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

BESIII

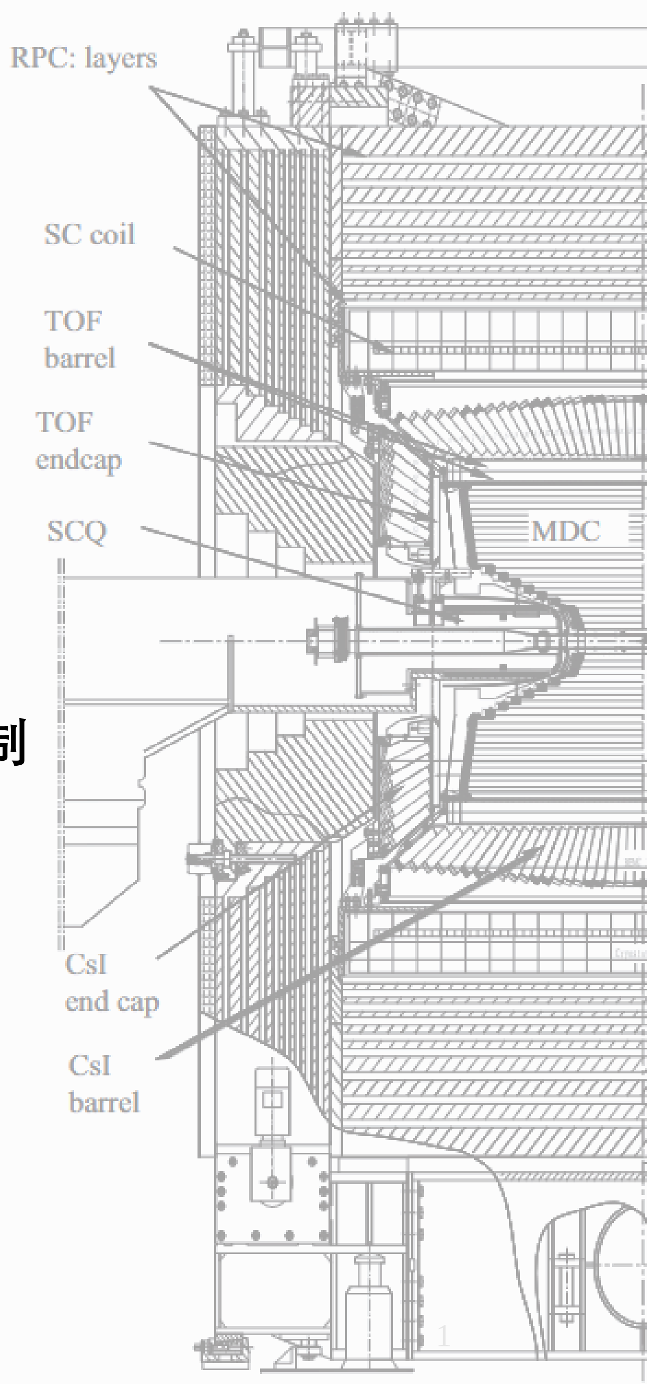
BESIII上超子衰变的实验研究

——探寻低能强相互作用的动力学机制

周小蓉

中国科学技术大学

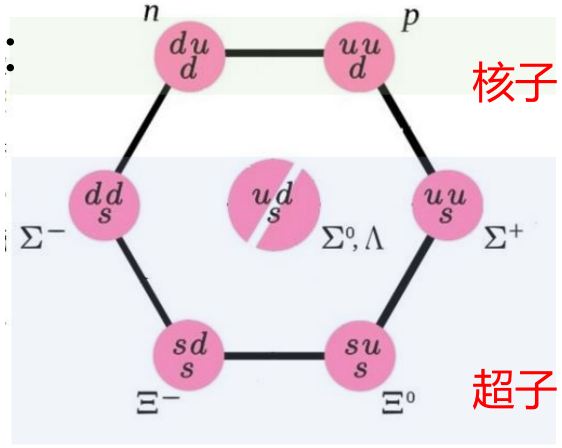
2026/4/9，味物理讲座



超子物理：检验标准模型与探索QCD非微扰特性

- 粒子物理学的基本理论——标准模型（1970s），描述物质的最基本组成和相互作用，成功解释了微观世界的各种实验现象。然而，由于描述强相互作用的量子色动力学QCD在低能区的非微扰特性，相关实验和理论面临中大挑战。

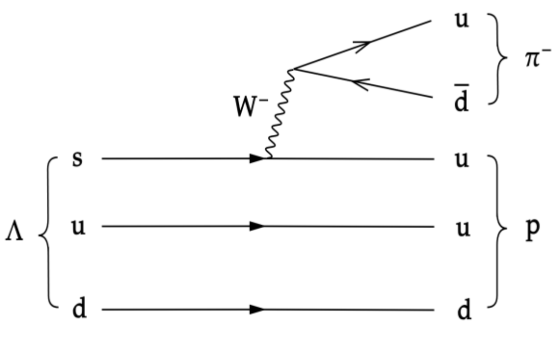
- 超子作为独特的“奇异探针”，在标准模型的建立中发挥重要作用：
  - ➢ 超子多重态检验夸克模型（1969，M. Gell-Mann）
  - ➢ 超子弱衰变中的不对称参数验证宇称不守恒（1957，杨振宁&李政道）
  - ➢ 超子半轻衰变首次提出夸克味混合，CKM矩阵的前身（2008，M. Kobayashi & T. Maskawa）



精确测量超子的衰变性质，不仅能够揭示其对称性信息，还能严格检验各类理论模型，为深入理解低能区QCD非微扰特性这一关键科学问题提供重要信息。

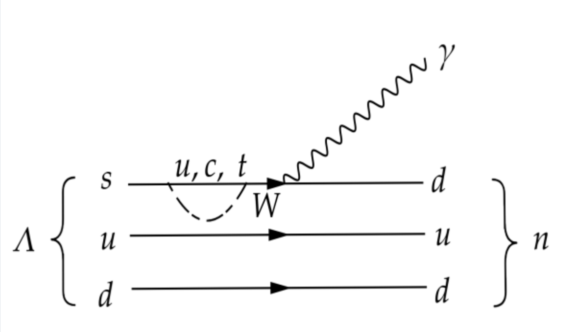
超子的衰变研究现状

超子的三类衰变模式



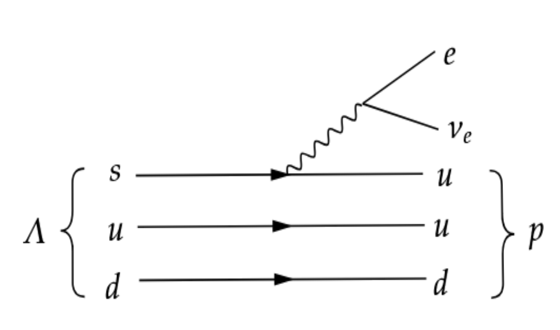
- **超子的强子末态弱衰变$\mathcal{O}(1)$**

  ➢ 超子衰变中同位旋振幅的ΔI=1/2规则
  ➢ 精确测量超子不对称参数（早期气泡室实验，HyperCP，CLAS实验)
  ➢ CP破坏观测量有限，尚未发现CP破坏



- **超子的弱辐射衰变$\mathcal{O}(10^{-3})$**

  ➢ 检验Hara定理及低能强相互作用模型
  ➢ 主要来自固定靶实验结果：质子打重靶（FNAL/CERN）、K打氢靶（BNL），分支比多为相对测量结果



- **超子的半轻衰变$\mathcal{O}(10^{-3})$**

  ➢ 理解Cabibbo角反常问题
  ➢ 提取形状因子，检验轻子普适性与新物理寻找

奇异强子衰变的$\Delta I = 1/2$规则

- $\Delta I = 1/2$ 规则：弱相互作用中同位旋改变1/2的振幅，比3/2振幅高一个数量级。
- 奇异介子$K \to \pi\pi$的S波衰变中首次发现并测量了振幅之比：

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

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

$$\frac{Re(A_2)}{Re(A_0)} \approx \frac{\sqrt{\mathcal{B}(K^+ \to \pi^+\pi^0)\tau_{K_S}}}{\sqrt{\mathcal{B}(K_S \to \pi^+\pi^-)\tau_{K^+}}} = \sqrt{\frac{0.21 \cdot 0.1ns}{0.69 \cdot 12ns}} = \frac{1}{22}$$

- K介子中直接CP破坏来源于$\Delta I = \frac{1}{2}$和$\Delta I = \frac{1}{2}$振幅的干涉项，与这一压低因子影响了K介子的直接CP破坏大小

$$\mathrm{Re}(\epsilon') = \frac{1}{3}Re\left(\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} - \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}\right) \approx (\xi_0 - \xi_2)\frac{A_2}{2A_0}$$

- 最新格点计算$\frac{Re(A_2)}{Re(A_0)} = 19.9 \pm 2.3 \pm 4.4$ (RBC-UKQCD)表明，QCD非微扰效应是$\Delta I = 1/2$规则的主要来源，新物理贡献不超过15%

超子的强子衰变和ΔI = 1/2规则

- 类似地，在超子的强子末态衰变中，同样也存在同位旋振幅分解，以$\Lambda \to p\pi^-$和 $\Lambda \to n\pi^0$为例：

$$S(\Lambda_-) = -\sqrt{\frac{2}{3}}S_{11}e^{i(\delta_{11}^S+\xi_1^S)} + \sqrt{\frac{1}{3}}S_{33}e^{i(\delta_{33}^S+\xi_3^S)},$$

$$S(\Lambda_0) = \sqrt{\frac{1}{3}}S_{11}e^{i(\delta_{11}^S+\xi_1^S)} + \sqrt{\frac{2}{3}}S_{33}e^{i(\delta_{33}^S+\xi_3^S}$$

$$P(\Lambda_-) = -\sqrt{\frac{2}{3}}P_{11}e^{i(\delta_{11}^P+\xi_1^P)} + \sqrt{\frac{1}{3}}P_{33}e^{i(\delta_{33}^P+\xi_3^P)},$$

$$P(\Lambda_0) = \sqrt{\frac{1}{3}}P_{11}e^{i(\delta_{11}^P+\xi_1^P)} + \sqrt{\frac{2}{3}}P_{33}e^{i(\delta_{33}^P+\xi_3^F}$$

δ_i 是强相位角，，ξ_i是弱相位角

- 超子的强子末态弱衰变可有以下三个实验观测量：

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

- 利用超子衰变的分宽度Γ和不对称参数α_Y可确定出 ΔI =1/2 和 ΔI =3/2 的振幅，若完全由ΔI =1/2振幅主导，则Λ的两个强子过程满足 $\frac{\alpha_0}{\alpha_-} = 1$， $\frac{\Gamma(\Lambda\to n\pi^0)}{\Gamma(\Lambda\to p\pi^-)} = 1/2$

超子的强子衰变和$\Delta I = 1/2$规则

- 超子衰变中不仅包括S波，还包含P波，$\Delta I = 1/2$规则是否在P波中存在，且在S波与K介子衰变是否一致，目前仍无实验定论
- 此外，$\Delta I = 1/2$规则的精确检验对超子衰变的CP破坏有重要影响

➢ 如果没有$\Delta I = 3/2$贡献，便不能通过衰变宽度构造CP破坏观测量

$$\Delta_{\rm CP} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = \frac{P_{1,1} P_{3,3} \sin\left(\xi^P_{1,1} - \xi^P_{3,3}\right) \sin\left(\delta^P_1 - \delta^P_3\right)}{P^2_{1,1} + S^2_{1,1}} + \frac{S_{1,1} S_{3,3} \sin\left(\xi^S_{1,1} - \xi^S_{3,3}\right) \sin\left(\delta^S_1 - \delta^S_3\right)}{P^2_{1,1} + S^2_{1,1}}$$

➢ 在$\Delta I = 3/2$很小的情况下，不对称参数构造的CP观测量与强弱相位角之间存在明确的关系。

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

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

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

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

超子ΔI = 1/2规则实验检验的早期里程碑

ASYMMETRY PARAMETER FOR $\Lambda^0 \to n\pi^0$ †*

S. Olsen, L. Pondrom, R. Handler, and P. Limon‡
University of Wisconsin, Madison, Wisconsin 53706

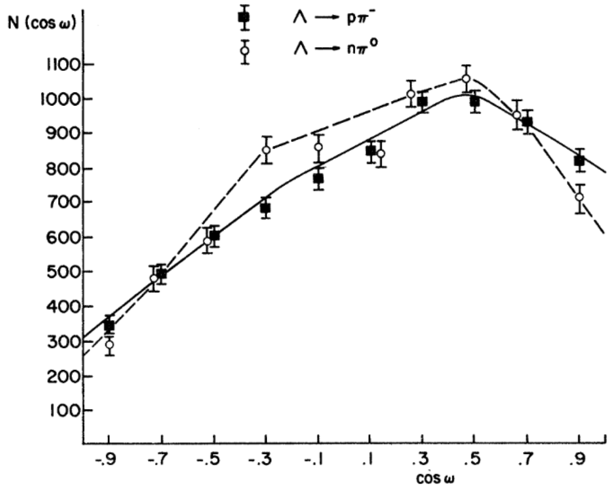
and

J. A. Smith and O. E. Overseth
University of Michigan, Ann Arbor, Michigan 48104
(Received 18 February 1970)

The asymmetry parameter α_0 for $\Lambda^0 \to n\pi^0$ has been measured relative to α_- by comparing the neutron distribution with the proton distribution from the decay $\Lambda^0 \to p\pi^-$ for polarized Λ^0 hyperons. A sample of 4760 neutron decay events and 8500 proton decay events gave $\alpha_0/\alpha_- = 1.000 \pm 0.068$ in good agreement with the $|\Delta \vec{I}| = \frac{1}{2}$ rule.

