CP violation of baryon decays

Fu-Sheng Yu

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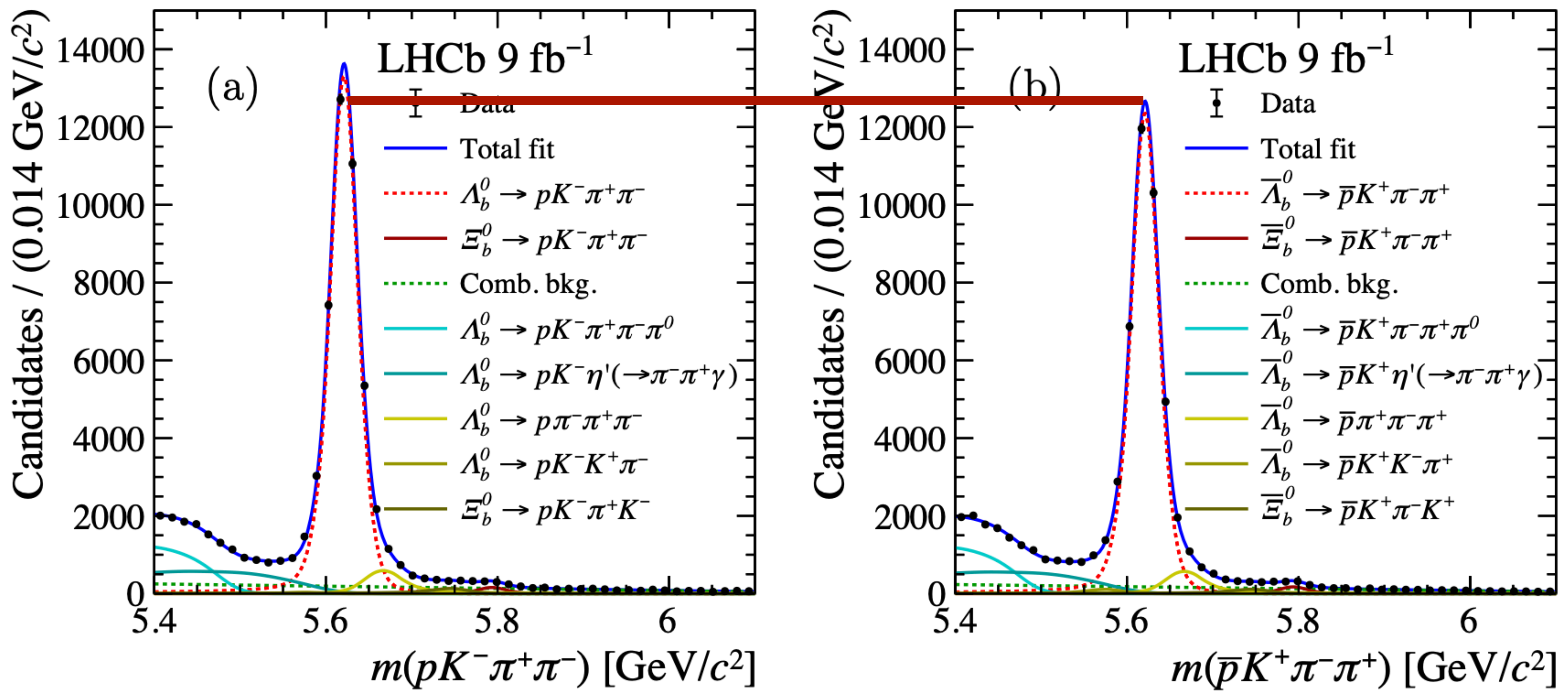
Heavy Flavor and QCD workshop @ Nanjing Normal University, 2025.04.19

A new horizon in particle physics: First observation of baryon CP violation

$$\Lambda_b^0 \to pK^-\pi^+\pi^-$$

$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\%$$

$$5.2\sigma$$



LHCb, arXiv: 2503.16954.   Congratulations to LHCb!   See Yanxi's talk

More interesting CP violation

Regional CPV

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$	
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$	4.0σ
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$	3.3σ
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$	6.0σ
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$	1.6σ

LHCb, arXiv: 2503.16954. Congratulations to LHCb! See Yanxi's talk

Outline

1. Why baryon CPV? Motivation
2. Two-body: Why baryon CPV are so small?
3. Multi-body: CPV with $N\pi$ rescatterings

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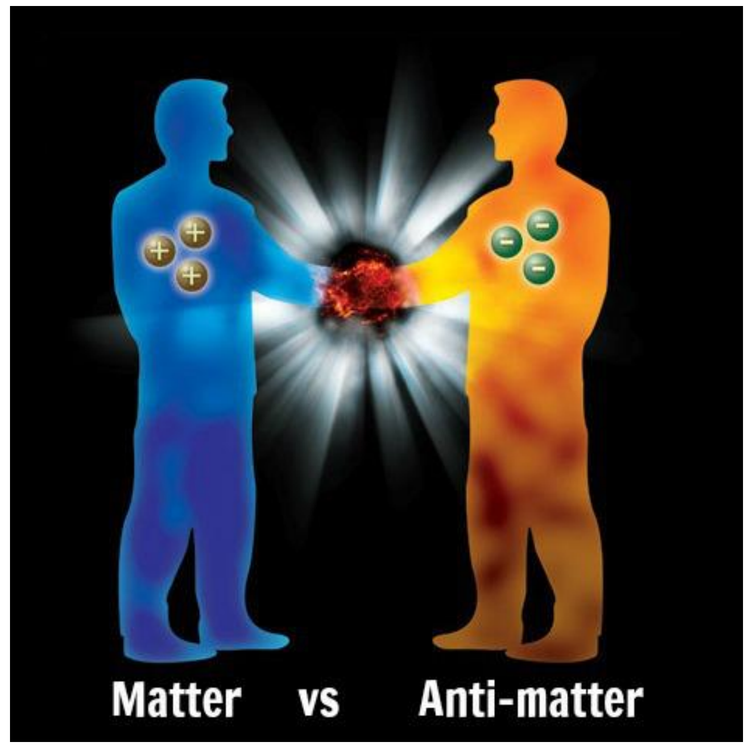
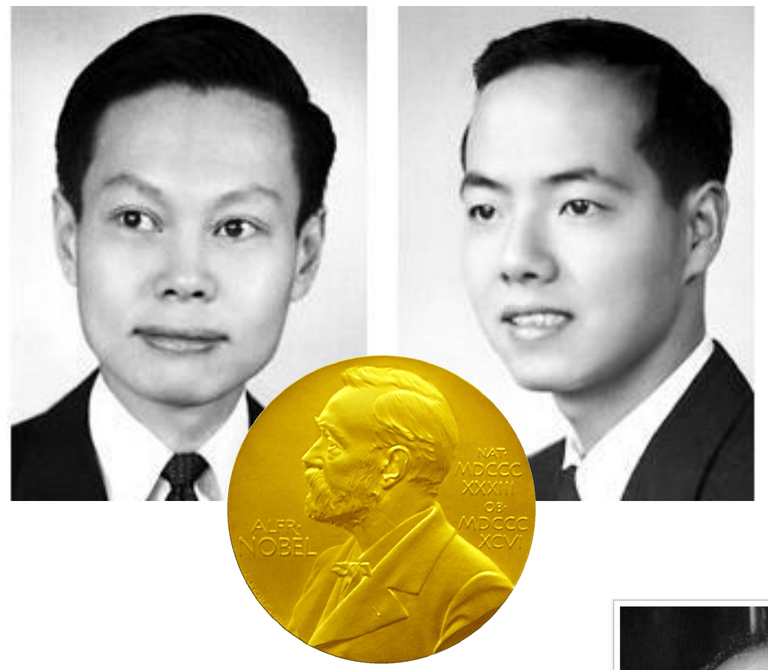
CP violation in baryons

- **CP violation** is a necessary condition for **matter-antimatter asymmetry of the Universe**
  - CPV: SM < matter-antimatter asymmetry.
    => new source of CPV, new physics
  - The visible universe is mainly made of **baryons**.
- CPV were only observed in mesons, **but not yet in baryons**
- **It is of great significance to search for baryon CPV.**



History of CP violation



- 1956, Parity violation in weak interaction

- 1964, Observation of CPV in Kaon
- 1973, Kobayashi-Maskawa mechanism
- 2001, Observation of CPV in B meson

- 2019, Observation of CPV in D meson

physicsworld TOP 10 BREAKTHROUGH 2019

- **CPV of baryons?**

First observations are always two-body decays, but four-body in baryon decays

- 1956, Parity violation in weak interaction
- 1964, Observation of CPV in Kaon ⟶ $K_L^0 \to \pi^+\pi^-$
- 1973, Kobayashi-Maskawa mechanism
- 2001, Observation of CPV in B meson ⟶ $B^0 \to J/\psi K_S^0,\ K^-\pi^+,\ \pi^+\pi^-$
- 2019, Observation of CPV in D meson ⟶ $D^0 \to \ K^+K^-,\ \pi^+\pi^-$
- **2025, Observation of CPV in baryon** ⟶ $\Lambda_b^0 \to pK^-\pi^+\pi^-$ 4-body

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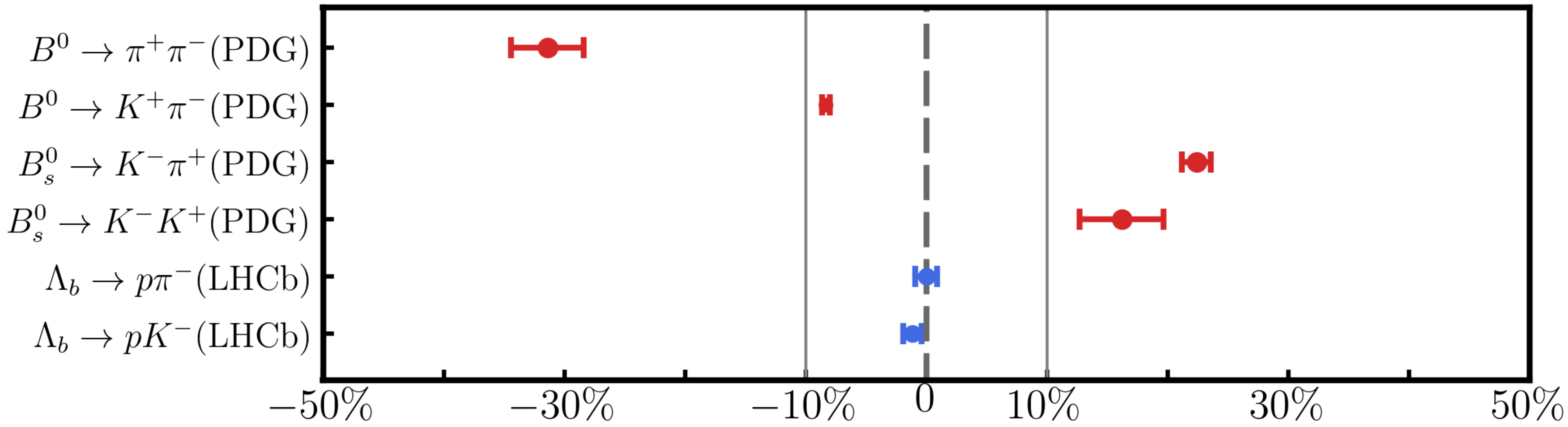
CPV of b-baryon

- Precision of b-baryon CPV measurements reaches the order **1%** [LHCb, 2024]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\,\%$$

- CPV in some B-meson decays are as large as **10%**:



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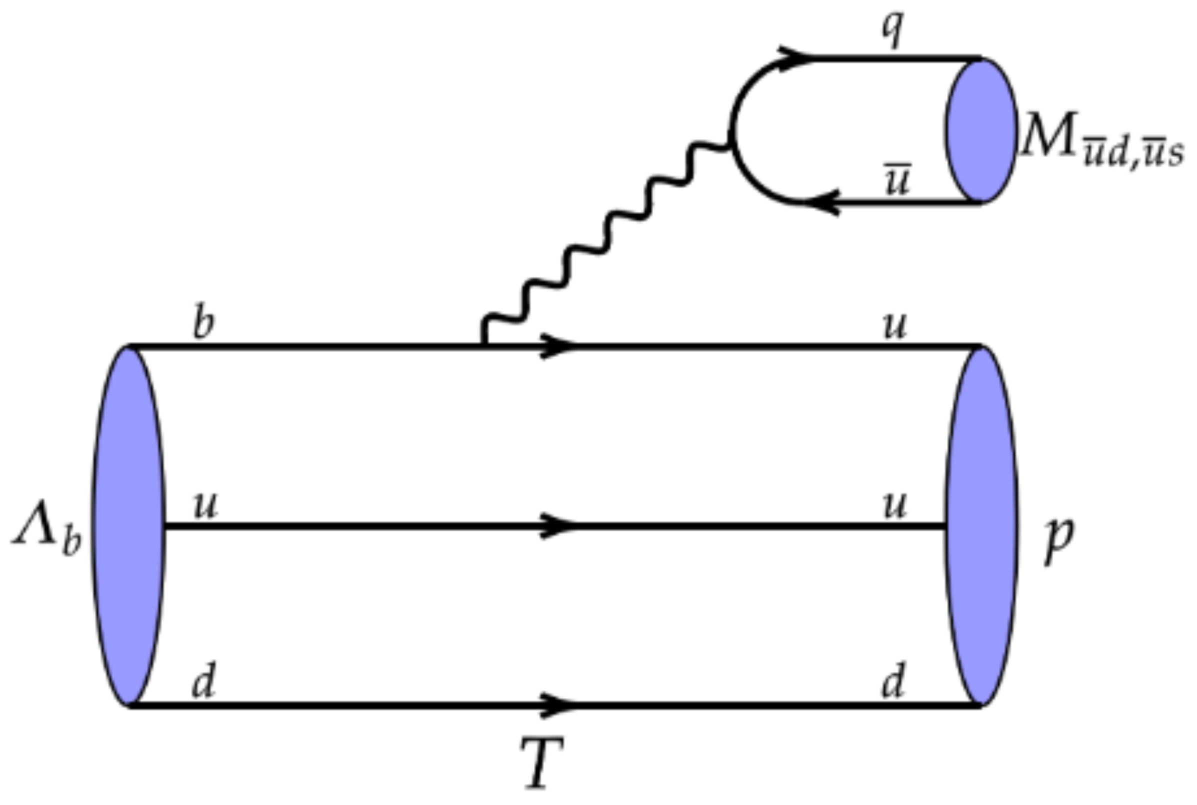
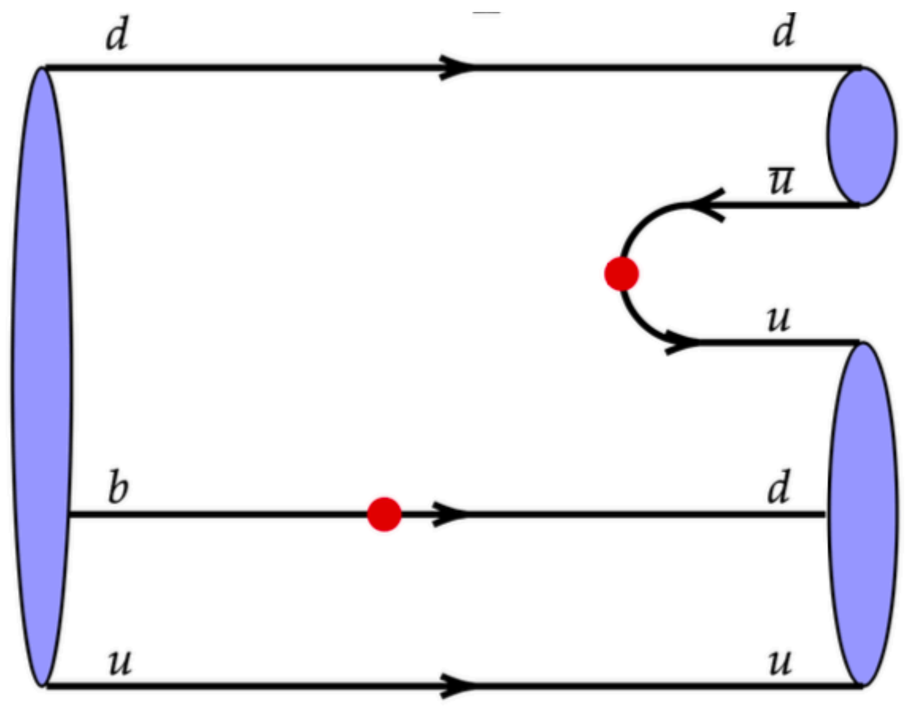
CPV cancelled between S- and P-waves

$$\mathscr{M} = \bar{u}_p\,(\,S \;+\; P\,\gamma_5\,)\,u_{\Lambda_b}$$

tree:



penguin:



$$q^\mu\;\bar{u}_p\gamma_\mu(1-\gamma_5)u_{\Lambda_b} \to m_{\Lambda_b}\bar{u}_p(1+\gamma_5)u_{\Lambda_b}$$

$$\bar{u}_p(1+\gamma_5)(\gamma_5\not{p}_\pi)(\not{v}_{\Lambda_b}\gamma_5)\not{p}_p(1-\gamma_5)u_{\Lambda_b} \to \bar{u}_p(1-\gamma_5)u_{\Lambda_b}$$

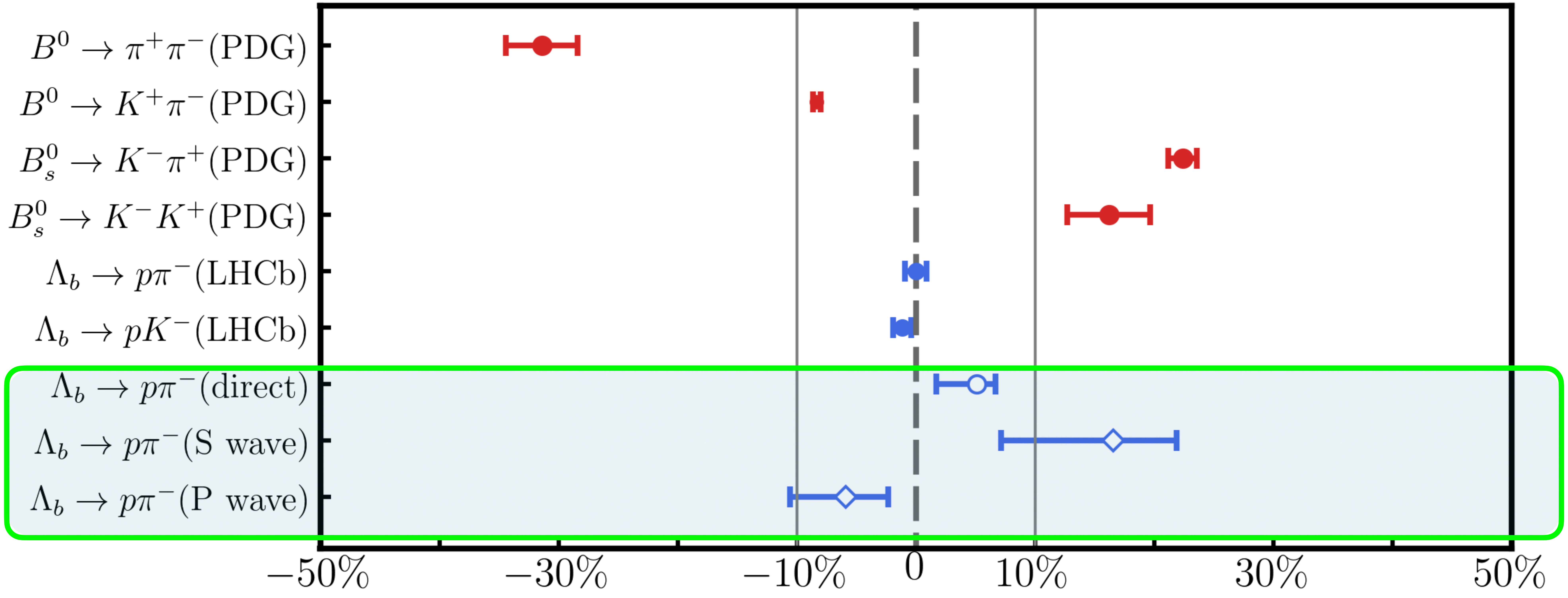
$$S_T \;\approx\; P_T$$

$$S_{PC_2} \approx -P_{PC_2}$$

- **CPVs of S- and P-waves might be as large as B mesons, but cancelled with each other.**
- **Baryons have spinors and Dirac structures, and thus partial waves.**

J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821

S- and P-wave CPV are large but cancelled



J.J.Han, J.X.Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821

See Jia-Jie Han's talk

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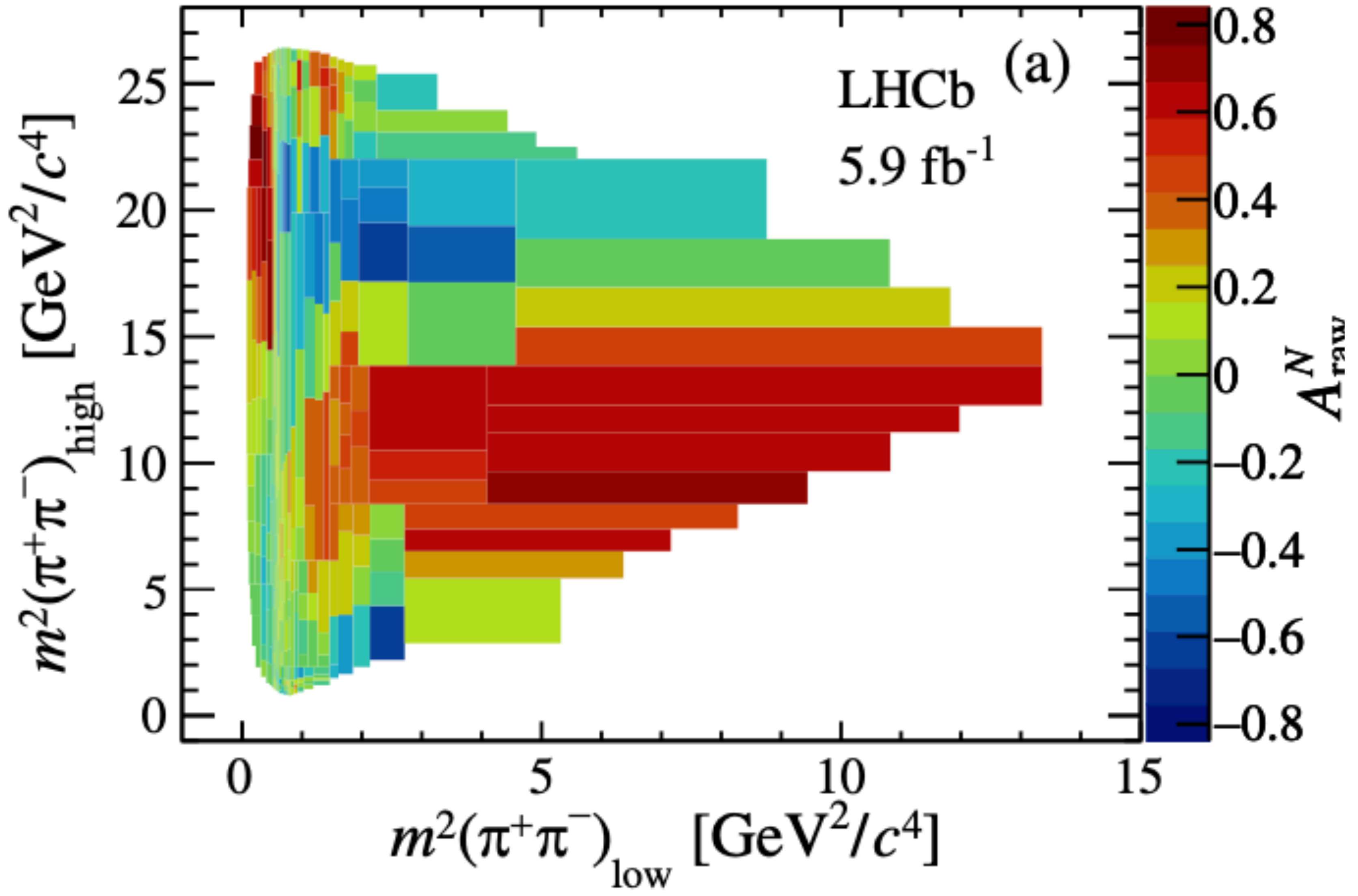
Multi-body decays

- For first observation of baryon CPV, it must be multi-body decays of Λ_b.
- More resonances, more partial waves, more chances for large CPV.
- Large CPV in multi-body decays of B mesons.

$B^+ \to \pi^+\pi^-\pi^+$

$$\mathcal{A}_{B^+\to K^+K^-\pi^+} = -0.115 \pm 0.008\,,$$
$$\mathcal{A}_{B^+\to K^+K^-K^+} = -0.0365 \pm 0.0036\,,$$
$$\mathcal{A}_{B^+\to \pi^+\pi^-\pi^+} = 0.076 \pm 0.005\,,$$



- Large regional CPV: Promising to measure CPV in some regions.
- Large data samples in $\Lambda_b^0 \to ph^-h^+h^-, h = \pi, K$

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Multi-body decays of Λ_b

- Advantage: more resonances, more chances for large CPV
- Disadvantage: Too many resonances, and with large uncertainties

$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****

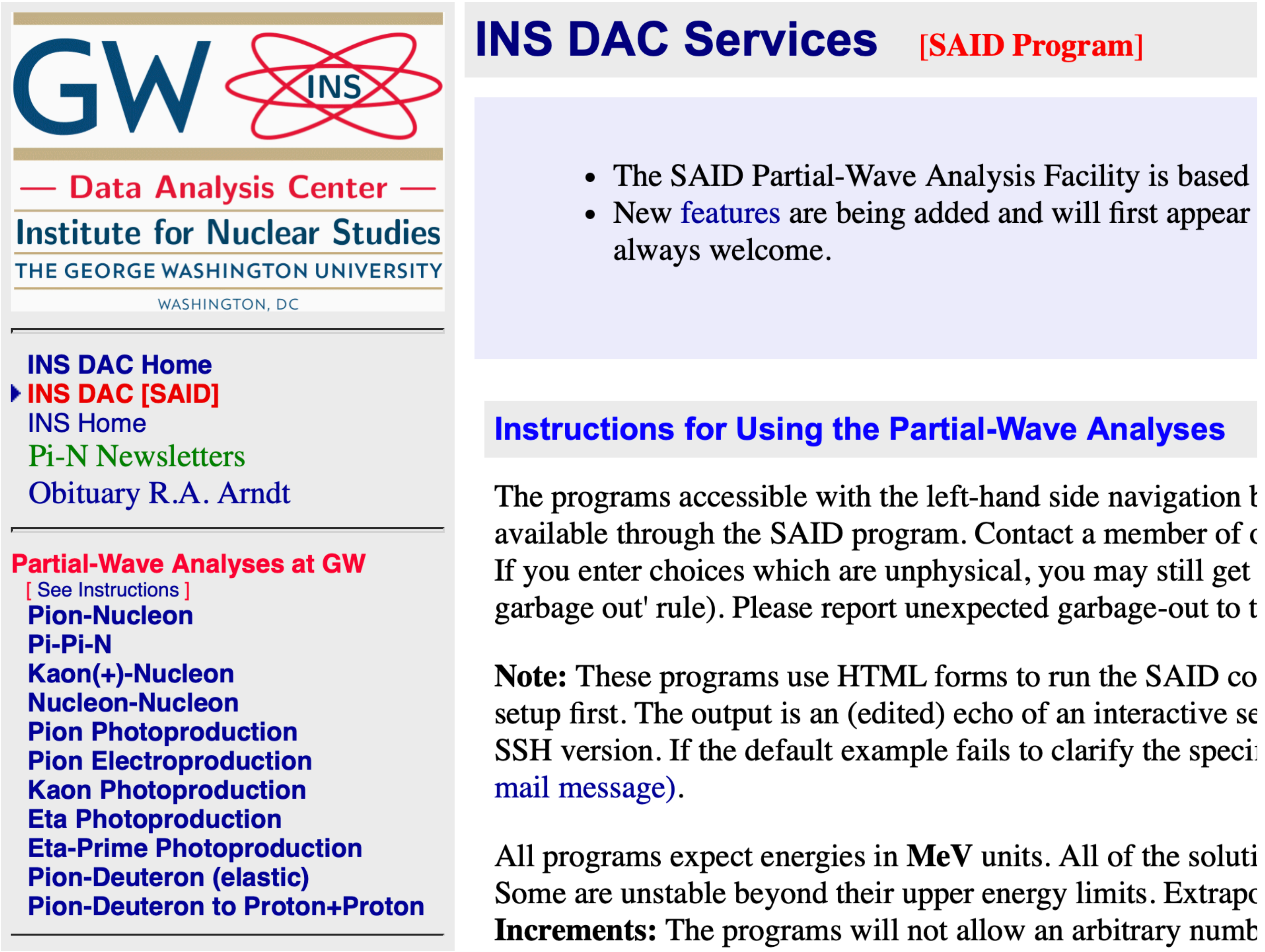
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 ($\approx$ 1720) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 ($\approx$ 200) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 ($\approx$ 1710) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 ($\approx$ 140) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 ($\approx$ 1720) MeV
$N(1720)$ BREIT-WIGNER WIDTH	150 to 400 ($\approx$ 250) MeV

- Close to each other, with large decay widths. No clear dominant one.

