CP violation of baryon decays

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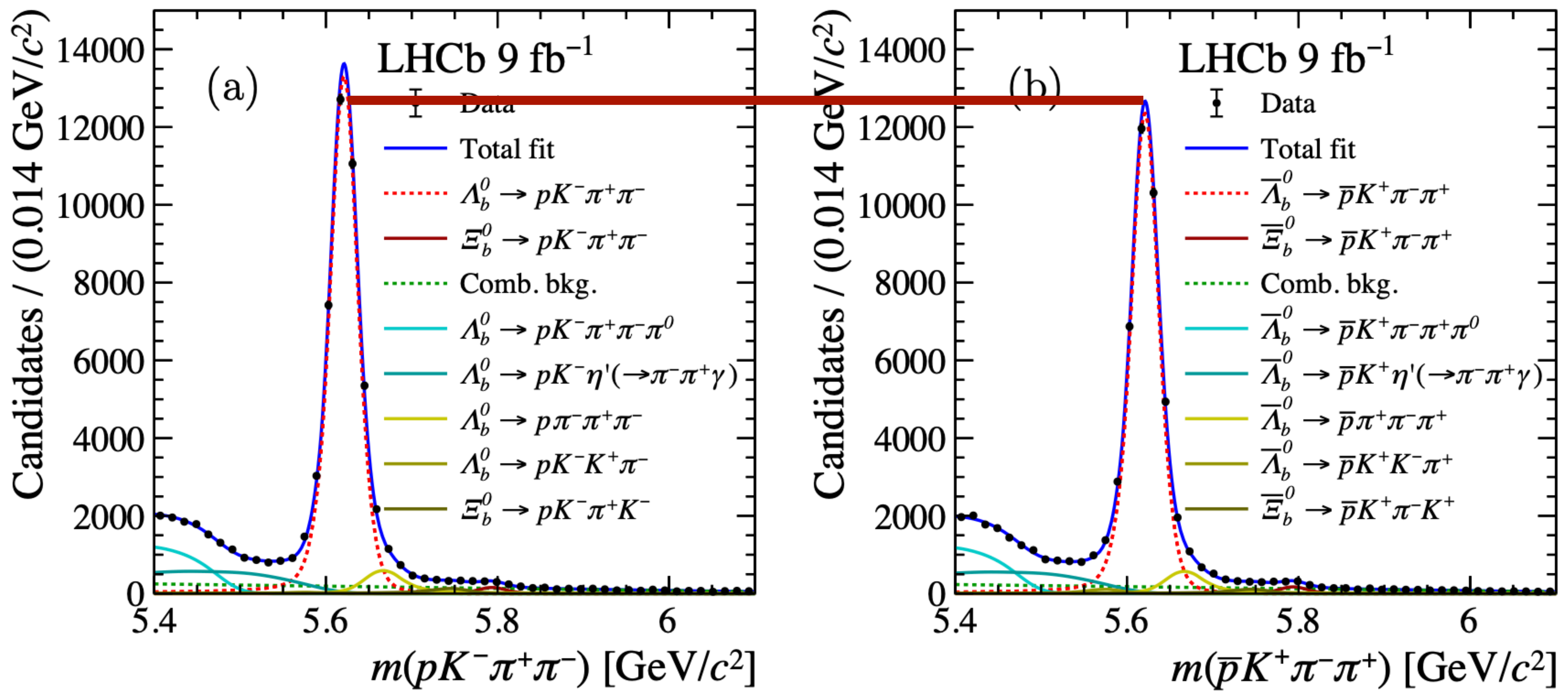
A new horizon in particle physics: First observation of baryon CP violation

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

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

5.2σ



LHCb, arXiv: 2503.16954, submitted to Nature

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, submitted to Nature

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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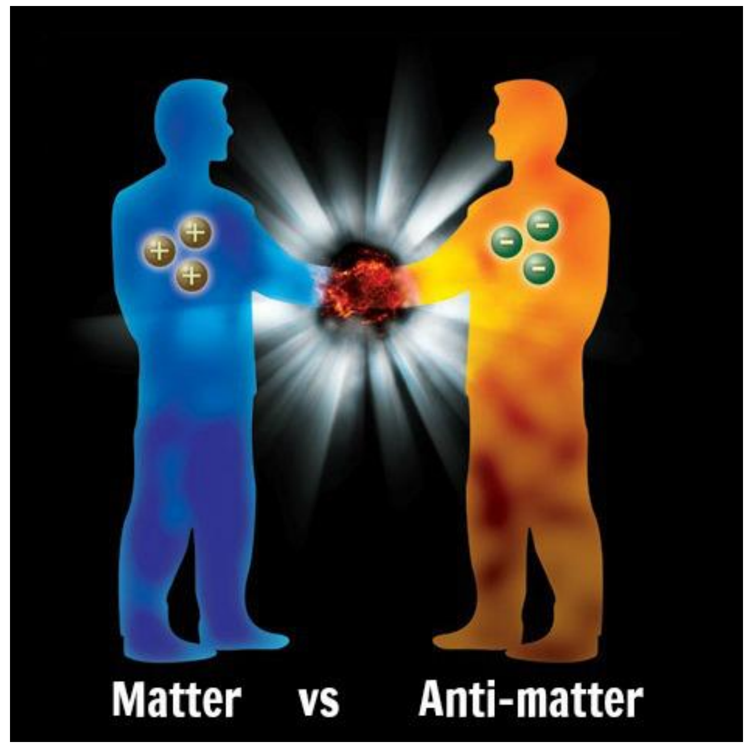
CP violation in baryons



- **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.**

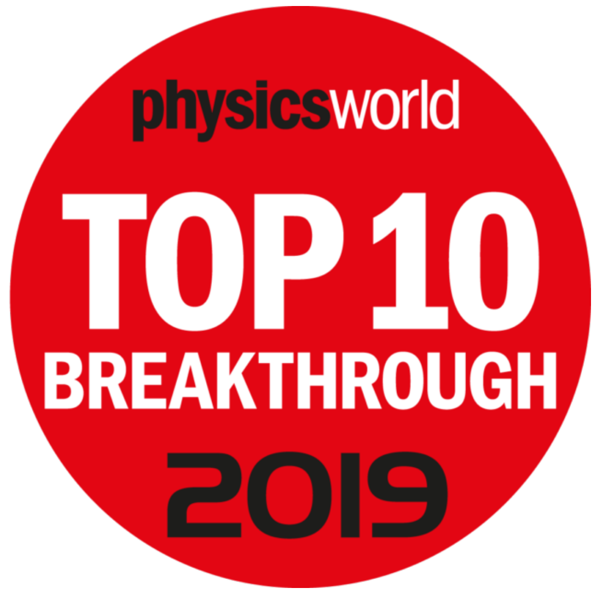
History of CP violation

- 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



- **CPV of baryons?**

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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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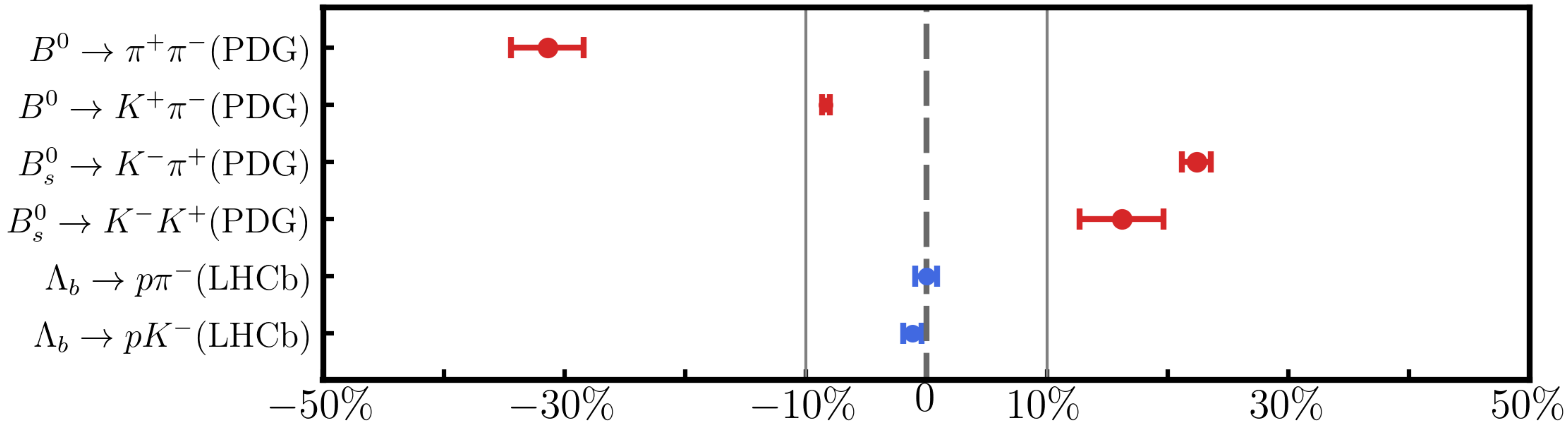
CPV of b-baryon

- 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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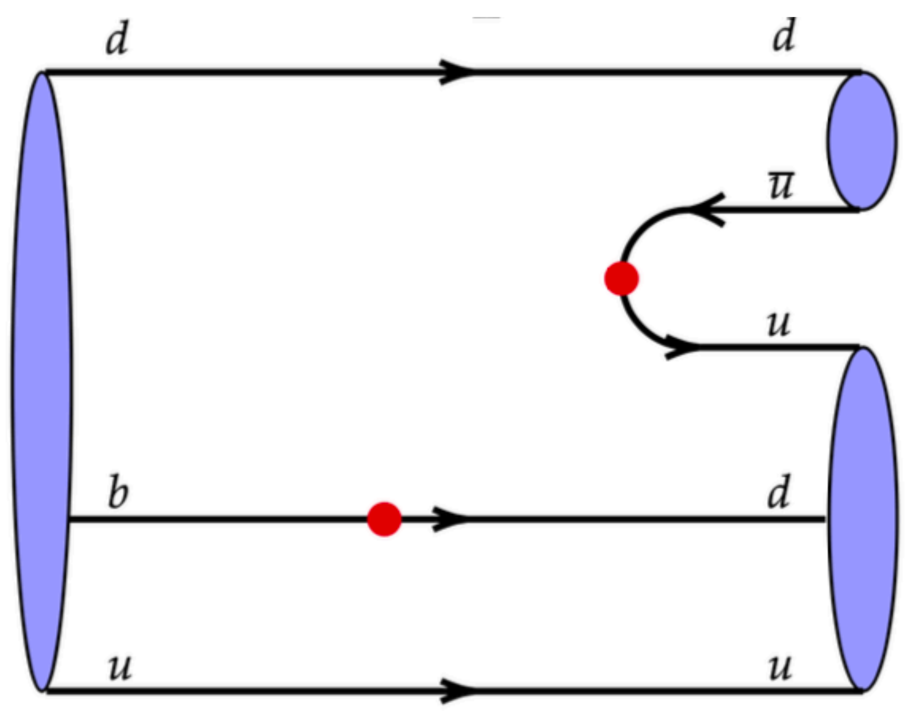
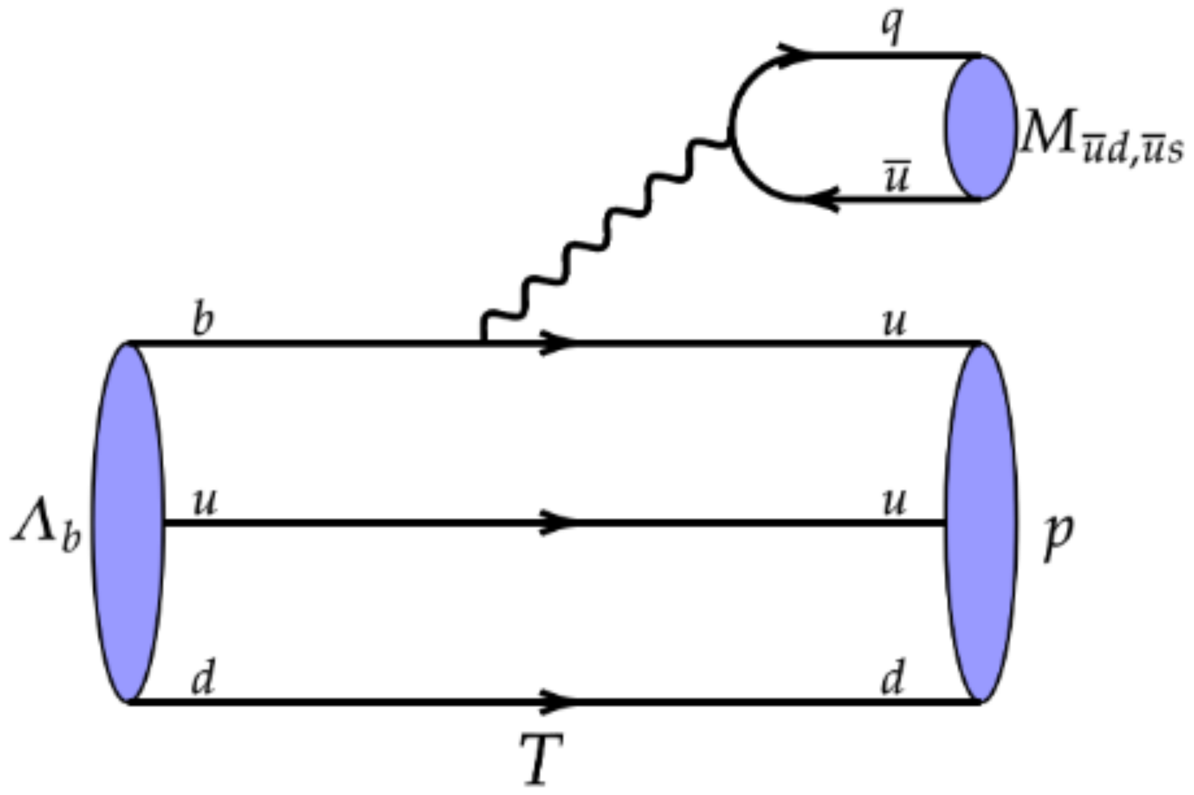
CPV cancelled between S- and P-waves

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

penguin: 

tree: 

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

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

$$S_{PC_2} \approx -P_{PC_2} \qquad\qquad S_{\mathcal{T}} \approx P_{\mathcal{T}}$$

- **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.**

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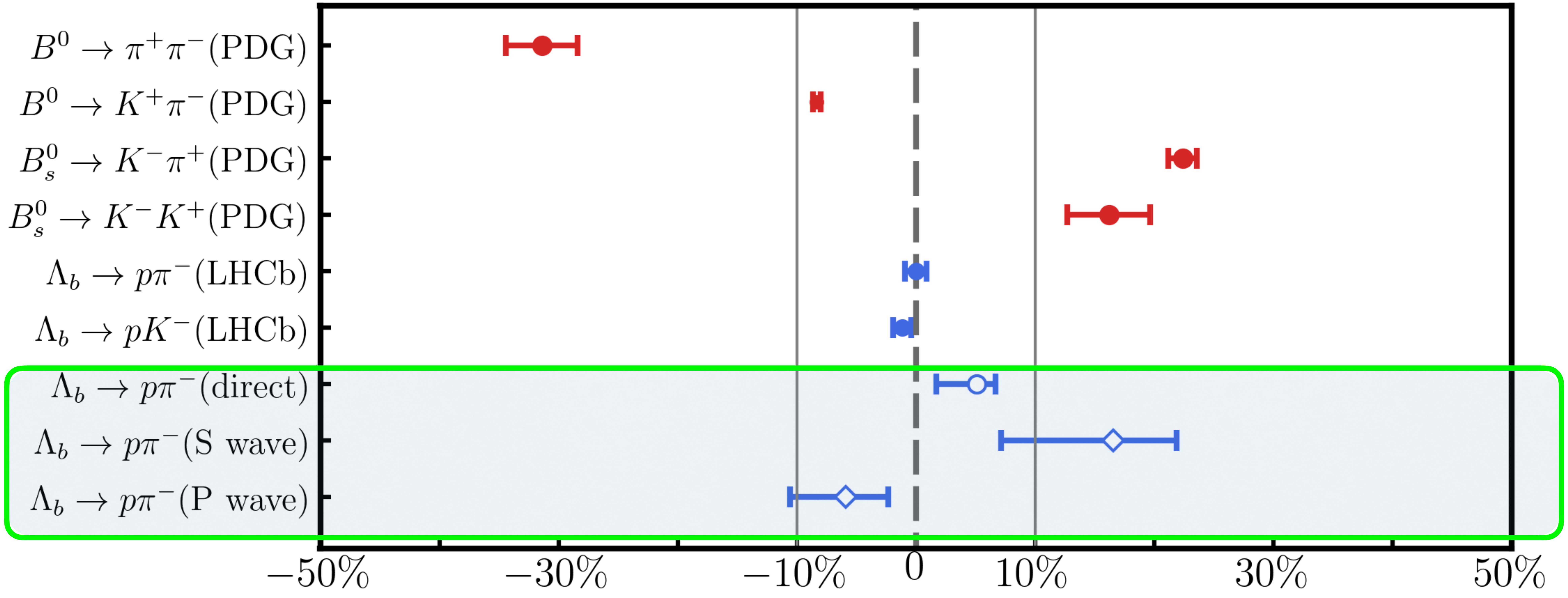
S- and P-wave CPV are large but cancelled



