中国科学技术大学
University of Science and Technology of China

BESIII

BESIII上超子衰变实验研究

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第十届手征有效场论研讨会

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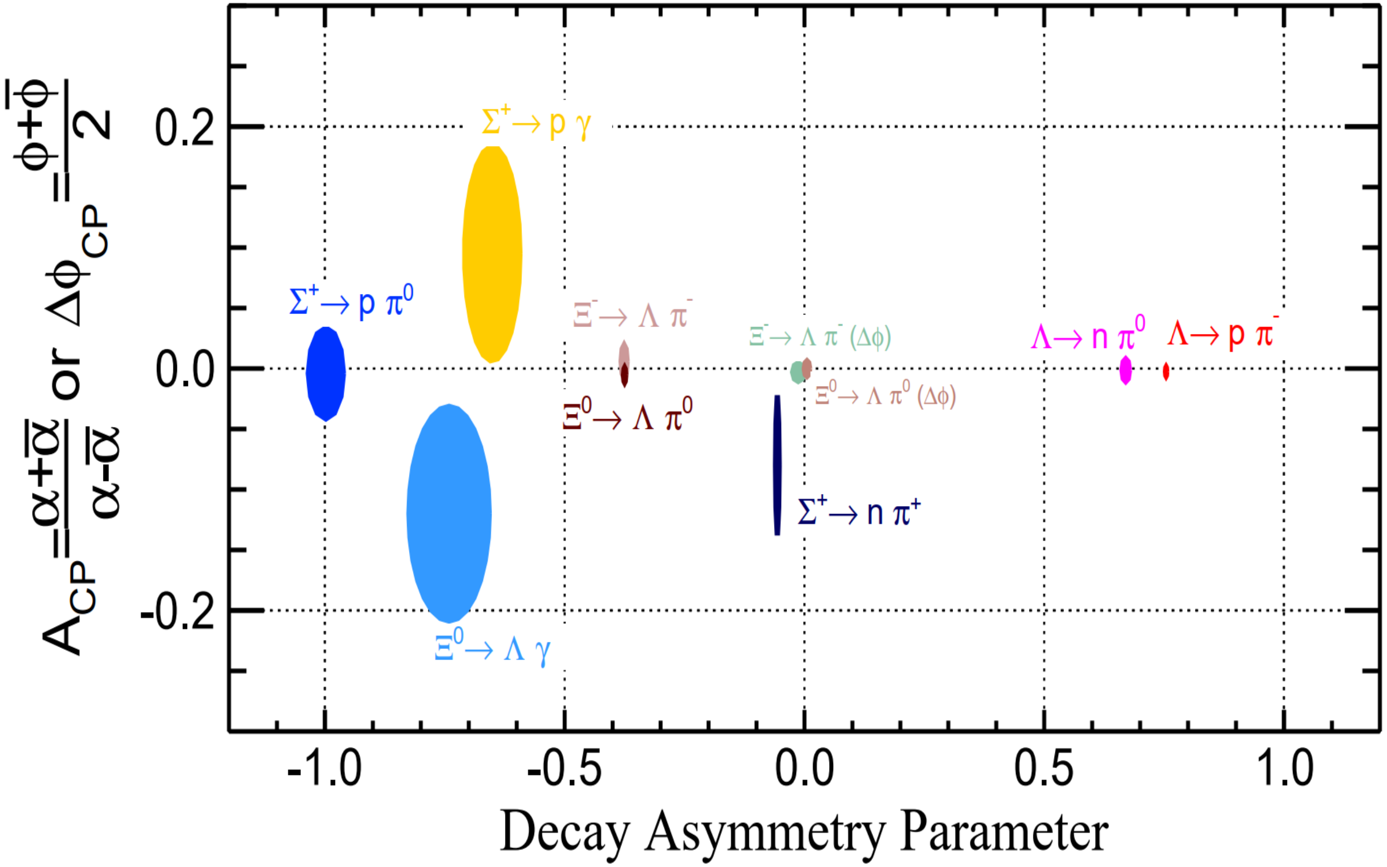
Hyperon decays and CP violation



- **Polarization** of hyperon disentangled
- Most precise **decay parameters** obtained
- More CPV observable constructed

$$A=\frac{\alpha+\overline{\alpha}}{\alpha-\overline{\alpha}}\,,\quad B=\frac{\beta+\overline{\beta}}{\beta-\overline{\beta}}\,.$$

$A_\Lambda = -0.0025 \pm 0.0046 \pm 0.0011$ (10billion J/ψ)

$A_\Sigma = -0.004 \pm 0.037 \pm 0.010$ (1.3 billion J/ψ)

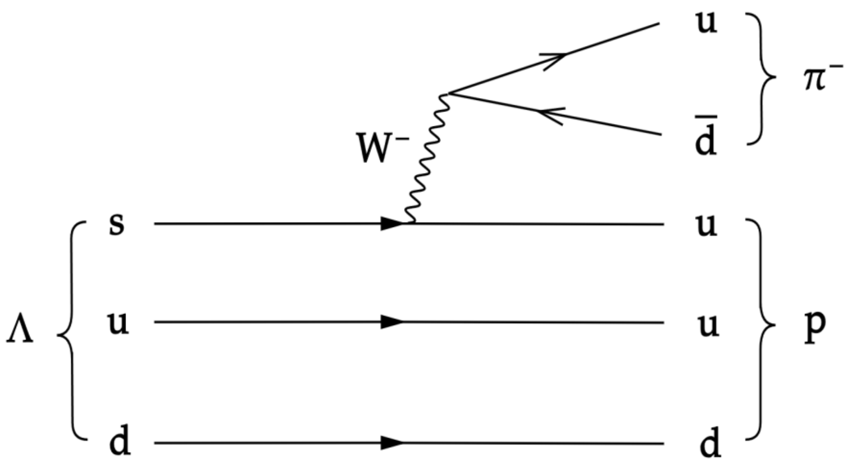
$A_\Xi = 0.006 \pm 0.013 \pm 0.006$ (1.3 billion J/ψ)

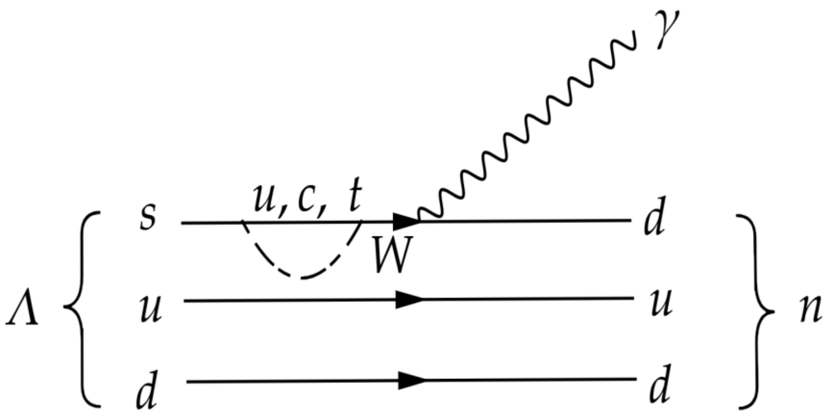
$\Delta\phi_\Xi = -0.005 \pm 0.014 \pm 0.003$ (1.3 billion J/ψ)

$\xi^P_\Lambda - \xi^S_\Lambda = (-1.1 \pm 2.1)^\circ \quad \in \{-4.5^\circ, +2.1^\circ\}$ (90% C.L.)

Hyperon decays and ChPT

- There are still **unsolved questions** in the domain of **low-q²** hyperon weak decays: the origin of the **ΔI=1/2 Rule**; the **S/P wave** puzzle in decay amplitudes; the violation of the **Hara Theorem**
- The **Chiral perturbation theory** provides a useful tool to systematically analyze the interplay of the strong, weak, and EM interactions.
- The processes of interest include hyperon **hadronic** decays $\boldsymbol{\Lambda \to p\pi^-}$ **and** $\boldsymbol{\Lambda \to n\pi^0}$ and **radiative** decays $\boldsymbol{\Sigma^+ \to p\gamma, \Lambda \to n\gamma, \Xi^0 \to \Lambda\gamma}$





ΔI =1/2 rule in Hyperon hadronic decay

- **In $K \to \pi\pi$ decay, their amplitudes:**

$$A(K^+ \to \pi^+\pi^0) = \frac{3}{2} A_2 e^{i\chi_2} \quad \Delta I = \frac{3}{2} \text{ transition}$$

$$A(K^0 \to \pi^+\pi^-) = A_0 e^{i\chi_0} + \frac{1}{\sqrt{2}} A_2 e^{i\chi_2} \quad \Delta I = \frac{1}{2} \text{ transition}$$

$$\frac{\mathrm{Re}(A_0)}{Re(A_1)} \approx \frac{\sqrt{\mathcal{B}(K^+ \to \pi^+\pi^0)\tau_{K_s}}}{\sqrt{\mathcal{B}(K_s \to \pi^+\pi^-)\tau_{K^+}}} = \sqrt{\frac{0.21 \cdot 0.1ns}{0.69 \cdot 12ns}} = \frac{1}{22}$$

- **The $\Delta I = 1/2$ rule:** the weak transitions changing isospin by 1/2 are enhanced over the 3/2 transitions in **S-wave** **"50 Years of Quantum Chromodynamics"**

- The ΔI =1/2 rule is also applicable in the decay of **hyperons, e.g. $\Lambda \to p\pi^-$ and $\Lambda \to n\pi^0$**

$$S(\Lambda_-) = -\sqrt{\frac{2}{3}} S_{11} e^{i(\delta^S_{11}+\xi^S_1)} + \sqrt{\frac{1}{3}} S_{33} e^{i(\delta^S_{33}+\xi^S_3)}, \qquad S(\Lambda_0) = \sqrt{\frac{1}{3}} S_{11} e^{i(\delta^S_{11}+\xi^S_1)} + \sqrt{\frac{2}{3}} S_{33} e^{i(\delta^S_{33}+\xi^S_3}$$

$$P(\Lambda_-) = -\sqrt{\frac{2}{3}} P_{11} e^{i(\delta^P_{11}+\xi^P_1)} + \sqrt{\frac{1}{3}} P_{33} e^{i(\delta^P_{33}+\xi^P_3)}, \qquad P(\Lambda_0) = \sqrt{\frac{1}{3}} P_{11} e^{i(\delta^P_{11}+\xi^P_1)} + \sqrt{\frac{2}{3}} P_{33} e^{i(\delta^P_{33}+\xi^F_3}$$

δ_i is the strong final-state interaction phase, ξ_i is the weak interaction phase

$\Delta I = 1/2$ rule in Hyperon hadronic decay

- Three parameters fully describe the **hyperon hadronic weak decays**:

$$\Gamma = \frac{e^2 G_F^2}{\pi}\left(|S|^2 + |P|^2\right) \qquad \alpha_Y = \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2} \qquad \phi_Y = \sin^{-1}\frac{\beta_Y}{\sqrt{1-\alpha_Y^2}}$$

- The $\Delta I = 1/2$ and $\Delta I = 3/2$ amplitudes in Hyperon is related with **decay widths** and **decay asymmetries**. If there no $\Delta I = 3/2$ transition in Λ decay: $\frac{\alpha_0}{\alpha_-} = 1, \frac{\Gamma(\Lambda \to n\pi^0)}{\Gamma(\Lambda \to p\pi^-)} = 1/2$

- **Why test $\Delta I = 1/2$ rule in Λ decay:**
  - Test the $\Delta I = 1/2$ rule in both S-wave and ***P*-wave**: S_1/S_3 and P_1/P_3
  - $\Delta I = 3/2$ transition contributes in CPV of decay width

$$\Delta_{\mathrm{CP}} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = \frac{P_{1,1} P_{3,3} \sin\left(\xi_{1,1}^P - \xi_{3,3}^P\right) \sin\left(\delta_1^P - \delta_3^P\right)}{P_{1,1}^2 + S_{1,1}^2} + \frac{S_{1,1} S_{3,3} \sin\left(\xi_{1,1}^S - \xi_{3,3}^S\right) \sin\left(\delta_1^S - \delta_3^S\right)}{P_{1,1}^2 + S_{1,1}^2}$$

S/P wave puzzle in Hyperon hadronic decay

- **S/P wave puzzle**: the S wave in hyperon decay follows SU(3) symmetry, while the P wave doesn't

- Using the **ChPT approaches**, with updated decay parameters, the updated S-wave and P-wave are obtained, where the **P-wave** differs from previous calculations.

