中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Λ_c spin and decay asymmetry parameters

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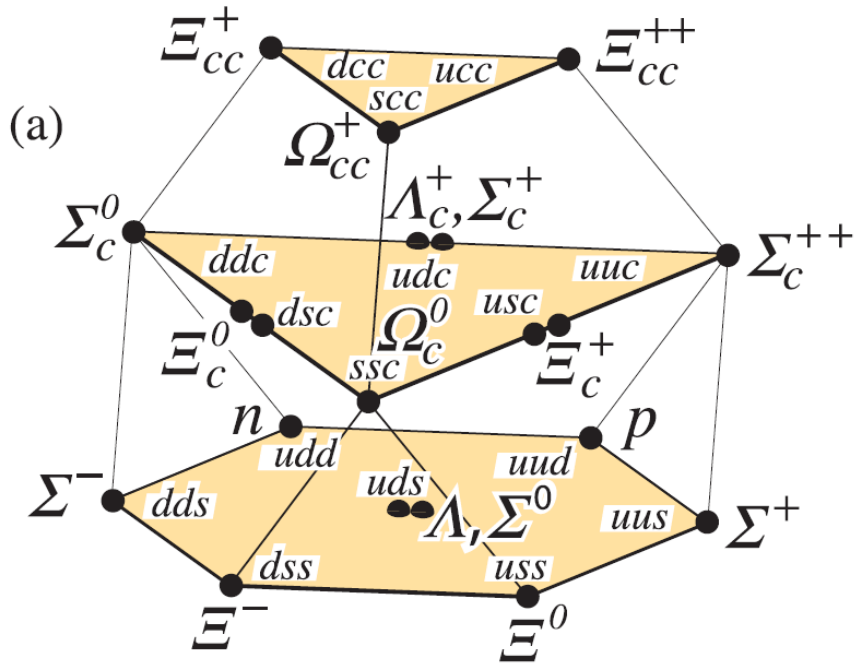
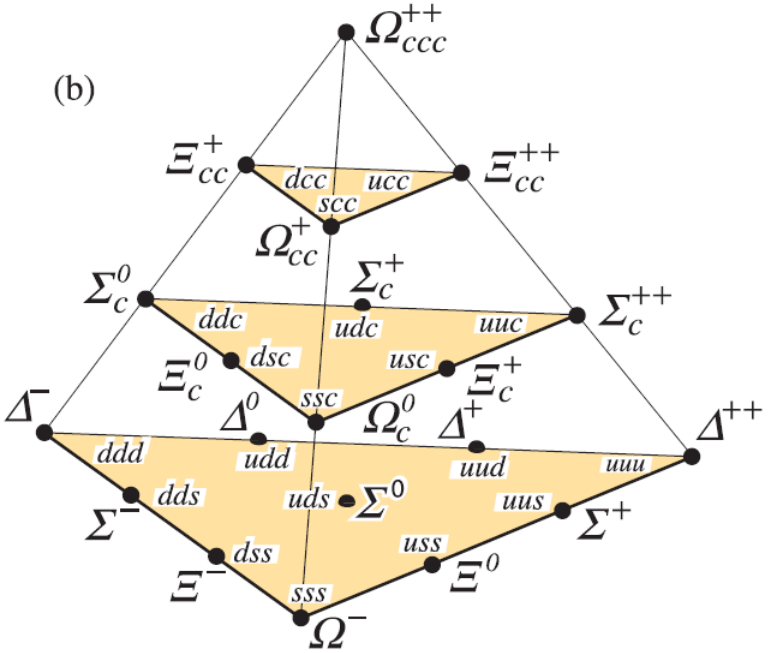
Workshop on form factor, polarization and CP violation in quantum-correlated hyperon-anti-hyperon production, 6-8 July 2019 Fudan University

Λ_c spin



20-plet baryon with SU(3)-octet

$$J = \frac{1}{2}$$



20-plet baryon with SU(3)-decuplet

$$J = \frac{3}{2}$$

Λ_c spin

Λ_c^+

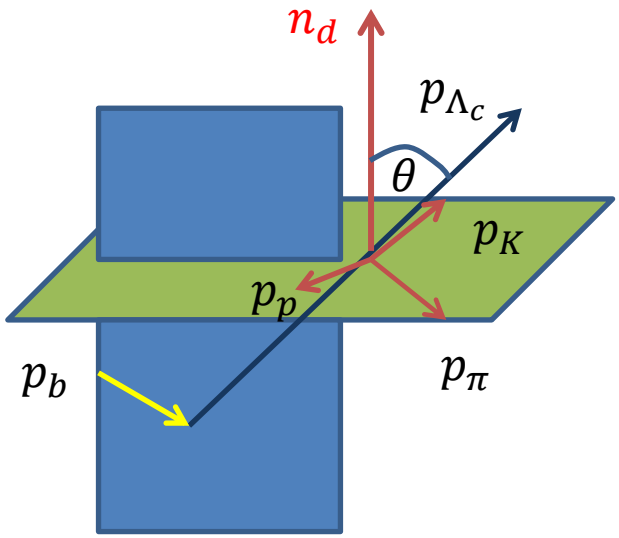
$I(J^P) = 0(\frac{1}{2}^+)$ Status: ****

The parity of the Λ_c^+ is defined to be positive (as are the parities of the proton, neutron, and Λ). The quark content is udc. Results of an analysis of $pK^-\pi^+$ decays (JEZABEK 92) are consistent with $J = 1/2$. Nobody doubts that the spin is indeed 1/2.

We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

Λ_c spin

- NA2 experiment at CERN-SPS: Phys.Lett., B286, 175 (1992)
- π Cu $\rightarrow \Lambda_c^+ \, \overline{D} \, X$
- 160 events for $\Lambda_c \rightarrow pK^-\pi^+$



- Angular distribution of three – body decay

$$I(\theta,\phi) = \frac{2J+1}{4\pi} \times \sum_{M,M'} \varrho^J_{MM'} \sum_{\mu} f^J_{\mu} D^{J*}_{M\mu}(\phi,\theta,0) D^J_{M'\mu}(\phi,\theta,0) \, ,$$

Simplified as:

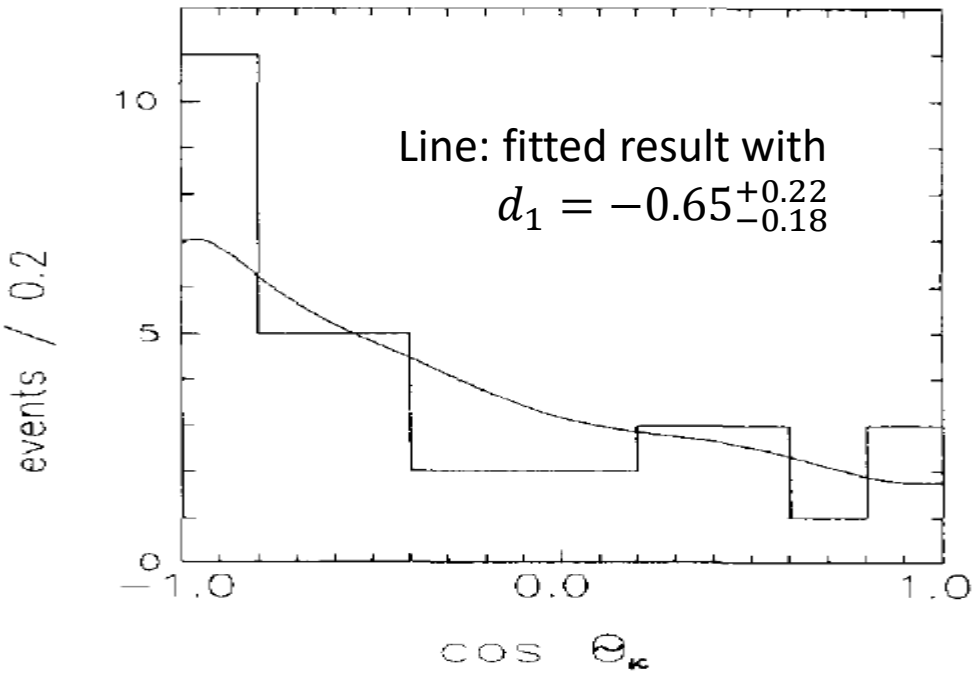
$$I(\theta) = \frac{1}{2}\left(1 + \sum_{l=1}^{2J} d_l P_l(\cos\theta)\right),$$

$$d_l \equiv p_l a_l \, ,$$

$$p_l = \sqrt{2l+1} \sum_m \varrho^J_{MM} \langle J, M; l, 0 | J, M\rangle \, ,$$