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

	$A_{CP}^{\rm dir}$	$A_{CP}^{S\text{-wave}}(\kappa_S)$	$A_{CP}^{P\text{-wave}}(\kappa_P)$	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%)	$0.04^{+0.03}_{-0.04}$	$-0.44^{+0.08}_{-0.04}$	$0.02^{+0.06}_{-0.05}$
	$A_{CP}^{\rm dir}$	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	$A_{CP}^{\mathcal{J}}$
$\Lambda_b \to p\rho^-$	$0.03^{+0.03}_{-0.05}$	$0.01^{+0.01}_{-0.04}$ (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%)	$0.02^{+0.04}_{-0.05}$
	$A_{CP}^{\rm dir}$	$A_{CP}^{S^T\text{-wave}}(\kappa_{S^T})$	$A_{CP}^{(D+S^L)\text{-wave}}(\kappa_{D+S^L})$	$A_{CP}^{P_1\text{-wave}}(\kappa_{P_1})$	$A_{CP}^{P_2\text{-wave}}(\kappa_{P_2})$	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

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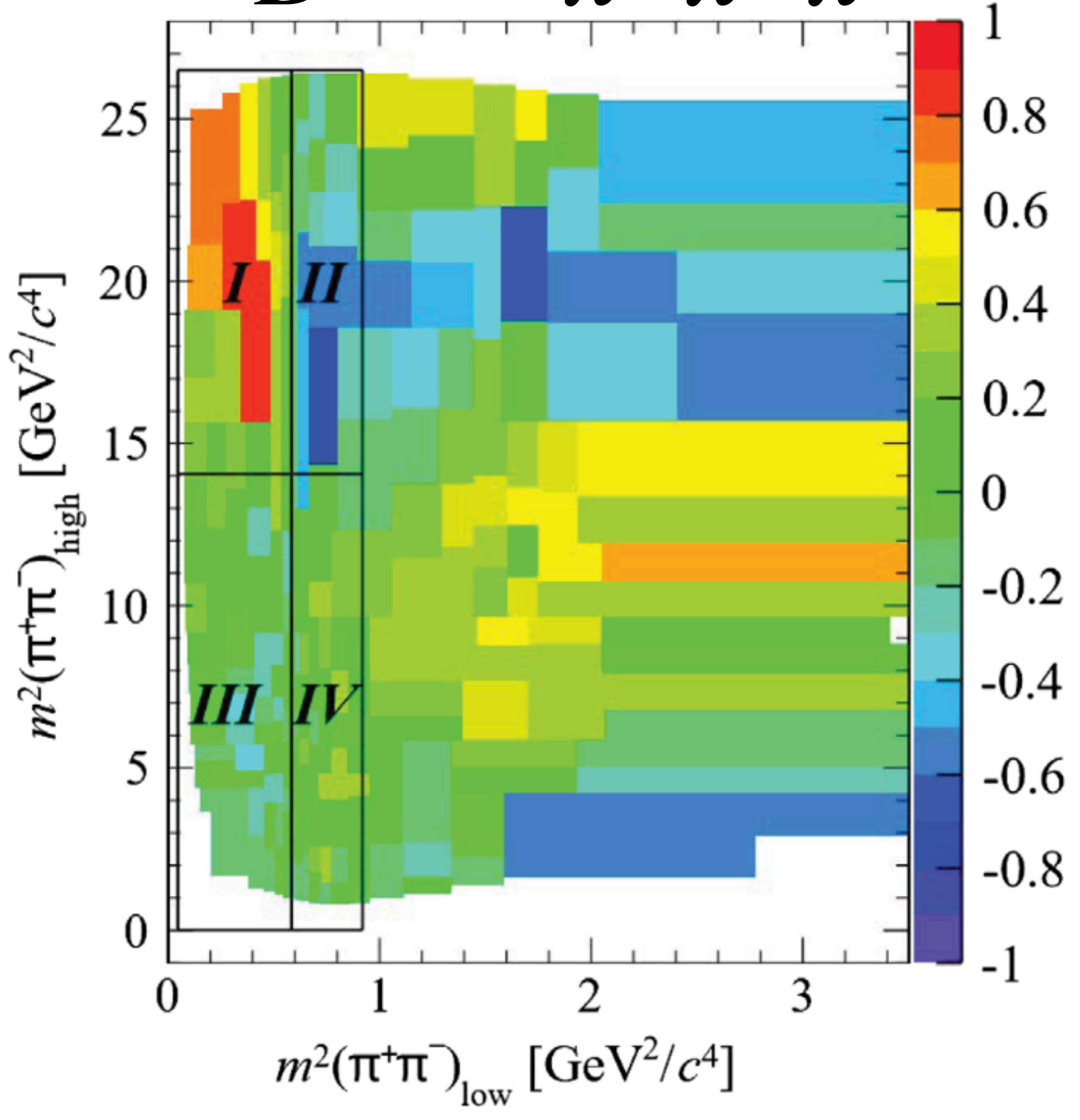
Multi-body decays

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

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

- Large regional CPV, such as S- & P-wave interference, $f_0(500) - \rho(770)$

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



- Large data samples in $\Lambda_b^0 \to p h^- h^+ h^-$, $h = \pi, K$

Multi-body decays of Λ_b

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

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

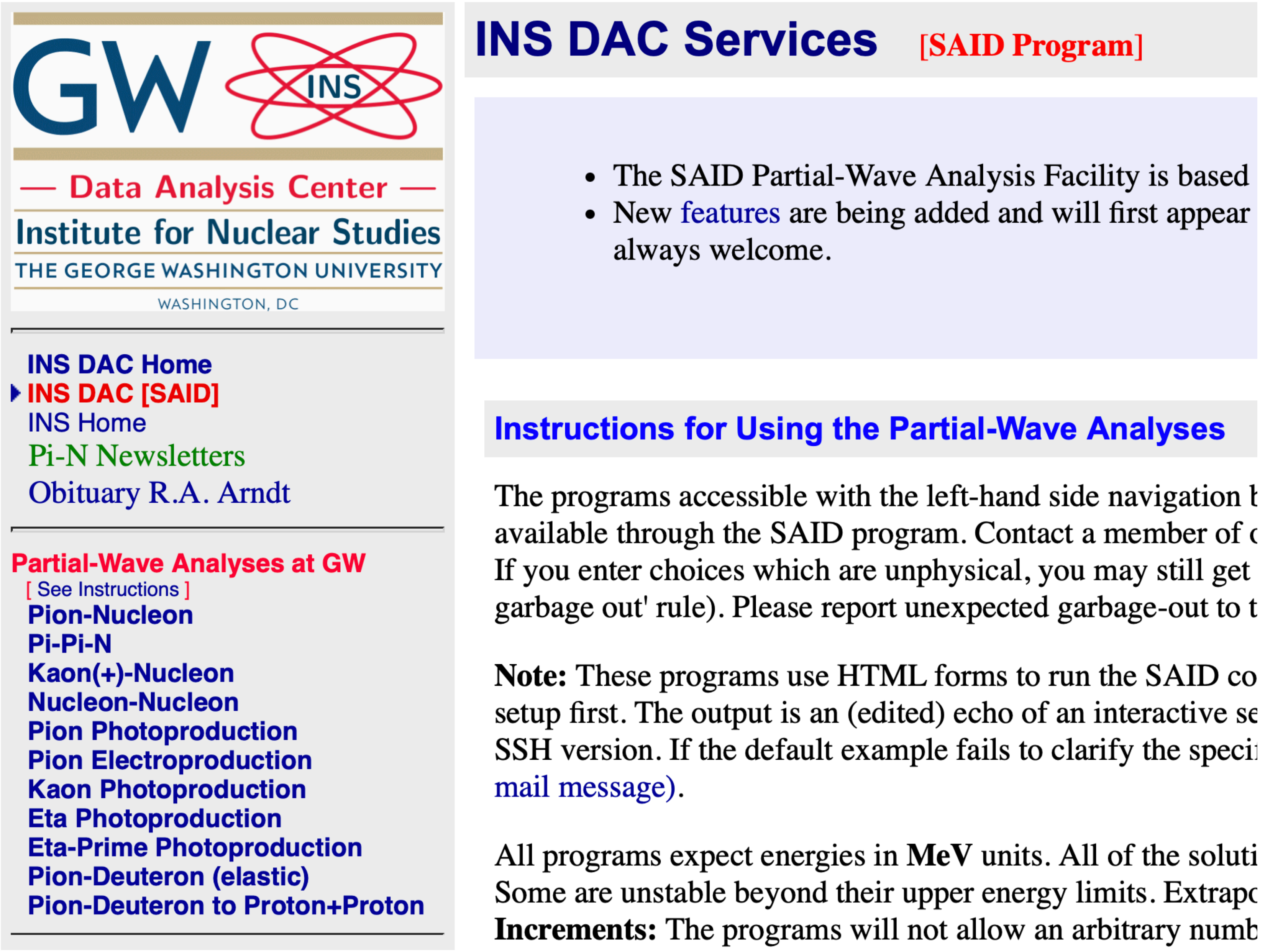
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 (≈ 1720) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 (≈ 200) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 (≈ 1710) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 (≈ 140) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 (≈ 1720) MeV
$N(1720)$ BREIT-WIGNER WIDTH	150 to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

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

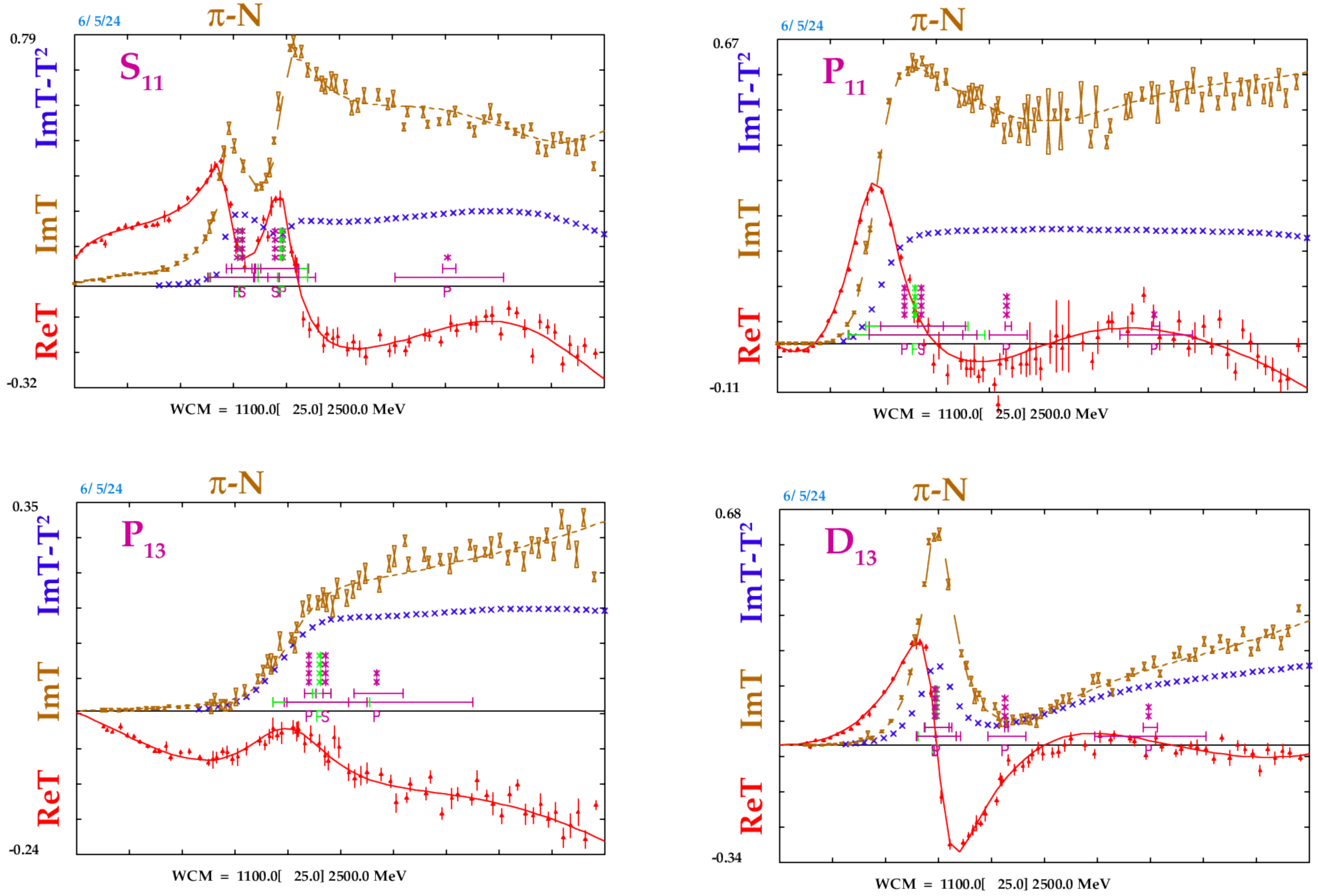
$N\pi$ scatterings

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

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



$N\pi \rightarrow N\pi$



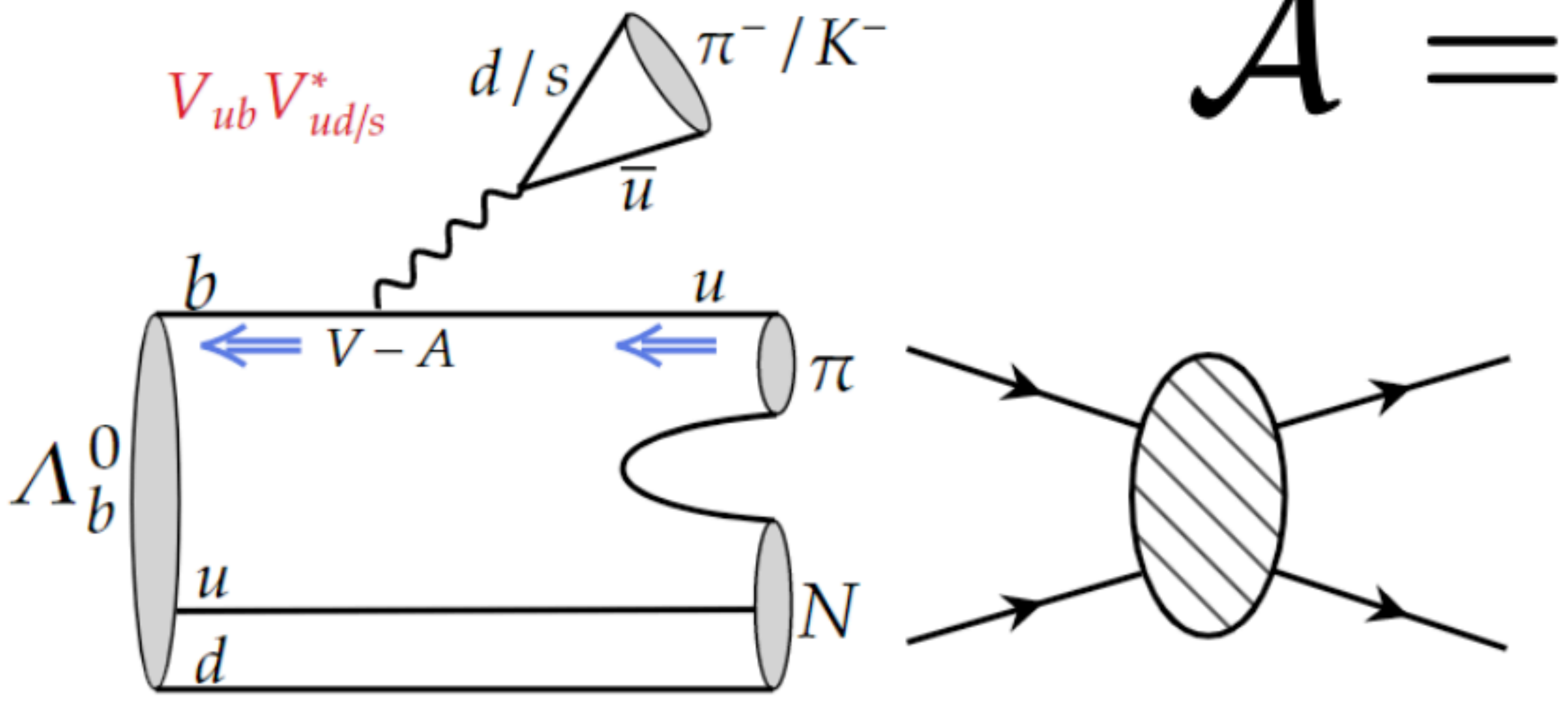
- Partial-wave amplitudes with strong phases!

