Spin-entanglement in Hyperon Decays

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Symmetries and conservation laws

Invariance

A physical theory may have a symmetry group = it is left **unchanged** by transformations that belong to that group.

Poincaré invariance:

- total energy-momentum conservation (space-time translations),
- angular momentum conservation (Lorentz, i.e. rotations and boosts).

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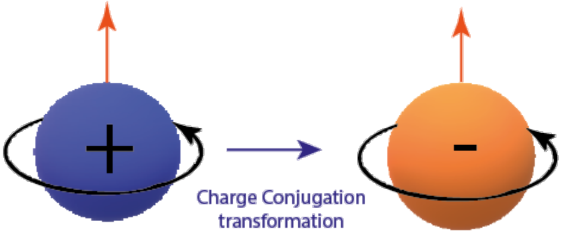
Other transformations (**not** symmetries!):

- Charge-conjugation (C)
- Parity (P)

Charge-conjugation



Credits: ICCUB

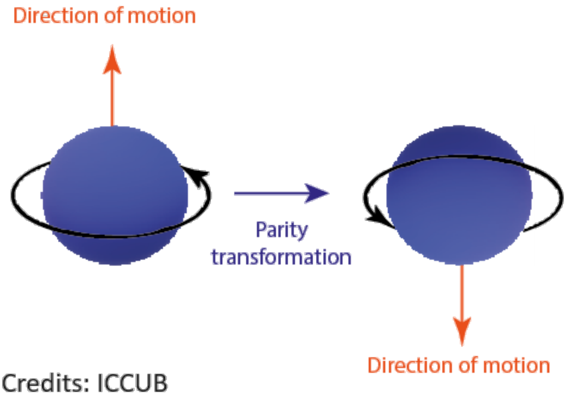
C **affects**:

- particle wavefunctions

C **does not** affect:

- time direction
- coordinates
- momenta
- angular momenta (spins)

Parity



***P* affects:**

- coordinates
- momenta

***P* does not affect:**

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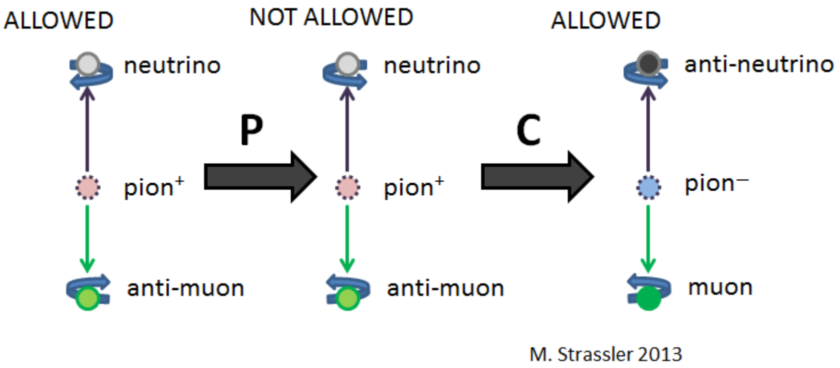
- particle wavefunctions
- angular momenta (spins)

Weak C and P violation



- Both *C* and *P* are violated separately in **weak** interactions (Wu, 1957).
- For $\pi^{\pm}$ decay, it is solved with *CP* invariance.

Weak CP violation

- *CP* violation in neutral kaons (Cronin, Fitch 1964)

N. Cabibbo at Berkeley conference, 1966.

This is is **relevant today**: there is a lot we haven't understood.

CP violation

Early stages of our Universe (*thermal equilibrium*): $\gamma + \gamma \rightleftharpoons p + \bar{p}$.

