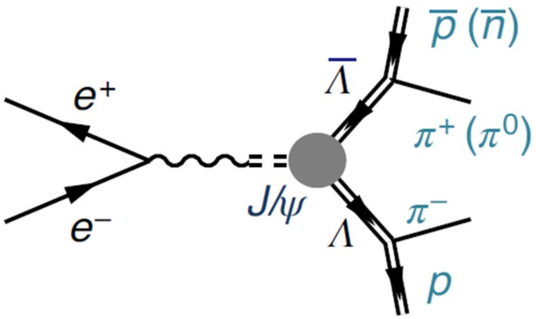
e^+e^-annihilation to baryon-antibaryon pair
(spin effects)

Andrzej Kupsc

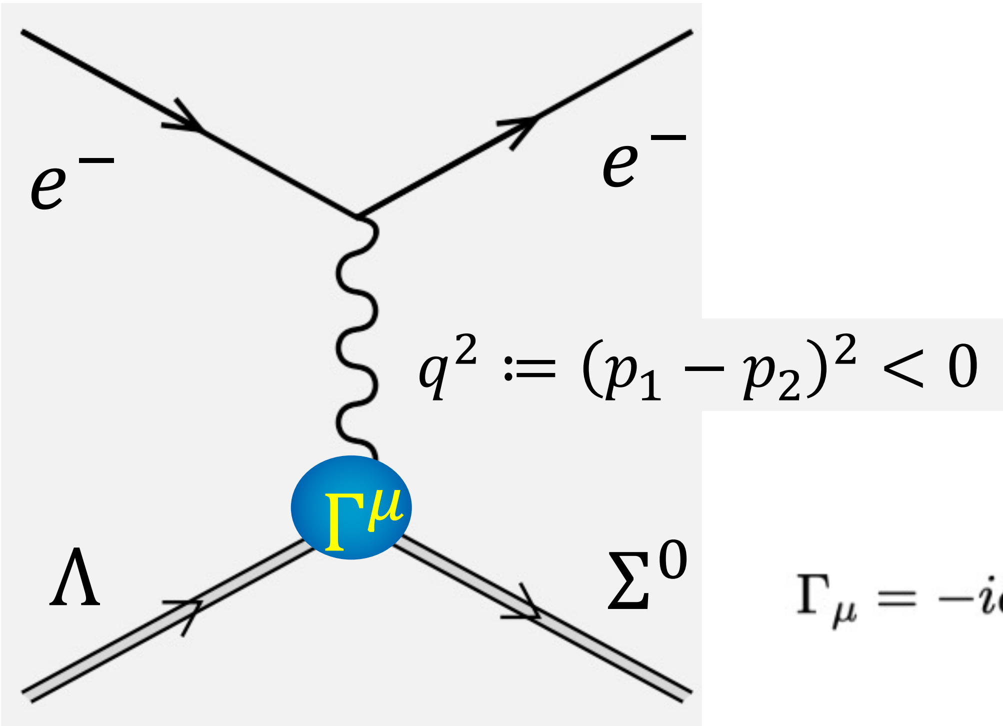
$$e^+e^- \to J/\psi \to B\overline{B}$$

- Transverse polarization
- Study of hyperon decays
- QM tests, edm



Matter to the Deepest, UŚ 17 Sept. 2025

(Transition) Form Factors



$B_{1/2}$

$$\Gamma_\mu = -ie\left[F_1(q^2)\,\gamma_\mu + F_2(q^2)\,\frac{i\sigma_{\mu\nu}q^\nu}{M_\Lambda + M_\Sigma}\right]$$

F_1 (Dirac) and F_2 (Pauli) form factors

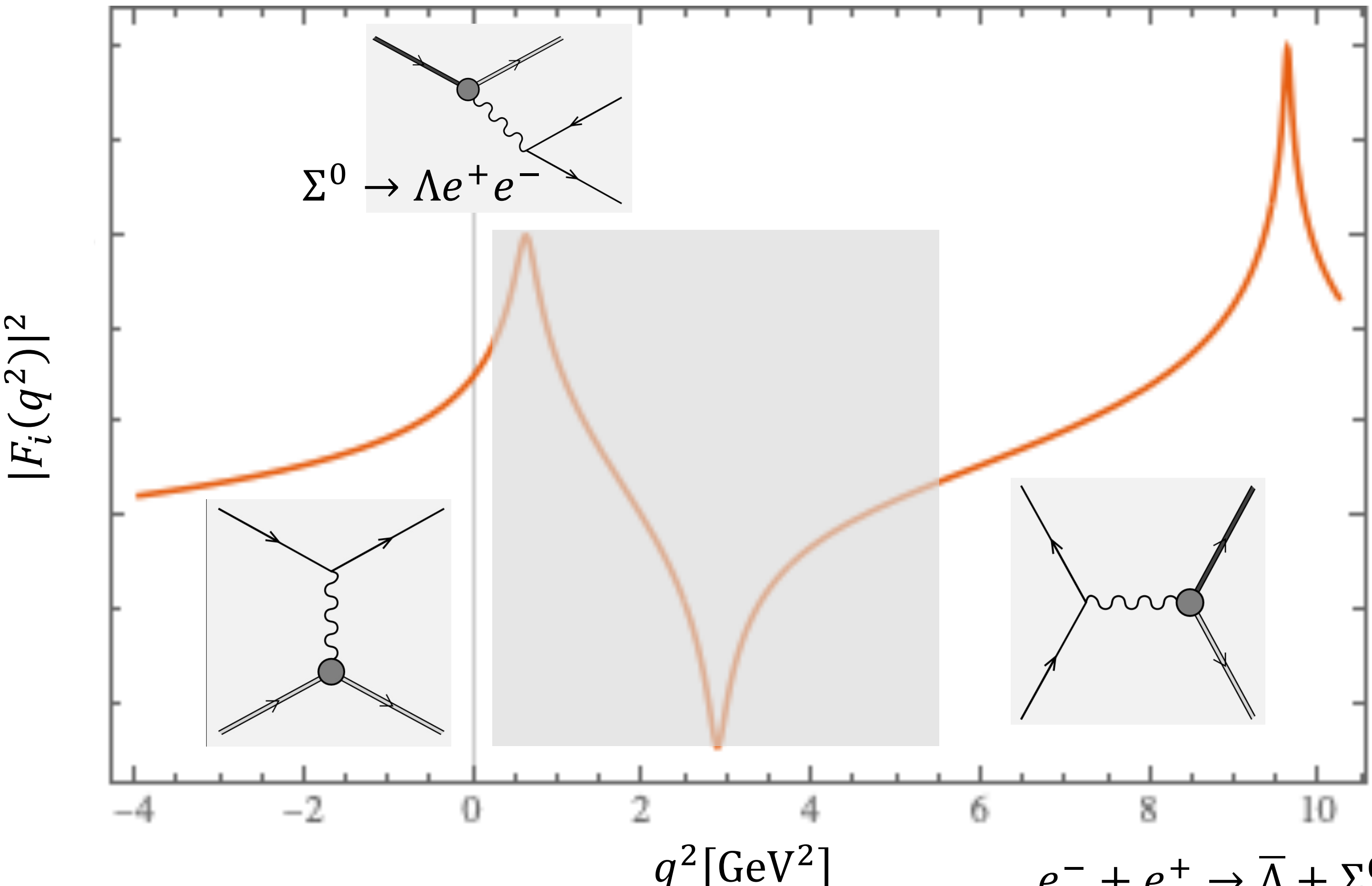
Sachs Form Factors (FFs) ⇔ helicity amplitudes:

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

helicity non-flip helicity flip

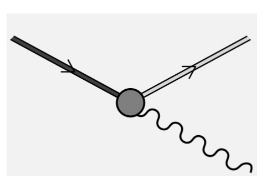
$$\tau = \frac{q^2}{(M_\Lambda + M_\Sigma)^2}$$

(Transition) Form Factors



$e^- + \Lambda \to e^- + \Sigma^0$

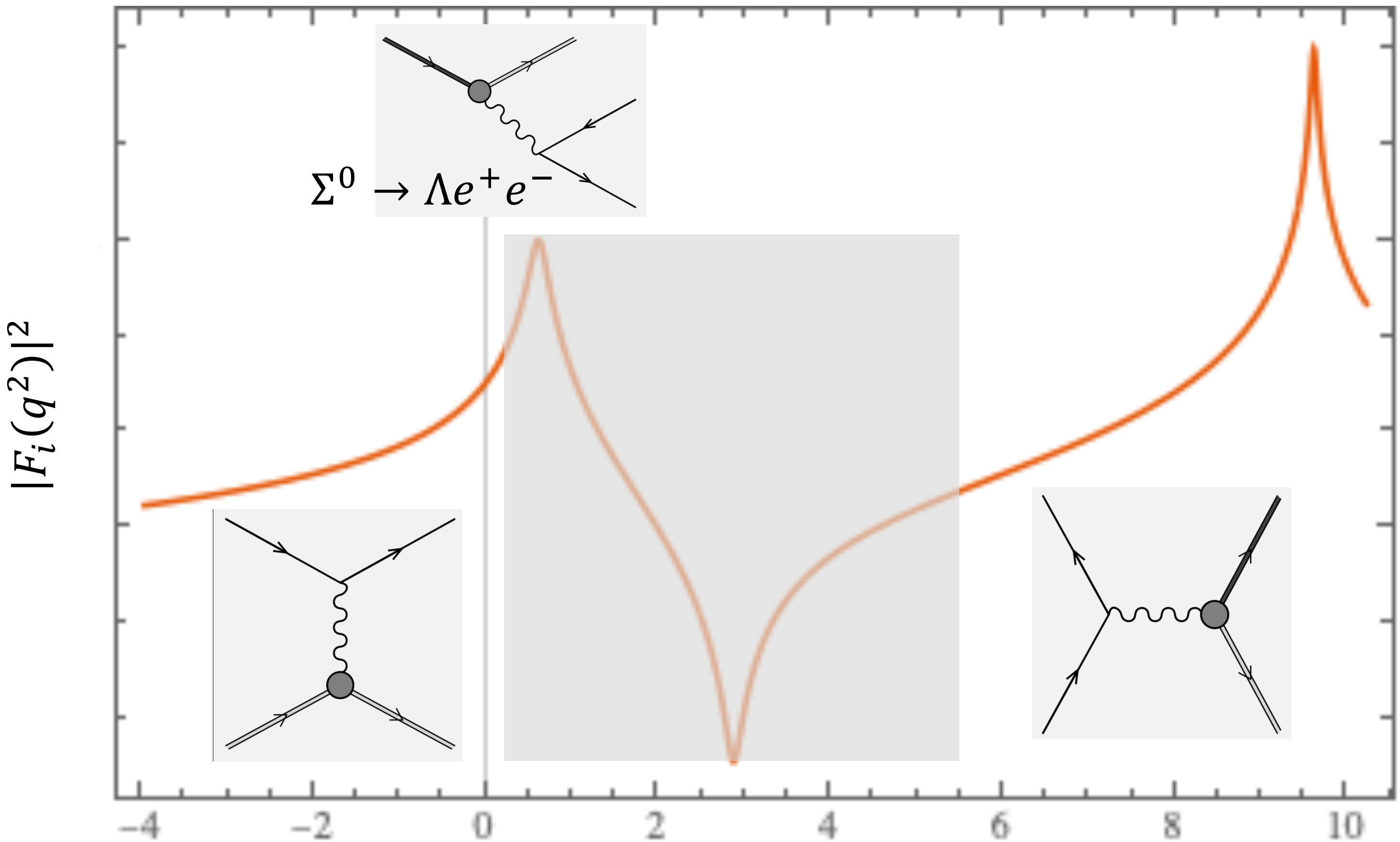
$e^- + e^+ \to \overline{\Lambda} + \Sigma^0$



$\Sigma^0 \to \Lambda + \gamma$

$$\langle r^2 \rangle = 6 \left. \frac{\mathrm{d} \ln F_i(q^2)}{\mathrm{d}q^2} \right|_{q^2=0} \qquad F_i(q^2) \approx F_i(0) \left[1 + \frac{1}{6} r_i^2 \, q^2 \right]$$

(Transition) Form Factors



BESIII

Nature Commun. 15 (2024) 8812

$\left|\frac{G_E}{G_M}\right| = 0.86(3)$

$\mathrm{Arg}\frac{G_E}{G_M} = 1.01(9)$ rad

$e^- + e^+ \to \bar{\Lambda} + \Sigma^0$

$e^- + \Lambda \to e^- + \Sigma^0$

$F_i(q^2)$ complex functions for $q^2 > 4m_\pi^2$
Observables: $|F_i(q^2)|^2$ and $\mathrm{Arg}\left(F_1(q^2)F_2^*(q^2)\right)$

