Spin effects in e^+e^- annihilation to baryon-antibaryon pair

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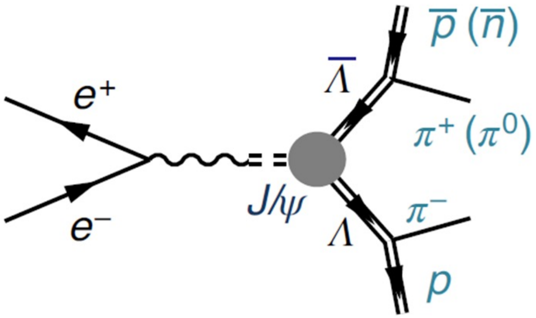
NCBJ

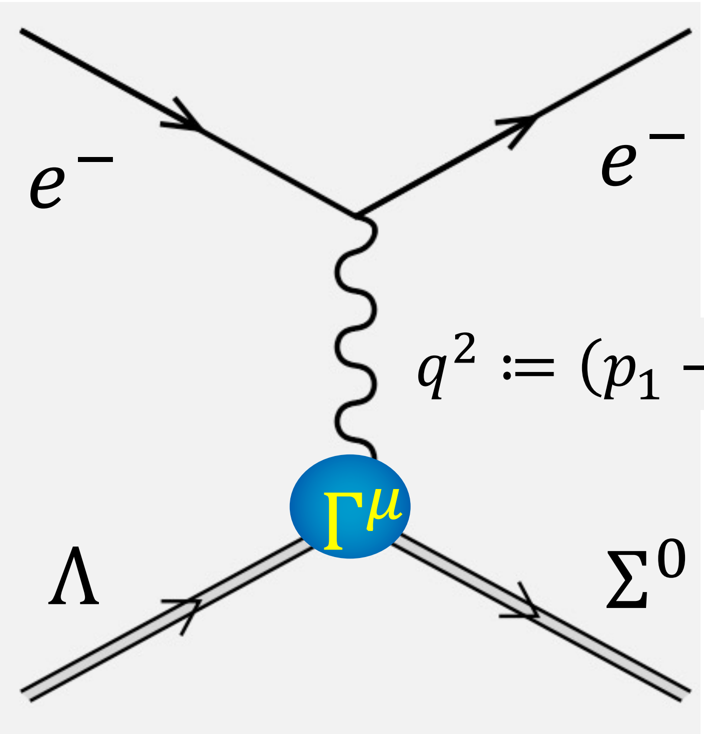
$e^+e^- \to B\overline{B}$



- Baryon form factors
- Spin polarization and correlations
- Polarimeters
- Modular formalism for angular distributions
- Example results

NATIONAL SCIENCE CENTRE POLAND

(Transition) Form Factors



$q^2 := (p_1 - p_2)^2 < 0$

$B_{1/2}$

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

F_1 (Dirac) and F_2 (Pauli) form factors

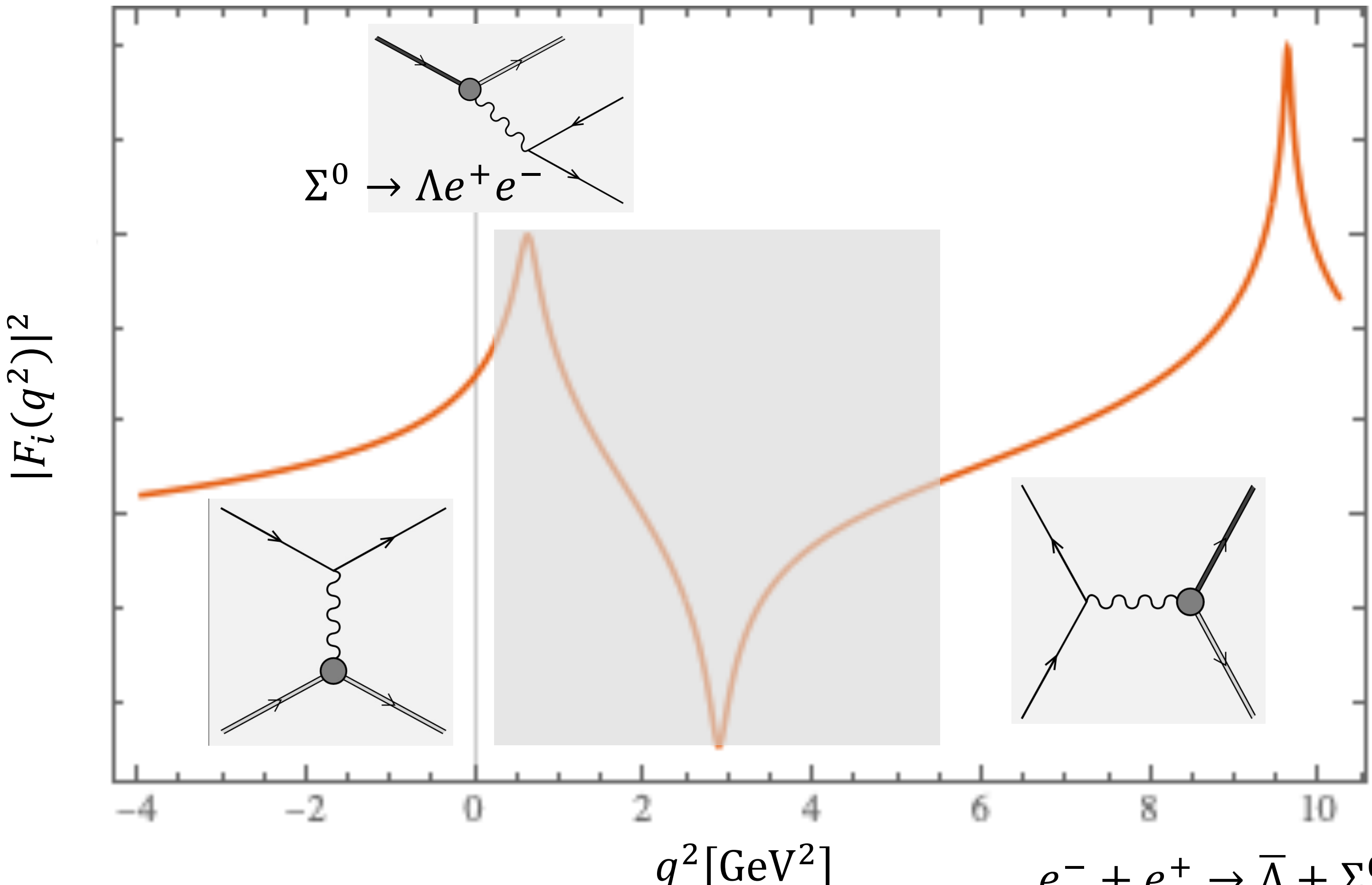
Sachs Form Factors (FFs) ⇔ helicity amplitudes:

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

helicity non-flip helicity flip

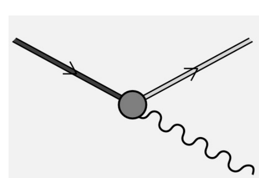
$$\tau = \frac{q^2}{(M_\Lambda + M_\Sigma)^2}$$

