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

BESIII

Study of Hyperon polaization at BESIII

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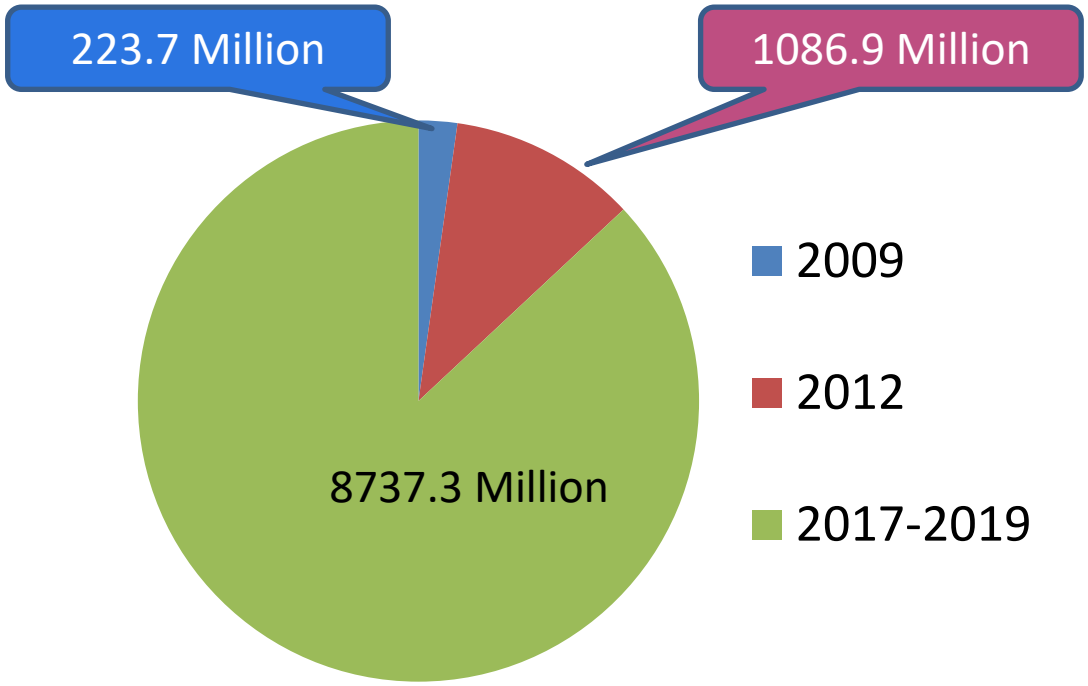
BINP-IHEP seminar, 16-18 December 2019, Budker INP:
"Tau and QCD physics at present and future electron-positron colliders"

BESIII $J/\psi, \psi'$ data sets



The analysis based on 2009+2012 J/ψ data:

~1.31 billion decays

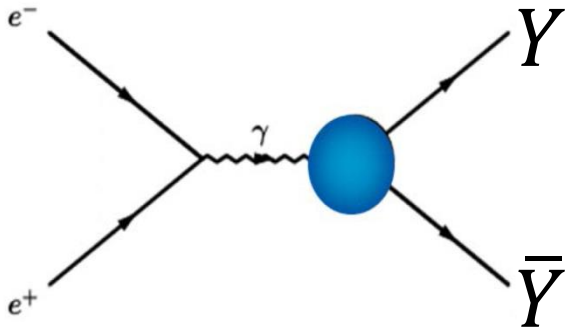
J/ψ : Total 10.047 billion J/ψ decays

ψ': 448 million decays

Continuum: 12/fb ($\sqrt{s} > 3.8$ GeV)

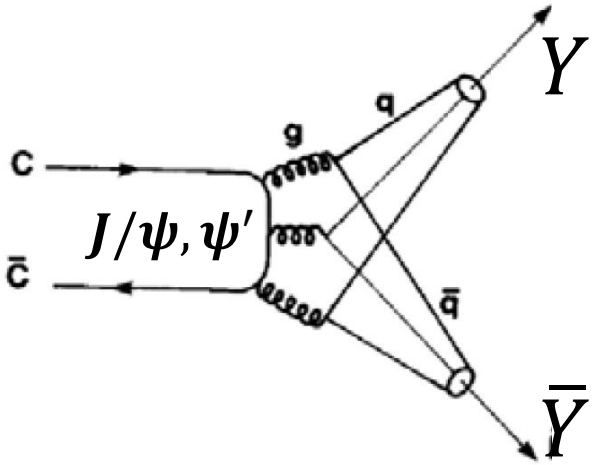
Hyperon pair production at BESIII

- $e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}, \Lambda_c^+\bar{\Lambda}_c^-, \quad @\ \sqrt{s} = 2.0 \sim 4.6\ \mathrm{GeV}$, or update for $\Lambda_c^+\bar{\Sigma}_c^-,\ \Sigma_c\bar{\Sigma}_c$



- Threshold enhancement
- Form factor
- Excited hyperon
- .....

- $J/\psi, \psi' \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}$

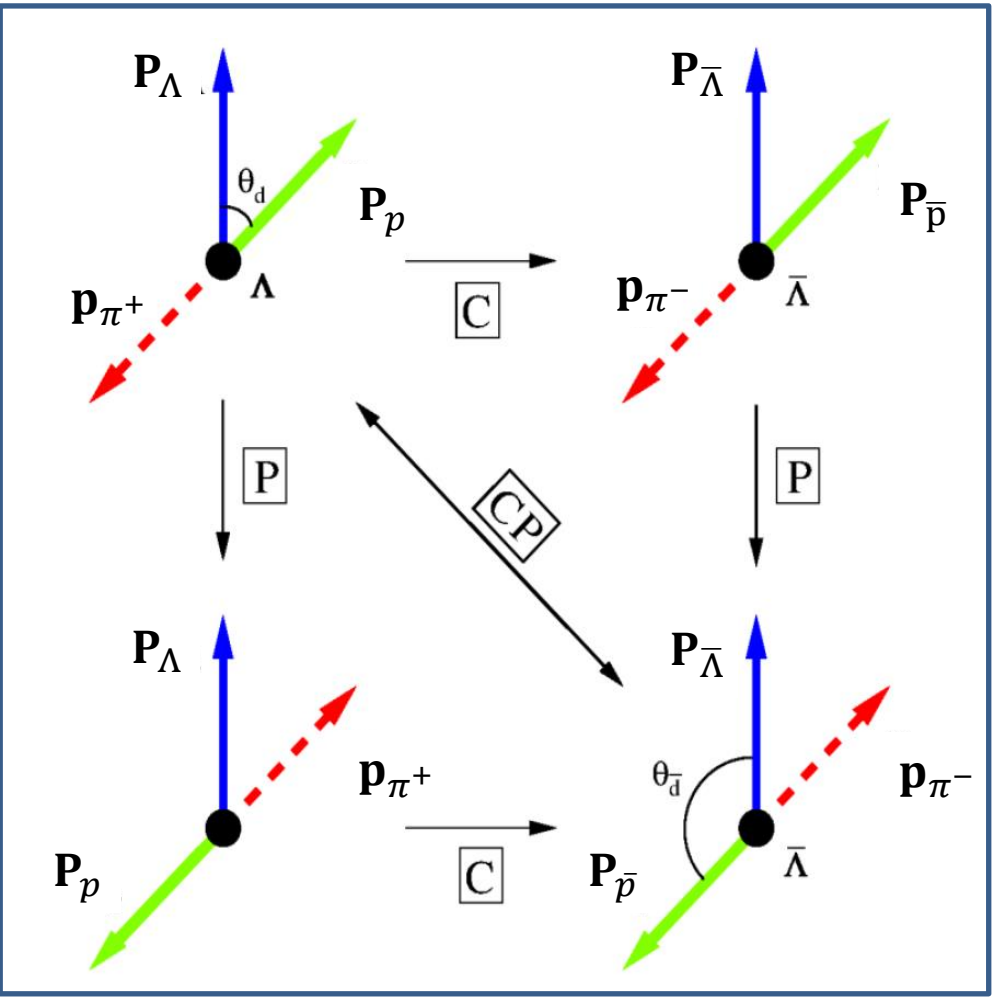


10 billion J/ψ:

16.1×10^6	$\Lambda\bar{\Lambda}$
12.0×10^6	$\Xi^0\bar{\Xi}^0$
12.9×10^6	$\Sigma^0\bar{\Sigma}^0$
8.6×10^6	$\Xi^-\bar{\Xi}^+$