This Letter reports the result of a second experiment designed to test the validity of the $|\Delta \vec{I}| = \frac{1}{2}$ rule in the hadronic decays of hyperons. The first experiment was a measurement of proton polarization in $\Sigma^+ \to p\pi^0$.[1] Because the Λ^0 hyperon is an isospin singlet, the $|\Delta \vec{I}| = \frac{1}{2}$ rule leads to a very simple relation between the amplitudes for $\Lambda^0 \to p\pi^-$ and $\Lambda^0 \to n\pi^0$, namely, $S_- = -\sqrt{2}S_0$, $P_- = -\sqrt{2}P_0$; here S and P represent the amplitudes for orbital angular momentum 0 and 1, respec-

The Princeton-Pennsylvania Accelerator furnished a secondary positive beam at 1.0 GeV/c. The π^+ intensity in the beam was 10^5/sec with a ±1% momentum spread; the spot size at the final focus was 3.5 cm × 4.5 cm. The polarized Λ^0 hyperons were produced in liquid deuterium by the reaction $\pi^+ n(p) \to K^+\Lambda^0(p)$, where (p) represents the spectator proton. The K^+ mesons were detected electronically to select associated production events. The nucleons from Λ^0 decay were



$$\alpha_0/\alpha_- = 1.000 \pm 0.068.$$

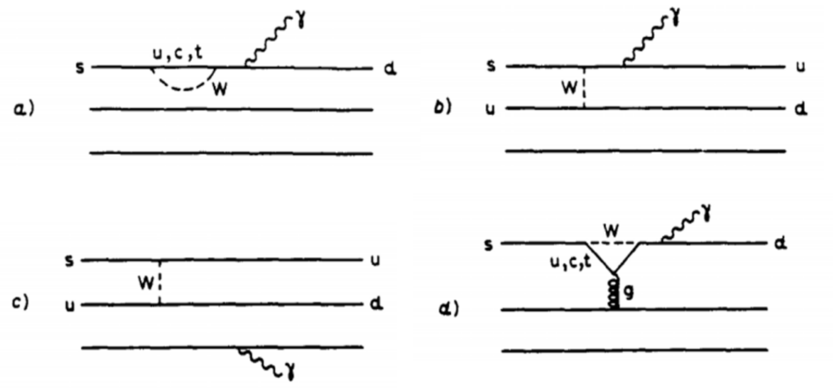
This result was combined with the results of Ref. 3 to give a weighted average

$$\alpha_0/\alpha_- = 1.006 \pm 0.066.$$

超子的弱辐射衰变和Hara定理

- 超子的弱辐射衰变包含强、弱、电磁三种相互作用。描述这一过程的有效拉格朗日量为：

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

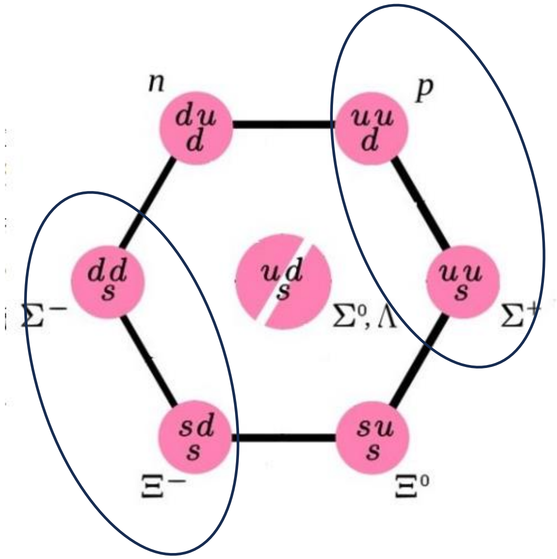


- 实验观测量： $\Gamma = \frac{e^2G_F^2}{\pi}\left(|a|^2 + |b|^2\right)\cdot\left|\vec{k}\right|^3$, $\alpha_\gamma = \frac{2\mathrm{Re}(ab^*)}{|a|^2+|b|^2}$

- **Hara定理（1964）：**
  - 考虑U-spin对称性和守恒矢量流，可以得出对于U-spin二重态，如p, Σ^+, or Σ^-, Ξ^-，其衰变的宇称破坏项为零

$$\alpha_\gamma(\Sigma^+ \to p\gamma) = \alpha_\gamma(\Xi^- \to \Sigma^-\gamma) = 0$$

  - 若考虑U-spin破缺，有 $\frac{b^{\mathrm{PV}}}{a^{\mathrm{PC}}} \sim \frac{m_s - m_d}{m_s + m_d} \sim 0.2$
  - 早期理论大多认为该过程由单夸克交换$\boldsymbol{s \to d\gamma}$主导



超子的弱辐射衰变理论预言

- 多个低能区有效理论对超子弱辐射进行描述，然而目前尚无统一模型描述所有过程

R. X. Shi et al., Chin.Phys.Lett. 42 (2025) 3, 032401

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	$[-0.74,\ -0.63]$
$\Xi^- \to \Sigma^-\gamma$	$1.0(13)$	$\cdots$	$\cdots$	$[-0.18,\ 0.38]$

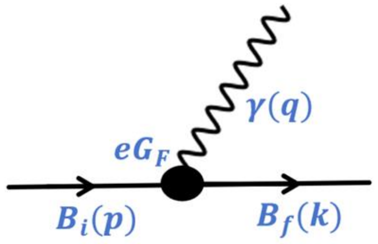
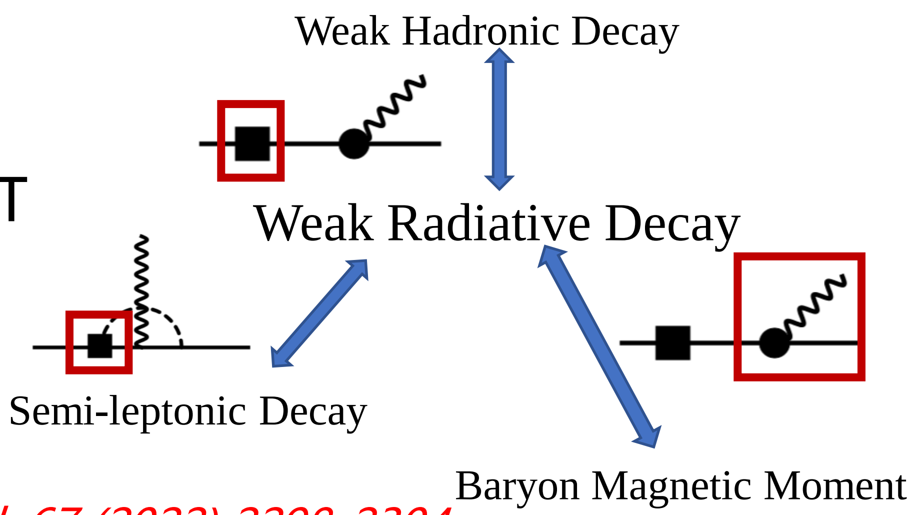


FIG. 2. The effective diagram for weak radiative hyperon $B_i \to B_f\gamma$ decays and $q = p - k$ in the figure.

- 此外，超子的弱辐射衰变也为低能有效理论，如ChPT等提供关键的低能常数约束，进而影响半轻子衰变和强子弱衰变的理论输入。



Sci.Bull. 67 (2022) 2298-2304

超子的弱辐射衰变实验研究： $\Sigma^+ \to p\gamma$

气泡室实验（60s）	…	KEK E-092实验（80s）	FNAL E761实验（90s）
$K^-p \to \Sigma^+\pi^-$	…	$\pi^+p \to K^+\Sigma^+$	$p + Cu \to \Sigma^+ + K^+ + X$
Σ^+极化率~87%	…	~40%	~12%，极化可偏转
31 events	…	190 events	32k events
$\mathcal{B} = (1.42 \pm 0.26) \times 10^{-3}$	…	$\mathcal{B} = (1.30 \pm 0.15) \times 10^{-3}$	$\mathcal{B} = (1.20 \pm 0.07) \times 10^{-3}$
$\alpha = -1.03^{+0.52}_{-0.42}$	…	$\alpha = -0.86 \pm 0.13$	$\alpha = -0.729 \pm 0.086$

E761, Phys. Rev. Lett. 68, 3004 (1992)

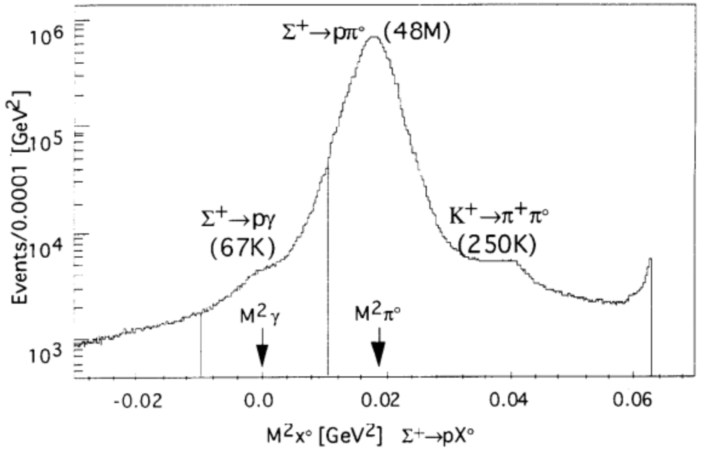


Fig. 5.4 Event distributions of the mass squared of the missing neutral particle (X°) for the hypothesis $\Sigma^+ \to pX^\circ$

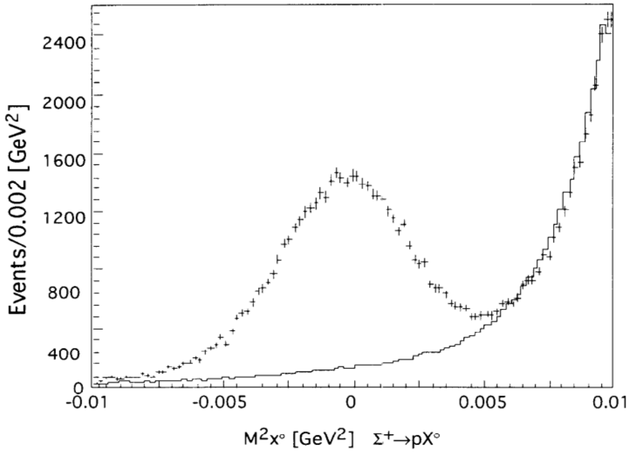
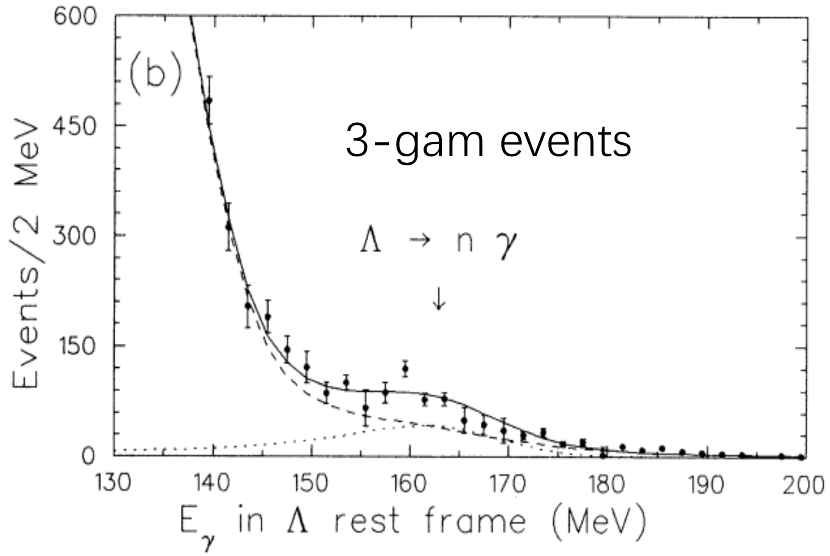


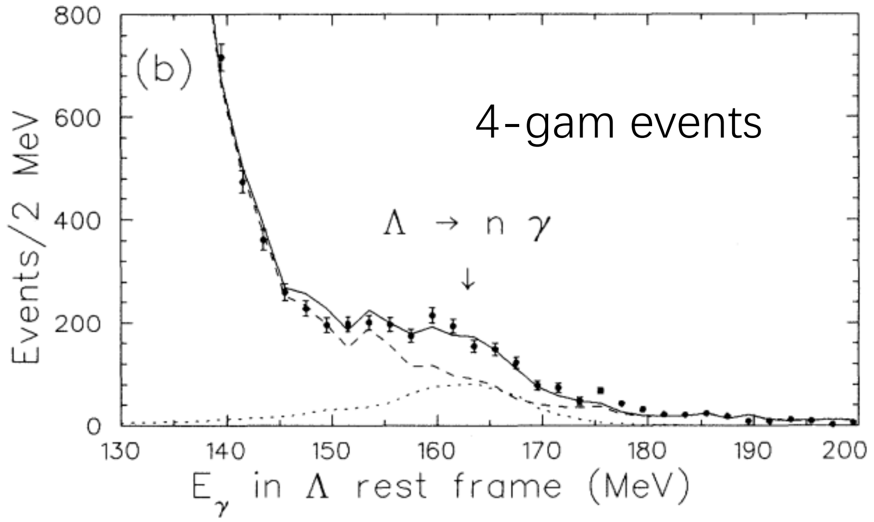
Fig. 5.5 Same as Fig. 5.4 after selection criteria are imposed. Note that one can estimate the background from the $\Sigma^+ \to pX^\circ$ peak.

超子的弱辐射衰变实验研究：$\Lambda \to n\gamma$

CERN SPS实验（80s）	BNL E811实验（90s）
$p + BeO \to \Xi^- + X$	$K^-p \to \Lambda\pi^0$，$K^-p \to \Sigma^0\pi^0$
24 events	1816 events
$\mathcal{B} = (1.02 \pm 0.33) \times 10^{-3}$	$\mathcal{B} = (1.75 \pm 0.15) \times 10^{-3}$

BNL E811 PRD47,799 (1993)

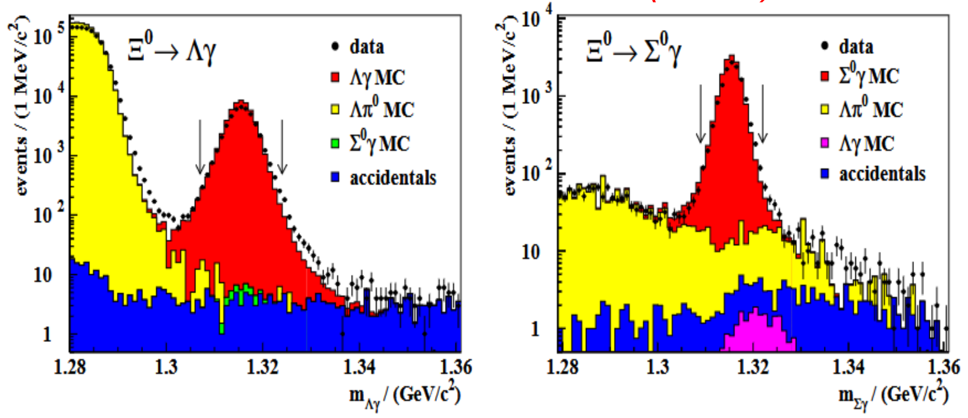


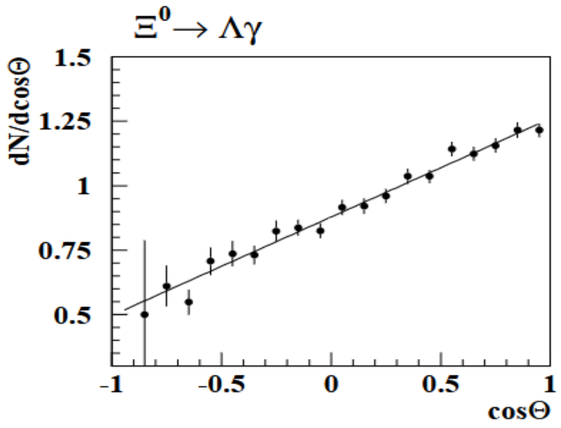


超子的弱辐射衰变实验研究：$\Xi^0 \to \Lambda\gamma$和$\Xi^0 \to \Sigma^0\gamma$

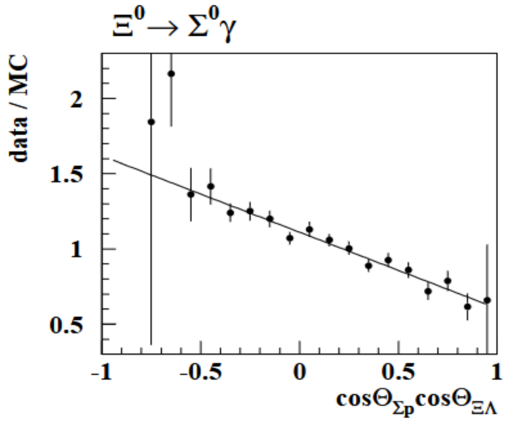
		FNAL E687实验（90s）	CERN /FNAL（00s）	CERN NA48 实验（10s）
		$p + Pb \to \Xi^0 + K^+ + X$	$p + Be \to \Xi^0 + X$	$p + Be \to \Xi^0 + X$
$\Xi^0 \to \Lambda\gamma$		116 events	672 events	52000
		$\mathcal{B} = (1.06 \pm 0.15) \times 10^{-3}$	$\mathcal{B} = (1.16 \pm 0.07) \times 10^{-3}$	
		$\alpha \cdot \alpha_\Lambda = 0.27 \pm 0.28$	$\alpha = -0.78 \pm 0.18$	$\alpha = -0.704 \pm 0.019 \pm 0.064$
$\Xi^0 \to \Sigma^0\gamma$		85 events	4045 events	15000
		$\mathcal{B} = (3.56 \pm 0.42) \times 10^{-3}$	$\mathcal{B} = (3.34 \pm 0.09) \times 10^{-3}$	
		$\alpha = 0.20 \pm 0.32$	$\alpha = -0.63 \pm 0.09$	$\alpha = -0.729 \pm 0.030 \pm 0.76$