(Transition) Form Factors



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

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

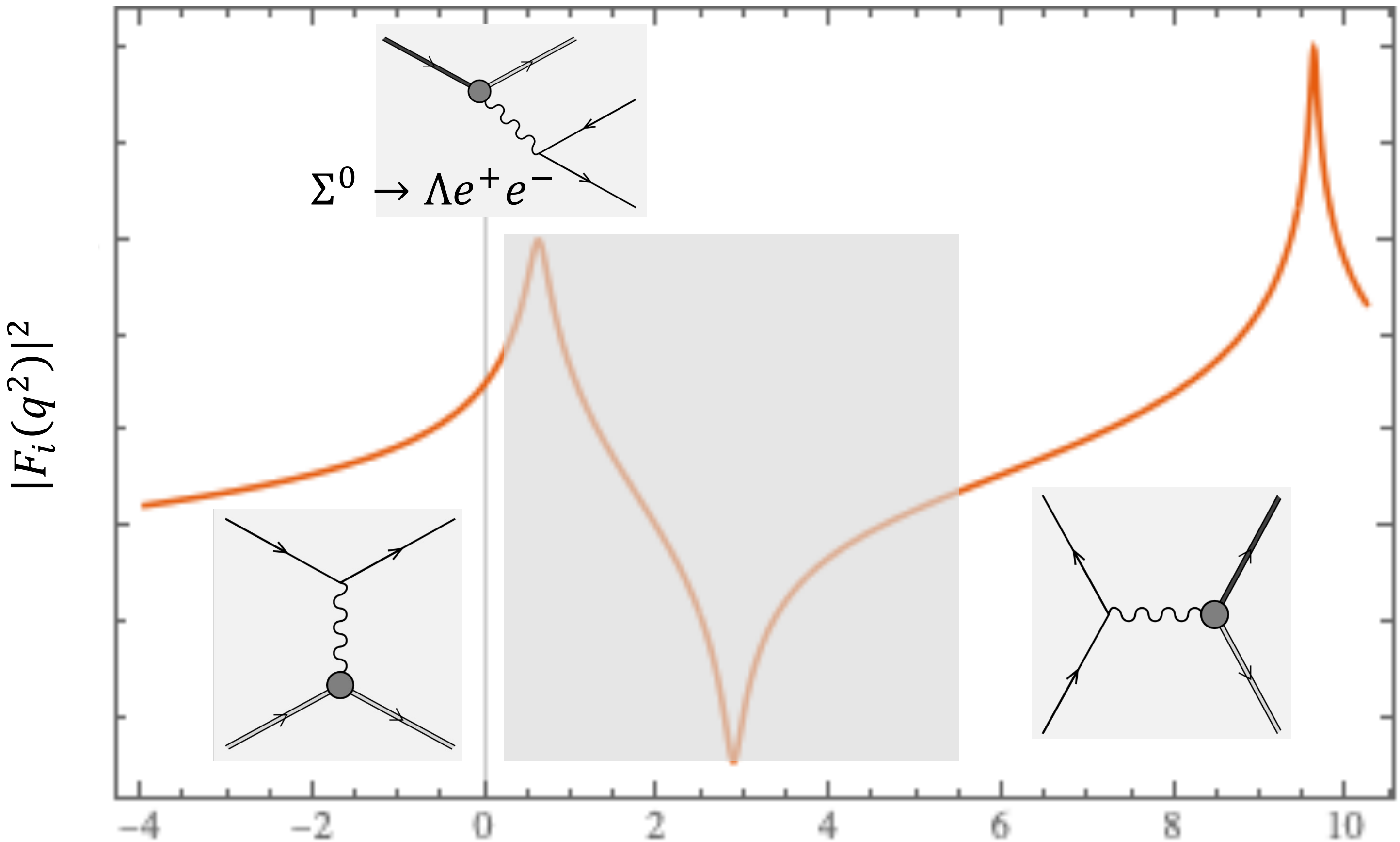


$\Sigma^0 \to \Lambda + \gamma$

$$F_i(q^2) \approx F_i(0)\left[1 + \frac{1}{6}\langle r_i^2\rangle\, q^2\right]$$

$$\langle r^2 \rangle = 6\,\frac{\mathrm{d}\ln F_i(q^2)}{\mathrm{d}q^2}\bigg|_{q^2=0}$$

(Transition) Form Factors



$q^2\,[\mathrm{GeV}^2]$

BESIII

Nature Commun. 15 (2024) 8812

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

$\mathrm{Arg}\frac{G_E}{G_M} = 58(5)^{\mathrm{o}}$

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

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

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

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

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

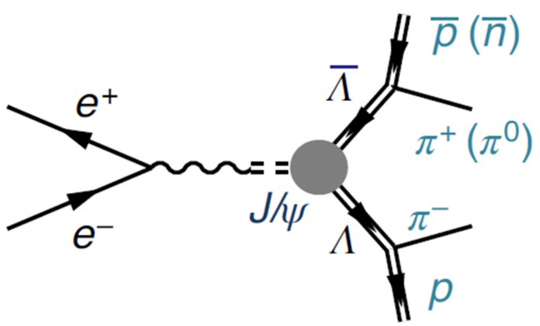
Baryon-antibaryon pair production

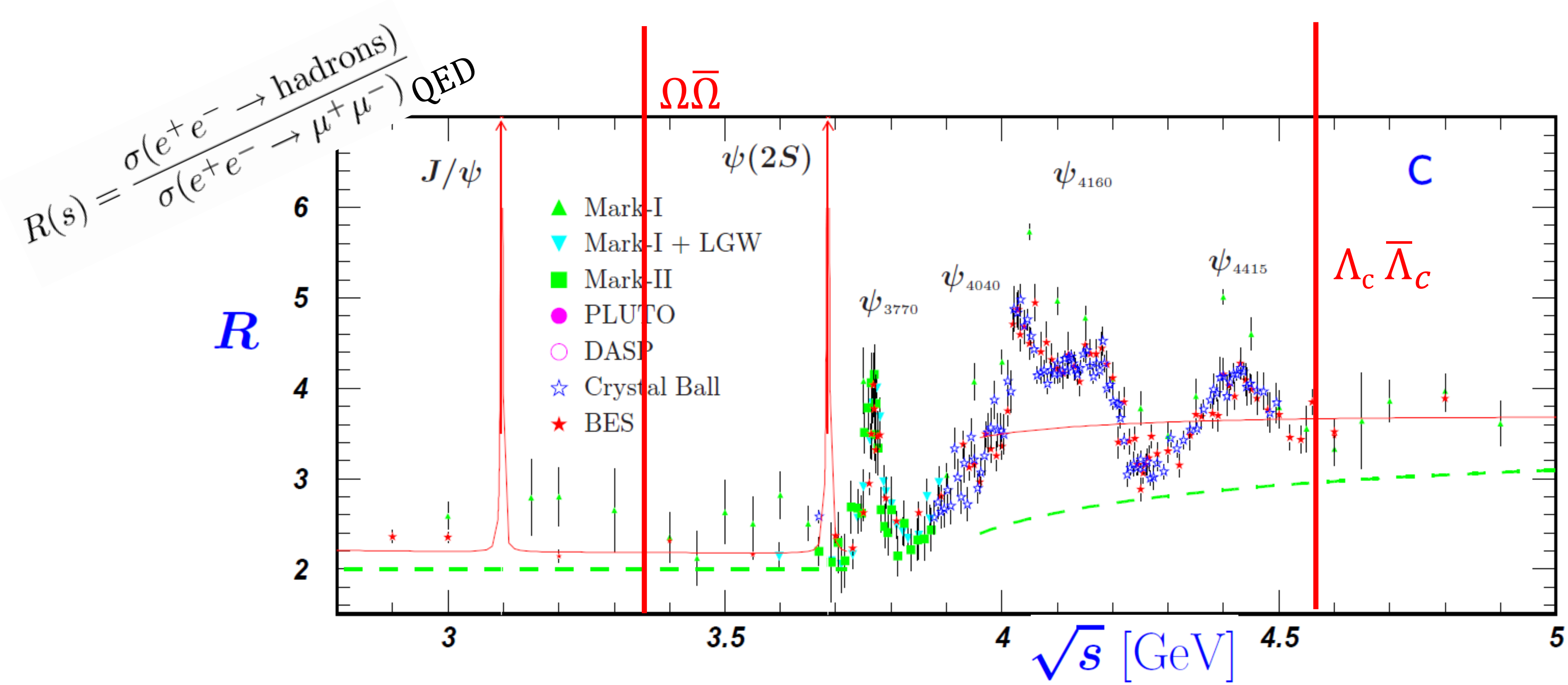
Thresholds:

$\Lambda\bar{\Lambda}$: 2.231 GeV

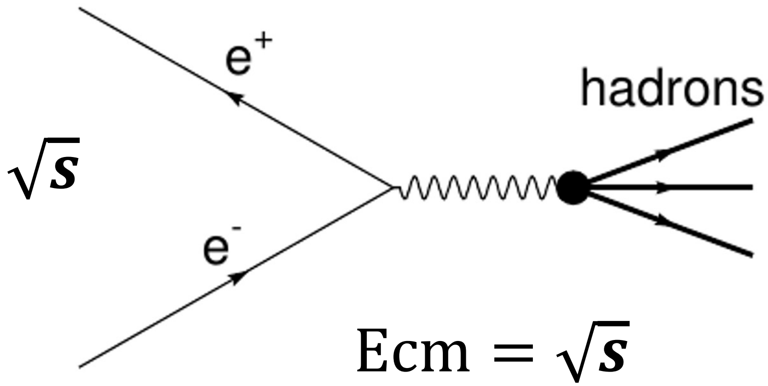
$\Xi^-\bar{\Xi}^+$ 2.643 GeV

($\Omega\bar{\Omega}$ 3.345 GeV)

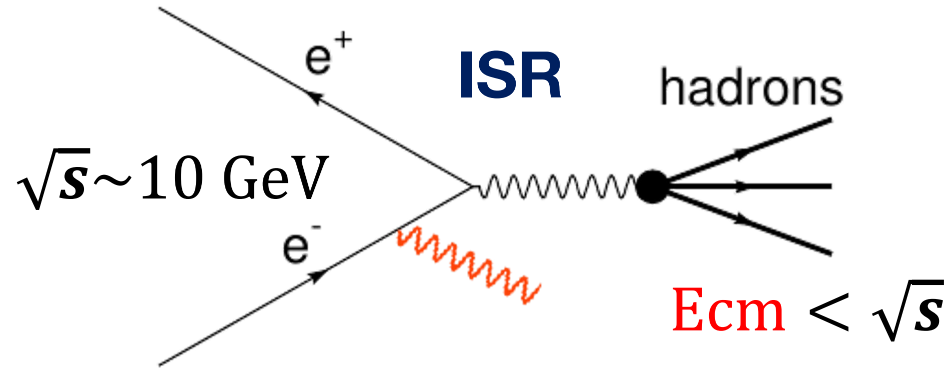




Direct scan BESIII

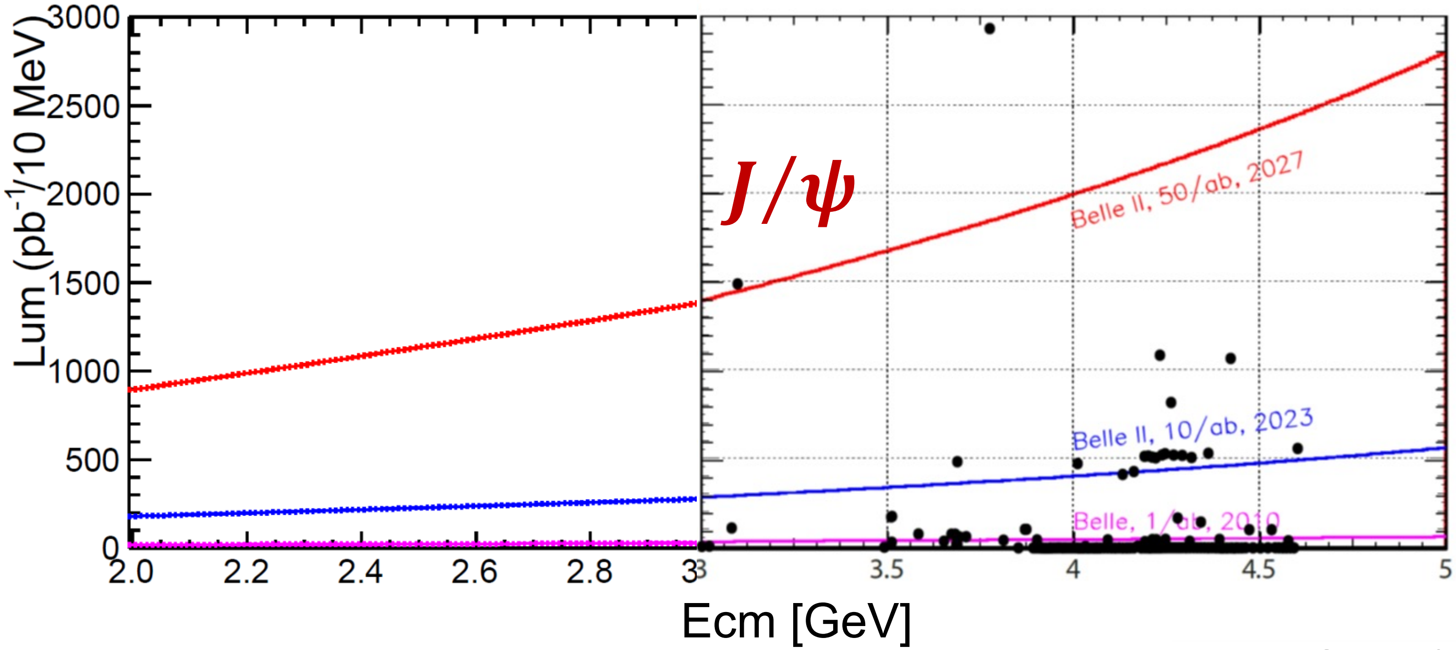


ISR BelleII



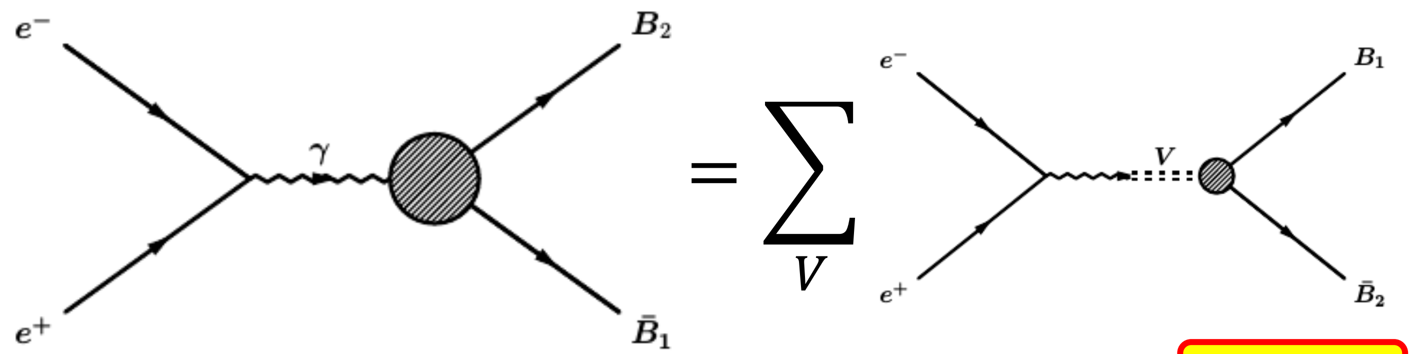
- ❑ (very) high luminosity at selected c.m. energies
- ❑ better resolution: at J/ψ 0.9 MeV: 10^{10} J/ψ

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



Picture:W. Gradl & X. Zhou

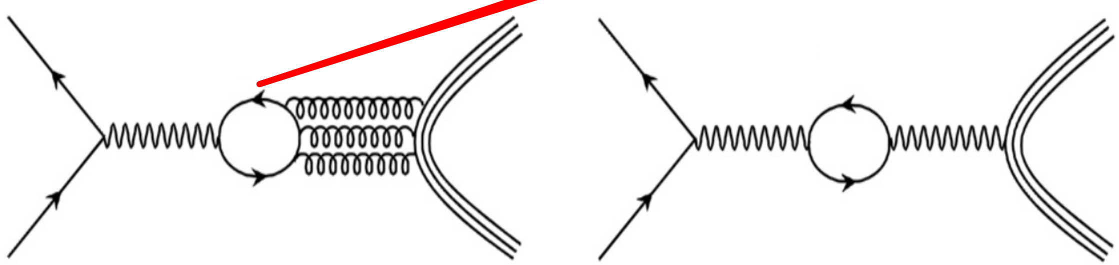
Baryon FFs (continuum):



