polarization is first studied and found to be non-zero with 2.1σ

- Best precision on the hadronic weak decay asymmetries
- The measurement of $\alpha_{\Lambda\pi}^+$ and $\alpha_{\Sigma^+\pi^0}$ are consistent but with improved precision.
- α_{pK_S} and $\alpha_{\Sigma^0\pi^+}$ are measured for the first time.
- The negative sign of $\alpha_{\Sigma^+\pi^0}$ is confirmed at >8σ, rule out a lot of models.
- So far, no model gives predictions fully consistent with all the measurements.

PROSPECT: APPROVED DATA TAKING BETWEEN 4.6~4.7GEV IN 2020

- We will accumulate at least **10~20x** more Λ_c pairs (1~2M)
- Irreplaceable sample to systematically refresh the whole Λ_c knowledge and impact relevant theoretical and experimental studies.
- BESIII data above 4.6GeV will follow a sharp rise of the Y(4660) or a flat cross section near threshold
- Accessible to the form factor and polarization of the Λ_c at higher Q^2



谢谢！！