Studies on Weak Radiative Hyperon Decays at BESIII

Zekun Jia

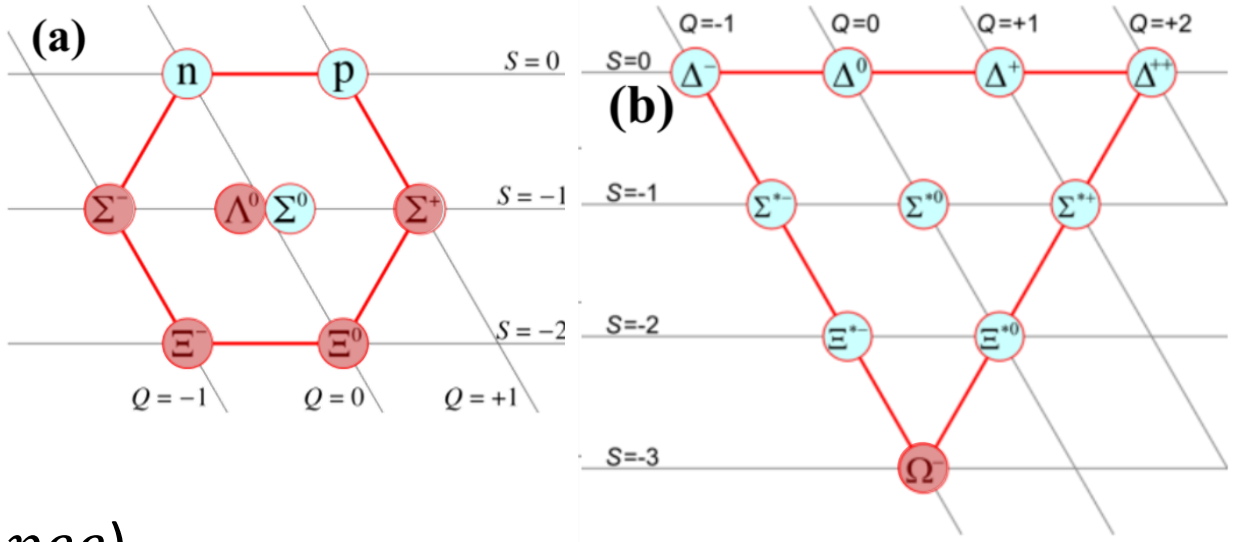
zekun.jia@cern.ch

On behalf of the workgroup

Introduction

Challenges facing the Standard Model

- The origin of hadron mass?
- Inner structure of hadrons?
- Hadron decay mechanism?
  - Significant non-perturbation QCD effects
  - Hyperon: baryons containing s quarks
  - Proving ground of basic symmetries: SU(3), *CP*
  - Decay of ground hyperons:
    - Weak hadronic decay ($\Sigma^+ \to p\pi^0$)
    - Semi-leptonic decay ($\Sigma^+ \to pe\nu_e, \Sigma^+ \to pee$)
    - Weak radiative decay (WRHD) ($\Sigma^+ \to p\gamma$)



Weak Radiative Hyperon Decays

Overview

- Flavor Changing Neutral Current process ($s \to d\gamma$ transition)
- A symphony of strong, weak and EM interaction
- Effective Lagrangian

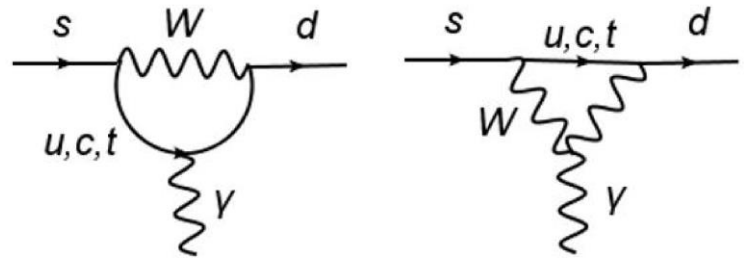
$$\mathcal{L} = \frac{eG_F}{2}\bar{Y}_f\left(a^{\mathrm{PC}} + b^{\mathrm{PV}}\gamma_5\right)\sigma^{\mu\nu}Y_i F_{\mu\nu}$$

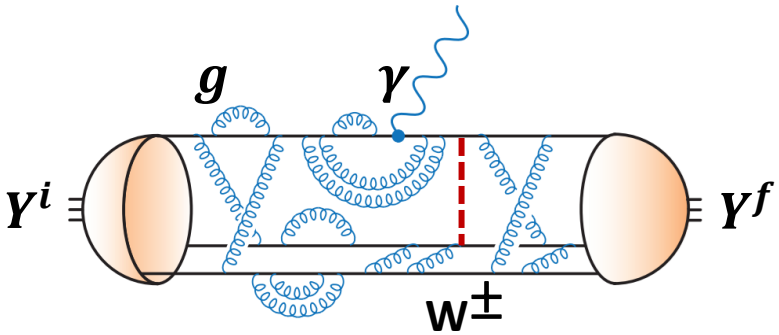
- Decay width & decay asymmetry

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

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

$\Lambda \to n\gamma$	$\Xi^0 \to \Lambda\gamma$
$\Sigma^+ \to p\gamma$	$\Xi^0 \to \Sigma^0\gamma$
$\Sigma^0 \to n\gamma$	$\Xi^- \to \Sigma^-\gamma$
	$\Omega^- \to \Xi^-\gamma$

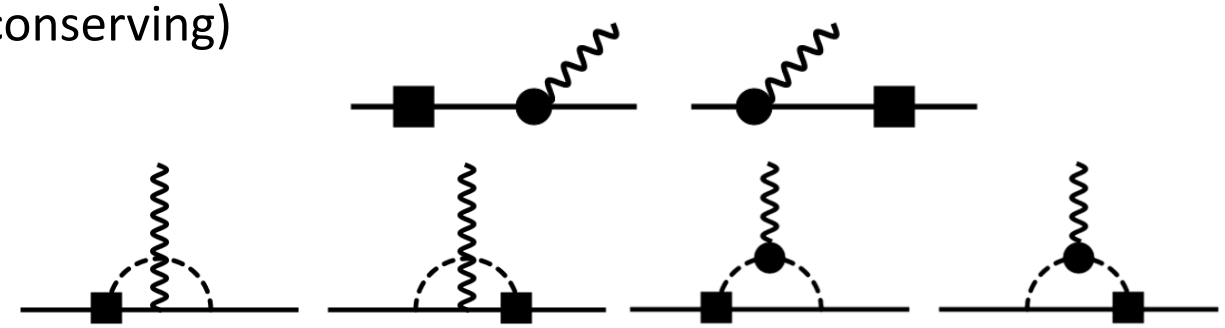




Weak Radiative Hyperon Decays

Effective Theory Point-of-view

- Hara's Theorem: $\alpha_{\gamma,\Sigma^+/\Xi^-} = 0$ under SU(3) symmetry
- Various predictions based on: VMD, Broken SU(3), Pole Model, Quark Model, NRCQM, Baryon ChPT …
- Topology diagrams based on baryon ChPT Sci.Bull. 67 (2022), 2298
  - LO contributions (parity conserving)
  - NLO contributions



■: share with weak hadronic decays

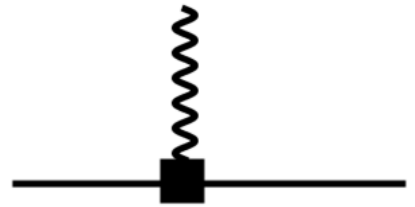
●: determined by octet baryon magnetic moments

Meson-Baryon interaction vertex: share with semi-leptonic decays

Weak Radiative Hyperon Decays

Effective Theory Point-of-view

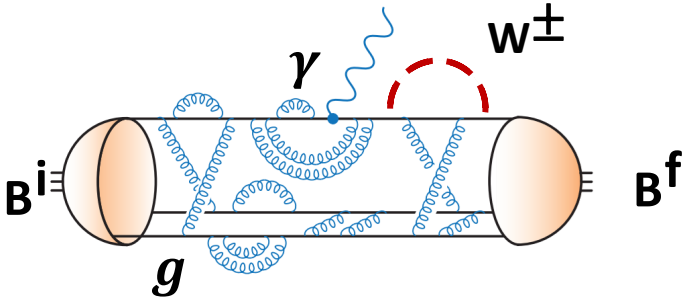
- Unique contribution from "direct photon emission"
  - Need experiment input from $\Xi^0 \to \Lambda(\Sigma^0)\gamma$ or $\Lambda \to n\gamma$ process



