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

BESIII

BESIII上自旋极化相关课题的研究

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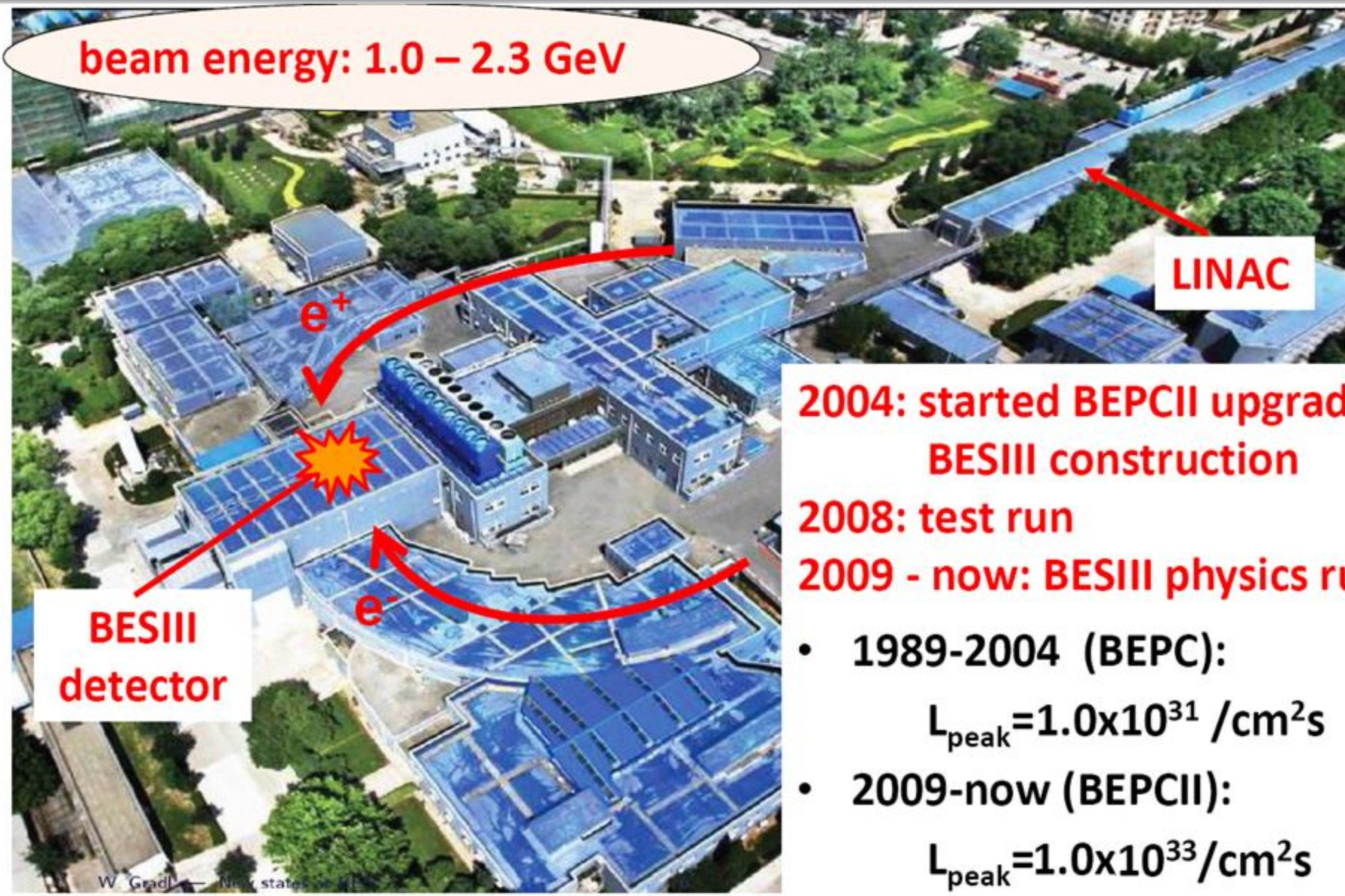
Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade, BESIII construction

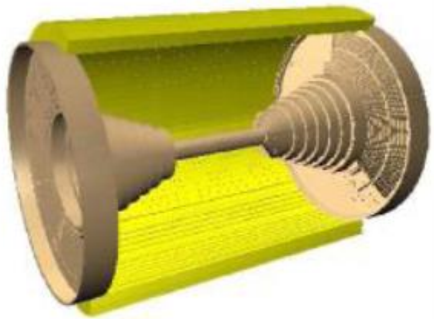
2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC): $L_{peak}=1.0\times10^{31}\ /cm^2s$
- 2009-now (BEPCII): $L_{peak}=1.0\times10^{33}/cm^2s$

BESIII Detector

MDC

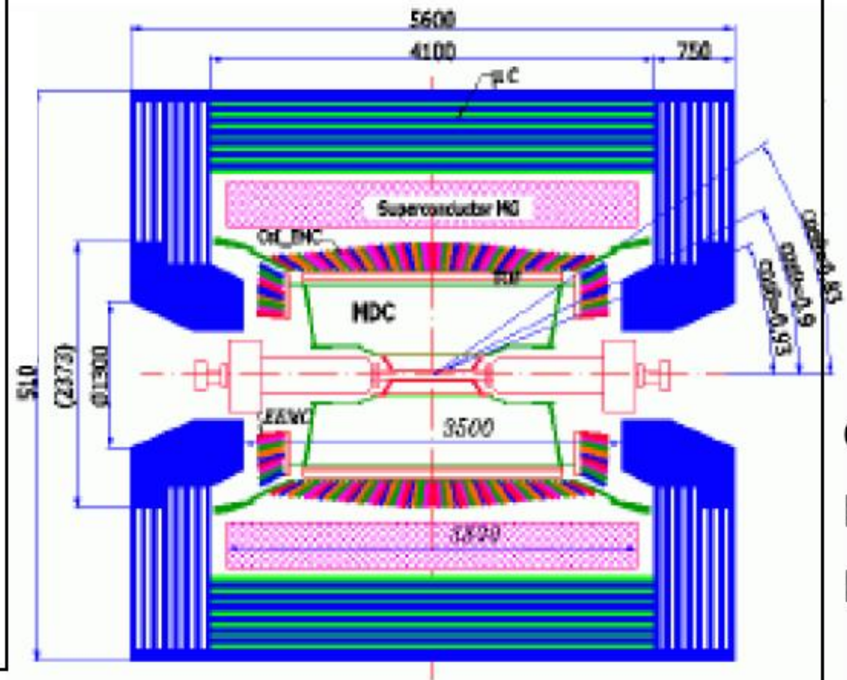


R inner: 63mm ;

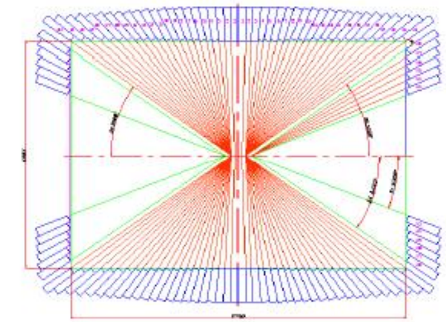
R outer: 810mm

Length: 2582 mm

Layers: 43



CsI(Tl) EMC



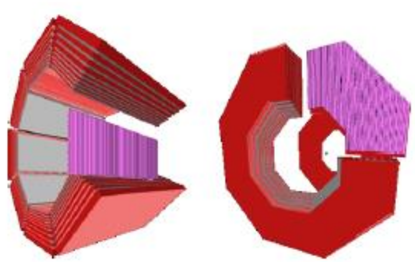
Crystals: 28 cm(15 X_0)

Barrel: $|\cos\theta|<0.83$

Endcap:

$0.85 < |\cos\theta| < 0.93$

RPC MUC



BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

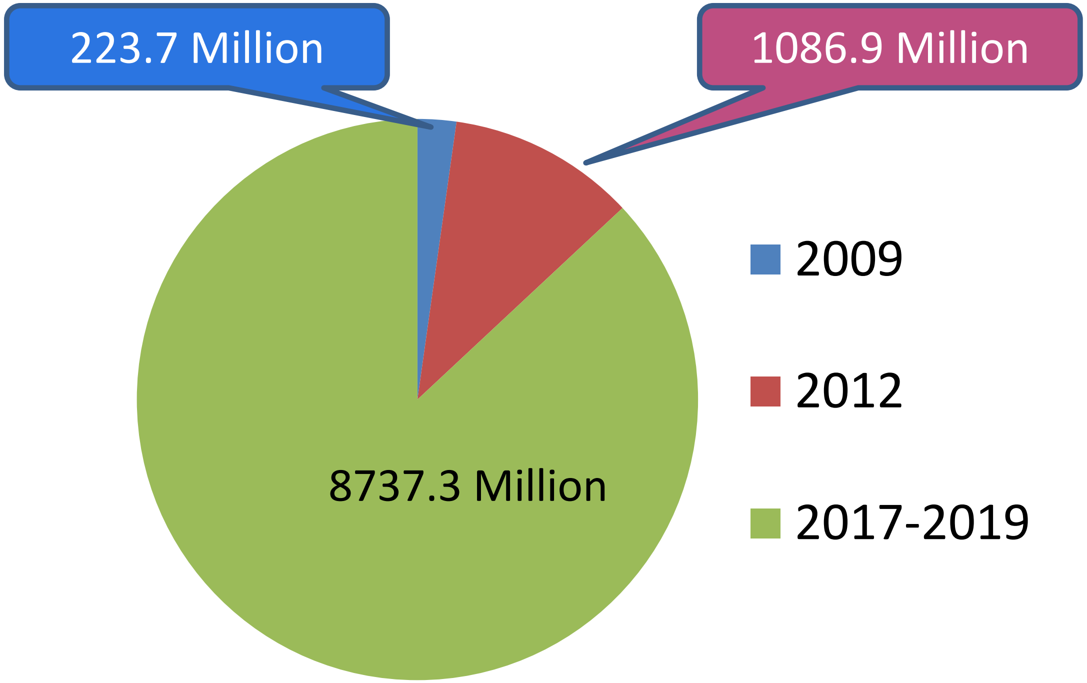
TOF

BTOF: two layers

ETOF: 48 scintillators for each

MRPC --- new ETOF

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



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

$\sim$1.31 billion decays

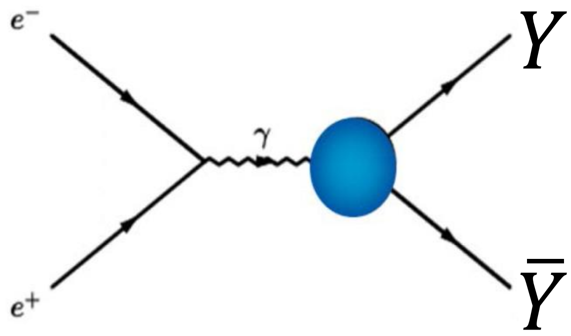
J/ψ : Total 10.047 billion J/ψ decays

ψ': 448 million decays

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

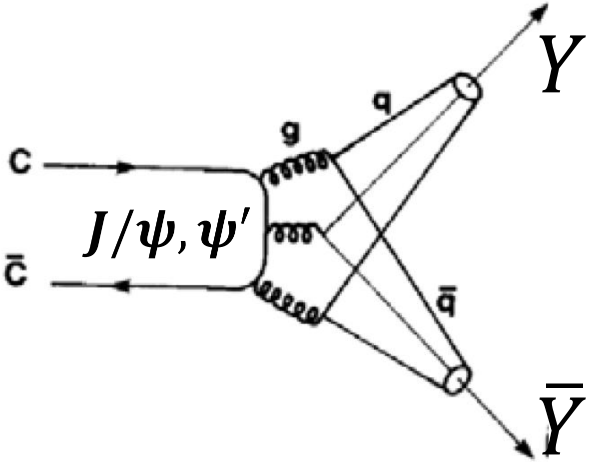
Hyperon pair production at BESIII

- $e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Xi\bar{\Xi}, \Omega\bar{\Omega}, \Lambda_c^+\bar{\Lambda}_c^-$, @ $\sqrt{s} =$ $2.0 \sim 4.6$ 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	$\Sigma^0\bar{\Sigma}^0$
$8.6 \quad \times 10^6$	$\Xi^-\bar{\Xi}^+$