$N\pi$ scatterings

- N^* usually from $N\pi$ scatterings
- Data from SAID program

https://gwdac.phys.gwu.edu/



GW INS
— Data Analysis Center —
Institute for Nuclear Studies
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WASHINGTON, DC

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Obituary R.A. Arndt

Partial-Wave Analyses at GW
[See Instructions]
Pion-Nucleon
Pi-Pi-N
Kaon(+)-Nucleon
Nucleon-Nucleon
Pion Photoproduction
Pion Electroproduction
Kaon Photoproduction
Eta Photoproduction
Eta-Prime Photoproduction
Pion-Deuteron (elastic)
Pion-Deuteron to Proton+Proton

INS DAC Services [SAID Program]

- The SAID Partial-Wave Analysis Facility is based
- New features are being added and will first appear always welcome.

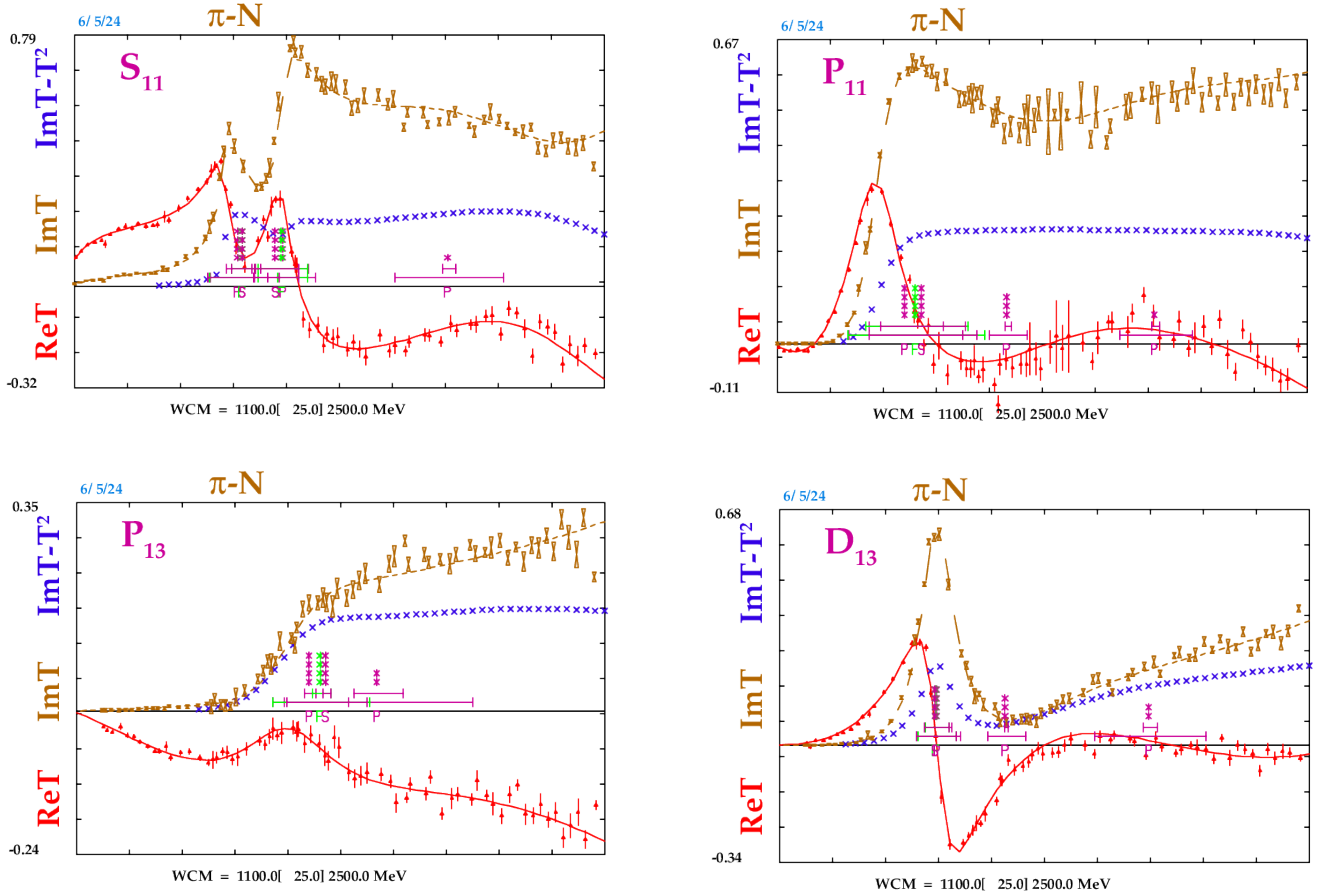
Instructions for Using the Partial-Wave Analyses

The programs accessible with the left-hand side navigation b available through the SAID program. Contact a member of c If you enter choices which are unphysical, you may still get garbage out' rule). Please report unexpected garbage-out to t

Note: These programs use HTML forms to run the SAID co setup first. The output is an (edited) echo of an interactive se SSH version. If the default example fails to clarify the speci mail message).

All programs expect energies in **MeV** units. All of the soluti Some are unstable beyond their upper energy limits. Extrapo **Increments:** The programs will not allow an arbitrary numb

$N\pi \to N\pi$



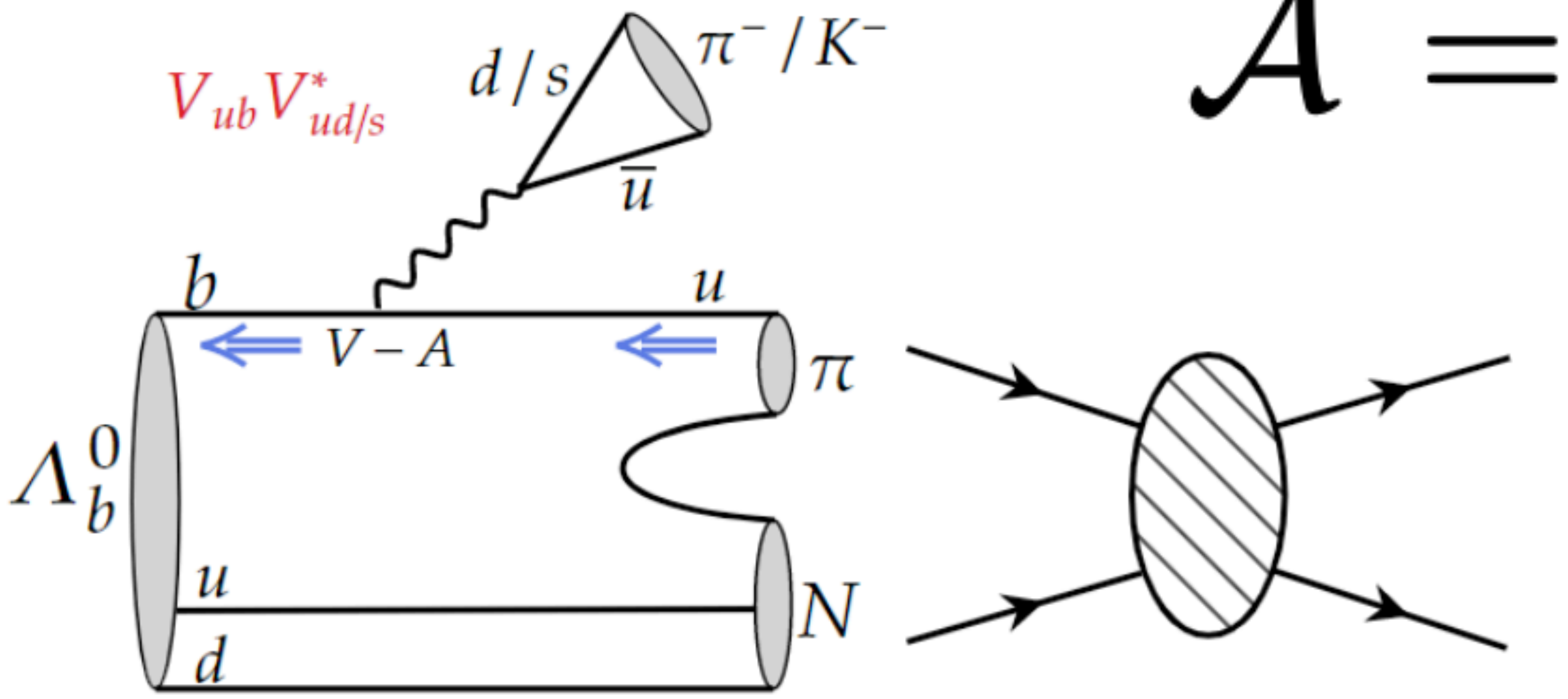
- Partial-wave amplitudes with strong phases!

- Data driven, **model independent**. Skip resonances, more precise strong phases.

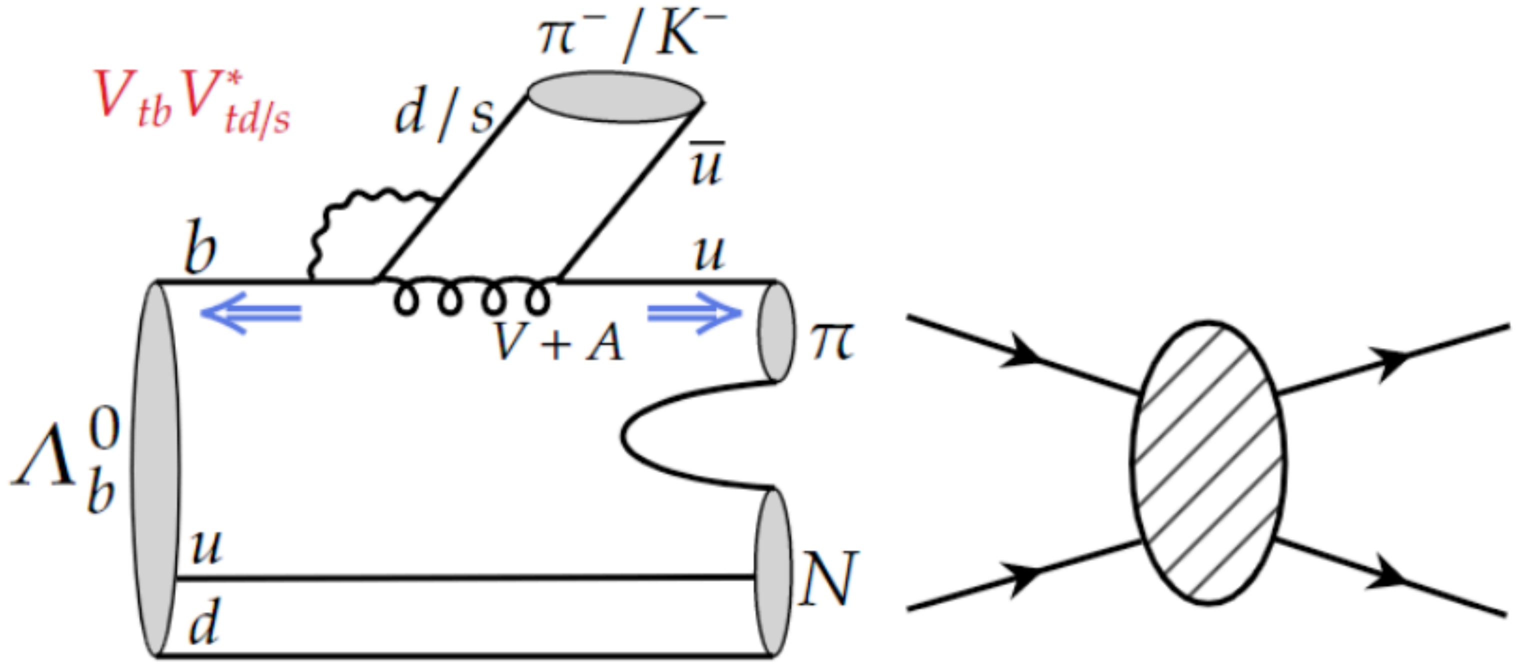
CPV via $N\pi$ rescatterings

$$\mathcal{A} = \mathcal{S}^{1/2}\mathcal{A}_0$$

•Tree:



•Penguin:



•Short-distance weak decays

•Long-distance $N\pi \to N\pi,\ N\pi\pi$

•weak phases

•strong phases

- Different chirality

➡ different helicity

➡ different partial waves

➡ PWA interference

➡ difference of strong phases

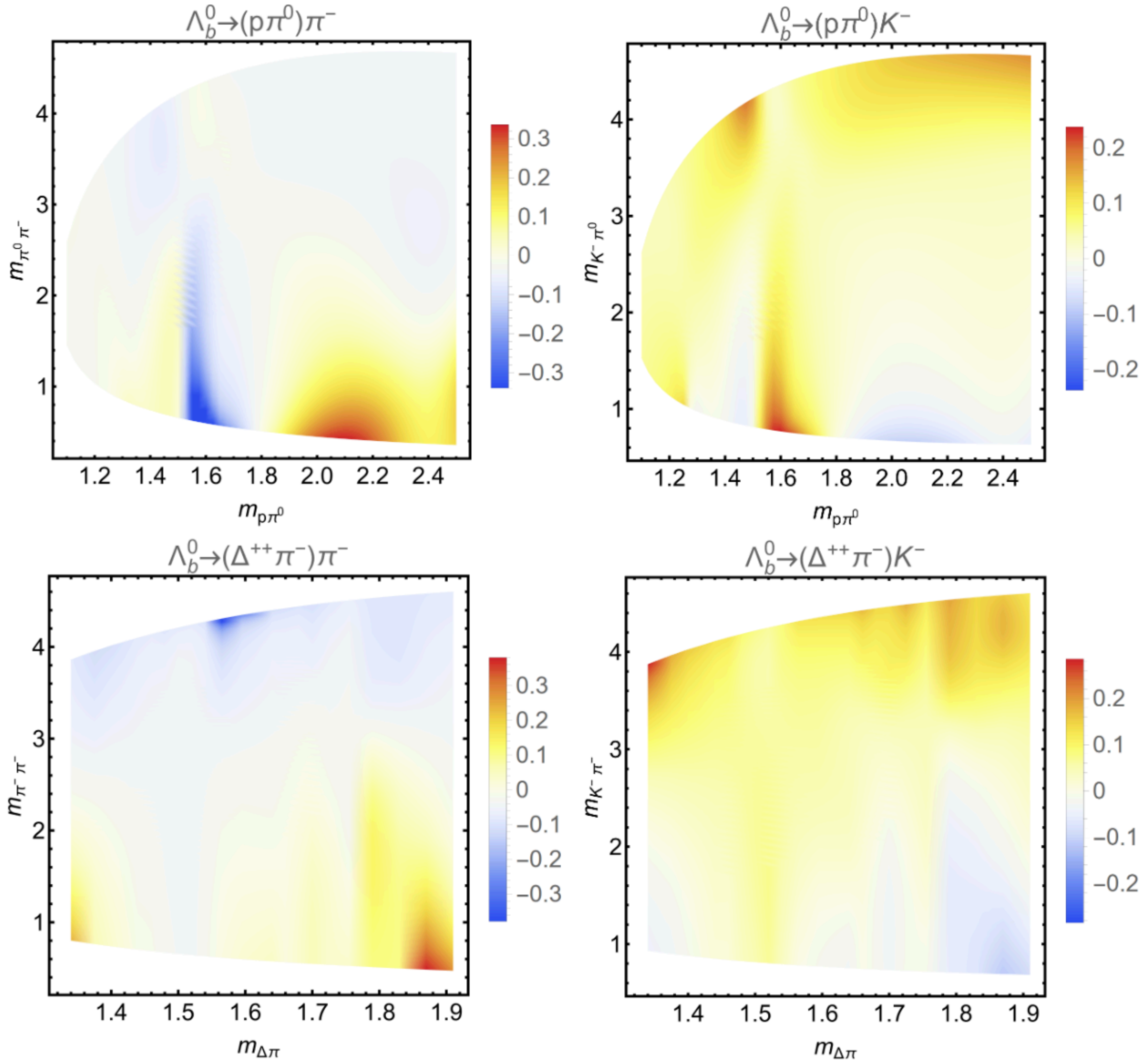
➡ **CPV**

J.P.Wang, **FSY**, 2407.04110

Dalitz CPV with $N\pi$ rescatterings

- More predictive power.
- All information are in the Dalitz plots
- In some regions, the local CPV could reach 20% or even 30%.

J.P.Wang, **FSY**, 2407.04110



CPV with $N\pi$ scatterings

$N\pi \to \Delta^{++}\pi^-$

$m_{N\pi} \in [1.2, 1.9]\mathrm{GeV}$

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$ $\to (p\pi^+\pi^-)K^-$	S1	5.9%	8.0%	3.6%
	S2	5.8%	6.3%	5.3%
	S3	5.6%	4.3%	7.0%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$	S1	−4.1%	−5.4%	−2.4%
	S2	−3.9%	−3.9%	−3.9%
	S3	−3.6%	−2.3%	−5.3%
$\Lambda_b^0 \to (p\pi^0)K^-$	S1	5.8%	8.2%	2.7%
	S2	5.8%	8.0%	3.0%
	S3	5.8%	7.8%	3.3%
$\Lambda_b^0 \to (p\pi^0)\pi^-$	S1	−3.9%	−3.9%	−3.7%
	S2	−3.9%	−3.8%	−4.3%
	S3	−3.8%	−3.6%	−4.8%

S1: $f_1 = 1.1,\ g_1 = 0.9$, S2: $f_1 = g_1 = 1.0$, and S3: $f_1 = 0.9,\ g_1 = 1.1$

J.P.Wang, **FSY**, 2407.04110 (CPC2024)

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J.P.Wang, **FSY**, 2407.04110 (CPC2024)

•LHCb:

$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$	6.0σ

2503.16954

a model-independent investigation of angular distributions [36] or utilising scattering data to extract the hadronic amplitude [28]. Applying this method using $\pi^+ n \to p\pi^+\pi^-$ scattering data [37], an estimate of the *CP* asymmetry in $\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$ decays aligns with the measurement in this work.

[28] J.-P. Wang and F.-S. Yu, *CP violation of baryon decays with $N\pi$ rescatterings*, Chin. Phys. **C48** (2024) 101002, arXiv:2407.04110.

CPV with $N\pi$ scatterings

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J.P.Wang, **FSY**, 2407.04110 (CPC2024)

- LHCb:

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- CPV observables: [J.P.Wang, Q.Qin, **FSY**, 2211.07332, 2411.18323]
- FSI triangle diagrams: [Z.D.Duan, J.P.Wang, R.H.Li, C.D.Lu, **FSY**, 2412.20458]
- $N\pi$ rescatterings: [J.P.Wang, **FSY**, 24007.04110(CPC2024)]

CPV with $N\pi$ scatterings

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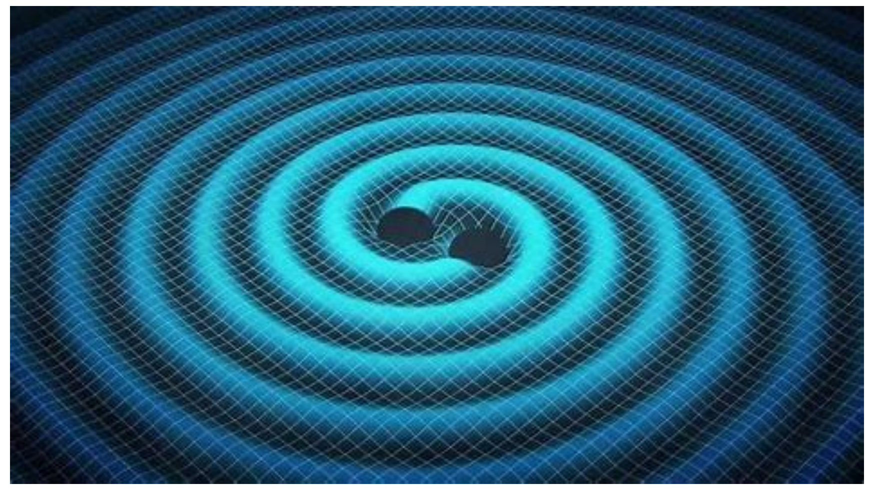
J.P.Wang, **FSY**, 2407.04110 (CPC2024)

- LHCb: $\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$ $\quad m_{p\pi^+\pi^-} < 2.7$ $\quad (5.4 \pm 0.9 \pm 0.1)\%$ $\quad 6.0\sigma$

- CPV observables: [Z.H.Zhang, X.H.Guo, 2103.11335]
- Generalized factorization: [C.Q.Geng, Y.K.Hsiao, 1702.05263]
- LCDAs and form factors: [W.Wang, Q.A.Zhang, J.Hua, et al; Y.M.Wang, Y.L.Shen, et al]

New horizon



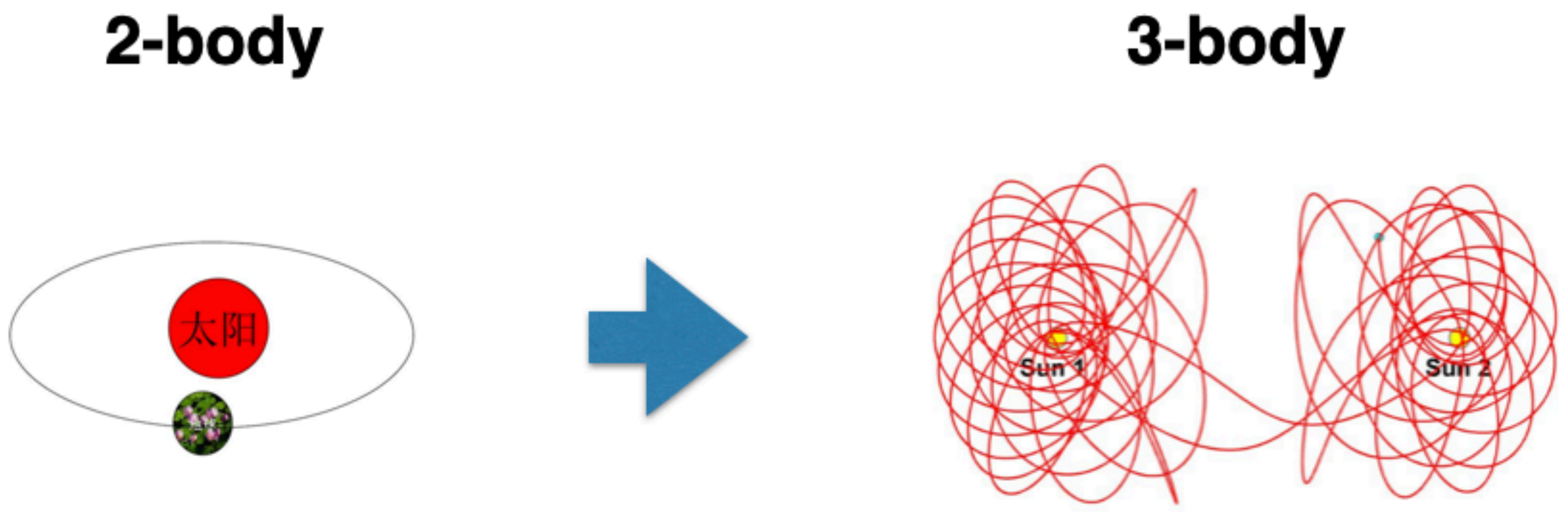
- Observation of gravitational waves

  => not only confirm the General Relativity,

  => but also open the Multi-messenger era of

  cosmology.

- Meson -> Baryon : More is different.
- New QCD dynamics: exclusive baryon.
- High power dominated, partial-wave CPV destruction, $N\pi$ rescatterings



Summary

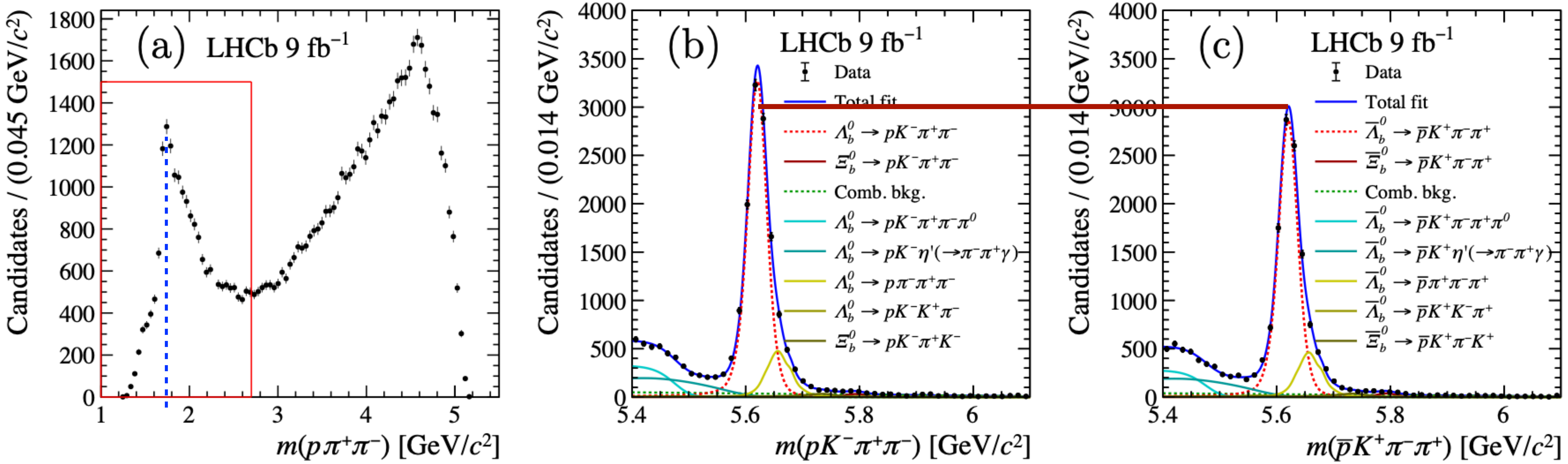
- Baryon CPV is now firstly observed in $\Lambda_b \to pK^-\pi^+\pi^-$
- It is a new horizon in particle physics.
- We find that the partial-wave CPVs are large but cancelled, resulting in small CPV of baryon decays.
- We propose a new CPV mechanism via $N\pi$ rescatterings. Our prediction is manifested by LHCb.

Thank you!