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

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

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



Weak Radiative Hyperon Decays

Experiment Research Status

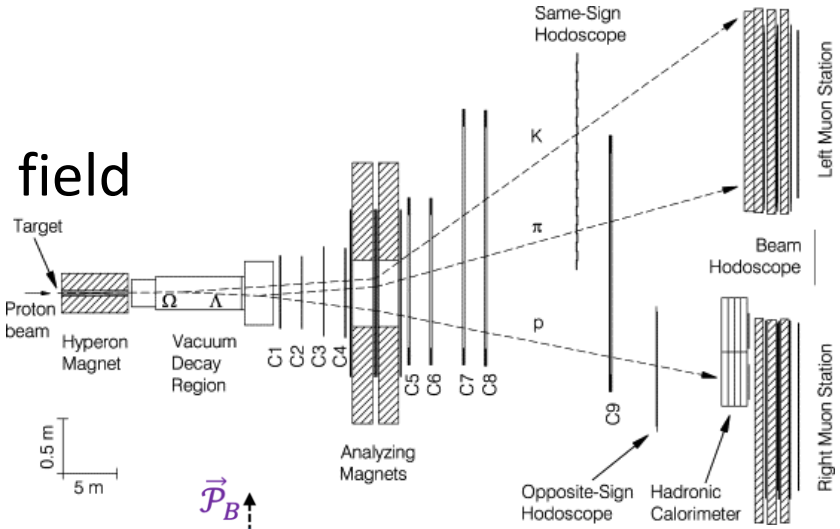
- Fixed target experiments govern the results before 2022 (~23 papers from over 5 experiment groups)
- After 2022, BESIII experiment provide fresh results to the field

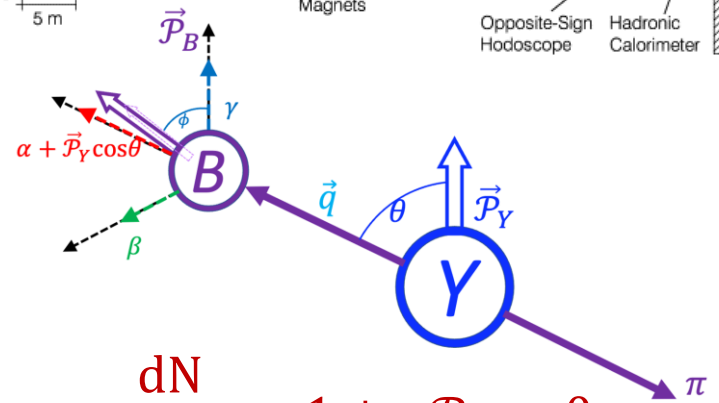
$\Lambda \to n\gamma$ Phys.Rev.Lett. 129 , 212002 (2022)		
Experiment	**BF ($\times 10^{-3}$)**	α_γ
2022, BESIII	0.846±0.039±0.052	-0.160±0.101±0.046
1994, E761	1.75±0.15	---

$\Xi^0 \to \Lambda\gamma$ Accepted by Sci. Bull.		
Experiment	**BF ($\times 10^{-3}$)**	α_γ
2024, BESIII	1.347±0.066±0.054	-0.741±0.062±0.019
2010, NA48	---	-0.704±0.064
2004, NA48	1.17±0.09	-0.78±0.18

$\Sigma^+ \to p\gamma$ Phys. Rev. Lett. 130, 211901 (2023)		
Experiment	**BF ($\times 10^{-3}$)**	α_γ
2022, BESIII	0.996±0.021±0.018	-0.652±0.056±0.020
1995, E761	1.20±0.08	---
1992, SPEC	---	-0.720±0.086

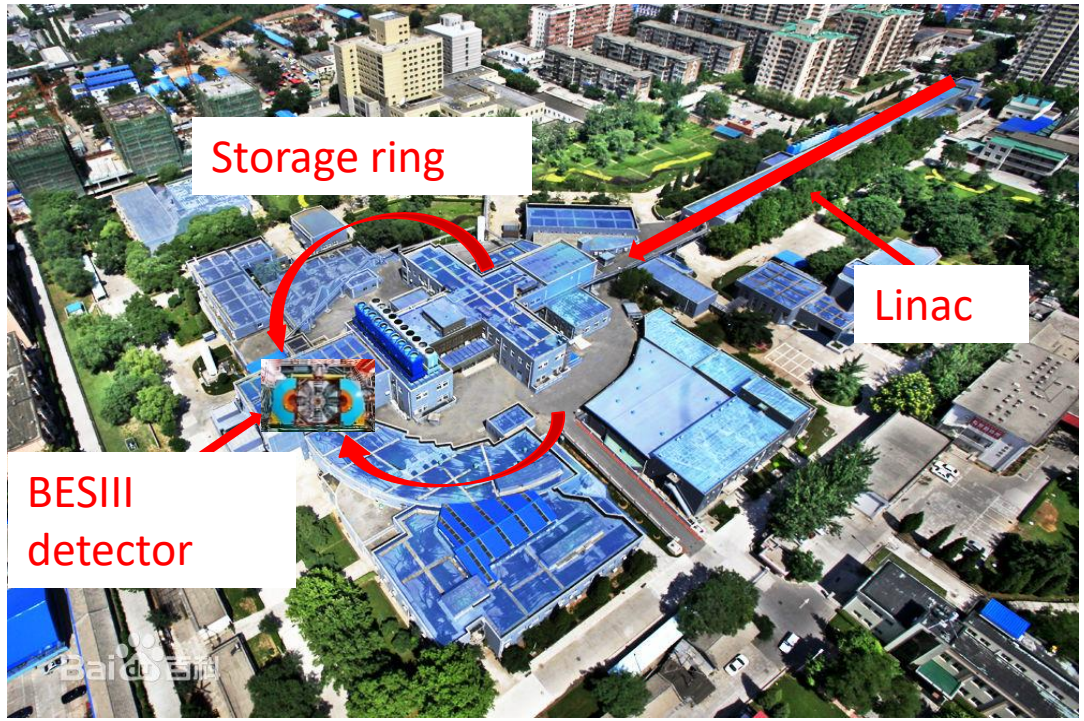
$\Xi^0 \to \Sigma^0\gamma$ Under Collaboration Review		
Experiment	**BF ($\times 10^{-3}$)**	α_γ
BESIII	xxx±0.21±0.12	xxx±0.095±0.011
2010, NA48	---	-0.729±0.076
2001, KTEV	3.34±0.09	-0.63±0.09





$$\frac{dN}{d\cos\theta} \propto 1 + \alpha \mathcal{P}_Y \cos\theta$$

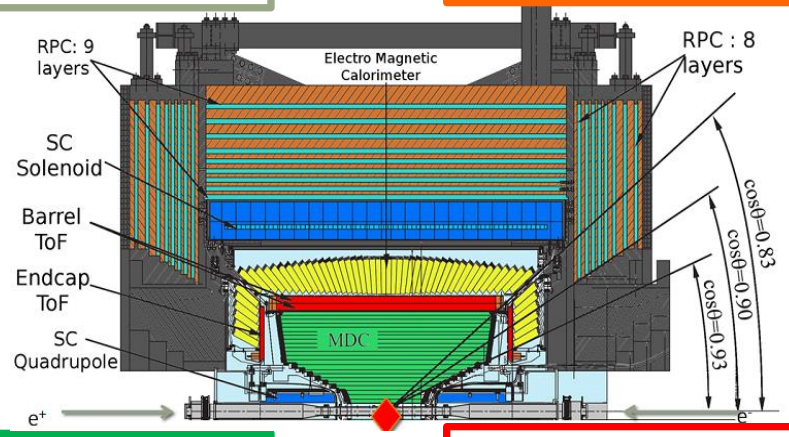
Beijing Electron and Positron Collider II and Beijing Spectrometer III



E_{cm} = 2.0–4.96 GeV
Peak luminosity @ E_{cm}= 3.77 GeV:
1.0×10^{33} $cm^{-1}s^{-1}$
Circumference: 237.53 m
Crossing angle: 2×11mrad

