Hyperon decays of spin-entangled baryon-antibaryon pairs

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Introduction

- More than 50 years of the knowledge about CP violation (CPV)
  - Confirmed only in meson decays

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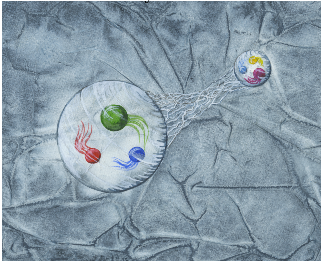


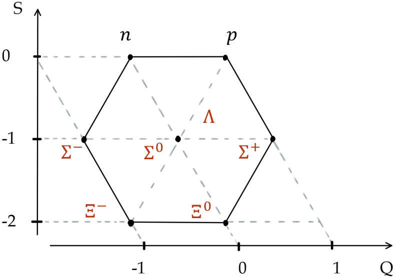
- SM CPV is not sufficient to explain observed matter-antimatter asymmetry
- Baryogenesis requires C and CP violation in the processes

[PismaZh.Eksp.Teor.Fiz.5(1967)32]

- Systematical mapping with different hadronic systems and complementary methods are needed for understanding CPV in flavour sector

Ground-state strange baryons

- Spin-$\frac{1}{2}$ baryon octet
- Weak $\Delta S = 1$ transitions



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$+ \; \Omega^-$ spin-$\frac{3}{2}$

Hyperon	Mass [GeV/c²]	Decay ($\mathcal{B}$) [%]
$\Lambda(uds)$	1.116	$p\pi^-(64.1)$ $n\pi^0(35.9)$ $pe^-\bar{\nu}_e(0.083)$
$\Sigma^-(dds)$	1.197	$n\pi^-(99.8)$ $ne^-\bar{\nu}_e(0.102)$
$\Sigma^+(uus)$	1.189	$p\pi^0(51.6)$ $n\pi^+(48.3)$ $\Lambda e^+\nu_e(0.002)$
$\Xi^0(uss)$	1.315	$\Lambda\pi^0(99.5)$ $\Sigma^+e^-\bar{\nu}_e(0.025)$
$\Xi^-(dss)$	1.322	$\Lambda\pi^-(99.9)$ $\Lambda e^-\bar{\nu}_e(0.056)$
$\Omega^-(sss)$	1.672	$\Lambda K^-(67.8)$ $\Xi^0\pi^-(23.6)$ $\Xi^-\pi^0(8.6)$ $\Xi^0 e^-\bar{\nu}_e(0.56)$

Study of hyperon decays of spin-1/2 baryon

- Presentation is based on recent paper: [PRD108(2023)016011]
- **Motivation (theory)**:
  - Development of formalism for SL baryon decays that allow to study the spin correlations and polarization
    $\rightarrow$ similar way as developed for hadronic hyperon decays [PRD99(2019)056008]
    $\rightarrow$ have not been done before
  - Test of CP symmetry in SL baryon decays

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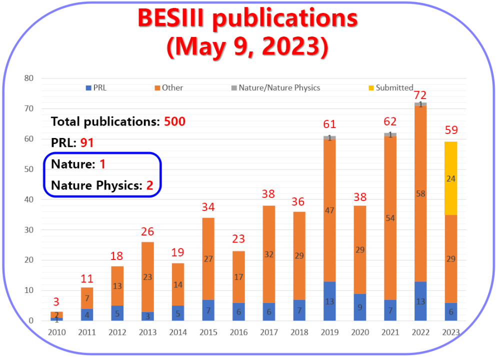
  - Test of CP symmetry in SL baryon decays
- **Motivation (experiment)**:
  - Analysis of process $e^+e^- \rightarrow J/\psi, \psi(2S) \rightarrow (B_1 \rightarrow SL)(\bar{B}_1 \rightarrow H)$ + c.c.
    $\rightarrow$ extraction of decay parameters using provided modular method
    $\rightarrow\rightarrow$ some of them has been measured > 30 y.a. (hyperon sector)
  - Measurement of V_{ij} matrix elements in SL baryon decays

Process	Final state	Reference
$J/\psi \rightarrow \Lambda\bar{\Lambda}$	$(p\pi^-)(\bar{p}\pi^+)$	[NaturePhys15(2019)631] [PRL129(2022)131801]
$\psi(2S) \rightarrow \Sigma^-\bar{\Sigma}^+$	$(n\pi^-)(\bar{n}\pi^+)$	[JHEP12(2022)016]
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^-$	$(p\pi^0)(\bar{p}\pi^0)$ $(n\pi^+)(\bar{n}\pi^-)$ $(p\gamma)(\bar{p}\pi^0)$	[PRL125(2020)052004] [PRL131(2023)191802] [PRL130(2023)211901]
$\psi(2S) \rightarrow \Sigma^+\bar{\Sigma}^-$	$(p\pi^0)(\bar{p}\pi^0)$	[PRL125(2020)052004]
$\psi(2S) \rightarrow \Xi^0\bar{\Xi}^0$	$(\Lambda\pi^0)(\bar{\Lambda}\pi^0)$	[PRD108(2023)L011101]
$J/\psi \rightarrow \Xi^-\bar{\Xi}^+$ $\psi(2S) \rightarrow \Xi^-\bar{\Xi}^+$	$(\Lambda\pi^-)(\bar{\Lambda}\pi^+)$	[Nature 606(2022)64] [PRD106(2022)L091101]
$\psi(2S) \rightarrow \Omega^-\bar{\Omega}^+$	$(\Lambda K^-)(\bar{\Lambda}K^+)$	[PRL126(2021)092002]

Non-leptonic decays of spin-1/2 baryon



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$\psi(2S) \to \Omega^-\bar{\Omega}^+$	$(\Lambda K^-)(\bar{\Lambda}K^+)$	[PRL126(2021)092002]

Production process

[PRD99(2019)056008]

- Two spin-1/2 particle state: $\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}}\sigma_{\mu}^{B_1} \otimes \sigma_{\bar{\nu}}^{\bar{B}_1}$