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TABLE V. Experimental S- and P-wave hyperon non-leptonic decay amplitudes extracted from the most recent pdgLive [3], BESIII measurements [51, 52] and CLAS data [53].

Decay modes	$\mathcal{B}$ [3]	α_π [3, 51–53]	ϕ_π (°) [3, 52]	$s = A_S^{(\mathrm{Expt})}$ This work	$s = A_S^{(\mathrm{Expt})}$ [49]	$p = A_P^{(\mathrm{Expt})}\lvert\vec{q}\rvert/(E_f+m_f)$ This work	$p = A_P^{(\mathrm{Expt})}\lvert\vec{q}\rvert/(E_f+m_f)$ [49]
$\Sigma^+ \to n\pi^+$	0.4831(30)	0.068(13)	167(20)	0.06(1)	0.06(1)	1.81(1)	1.81(1)
$\Sigma^- \to n\pi^-$	0.99848(5)	−0.068(8)	10(15)	1.88(1)	1.88(1)	−0.06(1)	−0.06(1)
$\Lambda \to p\pi^-$	0.639(5)	0.7462(88)	−6.5(35)	1.38(1)	1.42(1)	0.62(1)	0.52(2)
$\Xi^- \to \Lambda\pi^-$	0.99887(35)	−0.376(8)	0.6(12)	−1.99(1)	−1.98(1)	0.39(1)	0.48(2)
$\Sigma^+ \to p\pi^0$	0.5157(30)	−0.982(14)	36(34)	−1.50(3)	−1.43(5)	1.29(4)	1.17(7)
$\Lambda \to n\pi^0$	0.358(5)	0.74(5)	⋯	−1.09(2)	−1.04(1)	−0.48(4)	−0.39(4)
$\Xi^0 \to \Lambda\pi^0$	0.99524(12)	−0.356(11)	21(12)	1.62(10)	1.52(2)	−0.30(10)	−0.33(2)

The S/P wave puzzle limits the precision of SM predictions of hyperon CPV

$$\alpha_Y = \frac{2|S_Y||P_Y|\cos\left((\delta^P_{y\pi}-\delta^S_{y\pi})+(\xi^P_Y-\xi^S_Y)\right)}{|S_Y|^2+|P_Y|^2}$$

$$\alpha_{\bar{Y}} = -\frac{2|S_Y||P_Y|\cos\left((\delta^P_{y\pi}-\delta^S_{y\pi})-(\xi^P_Y-\xi^S_Y)\right)}{|S_Y|^2+|P_Y|^2}$$

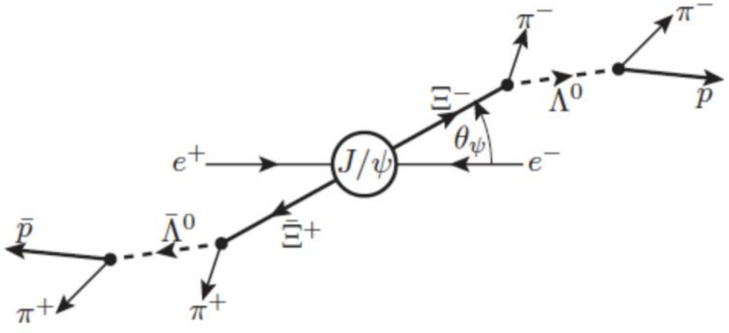
$$A^Y_{CP} \equiv \frac{\alpha_Y+\alpha_{\bar{Y}}}{\alpha_Y-\alpha_{\bar{Y}}} = -\sin(\delta^P_{y\pi}-\delta^S_{y\pi})\sin(\xi^P_Y-\xi^S_Y)$$

$$B^\Xi_{CP} \equiv \frac{\beta_\Xi+\beta_{\bar{\Xi}}}{\alpha_\Xi-\alpha_{\bar{\Xi}}} = \tan(\xi^P_\Xi-\xi^S_\Xi) \approx \xi^P_\Xi-\xi^S_\Xi$$

CPV observables	SM predictions	BESIII data
A^Λ_{CP}	$(-3\sim3)\times10^{-5}$	$(-2.5\pm4.6\pm1.2)\times10^{-3}$
A^Ξ_{CP}	$(0.5\sim6)\times10^{-5}$	$(6\pm13.4\pm5.6)\times10^{-3}$
B^Ξ_{CP}	$(-3.8\sim-0.3)\times10^{-4}$	$(1.2\pm3.4\pm0.8)\times10^{-2}$

Hyperon Hadronic Weak Decay at e$^+$e$^-$ collider

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



- J/ψ produced almost at rest
- $\Xi^-\bar{\Xi}^+$ produced back-to-back, spin-correlated
- Decay occurs within a few cm of IP
- Low momentum π^- and π^+
- Clean topology, low background rate: 1:400

☐ The first reaction: $J/\psi \to \Xi^-\bar{\Xi}^+$

- Two helicity amplitudes $|J;\, J_z\rangle = |1;\, +1\rangle, |1; -1\rangle$
- Interference between them produces a θ_ψ-dependent production for Ξ hyperons that are spin-polarized:

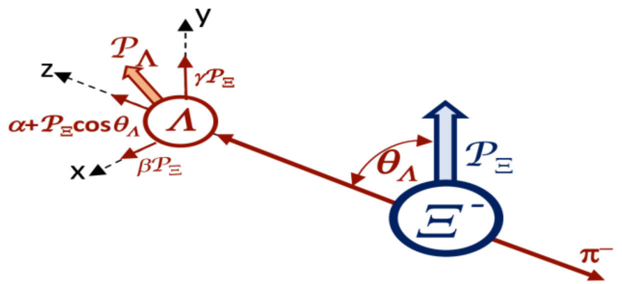
$$\frac{1}{N}\frac{dN}{d\cos\theta_\psi} = \frac{3}{4\pi}\frac{1+\alpha_\psi\cos^2\theta_\psi}{3+\alpha_\psi}$$

$$\mathcal{P}_\Xi = \frac{\sqrt{1-\alpha_\psi^2}\sin\theta_\psi\cos\theta_\psi\sin\Delta\Phi}{1+\alpha_\psi\cos^2\theta_\psi},$$

衰变道	α_ψ	$\Delta\Phi_\psi$	最大极化率（%）
$J/\psi \to \Lambda\bar{\Lambda}$	$0.475 \pm 0.002 \pm 0.003$	$0.752 \pm 0.004 \pm 0.007$	24.7
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	$-0.508 \pm 0.006 \pm 0.004$	$-0.270 \pm 0.012 \pm 0.009$	16.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	$0.586 \pm 0.012 \pm 0.010$	$1.213 \pm 0.046 \pm 0.016$	30.1
$J/\psi \to \Xi^0\bar{\Xi}^0$	$0.514 \pm 0.006 \pm 0.015$	$1.168 \pm 0.019 \pm 0.018$	32.1

Hyperon Hadronic Weak Decay at e+e- collider

The next two reactions: $\Xi^- \to \Lambda\pi^-(\bar{\Xi}^+ \to \bar{\Lambda}\pi^+)$

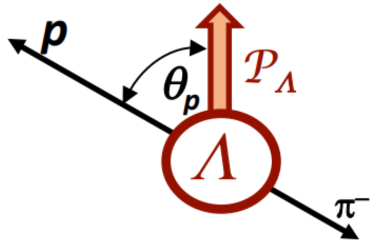


- In Ξ^- and $\bar{\Xi}^+$ rest frames: $\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha_\Xi \mathcal{P}_\Xi \cos\theta_\Lambda$

$$\mathbf{P}_\Lambda = \frac{(\alpha_\Xi + \mathcal{P}_\Xi \cos\theta_\Lambda)\hat{\mathbf{z}} + \mathcal{P}_\Xi \beta_\Xi \hat{\mathbf{x}} + \mathcal{P}_\Xi \gamma_\Xi \hat{\mathbf{y}}}{1 + \alpha_\Xi \mathcal{P}_\Xi \cos\theta_\Lambda}$$

- The decay angle $\theta_\Lambda(\theta_{\bar{\Lambda}})$ relative to P_Ξ direction
- P_Λ is polarization of Λ with $\hat{x}, \hat{y}, \hat{z}$ oriented in helicity frame
- $\boldsymbol{\alpha, \beta, \gamma}$ are the Lee-Yang decay parameters of $\boldsymbol{\Xi}$ that can be determined with $\frac{dN}{d\cos\theta}$ and P_Λ

The last two reactions: $\Lambda \to p\pi^-(\bar{\Lambda} \to \bar{n}\pi^0)$

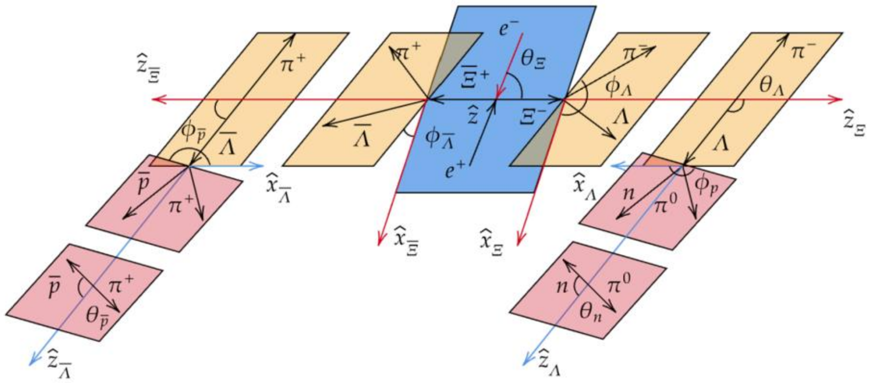


- In Λ and $\bar{\Lambda}$ rest frames: $\frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda \mathcal{P}_\Lambda \cos\theta_p.$
- The decay angle $\theta_p(\theta_{\bar{p}})$ relative to P_Λ direction
- Only **α of Λ can be determined** since proton polarization is not measured.

