Studies on Weak Radiative Hyperon Decays at BESIII

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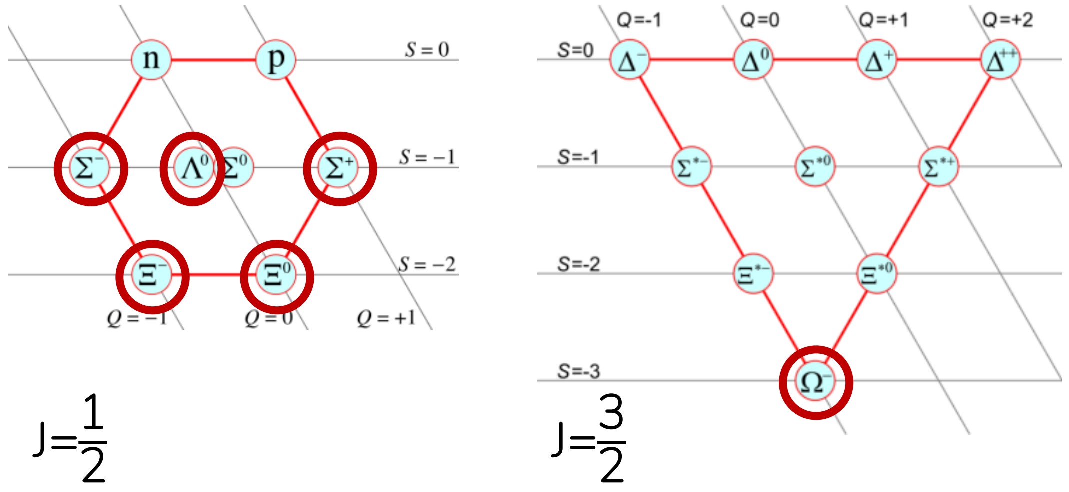
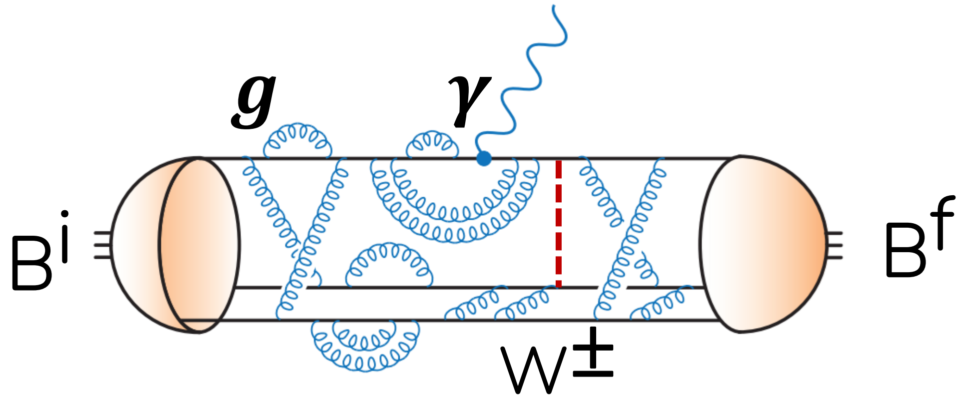
Physics Motivation

Overview

- Decay of ground hyperons:
  - Weak hadronic decay ($\Lambda \rightarrow p\pi^-$)
  - Semi-leptonic decay ($\Lambda \rightarrow pe\nu_e$)
  - Weak radiative decay (WRHD) ($\Lambda \rightarrow n\gamma$)
- Weak radiative decays
  - flavor changing neutral current (FCNC) process ($s \rightarrow d\gamma$ transition)
  - Significant non-perturbative QCD effects
  - A symphony of strong, weak and EM interaction