$$a_l = \sqrt{2l+1} \sum_\mu f^J_\mu \langle J, \mu; l, 0 | J, \mu\rangle \, .$$

Λ_c spin



$$\Lambda_c^+(\uparrow) = [ud]c(\uparrow)$$
$$c \to su\bar{d}$$

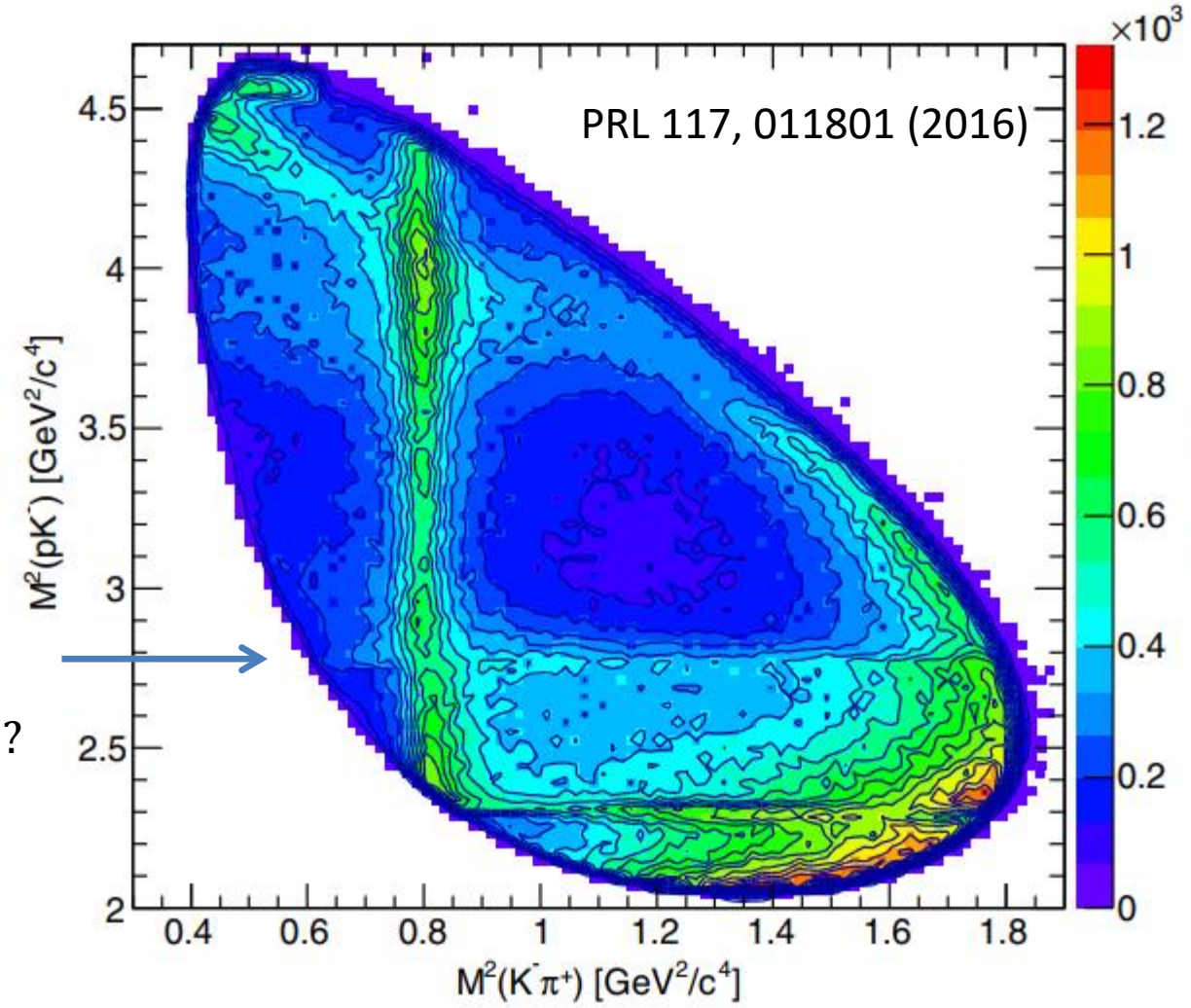
They concluded:

- Results consistent with assumption $J = 1/2$
- Unable to established $J = 1/2$ due to low statistics

Remarks:

- decay parameter should be modeled momentum dependent
- resonance structure in 3-body decay should be considered.
- only Λ_c longitudinal polarization is used (see $\rho_{M,M}$), and transverse component is missed

BELLE: $\Lambda_c \to pK^-\pi^+$



Signal evts:
1.45 million

New
$\boldsymbol{\Lambda^*(1670)\frac{3^-}{2}}$?

PWA results desired. BELLE, BESIII, or LHCb ??

Λ_c^+ decay asymmetry parameters

- Λ analogue of Lee-Yang parameters

$$\Lambda_c^+\left(\frac{1}{2}^+\right) \to B\left(\frac{1}{2}^+\right) P(0^-)$$

Partial waves: S (parity violation), P(parity conservation)

$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P^2|}, \quad \beta = \frac{2\mathrm{Im}(S^*P)}{|S|^2+|P^2|}, \quad \gamma = \frac{|S|^2-|P^2|}{|S|^2+|P^2|}.$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1.$$

Two independent parameters in PDG:

$$\alpha \text{ and } \phi = \tan^{-1}(\beta/\gamma)$$

PDG2018

Σ^+ DECAY PARAMETERS

α_0 FOR $\Sigma^+ \to p\pi^0$	$-0.980^{+0.017}_{-0.015}$
ϕ_0 ANGLE FOR $\Sigma^+ \to p\pi^0$ ($\phi_0 = \beta/\gamma$)	36 ± 34 °

Λ_c^+ decay asymmetry parameters

- In helicity amplitudes, asymmetry parameters defined as

$$S = \frac{1}{\sqrt{2}}\left(F_{\frac{1}{2}} + F_{-\frac{1}{2}}\right), \quad P = \frac{1}{\sqrt{2}}\left(F_{\frac{1}{2}} - F_{-\frac{1}{2}}\right),$$

so

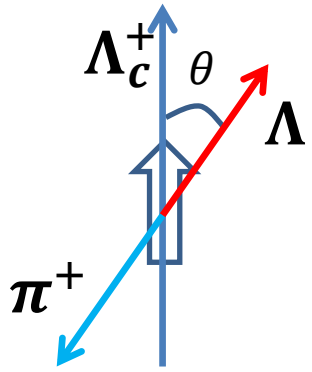
$$\alpha = \frac{|F_{1/2}|^2 - |F_{-1/2}|^2}{|F_{1/2}|^2 + |F_{-1/2}|^2}, \beta = \sqrt{1-\alpha^2}\sin\Delta, \quad \gamma = \sqrt{1-\alpha^2}\cos\Delta$$

Δ: phase angle difference between two helicity amplitudes.

Λ_c^+ decay asymmetry parameters

- α associated with parity violation, measure the Λ_c^+ decay asymmetry of polar angle distribution.

$$\frac{dN}{\mathrm{d}\cos\theta} \propto 1 + \alpha \cos\theta$$

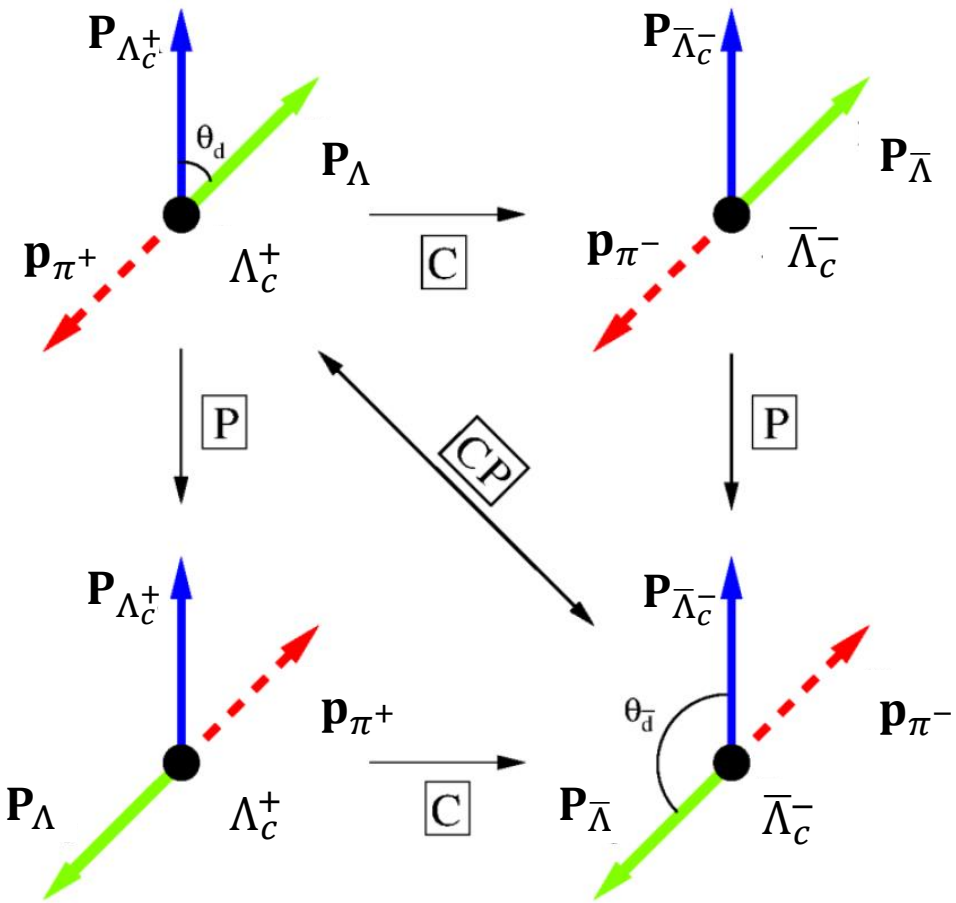


e.g. $\Lambda_c^+ \to \Lambda\pi^+$

- β measures physics associated with the time transform invariant

C- and P-transformation

$$\Lambda_c^+ \to \Lambda\pi^+ \Rightarrow \overline{\Lambda}_c^- \to \Lambda\pi^-$$



If CP conserved:

$$\overline{F}_{-\lambda_{\overline{\Lambda}}} = \eta_{\Lambda_c}\eta_\Lambda\eta_\pi(-1)^{(s_{\Lambda_c}-s_\Lambda-s_\pi)}F_{\lambda_\Lambda} = -F_{\lambda_\Lambda}$$

$$\overline{\alpha} = \frac{\left|\overline{F}_{1/2}\right|^2 - \left|\overline{F}_{-1/2}\right|^2}{\left|\overline{F}_{1/2}\right|^2 + \left|\overline{F}_{-1/2}\right|^2} = -\alpha$$

$$\beta = -\overline{\beta}$$

$$\gamma = \overline{\gamma}$$

$$\Gamma = \overline{\Gamma}$$

CP odd-observables

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \ , \qquad A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \ ,$$

$$B = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}, \qquad B' = \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}$$