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

Role of polarization physics

- Probing of spin degree freedom

  Test the dynamic of SM and low energy hadron interaction

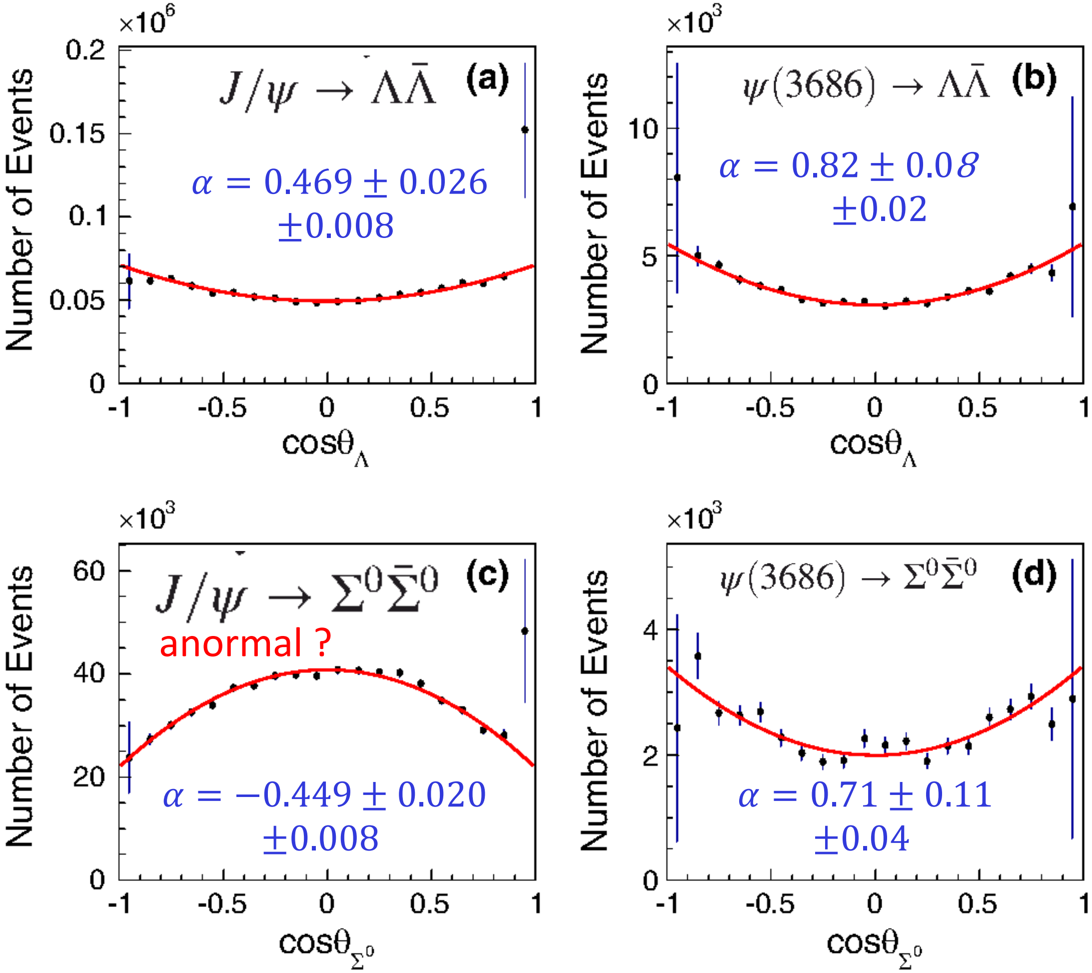
  Existant exp. : RHIC, Jlab, GRAAL, CERN and DESY
  Spin observable, spin-dependent structure function and parton distribution
  Spin crisis at eighties

- 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

Polarization puzzle in charmonium decays

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



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

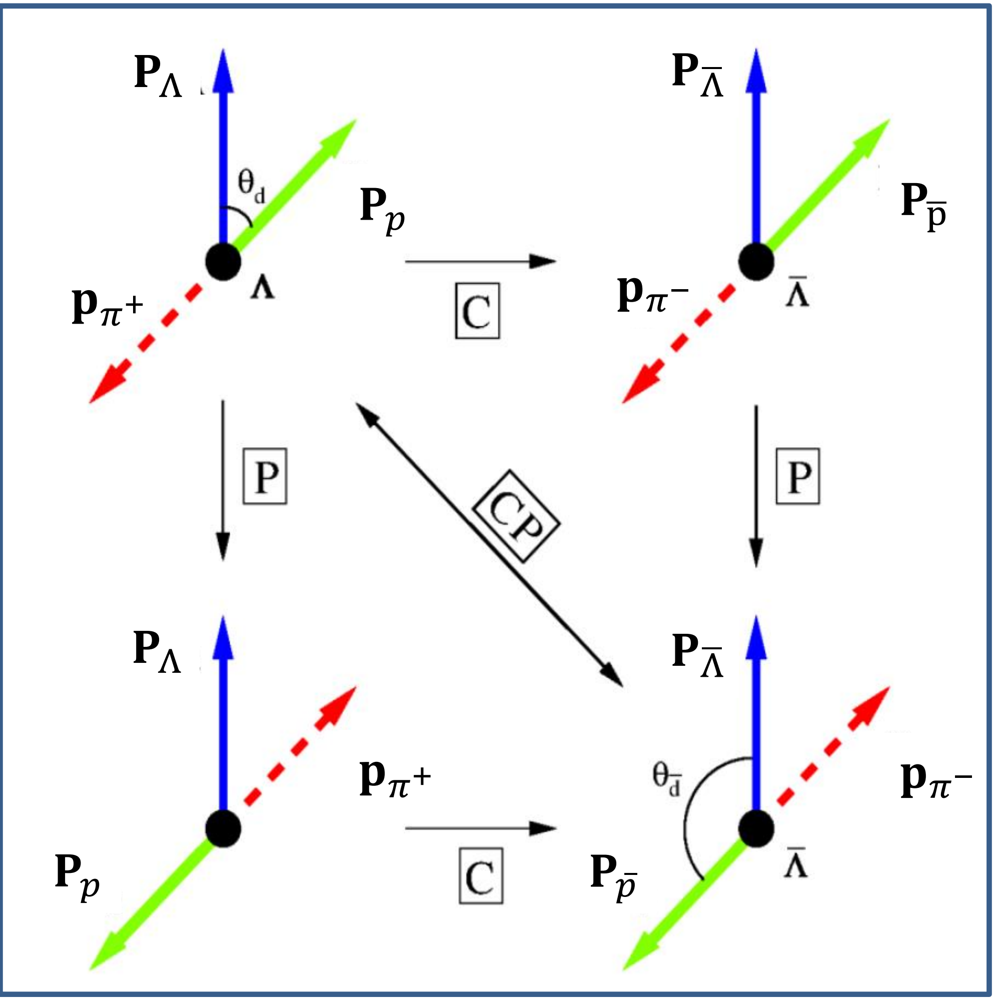
$|H_{\uparrow\uparrow}|/|H_{\uparrow\downarrow}| \sim 0$

Measurements:

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

Why enhanced for J/ψ?

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)

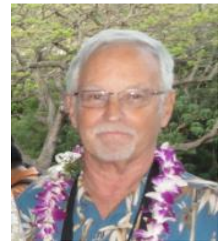
ASYMMETRY PARAMETER FOR $\Lambda^0 \to n\pi^0$ †*

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 $\Sigma^+ \to p\pi^0$ †*

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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

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AND

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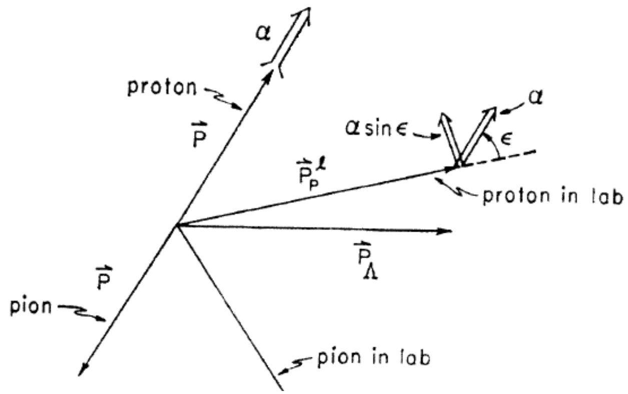
(Received 1 April 1969)

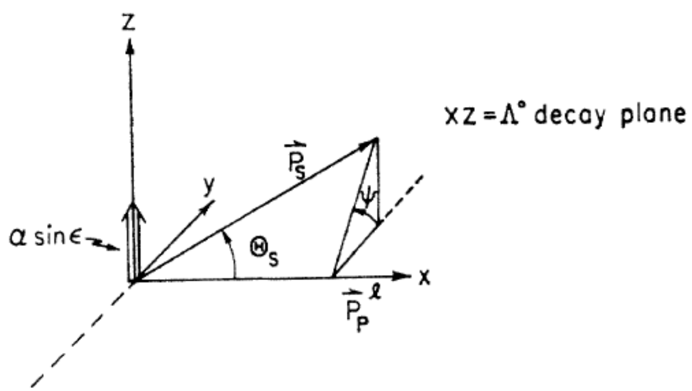
We discuss the consequences of including the final-state interactions in the analysis of Λ°, Σ, and Ξ nonleptonic decays. Emphasis is on the role that the final-state interactions play in tests for T invariance, in tests of the $\Delta I = \frac{1}{2}$ rule (including the resolution of sign ambiguities),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