j.ppnp.2016.07.001

Physics Motivation

Effecitve Theory Point-of-view

- Effective Lagrangian

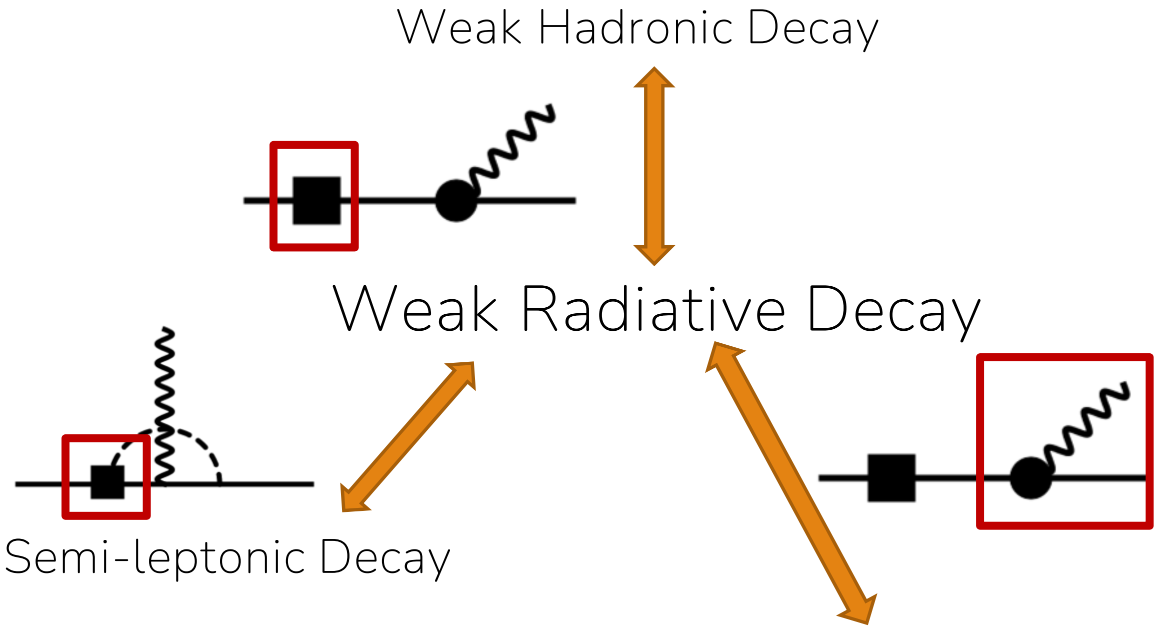
$$\mathcal{L} = \frac{eG_F}{2}\bar{B}_f\left(a^{\mathrm{PC}} + b^{\mathrm{PV}}\gamma_5\right)\sigma^{\mu\nu}B_i F_{\mu\nu}$$

- Decay width & decay asymmetry

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

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

- Reveal common hyperon properties
  - Decay mechanism
  - EM structure
  - ……



j.scib.2022.10.026

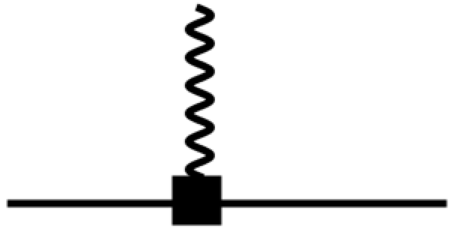
Physics Motivation

Effecitve Theory Point-of-view

- Unique contribution from "direct photon emission"
  - PV amplitude from direct photon emission:

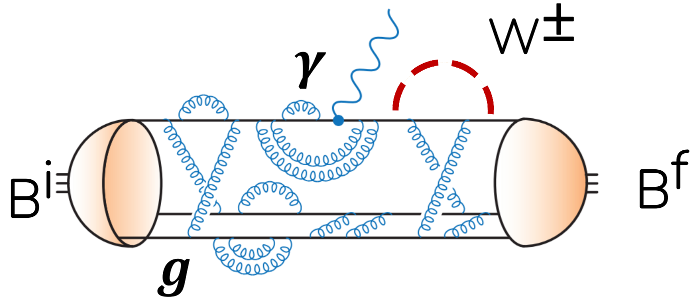
$$\mathrm{Re}(b)_{\Xi^0\Sigma^0} = \sqrt{3}\mathrm{Re}(b)_{\Xi^0\Lambda},\ \mathrm{Re}(b)_{\Lambda n} = -\mathrm{Re}(b)_{\Xi^0\Lambda}$$

$$\mathrm{Re}(b)_{\Sigma^0 n} = -\sqrt{3}\mathrm{Re}(b)_{\Xi^0\Lambda},\ \mathrm{Re}(b)_{\Sigma^+ p} = \mathrm{Re}(b)_{\Xi^-\Sigma^-=0}$$



  - Need experiment input from $\Xi^0 \to \Lambda(\Sigma^0)\gamma$ or $\Lambda \to n\gamma$ process

- Two quark exchange suppressed $\Xi^- \to \Sigma^-\gamma$ and $\Omega^- \to \Xi^-\gamma$ process
  - Much smaller decay width
  - More sensitive to effective models?



Physics Motivation

Physics Beyond the Scope of QCD Phenomenon

- New physics in $B_i \rightarrow B_f l^+ l^-$ decay
  - Smoke screen of new physics in $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay (PhysRevLett.94.021801)
  - Experiment results of WRHDs provide SM expectations on such decays – narrowing the range for NP! (JHEP10(2018)040, JHEP02(2022)178)

- CP Violation in WRHDs
  - CPV in heavy flavor radiative decays may be significantly enhanced by NP
  - Extensive experimental studies on D and B meson decays
  - Limited studies in baryon sector
  - WRHDs serve as a probe for CPV
  - PhysRevLett.109.171801, JHEP01(2013)027, JHEP04(2017)027, JHEP08(2017)09
  - PhysRevLett.70.2529, PhysRevLett.109.191801, PhysRevLett.118.051801, PhysRevLett.119.191802
  - PhysRevD.51.2271, PhysRevD.65.074038, PhysRevD.105.116001, Commun.Theor.Phys.19.4
  - PhysRevD.105.L051104

