粲重子衰变中的
超子CP破坏和新物理

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Based on J.P.Wang, FSY, arXiv:2208.01589

BESIII实验上粲强子、QCD及新物理研讨会 @ 兰州，2022.08.23

Outline

1. Introduction on baryon physics
2. Hyperon CP violation in charm decays
3. Baryon number violation decays of Λ_c
4. Summary

Baryon Physics

- The visible matter of the Universe is mainly made of baryons.
- In the modern particle physics and cosmology, one of the most crucial problems is how to understand the asymmetry between the matter and anti-matter in the Universe.
- Sakharov conditions for **Baryogenesis**:

  1) **baryon number violation**

  2) C and **CP violation**

  3) out of thermal equilibrium
- **CPV: SM < BAU. => new source of CPV, NP**
- CPV well established in K, B and D mesons, **but CPV never established in any baryon**
- Non-zero spin of baryons are helpful for CPV measurements

Hyperon CP violation

- The strange mesons are the system to firstly observe the CP violation in 1964 and firstly establish the CPV in the decay amplitudes in 1999.
- It can be expected that the strange baryons are of good opportunity to observe the CPV in the baryon sector, since the light strange quarks are more easily produced.
- CP violation in hyperon decays is estimated to be $\mathcal{O}(10^{-4} \sim 10^{-5})$

J.F.Donoghue, S.Pakvasa, PRL55,162(1985); J.H.Donoghue, X.G.He, S.Pakvasa, PRD34, 833 (1986)

- BESIII measured the most precise result via $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$:

$A^{\alpha}_{CP} = (-2.5 \pm 4.6 \pm 1.1) \times 10^{-3}$ BESIII, Nature Phys.15, 631 (2019); 2204.11058 No CPV observed

- Many other measurements at BESIII recently.
- No more data expected at BESIII. Are there other methods to measure hyperon CPV?

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

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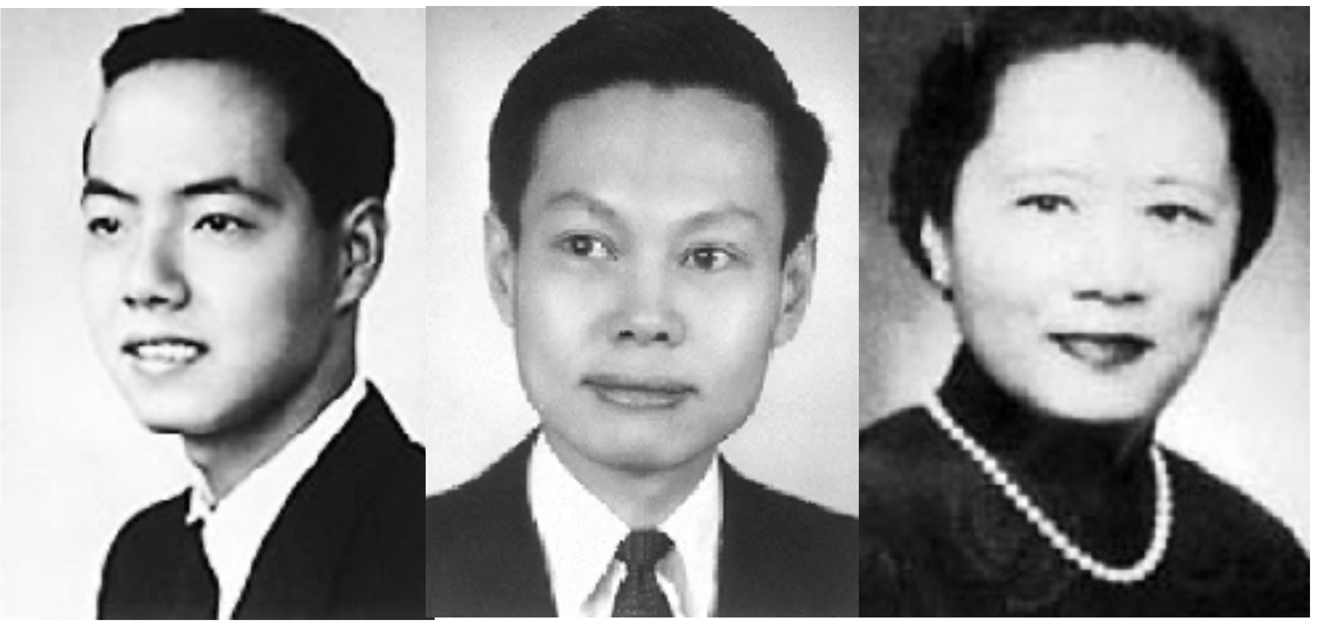
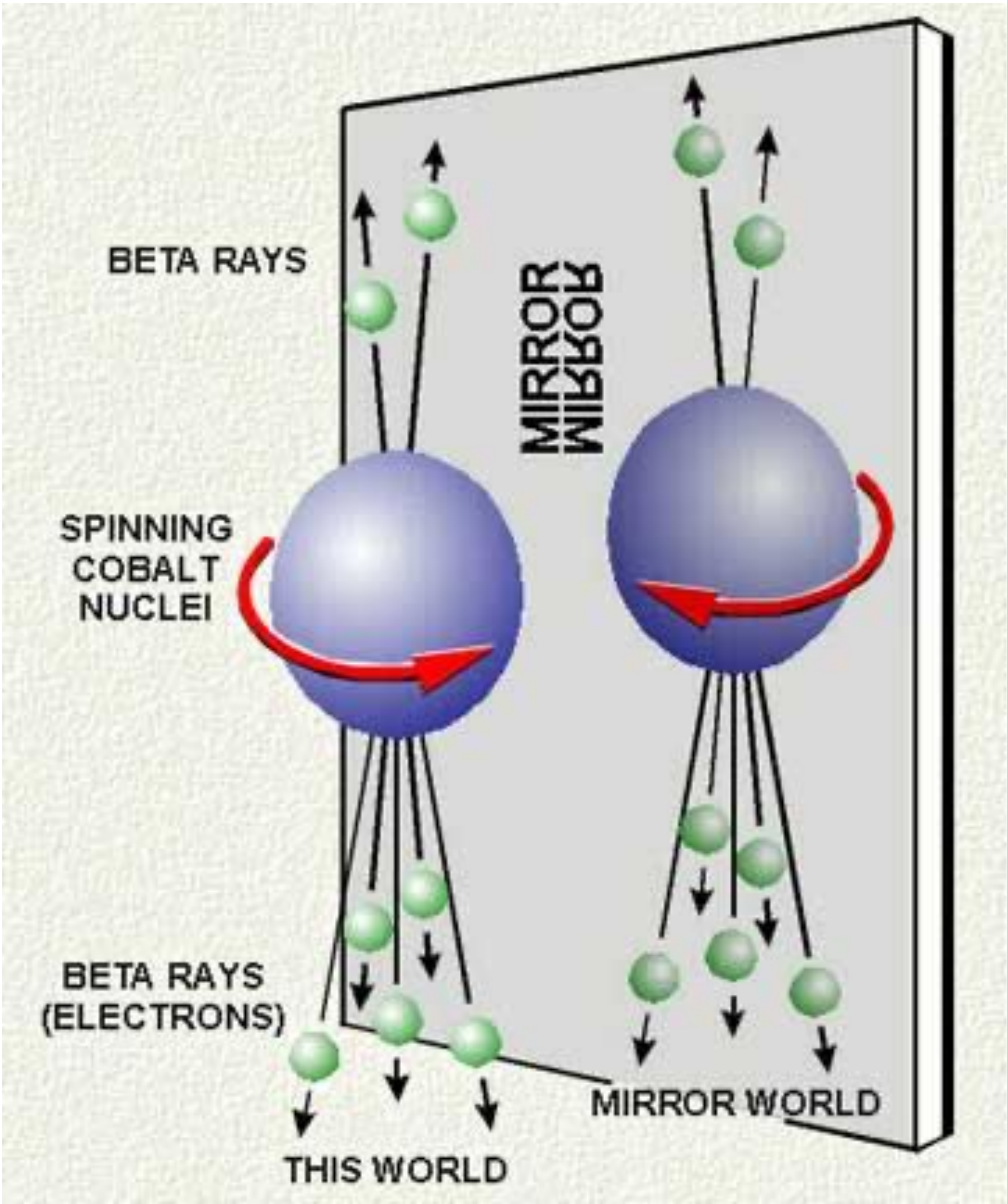
(Received June 22, 1956)





β decay of oriented nucleus, Co-60

parity-odd quantity:

$$\vec{p} \cdot \vec{s} \propto \cos\theta$$

$\vec{s}$: nuclei spin

$\vec{p}$: electron momentum

$$I(\theta)d\theta = (\text{constant})(1+\alpha\cos\theta)\sin\theta d\theta,$$

$$\alpha = 2\left[\int_0^{\pi/2} I(\theta)d\theta - \int_{\pi/2}^{\pi} I(\theta)d\theta\right] \Big/ \int_0^{\pi} I(\theta)d\theta.$$

Polarization of initial states

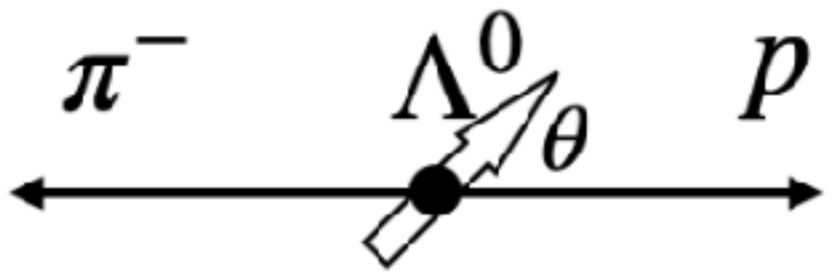
$\Lambda^0 \to p\pi^-$: completely polarized hyperon

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. Lee* and C. N. Yang
Institute for Advanced Study, Princeton, New Jersey
(Received October 22, 1957)

similar to the oriented Co-60,
polarization in the initial state

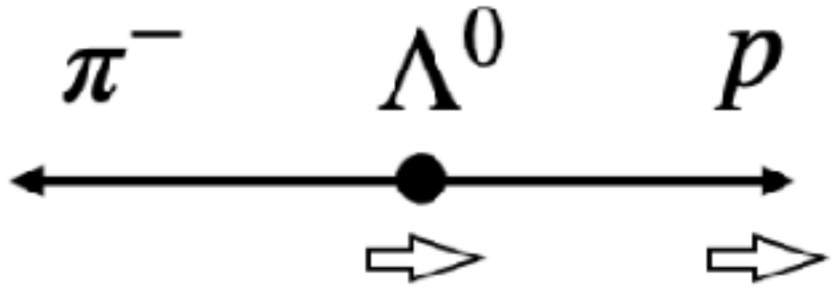
$$\mathcal{A}(\Lambda^0 \to p\pi^-) = \bar{u}_p(S + P\gamma_5)u_\Lambda$$



$$\boxed{\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos\theta}$$

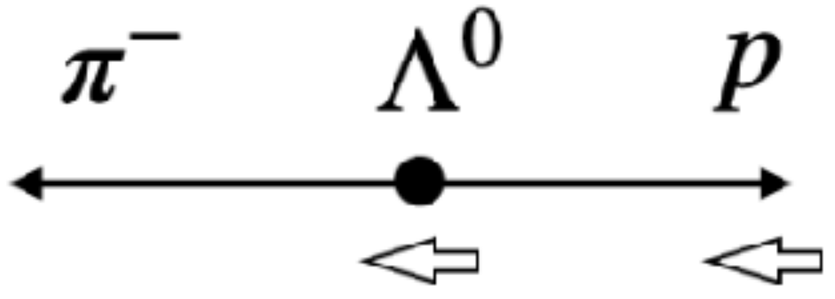
$$\boxed{\alpha = \frac{|h_+|^2 - |h_-|^2}{|h_+|^2 + |h_-|^2} = \frac{2\mathcal{R}e(SP^*)}{|S|^2 + |P|^2}}$$