Expanding Universe, decreasing temperatures (*thermal freeze-out*); B, $\bar{B}$ number density decreases to a fixed point (*Big Bang baryogenesis*):

$$n_B = n_{\bar{B}} \sim 10^{-18} n_\gamma$$

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Inferred by light isotopes formed in BBN:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9} \quad \text{matter-antimatter asymmetry}$$

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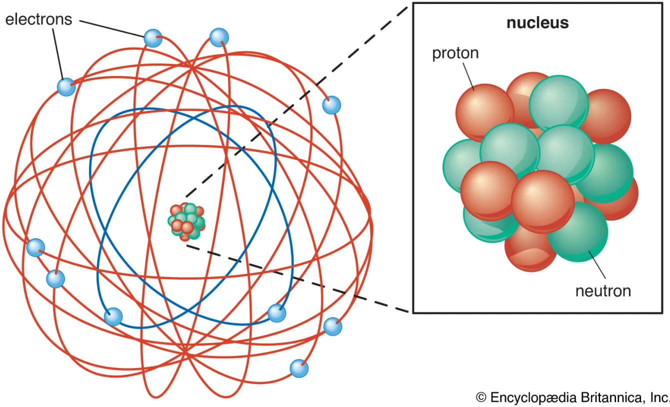
Sakharov conditions [Pisma Zh.Eksp.Teor.Fiz. 5 (1967)]

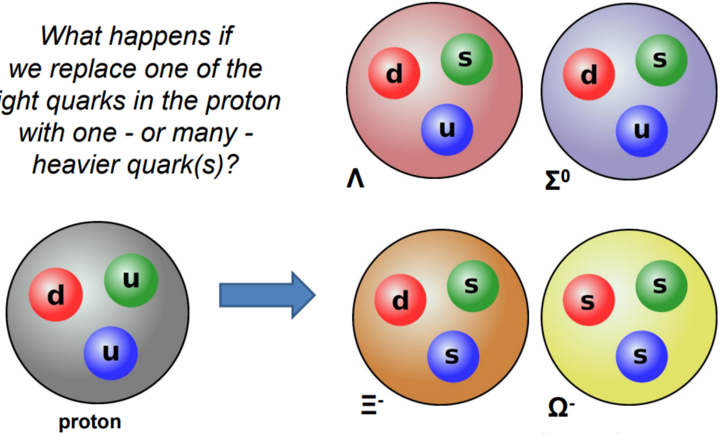
- $\mathcal{B}$ baryon number violation: $n_B - n_{\bar{B}} \neq 0$
- C and CP violation: unequal # of conjugate processes
- no thermal equilibrium

Hyperons: subatomic particles



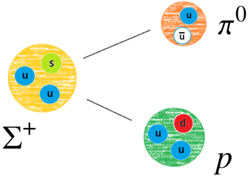
Hyperons: subatomic particles

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?



Credits: K. Schönning

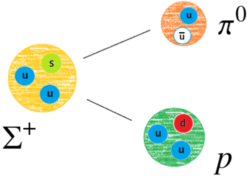
Decays, compared

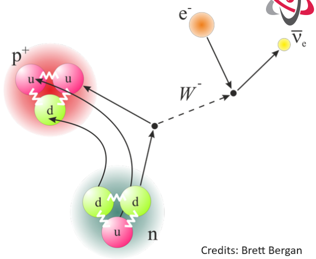


Nonleptonic decays $B \to b\pi$

- Fewer final-state combinations
- Extension of *CP*V kaon decays
- Direct *CP*V tests

Decays, compared





Credits: Brett Bergan

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Semileptonic decays $B \to bl\bar{\nu}_l$

- More final-state combinations
- Spin-density matrix of daughter baryon b (NEW)
- (future) *CP* tests

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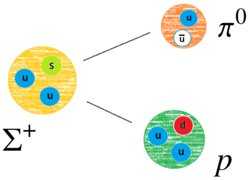

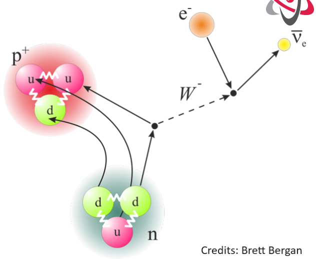

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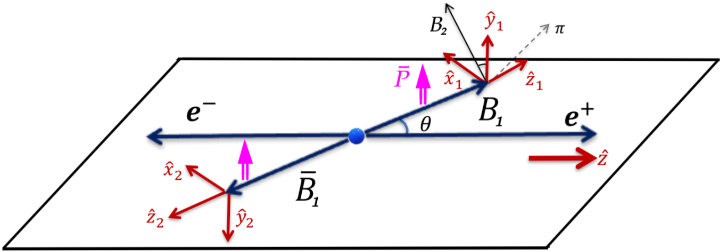
Background

Spin-entangled hyperon-antihyperon pairs produced at e^+e^- colliders.