Backup (I)

Most interesting CPV

$$A_{CP}(\Lambda_b^0 \to R(p\pi^+\pi^-)K^-) = (5.4 \pm 0.9 \pm 0.1)\%$$ 6.0σ

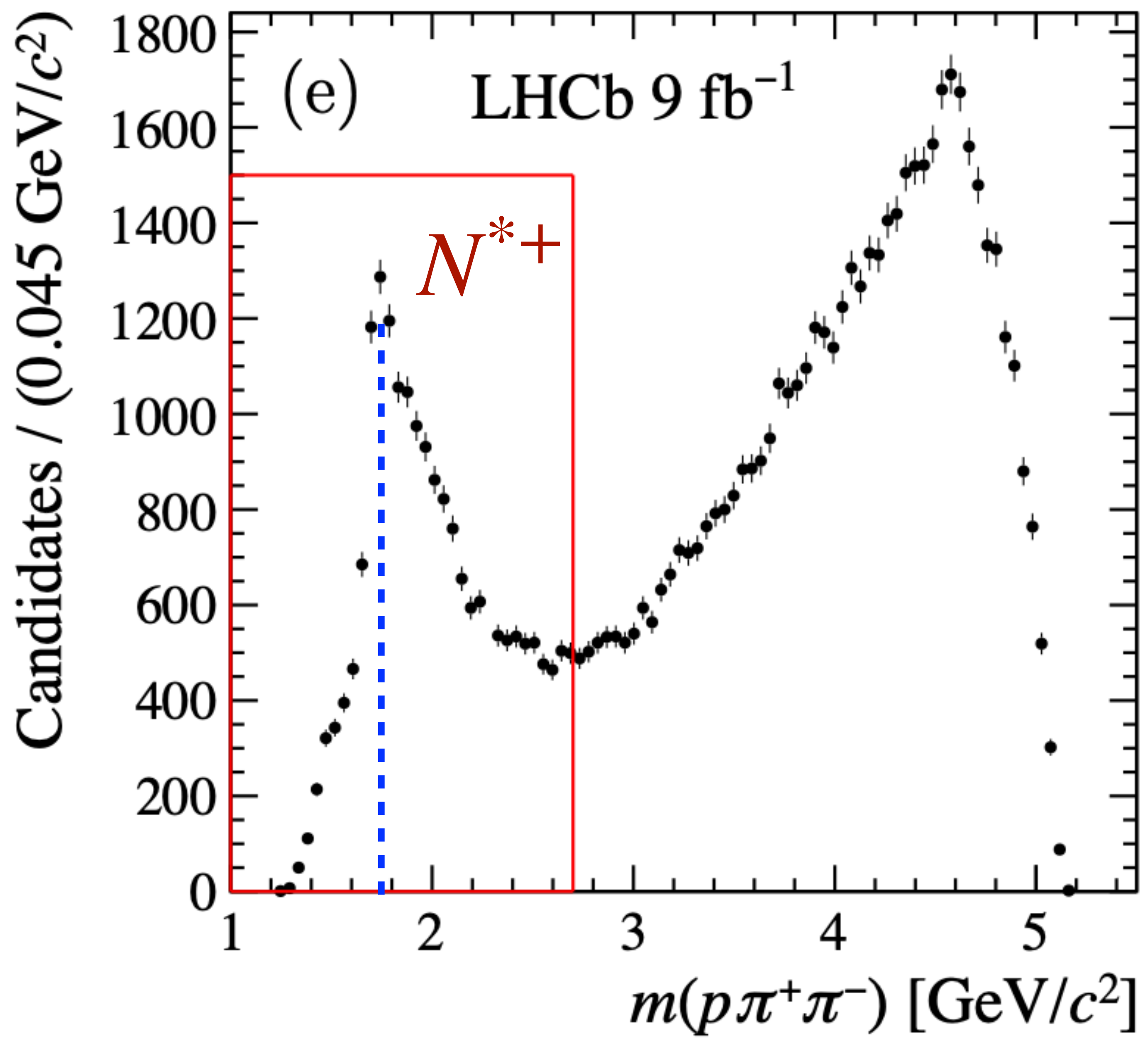


LHCb, arXiv: 2503.16954

Region (1)

LHCb

$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$



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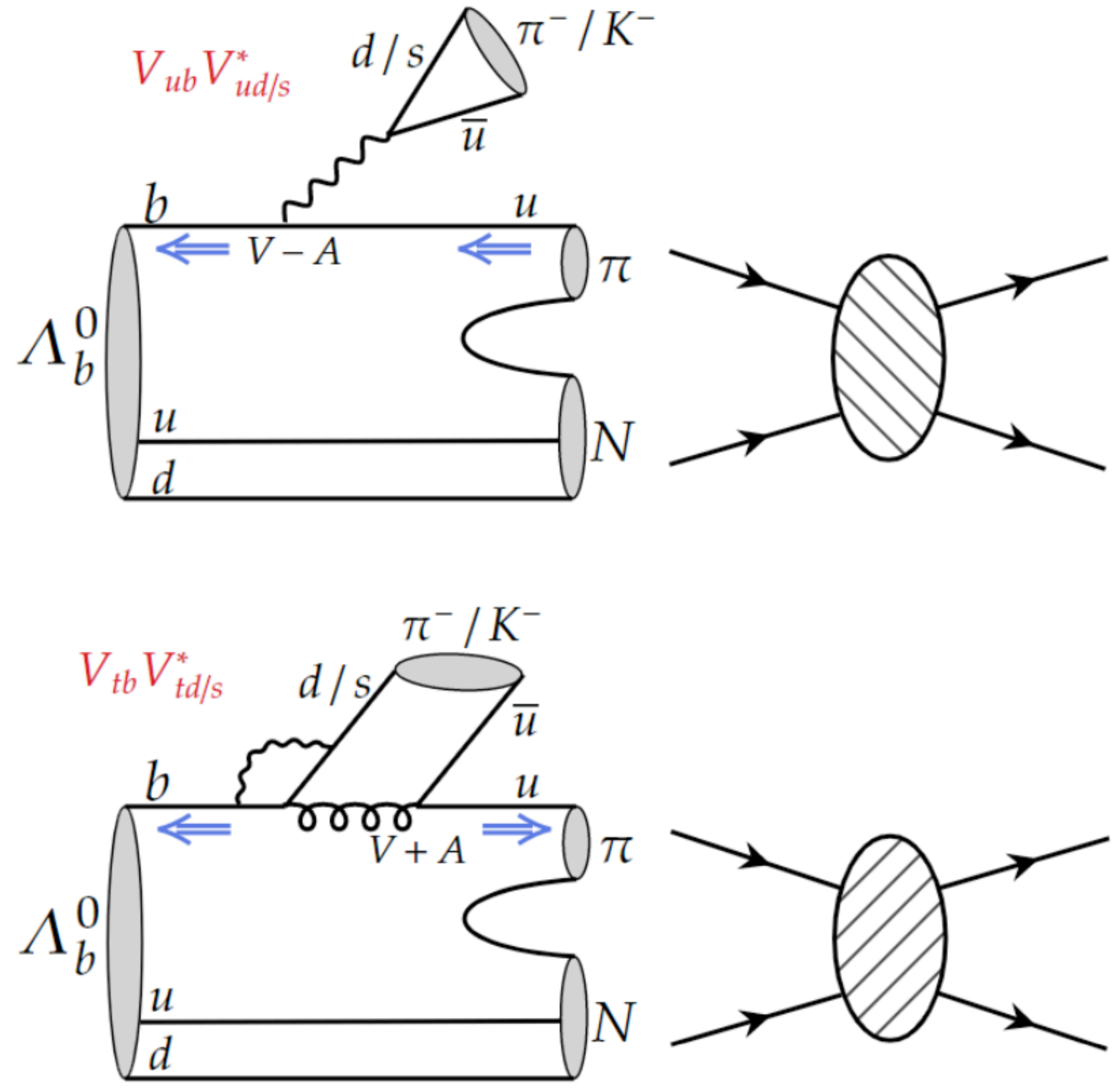
Theory

$(5.6 \sim 5.9)\ \%$

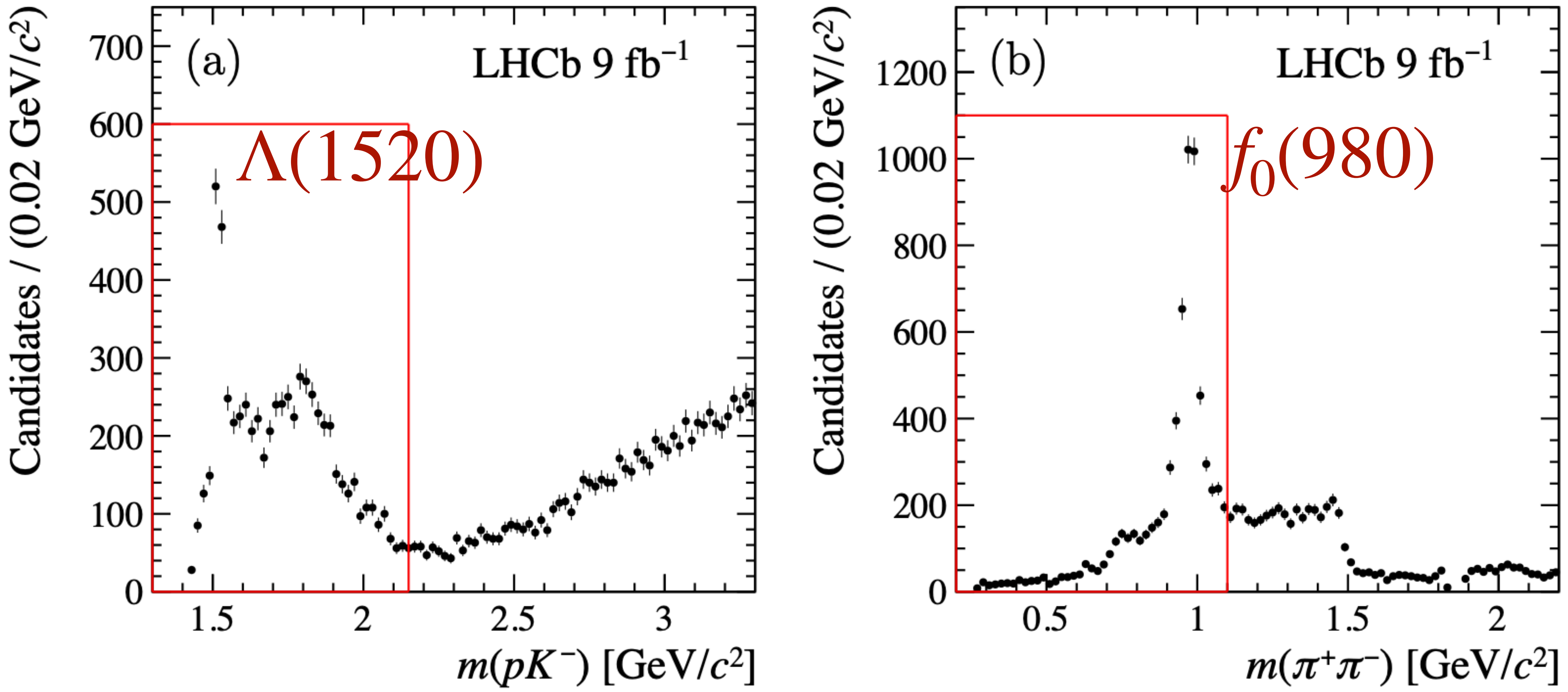


J.P.Wang, **FSY**, 2407.04110 (CPC2024)

Region (2)

LHCb

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$



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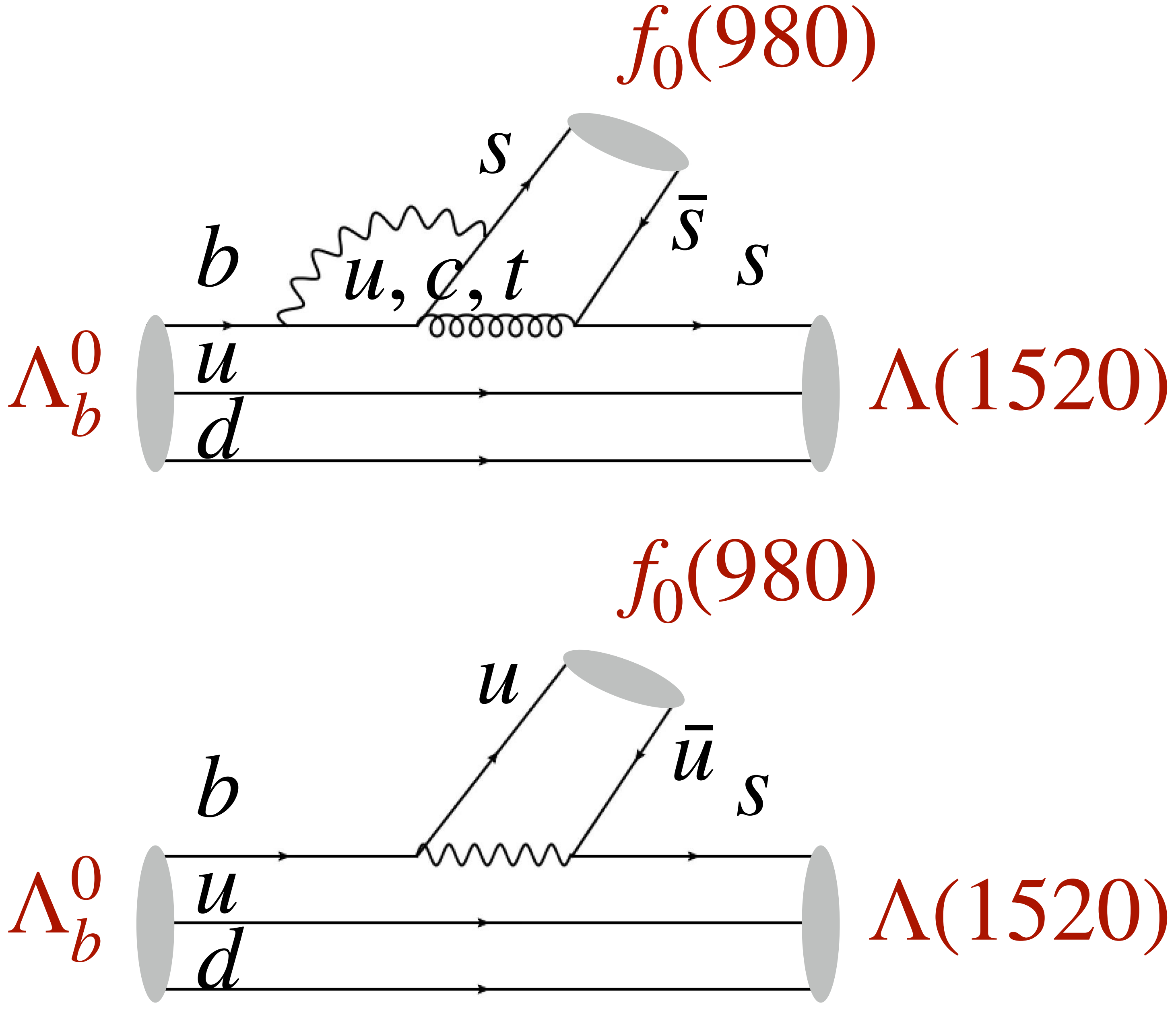
Theory

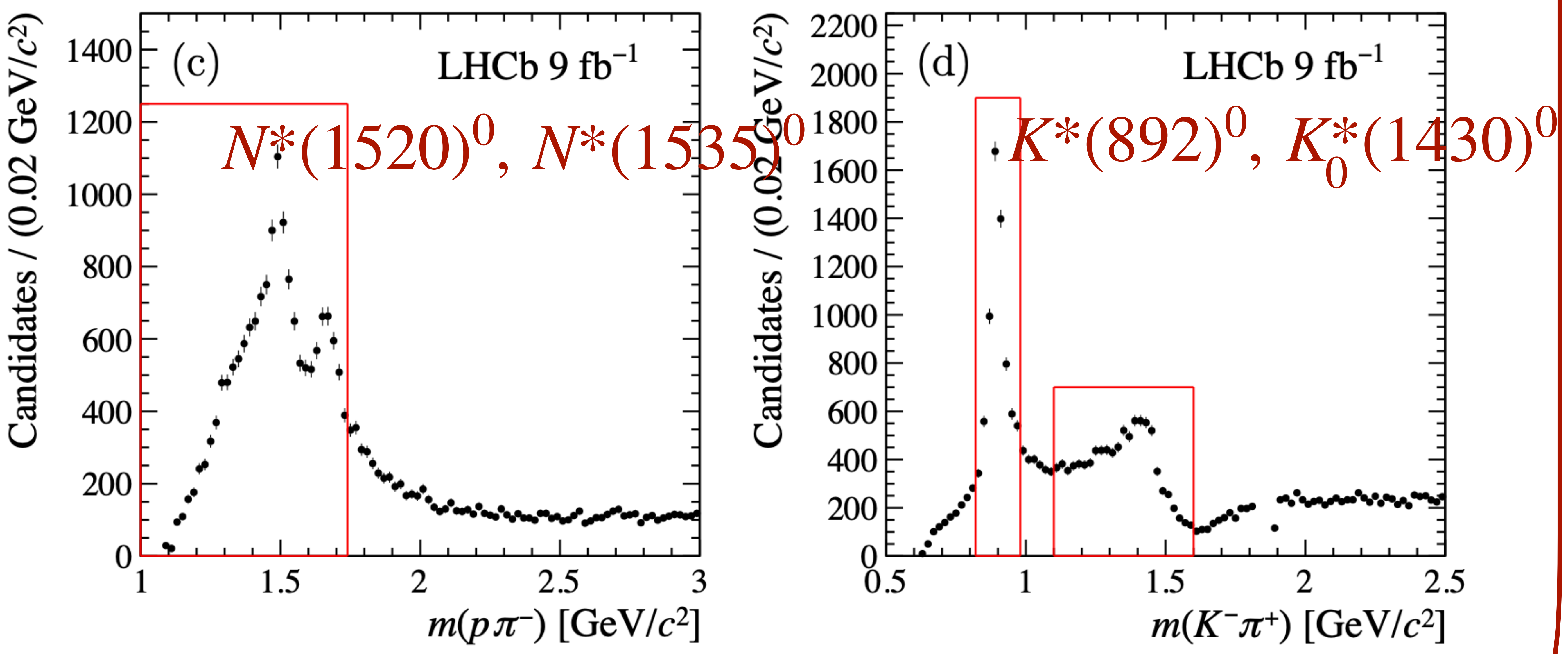
$$< 2\frac{a_2 |V_{ub}V_{us}^*|}{a_6 |V_{tb}V_{ts}^*|} \sim 4\,\%$$



Region (3)

LHCb

$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$



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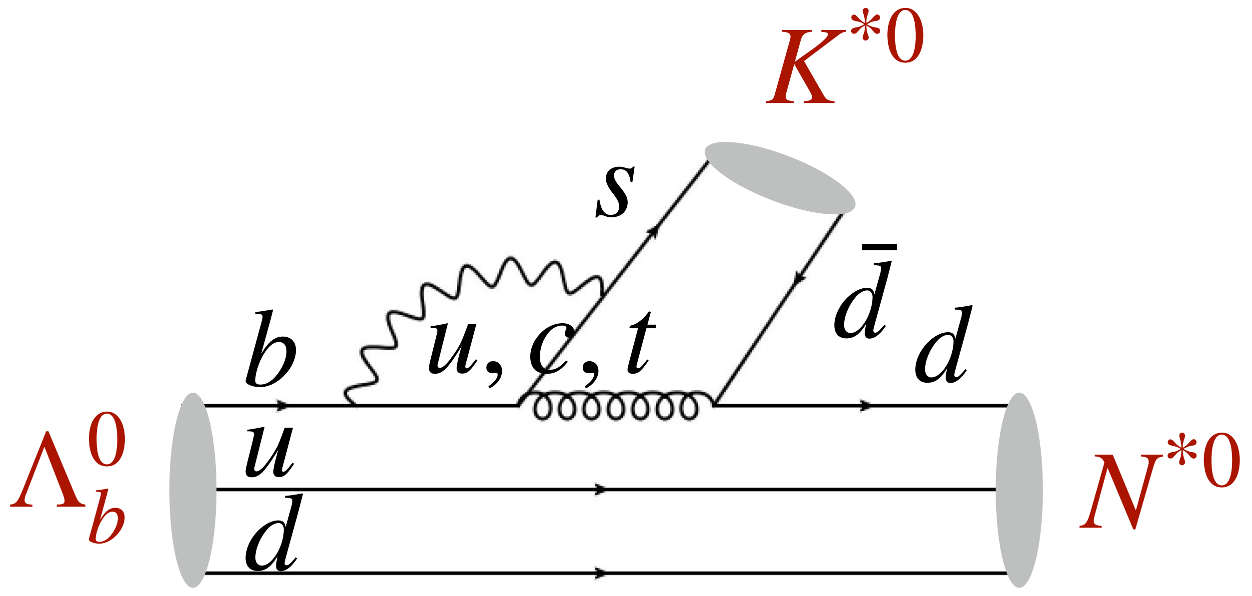
Theory

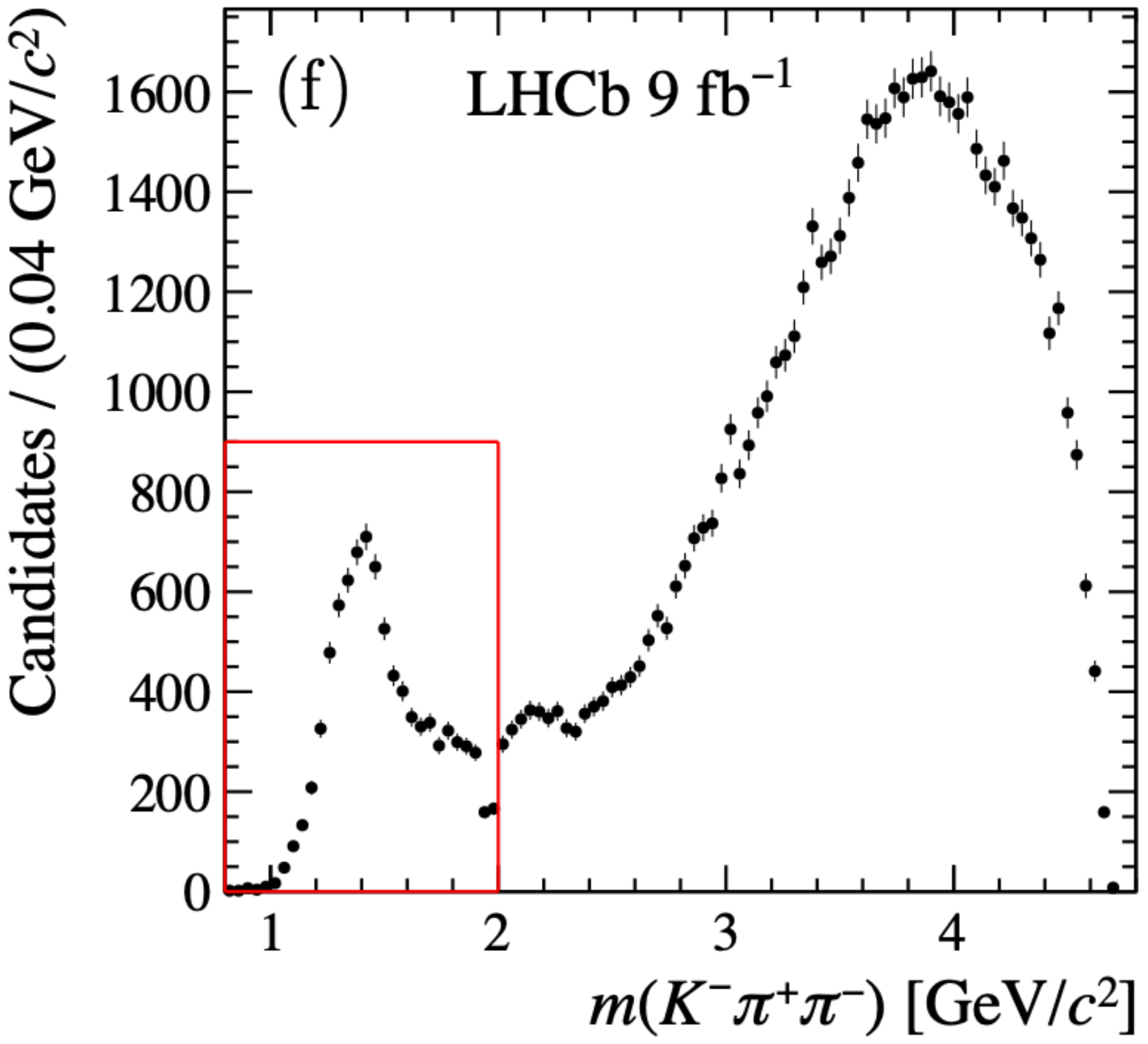
$$< 2\frac{|V_{ub}V_{us}^*|}{|V_{tb}V_{ts}^*|} \sim 2\,\%$$



Region (3)

LHCb

$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$



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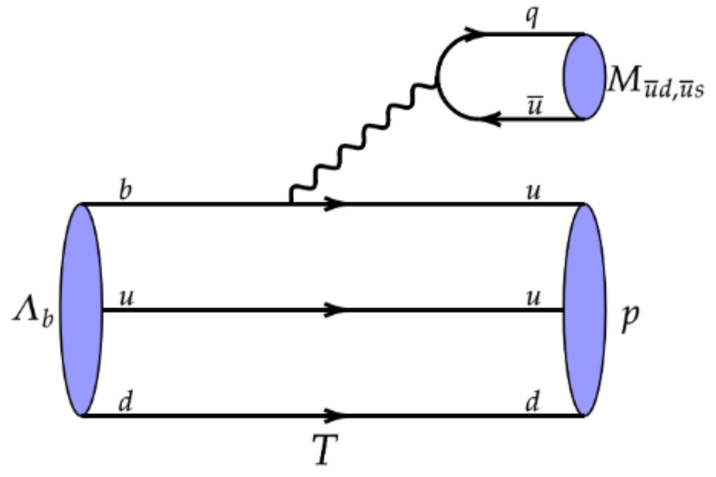
Theory

Partial-wave CPV destruction



J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821

Introduction on CP violation

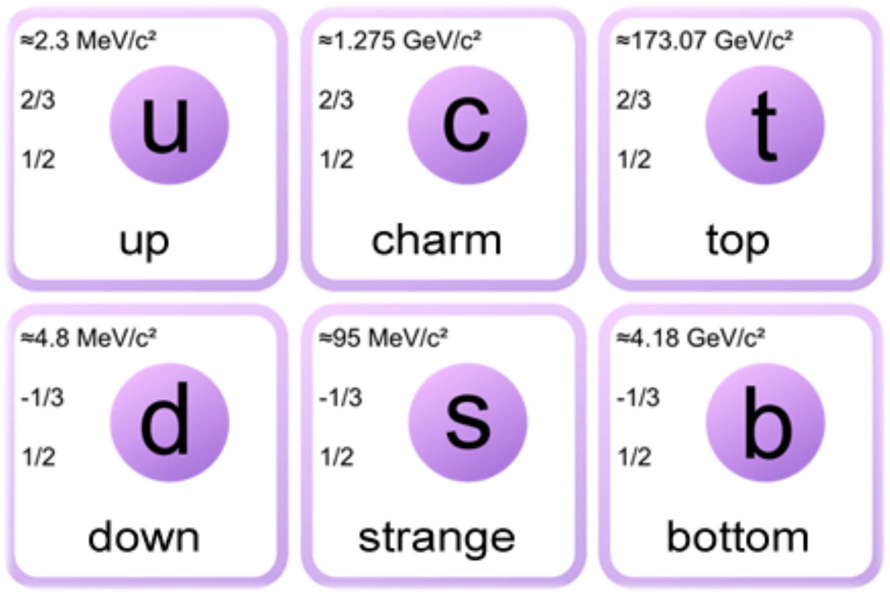
- Kobayashi-Maskawa mechanism: mixing among three generations of quarks

CP Violation in the Renormalizable Theory of Weak Interaction #5

Makoto Kobayashi (Kyoto U.), Toshihide Maskawa (Kyoto U.) (Feb, 1973)

Published in: *Prog.Theor.Phys.* 49 (1973) 652-657

DOI | cite | claim | reference search | 12,141 citations



- One weak phase in the CKM mixing matrix
  - Particle ≠ Anti-particle

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$V_{ij} \neq V_{ij}^*$ → **CP violation**

Introduction on CP violation

Definition: $$A_{CP} = \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

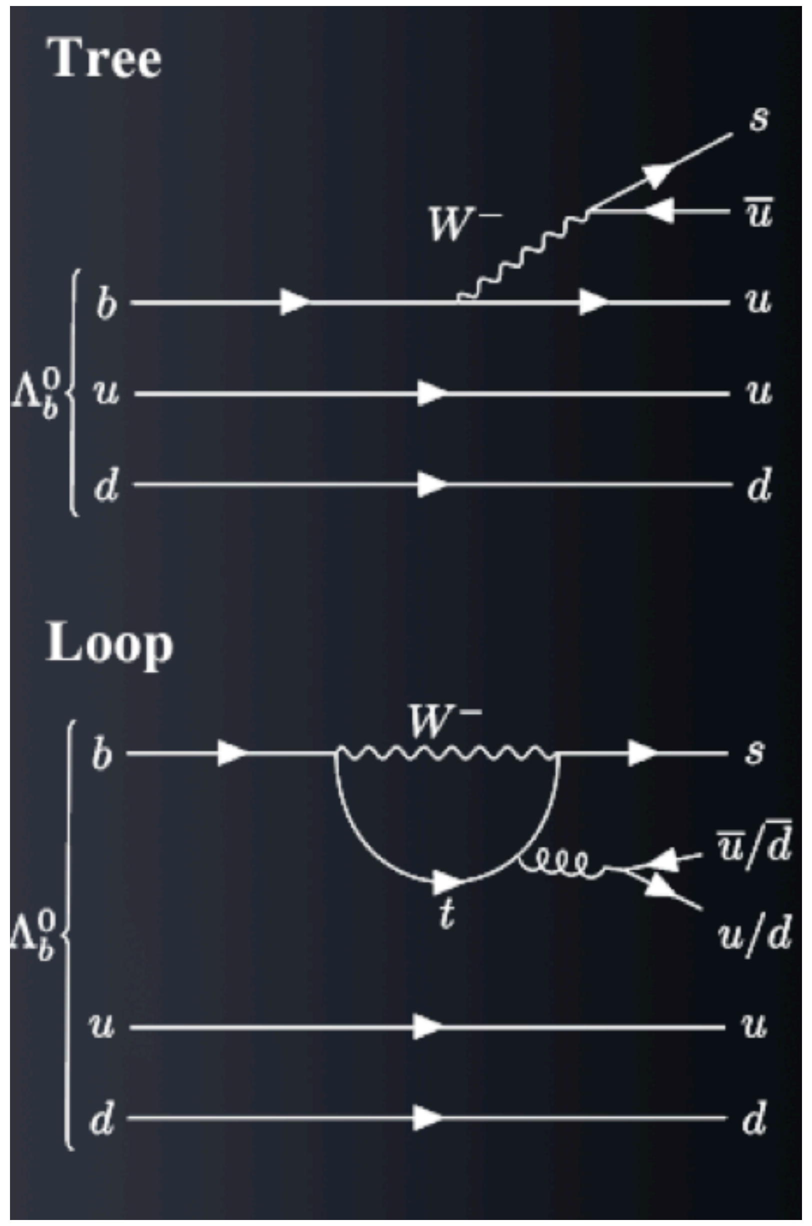
$$V_{\rm CKM} \leftrightarrow V^*_{\rm CKM}$$

$$A_f = |a_1|e^{i(\delta_1+\phi_1)} + |a_2|e^{i(\delta_2+\phi_2)}$$
$$\overline{A}_{\bar{f}} = |a_1|e^{i(\delta_1-\phi_1)} + |a_2|e^{i(\delta_2-\phi_2)}$$