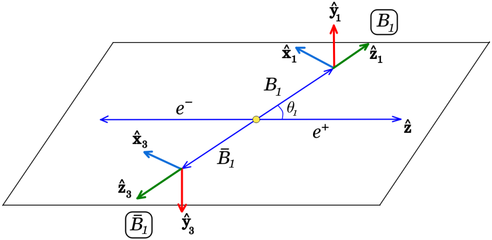
B_1 transverse polarization

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

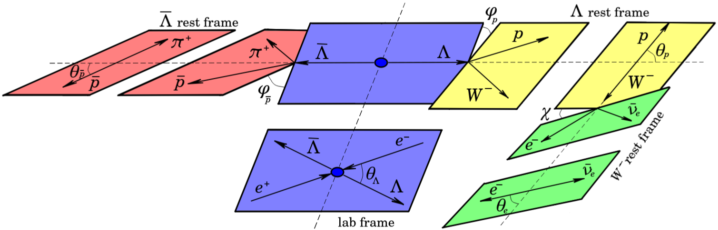
$\bar{B}_1$ transverse polarization

spin correlations

- $\beta_\psi = \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)$ and $\gamma_\psi = \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)$
- Main parameters of $C_{\mu\bar{\nu}}$: θ; $\alpha_\psi \in [-1,+1]$, $\Delta\Phi \in [-\pi,+\pi]$



Semileptonic/Hadronic Baryon decays



- $\bar{B}_1 \to \bar{B}_3 + \pi^+$
- $a_{\mu\nu}$ for $\{\frac{1}{2} \to \frac{1}{2} + 0\}$

$$\sigma_\mu^{\bar{B}_1} \to \sum_{\nu=0}^{3} a_{\mu\nu}\sigma_\nu^{\bar{B}_3}$$

$B_1 \to B_2 + W^-_{\text{off-shell}}(\to l^-\bar{\nu}_l)$

$\mathcal{B}_{\mu\nu}$ for $\{\frac{1}{2} \to \frac{1}{2} + \{0, \pm 1, t\}\}$

$$\sigma_\mu^{B_1} \to \frac{3(q^2 - m_l^2)}{4\pi^3}\sum_{\nu=0}^{3} \mathcal{B}_{\mu\nu}\sigma_\nu^{B_2}$$

- Helicity amplitudes:
  $B_{\frac{1}{2}}, B_{-\frac{1}{2}}$
  $H_{\frac{1}{2}0}, H_{-\frac{1}{2}0}, H_{\frac{1}{2}1}, H_{-\frac{1}{2}-1}, H_{\frac{1}{2}t}, H_{-\frac{1}{2}t}$
- Main parameters:
  $\Omega_3 = \{\bar{\varphi}_3, \bar{\theta}_3, 0\}$
  $\bar{\alpha}_D, \bar{\phi}_D$
  $\Omega_2 = \{\varphi_2, \theta_2, 0\}$, $\Omega_l = \{\varphi_l, \theta_l, 0\}$
  $q^2 \in (m_l^2, (M_1 - M_2)^2)$, $g_{\text{av}}^D(q^2), g_{\text{w}}^D(q^2)$

where $g_{\text{av}}^D(q^2) = F_1^A(q^2)/F_1^V(0), g_{\text{w}}^D(q^2) = F_2^V(q^2)/F_1^V(0)$

Hadronic baryon decay

- Momenta and masses: $B_1(p_1, M_1) \to B_2(p_2, M_2) + M(p_3, m_3)$
- Decay can be described by transition matrix [PRL55(1985)162]:

$$\langle B_2(p_2)|\mathcal{M}|B_1(p_1)\rangle = \bar{u}(p_2)\left[A_S + A_P\vec{\sigma}\cdot\hat{n}\right]u(p_1)$$

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- Asymmetry parameters [PRD99(2019)056008]:

$$\alpha = -2\frac{\Re(A_S * A_P)}{|A_S|^2+|A_P|^2} = \frac{|B_{\frac{1}{2}}|^2 - |B_{-\frac{1}{2}}|^2}{|B_{\frac{1}{2}}|^2 + |B_{-\frac{1}{2}}|^2},$$

$$\beta = -2\frac{\Im(A_S * A_P)}{|A_S|^2+|A_P|^2} = 2\frac{\Im(B_{\frac{1}{2}}B^*_{-\frac{1}{2}})}{|B_{\frac{1}{2}}|^2 + |B_{-\frac{1}{2}}|^2},$$

$$\gamma = \frac{|A_S|^2-|A_P|^2}{|A_S|^2+|A_P|^2} = 2\frac{\Re(B_{\frac{1}{2}}B^*_{-\frac{1}{2}})}{|B_{\frac{1}{2}}|^2 + |B_{-\frac{1}{2}}|^2},$$

where $\beta = \sqrt{1-\alpha^2}\sin\phi$ and $\gamma = \sqrt{1-\alpha^2}\cos\phi$

- Possible CPV tests:

$$A_{\mathrm{CP}} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} \quad \text{and} \quad \Phi_{\mathrm{CP}} = \frac{\phi+\bar{\phi}}{2}$$

Semileptonic baryon decay

- Momenta and masses: $B_1(p_1, M_1) \to B_2(p_2, M_2) + l^-(p_l, m_l) + \bar{\nu}_l(p_{\bar{\nu}_l}, 0)$
- FF for the weak current-induced baryonic $1/2^+ \to 1/2^+$ transitions [EPJ C59 (2009) 27]:

$$\langle B_2(p_2)|J_\mu^{V+A}|B_1(p_1)\rangle = \bar{u}(p_2)\left[\gamma_\mu(F_1^V(q^2) - F_1^A(q^2)\gamma_5) - \frac{i\sigma_{\mu\nu}q^\nu}{M_1}(F_2^V(q^2) - F_2^A(q^2)\gamma_5) + \frac{q^\mu}{M_1}(F_3^V(q^2) - F_3^A(q^2)\gamma_5)\right]u(p_1)$$

where $q_\mu = (p_1 - p_2)_\mu$

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- For $B_1 \to B_2 e^- \bar{\nu}_e$ at $\mathcal{O}(\frac{m_e^2}{2q^2}) \to 0 \Longrightarrow F_3^{V,A}(q^2) \to 0$
- $H_{\lambda_2 \lambda_W} = (H^V_{\lambda_2 \lambda_W} + H^A_{\lambda_2 \lambda_W})$ with $(\lambda_2 = \pm 1/2; \lambda_W = t, 0, \pm 1)$: $H^{V,A}_{\lambda_2 \lambda_W} \equiv H^{V,A}_{\lambda_2 \lambda_W}(F^{V,A}_{1,2}(q^2))$