Physics Motivation

Experiment Research Status

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

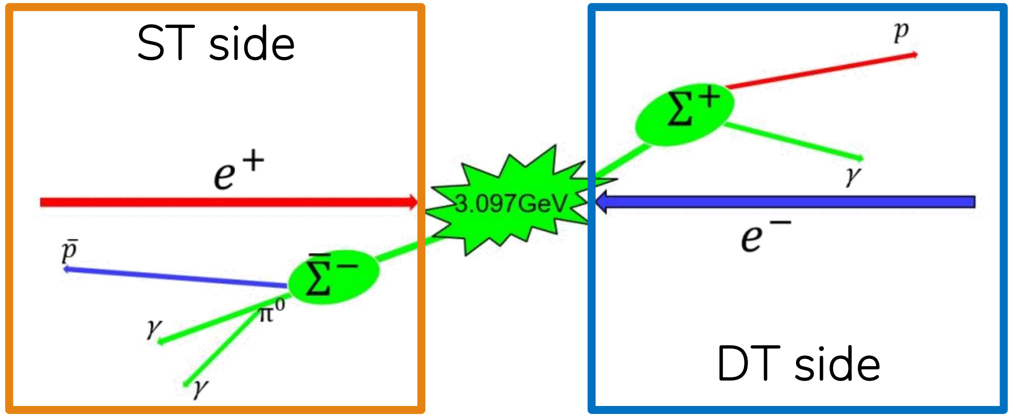
$\Xi^- \to \Sigma^-\gamma$			
时间	实验名或实验方案	分支比（$\times 10^{-3}$）	α_γ
1994	E761	0.122 ± 0.023	-
1987	SPEC	0.227 ± 0.102	-

$\Omega^- \to \Xi^-\gamma$			
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	-

Research Methods
Absolute BF Measurement

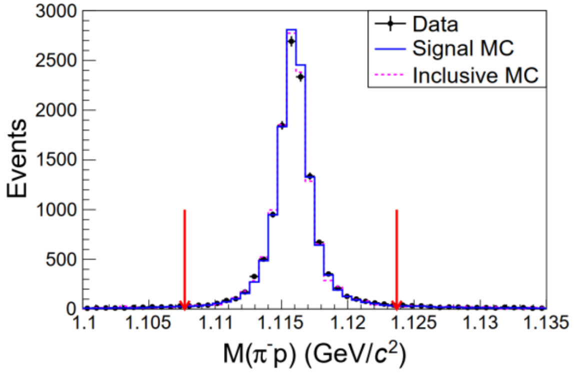
Double-tag method for BF measurement

$$\mathrm{BF} = \frac{N_{\mathrm{DT}}}{N_{\mathrm{ST}}} \times \frac{\varepsilon_{\mathrm{ST}}}{\varepsilon_{\mathrm{DT}}}$$

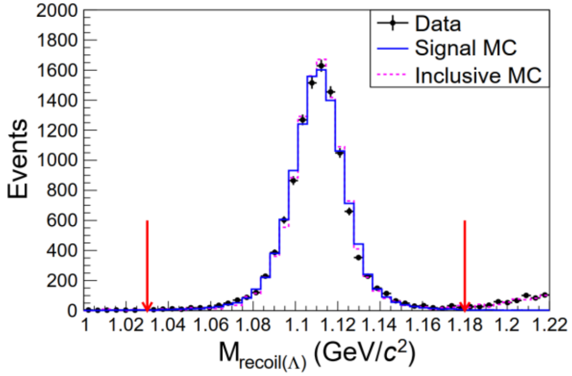


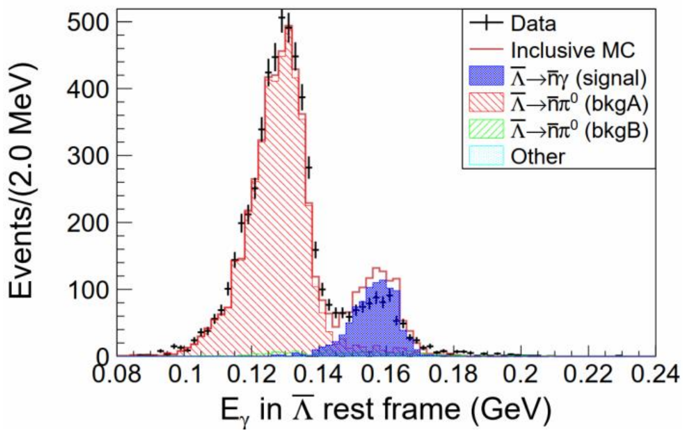
- Well constrained kinematics
- Absolute BF measurement
- Canceled ST selection *syst.* uncertainty