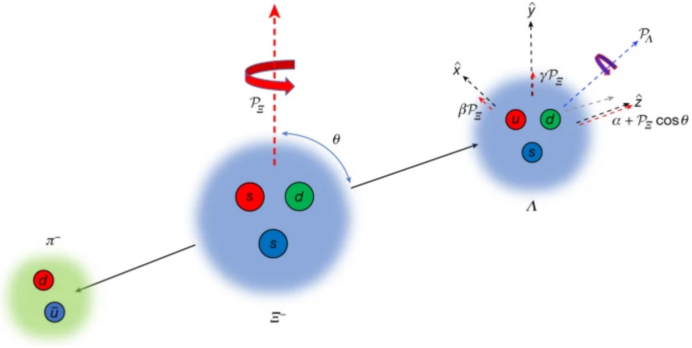
Lowest-lying hyperons @ BESIII

- World's largest charmonia sample - $10^{10} J/\psi,\ 3\times 10^9\ \psi(2S)$
- Baryon-antibaryon production in **spin-entangled** state



Decay	$\mathcal{B}(\times 10^{-4})$	$\epsilon(\%)$	N_{obs}	Reference
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	42.37 ± 0.14	441×10^3	[PRD95(2017)052003]
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	$11.64 \pm 0.04 \pm 0.23$	17.83 ± 0.06	111×10^3	[PRD93(2016)072003]
$J/\psi \to \Xi^-\bar{\Xi}^+$	$10.40 \pm 0.06 \pm 0.74$	18.40 ± 0.04	43×10^3	
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	42.83 ± 0.34	31×10^3	[PRD95(2017)052003]
$\psi(2S) \to \Sigma^0\bar{\Sigma}^0$	$2.44 \pm 0.03 \pm 0.11$	14.79 ± 0.12	6.6×10^3	[PRD93(2016)072003]
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	$2.78 \pm 0.05 \pm 0.14$	18.04 ± 0.04	5.3×10^3	

Baryon polarization



$\Xi^- \to \Lambda(\to p\pi^-)\pi^-$ decay [Nature 606, 64–69 (2022)]

Produced $B(\bar{B})$ at e^+e^- colliders (e.g. BESIII) are **inherently** polarized.

$$\mathbf{P}_\Lambda \cdot \hat{\mathbf{z}} = \frac{\alpha_\Xi + \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}{1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}, \quad \mathbf{P}_\Lambda \times \hat{\mathbf{z}} = |P_\Xi| \sqrt{1-\alpha_\Xi^2}\, \frac{\sin\phi_\Xi \hat{\mathbf{x}} + \cos\phi_\Xi \hat{\mathbf{y}}}{1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}},$$

Spin production matrix

Jacob-Wick formalism: $B\bar{B}$ spin-correlation matrix for $1/2 + \overline{1/2}$ [PRD99, 056008 (2019)]

$$\rho_{B,\bar{B}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}(\theta)\, \sigma_{\mu}^{B} \otimes \sigma_{\bar{\nu}}^{\bar{B}}$$

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Goal

Derive the **production** spin-density matrix $\rho_{B,\bar{B}}$ with e^- **beam polarization**.

At next-generation colliders: [PRD 105, 116022 (2022)]

B polarization

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

$\bar{B}$ polarization

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spin-correlation terms

Nonleptonic decay parameters

From partial waves to observables:

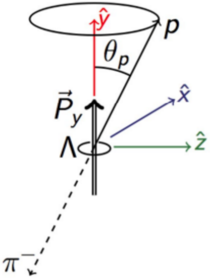
- Angular distribution $\frac{d\Gamma}{d\Omega} \propto 1 + \alpha \mathbf{P}_\Lambda \cdot \hat{\mathbf{n}}$

$$\alpha = \frac{2\Re(S^* P)}{|S|^2 + |P|^2}$$

- Spin $\mathbf{s}_\Lambda \to \mathbf{s}_p$ rotation

$$\beta = \frac{2\Im(S^* P)}{|S|^2 + |P|^2} = \sqrt{1-\alpha^2} \sin \phi$$

measurable with $\mathbf{P}_\Lambda$, $\mathbf{P}_p$.



