Future hyperon studies at BESIII

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Andrzej Kupsc

Prospects for baryon spin physics:

- $e^+e^- \to J/\psi, \psi' \to B_1\bar{B}_2$ (ground state hyperons): polarization, hyperon decay parameters
- $e^+e^- \to J/\psi, \psi' \to B_1\bar{B}_2V(P)$: spectroscopy

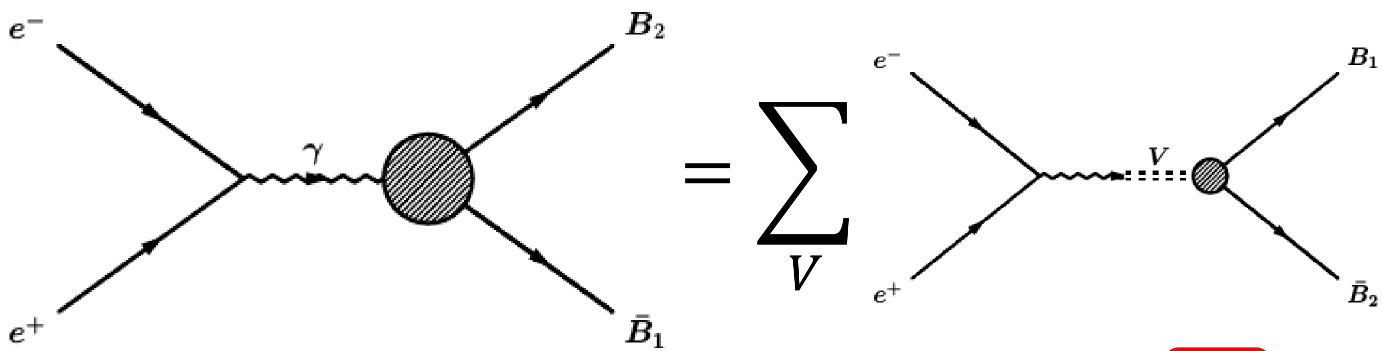
Methods:

1. G.Fäldt, AK PLB772 (2017) 16
2. E.Perotti,G.Fäldt,AK,S.Leupold,JJ.Song PRD99 (2019)056008
3. G. Fäldt, K. Schönning arXiv:1908.04157
4. P.Adlarson, AK arXiv:1908.03102

USTC 15-16 Sept. 2019 Workshop of the Baryon Production at BESIII

Baryon-antibaryon production in e^+e^- collisions

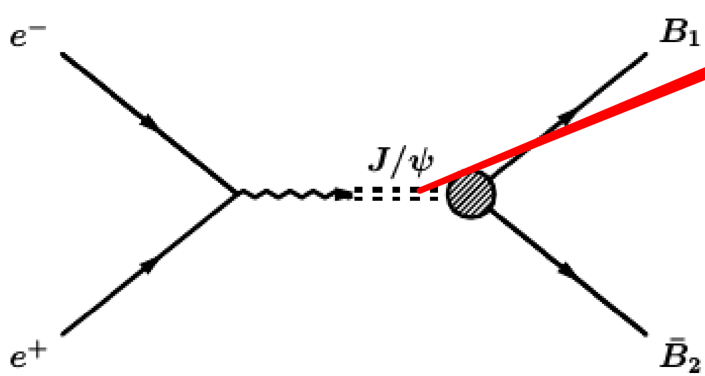
continuum:



Baryons B_1 and $\bar{B}_2$ (spin 1/2, ...)

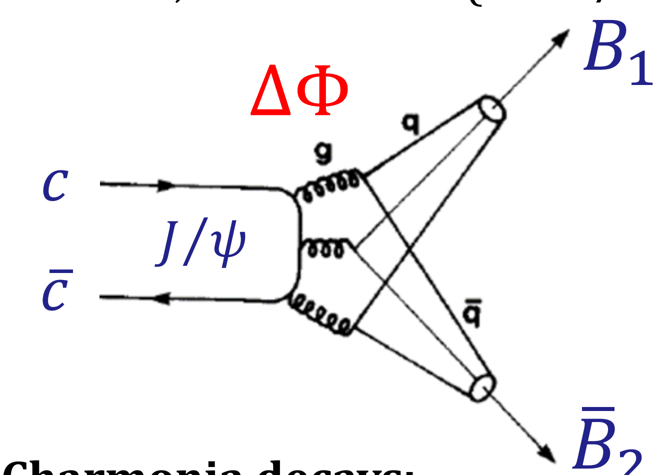
$V = \gamma, \rho, \omega, \varphi, \ldots, \boxed{J/\psi}, \psi(2S), \ldots$

J/ψ decay:



Both processes described by two complex FFs: relative phase $\Delta\Phi$

Cabibbo, Gatto PR124 (1961)1577



Time like spin 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
Fäldt EPJ A51 (2015) 74; EPJ A52 (2016)141

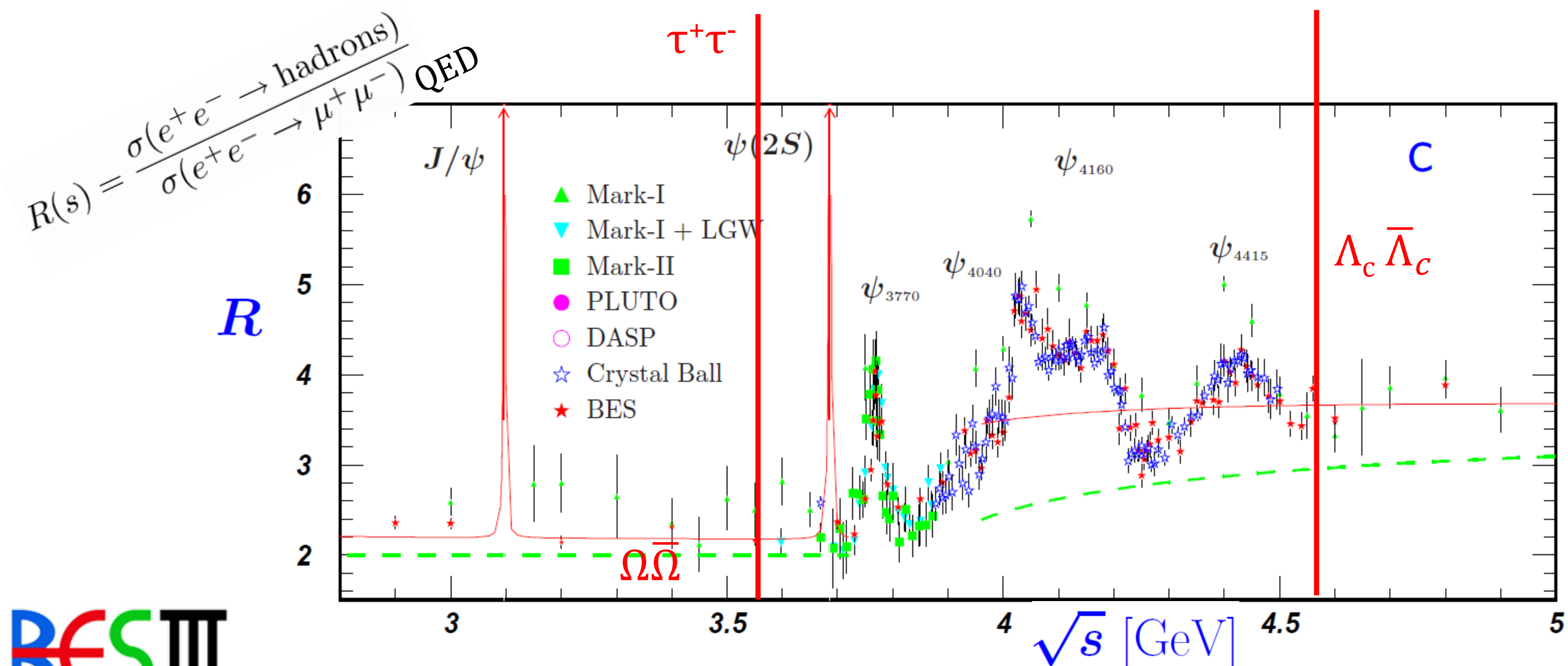
Charmonia decays:
Fäldt, AK PLB772 (2017) 16

Hyperon-$\overline{\text{hyperon}}$ pair production at BESIII

$2.0\ \text{GeV} \leq \sqrt{s} \leq 4.6\ \text{GeV}$

Thresholds:

$\Lambda\bar{\Lambda}$:	2.231 GeV	$\Sigma^+\bar{\Sigma}^-$	2.379 GeV	($\Omega\bar{\Omega}$	3.345 GeV)
$\Sigma^0\bar{\Sigma}^0$	2.385 GeV	$\Sigma^-\bar{\Sigma}^+$	2.395 GeV		
$\Xi^0\bar{\Xi}^0$	2.630 GeV	$\Xi^-\bar{\Xi}^+$	2.643 GeV		
$\Lambda\bar{\Sigma}^0$	2.308 GeV				