$$G_E = R G_M e^{i\Delta\Phi}$$

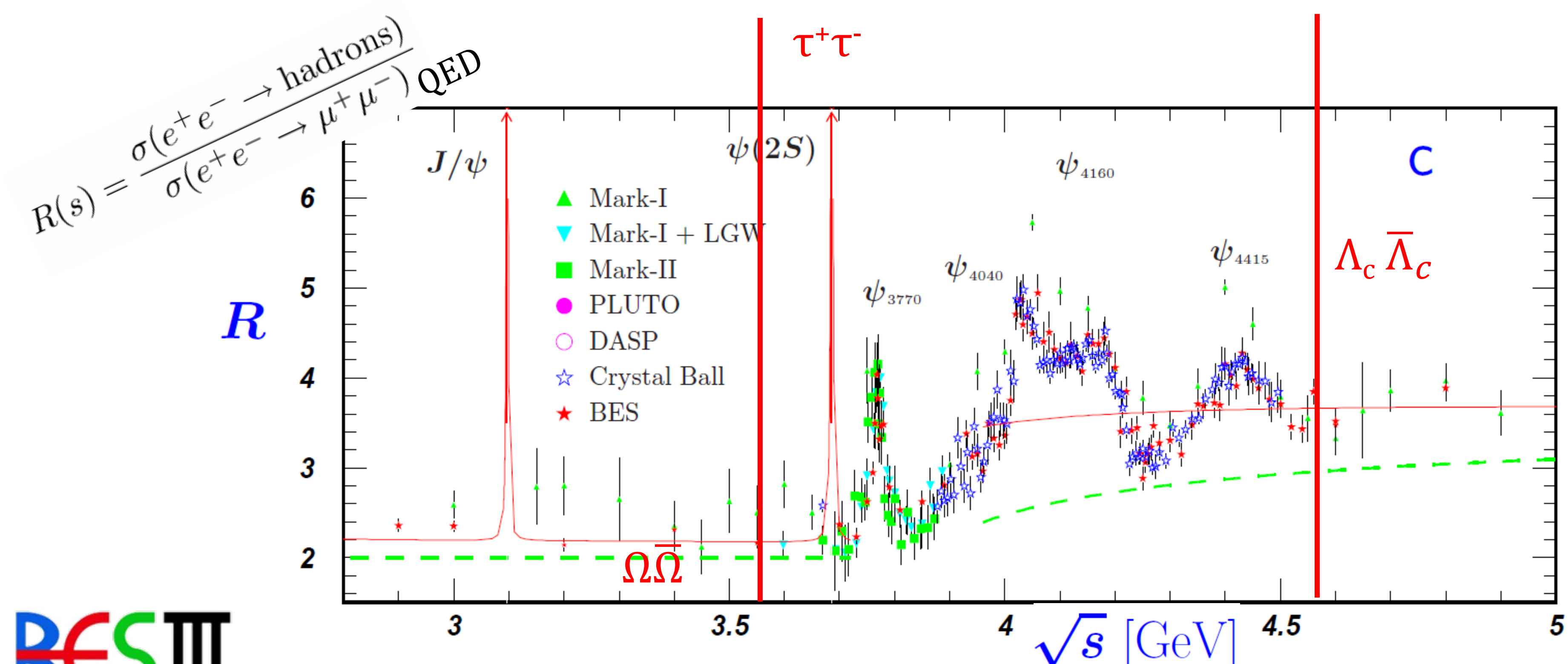
$$R = \left|\frac{G_E}{G_M}\right| \qquad \left(\alpha_\psi = \frac{\tau - R^2}{\tau + R^2}\right)$$

Baryon-antibaryon pair production at BESIII

$1.8 \text{ GeV} \leq \sqrt{s} \leq 5.0 \text{ GeV}$

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				



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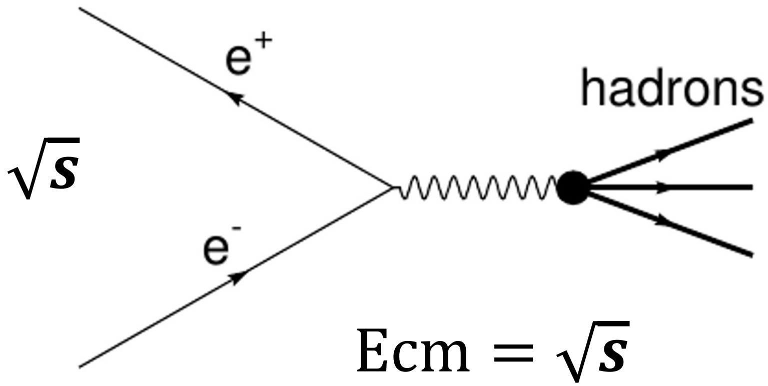
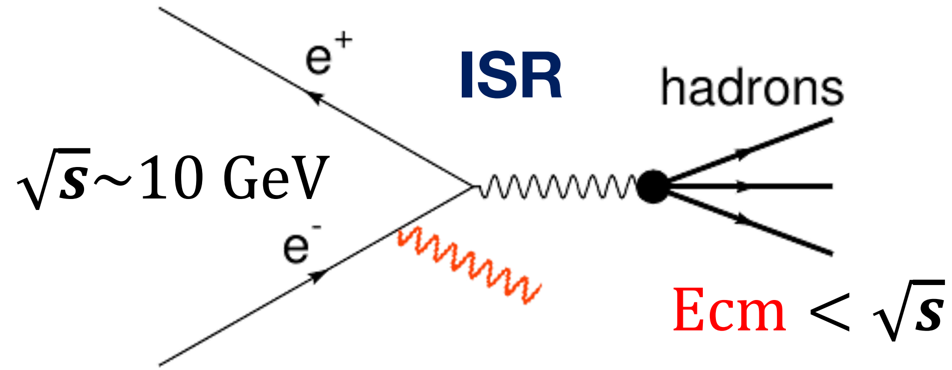
Direct scan BESIII

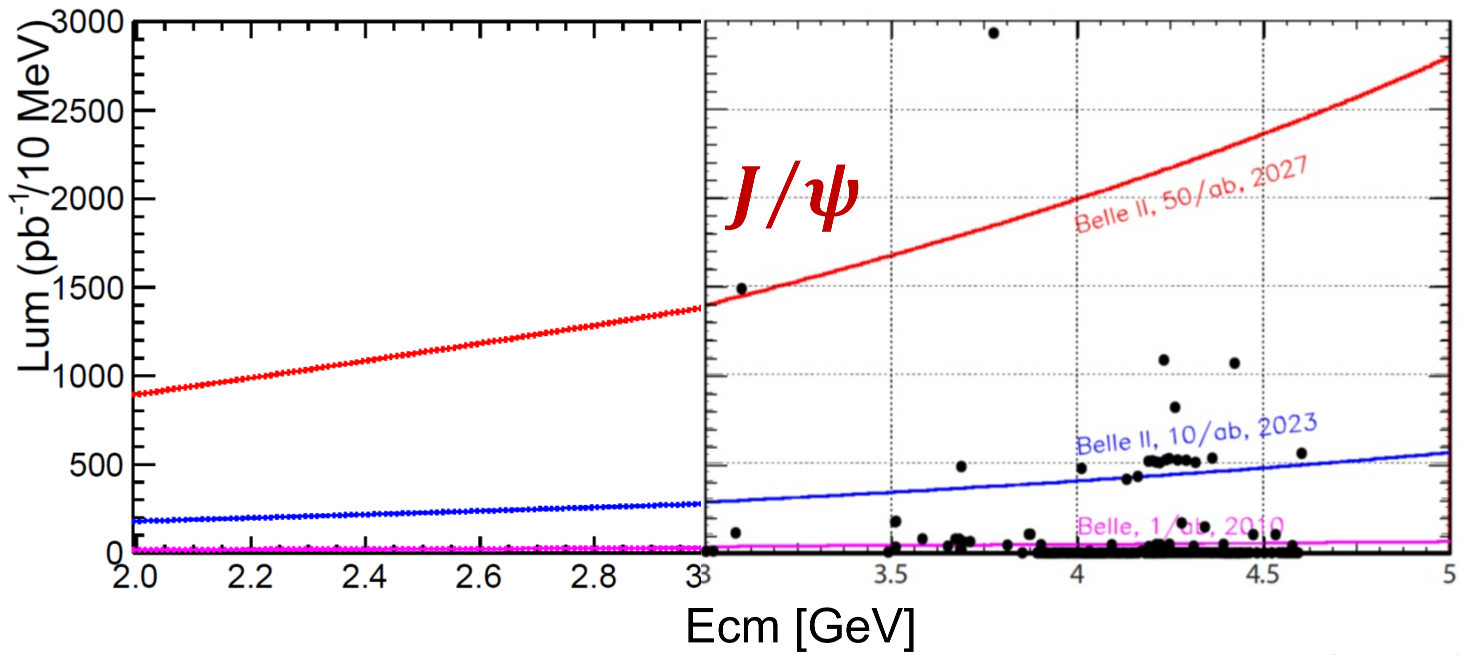


- (very) high luminosity at selected c.m. energies
- better resolution: at J/ψ 0.9 MeV: 10^{10} J/ψ