Baryons B_1 and $\bar{B}_2$

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

vs J/ψ decay:



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

10^{10} J/ψ

3.2×10^9 $\psi(2S)$

BF$(J/\psi \to B\bar{B}) \sim 10^{-3}$

Polarization and spin correlations in $e^+e^- \to B_1\bar{B}_2$

$V \to B\bar{B}$

Helicity bases: $J, \lambda = -J, \ldots, +J$

Multipole expansion using Q bases (⇐ real coef. and symmetries):

$$\rho_{1/2} = \frac{\mathbb{1}^{[2]}}{2} + \sum_{m=-1}^{1} r^1_m Q^{[2]1}_m$$

$$\rho_{1} = \frac{\mathbb{1}^{[3]}}{3} + \sum_{m=-1}^{1} r^1_m Q^{[3]1}_m + \sum_{m=-2}^{2} r^2_m Q^{[3]2}_m$$

$$\rho_{3/2} = \frac{\mathbb{1}^{[4]}}{4} + \sum_{m=-1}^{1} r^1_m Q^{[4]1}_m + \sum_{m=-2}^{2} r^2_m Q^{[4]2}_m + \sum_{m=-3}^{3} r^3_m Q^{[4]2}_m$$

Pauli matrices

Initial state

vector(3) dipole(5) octupole(7)

Doncel, Michel, Minnaert Nucl. Phys. B38, 477(1972)

Polarization and spin correlations in $e^+e^- \to B_1\bar{B}_2$

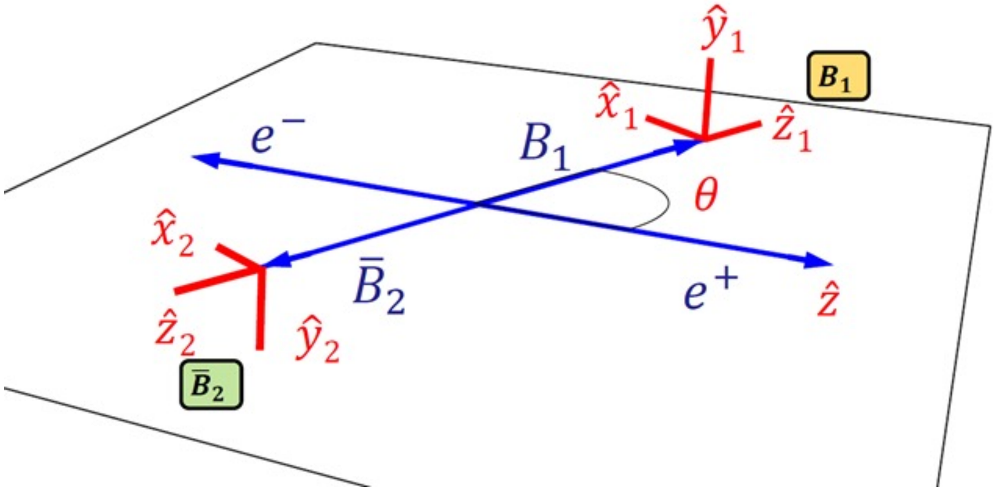
General two spin ½ particle state:

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

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

Unpolarized electron-positron annihilation ⇒ helicity ± 1 ⇒ γ^* / J/ψ have dipole polarization

$$C_{\mu\bar{\nu}} = (1+\alpha_\psi \cos^2\theta)\begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz} \end{pmatrix}$$

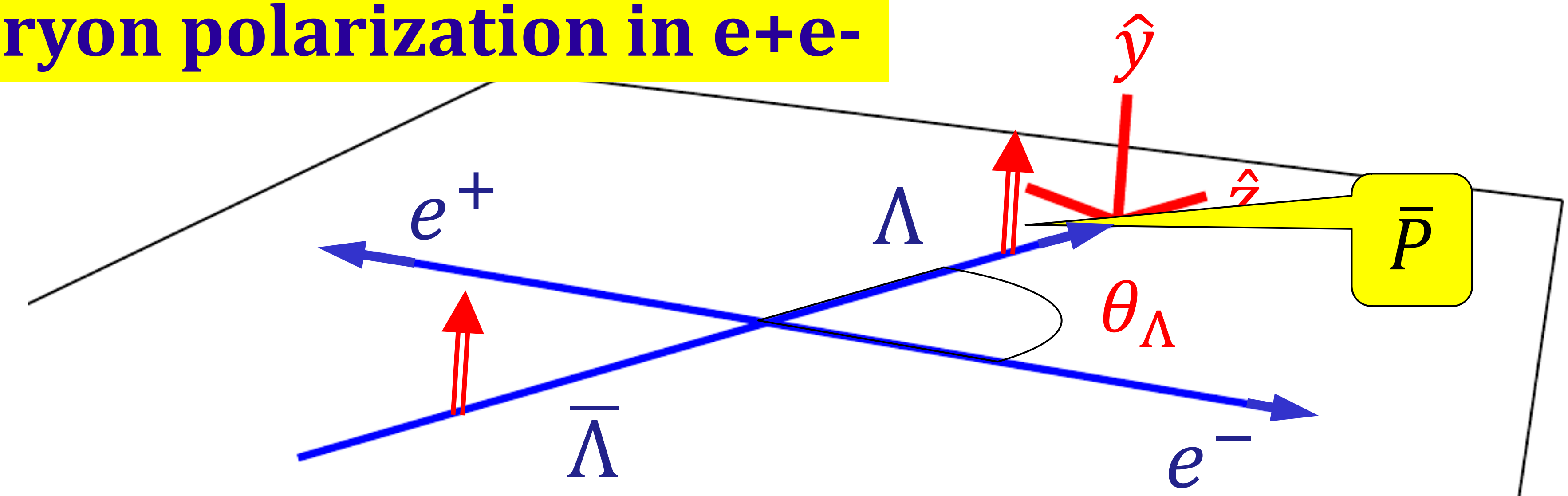


$$C_{\mu\bar{\nu}} = \begin{pmatrix} 1+\alpha_\psi\cos^2\theta & 0 & \beta_\psi \sin\theta\cos\theta & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi \sin\theta\cos\theta \\ -\beta_\psi \sin\theta\cos\theta & 0 & \alpha_\psi \sin^2\theta & 0 \\ 0 & -\gamma_\psi \sin\theta\cos\theta & 0 & -\alpha_\psi - \cos^2\theta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

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

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

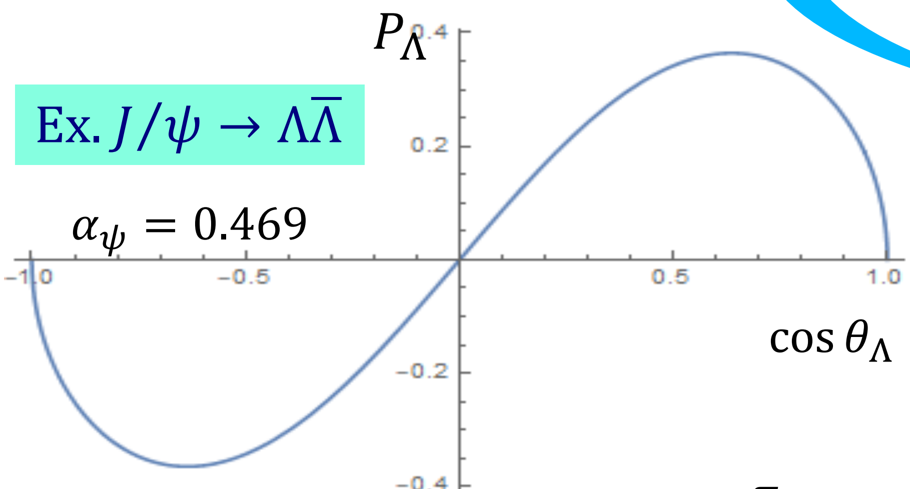
Baryon polarization in e+e-



Unpolarized e+e- beams ⇨ transverse polarization:

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

$\Delta\Phi \neq 0$

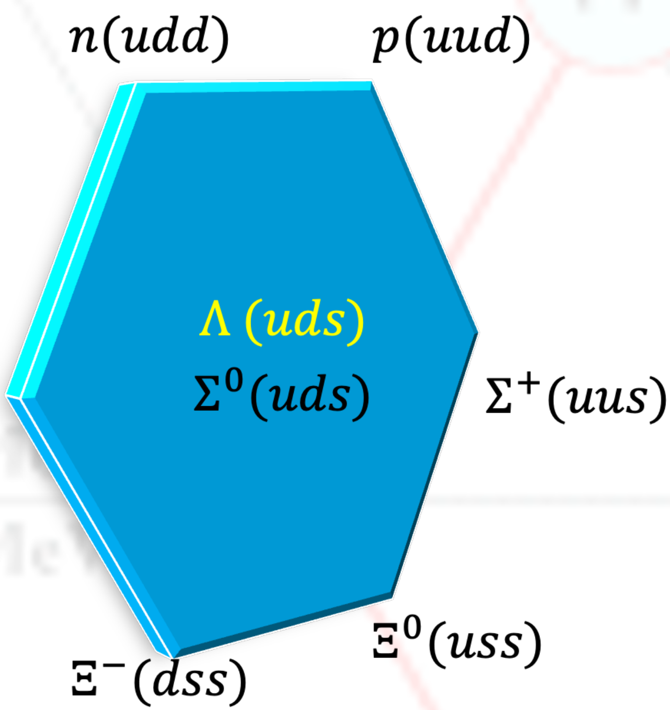


Ex. $J/\psi \to \Lambda\bar{\Lambda}$

$\alpha_\psi = 0.469$

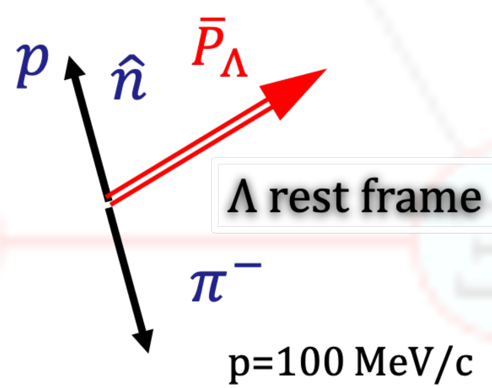
for $\Delta\Phi = \frac{\pi}{2}$

Spin polarization measurement: hyperons



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%)

$\Lambda \to p\pi^-$



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

Spin polarization measurement: $\Lambda \to p\pi^-$

$$\mathrm{B} \to \mathrm{B}_f \pi$$

$$\mathcal{F}(\xi;\vec{P}) = f_0(\xi) + P_x f_x(\xi) + P_y f_y(\xi) + P_z f_z(\xi)$$

p.d.f. of auxiliary variable ξ

$$\mathcal{F}^{\mathrm{B}\to\mathrm{B}_f\pi}(\varphi_f,\vartheta_f) = \frac{1}{4\pi}\sum_{\mu=0}^{3} P_\mu \sum_{\rho=0}^{3} \mathcal{R}^{(4)}_{\mu\rho}(\varphi_f,\vartheta_f) b^{\mathrm{B}\to\mathrm{B}_f\pi}_{\rho 0} = \frac{1}{4\pi}\sum_{\mu=0}^{3} P_\mu \sum_{\mu'=0}^{3} a^{\mathrm{B}\to\mathrm{B}_f\pi}_{\mu,0}$$

$\Lambda \to p\pi^-$

Decay matrices:

$$b^{\mathrm{B}\to\mathrm{B}_f\pi}_{\mu\nu} \propto \begin{pmatrix} 1 & 0 & 0 & \alpha_{\mathrm{B}} \\ 0 & \gamma_b & -\beta_{\mathrm{B}} & 0 \\ 0 & \beta_{\mathrm{B}} & \gamma_{\mathrm{B}} & 0 \\ \alpha_{\mathrm{B}} & 0 & 0 & 1 \end{pmatrix}$$

$$\sigma(\vec{P}) \propto \frac{1}{A_N\sqrt{N}} = \frac{1}{\alpha_B\sqrt{N}}$$

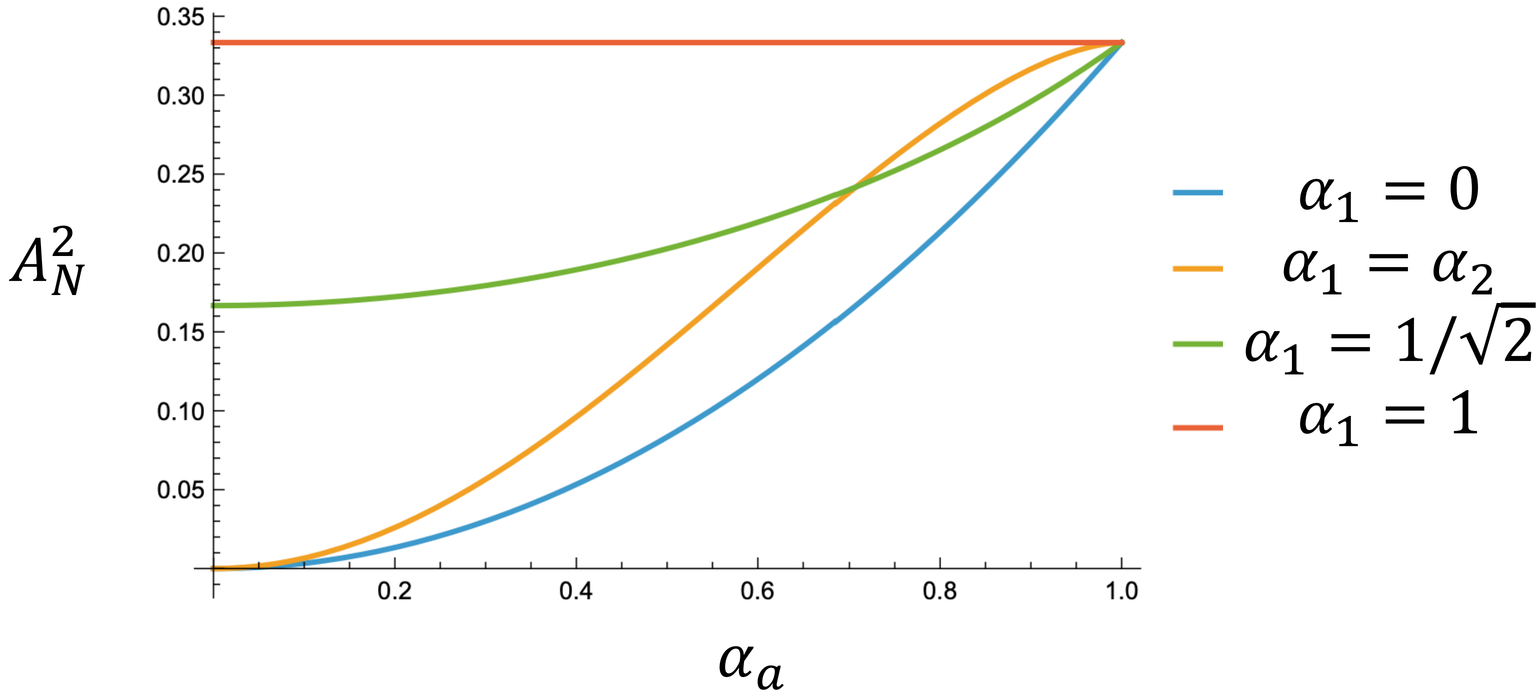
$$\beta = \sqrt{1-\alpha^2}\sin\phi$$

$$\gamma = \sqrt{1-\alpha^2}\cos\phi$$

Spin polarization measurement: $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$

$$\mathsf{B}(P_z) \to \mathsf{B}_1\pi_1 \to \mathsf{B}_a\pi_a\pi_1$$

$$b^{\mathsf{B}\to a}_{\rho\nu} = \sum_{\rho',\rho''=0}^{3} b^{\mathsf{B}\to 1}_{\rho\rho'} \mathcal{R}^{(4)}_{\rho'\rho''}(0,\vartheta_a) b^{1\to a}_{\rho''\nu}$$