$\theta = 0$



$$\mathcal{H}_{\lambda_\Lambda=+\frac{1}{2},\lambda_p=+\frac{1}{2}} = \frac{1}{\sqrt{2}}(S+P), \qquad \longrightarrow 1+\alpha$$

$\theta = \pi$



$$\mathcal{H}_{\lambda_\Lambda=-\frac{1}{2},\lambda_p=-\frac{1}{2}} = \frac{1}{\sqrt{2}}(S-P). \qquad \longrightarrow 1-\alpha$$

α is the longitudinal polarization of the final-state baryon

α-induced CP violation

Definition of CPV observables: $a_{CP} = \dfrac{\langle O \rangle - \langle (CP) O (CP)^\dagger \rangle}{\langle O \rangle + \langle (CP) O (CP)^\dagger \rangle}$ $\qquad a_{CP}^{\mathrm{dir}} = \dfrac{\Gamma(i \to f) - \bar{\Gamma}(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \bar{\Gamma}(\bar{i} \to \bar{f})}$

α-induced CPV: $a_{CP}^{\alpha} = \dfrac{\langle \alpha \rangle - \langle (CP) \alpha (CP)^\dagger \rangle}{\langle \alpha \rangle + \langle (CP) \alpha (CP)^\dagger \rangle} = \dfrac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$

- α is parity odd, $\hat{P} \alpha \hat{P}^\dagger = -\alpha$. $\bar{\alpha}$ is the charge conjugation, $\bar{\alpha} = \hat{C} \alpha \hat{C}^\dagger$.
- If CP is conserved, $\bar{\alpha} = -\alpha$.

$$S = |S_1| e^{i\delta_{s,1}} e^{i\phi_1} + |S_2| e^{i\delta_{s,2}} e^{i\phi_2}$$
$$P = |P_1| e^{i\delta_{p,1}} e^{i\phi_1} + |P_2| e^{i\delta_{p,2}} e^{i\phi_2}$$

Direct CPV: $|S_1|\,|S_2| \sin(\delta_{s,2} - \delta_{s,1}) \sin(\phi_2 - \phi_1) +$ (S↔P)

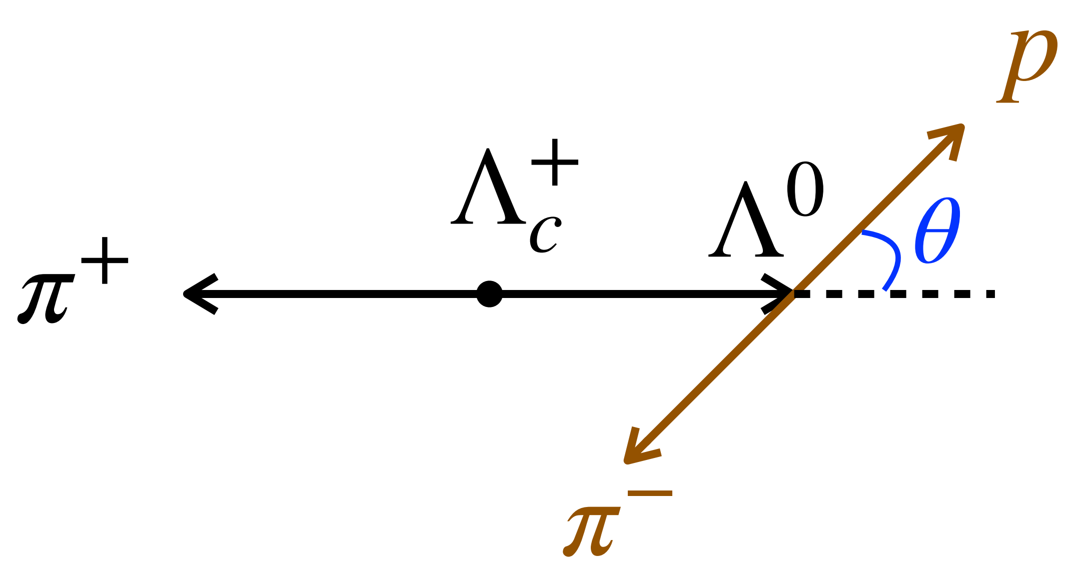
α-induced CPV: $\propto \sum_{i,j=1,2} |S_i|\,|P_j| \sin(\delta_{p,j} - \delta_{s,i}) \sin(\phi_2 - \phi_1)$

different dependences on the strong phases

Hyperon produced from Λ_c^+ decays

In the chain decay of $\Lambda_c^+ \to \pi^+\Lambda^0(\to p\pi^-)$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\theta \qquad \alpha_{\Lambda_c} = \alpha(\Lambda_c \to \Lambda\pi), \quad \alpha_\Lambda = \alpha(\Lambda \to p\pi)$$

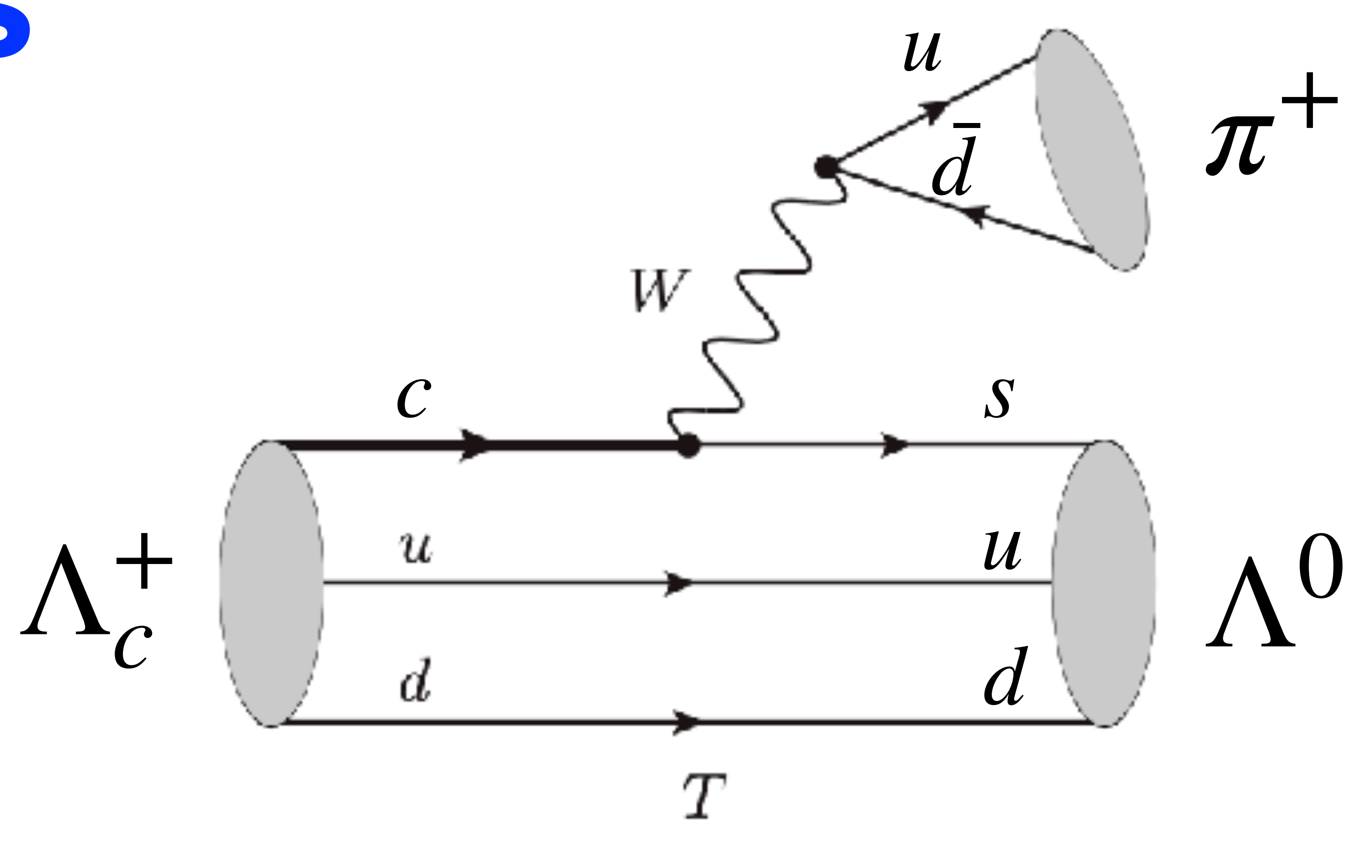


- α_{Λ_c} is the longitudinal polarization of Λ^0 produced in Λ_c^+ decays
- Compared to the case of complete polarized hyperon

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + 1 \cdot \alpha_\Lambda \cos\theta$$

- It is clear in the BESIII measurement BESIII, PRD100,072004 (2019)

Hyperon CPV from Λ_c^+ decays



$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\theta$$

CPV in the chain decay of $\Lambda_c^+ \to \pi^+\Lambda^0(\to p\pi^-)$

$$\boxed{A_{CP}^{\alpha}(\text{total}) = \frac{\alpha_{\Lambda_c}\cdot\alpha_\Lambda - \bar{\alpha}_{\Lambda_c}\cdot\bar{\alpha}_\Lambda}{\alpha_{\Lambda_c}\cdot\alpha_\Lambda + \bar{\alpha}_{\Lambda_c}\cdot\bar{\alpha}_\Lambda} = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda} = A_{CP}^{\alpha}(\Lambda^0 \to p\pi^-)}$$

- Since **CP is conserved** in the **Cabibbo-favored** (CF) charm decays, $\bar{\alpha}_{\Lambda_c} = -\alpha_{\Lambda_c}$