ST reconstruction



ST recoil





DT reconstruction

Research Methods

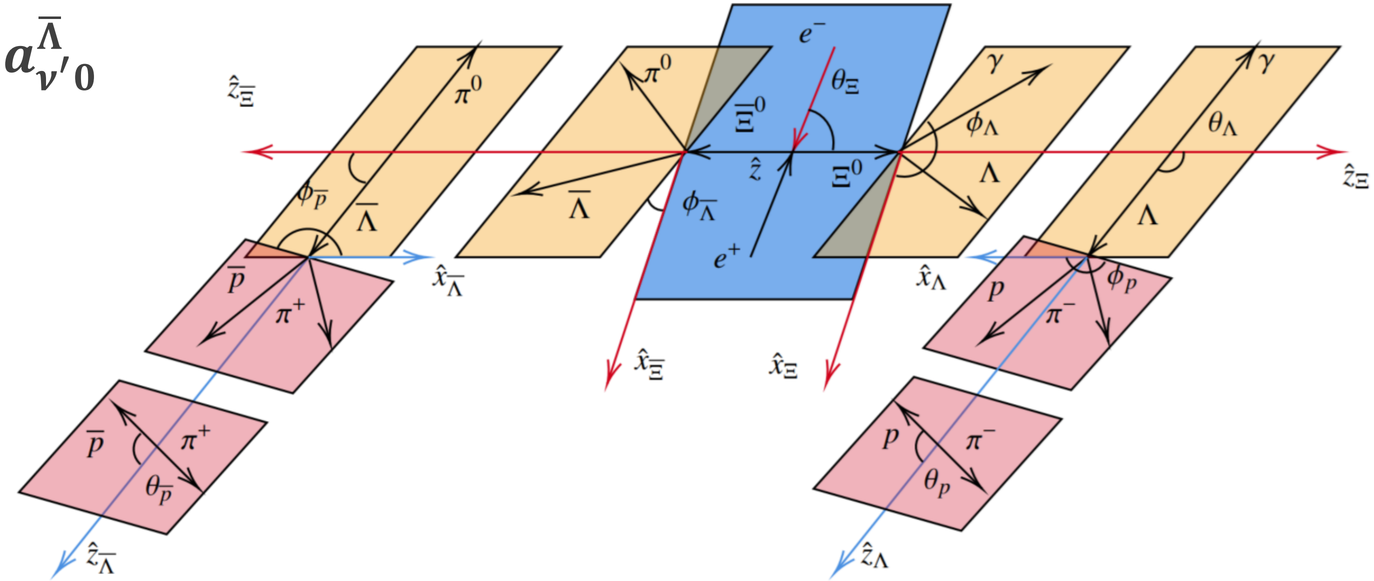
Decay Parameter Measurement

Uniquely pair-produced hyperons from ψ decay

- e.g. $e^+e^- \to J/\psi \to \Xi^0(\to \Lambda\gamma)\bar{\Xi}^0(\to \bar{\Lambda}\pi^0)$ $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$

Decay amplitude (Helicity):

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



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:

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

Research Methods

Decay Parameter Measurement

$\boldsymbol{C}$: polarization and spin correlation matrix of $\boldsymbol{B\bar{B}}$

$$C_{00} = 2(1 + \alpha_\Psi \cos^2\theta_{\Xi^0}),\quad C_{20} = -C_{02},$$
$$C_{02} = 2\sqrt{1-\alpha_\Psi^2}\sin\theta_{\Xi^0}\cos\theta_{\Xi^0}\sin(\Delta\Phi_\Psi),\quad C_{22} = \alpha_\Psi C_{11},$$
$$C_{11} = 2\sin^2\theta_{\Xi^0},\quad C_{31} = -C_{13},$$
$$C_{13} = 2\sqrt{1-\alpha_\Psi^2}\sin\theta_{\Xi^0}\cos\theta_{\Xi^0}\cos(\Delta\Phi_\Psi),\quad C_{33} = -2(\alpha_\Psi + \cos^2\theta_{\Xi^0}),$$

BESIII observation of non-zero $\boldsymbol{\Delta\Phi_\Psi}$

- Transverse polarization and spin-correlation between hyperon pairs (Nat. Phys. 15, 631–634 (2019))

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

$\boldsymbol{a}$: decay matrices of hyperons

$$\beta = \sqrt{1-\alpha^2}\sin(\Delta\Phi),\ \gamma = \sqrt{1-\alpha^2}\cos(\Delta\Phi)$$

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

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

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

$$a_r^\Xi = \begin{pmatrix} 1 & 0 & 0 & -\alpha \\ \alpha\cos\phi\sin\theta & 0 & 0 & -\sin\theta\cos\phi \\ \alpha\sin\theta\sin\phi & 0 & 0 & -\sin\theta\sin\phi \\ \alpha\cos\theta & 0 & 0 & -\cos\theta \end{pmatrix}$$

Decay parameters fitted from amplitude

- Sensitivity multiplicated by ~10 times (Chin. Phys. C 47, 093103 (2023))

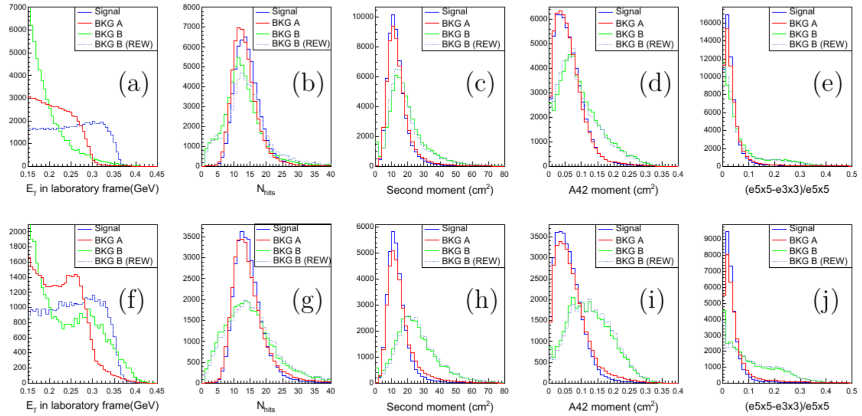
$\Lambda \to n\gamma$ Analysis
Analysis Method Highlights

