UPPSALA UNIVERSITET

A novel method to study hyperons

Andrzej Kupsc

nature physics

LETTERS

https://doi.org/10.1038/s41567-019-0494-8

Polarization and entanglement in baryon-antibaryon pair production in electron-positron annihilation

The BESIII Collaboration*

Nature Phys. 15 (2019) 631

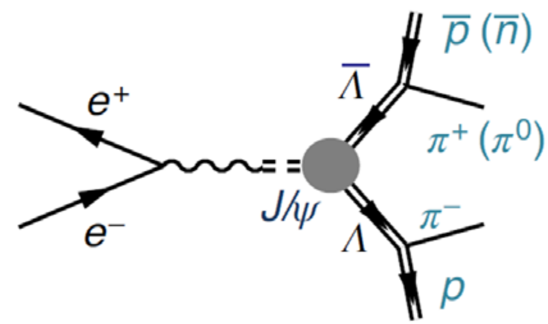
BESIII

arXiv:1808.08917

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

Observation of Λ transverse polarization

- Determination of Λ decay asymmetry
- CP test

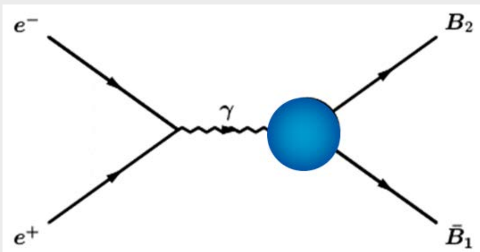


Methods (UU):

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

KEK, 6 Nov. 2019

Outline:



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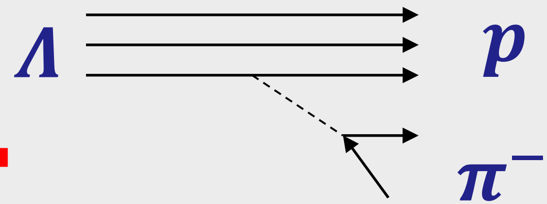

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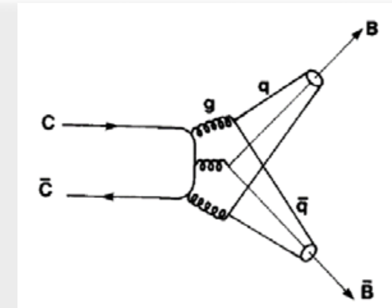
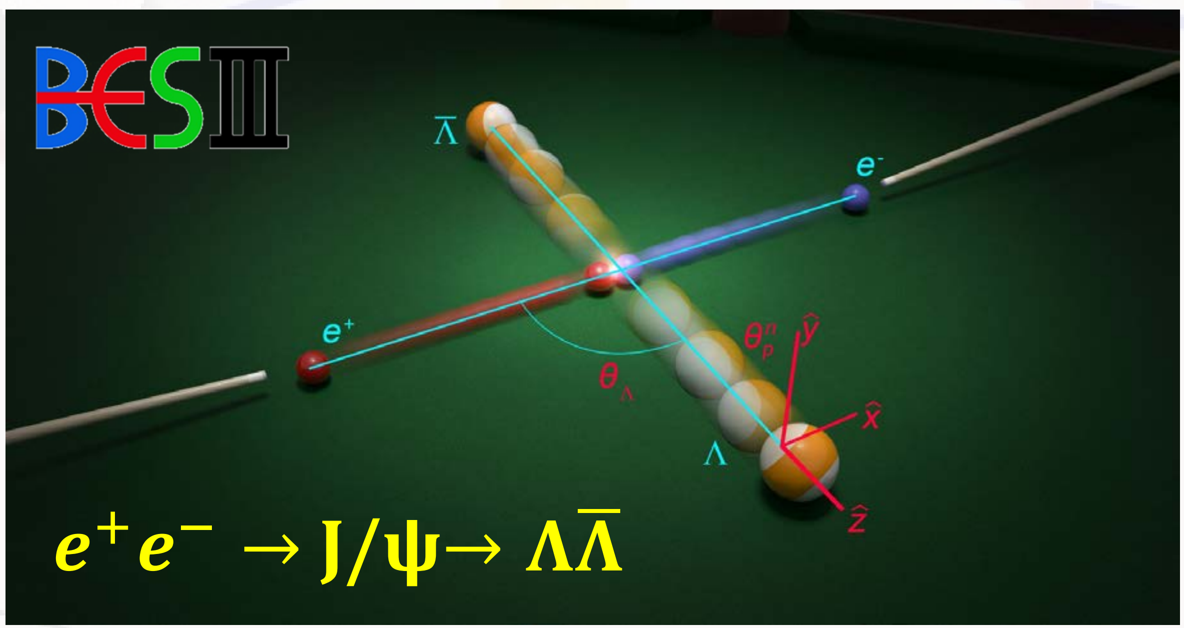


$e^+e^- \to f\bar{f}, B_1\bar{B}_2$ $\Lambda \to p\pi^-$ $J/\psi \to B_1\bar{B}_2$

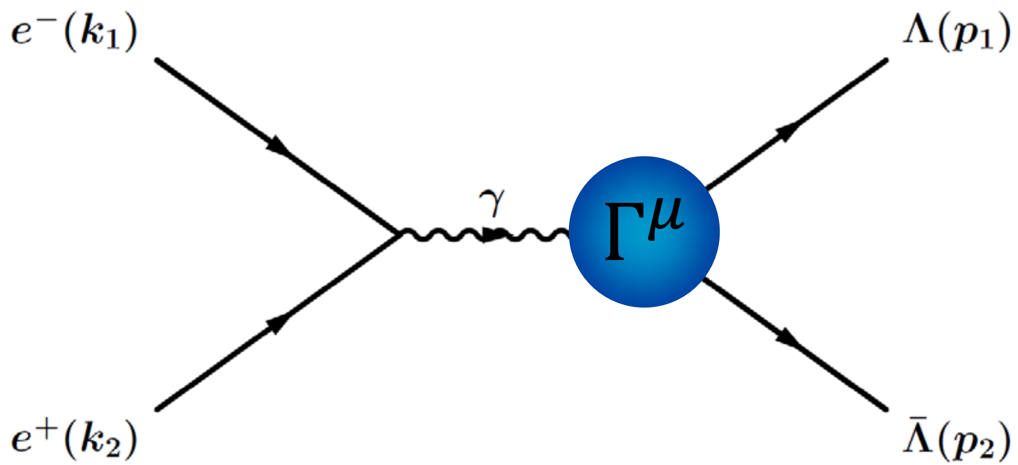


CP tests

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

Picture:Piotr Kupsc

$e^+e^- \rightarrow \gamma^* \rightarrow B\overline{B}$ (spin 1/2)



$$s = (p_1 + p_2)^2$$
$$q = p_1 - p_2$$

$$\Gamma^\mu(p_1, p_2) = -ie\left[\gamma^\mu F_1(s) + i\frac{\sigma^{\mu\nu}}{2M_B} q_\nu F_2(s)\right]$$

F_1 (Dirac) and F_2 (Pauli) Form Factors

Sachs Form Factors (FFs) ⇔ helicity amplitudes:

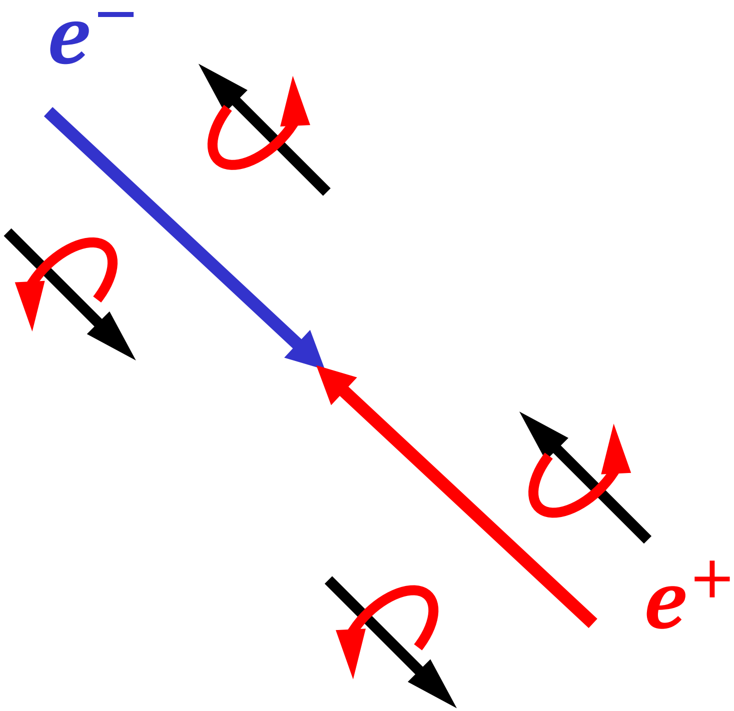
$$G_M(s) = F_1(s) + F_2(s), \quad G_E(s) = F_1(s) + \tau F_2(s)$$

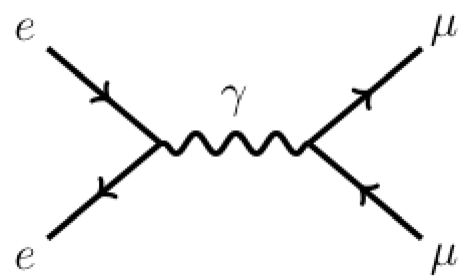
helicity non-flip — helicity flip

$$\tau = \frac{s}{4M_B^2}$$

$e^+e^- \to \mu^+\mu^-$

At high energies annihilating e+e- have opposite helicities.





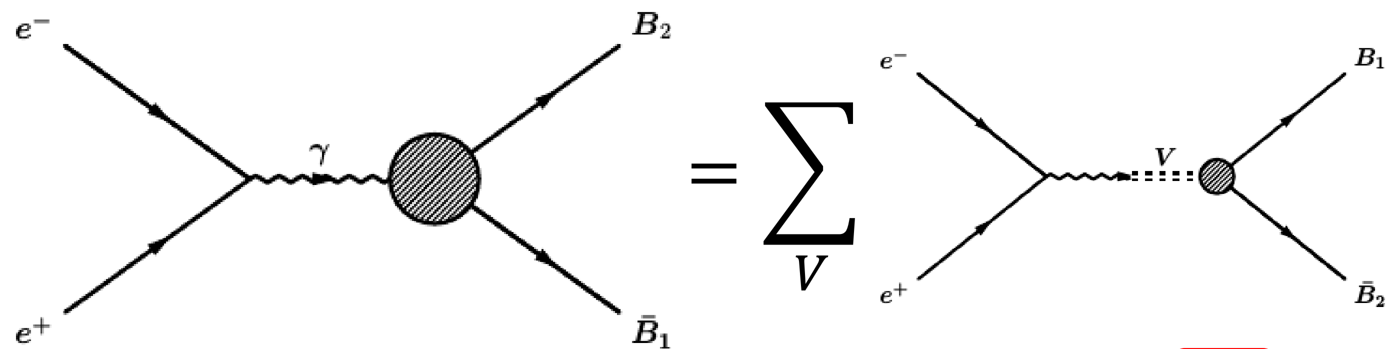
$$F_1(0) = 1, \quad F_2(0) = a_\mu$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1 + \cos^2\theta)$$