Only the CPV of hyperon is in the chain decay of $\Lambda_c^+ \to \pi^+\Lambda^0(\to p\pi^-)$

$$A_{CP}^{\alpha}(\text{total}) = A_{CP}^{\alpha}(\Lambda \to p\pi)$$

J.P.Wang, FSY, arXiv:2208.01589

Much more processes of hyperons produced in Λ_c^+ decays

$\Lambda_c^+ \to \Lambda$	BR(%)	$\Lambda_c^+ \to \Sigma^+$	BR(%)
$\Lambda_c^+ \to \Lambda\pi^+$	1.30 ± 0.07	$\Lambda_c^+ \to \Sigma^+\pi$	1.25 ± 0.10
$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	7.1 ± 0.4	$\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$	4.50 ± 0.25
$\Lambda_c^+ \to \Lambda\pi^+\eta$	1.84 ± 0.26	$\Lambda_c^+ \to \Sigma^+\eta'$	1.5 ± 0.6
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	3.64 ± 0.29	$\Lambda_c^+ \to \Sigma^+\pi^0\pi^0$	1.55 ± 0.15
$\Lambda_c^+ \to \Lambda\pi^+\omega$	1.5 ± 0.5	$\Lambda_c^+ \to \Sigma^+\omega$	1.70 ± 0.21
$\Lambda_c^+ \to \Lambda e^+\nu_e$	3.6 ± 0.4	—	—
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	3.5 ± 0.5	—	—

$$\boxed{Br(\Lambda_c^+ \to \Lambda X) = (38.2^{+2.9}_{-2.4})\ \%}$$

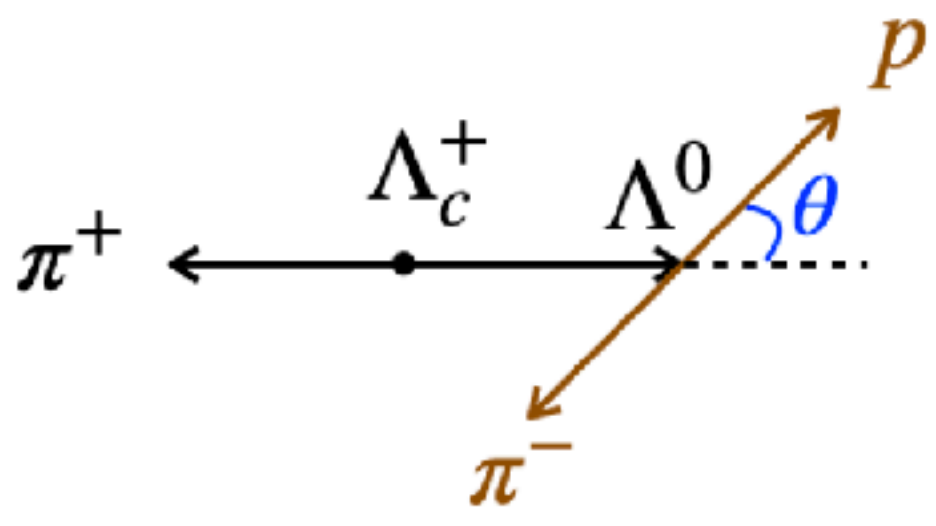
All measured by BESIII

Higher precision if combining all the processes

General formula for hyperon CPV from Λ_c^+ decays

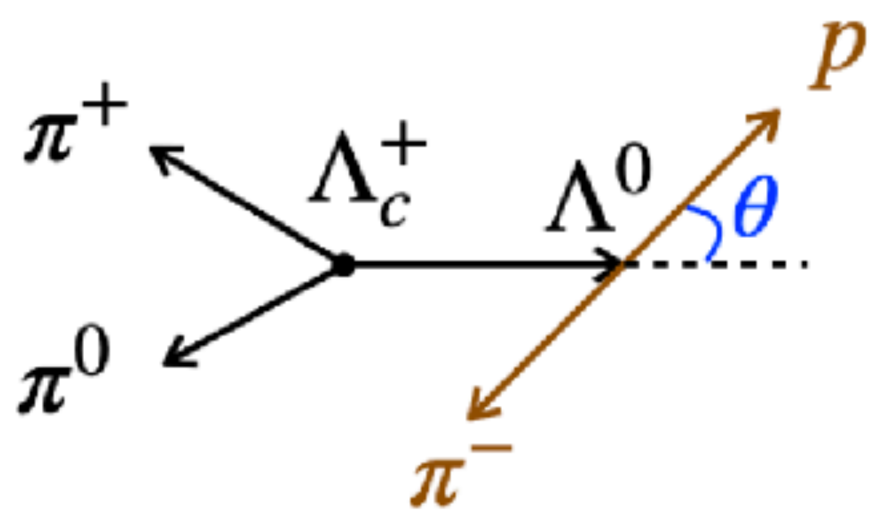
Two-body decays

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha_{\Lambda_c}\alpha_{\Lambda}\cos\theta$$



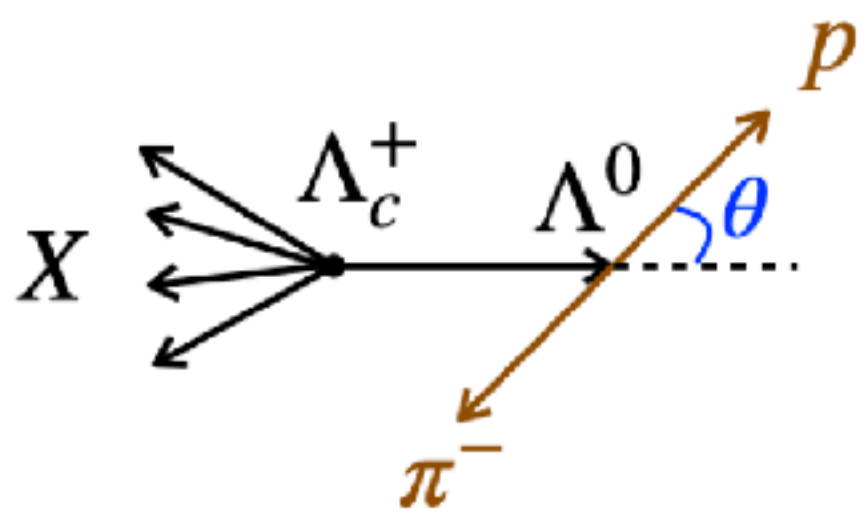
Multi-body decays

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \langle \alpha^i_{\Lambda_c}(q^2)\rangle\ \alpha_{\Lambda}\cos\theta$$



Inclusive decays

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \langle P(q^2)\rangle\ \alpha_{\Lambda}\cos\theta$$

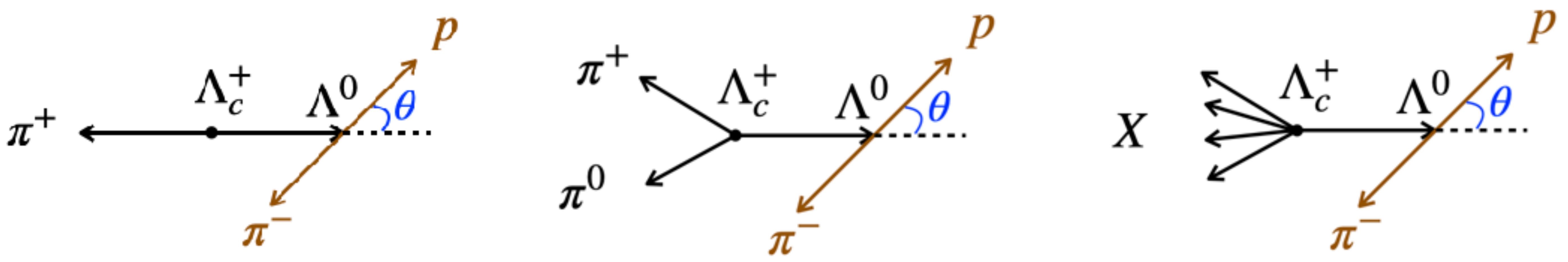


$q = p_{\Lambda_c} - p_{\Lambda}$

Averaged longitudinal polarization of Λ^0 from Λ_c^+ decays

J.P.Wang, FSY, arXiv:2208.01589

Remarks on experimental measurements



- Larger values of $\langle \alpha^i_{\Lambda_c}(q^2) \rangle$ are better to measure the hyperon CPV ==> BESIII.

- The CP violation in hyperon decays can be measured by Belle II and LHCb.

- $\Lambda_c^+ \to \Lambda^0 \pi^+,\ \Lambda^0 \to p\pi^-$ was very recently measured at Belle [Belle, 2208.08695], $A^\alpha_{CP}(\Lambda \to p\pi) = (+13 \pm 7 \pm 11) \times 10^{-3}$ v.s. BESIII: $A^\alpha_{CP} = (-2.5 \pm 4.6 \pm 1.1) \times 10^{-3}$

- Prospect: combination of all Λ^0 involved modes ($\times\, 10$), and $50\mathrm{ab}^{-1}$ at Belle II ($\times\, 100$). It is probably to reach the SM prediction of hyperon CPV at the order of 10^{-4}.

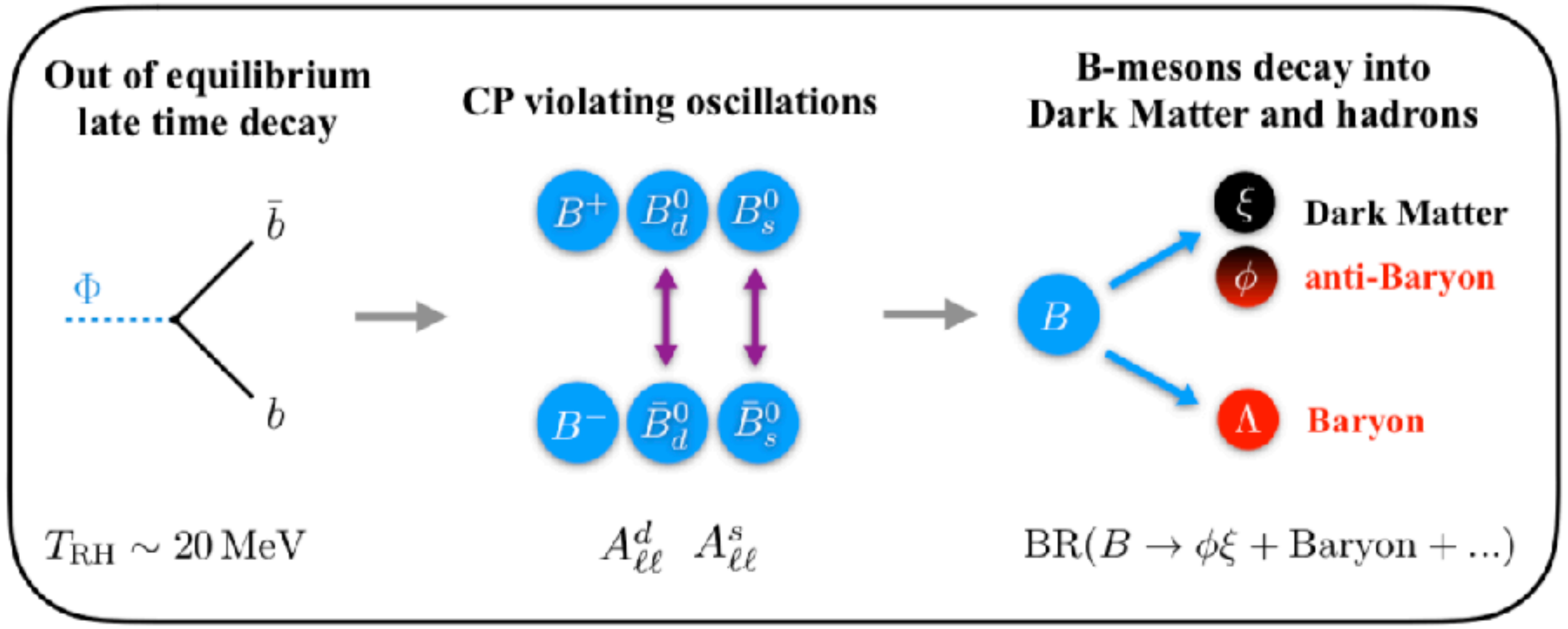
- LHCb has larger production of Λ_c^+. Current LHCb data might provide the most precise measurement on hyperon CPV.