Most earlier measurement on α_-

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

Phys.Rev. 129 (1963) 1795-1807





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

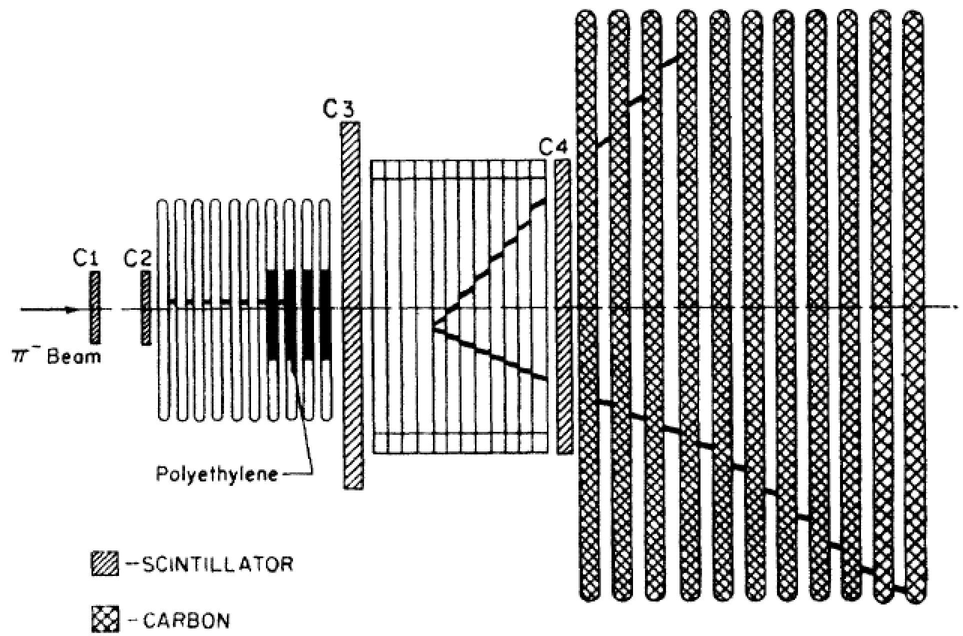


FIG. 1. Schematic diagram showing arrangement of apparatus. An example of an event has been sketched in.

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

1156 events

$\langle S\rangle = 0.565$

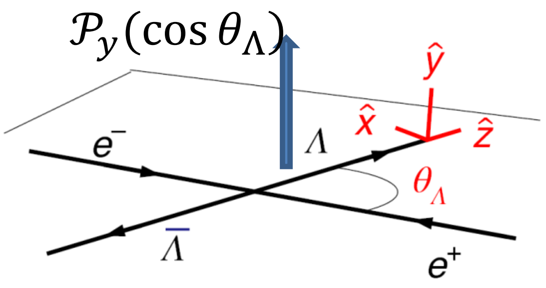
$\langle \sin\epsilon\rangle = 0.84,$

$\alpha = 0.62.$

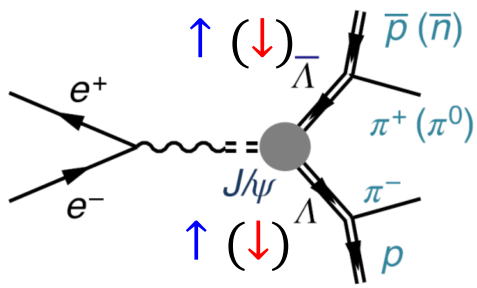
Observation of Λ polarization and entanglement in $J/\psi \to \Lambda\bar{\Lambda}$

Highlights!

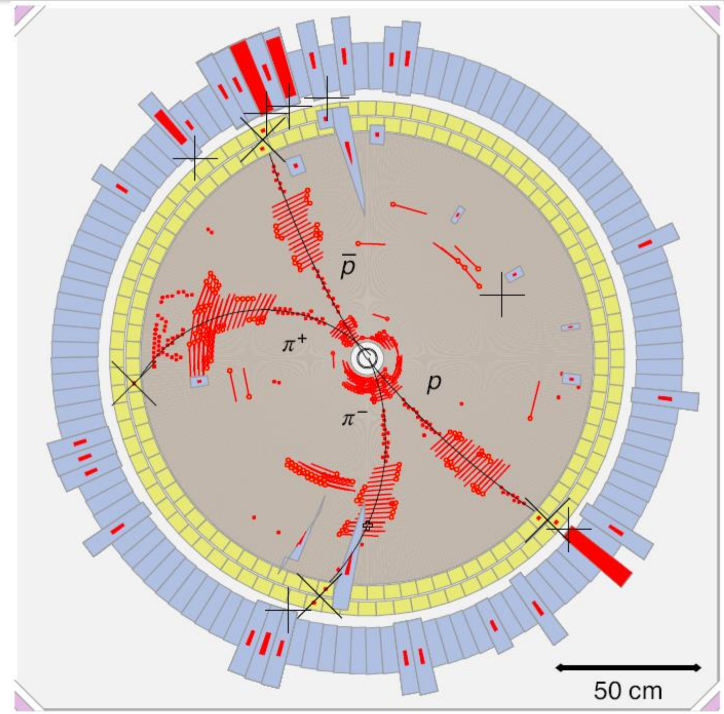
Published in Nature Physics, 15, 631 (2019)



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

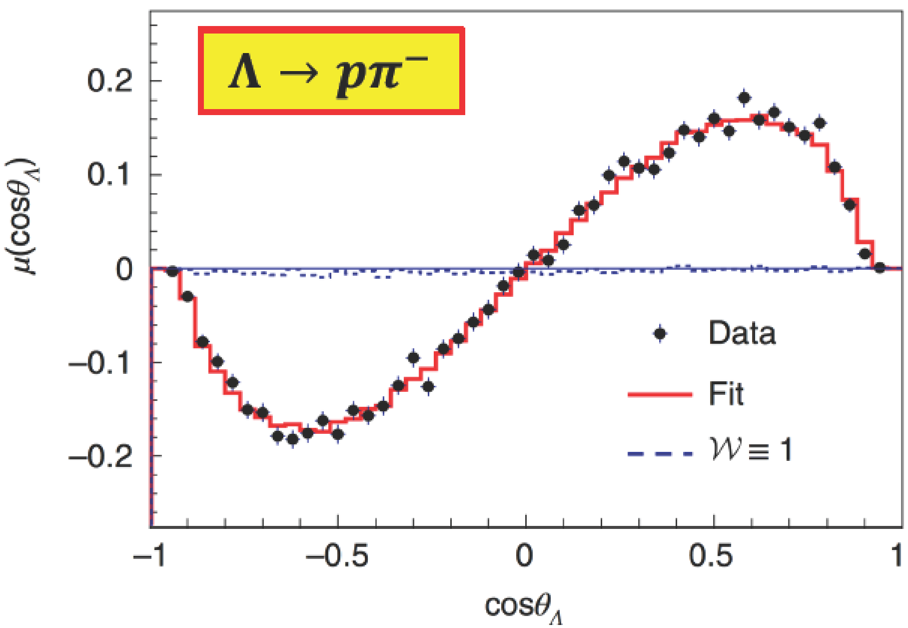
$$P_y(\cos\theta_\Lambda)=\frac{\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$

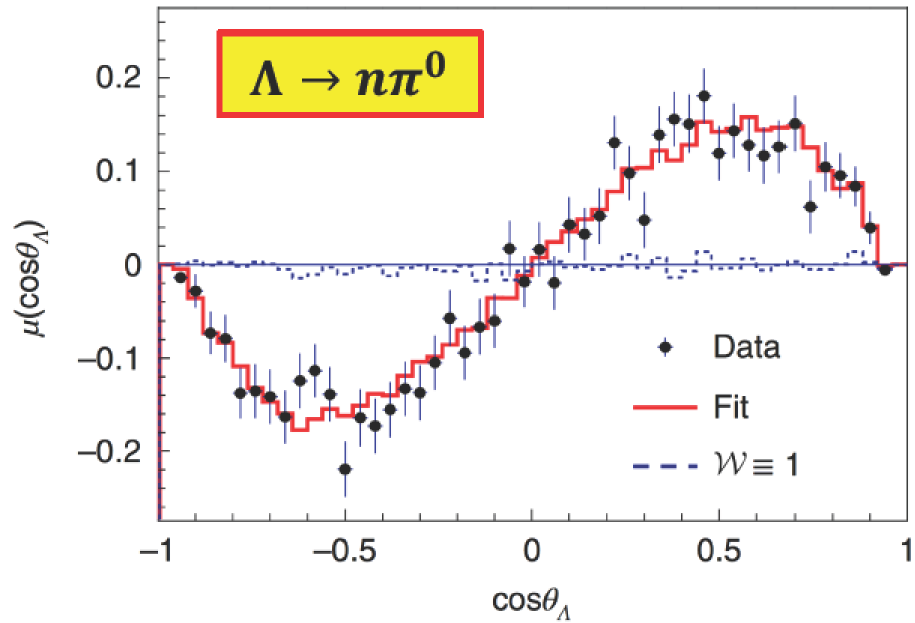
Observation of Λ polarization and entanglement in $J/\psi \to \Lambda\bar{\Lambda}$

Published in Nature Physics, 15, 631 (2019)

J/ψ data sample: 1.31×10^9

- Observation of $\Lambda / \bar{\Lambda}$ 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 $\Lambda / \bar{\Lambda}$ 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 $\Lambda/\bar{\Lambda}$ 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 $J/\psi \to \Lambda\bar{\Lambda}$

Highlights!

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	$J/\psi \to \Lambda\bar{\Lambda}$

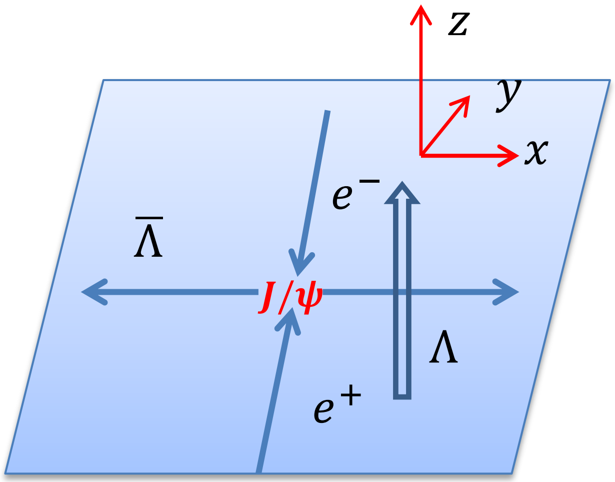
Where does the TP come from?