$J/\psi, \psi(2S) \to B\bar{B}$ Expected number of events at BESIII

$$\mathcal{B}(J/\psi \to p\bar{p}) = (21.21 \pm 0.29) \times 10^{-4}$$

decay mode	$\mathcal{B}$(units 10^{-4})	α_ψ	eff	events proposal
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	0.469 ± 0.026	40%	3200×10^3
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	0.824 ± 0.074	40%	650×10^3
$J/\psi \to \Xi^0\bar{\Xi}^0$	11.65 ± 0.04	0.66 ± 0.03	14%	670×10^3
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	2.73 ± 0.03	0.65 ± 0.09	14%	160×10^3
$J/\psi \to \Xi^-\bar{\Xi}^+$	10.40 ± 0.06	0.58 ± 0.04	19%	810×10^3
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	2.78 ± 0.05	0.91 ± 0.13	19%	210×10^3

$$\mathcal{B}(\psi' \to \Omega^-\bar{\Omega}^+) = (0.52 \pm 0.04) \times 10^{-4}$$ CLEO-c: PRD 96, 092004

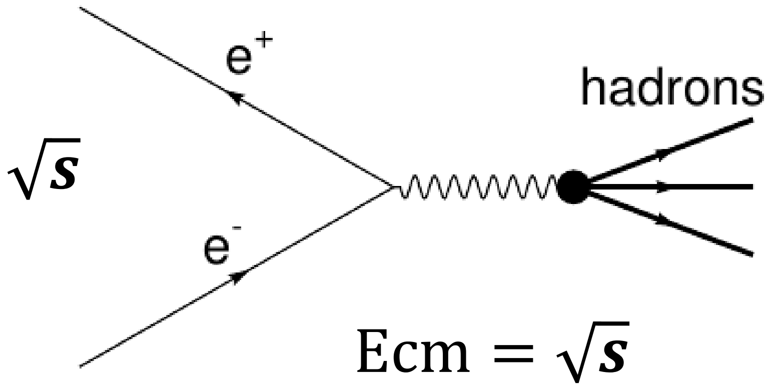
PRD 93, 072003 (2016)
PLB770,217 (2017)

PRD 95, 052003 (2017)

BESIII (Feb 2019): 10^{10} J/ψ

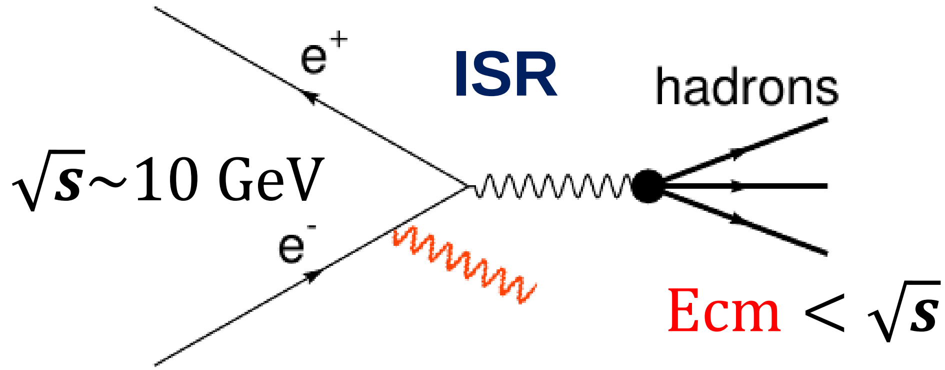
BESIII proposal:3.2x10^9 ψ(2S)

Direct scan BESIII

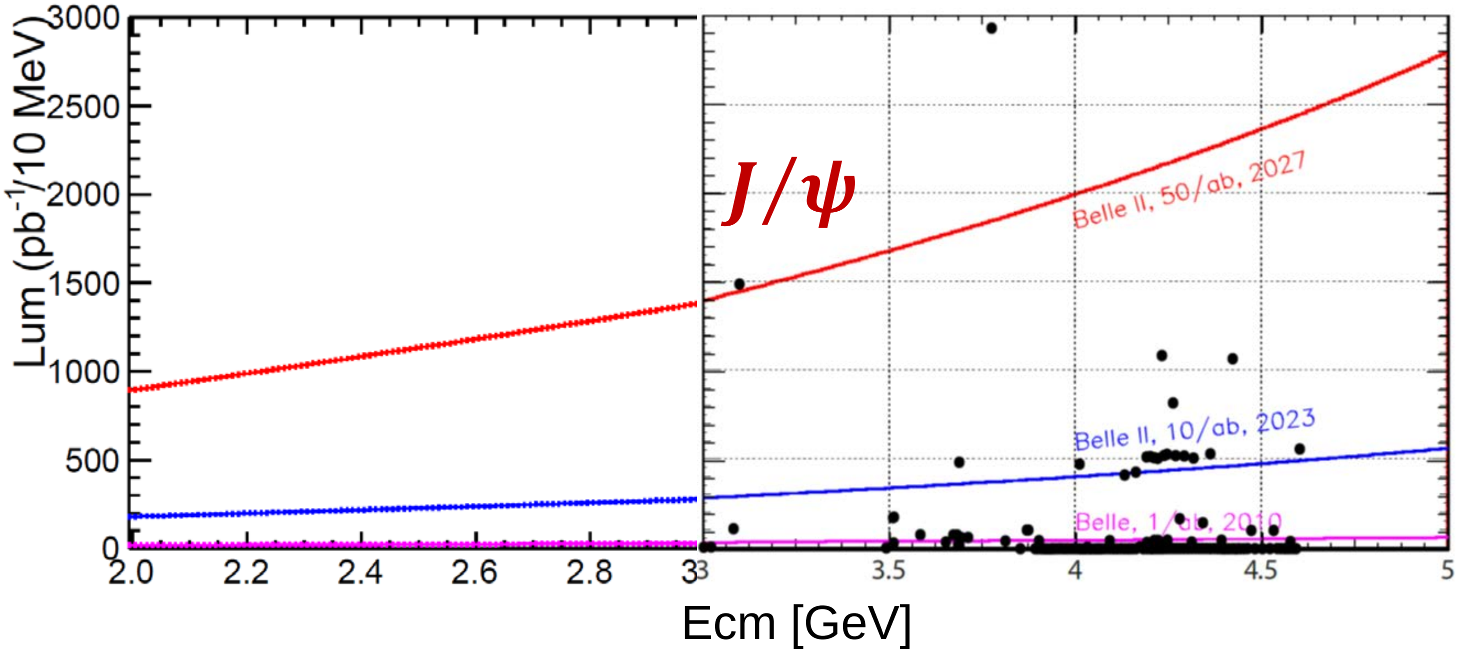


- (very) high luminosity at selected c.m. energies
- better resolution: at J/ψ 0.9 MeV: 10^{10} J/ψ

ISR BelleII



- many Ecm simultaneously
- reduced point-to-point systematics
- mass resolution limited by detector
- boost of hadronic system may help efficiency



Picture:Wolfgang Gradl & Xiaorong

Hyperon-antihyperon pairs from J/ψ and ψ(2S) decays

Motivations: CP violation, QM tests (entangled system) :

CP Asymmetries in Strange Baryon Decays
I. I. Bigi, Xian-Wei Kang, Hai-Bo Li CPC42 (2018) 013101
arXiv:1704.04708 & BESIII Hai-Bo: arXiv:1612.01775

Steve Olsen presentation on BESIII 30 years

Hyperon decay parameters, hyperon FSI, charmonium decay mechanism,...