Electromagnetic Calorimeter
CsI(Tl): L=28 cm
Barrel σ_E=2.5%
Endcap σ_E=5.0%

Muon Counter
RPC
Barrel: 9 layers
Endcap: 8 layers
$\sigma_{spatial}$: 1.48 cm



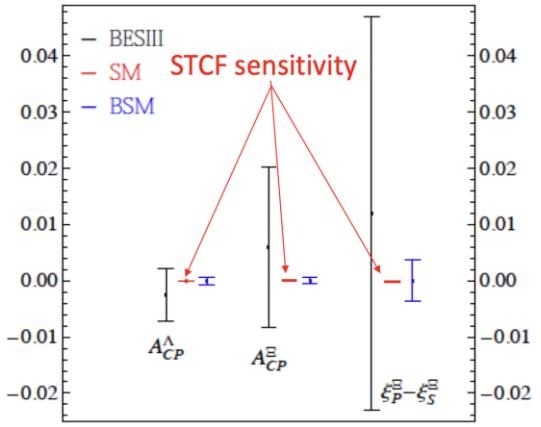
Main Drift Chamber
Small cell, 43 layer
σ_{xy}=130 μm
dE/dx~6%
σ_p/p= 0.5% at 1 GeV

Time Of Flight
Plastic scintillator
σ_T(barrel): 80 ps
σ_T(endcap): 110 ps
(update to 65 ps with MRPC)

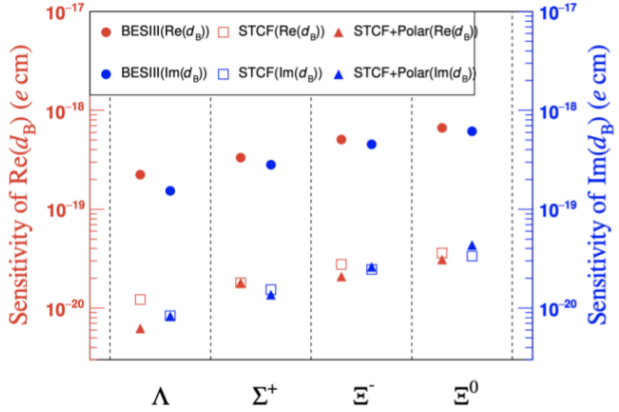
Hyperon Physics at BESIII

- Uniquely pair-produced hyperons from ψ decay, e.g. $e^+e^- \to J/\psi \to Y\bar{Y}$
- Over 70 million hyperon pair events collected from 2009-2019

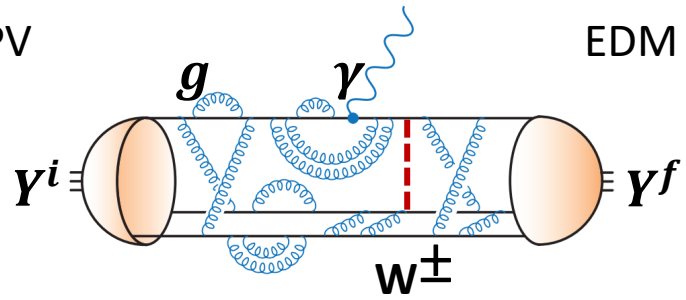
Decay Channel	BF ($\times 10^{-3}$)	N_{evt} ($\times 10^{6}$)
$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	19.1
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.07 ± 0.04	10.8
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.17 ± 0.03	11.8
$J/\psi \to \Sigma^-\bar{\Sigma}^+$	---	~15
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	11.8
$J/\psi \to \Xi^-\bar{\Xi}^-$	0.97 ± 0.08	9.8
Total		~78



CPV



EDM



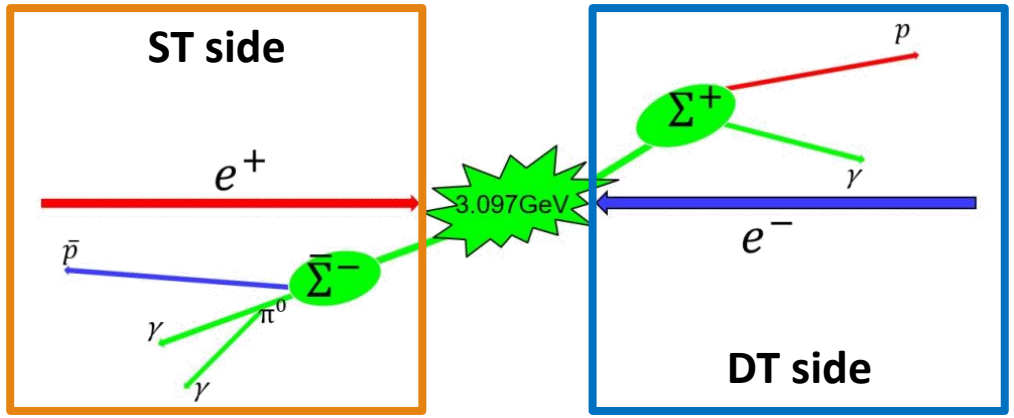
Rare Decay

Research Methods

Absolute BF Measurement

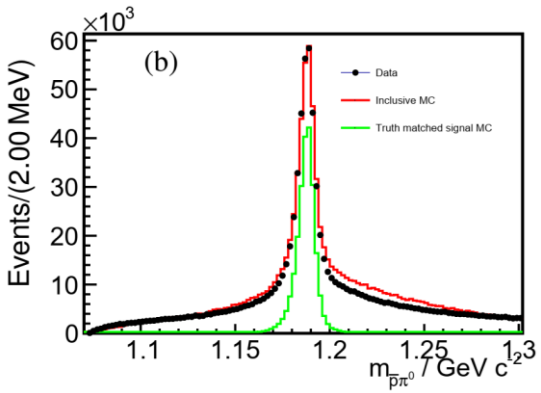
- Double-tag method for BF measurement

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

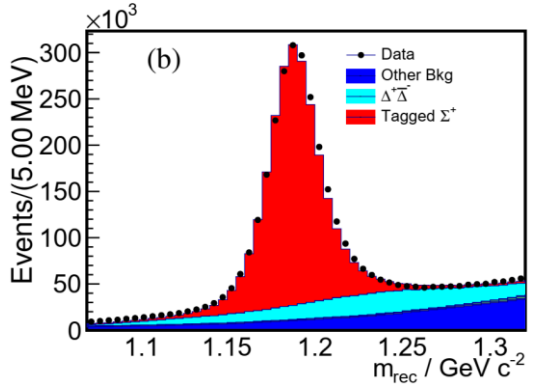


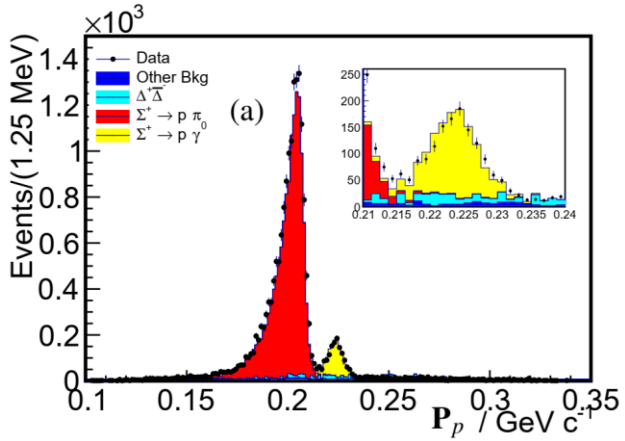
- Well constrained kinematics
- Absolute BF measurement
- Canceled ST selection *syst.* uncertainty

ST reconstruction



ST recoil





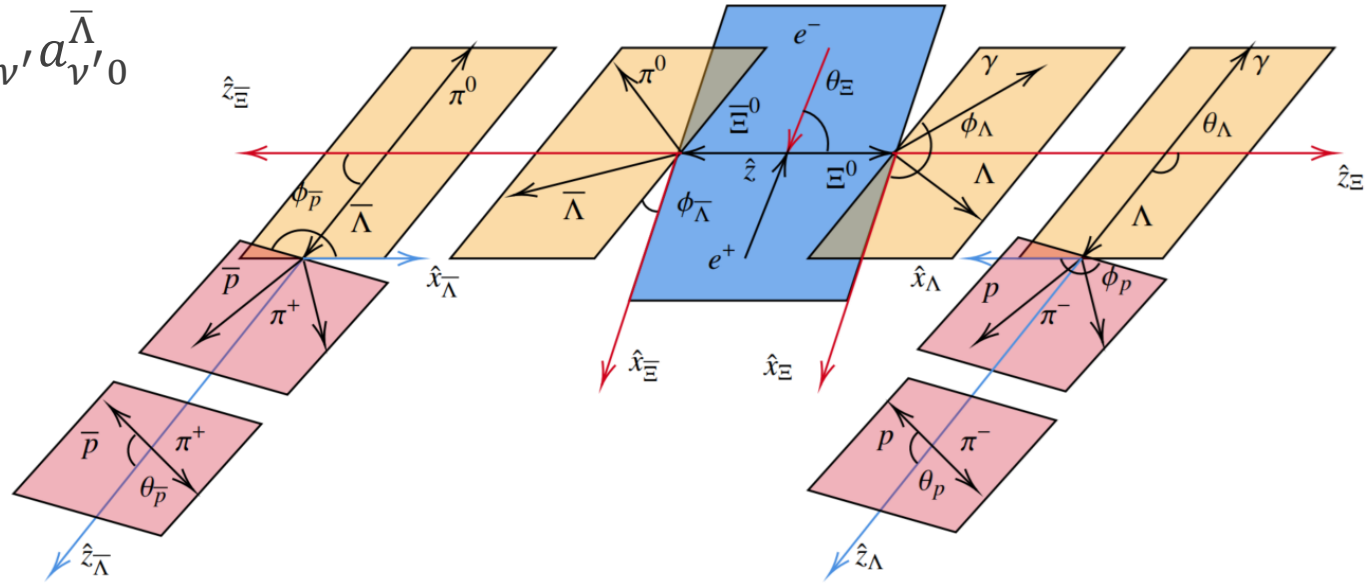
DT reconstruction

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

- C: polarization and spin correlation matrix of $Y\bar{Y}$

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

- BESIII observation of non-zero $\Delta\Phi_\Psi$
  - Transverse polarization and spin-correlation between hyperon pairs **Nature Phys. 15 (2019), 631**