γ^* has ± 1 helicity

$$\rho_1(\theta) = \begin{pmatrix} \frac{1+\cos^2\theta}{2} & -\frac{\cos\theta\sin\theta}{\sqrt{2}} & \frac{\sin^2\theta}{2} \\ -\frac{\cos\theta\sin\theta}{\sqrt{2}} & \sin^2\theta & \frac{\cos\theta\sin\theta}{\sqrt{2}} \\ \frac{\sin^2\theta}{2} & \frac{\cos\theta\sin\theta}{\sqrt{2}} & \frac{1+\cos^2\theta}{2} \end{pmatrix}$$

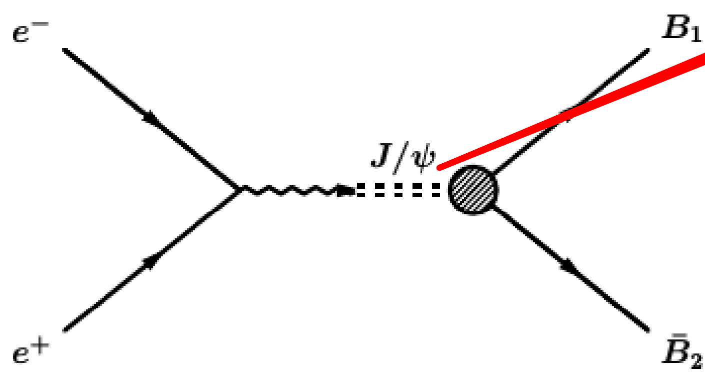
Baryon FFs (continuum):



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

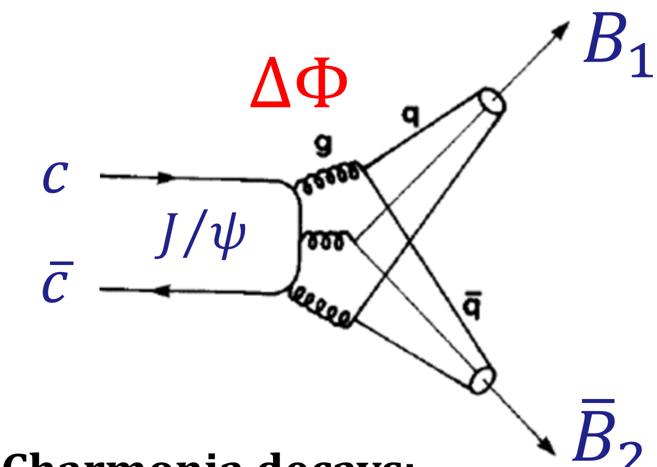
$V = \gamma, \rho, \omega, \varphi, \ldots, J/\psi, \psi(2S), \ldots$

vs 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, Kupsc PLB772 (2017) 16

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

For spin ½ $B\bar{B}$ production two complex FFs: $G_M(s)$, $G_E(s)$

⇨ process described by three parameters at fixed $\sqrt{s}$:

- cross section (σ)
- FFs ratio R or angular distribution parameter α_ψ
- relative phase between FFs ($\Delta\Phi$)

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

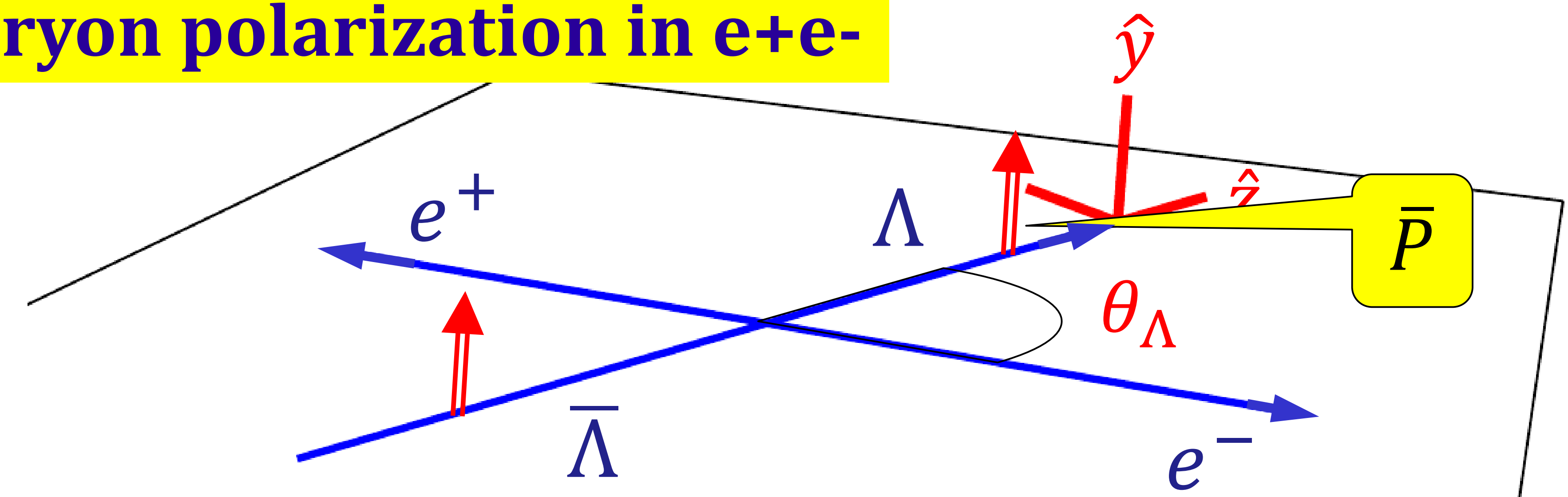
$$\tau = \frac{s}{4M_B^2}$$

Angular distribution:

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

Phase $\Delta\Phi$ expected/predicted for continuum but neglected/not expected for the decays

Baryon polarization in e+e-



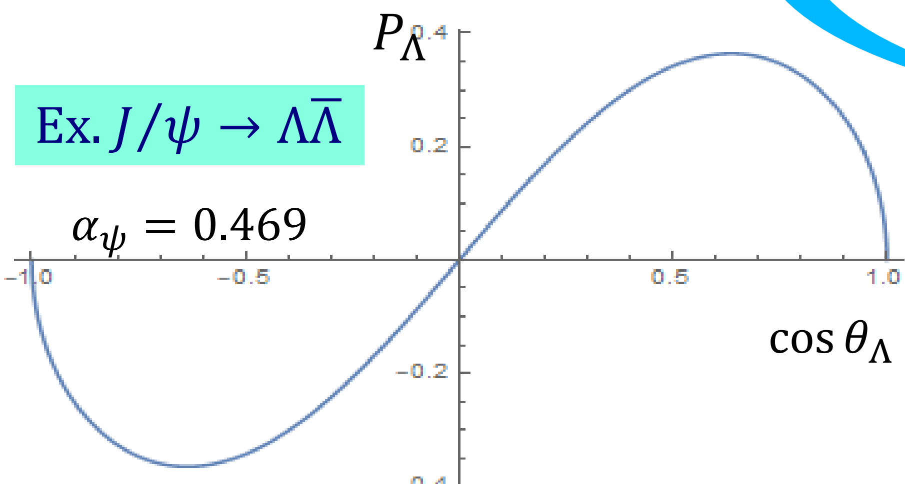
Unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$

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

$\alpha_\psi = 0.469$



Max P_Λ= 36.4%

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

Baryon-antibaryon spin density matrix

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

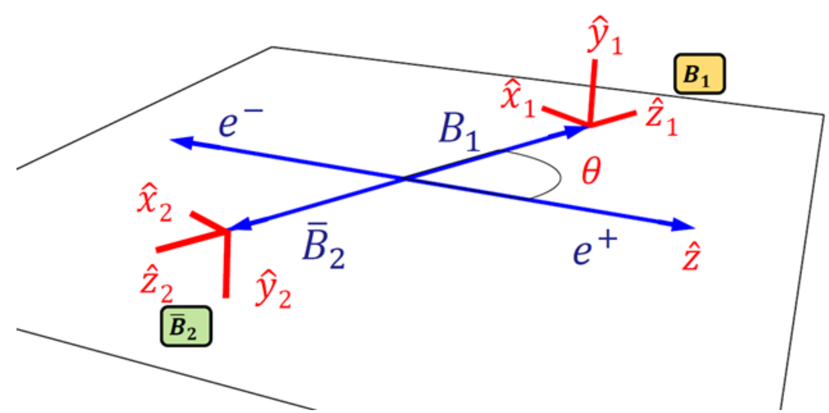
General two spin ½ particle state: $$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_2}$$

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

P_y

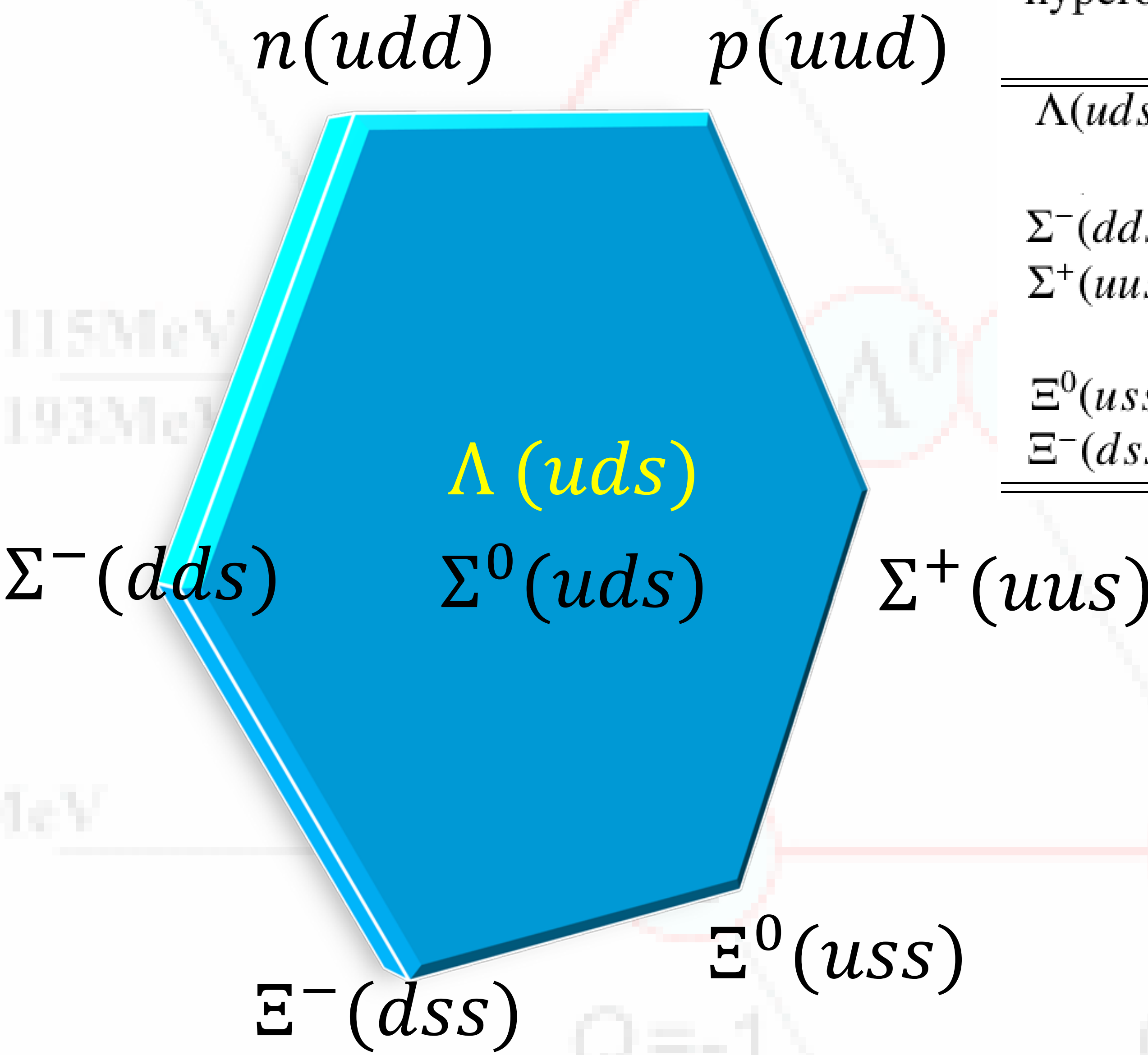
$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & 0 & \beta_\psi\sin\theta\cos\theta & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & 0 \\ 0 & -\gamma_\psi\sin\theta\cos\theta & 0 & -\alpha_\psi-\cos^2\theta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