- **Hyperon polarization**
- CP test
- Semileptonic decay
- Radiative decay
- Rare decay

C,P- transformation in $\Lambda \to p\pi^-$



$$\alpha = \frac{|B_+|^2 - |B_-|^2}{|B_+|^2 + |B_-|^2},$$

$$\bar\alpha = \frac{|\bar B_+|^2 - |\bar B_-|^2}{|\bar B_+|^2 + |\bar B_-|^2}$$

CP invariance :

$$\bar B_{-\lambda_p} = \eta_\Lambda \eta_p \eta_\pi (-1)^{s_\Lambda - s_p - s_\pi} B_{\lambda_p}$$

$$= -B_{\lambda_p}$$

$$\alpha = -\bar\alpha$$

CP odd-variable:

$$\Delta = \frac{\Gamma - \bar\Gamma}{\Gamma + \bar\Gamma}, A = \frac{\alpha + \bar\alpha}{\alpha - \bar\alpha}, B = \frac{\beta + \bar\beta}{\beta - \bar\beta}, B' = \frac{\beta + \bar\beta}{\alpha - \bar\alpha}$$

Ancient history

Phys. Rev. Lett. 24, 843 (1970)

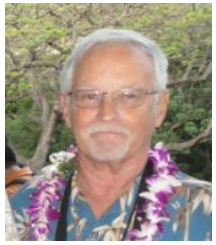
ASYMMETRY PARAMETER FOR $\Lambda^0 \to n\pi^0$ †*

S. Olsen, L. Pondrom, R. Handler, and P. Limon‡
University of Wisconsin, Madison, Wisconsin 53706

and

J. A. Smith and O. E. Overseth
University of Michigan, Ann Arbor, Michigan 48104
(Received 18 February 1970)

The asymmetry parameter α_0 for $\Lambda^0 \to n\pi^0$ has been measured relative to α_- by comparing the neutron distribution with the proton distribution from the decay $\Lambda^0 \to p\pi^-$ for polarized Λ^0 hyperons. A sample of 4760 neutron decay events and 8500 proton decay events gave $\alpha_0/\alpha_- = 1.000 \pm 0.068$ in good agreement with the $|\Delta\vec{I}| = \frac{1}{2}$ rule.



Phys. Rev. Lett. 24, 165 (1970)

PROTON POLARIZATION IN $\Sigma^+ \to p\pi^0$ †*

F. Harris and O. E. Overseth
University of Michigan, Ann Arbor, Michigan 48104

and

L. Pondrom and E. Dettmann
University of Wisconsin, Madison, Wisconsin 53706
(Received 10 November 1969)

The polarization of protons from the decay of polarized Σ^+ hyperons has been measured by scattering the protons in a carbon-plate spark chamber. A sample of 1335 useful scatters gave $\alpha_0 = -0.98 \pm 0.05$ and $\varphi_0 = 22° \pm 90°$, where $\tan\varphi_0 = \beta_0/\gamma_0$. Using the data on $\Sigma^+ \to n\pi^+$ and $\Sigma^- \to n\pi^-$ and fitting to the $|\Delta\vec{I}| = \frac{1}{2}$ rule gave $\chi^2 = 0.3$ for 2 degrees of freedom.

Phys. Rev. 184, 1663 (1969)

Final-State Interactions in Nonleptonic Hyperon Decay

O. E. Overseth*
The University of Michigan, Ann Arbor, Michigan 48104

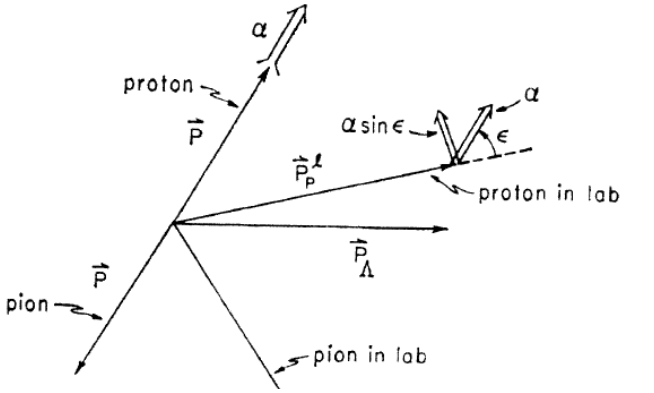
AND

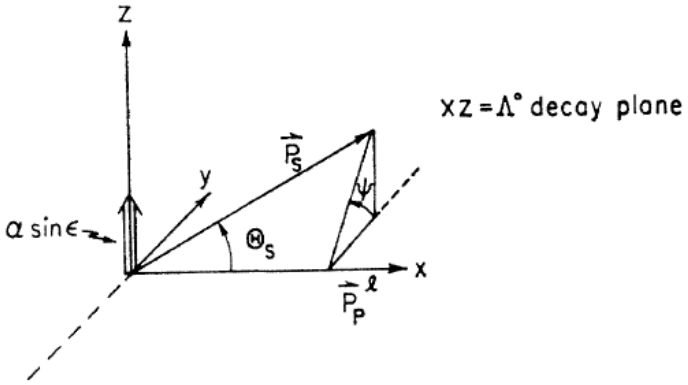
S. Pakvasa†
University of Hawaii, Honolulu, Hawaii 96822
(Received 1 April 1969)

We discuss the consequences of including the final-state interactions in the analysis of $\Lambda°$, Σ, and Ξ nonleptonic decays. Emphasis is on the role that the final-state interactions play in tests for T invariance, in tests of the $\Delta I = \frac{1}{2}$ rule (including the resolution of sign ambiguities), and in the determination of the decay amplitudes for these processes.

Most earlier measurement on α_-

- CNTR exp., $\pi^- + p \to \Lambda + K^0$
- Unpolarized $\Lambda \to p\pi^-$
- Proton polarization measured with carbon-plate spark chamber





$$W(\psi) = 1 + \alpha\, S \sin\epsilon \cos\psi$$

Phys.Rev. 129 (1963) 1795-1807

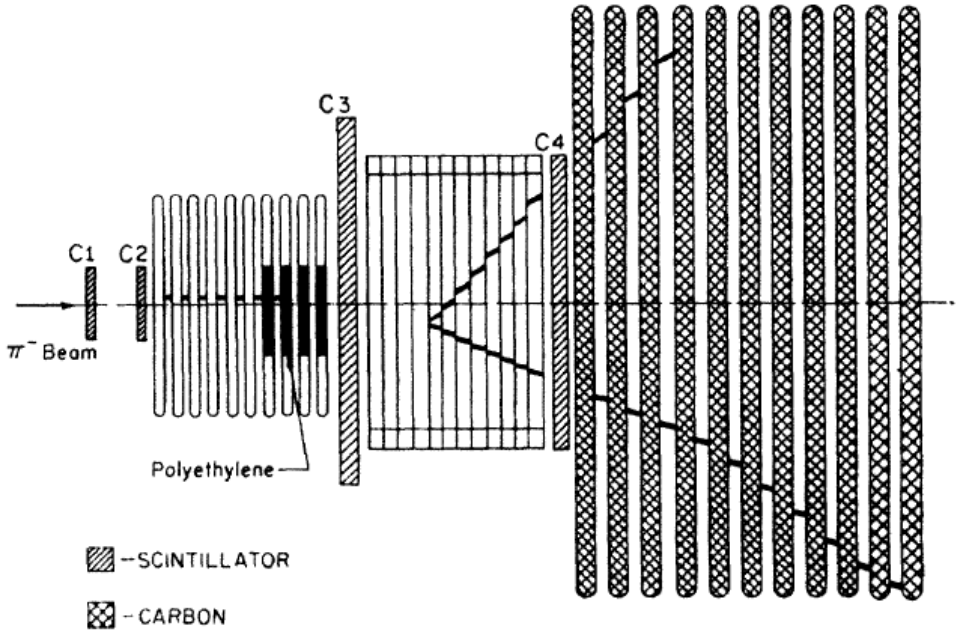


FIG. 1. Schematic diagram showing arrangement of apparatus. An example of an event has been sketched in.

$$\alpha = -\frac{2}{\pi}\,\frac{1}{\langle S\rangle\langle\sin\epsilon\rangle}\,\frac{N_+ - N_-}{N_+ + N_-},$$