Decay	$\alpha_{J/\psi}$	$\Delta\Phi_\Psi$	Polarization (%)
$J/\psi \to \Lambda\bar{\Lambda}$	$0.475 \pm 0.002 \pm 0.003$	$0.752 \pm 0.004 \pm 0.007$	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

- 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 ($\Xi^0 \to \Lambda\pi^0$)

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

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

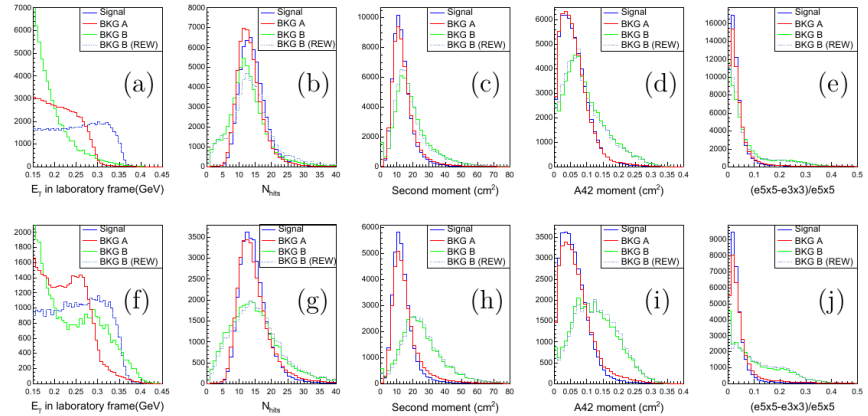
$$a_r^\Xi = \begin{pmatrix} 1 & 0 & 0 & -\alpha \\ \alpha\cos\phi\sin\theta & 0 & 0 & -\sin\theta\cos\phi \\ \alpha\sin\theta\sin\phi & 0 & 0 & -\sin\theta\sin\phi \\ \alpha\cos\theta & 0 & 0 & -\cos\theta \end{pmatrix}$$

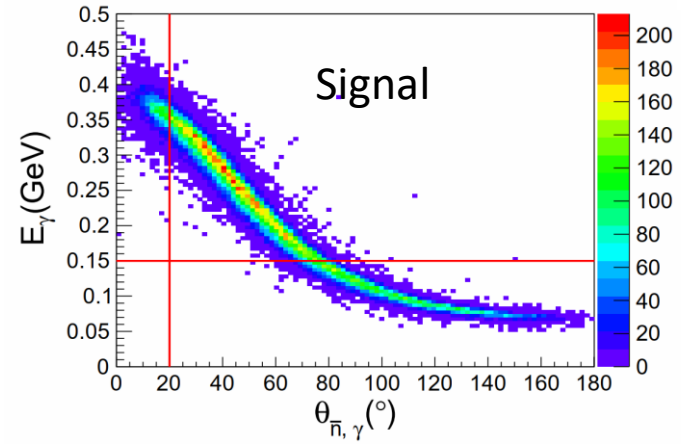
- Decay parameters fitted from amplitude
  - Sensitivity multiplicated by several times **Chin. Phys. C 47 (2023), 093103**

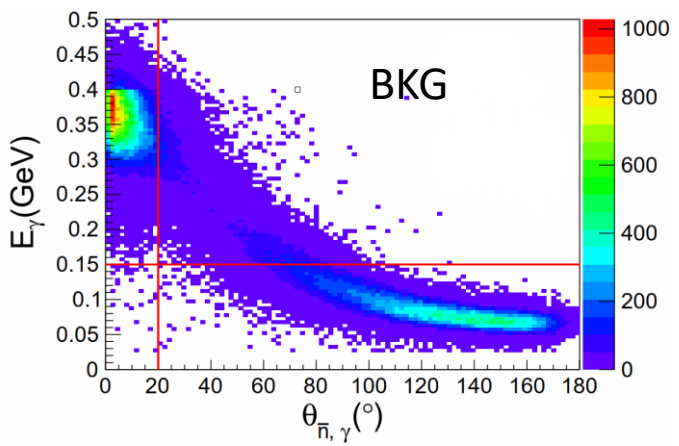
Analysis Method highlights

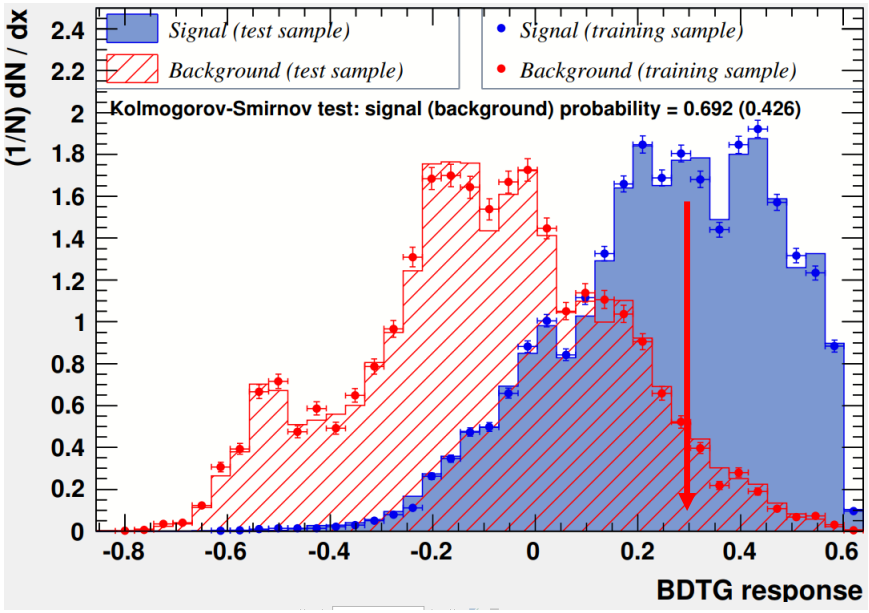
$\Lambda \to n\gamma$ Analysis

- Kinematic fit with missing particle/energy
  - Hypothesis: $\bar{\Lambda}(\to \bar{p}\pi^+)\gamma + n(\text{missing particle})$
  - Hypothesis: $\Lambda(\to p\pi^-)\gamma + \bar{n}(\text{missing energy})$
  - Superiority of well-constrained kinematics
- MVA-based fake photon suppression
  - $\varepsilon_{\text{bkg}} = 3.1\%, \varepsilon_{\text{sig}} = 50.1\%$