- Data driven, **model independent**. Circumvent N*, more precise strong phases.

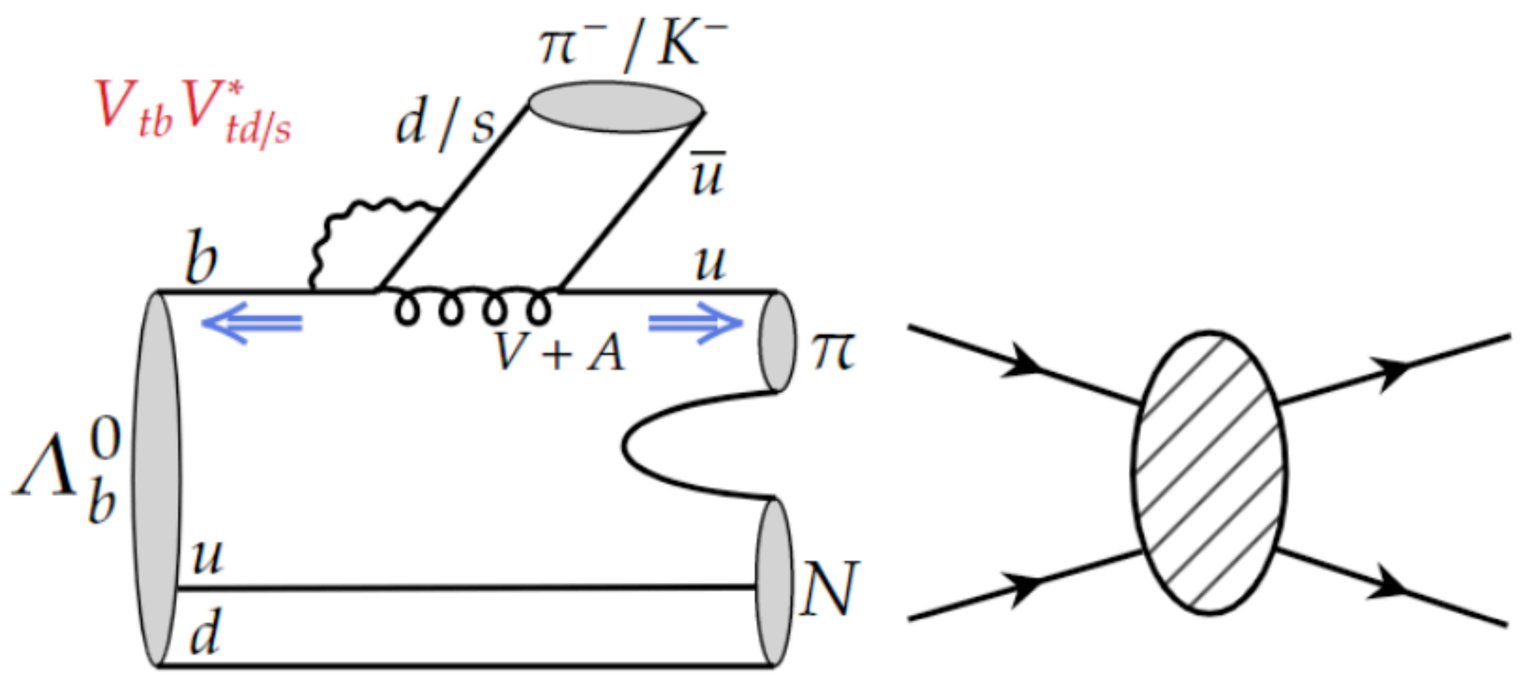
CPV via $N\pi$ rescatterings

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

•Tree:



•Penguin:



•Short-distance weak decays

•weak phases

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

•strong phases

- Different chirality

➡ different helicity

➡ different partial waves

➡ PWA interference

➡ difference of strong phases

➡ **CPV**

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CPV with $N\pi$ scatterings

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

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

decay processes	Scenarios	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$	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)

CPV with $N\pi$ scatterings

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

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	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%

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

LHCb: $(5.4 \pm 0.9 \pm 0.1)\,\%$

• LHCb: 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.

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%.

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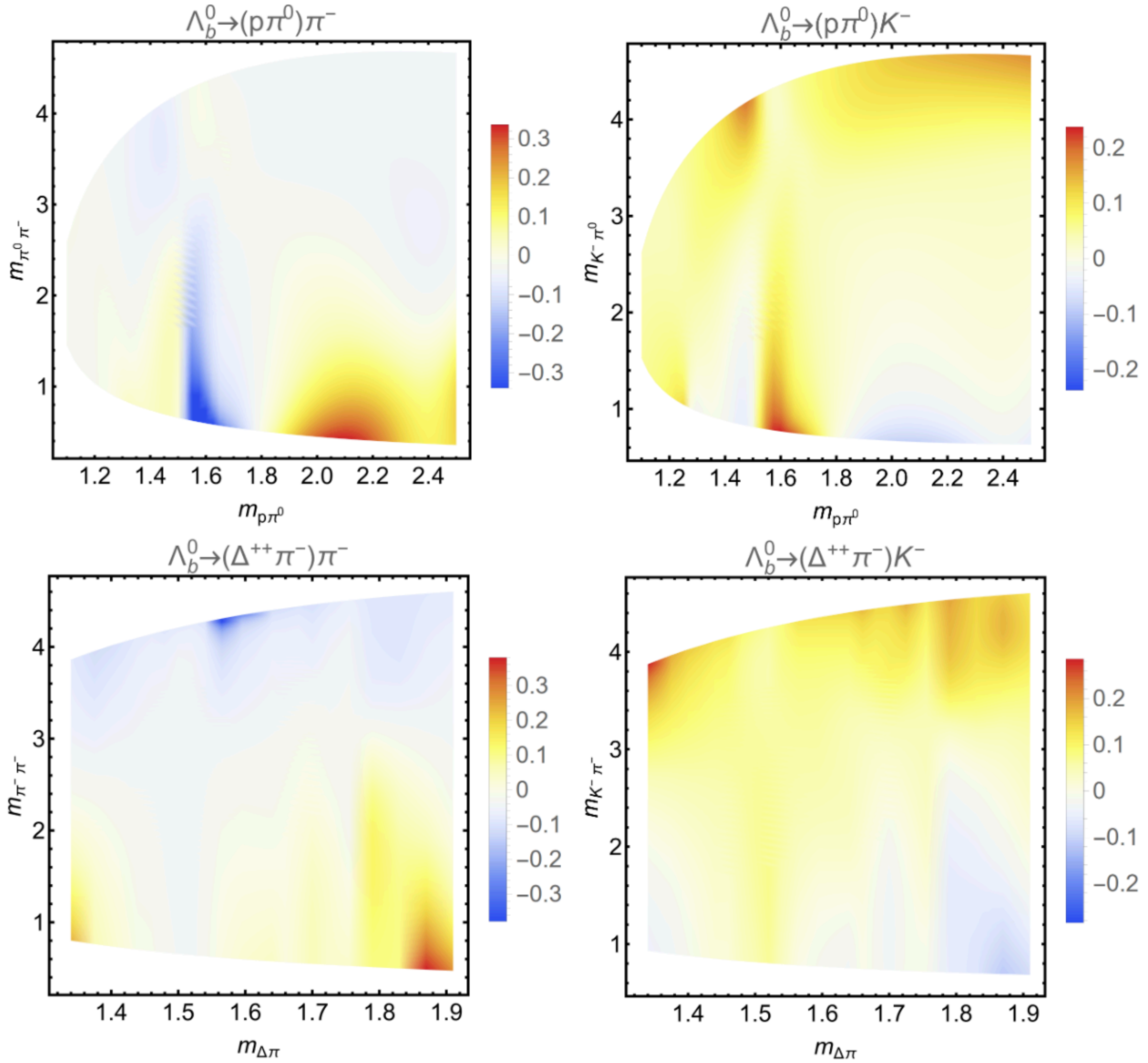
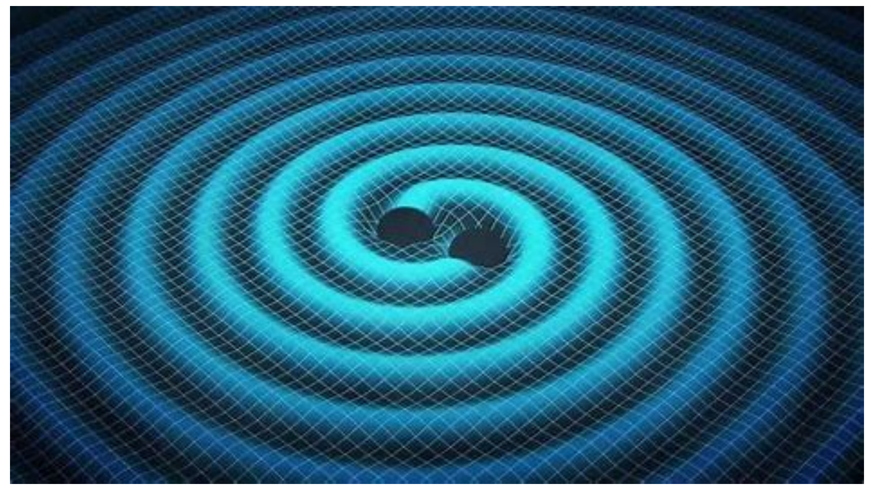


New horizon

•Observation of gravitational waves

=> not only confirm the General Relativity,

=> but also open the Multi-messenger era of cosmology.



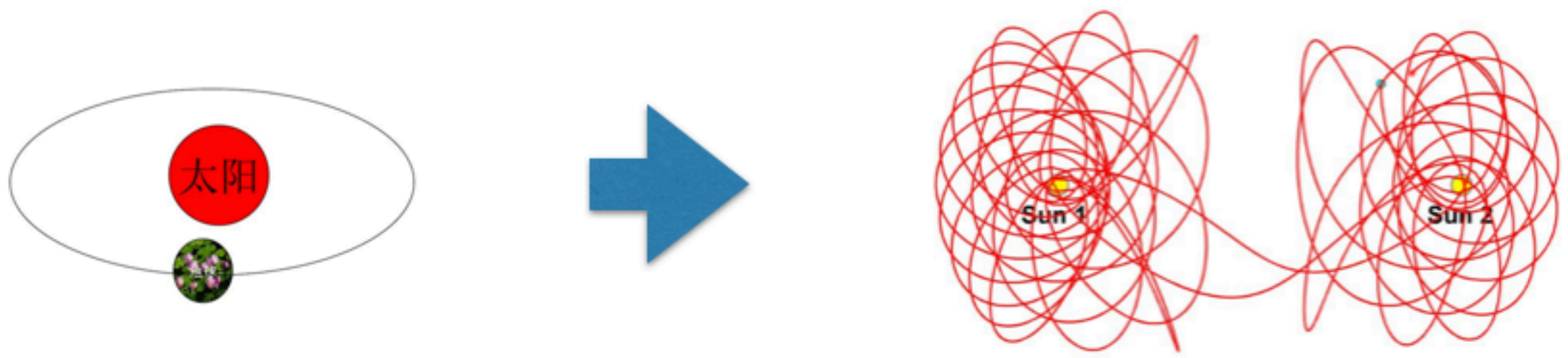
•Meson -> Baryon : More is different.

•New QCD dynamics: exclusive baryon.

•New challenges and opportunities.

2-body

3-body



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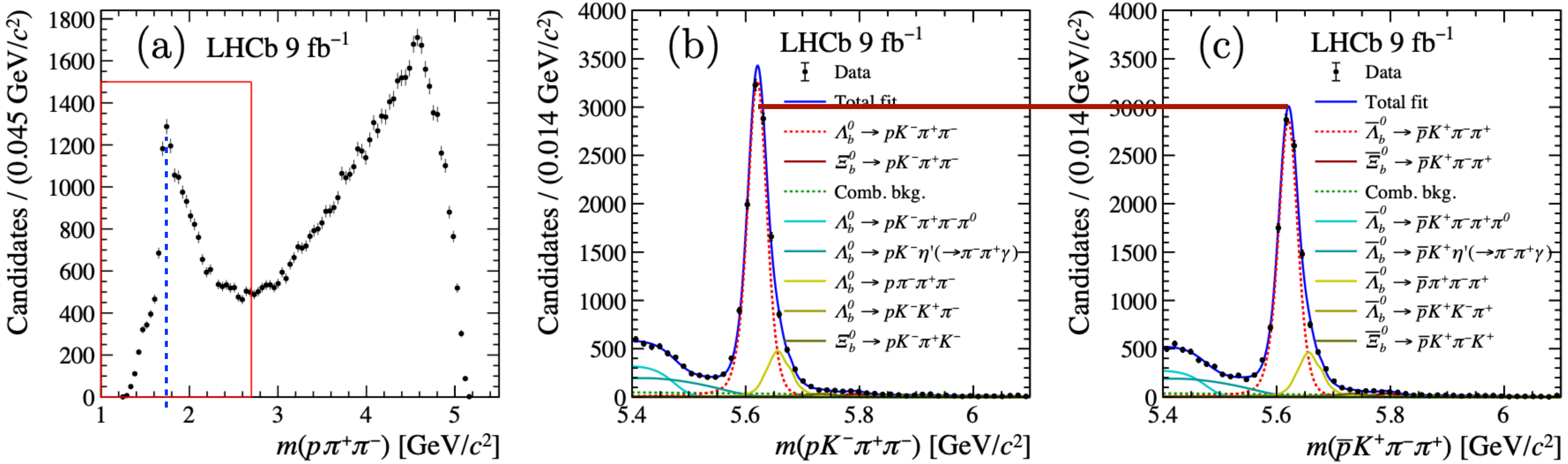
Summary

- 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.