A joint angular analysis of $J/\psi \to \Xi^-\bar{\Xi}^+$

$$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to n\pi^0)\pi^-\bar{\Lambda}(\to \bar{p}^-\pi^+)\pi^+, \text{(neutron channel)}$$
$$e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to p^+\pi^-)\pi^-\bar{\Lambda}(\to \bar{n}\pi^0)\pi^+. \text{(anti-neutron channel)}$$

$$\mathcal{W}(\xi;\omega) = \sum_{\mu,v=0}^{3} C_{\mu v} \sum_{\mu',v'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\Xi}_{vv'} a^{\Lambda}_{\mu'0} a^{\bar{\Lambda}}_{v'0}$$



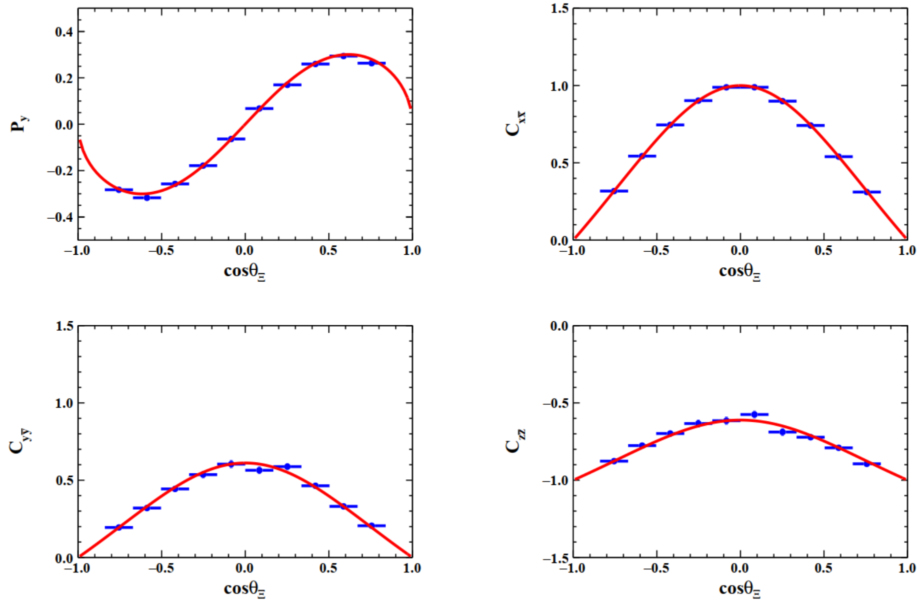
- Spin density matrix ($J/\psi \to \Xi^-\bar{\Xi}^+$):

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

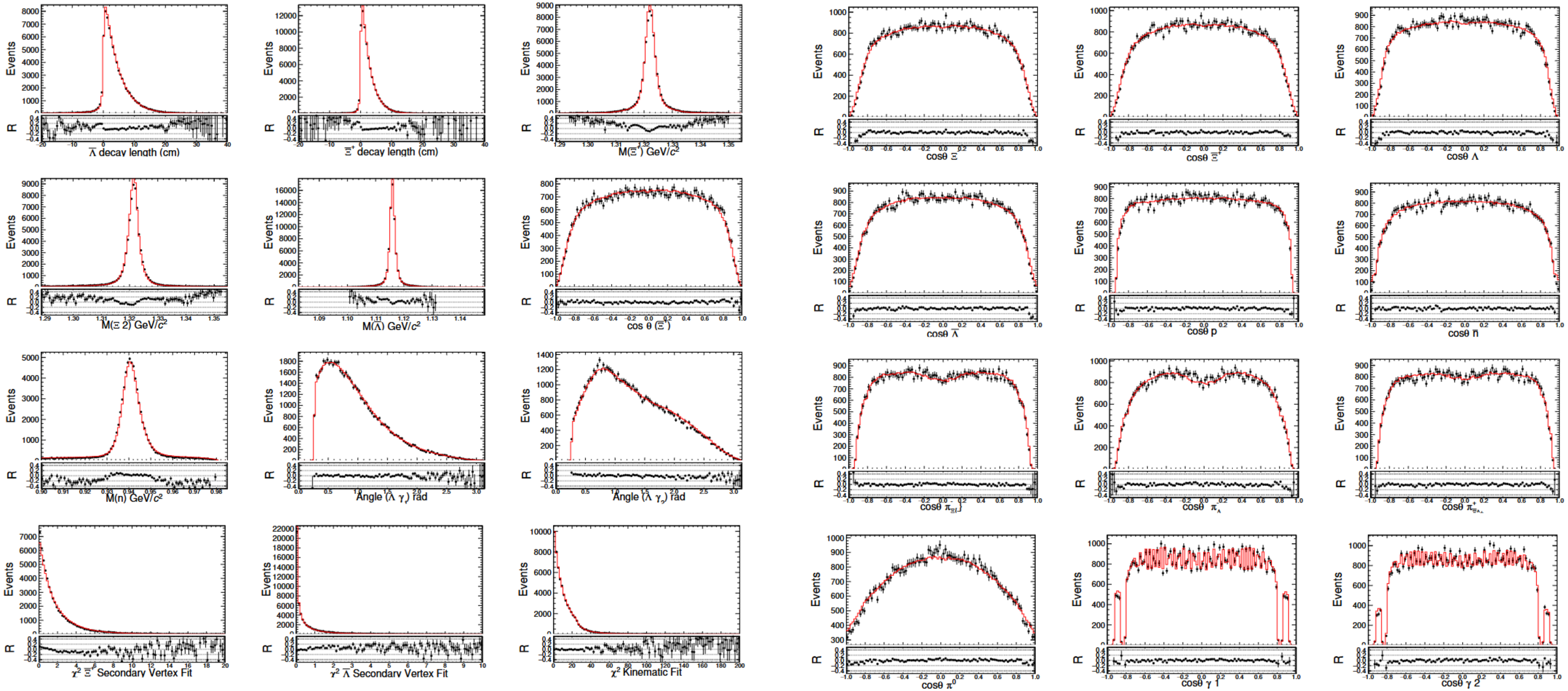
$$\beta_\psi = \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi) \quad \gamma_\psi = \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)$$

- For $\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$decay ($\Xi^- \to \Lambda\pi^-$):

$$a_h^{\Xi} = \begin{pmatrix} 1 & 0 & 0 & \alpha \\ \alpha\cos\phi\sin\theta & \gamma\cos\theta\cos\phi - \beta\sin\phi & -\beta\cos\theta\cos\phi - \gamma\sin\phi & \sin\theta\cos\phi \\ \alpha\sin\theta\sin\phi & \beta\cos\phi + \gamma\cos\theta\sin\phi & \gamma\cos\phi - \beta\cos\theta\sin\phi & \sin\theta\sin\phi \\ \alpha\cos\theta & -\gamma\sin\theta & \beta\sin\theta & \cos\theta \end{pmatrix}$$



A joint angular analysis of $J/\psi \to \Xi^-\bar{\Xi}^+$



The fit yields 143973$\pm$414 signal events and a purity of 91.2%.
Good consistence between data and simulation

A joint angular analysis of $J/\psi \to \Xi^- \bar{\Xi}^+$

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- **Production parameters** are consistent with previous results, verifying the polarization and spin correlation.
- Precision of $\boldsymbol{\alpha_0}$ **and** $\boldsymbol{\bar{\alpha}_0}$ are improved by factor of 4 and 1.7.
- **Strong and weak-phase** difference are measured.

$$(\delta_P - \delta_S)_{\mathrm{SM}} = (1.9 \pm 4.9) \times 10^2 \ \mathrm{rad}$$

$$(\xi_P - \xi_S)_{\mathrm{SM}} = (1.8 \pm 1.5) \times 10^4 \ \mathrm{rad}$$

$$(\delta_P - \delta_S)_{\mathrm{HyperCP}} = (10.2 \pm 3.9) \times 10^2 \ \mathrm{rad}$$

- **Four CP observables** are constructed from decay parameters.

Parameters	This work	Previous result
$\alpha_{J/\psi}$	$0.611 \pm 0.007^{+0.013}_{-0.007}$	$0.586 \pm 0.012 \pm 0.010$
$\Delta\Phi_{J/\psi}$ (rad)	$1.30 \pm 0.03^{+0.02}_{-0.03}$	$1.213 \pm 0.046 \pm 0.016$
α_Ξ	$-0.367 \pm 0.004^{+0.003}_{-0.004}$	$-0.376 \pm 0.007 \pm 0.003$
ϕ_Ξ (rad)	$-0.016 \pm 0.012^{+0.004}_{-0.008}$	$0.011 \pm 0.019 \pm 0.009$
$\bar{\alpha}_\Xi$	$0.374 \pm 0.004^{+0.002}_{-0.004}$	$0.371 \pm 0.007 \pm 0.002$
$\bar{\phi}_\Xi$ (rad)	$0.010 \pm 0.012^{+0.002}_{-0.013}$	$-0.021 \pm 0.019 \pm 0.007$
$\alpha_{\Lambda-}$	$0.764 \pm 0.008^{+0.005}_{-0.006}$	$0.7519 \pm 0.0036 \pm 0.0024$
$\alpha_{\Lambda+}$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$	$-0.7559 \pm 0.0036 \pm 0.0030$
$\alpha_{\Lambda 0}$	$0.670 \pm 0.009^{+0.009}_{-0.008}$	0.75 ± 0.05
$\bar{\alpha}_{\Lambda 0}$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$	$-0.692 \pm 0.016 \pm 0.006$
$\delta_P - \delta_S$ (rad)	$0.033 \pm 0.020^{+0.008}_{-0.012}$	$-0.040 \pm 0.033 \pm 0.017$
$\xi_P - \xi_S$ (rad)	$0.007 \pm 0.020^{+0.018}_{-0.005}$	$0.012 \pm 0.034 \pm 0.008$
A^Ξ_{CP}	$-0.009 \pm 0.008^{+0.007}_{-0.002}$	$0.006 \pm 0.013 \pm 0.006$
$\Delta\phi^\Xi_{\mathrm{CP}}$ (rad)	$-0.003 \pm 0.008^{+0.002}_{-0.007}$	$-0.005 \pm 0.014 \pm 0.003$
A^-_{CP}	$-0.007 \pm 0.008^{+0.002}_{-0.003}$	$-0.0025 \pm 0.0046 \pm 0.0012$
A^0_{CP}	$0.001 \pm 0.009^{+0.005}_{-0.007}$	-
A^Λ_{CP}	$-0.004 \pm 0.007^{+0.003}_{-0.004}$	-
$\alpha_{\Lambda 0}/\alpha_{\Lambda-}$	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07
$\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda+}$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$

Disparity in Λ decay that reveals ΔI =1/2 rule

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Test of CP violation

$$R\left(\cos\theta_p, \cos\theta_{\bar{p}}\right) = \frac{1 + \alpha_{\Lambda-}\alpha_{\Xi}\cos\theta_p}{1 + \alpha_{\Lambda+}\bar{\alpha}_{\Xi}\cos\theta_{\bar{p}}}$$

Test of $\Delta I = 1/2$ rule

$$R\left(\cos\theta_n, \cos\theta_p\right) = \frac{1 + \alpha_{\Lambda 0}\alpha_{\Xi}\cos\theta_n}{1 + \alpha_{\Lambda-}\alpha_{\Xi}\cos\theta_p}$$