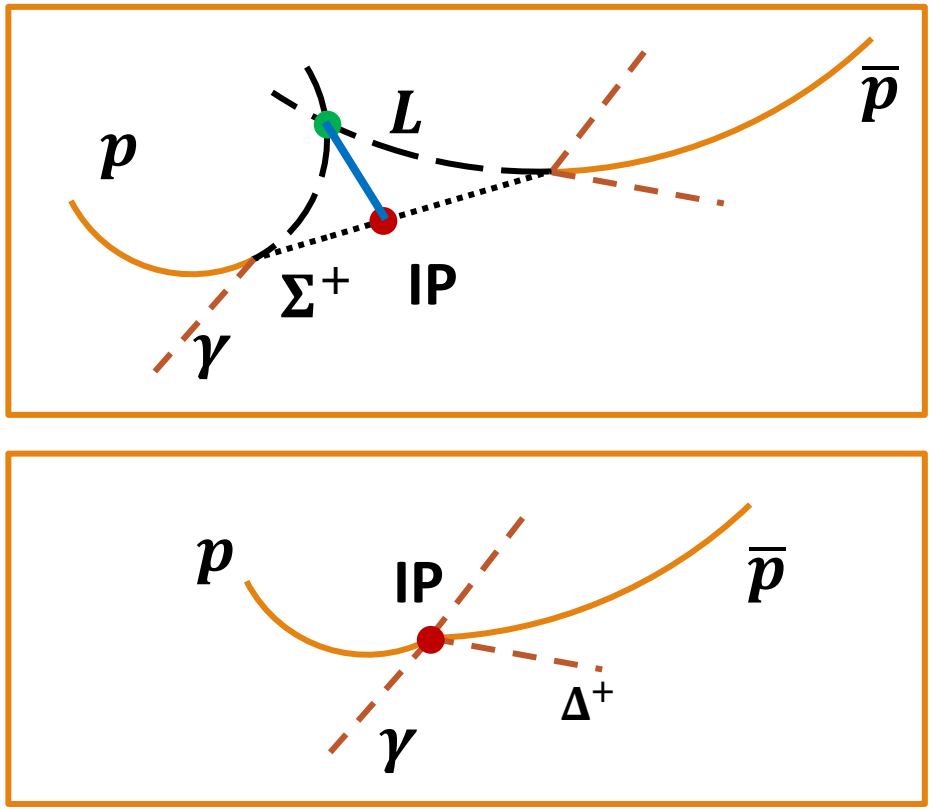


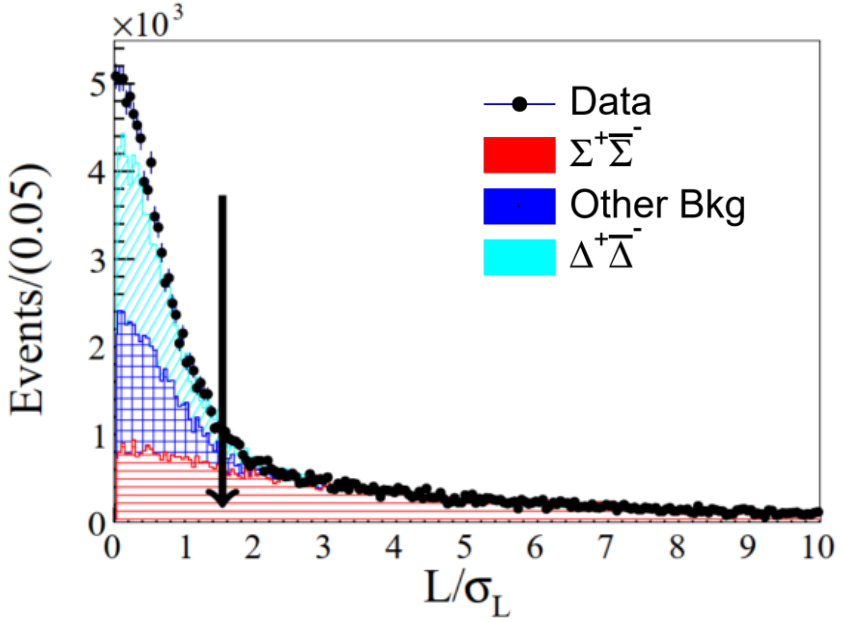


Analysis Method highlights

$\Sigma^+ \to p\gamma$ & $\Xi^0 \to \Lambda(\Sigma^0)\gamma$ Analysis

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





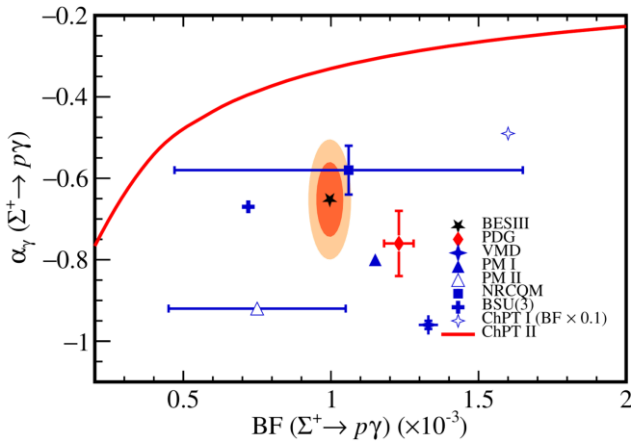
Signal efficiency > 78%
Background efficiency < 7%

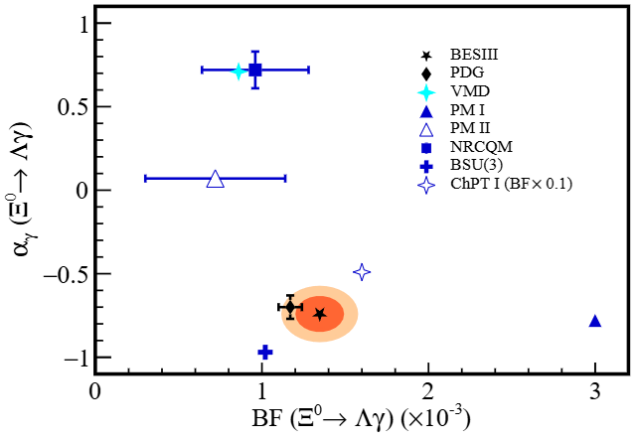
Summary & Prospects

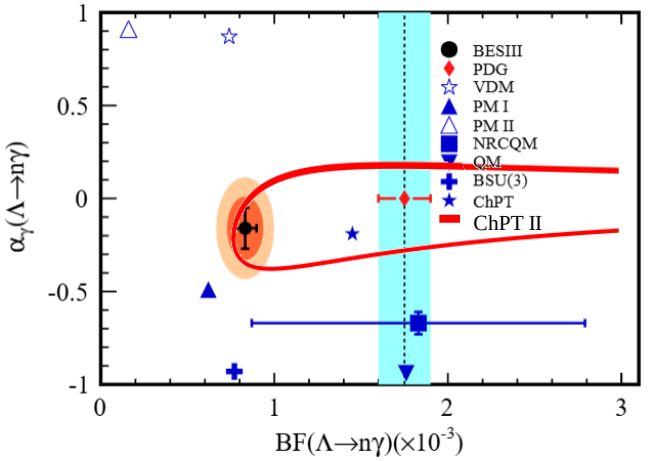
超级陶粲装置
Super Tau-Charm Facility

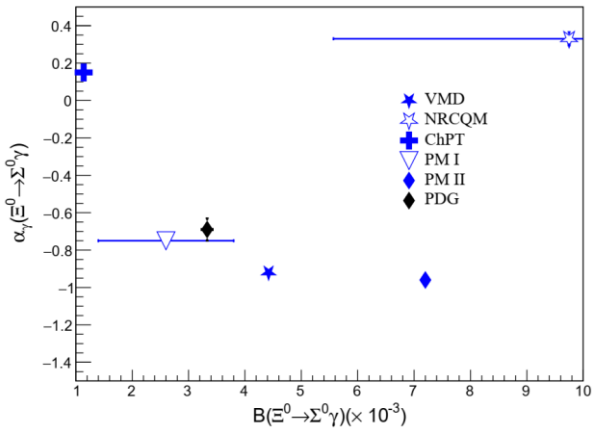
- Inconsistency between exp. results and theory predictions still exist
- More results with higher precision expected
- Working on "The last piece of the puzzle"

$\Xi^- \to \Sigma^- \gamma$		
Experiment	**BF ($\times 10^{-3}$)**	α_γ
BESIII	?	?
PDG	1.27±0.23	---
$\Omega^+ \to \Xi^- \gamma$		
Experiment	**BF ($\times 10^{-3}$)**	α_γ
BESIII	?	?
PDG	<0.46	---









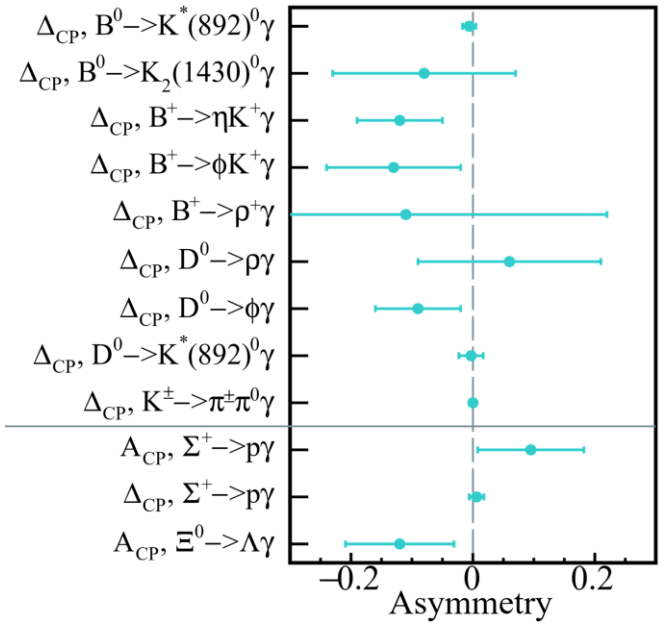
Summary & Prospects

- *CP* violation in radiative decays
  - *CP* violation in heavy flavor radiative decays extensively predicted under SM
    - Decrease as quark mass decreases
  - May be significantly enhanced by NP up to $\mathcal{O}(10)\%$