$\phi_{1,2}$: weak phases, flip signs under $A_f \leftrightarrow \overline{A}_{\bar{f}}$

$\delta_{1,2}$: strong phases, keep signs under $A_f \leftrightarrow \overline{A}_{\bar{f}}$

$$A_{CP} = -\frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)}$$



CPV conditions:
1. At least two amplitudes
2. with different weak phases
3. with different strong phases

CP violation in baryons

- **Hyperon**:

  -SM estimates: $\mathcal{O}(10^{-4}) \sim \mathcal{O}(10^{-5})$

  -BESIII [Nature 2022]: $A^{\alpha}_{CP}(\Lambda^0 \to p\pi^-) = (2.5 \pm 4.8) \times 10^{-3}$, and $\Xi^- \to \Lambda^0\pi^-$

- **Charmed baryon**:

  -SM estimates: $\mathcal{O}(10^{-3}) \sim \mathcal{O}(10^{-4})$

  -LHCb [JHEP 2018]: $A_{CP}(\Lambda_c \to pK^+K^-) - A_{CP}(\Lambda_c \to p\pi^+\pi^-) = (3.0 \pm 9.1 \pm 6.1) \times 10^{-3}$

- **Bottom baryon**:

  -SM estimates: $\mathcal{O}(10\%)$

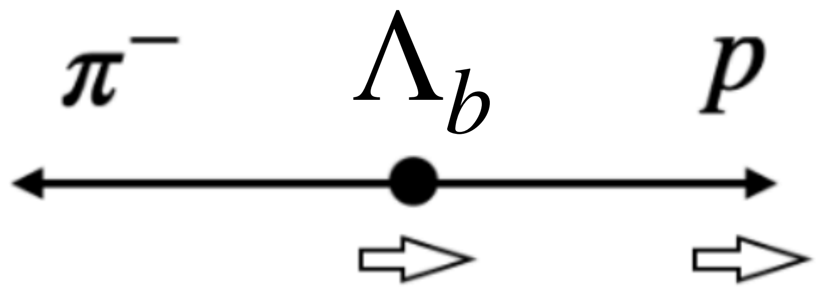
  -LHCb reported 3σ evidence of CPV in $\Lambda_b \to p\pi\pi\pi$ [Nature Physics 2017]

  -$A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\,\%$, $A_{CP}(\Lambda_b^0 \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\,\%$

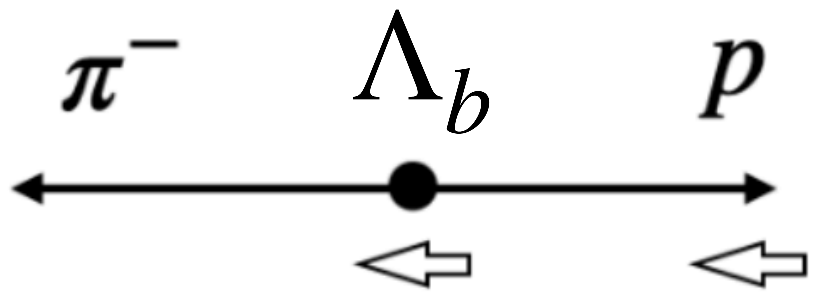
More is different

- **Baryons are very different from mesons!!**
  - **Non-zero spin**, more information from polarizations and partial waves

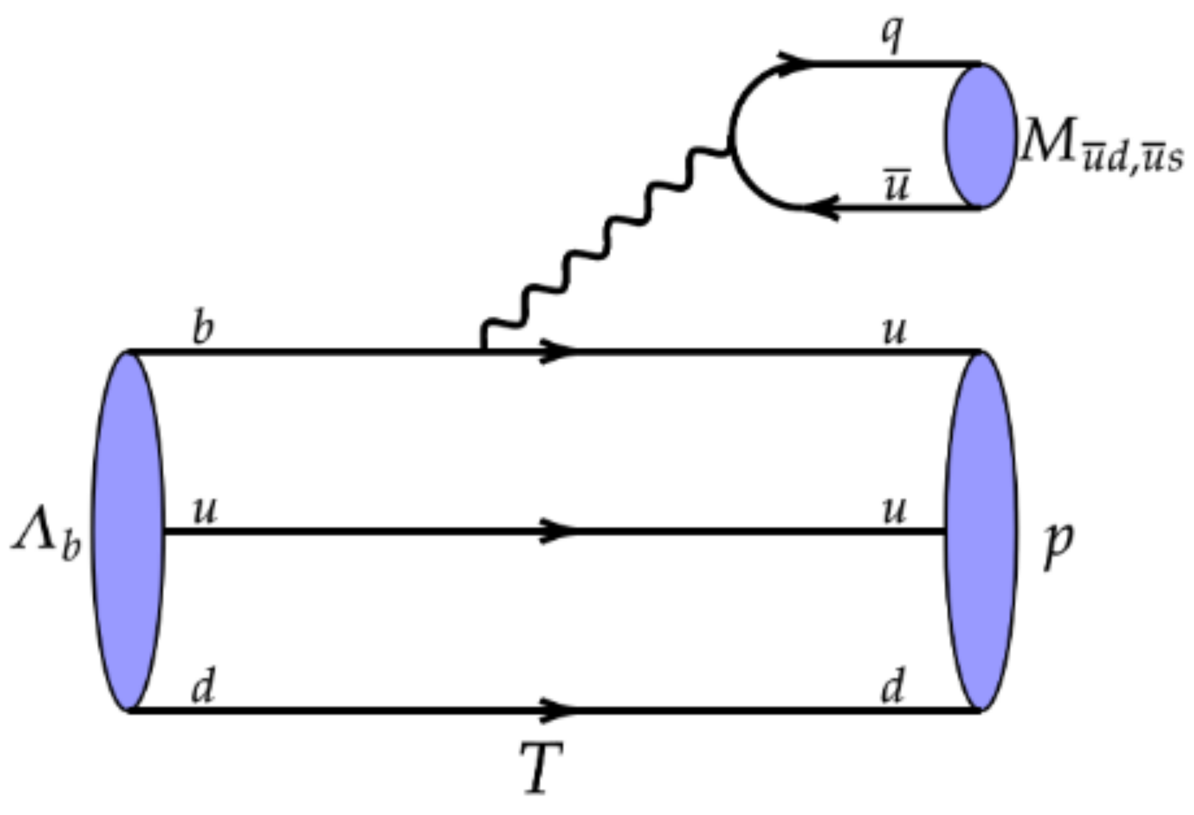
$$\mathcal{M} = \bar{u}_p \,(\, S \;+\; P\,\gamma_5 \,)\, u_{\Lambda_b}$$



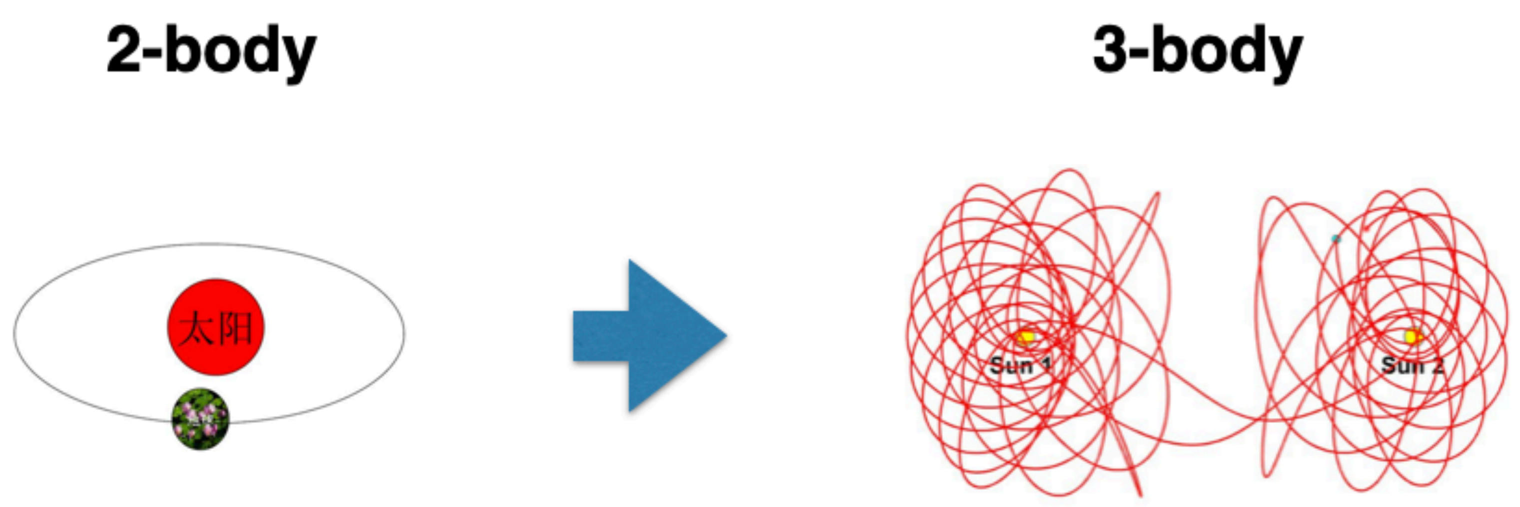
$$\mathcal{H}_{\lambda_\Lambda=+\frac{1}{2},\lambda_p=+\frac{1}{2}} = \frac{1}{\sqrt{2}}(S+P),$$



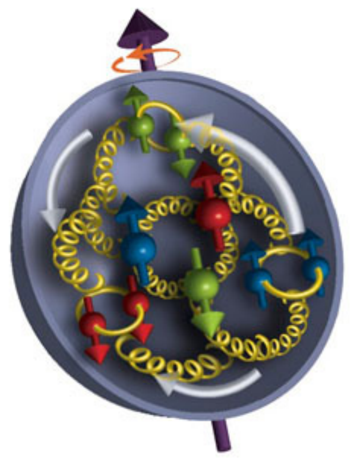
$$\mathcal{H}_{\lambda_\Lambda=-\frac{1}{2},\lambda_p=-\frac{1}{2}} = \frac{1}{\sqrt{2}}(S-P).$$

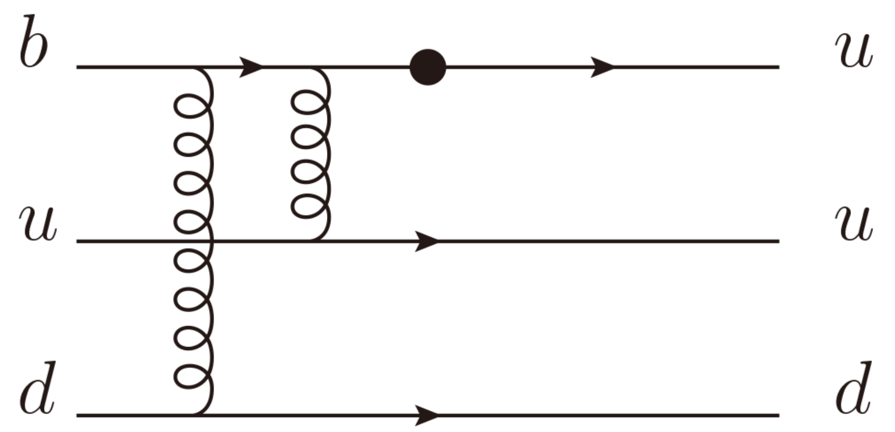


More is different



- **Baryons are very different from mesons!!**
  - **Non-zero spin**, more information from polarizations and partial waves
  - **Three valence quarks**, need at least two hard gluons





- SCET: **leading-power is one order of magnitude smaller** than the total one
  - Leading power: $\xi_\Lambda(0) = -0.012$ [W.Wang, 2011]
  - Total form factor: $\xi_\Lambda(0) = 0.18$ [Y.L.Shen, Y.M.Wang, 2016]

Partial-wave CPVs are large, but cancelled with each other

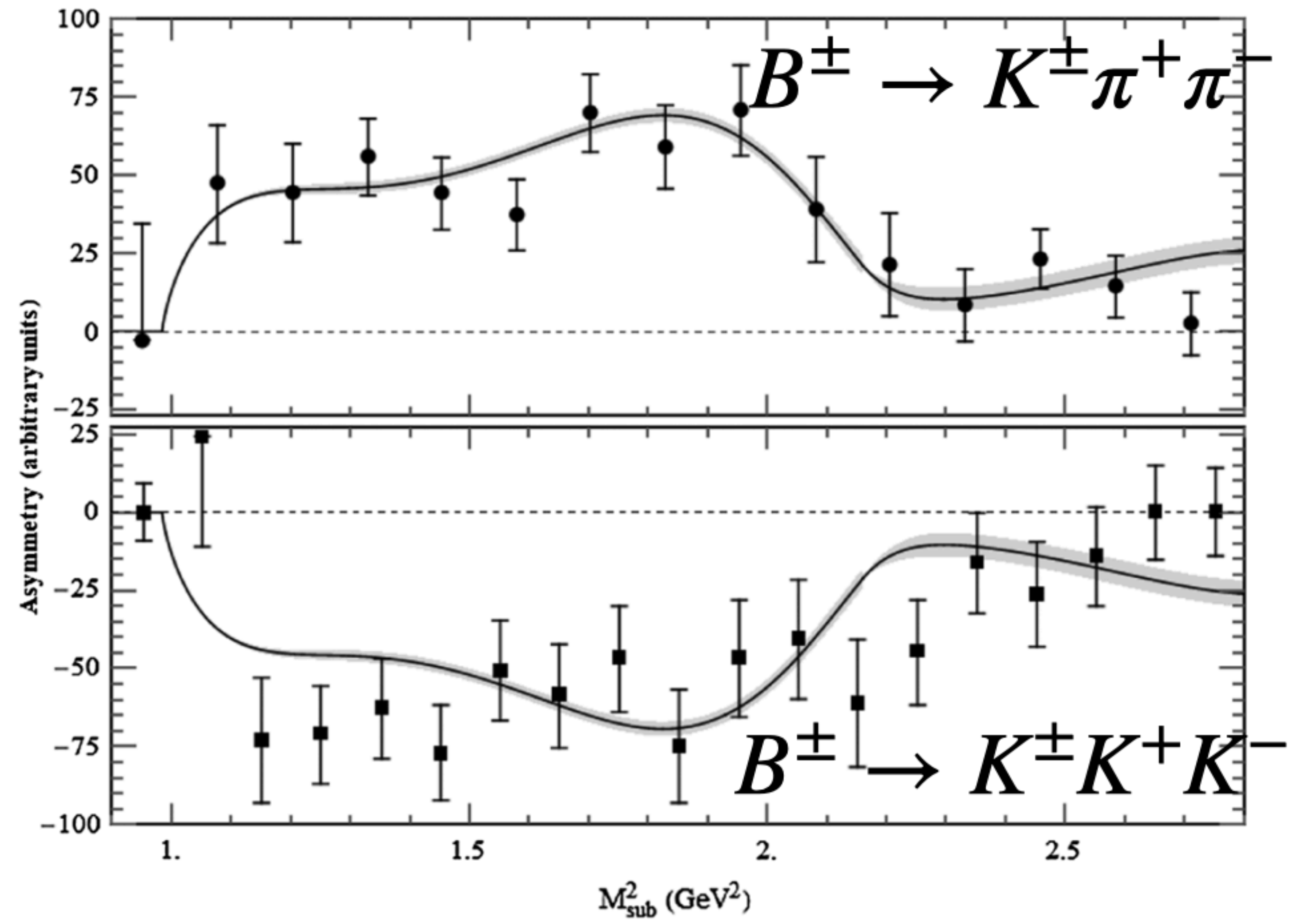
	A_{CP}^{dir}	$A_{CP}^{S\text{-wave}}(\kappa_S)$	$A_{CP}^{P\text{-wave}}(\kappa_P)$	A_{CP}^{α}	A_{CP}^{β}	A_{CP}^{γ}
$\Lambda_b \to p\pi^-$	$0.05^{+0.02}_{-0.03}$	$0.17^{+0.05}_{-0.09}$ (49%)	$-0.06^{+0.04}_{-0.05}$ (51%)	$0.02^{+0.01}_{-0.02}$	$0.22^{+0.08}_{-0.05}$	$0.11^{+0.05}_{-0.06}$
$\Lambda_b \to pK^-$	$-0.06^{+0.03}_{-0.02}$	$-0.05^{+0.05}_{-0.04}$ (94%)	$-0.21^{+0.39}_{-0.46}$ (6%)	$0.04^{+0.03}_{-0.04}$	$-0.44^{+0.08}_{-0.04}$	$0.02^{+0.06}_{-0.05}$
	A_{CP}^{dir}	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	$A_{CP}^{\mathcal{J}}$
$\Lambda_b \to p\rho^-$	$0.03^{+0.03}_{-0.05}$	$0.01^{+0.01}_{-0.04}$ (7%)	$0.02^{+0.07}_{-0.03}$ (44%)	$0.03^{+0.04}_{-0.12}$ (45%)	$0.17^{+0.04}_{-0.06}$ (4%)	$-0.01^{+0.01}_{-0.01}$
$\Lambda_b \to pK^{*-}$	$-0.05^{+0.10}_{-0.16}$	$-0.15^{+0.12}_{-0.06}$ (6%)	$0.27^{+0.09}_{-0.27}$ (33%)	$-0.23^{+0.10}_{-0.18}$ (55%)	$-0.14^{+0.02}_{-0.10}$ (6%)	$0.02^{+0.04}_{-0.05}$
	A_{CP}^{dir}	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	A_{CP}^{UD}
$\Lambda_b \to pa_1^-(1260)$	$-0.01^{+0.04}_{-0.03}$	$-0.22^{+0.10}_{-0.10}$ (6%)	$-0.11^{+0.03}_{-0.07}$ (46%)	$0.18^{+0.11}_{-0.06}$ (40%)	$-0.24^{+0.07}_{-0.13}$ (8%)	$-0.24^{+0.08}_{-0.13}$
$\Lambda_b \to pK_1^-(1270)$ $(\theta_K = 30^\circ)$	$0.09^{+0.08}_{-0.05}$	$0.34^{+0.02}_{-0.06}$ (8%)	$-0.11^{+0.12}_{-0.08}$ (42%)	$0.19^{+0.17}_{-0.15}$ (42%)	$0.33^{+0.04}_{-0.05}$ (8%)	$0.26^{+0.04}_{-0.10}$
$\Lambda_b \to pK_1^-(1270)$ $(\theta_K = 60^\circ)$	$0.07^{+0.05}_{-0.06}$	$0.46^{+0.02}_{-0.09}$ (9%)	$0.06^{+0.11}_{-0.08}$ (37%)	$-0.07^{+0.09}_{-0.10}$ (45%)	$0.46^{+0.06}_{-0.07}$ (9%)	$0.40^{+0.04}_{-0.09}$

- This is a general feature in baryon decays, $\Lambda_b \to pP,\ pV,\ pA$

J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821

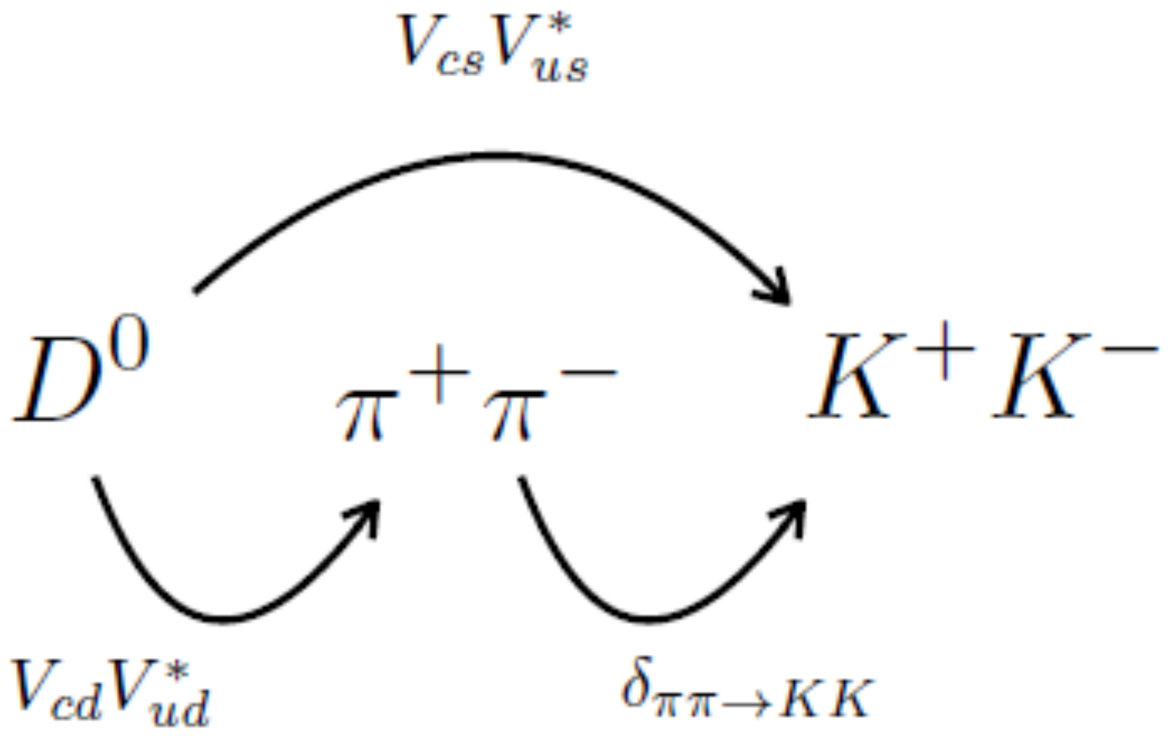
Rescatterings: Data driven

- Rescattering mechanism for CPV in $B^- \to (\pi^+\pi^-)K^-$, $(K^+K^-)K^-$. Model-independent analysis of $\pi\pi \to K\bar{K}$ data [Bediaga, Frederico, Lourenco, 2013; H.Y.Cheng, C.K.Chua, 2020; Álvarez Garrote, Cuervo, Magalhães, Peláez, PRL2023]



$$\begin{pmatrix} A(B^- \to \pi^+\pi^- P^-) \\ A(B^- \to K^+K^- P^-) \end{pmatrix}^{\text{FSI}}_{\text{S-wave}} = S^{1/2} \begin{pmatrix} A(B^- \to \pi^+\pi^- P^-) \\ A(B^- \to K^+K^- P^-) \end{pmatrix}_{\text{S-wave}}$$

- Rescattering mechanism for charm CPV. Model-independent analysis of $\pi\pi \to K\bar{K}$ data [Bediaga, Frederico, Magalhaes, PRL2023; Pich, Solomonidi, Silva, PRD2023].



$$|\Delta A_{CP}^{\text{short-distance}}| < 2 \times 10^{-4} \qquad \text{v.s.} \qquad \Delta A_{CP}^{\text{FSI}} = -(6.4 \pm 1.8) \times 10^{-4}$$

CPV via $N\pi$ rescatterings

$$\mathcal{A} = \mathcal{S}^{1/2}\mathcal{A}_0$$

$$\begin{aligned}\mathcal{A} = \ & \bar{u}_{N\pi,1/2^+}(A + B\gamma_5)u_{\Lambda_b}\ P_{11} \\ & + \bar{u}_{N\pi,1/2^-}(\tilde{A} + \tilde{B}\gamma_5)u_{\Lambda_b}\ S_{11} \\ & + q_\mu \bar{u}^\mu_{N\pi,3/2^+}(C + D\gamma_5)u_{\Lambda_b}\ P_{13} \\ & + q_\mu \bar{u}^\mu_{N\pi,3/2^-}(\tilde{C} + \tilde{D}\gamma_5)u_{\Lambda_b}\ D_{13} \\ & + \cdots .\end{aligned}$$

$$\begin{aligned}\mathcal{A}_0 = \ & \bar{u}_{N\pi,1/2^+}(A + B\gamma_5)u_{\Lambda_b} \\ & + \bar{u}_{N\pi,1/2^-}(\tilde{A} + \tilde{B}\gamma_5)u_{\Lambda_b} \\ & + q_\mu \bar{u}^\mu_{N\pi,3/2^+}(C + D\gamma_5)u_{\Lambda_b} \\ & + q_\mu \bar{u}^\mu_{N\pi,3/2^-}(\tilde{C} + \tilde{D}\gamma_5)u_{\Lambda_b} \\ & + \cdots .\end{aligned}$$

- Long-distance

$$\Lambda_b \to (N\pi)h \to (N\pi/N\pi\pi)h$$

- Short-distance

$$\Lambda_b \to (N\pi)h$$

$$\begin{aligned}&\bar{u}_{1/2^+}(f_1^{1/2^+}\gamma_\mu + g_1^{1/2^+}\gamma_\mu\gamma_5)u_{\Lambda_b} \\ &-\bar{u}_{1/2^-}(f_1^{1/2^-}\gamma_\mu + g_1^{1/2^-}\gamma_\mu\gamma_5)u_{\Lambda_b}\end{aligned}$$

CPV via $N\pi$ rescatterings

$$\mathcal{A}(\Lambda_b \to (\mathcal{B}M)h^-)$$

- Tree

$$= V_{ub}V_{ud}^* f_P\, \bar{u}_{N\pi} \Big[a_1 \left(-S_{11} f_1^{1/2^-} + P_{11} f_1^{1/2^+} + \ldots \right) (m_{\Lambda_b} - m_{N\pi}) + a_1 \left(-S_{11} g_1^{1/2^-} + P_{11} g_1^{1/2^+} + \ldots \right) (m_{\Lambda_b} + m_{N\pi}) \gamma_5 \Big] u_{\Lambda_b}$$

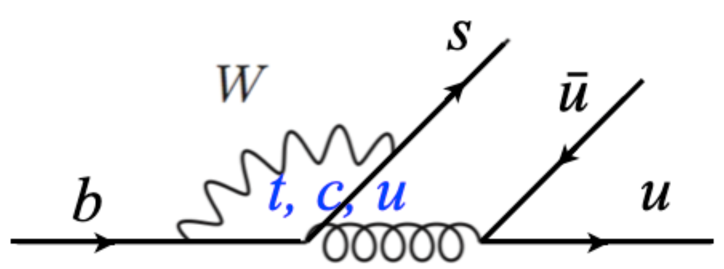
- Penguin

$$+ V_{tb}V_{td}^* f_P\, \bar{u}_{N\pi} \Big[\left(-(a_4 - R_\pi a_6) S_{11} f_1^{1/2^-} + (a_4 + R_\pi a_6) P_{11} f_1^{1/2^+} + \ldots \right) (m_{\Lambda_b} - m_{N\pi}) + \left(-(a_4 + R_\pi a_6) S_{11} g_1^{1/2^-} + (a_4 - R_\pi a_6) P_{11} g_1^{1/2^+} + \ldots \right) (m_{\Lambda_b} + m_{N\pi}) \gamma_5 \Big] u_{\Lambda_b}$$

- weak phase difference
- strong phase difference

- Under approximations of factorization and on-shell conditions

CPV via $N\pi$ rescatterings



$$d\Gamma \propto |P_{11}|^2(|A|^2+\kappa^2|B|^2)+|S_{11}|^2(|\tilde{A}|^2+\kappa^2|\tilde{B}|^2)$$
$$+2\mathcal{R}e\left[(A\tilde{A}^*+\kappa^2 B\tilde{B}^*)P_{11}S^*_{11}\right]\cos\theta$$

$$a_{46\pm}=a_4\pm R_h a_6$$

J.P.Wang, **FSY**, 2407.04110

- CPV (1): Strong phases from effective Wilson coefficients, BSS mechanism

$$|A|^2-|\bar{A}|^2 \propto 2\mathcal{R}e(\lambda_u\lambda_t a_1 a_{46+})-2\mathcal{R}e(\lambda_u^*\lambda_t^* a_1 a_{46+})$$
$$\propto \sin(\Delta\phi_w)\sin(\Delta\delta),$$

- CPV (2): Strong phase from different partial waves.

$$\mathcal{R}e\left[AP_{11}\tilde{A}^*S^*_{11}\right]-\mathcal{R}e\left[\bar{A}\bar{P}_{11}\bar{\tilde{A}}^*\bar{S}^*_{11}\right]$$
$$\propto \mathcal{R}e\left[(\lambda_u^*\lambda_t-\lambda_u\lambda_t^*)(a_{46+}P_{11})(a_1^*S^*_{11})\right]$$
$$+\mathcal{R}e\left[(\lambda_u\lambda_t^*-\lambda_u^*\lambda_t)(a_1P_{11})(a_{46-}^*S^*_{11})\right]$$

Backup (II)

Outlook

- CPV dynamics: LCSR, QCDF for $\Lambda_b \to p\pi, pK$?
- LCDAs of heavy and light baryons.
- QCDF for $\Lambda_b \to (N\pi)h$
- Form factors and di-hadron DAs of $\Lambda_b \to (N\pi \to p\pi^0)\ell\nu$, $B(D) \to (\pi\pi \to \pi\pi)\ell\nu$

Thank you!