The average of the ratio

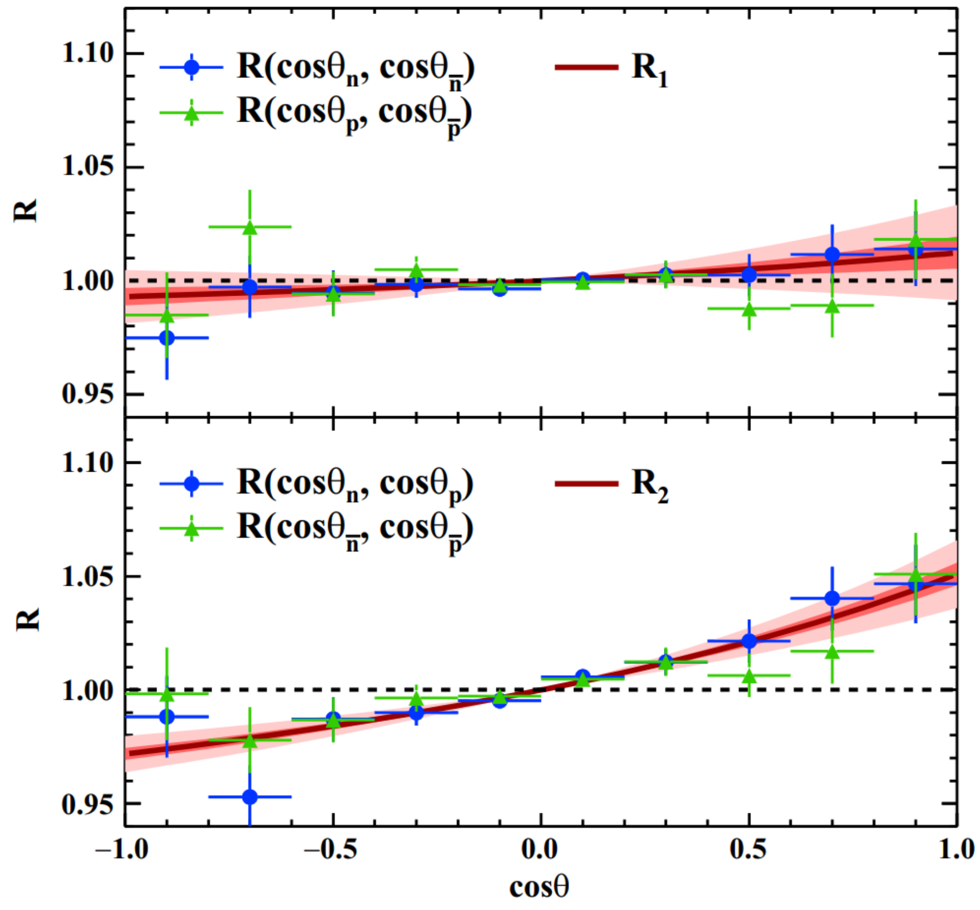
$$\langle\alpha_{\Lambda 0}\rangle / \langle\alpha_{\Lambda-}\rangle = 0.870 \pm 0.012^{+0.011}_{-0.010}$$

Consistent with kaon decay

$$S_1/S_3 = 28.4 \pm 1.3^{+1.1}_{-1.0} \pm 3.9$$

$$P_1/P_3 = -13.0 \pm 1.4^{+1.1}_{-1.2} \pm 0.7$$

Observed for the first time, different from S-wave



Weak Radiative Hyperon Decay

- The radiative decay was thought to be a simple reaction since it is free of final-state interaction.

- **Effective Lagrangian**

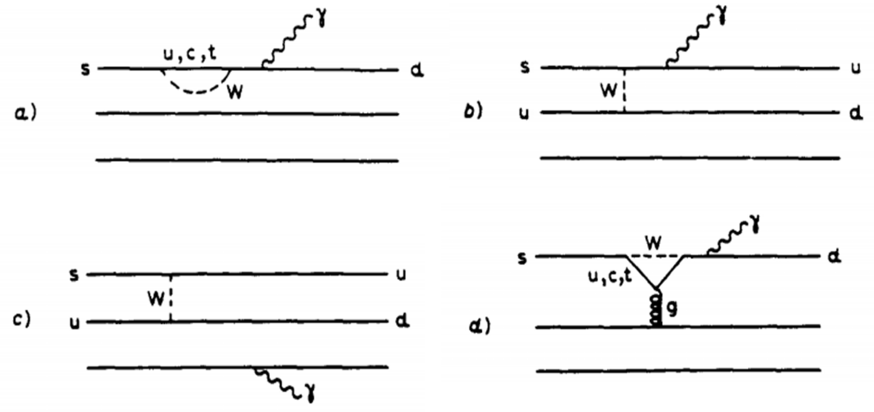
$$\mathcal{L} = \frac{eG_F}{2}\bar{B}_f\left(a^{\mathrm{PC}} + b^{\mathrm{PV}}\gamma_5\right)\sigma^{\mu\nu}B_i F_{\mu\nu}$$

- **Observables:**

$$\Gamma = \frac{e^2G_F^2}{\pi}\left(|a|^2 + |b|^2\right)\cdot\left|\vec{k}\right|^3,$$

$$\alpha_\gamma = \frac{2\mathrm{Re}(ab^*)}{|a|^2+|b|^2}$$

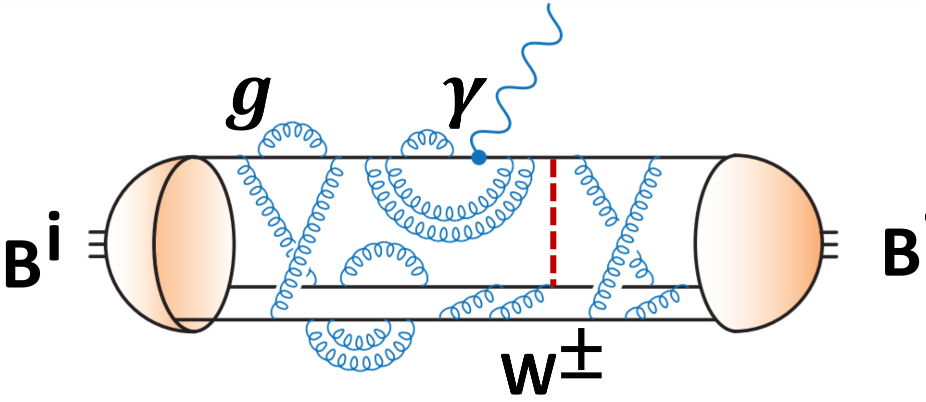
- **The “Hara theorem”:**
  - Focusing on **single quark transition operator for $s \to d\gamma$** while the remaining two quarks are assumed to be spectators.
  - The U-spin properties of the weak and EM Hamiltonian imply that the PV part of the radiative weak decay vanishes in **U-spin symmetry**
  - For a U-spin doublet such as p, Σ^+, or Σ^-, Ξ^-, Hara theorem requires the **PV amplitudes vanish**



Theoretical development for WRHD

- **Non-pQCD effect plays an essential role**, low energy effective theories needed

Decay modes	Data [19–21, 32, 33]	NRCQM [12]	LFQM [13]	EOMS χPT [14]
$\Lambda \to n\gamma$	$-0.16(10)(5)$	$-0.67(6)$	-0.25	$[-0.43,\ 0.15]$
$\Sigma^+ \to p\gamma$	$-0.652(56)(20)$	$-0.58(6)$	-0.1	$[-0.32, -0.27]$
$\Sigma^0 \to n\gamma$	$\cdots$	$0.37(4)$	-0.22	$[-0.70,\ 0.70]$
$\Xi^0 \to \Lambda\gamma$	$-0.741(62)(19)$	$0.72(11)$	0.23	$[-0.83, -0.59]$
$\Xi^0 \to \Sigma^0\gamma$	$-0.69(6)$	$0.33(4)$	-0.15	$[-0.74,\ -0.63]$
$\Xi^- \to \Sigma^-\gamma$	$1.0(13)$	$\cdots$	$\cdots$	$[-0.18,\ 0.38]$



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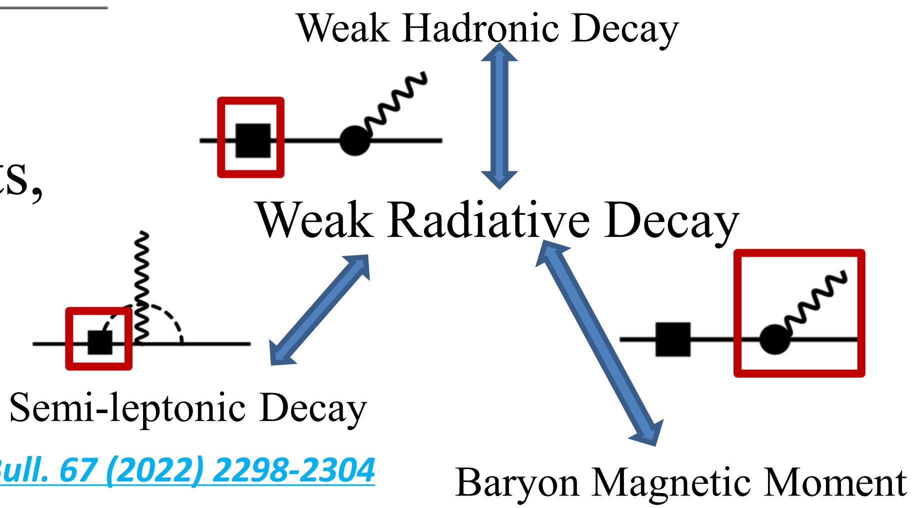
- The WRHD provide low-energy constants constraints, that will bring inputs for Semi-leptonic decay and weak hadronic decay



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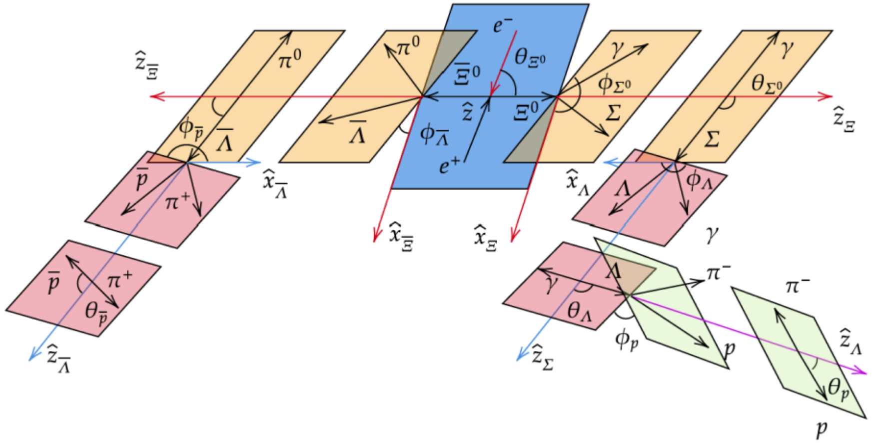
Joint angular analysis for WRHD at e⁺e⁻ collider

$$\mathcal{W} = \sum_{\mu,\,\nu=0}^{3} \sum_{\mu',\,\nu',\,\rho=0}^{3} C_{\mu\nu} b^{\Xi}_{\mu\mu'} a^{\bar{\Xi}}_{\nu\nu'} b^{\Sigma}_{\mu'\rho} a^{\bar{\Lambda}}_{\nu'0} a^{\Lambda}_{\rho 0}$$



For $J/\psi \to \Xi^0 \bar{\Xi}^-$

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

For $\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$ decay ($\Xi^0 \to \Lambda\pi^0$)

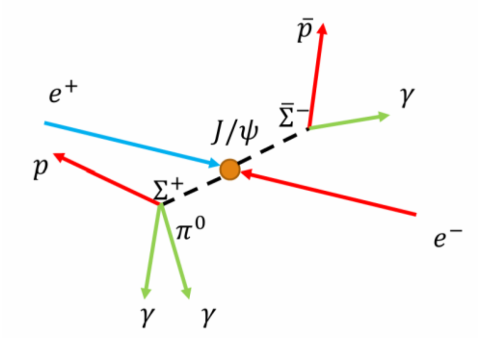
$$a_{\mu\mu'} = \begin{pmatrix} 1 & 0 & 0 & \alpha \\ \alpha\cos\phi\sin\theta & \gamma\cos\phi\cos\theta - \beta\sin\phi & -\beta\cos\phi\cos\theta - \gamma\sin\phi & \cos\phi\sin\theta \\ \alpha\sin\phi\sin\theta & \beta\cos\phi + \gamma\cos\theta\sin\phi & \gamma\cos\phi - \beta\cos\theta\sin\phi & \sin\phi\sin\theta \\ \alpha\cos\theta & -\gamma\sin\theta & \beta\sin\theta & \cos\theta \end{pmatrix}$$

