Rare decay and NP search with Hyperons at BESIII

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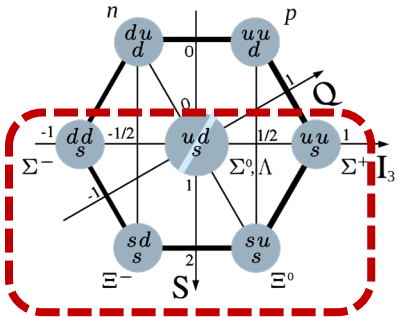
BESIII实验上粲强子、QCD及新物理研讨会

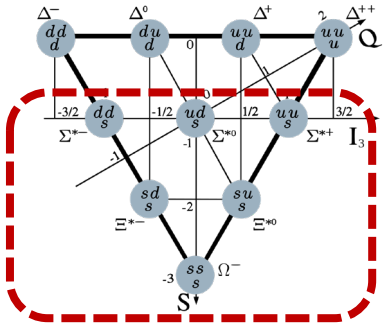
August 23, 2022

Introduction

- **Hyperon:** baryon with one or more s-quark, but without any heavy quarks

- **Role in HEP frontier problems**
  - Hadron structure and QCD test
  - Precision measurement of CKM matrix
  - CP violation
  - Lepton flavor universality
  - NP models
  - …





- **Experimental status**
  - Many results not updated for decades
  - Mainly conducted by fixed-target experiments
  - BESIII is making massive contributions

Decay	Last updated	Collaboration
$\Sigma^+ \to \Lambda e^+ \bar{\nu}_e$	1969	HBC (BNL)
$\Sigma^+ \to p e^+ e^-$	1969	HBC (BNL)
$\Sigma^+ \to n e^+ \nu_e$	1974	HBC (BNL)
$\Xi^0 \to p e^- \bar{\nu}_e$	1974	HBC (BNL)
$\Lambda \to p e^- \bar{\nu}_e$	1983	SPEC (CERN)
$\Sigma^- \to n e^- \bar{\nu}_e$	1983	SPEC (CERN)
$\Sigma^+ \to p\gamma$	1995	E761 (Fermilab)
…		
$\Xi^0 \to \Lambda e^+ e^-$	2007	NA48 (CERN)
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$	2007	NA48 (CERN)
$\Lambda \to \pi^+ e^-$	2015	CLAS
$\Sigma^+ \to p \mu^+ \mu^-$	2018	LHCb
$\Lambda \to p \mu^- \bar{\nu}_\mu$	2021	BESIII
$\Xi^- \to \Xi^0 e^- \bar{\nu}_e$	2021	BESIII
$\Sigma^- \to p e^- e^-$	2021	BESIII
$\Lambda \to invisible$	2022	BESIII

Hyperon rare decay at BESIII

- **Semileptonic decays**
  - Study of $\Lambda \to p\mu^-\bar{\nu}_\mu$ — PRL 127, 121802 (2021)
  - Search for $\Xi^- \to \Xi^0 e^-\bar{\nu}_e$ — PRD 104, 072007 (2021)
  - Search for $\Xi^0 \to \Sigma^- e^+\nu_e$ — arXiv:2208.09221
  - Study of $\Sigma^+ \to \Lambda e^+\nu_e$ — BAM-576 (ongoing)
- **Radiative decays**
  - Study of $\Lambda \to n\gamma$ — arXiv:2206.10791
  - Study of $\Sigma^+ \to p\gamma$ — BAM-559 (ongoing)
- **BNV & LNV decays**
  - Search for $\Sigma^- \to pe^-e^-$ — PRD 103, 052001 (2021)
  - Search for $\Xi^0 \to K^\pm e^\mp + c.c.$ — BAM-625 (ongoing)
- **Invisible decays**
  - Search for $\Lambda \to invisible$ — PRD 105, 071101 (2022)

Techniques for hyperon research

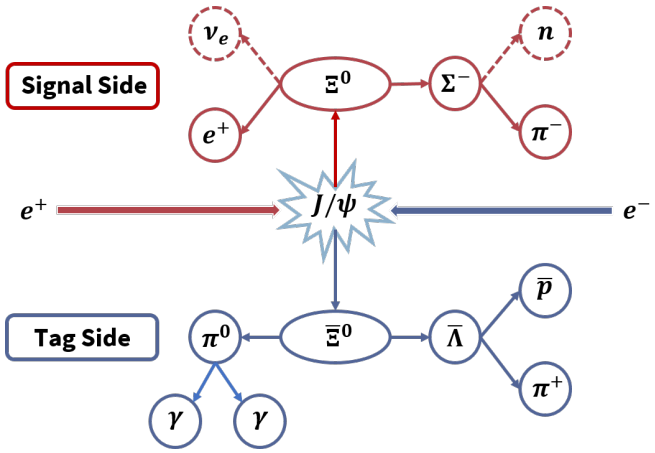
- **Datasets**
  - 10 billion $J/\psi \to B\bar{B}$
  - 2.7 billion $\psi(2S) \to B\bar{B}$