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



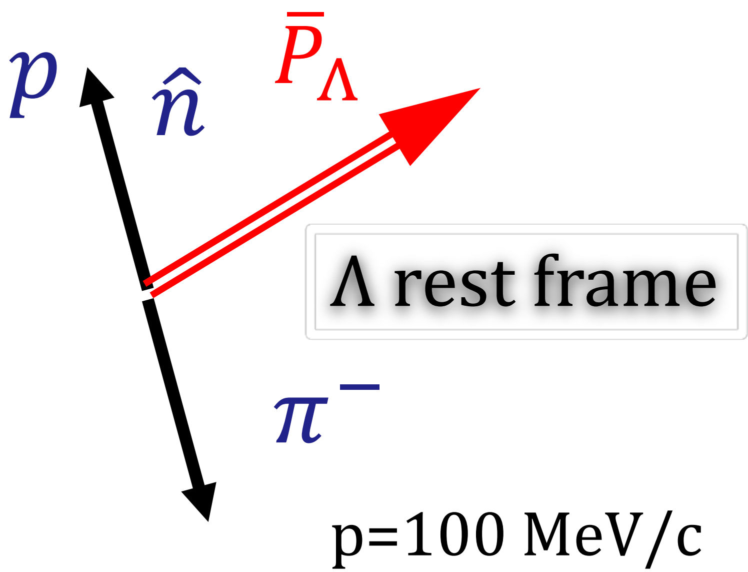
E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

Spin ½ baryon octet



hyperon	Mass [GeV/c^2]	$c\tau$ [cm]	decay (BF)
$\Lambda(uds)$	1.116	7.9	$p\pi^-$ (63.9%)
			$n\pi^0$ (35.8%)
$\Sigma^-(dds)$	1.197	4.4	$n\pi^-$ (99.8%)
$\Sigma^+(uus)$	1.189	2.4	$p\pi^0$ (51.6%)
			$n\pi^+$ (48.3%)
$\Xi^0(uss)$	1.315	8.7	$\Lambda\pi^0$ (99.5%)
$\Xi^-(dss)$	1.321	5.1	$\Lambda\pi^-$ (99.8%)

Weak decay $\Lambda \to p\pi^-$



$$\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_- \hat{n}\, \bar{P}_\Lambda)$$

α_-=0.642±0.013

Value in PDG≤2018 established in 1978 based on 1963-75 experiments

It was used/assumed in all experiments where Λ polarization is measured.
Also decay parameters of all baryons decays into final states with Λ: $\Xi \to \Lambda\pi$, $\Omega \to \Lambda K$, …

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*

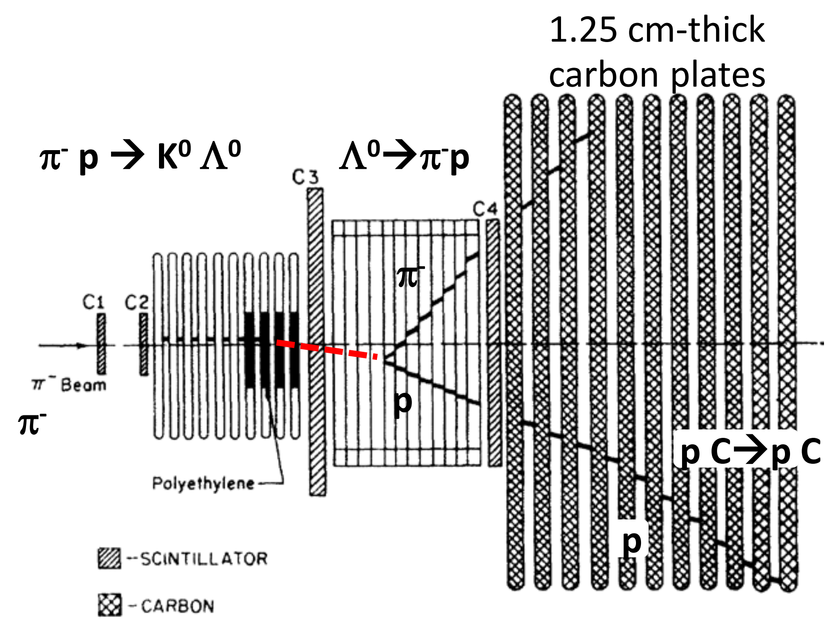
JAMES W. CRONIN AND OLIVER E. OVERSETH†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 26 September 1962)

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.

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



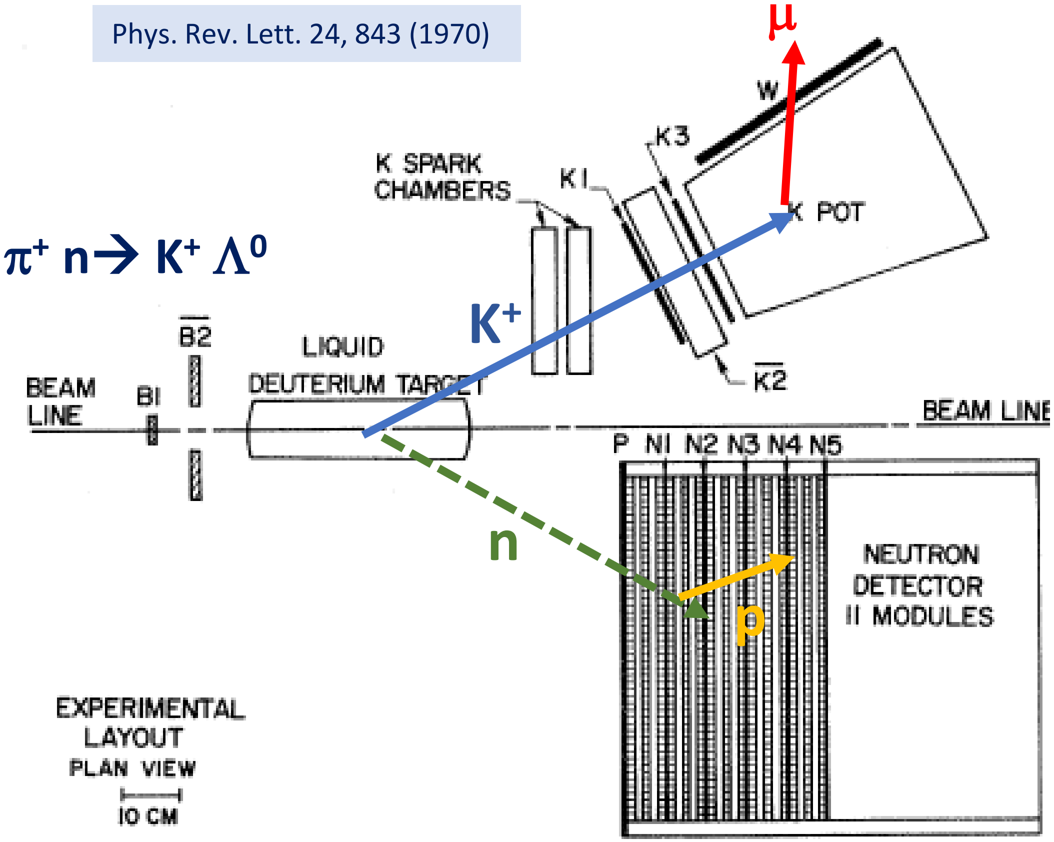
no H_2 target, no magnet;
use kinematics and proton's
range in carbon to infer E_p

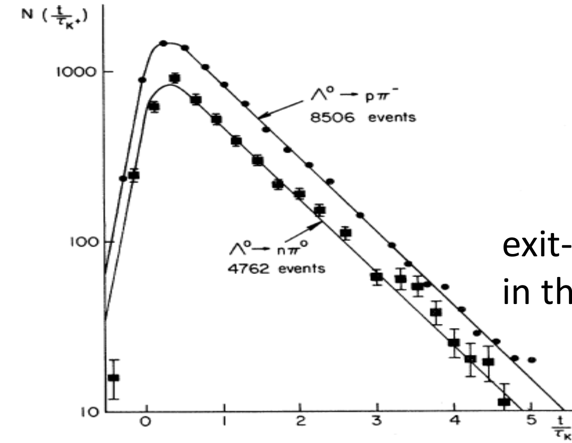
Slide from Steve Olsen

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

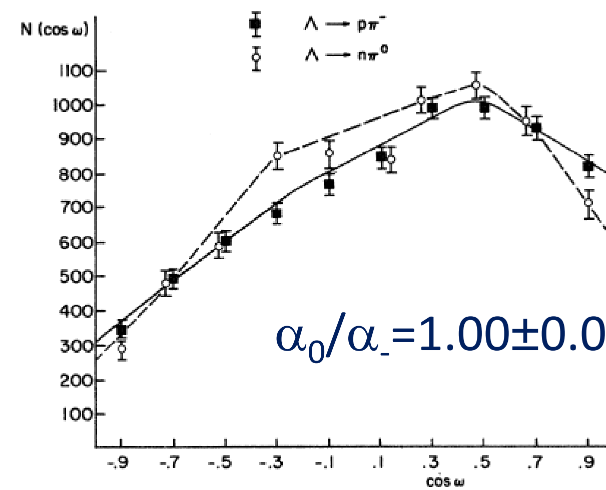
Phys. Rev. Lett. 24, 843 (1970)

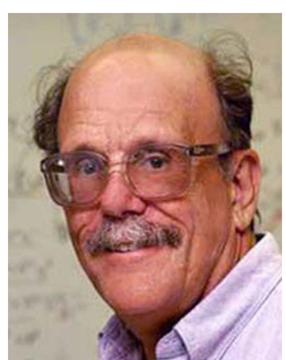
$\pi^+ n \rightarrow K^+ \Lambda^0$





exit-entry time in the H_2O tank

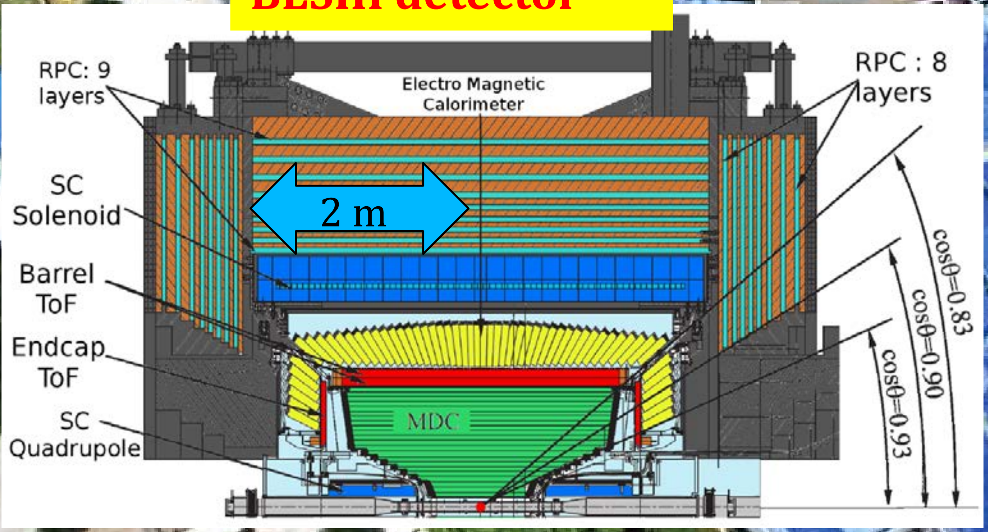




(Steve PhD thesis)