Λ_c^+ DECAY PARAMETERS

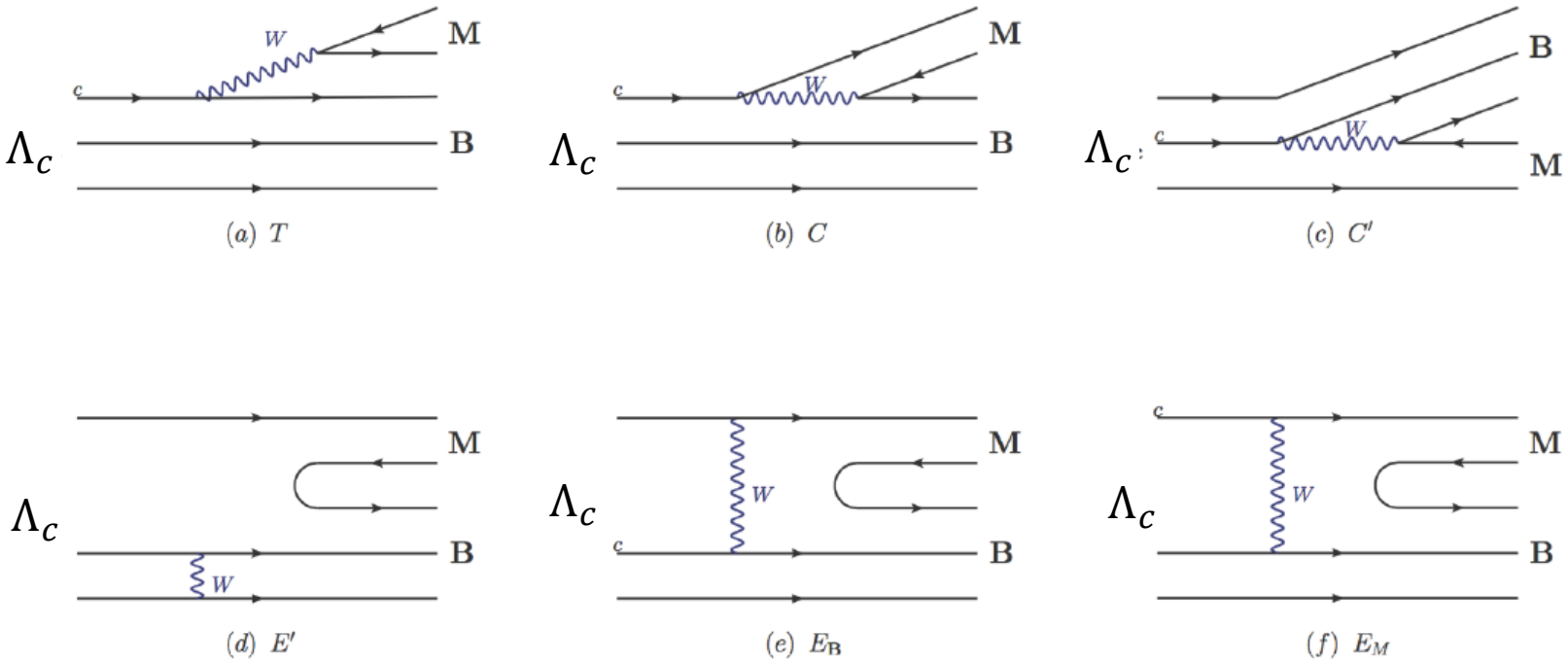
α FOR $\Lambda_c^+ \to \Lambda\pi^+$	-0.91 ± 0.15
α FOR $\Lambda_c^+ \to \Sigma^+\pi^0$	-0.45 ± 0.32
α FOR $\Lambda_c^+ \to \Lambda\ell^+\nu_\ell$	-0.86 ± 0.04

$\Lambda_c^+, \overline{\Lambda}_c^-$ CP-VIOLATING DECAY ASYMMETRIES

$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Lambda\pi^+$, $\overline{\Lambda}_c^- \to \overline{\Lambda}\pi^-$	-0.07 ± 0.31
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Lambda e^+\nu_e$, $\overline{\Lambda}_c^- \to \overline{\Lambda} e^-\overline{\nu}_e$	0.00 ± 0.04

Predictions on Λ_c asymmetry parameters

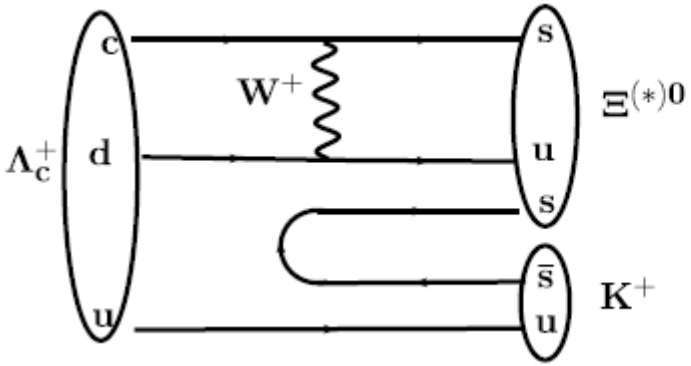
- Quark diagrams for hadronic weak decays $\Lambda_c \to B\ M$

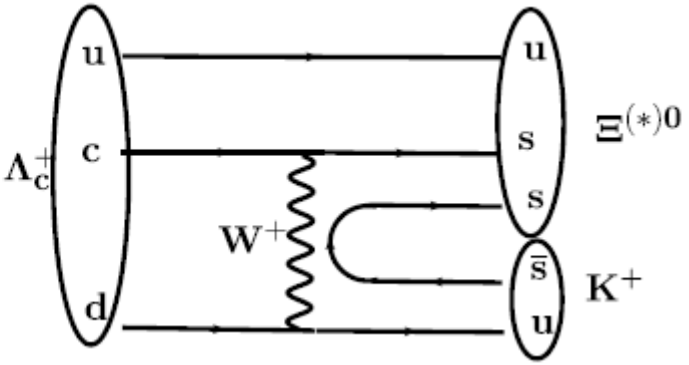


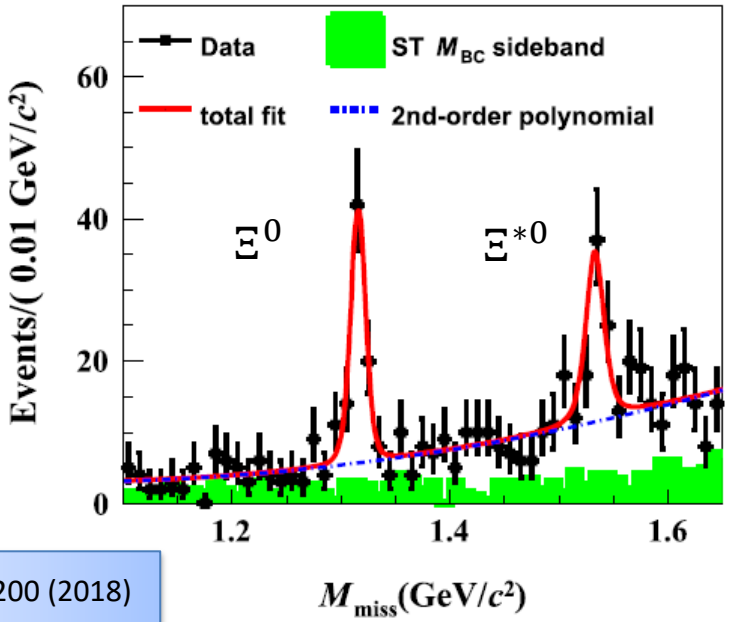
Contrary to the heavy meson decays, W-exchange diagrams make significant contribution to the Λ_c hadronic weak decays.

Predictions on Λ_c asymmetry parameters

- W-exchange decay: $\Lambda_c^+ \to \Xi^0 K^+$







$$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+) = (5.90 \pm 0.86 \pm 0.39) \times 10^{-3}$$

$$\mathcal{B}(\Lambda_c^+ \to \Xi^{*0} K^+) = (5.02 \pm 0.99 \pm 0.31) \times 10^{-3}$$

Compared to

$$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.29 \pm 0.07)\%$$

BESIII:PLB783,200 (2018)

Predictions on Λ_c asymmetry parameters

$\alpha^{[\Lambda_c^+]}_{[\Lambda\pi^+]}$ for $\Lambda_c^+ \to \Lambda\pi^+$, $\alpha^{[\Lambda_c^+]}_{[\Sigma^+\pi^0]}$ for $\Lambda_c^+ \to \Sigma^+\pi^0$, $\alpha^{[\Lambda_c^+]}_{[\Xi^0 K^+]}$ for $\Lambda_c^+ \to \Xi^0 K^+$ and $\alpha^{[\Lambda_c^+]}_{[pK_S^0]}$ for $\Lambda_c^+ \to pK_S^0$.