- **Double-tag method**
  - Absolute BF measurement
  - Kinematic constraints
  - Cancel ST related sys. uncertainty

- **Helicity formalism**
  - Extract form factor & decay asymmetry via angular distributions

- **(Semi-)blind procedure**
  - Avoid personal bias

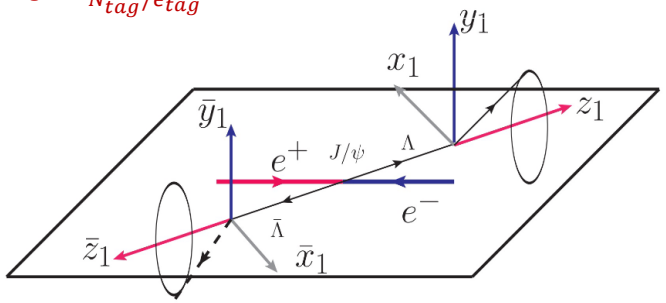
J/ψ Decay mode	Events ($\times 10^6$)	$\psi(2S)$ Decay mode	Events ($\times 10^6$)
$\Lambda\bar{\Lambda}$	18.9 ± 0.9	$\Lambda\bar{\Lambda}$	1.03 ± 0.03
$\Sigma^0\bar{\Sigma}^0$	11.7 ± 0.3	$\Sigma^0\bar{\Sigma}^0$	0.66 ± 0.03
$\Sigma^+\bar{\Sigma}^-$	10.7 ± 0.4	$\Sigma^+\bar{\Sigma}^-$	0.64 ± 0.02
$\Sigma(1385)^-\bar{\Sigma}^+(+c.c.)$	3.1 ± 0.5	$\Xi^0\bar{\Xi}^0$	0.78 ± 0.03
$\Sigma(1385)^-\bar{\Sigma}(1385)^+(+c.c.)$	11.6 ± 0.5	$\Xi^-\bar{\Xi}^+$	0.6 ± 0.1
$\Xi^0\bar{\Xi}^0$	11.7 ± 0.4	$\Omega^-\bar{\Omega}^+$	0.153 ± 0.008
$\Xi^-\bar{\Xi}^+$	9.7 ± 0.8		



$$N_{tag}^{obs} = 2N_{B\bar{B}}\mathcal{B}_{tag}\epsilon_{tag}$$

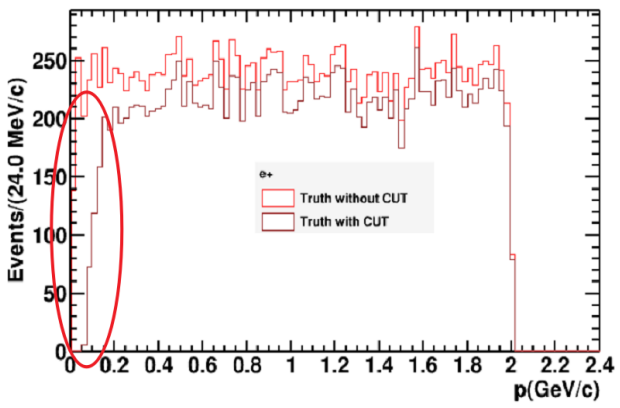
$$N_{sig}^{obs} = 2N_{B\bar{B}}\mathcal{B}_{tag}\mathcal{B}_{sig}\epsilon_{sig}$$

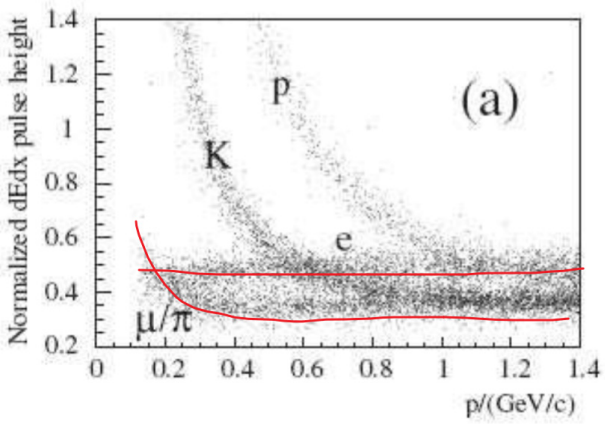
$$\mathcal{B}_{sig} = \frac{N_{sig}^{obs}/\epsilon_{sig}}{N_{tag}^{obs}/\epsilon_{tag}}$$