Baryon number violations: dark baryons

- Baryogenesis and dark matter:

B-mesogenesis

Elor, Escudero, Nelson, 1810.00880



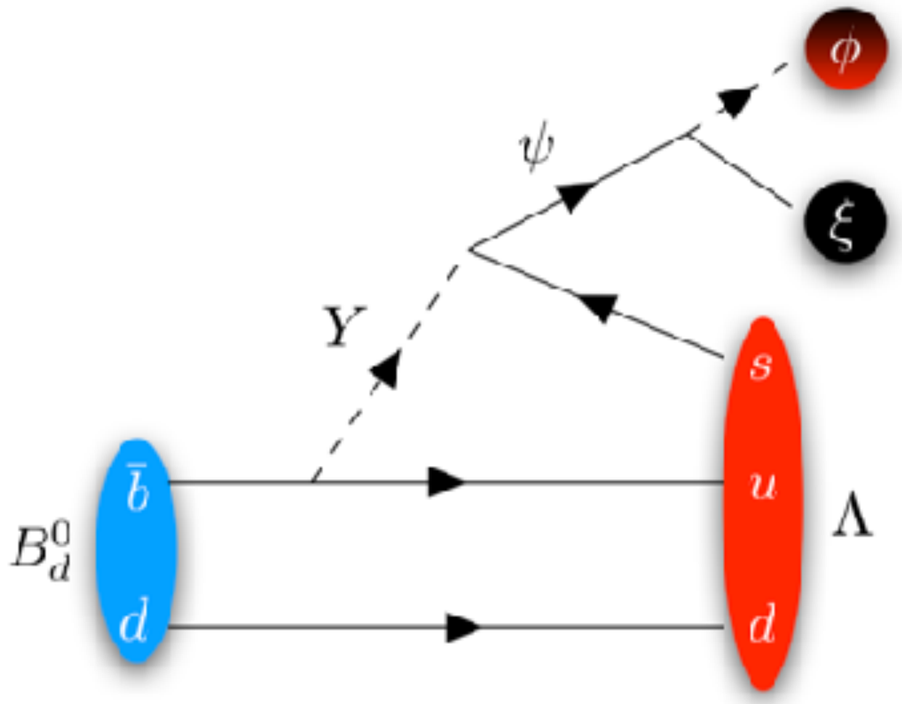
- Neutron lifetime puzzle:

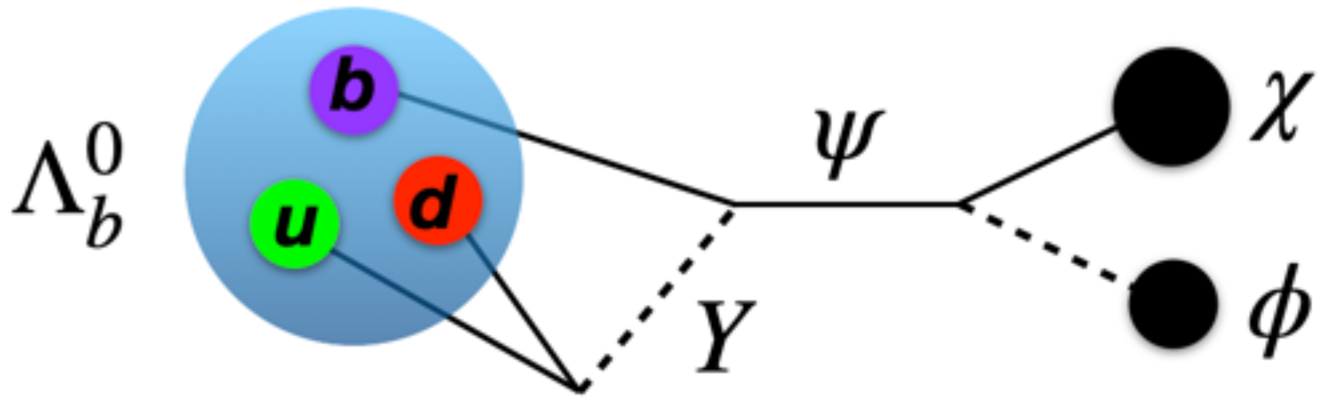
$$\tau_n^{\rm bottle} = 879.6 \pm 0.6\ \mathrm{s} \qquad < \qquad \tau_n^{\rm beam} = 888.0 \pm 2.0\ \mathrm{s}$$

1% of neutron dark decays ! Fortal, Grinstein, PRL120,91801 (2018)

Baryon number violations: dark baryons

- Baryogenesis and dark matter: B-mesogenesis   Elor, Escudero, Nelson, 1810.00880

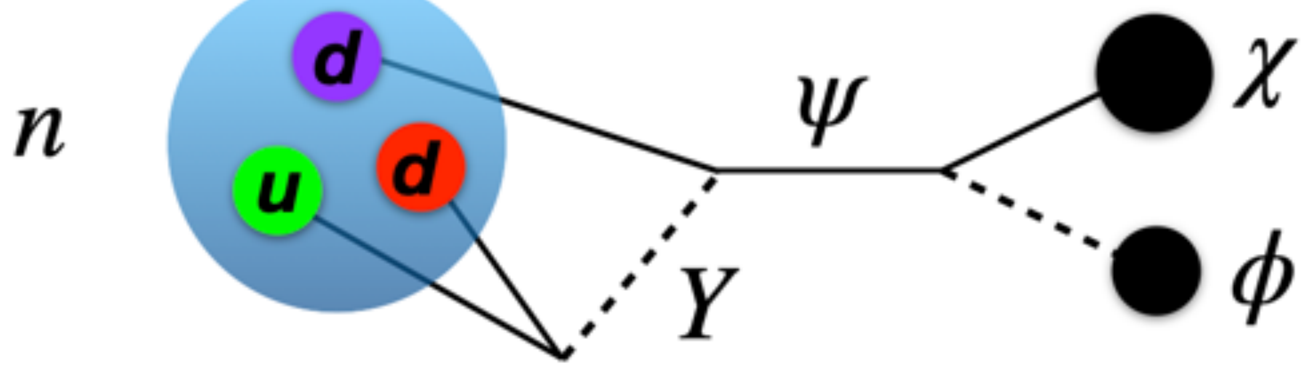




EFT: $\mathcal{O} = udb\psi$

3rd generation

- Neutron lifetime puzzle: 1% of neutron dark decays !   Fortal, Grinstein, PRL120,91801 (2018)

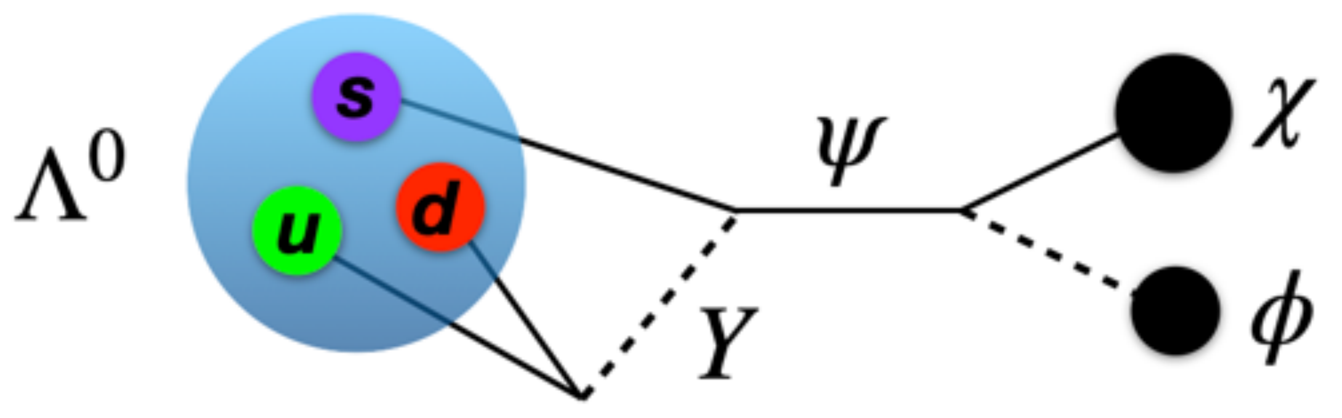


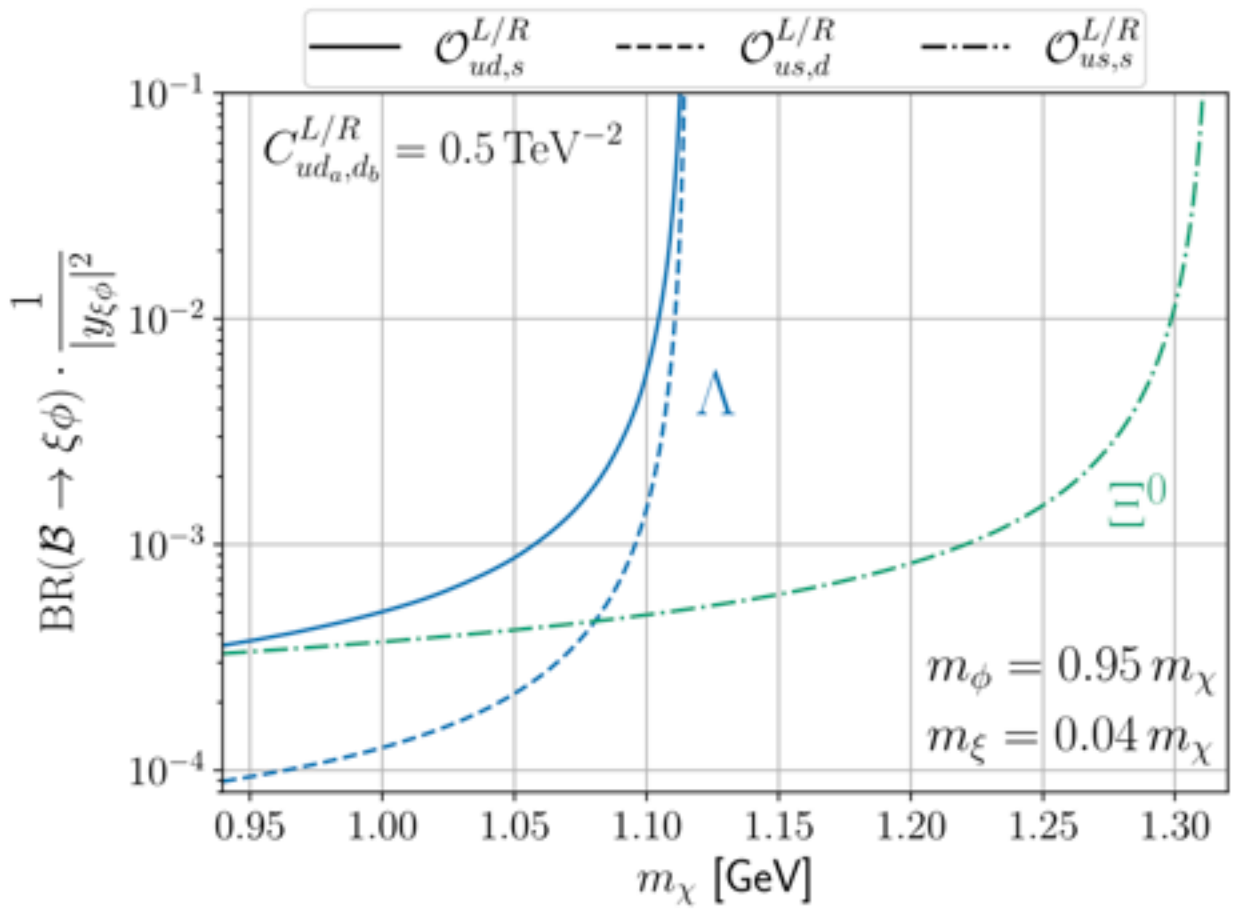
EFT: $\mathcal{O} = udd\psi$

1st generation

Lambda invisible decays

- From the theoretical perspective, it is expected that the baryonic dark sectors interact with all the Standard Model quarks.
- BESIII as a tau-charm factory can measure the interactions with the 2nd generation.
- Λ invisible decay: EFT: $\mathcal{O} = uds\psi$