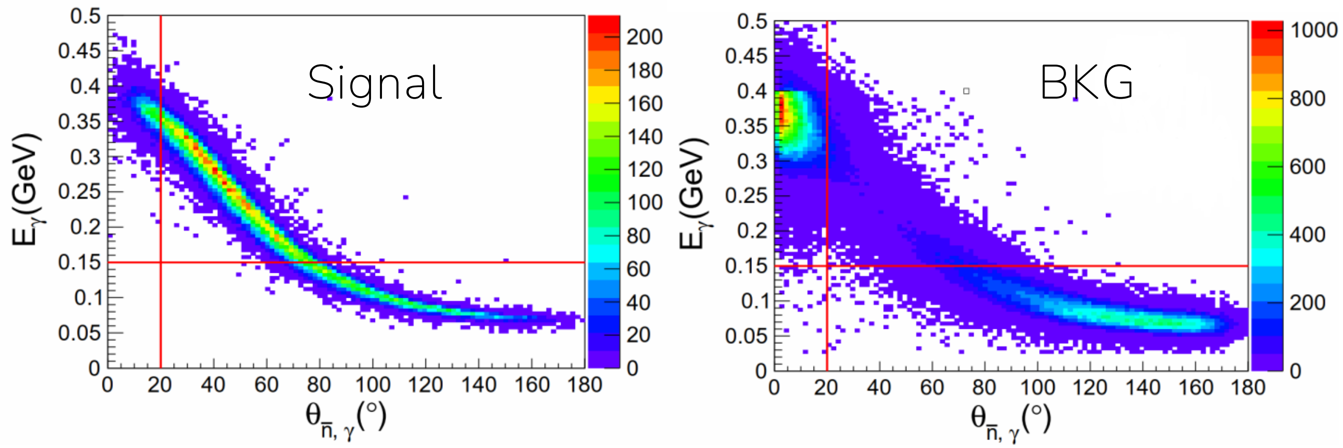
Kinematic fit with missing particle/energy

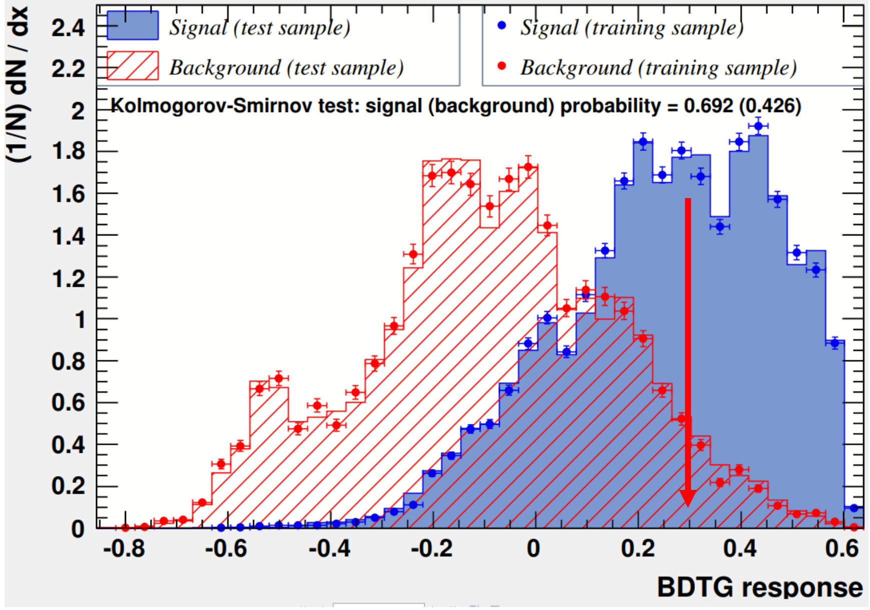
- Hypothesis: $\bar{\Lambda}(\to \bar{p}\pi^{+})\gamma + n$(missing particle)
- Hypothesis: $\Lambda(\to p\pi^{-})\gamma + \bar{n}$(missing energy)
- Superiority of well-constrained kinematics

MVA-based fake photon suppression

- $\boldsymbol{\varepsilon_{bkg} = 3.1\%}$, $\boldsymbol{\varepsilon_{sig} = 50.1\%}$