Ground state hyperons analyses: MLL fits of angular distributions:

- $\Lambda\bar{\Lambda}, \Sigma^+\bar{\Sigma}^-, (\Sigma^-\bar{\Sigma}^+)$
- $\Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$
- $\Xi\bar{\Xi}$
- $\Omega\bar{\Omega}$

Covariant formalism **Ref 1&3**

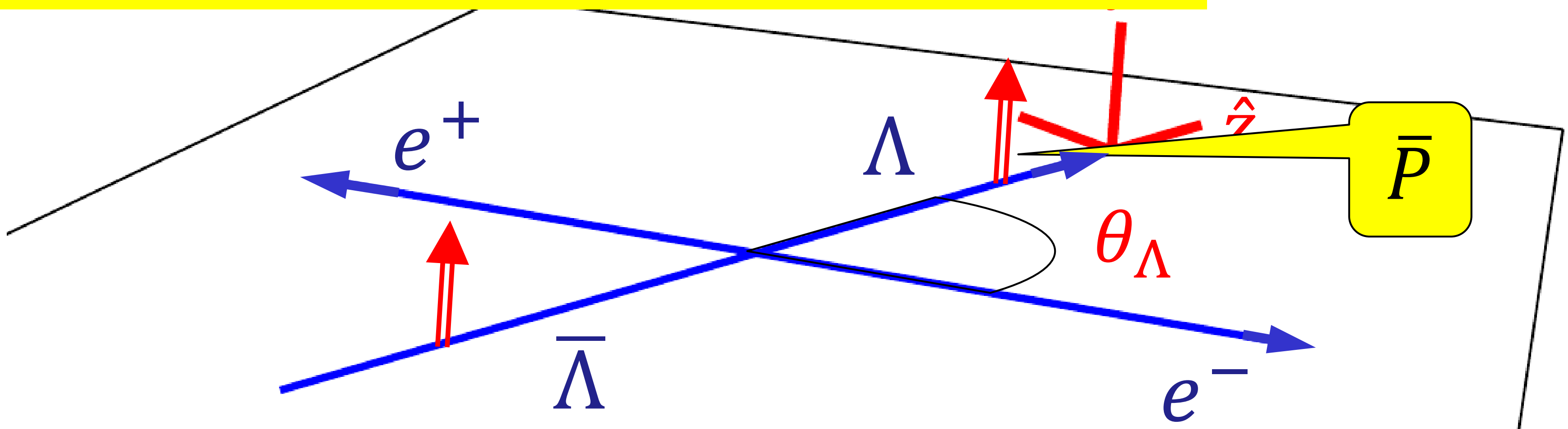
Jacob-Wick Helicity formalism (1959)

Amplitudes for precision BESIII:

$$e^+e^- \to \gamma^*(\to \psi)$$
$$\to B_{1/2}\ \bar{B}_{1/2}$$
$$\to B_{3/2}\ \bar{B}_{1/2}$$
$$\to B_{3/2}\ \bar{B}_{3/2}$$

Ref 2: Modular framework for entangled **exclusive (DT)** distributions with modifiable decay chains,
Use correct variables vs amplitudes
Weak decays sensitive to the helicity rotation definition

Baryon (spin ½) polarization in e+e-



Unpolarized e+e- beams ⇨ transverse polarization:

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

$$\Delta\Phi \neq 0$$

Angular distribution:

$$\boxed{\frac{d\Gamma}{d\Omega} \propto 1+\alpha_\psi\cos^2\theta \qquad -1 \leq \alpha_\psi \leq 1}$$

Notation:

$$R = \left|\frac{G_E}{G_M}\right| \qquad \tau = \frac{s}{4M_B^2} \qquad \left(\alpha_\psi = \frac{\tau - R^2}{\tau + R^2}\right) \qquad G_E = RG_M e^{i\Delta\Phi}$$

Baryon-antibaryon spin density matrix

$$e^+e^- \to B_1\bar{B}_2$$

General two spin ½ particle state:

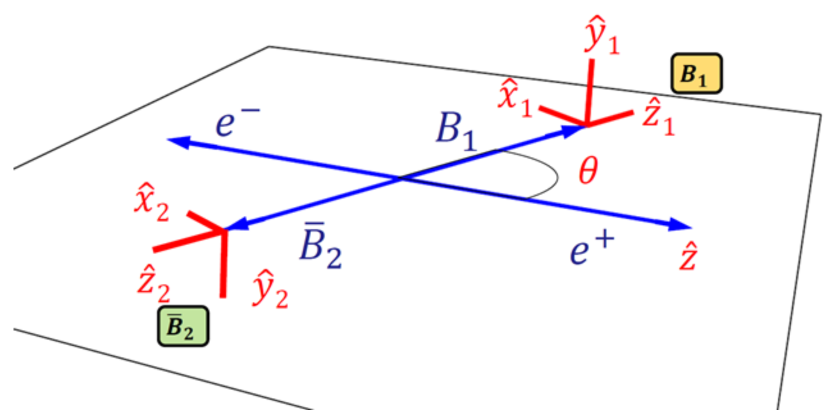
$$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\,\sigma_\mu^{B_1}\otimes\sigma_{\bar{\nu}}^{\bar{B}_2}$$

$(\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z)$

$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & 0 & \underbrace{\boxed{\beta_\psi\sin\theta\cos\theta}}_{} & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & 0 \\ 0 & -\gamma_\psi\sin\theta\cos\theta & 0 & -\alpha_\psi-\cos^2\theta \end{pmatrix}$$

P_y

$$\beta_\psi = \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi) \quad \gamma_\psi = \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)$$



E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

Hyperon decay parameters

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. LEE* AND C. N. YANG

Institute for Advanced Study, Princeton, New Jersey

Phys. Rev. 108 1645 (1957)

s wave parity violating
p wave parity conserving

$\boldsymbol{Y \to B\pi}$: $\quad {}^{1}/_{2} \to {}^{1}/_{2} + 0$

$$\alpha_Y = \frac{2\mathrm{Re}(s^* p)}{|s|^2 + |p|^2}, \quad \beta_Y = \frac{2\mathrm{Im}(s^* p)}{|s|^2 + |p|^2} = \sqrt{1-\alpha_Y^2}\sin\phi_Y$$

$$\gamma_Y = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2} = \sqrt{1-\alpha_Y^2}\cos\phi_Y$$

α_- or α_Λ

hyperon	decay (BF)	α	ϕ
$\Lambda(uds)$	$p\pi^-$ (63.9%)	$\boxed{\mathbf{0.642 \pm 0.013}}$	$-6.5^\circ \pm 3.5^\circ$
α_0	$n\pi^0$ (35.8%)		
$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$	$\bar{p}\pi^+$ (63.9%)	$\boxed{\mathbf{-0.71 \pm 0.08}}$	–
$\Sigma^-(dds)$	$n\pi^-$ (99.8%)	-0.068 ± 0.008	$10^\circ \pm 15^\circ$
$\Sigma^+(uus)$	$p\pi^0$ (51.6%)	-0.980 ± 0.017	$36^\circ \pm 34^\circ$
	$n\pi^+$ (48.3%)	-0.068 ± 0.013	$167 \pm 20^\circ$
$\Xi^0(uss)$	$\Lambda\pi^0$ (99.5%)	-0.406 ± 0.085	$21^\circ \pm 12^\circ$
$\Xi^-(dss)$	$\Lambda\pi^-$ (99.8%)	-0.458 ± 0.012	$-2.1^\circ \pm 0.8^\circ$

α_+ or $\bar{\alpha}_\Lambda$

CP asymmetry

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

Obsolete!

PDG 2018

Polarization of daughter baryons:

$$Y \to B\pi$$

$$\mathbf{P}_B = \frac{(\alpha + \mathbf{P}_Y \cdot \hat{\mathbf{n}})\hat{\mathbf{n}} + \beta(\mathbf{P}_Y \times \hat{\mathbf{n}}) + \gamma \hat{\mathbf{n}} \times (\mathbf{P}_Y \times \hat{\mathbf{n}})}{1 + \alpha \mathbf{P}_Y \cdot \hat{\mathbf{n}}}$$ PDG

$$\mathbf{P}_Y = 0 \;\Rightarrow\; \mathbf{P}_B = \alpha\, \hat{\mathbf{n}}$$

Density matrix for a spin ½ particle in the rest frame:

$$\rho_{1/2} = \frac{1}{2}\sum_{\mu=0}^{3} I_\mu \sigma_\mu = \frac{1}{2} I_0 \begin{pmatrix} 1 + P_z & P_x - iP_y \\ P_x + iP_y & 1 - P_z \end{pmatrix}$$

$$\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z$$

Transformation of base matrices:

$$\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^- \quad e.g.\ \Lambda \to p + \pi^-$$

Decay matrices

$$\boxed{\sigma_\mu \to \sum_{\nu=0}^{3} a_{\mu,\nu} \sigma_\nu^d}$$

4×4 decay matrix: $a_{\mu,\nu}$

E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

Measuring α, β, γ in the 20th century

James Cronin
1931-2016

Oliver Overseth
1928-2008

PHYSICAL REVIEW VOLUME 129, NUMBER 4 15 FEBRUARY 1963

Measurement of the Decay Parameters of the Λ^0 Particle*

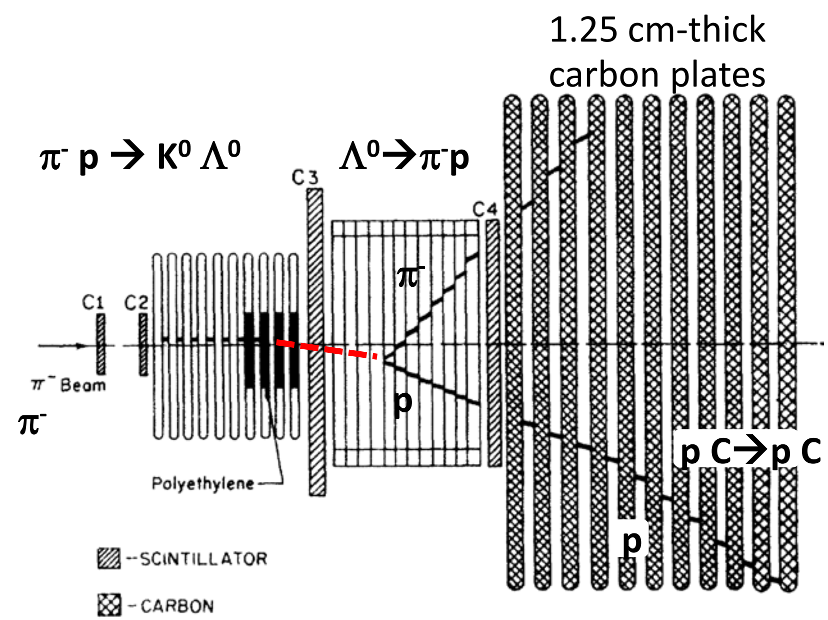
JAMES W. CRONIN AND OLIVER E. OVERSETH†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 26 September 1962)