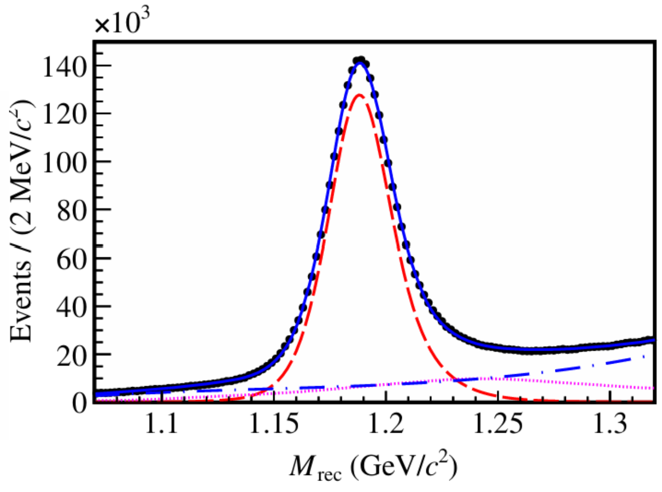
For $\frac{1}{2}^+ \to \frac{1}{2}^+ + 1^-$ decay ($\Xi^0 \to \Sigma^0\gamma$)

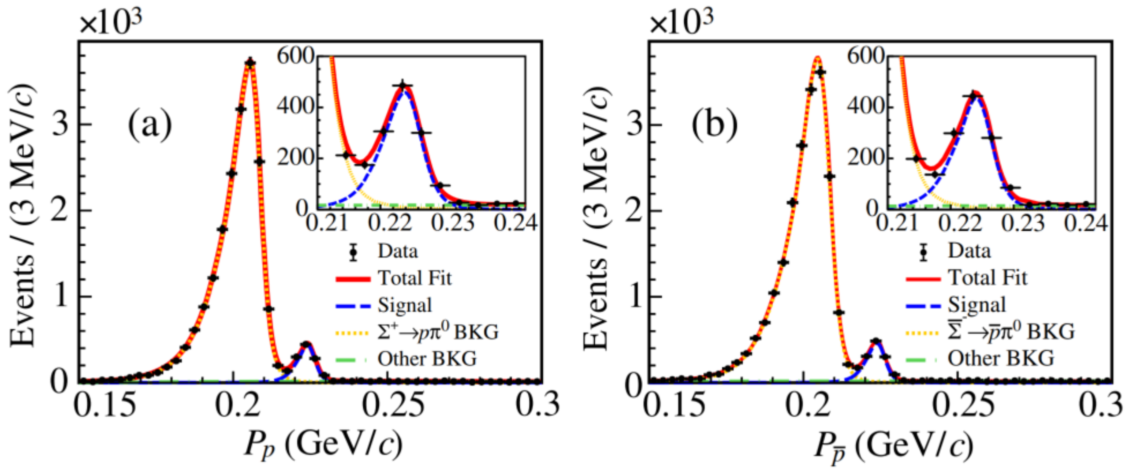
$$b_{\nu\nu'} = \begin{pmatrix} 1 & 0 & 0 & -\alpha \\ \alpha\cos\phi\sin\theta & 0 & 0 & -\cos\phi\sin\theta \\ \alpha\sin\theta\sin\phi & 0 & 0 & -\sin\theta\sin\phi \\ \alpha\cos\theta & 0 & 0 & -\cos\theta \end{pmatrix}$$

WRHD process $\Sigma^+ \to p\gamma$

PRL130, 211901 (2023)







Double-tag method:

$$N_{ST} = N_{J/\psi\to\Sigma^+\bar{\Sigma}^-} \times \mathcal{B}_{\bar{\Sigma}^-\to\bar{p}\pi^0} \times \varepsilon_{ST}$$

$$N_{DT} = N_{J/\psi\to\Sigma^+\bar{\Sigma}^-} \times \mathcal{B}_{\bar{\Sigma}^-\to\bar{p}\pi^0} \times \mathcal{B}_{\Sigma^+\to p\gamma} \times \varepsilon_{DT}$$

$$\mathcal{B}_{\Sigma^+\to p\gamma} = \frac{N_{DT}}{N_{ST}} \times \frac{\varepsilon_{ST}}{\varepsilon_{DT}}$$

Modes	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
ST Yield	$2\,177\,771 \pm 2285$	$2\,509\,380 \pm 2301$
ST Eff (%)	39.02	44.31
DT Eff (%)	21.16	23.20
Individual BF	$(1.007 \pm 0.032) \times 10^{-3}$	$(0.994 \pm 0.030) \times 10^{-3}$
Simultaneous BF	$(0.997 \pm 0.022) \times 10^{-3}$	

WRHD process $\Sigma^+ \to p\gamma$

$$\mathcal{L} = \prod_{i=1}^{N} \frac{\mathcal{W}_i(\xi, H)}{\mathcal{N}} \qquad \mathcal{N} = \frac{1}{N_{\mathrm{MC}}} \sum_{j=1}^{N_{\mathrm{MC}}} \mathcal{W}_i^{\mathrm{MC}}(\xi, H)$$

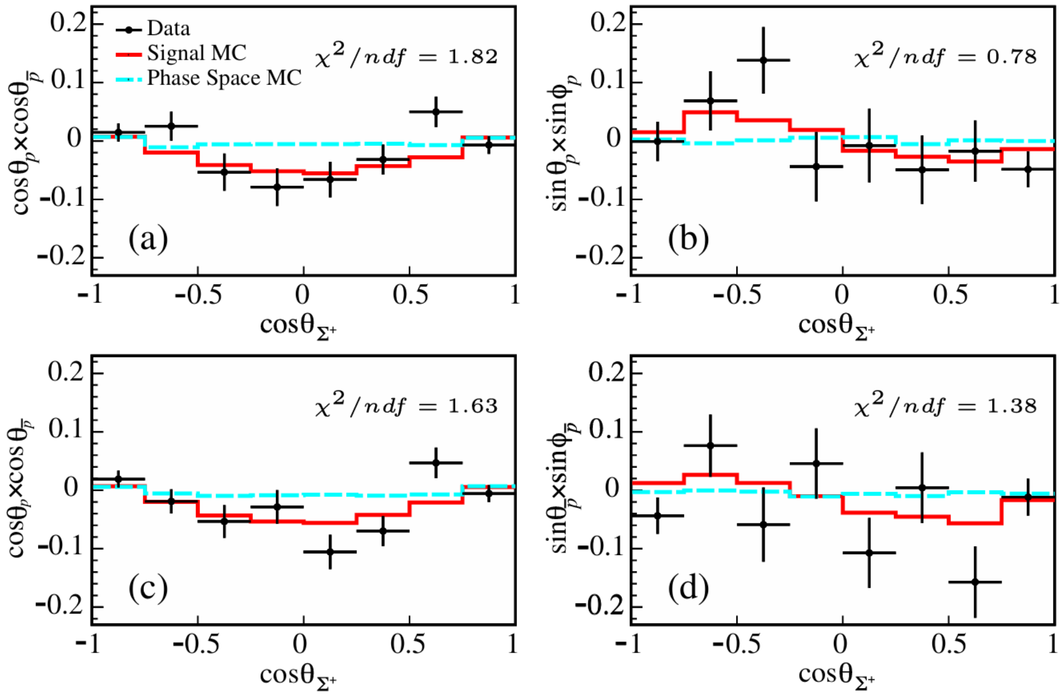
- $\mathcal{W}_i$: differential cross section
- $\mathcal{N}$: normalization factor based on PHSP MC
- $H = \left(\alpha_{J/\psi}, \Delta\Phi_\Psi, \alpha_{\Sigma^+\to p\gamma}, \alpha_{\bar{\Sigma}^-\to\bar{p}\pi^0}\right)$

$$M_1(\cos\theta_{\Sigma^+}) = \frac{m}{N}\sum_{i=1}^{N_k} \cos\theta^i_{\bar{p}} \cos\theta^i_p,$$

$$M_2(\cos\theta_{\Sigma^+}) = \frac{m}{N}\sum_{i=1}^{N_k} \sin\theta^i_p \sin\phi^i_p,$$

Parameter	value
α_ψ	-0.508 ± 0.006
$\Delta\Phi$	-0.270 ± 0.012
$\alpha_{\Sigma^+\to p\pi^0}$	-0.980 ± 0.017
$\alpha_{\Sigma^+\to p\gamma}$	**Iterated from this analysis**

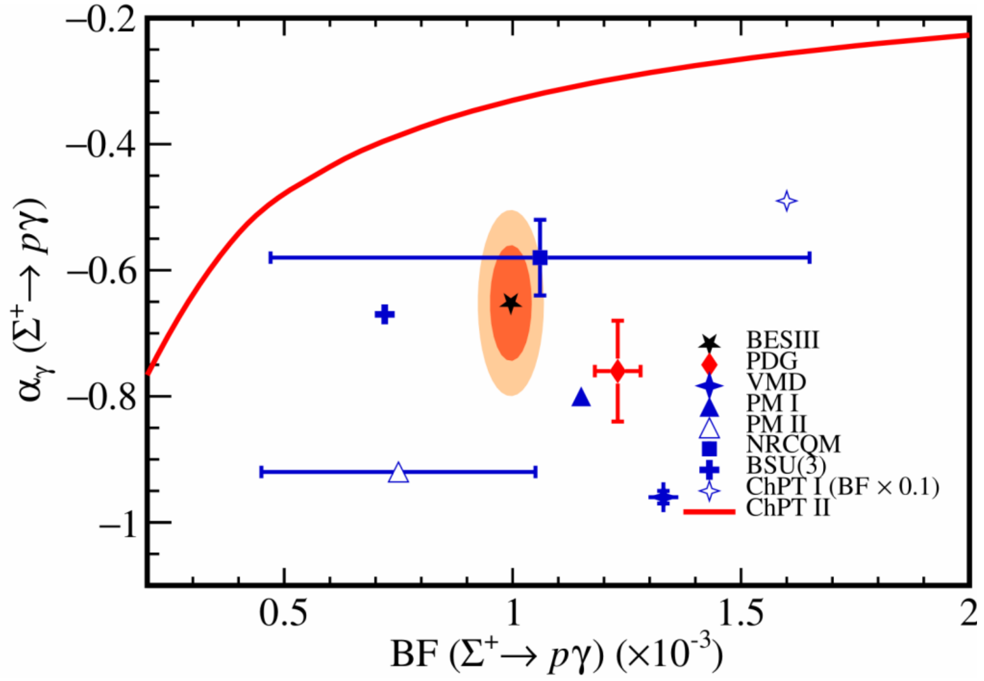
PRL130, 211901 (2023)



Processes	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
Individual fit	-0.587 ± 0.082	0.710 ± 0.076
Simultaneous fit	-0.651 ± 0.056	

WRHD process $\Sigma^+ \to p\gamma$

PRL130, 211901 (2023)



Mode	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
$N_{\mathrm{ST}}^{\mathrm{obs}}$	$2\,177\,771 \pm 2285$	$2\,509\,380 \pm 2301$
$\varepsilon_{\mathrm{ST}}$ (%)	39.00 ± 0.04	44.31 ± 0.04
$N_{\mathrm{DT}}^{\mathrm{obs}}$	1189 ± 38	1306 ± 39
$\varepsilon_{\mathrm{DT}}$ (%)	21.16 ± 0.03	23.20 ± 0.03
Individual BF (10^{-3})	1.005 ± 0.032	0.993 ± 0.030
Simultaneous BF (10^{-3})	$0.996 \pm 0.021 \pm 0.018$	
Individual α_γ	-0.587 ± 0.082	0.710 ± 0.076
Simultaneous α_γ	$-0.651 \pm 0.056 \pm 0.020$	

- The **accuracies** of the BF and α_γ are **improved by 78% and 34%**
- The measured BF is **lower than the world average value by 4.2σ**
- The accurate result will provide **input and constraints for ChPT**