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

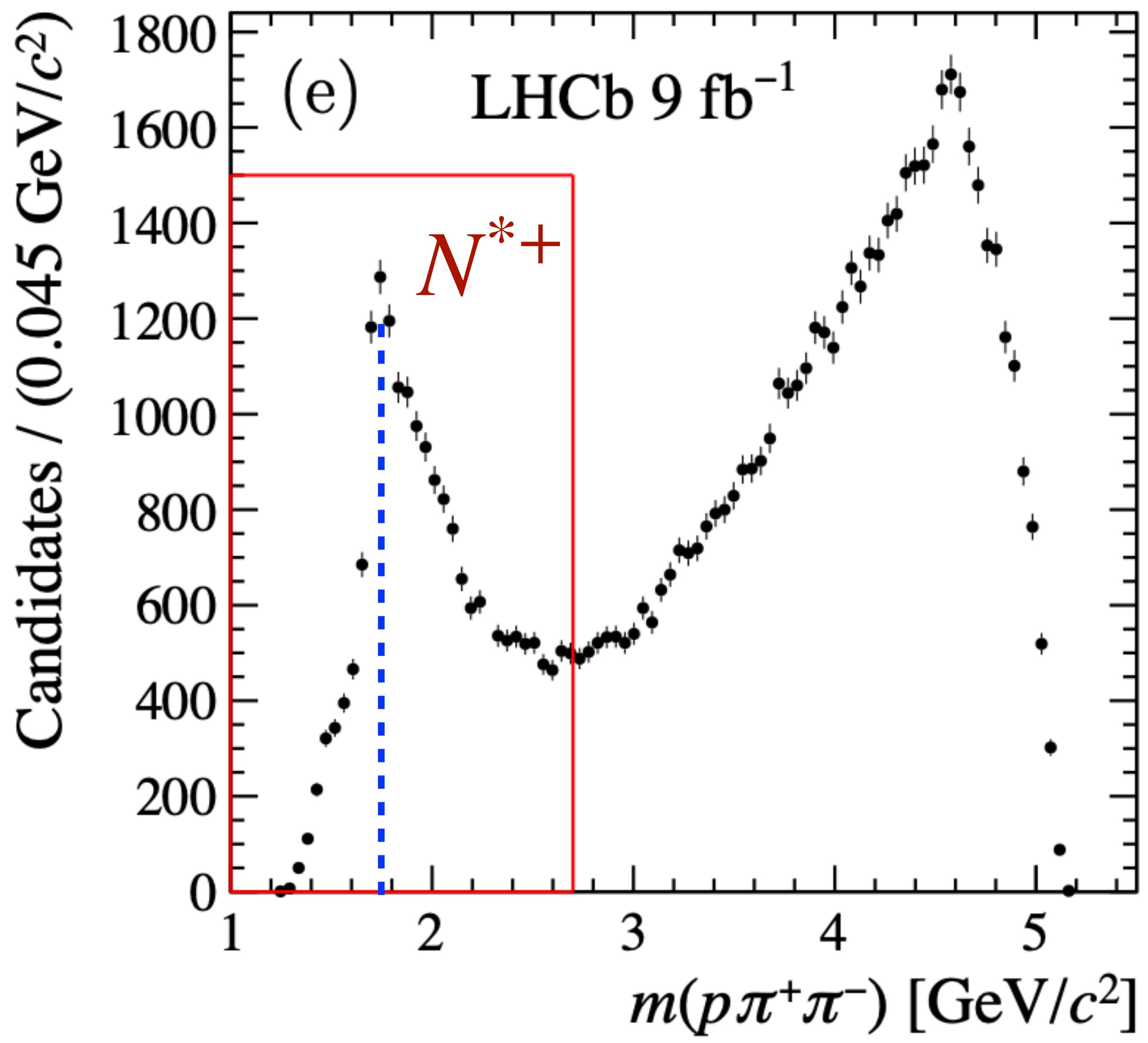


LHCb, arXiv: 2503.16954

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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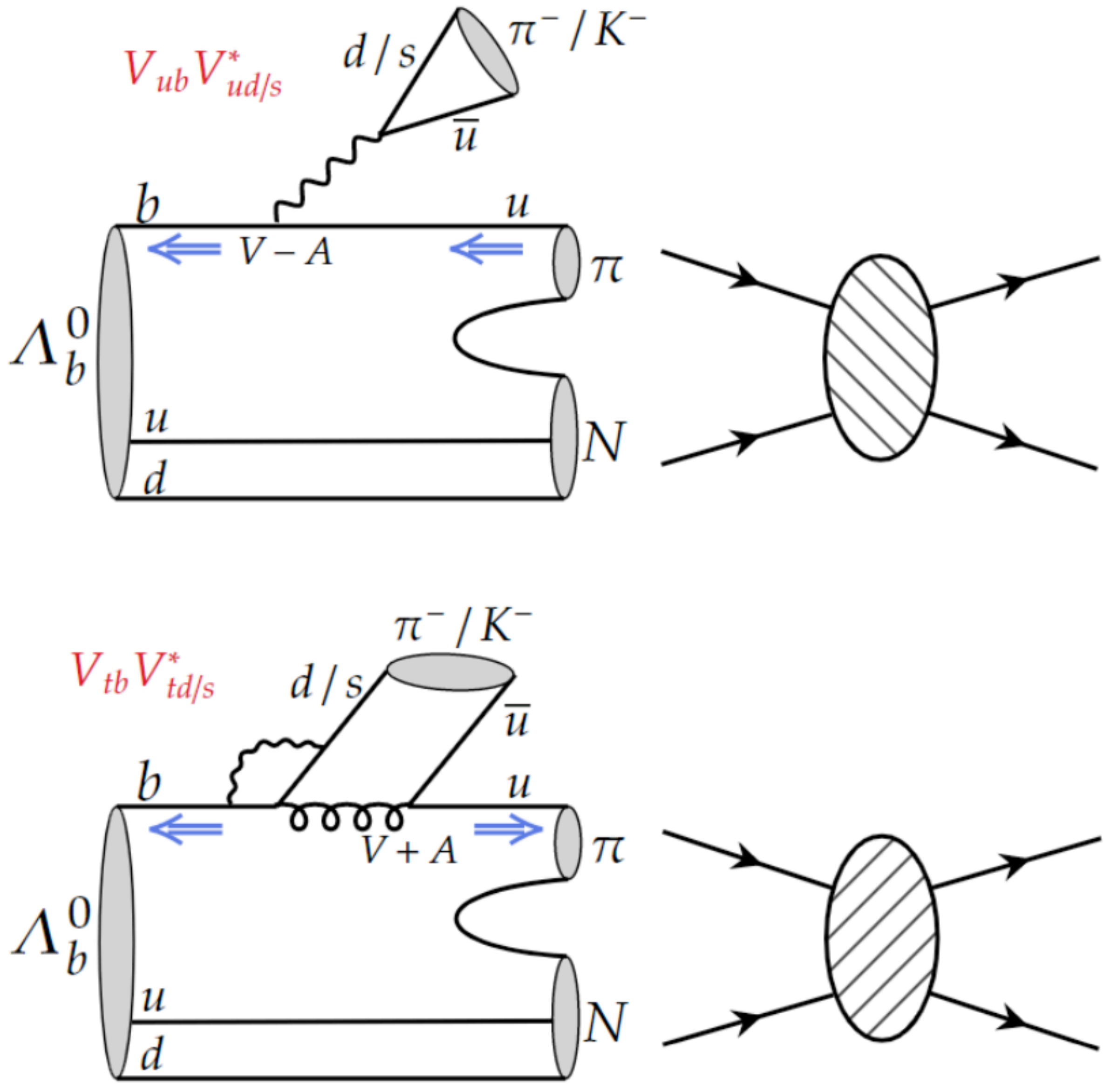
Theory

$(5.6 \sim 5.9)\ \%$



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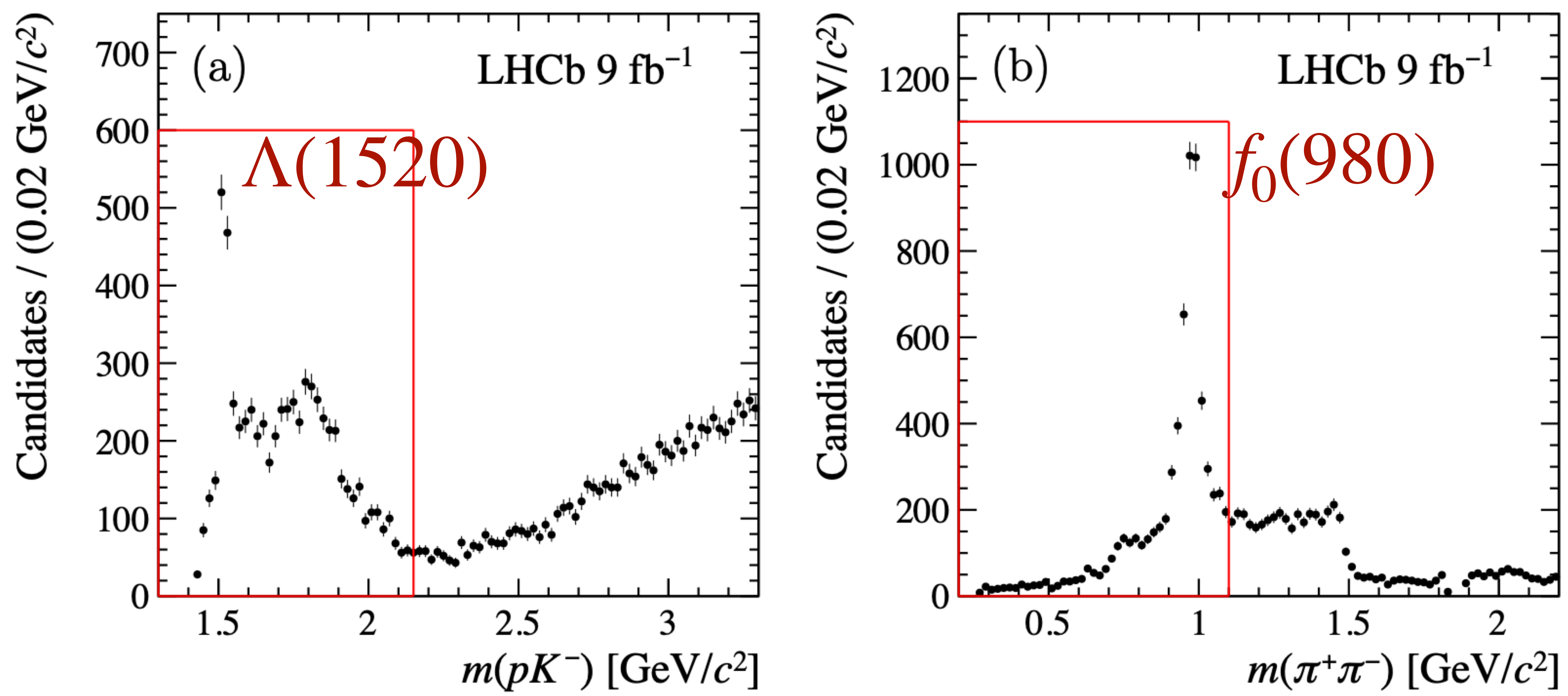
Region (2)

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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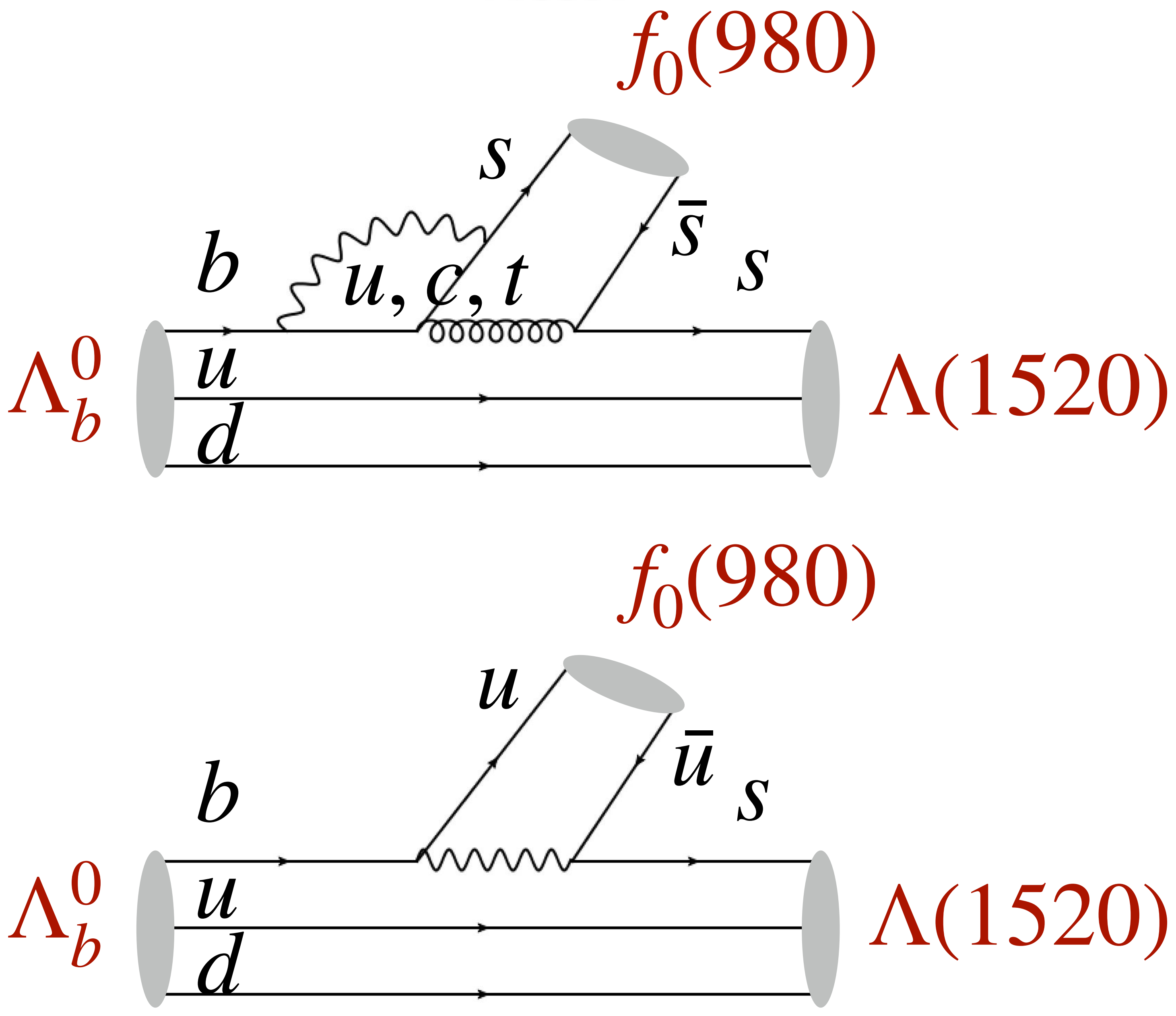
Theory