Parameters	Predictions	Experiments	PDG
$\alpha^{[\Lambda_c^+]}_{[\Lambda\pi^+]}$	$-0.70[8],\ -0.67[3]$ $-0.95[4],-0.95[5]$ $-0.99[6],-0.99[7]$	$-0.78 \pm 0.16 \pm 0.19[13]$ $-0.94^{+0.21+0.12}_{-0.06-0.06}[14]$ $-0.96 \pm 0.42[17],-1.1^{+0.4}_{-0.1}[15]$	-0.91 ± 0.15
$\alpha^{[\Lambda_c^+]}_{[\Sigma^+\pi^0]}$	$0.71[8],0.92[3]$ $0.78[4],0.43[5]$ $0.39[6],-0.31[7]$	$-0.45 \pm 0.31 \pm 0.06$	-0.45 ± 0.32
$\alpha^{[\Lambda_c^+]}_{[\Xi^0 K^+]}$	$0[8],0[3]$ $0[5],0[6]$ $0[7]$	...	...
$\alpha^{[\Lambda_c^+]}_{[pK_S^0]}$	-1.0[8],0.51[3] -0.49[4],-0.97[5] -0.66[6],-0.99[7]	...	...

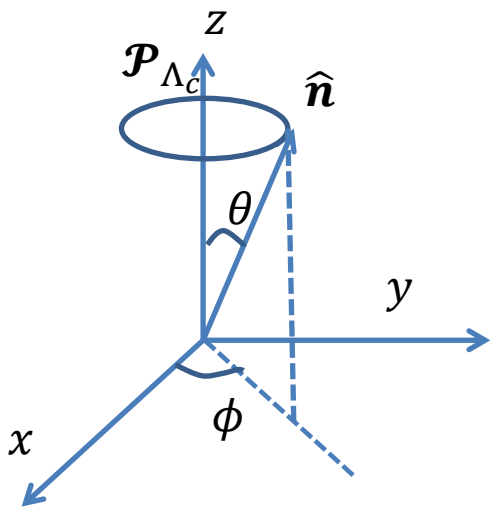
Previous measurements of Λ_c^+ asymmetry parameters

- **α for $\Lambda_c^+ \to \Lambda\pi^+$**

$$\mathcal{P}_\Lambda = \frac{(\alpha+\mathcal{P}_{\Lambda_c}\cdot\hat{n})\hat{n}+\beta(\mathcal{P}_{\Lambda_c}\times\hat{n})+\gamma\hat{n}\times(\mathcal{P}_{\Lambda_c}\times\hat{n})}{1+\alpha\mathcal{P}_{\Lambda_c}\cdot\hat{n}}$$

$\mathcal{P}_\Lambda, \mathcal{P}_{\Lambda_c}$: polarization vector for Λ and Λ_c

$\hat{n}$: unit vector along Λ momentum defined in the Λ_c rest frame

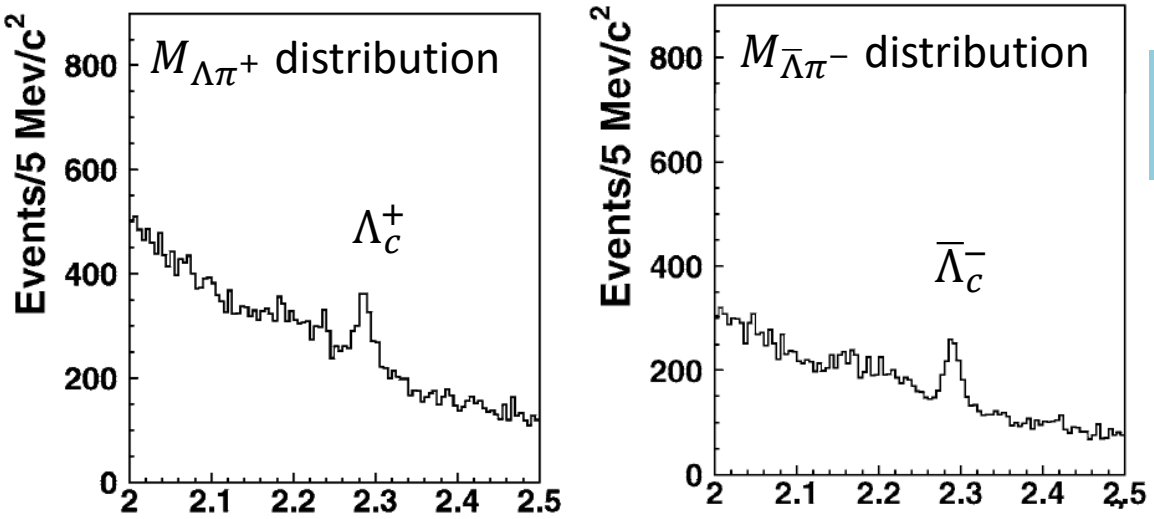


- decompose $\mathcal{P}_\Lambda$ into longitudinal and two transverse polarizations
- If Λ_c is unpolarized, then Λ with degree of polarization α

Previous measurements of Λ_c^+ asymmetry parameters (cont.)

- **FOCUS experiment: Phys.Lett.B634, 165 (2006)**
  - FOCUS, $\gamma^*\,(beam) + \mathrm{BeO}(target) \to \Lambda_c^+ + X$
  - Assume unpolarized Λ_c^+, Λ is polarized longitudinally with α_{Λ_c} degree
  - Polarimetry: $\Lambda \to p\pi^-$

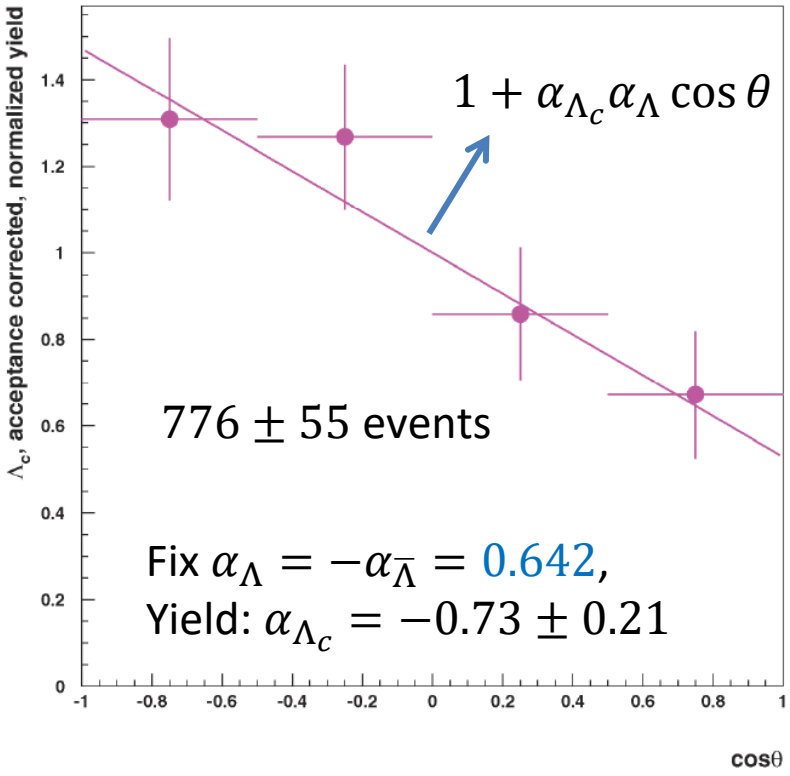
$$\frac{dW}{d\cos\theta} = \frac{1}{2}(1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\theta)\,,\ \theta\text{: proton helicity angle}$$



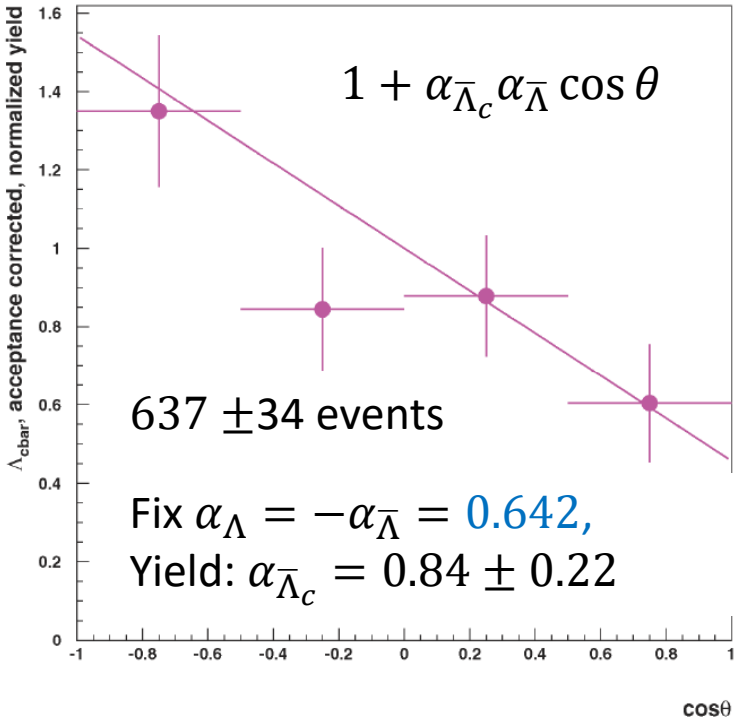
FOCUS:
Phys.Lett.B634, 165

Previous measurements of Λ_c^+ asymmetry parameters (cont.)