1156 events

$\langle S\rangle = 0.565$

$\langle \sin\epsilon\rangle = 0.84,$

$\alpha = 0.62.$

Role of polarization physics

- Probing of spin degree freedom

  Test the dynamic of SM and low energy hadron interaction

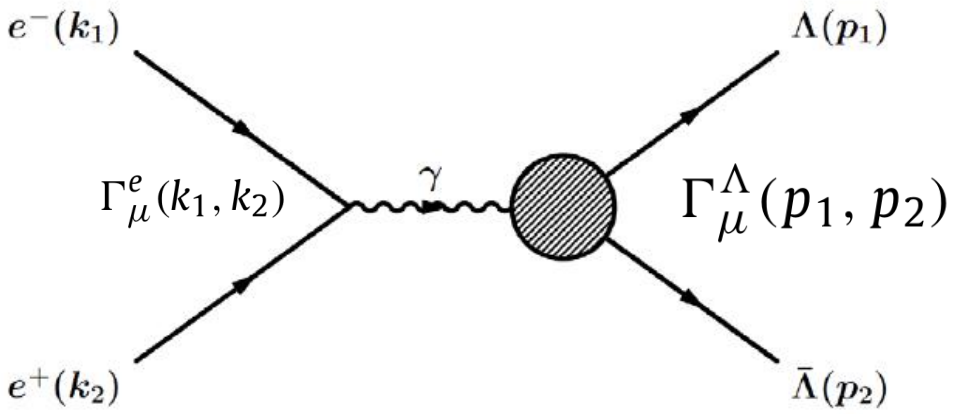
  Existant exp. : RHIC, Jlab, GRAAL, CERN and DESY
  Spin observable, spin-dependent structure function and parton distribution
  Spin crisis at eighties

- BEPCII/BESIII, unpolarized beam, inaccessible polarization of final state by BESIII

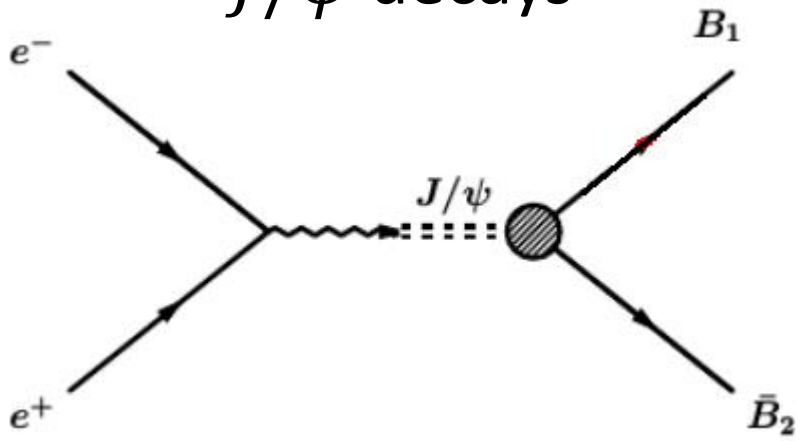
  - Polarized beam for post-BEPCII options, CPV in tau decay, Hyperon weak decay,……
  - Useful tool: transverse polarization of hyperon, spontaneous production at e^+e^- collision
  - $\Lambda \to p\pi^-$ decay plays important role in particle physics

Transverse polarization (TP) of baryons in e^+e^- collisions

FFs in continuum



J/ψ decays



Time likespin ½ baryon FFs:

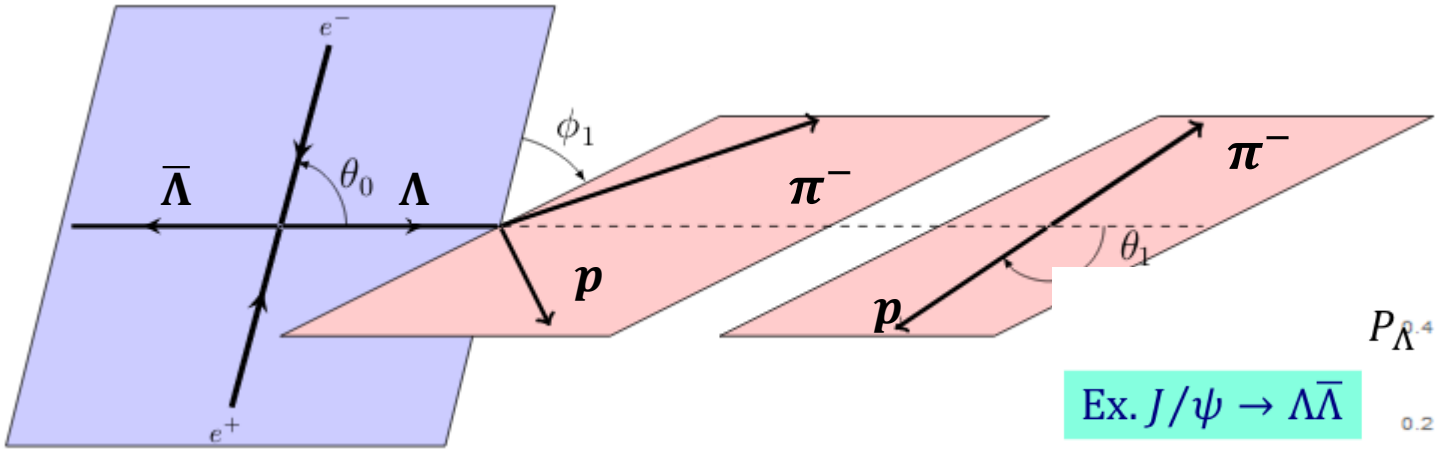
Dubnickova, Dubnicka, Rekalo
Nuovo Cim. A109 (1996) 241
W. Lu, et.al., Phys.Lett., B368, 261 (1996)
Gakh, Tomasi-Gustafsson Nucl.Phys. A771 (2006) 169
Czyz, Grzelinska, Kuhn PRD75 (2007) 074026
FäldtEPJ A51 (2015) 74; EPJ A52 (2016)141
Fäldt, G. & Kupsc, A, Phys. Lett. B 772 (2017) 16

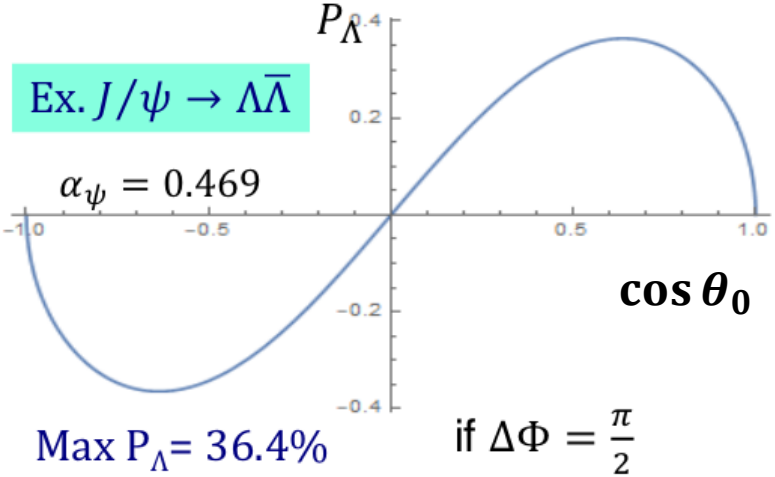
$$\Gamma^e_\mu(k_1,k_2) = -ie_\psi\gamma_\mu$$

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

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

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





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

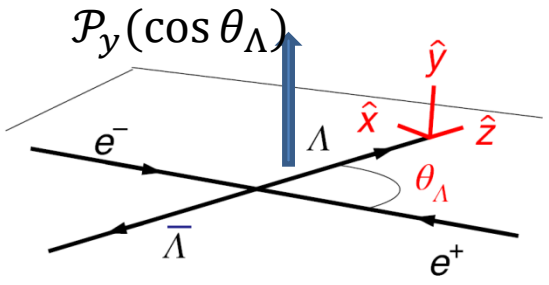
$$P_Y = \frac{\sqrt{1-\alpha_\psi^2}\cos\theta_0 \ \sin\theta_0}{1+\alpha_\psi\cos^2\theta_0}\sin(\Delta\Phi)$$

P_Y along $\boldsymbol{k}_{e^+} \times \boldsymbol{p}_\Lambda$

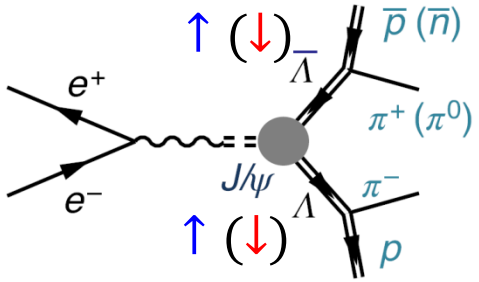
Observation of Λ polarization and entanglement in $J/\psi \to \Lambda\bar{\Lambda}$

Highlights!