Phys.Rev.Lett.109.171801, JHEP 01 (2013) 027, JHEP 04 (2017) 027

	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}	

- First Measurement of CP asymmetry of $\Sigma^+ \to p\gamma$ and $\Xi^0 \to \Lambda\gamma$ decay
  - Statistical uncertainty dominated
  - Need more statistics to reach the precision of theory predictions

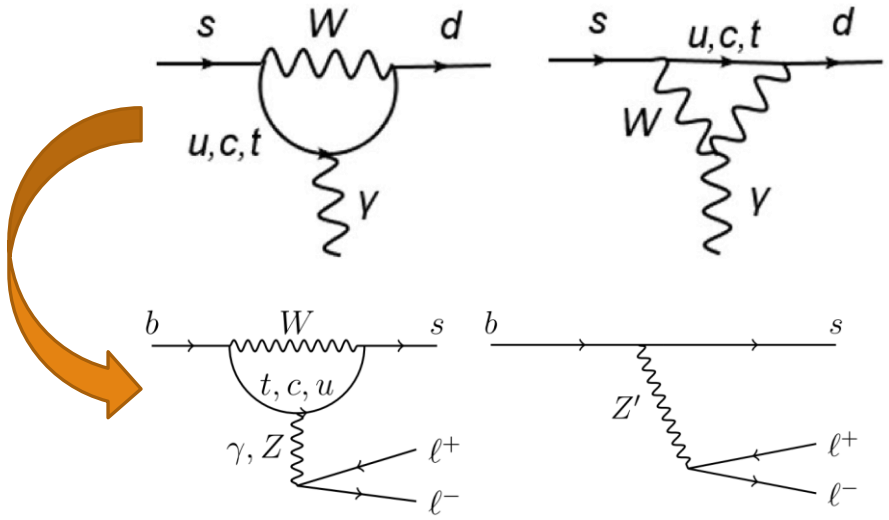


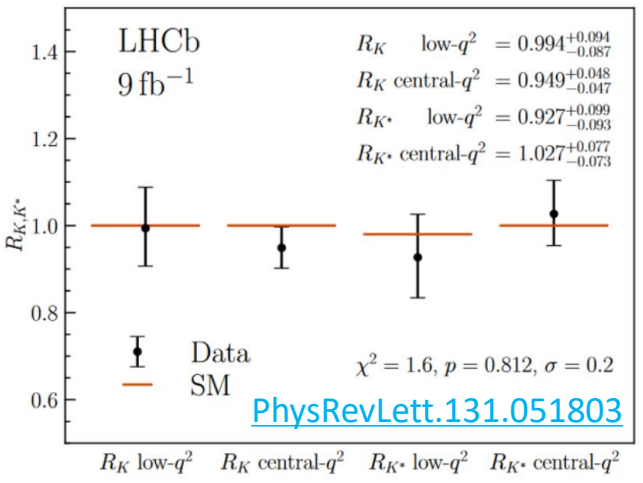
My Current Interest

- Effective Hamiltonian:

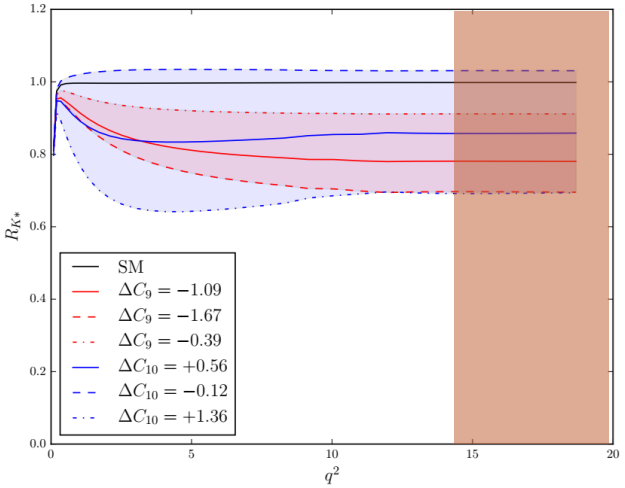
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \left[C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)\right].$$

- SM expectations:
  - $C_i' \sim \frac{m_s}{m_b} C_i$
  - $C_{S,P}^{\text{SM}} \sim \frac{m_\ell m_b}{m_W^2}$
  - $R_H \equiv \frac{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}}{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B\to He^+e^-)}{dq^2}} = 1 + O(m_\mu^2/m_b^2)$