Puzzle & Opportunities

- Precision of baryon CPV measurements reaches the order **1%** [LHCb, 2024]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\,\%$$

- CPV in some B-meson decays are as large as **10%**

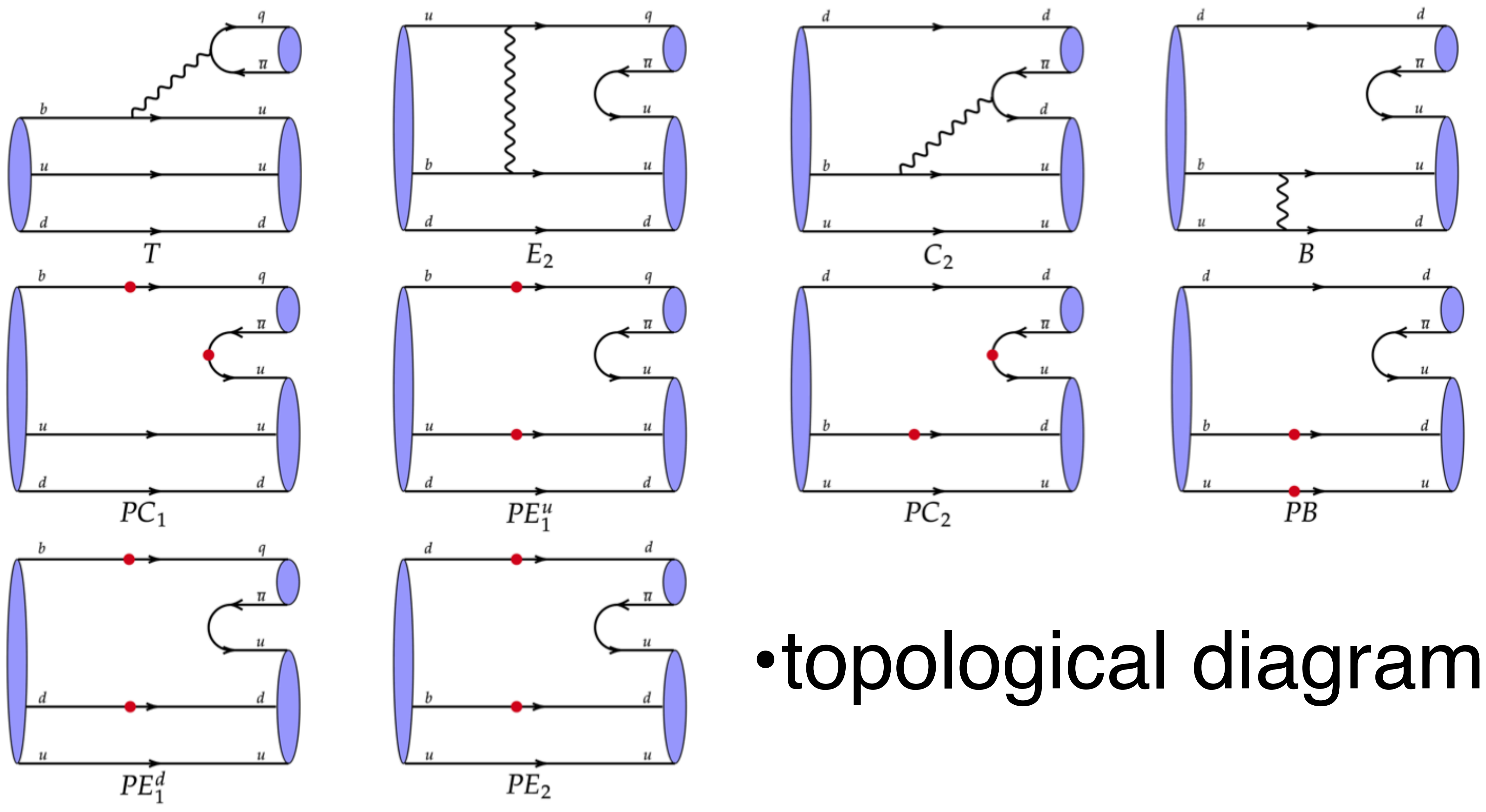
- **LHCb is a baryon factory** !! $\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \Longrightarrow \frac{N_{\Lambda_b}}{N_{B^{0(-)}}} \sim 0.5$

- **It can be expected that CPV in b-baryons might be observed soon !!**

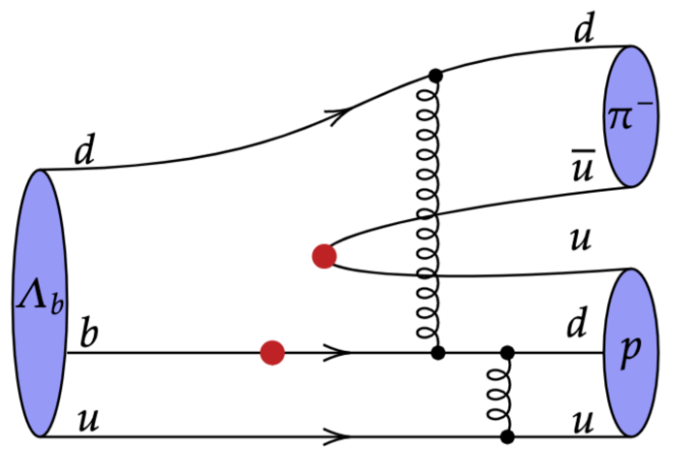
- **Questions: 1. Why not yet observed for baryon CPV ? What dynamics ?**
  2. What processes to observe baryon CPV ?

Theoretical approach for dynamics

- The above crude argument needs to be justified by comprehensive QCD calculations
- There are more non-factorizable topological diagrams, such as PC2 and the exchange diagrams PE1, PE2
- They can be calculated by PQCD based on the k_T factorization



- topological diagrams



- Feynman diagram

$\Lambda_b \to p$ form factors in PQCD

- In 2009, form factors are two orders smaller than LatticeQCD/experiments, considering only the leading twist of LCDAs [C.D.Lu, Y.M.Wang, et al, 2009]
- In 2022, considering high-twist LCDAs, results are consistent with Lattice QCD [J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, **FSY**, 2022]. Consistent with power counting by SCET.

	Lattice/exp	PQCD(2009)	PQCD(2022)
$f_1^{\Lambda_b \to p}(0)$	0.22 ± 0.08	0.002 ± 0.001	0.27 ± 0.12

	twist-3	twist-4	twist-5	twist-6	total
exponential					
twist-2	0.0007	-0.00007	-0.0005	-0.000003	0.0001
twist-3^{+-}	-0.0001	0.002	0.0004	-0.000004	0.002
twist-3^{-+}	-0.0002	0.0060	0.000004	0.00007	0.006
twist-4	0.01	0.00009	0.25	0.0000007	0.26
total	0.01	0.008	0.25	0.00007	$0.27 \pm 0.09 \pm 0.07$

Up-down asymmetry

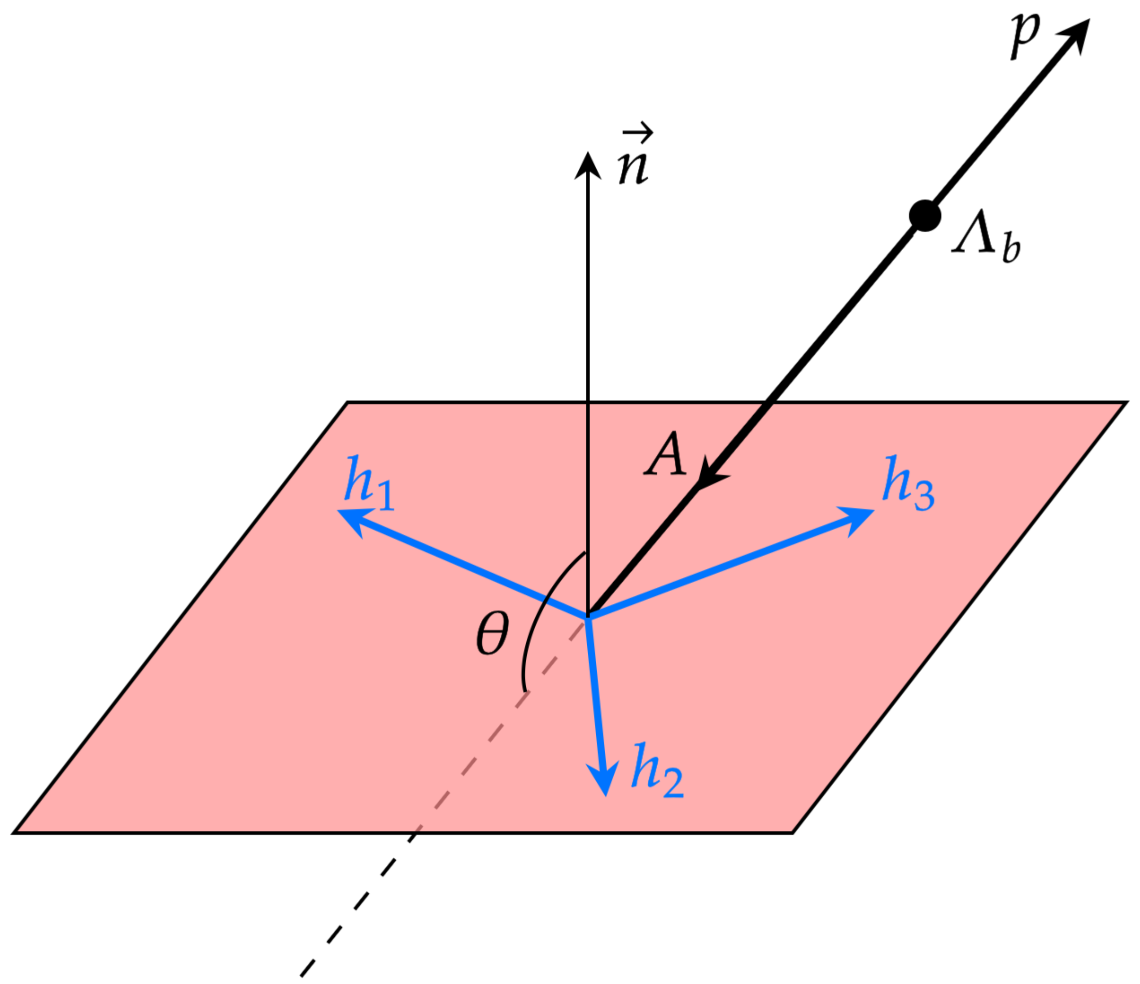
- How to measure the large partial-wave CPV?
- They usually need the polarizations of baryons.
- But the angular distributions may help.

$$\Lambda_b^0 \to p a_1(\to \pi\pi\pi) \qquad \Lambda_b^0 \to p K_1(\to K\pi\pi)$$

$$\frac{d\Gamma}{d\cos\theta} \supset R\ \mathcal{R}e(S^T P_2^*)\ \cos\theta$$

$$A_{UD} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)} = R\ \mathcal{R}e(S^T P_2^*)$$

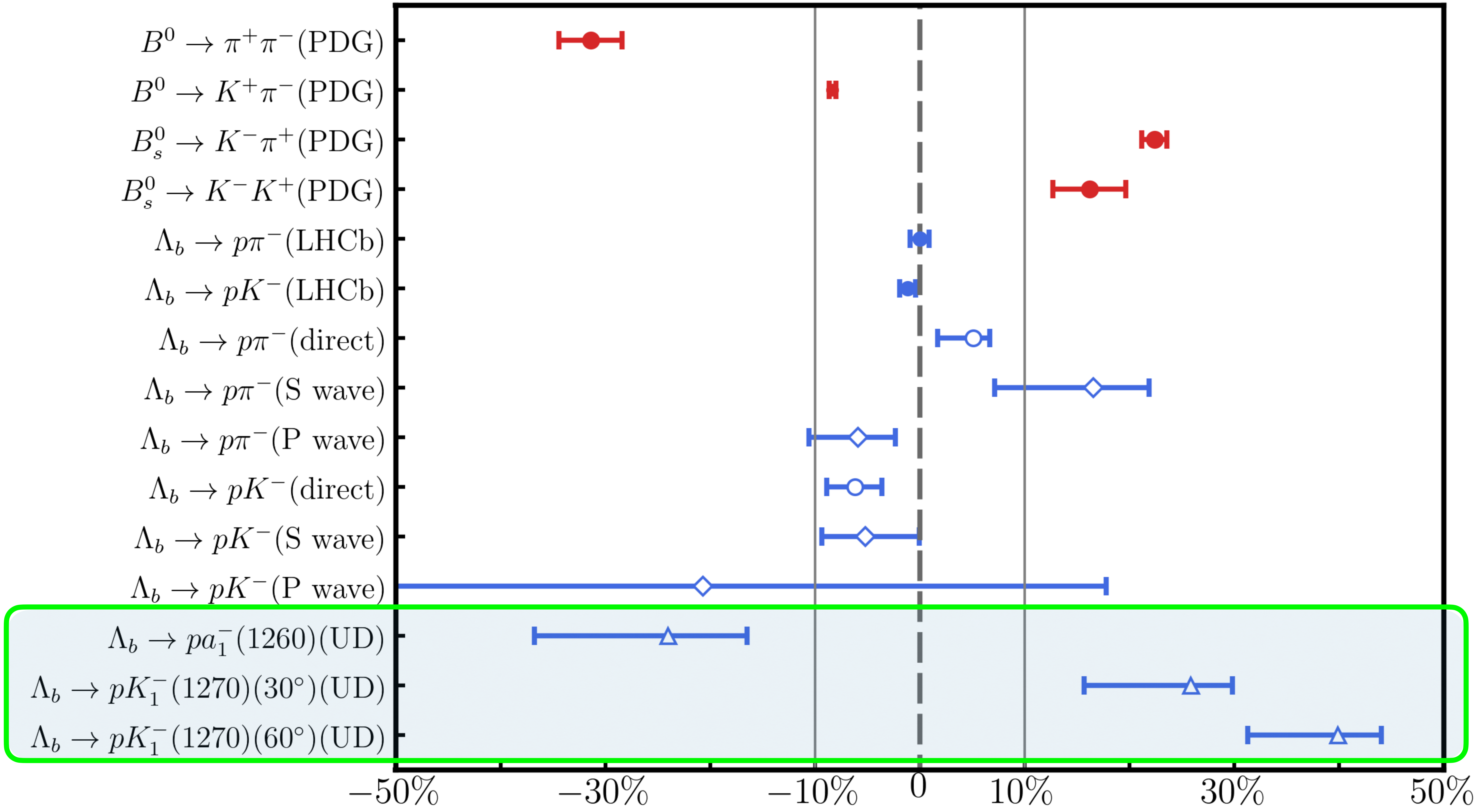
$$A_{CP}^{UD} = \frac{A_{UD} + \bar{A}_{UD}}{A_{UD} - \bar{A}_{UD}}$$



	A_{CP}^{UD}
$\Lambda_b \to p a_1^-(1260)$	$-0.24^{+0.08}_{-0.13}$
$\Lambda_b \to p K_1^-(1270)$ ($\theta_K = 30°$)	$0.26^{+0.04}_{-0.10}$
$\Lambda_b \to p K_1^-(1270)$ ($\theta_K = 60°$)	$0.40^{+0.04}_{-0.09}$

J.P.Wang, Q.Qin, **FSY**, 2411.18323;
J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821

Up-down asymmetries are large enough to be observed



J.J.Han, J.X,Yu, Y.Li, H.n.Li, J.P.Wang, Z.J.Xiao, **FSY**, 2409.02821

Direct CPV

$$\mathscr{M} = \bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$

$$\Gamma = \frac{|\vec{p}|}{8\pi M^2}\left(|S|^2 + |P|^2\right), \quad \bar{\Gamma} = \frac{|\vec{p}|}{8\pi M^2}\left(|\bar{S}|^2 + |\bar{P}|^2\right)$$

$$S = |S_t|e^{i\delta_{s,t}}e^{i\phi_t} + |S_p|e^{i\delta_{s,p}}e^{i\phi_p}$$

$$P = |P_t|e^{i\delta_{p,t}}e^{i\phi_t} + |P_p|e^{i\delta_{p,p}}e^{i\phi_p}$$

$$\bar{S} = -\left\{|S_t|e^{i\delta_{s,t}}e^{-i\phi_t} + |S_p|e^{i\delta_{s,p}}e^{-i\phi_p}\right\}$$

$$\bar{P} = |P_t|e^{i\delta_{p,t}}e^{-i\phi_t} + |P_p|e^{i\delta_{p,p}}e^{-i\phi_p}$$

- Four strong phases
- Two terms of CPV

$$a_{CP}^{dir} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = \frac{|S|^2 + |P|^2 - |\bar{S}|^2 - |\bar{P}|^2}{|S|^2 + |P|^2 + |\bar{S}|^2 + |\bar{P}|^2}$$
$$= -\frac{\sin(\delta_{s,t} - \delta_{s,p}) + r\sin(\delta_{p,t} - \delta_{p,p})}{K + [\cos(\delta_{s,t} - \delta_{s,p}) + r\cos(\delta_{p,t} - \delta_{p,p})]\cos\Delta\phi}\sin\Delta\phi$$

J.P.Wang, Q.Qin, **FSY**, 2411.18323

Direct and partial-wave CPVs

$$\mathcal{A}(\Lambda_b \to ph) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$

$$A_{CP}^{\rm dir}(\Lambda_b \to ph) \equiv \frac{\Gamma(\Lambda_b \to ph) - \bar{\Gamma}(\bar{\Lambda}_b \to \bar{p}\bar{h})}{\Gamma(\Lambda_b \to ph) + \bar{\Gamma}(\bar{\Lambda}_b \to \bar{p}\bar{h})}$$

$$\Gamma \propto |S|^2 + \kappa |P|^2$$

$$\kappa \approx 0.5$$

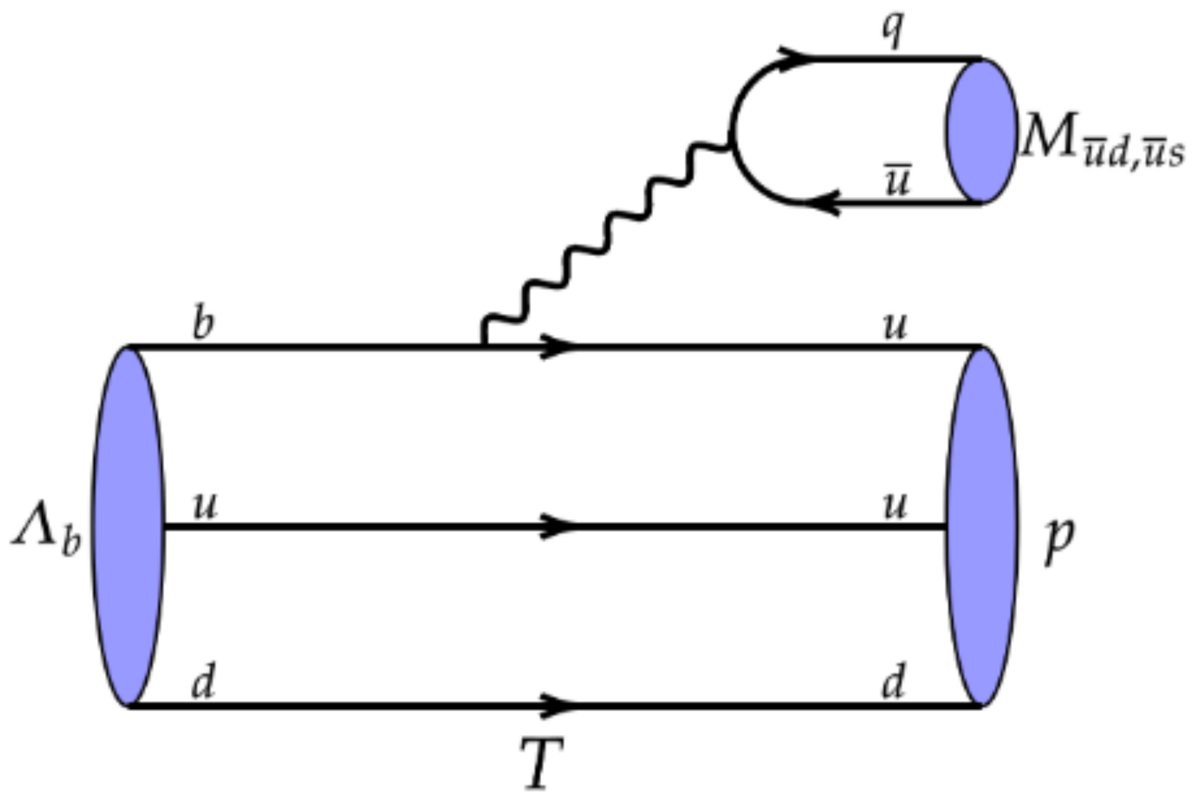
$$A_{CP}^{S\text{-wave}} \equiv \frac{|S|^2 - |\bar{S}|^2}{|S|^2 + |\bar{S}|^2}, \qquad A_{CP}^{P\text{-wave}} \equiv \frac{|P|^2 - |\bar{P}|^2}{|P|^2 + |\bar{P}|^2}.$$

$$A_{CP}^{\rm dir} \approx \kappa_S A_{CP}^{S\text{-wave}} + \kappa_P A_{CP}^{P\text{-wave}}$$

$$\kappa_S = \frac{|S|^2}{|S|^2 + \kappa |P|^2} \qquad \kappa_P = \frac{\kappa |P|^2}{|S|^2 + \kappa |P|^2}$$

Heavy quark limit

$$\mathcal{A}(\Lambda_b \to ph) = i\bar{u}_p(S + P\gamma_5)u_{\Lambda_b}$$



$$\langle p(p,s')\,|\bar{u}\gamma^\mu b|\,\Lambda_b(P,s)\rangle = \bar{u}\,(p,s')\,(f_1\gamma^\mu + f_2 i\sigma^{\mu\nu}\hat{q}_\nu + f_3\hat{q}^\mu)\,u\,(P,s)\,,$$
$$\langle p(p,s')\,|\bar{u}\gamma^\mu\gamma_5 b|\,\Lambda_b(P,s)\rangle = \bar{u}\,(p,s')\,(g_1\gamma^\mu + g_2 i\sigma^{\mu\nu}\hat{q}_\nu + g_3\hat{q}^\mu)\,\gamma_5 u\,(P,s)\,,$$

- In the heavy quark limit,

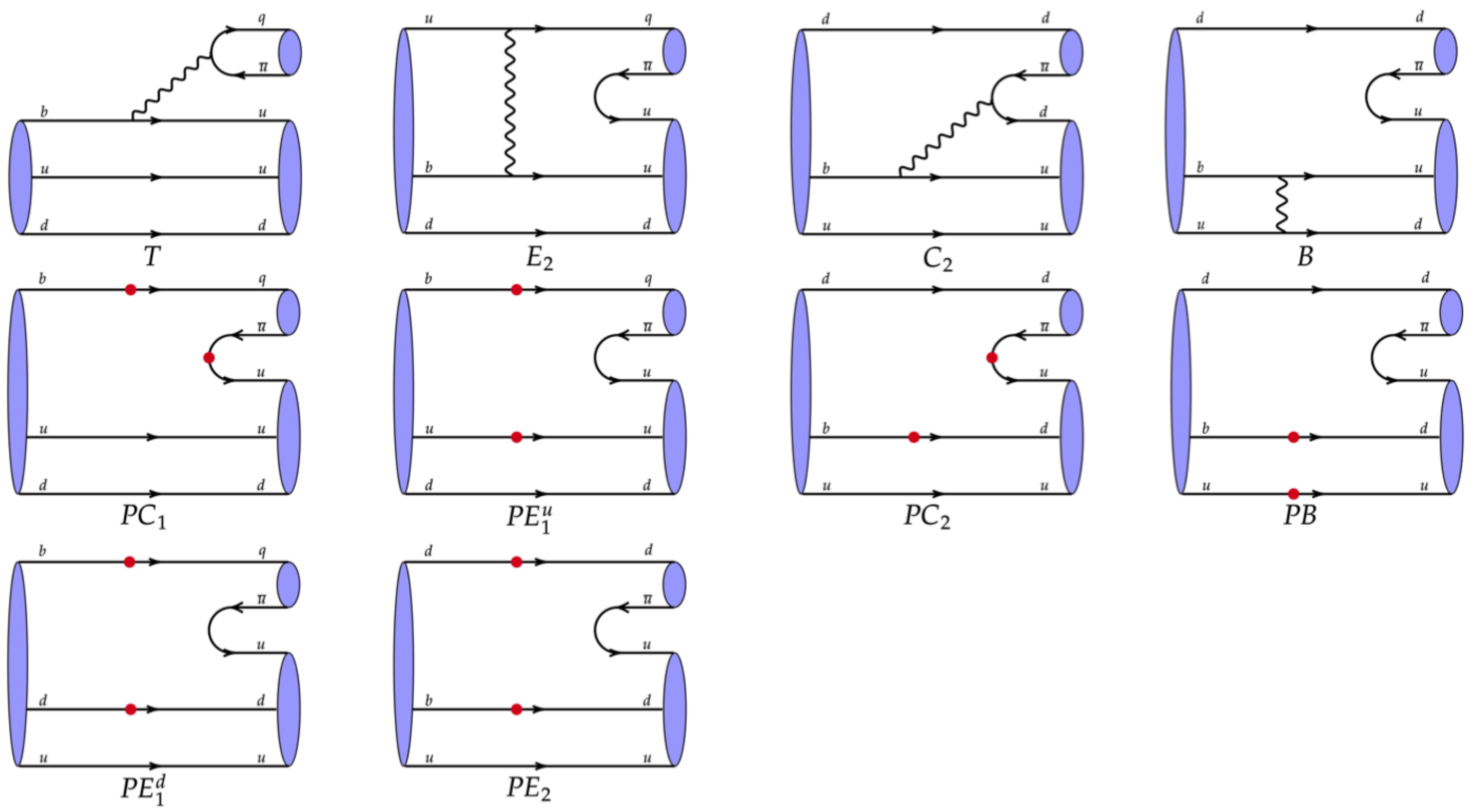
$$f_1 = g_1, \quad f_2 = f_3 = g_2 = g_3 = 0$$

T. Mannel, W. Roberts and Z. Ryzak, NPB1991

- Under factorization approximation,

$$S = \lambda a_{1,2} f_P(m_i - m_f) f_1(m_P^2),$$
$$P = \lambda a_{1,2} f_P(m_i + m_f) g_1(m_P^2),$$

Topological diagrams



$$S = \lambda_{\mathcal{T}} |S_{\mathcal{T}}| e^{i\delta^S_{\mathcal{T}}} + \lambda_{\mathcal{P}} |S_{\mathcal{P}}| e^{i\delta^S_{\mathcal{P}}},$$

$$P = \lambda_{\mathcal{T}} |P_{\mathcal{T}}| e^{i\delta^P_{\mathcal{T}}} + \lambda_{\mathcal{P}} |P_{\mathcal{P}}| e^{i\delta^P_{\mathcal{P}}},$$