α_{Λ_c} : for $\Lambda_c^+ \to \Lambda\pi^+$



$\alpha_{\bar{\Lambda}_c}$: for $\bar{\Lambda}_c^- \to \bar{\Lambda}\pi^-$

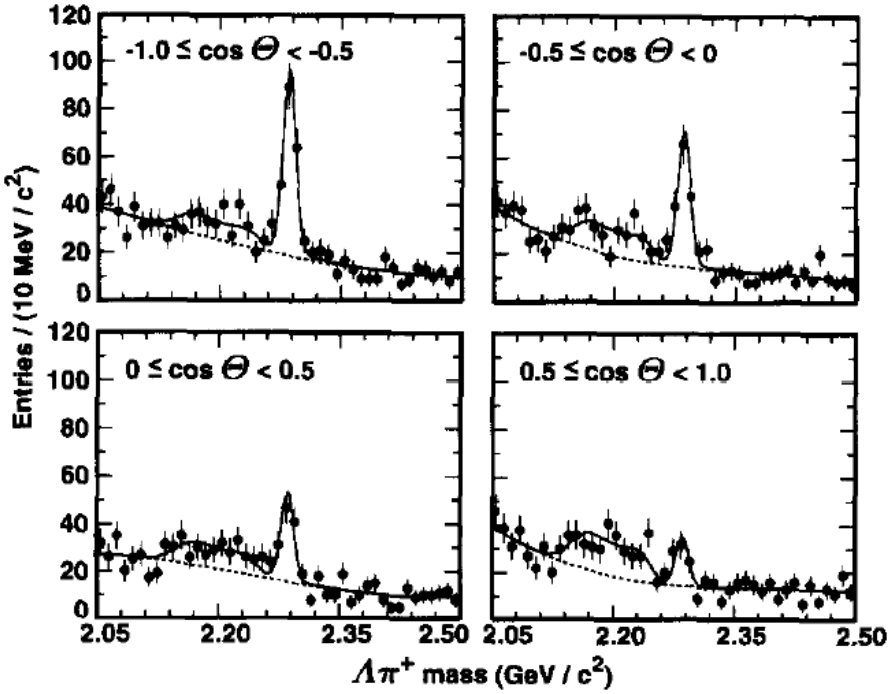


After bias correction: $\alpha_{\Lambda_c} = -0.78 \pm 0.16 \pm 0.19$, $\mathcal{A} = \frac{\alpha_{\Lambda_c} - \alpha_{\bar{\Lambda}_c}}{\alpha_{\Lambda_c} + \alpha_{\bar{\Lambda}_c}} = -0.07 \pm 0.16 \pm 0.19$

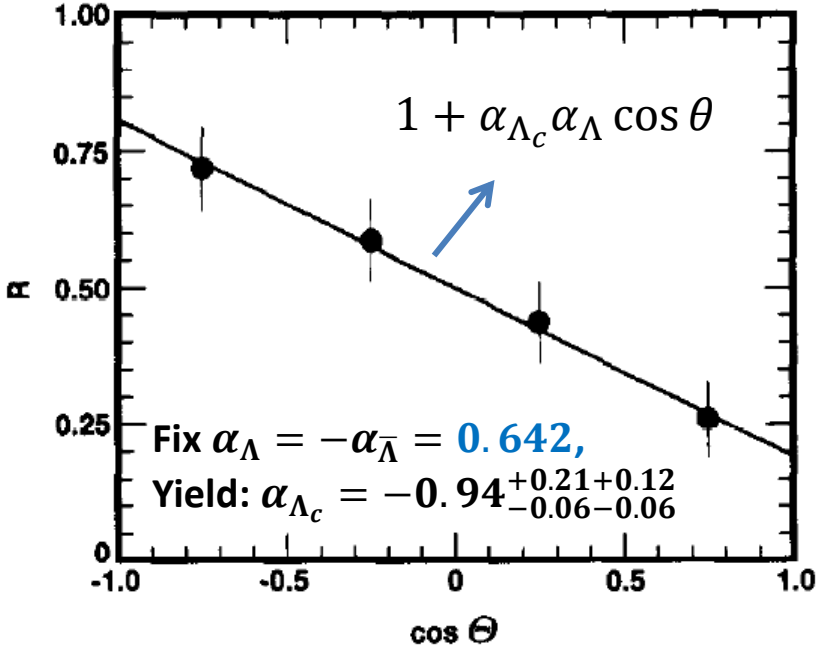
Previous measurements of Λ_c^+ asymmetry parameters (cont.)

- CLEO experiment: PLB, 350, 256(1995)
  - 1.9/fb, $e^+e^- \to c\bar{c}, \sqrt{s} \leq \Upsilon(4S)$

$\Lambda_c^+ \to \Lambda\pi^+$



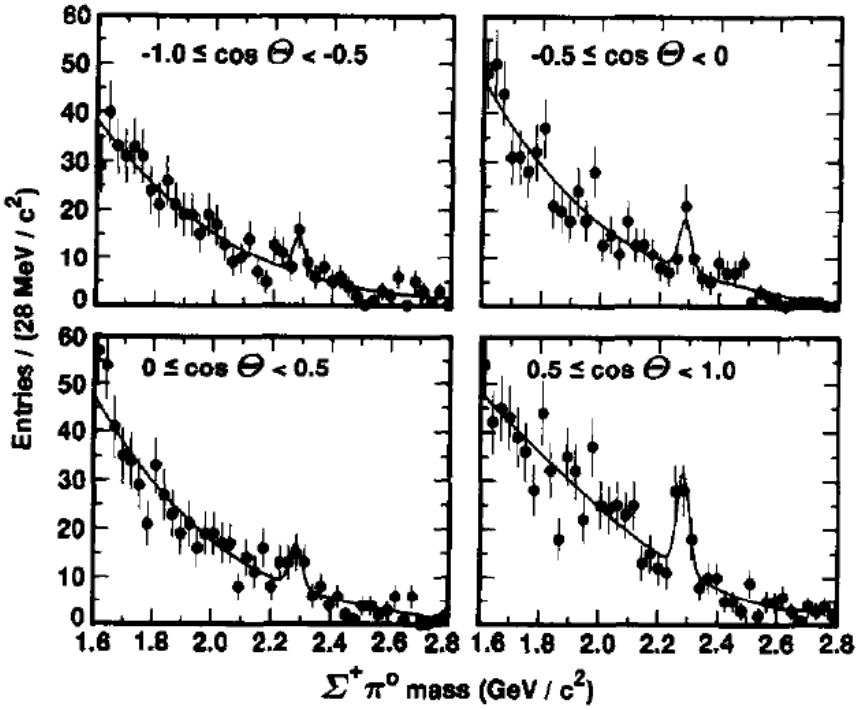
Efficiency corrected yield ratio



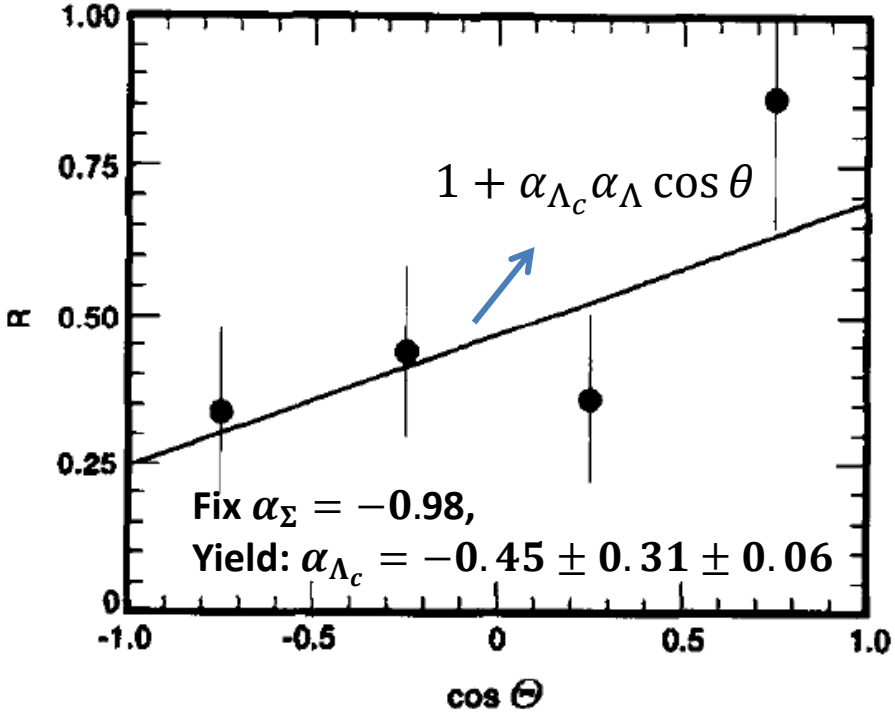
Previous measurements of Λ_c^+ asymmetry parameters (cont.)

- CLEO experiment: PLB, 350, 256(1995)

$\Lambda_c^+ \to \Sigma^+\pi^0, \Sigma^+ \to p\pi^0$



Efficiency corrected yield ratio



Previous measurements of Λ_c^+ asymmetry parameters (cont.)