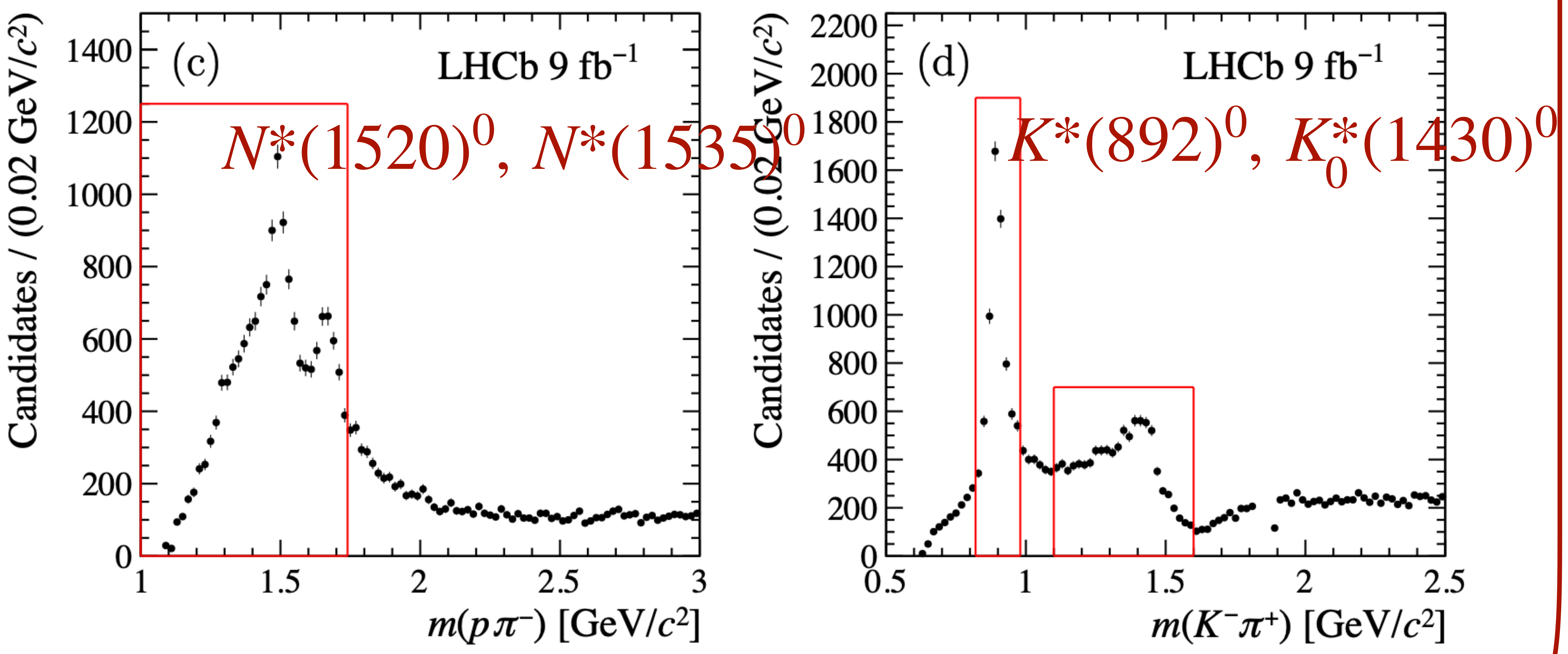
$$< 2\frac{a_2 |V_{ub}V_{us}^*|}{a_6 |V_{tb}V_{ts}^*|} \sim 4\,\%$$



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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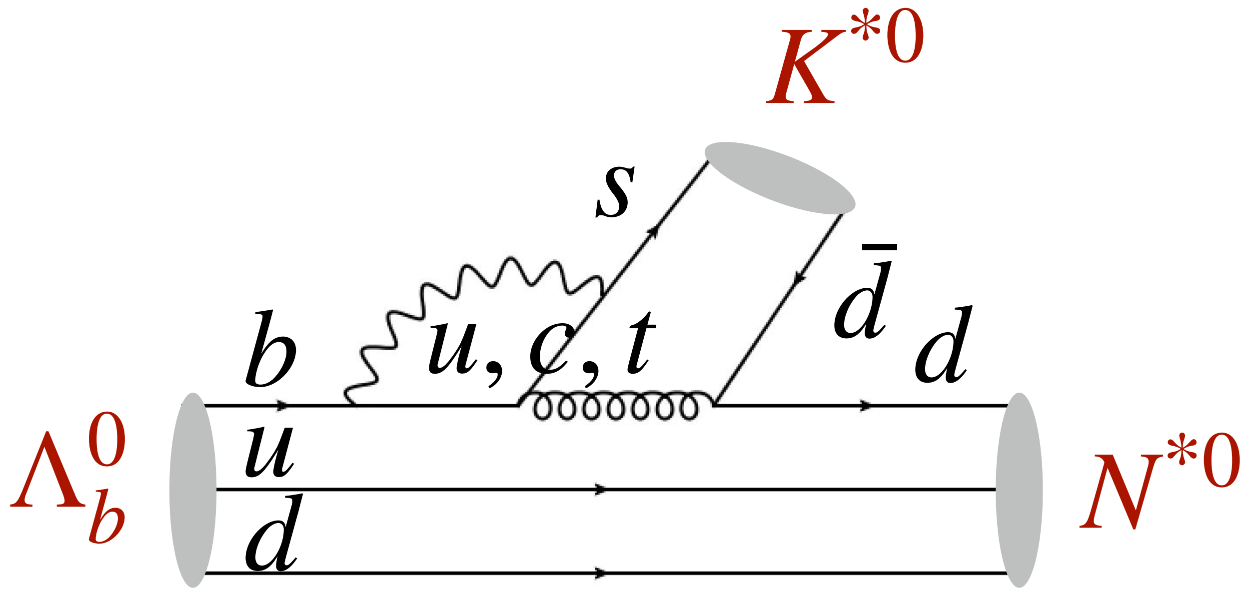
Theory

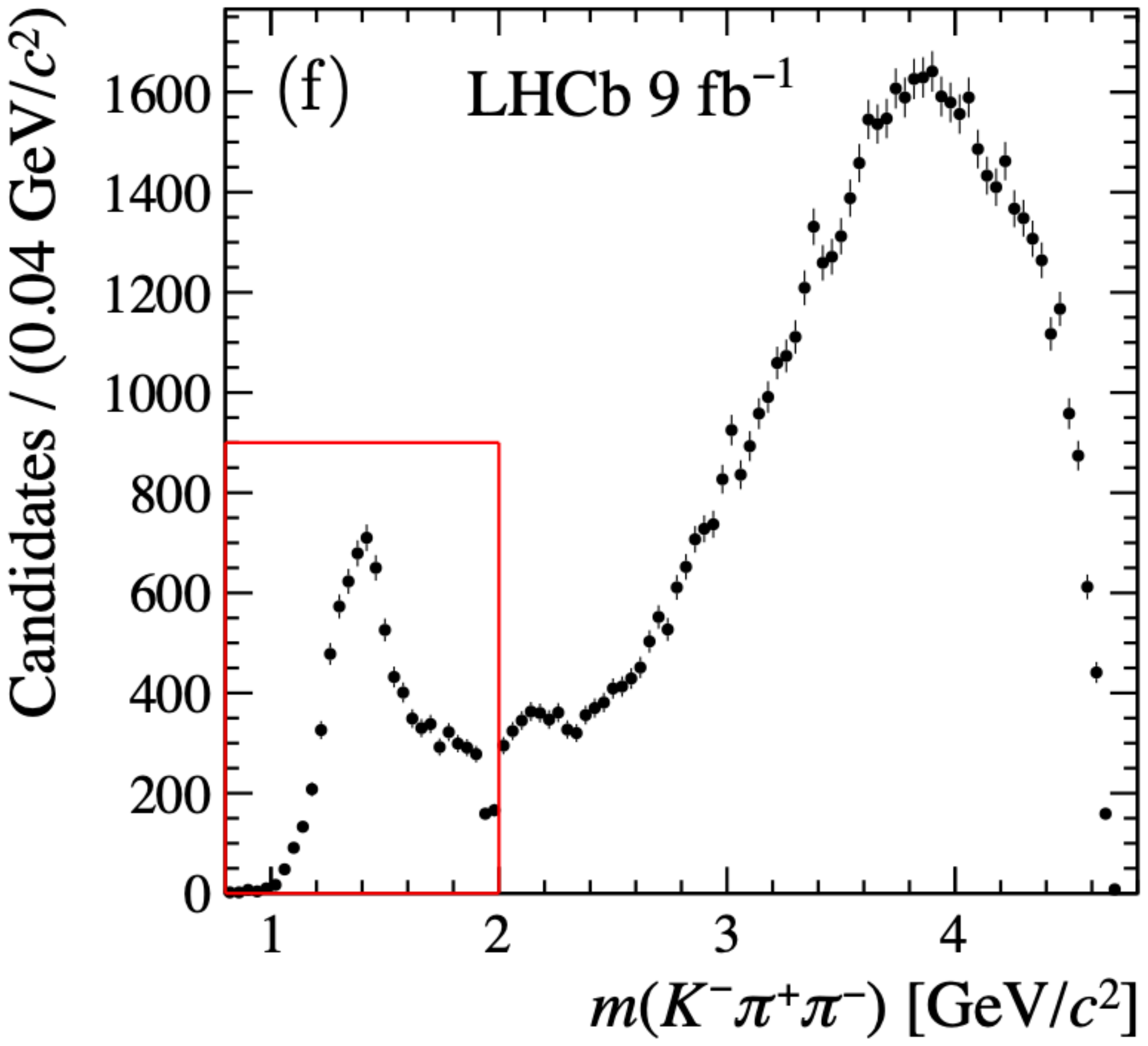
$$< 2\frac{|V_{ub}V_{us}^*|}{|V_{tb}V_{ts}^*|} \sim 2\,\%$$



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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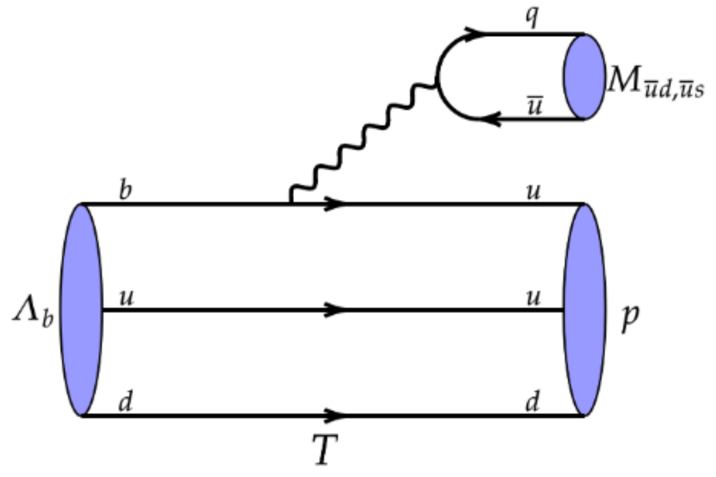
Theory

Partial-wave CPV destruction



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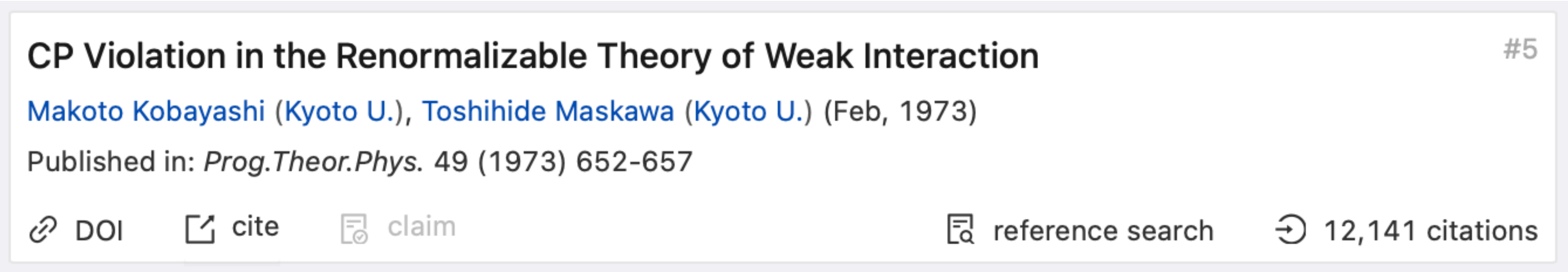
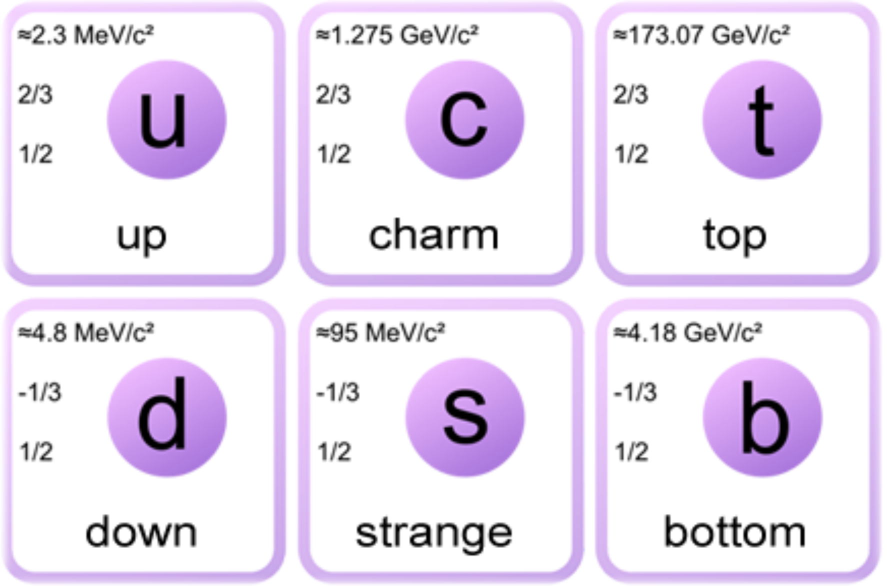
Introduction on CP violation

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

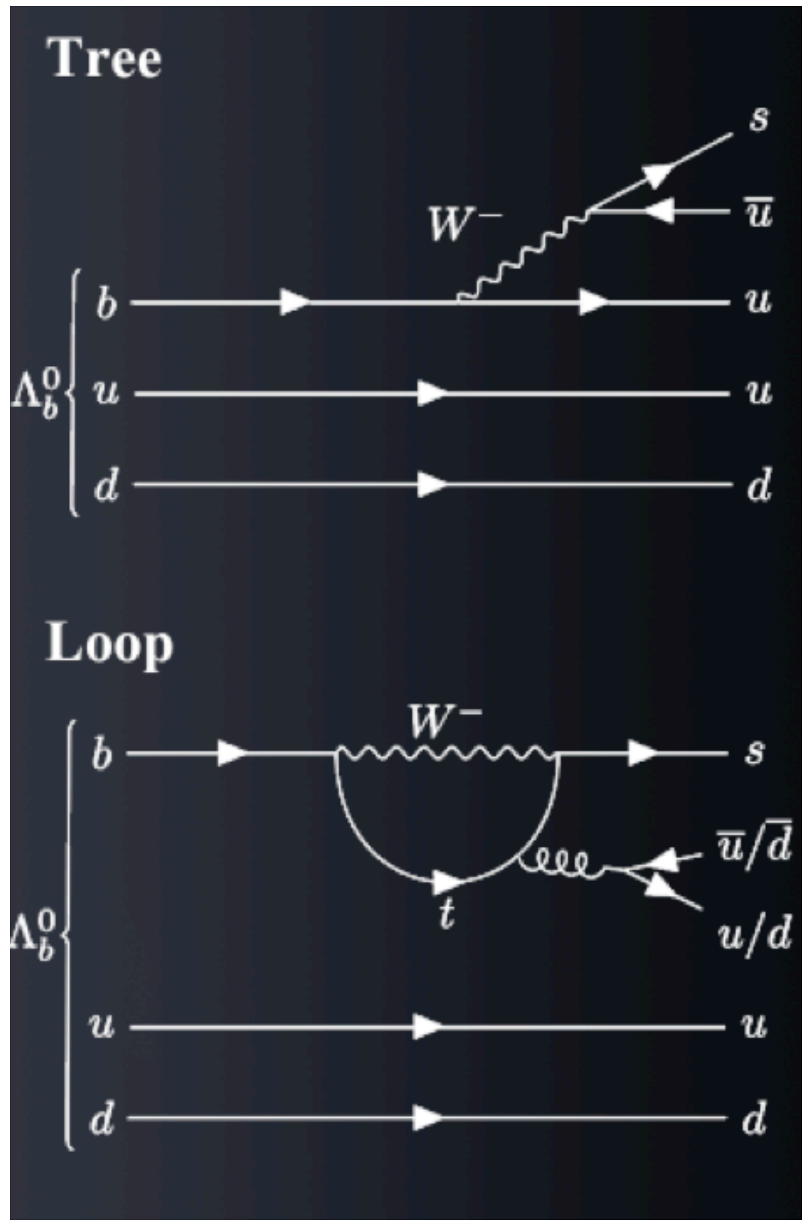
$V_{\text{CKM}} \leftrightarrow V^*_{\text{CKM}}$