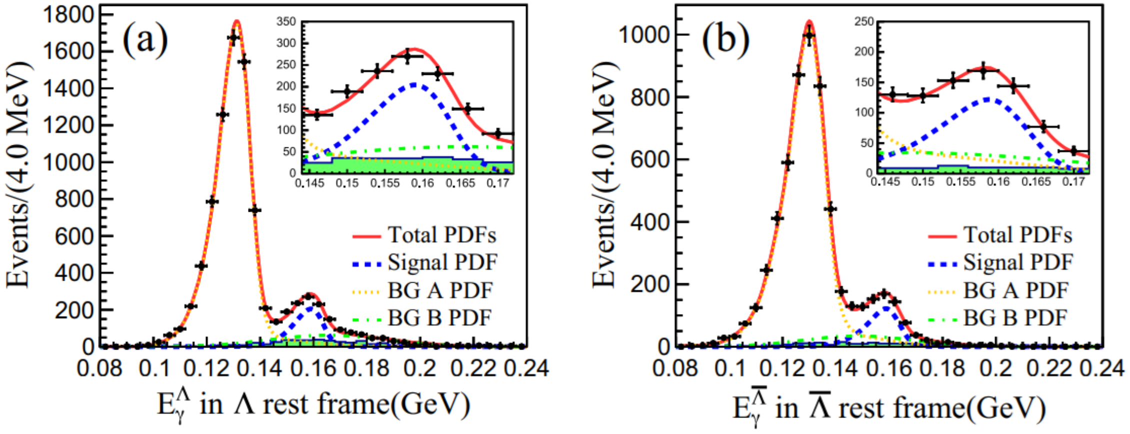




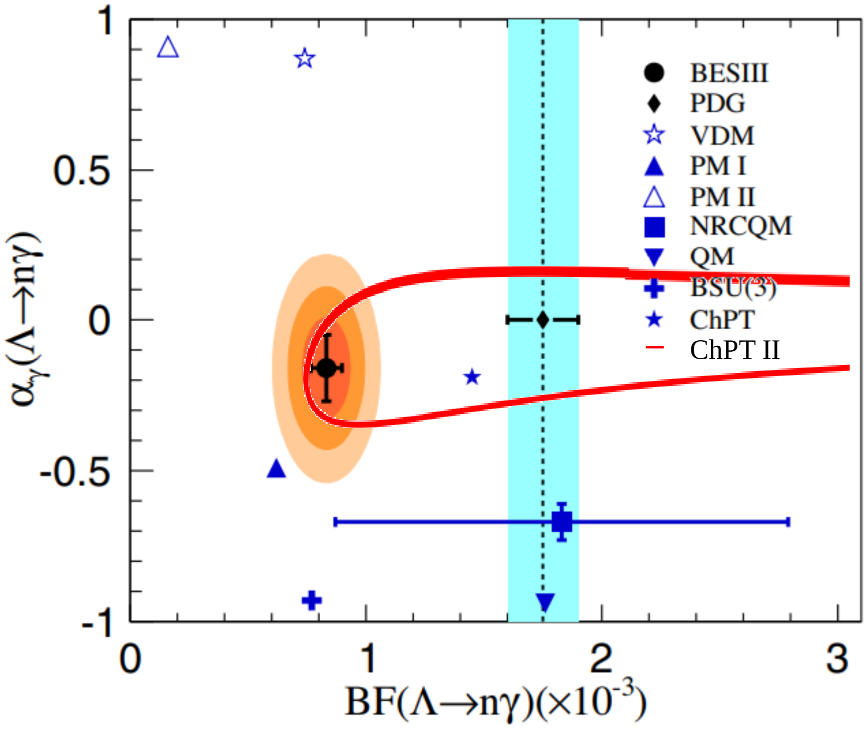


$\Lambda \to n\gamma$ Analysis

Analysis Results



Decay mode	$\Lambda \to n\gamma$	$\bar\Lambda \to \bar{n}\gamma$
N_{ST} $(\times 10^3)$	6853.2 ± 2.6	7036.2 ± 2.7
ε_{ST} (%)	51.13 ± 0.01	52.53 ± 0.01
N_{DT}	723 ± 40	498 ± 41
ε_{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	$-0.13 \pm 0.13 \pm 0.03$	$0.21 \pm 0.15 \pm 0.06$
	$-0.16 \pm 0.10 \pm 0.05$	