ISR BelleII

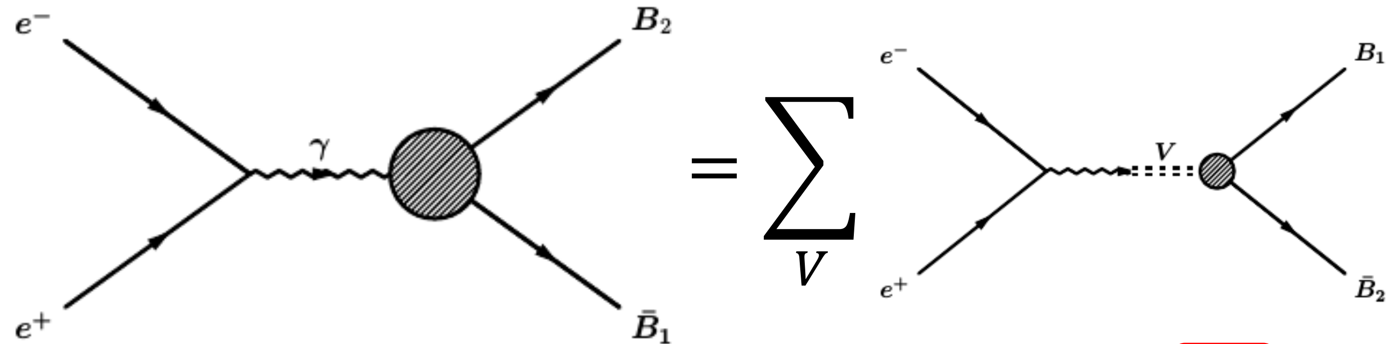


- many Ecm simultaneously
- reduced point-to-point systematics
- mass resolution limited by detector
- boost of hadronic system may help efficiency



Picture:Wolfgang Gradl & Xiaorong

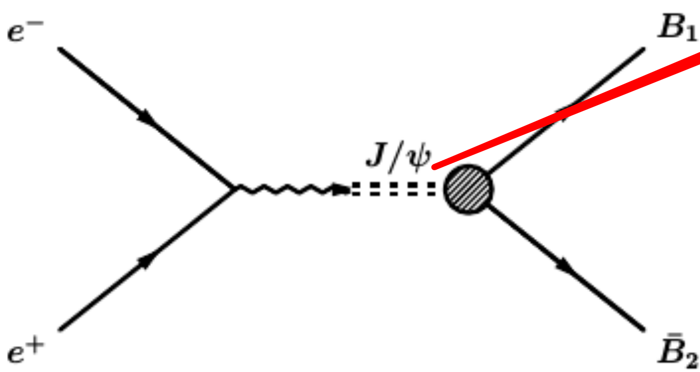
Baryon FFs (continuum):



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

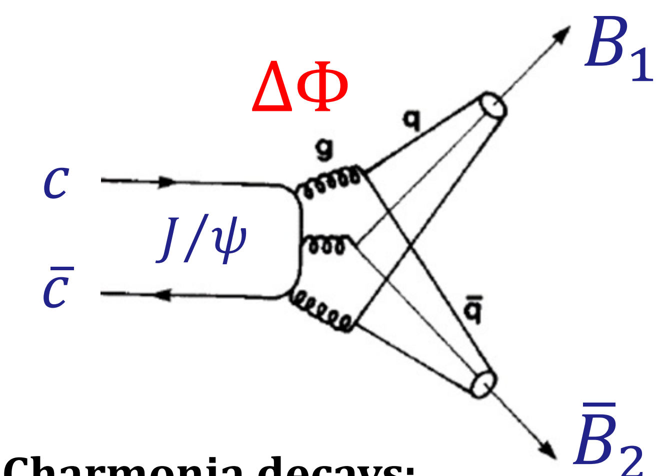
$V = \gamma, \rho, \omega, \varphi, \ldots, \boxed{J/\psi}, \psi(2S), \ldots$

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

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

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

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

3.2x10^9 ψ(2S)

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

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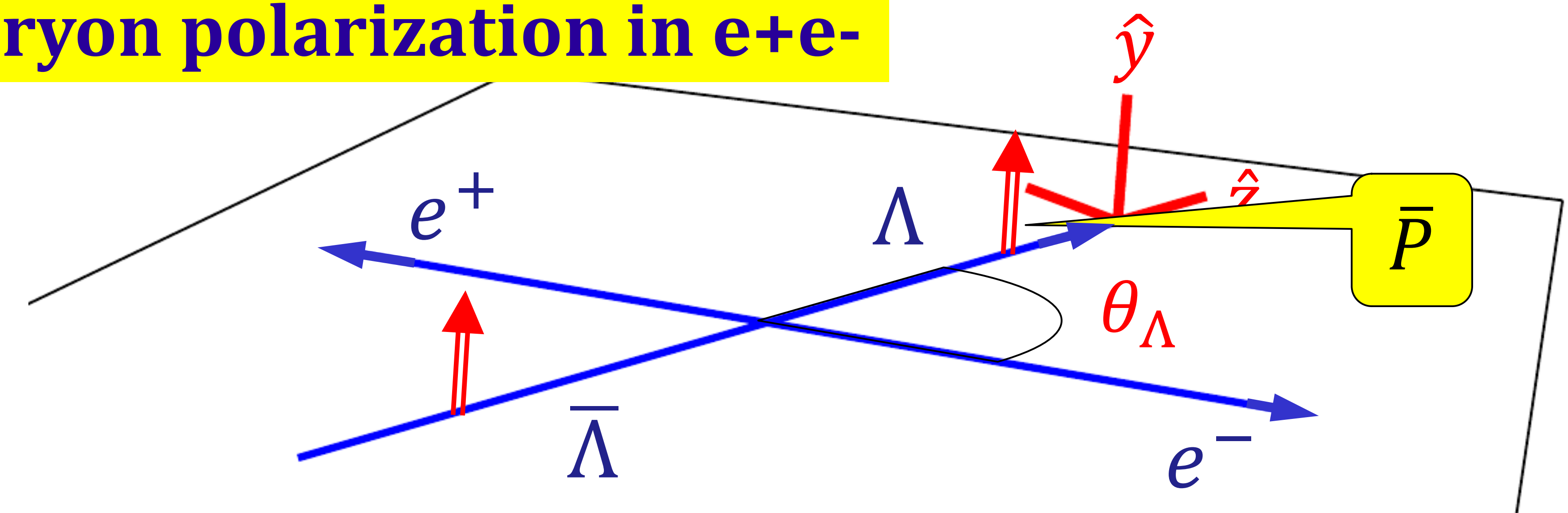
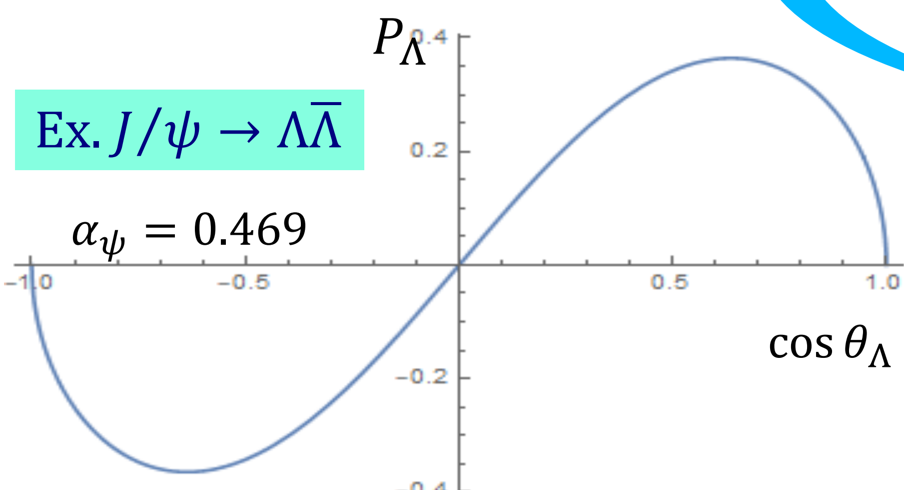
Baryon polarization in e+e-



Unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$



Max P_Λ= 36.4%

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

Baryon-antibaryon spin density matrix

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

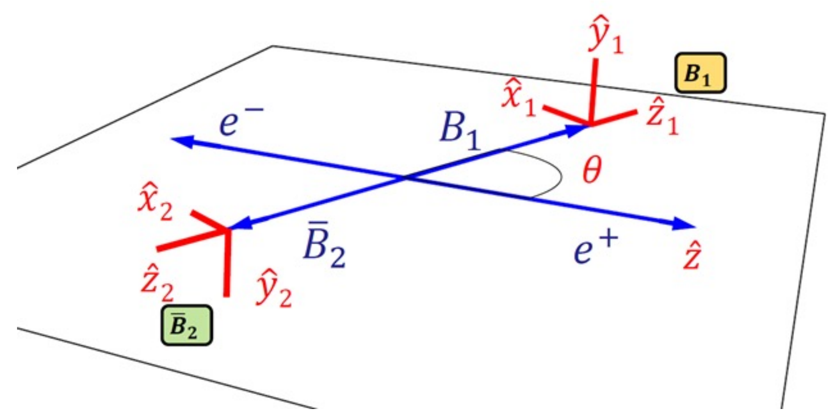
General two spin ½ particle state: $$\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\, \sigma_\mu^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_2}$$

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

P_y

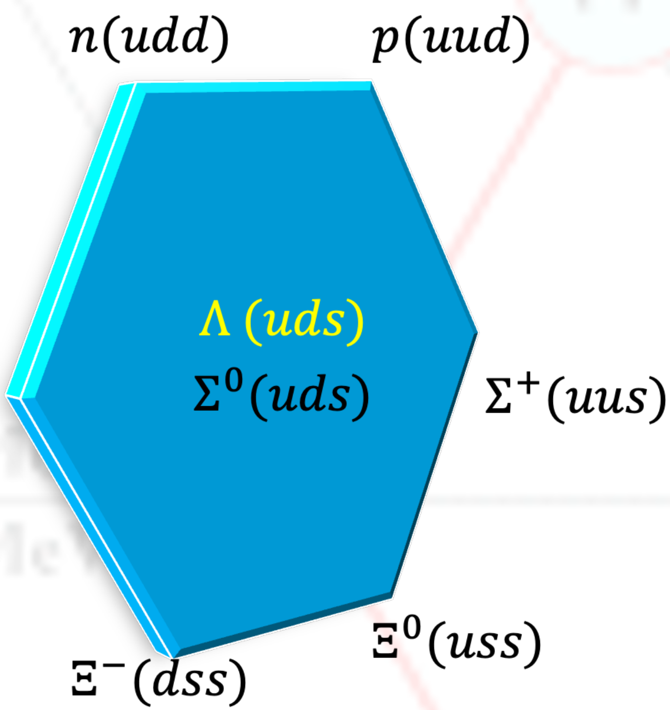
$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & 0 & \boxed{\beta_\psi \sin\theta\cos\theta} & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi \sin\theta\cos\theta \\ -\beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & 0 \\ 0 & -\gamma_\psi\sin\theta\cos\theta & 0 & -\alpha_\psi -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