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

$\phi_{1,2}$: 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: $O(10^{-4}) \sim O(10^{-5})$

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

  -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: $O(10\%)$

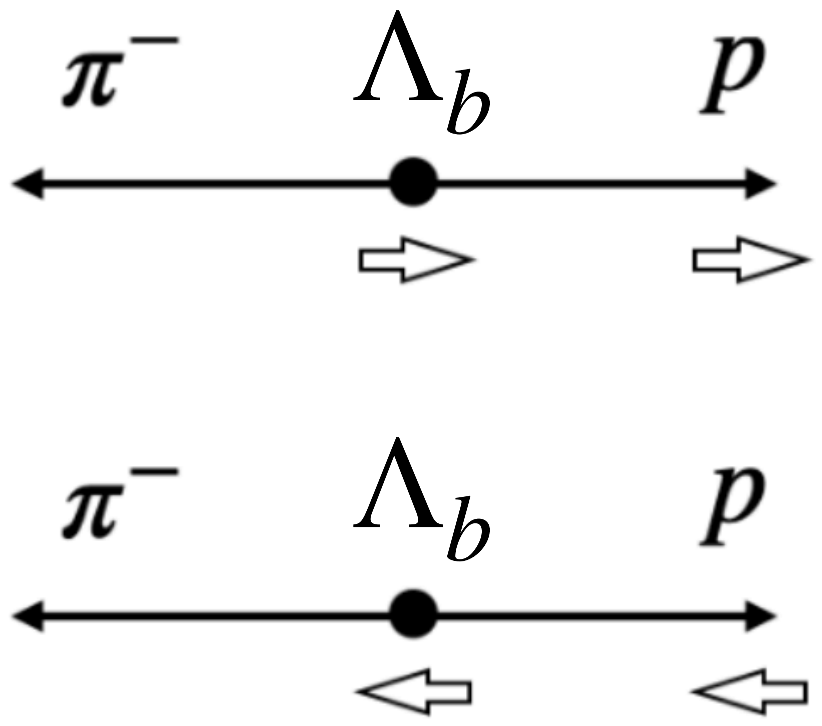
  -LHCb reported 3σ evidence of CPV in $\Lambda_b \to p\pi\pi\pi$ [Nature Physics 2017]

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

More is different

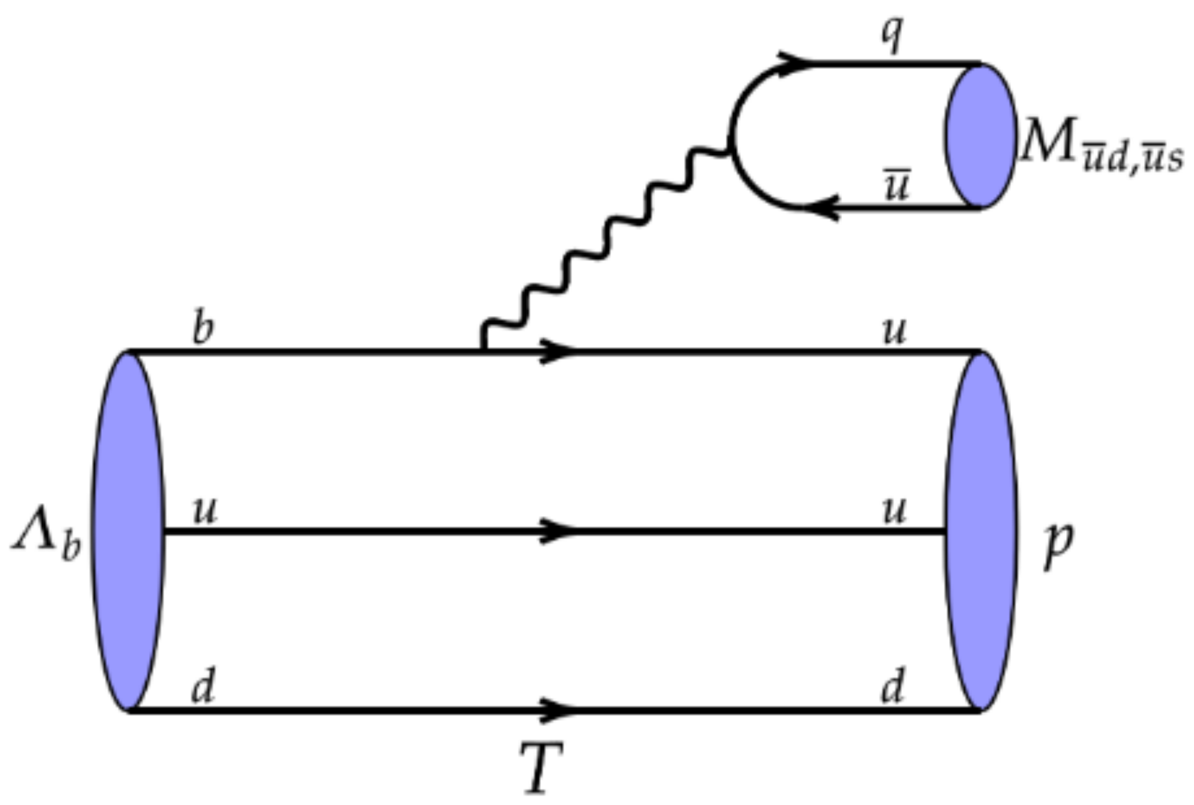
- **Baryons are very different from mesons!!**
  - **Non-zero spin**, more information from polarizations and partial waves

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



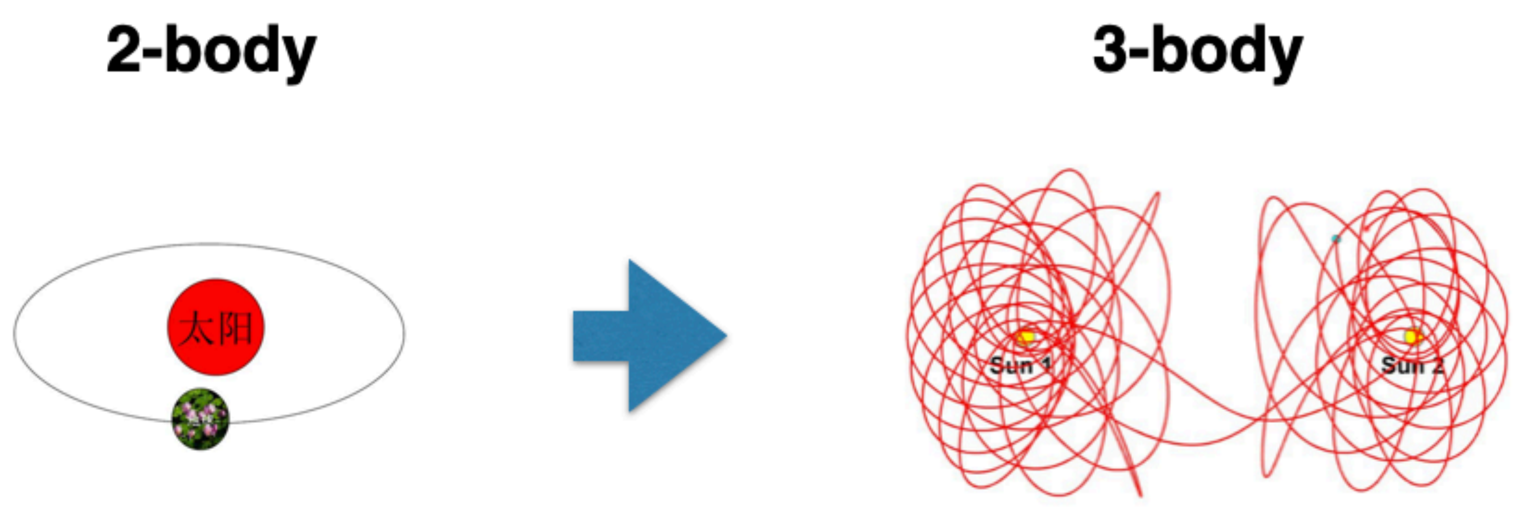
$$\mathcal{H}_{\lambda_\Lambda=+\frac{1}{2},\lambda_p=+\frac{1}{2}} = \frac{1}{\sqrt{2}}(S+P),$$

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

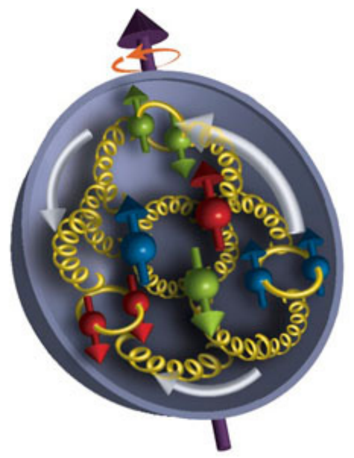


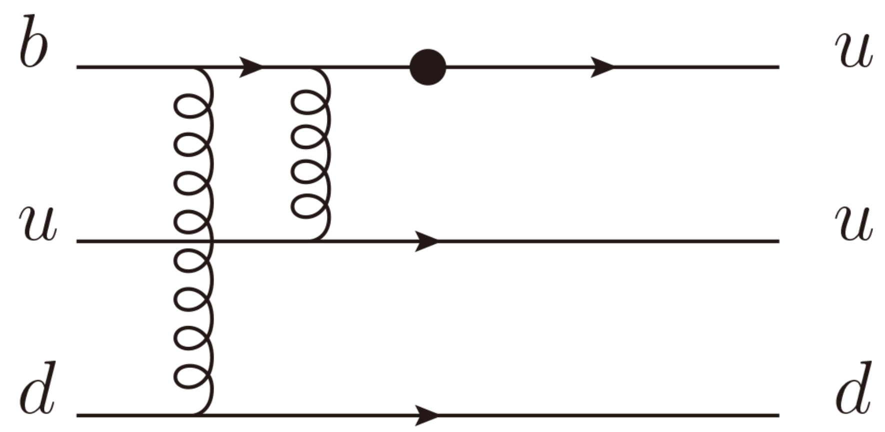
Fu-Sheng Yu

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]

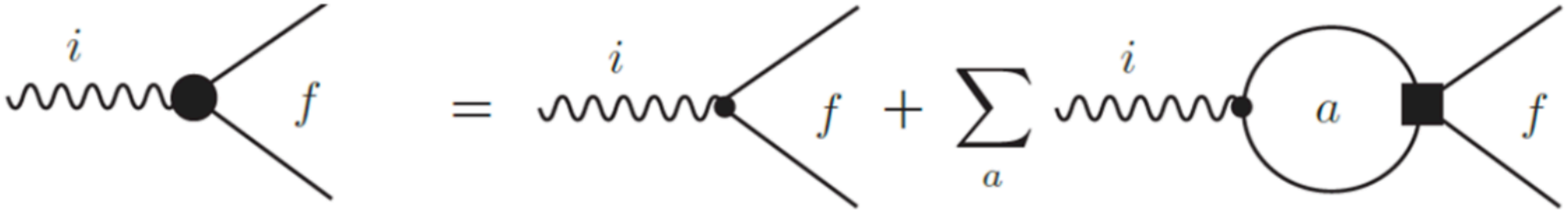
Final-state rescatterings

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

Long-time long-distance strong interaction

Short-time short-distance weak interaction

$$\langle f|\mathcal{H}_W|i\rangle = \sum_a \langle f|a\rangle\langle a|\mathcal{H}_W|i\rangle$$

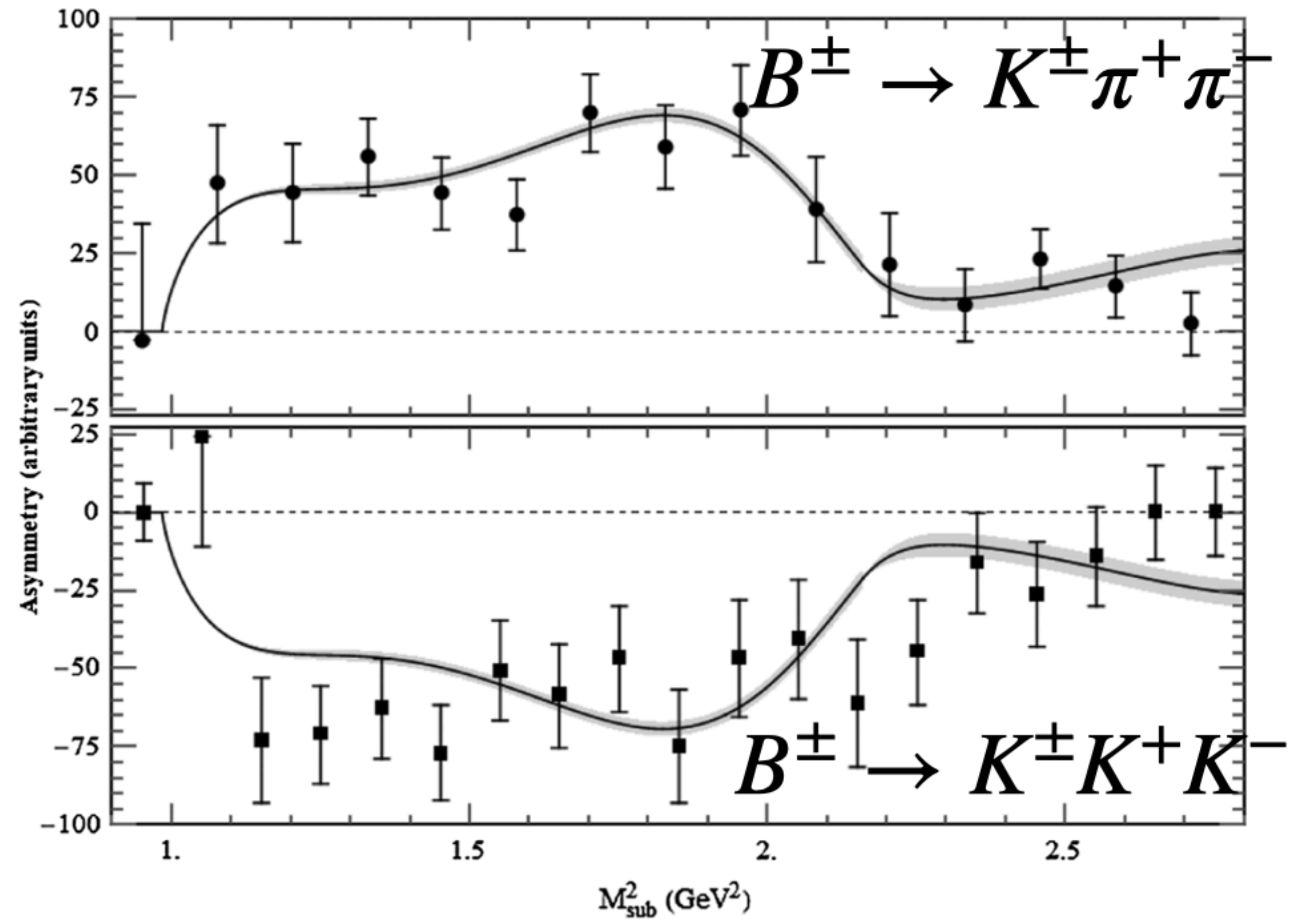


L. Wolfenstein, Phys. Rev. D 43, 151 (1991).

- Extensively studied in heavy flavor physics

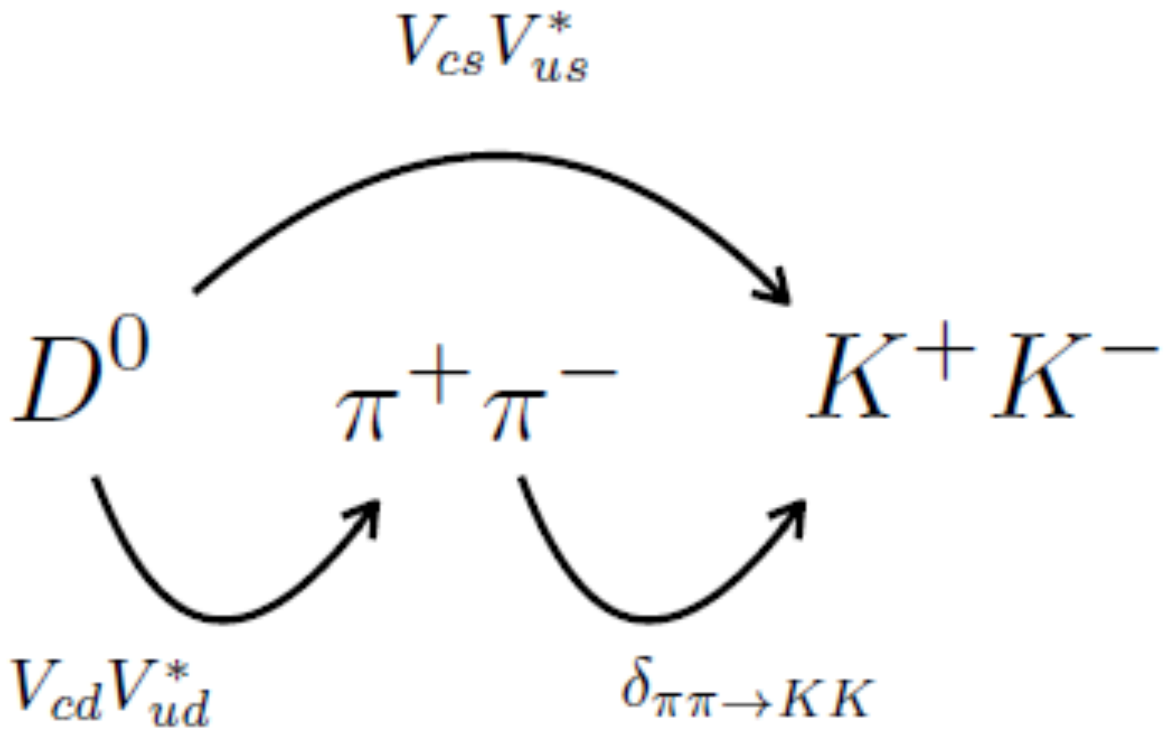
Rescatterings: Data driven

- 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].