- CLEO experiment: PLB, 350, 256(1995)

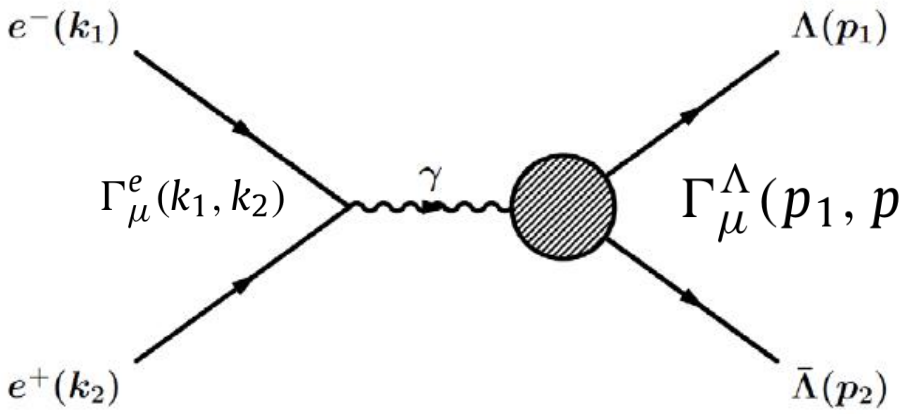
Comparison of experimental decay widths and asymmetries with model predictions

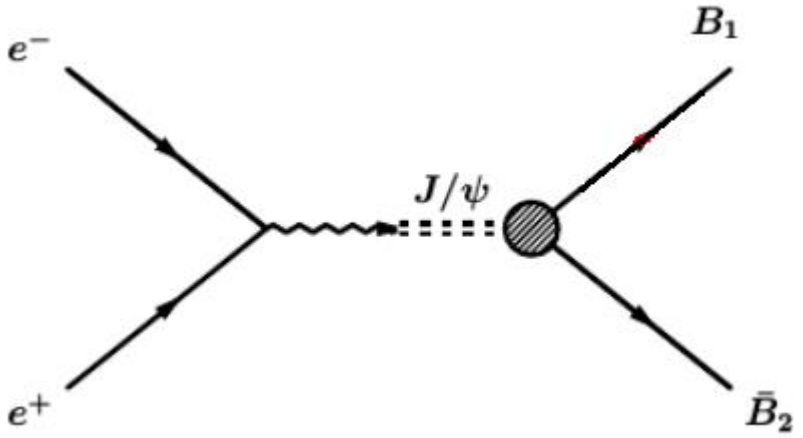
Reference	$\Lambda_c^+ \to \Lambda\pi^+$	$\Lambda_c^+ \to \Sigma^+\pi^0$
	α	α
CLEO	$-0.94^{+0.21+0.12}_{-0.06-0.06}$	$-0.45 \pm 0.31 \pm 0.06$
Xu and Kamal [10]	−0.67	0.91
Cheng and Tseng [11]	−0.96	0.83
Körner and Krämer [12]	−0.70	0.71
Uppal, Verma and Khanna [13]	−0.85	−0.32
Żenczykowski [14]	−0.86	−0.76

[10] Q.P. Xu and An. N. Kamal, Phys. Rev. D 46 (1992) 270.
[11] H. Cheng and B. Tseng, Phys. Rev. D 46 (1992) 1042.
[12] J.G. Körner and M. Krämer, Z. Phys. C 55 (1992) 659.
[13] T. Uppal, R.C. Verma and M.P. Khanna, Phys. Rev. D 49 (1994) 3417.
[14] P. Żenczykowski, Phys. Rev. D 50 (1994) 410.

Transverse polarization of baryons in e^+e^- collisions

FFs in continuum





Time likespin ½ baryon FFs:

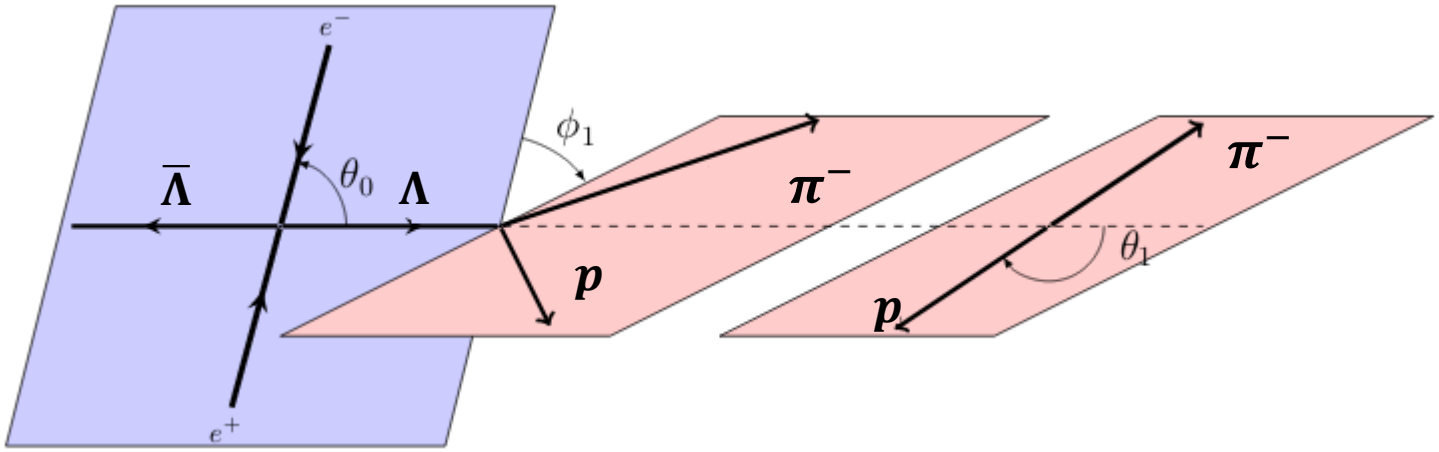
Dubnickova, Dubnicka, Rekalo
Nuovo Cim. A109 (1996) 241
Gakh, Tomasi-Gustafsson Nucl.Phys. A771 (2006) 169
Czyz, Grzelinska, Kuhn PRD75 (2007) 074026
FäldtEPJ A51 (2015) 74; EPJ A52 (2016)141
W. Lu, et.al., Phys.Lett., B368, 281 (1996)

$$\Gamma^e_\mu(k_1,k_2) = -ie_\psi\gamma_\mu$$

$$\Gamma^\Lambda_\mu(p_1,p_2) =$$

$$-ie_g\left[G^\psi_M\gamma_\mu - \frac{2M}{Q^2}(G^\psi_M - G^\psi_E)Q_\mu\right]$$

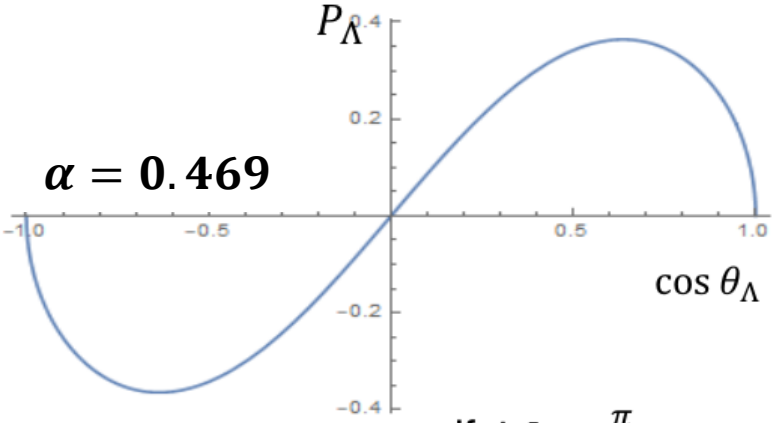
Transverse polarization of baryons in e^+e^- collisions



Unpolarized e^+e^- beam ➔ transverse polarization baryon

$$\mathcal{P}_T = \frac{\sqrt{1-\alpha^2}\sin\theta\cos\theta\sin\Delta}{1+\alpha\cos^2\theta}$$

$\mathcal{P}_T$ along $\boldsymbol{k}_{e^+} \times \boldsymbol{p}_{\mathrm{B}}$



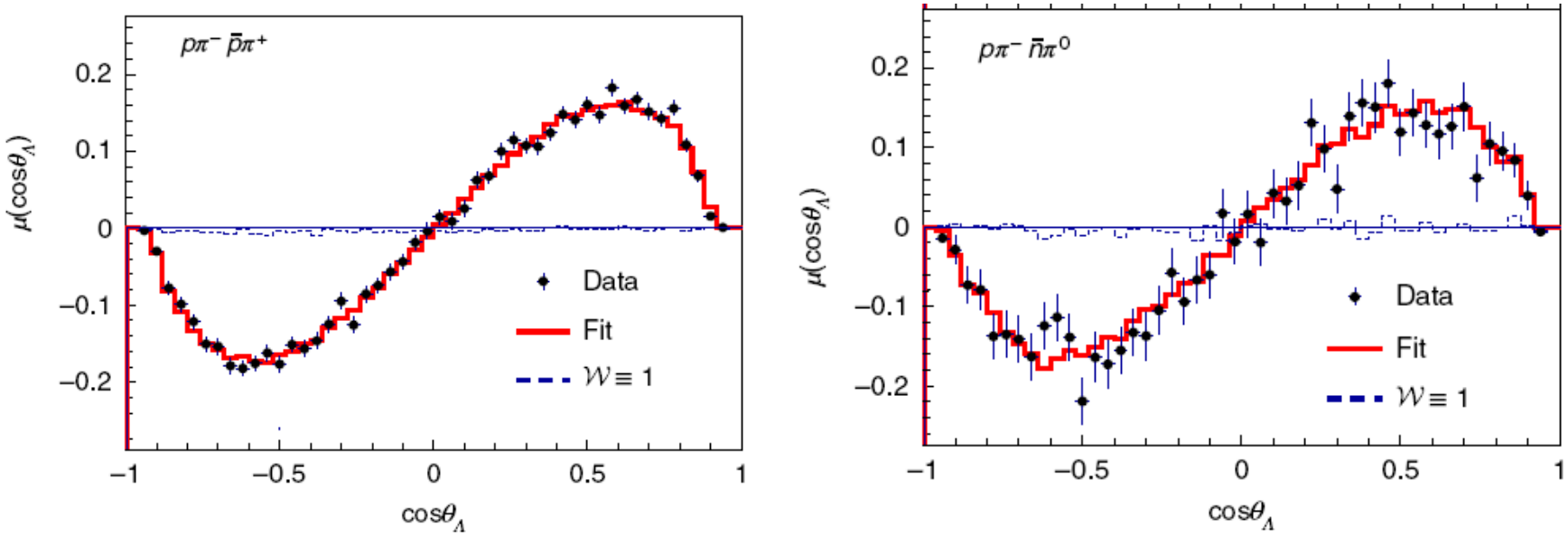
Max P_Λ= 36.4%

if $\Delta\Phi = \frac{\pi}{2}$

Transverse polarization of baryons in e^+e^- collisions

- Same formula applicable to $e^+e^- \to J/\psi \to B\bar{B}$

BESIII, arXiv: 1808.08917, Nature Physics (2009)