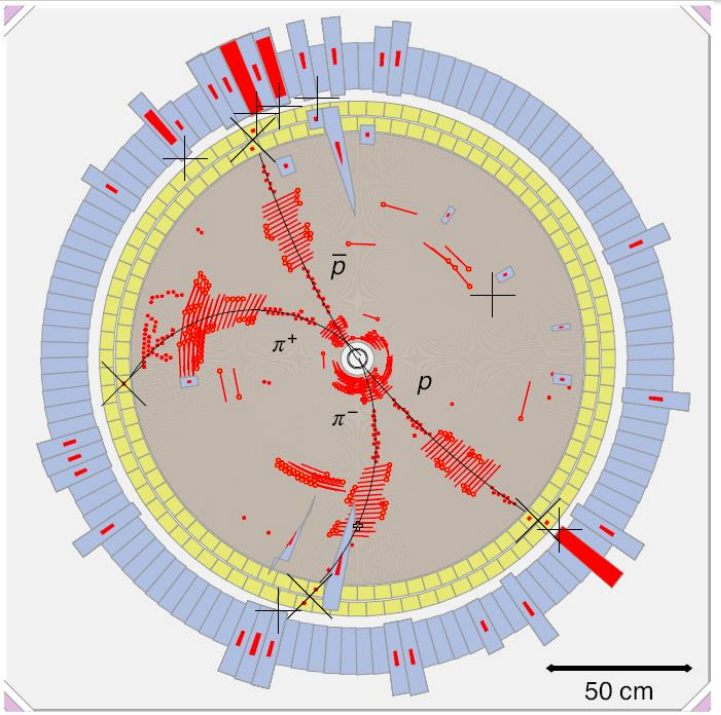
Published in Nature Physics, 15, 631 (2019)



Helicity system



Spin entanglement



Event display in BESIII detector

- Joint angular distribution

$$\mathcal{W}(\xi;\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+)$$
$$=1+\alpha_\psi\cos^2\theta_\Lambda+\alpha_-\alpha_+[\sin^2\theta_\Lambda(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y})$$
$$+(\cos^2\theta_\Lambda+\alpha_\psi)n_{1,z}n_{2,z}]$$

Entanglement term

$$+\alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda(n_{1,x}n_{2,z}+n_{1,z}n_{2,x})$$
$$+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda(\alpha_-n_{1,y}+\alpha_+n_{2,y})$$

Transverse polarization

- Transverse polarization

$$P_y(\cos\theta_\Lambda)=\frac{\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$

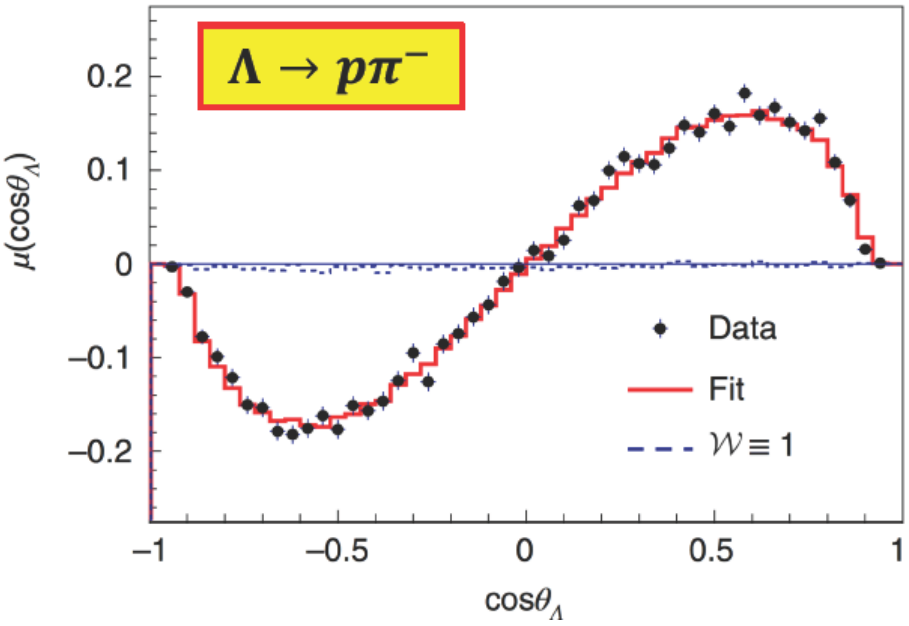
Observation of Λ polarization and entanglement in $J/\psi \to \Lambda\bar{\Lambda}$

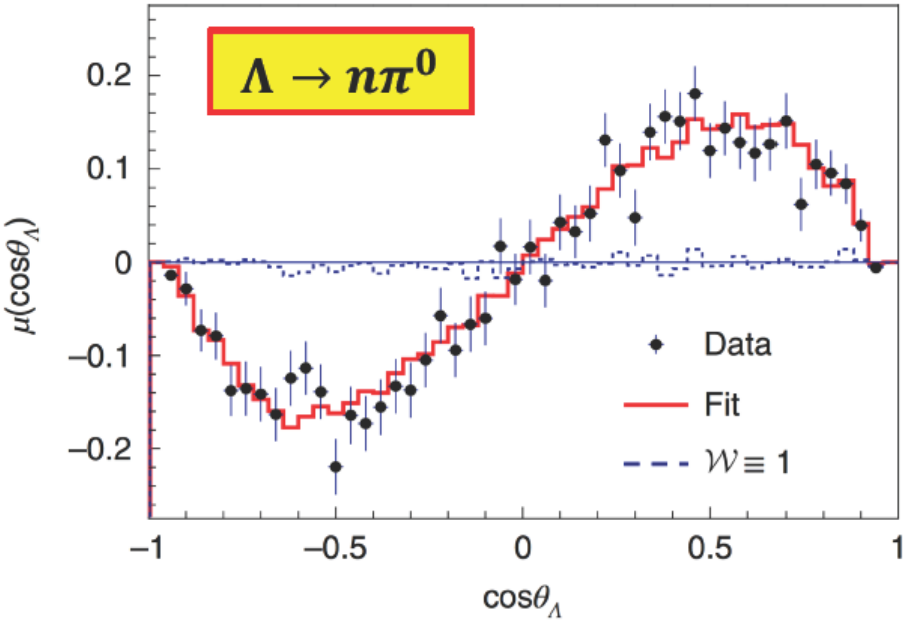
Highlights!

Published in Nature Physics, 15, 631 (2019)

J/ψ data sample: 1.31×10^9

- Observation of Λ /$\bar{\Lambda}$ transverse polarization





- spin observable

$$\mu(\cos\theta_\Lambda) = \frac{m}{N} \sum_{i=1}^{N_k} (n_{1,y}^{(i)} - n_{2,y}^{(i)})$$

- Maximum Λ / $\bar{\Lambda}$ polarization: ~25%
- Net polarization vanishing

Observation of Λ polarization and entanglement in $J/\psi \to \Lambda\bar{\Lambda}$

Highlights!

Published in Nature Physics, 15, 631 (2019)

J/ψ data sample: 1.31×10^9

First observation of the Λ /$\bar{\Lambda}$ transverse polarization

Higher than PDG value 17%, deviation with sig.> 5σ

CP odd observable: $A_{CP} = \frac{\alpha_\Lambda - \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}}$

Test selection rule $\Delta I = \frac{1}{2}$

Table 1 | Summary of the results

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 (ref. [14])
$\Delta\Phi$	$42.4 \pm 0.6 \pm 0.5°$	-
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 (ref. [6])
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 (ref. [6])
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	-
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 (ref. [6])
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	-

- **Verification $\alpha_\Lambda/\alpha_{\bar{\Lambda}}$: $J/\psi \to \Xi^-\bar{\Xi}^+ \to (\Lambda\pi^-)(\bar{\Lambda}\pi^+)$**
- **Transverse polarization allows to improve CP test precision over previous measurements.**
- **Standard model precision $A_{CP} \sim 10^{-4}$.**

Observation of Λ polarization and entanglement in $J/\psi \to \Lambda\bar{\Lambda}$

α_- FOR $\Lambda \to p\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$0.750 \pm 0.009 \pm 0.004$	420k	ABLIKIM	2018AG	BES3	J/ψ to $\Lambda\bar{\Lambda}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.584 ± 0.046	8500	ASTBURY	1975	SPEC	
0.649 ± 0.023	10325	CLELAND	1972	OSPK	
0.67 ± 0.06	3520	DAUBER	1969	HBC	From Ξ decay
0.645 ± 0.017	10130	OVERSETH	1967	OSPK	Λ from $\pi^- p$
0.62 ± 0.07	1156	CRONIN	1963	CNTR	Λ from $\pi^- p$

α_+ FOR $\bar{\Lambda} \to \bar{p}\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.758 \pm 0.010 \pm 0.007$	420k	ABLIKIM	2018AG	BES3	J/ψ to $\Lambda\bar{\Lambda}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-0.755 \pm 0.083 \pm 0.063$	$\approx$ 8.7k	ABLIKIM	2010	BES	$J/\psi \to \Lambda\bar{\Lambda}$
-0.63 ± 0.13	770	TIXIER	1988	DM2	$J/\psi \to \Lambda\bar{\Lambda}$

Where does the TP come from?