The decay parameters of $\Lambda^0 \to \pi^- + p$ have been measured by observing the polarization of the decay protons by scattering in a carbon-plate spark chamber. The experimental procedure is discussed in some detail. A total of 1156 decays with useful proton scatters was obtained. The results are expressed in terms of polarization parameters, α, β, and γ given below:

$$\alpha = 2\,\mathrm{Re}\,sp^*/(|s|^2+|p|^2) = +0.62\pm0.07,$$
$$\beta = 2\,\mathrm{Im}\,sp^*/(|s|^2+|p|^2) = +0.18\pm0.24,$$
$$\gamma = |s|^2-|p|^2/(|s|^2+|p|^2) = +0.78\pm0.06,$$

where s and p are the s- and p-wave decay amplitudes in an effective Hamiltonian $s+p\boldsymbol{\sigma}\cdot\mathbf{p}/|\mathbf{p}|$, where $\mathbf{p}$ is the momentum of the decay proton in the center-of-mass system of the Λ^0, and $\boldsymbol{\sigma}$ is the Pauli spin operator. The helicity of the decay proton is positive. The ratio $|p|/|s|$ is $0.36_{-0.06}^{+0.05}$ which supports the conclusion that the $K\Lambda N$ parity is odd. The result $\beta=0.18\pm0.24$ is consistent with the value $\beta=0.08$ expected on the basis of time-reversal invariance.

$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\dot{z}' + \beta P_\Lambda \dot{x}' + \gamma P_\Lambda \dot{y}'}{1+\alpha P_\Lambda \cos\theta}$$



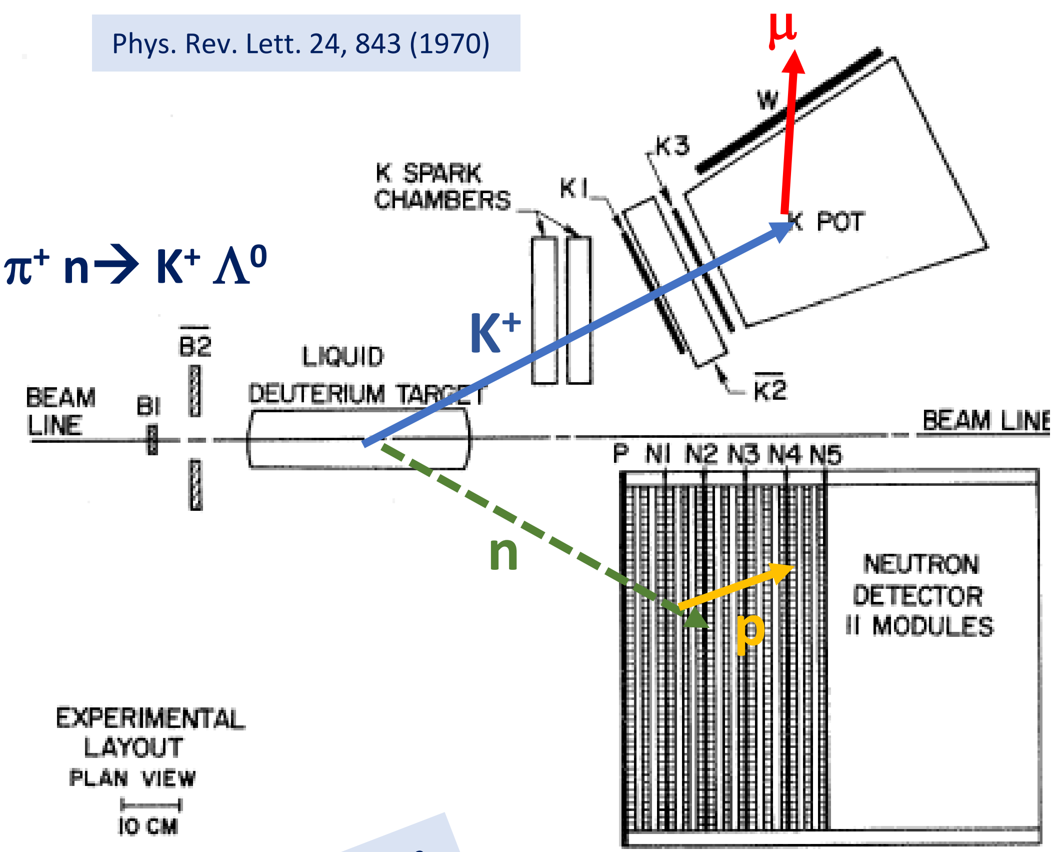
no H_2 target, no magnet; use kinematics and proton's range in carbon to infer E_p

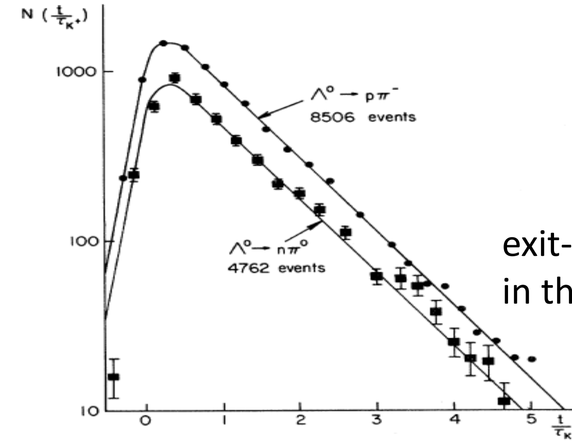
Slide from Steve Olsen

Olsen et al., α_0 parameter in $\Lambda^0 \rightarrow n\pi^0$ decays

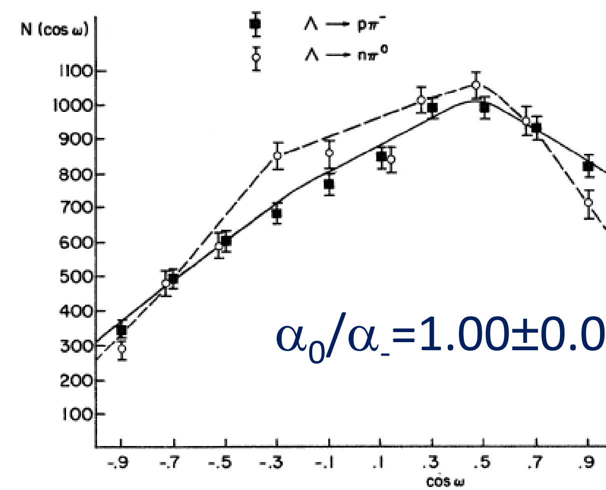
Phys. Rev. Lett. 24, 843 (1970)