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

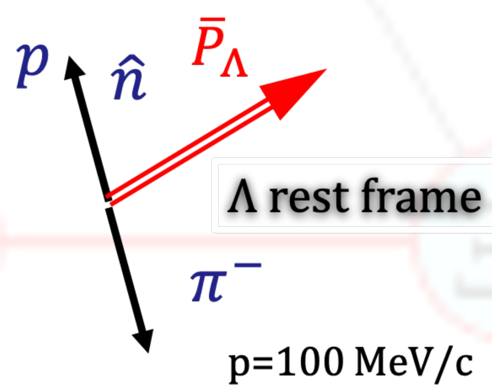


E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

Spin ½ baryon octet

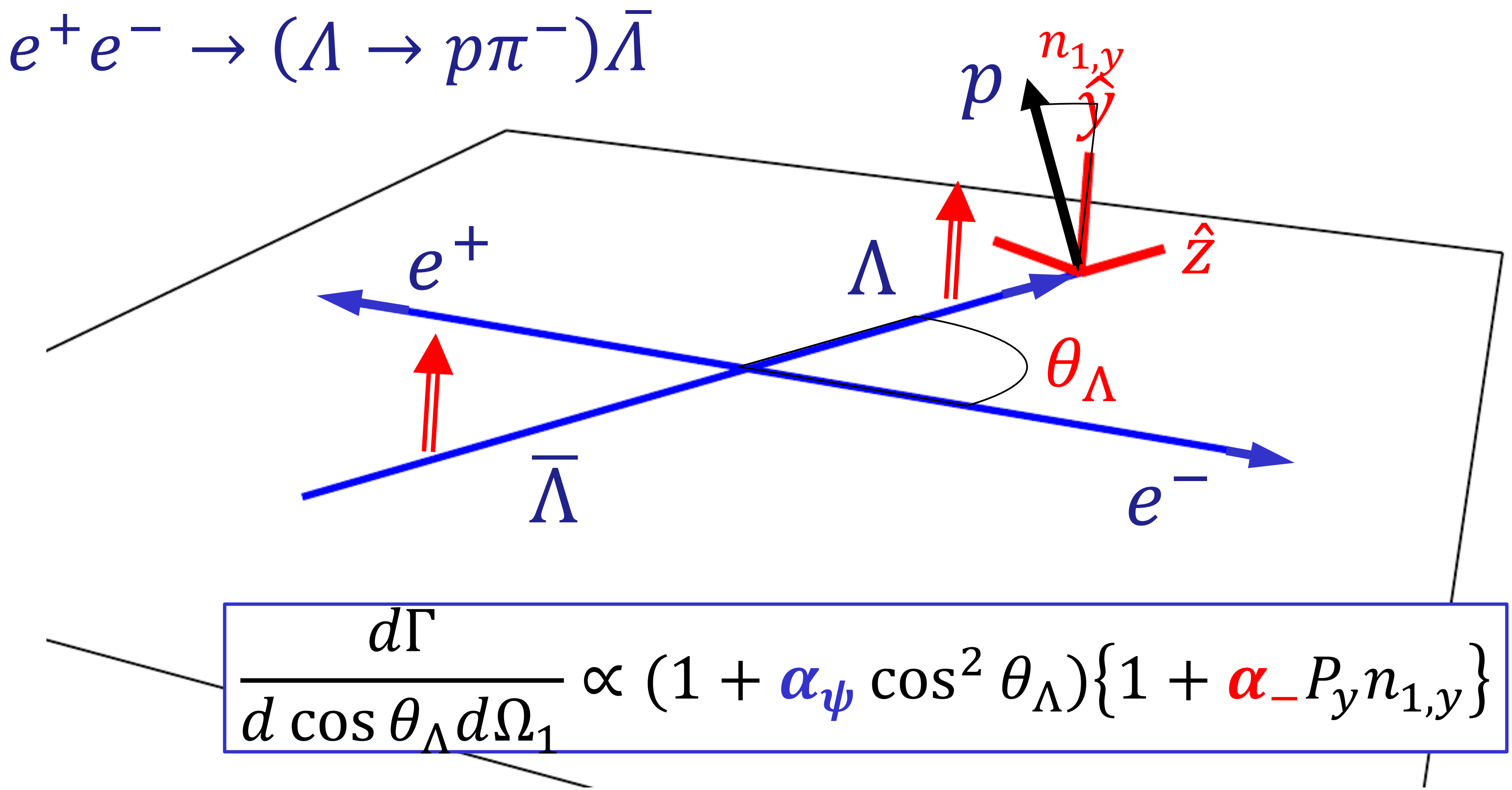


hyperon	Mass [GeV/c²]	$c\tau$ [cm]	decay (BF)
$\Lambda(uds)$	1.116	7.9	$p\pi^-$ (63.9%) $n\pi^0$ (35.8%)
$\Sigma^-(dds)$	1.197	4.4	$n\pi^-$ (99.8%)
$\Sigma^+(uus)$	1.189	2.4	$p\pi^0$ (51.6%) $n\pi^+$ (48.3%)
$\Xi^0(uss)$	1.315	8.7	$\Lambda\pi^0$ (99.5%)
$\Xi^-(dss)$	1.321	5.1	$\Lambda\pi^-$ (99.8%)



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

Inclusive decay angular distribution



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

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

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

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

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

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

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

Cross section

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

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

Spin correlations

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

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:

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

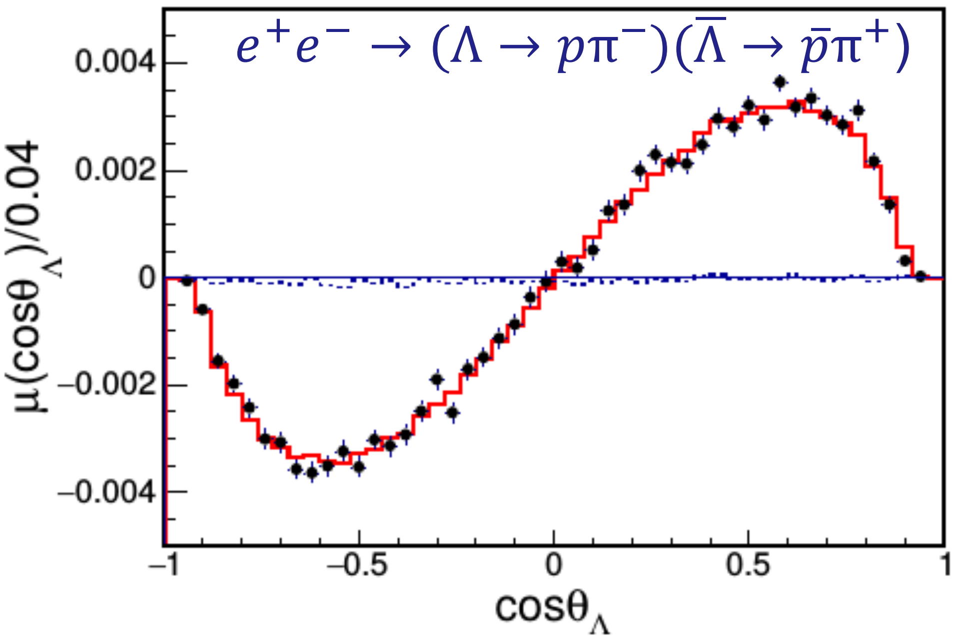
The angular distribution:

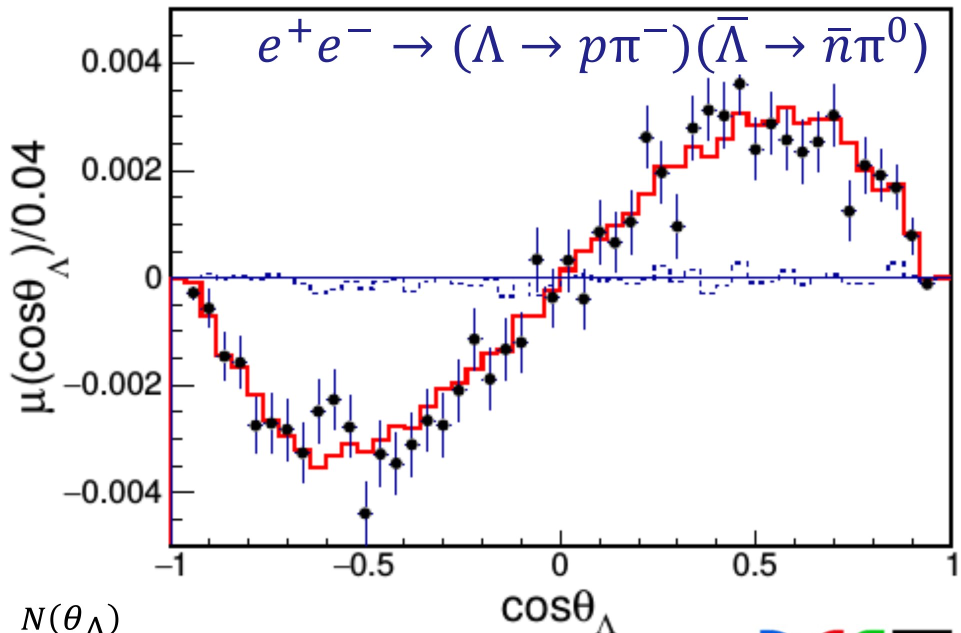
$$W = Tr\rho_{p,\bar{p}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} a_{\mu,0}^{\Lambda} a_{\bar{\nu},0}^{\bar{\Lambda}}$$