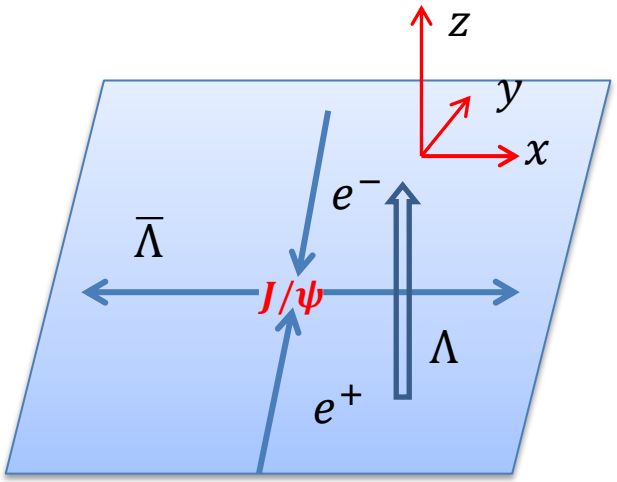
- **From the e^+/e^- beam ?**
  - ✘ No, BEPC beams unpolarized
- **From the e^+/e^- natural polarization when circulating in the BEPCII storage ring ?**
  - ✘ Sokolov-Ternov effects: 4.3 hrs @ψ' peak, but beam lifetime ~ 2.0 hrs
- **From the J/ψ spin transfer ?**
  - ✓ Yes, it does from the J/ψ tensor polarization

J/ψ polarization: $\mathcal{P}_z = 0,\ T_{zz} = \frac{1}{\sqrt{6}}$

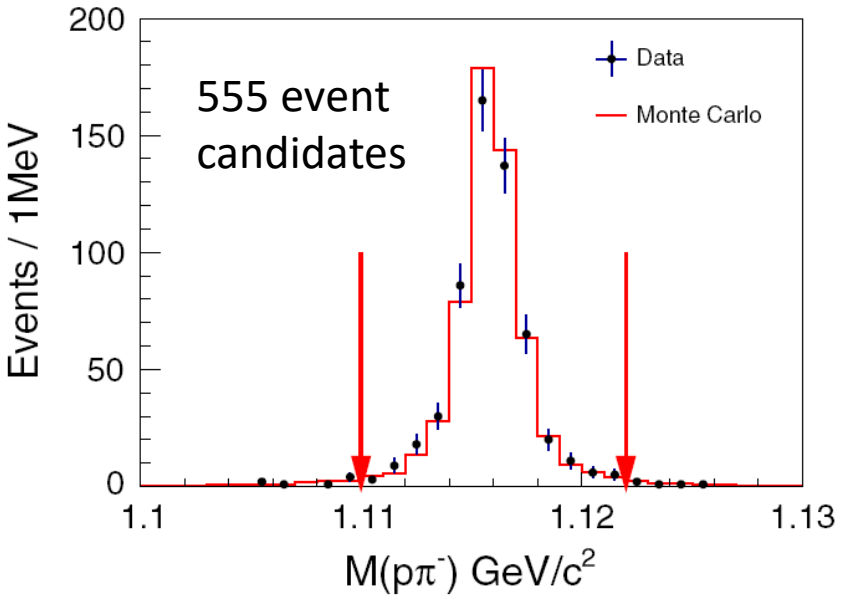
Λ transverse polarization:

$$\mathcal{P}_y = \sqrt{6}\frac{T_{zz}\sin\theta\cos\theta\sin\Delta\sqrt{1-\alpha_\psi^2}}{1+\alpha_\psi\left[\frac{1}{3}+\frac{1}{\sqrt{6}}T_{zz}(1+3\cos 2\theta)\right]}$$

$\mathcal{P}_y$ manifest if $\sin\Delta \neq 0$



Λ / $\bar{\Lambda}$ polarization in continuum production

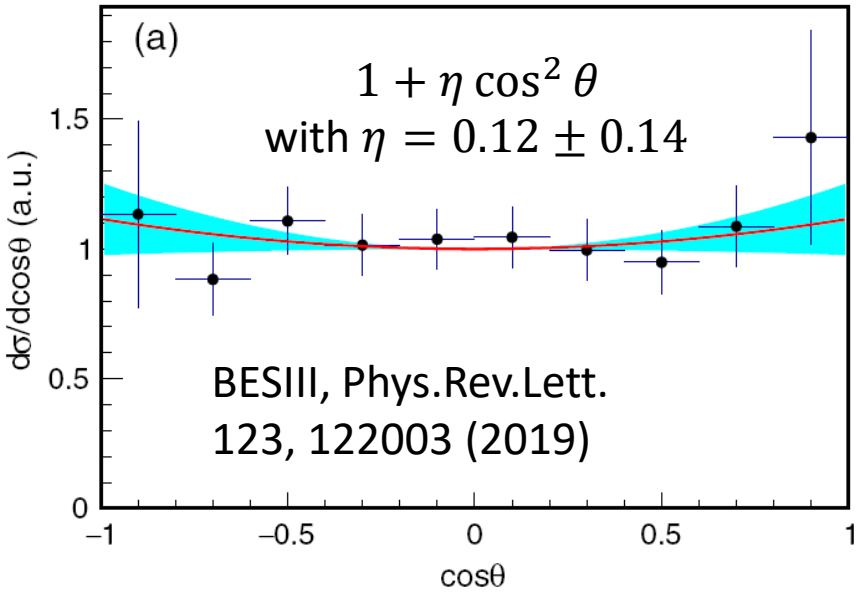


- data set: 2.396 GeV, L=66.9 pb^{-1}

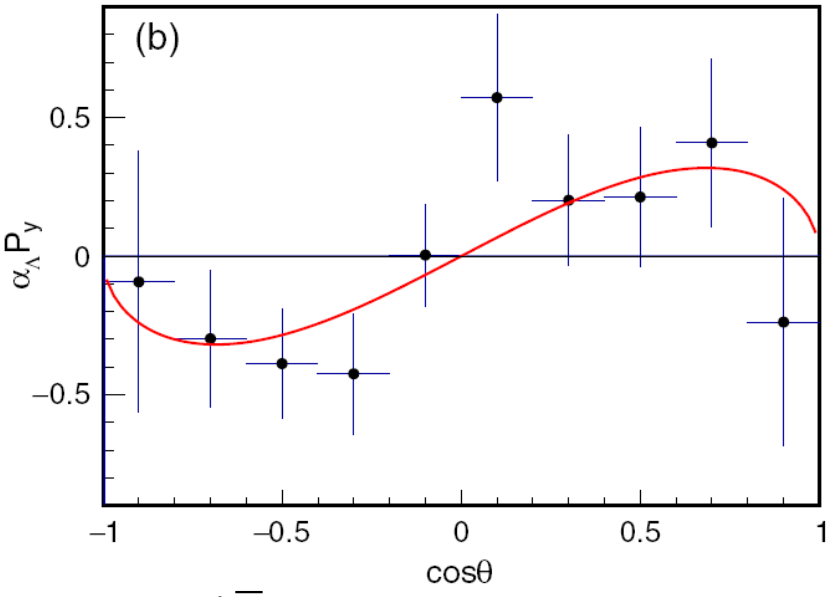
$$e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}$$

- 555 candidate events
- $\Delta\Phi = 37^\circ \pm 12^\circ(stat) \pm 6^\circ(syst)$
- Maximum polarization degree is ~30%

$$P_y = \frac{\sqrt{1-\eta^2}\sin\theta\cos\theta}{1+\eta\cos^2\theta}\sin(\Delta\Phi).$$