Slide from Steve Olsen

BEPCII (Beijing)



τ –charm factory 2<√s<4.6 GeV:

- Charmonium spectroscopy/decays
- Light hadrons
- Charm
- τ physics
- R-scan

$J/\psi, \psi(2S) \to B\bar{B}$

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

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

(Feb 2019): 10^{10} J/ψ

PRD 93, 072003 (2016)
PLB770,217 (2017)
PRD 95, 052003 (2017)

BESIII proposal:3.2x10^9 ψ(2S)

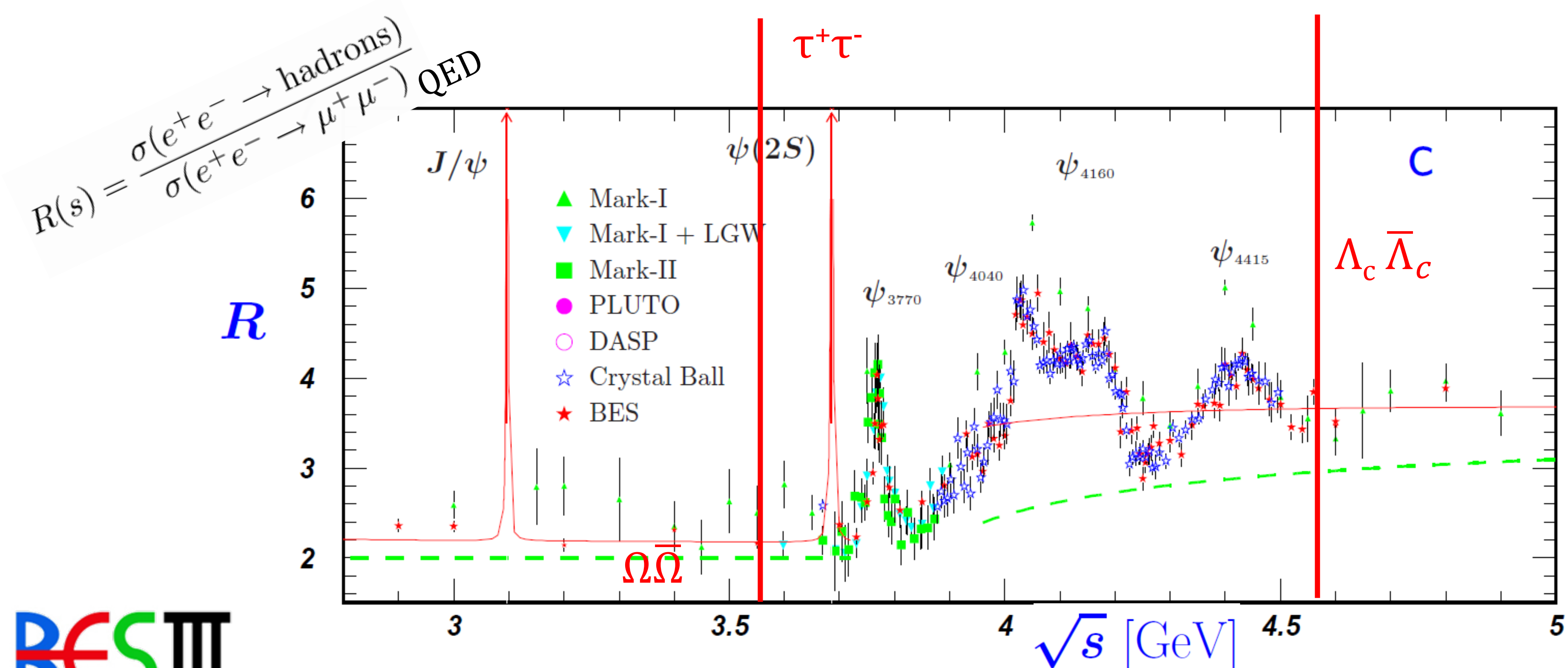
BESIII

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

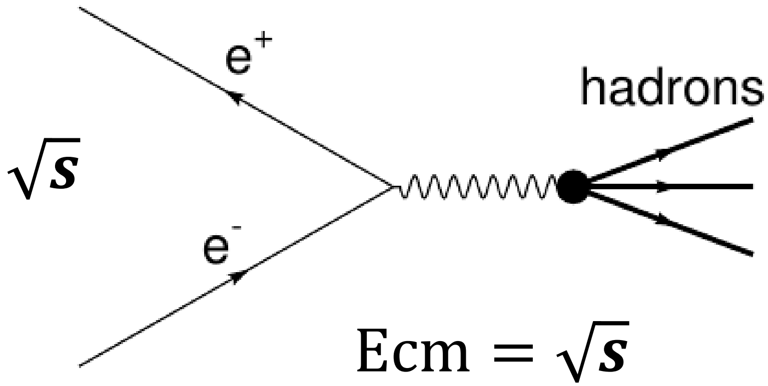
$2.0\ \text{GeV} \leq \sqrt{s} \leq 4.6\ \text{GeV}$

Thresholds:

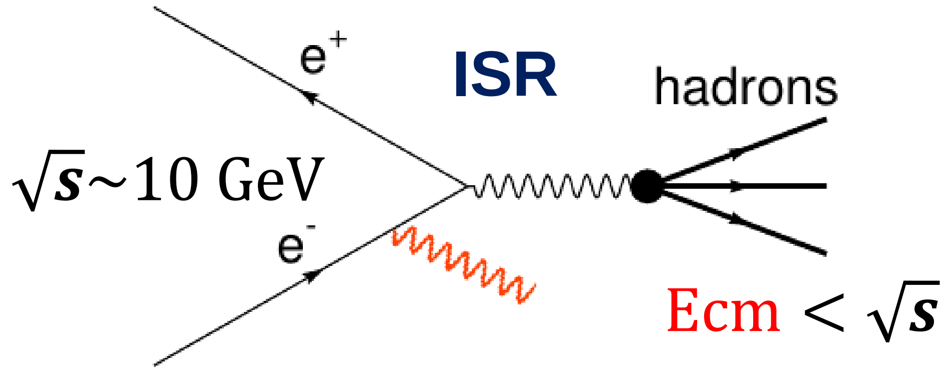
$\Lambda\bar{\Lambda}$:	2.231 GeV	$\Sigma^+\bar{\Sigma}^-$	2.379 GeV	($\Omega\bar{\Omega}$	3.345 GeV)
$\Sigma^0\bar{\Sigma}^0$	2.385 GeV	$\Sigma^-\bar{\Sigma}^+$	2.395 GeV		
$\Xi^0\bar{\Xi}^0$	2.630 GeV	$\Xi^-\bar{\Xi}^+$	2.643 GeV		
$\Lambda\bar{\Sigma}^0$	2.308 GeV				



Direct scan BESIII

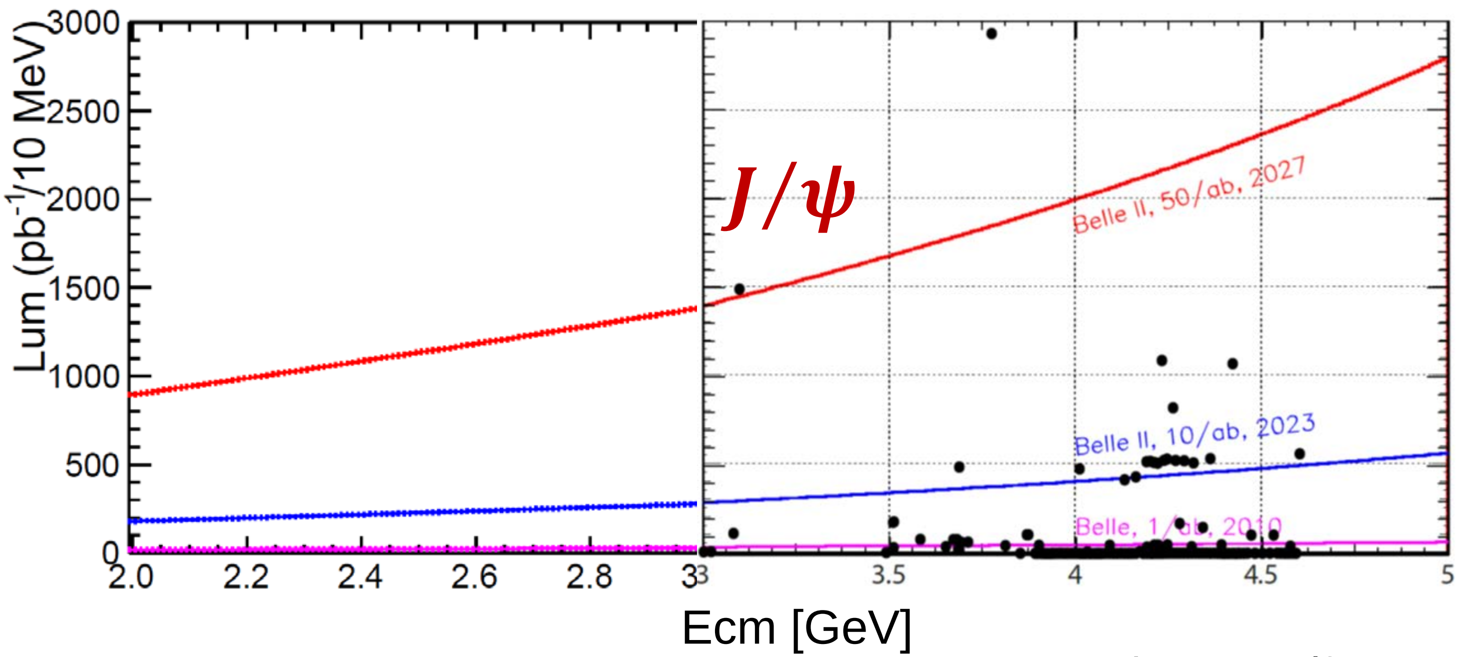


ISR BelleII



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

- 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

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)