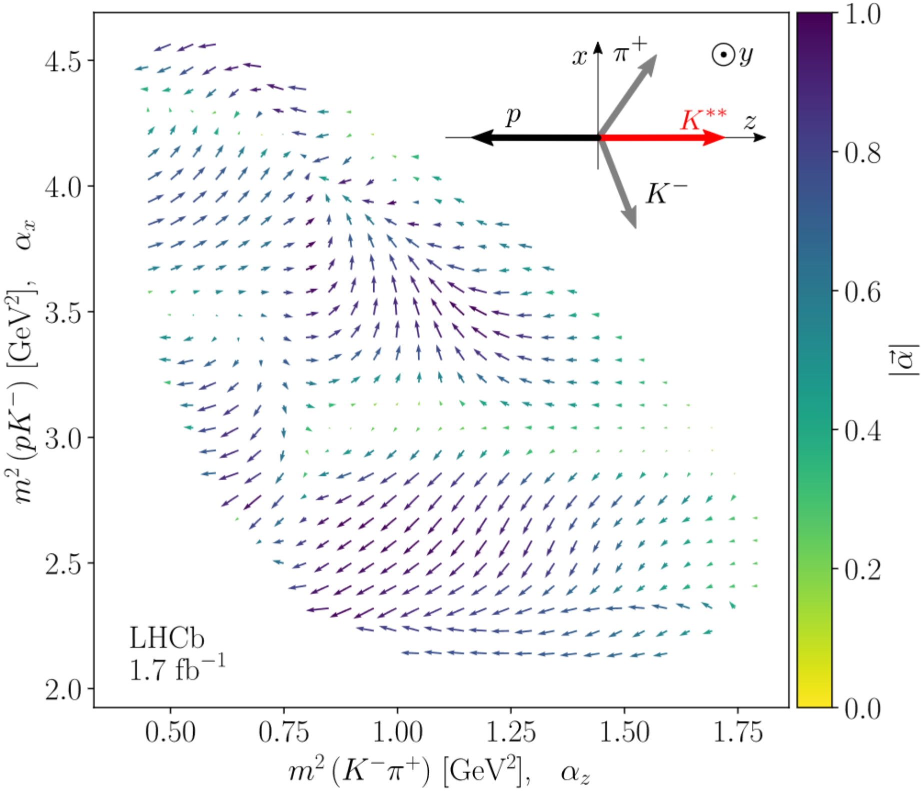


$$A_N^2 = \frac{1}{3} - \frac{(1-\alpha_1^2)(1-\alpha_a^2)\,\mathrm{atanh}(\alpha_1\alpha_a)}{3\alpha_1\alpha_a}$$

Spin polarization measurement: charmed baryons

$\Lambda_c^+ \to pK^-\pi^+$ BF=6.4(2)%

$$\mathcal{F}(s,t,\phi_2,\theta_2,-\chi_2) = \sum_{\mu=0}^{3} P_\mu \sum_{\kappa=0}^{3} \mathcal{R}^{(4)}_{\mu\kappa}(\phi_2,\theta_2,-\chi_2) b_{\kappa 0}(s,t)$$



$$b_{k0}(s,t) = \begin{bmatrix} 1 \\ \alpha_x(s,t) \\ \alpha_y(s,t) \\ \alpha_z(s,t) \end{bmatrix}$$

$$A_N^2 = \alpha_x^2 + \alpha_y^2 + \alpha_z^2$$

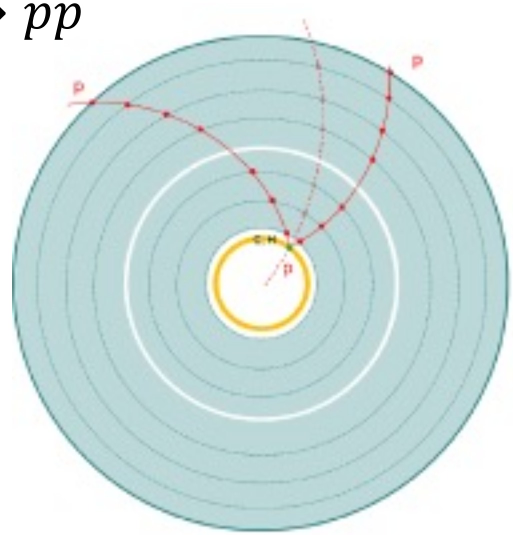
$$A_N = 0.67(2)$$

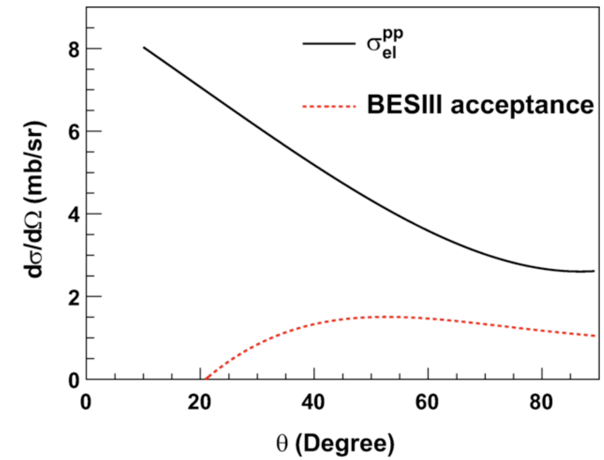
LHCb Phys.Rev.D 108 (2023) 012023 *JHEP* 07 (2023) 228

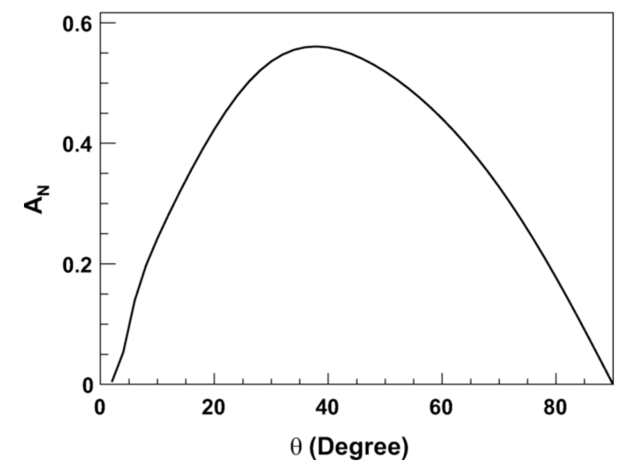
Spin polarization measurement: protons

Secondary scattering feasibility at BESIII

Example: $J/\psi \to p\bar{p}$







$$\frac{d\sigma}{d\varphi d\cos\vartheta} = \frac{1}{2\pi}\frac{d\sigma_0}{d\cos\vartheta}\left[1 + P_x A_N(\vartheta)\cos\varphi + P_y A_N(\vartheta)\sin\varphi\right]$$

probability of the proton elastically scattering off a proton in the oil layer of 0.8 mm is ca 1.2×10^{-4}