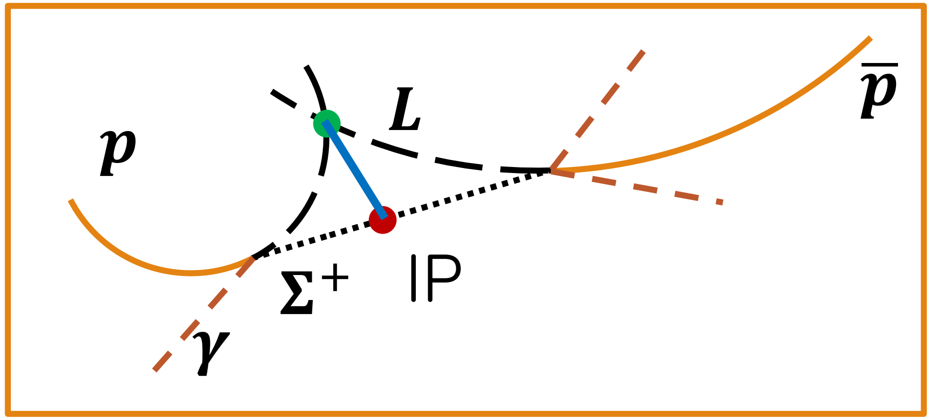
First measurement on α_γ

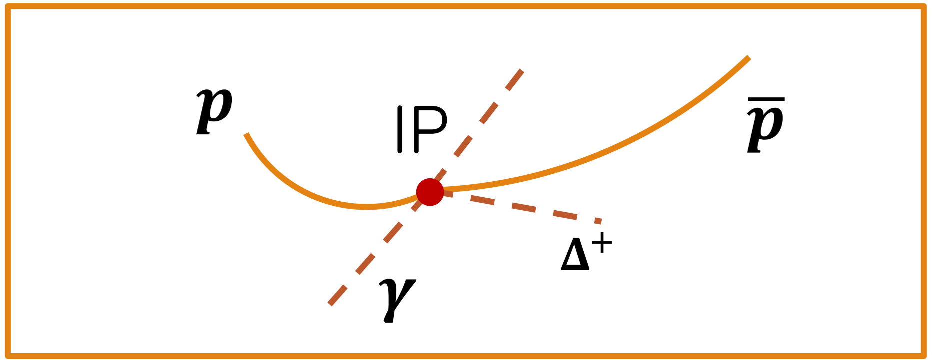
5.6σ deviation of BF

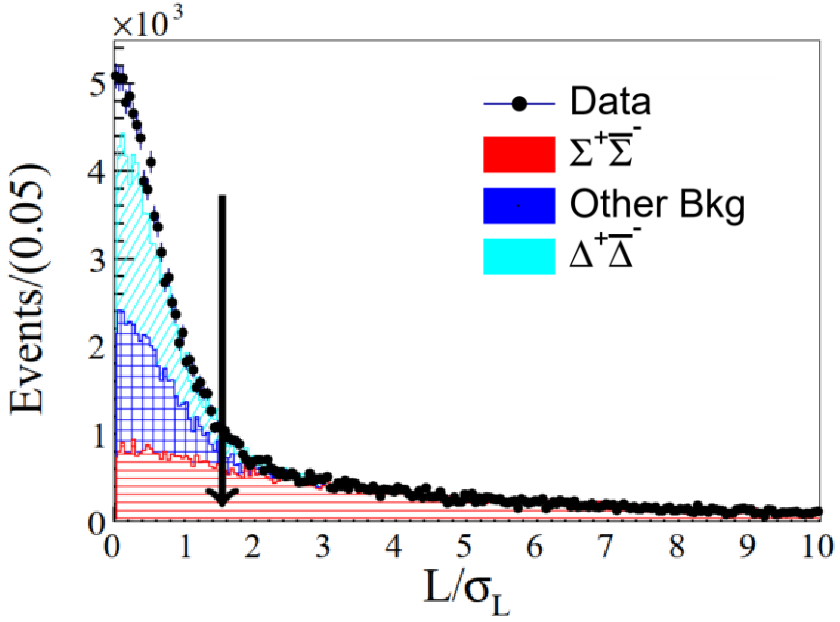
$\Sigma^+ \to p\gamma$ Analysis

Analysis Method Highlights

Utilize joint decay length to discriminate short-lived baryons from signals



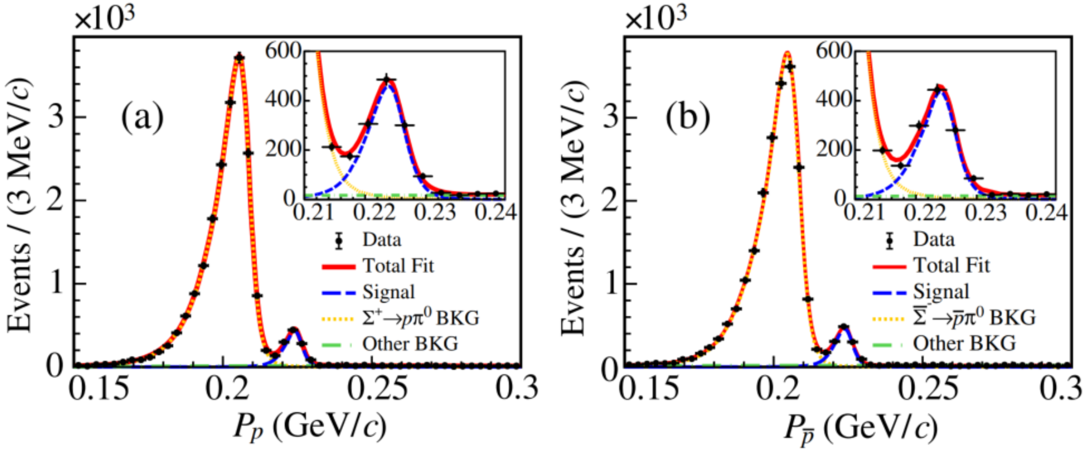




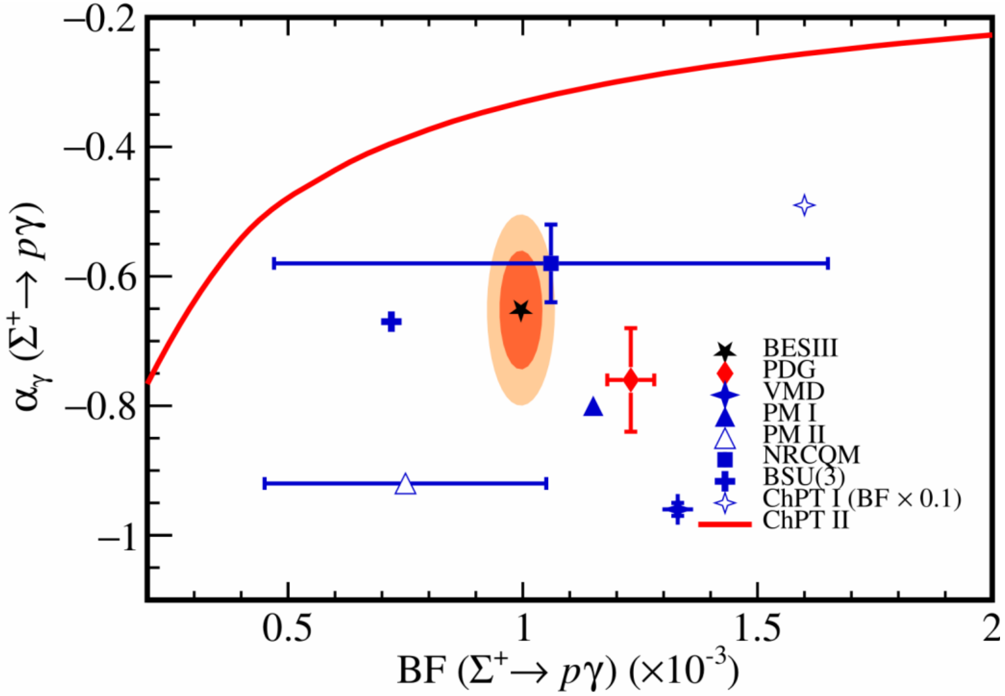
Signal efficiency > 78%
Background efficiency < 7%

$\Sigma^+ \to p\gamma$ Analysis

Analysis Results



Mode	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
N^{obs}_{ST}	$2\,177\,771 \pm 2285$	$2\,509\,380 \pm 2301$
ε_{ST} (%)	39.00 ± 0.04	44.31 ± 0.04
N^{obs}_{DT}	1189 ± 38	1306 ± 39
ε_{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	$-0.652 \pm 0.056 \pm 0.020$	

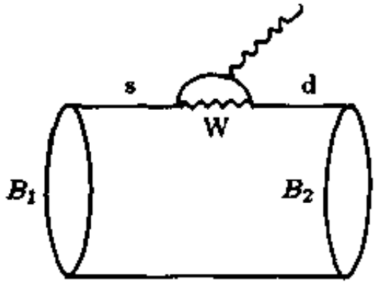


Significantly improved accuracy
- BF: 78%
- α_γ: 34%

$\Sigma^+ \to p\gamma$ Analysis
CP Asymmetry Test

Potential CP asymmetry sources:

- Loop diagram contribution:



- Other terms - strong phase dependent on QCD models:

$$S = \sum_j S_j e^{i(\xi_j^S + \delta_{2I}^S)}$$

$$P = \sum_j P_j e^{i(\xi_j^P + \delta_{2I}^P)}$$

First Measurement of CP asymmetry of $\Sigma^+ \to p\gamma$ decay

- Statistical uncertainty dominated
- Need more statistics to reach the precision of theory predictions