- **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: $\mathcal{P}_z = 0$, $T_{zz} = \frac{1}{\sqrt{6}}$

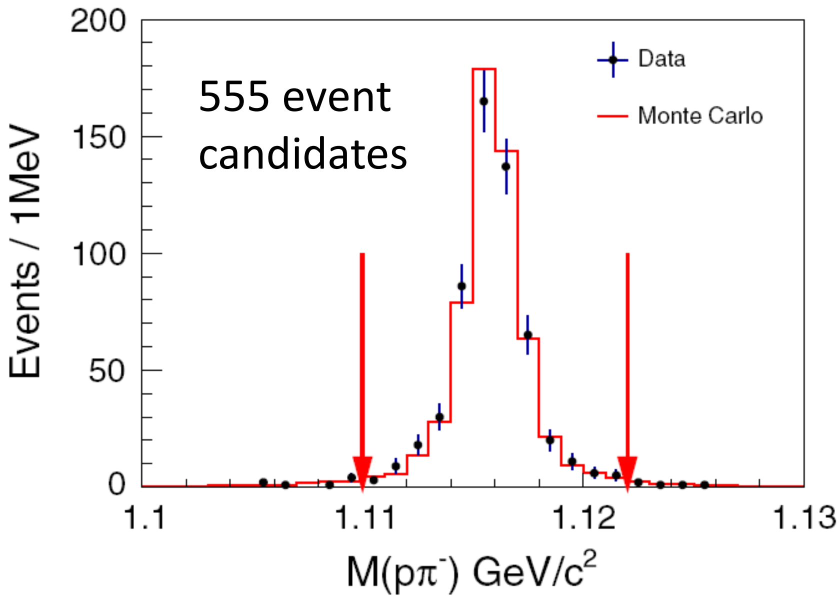
Λ transverse polarization:

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



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

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

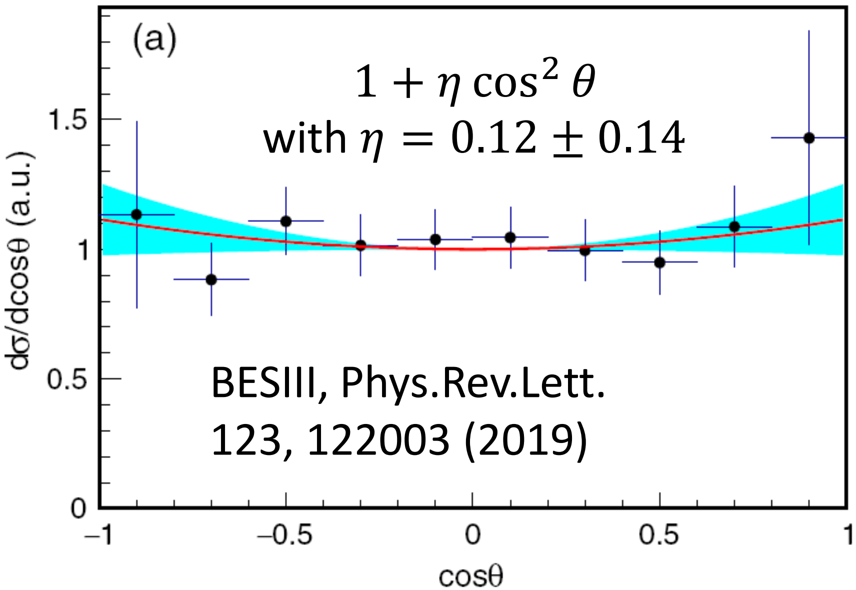


- data set: 2.396 GeV, L=66.9 pb^{-1}

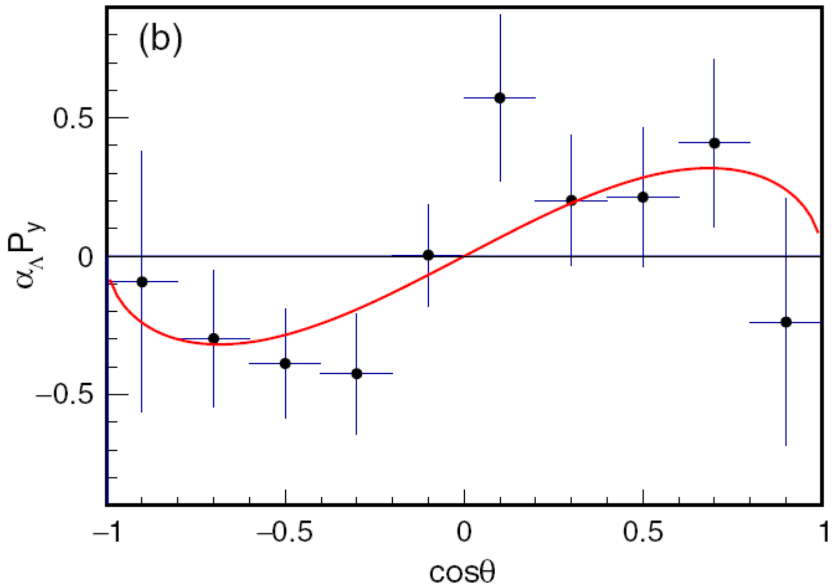
$$e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}$$

- 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

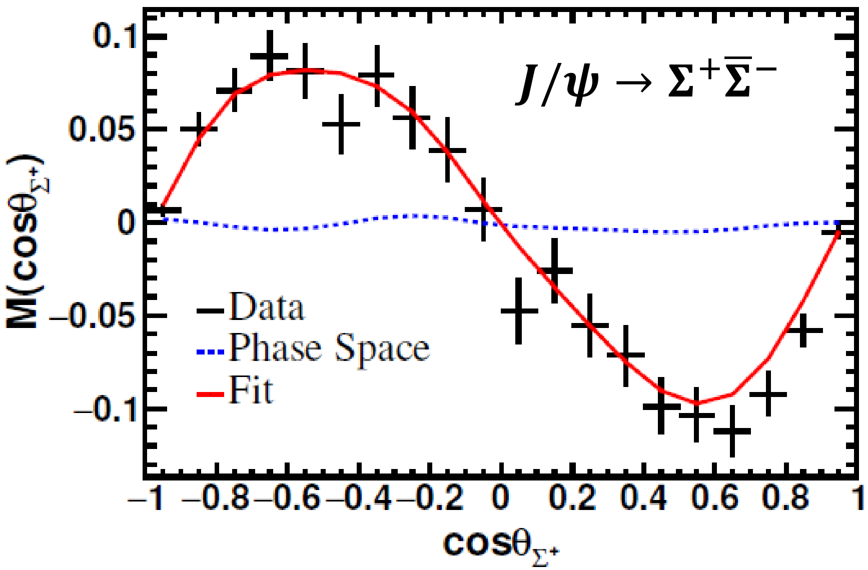


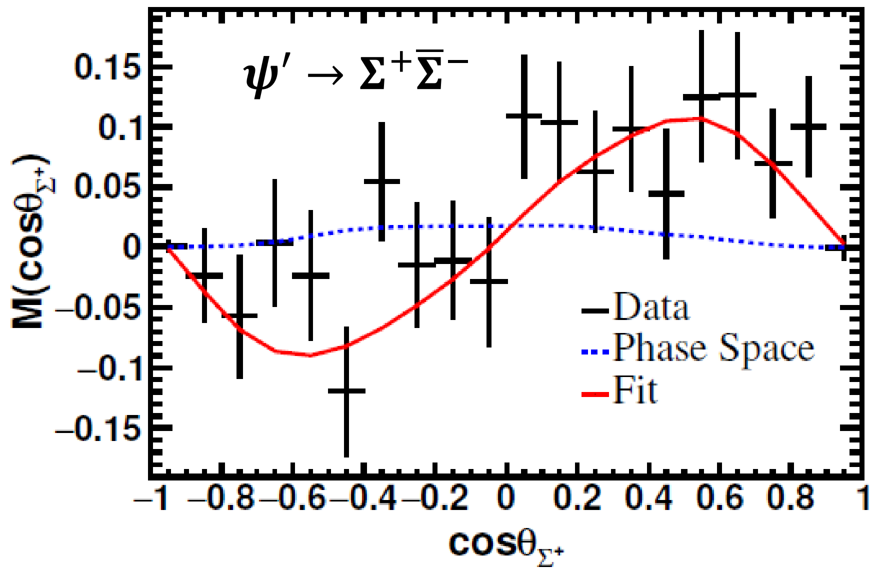
Λ / $\bar{\Lambda}$ transverse polarization

$\Sigma^+ / \bar{\Sigma}^-$ transverse polarization

$$J/\psi\ (\psi') \to \Sigma^+\bar{\Sigma}^-$$

BESIII: arXiv: 2004.07701





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

$$\Delta\Phi = (-15.5 \pm 0.7 \pm 0.5\,)^\circ \quad \text{for } J/\psi$$
$$\Delta\Phi = (+21.7 \pm 4.0 \pm 0.7\,)^\circ \quad \text{for } \psi'$$

$$A_{CP} = \frac{\alpha_0 + \bar{\alpha}_0}{\alpha_0 - \bar{\alpha}_0} = -0.004 \pm 0.037 \pm 0.010$$

$$\Sigma^+ \to p\pi^0\ (\alpha_0 = -0.998 \pm 0.037 \pm 0.009)$$
$$\bar{\Sigma}^- \to \bar{p}\pi^0\ (\bar{\alpha}_0 = 0.990 \pm 0.037 \pm 0.011)$$

PDG:

α_0 FOR $\Sigma^+ \to p\pi^0$ $\quad -0.980^{+0.017}_{-0.015}$

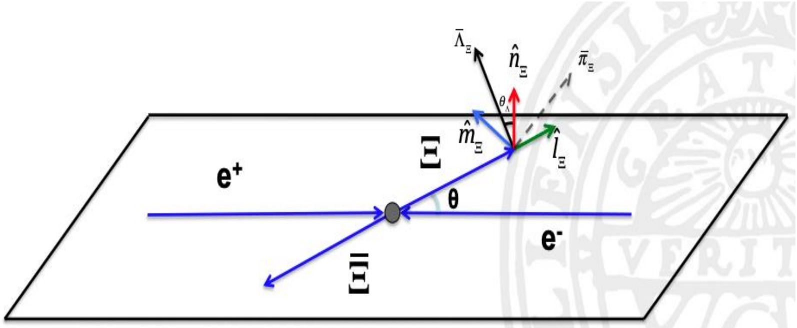
CPV with $J/\psi \rightarrow \Xi^{-}(\Lambda\pi^{-})\overline{\Xi}^{+}(\Lambda\pi^{+})$+c.c.