Alonso-Alvarez, et al, 2111.12712

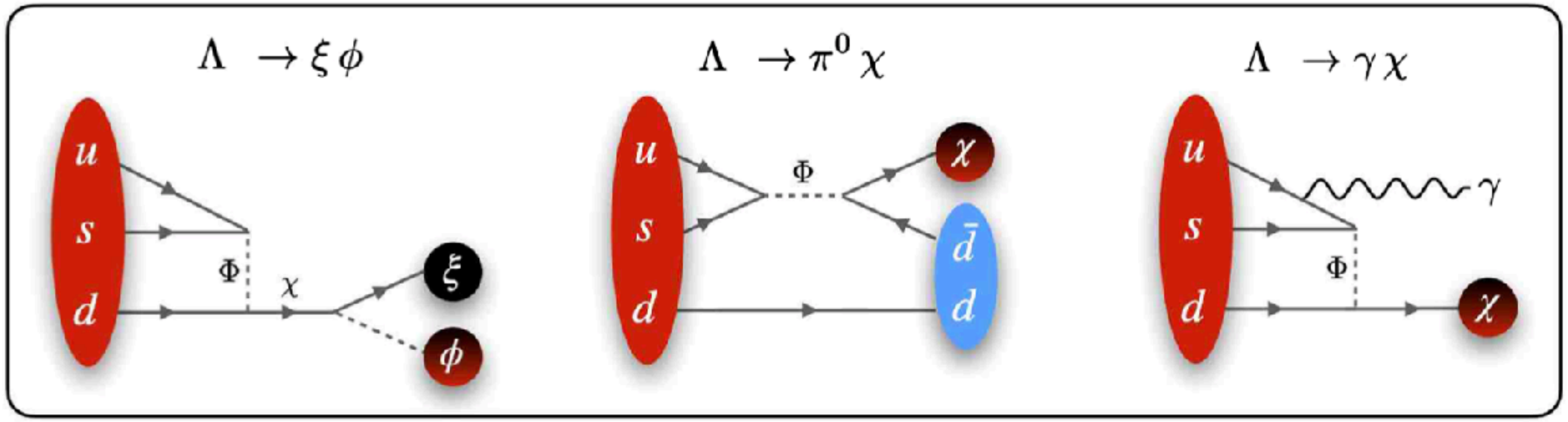
- BESIII measurement: BR($\Lambda \to$ invisible) $< 7.4 \times 10^{-5}$

BESIII, PRD105, L071102 (2022)

See Dayong's and Yang's talk

Invisible decays

- More processes of hyperon decays:



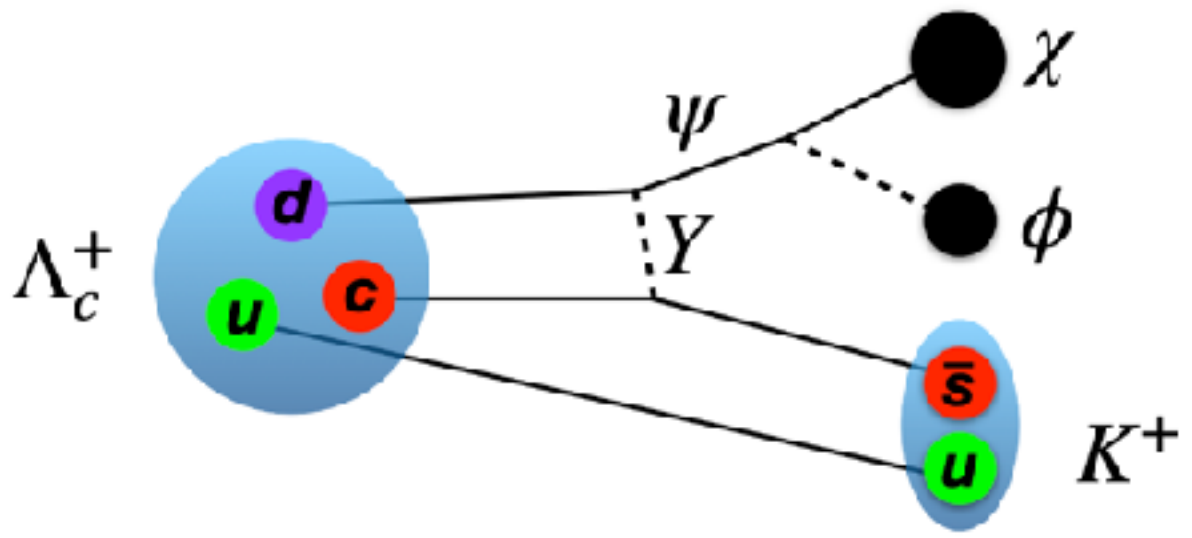
Alonso-Alvarez, et al, 2111.12712

- More processes of charmed hadron decays: EFT: $\mathcal{O} = cds\psi$

$\Lambda_c^+ \to K^+ +$ **invisible**

$\Lambda_c^+ \to \pi^+ +$ **invisible**

$D^0 \to \overline{\Lambda}^0 +$ **invisible**



Summary

- We propose to search for hyperon CPV in the Cabibbo-favored charmed baryon decays, which is probably accessible to reach the SM prediction.
- Invisible hyperon decays and invisible charmed hadron decays are suggested to search for new physics.

Thank you!

Backups

Introduction

- Discrete symmetries and their violation play significant roles in elementary particle physics
  - Charge conjugate, Parity, Time reversal (C, P, T)
- CP violation (CPV) has been well established in K, B and D mesons, but never in baryons until now
  - CPV is one of the key conditions for matter-antimatter asymmetry in the Universe
  - The visible universe is mostly made of baryons
  - Searching for baryon CPV is one of key problems in flavor physics
- In history, the parity non-conversation in weak decays was proposed by Lee and Yang
  - It was manifested by the beta decay of Co-60 by Wu
  - The decay asymmetry parameters were proposed by Lee and Yang very soon later

Introduction

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

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C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

Possible Detection of Parity Nonconservation in Hyperon Decay*

T. D. LEE, J. STEINBERGER,
Columbia University, New York, New York

AND

G. FEINBERG, P. K. KABIR, AND C. N. YANG,
Institute for Advanced Study, Princeton, New Jersey

(Received May 2, 1957)

PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

Remarks on Possible Noninvariance under Time Reversal and Charge Conjugation*

T. D. LEE, *Columbia University, New York, New York*

AND

REINHARD OEHME AND C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(Received January 7, 1957)

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

T. D. LEE* AND C. N. YANG

Institute for Advanced Study, Princeton, New Jersey

(Received October 22, 1957)

Parity transformation

space	$\vec{x} \rightarrow -\vec{x}$	odd
time	$t \rightarrow t$	even
momentum	$\vec{p} \rightarrow -\vec{p}$	odd
angular momentum	$\vec{L} \rightarrow \vec{L}$	even
spin	$\vec{s} \rightarrow \vec{s}$	even
$\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$	$\rightarrow -\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$	odd
$\vec{p} \cdot \vec{s}$	$\rightarrow -\vec{p} \cdot \vec{s}$	odd

$\Lambda^0 \to p\pi^-$: completely polarized hyperon

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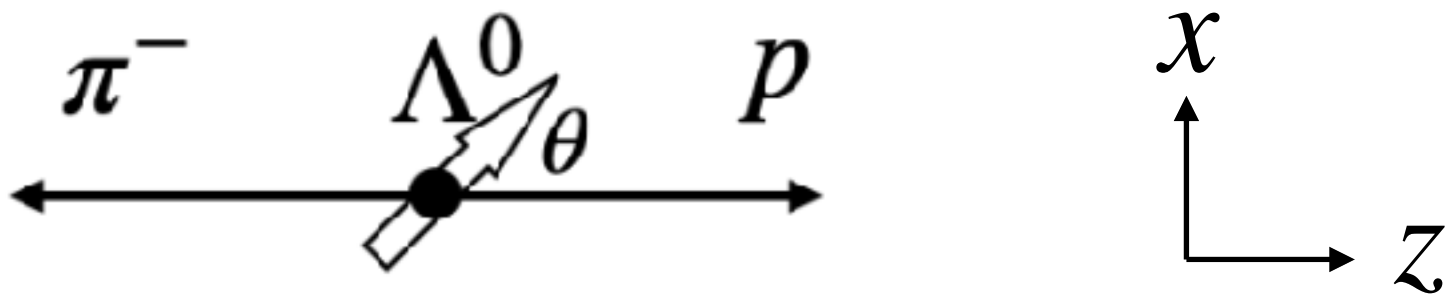

Polarization in the final-state proton: $$P_p = \frac{(\alpha + \cos\theta)\hat{p} + \beta\hat{p}\times\hat{s} + \gamma(\hat{p}\times\hat{s})\times\hat{p}}{1+\alpha\cos\theta}$$

z-direction: longitudinal polarization of proton, $\alpha = \dfrac{2Re(S^*P)}{|S|^2+|P|^2}$

y-direction: normal polarization of proton, $\beta = \dfrac{2Im(S^*P)}{|S|^2+|P|^2}$

x-direction: transverse polarization of proton, $\gamma = \dfrac{|S|^2-|P|^2}{|S|^2+|P|^2}$