Amplitudes	Real(S)	Imag(S)	Real(P)	Imag(P)
$\Lambda_b \to p\pi^-$				
T	701.19	−51.38	967.54	−265.17
C_2	−26.61	12.43	−41.51	0.14
E_2	−55.01	−38.14	−36.23	62.89
B	−4.00	9.60	−12.73	−19.93
Tree $\mathcal{T}$	615.57	−67.49	877.08	−222.06
PC_1	57.90	−1.12	1.88	−11.11
PC_2	−5.88	−12.00	4.62	14.20
PE_1^u	0.39	−9.47	−3.65	8.04
PB	0.85	−1.06	−1.46	−0.53
$PE_1^d + PE_2$	−0.55	−3.83	1.37	-0.31
Penguin $\mathcal{P}$	52.71	−27.49	2.77	10.28
$\Lambda_b \to pK^-$				
T	853.60	−52.08	1190.21	−340.84
E_2	−66.28	−59.48	−50.31	79.56
Tree $\mathcal{T}$	787.31	−111.55	1139.90	−261.28
PC_1	75.64	−0.82	−4.35	−13.81
PE_1^u	0.10	−11.80	−4.76	9.93
PE_1^d	−1.50	−7.38	1.66	2.09
Penguin $\mathcal{P}$	74.23	−20.00	−7.45	−1.79

Direct and partial-wave CPVs of $\Lambda_b \to pA, pV$

$$\mathcal{A}^L(\Lambda_b \to pA) = \bar{u}_p \epsilon^*_{L\mu} \left(A_1^L \gamma^\mu \gamma_5 + A_2^L \frac{p_p^\mu}{m_{\Lambda_b}} \gamma_5 + B_1^L \gamma^\mu + B_2^L \frac{p_p^\mu}{m_{\Lambda_b}} \right) u_{\Lambda_b},$$

$$\mathcal{A}^T(\Lambda_b \to pA) = \bar{u}_p \epsilon^*_{T\mu} (A_1^T \gamma^\mu \gamma_5 + B_1^T \gamma^\mu) u_{\Lambda_b},$$

$$S^L = -A_1^L,\ S^T = -A_1^T,\ P_1 \approx -2B_1^L - B_2^L,\ P_2 \approx B_1^T \text{ and } D \approx -A_1^{\bar{L}} + A_2^L.$$

$$\Gamma = \frac{p_c}{4\pi} \frac{E_p + m_p}{m_{\Lambda_b}} \left\{ 2(|S^T|^2 + |P_2|^2) + \frac{E_h^2}{m_h^2} (|S^L + D|^2 + |P_1|^2) \right\}$$

$$A_{CP}^{dir} \approx \kappa_{S^T} A_{CP}^{S^T} + \kappa_{P_2} A_{CP}^{P_2} + \kappa_{D+S^L} A_{CP}^{D+S^L} + \kappa_{P_1} A_{CP}^{P_1}$$

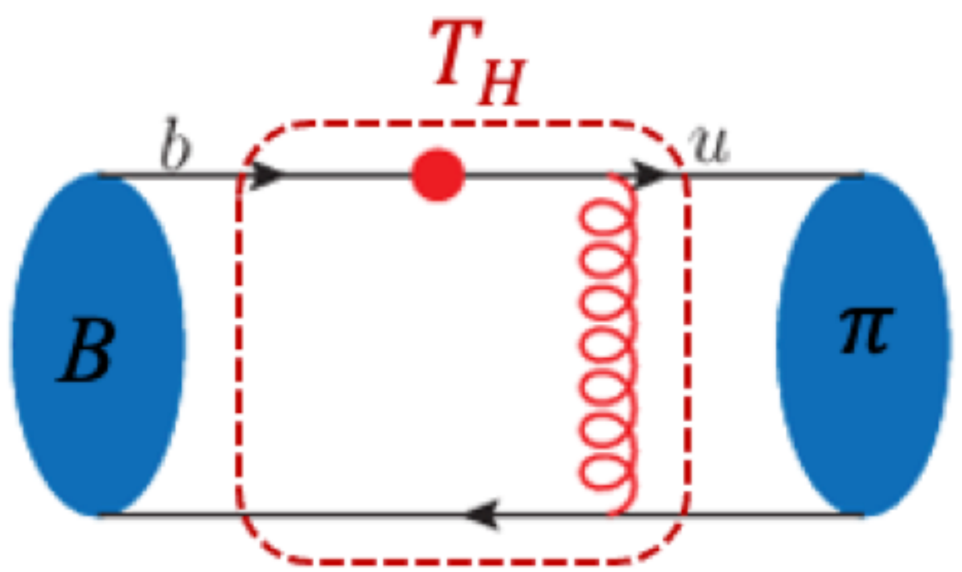
PQCD approach

- PQCD successfully predicted CPV in B meson decays [Keum, H.n.Li, Sanda, 2000; C.D.Lu, Ukai, M.Z.Yang, 2000].

直接CP破坏(%)	GFA	QCDF	2000 PQCD	2004 exp.
$B \to \pi^+\pi^-$	-5 ± 3	-6 ± 12	$+30 \pm 20$	$+32 \pm 4$
$B \to K^+\pi^-$	$+10 \pm 3$	$+5 \pm 9$	-17 ± 5	-8.3 ± 0.4

- under collinear factorization:
  - Endpoint singularity: propagator $\sim 1/x_1 x_2 Q^2 \to \infty$ when $x_{1,2} \to 0{,}1$

$$M(Q^2) = \int_0^1 dx_1 dx_2\, \phi_B(x_2, \mu^2) * T_H\left(x_1, x_2, \frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right) * \phi_\pi(x_1, \mu^2)$$



- PQCD approach (based on k_T factorization): retain transverse momentum of parton k_T,
  - propagator $\sim 1/(x_1 x_2 Q^2 + k_T^2)$

$$M(Q^2) = \int_0^1 dx_1 dx_2 \int d\mathbf{k}_{1T} d\mathbf{k}_{2T} \phi_B(x_2, \mathbf{k}_{2T}, \mu^2) * T_H\left(x_1, x_2, \mathbf{k}_{2T}, \mathbf{k}_{1T}, \frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right) * \phi_\pi(x_1, \mathbf{k}_{1T}, \mu^2)$$

Light-Cone Distribution Amplitudes

Pseudoscalar
$$\Phi_{\pi(K)}(q,y) = \frac{i}{\sqrt{2N_C}}\left[\gamma_5 \not{q}\phi^A_{\pi(K)}(y) + m_0^{\pi(K)}\gamma_5\phi^P_{\pi(K)}(y) + m_0^{\pi(K)}\gamma_5(\not{v}\not{n} - 1)\phi^T_{\pi(K)}(y)\right]_{\alpha\beta},$$

Vector meson
$$\Phi^L_V(q,\epsilon^*_L,y) = \frac{-1}{\sqrt{2N_c}}\left[m_V \not{\epsilon}^*_L\phi_V(y) + \not{\epsilon}^*_L\not{q}\phi^t_V(y) + m_V\phi^s_V(y)\right]_{\alpha\beta},$$

Λ_b baryon
$$(Y_{\Lambda_b})_{\alpha\beta\gamma}(x_i,\mu) = \frac{1}{8N_c}\left\{f^{(1)}_{\Lambda_b}(\mu)[M_1(x_2,x_3)\gamma_5 C^T]_{\gamma\beta} + f^{(2)}_{\Lambda_b}(\mu)[M_2(x_2,x_3)\gamma_5 C^T]_{\gamma\beta}\right\}[\Lambda_b(p)]_\alpha,$$

$$M_1(x_2,x_3) = \frac{\not{\bar{n}}\not{n}}{4}\psi_3^{+-}(x_2,x_3) + \frac{\not{n}\not{\bar{n}}}{4}\psi_3^{-+}(x_2,x_3),$$
$$M_2(x_2,x_3) = \frac{\not{n}}{\sqrt{2}}\psi_2(x_2,x_3) + \frac{\not{\bar{n}}}{\sqrt{2}}\psi_4(x_2,x_3),$$

Light-Cone Distribution Amplitudes

Proton

$$
\begin{aligned}
(\overline{Y}_P)_{\alpha\beta\gamma}(x_i',\mu) = \frac{1}{8\sqrt{2}N_c}\Big\{ & S_1 m_p C_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + S_2 m_p C_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + P_1 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^+_\gamma \\
& + P_2 m_p (C\gamma_5)_{\beta\alpha}\bar{N}^-_\gamma + V_1(C\not{P})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma + V_2(C\not{P})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma \\
& + V_3\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma + V_4\frac{m_p}{2}(C\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + V_5\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma \\
& + V_6\frac{m_p^2}{2Pz}(C\not{z})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma + A_1(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^+)_\gamma + A_2(C\gamma_5\not{P})_{\beta\alpha}(\bar{N}^-)_\gamma \\
& + A_3\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^+\gamma^\perp)_\gamma + A_4\frac{m_p}{2}(C\gamma_5\gamma_\perp)_{\beta\alpha}(\bar{N}^-\gamma^\perp)_\gamma + A_5\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^+)_\gamma \\
& + A_6\frac{m_p^2}{2Pz}(C\gamma_5\not{z})_{\beta\alpha}(\bar{N}^-)_\gamma - T_1(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma - T_2(iC\sigma_{\perp P})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma \\
& - T_3\frac{m_p}{Pz}(iC\sigma_{Pz})_{\beta\alpha}(\bar{N}^+\gamma_5)_\gamma - T_4\frac{m_p}{Pz}(iC\sigma_{zP})_{\beta\alpha}(\bar{N}^-\gamma_5)_\gamma - T_5\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^+\gamma_5\gamma^\perp)_\gamma \\
& - T_6\frac{m_p^2}{2Pz}(iC\sigma_{\perp z})_{\beta\alpha}(\bar{N}^-\gamma_5\gamma^\perp)_\gamma + T_7\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^+\gamma_5\sigma^{\perp\perp'})_\gamma \\
& + T_8\frac{m_p}{2}(C\sigma_{\perp\perp'})_{\beta\alpha}(\bar{N}^-\gamma_5\sigma^{\perp\perp'})_\gamma\Big\}, \qquad (16)
\end{aligned}
$$

	twist-3	twist-4	twist-5	twist-6
Vector	V_1	V_2, V_3	V_4, V_5	V_6
Pseudo-Vector	A_1	A_2, A_3	A_4, A_5	A_6
Tensor	T_1	T_2, T_3, T_7	T_4, T_5, T_8	T_6
Scalar		S_1	S_2	
Pesudoscalar		P_1	P_2	

CPV cancellation is general phenomenon?

In unit of %	(Data from PDG)	
$B \to PP$	$B \to VP$	$B \to PV$
$C(B^0 \to \pi^+\pi^-) = -31 \pm 3$	$A_{CP}(B^0 \to \rho^+\pi^-) = 13 \pm 6$	$A_{CP}(B^0 \to \pi^+\rho^-) = -8 \pm 8$
$C(B^0 \to \pi^0\pi^0) = -25 \pm 20$	$C(B^0 \to \rho^0\pi^0) = -27 \pm 24$	
$A_{CP}(B^0 \to \pi^-K^+) = -8.3 \pm 0.3$	$A_{CP}(B^0 \to \rho^-K^+) = 20 \pm 11$	$A_{CP}(B^0 \to \pi^-K^{*+}) = -27 \pm 4$
$A_{CP}(B^+ \to \pi^0K^+) = 2.7 \pm 1.2$	$A_{CP}(B^+ \to \rho^0K^+) = 16 \pm 2$	$A_{CP}(B^+ \to \pi^0K^{*+}) = -39 \pm 21$
$A_{CP}(B^+ \to \pi^+\pi^0) = -1 \pm 4$	$A_{CP}(B^+ \to \rho^+\pi^0) = 3 \pm 10$	$A_{CP}(B^+ \to \pi^+\rho^0) = 0.3 \pm 1.4$

- S-wave
- P-wave
- P-wave

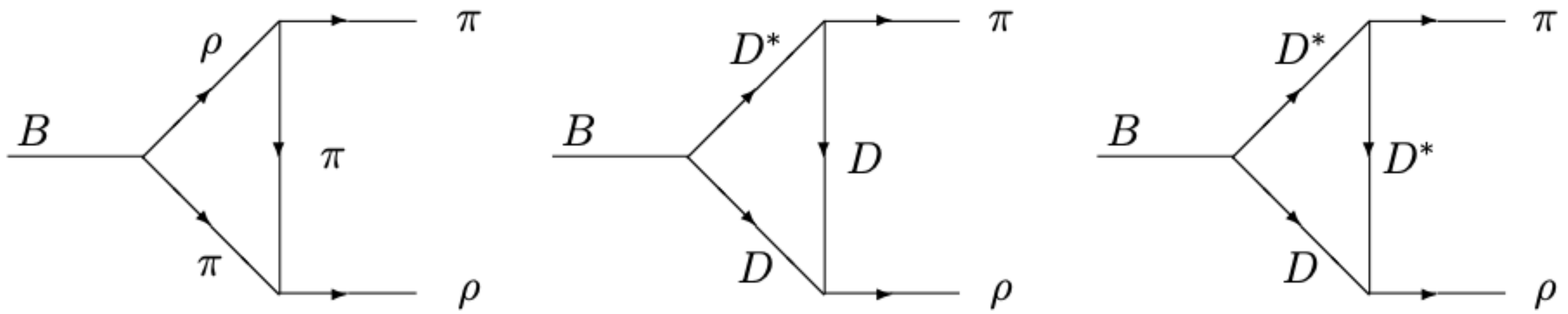
CPV cancellation is general phenomenon?

In unit of % (Data from PQCD [Chai, et. al.,2022])		
$B \to PP$	$B \to VP$	$B \to PV$
$C(B^0 \to \pi^+\pi^-) = -23$	$A_{CP}(B^0 \to \rho^+\pi^-) = 7$	$A_{CP}(B^0 \to \pi^+\rho^-) = -24$
$C(B^0 \to \pi^0\pi^0) = -3$	$C(B^0 \to \rho^0\pi^0) = -43$	
$A_{CP}(B^0 \to \pi^-K^+) = -15$	$A_{CP}(B^0 \to \rho^-K^+) = 61$	$A_{CP}(B^0 \to \pi^-K^{*+}) = -47$
$A_{CP}(B^+ \to \pi^0K^+) = -11$	$A_{CP}(B^+ \to \rho^0K^+) = 70$	$A_{CP}(B^+ \to \pi^0K^{*+}) = -32$
$A_{CP}(B^+ \to \pi^+\pi^0) = -0.05$	$A_{CP}(B^+ \to \rho^+\pi^0) = -0.6$	$A_{CP}(B^+ \to \pi^+\rho^0) = 1.1$

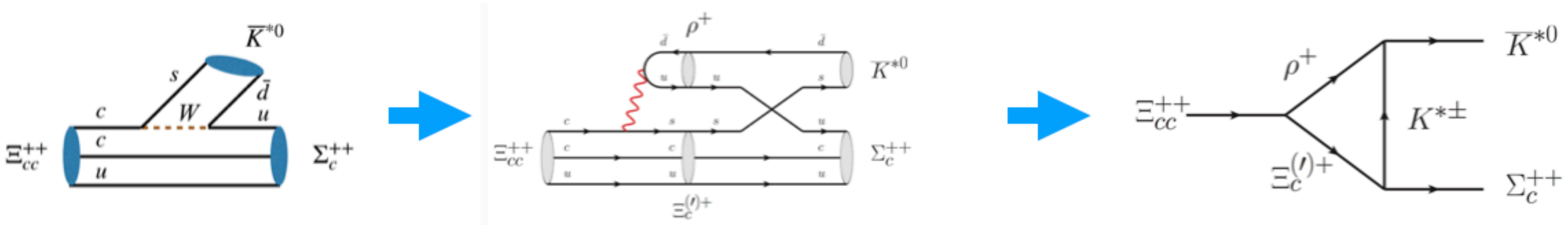
- S-wave
- P-wave
- P-wave

Rescatterings: Hadronic loops

- CP violation can be enhanced by final-state interaction in B meson decays [Suzuki, Wolfenstein, 1999; H.Y.Cheng, C.K,Chua, Soni, 2005] and charmed baryon decays [X.G.He, C.W.Liu, 2024; C.P.Jia, H.Y.Jiang, J.P.Wang, **FSY**, 2024]



- Rescattering mechanism have been successfully used to predict the discovery channel of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [**FSY**, Jiang, Li, Lu, Wang, Zhao, 2017]



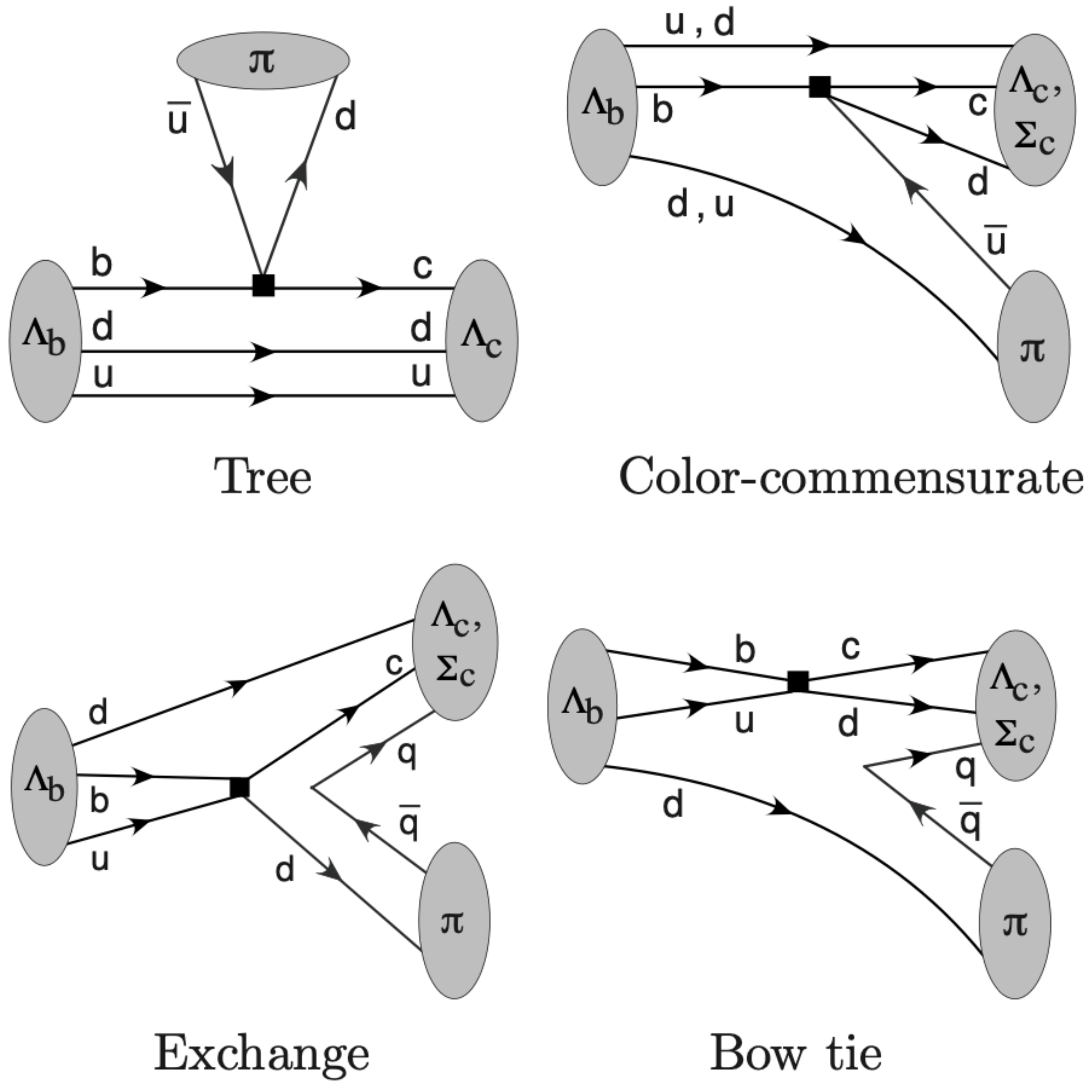
Topology: C → quark exchange → hadronic triangle

Hierarchy to topological diagrams

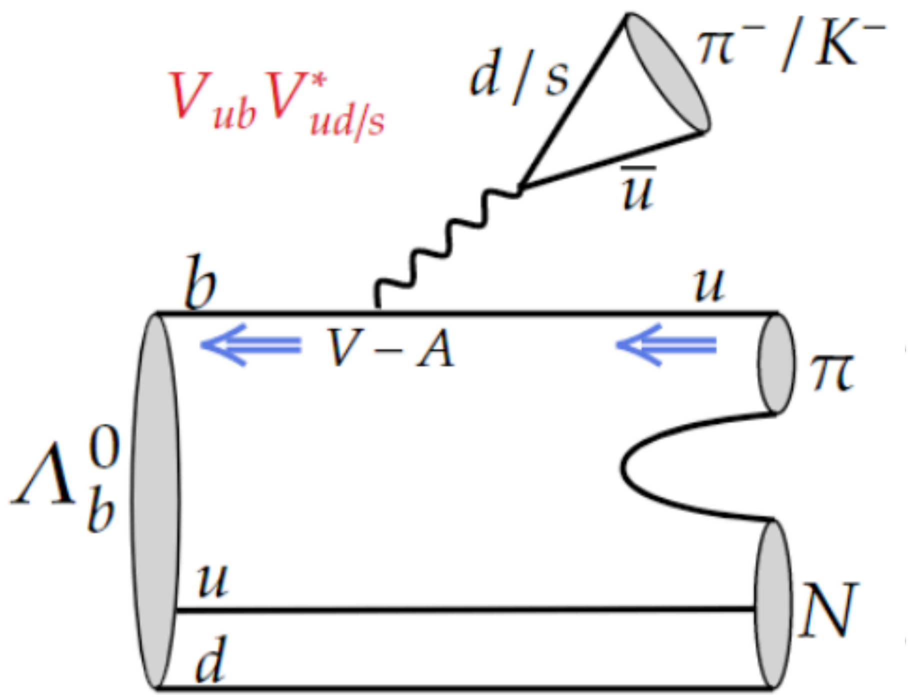
- In the heavy quark expansion,

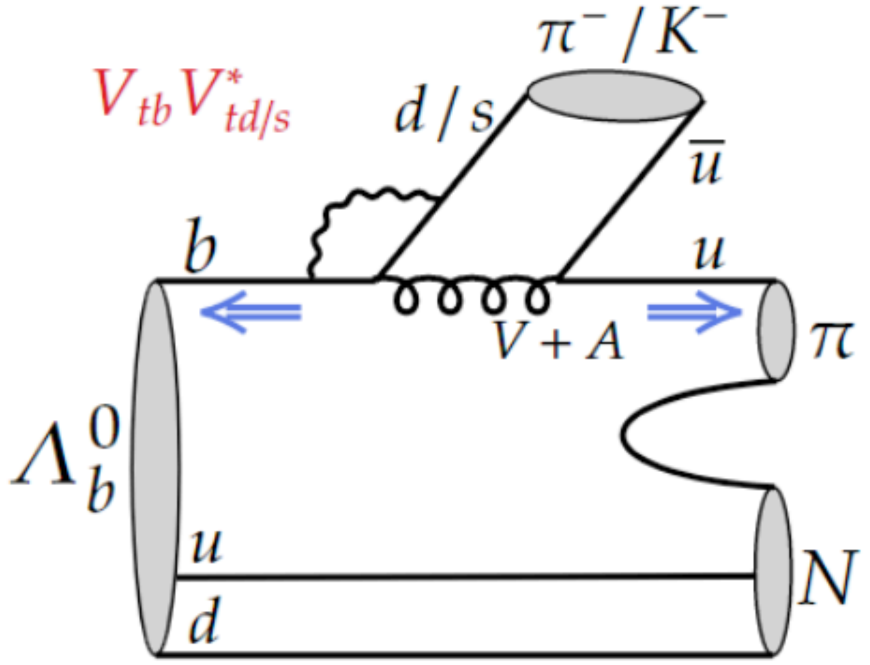
$$\left|\frac{C}{T}\right| \sim \left|\frac{E}{T}\right| \sim O\left(\frac{\Lambda_{\mathrm{QCD}}}{m_Q}\right) \qquad \left|\frac{B}{C}\right| \sim O\left(\frac{\Lambda_{\mathrm{QCD}}}{m_Q}\right)$$

Leibovich, Ligeti, Stewart, Wise, 2004

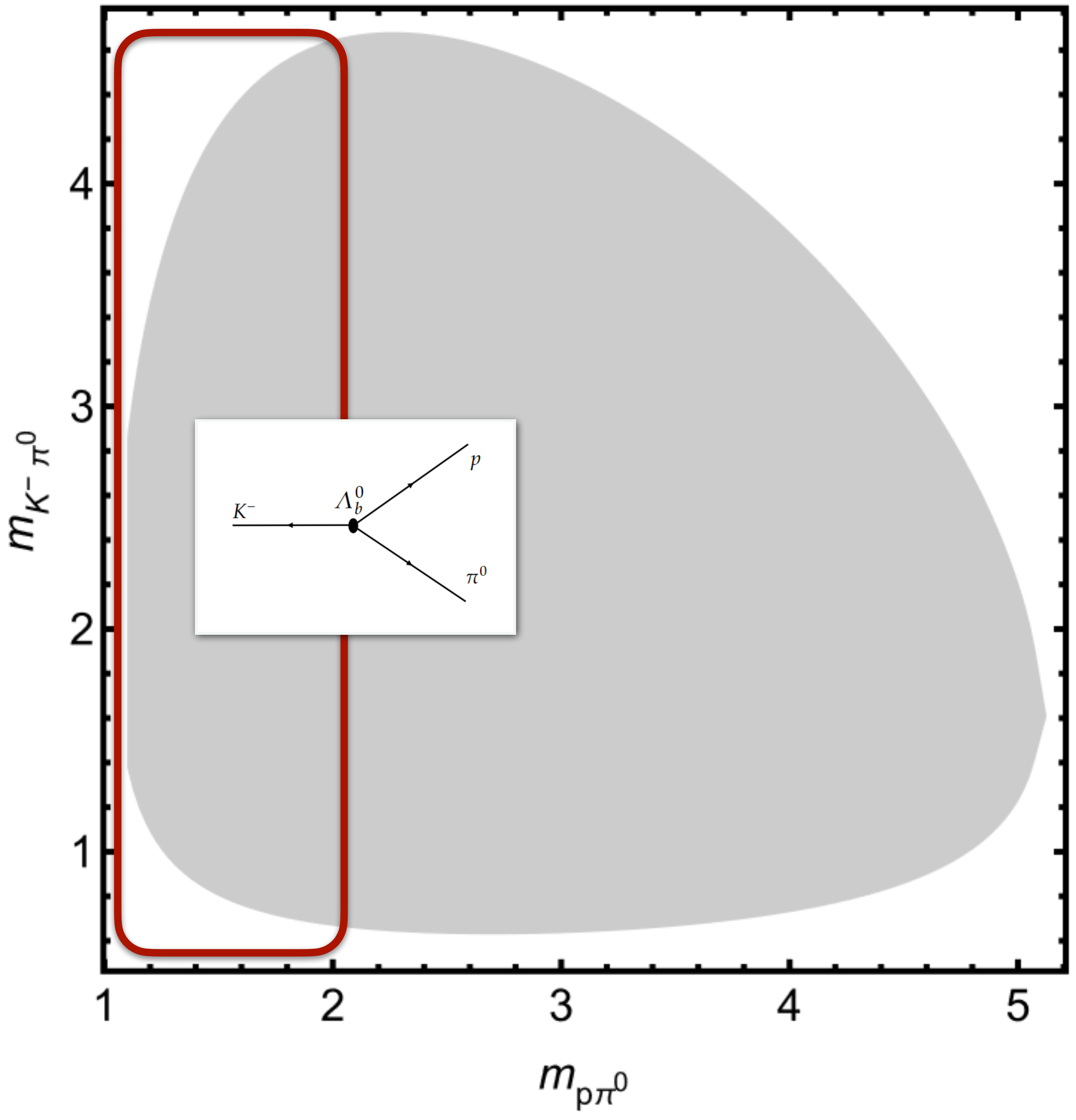


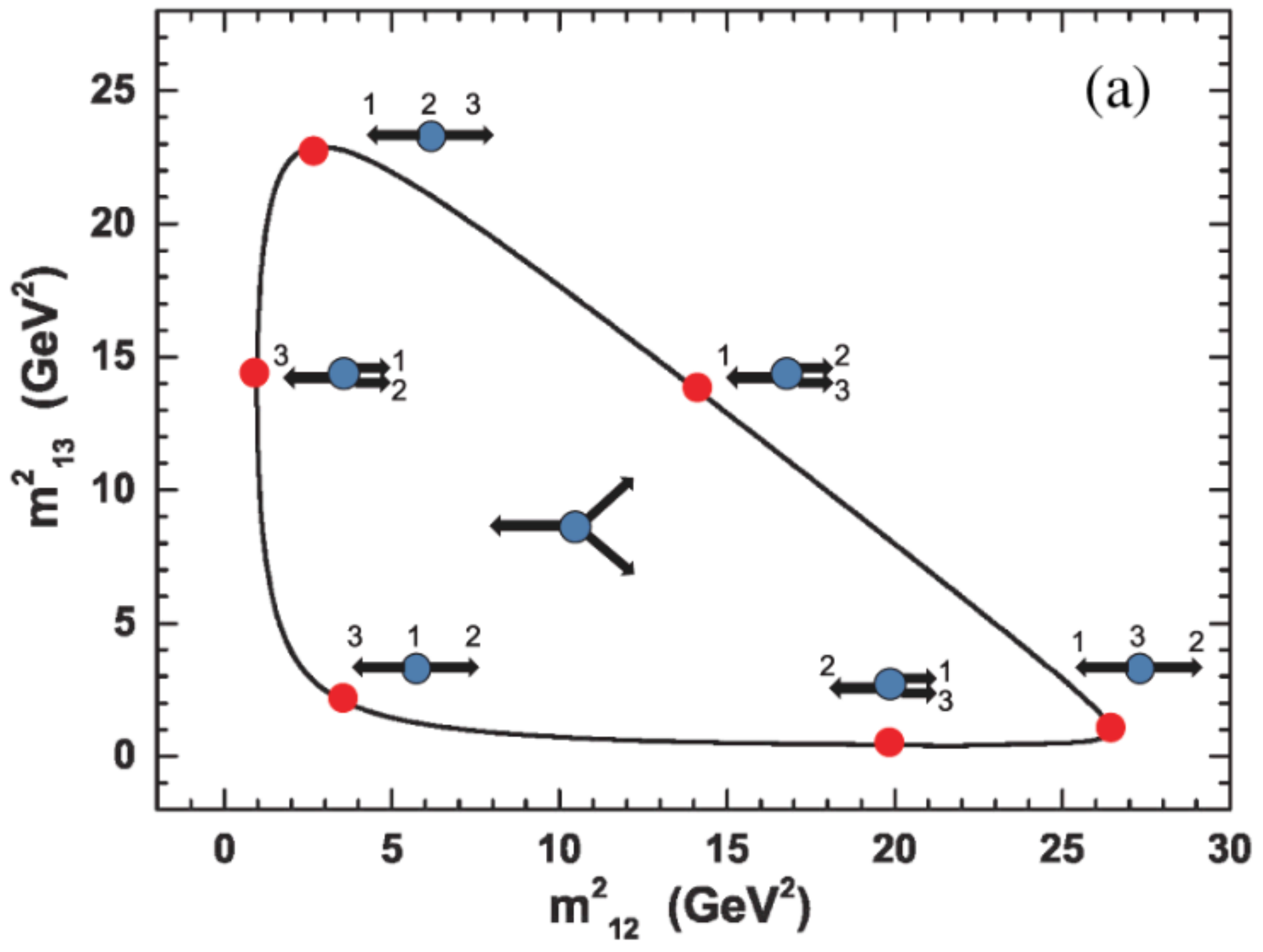
- So we only consider the color-favored emitted tree diagram and corresponding penguin diagram.