NA48, PLB 693 (2010) 241-248





$1 - \alpha_{\Xi^0 \to \Lambda\gamma}\, \alpha_{\Lambda \to p\pi^-} \cos\Theta_\Lambda$



$1 + \alpha_{\Xi^0 \to \Sigma^0\gamma}\, \alpha_{\Lambda \to p\pi^-} \cos\Theta_{\Xi\Lambda} \cos\Theta_{\Sigma p}$

固定靶实验研究小结

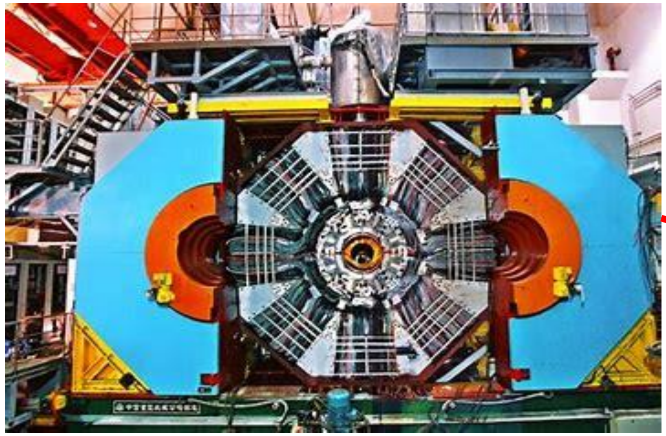
- 固定靶实验为超子衰变研究奠定了重要基础
  - ➢ 束流来源：早期使用π, K介子打氢/氘靶，后期发展了高能质子打重离子靶产生大样本超子束流
  - ➢ 超子种类：单个实验以一种超子为主，且主要产生正粒子
  - ➢ 统计量：能够获得数千或数万个弱辐射事例，不对称参数精度0.1
  - ➢ 极化情况：理论可计算，但由于各类效应，精度不高
  - ➢ 研究方法：通过1维角分布拟合获得不对称参数，稀有衰变如弱辐射过程依赖相对测量，无绝对测量，系统误差逐渐占主导
- BESIII作为正负电子对撞机实验，在超子的研究中有独特的优势，能够对超子的衰变开展精细的实验测量，在固定靶实验基础上取得新突破

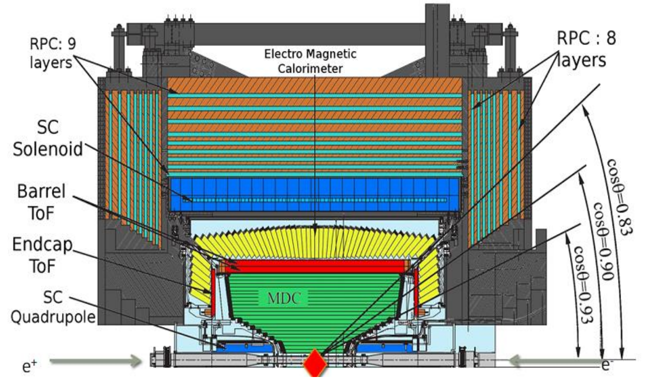
BESIII实验和超子研究优势

北京谱仪(BESIII)实验

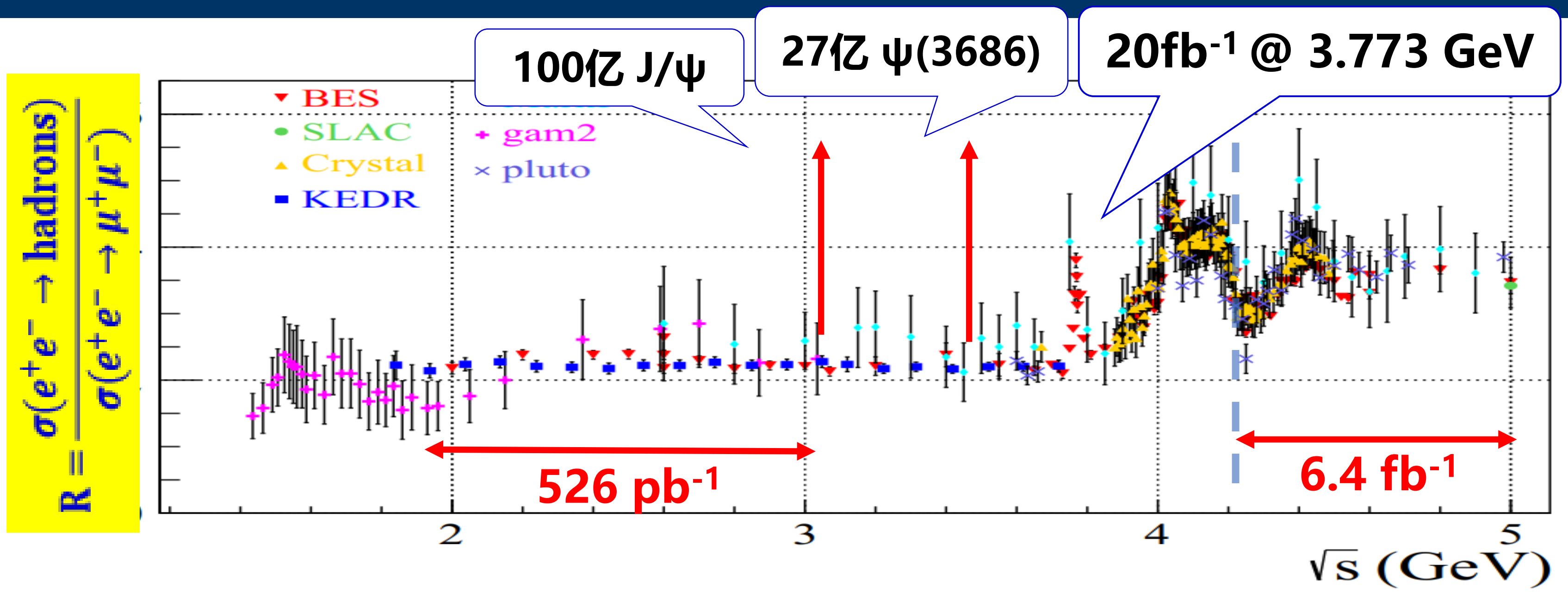
- 运行在北京正负电子对撞机(BEPCII)上，国际上唯一正在运行的陶粲装置
- 能区1.84 - 4.95 GeV，位于微扰和非微扰量子色动力学的过渡能区，是检验和发展强相互作用理论的重要场所

BESIII探测器





超子样本丰富、统计样本大



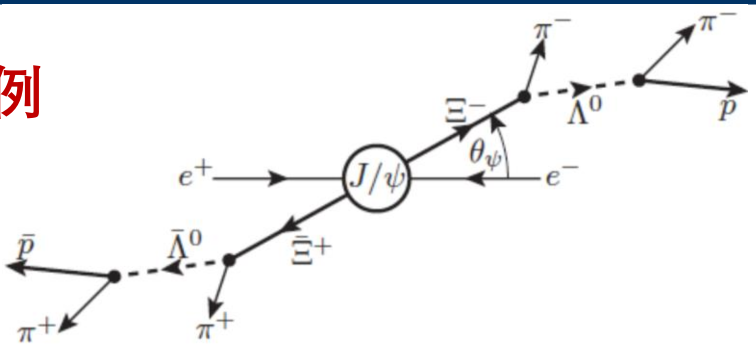
- 独特的扫描数据：覆盖各种超子-反超子对产生阈值
- 100亿J/ψ和27亿ψ(3686)：获得几百万Λ、Σ、Ξ超子样本用于衰变不对称参数研究和稀有衰变寻找

Decay mode	$\mathcal{B}(\times 10^{-3})$	$N_B\ (\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 0.5
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.10 ± 0.12	11.0 ± 1.2
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03

Decay mode	$\mathcal{B}(\times 10^{-4})$	$N_B\ (\times 10^6)$
$J/\psi \to pK^-\bar{\Lambda}$	8.9 ± 1.6	8.9 ± 1.6
$J/\psi \to \Lambda\bar{\Lambda}\pi^+\pi^-$	43 ± 10	43 ± 10
$J/\psi \to pK^-\bar{\Sigma}^0$	2.9 ± 0.8	2.9 ± 0.8
$J/\psi \to \Lambda\bar{\Sigma}^-\pi^+$ (or c.c.)	8.3 ± 0.7	8.3 ± 0.7
$J/\psi \to \Lambda\bar{\Sigma}^+\pi^{-*}$ (or c.c.)	8.3 ± 0.7	8.3 ± 0.7
$J/\psi \to pK^-\bar{\Sigma}(1385)^0$	5.1 ± 3.2	5.1 ± 3.2

超子的产生拓扑清晰，极化明确

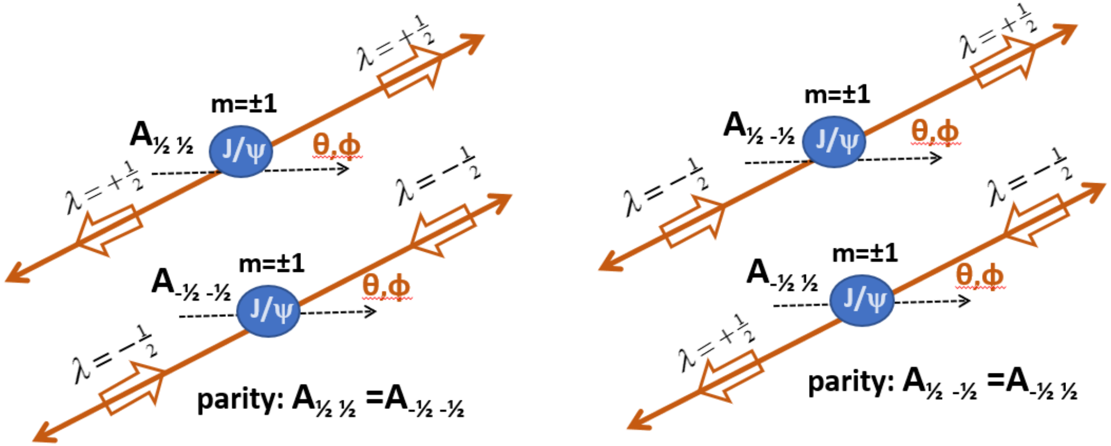
以 $e^+e^- \to J/\psi \to \Xi^-(\to \Lambda(\to p\pi^-)\pi^-)\bar{\Xi}^+(\to \bar{\Lambda}(\to \bar{p}\pi^+)\pi^+)$ 为例



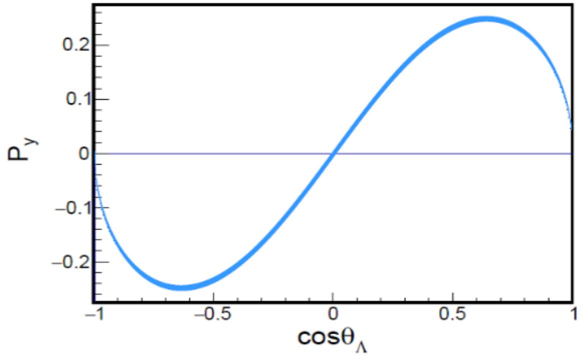
The first reaction: $J/\psi \to \Xi^-\bar{\Xi}^+$

- 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:

$$P_y = -\frac{\sqrt{1-\alpha^2}\sin\theta\cos\theta}{1+\alpha\cos^2\theta}\sin\ (\Delta\Phi).$$



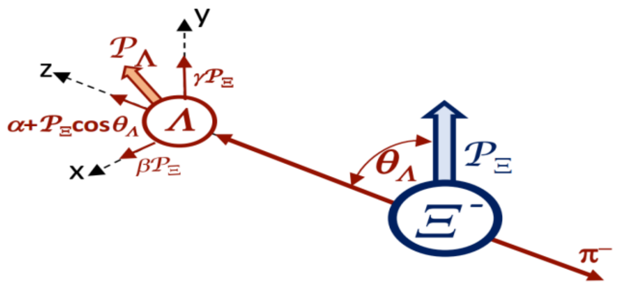
衰变道	α_ψ	$\Delta\Phi_\psi$	最大极化率（%）
$J/\psi \to \Lambda\bar{\Lambda}$	$0.475 \pm 0.002 \pm 0.003$	$0.752 \pm 0.004 \pm 0.007$	24.7
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	$-0.508 \pm 0.006 \pm 0.004$	$-0.270 \pm 0.012 \pm 0.009$	16.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	$0.586 \pm 0.012 \pm 0.010$	$1.213 \pm 0.046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



超子的产生拓扑清晰，极化明确

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

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

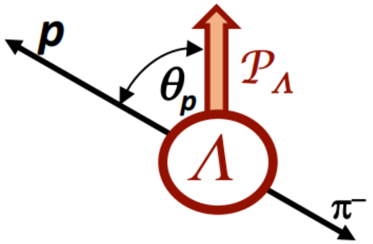


$$\mathbf{P}_\Lambda = \frac{(\alpha_\Xi + \mathcal{P}_\Xi \cos\theta_\Lambda)\hat{\mathbf{z}} + \mathcal{P}_\Xi \beta_\Xi \hat{\mathbf{x}} + \mathcal{P}_\Xi \gamma_\Xi \hat{\mathbf{y}}}{1 + \alpha_\Xi \mathcal{P}_\Xi \cos\theta_\Lambda}$$

- 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
- $\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma}$ are the Lee-Yang decay parameters of Ξ 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: $\frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda \mathcal{P}_\Lambda \cos\theta_p.$

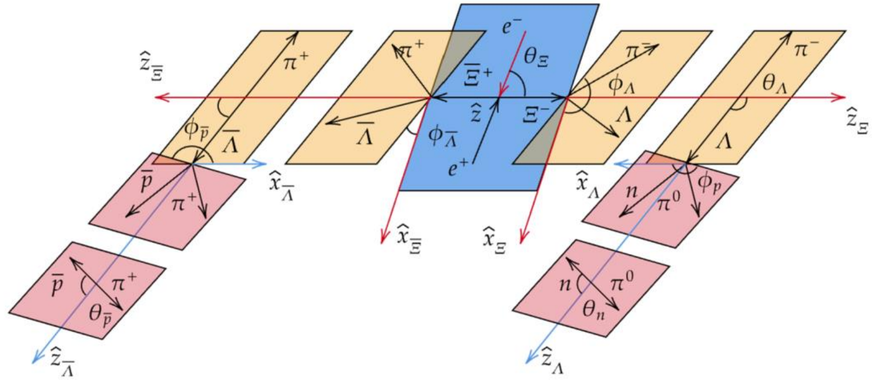


- The decay angle $\theta_p(\theta_{\bar{p}})$ relative to P_Λ direction
- Only **α of Λ can be determined** since proton polarization is not measured.