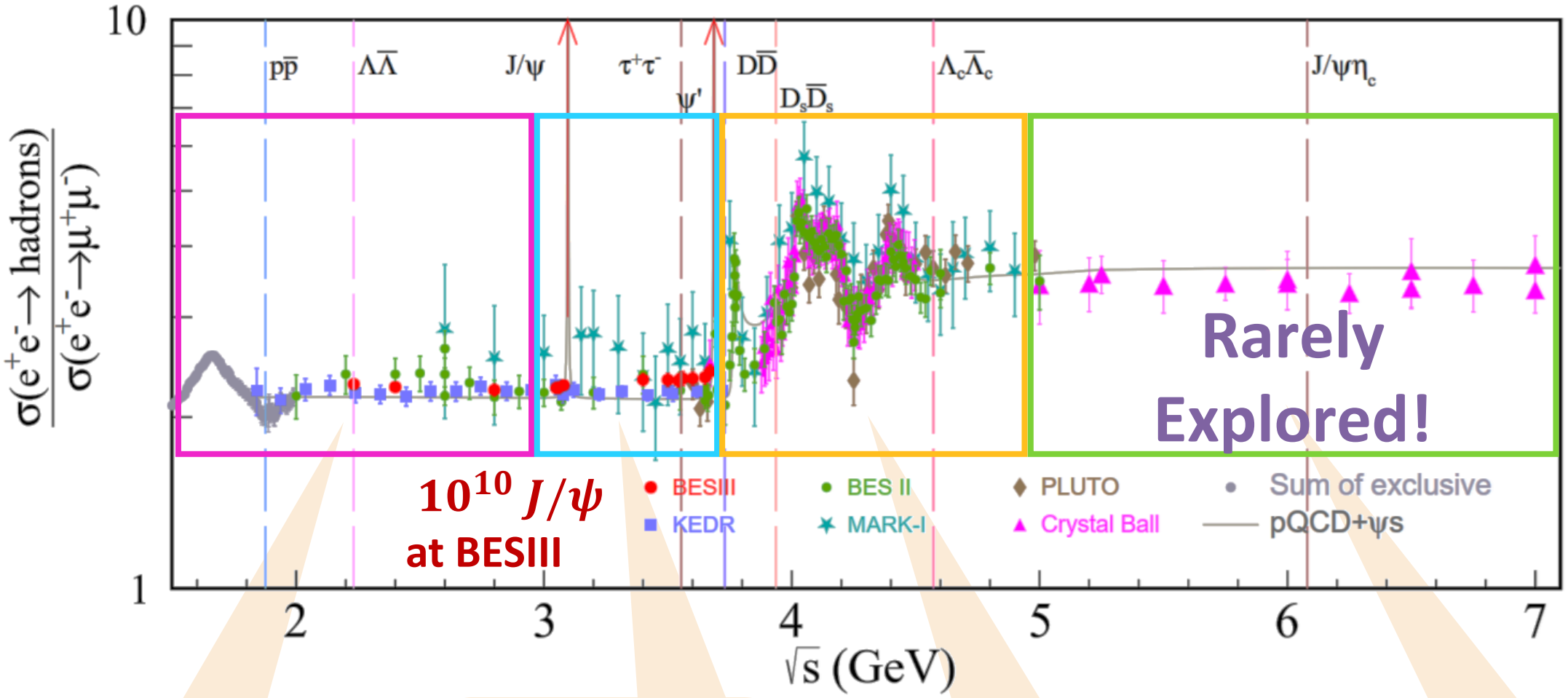




PhysRevLett.131.051803



BACKUP



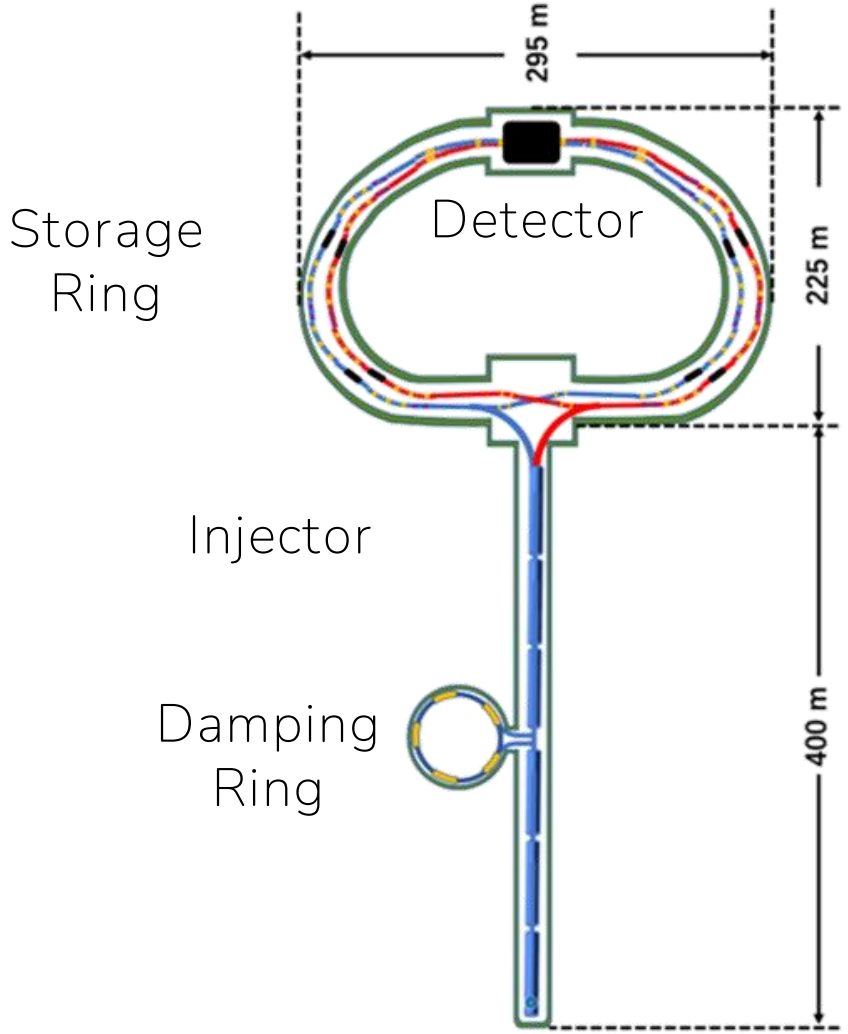
- Nucleon/Hadron form factors
- Y(2175) resonance
- Lightest mutltiquark states

- LH spectroscopy
- Gluonic and exotic
- Hyperon physics
- Rare decays
- τ physics
- Ditauonium

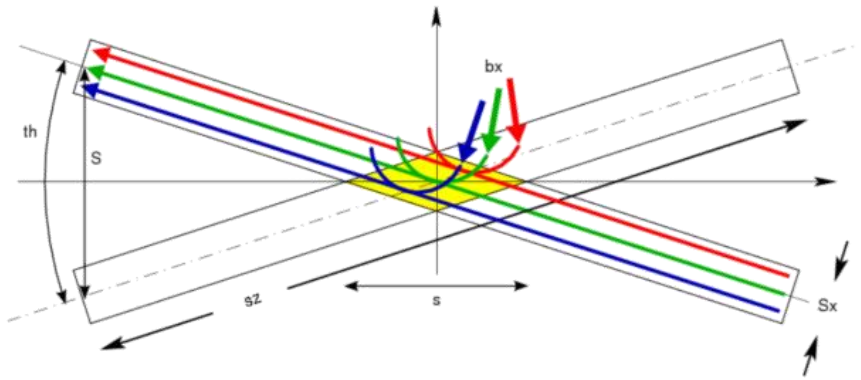
- XYZ particles
- CKM matrix & γ
- f_D and f_{Ds}
- D_0-$\bar{D}_0$ mixing
- Charm baryons

- New XYZ particle
- Multiquark state
- Di-charmonium state
- Charm baryons
- Hadron fragmentation

Super Tau-Charm Facility



Lattice Design



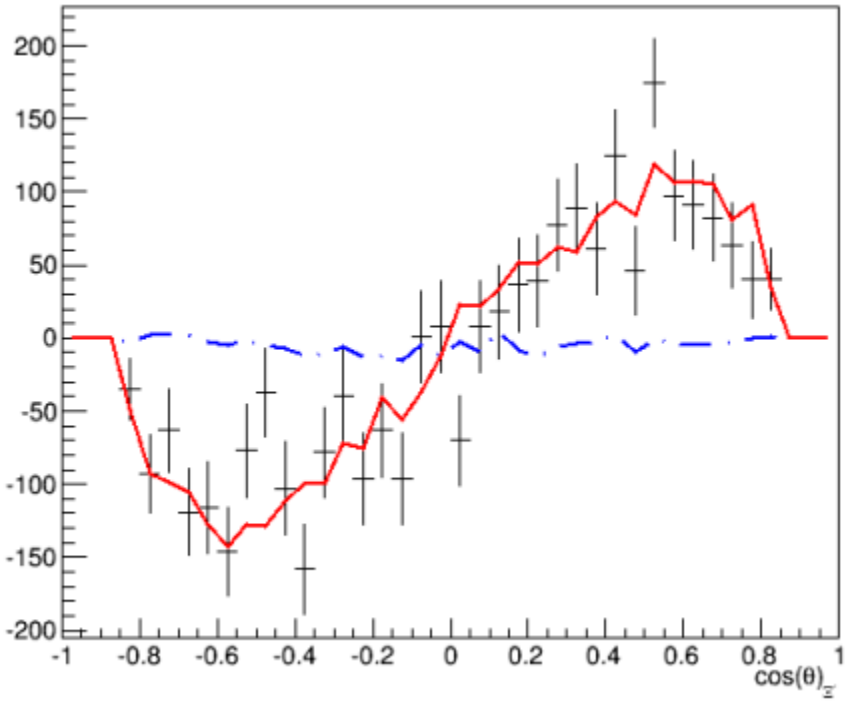
- Large Piwinski angle + Crab Waist
- Multi-Bend Achromat lattice
- Design $\mathcal{L} > 0.5 \times 10^{35}$ cm^{-2}s^{-1}
- E_{cms}= 2–7 GeV
- **Potential for beam polarization**

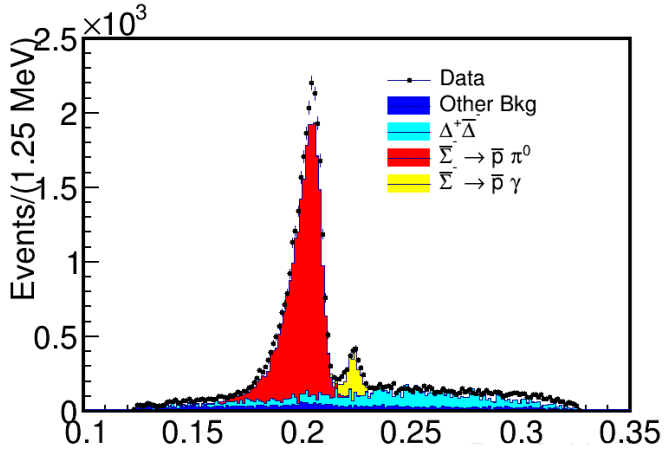
Physics Motivation

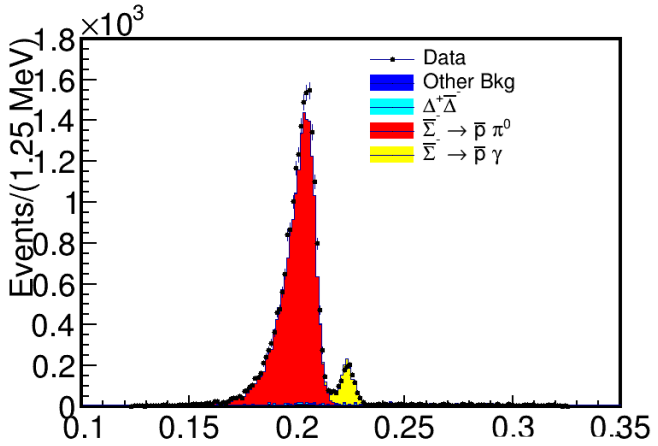
Physics Beyond the Scope of QCD Phenomenon