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vector helicity amplitudes

$$H^V_{\frac{1}{2}1} = \sqrt{2Q_-}\left(-F_1^V - \frac{M_+}{M_1}F_2^V\right),$$
$$H^V_{\frac{1}{2}0} = \sqrt{\frac{Q_-}{q^2}}\left(M_+F_1^V + \frac{q^2}{M_1}F_2^V\right),$$
$$H^V_{\frac{1}{2}t} = \sqrt{\frac{Q_+}{q^2}}\left(M_-F_1^V + \frac{q^2}{M_1}F_3^V\right),$$

axial-vector helicity amplitudes

$$H^A_{\frac{1}{2}1} = \sqrt{2Q_+}\left(F_1^A - \frac{M_-}{M_1}F_2^A\right),$$
$$H^A_{\frac{1}{2}0} = \sqrt{\frac{Q_+}{q^2}}\left(-M_-F_1^A + \frac{q^2}{M_1}F_2^A\right),$$
$$H^A_{\frac{1}{2}t} = \sqrt{\frac{Q_-}{q^2}}\left(-M_+F_1^A + \frac{q^2}{M_1}F_3^A\right)$$

where $Q_\pm = (M_1 \pm M_2)^2 - q^2 \equiv M_\pm^2 - q^2$, $\quad H^{V,A}_{-\lambda_2,-\lambda_W} = \pm H^{V,A}_{\lambda_2,\lambda_W}$

Semileptonic Baryon decays (1)

- Initial baryon B_1 with spin-density matrix $\rho_1^{\kappa\kappa'}$ transforms to final baryon B_2 with spin-density matrix $\rho_2^{\lambda_2\lambda_2'}$

$$\rho_2^{\lambda_2\lambda_2'} = T^{\kappa\kappa',\lambda_2\lambda_2'}\rho_1^{\kappa\kappa'}$$

- Transition tensor:

$$T^{\kappa\kappa',\lambda_2\lambda_2'} = \frac{1}{4\pi}\sum_{\underline{\lambda}_W,\underline{\lambda}_W'} T^{\kappa\kappa',\lambda_2\lambda_2'}_{\underline{\lambda}_W,\underline{\lambda}_W'}(q^2,\Omega_2) L_{\underline{\lambda}_W,\underline{\lambda}_W'}(q^2,\Omega_l)$$

  - Hadronic tensor

    $$T^{\kappa\kappa',\lambda_2\lambda_2'}_{\underline{\lambda}_W,\underline{\lambda}_W'}(q^2,\Omega_2) = H_{\lambda_2\underline{\lambda}_W} H^*_{\lambda_2'\underline{\lambda}_W'} \mathcal{D}^{1/2*}_{\kappa,\lambda_2-\lambda_W}(\Omega_2)\mathcal{D}^{1/2}_{\kappa',\lambda_2'-\lambda_W'}(\Omega_2)$$

  - Lepton tensor with $\varepsilon = m_l^2/(2q^2)$

    $$L_{\underline{\lambda}_W,\underline{\lambda}_W'}(q^2,\Omega_l) = \frac{8(q^2-m_l^2)}{4\pi}\left[\ell^{\text{nf}}_{\underline{\lambda}_W,\underline{\lambda}_W'}(\Omega_l) + \varepsilon\ell^{\text{f}}_{\underline{\lambda}_W,\underline{\lambda}_W'}(\Omega_l)\right]$$

    - nonflip($\underline{\lambda}_W = \mp 1$) : $|h^l_{\lambda_l=\mp\frac{1}{2},\lambda_\nu=\pm\frac{1}{2}}|^2 = 8\delta(\lambda_l+\lambda_\nu)(q^2-m_l^2)$
    - flip($\underline{\lambda}_W = 0, t$) : $|h^l_{\lambda_l=\pm\frac{1}{2},\lambda_\nu=\pm\frac{1}{2}}|^2 = 8\delta(\lambda_l-\lambda_\nu)\varepsilon(q^2-m_l^2)$

Semileptonic Baryon decays (2)

$$\sigma_{\mu}^{B_1} \longrightarrow \frac{3(q^2 - m_l^2)}{4\pi^3} \sum_{\nu=0}^{3} \mathcal{B}_{\mu\nu} \sigma_{\nu}^{B_2}$$

- $\mathcal{B}_{\mu\nu}$ can be obtained by inserting Pauli matrices for mother and daughter baryons in $T^{\kappa\kappa',\lambda_2\lambda_2'}$ tensor expression

$$\mathcal{B}_{\mu\nu} = \frac{2\pi^3}{3(q^2-m_l^2)} \sum_{\lambda_2,\lambda_2'=-1/2}^{1/2} \sum_{\kappa,\kappa'=-1/2}^{1/2} T^{\kappa\kappa',\lambda_2\lambda_2'} \sigma_{\mu}^{\kappa,\kappa'} \sigma_{\nu}^{\lambda_2',\lambda_2}$$

$$\Downarrow$$

$$\mathcal{B}_{\mu\nu} = \sum_{\kappa=0}^{3} \mathcal{R}_{\mu\kappa}(\Omega_2) b_{\kappa\nu}(q^2, \Omega_l)$$