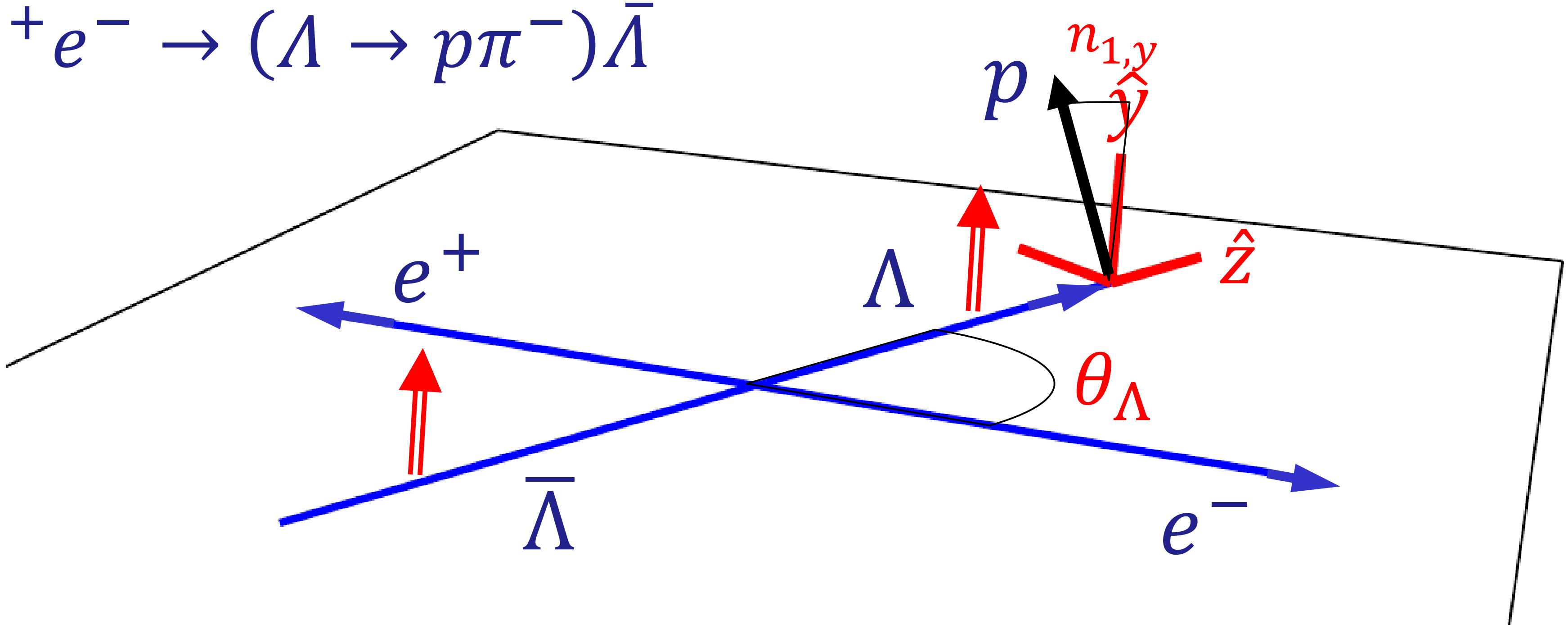
Amplitudes for precision BESIII data:

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

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

Inclusive decay angular distribution

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



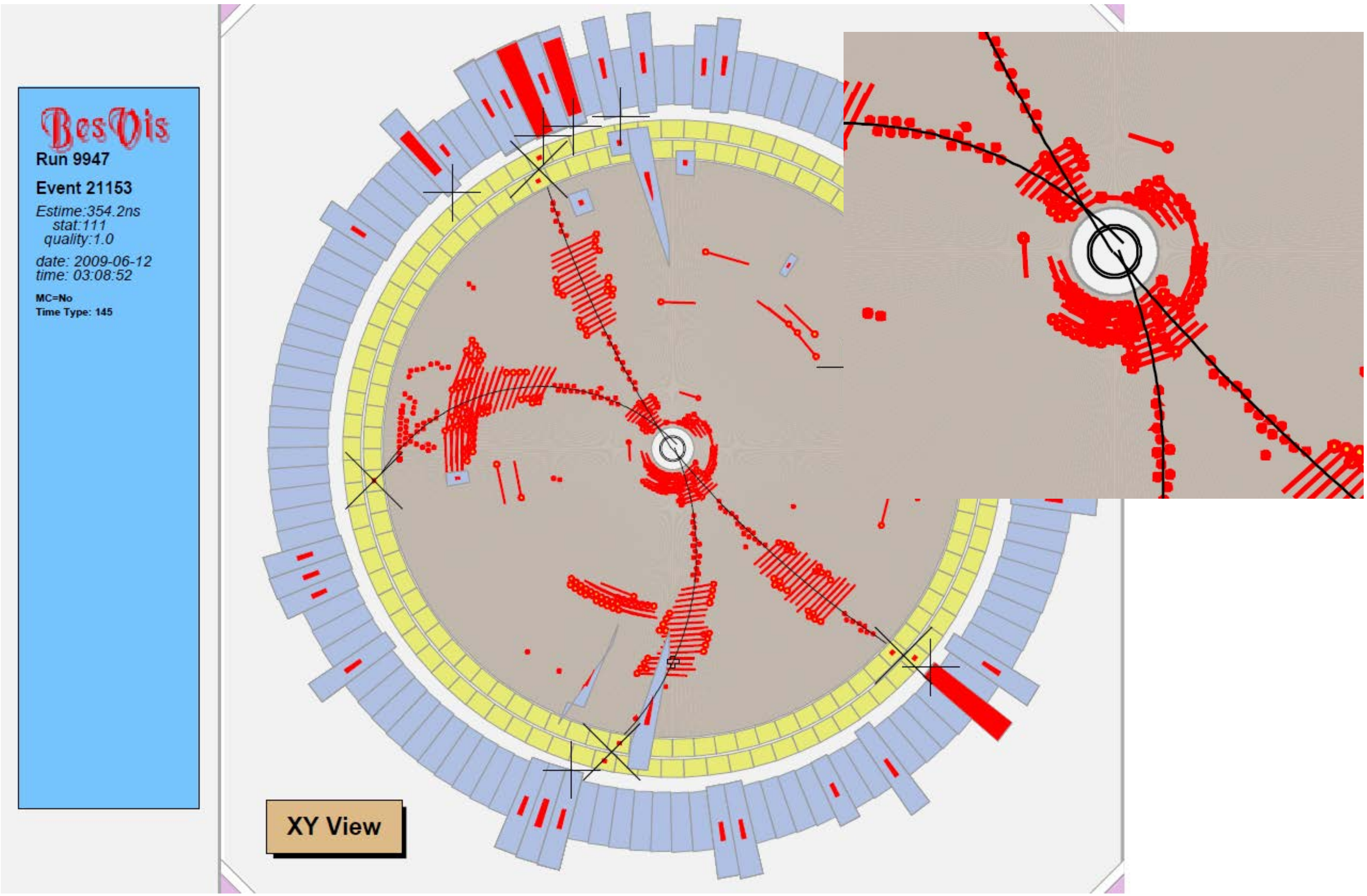
$$\frac{d\Gamma}{d\cos\theta_\Lambda d\Omega_1} \propto (1 + \alpha_\psi \cos^2\theta_\Lambda)\{1 + \alpha_- P_y n_{1,y}\}$$

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

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

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

event in BESIII detector



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_+

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

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

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

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, Kupsc 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:

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

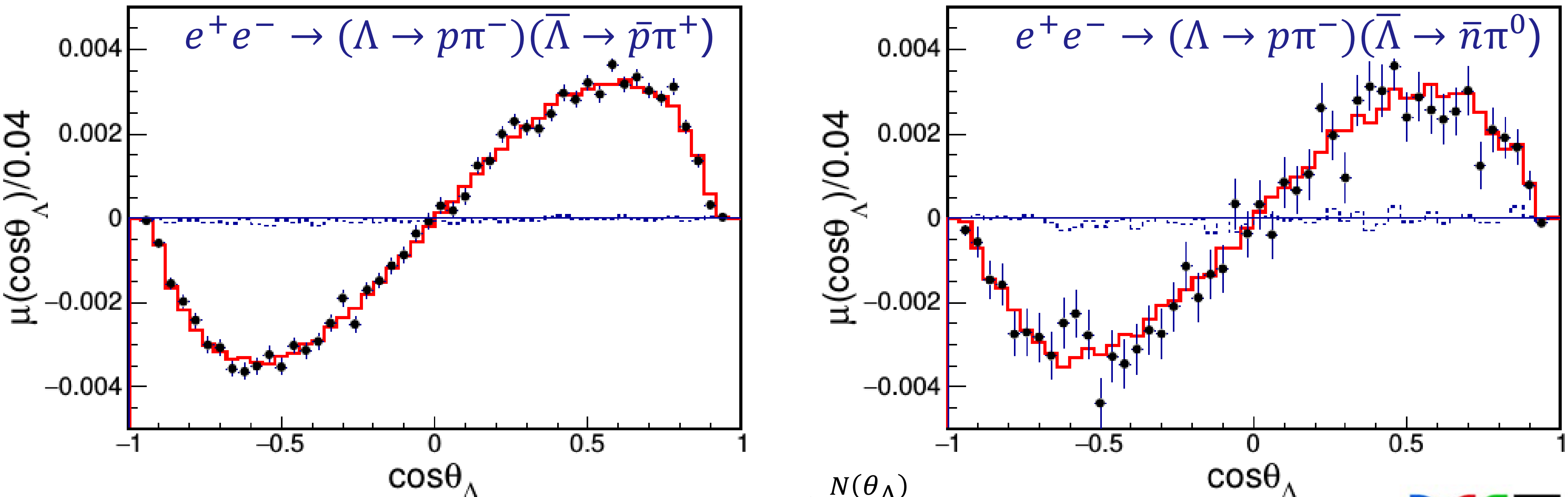
The angular distribution:

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

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

Fit results

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



BESIII

moment: $$\mu(\cos\theta_\Lambda) = \frac{1}{N}\sum_{i=1}^{N(\theta_\Lambda)}\left(n_{1,y}^{(i)} - n_{2,y}^{(i)}\right)$$

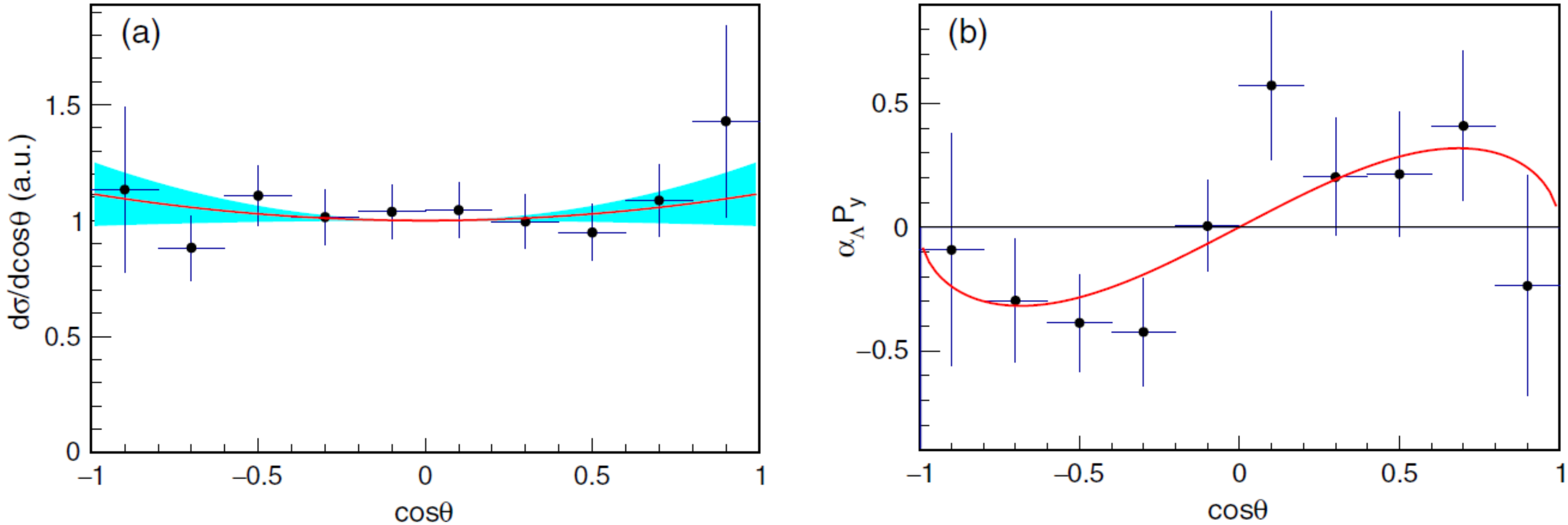
(uncorrected for acceptance)