Kinematics: Dalitz of $\Lambda_b \to (p\pi^0)K^-$





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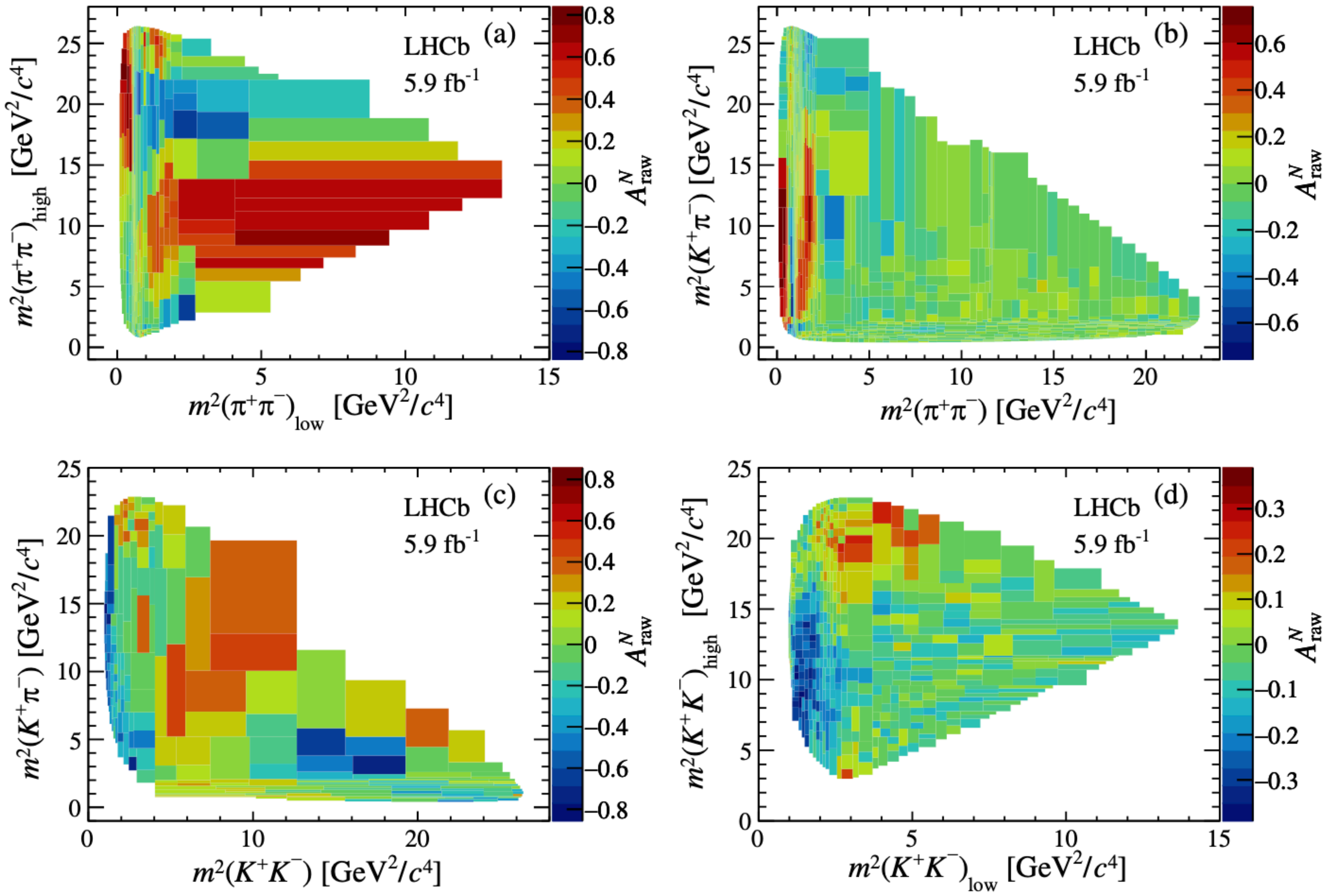
CPV in three-body decays of B mesons



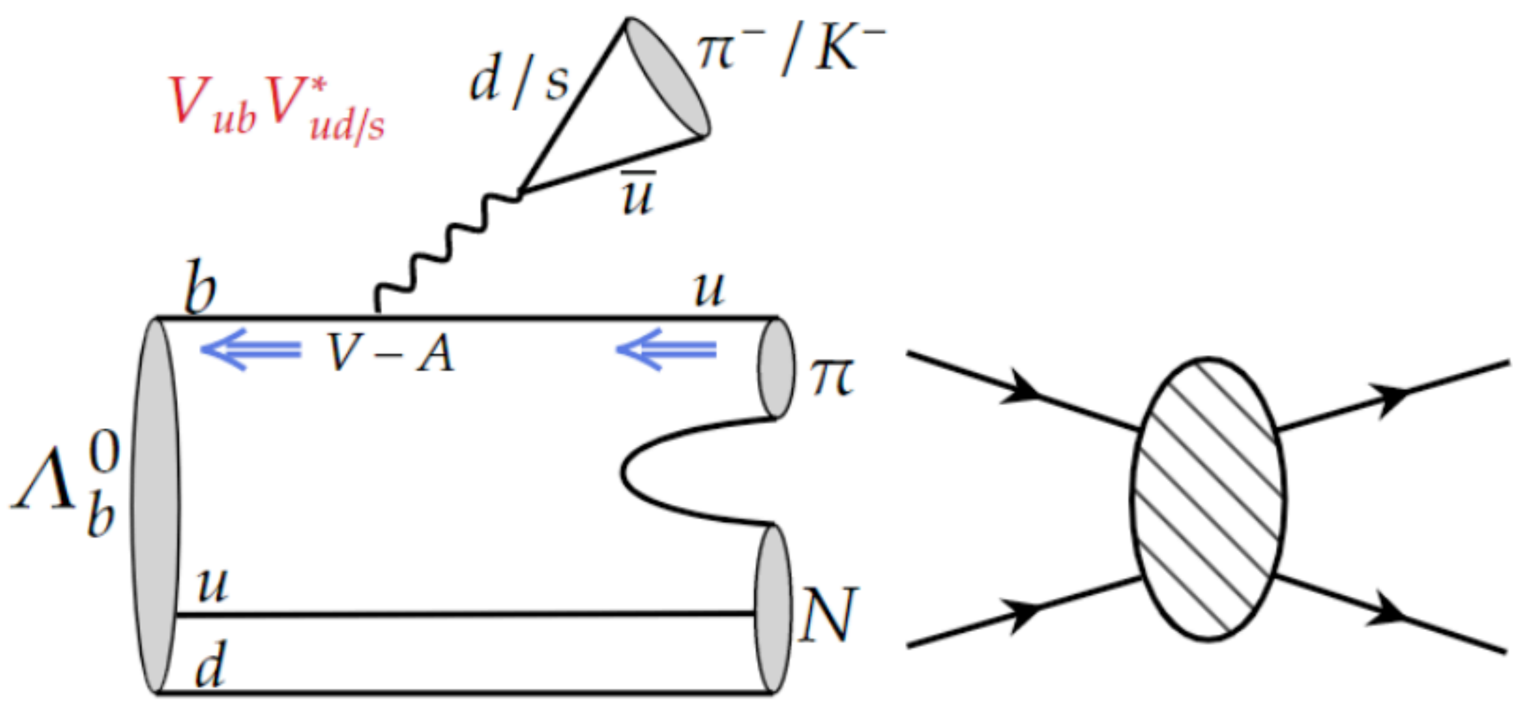
LHCb, 2206.07622

CPV from $N\pi$ scatterings

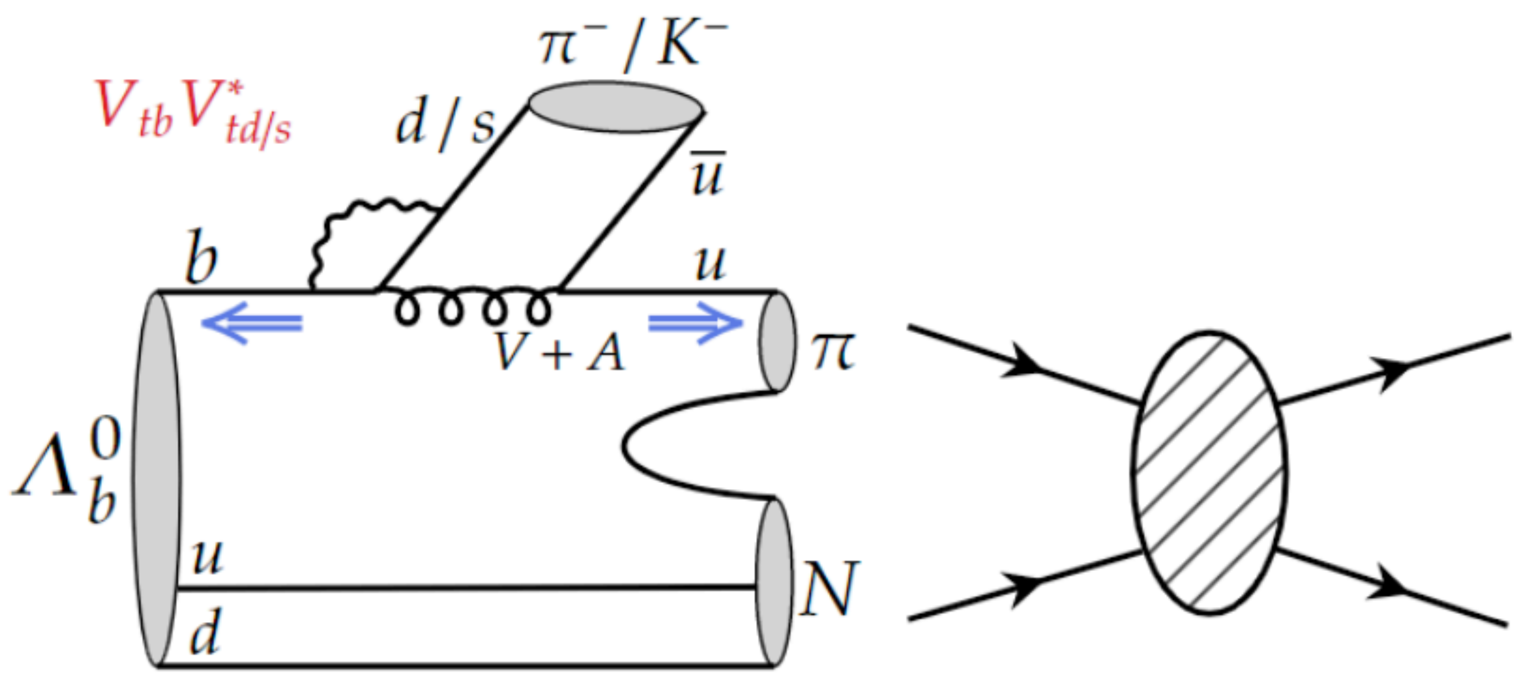
: $\mathcal{S}^{1/2}\mathcal{A}_0$

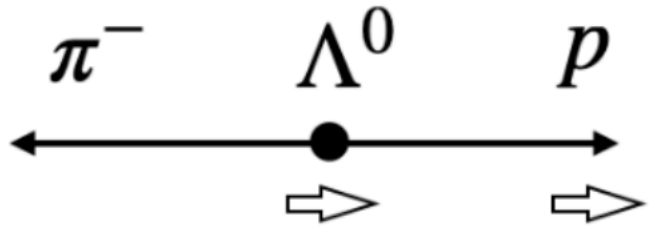
$$\mathcal{A}(\Lambda^0 \to p\pi^-) = \bar{u}_p(S + P\gamma_5)u_\Lambda$$

- Tree:

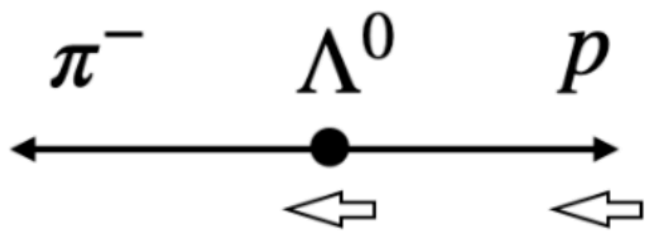


- Penguin:





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



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

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

- Short-distance weak decays
- Long-distance $N\pi$ scatterings
- weak phase
- strong phase

CPV via $N\pi$ rescatterings

- Suggestions: processes

$$(N\pi \to N\pi): \quad \Lambda_b^0 \to (p\pi^0)\pi^-, \quad (p\pi^0)K^-$$

$$(N\pi \to \Lambda\bar{K}): \quad \Lambda_b^0 \to (\Lambda^0 K^+)\pi^-, \quad (\Lambda^0 K^+)K^-$$

$$(N\pi \to p\pi\pi): \quad \Lambda_b^0 \to (p\pi^+\pi^-)\pi^-, \quad (p\pi^+\pi^-)K^-$$

- Currently, only consider $N\pi \to p\pi^0$ and $N\pi \to \Delta^{++}\pi^-$ to show the results
- $N\pi \to \Lambda\bar{K}$ and full analysis of $N\pi \to p\pi^+\pi^-$ will be done in the near future

CPV from $N\pi$ scatterings

$$\mathcal{A} = \bar{u}_{N\pi,1/2^+}(A + B\gamma_5)u_{\Lambda_b}\, P_{11} + \bar{u}_{N\pi,1/2^-}(\tilde{A} + \tilde{B}\gamma_5)u_{\Lambda_b}\, S_{11}$$

$$A = (\lambda_u a_1 - \lambda_t a_{46+}) f_1^{\frac{1}{2}^+} m_-$$

$$B = (\lambda_u a_1 - \lambda_t a_{46-}) g_1^{\frac{1}{2}^+} m_+$$

$$\tilde{A} = (-\lambda_u a_1 + \lambda_t a_{46-}) f_1^{\frac{1}{2}^-} m_- \qquad a_{46\pm} = a_4 \pm R_h a_6$$

$$\tilde{B} = (-\lambda_u a_1 + \lambda_t a_{46+}) g_1^{\frac{1}{2}^-} m_+$$

$$\Lambda_b \to (N\pi)K^- : \quad \lambda_u = V_{ub}V_{us}^*, \quad \lambda_t = V_{tb}V_{ts}^*$$

$$\Lambda_b \to (N\pi)\pi^- : \quad \lambda_u = V_{ub}V_{ud}^*, \quad \lambda_t = V_{tb}V_{td}^*$$

$$m_\pm = m_{\Lambda_b} \pm m_{N\pi}$$

$$\mathcal{A}(\Lambda_b \to (\mathcal{B}M)h^-)$$

- Tree

$$= \lambda_u f_h \bar{u}_{N\pi}\Big[a_1\left(P_{11} f_1^{1/2^+} - S_{11} f_1^{1/2^-} + \cdots\right) m_- + a_1\left(P_{11} g_1^{1/2^+} - S_{11} g_1^{1/2^-} + \cdots\right) m_+\gamma_5\Big] u_{\Lambda_b}$$

- Penguin

$$+ \lambda_t f_h \bar{u}_{N\pi}\Big[\left(a_{46+} P_{11} f_1^{1/2^+} - a_{46-} S_{11} f_1^{1/2^-} + \cdots\right) m_- + \left(a_{46-} P_{11} g_1^{1/2^+} - a_{46+} S_{11} g_1^{1/2^-} + \cdots\right) m_+\gamma_5\Big] u_{\Lambda_b}$$

- weak phase difference
- strong phase difference

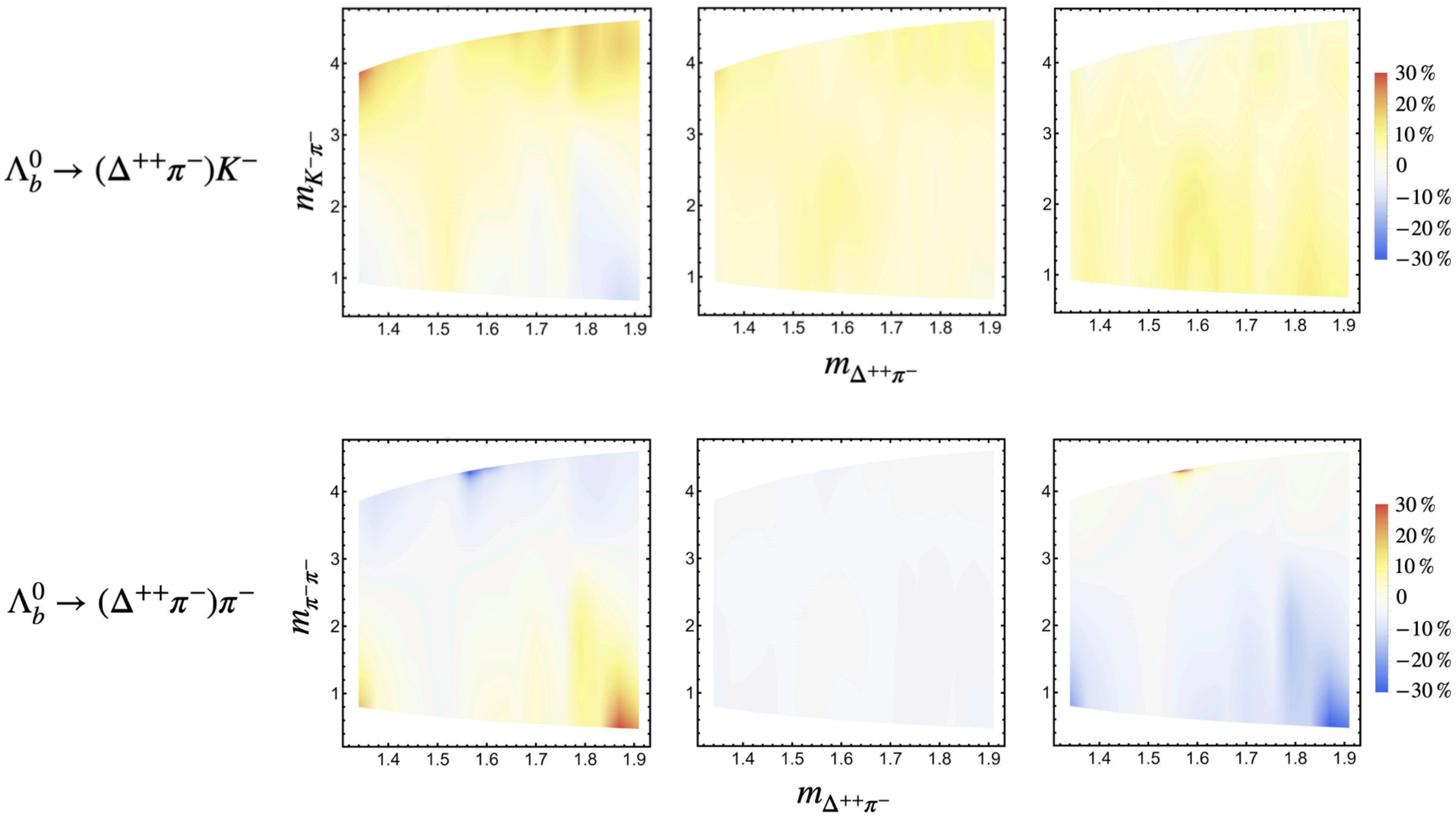
J.P.Wang, **FSY**, CPC48,101002(2024)

CPV from $N\pi$ scatterings

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
	S1	5.9%	8.0%	3.6%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$	S2	5.8%	6.3%	5.3%
	S3	5.6%	4.3%	7.0%
	S1	−4.1%	−5.4%	−2.4%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$	S2	−3.9%	−3.9%	−3.9%
	S3	−3.6%	−2.3%	−5.3%
	S1	5.8%	8.2%	2.7%
$\Lambda_b^0 \to (p\pi^0)K^-$	S2	5.8%	8.0%	3.0%
	S3	5.8%	7.8%	3.3%
	S1	−3.9%	−3.9%	−3.7%
$\Lambda_b^0 \to (p\pi^0)\pi^-$	S2	−3.9%	−3.8%	−4.3%
	S3	−3.8%	−3.6%	−4.8%

S1: $f_1 = 1.1,\ g_1 = 0.9$, S2: $f_1 = g_1 = 1.0$, and S3: $f_1 = 0.9,\ g_1 = 1.1$

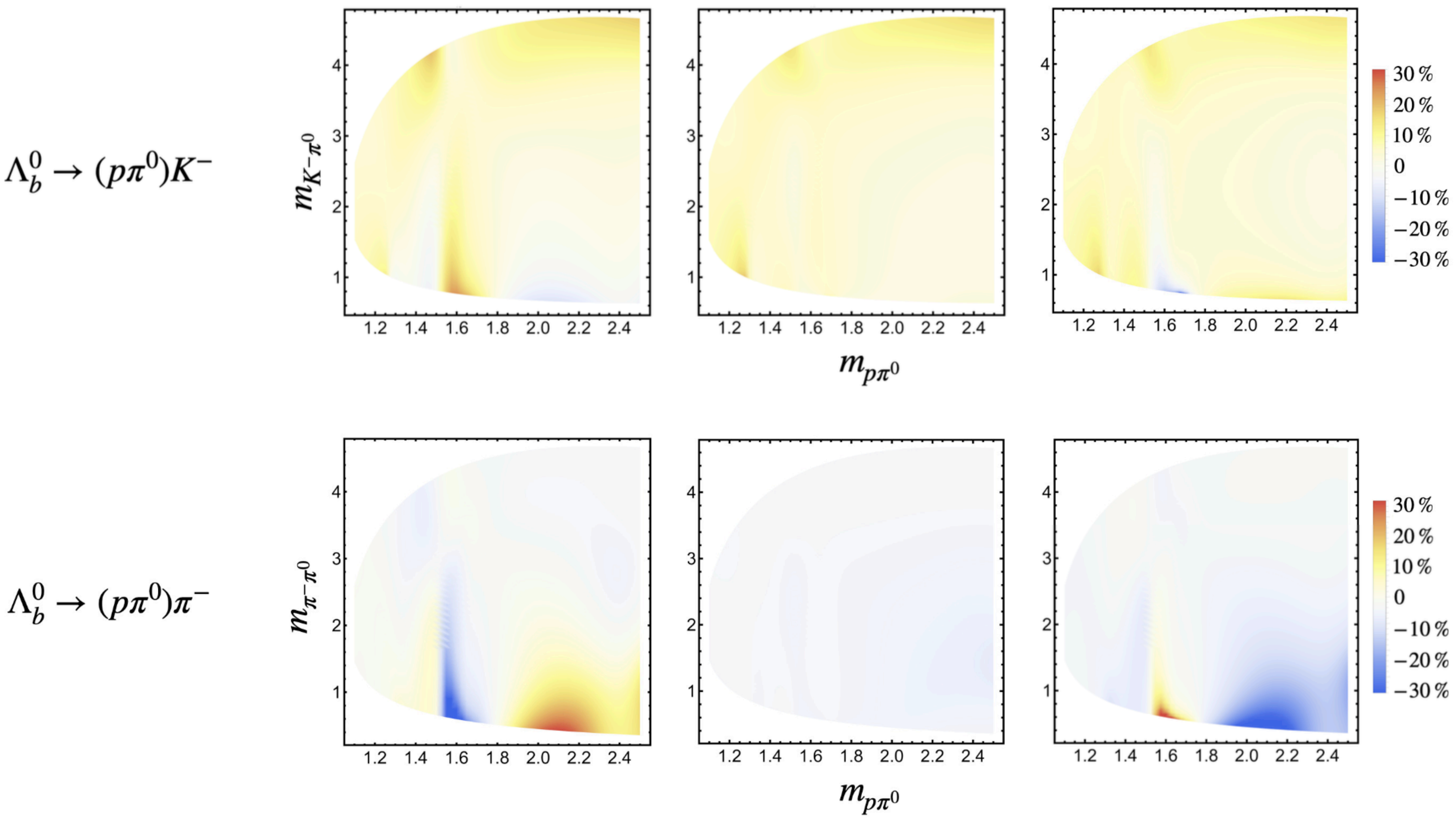
CPV from $N\pi$ scatterings



S1: $f_1 = 1.1,\ g_1 = 0.9$, S2: $f_1 = g_1 = 1.0$, and S3: $f_1 = 0.9,\ g_1 = 1.1$

- All information are in the Dalitz plots
- In some regions, the local CPV could reach 20% or even 30%.