缺点:

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 $\Lambda\bar{\Lambda}$

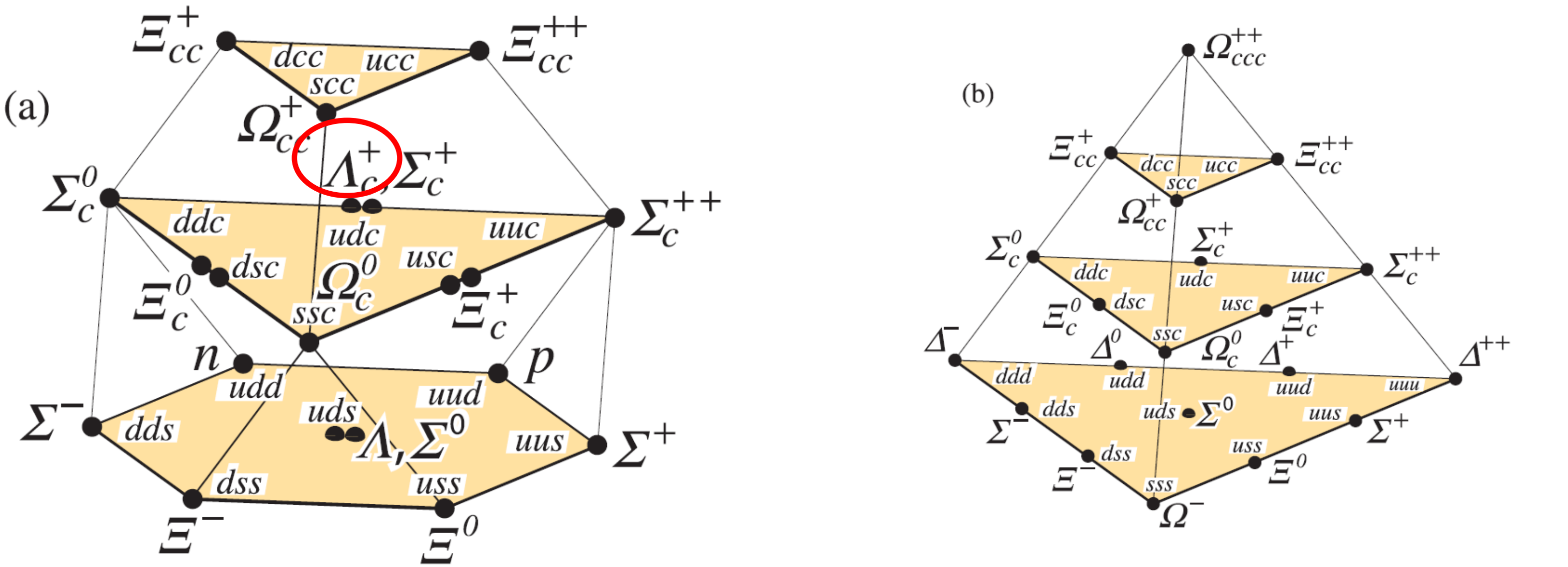
1.3B J/ψ: 420K $\Lambda(p\pi^{-})\bar{\Lambda}(\bar{p}\pi^{+})$evts

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

优点:

- **$\Lambda\bar{\Lambda}$ 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.**

Λ_c spin and decay asymmetry parameter



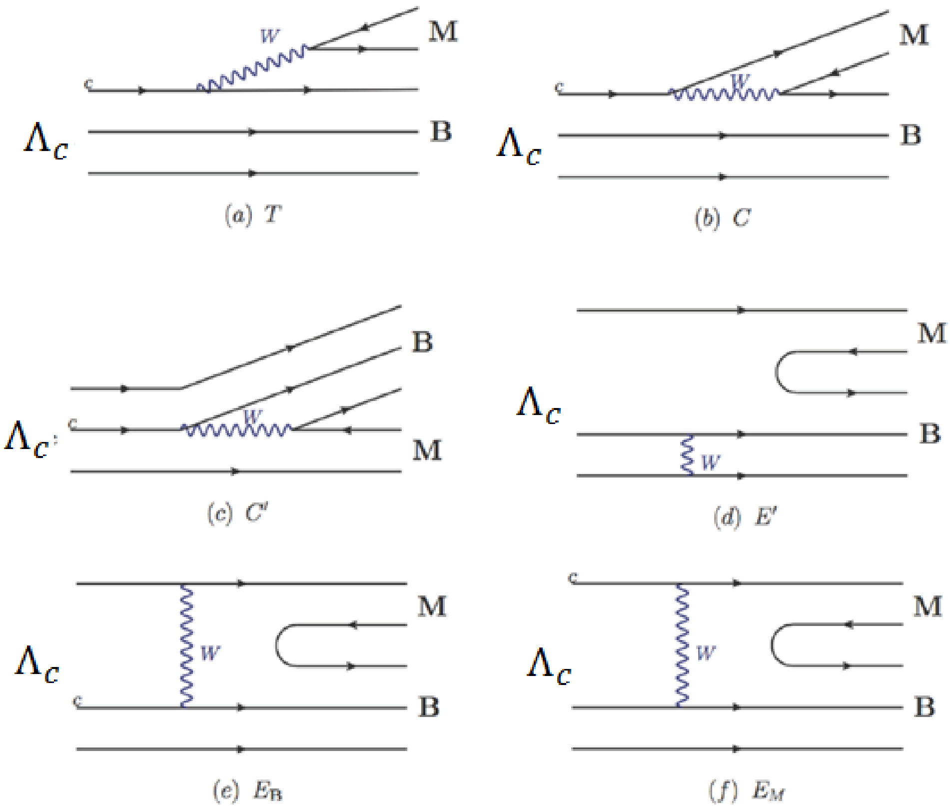
Λ_c^+ udc $I(J^P) = 0(\frac{1}{2}^+)$ Status: ∗∗∗∗

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.

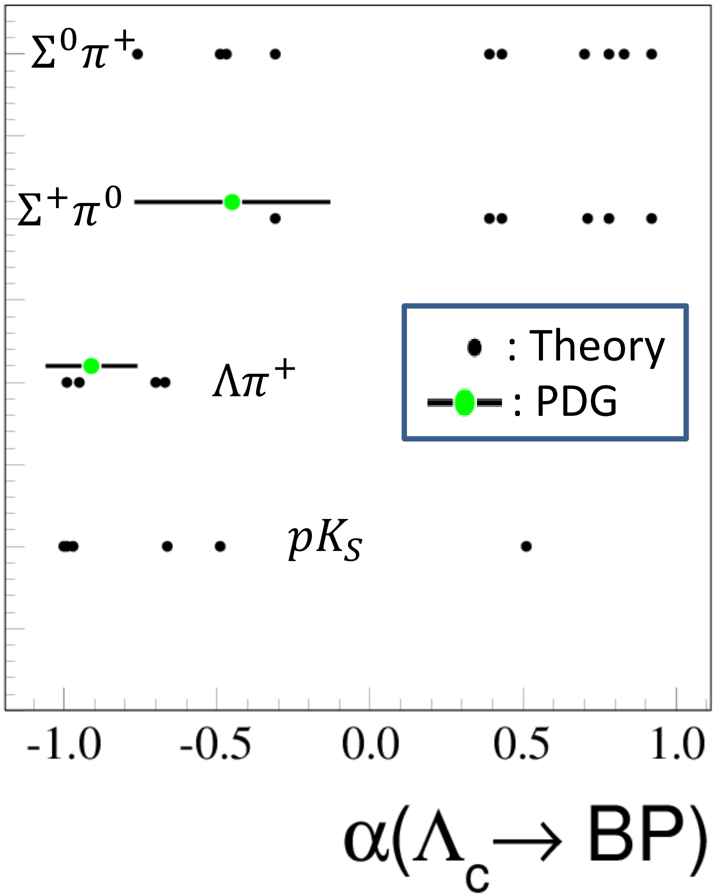
We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