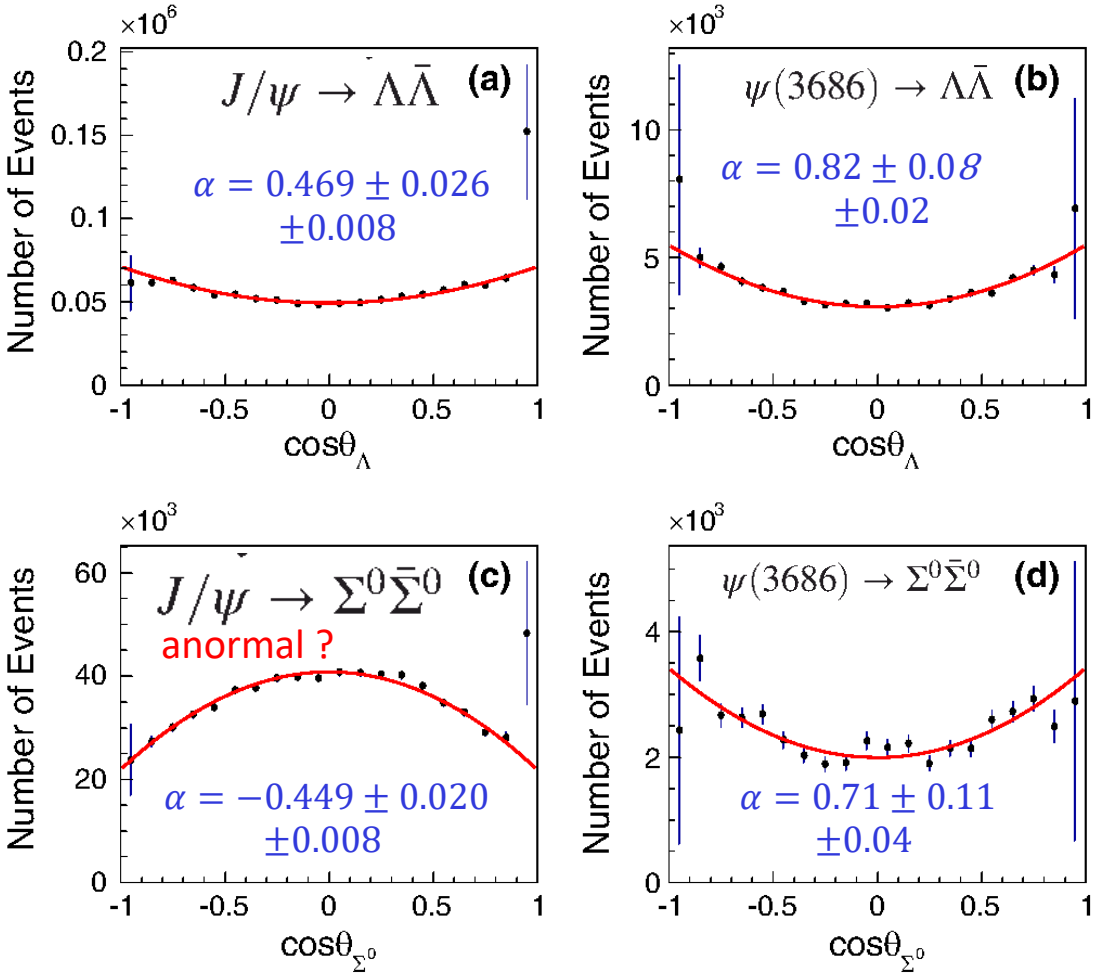
Λ angular distribution



Λ / $\bar{\Lambda}$ transverse polarization

Polarization puzzle in charmonium decays

Angular distribution: $\frac{dN}{dcos\theta} \propto (1 + \alpha \cos^2 \theta)$



BESIII, Phys.Rev., D95, 052003

- Branching ratios

$$\frac{\mathcal{B}(\psi(3686)\to\Lambda\bar{\Lambda})}{\mathcal{B}(J/\psi\to\Lambda\bar{\Lambda})} = (20.43 \pm 0.11 \pm 0.58)\%$$

$$\frac{\mathcal{B}(\psi(3686)\to\Sigma^0\bar{\Sigma}^0)}{\mathcal{B}(J/\psi\to\Sigma^0\bar{\Sigma}^0)} = (20.96 \pm 0.27 \pm 0.92)\%$$

- Angular distribution

$$\alpha = \frac{|H_{\uparrow\downarrow}|^2 - 2|H_{\uparrow\uparrow}|^2}{|H_{\uparrow\downarrow}|^2 + 2|H_{\uparrow\uparrow}|^2}$$

Helcity selection rule

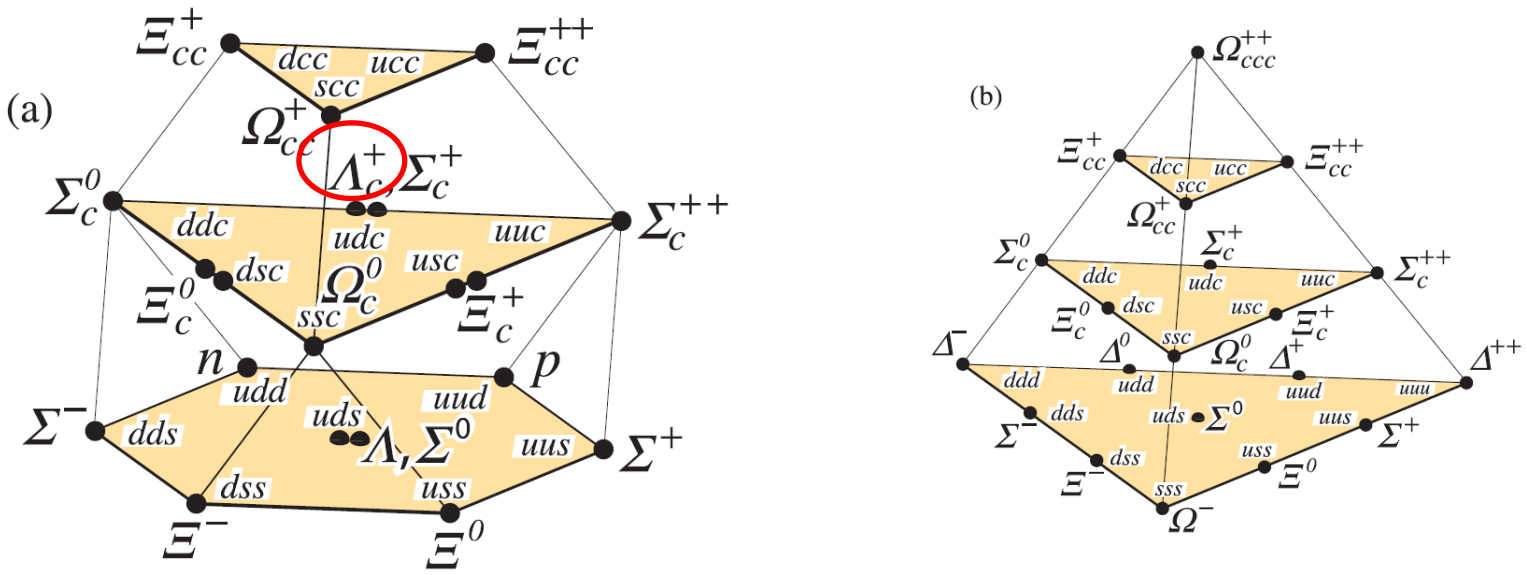
$|H_{\uparrow\uparrow}|/|H_{\uparrow\downarrow}| \sim 0$

Measurements:

$|H_{\uparrow\uparrow}|/|H_{\uparrow\downarrow}|=$ $\sim 1.3\ (J/\psi \to \Sigma^0\bar{\Sigma}^0)$, $\sim 0.08 (\psi' \to \Sigma^0\bar{\Sigma}^0)$

Why enhanced for J/ψ?