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

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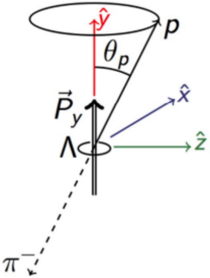

$\Lambda \to p\pi^-$ decay

CP tests [PRD 100, 114005 (2019)]

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \quad B_{CP} := \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}, \quad \Phi_{CP} = \frac{\phi + \bar{\phi}}{2}$$

CPV in hyperon decays

Introducing CP-odd and final-state interaction [PRD 105, 116022 (2022)], [Phys. Rev. D 34, 833(1986)]:

$$S = |S| \exp(i\xi_S + i\delta_S)$$
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Some first times:

- CP-odd phase difference [Nature 606, 64–69 (2022)]

$$\xi_P - \xi_S = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2}\text{rad} \qquad \text{SM}: \ \xi_P - \xi_S = (-2.1 \pm 1.7) \times 10^{-4}\text{rad}$$

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- Ξ^- polarization and decay parameters (directly)

$$\alpha_\Xi = -0.376 \pm 0.007 \pm 0.003, \ \phi_\Xi = 0.011 \pm 0.019 \pm 0.009 \text{ rad}$$

$$A_{CP}^{\Xi} = (6 \pm 13 \pm 6) \times 10^{-3} \qquad \text{SM}: \ A_{CP}^{\Xi} = (-0.6 \pm 1.6) \times 10^{-5}$$

Motivation: new data landscape

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]

Article | Open Access | Published: 01 June 2022

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

The BESIII Collaboration

Nature **606**, 64–69 (2022) | Cite this article

11k Accesses | **7** Citations | **96** Altmetric | Metrics

[Nature 606, 64–69 (2022)]

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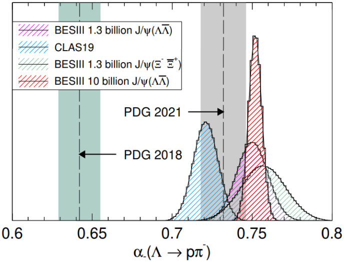
Precise Measurements of Decay Parameters and CP Asymmetry with Entangled Λ–$\bar{\Lambda}$ Pairs

M. Ablikim *et al.* (BESIII Collaboration)

Phys. Rev. Lett. **129**, 131801 – Published 22 September 2022

[Phys.Rev.Lett. 129 (2022) 131801]



Two-step decays [PRD 105, 116022 (2022)]

For $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$, simultaneous $A_{\mathrm{CP},\Xi}$, $\Phi_{\mathrm{CP},\Xi}$ measurements are possible.

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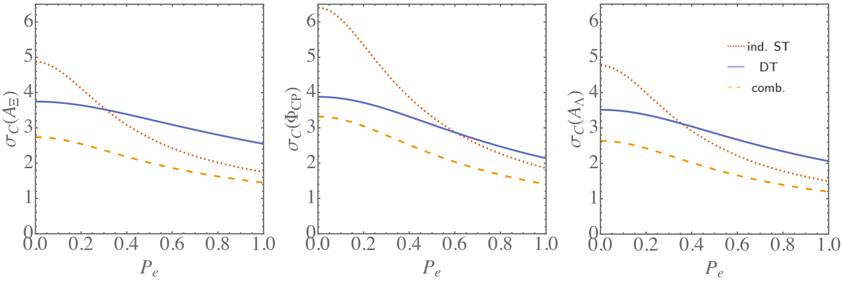
For $\Xi^- \to \Lambda(\to p\pi^-)\pi^-$, simultaneous $A_{\text{CP},\Xi}$, $\Phi_{\text{CP},\Xi}$ measurements are possible.