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

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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

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

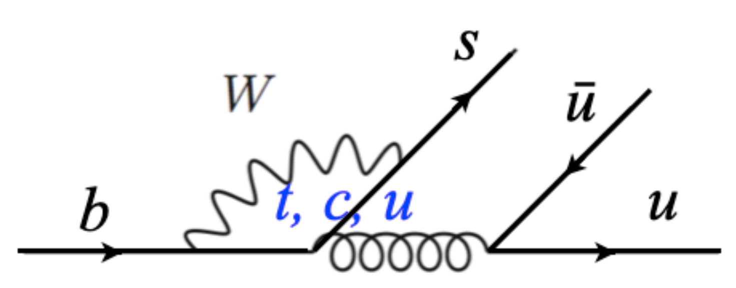
- Penguin

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

- 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** !! $\frac{f_{\Lambda_b}}{f_{u,d}} \sim 0.5 \longrightarrow \frac{N_{\Lambda_b}}{N_{\overset{(-)}{B^0}}} \sim 0.5$

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

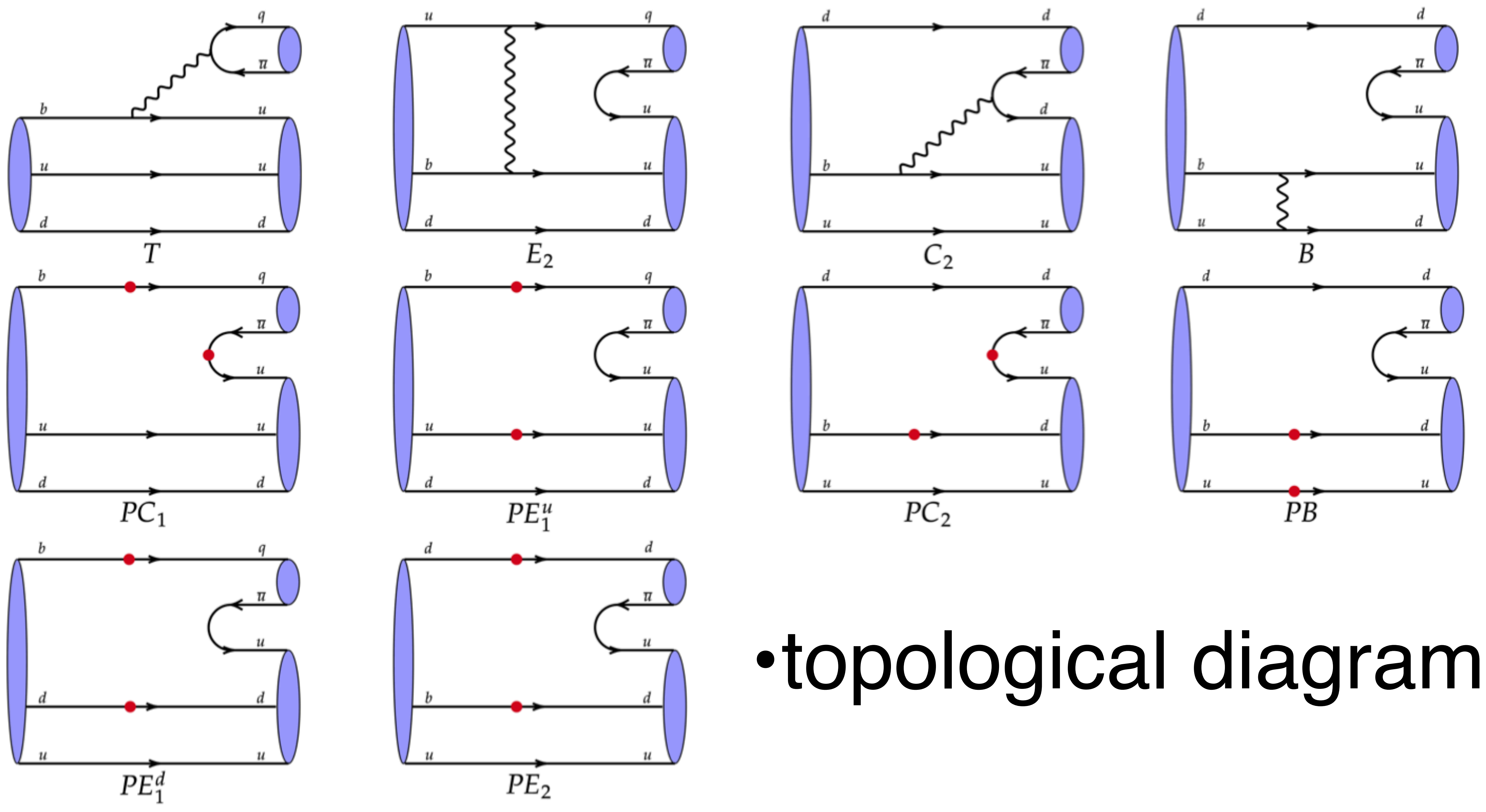
- **Questions: 1. Why not yet observed for baryon CPV ? What dynamics ?**
  2. What processes to observe baryon CPV ?

Theoretical approach for dynamics

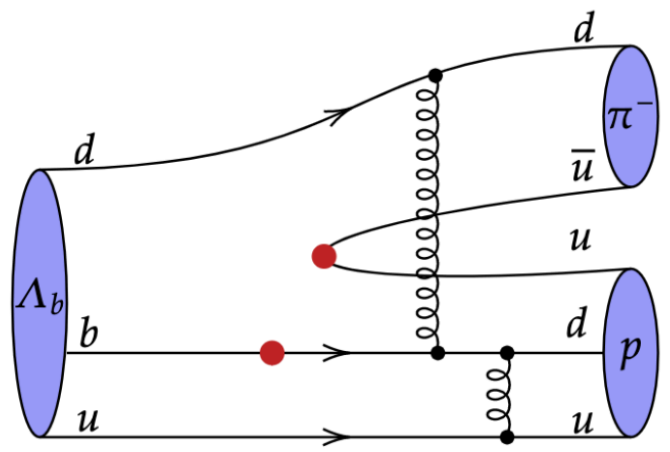
- The above crude argument needs to be justified by comprehensive QCD calculations

- 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

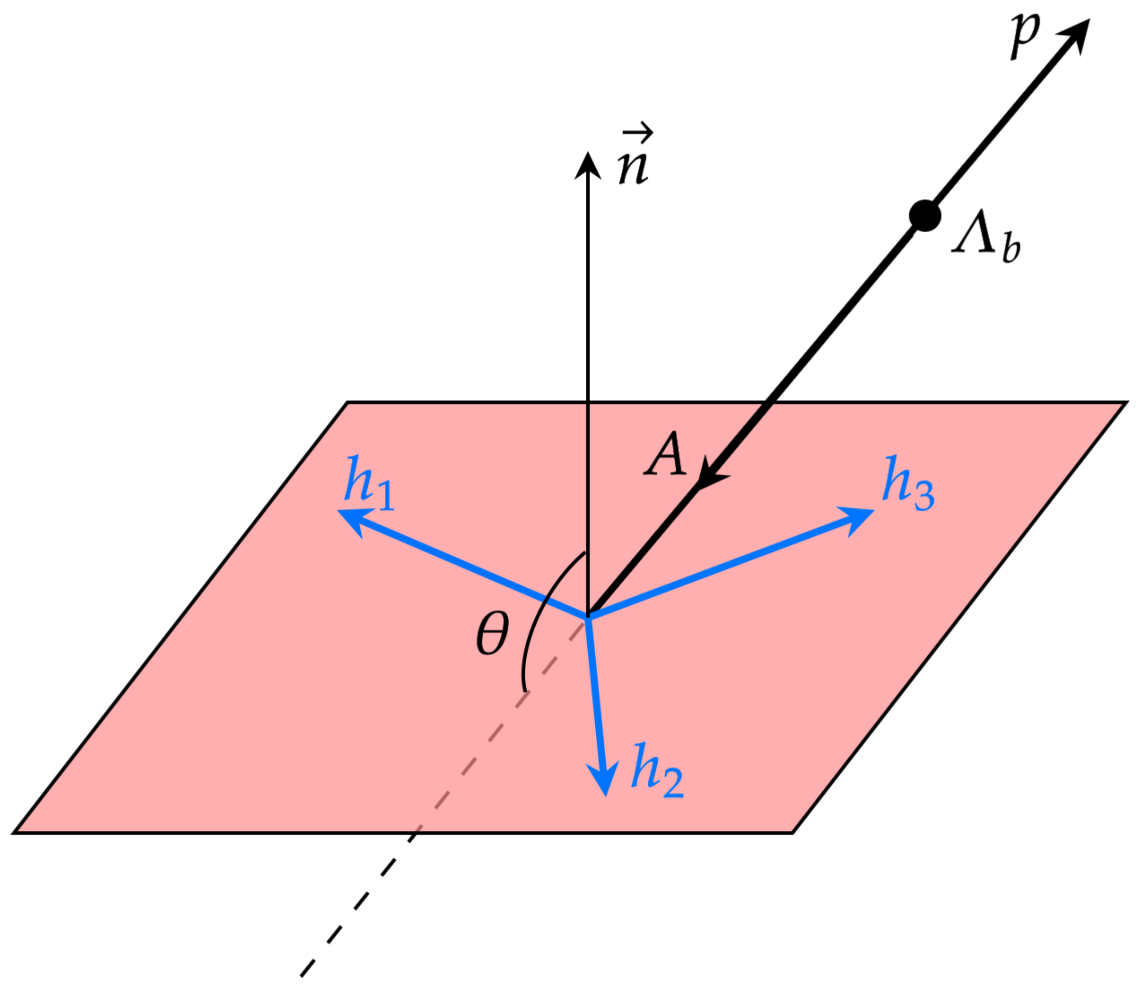
- In 2009, form factors are two orders smaller than LatticeQCD/experiments, considering only the leading twist of LCDAs [C.D.Lu, Y.M.Wang, et al, 2009]
- In 2022, considering high-twist LCDAs, results are consistent with Lattice QCD [J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, **FSY**, 2022]. Consistent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



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

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

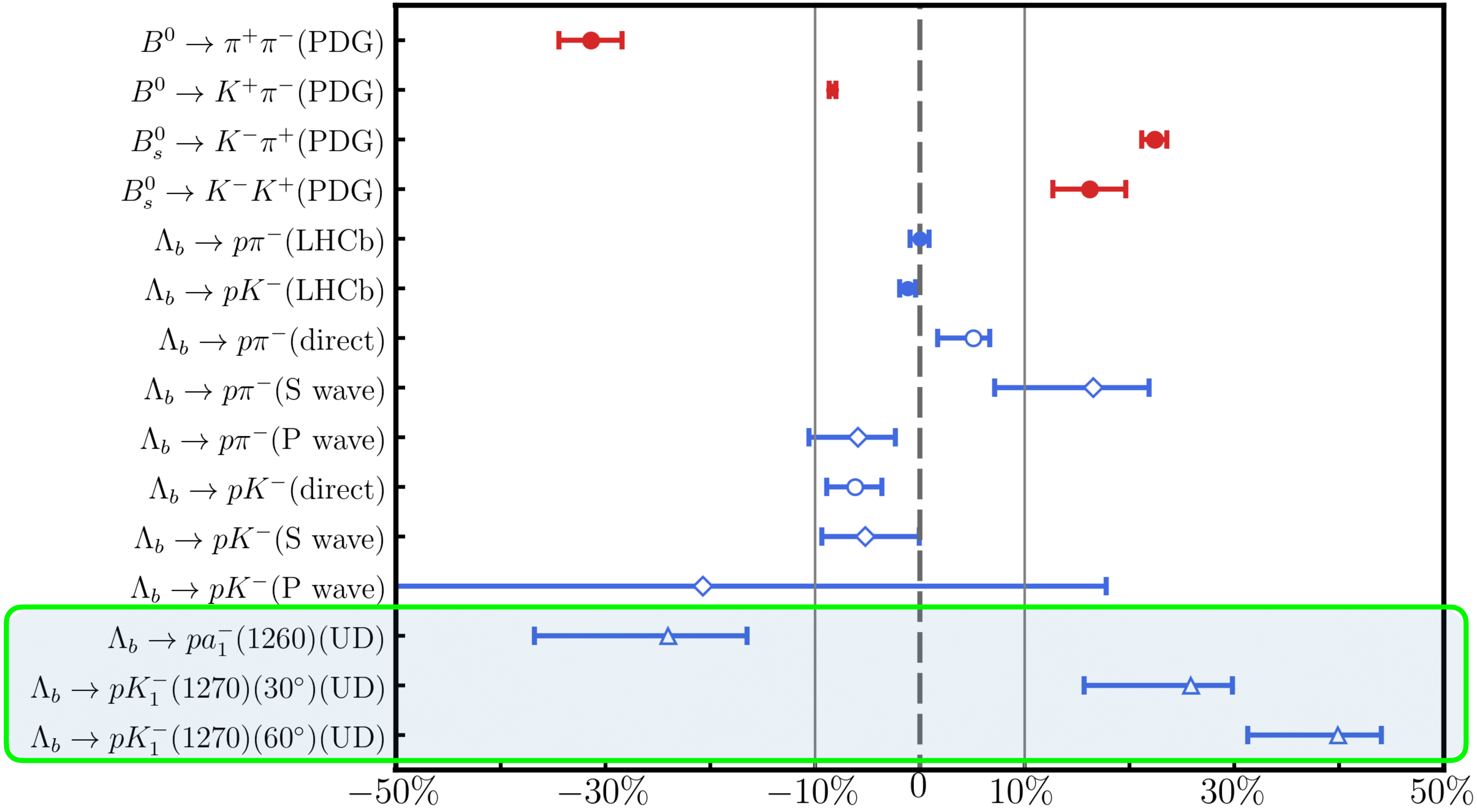
$$A_{UD} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)} = R\,\mathcal{R}e(S^T P_2^*)$$