Λ_c spin and decay asymmetry parameter



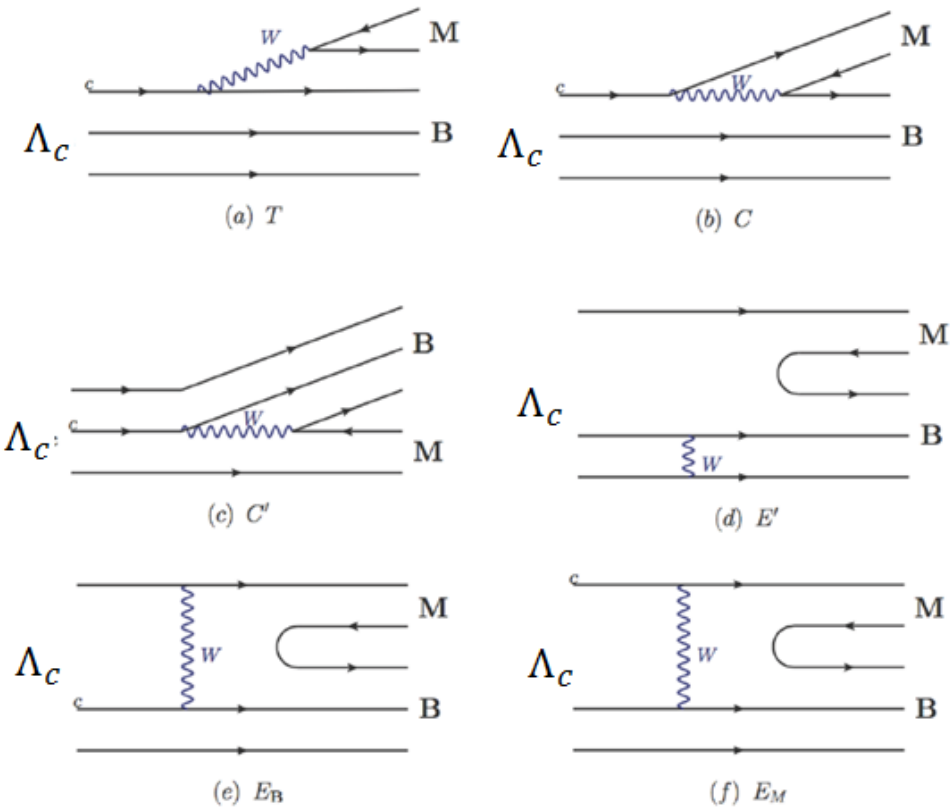
Λ_c^+ udc $I(J^P) = 0(\frac{1}{2}^+)$ Status: ****

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 $u\,d\,c$. Results of an analysis of $p\,K^-\,\pi^+$ decays (JEZABEK 92) are consistent with $J = 1/2$. Nobody doubts that the spin is indeed 1/2.

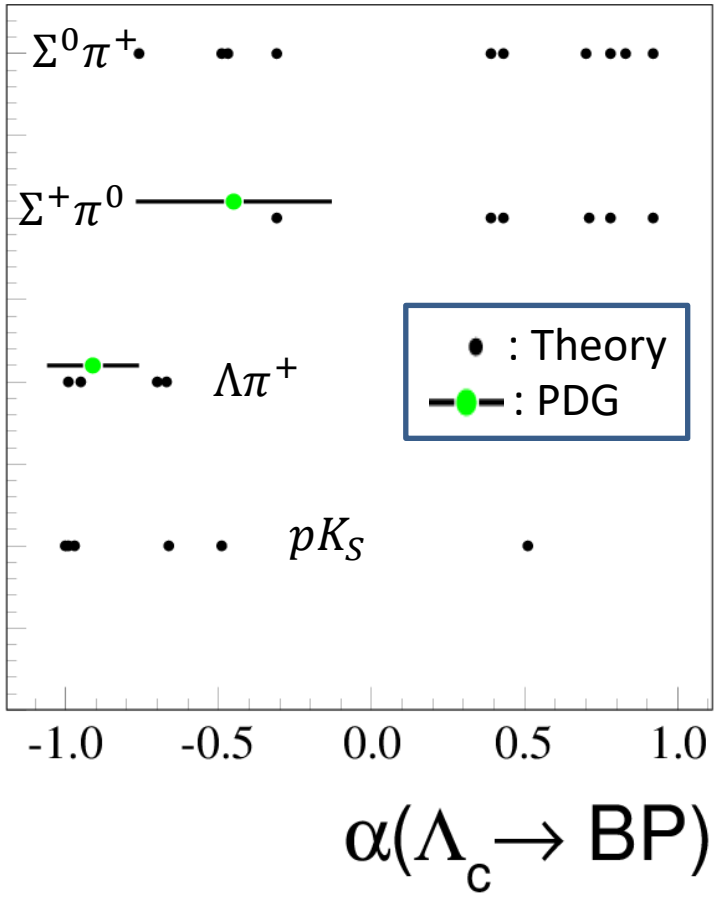
We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