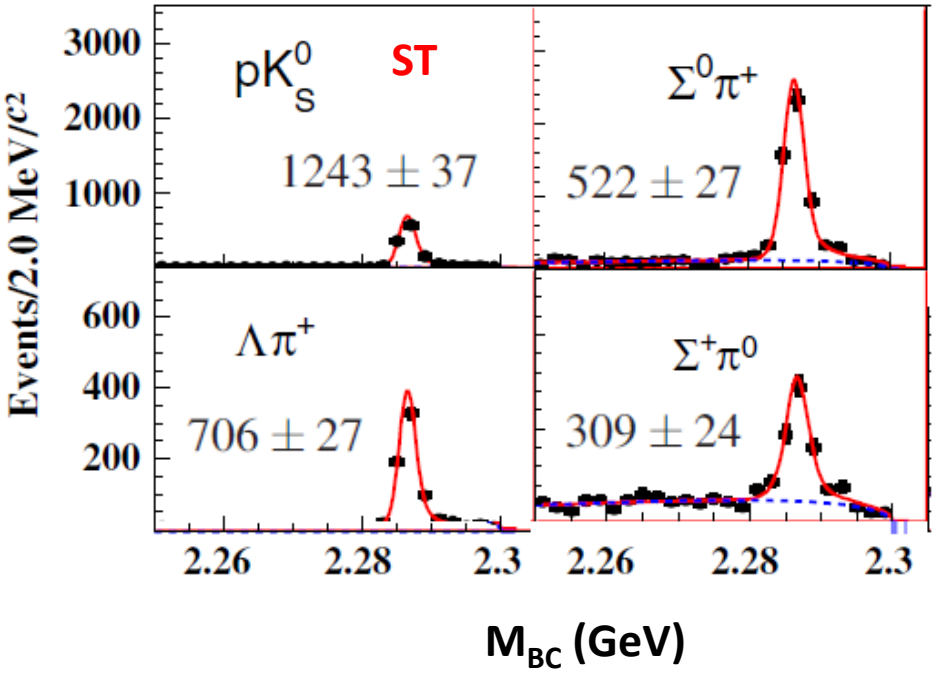
Polarimetry : $\Lambda \to p\pi^-, \quad \bar{\Lambda} \to \bar{p}\pi^+$

Spin observables: $\mu = \langle \sin\theta_1 \sin\phi_1 \rangle \propto \mathcal{P}_T$

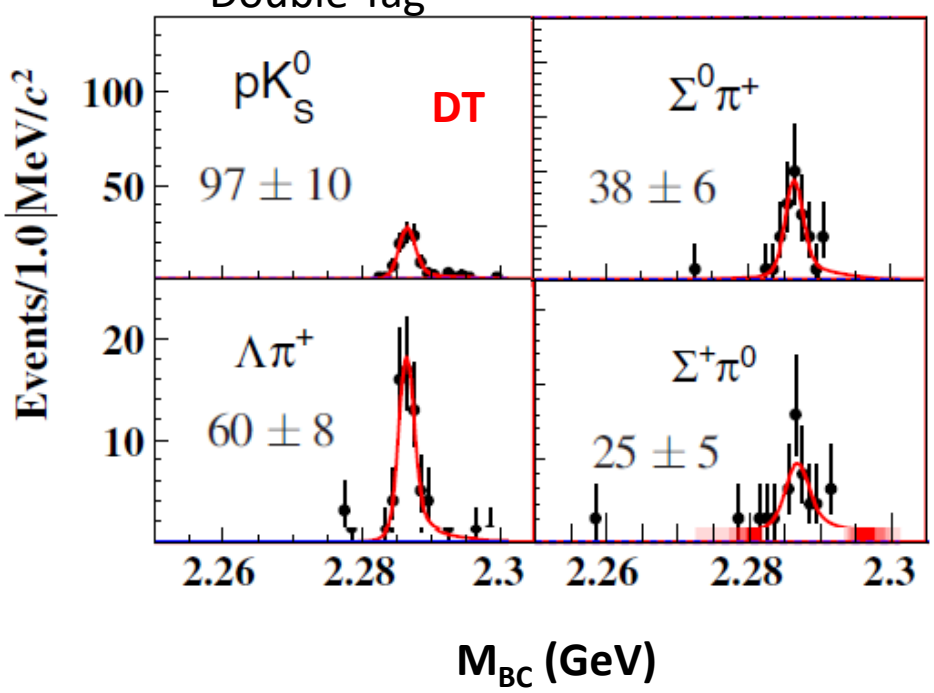
Transverse polarization: a probe to study Λ_c asymmetry parameters

- Prefer single tag to reconstruct Λ_c events

Single Tag



Double Tag

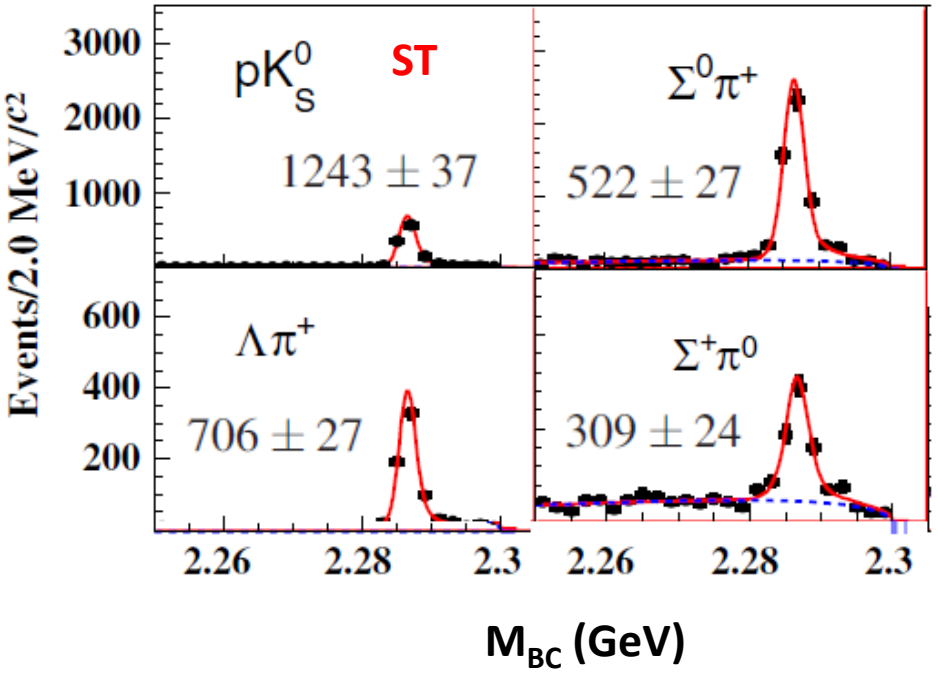


BESIII: PRL 116, 052001 (2016)

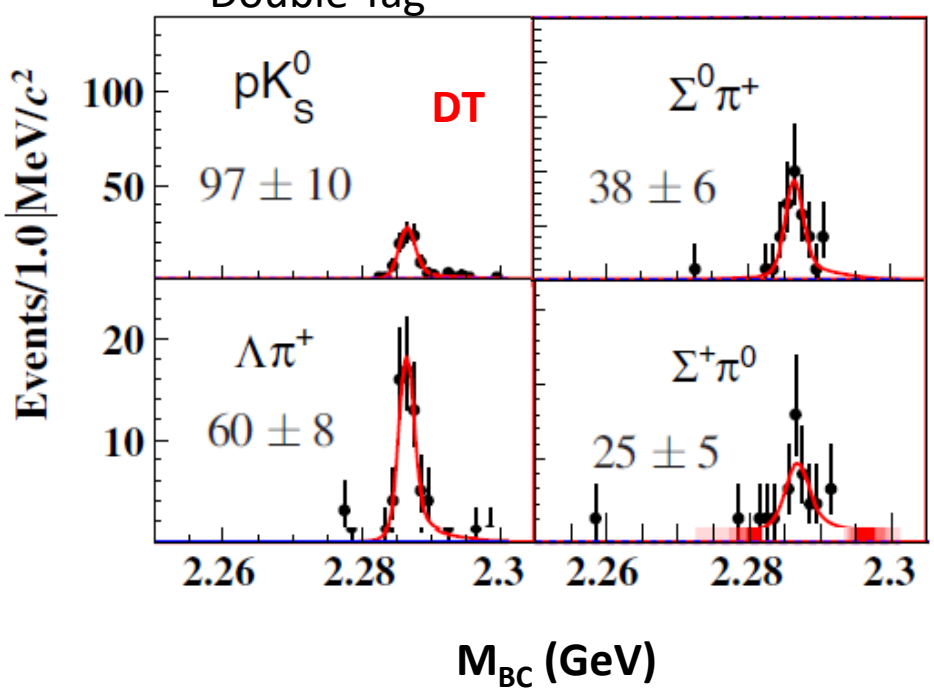
Transverse polarization: a probe to study Λ_c asymmetry parameters