Challenges in hyperon research

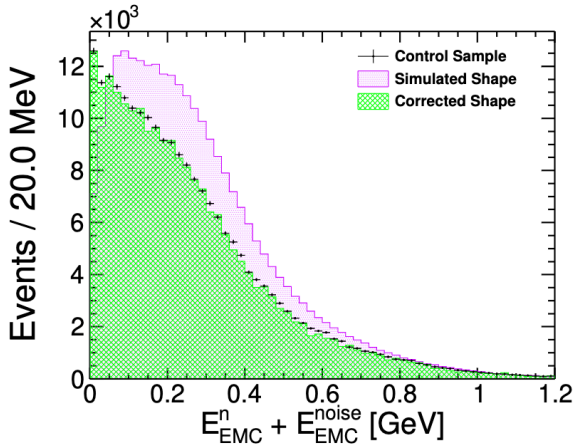
- **Low momentum final particles**
  - Efficiency loss / noise
  - e/π, μ/π identification
  - Systematic uncertainty





- **Dominant BKG from hadronic decays**
  - BF about $10^3 \sim 10^4$ larger than signal

- **Neutron reconstruction**
  - Interaction with EMC: scattering, annihilation, fission, absorption…
  - Efficiency, identification and reconstruction issues
  - Unprecise MC simulation by Geant4



- **Physical model for MC generator**
  - SM / NP calculations translated to decay amplitude

Semileptonic decays

- Help understand the interplay between weak and strong interactions
- **SU(3) symmetry breaking**
  - Theoretical studies still rely on SU(3) method due to light quarks
  - Indications of breaking for a few percents
- **Transition form factor**
  - Predictable at SU(3) limit
  - Poorly measured in experiments
- **CKM matrix element**
  - Precision for $|V_{us}|$ could be comparable with kaon decays
- **Lepton flavor universality**
  - $R^{\mu e} = \Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)/\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)$

PRD 100, 076008 (2019)

Decay modes	$g_1(0)/f_1(0)$	$f_2(0)/f_1(0)$
$\Xi^- \to \Sigma^0 \ell^- \bar{\nu}_\ell$	1.22 ± 0.05^a	2.609^b
$\Xi^- \to \Lambda^0 \ell^- \bar{\nu}_\ell$	0.25 ± 0.05	0.085^b
$\Xi^0 \to \Sigma^+ \ell^- \bar{\nu}_\ell$	1.22 ± 0.05	2.0 ± 0.9
$\Lambda^0 \to p \ell^- \bar{\nu}_\ell$	0.718 ± 0.015	1.066^b
$\Sigma^0 \to p \ell^- \bar{\nu}_\ell$	-0.340 ± 0.017^a	-1.292^b
$\Sigma^- \to n \ell^- \bar{\nu}_\ell$	-0.340 ± 0.017	-0.97 ± 0.14
$\Sigma^- \to \Sigma^0 e^- \bar{\nu}_e$	$\frac{1}{2}[(1.2724 \pm 0.0023) + (-0.340 \pm 0.017)]^a$	0.534^b
$\Sigma^- \to \Lambda^0 e^- \bar{\nu}_e$	$(-0.01 \pm 0.10)^{-1}$	1.490^b
$\Sigma^0 \to \Sigma^+ e^- \bar{\nu}_e$	$-\frac{1}{2}[(1.2724 \pm 0.0023) + (-0.340 \pm 0.017)]^a$	0.531^b
$\Sigma^+ \to \Lambda^0 e^+ \nu_e$	$(-0.01 \pm 0.10)^{-1\,a}$	1.490^b
$\Xi^- \to \Xi^0 e^- \bar{\nu}_e$	-0.340 ± 0.017^a	-1.432^b
$n \to p e^- \bar{\nu}_e$	1.2724 ± 0.0023	1.855^b

PRL 92, 251803 (2004)

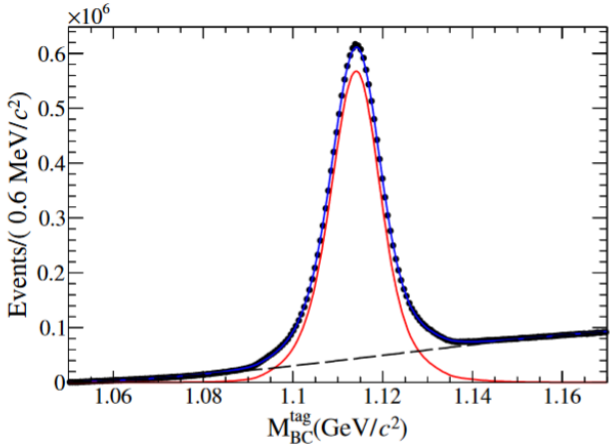
Decay Process	Rate (μsec^{-1})	g_1/f_1	V_{us}
$\Lambda \to p e^- \overline{\nu}$	3.161(58)	0.718(15)	0.2224 ± 0.0034
$\Sigma^- \to n e^- \overline{\nu}$	6.88(24)	−0.340(17)	0.2282 ± 0.0049
$\Xi^- \to \Lambda e^- \overline{\nu}$	3.44(19)	0.25(5)	0.2367 ± 0.0099
$\Xi^0 \to \Sigma^+ e^- \overline{\nu}$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