超子的自旋关联增强约束

以 $e^+e^- \to J/\psi \to \Xi^-(\to \Lambda(\to n\pi^0)\pi^-)\bar{\Xi}^+(\to \bar{\Lambda}(\to \bar{p}\pi^+)\pi^+)$ 为例

完整的角分布描述： $\mathcal{W}(\xi;\omega) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu',\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\bar{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\bar{\Lambda}}_{\nu'0}$



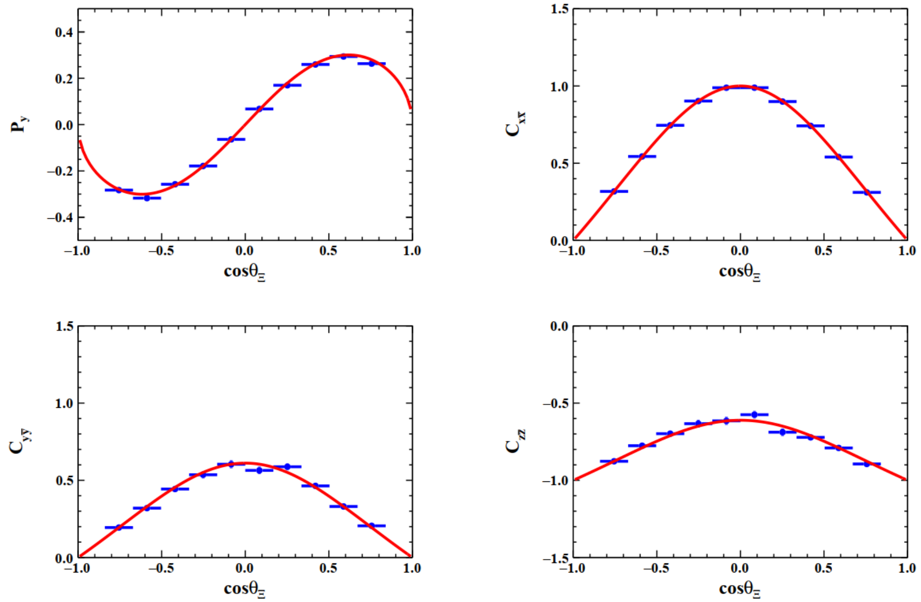
- 自旋密度矩阵($J/\psi \to \Xi^-\bar{\Xi}^+$):

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

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

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

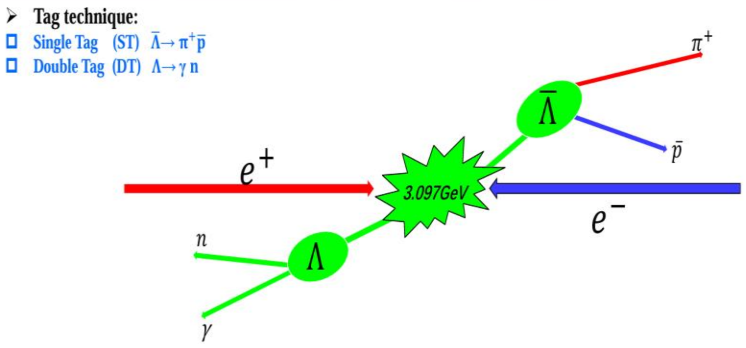
$$a_h^{\Xi} = \begin{pmatrix} 1 & 0 & 0 & \alpha \\ \alpha\cos\phi\sin\theta & \gamma\cos\theta\cos\phi-\beta\sin\phi & -\beta\cos\theta\cos\phi-\gamma\sin\phi & \sin\theta\cos\phi \\ \alpha\sin\theta\sin\phi & \beta\cos\phi+\gamma\cos\theta\sin\phi & \gamma\cos\phi-\beta\cos\theta\sin\phi & \sin\theta\sin\phi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



相较于固定靶实验的1维拟合$1+\alpha P\cos\theta$，正负电子对上超子对产生展开后有数十至数百项，结合多维角分布的拟合，最大化约束衰变参数

本底干净，高精度绝对测量

➢ 双标记方法实现绝对分支比测量，以$\Lambda \to n\gamma$为例



$$N_{ST} = N_{J/\psi\to\Lambda\bar{\Lambda}} \times \mathscr{B}_{\bar{\Lambda}\to\pi^+\bar{p}} \times \varepsilon_{ST},$$

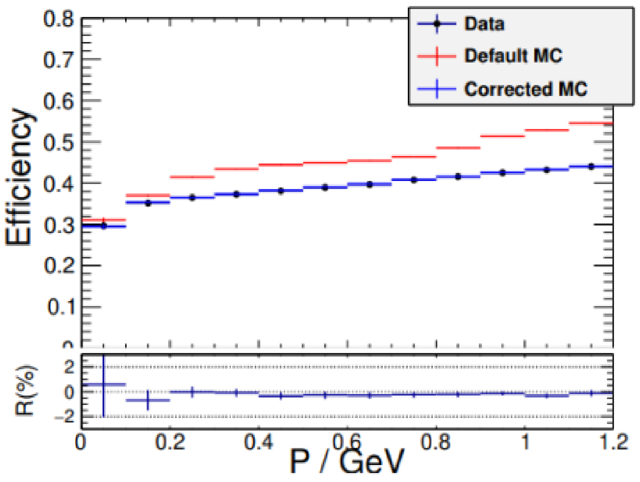
$$N_{DT} = N_{J/\psi\to\Lambda\bar{\Lambda}} \times \mathscr{B}_{\bar{\Lambda}\to\pi^+\bar{p}} \times \mathscr{B}_{\Lambda\to\gamma n} \times \varepsilon_{DT},$$

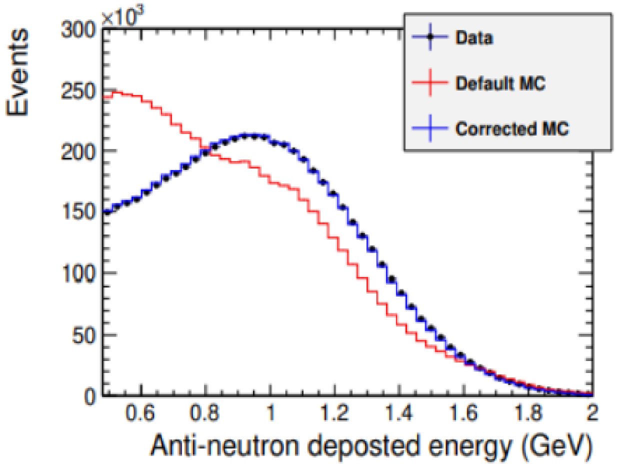
$$\mathscr{B}_{\Lambda\to\gamma n} = \frac{N_{DT}}{N_{ST}} \times \frac{\varepsilon_{ST}}{\varepsilon_{DT}}$$

- □ N_{ST} ST yield
- □ N_{DT} DT yield
- □ ε_{ST} ST efficiency
- □ ε_{DT} DT efficiency

➢ 丢失粒子法实现中性末态重建，且BESIII上能够选择出干净的低动量中性粒子样本修正模拟性能

- Geant4中反中子的模拟与实验数据存在较大差别（>10%)
- 选择控制样本，通过data-driven方式修正反中子在探测器中的响应，包括探测效率，特征变量分布
- 最终反中子模拟与实验数据差别降低至<1%





L. Liu et al., NIMA 1033 (2022) 166672

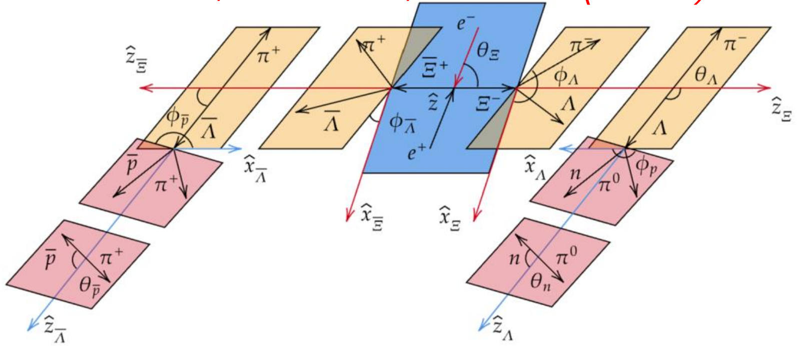
BESIII上超子实验研究进展

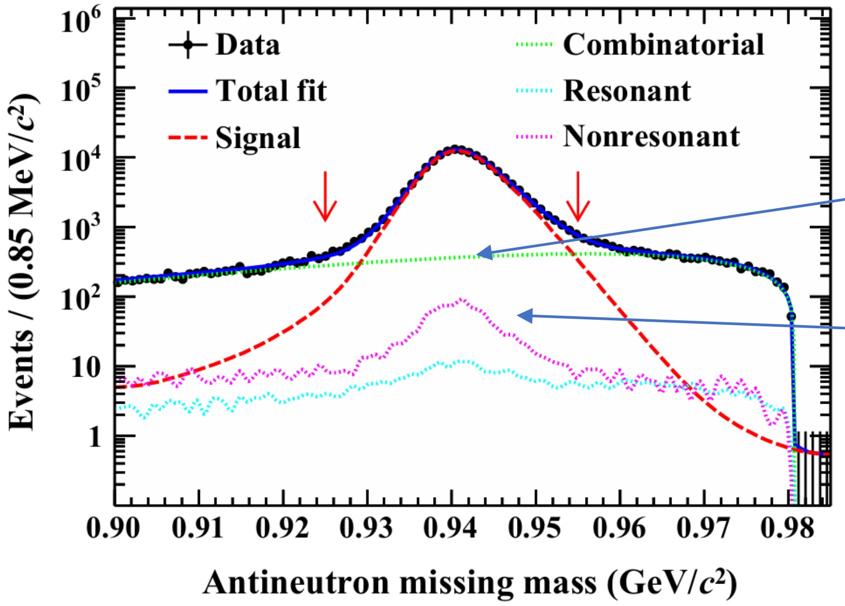
Λ含中性的强子末态衰变

BESIII, PRL 132, 101801(2024)

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

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





π^0误选的信号过程是主要本底，如噪声光子，（反）中子相关簇射

$J/\psi \to \gamma\eta_c \to \gamma\Xi^-\bar{\Xi}$

$J/\psi \to \Xi^-\bar{\Xi}^+ \to \Lambda(\to p\pi^-)\pi^-\bar{\Lambda}(\bar{p}\pi^+)\pi^+$

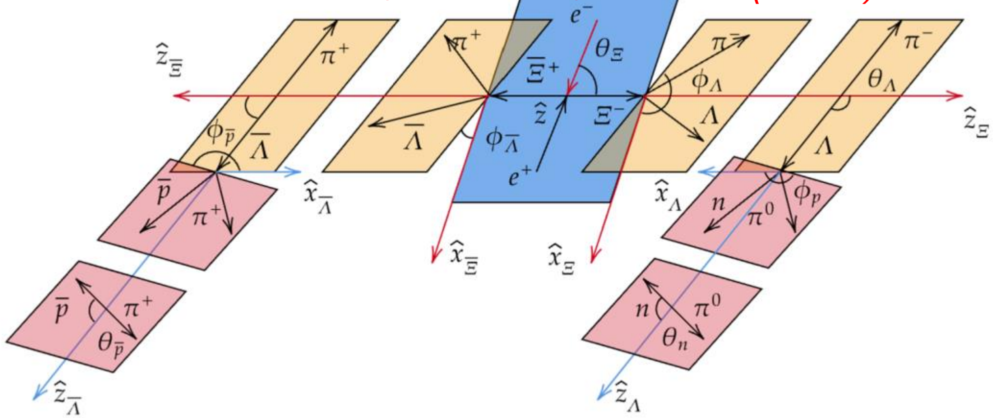
$\bar{\Lambda} \to \bar{n}\pi^0$过程: 信号事例数143 973±414，纯度91.2%

$\Lambda \to n\pi^0$过程: 信号事例数123 208±382，纯度91.0%

Λ含中性的强子末态衰变

BESIII, PRL 132, 101801(2024)

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



9维联合最大似然值拟合：

$$\mathcal{P}(\xi;\Omega) = \mathcal{W}(\xi;\Omega)\varepsilon(\xi)/\mathcal{N}(\Omega)$$

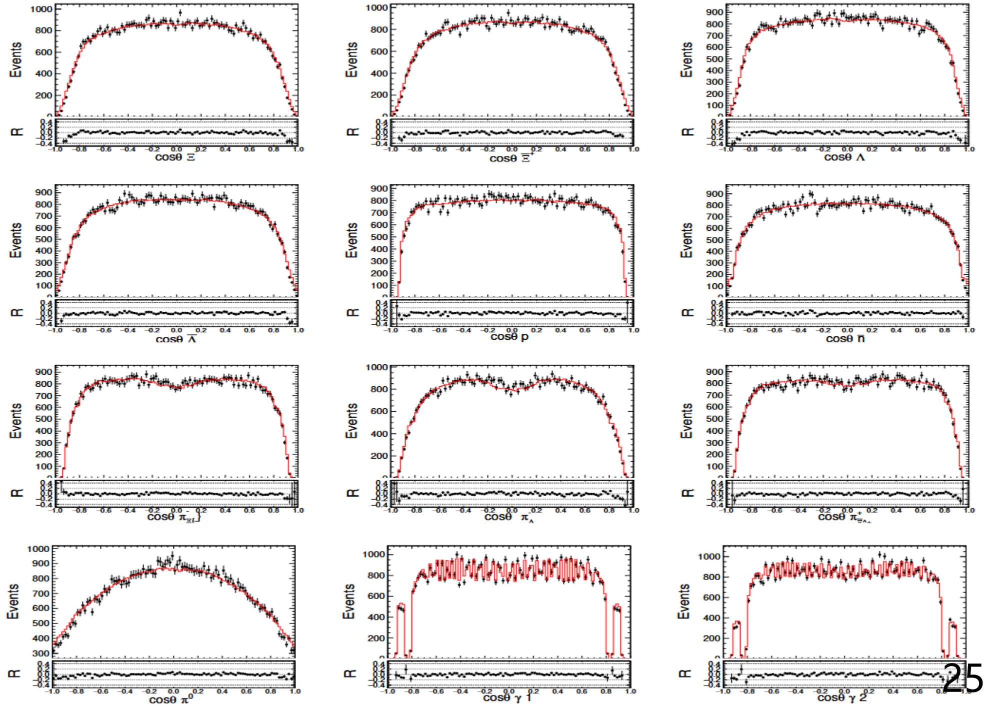
$$\mathcal{S} = -\mathcal{G}\left(\sum_{i=1}^{N} \ln \mathcal{P}(\xi_i;\omega) - \sum_{j} w_j \sum_{i}^{N_j^{\mathrm{bkg}}} \ln \mathcal{P}(\xi_i;\omega)\right)$$

$\bar{\Lambda} \to \bar{n}\pi^0$过程: $\xi = (\theta_{\Xi}, \theta_{\Lambda}, \phi_{\Lambda}, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_{p}, \phi_{p}, \theta_{\bar{n}}, \phi_{\bar{n}})$

$\Omega = (\alpha_{J/\psi}, \Delta\Phi, \alpha_{\Xi^-}, \phi_{\Xi^-}, \alpha_{\Xi^+}, \phi_{\Xi^+}, \alpha_{-}, \alpha_0)$

$\Lambda \to n\pi^0$过程: $\xi = (\theta_{\Xi}, \theta_{\Lambda}, \phi_{\Lambda}, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_{n}, \phi_{n}, \theta_{\bar{p}}, \phi_{\bar{p}})$

$\Omega = (\alpha_{J/\psi}, \Delta\Phi, \alpha_{\Xi^-}, \phi_{\Xi^-}, \alpha_{\Xi^+}, \phi_{\Xi^+}, \alpha_0, \alpha_+)$



Λ含中性的强子末态衰变

- **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.