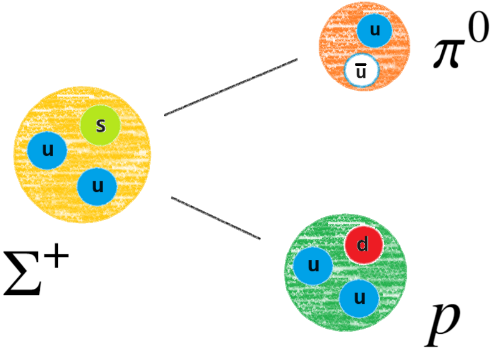
$$\sigma(\omega_i) \propto \mathcal{I}_0^{-1}(\omega_i, \omega_j), \text{ with } \mathcal{I}_0(\omega_i, \omega_j) = N\left[\mathbb{a}_{ij} + \mathbb{b}_{ij}\,\langle \mathbb{P}^2_{\Xi}\rangle + \mathbb{c}_{ij}\,\langle \mathbb{S}^2_{\Xi\Xi}\rangle\right]$$



ST has larger yields, but too low statistical precision: **with P_e, its larger yields can be used**.

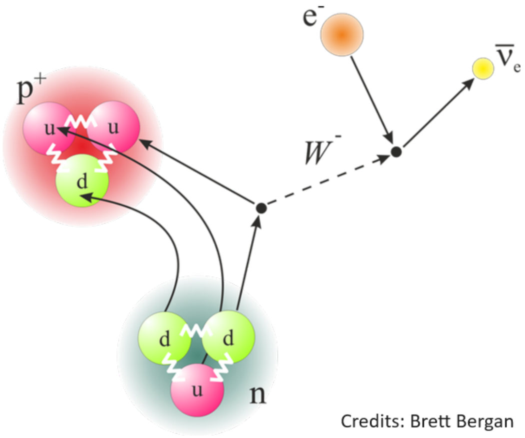
Semileptonic decays

So far, we talked about **nonleptonic decays:**



Semileptonic decays

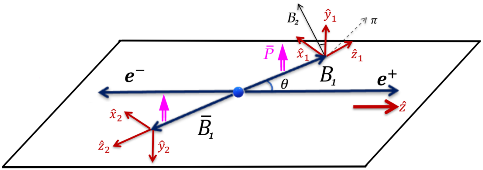
Let’s switch to **semileptonic decays:**



Credits: Brett Bergan

Spin-density matrix

At BESIII, e^- beam is **not polarized**:



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B polarization

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$\bar{B}$ polarization

spin-correlation terms

Spin-density matrix

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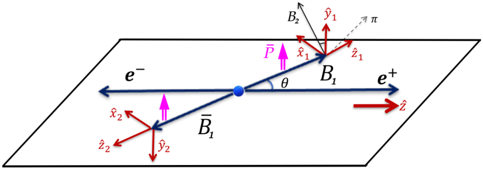

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Change of basis

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Goal [PRD 108, 016011 (2023)]

Decay matrix for semileptonic decay $b_{\mu\nu}$ from **spin-entangled** $Y\bar{Y}$.

$$\rho_{B,\bar{B}} = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}}(\theta)\, \sigma_{\mu}^{B} \otimes \sigma_{\bar{\nu}}^{\bar{B}} \quad \text{with} \quad \sigma_{\mu}^{m} \to \sum_{\nu=0}^{3} b_{\mu\nu}\sigma_{\nu}^{d}$$

Change of basis

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Decay matrix for semileptonic decay $b_{\mu\nu}$ from **spin-entangled** $Y\bar{Y}$.

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$$\langle \Omega_2, \lambda_2, \underline{\lambda}_W | S | J = 1/2, \kappa \rangle = \frac{1}{2\pi} H_{\lambda_2,\underline{\lambda}_W}(q^2) \mathcal{D}^{1/2*}_{\kappa,\lambda_2-\lambda_W}(\Omega_2)$$

Helicity amplitudes:

SL: $\left(\frac{1}{2},0\right), \left(-\frac{1}{2},0\right), \left(\frac{1}{2},1\right), \left(-\frac{1}{2},-1\right)$ NL: $\left(\frac{1}{2},0\right), \left(-\frac{1}{2},0\right)$

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SL: $\left(\frac{1}{2},0\right), \left(-\frac{1}{2},0\right), \left(\frac{1}{2},1\right), \left(-\frac{1}{2},-1\right)$

NL: $\left(\frac{1}{2},0\right), \left(-\frac{1}{2},0\right)$

Use **helicity amplitudes** to write **decay parameters** e.g. α, ϕ.