PRL 114, 161802 (2015)

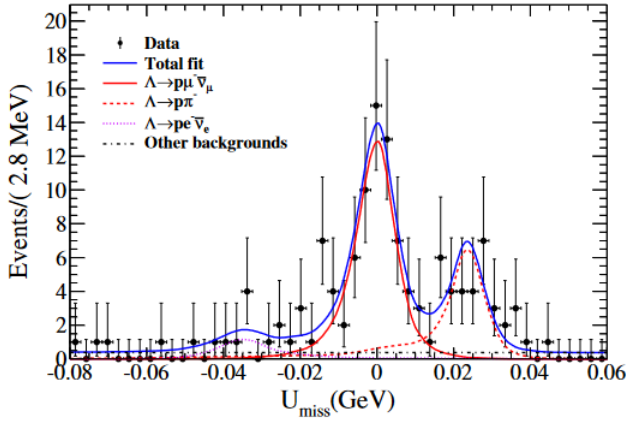
	$\Lambda \to p$	$\Sigma^- \to n$	$\Xi^0 \to \Sigma^+$	$\Xi^- \to \Lambda$
Expt.	0.189(41)	0.442(39)	0.0092(14)	0.6(5)
SM-NLO	0.153(8)	0.444(22)	0.0084(4)	0.275(14)

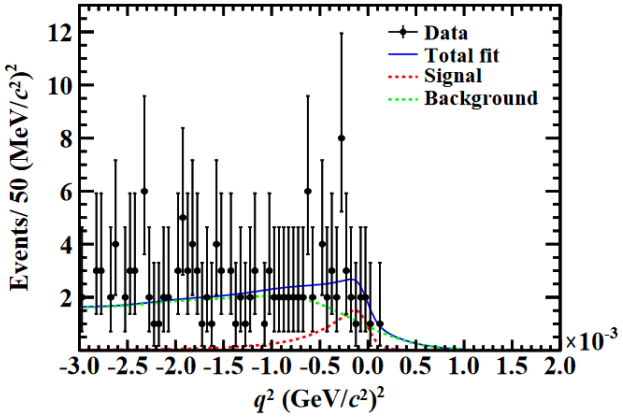
Semileptonic decays

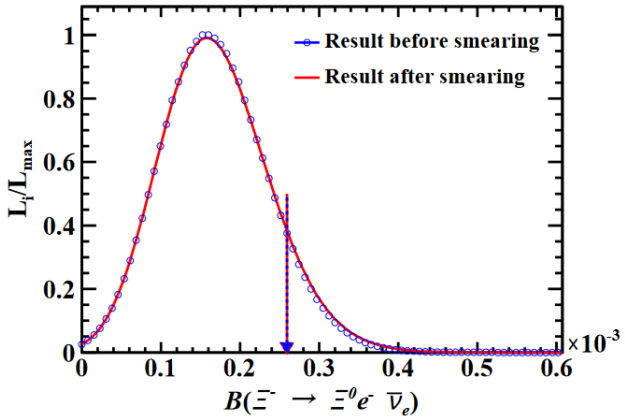
- **Study of $\Lambda \to p\mu^-\bar{\nu}_\mu$** PRL 127, 121802 (2021)
  - First measurement of absolute BF to be $(1.48 \pm 0.21_{stat.} \pm 0.08_{syst.}) \times 10^{-4}$
  - Precision improved by about 30% after half a century
  - Obtain $R^{\mu e} = 0.178 \pm 0.028$, consistent with SM
  - Obtain $\mathcal{A}_{CP} = (0.02 \pm 0.14_{stat.} \pm 0.02_{syst.})$, no CPV found
  - Study of $\Lambda \to pe^-\bar{\nu}_e$ is ongoing, capable to extract form factors



- **Search for $\Xi^- \to \Xi^0 e^-\bar{\nu}_e$** PRD 104, 072007 (2021)
  - Upper limit of BF determined to be 2.59×10^{-4} @ 90% C. L.
  - Constraint improved by one order of magnitude