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

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

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

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

BESIII, PRL 132, 101801(2024)

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)	$0.007 \pm 0.020^{+0.018}_{-0.005}$	$0.012 \pm 0.034 \pm 0.008$
$A^{\Xi}_{\rm CP}$	$-0.009 \pm 0.008^{+0.007}_{-0.002}$	$0.006 \pm 0.013 \pm 0.006$
$\Delta\phi^{\Xi}_{\rm CP}$ (rad)	$-0.003 \pm 0.008^{+0.002}_{-0.007}$	$-0.005 \pm 0.014 \pm 0.003$
$A^{-}_{\rm CP}$	$-0.007 \pm 0.008^{+0.002}_{-0.003}$	$-0.0025 \pm 0.0046 \pm 0.0012$
$A^{0}_{\rm CP}$	$0.001 \pm 0.009^{+0.005}_{-0.007}$	-
$A^{\Lambda}_{\rm CP}$	$-0.004 \pm 0.007^{+0.003}_{-0.004}$	-
$\alpha_{\Lambda 0}/\alpha_{\Lambda-}$	$0.877 \pm 0.015^{+0.014}_{-0.010}$	1.01 ± 0.07
$\bar{\alpha}_{\Lambda 0}/\alpha_{\Lambda+}$	$0.863 \pm 0.014^{+0.012}_{-0.008}$	$0.913 \pm 0.028 \pm 0.012$

Λ含中性的强子末态衰变

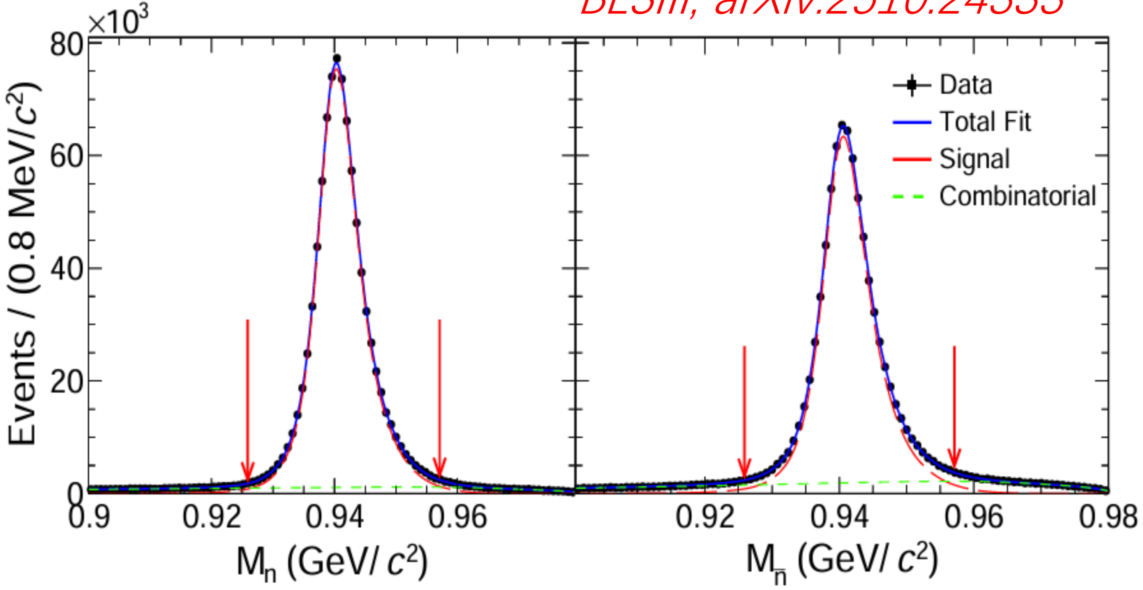
- $e^+e^- \to J/\psi \to \Lambda(\to n\pi^0)\bar{\Lambda}(\to \bar{p}\pi^+)$, (neutron channel)
- $e^+e^- \to J/\psi \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{n}\pi^0)$, (anti-neutron channel)

Unpolarised part Polarised part Spin correlated part

$$W(\xi) = \mathcal{T}_0(\xi) + \alpha_\psi \mathcal{T}_5(\xi) - \boldsymbol{\alpha}\bar{\boldsymbol{\alpha}}[\mathcal{T}_1(\xi) + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathcal{T}_2(\xi) + \alpha_\psi \mathcal{T}_6(\xi)] + \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)[\boldsymbol{\alpha}\mathcal{T}_3(\xi) - \bar{\boldsymbol{\alpha}}\mathcal{T}_4(\xi)]$$

$, \theta_n, \phi_n, \theta_{\bar{p}}, \phi_{\bar{p}})$

BESIII, arXiv:2510.24333



- $\Lambda \to n\pi^0$过程：信号事例数872 450±982，纯度95.3%

$$\xi = (\theta_\Lambda, \theta_n, \phi_n, \theta_{\bar{p}}, \phi_{\bar{p}})$$

$$\Omega = (\alpha_{J/\psi}, \Delta\Phi, \alpha_0, \alpha_+)$$

- $\bar{\Lambda} \to \bar{n}\pi^0$过程: 信号事例数759 770 ± 963，纯度91.1%

$$\xi = (\theta_\Lambda, \theta_p, \phi_p, \theta_{\bar{n}}, \phi_{\bar{n}})$$

$$\Omega = (\alpha_{J/\psi}, \Delta\Phi, \alpha_0, \alpha_-)$$

Λ含中性的强子末态衰变

[1] BESIII, arXiv:2510.24333
[2] BESIII, PRL 132, 101801(2024)

Parameter	[1] $J/\psi \to \Lambda\bar{\Lambda}$	[2] $J/\psi \to \Xi^-\bar{\Xi}^+$
α_-	$0.756 \pm 0.008 \pm 0.003$	$0.764 \pm 0.008^{+0.005}_{-0.006}$
α_+	$-0.764 \pm 0.008 \pm 0.001$	$-0.774 \pm 0.009^{+0.005}_{-0.005}$
α_0	$0.668 \pm 0.007 \pm 0.002$	$0.670 \pm 0.009^{+0.009}_{-0.008}$
$\bar{\alpha}_0$	$-0.677 \pm 0.007 \pm 0.003$	$-0.668 \pm 0.008^{+0.006}_{-0.008}$
A_{CP}^-	$-0.005 \pm 0.007 \pm 0.002$	$-0.007 \pm 0.008^{+0.002}_{-0.003}$
A_{CP}^0	$-0.006 \pm 0.007 \pm 0.002$	$0.001 \pm 0.009^{+0.005}_{-0.007}$
α_0/α_-	$0.884 \pm 0.013 \pm 0.006$	$0.877 \pm 0.015^{+0.014}_{-0.010}$
$\bar{\alpha}_0/\alpha_+$	$0.885 \pm 0.013 \pm 0.004$	$0.863 \pm 0.014^{+0.012}_{-0.008}$

The most precise results of Λ neutral decay
43% and 27% improvement in $J/\psi \to \Lambda\bar{\Lambda}$ compared with $J/\psi \to \Xi^-\bar{\Xi}^+$
Systematic uncertainty improved significantly

Most precise CP test in Λ neutral decay
SM prediction: $A_{CP} \sim 10^{-5}$ (PRD 67, 056001(2003))

Deviate from unity more than 5σ, indicates the $\Delta I = 3/2$ contributions in Λ decay

Λ的强子末态衰变和$\Delta I = 1/2$规则

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

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

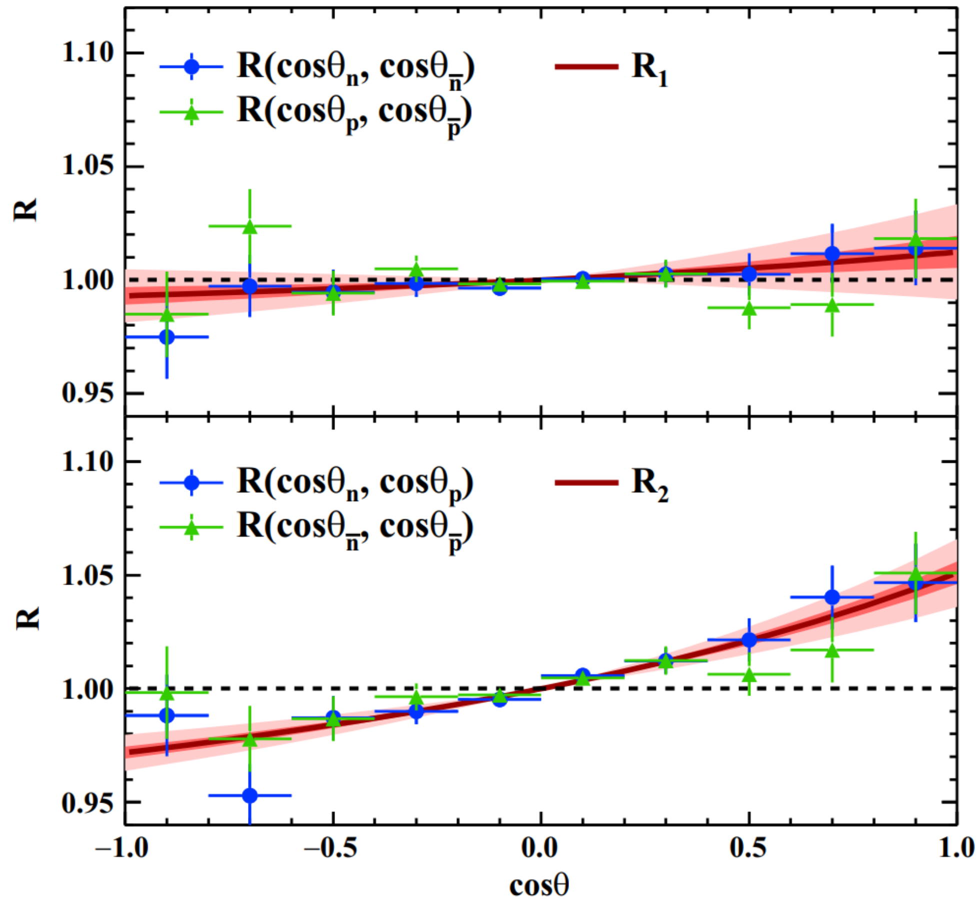
Consistent with kaon decay

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

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

Observed for the first time, different from S-wave

BESIII, PRL 132, 101801(2024)

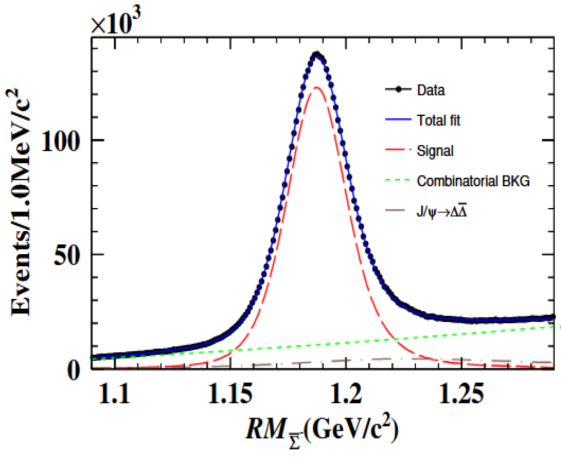


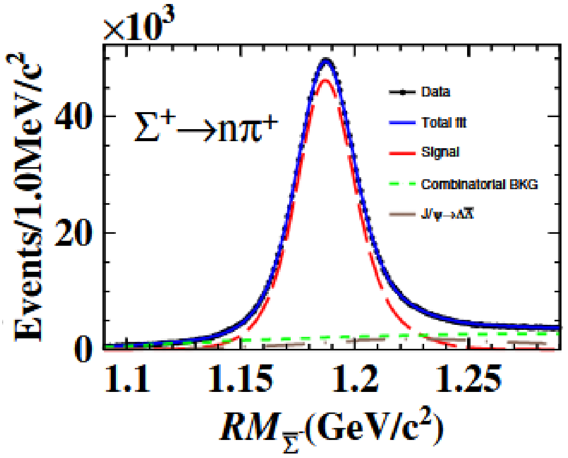
Σ^+含中性的强子末态衰变

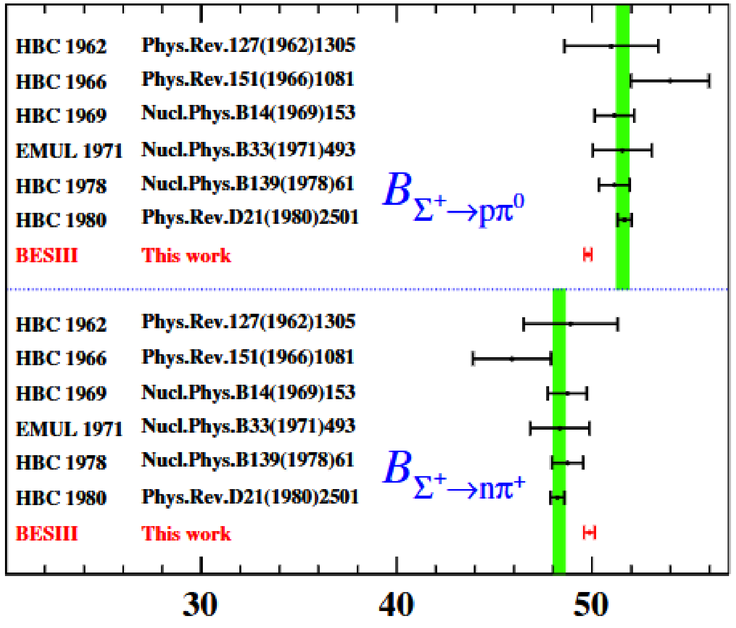
BESIII, arXiv: 2512.09628

$$e^+e^- \to J/\psi \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{n}\pi^- + c.c$$