Aligned decay matrices

$B \to b\gamma$:

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

$B \to b\pi$:

$$b_{\mu\nu} \propto \begin{pmatrix} 1 & 0 & 0 & \alpha_\pi \\ 0 & \gamma_\pi & -\beta_\pi & 0 \\ 0 & \beta_\pi & \gamma_\pi & 0 \\ \alpha_\pi & 0 & 0 & 1 \end{pmatrix}$$

Aligned decay matrices

$B \to b\gamma$:

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

$B \to b\pi$:

$$b_{\mu\nu} \propto \begin{pmatrix} 1 & 0 & 0 & \alpha_\pi \\ 0 & \gamma_\pi & -\beta_\pi & 0 \\ 0 & \beta_\pi & \gamma_\pi & 0 \\ \alpha_\pi & 0 & 0 & 1 \end{pmatrix}$$

$B \to bW^-_{\text{off-shell}}(\to l^-\bar{\nu}_l)$: $\qquad b_{\mu\nu} = b^{\text{nf}}_{\mu\nu} + \epsilon b^{\text{f}}_{\mu\nu}$

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

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

Aligned decay matrices [PRD 108, 016011 (2023)]

$B \to b\gamma$:

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

$B \to b\pi$:

$$b^{D}_{\mu\nu} \propto \begin{pmatrix} 1 & 0 & 0 & \alpha_\pi \\ 0 & \gamma_\pi & -\beta_\pi & 0 \\ 0 & \beta_\pi & \gamma_\pi & 0 \\ \alpha_\pi & 0 & 0 & 1 \end{pmatrix}$$

$$B \to bW^{-}_{\text{off-shell}}(\to l^- \bar{\nu}_l) : \qquad b_{\mu\nu} = b^{\text{nf}}_{\mu\nu} + \epsilon b^{\text{f}}_{\mu\nu}$$

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

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

Conclusions

1. Hyperon-antihyperon pairs produced at e^+e^- colliders feature relevant spin-correlation and polarization properties.
2. Nonleptonic Y decays can provide a CPV source of information complementary complementary to kaon decays.
3. At next-generation e^+e^- colliders (STCF), a polarized beam affects the final baryon polarization impacting **directly** on the statistical uncertainties of CPV observables.
4. The same spin-correlation and polarization features may be employed to derive a description of semileptonic Y decays, using the *helicity formalism*.

Thank You! Any Questions?

Time reversal

Credits: Massimo Ravera//Getty Images

T affects:

- time direction
- coordinates
- momenta
- angular momenta (spins)

T does not affect:

- particle wavefunctions

CPT theorem

CPT theorem [Am. J. Phys. 24, 292 (1956)]

Any (SM) interaction possesses an exact symmetry under the combined operation of C, P, T, in any order.

Based on

- Lorentz invariance
- quantum mechanics
- particles as fields

- If CPT holds, CP violation $\Longrightarrow$ T violation: observed in neutral kaons decay.
- In Y decays, T-invariance **does not** imply S and P to be relatively real because final-state strong interaction.

Nonleptonic decays

- **Pseudoscalar** in final state

$$B \to b\pi \qquad \vec{J}_B = \vec{S}_b + \vec{S}_\pi + \vec{L}$$

If $J_B = S_b = 1/2$, the only possible L values are

$$L = 0 \quad \Longrightarrow \quad S-\text{wave } (P\text{-violating})$$
$$L = 1 \quad \Longrightarrow \quad P-\text{wave } (P\text{-conserving})$$

- Introducing CP-odd and final state interaction [Phys. Rev. D 34, 833(1986)]:

$$S = |S| \exp(i\xi_S + i\delta_S), \qquad \bar{S} = -|S| \exp(-i\xi_S + i\delta_S)$$
$$P = |P| \exp(i\xi_P + i\delta_P), \qquad \bar{P} = \quad |P| \exp(-i\xi_P + i\delta_P)$$

Jacob-Wick formalism

Nonleptonic decay matrix:

$$a_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & \alpha_D \\ \alpha_D \sin\theta\cos\varphi & \gamma_D\cos\theta\cos\varphi - \beta_D\sin\varphi & -\beta_D\cos\theta\cos\varphi - \gamma_D\sin\varphi & \sin\theta\cos\varphi \\ \alpha_D\sin\theta\sin\varphi & \beta_D\cos\varphi + \gamma_D\cos\theta\sin\varphi & \gamma_D\cos\varphi - \beta_D\cos\theta\sin\varphi & \sin\theta\sin\varphi \\ \alpha_D\cos\theta & -\gamma_D\sin\theta & \beta_D\sin\theta & \cos\theta \end{pmatrix}$$