How to determine nucleon polarization at existing collider experiments?
Y.Liang, X.Lv, AK, B. Gou, and H. Li PRD **112**, L031502 (2025)

Decay angular distributions

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

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

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

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

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

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

⇒ Parameters: 2 production + 2 for decays

$$(\alpha_\psi, \Delta\Phi, \alpha_\Lambda, \bar{\alpha}_\Lambda)$$

Fäldt, AK PLB772 (2017) 16 E.Perotti, G.Faldt, AK, S.Leupold,JJ.Song PRD99 (2019)056008

BESIII breakthrough measurements

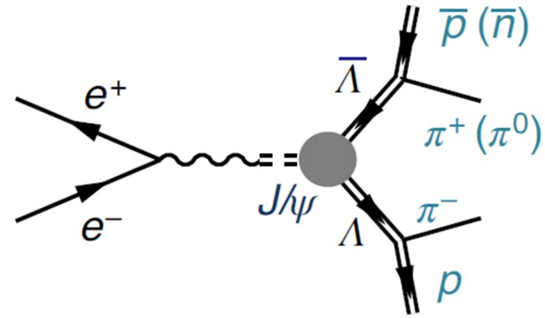
$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

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



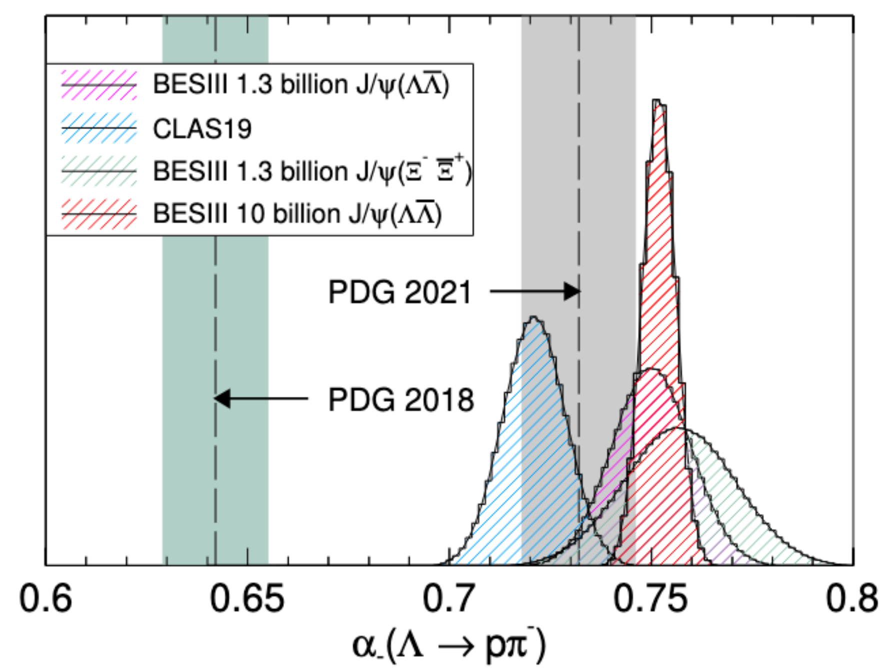
BESIII

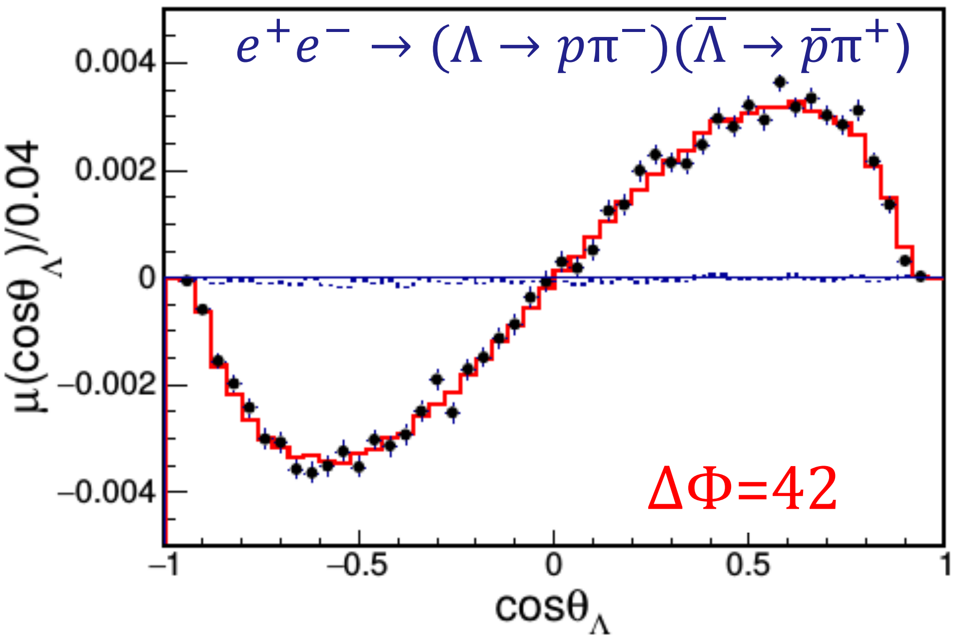
Probing CP symmetry and weak phases with entangled double-strange baryons

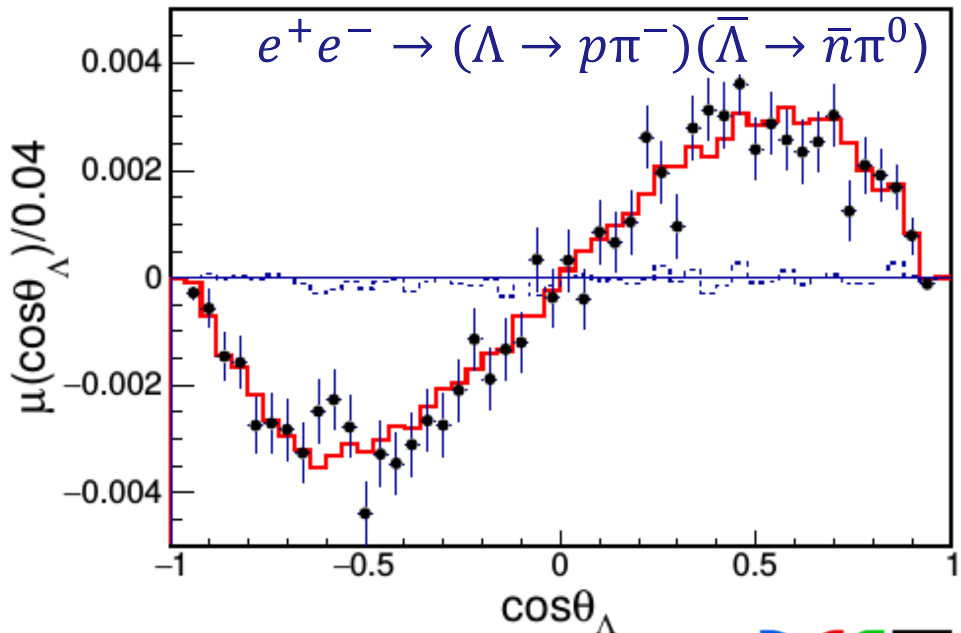
The BESIII Collaboration

Nature **606**, 64–69 (2022)