$\pi^+ n \rightarrow K^+ \Lambda^0$



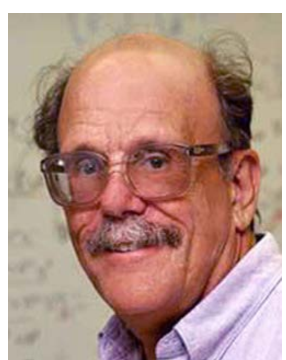


exit-entry time in the H_2O tank



$\alpha_0/\alpha_- = 1.00 \pm 0.07$

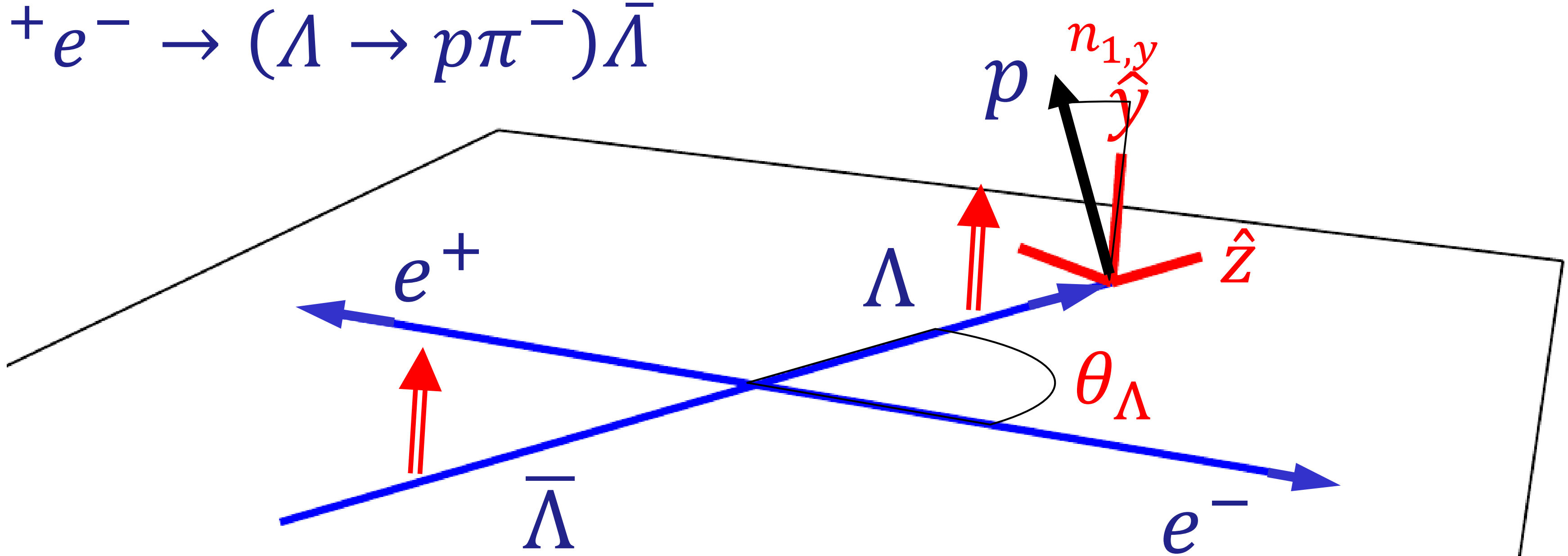
Slide from Steve Olsen



(Steve PhD thesis)

Inclusive decay angular distributions

$e^+e^- \to (\Lambda \to p\pi^-)\bar{\Lambda}$



$$\frac{d\Gamma}{d\cos\theta_\Lambda d\Omega_1} \propto \left(1+\alpha_\psi \cos^2\theta_\Lambda\right) + \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\,\alpha_- n_{1,y}$$

$\Lambda \to p\pi^-$: $\hat{\mathbf{n}}_1 \to \Omega_1 = (\cos\theta_1, \phi_1)$: α_-

$\Rightarrow$Determine product: $\alpha_- P_y \sim \alpha_- \sin(\Delta\Phi)$

Exclusive joint angular distribution

$$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$$

$\Lambda \to p\pi^-$: $\hat{\mathbf{n}}_1 \to (\cos\theta_1, \phi_1)$: α_- $\bar{\Lambda} \to \bar{p}\pi^+$: $\hat{\mathbf{n}}_2 \to (\cos\theta_2, \phi_2)$: α_+

ξ : $(\cos\theta_\Lambda, \hat{\mathbf{n}}_1, \hat{\mathbf{n}}_2)$ 5D PhSp

$$d\Gamma \propto W(\xi; \alpha_\psi, \Delta\Phi, \alpha_-, \alpha_+) =$$

$$1 + \alpha_\psi \cos^2\theta_\Lambda$$

Cross section

Spin correlations

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

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

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

Polarization

$\Delta\Phi \neq 0 \Rightarrow$ independent determination of α_- and α_+

Fäldt, AK PLB772 (2017) 16

Exclusive joint angular distribution (modular form)

$$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$$

General two spin ½ particle state: $$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^{\Lambda} \otimes \sigma_{\bar{\nu}}^{\bar{\Lambda}}$$

$(\sigma_0 = \mathbf{1}_2, \sigma_1 = \sigma_x, \sigma_2 = \sigma_y, \sigma_3 = \sigma_z)$

$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi \cos^2\theta & 0 & \beta_\psi \sin\theta\cos\theta & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi \sin\theta\cos\theta \\ -\beta_\psi \sin\theta\cos\theta & 0 & \alpha_\psi \sin^2\theta & 0 \\ 0 & -\gamma_\psi \sin\theta\cos\theta & 0 & -\alpha_\psi - \cos^2\theta \end{pmatrix}$$

$$\beta_\psi = \sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi) \qquad \gamma_\psi = \sqrt{1-\alpha_\psi^2}\,\cos(\Delta\Phi)$$

Apply decay matrices:

$$\sigma_\mu^{\Lambda} \to \sum_{\mu'=0}^{3} a_{\mu,\mu'}^{\Lambda}\, \sigma_{\mu'}^{p}$$

The angular distribution:

$$\boxed{W = Tr\,\rho_{p,\bar{p}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}\, a_{\mu,0}^{\Lambda}\, a_{\bar{\nu},0}^{\bar{\Lambda}}}$$

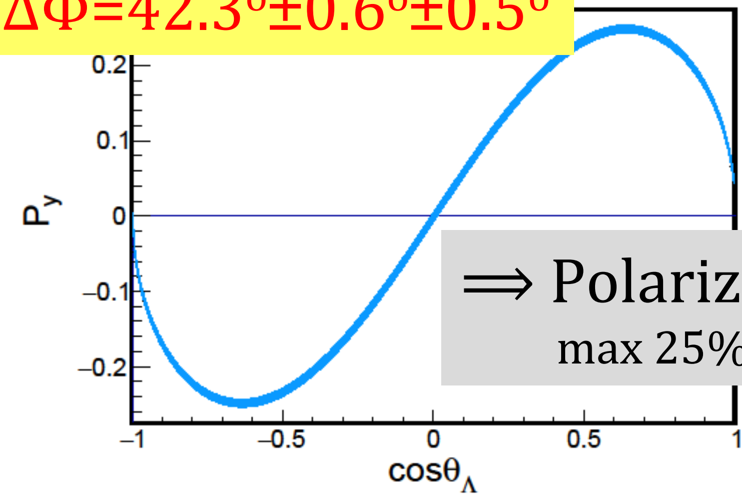
E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

BESIII results: $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

BESIII Nature Phys. 15,631(2019)

$\Lambda \to p\pi^-$: $\alpha_- = 0.750 \pm 0.009 \pm 0.004$

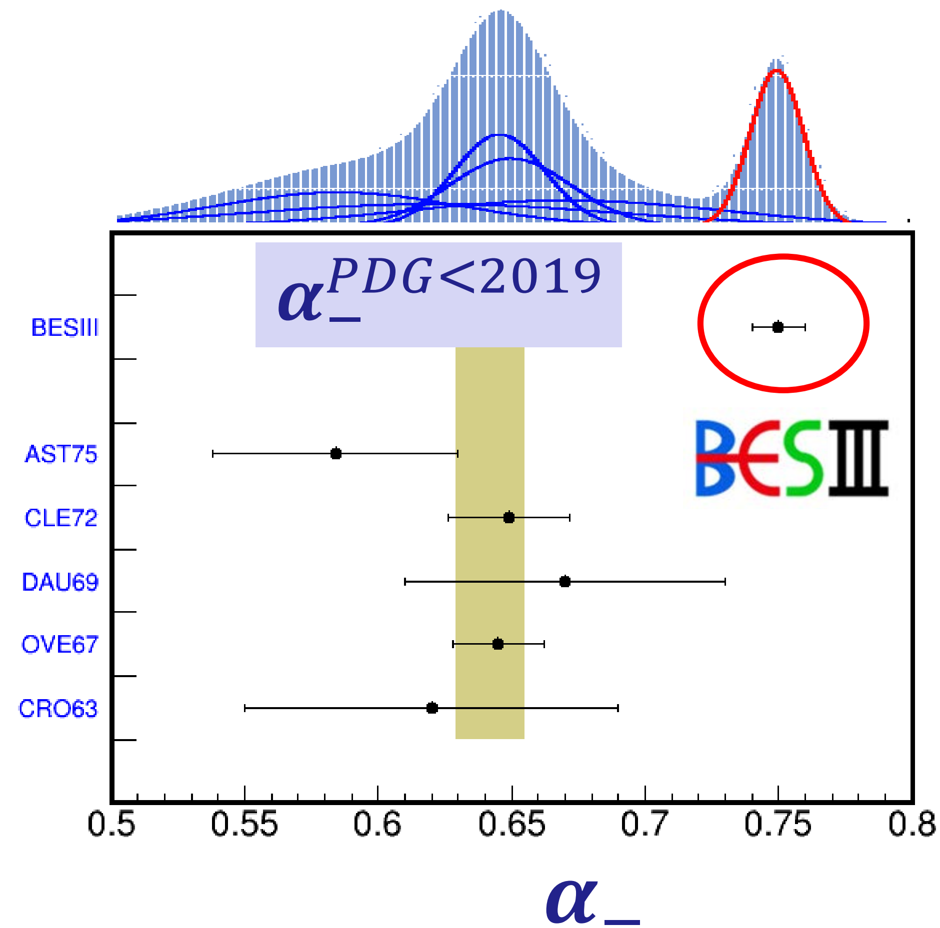
$\Delta\Phi = 42.3^o \pm 0.6^o \pm 0.5^o$