Predictions on Λ_c asymmetry parameters

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

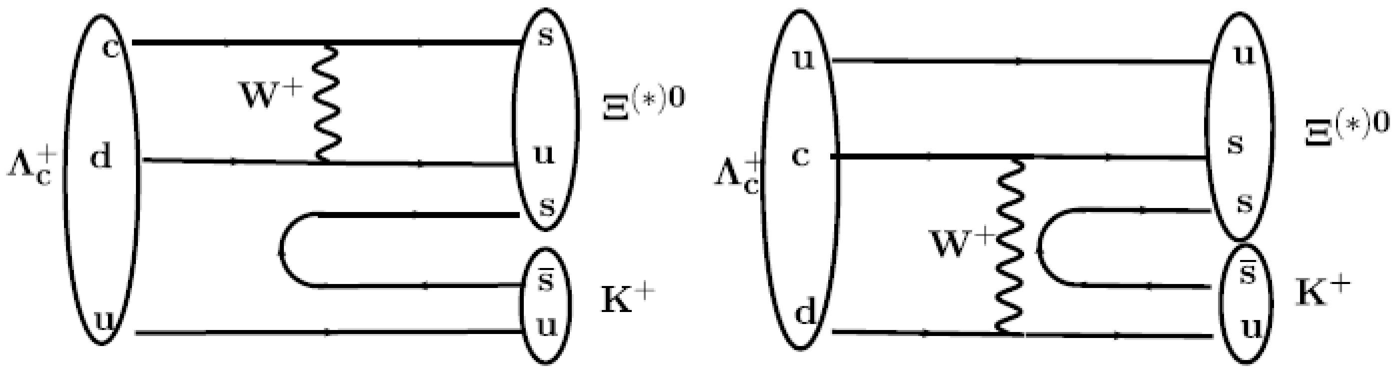


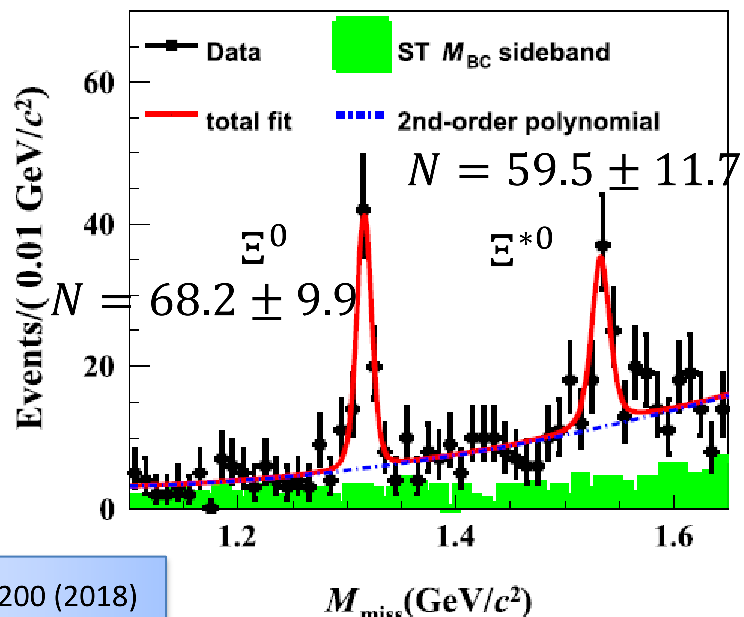
$\Lambda_c^+ \to BP$ decay asymmetry



Predictions on Λ_c asymmetry parameters

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





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

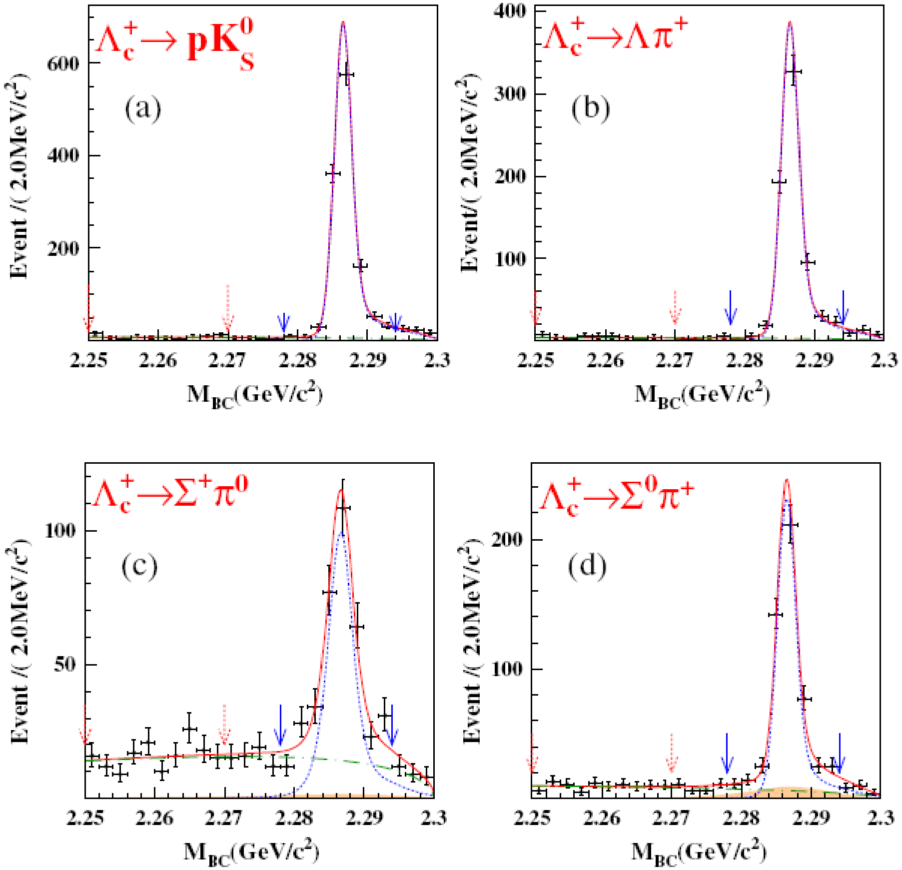
$\mathcal{B}(\Lambda_c^+ \to \Xi^{*0} K^+) =$
$(5.02 \pm 0.99 \pm 0.31) \times 10^{-3}$

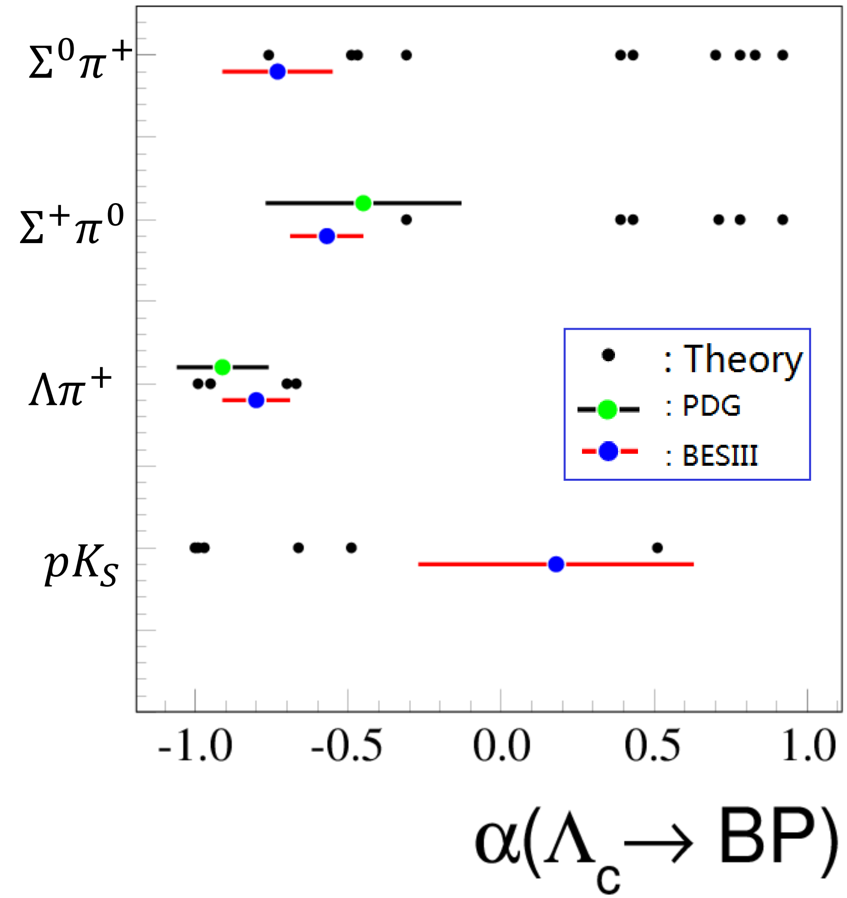
Compared to
$\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+) = (1.29 \pm 0.07)\%$

BESIII:PLB783,200 (2018)

Λ_c decay asymmetry parameter

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





Phys. Rev. D 100, 072004 (2019)

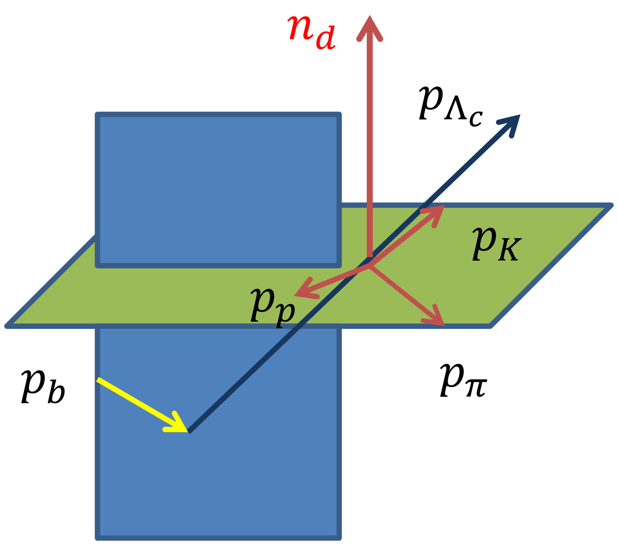
- Significance for Λ_c transverse polarization: 2.1σ

Λ_c spin

- NA2 experiment at CERN-SPS
- $\pi\,\mathrm{Cu} \to \Lambda_c^+ \,\overline{D}\, X$

Phys.Lett., B286, 175 (1992)

- 160 events for $\Lambda_c \to pK^-\pi^+$



- 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:

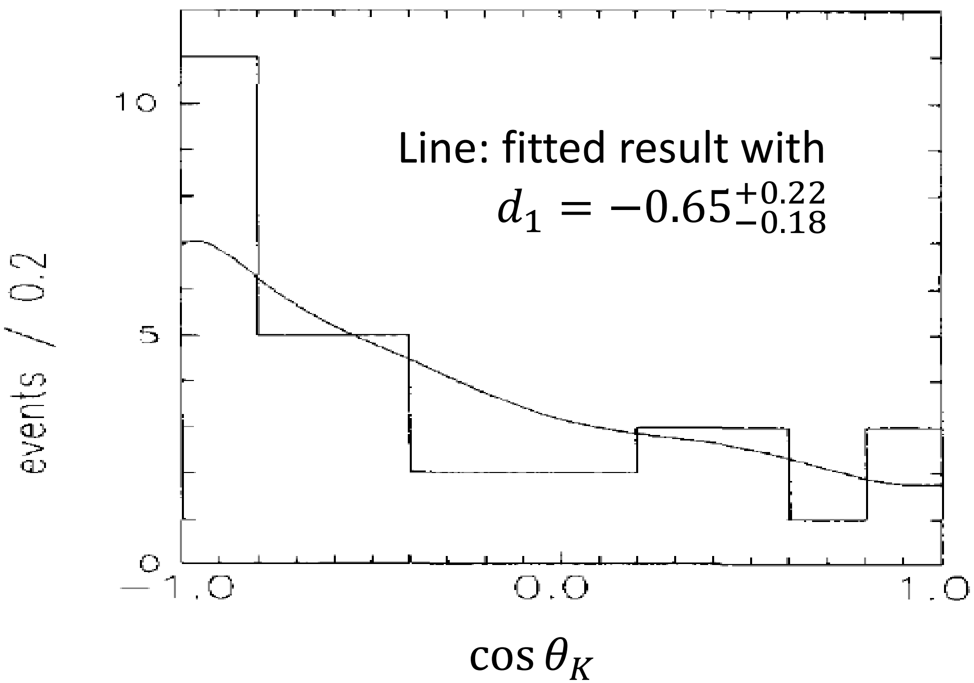
$$I(\theta) = \frac{1}{2}\left(1 + \sum_{l=1}^{2J} d_l P_l(\cos\theta)\right),$$

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

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

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

Λ_c spin



Assume $J = 1/2$, then

$$p_1 = \rho^{1/2}_{1/2,1/2} - \rho^{-1/2}_{-1/2,-1/2}$$

$$a_1 = f^{1/2}_{1/2} - f^{1/2}_{-1/2}$$

They concluded:

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

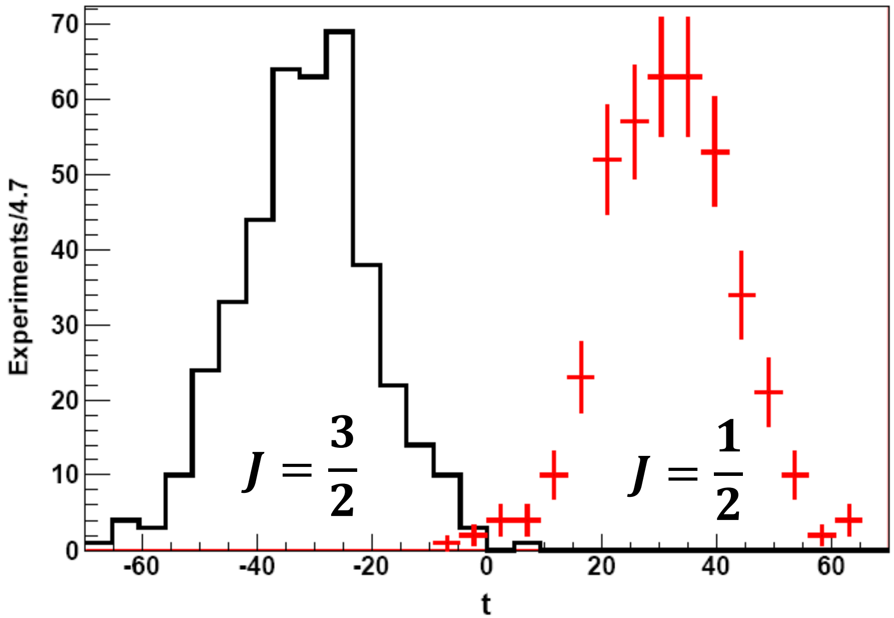
Remarks:

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

Determination of Λ_c spin

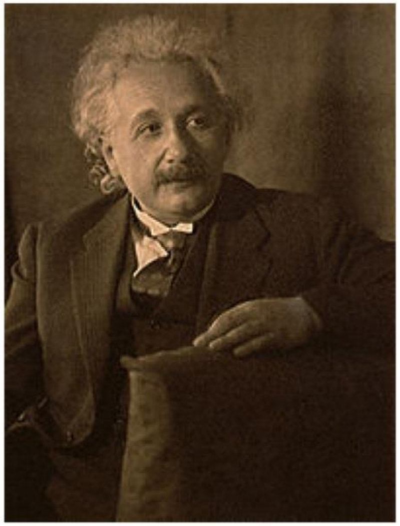
- Toy MC study: ($L = 567 pb^{-1}$ @ $\sqrt{s} = 4.6$ GeV)

Decays	Br [9]	$\alpha_{[BM]}^{[\Lambda_c^+]}$	N^{obs} [1]
$\Lambda_c^+ \to pK_S^0$	$(1.58 \pm 0.08)\%$	-0.75	1243
$\Lambda_c^+ \to \Lambda\pi^+$	$(1.29 \pm 0.07)\%$	-0.91 ± 0.15 [9]	706
$\Lambda_c^+ \to \Sigma^0\pi^+$	$(1.28 \pm 0.07)\%$	-0.45 ± 0.32 [9]	522



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

Einstein-Podolsky-Rosen (EPR) paradox



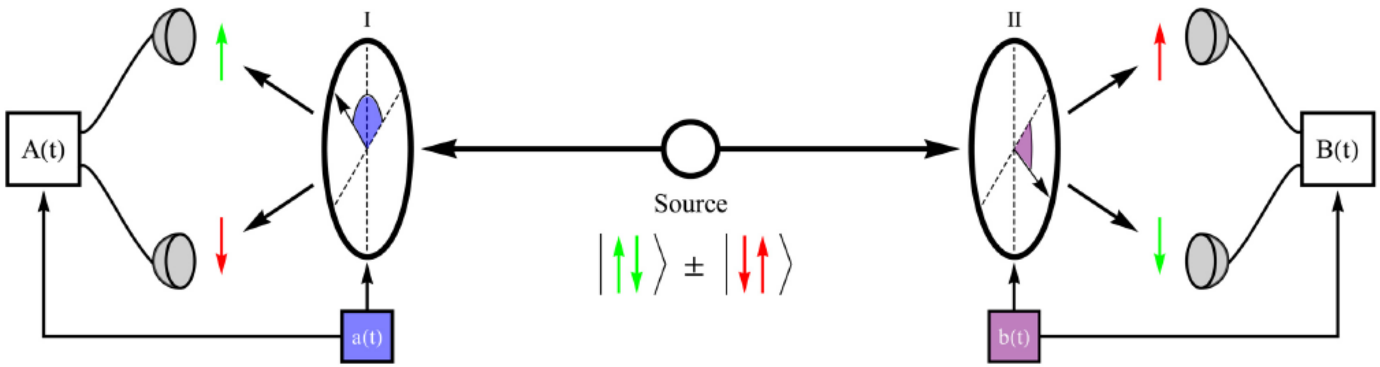
Albert Einstein

- EPR paradox[1] (1935) initiated an intense discussion on the philosophical foundations of quantum mechanics.
- Physics quantity corresponding to "element of reality" can be predicted without any uncertainty.
- A given example: two particle system with sum of momentum $(p_1 + p_2)$ and position difference $(x_1 - x_2)$
- They concluded: the premises of "element of reality" is wrong or Q.M. is incomplete.

Ref.[1] . Einstein, A; B Podolsky and N. Rosen, Phys. Rev. 47, 10 (1935), "Can Quantum-Mechanical description of Physical Reality be considered Complete?"

Local hidden variable theory (LHVT)

Bohm Spin setup



- Local hidden variable theory:

  A spin singlet formed by two spin-1/2 particles

  $|\psi_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)$. In Q.M.

  $A: \ \vec{\sigma}_1 \cdot \vec{a} \qquad\qquad B: \vec{\sigma}_2 \cdot \vec{a}$

- In LHVT, $A(\vec{a},\vec{\lambda}) = \mathrm{sign}\,(\vec{a}\cdot\vec{\lambda}), B(\vec{b},\vec{\lambda}) = \mathrm{sign}\,(\vec{a}\cdot\vec{\lambda})$, probability describing correlation between them

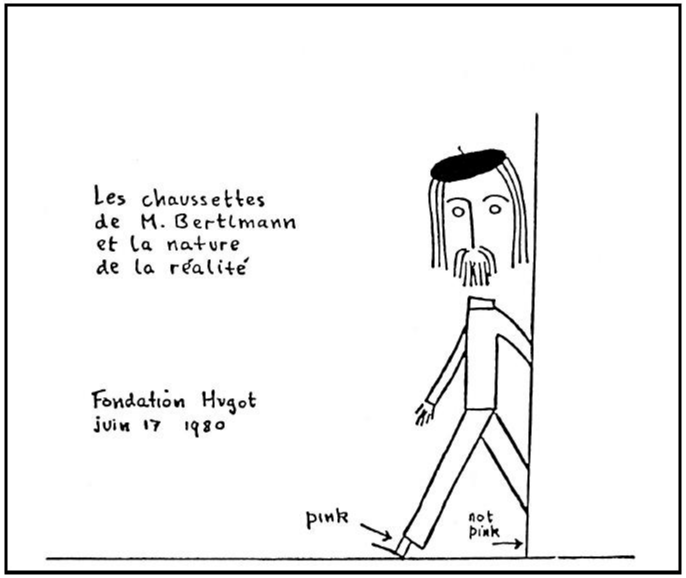
  $$P(\vec{a},\vec{b}) = \int d\lambda \rho(\lambda) A(\vec{a},\vec{\lambda}) B(\vec{b},\vec{\lambda})$$

BELL inequality(BI)

John S. Bell

John Stewart Bell, CERN, 1973

Cartoon of Berltmann's socks *by Bell (1980)*



- BELL inequality (J.S. Bell, Physics, 1, 195(1964)):

$$1 + P(\vec{b}, \vec{c}) \geq |P(\vec{a}, \vec{b}) - P(\vec{a}, \vec{c})|$$

- BI developed many variants, and tested in optics and high energy physics.

Test BI in charmonium decays

- $\eta_c \to \Lambda\bar{\Lambda} \to p\bar{p}\pi^+\pi^-$
  - Q.M.: Λ: $\mathrm{M_A} = (4\pi)^{-1/2}\left(S + P\vec{\sigma}_A \cdot \vec{A}\right)$,

    $\bar{\Lambda}$: $\mathrm{M_B} = (4\pi)^{-1/2}\left(S + P\vec{\sigma}_B \cdot \vec{B}\right)$;

$$I\left(\vec{A},\vec{B}\right) = \left(\frac{|S|^2 + |P|^2}{4\pi}\right)^2 (1 + \alpha_\Lambda^2 \vec{A} \cdot \vec{B}\ )$$

- In LHVT

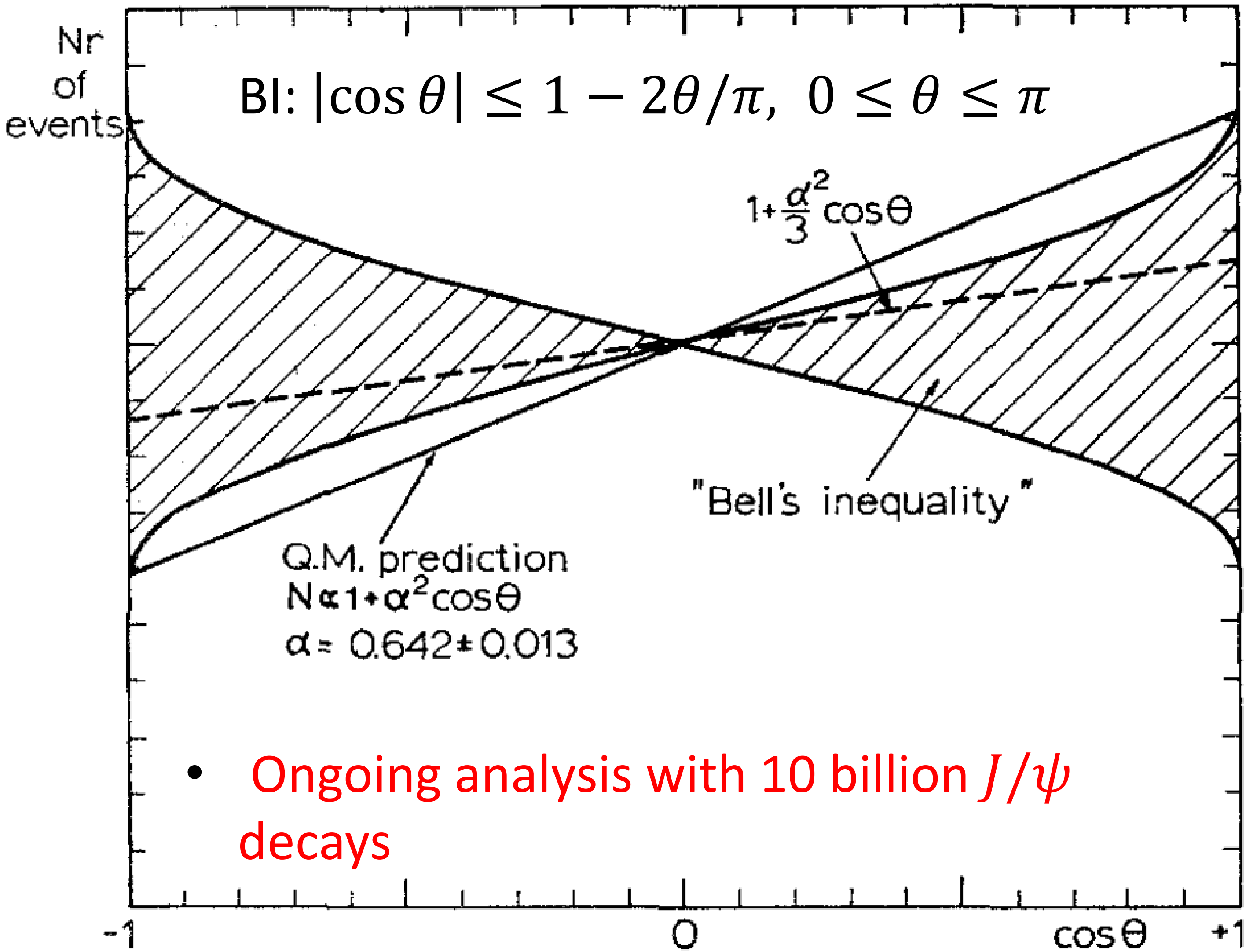
$$I\left(\vec{A},\vec{B}\right) = \left(\frac{|S|^2+|P|^2}{4\pi}\right)^2 \frac{1}{4\pi} \int (1 + \alpha_\Lambda X \cdot A)(1 + \alpha_\Lambda X.B) d\Omega$$