$\Lambda^0 \to p\pi^-$: completely polarized hyperon

General Partial Wave Analysis of the Decay of a Hyperon of Spin $\frac{1}{2}$

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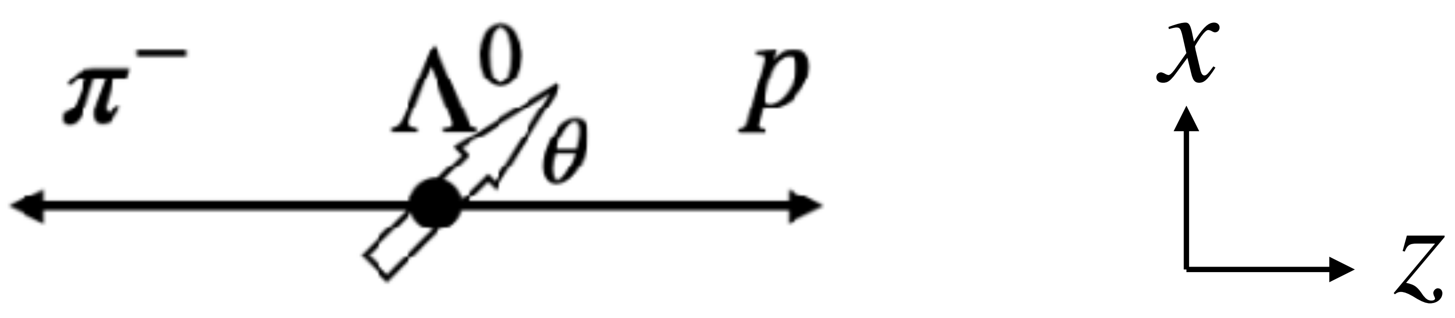
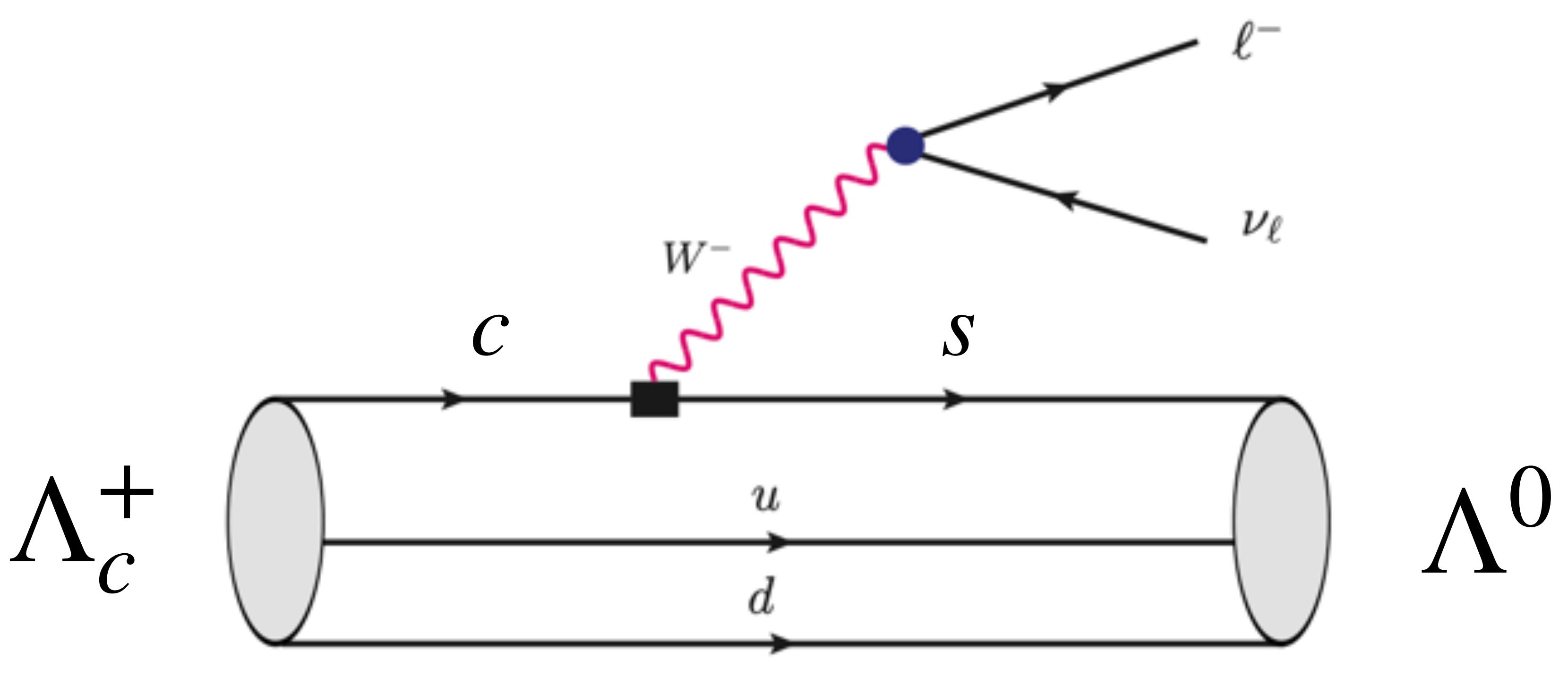


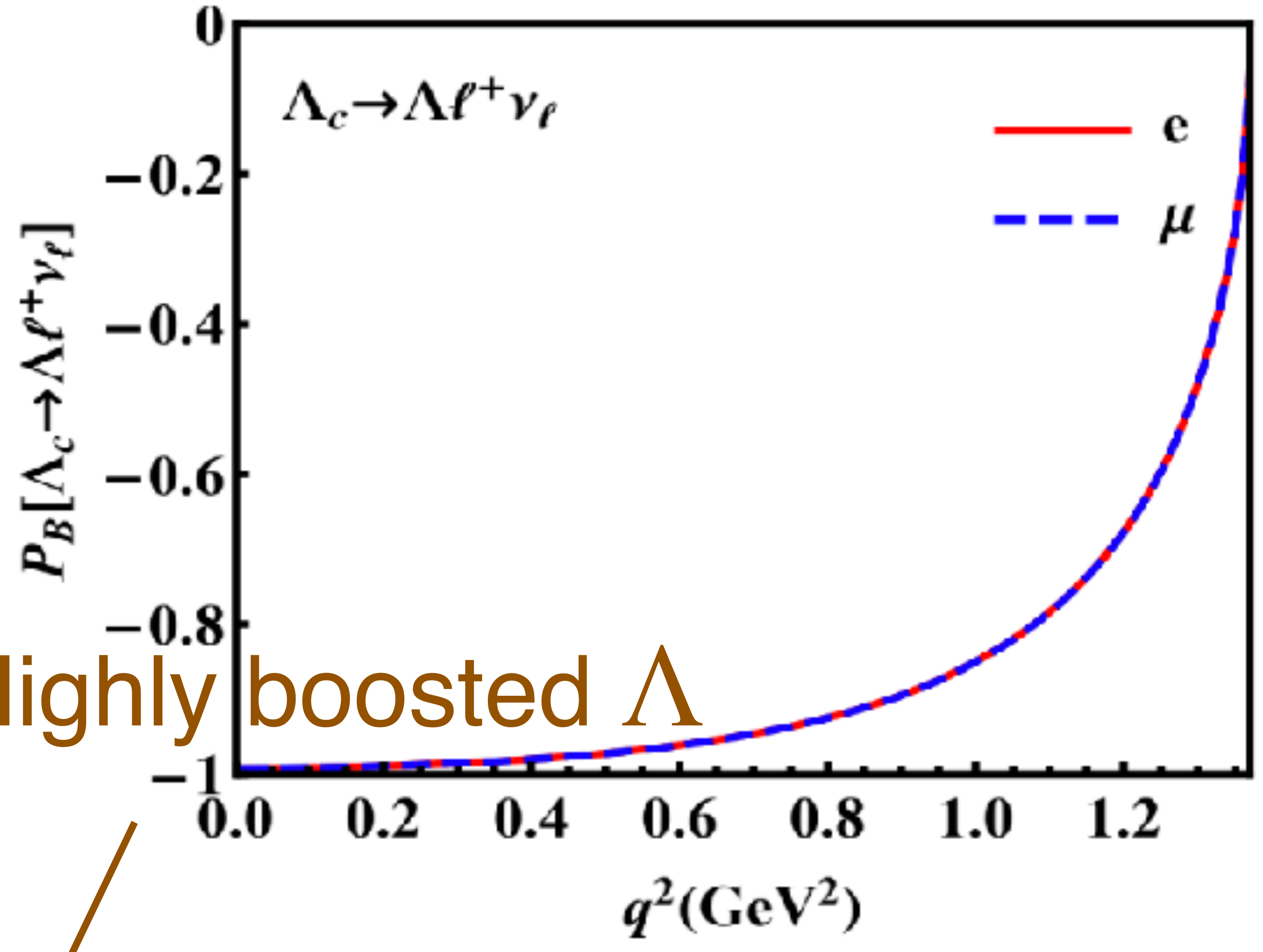
$$\alpha = \frac{2Re(S^*P)}{|S|^2+|P|^2},\ \beta = \frac{2Im(S^*P)}{|S|^2+|P|^2},\ \gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

- α, β, γ are not independent: $\alpha^2+\beta^2+\gamma^2=1$
- Together with the decay width, $\Gamma \propto |S|^2+|P|^2$, there are three independent observables
- There are three free parameters in the amplitude, $|S|,\ |P|,\ \delta_{SP}$
- In case of CP conserving, all the three observables are required to understand the decay dynamics. All the above arguments are the same as charmed baryon decays.

Hyperon polarization in $\Lambda_c^+ \to \Lambda^0 \ell^- \nu_\ell$



static Λ



Highly boosted Λ

Y.S.Li, X.Liu, F.S.Yu, PRD104,013005(2021)

$$P_B(q^2) = \frac{d\Gamma^{\lambda_2=1/2}/dq^2 - d\Gamma^{\lambda_2=-1/2}/dq^2}{d\Gamma/dq^2}$$

Purely left-handed weak interaction

$\langle P(q^2) \rangle = -0.86 \pm 0.04$ CLEO 2005

$\alpha(\Lambda_c \to \Lambda\pi) = -0.84 \pm 0.09$ BESIII 2019

Similar in factorizable decays like $\Lambda_c^+ \to \Lambda^0 \pi^+ \pi^0$

General formula for hyperon CPV from Λ_c^+ decays

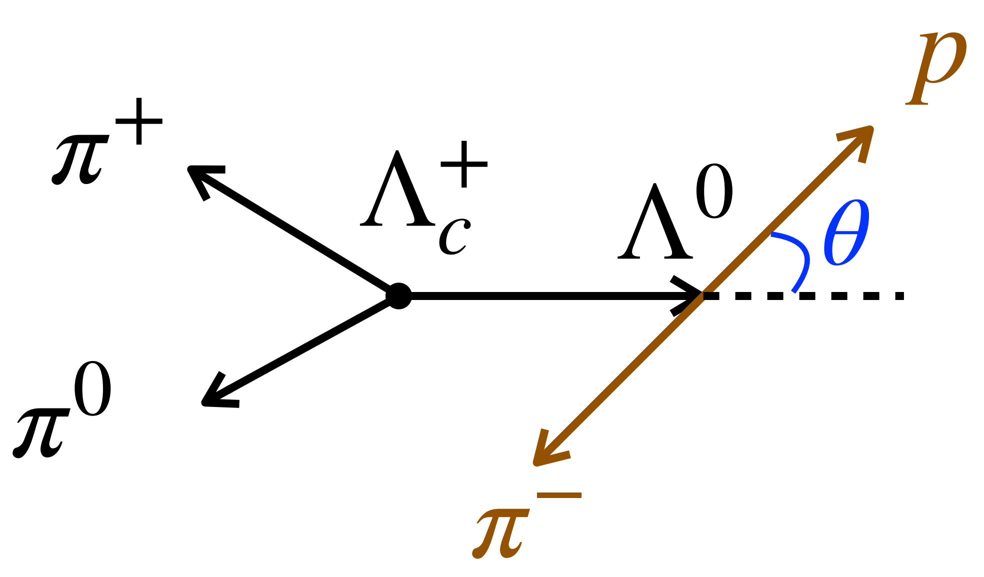
Two-body decays like $\Lambda_c^+ \to \Lambda^0 \pi^+$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha_{\Lambda_c} \alpha_\Lambda \cos\theta$$

Multi-body decays like $\Lambda_c^+ \to \Lambda^0 \pi^+ \pi^0$

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + P \alpha_\Lambda \cos\theta$$