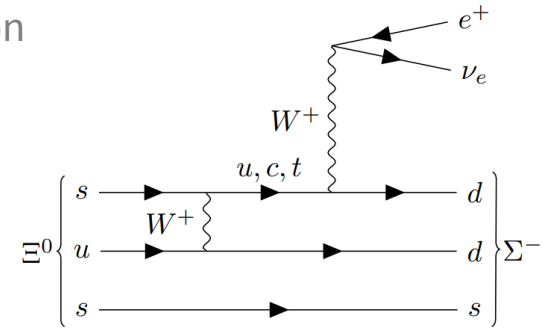


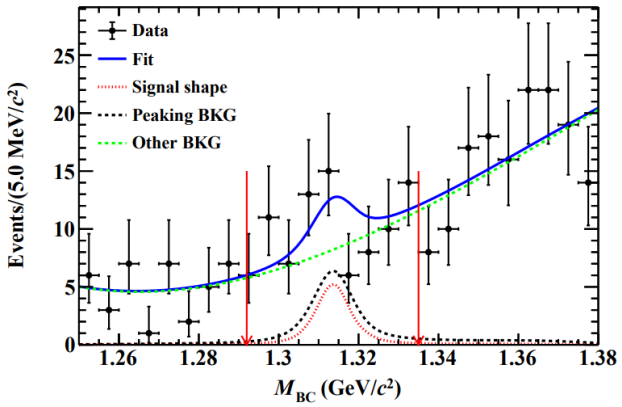




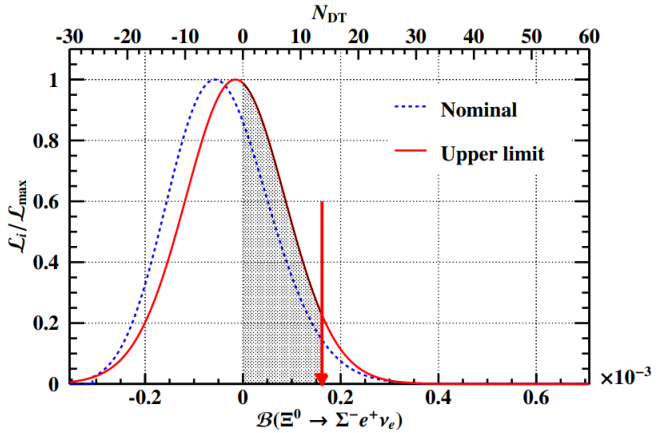
Semileptonic decays

- **Search for $\Xi^0 \to \Sigma^- e^+ \nu_e$** arXiv: 2208.09221
  - Violate the $\Delta S = \Delta Q$ selection rule
    - One basic assumption in Cabibbo's weak theory
    - Allowed by SM via second-order weak interaction
  - Could be a new probe for SU(3) symmetry breaking
  - Upper limit of BF to be 1.6×10^{-4} @ 90% C. L.
  - Constraint improved by one order of magnitude





- **Study of $\Sigma^+ \to \Lambda e^+ \nu_e$** BAM-576 (ongoing)
  - First measurement of absolute BF
  - Test the SM prediction of $R = \frac{\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)}{\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)}$
    - Weinberg for the absence of second-class currents
    - Lee & Yang for the strangeness-conserving weak current transforming as an isotopic vector
  - Challenging to push sensitivity up to $\sim 2 \times 10^{-5}$



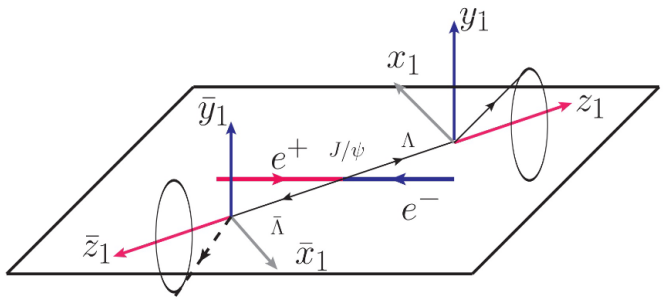
Radiative decays

- A unique probe for strong/weak/EM interactions
- Description complicated by the presence of strong force
  - $\boldsymbol{A}$: parity-conserving (M1) amplitude
  - $\boldsymbol{B}$: parity-violating (E1) amplitude

$$T = G_F \frac{e}{\sqrt{4\pi}} \epsilon_\nu \bar{u}(p')(\boldsymbol{A} + \boldsymbol{B}\gamma_5)\sigma_{\mu\nu} q_\mu u(p) \qquad \alpha_\gamma = \frac{2Re(\boldsymbol{A} * \boldsymbol{B})}{|\boldsymbol{A}|^2 + |\boldsymbol{B}|^2}$$