- $\mathcal{R}_{\mu\kappa}$ - 4×4 rotation matrix
- $b_{\kappa\nu}$ coefficients correspond to $B_1 \to B_2$ transition where axes orientation of the r.s. are aligned $\Omega_2 = \{0, 0, 0\}$

$$b_{\kappa\nu} = \frac{\pi}{6(q^2-m_l^2)} \sum_{\underline{\lambda}_W,\underline{\lambda}_W'} \sum_{\lambda_2,\lambda_2'} H_{\lambda_2\underline{\lambda}_W} H^*_{\lambda_2'\underline{\lambda}_W'} \sigma_{\kappa}^{\lambda_2-\underline{\lambda}_W,\lambda_2'-\underline{\lambda}_W'} \sigma_{\nu}^{\lambda_2',\lambda_2} L_{\underline{\lambda}_W,\underline{\lambda}_W'}(q^2, \Omega_l)$$

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- Replace $b_{\kappa\nu}$ by other decay matrices
  $\to$ can describe $B_1 \to B_2 + \pi$, $B_1 \to B_2 + \gamma$ and others

Rotation matrix $\mathcal{R}_{\mu\kappa}$

- 4D rotation matrix $\mathcal{R}_{\mu\kappa}(\Omega)$ with $\Omega \equiv \{\varphi, \theta, \chi\}$

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta\cos\chi\cos\varphi - \sin\chi\sin\varphi & -\cos\theta\sin\chi\cos\varphi - \cos\chi\sin\varphi & \sin\theta\cos\varphi \\ 0 & \cos\theta\cos\chi\sin\varphi + \sin\chi\cos\varphi & \cos\chi\cos\varphi - \cos\theta\sin\chi\sin\varphi & \sin\theta\sin\varphi \\ 0 & -\sin\theta\cos\chi & \sin\theta\sin\chi & \cos\theta \end{pmatrix}$$

- BESIII: $\mathcal{R}_{\mu\kappa}(\Omega_2) = \mathcal{R}_{\mu\kappa}(\varphi_2, \theta_2, 0)$

Decay matrices $b^i_{\kappa\nu}$

$B_1 \to B_2 + \pi$

$$b^D_{\kappa\nu} \propto \begin{pmatrix} 1 & 0 & 0 & \alpha_D \\ 0 & \gamma_D & -\beta_D & 0 \\ 0 & \beta_D & \gamma_D & 0 \\ \alpha_D & 0 & 0 & 1 \end{pmatrix}$$

$B_1 \to B_2 + \gamma$

$$b^\gamma_{\kappa\nu} \propto \begin{pmatrix} 1 & 0 & 0 & \alpha_\gamma \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\alpha_\gamma & 0 & 0 & -1 \end{pmatrix}$$

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$B_1 \to B_2 + W^-_{\text{off-shell}}(\to l^-\bar{\nu}_l)$: $b^{\text{SLW}}_{\kappa\nu} = b^{\text{nf}}_{\kappa\nu} + \varepsilon b^{\text{f}}_{\kappa\nu}$

$$b^{\text{nf}}_{\kappa\nu} = \begin{pmatrix} b^{\text{nf}}_{00} & -\Re(\mathcal{I}^{\text{nf}}_{01}) & \Im(\mathcal{I}^{\text{nf}}_{10}) & b^{\text{nf}}_{03} \\ -\Re(\mathcal{I}^{\text{nf}}_{10}) & \Re(\mathcal{E}^{\text{nf}}_{00} + \mathcal{E}^{\text{nf}}_{11}) & -\Im(\mathcal{E}^{\text{nf}}_{00} + \mathcal{E}^{\text{nf}}_{11}) & \Re(\mathcal{I}^{\text{nf}}_{13}) \\ \Im(\mathcal{I}^{\text{nf}}_{10}) & \Im(\mathcal{E}^{\text{nf}}_{00} - \mathcal{E}^{\text{nf}}_{11}) & \Re(\mathcal{E}^{\text{nf}}_{00} + \mathcal{E}^{\text{nf}}_{11}) & -\Im(\mathcal{I}^{\text{nf}}_{13}) \\ b^{\text{nf}}_{30} & -\Re(\mathcal{I}^{\text{nf}}_{31}) & \Im(\mathcal{I}^{\text{nf}}_{31}) & b^{\text{nf}}_{33} \end{pmatrix}$$

$$b^{\text{f}}_{\kappa\nu} = \begin{pmatrix} b^{\text{f}}_{00} & -\Re(\mathcal{I}^{\text{f}}_{01}) & \Im(\mathcal{I}^{\text{f}}_{10}) & b^{\text{f}}_{03} \\ -\Re(\mathcal{I}^{\text{f}}_{10}) & \Re(\mathcal{E}^{\text{f}}_{00} - \mathcal{E}^{\text{f}}_{11}) & -\Im(\mathcal{E}^{\text{f}}_{00} - \mathcal{E}^{\text{f}}_{11}) & \Re(\mathcal{I}^{\text{f}}_{13}) \\ \Im(\mathcal{I}^{\text{f}}_{10}) & \Im(\mathcal{E}^{\text{f}}_{00} + \mathcal{E}^{\text{f}}_{11}) & \Re(\mathcal{E}^{\text{f}}_{00} + \mathcal{E}^{\text{f}}_{11}) & -\Im(\mathcal{I}^{\text{f}}_{13}) \\ b^{\text{f}}_{30} & -\Re(\mathcal{I}^{\text{f}}_{31}) & \Im(\mathcal{I}^{\text{f}}_{31}) & b^{\text{f}}_{33} \end{pmatrix}$$

Polarization $\vec{P}$ of baryon B_2

- Represent first row of $b_{0\kappa}$ matrix

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \frac{1}{b_{00}^{\rm nf}+\varepsilon b_{00}^{\rm f}} \begin{bmatrix} -\cos\varphi_l & \sin\varphi_l & 0 \\ \sin\varphi_l & \cos\varphi_l & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Re(\mathcal{I}_{01}) \\ \Im(\mathcal{I}_{01}) \\ b_{03}^{\rm nf}+\varepsilon b_{03}^{\rm f} \end{bmatrix}$$

where

$$b_{00/03}^{\rm nf} = \frac{1}{4}(1\mp\cos\theta_l)^2|H_{\frac{1}{2}1}|^2+-\frac{1}{4}(1\pm\cos\theta_l)^2|H_{-\frac{1}{2}-1}|^2+-\frac{1}{2}\sin^2\theta_l(|H_{-\frac{1}{2}0}|^2+-|H_{\frac{1}{2}0}|^2),$$