- Prefer single tag to reconstruct Λ_c events

Single Tag



Double Tag

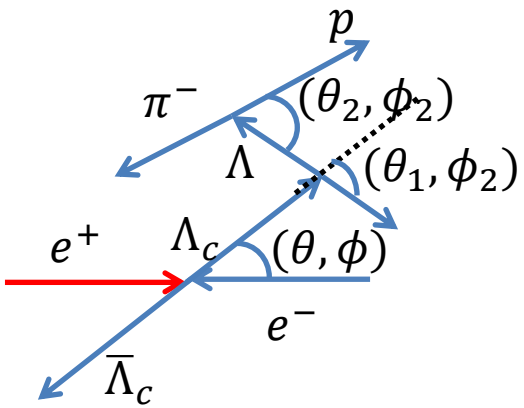


BESIII: PRL 116, 052001 (2016)

Transverse polarization: a probe to study Λ_c asymmetry parameters

- Transverse polarization play the same role as longitudinal polarization to do spin analysis

Example: $e^+e^- \to \gamma^* \to \Lambda_c^+\bar{\Lambda}_c^-$, $\quad \Lambda_c^+ \to \Lambda\pi^+$



Λ_c plays the role of polarimetry:

$$\mathcal{W}(\theta, \theta_1, \phi_1) \propto 1 + \alpha \cos^2\theta + (\sqrt{1-\alpha^2} \sin\theta \cos\theta \sin\Delta) \sin\theta_1 \sin\phi_1 \alpha_{\Lambda_c}$$

If take $\Lambda \to p\pi^-$ as polarimetry:

$$\mathcal{W}(\theta_2) \propto 1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\ \theta_2$$

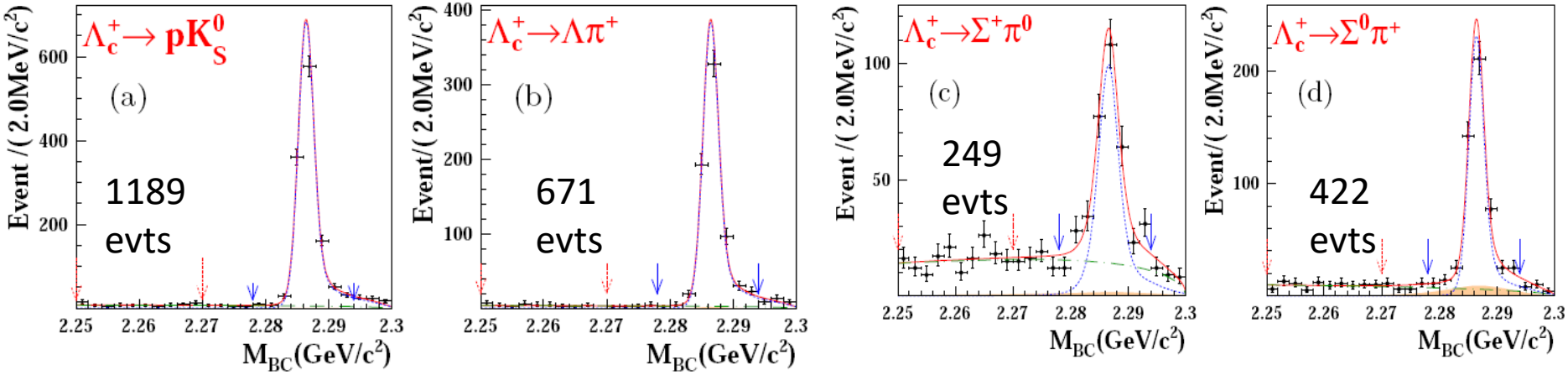
Strategy to measure Λ_c asymmetry parameters

- Prefer single tag method, e.g. $e^+e^- \to \Lambda_c^+ \overline{\Lambda}_c^-$, $\Lambda_c^+ \to B\left(\frac{1}{2}^+\right) P(0^-), \overline{\Lambda}_c^- \to$anything, and its conjugate mode
- Simultaneous fit to multiple Λ_c decay modes, e.g. $\Lambda_c^+ \to \Lambda\pi^+, \Sigma^+\pi^0, \Sigma^0\pi^+, pK_S^0$
- Formula involved Λ_c transverse polarization, and assume CP conservation, and spin-1/2 for Λ_c.
- Physics outcome: α, Δ, $\alpha_{\Lambda_c}(\Lambda_c^+ \to \Lambda\pi^+)$, $\alpha_{\Lambda_c}(\Lambda_c^+ \to \Sigma^0\,\pi^+)$, $\alpha_{\Lambda_c}(\Lambda_c^+ \to \Sigma^+\pi^0)$, $\alpha_{\Lambda_c}(\Lambda_c^+ \to pK_S^0)$

Decay asymmetry parameters @BESIII

- $\mathcal{L} = 567\ \mathrm{pb}^{-1}$ at $\sqrt{s} = 4.6\ \mathrm{GeV}$
- **Simultaneously fit to 4 decay modes, with $\bar{\Lambda}_c^-$ decays incorporated.**
- 2.1σ Λ_c^+ **transverse polarization.**

BESIII, arXiv:1905.04707



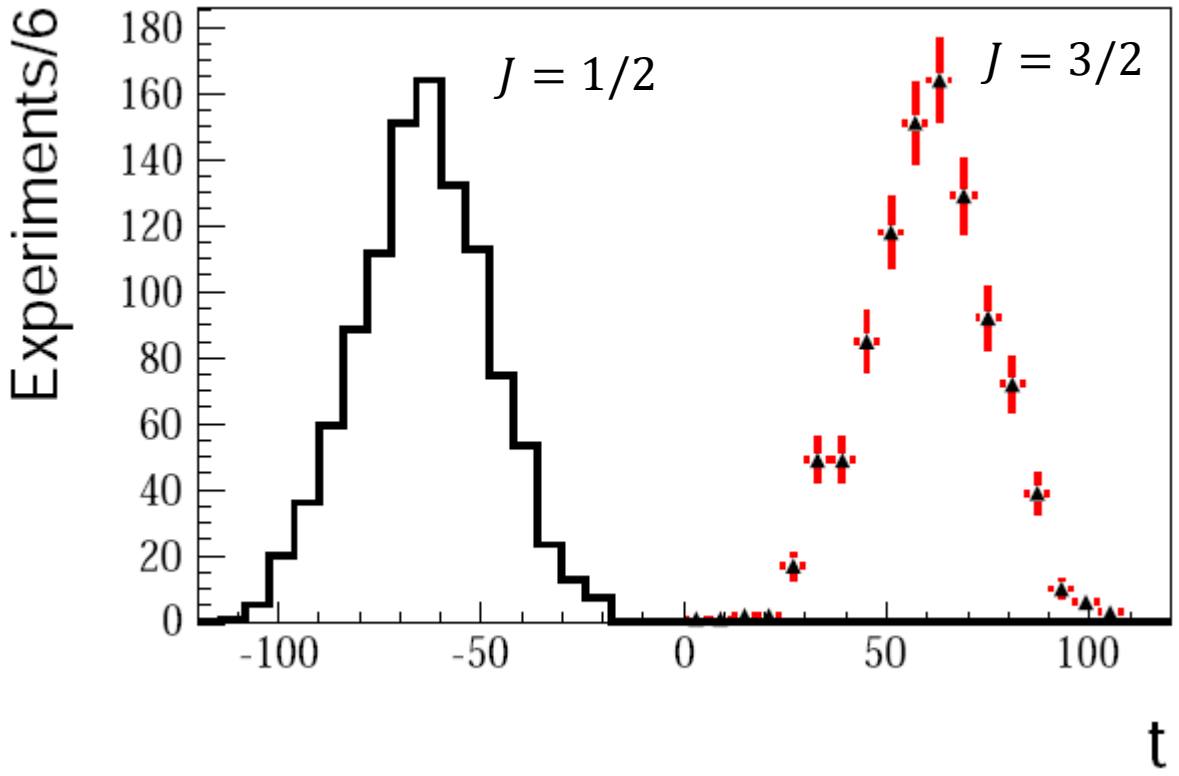
Parameters	$\Lambda_c^+ \to pK_S^0$	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
α_{BP}^+	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$
α_{BP}^+ (PDG)	...	-0.91 ± 0.15	-0.45 ± 0.32	...
β_{BP}	...	$0.06^{+0.58+0.05}_{-0.47-0.06}$	$-0.66^{+0.46+0.22}_{-0.25-0.02}$	$0.48^{+0.35+0.07}_{-0.57-0.13}$
γ_{BP}	...	$-0.60^{+0.96+0.17}_{-0.05-0.03}$	$-0.48^{+0.45+0.21}_{-0.42-0.04}$	$0.49^{+0.35+0.07}_{-0.56-0.12}$
Δ_1^{BP}(rad)	...	$3.0 \pm 2.4 \pm 1.0$	$4.1 \pm 1.1 \pm 0.6$	$0.8 \pm 1.2 \pm 0.2$

Issues to distinguish between spin $J = 1/2$ and $J = 3/2$ for Λ_c

- For simplicity, we use decays $\Lambda_c \to B\left(\frac{1}{2}^+\right) M(0^-)$ to study Λ_c-spin
- Equivalent to measure spin density matrix of Λ_c, spin-3/2 case introduces more parameters. It's difficult to distinguish these two case in angular distribution if $J = 1/2$.
- Likelihood test applicable to do significance test.
- Intend to do simultaneous fit to $\Lambda_c(\overline{\Lambda}_c)$ decays to the baryon and meson.

Likelihood test for spin $J = 1/2$ and $J = 3/2$ for Λ_c

- Example of ToyMC study



$$t = -2Ln[\mathcal{L}^{J=3/2}/\mathcal{L}^{J=1/2}]$$

Summary and outlook

- Transverse polarization offers us a unique tool to study the Λ_c asymmetry parameters.
- With the accumulated 567/pb data at 4.6 GeV at BESIII, analysis result of Λ_c spin will come soon.
- BESIII will taken a large date set for study Λ_c properties.

Thanks for your attention!