- New physics in $B_i \to B_f l^+ l^-$ decay
  - Smoke screen of new physics in $\Sigma^+ \to p\mu^+\mu^-$ 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

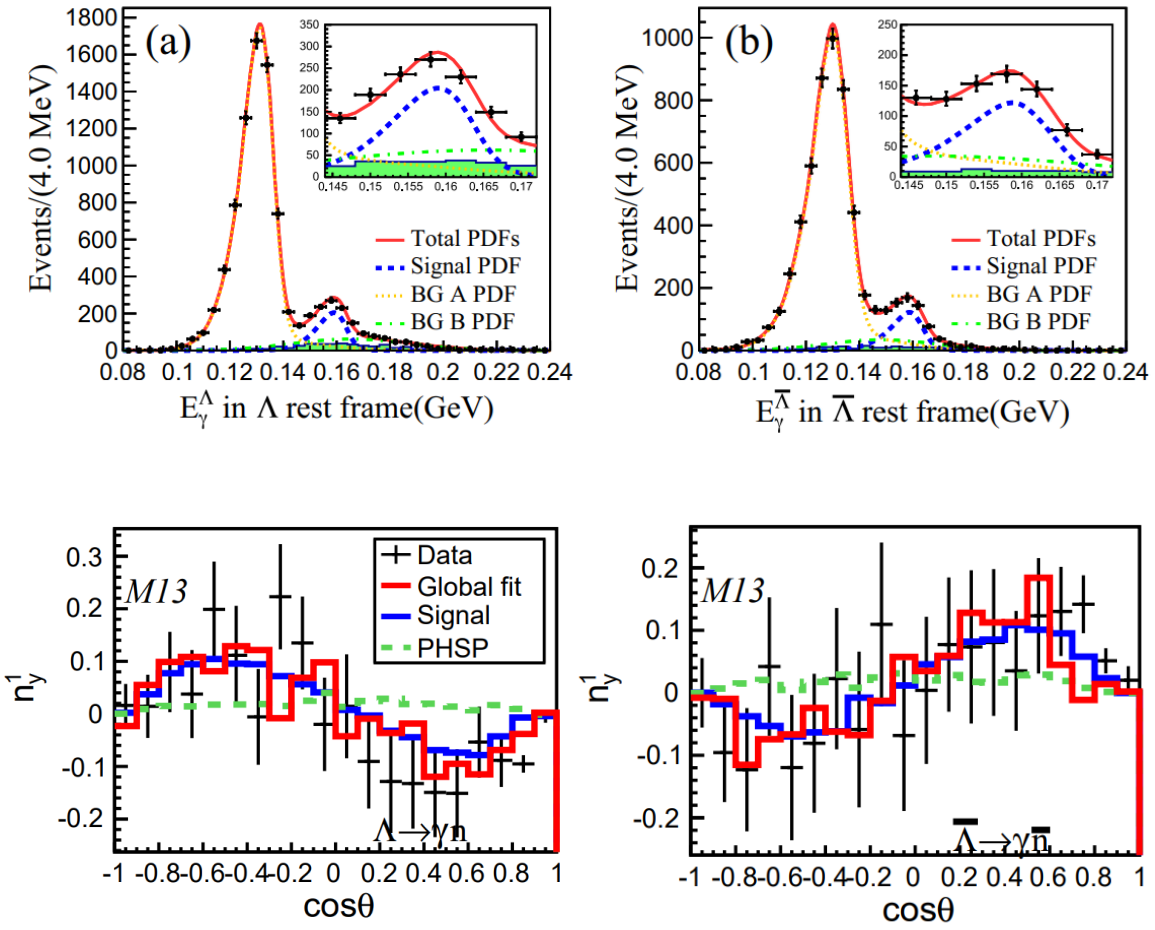

200
150
100
50
0
-50
-100
-150
-200
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos(θ)


×10³
Events/(1.25 MeV)
2.5
2
1.5
1
0.5
0
0.1
0.15
0.2
0.25
0.3
0.35
Data
Other Bkg
Δ⁺Δ̄⁻
Σ̄⁻ → p̄ π⁰
Σ̄⁻ → p̄ γ


×10³
Events/(1.25 MeV)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.15
0.2
0.25
0.3
0.35
Data
Other Bkg
Δ⁺Δ̄⁻
Σ̄⁻ → p̄ π⁰
Σ̄⁻ → p̄ γ

$\Lambda \to n\gamma$ Analysis

Analysis Results



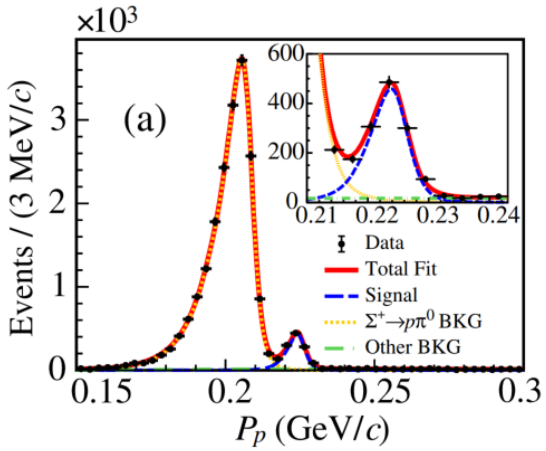
Decay mode	$\Lambda \to n\gamma$	$\bar{\Lambda} \to \bar{n}\gamma$
N_{ST} $(\times 10^3)$	6853.2 ± 2.6	7036.2 ± 2.7
ε_{ST} (%)	51.13 ± 0.01	52.53 ± 0.01
N_{DT}	723 ± 40	498 ± 41
ε_{DT} (%)	6.58 ± 0.04	4.32 ± 0.03
BF $(\times 10^{-3})$	$0.820 \pm 0.045 \pm 0.066$	$0.862 \pm 0.071 \pm 0.084$
	$\mathbf{0.832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

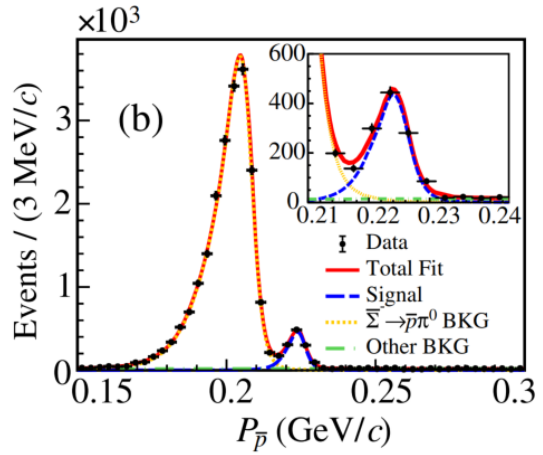
First measurement on α_γ

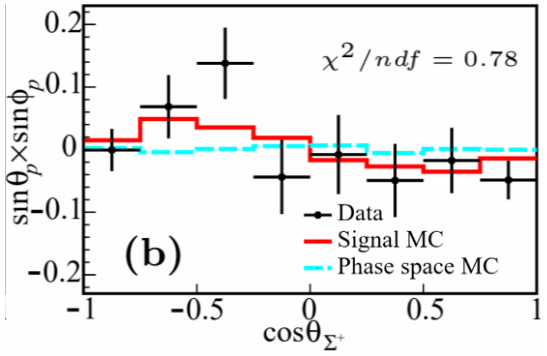
5.6σ deviation of BF

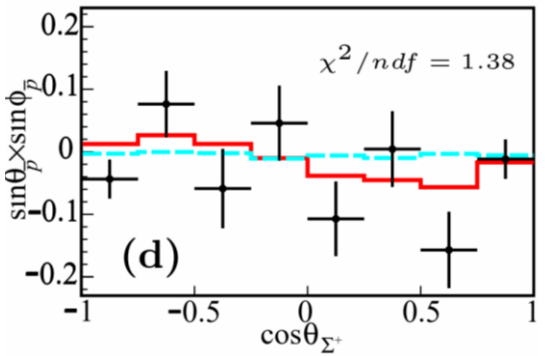
$\Sigma^+ \to p\gamma$ Analysis

Analysis Results









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	$-0.652 \pm 0.056 \pm 0.020$	

Significantly improved accuracy

- **BF: 78%**
- **α_γ: 34%**