$$b_{00/03}^{\rm f} = |H_{\frac{1}{2}t}|^2+-|H_{-\frac{1}{2}t}|^2+\frac{1}{2}\sin^2\theta_l(|H_{\frac{1}{2}1}|^2+-|H_{-\frac{1}{2}-1}|^2)+-\cos^2\theta_l(|H_{\frac{1}{2}0}|^2+-|H_{-\frac{1}{2}0}|^2)$$
$$-\cos\theta_l\Re(H^*_{\frac{1}{2}0}H_{\frac{1}{2}t}+-H^*_{-\frac{1}{2}0}H_{-\frac{1}{2}t}),$$

$$\mathcal{I}_{01}^{\rm nf} = \pm\frac{1}{2\sqrt{2}}\sin\theta_l\left[(1\pm\cos\theta_l)H^*_{-\frac{1}{2}-1}H_{\frac{1}{2}0}+(1\mp\cos\theta_l)H^*_{-\frac{1}{2}0}H_{\frac{1}{2}1}\right],$$

$$\mathcal{I}_{01}^{\rm f} = \frac{1}{\sqrt{2}}\sin\theta_l\left[(H^*_{-\frac{1}{2}-1}H_{\frac{1}{2}t}-H^*_{-\frac{1}{2}t}H_{\frac{1}{2}1})+\cos\theta_l(H^*_{-\frac{1}{2}0}H_{\frac{1}{2}1}-H^*_{-\frac{1}{2}-1}H_{\frac{1}{2}0})\right].$$

Joint angular distribution (1)

- $e^+e^- \to J/\psi, \psi(2S) \to (B_1 \to B_3\pi^-)(\bar{B}_1 \to \bar{B}_3\pi^+)$

$$\mathrm{Tr}\rho_{B_3\bar{B}_3} \propto \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} a_{\mu 0}^{B_1 B_3} a_{\bar{\nu}0}^{\bar{B}_1\bar{B}_3}$$

- $C_{\mu\bar{\nu}} \equiv C_{\mu\bar{\nu}}(\theta_1; \alpha_\psi, \Delta\Phi)$
- $a_{\mu 0}^{B_1 B_3} \equiv a_{\mu 0}(\theta_3, \varphi_3; \alpha_{B_1})$
- $a_{\bar{\nu}0}^{\bar{B}_1\bar{B}_3} \equiv a_{\bar{\nu}0}(\bar{\theta}_3, \bar{\varphi}_3; \bar{\alpha}_{B_1})$

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$$\mathrm{Tr}\rho_{B_2\bar{B}_3} \propto \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} \mathcal{B}_{\mu 0}^{B_1 B_2} a_{\bar{\nu}0}^{\bar{B}_1\bar{B}_3} \equiv \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} \sum_{\kappa=0}^{3} \mathcal{R}_{\mu\kappa}(\Omega_2) b_{\kappa 0}^{B_1 B_2}(q^2, \Omega_l) a_{\bar{\nu}0}^{\bar{B}_1\bar{B}_3}$$

  - $\mathcal{B}_{\mu 0}^{B_1 B_2} \equiv \mathcal{R}_{\mu\kappa}(\theta_2, \varphi_2) b_{\kappa 0}(\theta_l, \phi_l, q^2; g_{\text{av}}^{B_1}, g_{\text{w}}^{B_1})$

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$$\mathrm{d}\Gamma \propto \mathcal{W}(\boldsymbol{\xi}; \alpha_\psi, \Delta\Phi, \alpha_{B_1}, \bar{\alpha}_{B_1}) =$$

$$1 + \alpha_\psi \cos^2\theta_1$$

Cross section

Spin correlations

$$+\alpha_{B_1}\bar{\alpha}_{B_1}(\sin^2\theta_1(st_3cp_3\bar{s}t_3\bar{c}p_3 + \alpha_\psi st_3sp_3\bar{s}t_3\bar{s}p_3) - (\cos^2\theta_1 + \alpha_\psi)ct_3\bar{c}t_3)$$

$$+\alpha_{B_1}\bar{\alpha}_{B_1}\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_1\cos\theta_1(st_3cp_3\bar{c}t_3 - ct_3\bar{s}t_3\bar{c}p_3)$$

$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\sin\theta_1\cos\theta_1(-\alpha_{B_1}st_3sp_3 + \bar{\alpha}_{B_1}\bar{s}t_3\bar{s}p_3)$$

Polarization

Joint angular distribution (2)

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$$\mathrm{d}\Gamma \propto \mathcal{W}(\boldsymbol{\xi}'; \alpha_\psi, \Delta\Phi, g_{\text{av}}^{B_1}, g_{\text{w}}^{B_1}, \bar{\alpha}_{B_1}) =$$

$$b_{00}(1 + \alpha_\psi \cos^2\theta_1)$$

Cross section

Spin correlations

$$+b_{30}\bar{\alpha}_{B_1}(\sin^2\theta_1(st_2cp_2\bar{st}_3\bar{cp}_3 + \alpha_\psi st_2sp_2\bar{st}_3\bar{sp}_3) - (\cos^2\theta_1 + \alpha_\psi)ct_2\bar{ct}_3)$$

$$+b_{10}\bar{\alpha}_{B_1}(-\sin^2\theta_1(ct_2cp_2\bar{st}_3\bar{cp}_3 + \alpha_\psi ct_2sp_2\bar{st}_3\bar{sp}_3) - (\cos^2\theta_1 + \alpha_\psi)st_2\bar{ct}_3)$$

$$+b_{30}\bar{\alpha}_{B_1}\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_1\cos\theta_1(st_2cp_2\bar{ct}_3 - ct_2\bar{st}_3\bar{cp}_3)$$

$$+b_{10}\bar{\alpha}_{B_1}\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_1\cos\theta_1(-ct_2cp_2\bar{ct}_3 + st_2\bar{st}_3\bar{cp}_3)$$

$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\sin\theta_1\cos\theta_1(-b_{30}st_2sp_2 + \bar{\alpha}_{B_1}\bar{st}_3\bar{sp}_3 + b_{10}ct_2sp_2)$$