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

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

	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}	

Summary & Prospects

Since 2022, BESIII experiment has provided fresh results to the field

Inconsistency between exp. results and theory predictions still exist

More results with higher precision expected

$\Lambda \to n\gamma$(Phys.Rev.Lett. 129 (2022))		
	BF (x10^{-3})	α_γ
2022, BESIII	0.846±0.039±0.052	-0.160±0.101±0.046
PDG	1.75±0.15	---

$\Xi^0 \to \Lambda\gamma$ (BAM-760)		
Experiment	BF (x10^{-3})	α_γ
2024, BESIII	xxx	xxx
PDG	1.17±0.07	-0.70±0.07

$\Sigma^+ \to p\gamma$(Phys. Rev. Lett. 130, 211901 (2023))		
Experiment	BF (x10^{-3})	α_γ
2022, BESIII	0.996±0.021±0.018	-0.652±0.056±0.020
PDG	1.23±0.05	-0.76±0.08

$\Xi^0 \to \Sigma^0\gamma$		
Experiment	BF (x10^{-3})	α_γ
BESIII	xxx	xxx
PDG	3.33±0.10	-0.69±0.06

Significantly improved precision

Competitive precision

Summary & Prospects

Studies on $\Xi^- \to \Sigma^- \gamma$ and $\Omega^+ \to \Xi^- \gamma$ decays undergoing

"The last piece of the puzzle"

$\Xi^- \to \Sigma^- \gamma$		
Experiment	BF (x10^{-3})	α_γ
BESIII	?	?
PDG	1.27$\pm$0.23	---

$\Omega^+ \to \Xi^- \gamma$		
Experiment	BF (x10^{-3})	α_γ
BESIII	?	
PDG	<0.46	---

Special thanks to Prof. L.-S. Geng and Dr. R.-X. Shi