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}\ \epsilon_{\rm ST}}{N_{\rm ST}\ \epsilon_{\rm DT}} = \frac{N_{\rm DT}}{N_{\rm ST}\ \epsilon_{\rm sig}}$$







	$\mathcal{B}_{\Sigma^+\to p\pi^0}(\%)$	$\mathcal{B}_{\Sigma^+\to n\pi^+}(\%)$	$\mathcal{B}_{\Sigma^+\to p\pi^0}/B_{\Sigma^+\to n\pi^+}$
This work	$49.79 \pm 0.06 \pm 0.22$	$49.87 \pm 0.05 \pm 0.29$	$0.9984 \pm 0.0016 \pm 0.0073$
PDG	51.47 ± 0.30	48.43 ± 0.30	1.0628 ± 0.0090
Difference	4.4σ	3.4σ	5.5σ

Σ^+的强子末态衰变和$\Delta I = 1/2$规则

$\Sigma \to \pi N$的同位旋分解($L_{2\Delta I,2I}$)：

$$L(\Sigma^+ \to p\pi^0) = \frac{\sqrt{2}}{3}\left(L^{\Sigma}_{1,1} + \frac{1}{2}L^{\Sigma}_{3,1}\right)\exp(i\delta^L_1) + \left(-\frac{\sqrt{2}}{3}L^{\Sigma}_{1,3} + \frac{2\sqrt{2}}{3}L^{\Sigma}_{3,3}\right)\exp(i\delta^L_3),$$

$$L(\Sigma^- \to n\pi^-) = (L^{\Sigma}_{1,3} + L^{\Sigma}_{3,3})\exp(i\delta^L_3),$$

$$L(\Sigma^+ \to n\pi^+) = \frac{2}{3}\left(L^{\Sigma}_{1,1} + \frac{1}{2}L^{\Sigma}_{3,1}\right)\exp(i\delta^L_1) + \left(\frac{1}{3}L^{\Sigma}_{1,3} - \frac{2}{3}L^{\Sigma}_{3,3}\right)\exp(i\delta^L_3),$$

纯的 $\Delta I = 1/2$ 振幅有如下关系： $\sqrt{2}L(\Sigma^+ \to p\pi^0) - L(\Sigma^+ \to n\pi^+) + L(\Sigma^- \to n\pi^-) = 0$

Decay mode	α	$\mathcal{B}(\%)$	$A\ (G_F m^2_{\pi^+})$	$B\ (G_F m^2_{\pi^+})$
$\Sigma^+ \to p\pi^0$	-0.9869 ± 0.0019	49.79 ± 0.23	-1.385 ± 0.008	11.80 ± 0.09
$\Sigma^+ \to n\pi^+$	0.0506 ± 0.0032	49.87 ± 0.30	0.047 ± 0.003	18.84 ± 0.07

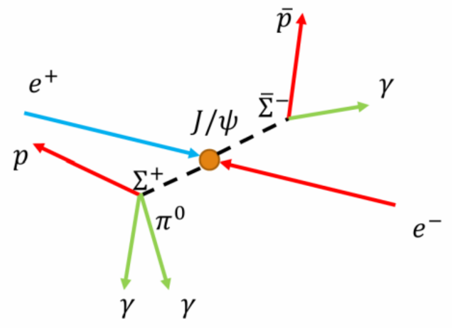
BESIII, arXiv: 2512.09628

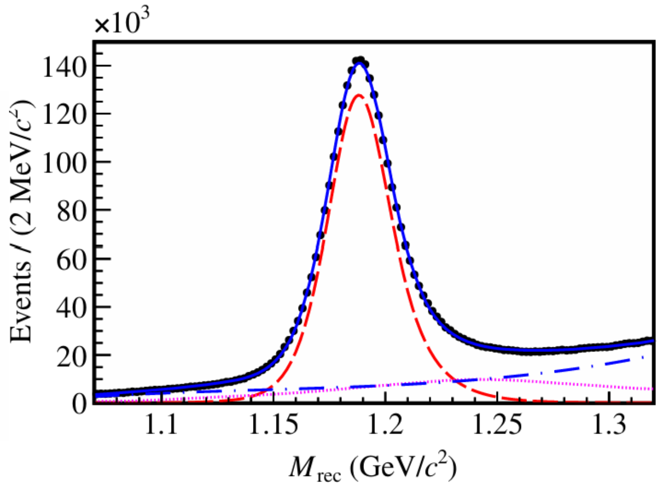
$$\begin{aligned} A^{\Sigma^-}_{n\pi^-} - A^{\Sigma^+}_{n\pi^+} + \sqrt{2}A^{\Sigma^+}_{p\pi^0} &= -0.127 \pm 0.014(\text{this work}) \\ &= -0.180 \pm 0.063(\text{PDG}), \\ B^{\Sigma^-}_{n\pi^-} - B^{\Sigma^+}_{n\pi^+} + \sqrt{2}B^{\Sigma^+}_{p\pi^0} &= -2.78 \pm 0.16(\text{this work}) \\ &= -2.50 \pm 0.76(\text{PDG}). \qquad (5) \end{aligned}$$

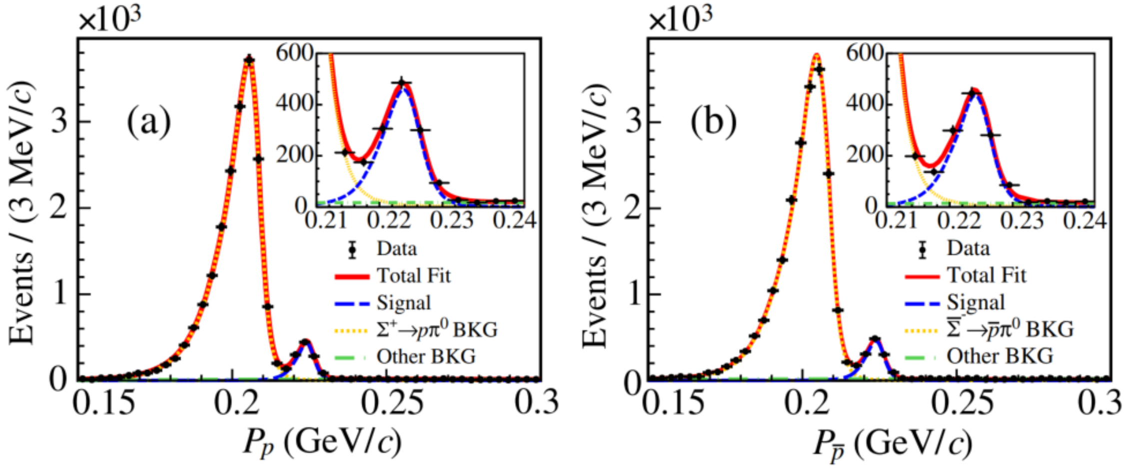
Deviate from zero over 5σ, indicate the non-negligible $\Delta I = \frac{3}{2}$ contribution

超子弱辐射衰变$\Sigma^+ \rightarrow p\gamma$

BESIII, 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 ± 2285	2 509 380 ± 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	$(0.997 \pm 0.022) \times 10^{-3}$	

超子弱辐射衰变$\Sigma^+ \to p\gamma$

BESIII, PRL130, 211901 (2023)

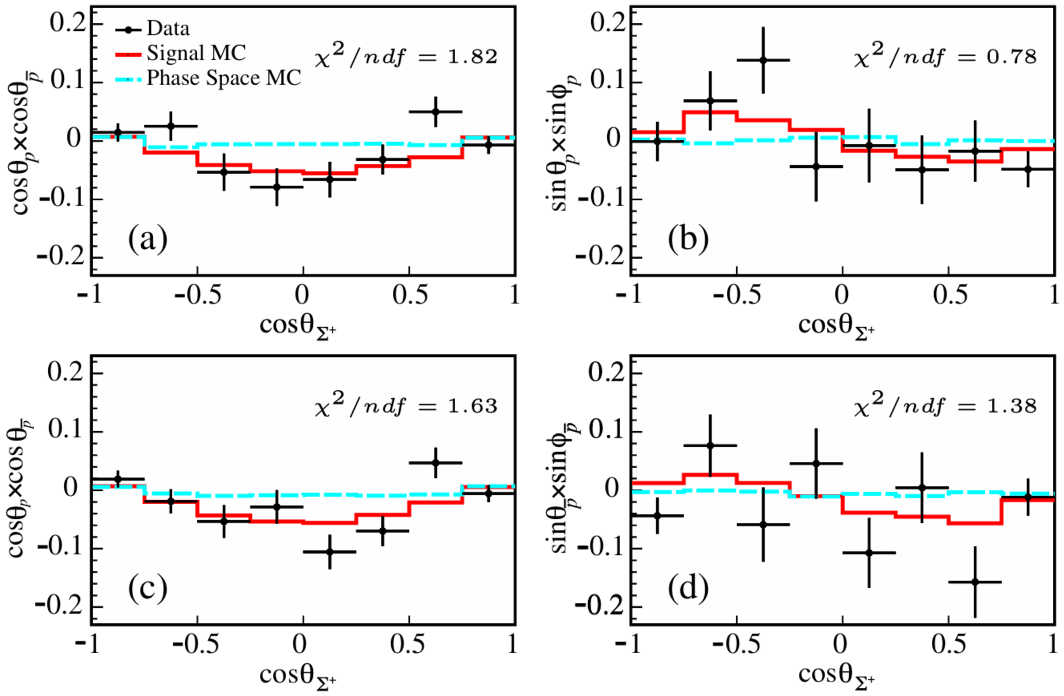
$$\mathcal{L} = \prod_{i=1}^{N} \frac{\mathcal{W}_i(\xi, H)}{\mathcal{N}} \qquad \mathcal{N} = \frac{1}{N_{\rm MC}} \sum_{j=1}^{N_{\rm MC}} \mathcal{W}_i^{\rm MC}(\xi, H)$$

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

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

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

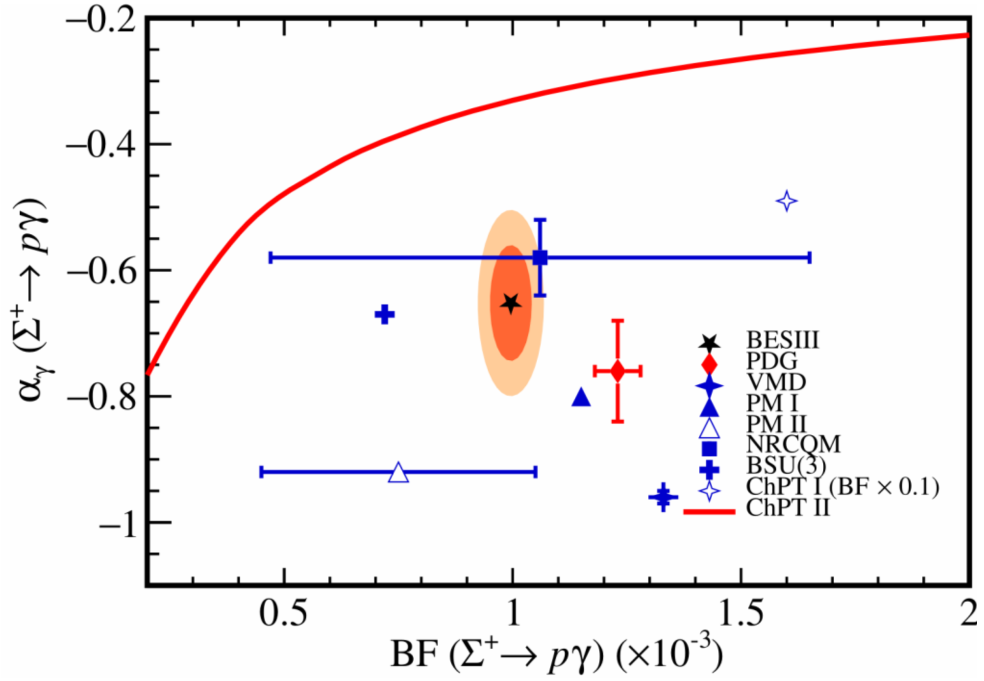
Parameter	value
α_ψ	-0.508 ± 0.006
$\Delta\Phi$	-0.270 ± 0.012
$\alpha_{\Sigma^+\to p\pi^0}$	-0.980 ± 0.017
$\alpha_{\Sigma^+\to p\gamma}$	**Iterated from this analysis**



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	

超子弱辐射衰变$\Sigma^+ \to p\gamma$

BESIII, PRL130, 211901 (2023)



Mode	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
$N_{\rm ST}^{\rm obs}$	$2\,177\,771 \pm 2285$	$2\,509\,380 \pm 2301$
$\varepsilon_{\rm ST}$ (%)	39.00 ± 0.04	44.31 ± 0.04
$N_{\rm DT}^{\rm obs}$	1189 ± 38	1306 ± 39
$\varepsilon_{\rm DT}$ (%)	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	$-0.651 \pm 0.056 \pm 0.020$	

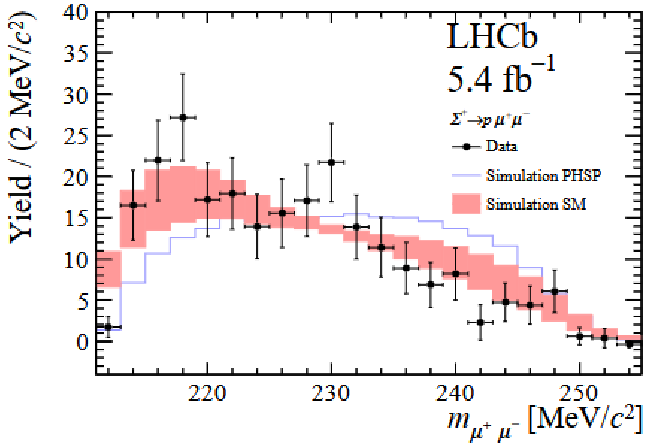
- The **accuracies** of the BF and α_γ are **improved by 78% and 34%**
- The measured BF is **lower than the world average value by 4.2σ**
- The accurate result will provide **input and constraints for ChPT**