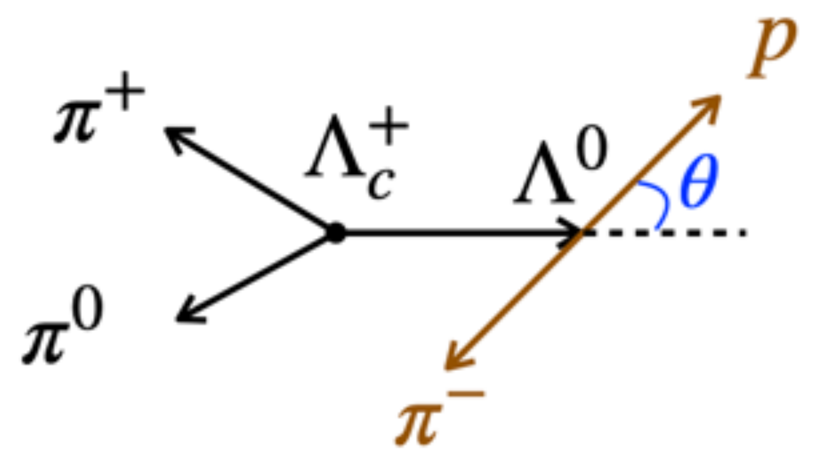
Longitudinal polarization of Λ^0 from Λ_c^+ decays



- Dynamical calculation is difficult for multi-body decays
- Intermediate states are required for dynamical calculations
- No matter how large it is, there must be such a polarization in the weak decays violating the parity

General formula for hyperon CPV from Λ_c^+ decays

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + P\,\alpha_\Lambda \cos\theta$$



- In general, this polarization is q^2 dependent, $P(q^2)$. Reasonable for intermediate resonant states
- If we only measure the distribution of $\cos\theta$ which is defined by $\Lambda^0 \to p\pi$ but un-related to Λ_c^+ decays, the polarization can be averaged

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \langle P(q^2)\rangle\, \alpha_\Lambda \cos\theta$$

Then CPV in the Cabibbo-favored Λ_c^+ decays is the same as two-body decays

$$A_{CP}^{\alpha}(\text{total}) = A_{CP}^{\alpha}(\Lambda \to p\pi)$$

$$A_{CP}^{\alpha}(\text{total}) = \frac{\alpha_{\Lambda_c} \cdot \alpha_{\Lambda} - \bar{\alpha}_{\Lambda_c} \cdot \bar{\alpha}_{\Lambda}}{\alpha_{\Lambda_c} \cdot \alpha_{\Lambda} + \bar{\alpha}_{\Lambda_c} \cdot \bar{\alpha}_{\Lambda}} = A_{CP}^{\alpha}(\Lambda \to p\pi)$$

- α_{Λ_c} or $\langle P(q^2)\rangle$ is cancelled in the above equations
- But a larger value of α_{Λ_c} is better for measurement

$$\Delta A_{CP}^{\alpha} = \sqrt{\left(\frac{2\bar{\alpha}_{\Lambda_c}\bar{\alpha}_{\Lambda}\alpha_{\Lambda}}{(\alpha_{\Lambda_c}\alpha_{\Lambda} + \bar{\alpha}_{\Lambda_c}\bar{\alpha}_{\Lambda})^2}\Delta\alpha_{\Lambda_c}\right)^2 + (\alpha_{\Lambda_c} \leftrightarrow \bar{\alpha}_{\Lambda_c})}$$

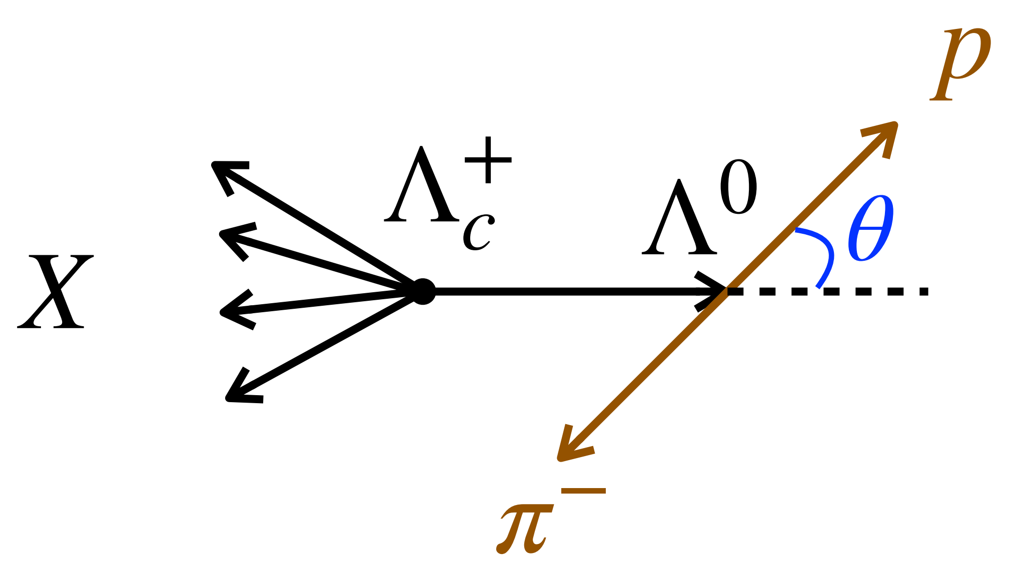
$$= \sqrt{\left(\frac{2}{\alpha_{\Lambda_c}}\Delta\alpha_{\Lambda_c}\right)^2 + (\alpha_{\Lambda_c} \leftrightarrow \bar{\alpha}_{\Lambda_c})}$$

$\bar{\alpha}_{\Lambda_c} = -\alpha_{\Lambda_c}, \bar{\alpha}_{\Lambda} \approx -\alpha_{\Lambda}$

Inclusive decays in $\Lambda_c^+ \to \Lambda^0 X$

- Inclusive decays have large branching fractions

$$Br(\Lambda_c^+ \to \Lambda X) = (38.2^{+2.9}_{-2.4})\,\%$$

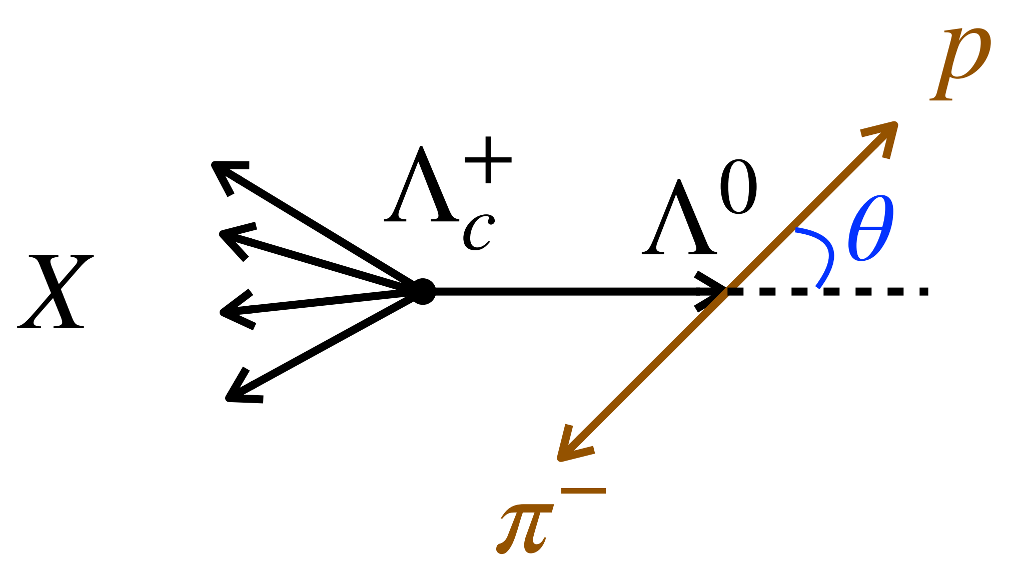


- The formulas are similar to multi-body decays

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \langle P(q^2)\rangle\, \alpha_\Lambda \cos\theta$$

- It can be used to measure CPV

Inclusive decays in $\Lambda_c^+ \to \Lambda^0 X$

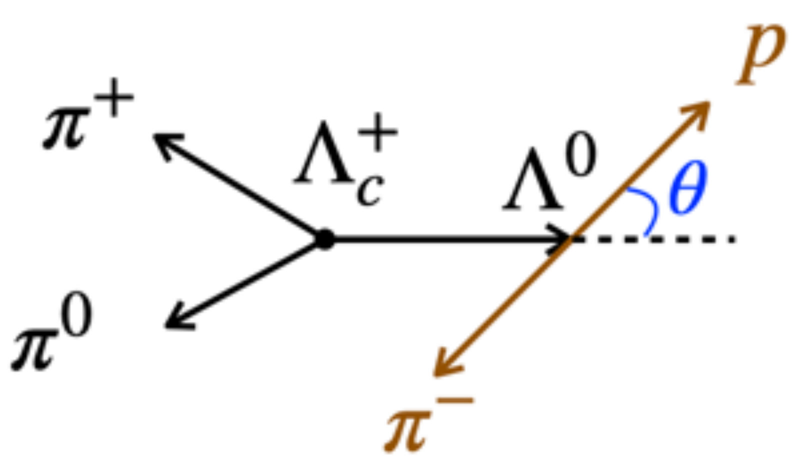


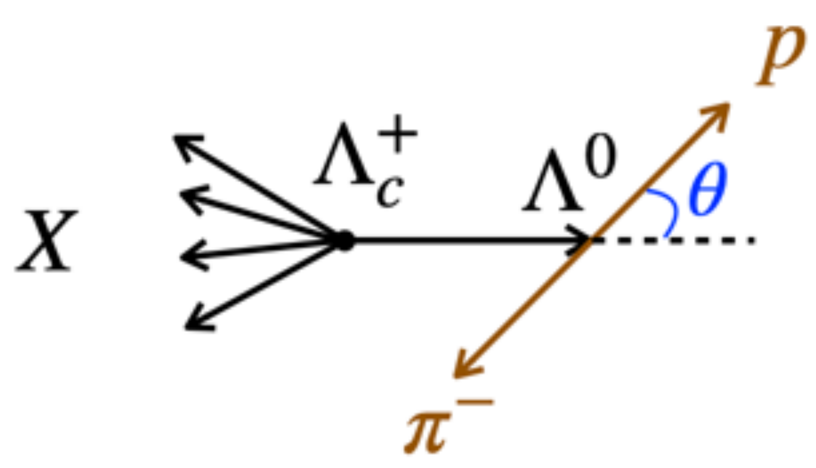
$$Br(\Lambda_c^+ \to \Lambda X) \approx Br(CF) + Br(SCS)$$

$$A_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda X) \approx \frac{Br(SCS)}{Br(\Lambda_c^+ \to \Lambda X)} \times A_{CP}^{\alpha}(\Lambda_c^+) \approx \lambda^2 A_{CP}^{\alpha}(\Lambda_c^+)$$

- Singly Cabibbo-suppressed Λ_c^+ decays have CPV at the order of $\mathcal{O}(10^{-3} \sim 10^{-4})$
- Thus $A_{CP}^{\alpha}(\Lambda_c^+ \to \Lambda X) = \mathcal{O}(10^{-4} \sim 10^{-5})$.
- It is at the same order of $A_{CP}^{\alpha}(\Lambda \to p\pi)$
- If observed, not clear for charmed baryon or hyperon, but definitely for baryon CPV!

Remarks





- For multi-body decays or inclusive decays, the formula are all the same, since $\cos\theta$ is only related to the Λ and its product, but irrelevant to any other particles in Λ_c decay.