Polarization

Form factors

- Neglecting possible CP-odd weak phase, $\mathrm{FF}(l^-, \bar{\nu}_l) = sign\, \mathrm{FF}(l^+, \nu_l)$
- In limit of exact SU(3) symmetry, F_2^A and $F_3^V \to 0$

Form factors

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- FF parametrization for **hyperons** [PLB478(2000)417][EPJC81(2021)226]:

$$F_i^{V,A}(q^2) = \frac{F_i^{V,A}(0)}{1-\frac{q^2}{M_{V,A}^2}} \frac{1}{1-\alpha_{\rm BK}\frac{q^2}{M_{V,A}^2}} \Longrightarrow F_i^{V,A}(q^2) = F_i^{V,A}(0)\left[1 + r_i^{V,A} q^2 + \ldots\right]$$

with $r^{V,A} = 2/m_{V,A}^2$ [AnnRevNuclPartSci34(1984)351] [AnnRevNuclPartSci53(2003)39]

- $\Delta S = 0$: $m_V = 0.84$ GeV [RivNuovoCim2(1972)241], $m_A = 1.08$ GeV [BNL-24848]
- $|\Delta S| = 1$: $m_V = m_{K^*(892)} = 0.89$ GeV, $m_A = m_{K^*(1270)} = 1.27$ GeV

Decay	$\mathcal{B}(\times 10^{-4})$	$g_{av}^D(0)$ [a]	$g_w^D(0)$ [a]	$M_1 - M_2$ [MeV]	Ref.
$\Lambda \to p e^- \bar{\nu}_e$	8.32(14)	0.718(15)	1.066	177	[1, 2]
$\Sigma^+ \to \Lambda e^+ \nu_e$ [b]	0.20(05)	0.01(10)	2.4(17)	74	[1]
$\Xi^- \to \Lambda e^- \bar{\nu}_e$	5.63(31)	0.25(5)	0.085	206	[2, 3]

[a] $g_{av} = F_1^A(0)/F_1^V(0)$ and $g_w = F_2^V(0)/F_1^V(0)$

[b] Since $F_1^{\Sigma} = 0$, g_{av} and g_w are defined as F_1^V/F_1^A and F_2^V/F_1^A, respectively

[1] PTEP2022 083C01(2022) [2] AnnRevNuclPartSci53(2003)39 [3] ZPhysC21(1983)1

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[1] PTEP2022 083C01(2022) [2] AnnRevNuclPartSci53(2003)39 [3] ZPhysC21(1983)1

- FF parametrization for **charm baryons**:
  [EPJC76(2016)628] [PRD93(2016)034008] [PRD80(2009)074011][PRC72(2005)035201]

  and many others

Form factors for charm baryons (1)

- Light-front approach [Chin.Phys.C42(2018)093101]:

$$F_i(q^2) = F_i(0) / \left(1 \mp \frac{q^2}{m_{\rm fit}^2} + \delta \left(\frac{q^2}{m_{\rm fit}^2}\right)^2\right)$$

where $m_{\rm fit}$, δ fitted from numerical results

- Pole-dominance model:
SU(4)-symmetry limit [PRD40(1989)2944], MIT bag model [PRD40(1989)2955]:

$$F_i^{V,A}(q^2) = F_i^{V,A}(0)\left[1 + r_i^{V,A} q^2\right] \quad \text{with} \quad r^{V,A} = n/m_{V,A}^2$$

  - $|\Delta C| = 1, \Delta S = 0$: $m_V = m_{D^*} = 2.01$ GeV, $m_A = m_{D^{*0}} = 2.42$ GeV
  - $|\Delta C| = |\Delta S| = 1$: $m_V = m_{D_s^*} = 2.11$ GeV, $m_A = m_{D_{s1}} = 2.54$ GeV

Form factors for charm baryons (2)

- Relativistic quark model based on quasi-potential approach with QCD-motivated potential:

$$F_i(q^2) = \frac{1}{1 - q^2/(M_{\text{pole}}^{F_i})^2} \sum_{n=0}^{n_{\max}} a_n^{F_i} [z(q^2)]^n$$

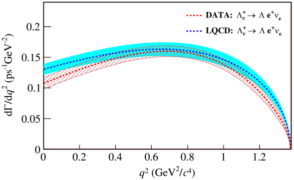
where $z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$ with $t_0 = (M_1 - M_2)^2$

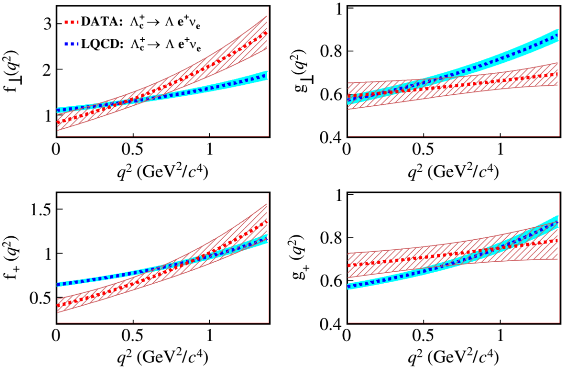
Decay	$\sqrt{t_+}$	$m(F^V_{1,2})$ [GeV]	$m(F^V_3)$ [GeV]	$m(F^A_{1,2})$ [GeV]	$m(F^A_3)$ [GeV]	$M_1 - M_2$ [GeV]	Ref.
$\Lambda_c^+ \to \Lambda l^+ \nu_l$	$m_D + m_K$	2.11	2.32	2.46	1.97	1.17	[1]
$\Xi_c \to \Xi l \nu_l$	$m_{D_s} + m_K$	2.11	2.54	2.54	1.97	1.15	[2]
$\Xi_c \to \Lambda l \nu_l$	$m_D + m_\pi$	2.01	2.42	2.42	1.87	1.35	[2]

[1] [PRL118(2017)082001] [2] [EPJC79(2019)695]