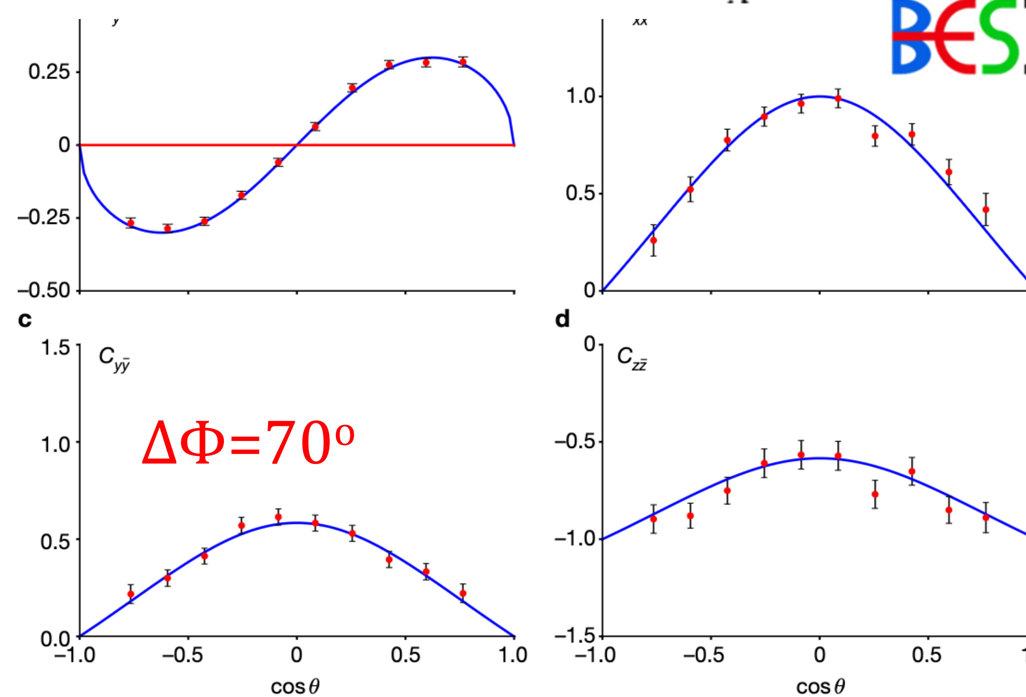
$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$





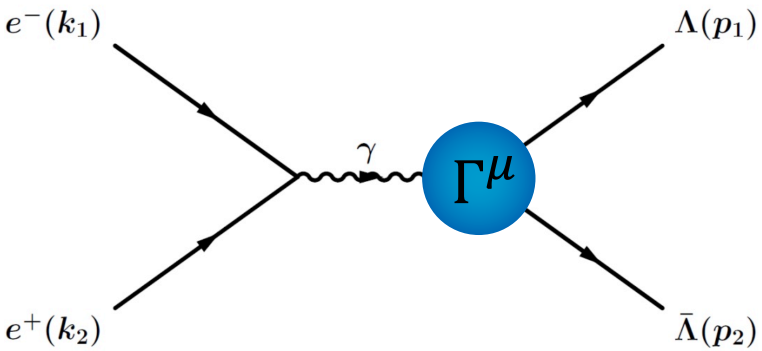


$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$



BESIII Nature Phys. (2019), Nature (2022)

$e^+e^- \to \gamma^*, Z^* \to B\bar{B}$ (spin 1/2)



$$\Gamma^\mu = \Gamma^\mu_V + \Gamma^\mu_A \gamma_5$$

$$\Gamma^\mu_l = \gamma^\mu F^l_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{m_1+m_2} F^l_2(q^2) + \frac{q_\mu}{m_1+m_2} F^l_3(q^2), \quad l = V, A$$

$$G_E = F^V_1 + \tau F^V_2 \text{ and } G_M = F^V_1 + F^V_2$$

$$^3S \propto 2G_M + \frac{1}{\sqrt{\tau}} G_E$$

$$^3D \propto \sqrt{2} G_M - \sqrt{\frac{2}{\tau}} G_E$$

$J^P = 1^-$

$$^1P = \sqrt{2Q_+}\left(\frac{m_1 - m_2}{m_1 + m_2}\sqrt{\frac{1}{\tau}} F^A_1 - \sqrt{\tau} F^A_2\right)$$

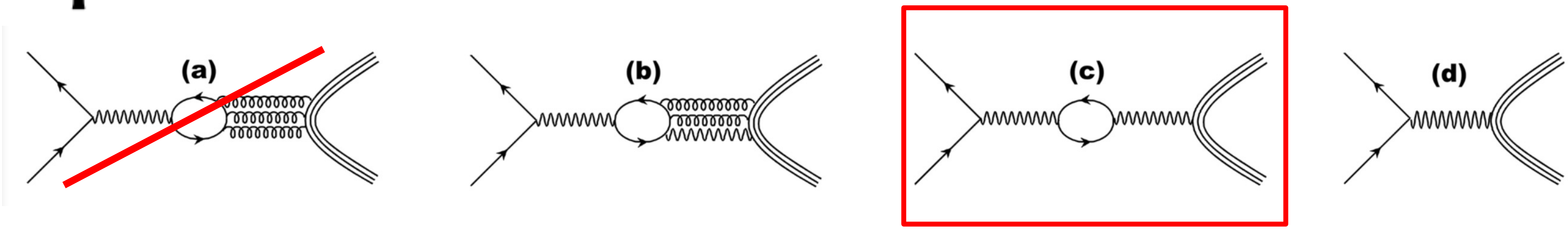
$$^3P = 2\sqrt{Q_+}\left(-F^A_1 + \frac{m_1 - m_2}{m_1 + m_2} F^A_2\right)$$

$J^P = 1^+$

nature communications

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

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



$\Delta I \neq 0$ $gg\gamma^*$ HVP

$\sqrt{s} = m_{J/\psi}$

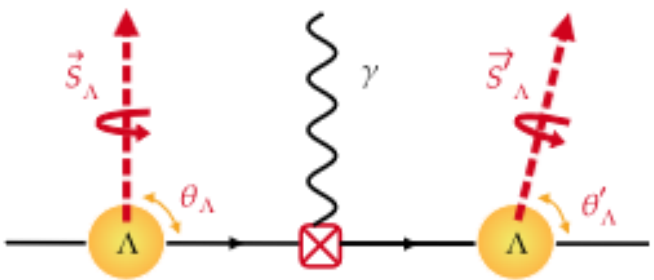
$e^- + e^+ \rightarrow \bar{\Lambda} + \Sigma^0$

$\left|\frac{G_E}{G_M}\right| = 0.86(3)$ $\mathrm{Arg}\frac{G_E}{G_M} = 58(5)^{\circ}$

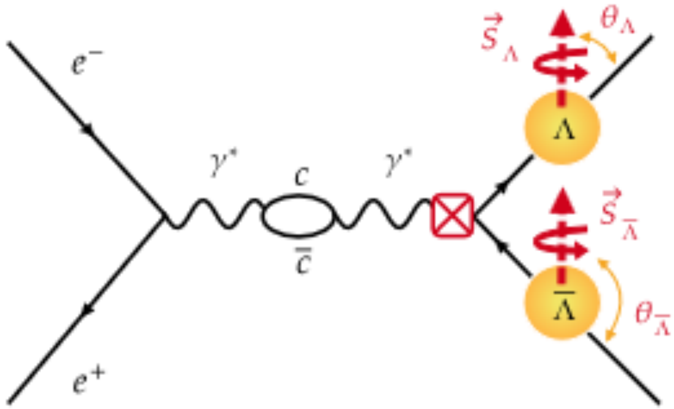
Measurement of the Λ Electric Dipole Form Factor at $\sqrt{s} = m_{J/\psi}$

2506.19180 [hep-ex]

BESIII



(A)



(B)

$|d_\Lambda| < 6.5 \times 10^{-19}\ e$ cm.

X. He et al. Phys.Lett.B 839 (2023) 137834

$$F_2^A(m_{J/\psi}^2) = \frac{2e}{3m_{J/\psi}^2} g_V d_\Lambda$$

$Re(d_\Lambda)$	$(-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\ e$ cm
$Im(d_\Lambda)$	$(2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\ e$ cm

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

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

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

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

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

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):

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

decay 3/2->1/2 0 (Ω->ΛK)

decay 1/2->1/2 0 (Λ->pπ)

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 samples at J/ψ and $\psi(2S)$

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

Prospects: charmed baryons, proton polarization

Inclusion of higher order em effects will be needed for precision experiments