Semileptonic decay matrix

$$b_{\mu\nu} := \frac{\pi}{6(q^2 - m_l^2)} \sum_{\underline{\lambda}_W, \underline{\lambda}'_W} \sum_{\lambda_2, \lambda'_2 = -1/2}^{1/2} H_{\lambda_2 \underline{\lambda}_W} H^*_{\lambda'_2 \underline{\lambda}'_W} \underbrace{\sigma_\mu^{\lambda_2 - \lambda_W, \lambda'_2 - \lambda'_W} \sigma_\nu^{\lambda'_2, \lambda_2} L_{\underline{\lambda}_W, \underline{\lambda}'_W}(q^2, \Omega_l)}_{\mathcal{T}_{\mu\nu}^{\underline{\lambda}_W, \underline{\lambda}'_W, \lambda_2, \lambda'_2}}$$

Approximate maximum likelihood method

Fisher information matrix

$$\mathcal{I}(\omega_k, \omega_l) := N \int \frac{1}{\mathcal{P}} \frac{\partial \mathcal{P}}{\partial \omega_k} \frac{\partial \mathcal{P}}{\partial \omega_l} \mathrm{d}\boldsymbol{\xi}$$

To compute e.g. $\mathcal{I}_0(A_{\mathrm{CP}})$ assume

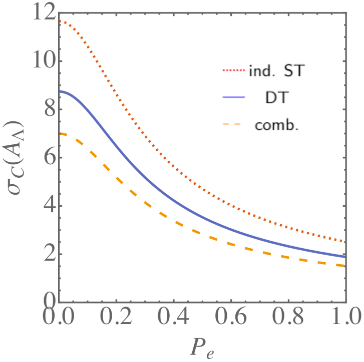
$$\frac{1}{\mathcal{P}} = \frac{\mathcal{V}}{C_{00}} \frac{1}{1+\mathcal{G}} = \frac{\mathcal{V}}{C_{00}} \sum_{i=0}^{\infty} (-\mathcal{G})^i \text{ with } \int \mathcal{G} \mathrm{d}\boldsymbol{\xi} = 0\,,\ \mathcal{G} \geq -1$$

$$\mathcal{I}_0(A_{\mathrm{CP}}) = \frac{2N}{3} \alpha^2 \langle \mathbf{P}_B^2 \rangle \implies \sigma(A_{\mathrm{CP}}) \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha \sqrt{N \langle \mathbf{P}_B^2 \rangle}}\,.$$

Single-step decays

For $\Lambda \to p\pi^-$, only $A_{\text{CP},\Lambda}$ is available (no final-state polarization detector).

$$\sigma(A_{\text{CP}}) \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha \sqrt{N \langle \mathbf{P}_B^2 \rangle}}$$

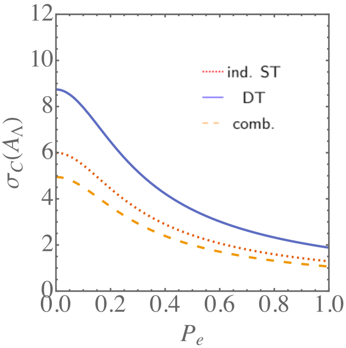


- $\epsilon_\Lambda = \epsilon_{\bar{\Lambda}} = 1$
- Single-Tag: **aut** B **aut** $\bar{B}$
- Double-Tag: B **and** $\bar{B}$
- Combination: B **or** $\bar{B}$

ST-DT combined corresponds to a **two-times** σ improvement.

Single-step decays

For $\Lambda \to p\pi^-$ with detection efficiency $\epsilon_\Lambda = \epsilon_{\bar{\Lambda}} = 0.5$



$$\sigma(A_{\mathrm{CP}}) \approx \sqrt{\frac{3}{2}} \frac{1}{\alpha \sqrt{N \langle \mathbf{P}_B^2 \rangle}}$$