$\Longrightarrow$ Polarization:
max 25%

$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$

$\Delta I = \frac{1}{2}$ **rule violation**



CP test: $$A_\Lambda = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

$\boxed{A_\Lambda = -0.006 \pm 0.012 \pm 0.007}$

17(3)% larger

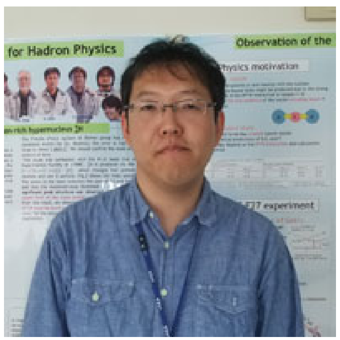
$A_\Lambda = 0.013 \pm 0.021$
PS185 PRC54(96)1877

Liang's talk $J/\psi, \psi' \to \Sigma^+\bar{\Sigma}^-$

2) Why the big change in α?

Why different?

from: Kiyoshi Tanida
JAEA Japan



- Multiple scattering:
  - E.g., at 95 MeV with 3 cm scatterer (target), θ_0 becomes as large as 1.5 degree.
    → 5 degree multiple scattering occurs with a probability of 1 % order and dominates over single scattering
  - Actual scatterer thickness is even larger
  - Of course, analyzing power for multiple Coulomb scattering is almost 0
    → Can explain the difference
- Note: effective A_N depends on target thickness
  - This is why target thickness is explicit in the new data.
  - We have to be careful!!

Also: in PDG$\leq$ 2018 syst uncertainty was not included

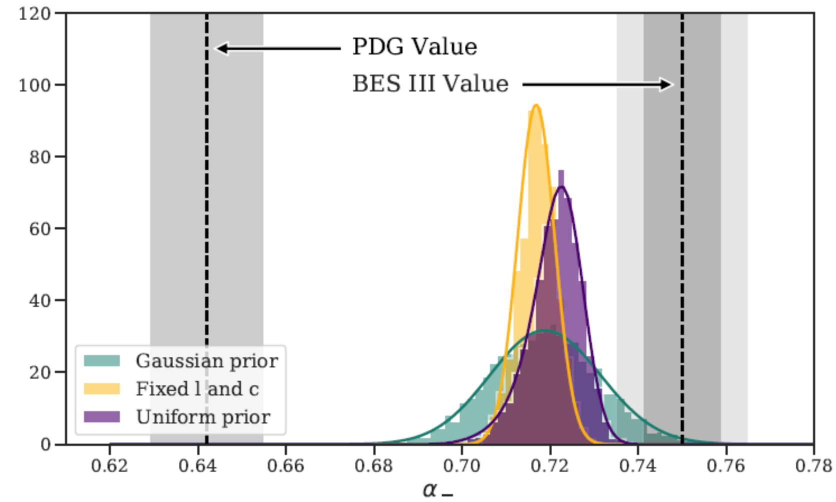
Slide from Steve Olsen

How to verify the result?

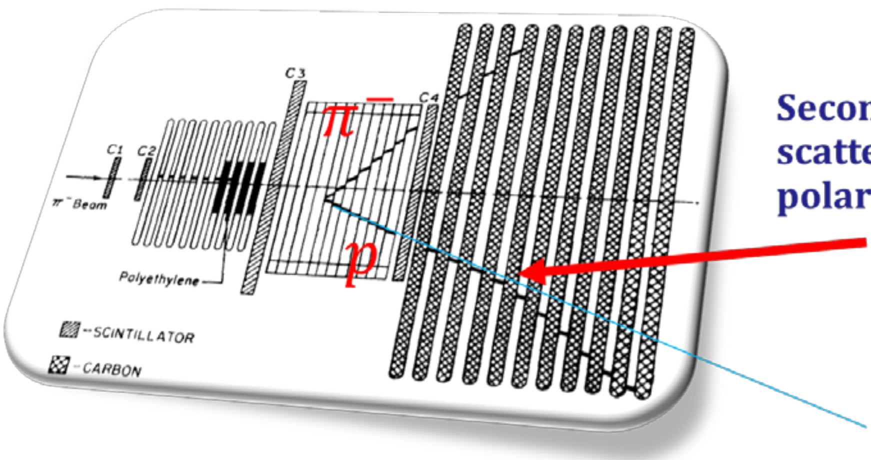
$\vec{\gamma}p \to K^+\Lambda$

$\alpha_- = 0.721(6)(5)$

D. Ireland et al arXiv:1904.07616



Measure proton polarization?



Secondary scattering of polarized proton

$$\langle\alpha_-\rangle_{\text{BESIII}} = \frac{\alpha_- - \alpha_+}{2} = 0.754(3)(2)$$

Since $\rho(stat) = 0.82$ and using quoted syst uncertainties for $\alpha_-, \alpha_+, A_\Lambda$ to deduce $\rho(syst) = 0.835$

ie 4% difference with 3.8 σ
new puzzle?...

Independent verifications at BESIII:

$$\eta_c \to \Lambda\bar{\Lambda}$$

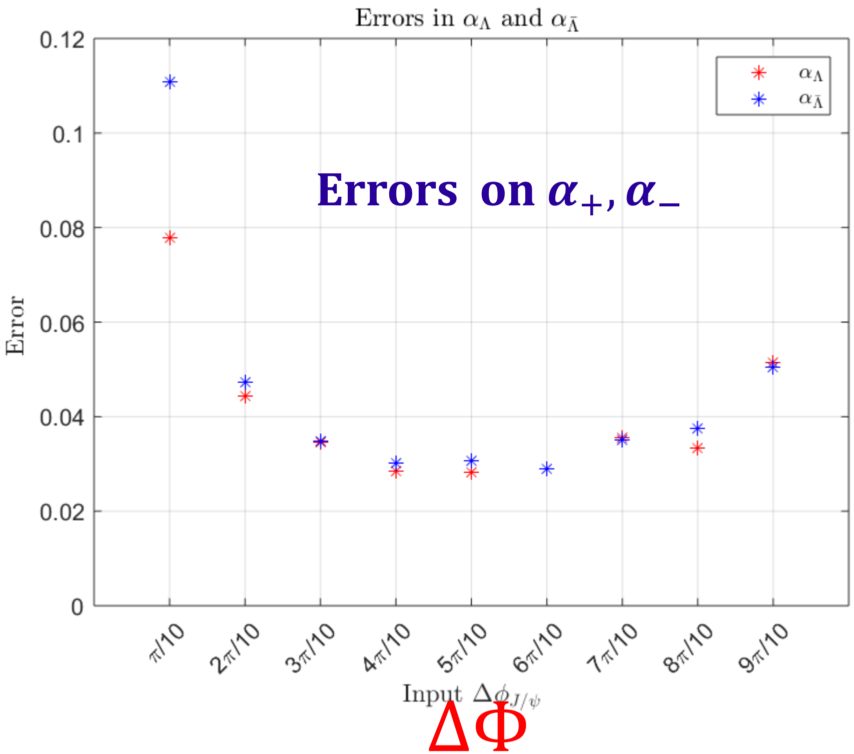
$$J/\psi \to \gamma\eta_c \to \gamma\Lambda\bar{\Lambda}$$

$$BF = 1.7\% \times 1.1 \times 10^{-3}$$

$$W = (1 - \alpha_-\alpha_+ \cos\theta_{p\bar{p}})$$

$e^+e^- \to J/\psi \to \Sigma^0\overline{\Sigma}^0 \to \Lambda\gamma\overline{\Lambda}\gamma \to p\pi^-\gamma\bar{p}\pi^+\gamma$

$$W = \sum_{\mu,\bar{\nu}} C_{\mu\bar{\nu}} \sum_{\mu',\bar{\nu}'} \breve{a}^{\Sigma^0}_{\mu,\mu'} \breve{a}^{\overline{\Sigma}^0}_{\bar{\nu},\bar{\nu}'} a^{\Lambda}_{\mu',0} a^{\overline{\Lambda}}_{\bar{\nu}',0}$$