Parameters	This work	Previous results
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027 BESIII
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–
α_-	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013 PDG
α_+	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08 PDG
$\bar{\alpha}_0$	$\mathbf{-0.692 \pm 0.016 \pm 0.006}$	–

BESIII Nature Phys. (2019)

$e^+e^- \to \gamma^* \to \Lambda\bar{\Lambda}$ (continuum: 2.396 GeV)

PHYSICAL REVIEW LETTERS **123**, 122003 (2019)



555 events selected

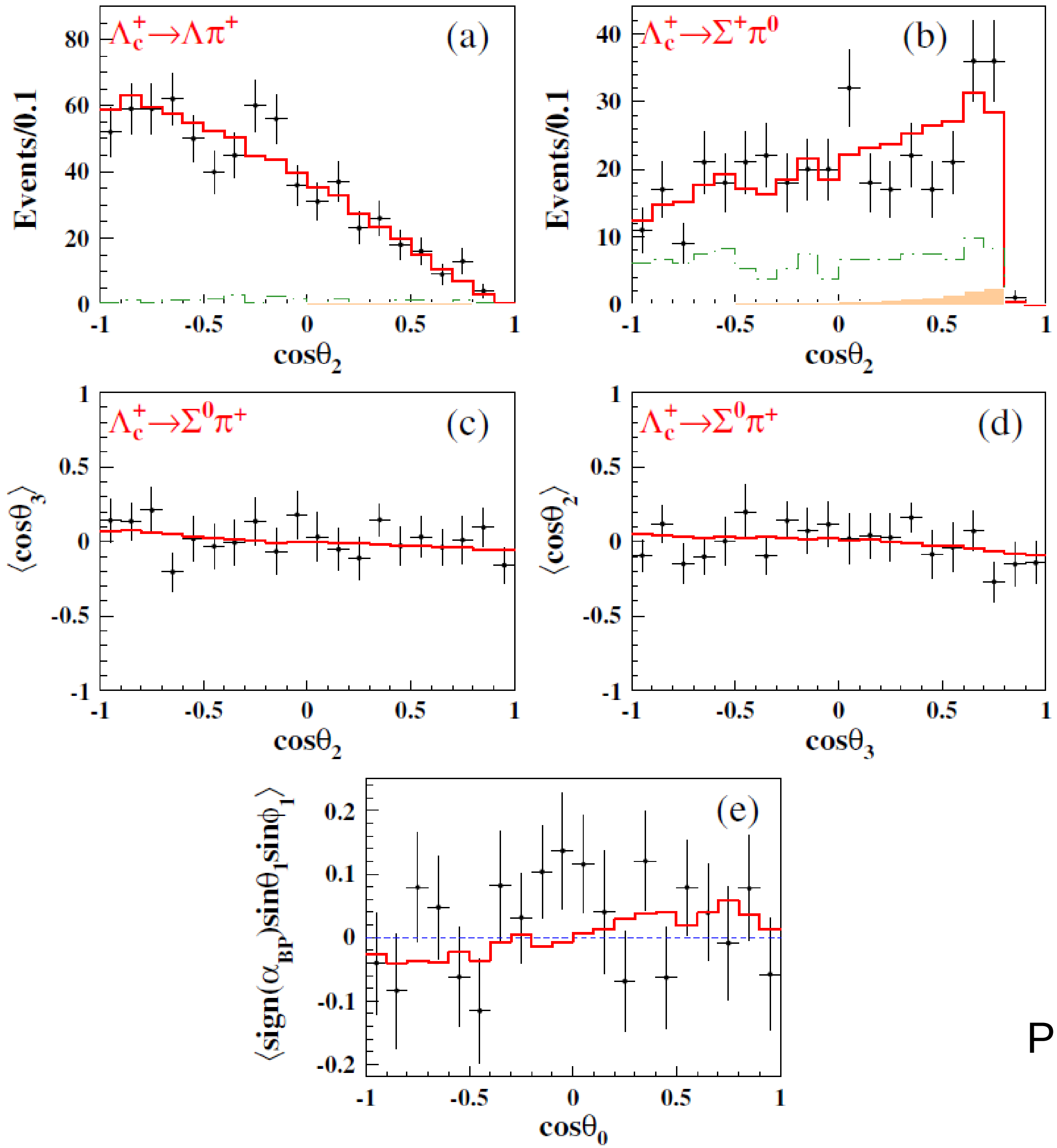
("α_ψ"=0.13±0.16)

$\Delta\Phi = 37^o \pm 12^o \pm 6^o$

R = 0.94 ± 0.16(stat.) ± 0.03(sys.) ± 0.02(α_)

The same fit as for $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ but $\alpha_- = \alpha_+$ and fixed

$$e^+e^- \to (\Lambda_c^+ \to B\pi)(\bar{\Lambda}_c^- \to X)$$

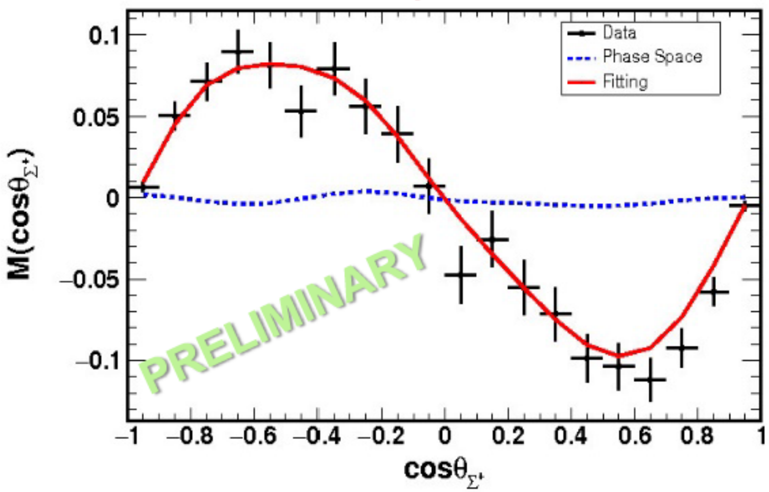


Phys.Rev. D100 (2019) 072004

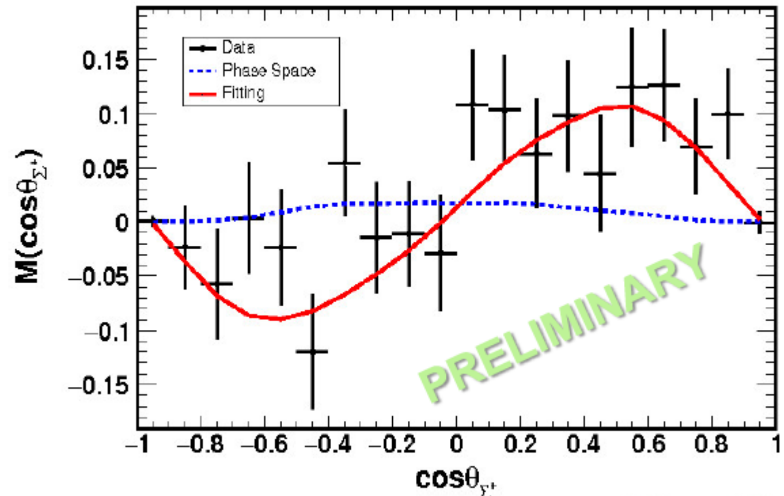
$e^+e^- \to J/\psi, \psi' \to \Sigma^+\bar{\Sigma}^- \to p\pi^-\bar{p}\pi^+$

The same formalism as for $J/\psi \to \Lambda\bar{\Lambda}$

$J/\psi \to \Sigma^+ \Sigma^-$



$\psi' \to \Sigma^+ \Sigma^-$



$\alpha_{J/\psi}/\alpha_{\psi}$ = -0.507±0.006±0.002 / 0.676±0.030±0.006

$\Delta\Phi(J/\psi, \psi)$ = (-15.4±0.7±0.3)° / (21.5 ± 0.4 ± 0.5)°

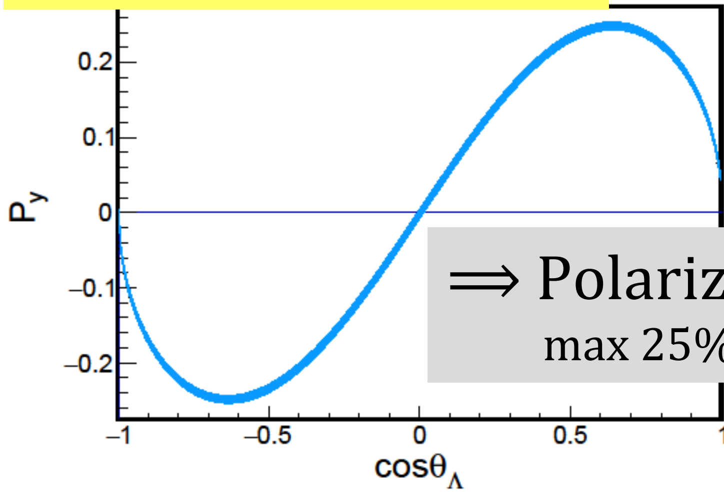
α_0 = -0.999±0.037±0.010

$\bar{\alpha}_0$ = 0.992±0.037±0.008

A_{CP} = -0.015±0.037±0.008

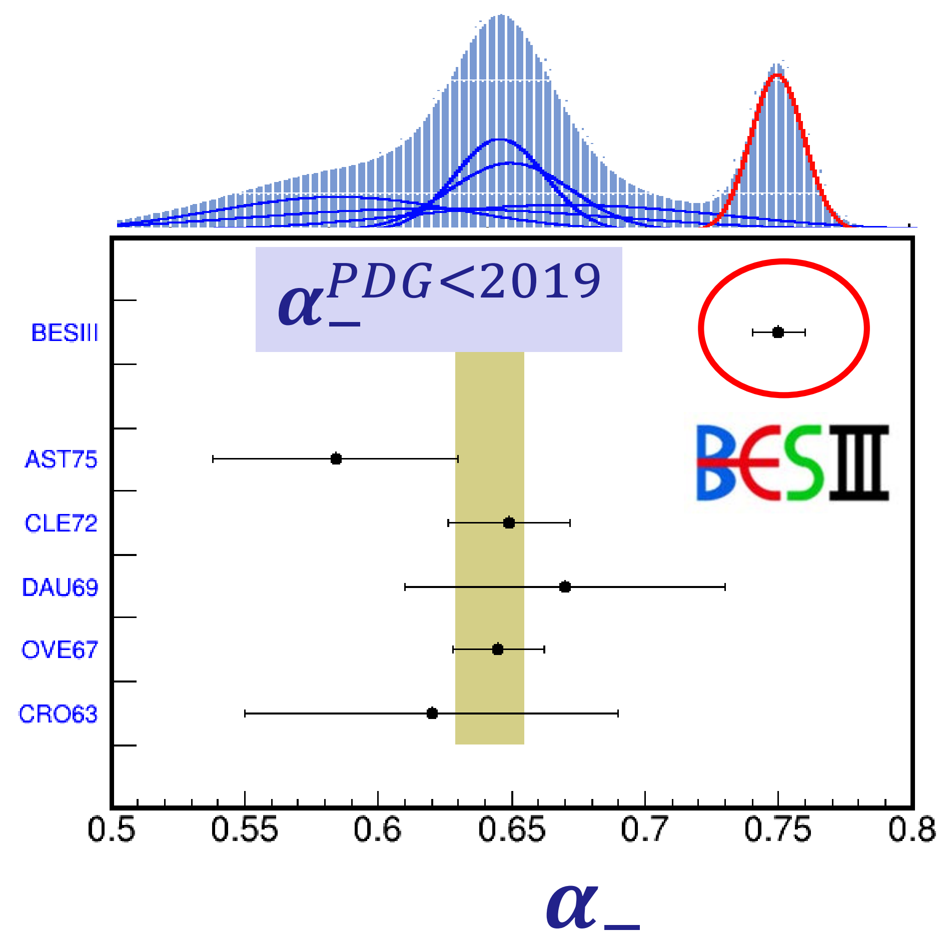
Implications of the BESIII result

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



$\Longrightarrow$ Polarization: max 25%

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



17(3)% larger

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

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

CP test:

$$A_\Lambda = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

$A_\Lambda = -0.006 \pm 0.012 \pm 0.007$

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

PDG 2019 update:

α_- FOR $\Lambda \to p\pi^-$

INSPIRE search

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.750 ±0.009 ±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 $\pi^- p$

Reset of α_- value

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

INSPIRE search

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.758 ±0.010 ±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 ±0.083 ±0.063	≈ 8.7k	ABLIKIM	2010	BES	$J/\psi \to \Lambda\bar{\Lambda}$
−0.63 ±0.13	770	TIXIER	1988	DM2	$J/\psi \to \Lambda\bar{\Lambda}$

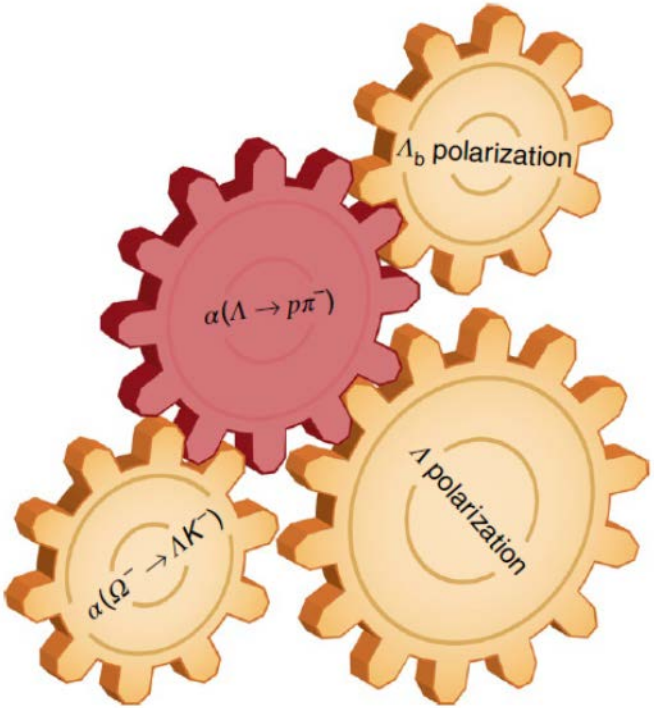
news & views

PARTICLE PHYSICS

Anomalous asymmetry

A measurement based on quantum entanglement of the parameter describing the asymmetry of the Λ hyperon decay is inconsistent with the current world average. This shows that relying on previous measurements can be hazardous.

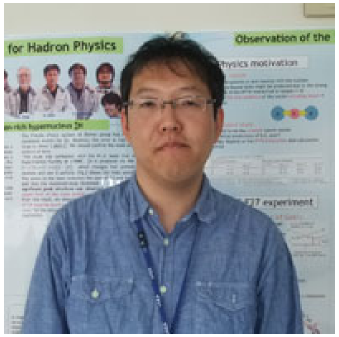
Ulrik Egede



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≤ 2018 syst uncertainty was not included

Slide from Steve Olsen

Parity conserving / violating amplitudes

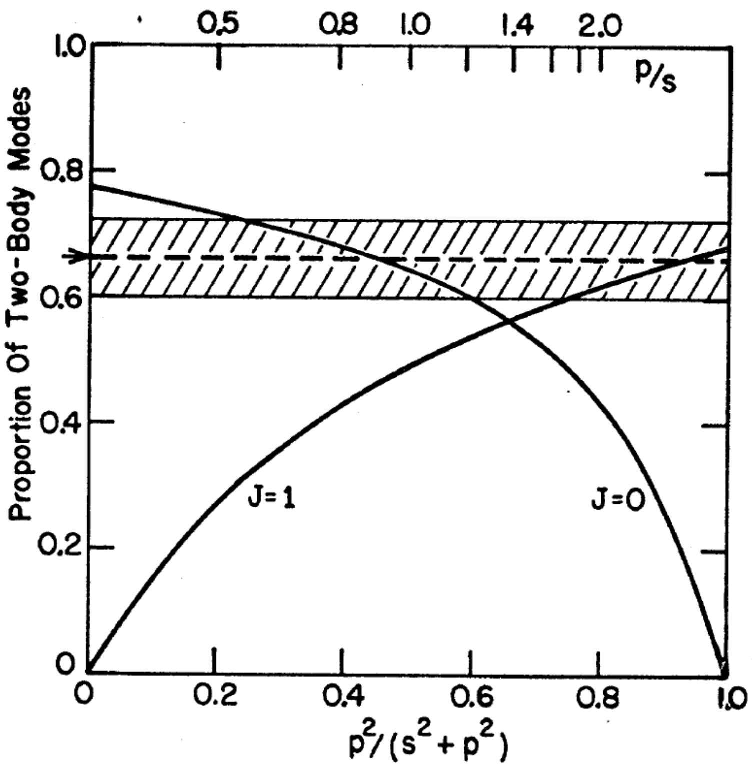
	$\frac{p^2}{p^2+s^2}$	p^2/s^2	p/s
PDG	0.119(6)	0.135(8)	0.368(11)
BESIII	0.171(6)	0.207(9)	0.455(10)

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

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

$${}_\Lambda H^4 \longrightarrow \pi^- + He^4$$

Dalitz,Liu PR116,1312

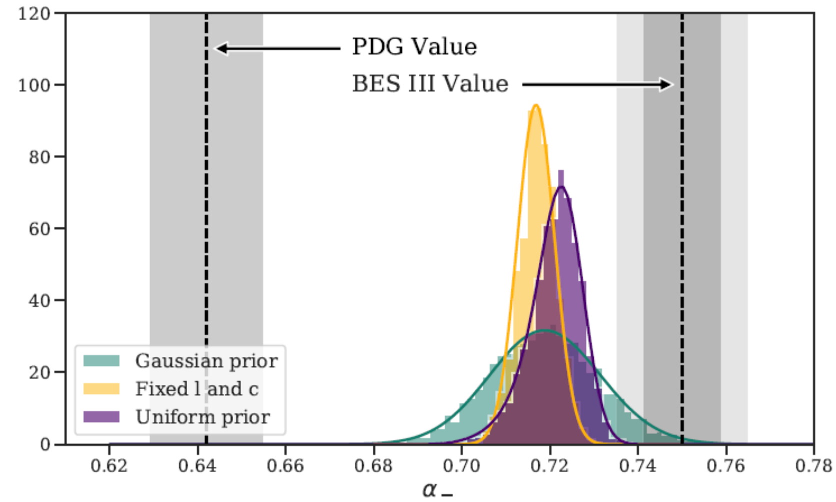


How to verify the result?

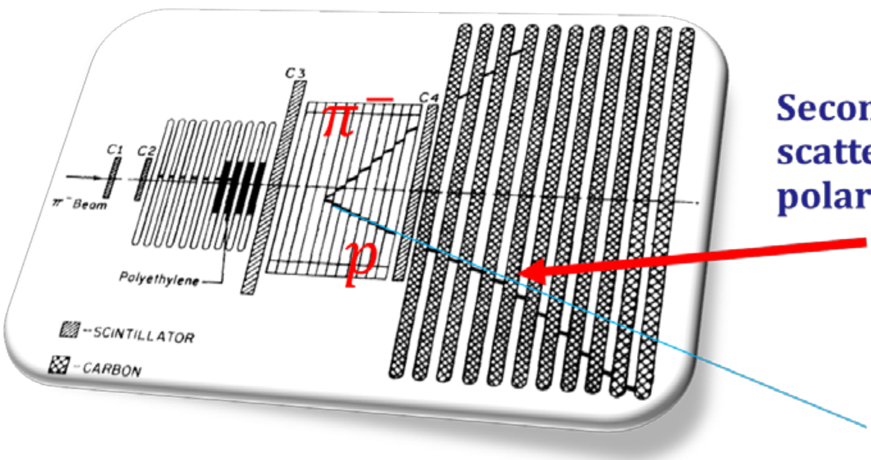
$\vec{\gamma} p \to K^+ \Lambda$

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

D. Ireland et al arXiv:1904.07616



Measure proton polarization?



Secondary scattering of polarized proton

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

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 verification at BESIII eg:

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

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

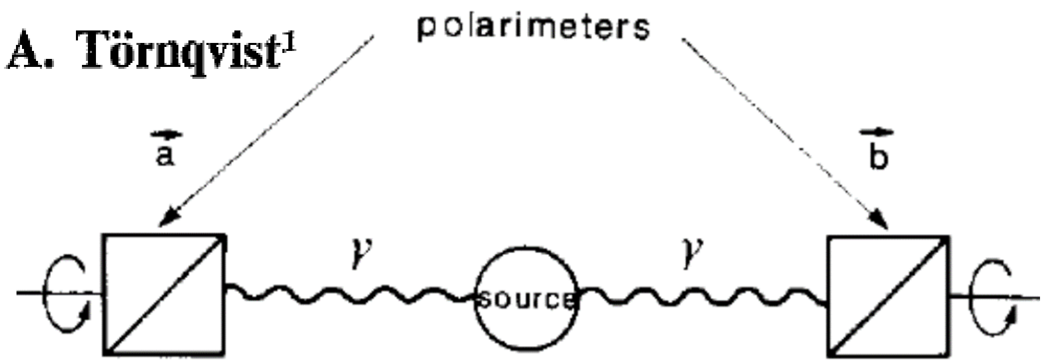
$J/\psi \to \gamma \eta_c \to \gamma \Lambda\bar{\Lambda}$