$\Sigma^+ \to p\gamma$对新物理的约束

$\Sigma^+ \to p\mu^+\mu^-$过程的实验测量：

*LHCb, PRL*135 (2025) 5, 051801

HyperCP实验（00s）	LHCb（10s）	LHCb实验（20s）
3 events	10.2 events	237 events
$\mathcal{B} = (8.6^{+6.6}_{-5.4}) \times 10^{-8}$	$\mathcal{B} = (2.2 \pm 0.7) \times 10^{-8}$	$\mathcal{B} = (1.08 \pm 0.17) \times 10^{-8}$



$\Sigma^+ \to p\mu^+\mu^-$过程的理论预言：

- 在标准模型中由长程贡献$\Sigma^+ \to p\gamma^* \to p\mu^+\mu^-$主导。

$$\mathcal{M}(\Sigma^+ \to p\gamma^*) = -eG_F\,\bar{u}_p\left[i\sigma^{\kappa\nu}q_\kappa\left(a+\gamma_5 b\right) + \left(\gamma^\nu q^2 - \not{q}\,q^\nu\right)\left(c+\gamma_5 d\right)\right]u_\Sigma\,\varepsilon_\nu^*\,,$$

- BESIII上$\Sigma^+ \to p\gamma$实验测量（缩小了形状因子a,b，影响衰变率），能够有效提高标准模型预言，并约束新物理参数空间

Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$	$10^8\,\mathcal{B}_{\mu\mu}^{\mathrm{Re}(c,d)=0}$	$10^5\,\tilde{A}_{\rm FB}$	$10^6\,\mathcal{B}_{ee}$	$10^7\,\mathcal{B}_{ee}^{M_{ee}\geq 100\,\mathrm{MeV}}$
-12.15 ± 0.24	4.78 ± 0.42	2.7 ± 0.2	1.8 ± 0.1	-1.59 ± 0.04	7.6 ± 0.3	8.5 ± 0.4
-4.78 ± 0.42	12.15 ± 0.24	7.8 ± 0.3	5.8 ± 0.2	-0.32 ± 0.02	8.3 ± 0.3	13.5 ± 0.4
4.78 ± 0.42	-12.15 ± 0.24	4.2 ± 0.2	5.8 ± 0.2	0.91 ± 0.04	7.8 ± 0.3	9.9 ± 0.4
12.15 ± 0.24	-4.78 ± 0.42	1.2 ± 0.1	1.8 ± 0.1	4.55 ± 0.08	7.4 ± 0.3	6.9 ± 0.3
Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$	$10^8\,\mathcal{B}_{\mu\mu}^{\mathrm{Re}(c,d)=0}$	$10^5\,\tilde{A}_{\rm FB}$	$10^6\,\mathcal{B}_{ee}$	$10^7\,\mathcal{B}_{ee}^{M_{ee}\geq 100\,\mathrm{MeV}}$
-9.74 ± 0.54	6.17 ± 0.74	3.7 ± 0.5	2.7 ± 0.3	-0.73 ± 0.06	7.9 ± 0.5	10.2 ± 0.8
-6.17 ± 0.74	9.74 ± 0.54	6.1 ± 0.5	4.5 ± 0.4	-0.29 ± 0.05	8.3 ± 0.6	12.6 ± 0.8
6.17 ± 0.74	-9.74 ± 0.54	3.2 ± 0.3	4.5 ± 0.4	1.49 ± 0.09	7.8 ± 0.6	9.7 ± 0.7
9.74 ± 0.54	-6.17 ± 0.74	1.9 ± 0.2	2.7 ± 0.3	3.2 ± 0.1	7.6 ± 0.5	8.3 ± 0.6

TABLE I. The four solutions for the real parts of the form factors a and b (columns 1 and 2) obtained in relativistic baryon χPT (first four rows) and in its heavy-baryon formulation (last four rows) and the corresponding predictions in the SM for each case (columns 3-7). In the third and fourth columns $\mathcal{B}_{\mu\mu} \equiv \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-)$ is from the complete SM amplitude and $\mathcal{B}_{\mu\mu}^{\mathrm{Re}(c,d)=0}$ gets no contribution from the real parts of the form factors c and d. In the fifth column $\tilde{A}_{\rm FB}$ is the integrated muon forward-backward asymmetry. The last two columns exhibit $\mathcal{B}_{ee} \equiv \mathcal{B}(\Sigma^+ \to pe^+e^-)$ without and with a cut in the dielectron invariant mass.

A. Roy et al.,arXiv: 2404.15268

$\Sigma^+ \to p\gamma$对新物理的约束

CP observables:

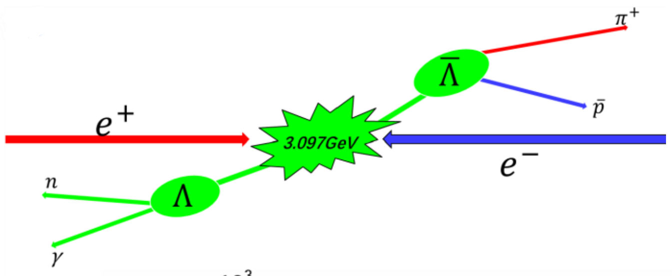
$$\Delta_{CP} = \frac{\mathcal{B}_+ - \mathcal{B}_-}{\mathcal{B}_+ + \mathcal{B}_-} = 0.006 \pm 0.011_{\text{stat.}} \pm 0.004_{\text{syst.}},$$
$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = 0.095 \pm 0.087_{\text{stat.}} \pm 0.018_{\text{syst.}}.$$

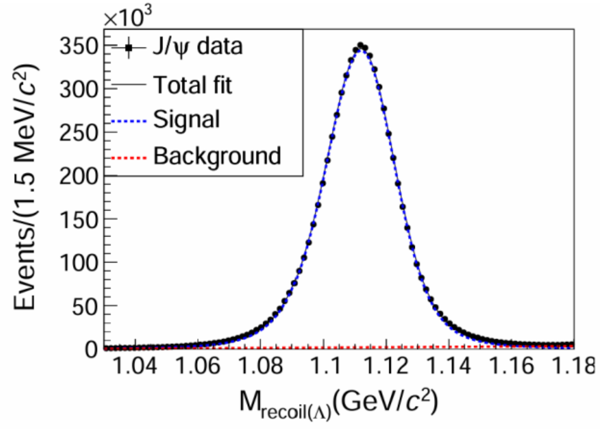
- May be significantly enhanced by NP up to $\mathcal{O}$ 10 % (PRL109 (2012), 171801, JHEP 01 (2013) 027, JHEP 04 (2017) 027, JHEP 08 (2017) 09
- Extensive experimental studies on K, D and B meson radiative decays

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}	

超子弱辐射衰变$\Lambda \to n\gamma$

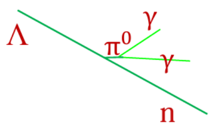
BESIII, PRL 129, 212002 (2022)





- **Dominant background:**

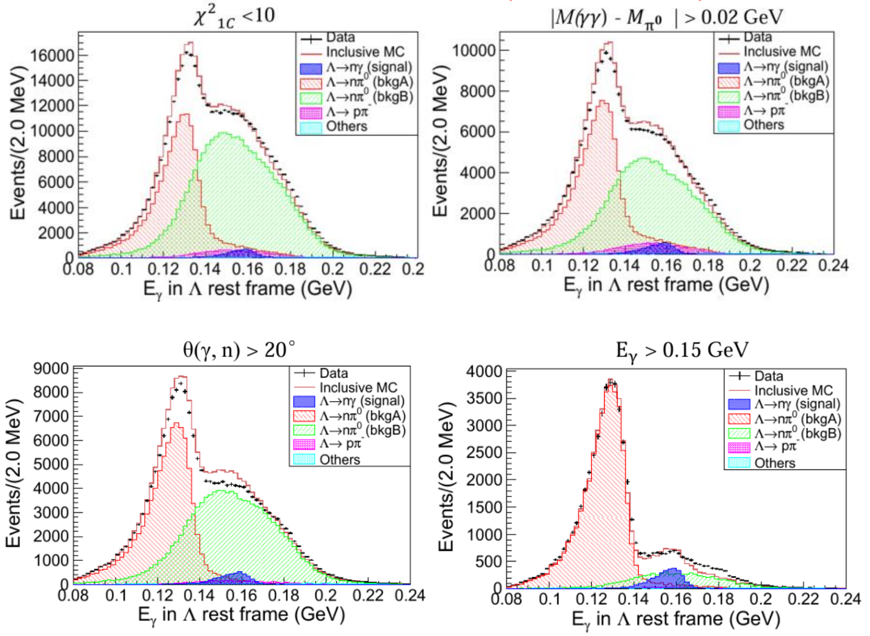
$\Lambda \to n\pi^0$



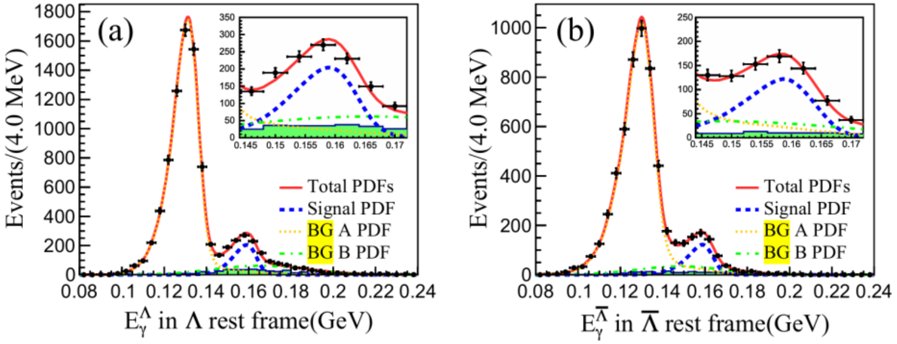
- **BKG A:** photon candidate is from π^0 decay.
- **BKG B:** photon candidate is not from π^0 decay.

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

显著的噪声中性簇设本底



After further BDT selection



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	$-0.13 \pm 0.13 \pm 0.03$	$0.21 \pm 0.15 \pm 0.06$
	$-0.16 \pm 0.10 \pm 0.05$	

超子弱辐射衰变$\Lambda \to n\gamma$

BESIII, PRL 129, 212002 (2022)

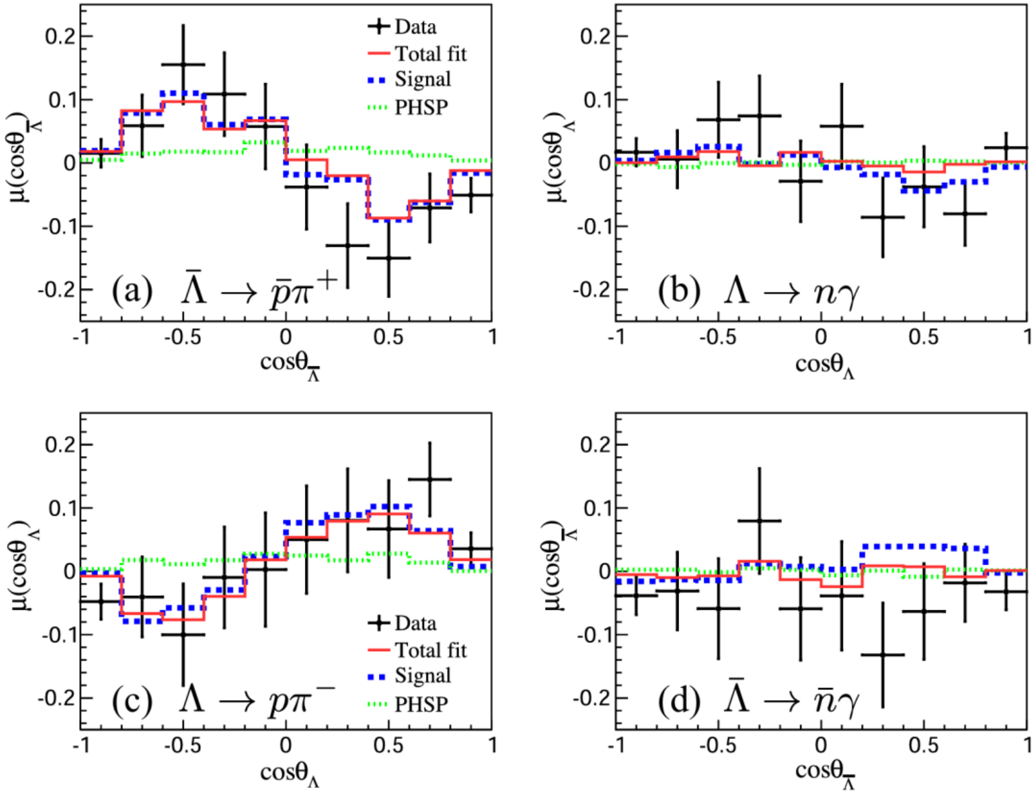
$$-\ln\mathcal{L}_{sig} = -\ln\mathcal{L}_{data} + \ln\mathcal{L}_{bkgA} + \ln\mathcal{L}_{bkgB}$$

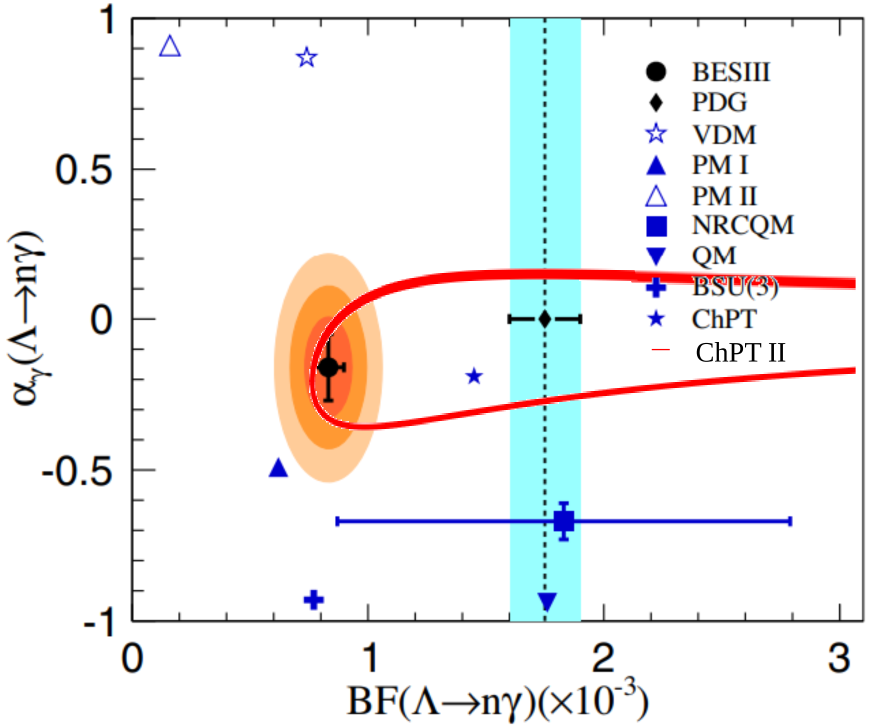
- **Contributions of BKG A / B should be subtracted .**

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

- **BKG A and BKG B contributions are estimated by DIY MC with same numbers in data**