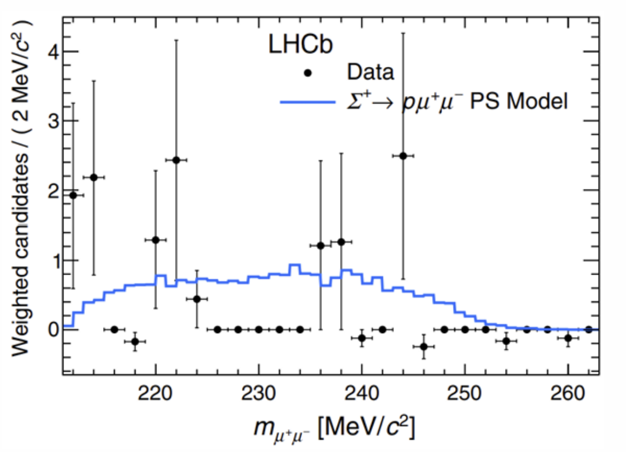
WRHD process $\Sigma^+ \to p\gamma$

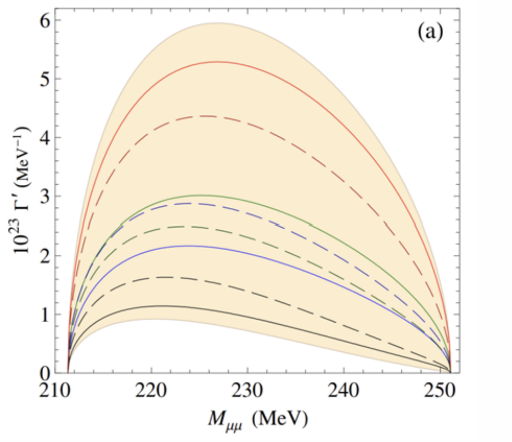
PRL130, 211901 (2023)

Input for new physics in $\Sigma^+ \to p l^+ l^-$

- Smoke screen of new physics in $\Sigma^+ \to p\mu^+\mu^-$ decay PRL94 (2005) 021801, PRL120 (2018) 22, 22180

- Experiment results of WRHDs provide SM expectations on such decays – narrowing the range for NP!





CP observables:

$$\Delta_{CP} = \frac{\mathcal{B}_+ - \mathcal{B}_-}{\mathcal{B}_+ + \mathcal{B}_-} = 0.006 \pm 0.011_{\text{stat.}} \pm 0.004_{\text{syst.}},$$

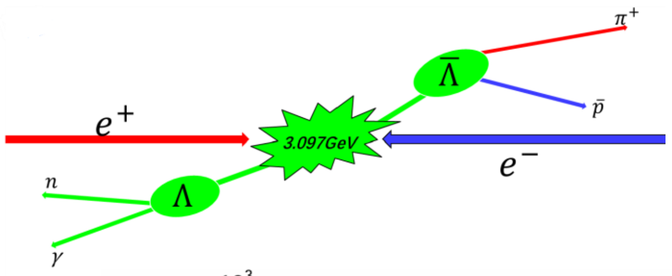
$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = 0.095 \pm 0.087_{\text{stat.}} \pm 0.018_{\text{syst.}}.$$

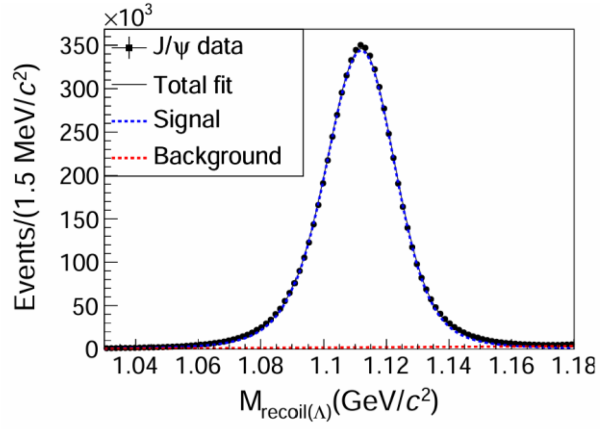
- May be significantly enhanced by NP up to $\mathcal{O}(10\ \%)$ (PRL109 (2012), 171801, JHEP 01 (2013) 027, JHEP 04 (2017) 027, JHEP 08 (2017) 09
- Extensive experimental studies on K, D and B meson radiative decays

SM on $\Sigma^+ \to p\gamma$	Δ_{CP}	A_{CP}
PhysRevD.51.2271	$10^{-5} - 10^{-4}$	
Commun. Theor. Phys. 19.475		$10^{-5} - 10^{-4}$
arxiv:2312.17568	2×10^{-5}	

WRHD process $\Lambda \to n\gamma$

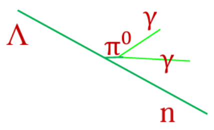
PRL 129, 212002 (2022)





- **Dominant background:**

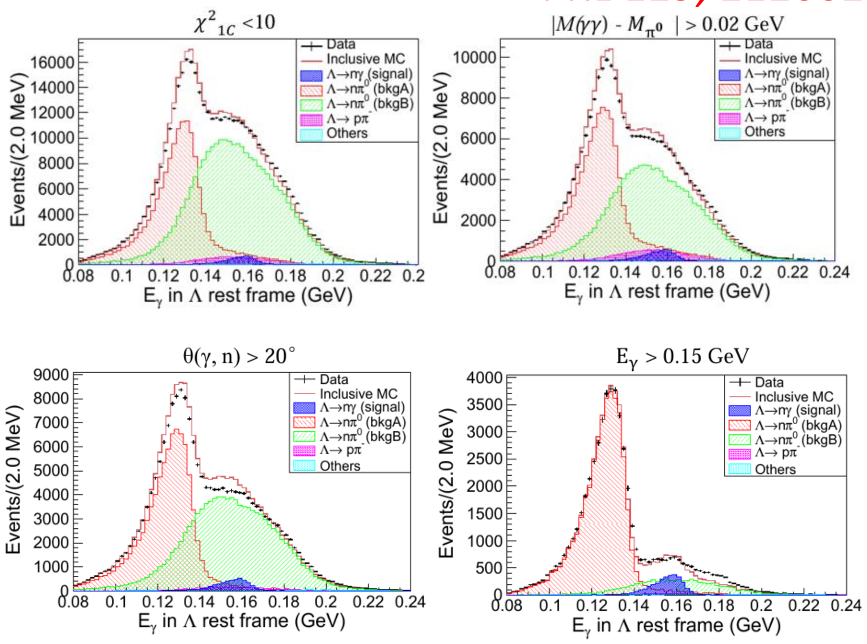
$\Lambda \to n\pi^0$



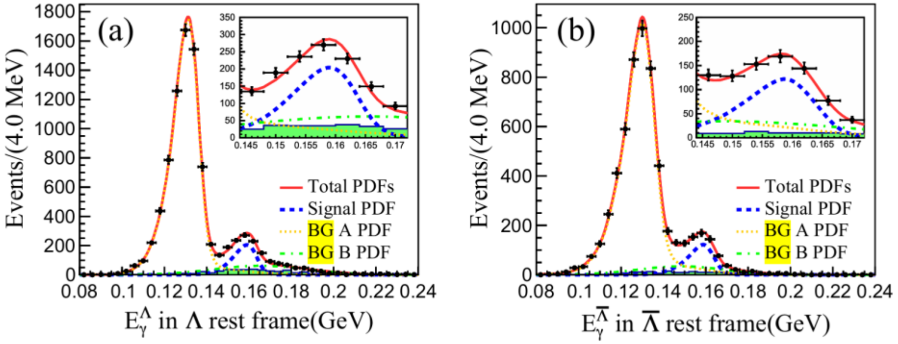
- **BKG A:** photon candidate is from π^0 decay.
- **BKG B:** photon candidate is not from π^0 decay.

- **Sources of noise photons:**
  - (Anti-)neutron-related secondary shower;
  - Mis-identification of photons and neutron showers;
  - Noise showers from beam-BKG.

Decay mode	$\Lambda \to n\gamma$	$\bar{\Lambda} \to \bar{n}\gamma$
$N_{\rm ST}$ $(\times 10^3)$	6853.2 ± 2.6	7036.2 ± 2.7
$\varepsilon_{\rm ST}$ (%)	51.13 ± 0.01	52.53 ± 0.01
$N_{\rm DT}$	723 ± 40	498 ± 41
$\varepsilon_{\rm DT}$ (%)	6.58 ± 0.04	4.32 ± 0.03
BF $(\times 10^{-3})$	$0.820 \pm 0.045 \pm 0.066$	$0.862 \pm 0.071 \pm 0.084$
	$0.832 \pm 0.038 \pm 0.054$	
α_γ	$-0.13 \pm 0.13 \pm 0.03$	$0.21 \pm 0.15 \pm 0.06$
	$-0.16 \pm 0.10 \pm 0.05$	



After further BDT selection



WRHD process $\Lambda \to n\gamma$

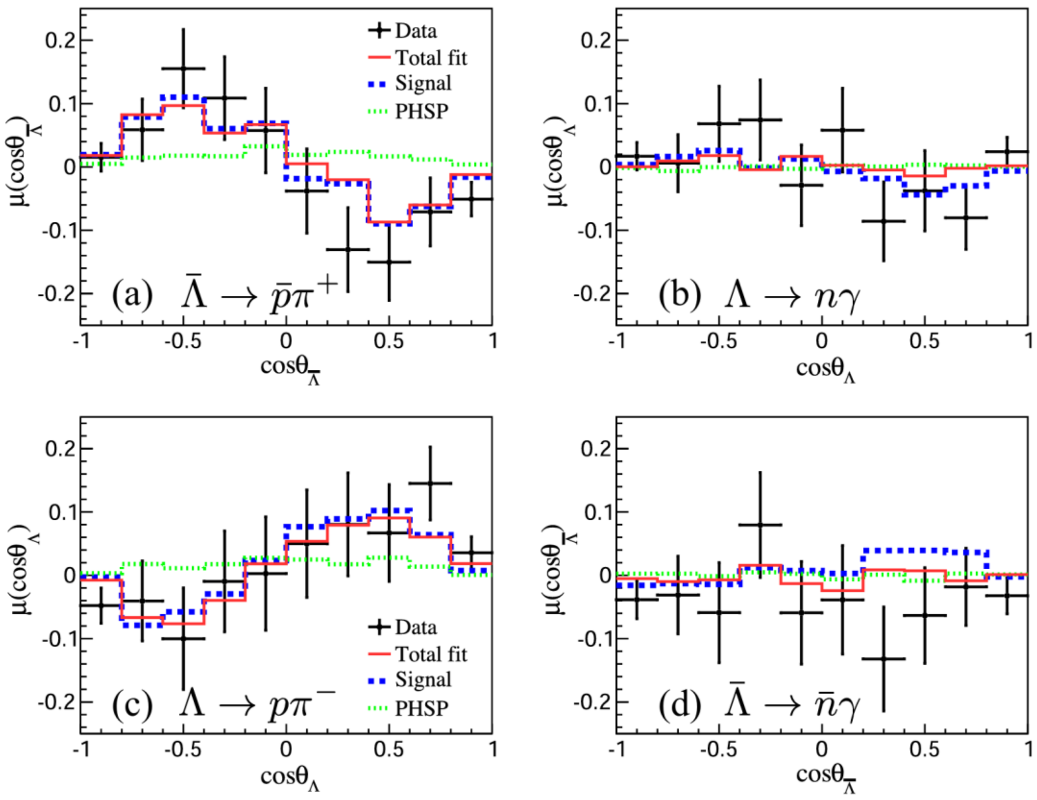
PRL 129, 212002 (2022)