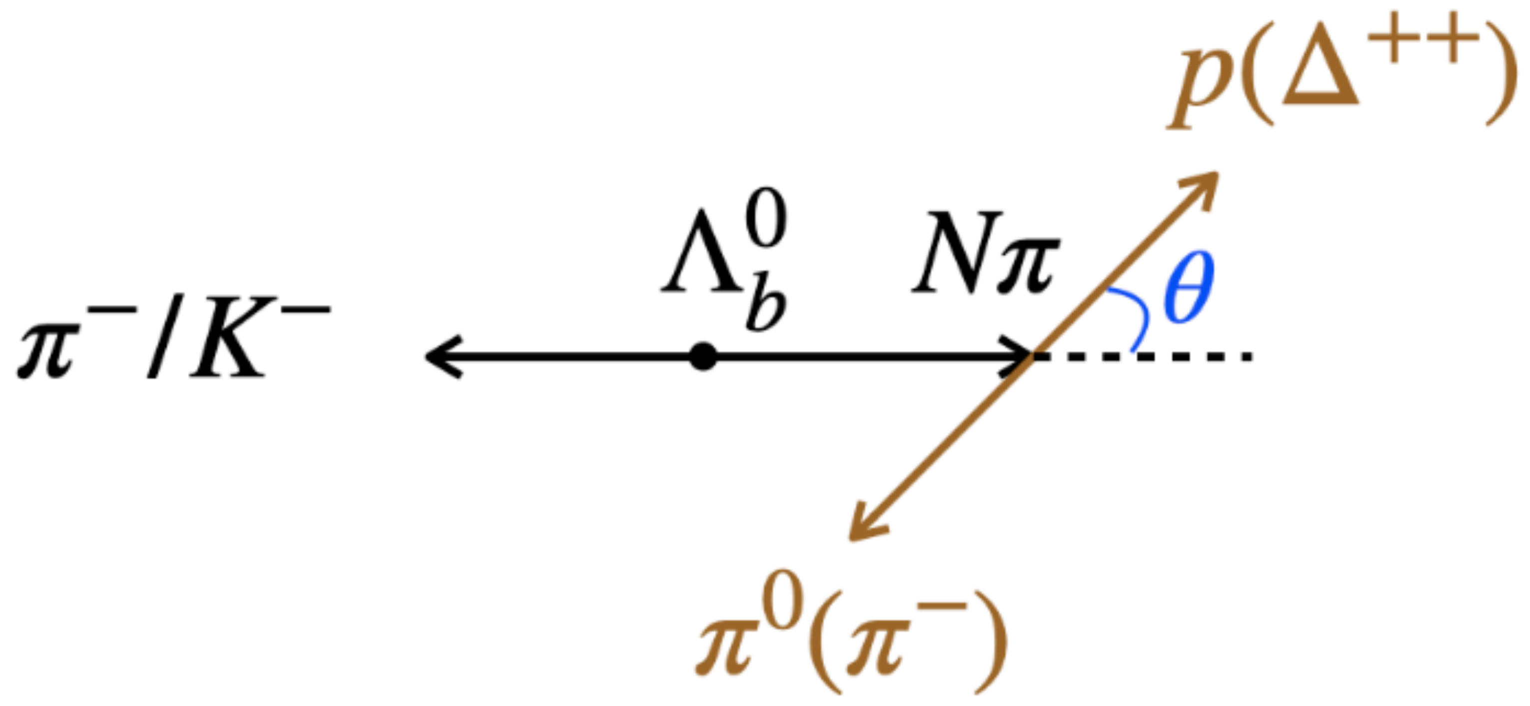
CPV from $N\pi$ scatterings



S1: $f_1 = 1.1,\ g_1 = 0.9$, S2: $f_1 = g_1 = 1.0$, and S3: $f_1 = 0.9,\ g_1 = 1.1$

- All information are in the Dalitz plots
- In some regions, the local CPV could reach 20% or even 30%.

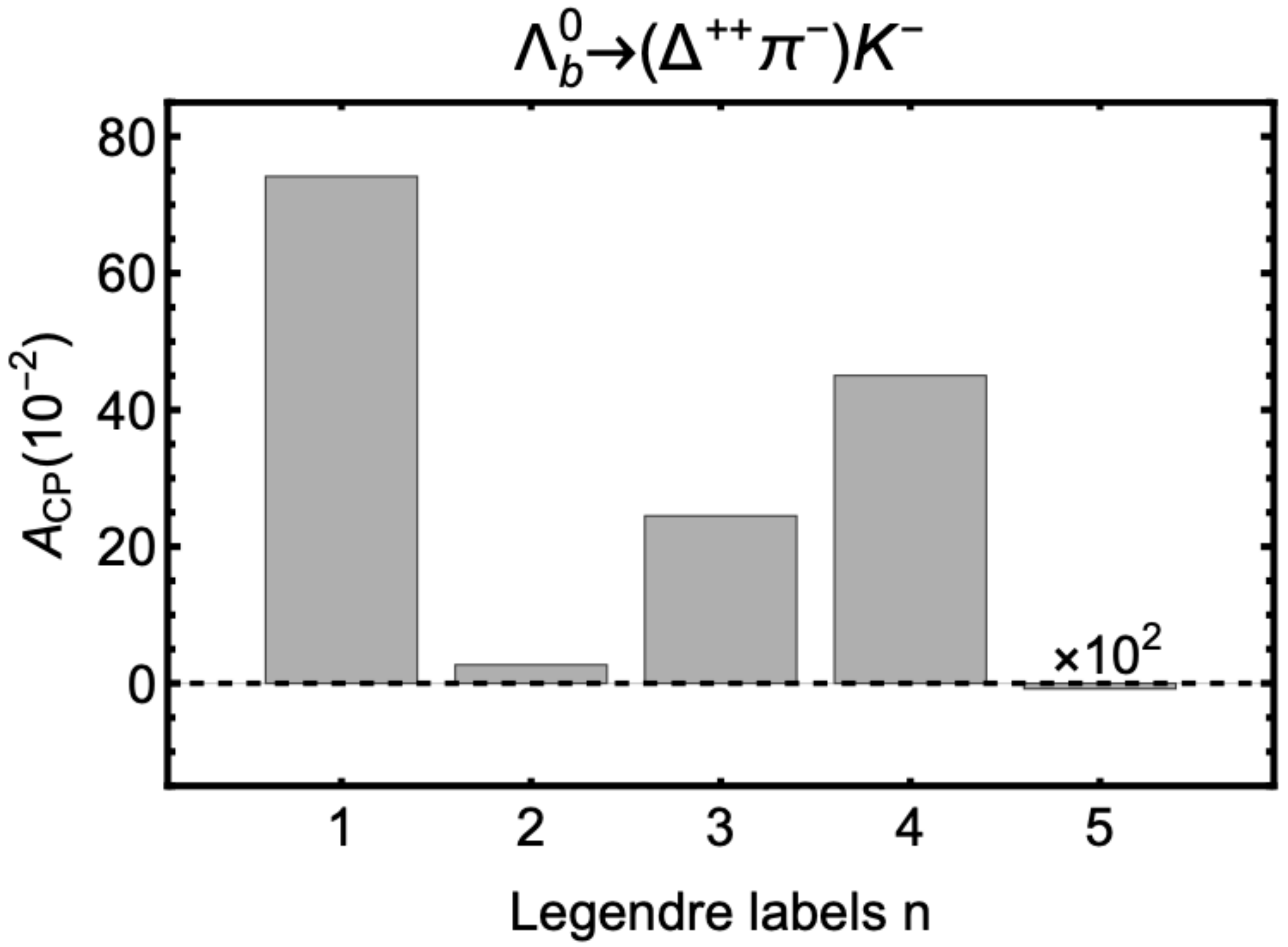
CPV of Legendre moments



$$\frac{d\Gamma}{d\cos\theta} \propto \sum_{n=0} \mathcal{L}_n P_n(\cos\theta)$$

$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$:

$$\mathscr{L}_n = (1, -0.10, 0.20, -0.05, 0.009, 0.05)$$



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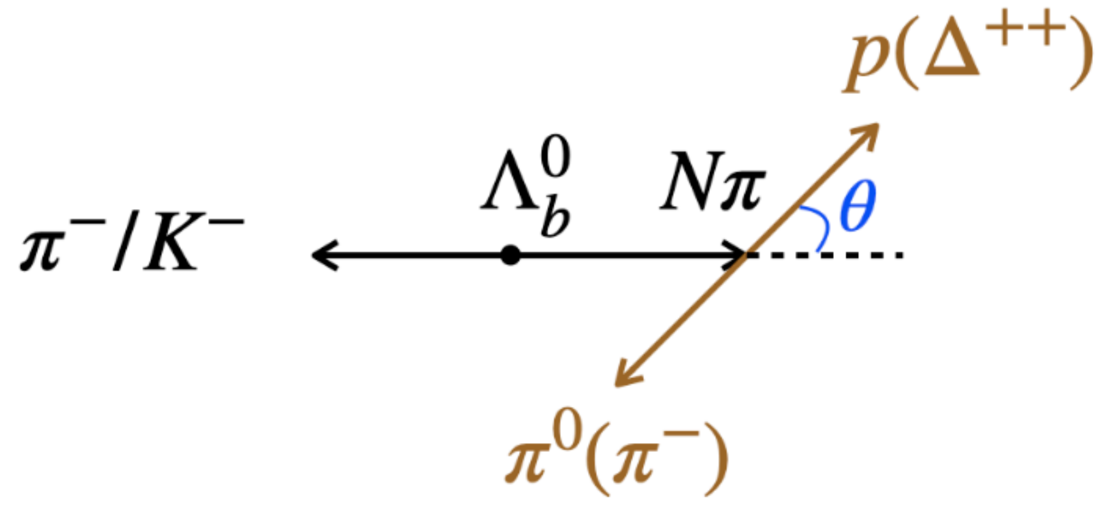
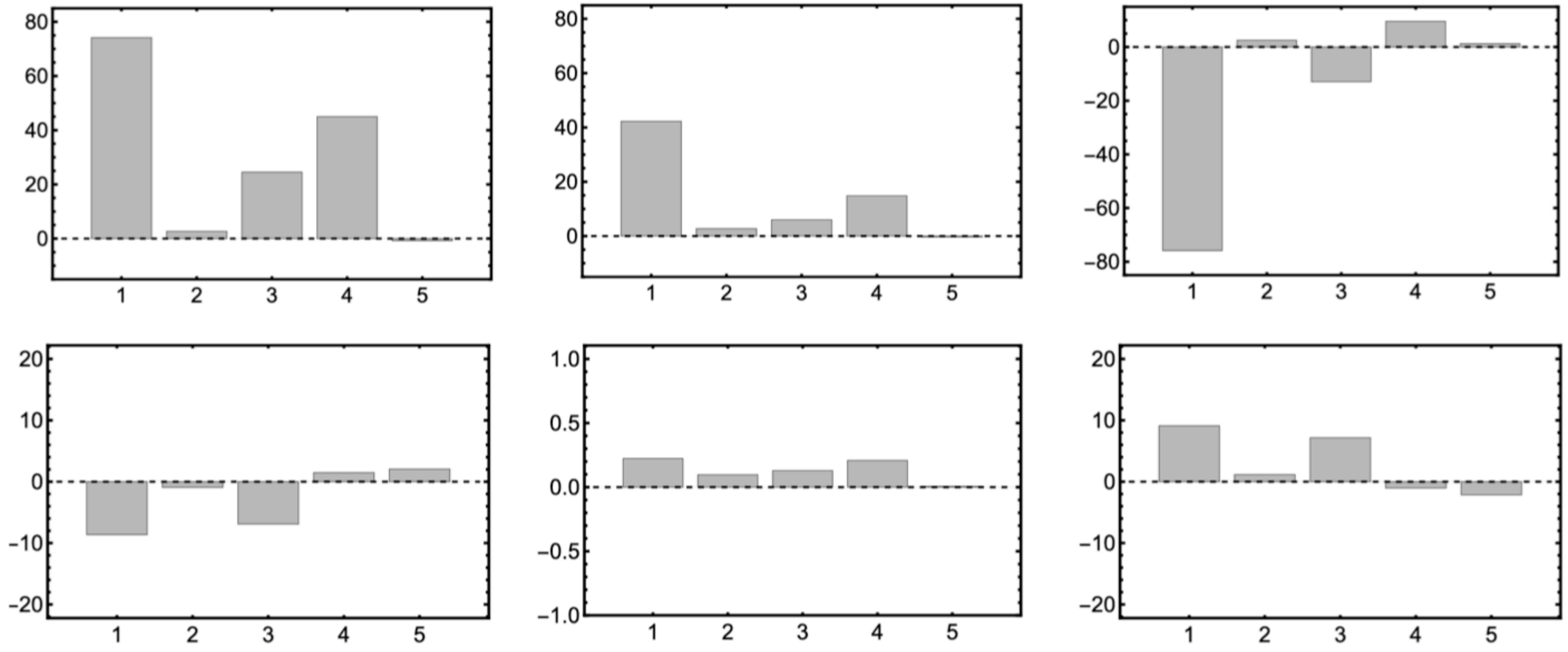
CPV of Legendre moments

$$\frac{d\Gamma}{d\cos\theta} \propto \sum_{n=0} \mathcal{L}_n P_n(\cos\theta)$$



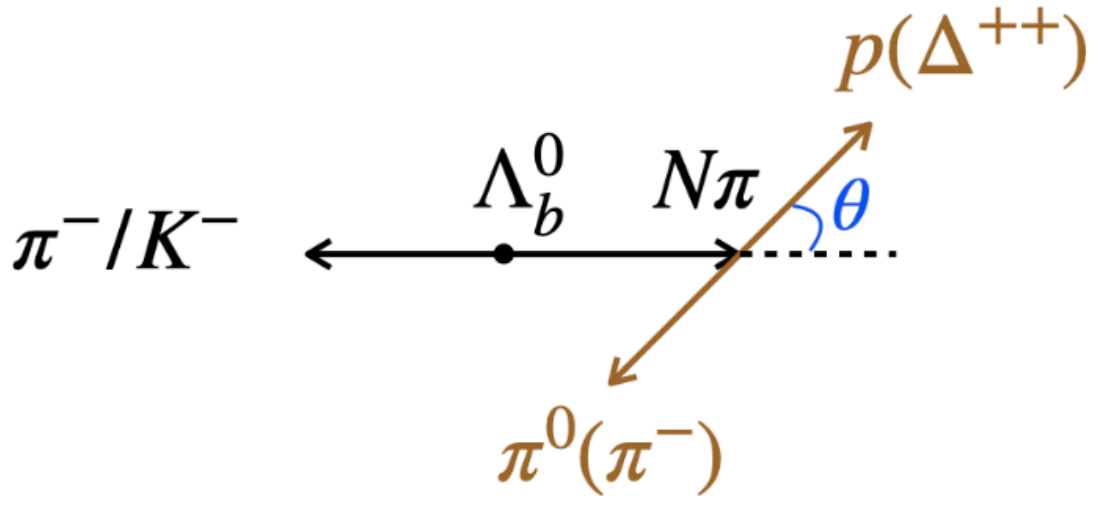
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$

$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$



S1: $f_1 = 1.1,\ g_1 = 0.9$, S2: $f_1 = g_1 = 1.0$, and S3: $f_1 = 0.9,\ g_1 = 1.1$

CPV of Legendre moments



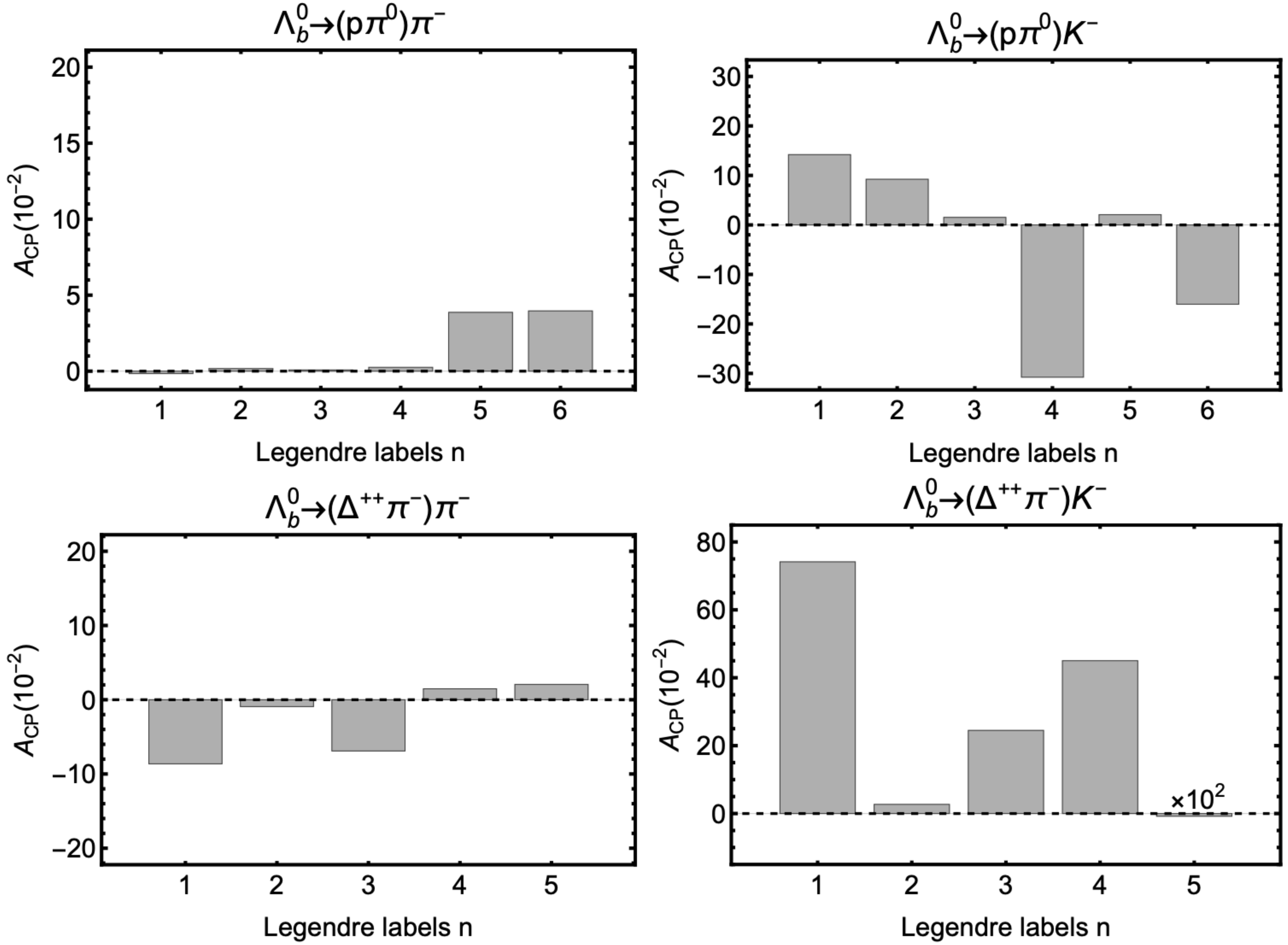
$$\frac{d\Gamma}{d\cos\theta} \propto \sum_{n=0} \mathcal{L}_n P_n(\cos\theta)$$

$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$:

$\mathscr{L}_n = (1, -0.10, 0.20, -0.05, 0.009, 0.05)$

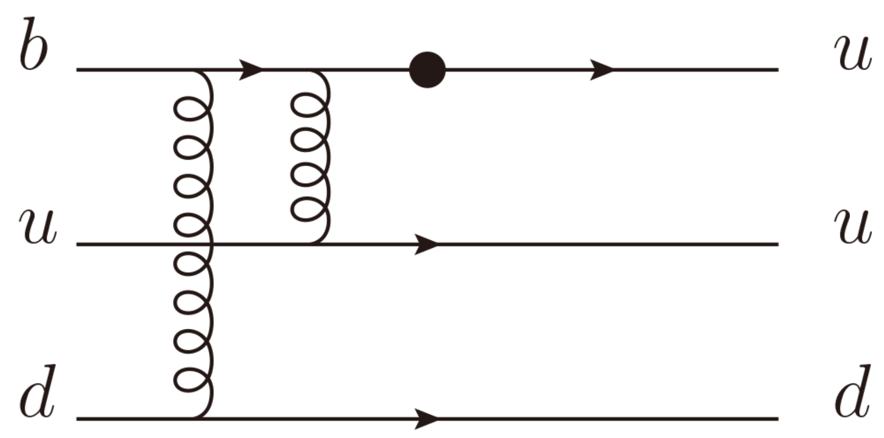
$\Lambda_b^0 \to (p\pi^0)K^-$:

$(1, -0.4, 0.4, -0.5, -0.03, -0.12, -0.005)$



Theoretical Challenges

1. **QCD dynamics for non-leptonic decays**



- One more energetic quark, one more hard gluon. Counting rule of power expansion is violated by α_s .
- Factorization of $\Lambda_b \to (N\pi)h$

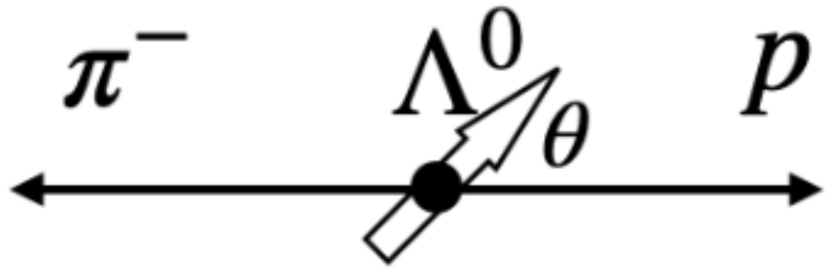
2. **Non-perturbative inputs**

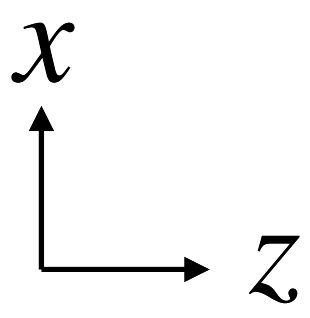
- Theoretical uncertainties are dominated by the non-perturbative input parameters, such as the light-cone distribution amplitudes (LCDA) of baryons and di-hadrons.
- Form factors of $\Lambda_b \to (N\pi)$

3. **Observables**

- T-odd triple products $(\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$, 3σ signal in $\Lambda_b \to p\pi\pi\pi$[LHCb2017]. Defined by kinematics, but unclear relation to the decay amplitudes. No way for theoretical explanations and predictions.

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





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

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(Received October 22, 1957)

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

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

Polarization in final state: $$\alpha = \frac{\left|\mathcal{H}_{+\frac{1}{2}}\right|^2 - \left|\mathcal{H}_{-\frac{1}{2}}\right|^2}{\left|\mathcal{H}_{+\frac{1}{2}}\right|^2 + \left|\mathcal{H}_{-\frac{1}{2}}\right|^2}$$

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, $\gamma = \dfrac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$

Lee-Yang parameter, or decay asymmetry parameter

CPV of Polarizations

Definition of CPV observables: $$a_{CP} = \frac{\langle O \rangle - \langle (CP) O (CP)^\dagger \rangle}{\langle O \rangle + \langle (CP) O (CP)^\dagger \rangle}$$

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

T-even: $\vec{s}_i \cdot \vec{p}$

T-odd: $(\vec{s}_i \times \vec{s}_f) \cdot \vec{p}$

$$a_{CP}^{\alpha} \propto [r_s \sin(\delta_{p,p} - \delta_{s,t}) - r_p \sin(\delta_{p,t} - \delta_{s,p})] \sin \Delta\phi$$
$$a_{CP}^{\beta} \propto [r_p \cos(\delta_{p,t} - \delta_{s,p}) - r_s \cos(\delta_{p,p} - \delta_{s,t})] \sin \Delta\phi$$
$$a_{CP}^{\gamma} \propto [|S_t||S_p| \sin(\delta_{s,t} - \delta_{s,p}) - |P_t||P_p| \sin(\delta_{p,t} - \delta_{p,p})] \sin \Delta\phi$$

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Why $\cos\delta_s$? What conditions?

- **Why $\cos\delta_s$?**
  - T-odd operator Q_-: $TQ_-T^{-1} = -Q_-$
  - T is anti-unitary, $T = UK$ with U a unitary operator and K a complex conjugation
- **Two conditions:**

(1) For a basis of final states and a unitary transformation so that $UT|\psi_n\rangle = e^{i\alpha}|\psi_n\rangle$

(2) Q_- is invariant under this unitary transformation, $UQ_-U^\dagger = Q_-$

$$a_{CP}^{\mathrm{T-odd}} \propto \sum_{m,n} Im(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \cos\delta_s \sin\phi_w$$

$$a_{CP}^{\mathrm{T-even}} \propto \sum_{m,n} Re(A_m^* A_n - \bar{A}_m^* \bar{A}_n) \propto \sin\delta_s \sin\phi_w$$

complimentary

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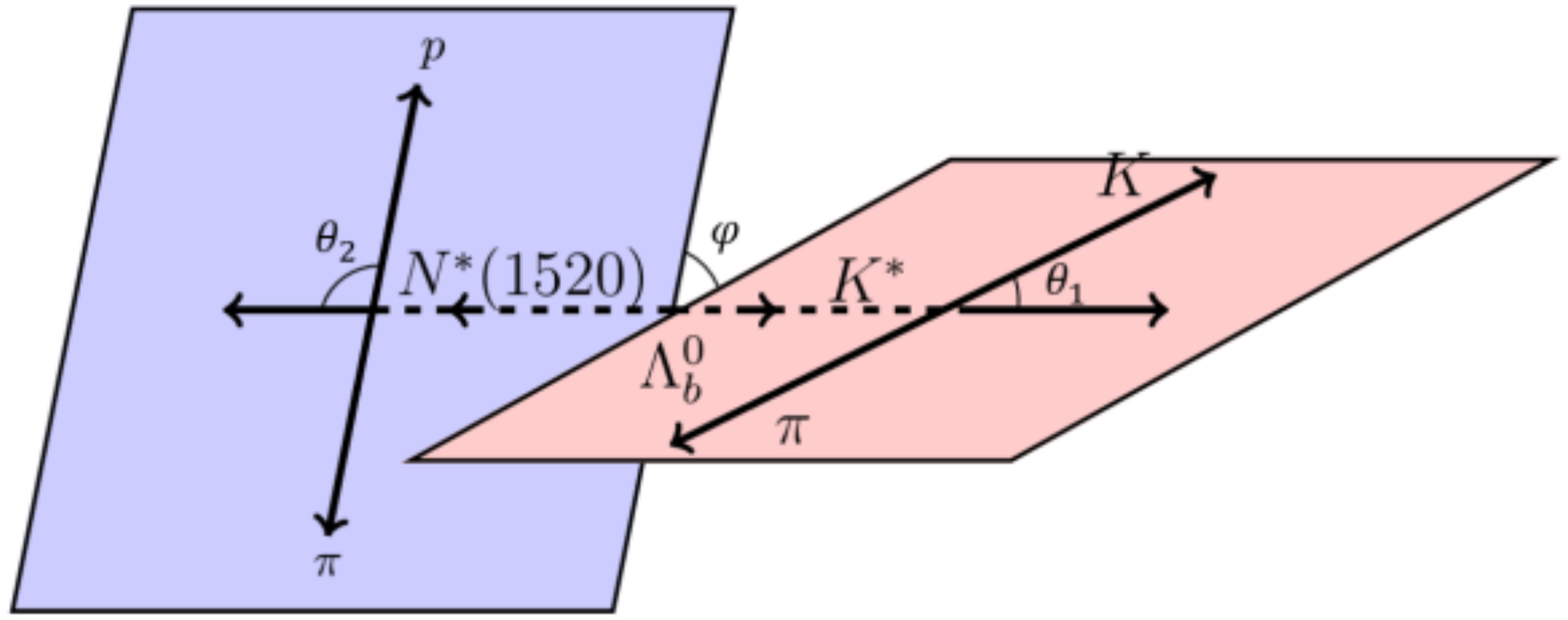
Angular distributions

$$\frac{d\Gamma}{dc_1\,dc_2\,d\varphi} \propto -\frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi$$
$$+\frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi$$
$$-\frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi$$
$$+\frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi$$



$$\sin\varphi = (\vec{n}_a \times \vec{n}_b)\cdot\hat{p}_b = \vec{n}_a\cdot(\vec{n}_b\times\hat{p}_b) \propto (\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_4$$

$$\sin 2\varphi = 2\sin\varphi\cos\varphi \propto [(\vec{p}_1\times\vec{p}_2)\cdot(\vec{p}_3\times\vec{p}_4)][(\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_4].$$

- Triple-product of momentum, $(\vec{p}_1\times\vec{p}_2)\cdot\vec{p}_3$, is not good. $\sin\varphi$ with $\sin\theta_1\cos\theta_1\sin\theta_2\cos\theta_2$
- Angular distributions of resonant contributions are necessary. It is more clear in theory.

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Suggestions for experiments

	$A_{CP}(\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-)$	$A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
LHCb Run 1 (3 fb^-1)	$(+4.4 \pm 2.6 \pm 0.6)\,\%$ LHCb, 1903.06792 $\times 1/3$	$(-0.10 \pm 0.08 \pm 0.03)\,\%$ LHCb, 1602.03160 $\times 1/3$
LHCb Run 2 (6 fb^-1)	$(+6 \pm 1)\,\%$??	$(-0.18 \pm 0.03 \pm 0.01)\,\%$ LHCb, 1903.08726

- Suggestion: measure CPV in $\Lambda_b^0 \to (p\pi^+\pi^-)K^-$. Global CPV is $+6\,\%$.
- LHCb precision reaches O(1%). It has a large possibility to observe baryon CPV very soon.