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

Fit results

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





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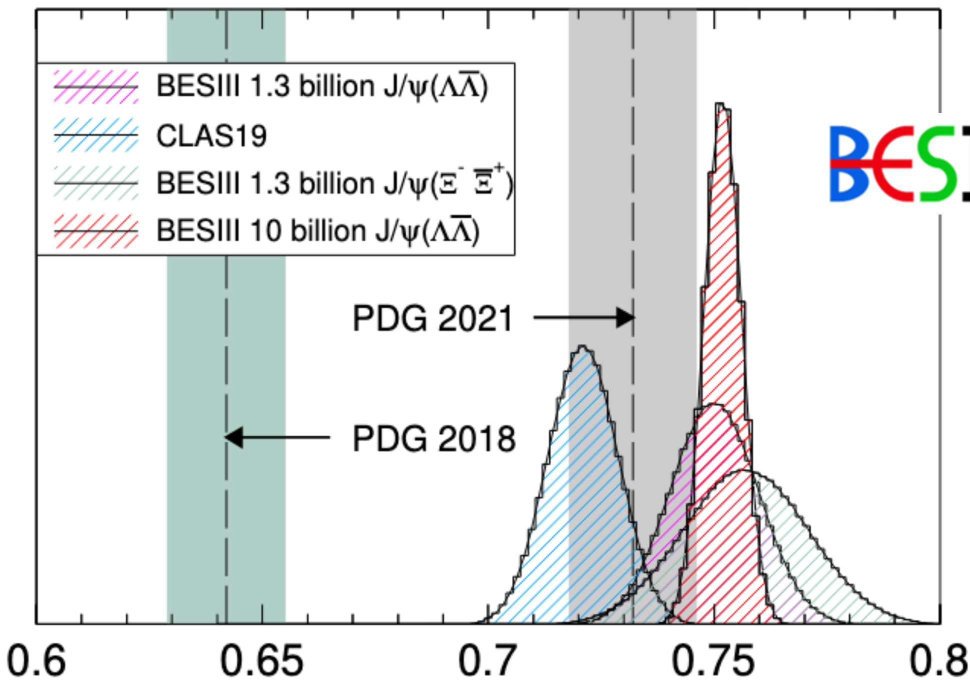
moment: $$\mu(\cos\theta_\Lambda) = \frac{1}{N}\sum_{i=1}^{N(\theta_\Lambda)}\left(n_{1,y}^{(i)} - n_{2,y}^{(i)}\right)$$

(uncorrected for acceptance)

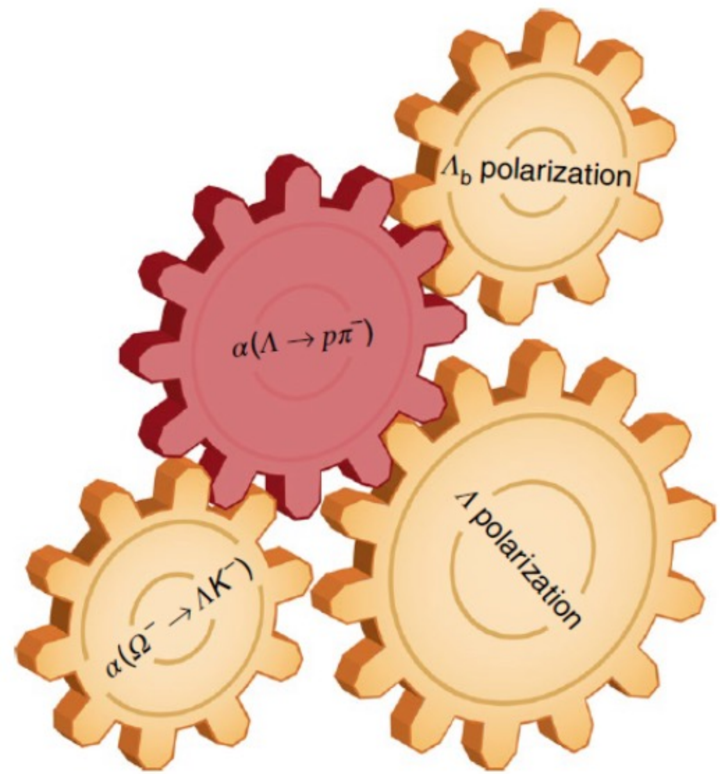
Parameters	This work	Previous results	
α_ψ	$\mathbf{0.461 \pm 0.006 \pm 0.007}$	0.469 ± 0.027	BESIII
$\Delta\Phi$ (rad)	$\mathbf{0.740 \pm 0.010 \pm 0.008}$	–	
α_-	$\mathbf{0.750 \pm 0.009 \pm 0.004}$	0.642 ± 0.013	PDG
α_+	$\mathbf{-0.758 \pm 0.010 \pm 0.007}$	-0.71 ± 0.08	PDG
$\bar{\alpha}_0$	$\mathbf{-0.692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

BESIII Nature Phys. (2019)

Decay parameters



$\alpha(\Lambda \to p\pi^-)$



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

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

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

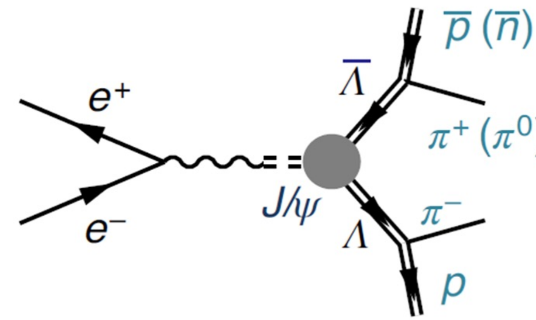
Polarization and entanglement in baryon-antibaryon pair production in electron-positron annihilation

The BESIII Collaboration*

Nature Phys. 15 (2019) 631

BESIII

Phys.Rev.Lett. 129 (2022) 131801

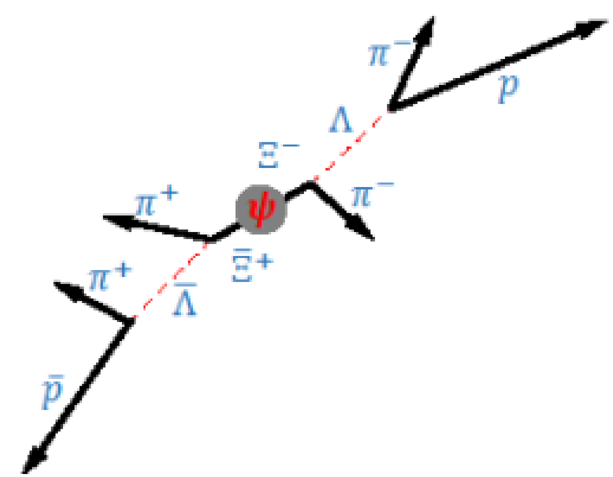


$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$

Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

Nature **606**, 64–69 (2022)



Methods:

Fäldt, AK PLB 772, 16
Perotti, Fäldt, AK, Leupold, Song PRD99,056008
Adlarson, AK PRD 100, 114005
Salone,Adlarson,Batozskaya, AK,Leupold,Tandean PRD 105, 116022
Batozskaya, AK, Salone,Wiechnik PRD 108, 016011

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

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

Parameters: 2 production + 6 for decay chains

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

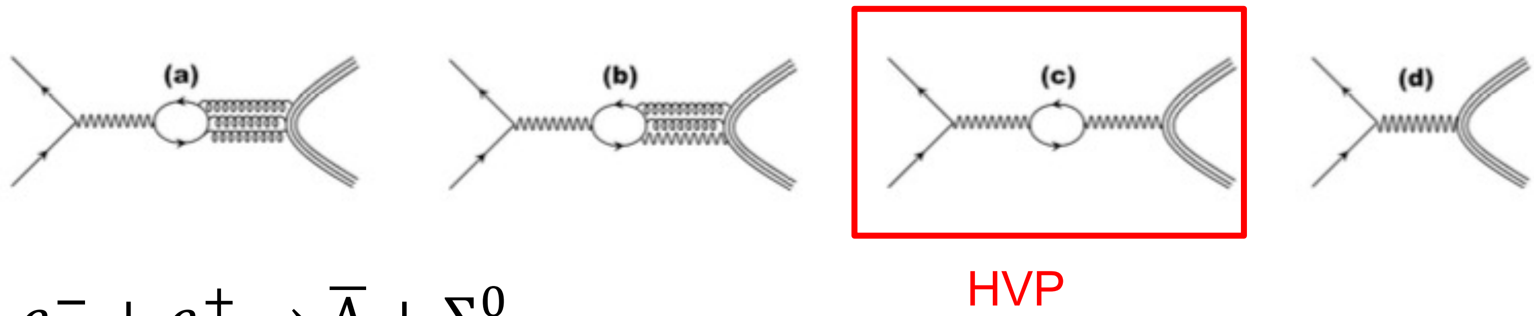
$$W = \sum_{\mu,\overline{\nu}} C_{\mu\overline{\nu}} \sum_{\mu',\overline{\nu}'} a^{\Xi}_{\mu,\mu'} a^{\overline{\Xi}}_{\overline{\nu},\overline{\nu}'} a^{\Lambda}_{\mu',0} a^{\overline{\Lambda}}_{\overline{\nu}',0}$$