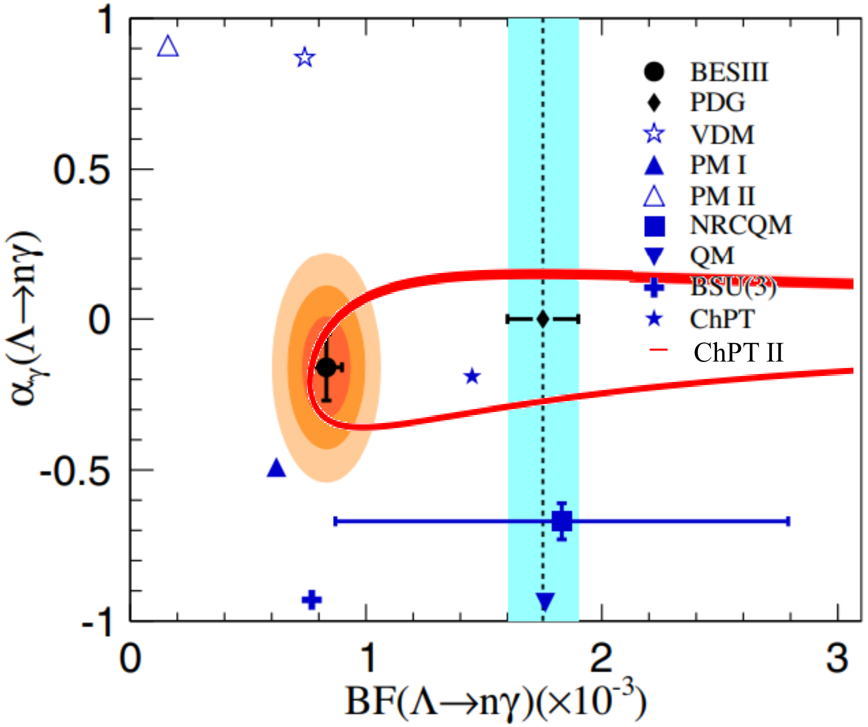
$$-\ln\mathcal{L}_{sig} = -\ln\mathcal{L}_{data} + \ln\mathcal{L}_{bkgA} + \ln\mathcal{L}_{bkgB}$$

- Contributions of BKG A / B should be subtracted .
- BKG A and BKG B contributions are estimated by DIY MC with same numbers in data

$$-\ln\mathcal{L} = -\sum_{i=1}^{i=N} \ln\frac{\omega(\xi,\alpha_\gamma)}{\mathcal{S}}$$

α_ψ (J/ψ decay parameter) = 0.461, $\Delta\Phi$ (helicity phase) = 0.74, $\alpha_1(\Lambda \to p\pi^-)$ = 0.75 , α_γ ($\bar{\Lambda}\to\gamma\bar{n}$)= ?

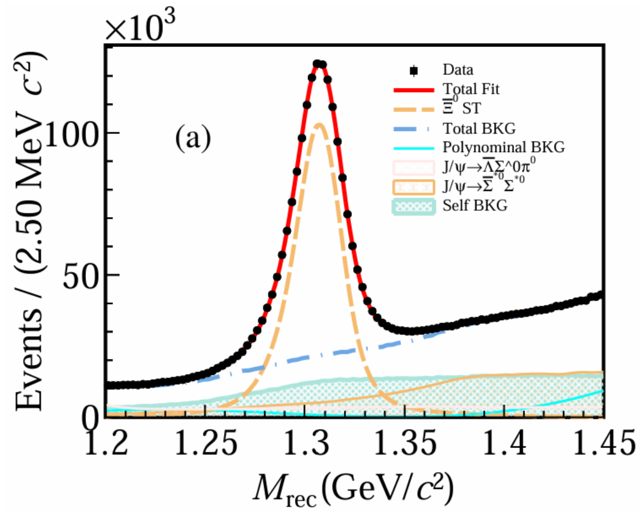


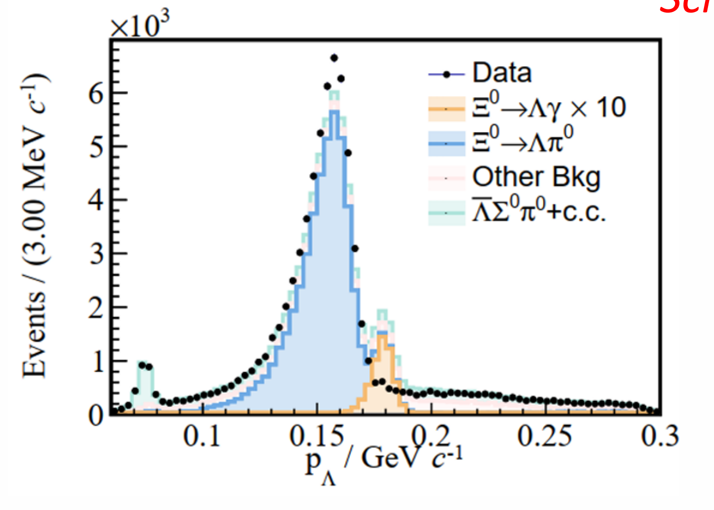


- **First** measurement on α_γ
- **5.6σ** deviation of BF from world average value

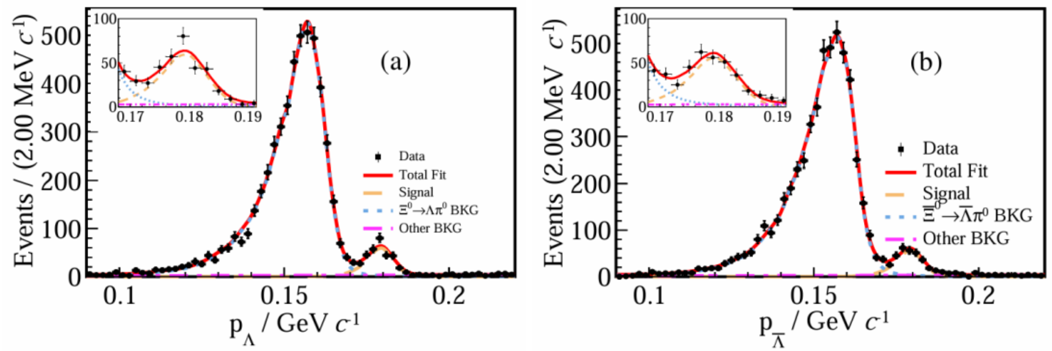
WRHD process $\Xi^0 \to \Lambda\gamma$

Sci.Bull. 70 (2025) 454-459



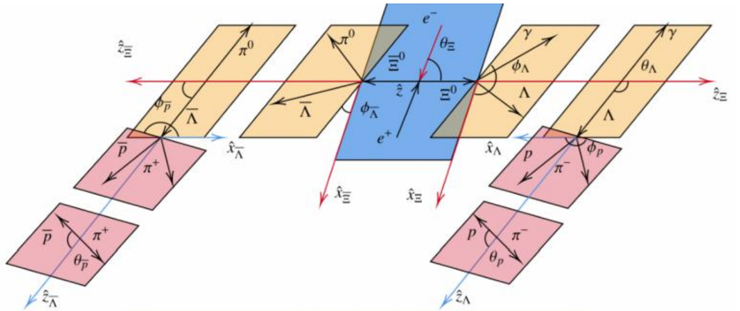


Modes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
ST Yield	1 400 541 ± 1989	1 611 216 ± 2111
ε_{ST} (%)	17.61 ± 0.01	19.77 ± 0.01
ε_{DT} (%)	4.43 ± 0.02	4.77 ± 0.02
Individual BF	$(1.391 \pm 0.093) \times 10^{-3}$	$(1.344 \pm 0.099) \times 10^{-3}$
Simultaneous BF	$(1.379 \pm 0.068) \times 10^{-3}$	
Correction factor	1.032	1.014
Corrected individual BF	$(1.348 \pm 0.090) \times 10^{-3}$	$(1.326 \pm 0.098) \times 10^{-3}$
Corrected simultaneous BF	$(1.347 \pm 0.066) \times 10^{-3}$	



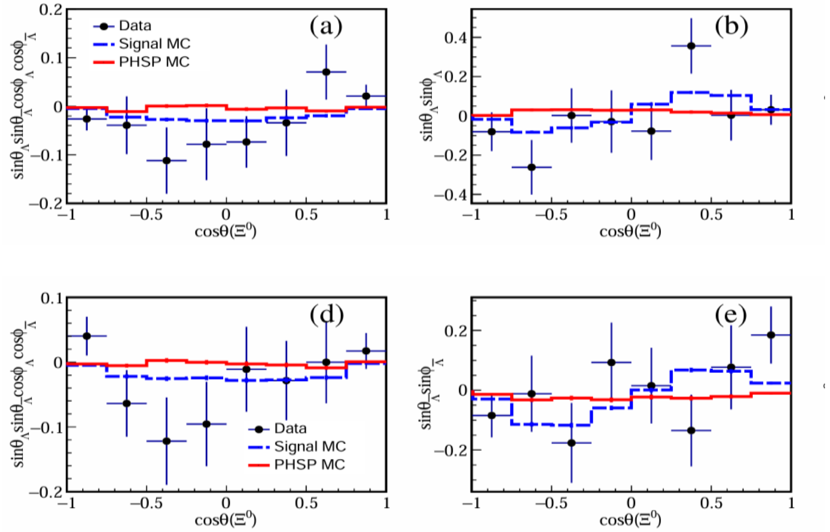
WRHD process $\Xi^0 \to \Lambda\gamma$

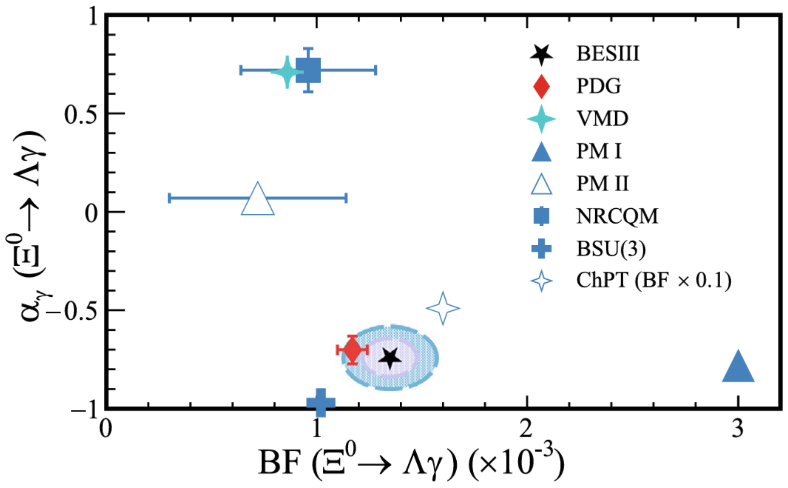
Sci.Bull. 70 (2025) 454-459

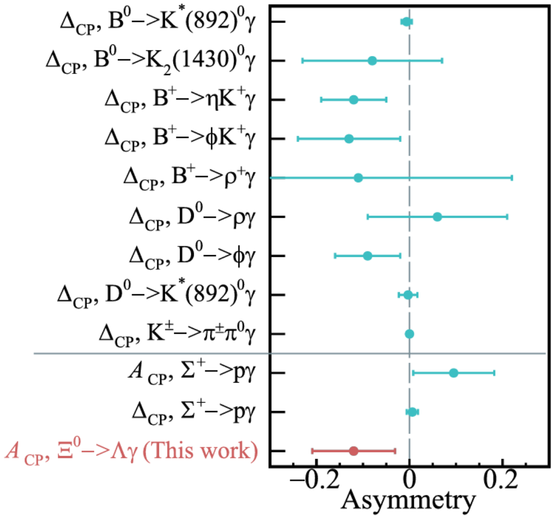


Helicity angles:
$\theta_\Xi, \theta_\Lambda, \phi_\Lambda, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}}$
Decay parameters:
$\alpha_{J/\psi}, \Delta\Phi_{J/\psi}, \alpha_\Xi, \Delta\Phi_\Xi, \alpha_{\bar{\Xi}}, \Delta\Phi_{\bar{\Xi}}, \alpha_\Lambda, \alpha_{\bar{\Lambda}}$