For EM decay $\Sigma \to \Lambda\gamma$

$$\breve{a}_{00} = 1\,,$$

$$\breve{a}_{13} = -\sin\theta\cos\phi\,,$$

$$\breve{a}_{23} = -\sin\theta\sin\phi\,,$$

$$\breve{a}_{33} = -\cos\theta\,,$$

G. Fäldt, K. Schönning arXiv:1908.04157

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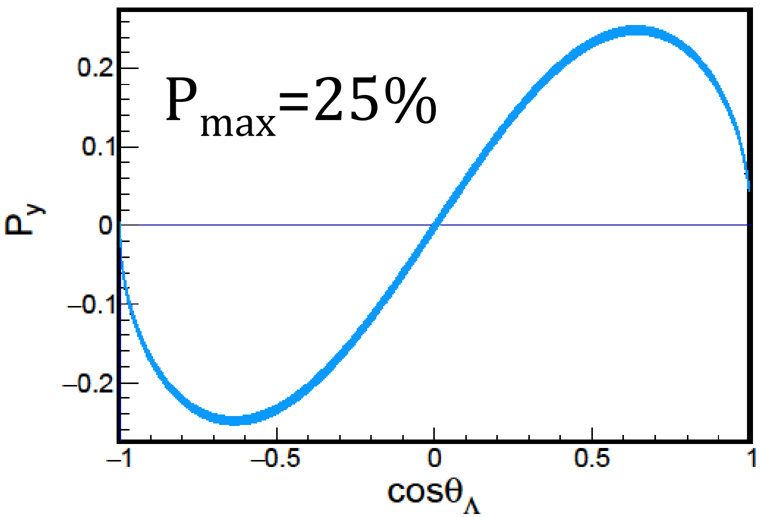
Comparison of $\Lambda\bar{\Lambda}$ and $\Lambda\bar{\Lambda}$ (simplified)

$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda\pi^-\bar{\Lambda}\pi^+$



P_{avg}=11%

Λ from $\Xi^- \to \Lambda\pi^-$ is polarized even if Ξ^- unpolarized:
$P_\Lambda = |\alpha_\Xi| \approx 39\%$

$$W \propto 1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p$$

Question: Can one determine α_Λ in unique way?

$$e^+e^- \to J/\psi \to \Xi^-\overline{\Xi}^+ \to \Lambda\pi^-\overline{\Lambda}\pi^+ \to \mathrm{p}\pi^-\pi^-\overline{\mathrm{p}}\pi^+\pi^+$$

$d\Gamma \propto W(\xi;\omega)$ ξ 9 kinematical variables 9D PhSp

Parameters: 2 production + 6 for decay chains

$$\omega = (\alpha_\psi, \Delta\Phi, \overbrace{\alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda})$$

$$\boxed{W = \sum_{\mu,\bar{\nu}} C_{\mu\bar{\nu}} \sum_{\mu',\bar{\nu}'} a^{\Xi}_{\mu,\mu'} a^{\overline{\Xi}}_{\bar{\nu},\bar{\nu}'} a^{\Lambda}_{\mu',0} a^{\overline{\Lambda}}_{\bar{\nu}',0}}$$

$\Delta\Phi \neq 0$ is not needed!

Variables and parameters factorize:

$$W(\xi;\omega) = \sum_{k=1}^{M} f_k(\omega) T_k(\xi)$$

	$\Xi^-\overline{\Xi}^+$	$\Lambda\overline{\Lambda}$
$\Delta\Phi \neq 0$:	$M = 72$	(7)
$\Delta\Phi = 0$:	$M = 56$	(5)

E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

Asymptotic likelihood method

$$\boxed{V_{kl}^{-1} = E\left(-\frac{\partial^2 \ln \mathcal{L}}{\partial\omega_k \partial\omega_l}\right) = N\int \frac{1}{\mathcal{P}}\frac{\partial\mathcal{P}}{\partial\omega_k}\frac{\partial\mathcal{P}}{\partial\omega_l}d\xi}$$

V_{kl} – covariance matrix

$$\mathcal{L}(\omega) = \prod_{i=1}^{N}\mathcal{P}(\xi_i,\omega) \equiv \prod_{i=1}^{N}\frac{\mathcal{W}(\xi_i,\omega)}{\int \mathcal{W}(\xi,\omega)d\xi},$$

Tool to determine:

- Best possible (ultimate) sensitivity and correlations for parameters
- Structure of complicated angular distribution:
  e.g. V_{kl}^{-1}singular – parameters cannot be determined separately

Validation of the method

$$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$$

	$\bar{\alpha}_\Lambda$	α_ψ	$\Delta\Phi$
α_Λ	0.87	-0.05	-0.07
$\bar{\alpha}_\Lambda$		0.05	0.07
α_ψ			0.28

$$\sigma(\alpha_\Lambda) = \frac{7}{\sqrt{N}} \qquad (0.011)$$

$$\sigma(A_\Lambda) = \frac{9}{\sqrt{N}} \qquad (0.014)$$

Consistent with BESIII Nature Phys. 15,631(2019)

$e^+e^- \to J/\psi \to \Xi\bar{\Xi}$

Correlation matrix:

$\sigma(\alpha_\Xi) = \frac{2}{\sqrt{N}}$

$\sigma(\phi_\Xi) = \frac{6}{\sqrt{N}}$

$\sigma(\alpha_\Lambda) = \frac{3}{\sqrt{N}}$

	$\bar{\alpha}_\Xi$	α_Λ	$\bar{\alpha}_\Lambda$	ϕ_Ξ	$\bar{\phi}_\Xi$	α_ψ	$\Delta\Phi$
α_Ξ	0.03	0.37	0.11	0.0	0.0	0.0	0.0
$\bar{\alpha}_\Xi$		0.11	0.37	0.0	0.0	0.0	0.0
α_Λ			0.43	0.0	0.0	−0.1	0.0
$\bar{\alpha}_\Lambda$				0.0	0.0	0.1	0.0
ϕ_Ξ					0.0	0.0	0.0
$\bar{\phi}_\Xi$						0.0	0.0
α_ψ							0.0

$\Delta\Phi = 0$

$\sigma(A_\Lambda) = \frac{3.3}{\sqrt{N}}$

P.Adlarson, AK arXiv:1908.03102

$e^+e^- \rightarrow J/\psi \rightarrow \Xi\bar{\Xi}$

Correlation matrix:

$\Delta\Phi = 0$

	$\bar{\alpha}_\Xi$	α_Λ	$\bar{\alpha}_\Lambda$	ϕ_Ξ	$\bar{\phi}_\Xi$	α_ψ	$\Delta\Phi$
α_Ξ	0.03	0.37	0.11	0.0	0.0	0.0	0.0
$\bar{\alpha}_\Xi$		0.11	0.37	0.0	0.0	0.0	0.0
α_Λ			0.43	0.0	0.0	-0.1	0.0
$\bar{\alpha}_\Lambda$				0.0	0.0	0.1	0.0
ϕ_Ξ					0.0	0.0	0.0
$\bar{\phi}_\Xi$						0.0	0.0
α_ψ							0.0

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

	$\bar{\alpha}_\Xi$	α_Λ	$\bar{\alpha}_\Lambda$
α_Ξ	0.01	0.31	0.07
$\bar{\alpha}_\Xi$		0.07	0.31
α_Λ			0.39

$$\sigma(\alpha_\Xi) = \frac{2}{\sqrt{N}}$$

$$\sigma(\phi_\Xi) = \frac{6}{\sqrt{N}}$$

$$\sigma(\alpha_\Lambda) = \frac{3}{\sqrt{N}}$$

$$\sigma(A_\Lambda) = \frac{3.3}{\sqrt{N}}$$

P.Adlarson, AK arXiv:1908.03102

Spin density matrix for e^+e^- -> $\Omega^-\Omega^+$

$$\rho_{3/2,\overline{3/2}}^{\lambda_1\lambda_2,\lambda_{1'}\lambda_{2'}} = \sum_{\kappa=\pm1} D^{1*}_{\kappa,\lambda_1-\lambda_2}(0,\theta_\Omega,0) D^{1}_{\kappa,\lambda_{1'}-\lambda_{2'}}(0,\theta_\Omega,0) A_{\lambda_1\lambda_2} A^*_{\lambda_{1'}\lambda_{2'}}$$

$$A = \begin{pmatrix} \mathbf{h}_4 & \mathbf{h}_3 & 0 & 0 \\ \mathbf{h}_3 & \mathbf{h}_1 & \mathbf{h}_2 & 0 \\ 0 & \mathbf{h}_2 & \mathbf{h}_1 & \mathbf{h}_3 \\ 0 & 0 & \mathbf{h}_3 & \mathbf{h}_4 \end{pmatrix}$$

(Complex) Form Factors

$$\mathbf{h}_k \to h_k \exp(i\phi_k)$$

Using base 3/2 spin matrices Q:

M.G.Doncel, L.Michel, P.Minnaert Nucl. Phys. B38, 477(1972)

$$\rho_{3/2,\overline{3/2}} = \sum_{\mu=0}^{15} \sum_{\bar{\nu}=0}^{15} C_{\mu,\bar{\nu}}\, Q_\mu \otimes Q_{\bar{\nu}}$$