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

nature communications

Article https://doi.org/10.1038/s41467-024-51802-y

Extracting the femtometer structure of strange baryons using the vacuum polarization effect



$$e^- + e^+ \rightarrow \bar{\Lambda} + \Sigma^0$$

$$\left|\frac{G_E}{G_M}\right| = 0.86(3) \quad \mathrm{Arg}\frac{G_E}{G_M} = 1.01(9)\ \mathrm{rad}$$

Precise Measurement of the Λ Electric Dipole Moment through the Entangled Strange Baryon-Antibaryon System

BESIII Collaboration • Medina Ablikim (Beijing, Inst. High Energy Phys.) et al. (Jun 23, 2025)

e-Print: 2506.19180 [hep-ex]

The amplitude for the $J/\psi \to \Lambda\bar{\Lambda}$ decay is written as (14)

$$\mathcal{M}_{\lambda_\Lambda,\lambda_{\bar{\Lambda}}} = \epsilon_\mu(\lambda_\Lambda - \lambda_{\bar{\Lambda}})\bar{u}(\lambda_\Lambda, p_\Lambda)(F_V\gamma^\mu + \frac{i}{2m_\Lambda}\sigma^{\mu\nu}q_\nu H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu\nu}\gamma^5 q_\nu H_T)v(\lambda_{\bar{\Lambda}}, p_{\bar{\Lambda}}),$$

Parameter	Fitting results
P_L	$(-1.8 \pm 1.2 \pm 0.8) \times 10^{-3}$
$Re(F_A)$	$(-2.4 \pm 1.6 \pm 3.1) \times 10^{-6}$
$Im(F_A)$	$(-7.9 \pm 3.7 \pm 2.5) \times 10^{-6}$
$Re(H_T)$	$(-1.4 \pm 1.4 \pm 0.2) \times 10^{-6}$ GeV^{-1}
$Im(H_T)$	$(1.3 \pm 1.2 \pm 0.4) \times 10^{-6}$ GeV^{-1}
$Re(d_\Lambda)$	$(-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}$ e cm
$Im(d_\Lambda)$	$(2.9 \pm 2.6 \pm 0.6) \times 10^{-19}$ e cm

$$H_T = \frac{2e}{3m_{J/\psi}^2} g_V d_\Lambda.$$

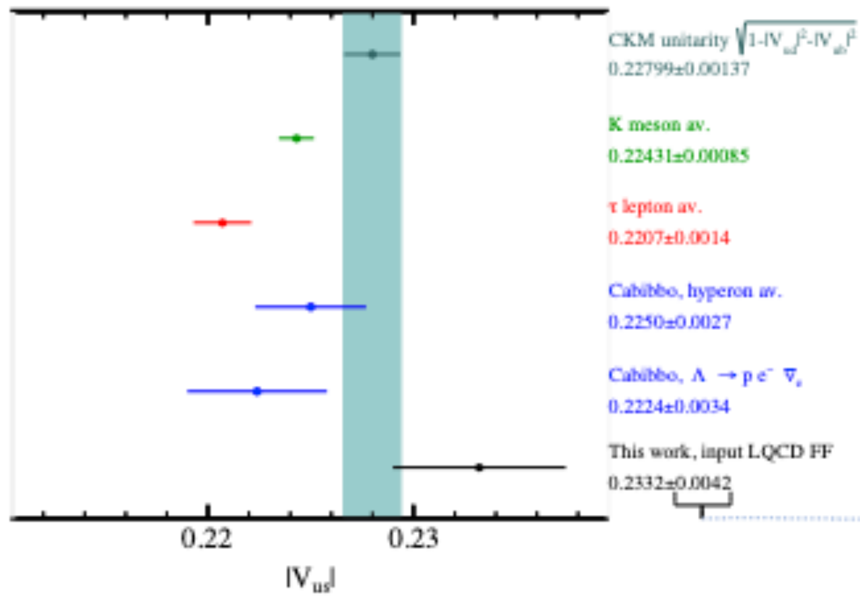
Determination of CKM matrix element and axial vector form factors from weak decays of quantum-entangled strange baryons

BESIII Collaboration • M. Ablikim Show All(698)

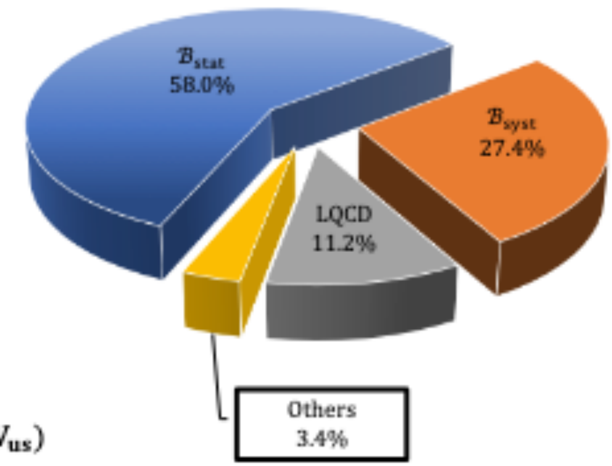
Sep 11, 2025

24 pages
e-Print: 2509.09266

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



$\sigma^2(V_{us})$



Study of the $\Lambda \to p\ell\bar{\nu}_\ell$ semileptonic decay in lattice QCD

Simone Bacchio (Cyprus Inst.), Andreas Konstantinou (Cyprus U.)

Jul 14, 2025

5 pages
e-Print: 2507.09970 [hep-lat]

Semileptonic decays of spin-entangled baryon-antibaryon pairs

Varvara Batozskaya[1,2,*], Andrzej Kupsc[3,2], Nora Salone[2], and Jakub Wiechnik[2,4]

Show more

Phys. Rev. D **108**, 016011 – **Published 18 July, 2023**

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 $e^+e^- \to \Omega^-\bar{\Omega}^+$

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):

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

decay 1/2->1/2 0 (Λ->pπ)

decay 3/2->1/2 0 (Ω->ΛK)

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

Model-Independent Determination of the Spin of the Ω^- and Its Polarization Alignment in $\psi(3686) \to \Omega^-\bar{\Omega}^+$

BESIII Collaboration • Medina Ablikim (Beijing, Inst. High Energy Phys.) Show All(511)

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Conclusions

Hyperon decays, CP violation, QM tests
using BESIII data sample of 10^{10} J/ψ

Baryon form factors at BESIII, BelleII, STCF using scan and ISR

Higher order em effects and event generators needed for precision experiments

Two photon baryon-antibaryon production?