α_Ψ	0.514
$\Delta\Phi$	1.168
$\alpha_{\Xi^0\to\Lambda\gamma}$	this analysis
$\alpha_{\bar{\Xi}^0\to\bar{\Lambda}\gamma}$	this analysis
$\alpha_{\Xi^0\to\Lambda\pi^0}$	-0.375
$\Delta\Phi_{\Xi^0\to\Lambda\pi^0}$	0.005
$\alpha_{\bar{\Xi}^0\to\bar{\Lambda}\pi^0}$	0.379
$\Delta\Phi_{\bar{\Xi}^0\to\bar{\Lambda}\pi^0}$	-0.005
α_Λ	0.755
$\alpha_{\bar{\Lambda}}$	-0.745







Processes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Individual fit	-0.652 ± 0.092	0.830 ± 0.080
Simultaneous fit	-0.741 ± 0.062	

$$A_{CP} = \frac{\alpha_\gamma + \bar{\alpha}_\gamma}{\alpha_\gamma - \bar{\alpha}_\gamma} = -0.120 \pm 0.084_{\text{stat.}} \pm 0.029_{\text{syst.}}$$

HWRD at fix-target experiments

- Fixed target experiments govern the results in 1965-2010 (~23 papers from over 5 experiments)

$\Sigma^+ \to p\gamma$			
时间	实验名或实验方案	分支比（$\times 10^{-3}$）	α_γ
2023	BESIII	$0.996 \pm 0.021 \pm 0.018$	$-0.652 \pm 0.056 \pm 0.020$
1995	E761	1.20 ± 0.08	-
1992	SPEC	-	-0.720 ± 0.086
1989	CNTR	1.45 ± 0.31	-
1987	CNTR	1.23 ± 0.20	-
1985	CNTR	1.27 ± 0.18	-
1980	HBC	1.09 ± 0.20	-0.53 ± 0.36
1969	HBC	1.1 ± 0.2	-
1969	HBC	1.42 ± 0.26	-1.03 ± 0.52
1965	HBC	1.9 ± 0.4	-

$\Lambda \to n\gamma$			
时间	实验名或实验方案	分支比（$\times 10^{-3}$）	α_γ
2022	BESIII	$0.846 \pm 0.039 \pm 0.052$	$-0.160 \pm 0.101 \pm 0.046$
1994	E761	1.75 ± 0.15	-
1992	SPEC	1.78 ± 0.24	-

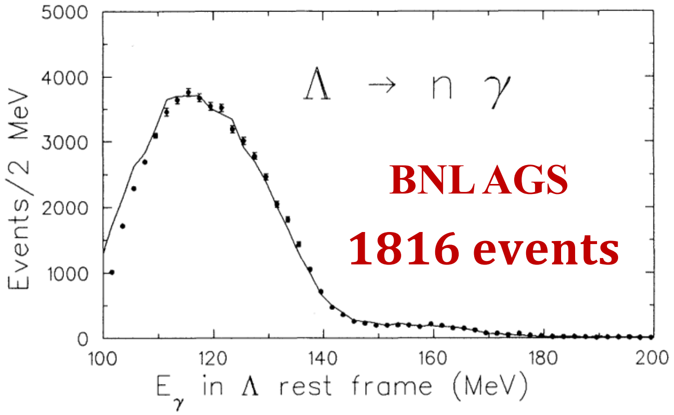
$\Xi^0 \to \Lambda\gamma$			
时间	实验名或实验方案	分支比（$\times 10^{-3}$）	α_γ
2010	NA48	-	-0.704 ± 0.064
2004	NA48	1.17 ± 0.09	-0.78 ± 0.18
2000	NA48	1.91 ± 0.34	-
1990	SPEC	1.06 ± 0.18	-0.43 ± 0.44

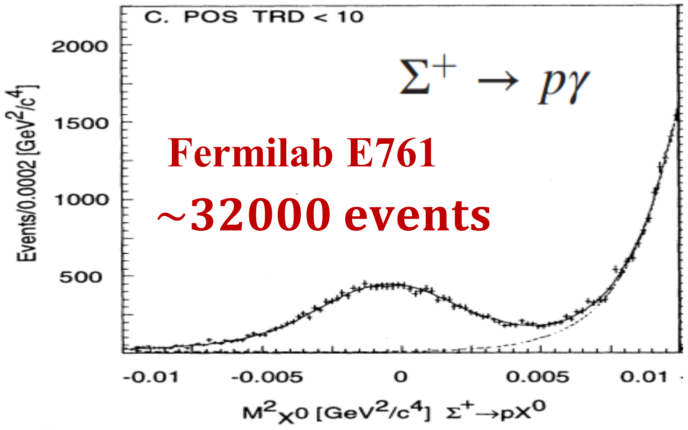
$\Xi^0 \to \Sigma^0\gamma$			
时间	实验名或实验方案	分支比（$\times 10^{-3}$）	α_γ
2010	NA48	-	-0.729 ± 0.076
2001	KTEV	3.34 ± 0.09	-0.63 ± 0.09
2000	NA48	3.16 ± 0.76	-
1989	SPEC	3.56 ± 0.42	0.20 ± 0.32

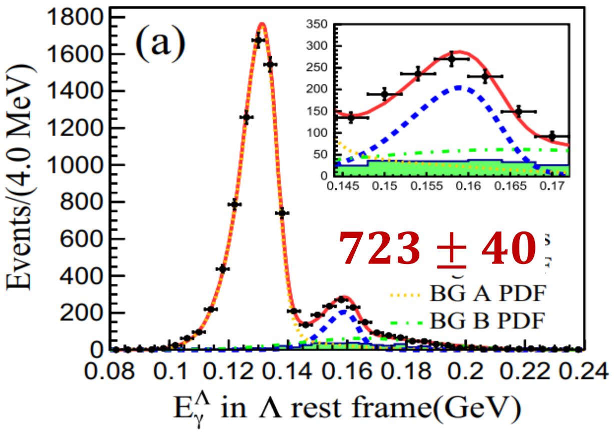
$\Xi^- \to \Sigma^-\gamma$			
时间	实验名或实验方案	分支比（$\times 10^{-3}$）	α_γ
1994	E761	0.122 ± 0.023	-
1987	SPEC	0.227 ± 0.102	-

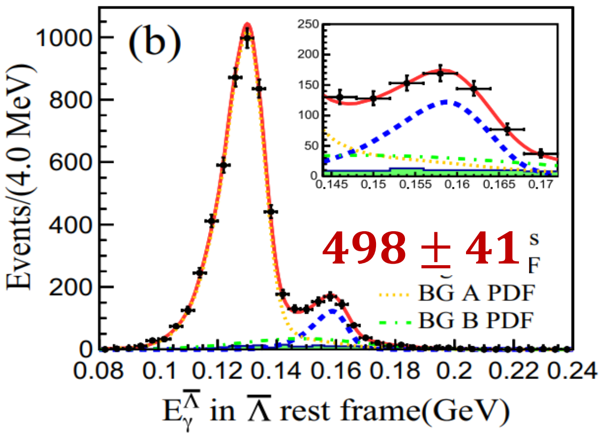
$\Omega^- \to \Xi^-\gamma$			
时间	实验名或实验方案	分支比（$\times 10^{-3}$）	α_γ
1994	E761	<0.46	-
1984	SPEC	<0.22	-
1979	SPEC	<0.31	-

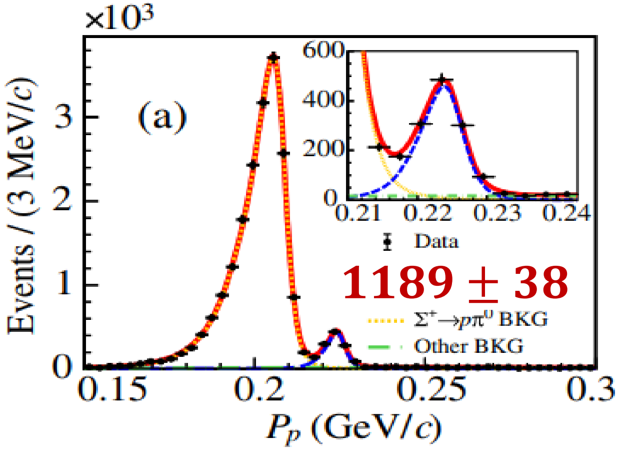
HWRD at fix-target and e^+e^- and Experiments

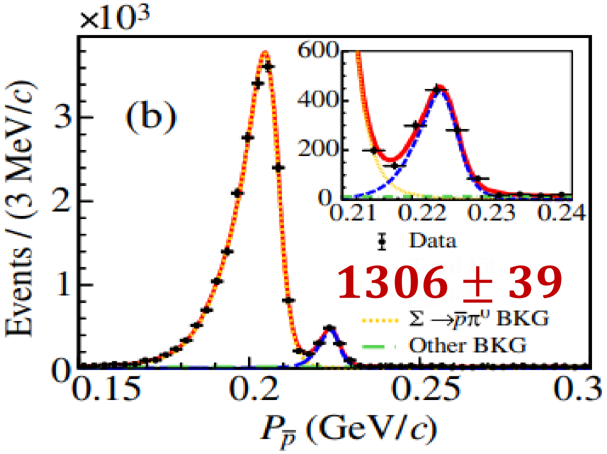












- Hyperons at e^+e^- : less statistics compare with large flux hyperon beam with polarization, but with better precision, charge-conjugate channels

The power of quantum correction and joint angular analysis

More BESIII results of HWRD are coming……

- Study of $\Xi^0 \to \gamma\Sigma^0$
- Study of $\Xi^- \to \gamma\Sigma^-$
- Study of $\Omega^- \to \gamma\Xi^-$
- Study of $\Sigma^0 \to \gamma n$
- Study of $\Sigma^+ \to pe^+e^-$
- Study of $\Sigma^0 \to \Lambda e^+e^-$
- …

Decay modes	Data [19–21, 32, 33]	NRCQM [12]	LFQM [13]	EOMS χPT [14]
$\Lambda \to n\gamma$	$-0.16(10)(5)$	$-0.67(6)$	-0.25	$[-0.43,\ 0.15]$
$\Sigma^+ \to p\gamma$	$-0.652(56)(20)$	$-0.58(6)$	-0.1	$[-0.32, -0.27]$
$\Sigma^0 \to n\gamma$	$\cdots$	$0.37(4)$	-0.22	$[-0.70,\ 0.70]$
$\Xi^0 \to \Lambda\gamma$	$-0.741(62)(19)$	$0.72(11)$	0.23	$[-0.83, -0.59]$
$\Xi^0 \to \Sigma^0\gamma$	$-0.69(6)$	$0.33(4)$	-0.15	$[-0.74,\ -0.63]$
$\Xi^- \to \Sigma^-\gamma$	$1.0(13)$	$\cdots$	$\cdots$	$[-0.18,\ 0.38]$

Chin.Phys.Lett. 42, 032401 (2025)

Summary

- In addition to the hyperon CP violation tests, BESIII also conducted extensive studies on **hyperon weak decays** providing inputs to **long-standing challenges at low q^2 region**, such as. ΔI=1/2 rule, S/P puzzle and Hara theorem.
- ChPT provides important interpretation to experimental results, offering a **unified framework** to understand the dynamics of hyperon weak decays.
- Further dedicated analyses and theoretical efforts are underway, which will continue to deepen the understanding of hyperon decays, and help provide better predication for **hyperon CP violation**.

谢谢