$\Lambda_c^+ \to \Lambda e^+ \nu_e$ FFs

- First measurement by BESIII [PRL129(2022)231803]
  - $z(q^2)$ expansion
- Comparison with LQCD calculation [PRL118(2017)082001]
  - Different kinematic behaviour for FF(q^2)
  - Agreement for decay rate
- $\{F_1^V, F_2^V, F_1^A, F_2^A\} \longrightarrow \{f_+, f_\perp, g_+, g_\perp\}$





Summary

- General formalism [PRD108(2023)016011] can be applied to data analyses performing in e^+e^- collider experiments
- Modular description is very flexible:
  - Non-leptonic, semileptonic, radiative and electromagnetic decays of baryons with spin 1/2
  - One- and two-step decays
- Different FFs parametrization can be taken into account

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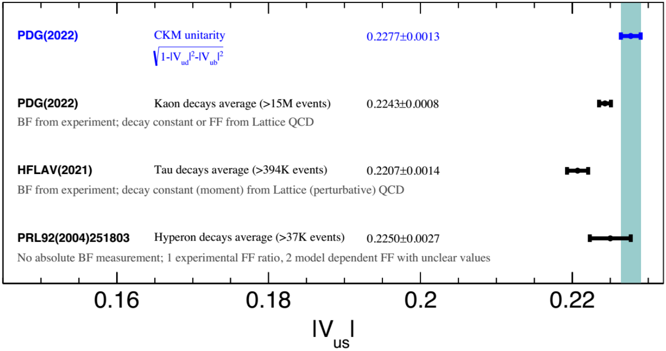
- Modular description is very flexible:
  - Non-leptonic, semileptonic, radiative and electromagnetic decays of baryons with spin 1/2
  - One- and two-step decays
- Different FFs parametrization can be taken into account
- Neglecting hadronic CP-violating effects, CP-symmetry tests can be performed using FFs
- Measurement of FFs and $\mathcal{BR}$ will allow to measure CKM matrix elements V_{ij} within one data analysis

V_{us} measurement

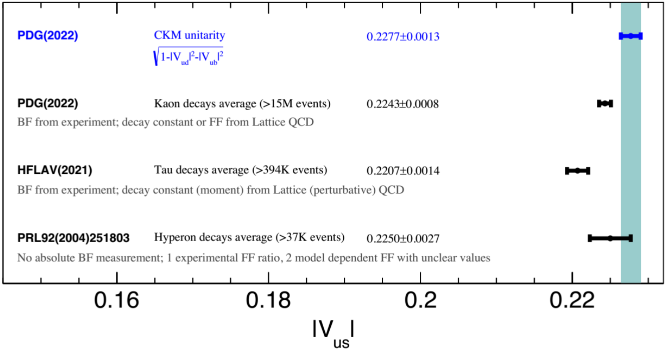


$s \to u$ transition SL: $$\frac{d\Gamma}{dq^2} \propto G_F^2 |V_{us}|^2 V_{Ph}(q^2)(q^2 - m_l^2) b_{00}$$

[PRL92(2004)251803]

Decay Process	Rate (μsec^{-1})	g_1/f_1	V_{us}
$\Lambda \to p e^- \overline{\nu}$	3.161(58)	0.718(15)	0.2224 ± 0.0034
$\Sigma^- \to n e^- \overline{\nu}$	6.88(24)	−0.340(17)	0.2282 ± 0.0049
$\Xi^- \to \Lambda e^- \overline{\nu}$	3.44(19)	0.25(5)	0.2367 ± 0.0099
$\Xi^0 \to \Sigma^+ e^- \overline{\nu}$	0.876(71)	1.32(+.22/−.18)	0.209 ± 0.027
Combined			0.2250 ± 0.0027

V_{us} measurement



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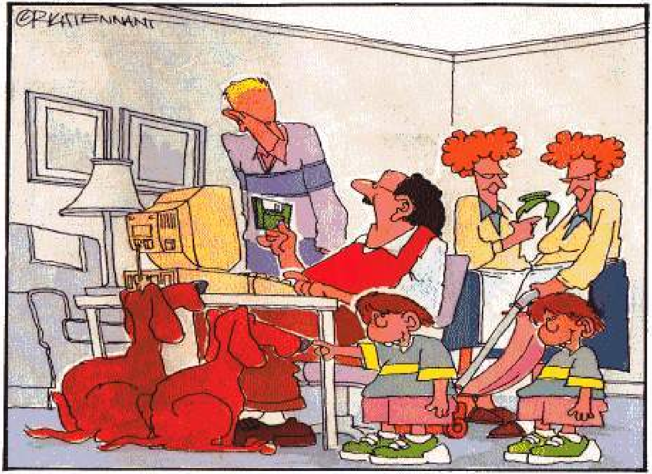
Thank you for your attention! 谢谢您的关注！

Backups



" I ALWAYS BACK UP EVERYTHING."

$B_1 \to B_2\gamma^* \to B_2 l^+ l^-$

- Differential decay rate

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} \propto \frac{\alpha_{\text{em}}^2}{q^2} V_{Ph}(q^2)(1-\frac{4m_l^2}{q^2}) b_{00}^{\text{em}}$$

- Unrotated decay matrix:

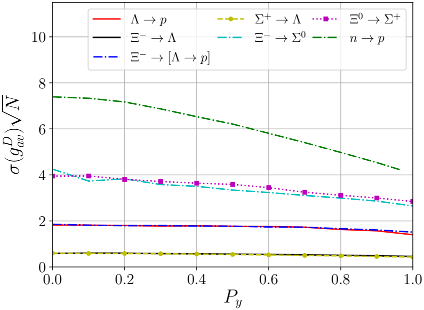
$$b_{\kappa\nu}^{\text{em}} = \frac{1}{2(q^2-4m_l^2)} \sum_{\lambda_\gamma,\lambda'_\gamma} \sum_{\lambda_2,\lambda'_2} H_{\lambda_2\lambda_\gamma} H^*_{\lambda'_2\lambda'_\gamma} \sigma_\kappa^{\lambda_2-\lambda_\gamma,\lambda'_2-\lambda'_\gamma} \sigma_\nu^{\lambda'_2,\lambda_2} L_{\lambda_\gamma,\lambda'_\gamma}(q^2,\Omega_l)$$