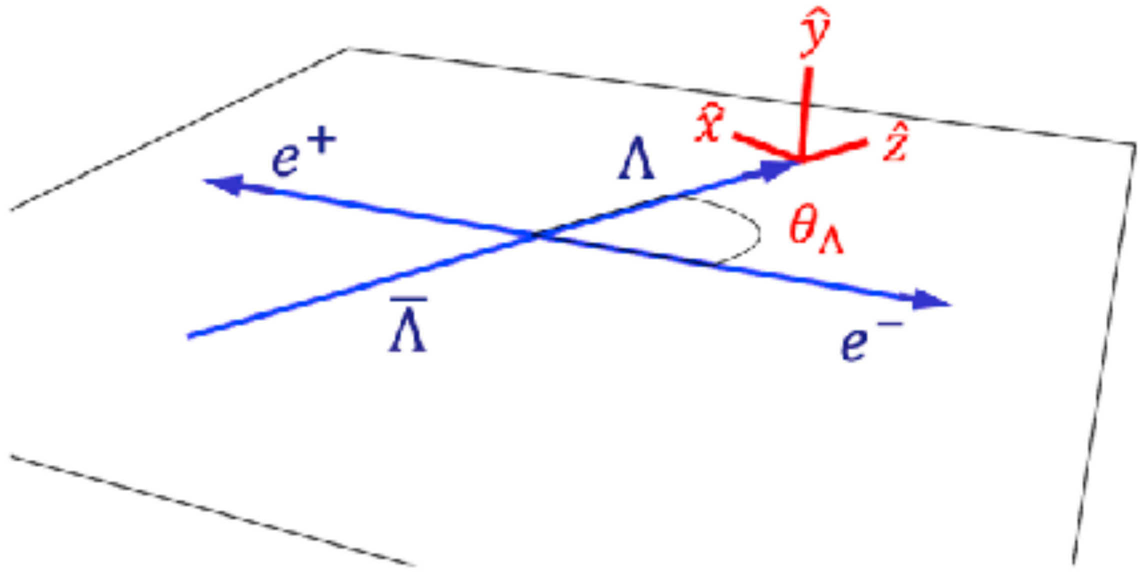
$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \langle P(q^2)\rangle\, \alpha_\Lambda \cos\theta$$

- It does not depend on the intermediate resonant states, even including Ξ
- The intermediate states only change the values of the averaged polarization, but not the above formula

Backups: $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$

BESIII, Nature Phys.15, 631 (2019)

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi};\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+) =&1+\alpha_\psi\cos^2\theta_\Lambda \\ &+\alpha_-\alpha_+\left[\sin^2\theta_\Lambda\left(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y}\right)+\left(\cos^2\theta_\Lambda+\alpha_\psi\right)n_{1,z}n_{2,z}\right] \\ &+\alpha_-\alpha_+\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(n_{1,x}n_{2,z}+n_{1,z}n_{2,x}\right) \\ &+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\,\sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_-n_{1,y}+\alpha_+n_{2,y}\right),\end{aligned}$$



Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [25]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [27]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [27]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [27]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

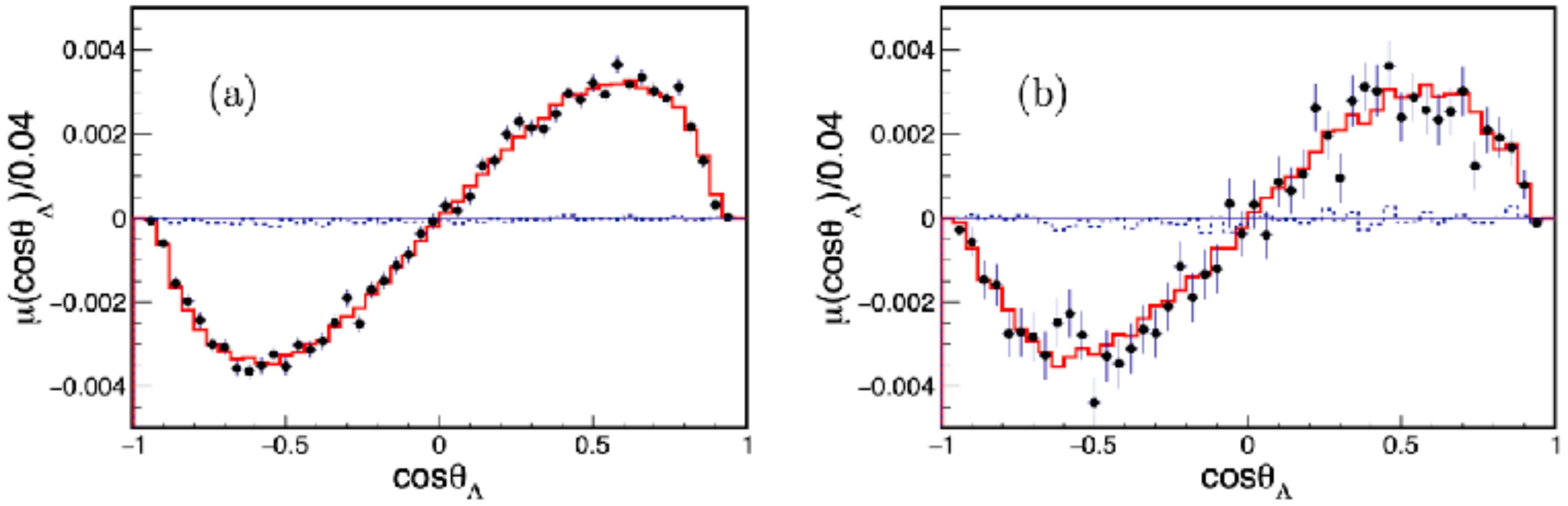


FIG. 2. Moments $\mu(\cos\theta_\Lambda)$ for acceptance uncorrected data as a function of $\cos\theta_\Lambda$ for (a) $p\pi^-\bar{p}\pi^+$ and (b) $p\pi^-\bar{n}\pi^0$ data sets. The points with error bars are the data, and the solid-line histogram is the global fit result. The dashed histogram shows the no polarization scenario ($\mathcal{W}(\boldsymbol{\xi};0,0,0,0)=1$).

Backups: $\Lambda_c^+ \to \Lambda\pi^+, \Sigma^+\pi^0$

BESIII, PRD100,072004 (2019)

$$
\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_0 d\cos\theta_1 d\cos\theta_2 d\phi_1 d\phi_2} \\
&\propto 2 + 2\alpha_0\cos^2\theta_0 \\
&+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\Delta_0 \sin(2\theta_0)\sin\theta_1\cos\theta_2\sin\phi_1 \\
&+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\Delta_0 \sin(2\theta_0)\cos\theta_1\sin\theta_2\sin\phi_1 \\
&\times \sqrt{1-(\alpha^+_{\Lambda\pi^+})^2}\cos(\Delta_1^{\Lambda\pi^+}+\phi_2) \\
&+ \sqrt{1-\alpha_0^2}\alpha_\Lambda \sin\Delta_0 \sin(2\theta_0)\sin\theta_2\cos\phi_1 \\
&\times \sqrt{1-(\alpha^+_{\Lambda\pi^+})^2}\sin(\Delta_1^{\Lambda\pi^+}+\phi_2) \\
&+ \sqrt{1-\alpha_0^2}\sin\Delta_0\sin(2\theta_0)\sin\theta_1\sin\phi_1\alpha^+_{\Lambda\pi^+} \\
&+ 2\alpha_0\alpha_\Lambda\cos^2\theta_0\cos\theta_2\alpha^+_{\Lambda\pi^+} + 2\alpha_\Lambda\cos\theta_2\alpha^+_{\Lambda\pi^+},
\end{aligned}
$$

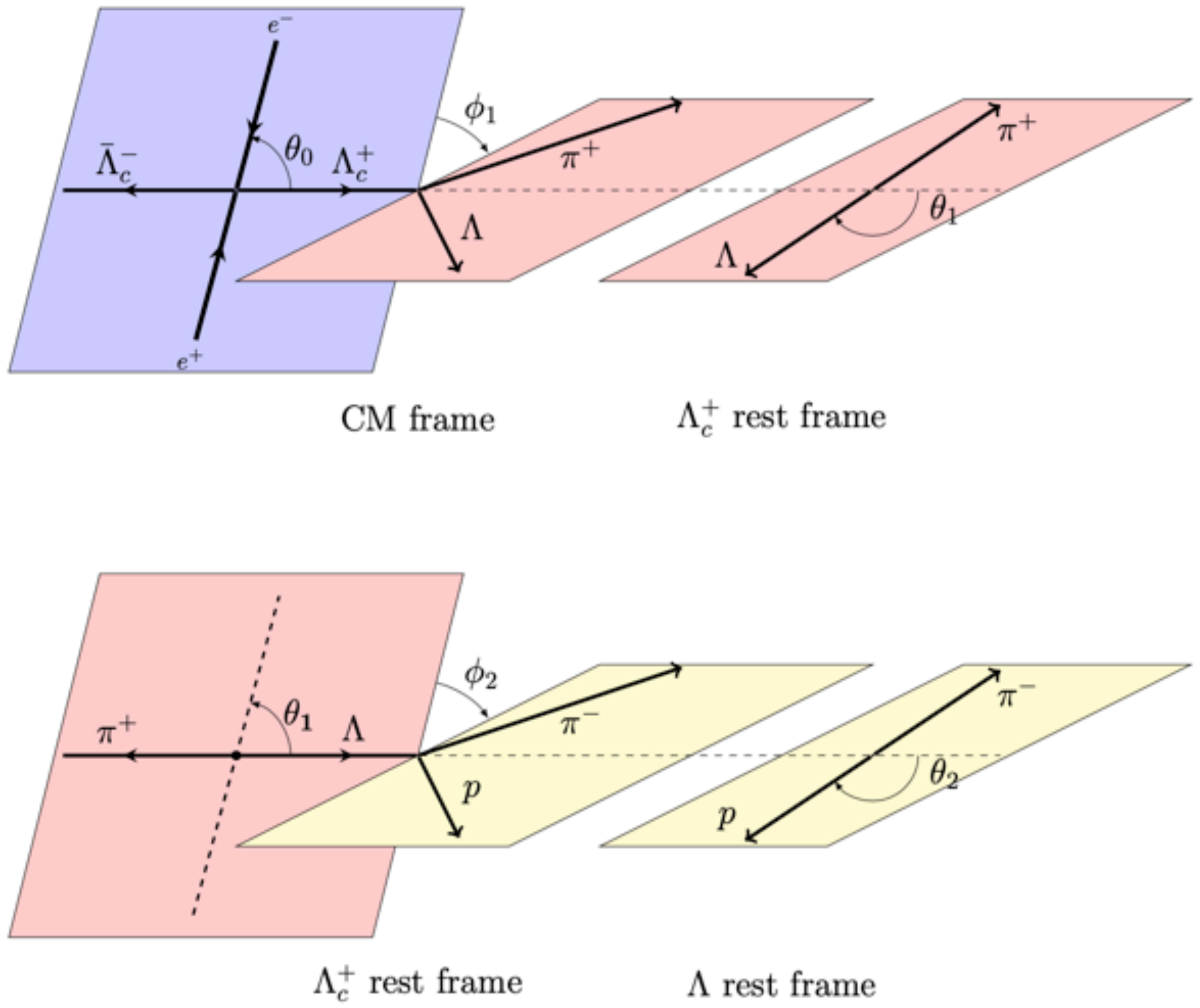


FIG. 2. (color online) Definition of the helicity frame for $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$, $\Lambda_c^+ \to \Lambda\pi^+$, $\Lambda \to p\pi^-$