Single tag angular distribution

Single 3/2-spin baryon density matrix is

$$\rho_{3/2} = \sum_{\mu=0}^{15} r_\mu Q_\mu = \sum_{\mu=0}^{15} C_{\mu,0} Q_\mu$$

Angular distribution (using decay matrices in helicity frames):

$$W = \sum_{\mu=0}^{15}\sum_{\kappa=0}^{3} C_{\mu,0}\, \boxed{b^{\Omega}_{\mu,\kappa}}\, \boxed{a^{\Lambda}_{\kappa,0}}$$

decay 1/2->1/2 0 (Λ->pπ)

decay 3/2->1/2 0 (Ω->ΛK)

$$r_0 = (1+\cos^2\theta_\Omega)(h_2^2+2h_3^2) + 2\sin^2\theta_\Omega(h_1^2+h_4^2)$$

$$r_1 = 2\sin 2\theta_\Omega \frac{2\Im(\mathbf{h}_1\mathbf{h}_2^*) + \sqrt{3}\Im(\mathbf{h}_3^*(\mathbf{h}_1+\mathbf{h}_4))}{\sqrt{30}}$$

$$r_6 = -\frac{2\sin^2\theta_\Omega(h_1^2-h_4^2) + h_2^2(\cos^2\theta+1)}{\sqrt{3}}$$

$$r_7 = \sqrt{2}\sin 2\theta_\Omega \frac{\Re(\mathbf{h}_3^*(\mathbf{h}_4-\mathbf{h}_1))}{\sqrt{3}}$$

$$r_8 = 2\sin^2\theta_\Omega \frac{\Re(\mathbf{h}_3\mathbf{h}_2^*)}{\sqrt{3}}$$

$$r_{10} = 2\sin^2\theta_\Omega \frac{\Im(\mathbf{h}_3\mathbf{h}_2^*)}{\sqrt{3}}$$

$$r_{11} = 2\sin 2\theta_\Omega \frac{\Im(\sqrt{3}\mathbf{h}_2\mathbf{h}_1^* + \mathbf{h}_3^*(\mathbf{h}_1+\mathbf{h}_4))}{\sqrt{15}}$$

$$\alpha_\psi = \frac{h_2^2 - 2(h_1^2 - h_3^2 + h_4^2)}{h_2^2 + 2(h_1^2 + h_3^2 + h_4^2)}$$

$$\frac{d\Gamma}{d\cos\theta_\Omega} = 1 + \alpha_\psi \cos^2\theta_\Omega$$

E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

Polarization of a spin 3/2 particle:

$$\rho_{3/2} = r_0 \left(Q_0 + \frac{3}{4} \sum_{M=-1}^{1} \overbrace{r^1_M}^{r^1_{-1} \to P_y \;\; r^1_0 \to P_x \;\; r^1_1 \to P_z} Q^1_M + \frac{3}{4} \sum_{M=-2}^{2} r^2_M Q^2_M + \frac{3}{4} \sum_{M=-3}^{3} r^3_M Q^3_M \right)$$

M.G.Doncel, L.Michel, P.Minnaert Nucl. Phys. B38, 477(1972)

real coefficients,
scalable J=1/2,3/2,...

$$\frac{3}{4} Q^L_M \to Q_\mu \,, \mu = 1, \dots, 15$$

$$Q_0 = \frac{1}{4} I$$

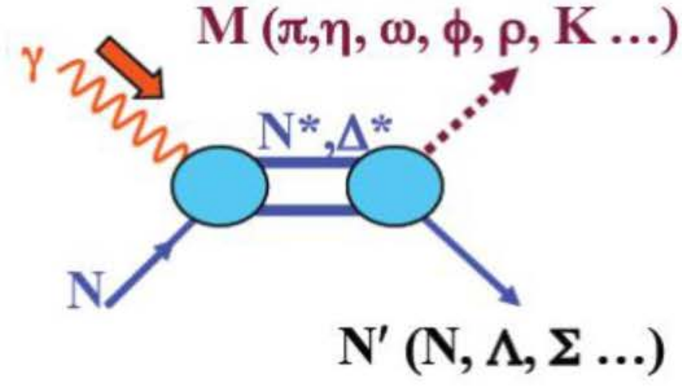
$$\rho_{3/2} = \sum_{\mu=0}^{15} r_\mu Q_\mu$$

Degree of polarization

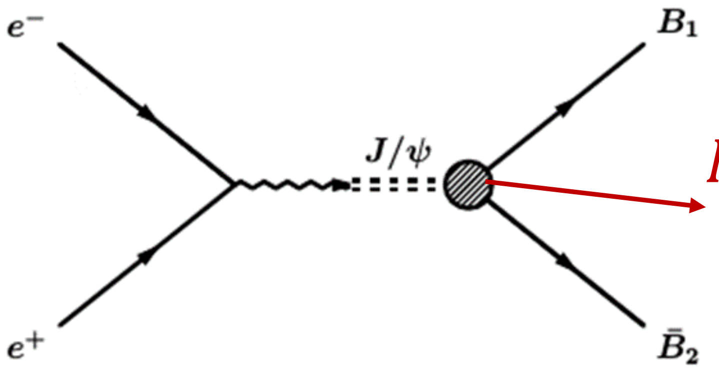
$$d(\rho_{3/2}) = \sqrt{\sum_{L=1}^{3} \sum_{M=-L}^{L} (r^L_M)^2}$$

At threshold: d(3/2)=23%

Light baryon spectroscopy



$$e^+e^- \to J/\psi, \psi' \to B_1\bar{B}_2M$$



If there are (anti)hyperons one can determine spin density matrix for free

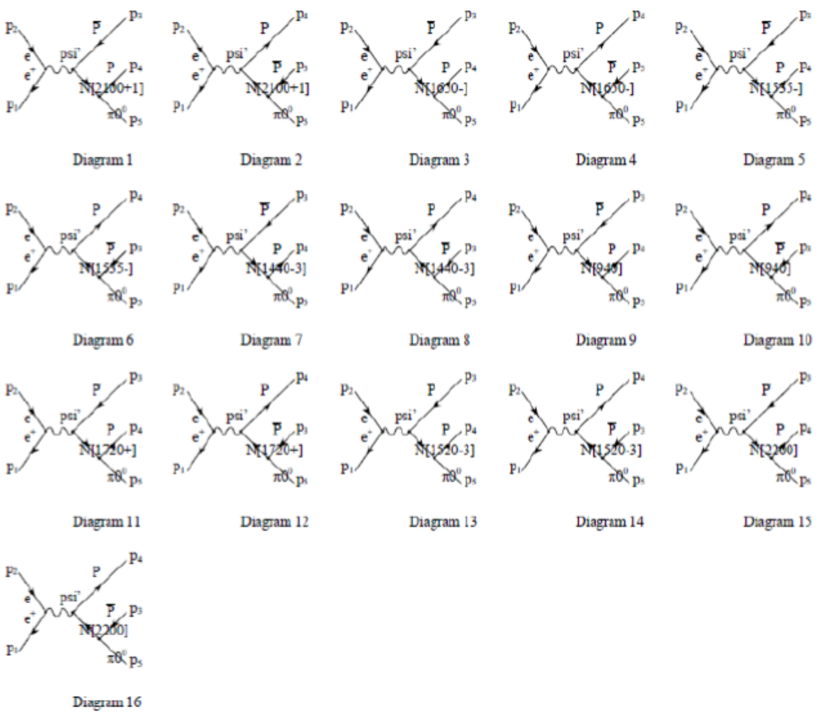
Picture: Beijiang LIU

$e^+e^- \to J/\psi, \psi' \to B_1\bar{B}_2V(P)$

Feynman Diagram Calculation: FDC-PWA Nucl.Instrum.Meth. A534 (2004) 241
Package used for baryon PWA at BESIII

mesons and baryons
J=(0, 1/2, 1, 3/2, 2, 5/2, 3 , 7/2, 4, 9/2)

Automatically generated
Feynman diagrams in $\psi' \to \pi^0 p\bar{p}$



From effective Lagrangian Feynman rules are generated and angular distribution is calculated. Fit parameters are:

- Resonance parameters
- Coupling constants (complex)

However hyperons are treated as stable particles…

Conclusions:

BESIII Hyperon group: goal to develop and verify formalism and methods for precision hyperon production and decay studies at BESIII in $e^+e^- \to B_1\bar{B}_2(M)$ including spin degrees of freedom.

J/ψ and ψ' decays into hyperon-antihyperon:
unique spin entangled system for CP tests and for determination of (anti-)hyperon decay parameters.
BESIII in progress: analyses using collected 10^{10} J/ψ
Plan: more ψ' data …

Prospects for a CP violation signal at Super Tau Charm Factories.
Methods can be extended for analyses at BelleII and PANDA

Thank you!