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

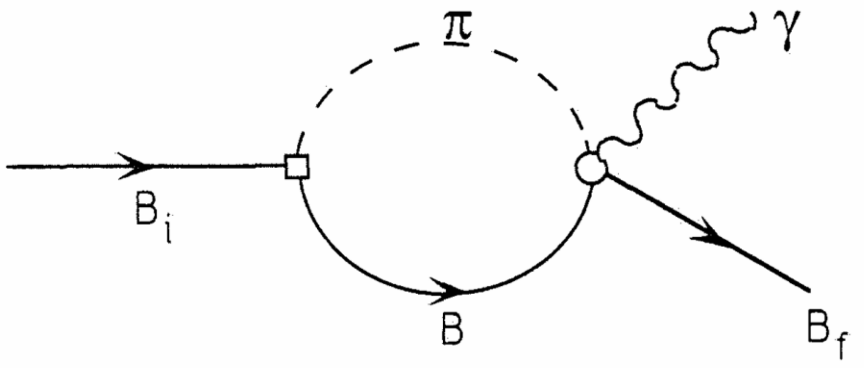




- **First** measurement on α_γ
- **5.6σ** deviation of BF from world average value

超子弱辐射衰变$\Lambda \to n\gamma$

Unitarity Bounds:



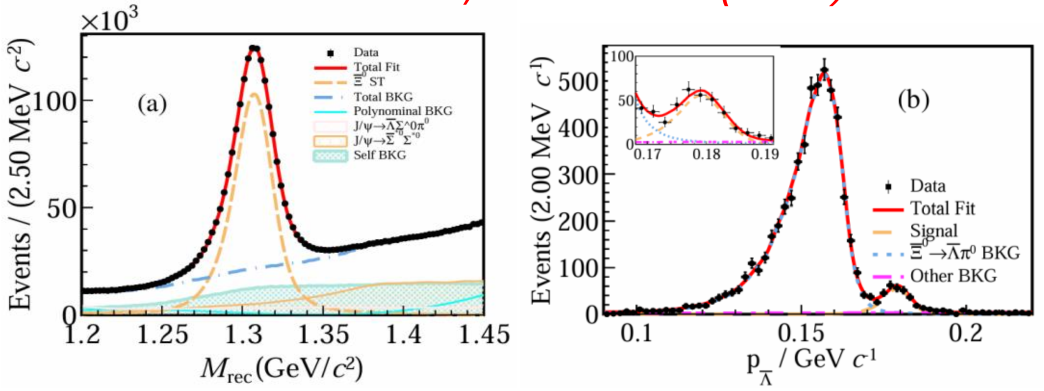
- For the WRHD processes, $Im\ M(Y \to B\gamma)$ can be expressed in terms of the amplitudes of the $\boldsymbol{Y \to B\pi^0}$ and of those of **pion photoproduction on nucleons ($\boldsymbol{\gamma B \to \pi B'}$)**
- However, the updated BF of $\boldsymbol{\Lambda \to n\gamma}$, $\boldsymbol{(0.832 \pm 0.038 \pm 0.054) \times 10^{-3}}$**, is close to the lower bounds.**

Table 4.1 Comparison of estimates of πB contributions to the branching fractions of WRHD. (in units of 10^{-3})

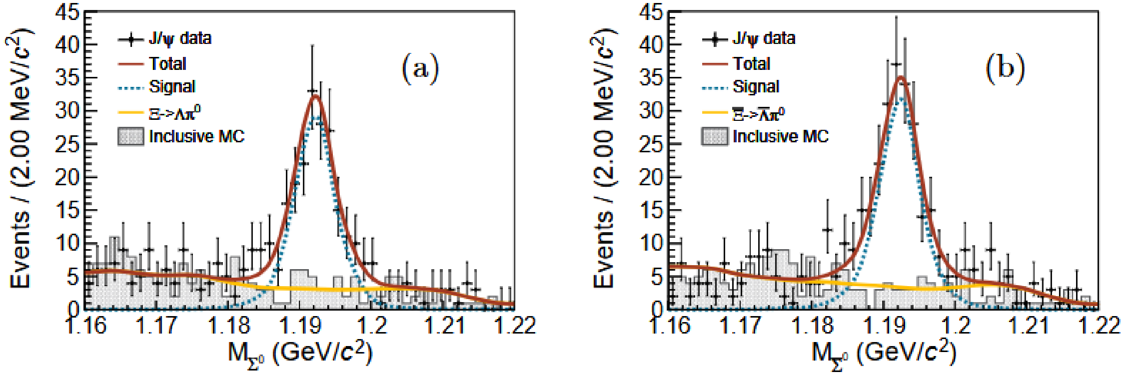
	Zakharov[52]	Farrar[53]		Kogan[54]		Reid[55,56]
Process	lower bound	lower bound	full estimate	lower bound	full estimate	full estimate
$\Sigma^+ \to p\gamma$	0.07±0.04	0.007	0.3±1.2			$0.77^{+1.29}_{-0.49}$
$\Lambda \to n\gamma$	0.83	0.85	1.9±0.8			$1.20^{+0.46}_{-0.04}$
$\Xi^- \to \Sigma^-\gamma$	0.13			0.10	0.17	
$\Omega^- \to \Xi^-\gamma$				0.008	0.01	

超子弱辐射衰变$\Xi^0 \to \Lambda\gamma$和$\Xi^0 \to \Sigma^0\gamma$

BESIII, Sci.Bull. 70 (2025) 454-459



BESIII, arXiv: 2512.03877

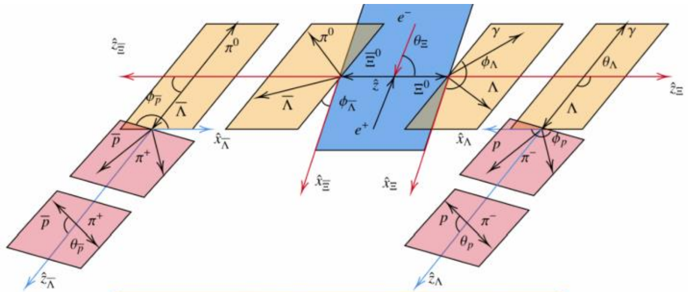


Modes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
ST Yield	1 400 541 ± 1989	1 611 216 ± 2111
ε_{ST} (%)	17.61 ± 0.01	19.77 ± 0.01
ε_{DT} (%)	4.43 ± 0.02	4.77 ± 0.02
Individual BF	$(1.391 \pm 0.093) \times 10^{-3}$	$(1.344 \pm 0.099) \times 10^{-3}$
Simultaneous BF	$(1.379 \pm 0.068)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

Decay	$\Xi^0 \to \gamma\Sigma^0$	$\bar{\Xi}^0 \to \gamma\bar{\Sigma}^0$
N_{DT}	178 ± 16	214 ± 17
ε_{DT} (%)	1.01	1.04
Individual $\mathcal{B}$ ($\times 10^{-3}$)	3.45 ± 0.29	3.95 ± 0.29
Correction factor	1.018	0.991
Corrected individual $\mathcal{B}$ ($\times 10^{-3}$)	3.39 ± 0.28	3.98 ± 0.29
Simultaneous $\mathcal{B}$ ($\times 10^{-3}$)	3.71 ± 0.22	
Corrected simultaneous $\mathcal{B}$ ($\times 10^{-3}$)	3.69 ± 0.21	

超子弱辐射衰变$\Xi^0 \to \Lambda\gamma$和$\Xi^0 \to \Sigma^0\gamma$

BESIII, Sci.Bull. 70 (2025) 454-459

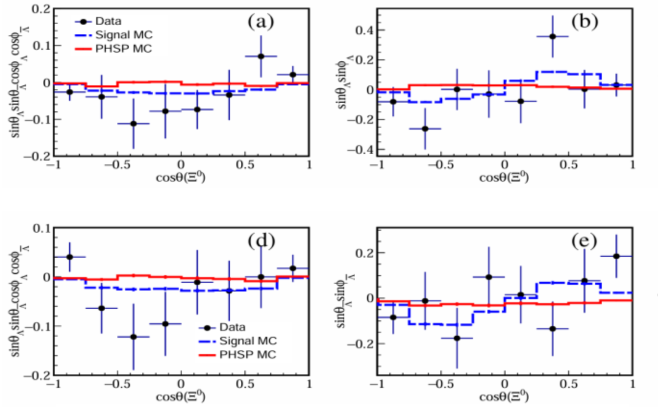


Helicity angles:

$\theta_\Xi, \theta_\Lambda, \phi_\Lambda, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}}$

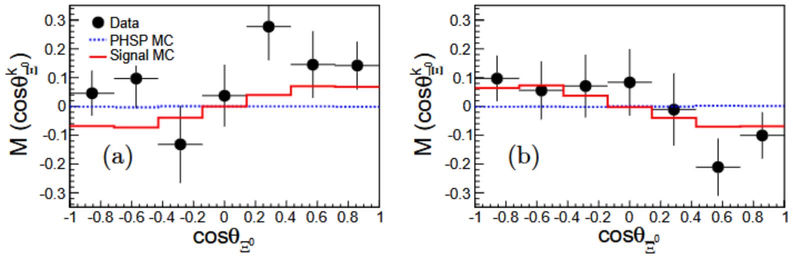
Decay parameters:

$\alpha_{J/\psi}, \Delta\Phi_{J/\psi}, \alpha_\Xi, \Delta\Phi_\Xi, \alpha_{\bar{\Xi}}, \Delta\Phi_{\bar{\Xi}}, \alpha_\Lambda, \alpha_{\bar{\Lambda}}$

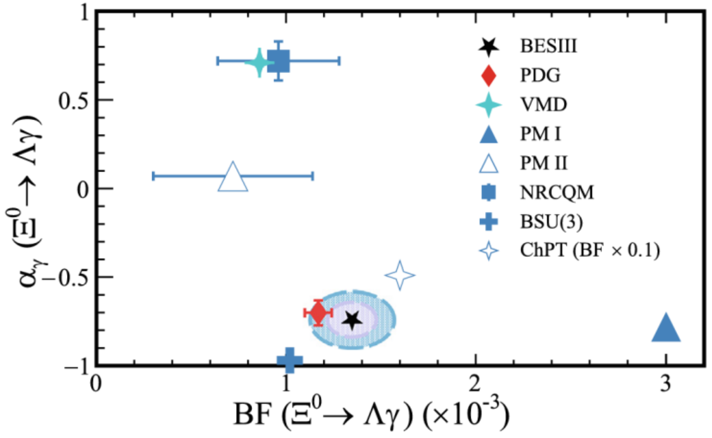


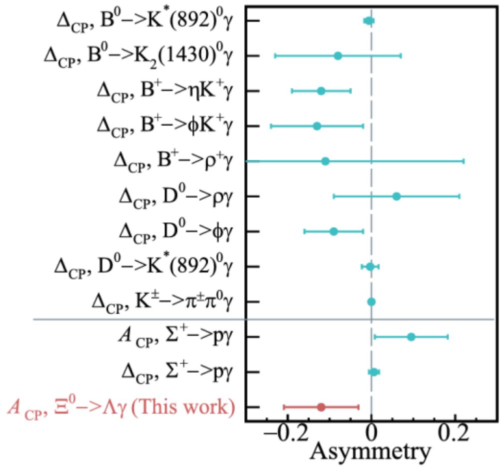
Processes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Individual fit	-0.652 ± 0.092	0.830 ± 0.080
Simultaneous fit	-0.741 ± 0.062	

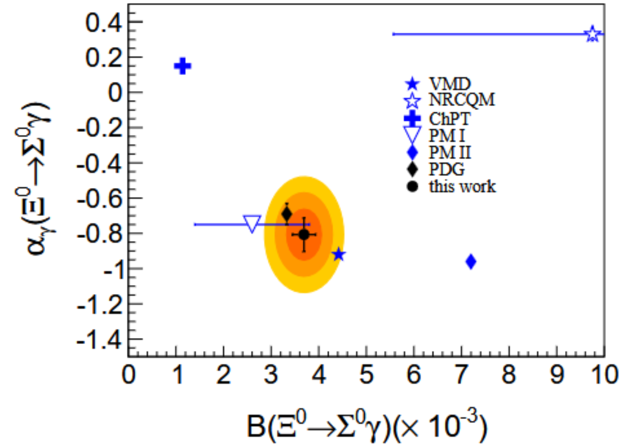
BESIII, arXiv: 2512.03877



Decay asymmetry	$\Xi^0 \to \gamma\Sigma^0$	$\bar{\Xi}^0 \to \gamma\bar{\Sigma}^0$
Individual fits	$-0.693 \pm 0.139_{\rm stat}$	$0.956 \pm 0.139_{\rm stat}$
Simultaneous fit	$-0.807 \pm 0.095_{\rm stat}$	







BESIII 超子衰变

BESIII研究list:

- $\Xi^- \to \gamma\Sigma^-$
- $\Omega^- \to \gamma\Xi^-$
- $\Sigma^0 \to \gamma n$
- $\Sigma^+ \to pe^+e^-$
- $\Sigma^0 \to \Lambda e^+e^-$
- $\Lambda \to pe^-\bar{\nu}_e$
- $\Xi^- \to \Lambda\, e^-\bar{\nu}_e$
- $\Xi^0 \to p\, e^-\bar{\nu}_e$ ($|\Delta S| = 2$)
- $\Xi^0 \to \Lambda$+invisible
- LNV $\Xi^- \to \Sigma^+ e^- e^-$
- $\Omega^- \to \Sigma^0\pi^-/nK^-$ ($|\Delta S| = 2$)
- …

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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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PERSPECTIVE

Prospects for rare and forbidden hyperon decays at BESIII

Hai-Bo Li[1,2,†]

[1] *Institute of High Energy Physics, Beijing 100049, China*
[2] *University of Chinese Academy of Sciences, Beijing 100049, China*
Corresponding author. E-mail: †*lihb@ihep.ac.cn*

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The study of hyperon decays at the Beijing Electron Spectrometer III (BESIII) is proposed to investigate the events of J/ψ decay into hyperon pairs, which provide a pristine experimental environment at the Beijing Electron–Positron Collider II. About 10^6–10^8 hyperons, i.e., Λ, Σ, Ξ, and Ω, will be produced in the J/ψ and $\psi(2S)$ decays with the proposed data samples at BESIII. Based on these samples, the measurement sensitivity of the branching fractions of the hyperon decays is in the range of 10^{-5}–10^{-8}. In addition, with the known center-of-mass energy and "tag technique", rare decays and decays with invisible final states can be probed.

Keywords BESIII, J/ψ decay, hyperon, rare decay, FCNC, lepton flavor violation

总结

- 早期固定靶实验为超子研究奠定基础，但在极化率、系统误差、绝对测量等方面存在局限，BESIII实验提供了全新的正反超子对产生环境，在样本类型、极化确定和系统误差控制上具有显著优势；
- 本报告介绍了BESIII上超子含中性强子衰变的研究、以及超子弱辐射衰变的最新测量结果，为低能强相互作用是如何导致$\Delta I=1/2$规则以及如何破坏Hara定理等长期问题提供了关键输入；
- BESIII的超子研究成果为进一步预言超子CP破坏及寻找新物理奠定了基础。

谢谢！