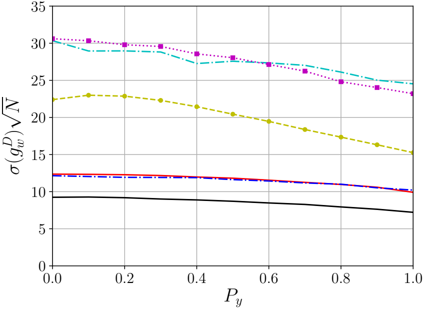
where $\lambda_\gamma = \{-1,0,1\}$ for γ^* decay and its elements:

$$b_{\kappa\nu}^{\text{em}} = \begin{pmatrix} b_{00}^{\text{em}} & b_{01}^{\text{em}} & b_{02}^{\text{em}} & 0 \\ b_{01}^{\text{em}} & b_{11}^{\text{em}} & b_{12}^{\text{em}} & b_{13}^{\text{em}} \\ b_{02}^{\text{em}} & b_{12}^{\text{em}} & b_{22}^{\text{em}} & b_{23}^{\text{em}} \\ 0 & -b_{13}^{\text{em}} & -b_{23}^{\text{em}} & b_{33}^{\text{em}} \end{pmatrix}$$

- Non zero FFs: $H^V_{\frac{1}{2}1} = H^V_{-\frac{1}{2}-1}$ and $H^V_{\frac{1}{2}0} = H^V_{-\frac{1}{2}0}$
- Full definition of $b_{\kappa\nu}$ elements is provided in [PRD108(2023)016011]

$g_{\rm av}$ and $g_{\rm w}$ sensitivity





Joint angular distribution (1)

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$$\mathrm{Tr}\rho_{B_2} \propto \sum_{\mu=0}^{3} C_{\mu 0} \mathcal{B}^{B_1 B_2}_{\mu 0} = \sum_{\mu=0}^{3} C_{\mu 0} \sum_{\kappa=0}^{3} \mathcal{R}_{\mu\kappa}(\Omega_2) b^{B_1 B_2}_{\kappa 0}(q^2, \Omega_l)$$

  - $C_{\mu 0} \equiv (1, P_x, P_y, P_z)$
  - $\mathcal{B}^{B_1 B_2}_{\mu 0} \equiv \mathcal{R}_{\mu\kappa}(\theta_2, \phi_2) b_{\kappa 0}(\theta_l, \phi_l, q^2; g^{B_1}_{\text{av}}, g^{B_1}_{\text{w}})$

- $e^+e^- \to J/\psi, \psi(2S) \to (B_1 \to B_2 W^-_{\text{off-shell}}(\to l^- \bar{\nu}_l))(\bar{B}_1 \to \bar{B}_3 \pi^+)$

$$\mathrm{Tr}\rho_{B_2 \bar{B}_3} \propto \sum_{\mu, \bar{\nu}=0}^{3} C_{\mu\bar{\nu}} \mathcal{B}^{B_1 B_2}_{\mu 0} a^{\bar{B}_1 \bar{B}_3}_{\bar{\nu} 0}$$

  - $C_{\mu\bar{\nu}} \equiv C_{\mu\bar{\nu}}(\theta_1; \alpha_\psi, \Delta\Phi)$
  - $\mathcal{B}^{B_1 B_2}_{\mu 0} \equiv \mathcal{R}_{\mu\kappa}(\theta_2, \phi_2) b_{\kappa 0}(\theta_l, \phi_l, q^2; g^{B_1}_{\text{av}}, g^{B_1}_{\text{w}})$
  - $a^{\bar{B}_1 \bar{B}_3}_{\bar{\nu} 0} \equiv a_{\bar{\nu} 0}(\bar{\theta}_3, \bar{\phi}_3; \bar{\alpha}_{B_1})$

Joint angular distribution (2)

- $e^+e^- \to J/\psi, \psi(2S) \to (\Xi^- \to \Lambda(\to pe^-\bar{\nu}_e)\pi^-)(\bar{\Xi}^+ \to \bar{\Lambda}(\to \bar{p}\pi^+)\pi^+)$

$$\mathrm{Tr}\rho_{p\bar{p}} \propto \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}^{\Xi\bar{\Xi}} \sum_{\mu'=0}^{3} a_{\mu\mu'}^{\Xi\Lambda} \mathcal{B}_{\mu'0}^{\Lambda p} \sum_{\bar{\nu}'=0}^{3} a_{\bar{\nu}\bar{\nu}'}^{\bar{\Xi}\bar{\Lambda}} a_{\bar{\nu}'0}^{\bar{\Lambda}\bar{p}}$$

  - $\mathcal{B}_{\mu'0}^{\Lambda p} \equiv \mathcal{R}_{\mu'\kappa}(\theta_p, \phi_p) b_{\kappa 0}(\theta_e, \phi_e, q^2; g_{\mathrm{av}}^{\Lambda}, g_{\mathrm{w}}^{\Lambda})$

- $e^+e^- \to J/\psi, \psi(2S) \to (\Xi^- \to \Lambda(\to p\pi^-)e^-\bar{\nu}_e)(\bar{\Xi}^+ \to \bar{\Lambda}(\to \bar{p}\pi^+)\pi^+)$

$$\mathrm{Tr}\rho_{p\bar{p}} \propto \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}^{\Xi\bar{\Xi}} \sum_{\mu'=0}^{3} \mathcal{B}_{\mu\mu'}^{\Xi\Lambda} a_{\mu'0}^{\Lambda p} \sum_{\bar{\nu}'=0}^{3} a_{\bar{\nu}\bar{\nu}'}^{\bar{\Xi}\bar{\Lambda}} a_{\bar{\nu}'0}^{\bar{\Lambda}\bar{p}}$$

  - $\mathcal{B}_{\mu\mu'}^{\Xi\Lambda} \equiv \mathcal{R}_{\mu\kappa}(\theta_\Lambda, \phi_\Lambda) b_{\kappa\mu'}(\theta_e, \phi_e, q^2; g_{\mathrm{av}}^{\Xi}, g_{\mathrm{w}}^{\Xi})$