$$= \left(\frac{|S|^2 + |P|^2}{4\pi}\right)^2 (1 + \frac{1}{3}\alpha_\Lambda{}^2 \vec{A} \cdot \vec{B}\ )$$

Test BI in $\eta_c \rightarrow \Lambda\bar{\Lambda}$ decays

N.A. Tornqvist, Foundation of Physics, 11, 171(1981)

BI: $|\cos\theta| \leq 1 - 2\theta/\pi,\ 0 \leq \theta \leq \pi$



- Ongoing analysis with 10 billion J/ψ decays

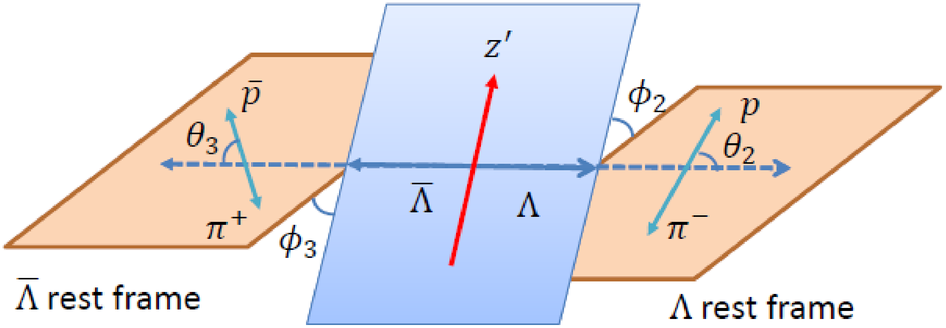
Test CH inequatlity in $\eta_c \to \Lambda\bar{\Lambda}$ decays

Generalized CH inequality: C. Qian, et al. arXiv:2002.04283

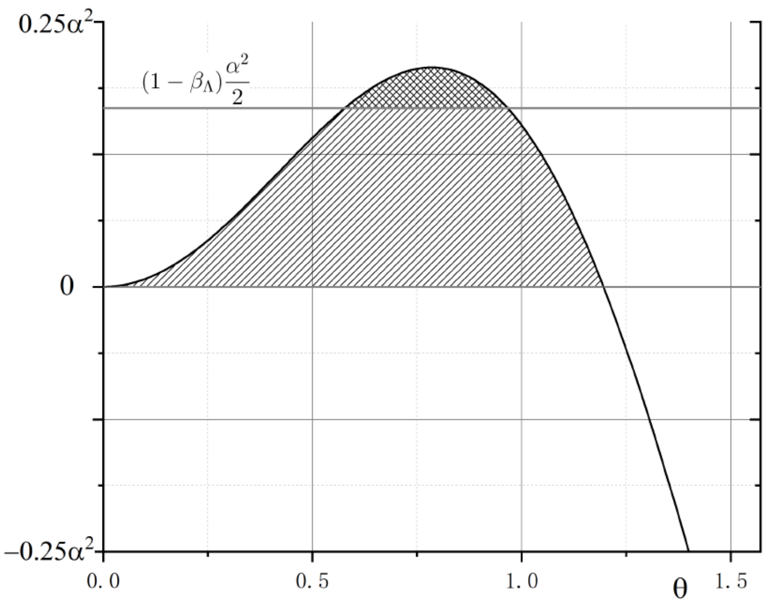
$$P(\vec{n}_1,\vec{n}_2) - P(\vec{n}_1,\vec{n}_2') + P(\vec{n}_1',\vec{n}_2) + P(\vec{n}_1',\vec{n}_2')$$

$$-(a_2+b_2)P(\vec{n}_1') - (a_1+b_1)P(\vec{n}_2) + a_1 b_2 + b_1 a_2 \leq 0 \,.$$

$$P(\vec{n}_1,\vec{n}_2) = \int_\Gamma p_m(\lambda,\vec{n}_1)p_m(\lambda,\vec{n}_2)\rho(\lambda)\,\mathrm{d}\lambda$$



$$\alpha^2\left[\frac{3\cos\theta-\cos(3\theta)}{4}-\frac{1}{2}\right] \leq 0\,.$$



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)
- $\eta_c \to \Lambda\bar{\Lambda}$ (EPR test)
- $e^{+}e^{-} \to \Lambda_c^{+}\bar{\Lambda}_c^{-}$
  - $\Lambda_c^{+} \to \Lambda\pi^{+}, \Sigma^{+}\pi^{0}, \Sigma^{0}\pi^{+}, K_S p$ (update)
  - Λ_c spin
- future charmed baryon program
  - Update Ecms up to 4.9 GeV
  - Taken data around $\Lambda_c\bar{\Lambda}_c$ threshold this year

Summary

- $\Lambda/\bar{\Lambda}$ 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.

敬请指教！

backup

Proton polarization from $\Lambda \rightarrow p\pi^-$

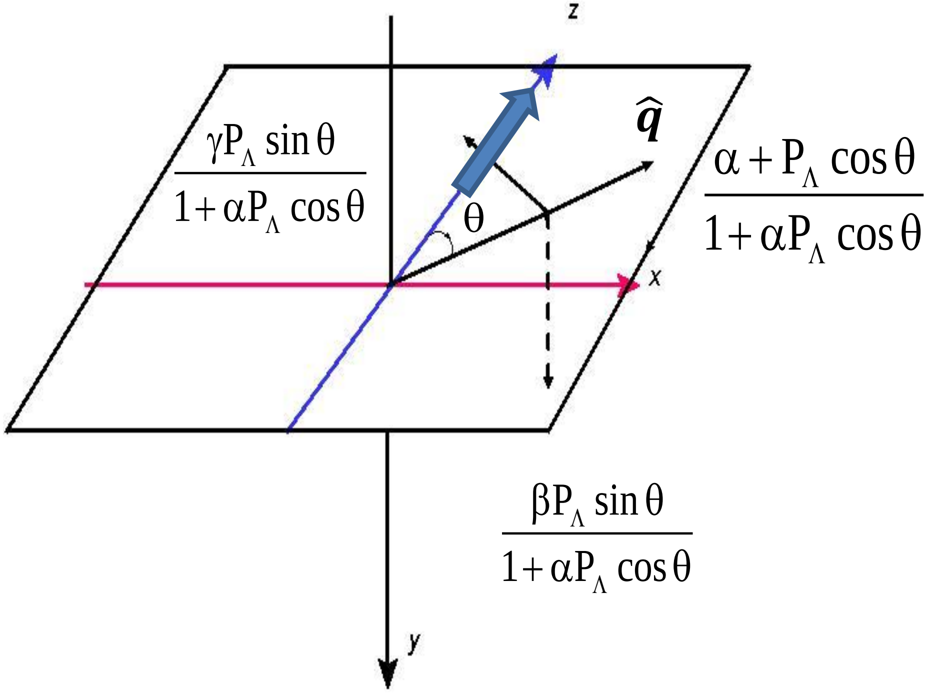
$$\vec{P}_p = \frac{(\alpha + \vec{P}_\Lambda \cdot \hat{q})\hat{q} + \beta\,(\vec{P}_\Lambda \times \hat{q}) + \gamma\,\hat{q} \times (\vec{P}_\Lambda \times \hat{q})}{(1 + \alpha \vec{P}_\Lambda \cdot \hat{q})}$$

- If $P_\Lambda = 0$ then $P_p = \alpha P_\Lambda \cdot q$
- $T-$odd transverse polarization

  $\beta \neq 0$
- If CP is conserved:

  $\alpha = -\bar{\alpha},\ \beta = -\bar{\beta},$

  $\gamma = \bar{\gamma}$ and $\Gamma = \bar{\Gamma}$



Previous Measurements

2018 PDG list

α_- FOR $\Lambda \to p\pi^-$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.642 \pm 0.013}$	**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
$\mathbf{-0.71 \pm 0.08}$	**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	$J/\psi \to \Lambda\overline{\Lambda}$

Previous Measurements

2018 PDG list

$(\alpha + \overline{\alpha})/(\alpha - \overline{\alpha})$ in $\Lambda \to p\pi^-$, $\overline{\Lambda} \to \overline{p}\pi^+$

Zero if CP is conserved; α_- and α_+ are the asymmetry parameters for $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \overline{p}\pi^+$ decay. See also the Ξ^- for a similar test involving the decay chain $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ and the corresponding antiparticle chain.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.006±0.021 OUR AVERAGE					
$-0.081 \pm 0.055 \pm 0.059$	≈ 8.7k	ABLIKIM	10	BES	$J/\psi \to \Lambda\overline{\Lambda}$
$+0.013 \pm 0.022$	96k	BARNES	96	CNTR	LEAR $\overline{p}p \to \overline{\Lambda}\Lambda$
$+0.01 \pm 0.10$	770	TIXIER	88	DM2	$J/\psi \to \Lambda\overline{\Lambda}$
-0.02 ± 0.14	10k	[1] CHAUVAT	85	CNTR	pp, $\overline{p}p$ ISR
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.07 ± 0.09	4063	BARNES	87	CNTR	See BARNES 96

[1] CHAUVAT 85 actually gives $\alpha_+(\overline{\Lambda})/\alpha_-(\Lambda) = -1.04 \pm 0.29$. Assumes polarization is same in $\overline{p}p \to \overline{\Lambda}$X and $pp \to \Lambda$X. Tests of this assumption, based on C-invariance and fragmentation, are satisfied by the data.