$B_i \to \gamma B_f$	BF(10^{-3})	α_γ
$\Lambda \to \gamma n$	1.75±0.15	–
$\Sigma^+ \to \gamma p$	1.23 ± 0.05	-0.76 ± 0.08
$\Sigma^0 \to \gamma n$	–	BESIII ongoing
$\Xi^0 \to \gamma \Lambda$	1.17 ± 0.07	-0.70 ± 0.07
$\Xi^0 \to \gamma \Sigma^0$	3.33 ± 0.10	-0.69 ± 0.06
$\Xi^- \to \gamma \Sigma^-$	0.127 ± 0.023	1.0 ± 1.3
$\Omega^- \to \gamma \Xi^-$	$< 0.46(90\%C.L.)$	–

- **Puzzle of Hara's theorem**
  - Parity-violating amplitude should vanish at SU(3) limit
  - Decay asymmetry parameter α_γ calculated to be $\sim \pm 0.2$
  - Yet large negative α_γ are observed in Σ^+ and Ξ^0 decays
  - Still controversial in theory to date

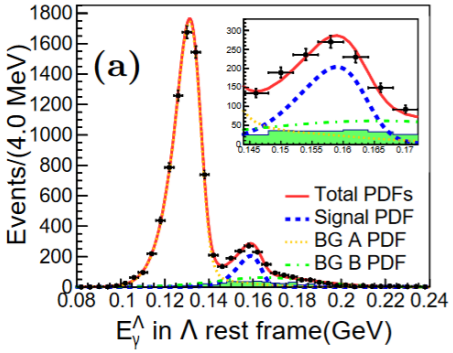


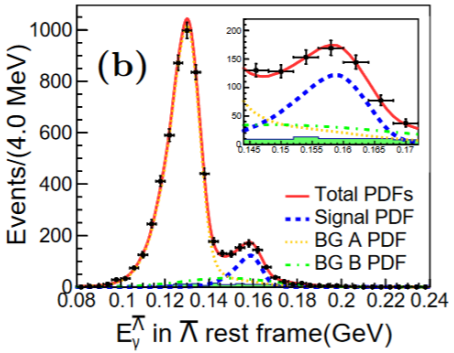
- **Helicity method at BESIII**
  - Extract α_γ via joint angular distributions

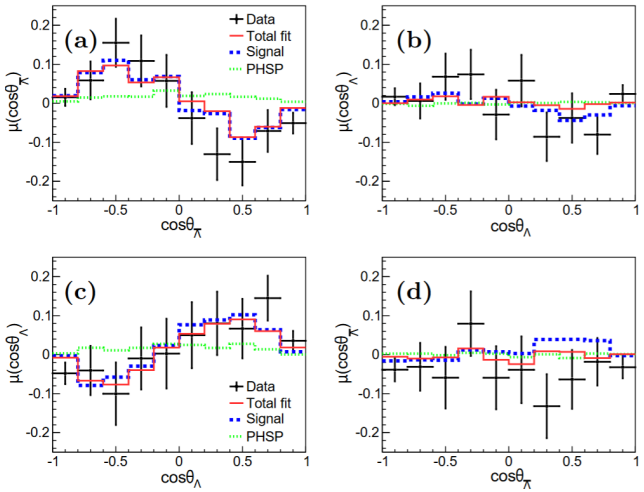
$$\omega(\xi, \alpha_{J/\psi}, \Delta\Phi, \alpha_-, \alpha_\gamma) = 1 + \alpha_\psi cos^2\theta_\Lambda$$
$$+ \alpha_-\alpha_\gamma[sin^2\theta_\Lambda(n_{1,x}, n_{2,x} - \alpha_\psi n_{1,y}, n_{2,y}) + (cos^2\theta_\Lambda + \alpha_\psi)n_{1,z}, n_{2,z}]$$
$$+ \alpha_-\alpha_\gamma \sqrt{1-\alpha_\psi^2} cos(\Delta\Phi) sin\theta_\Lambda cos\theta_\Lambda (n_{1,x}, n_{2,z} + n_{1,z}, n_{2,x})$$
$$+ \sqrt{1-\alpha_\psi^2} sin(\Delta\Phi) sin\theta_\Lambda cos\theta_\Lambda (\alpha_- n_{1,y} + \alpha_\gamma n_{2,y})$$