Predictions on Λ_c asymmetry parameters

- W-exchange complicate $\Lambda_c \to B\ M$

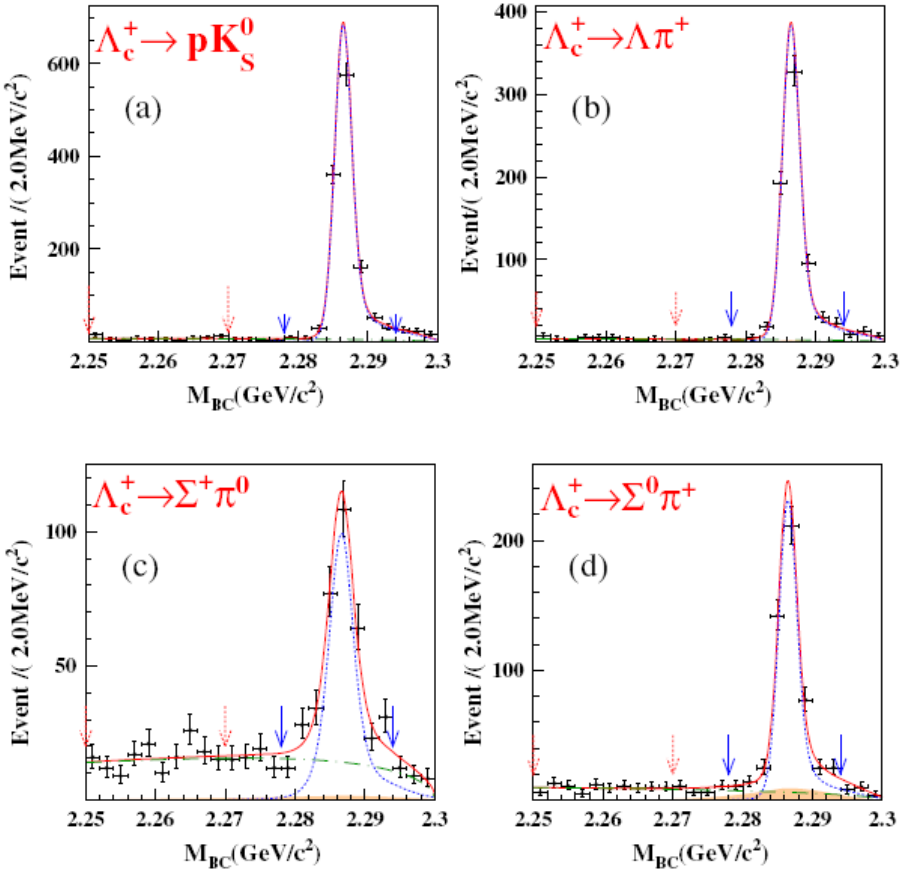


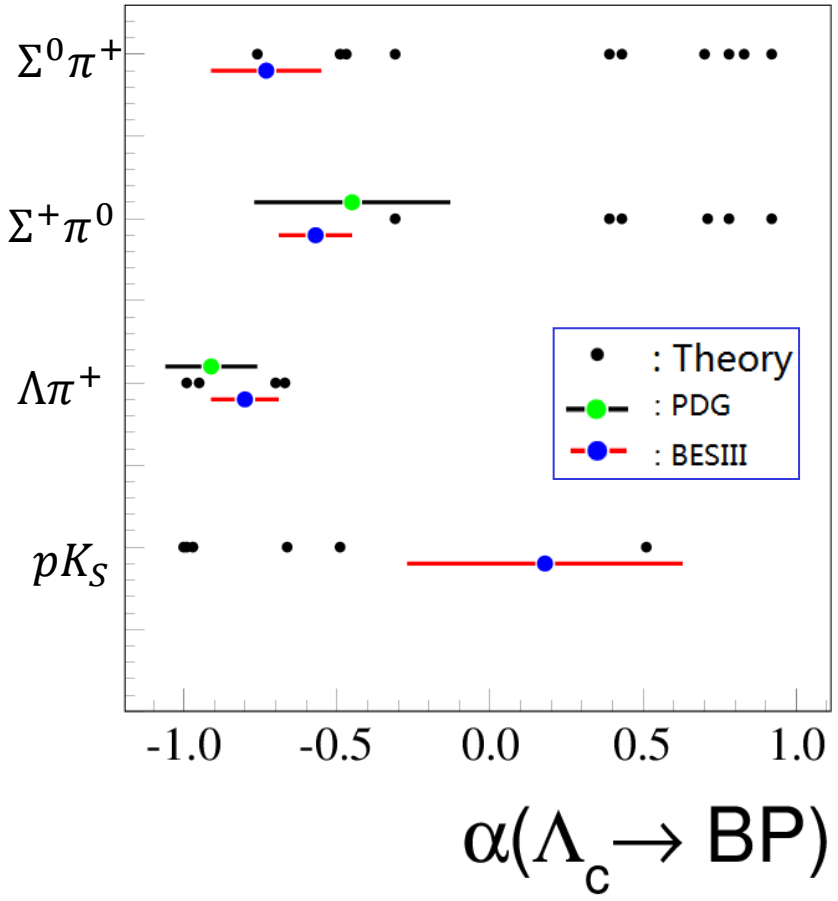
$\Lambda_c^+ \to BP$ decay asymmetry



Λ_c decay asymmetry parameter

- $L = 567\text{pb}^{-1}$ @ $\sqrt{s} = 4.6$ GeV with single tag





Phys. Rev. D 100, 072004 (2019)

- Significance for Λ_c transverse polarization: 2.1σ

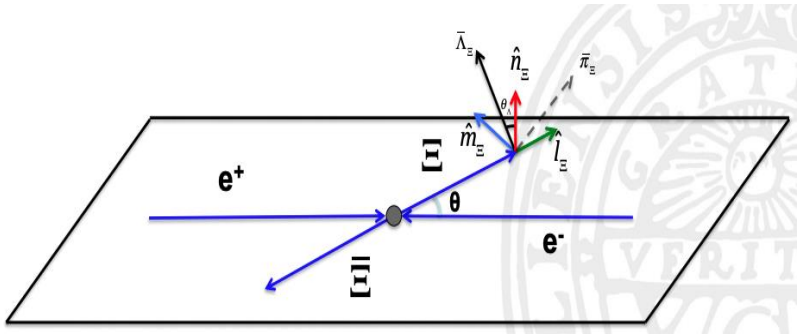
CPV with $J/\psi \to \Xi^-(\Lambda\pi^-)\bar{\Xi}^+(\Lambda\pi^+)$+c.c.

Disadvantages

complicated topology: 9-dimensions

$\theta_\Xi, \theta_\Lambda, \phi_\Lambda, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}}$

72 terms, 8 parameters to determine



Low rate compared to $\Lambda\bar{\Lambda}$

1.3B J/ψ: 420K $\Lambda(p\pi^-)\bar{\Lambda}(\bar{p}\pi^+)$evts

61K $\Xi(\Lambda\pi^-)$ $\bar{\Xi}(\bar{\Lambda}\pi^+)$

Advantages:

- **$\Lambda\bar{\Lambda}$ polarizations are measureable via their parity-violating $p\pi^-$ ($p\pi^+$) decays;**
- **β_- and β_0 parameters can be determined.**
- **Preliminary results indicate that the Ξs are even more polarized than the Λs.**

Ongoing polarization analyses at BESIII

- $J/\psi, \psi' \to \Sigma^- \bar{\Sigma}^+$
- $J/\psi \to \Xi^- \bar{\Xi}^+$ (Ξ, Λ asymmetry par., CP test)
- $\psi' \to \Omega^- \bar{\Omega}^+$ (polarization analysis)
- $\eta_c \to \Lambda\bar{\Lambda}$ (QM nonlocatlity& reality)
- $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$
  - $\Lambda_c^+ \to \Lambda\pi^+, \Sigma^+\pi^0, \Sigma^0\pi^+, pK_S$, to be improved
  - Λ_c spin
- future charmed baryon program
  - **Update Ecms up to 4.9 GeV**
  - **Approved $\sim 10\ \mathrm{fb}^{-1}$ data taking around $\Lambda_c\bar{\Lambda}_c$ threshold**

Summary

- $\Lambda/\ \overline{\Lambda}$ transverse polarization significantly observed at BESIII in J/ψ or continuum processes
- BESIII 10 billion J/ψ data provides us chances to access hyperon physics.
- Extension study to charmed hyperon are ongoing.
- Polarized beam in the future super-tau charm facility (STCF) help to improve the precision.

backup

Previous Measurements

2018 PDG list

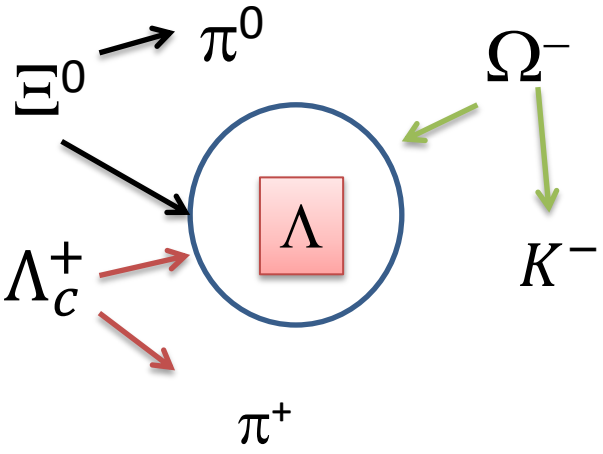
α_- FOR $\Lambda \to p\pi^-$

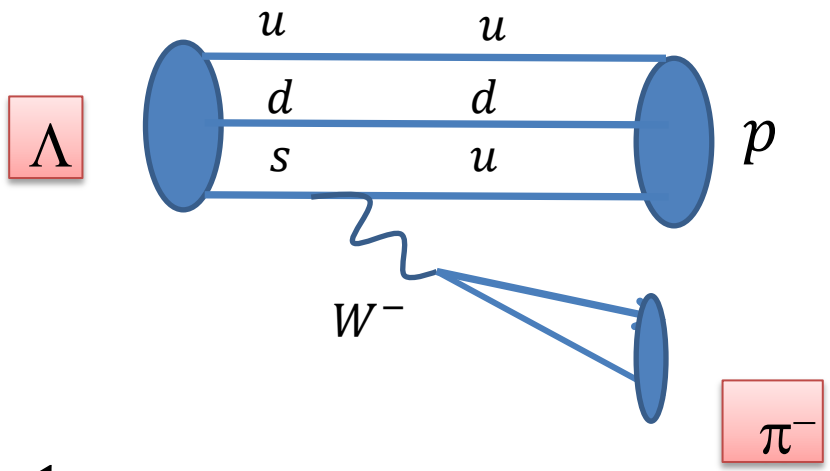
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.642 ± 0.013	**OUR AVERAGE**				
0.584 ± 0.046	8500	ASTBURY	1975	SPEC	
0.649 ± 0.023	10325	CLELAND	1972	OSPK	
0.67 ± 0.06	3520	DAUBER	1969	HBC	From Ξ decay
0.645 ± 0.017	10130	OVERSETH	1967	OSPK	Λ from $\pi^- p$
0.62 ± 0.07	1156	CRONIN	1963	CNTR	Λ from $\pi^- p$

α_+ FOR $\overline{\Lambda} \to \overline{p}\pi^+$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
-0.71 ± 0.08	**OUR AVERAGE**				
$-0.755 \pm 0.083 \pm 0.063$	$\approx$ 8.7k	ABLIKIM	2010	BES	$J/\psi \to \Lambda\overline{\Lambda}$
-0.63 ± 0.13	770	TIXIER	1988	DM2	$J/\psi \to \Lambda\overline{\Lambda}$

$\Lambda \to p\pi^-$ as polarimeter





$$\frac{dN}{d\Omega} = \frac{1}{4\pi}\left(1 + \alpha_\Lambda \vec{P}\cdot\hat{q}\right) = \frac{1}{4\pi}\left(1 + \alpha_\Lambda P_\Lambda cos\theta_p\right)$$

Lee-Yang parameters:

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

Note: $\alpha^2 + \beta^2 + \gamma^2 = 1$

PDG2018: $\alpha_\Lambda = 0.642 \pm 0.013, \alpha_{\bar{\Lambda}} = -0.71 \pm 0.08$