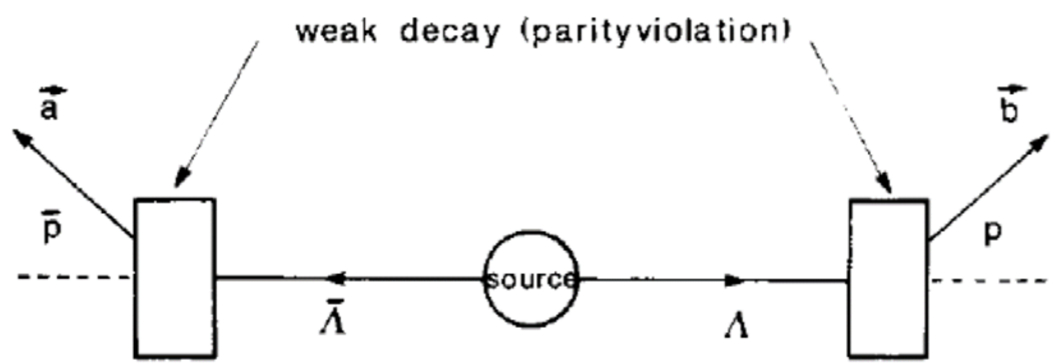
$BF = 1.7\% \times 1.1 \times 10^{-3}$

Foundations of Physics, Vol. 11, Nos. 1/2, 1981

Suggestion for Einstein–Podolsky–Rosen Experiments Using Reactions Like $e^+e^- \to \Lambda\bar{\Lambda} \to \pi^- p \pi^+ \bar{p}$

Nils A. Törnqvist[1]





THE DECAY $J/\psi \to \Lambda\bar{\Lambda} \to \pi^- p \pi^+ \bar{p}$ AS AN EINSTEIN–PODOLSKY–ROSEN EXPERIMENT

Nils A. TÖRNQVIST PLA117(1986)1

Modern view:

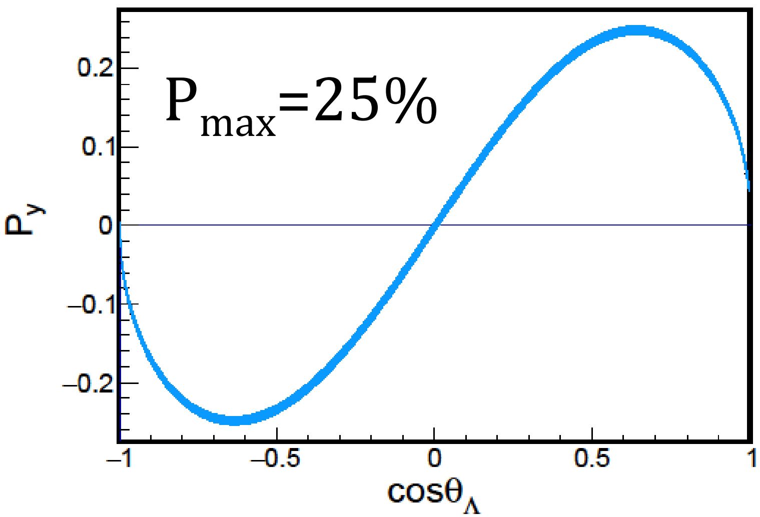
S. Chen, Y. Nakaguchi, and S. Komamiya, PTEP 2013, 063A01 (2013)

B.C. Hiesmayr, Sci.Rep. 5 (2015) 11591

Comparison of $\Lambda\bar{\Lambda}$ and $\Xi\bar{\Xi}$ (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?

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

$$d\Gamma \propto W(\xi;\boldsymbol{\omega})$$

ξ 9 kinematical variables 9D PhSp

Parameters: 2 production + 6 for decay chains

$$\boldsymbol{\omega} = (\alpha_\psi, \Delta\Phi, \underbrace{\alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \overline{\alpha}_\Xi, \overline{\phi}_\Xi, \overline{\alpha}_\Lambda})$$

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

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

Variables and parameters factorize:

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

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

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

Asymptotic likelihood method

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

V_{kl} – covariance matrix

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

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

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

Error correlation matrix

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

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

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

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

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

Correlation matrix:

	$\bar{\alpha}_\Xi$	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

$\Delta\Phi = 0$

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

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

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

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

P.Adlarson, AK arXiv:1908.03102

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

Correlation matrix:

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

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

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

$\Delta\Phi = 0$

	$\bar{\alpha}_\Xi$	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

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

P.Adlarson, AK arXiv:1908.03102

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

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

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

(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)

$$r^1_{-1} \to P_y \quad r^1_0 \to P_x \quad r^1_1 \to P_z$$

$$\rho_{3/2} = r_0 \left(Q_0 + \frac{3}{4}\sum_{M=-1}^{1} r^1_M Q^1_M + \frac{3}{4}\sum_{M=-2}^{2} r^2_M Q^2_M + \frac{3}{4}\sum_{M=-3}^{3} r^3_M Q^3_M \right)$$

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

$$Q_0 = \frac{1}{4} I \qquad \rho_{3/2} = \sum_{\mu=0}^{15} r_\mu Q_\mu$$

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

Single tag $e^+e^- \to \Omega^-\overline{\Omega}^+$

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):

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

decay 1/2->1/2 0 (Λ->pπ)

decay 3/2->1/2 0 (Ω->ΛK)

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

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

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

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

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

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

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

Degree of polarization

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

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

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

Conclusions:

Polarization in $e^+e^- \to \Lambda\bar{\Lambda}$ observed at J/ψ [phase close to 40°]

J/ψ and ψ' decays into hyperon-antihyperon:
unique spin entangled system for CP tests and for determination of (anti-)hyperon decay parameters

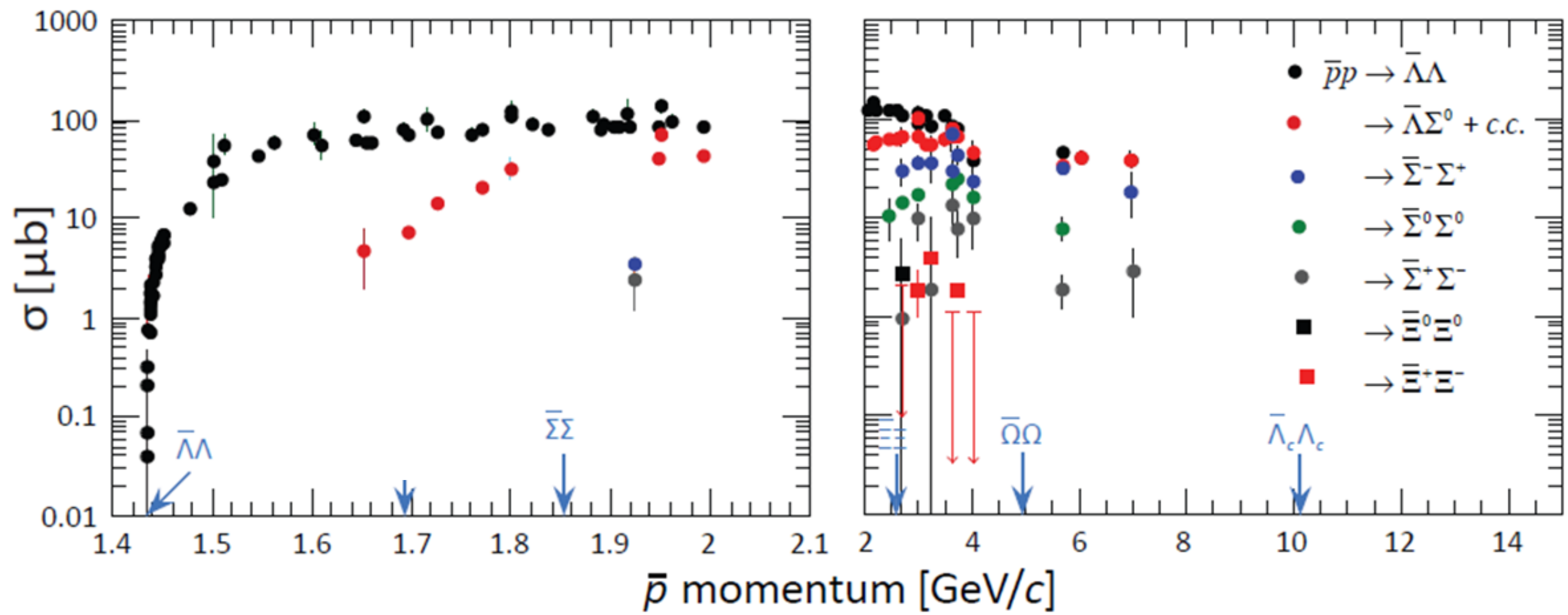
BESIII In progress: analyses using 10^{10} J/ψ ...

17(3)% larger value for the $\Lambda \longrightarrow p\pi^-$ decay asymmetry (α_-)
⇒ calls for reinterpretation of **all** Λ polarization measurements!

α_-: 0.642±0.012 (PDG1978-2018) ⇨ 0.750±0.009±0.004 (PDG 2019)

Thank you!

Reaction	σ (μb)	Efficiency (%)	Rate (with 10^{31} $cm^{-1}s^{-1}$)
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64	10	30 s^{-1}
$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$	~40	30	30 s^{-1}
$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	~2	20	2 s^{-1}
$\bar{p}p \rightarrow \bar{\Omega}\Omega$	~0.002	30	~4 h^{-1}
$\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$	~0.1	35	~2 day^{-1}



Nuclear Physics News, Vol. 27, No. 3, 2017

3) $\alpha_+/\bar{\alpha}_0 \neq 1$: $\Delta I=1/2$ law violation

lifetime=12 ns

$\Delta I=1/2$ law: $K^+ \rightarrow \pi^+\pi^0$ ($\Delta I=3/2$ transition) : $\Gamma(K^+ \rightarrow \pi^+\pi^0) = |T_{3/2}|^2 \approx Bf\,(K^+ \rightarrow \pi^+\pi^0)/\tau_{K+}$

$K_S \rightarrow \pi^+\pi^-$ ($\Delta I=1/2$ transition) : $\Gamma(K_S \rightarrow \pi^+\pi^-) = |T_{1/2}|^2 \approx Bf\,(K_S \rightarrow \pi^+\pi^-)/\tau_{KS}$

lifetime=0.21 ns

$$\frac{\left|T_{3/2}\right|}{\left|T_{1/2}\right|} \approx \frac{\sqrt{Bf(K^+ \rightarrow \pi^+\pi^0)\tau_{KS}}}{\sqrt{Bf(K_S \rightarrow \pi^+\pi^-)\tau_{K+}}} = \sqrt{\frac{0.21\times 0.1\text{ns}}{0.69\times 12\text{ns}}} \square \frac{1}{22}$$

$$\langle\bar{\Lambda}|\bar{p}\pi^+\rangle = T_{1/2}\left(1+\tfrac{1}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)\right) \Rightarrow \alpha_+ = \alpha_{\Delta I=1/2}\left(1+\tfrac{1}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)\right)$$

$$\langle\bar{\Lambda}|\bar{n}\pi^0\rangle = T_{1/2}\left(1-\sqrt{2}\left(T_{3/2}/T_{1/2}\right)\right) \Rightarrow \bar{\alpha}_0 = \alpha_{\Delta I=1/2}\left(1-\sqrt{2}\left(T_{3/2}/T_{1/2}\right)\right)$$

$$\frac{\alpha_+}{\bar{\alpha}_0} = \frac{1+\frac{1}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)}{1-\sqrt{2}\left(T_{3/2}/T_{1/2}\right)} \approx 1+\left(\tfrac{1}{\sqrt{2}}+\sqrt{2}\right)\left(T_{3/2}/T_{1/2}\right) = 1+\tfrac{3}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right)$$

$$\frac{\alpha_+}{\bar{\alpha}_0} - 1 = 0.087 \pm 0.030 = \tfrac{3}{\sqrt{2}}\left(T_{3/2}/T_{1/2}\right) \quad \Rightarrow \left(T_{3/2}/T_{1/2}\right) = 0.041 \pm 0.014$$

good agreement

Slide from Steve Olsen