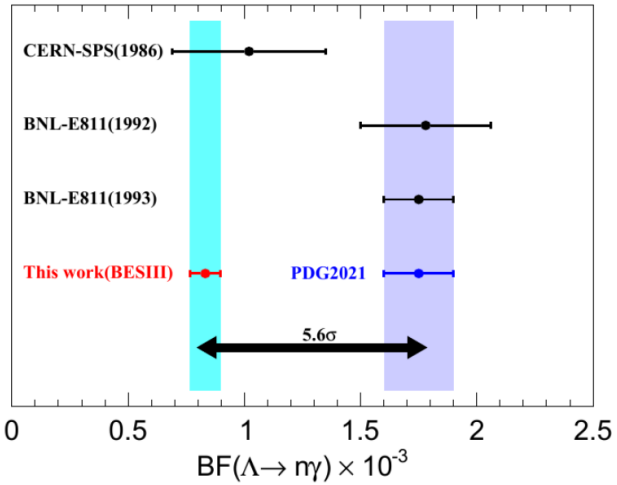
Radiative decays

- **Study of $\Lambda \to n\gamma$** arXiv: 2206.10791
  - Absolute BF as $(0.832 \pm 0.038_{stat.} \pm 0.054_{syst.}) \times 10^{-3}$
  - Improved precision, smaller than PDG value by 5.6σ
  - First determination of $\alpha_\gamma = -0.16 \pm 0.10_{stat.} \pm 0.05_{syst.}$
  - Provide essential inputs to theoretical models





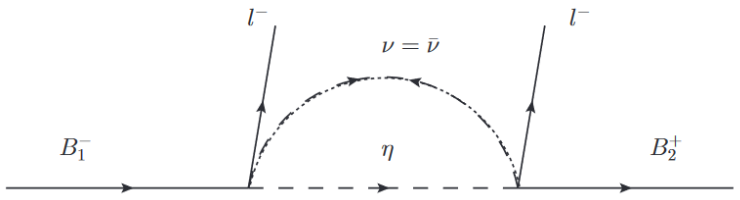




- **Study of $\Sigma^+ \to p\gamma$** BAM-559 (ongoing)
  - First measurement of absolute BF
  - Capable to improve the precision of α_γ

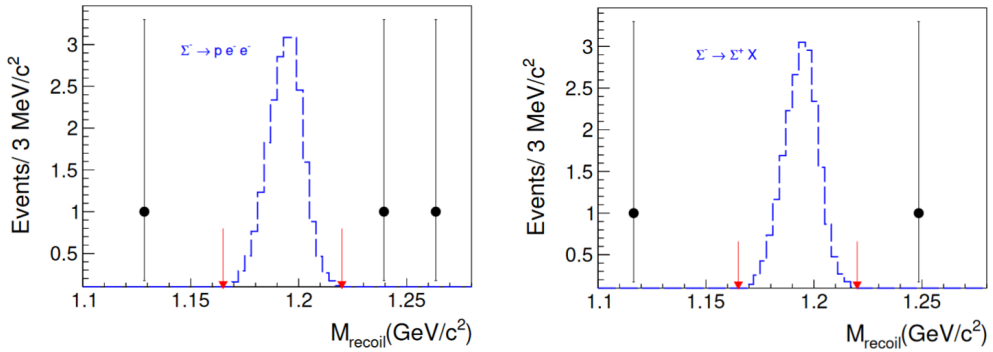
BNV & LNV decays

- **BNV:** required by baryon-antibaryon asymmetry in the universe
  - NP models allow $\Delta(B-L) = 0\ or\ -2$ decays

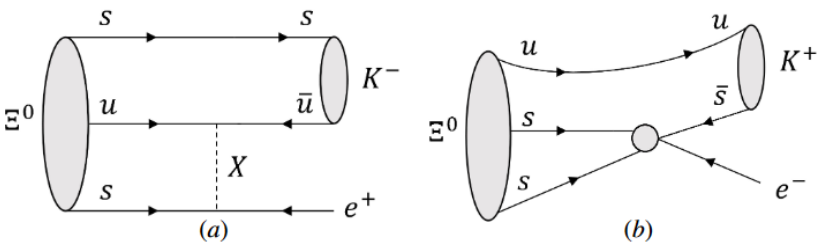


- **LNV:** Majorana neutrinos → $0\nu\beta\beta$ decays → $\Delta L = 2$
  - Provide additional constraint from collider experiment

- **Search for $\Sigma^- \to pe^-e^-$** PRD 103, 052001 (2021)
  - Upper limit of BF determined to be 6.7×10^{-5} @ 90% C. L.
  - Conducted using 1.3B J/ψ events
  - The inclusive decay $\Sigma^- \to \Sigma^+ + X$ is also searched for



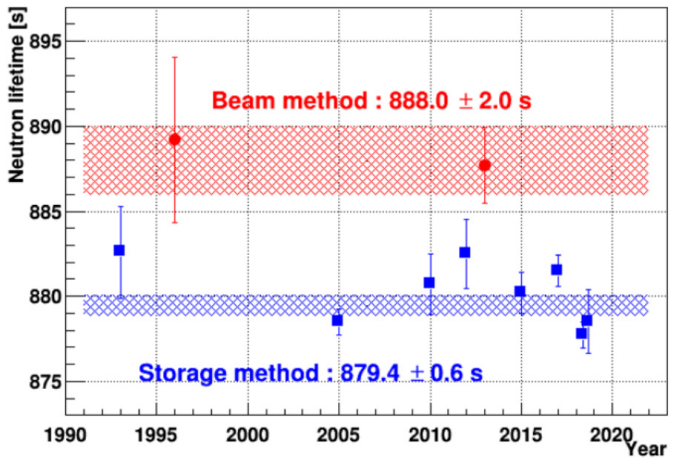
- **Search for $\Xi^0 \to K^\pm e^\mp + c.c.$** BAM-625 (ongoing)
  - Sensitivity could reach 10^{-6}



Invisible decays

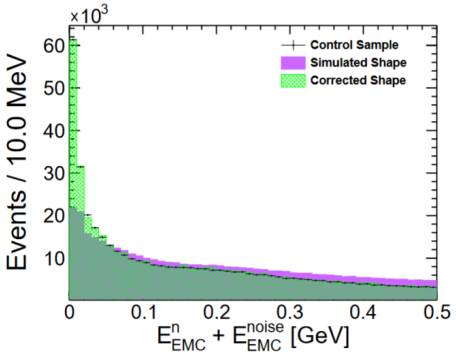
- Candidate for dark matter and baryon asymmetry
  - Dark matter ↔ "dark sector" ↔ baryon asymmetry

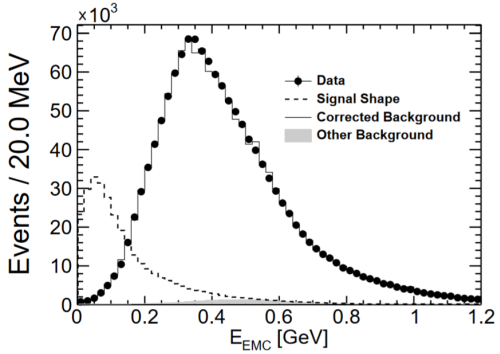
- **Neutron lifetime puzzle**
  - Beam method ($n \to pe^-\bar{\nu}_e$) and storage method ($n \to X$)
  - Discrepancy may indicate $\mathcal{B}(n \to invisible) \sim 1\%$



JPS Conf.Proc. 33 (2021) 011056

- **Search for $\Lambda \to invisible$** PRD 105, 071101 (2022)
  - First search of baryon invisible decay
  - Upper limit of BF to be 7.4×10^{-5} @ 90% C. L.
  - Data-driven correction for n deposited energy at EMC





Summary & Outlook

- **Summary**
  - Studies of rare hyperon decays at BESIII are reviewed.
  - Many NP models can be examined and constrained via hyperon decays.
  - Various analysis techniques are applied to solve the challenges.

- **Outlook**
  - Full J/ψ and $\psi(2S)$ datasets now available, more analyses on the go.
  - The FCNC searches in hyperons are still absent
    - Strongly suppressed in SM ($\mathcal{B}\sim10^{-12}$)
    - Enhanced in some NP models up to 10^{-6}
    - Prospects: Front. Phys. 12, 121301 (2017)
    - Methodology: Dong Xiao's talk at NPG workshop 2021

Decay mode	Current data $\mathcal{B}$ ($\times10^{-6}$)	Sensitivity $\mathcal{B}$ (90% C.L.) ($\times10^{-6}$)	Type
$\Lambda \to ne^+e^-$	–	< 0.8	Type A
$\Sigma^+ \to pe^+e^-$	< 7	< 0.4	
$\Xi^0 \to \Lambda e^+e^-$	7.6 ± 0.6	< 1.2	
$\Xi^0 \to \Sigma^0 e^+e^-$	–	< 1.3	
$\Xi^- \to \Sigma^- e^+e^-$	–	< 1.0	
$\Omega^- \to \Xi^- e^+e^-$	–	< 26.0	
$\Sigma^+ \to p\mu^+\mu^-$	$(0.09^{+0.09}_{-0.08})$	< 0.4	
$\Omega^- \to \Xi^- \mu^+\mu^-$	–	< 30.0	
$\Lambda \to n\nu\bar{\nu}$	–	< 0.3	Type B
$\Sigma^+ \to p\nu\bar{\nu}$	–	< 0.4	
$\Xi^0 \to \Lambda\nu\bar{\nu}$	–	< 0.8	
$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	–	< 0.9	
$\Xi^- \to \Sigma^-\nu\bar{\nu}$	–	–*	
$\Omega^- \to \Xi^-\nu\bar{\nu}$	–	< 26.0	

Thanks for your attention!