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

	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

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

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

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

$$\kappa \approx 0.5$$

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

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

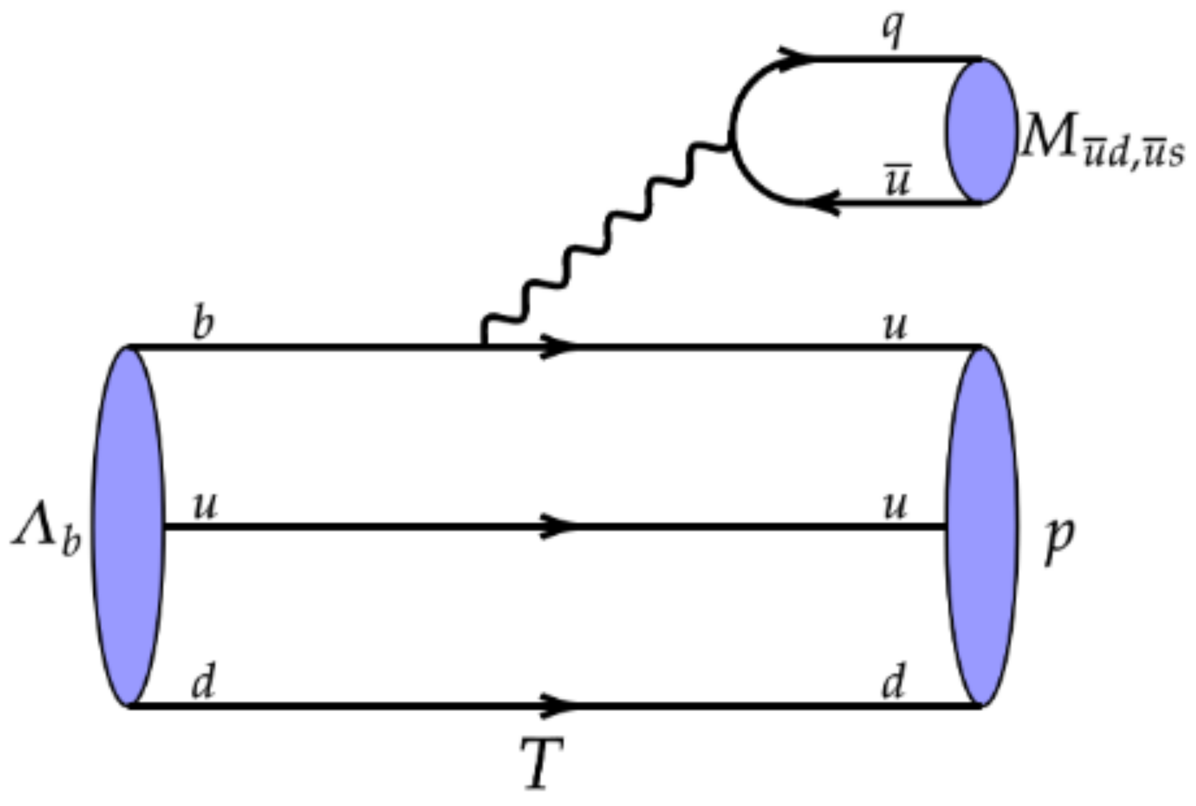
$$\kappa_S = \frac{|S|^2}{|S|^2 + \kappa |P|^2}$$

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

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,

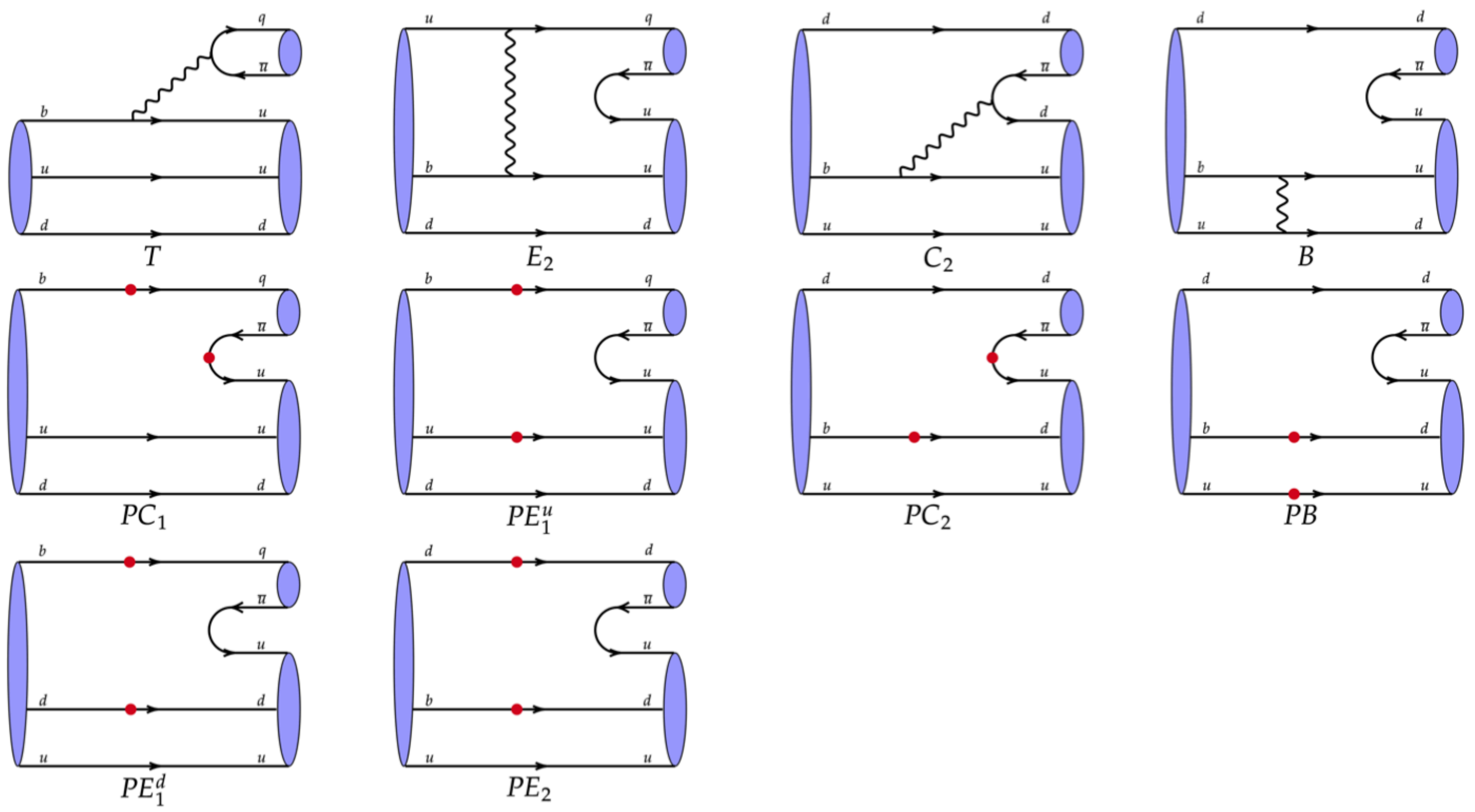
$$f_1 = g_1, \quad f_2 = f_3 = g_2 = g_3 = 0$$

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 $\Lambda_b \to pA, pV$

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

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

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

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

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

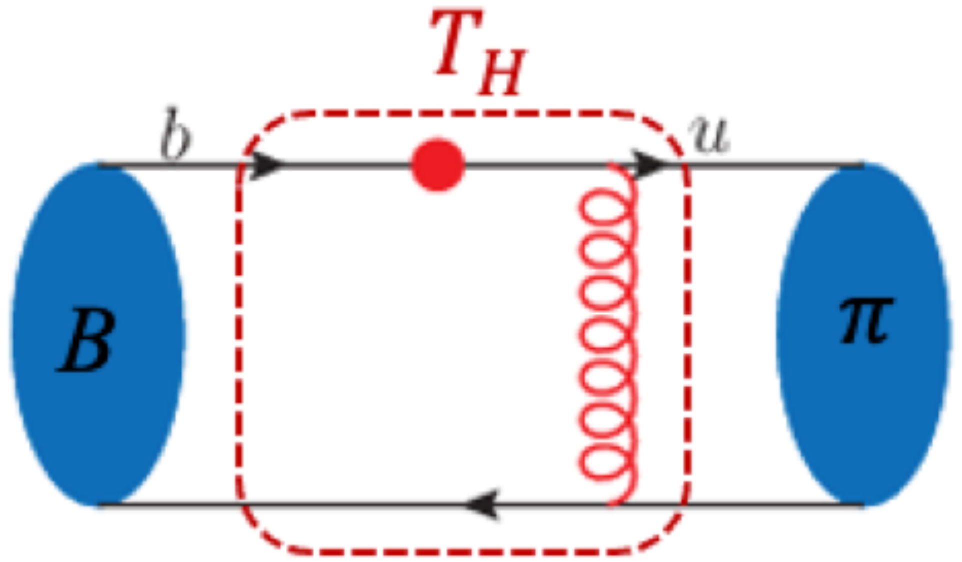
PQCD approach

- 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 $\sim 1/x_1x_2Q^2 \to \infty$ 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 $\sim 1/(x_1x_2Q^2 + k_T^2)$

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

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

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

	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

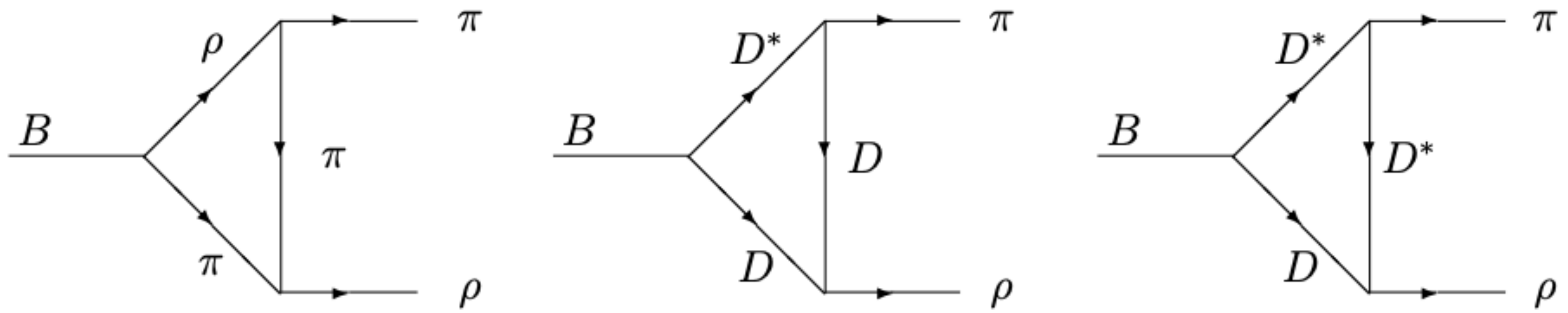
CPV cancellation is general phenomenon?

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

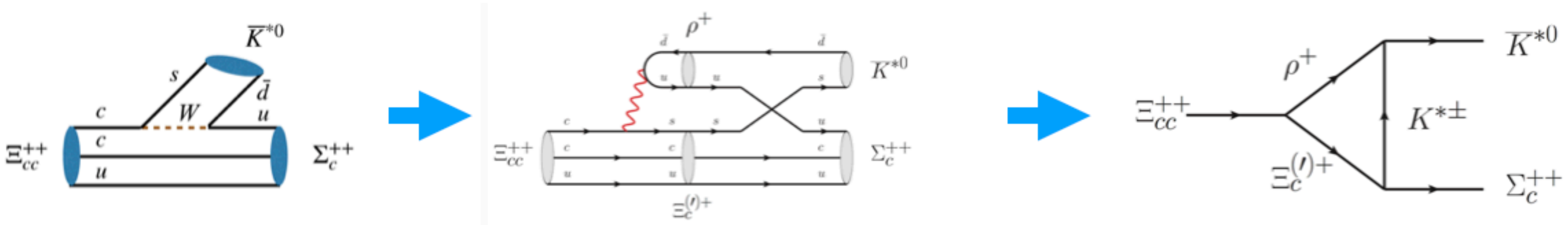
•S-wave •P-wave •P-wave

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

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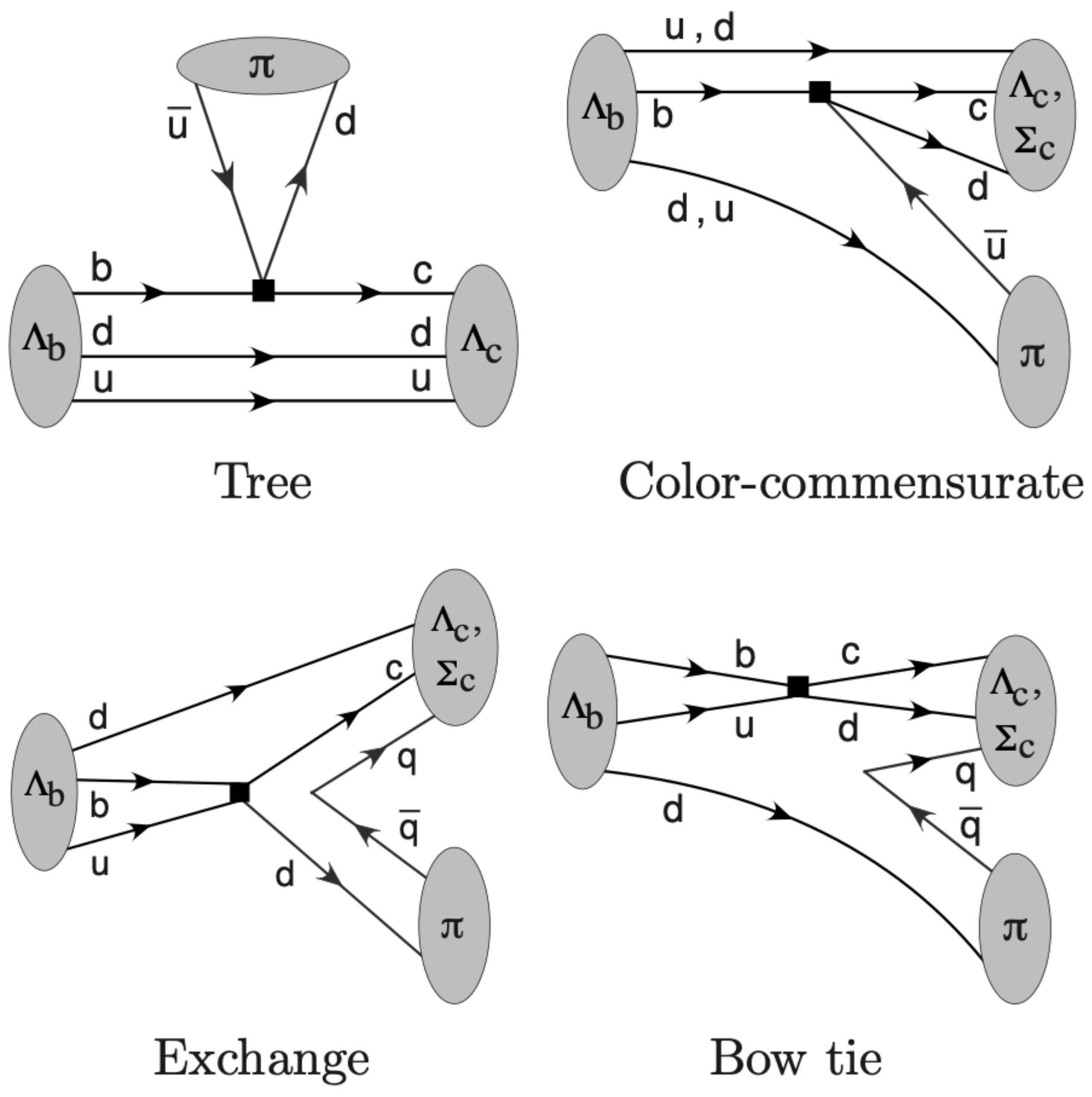
Hierarchy to topological diagrams

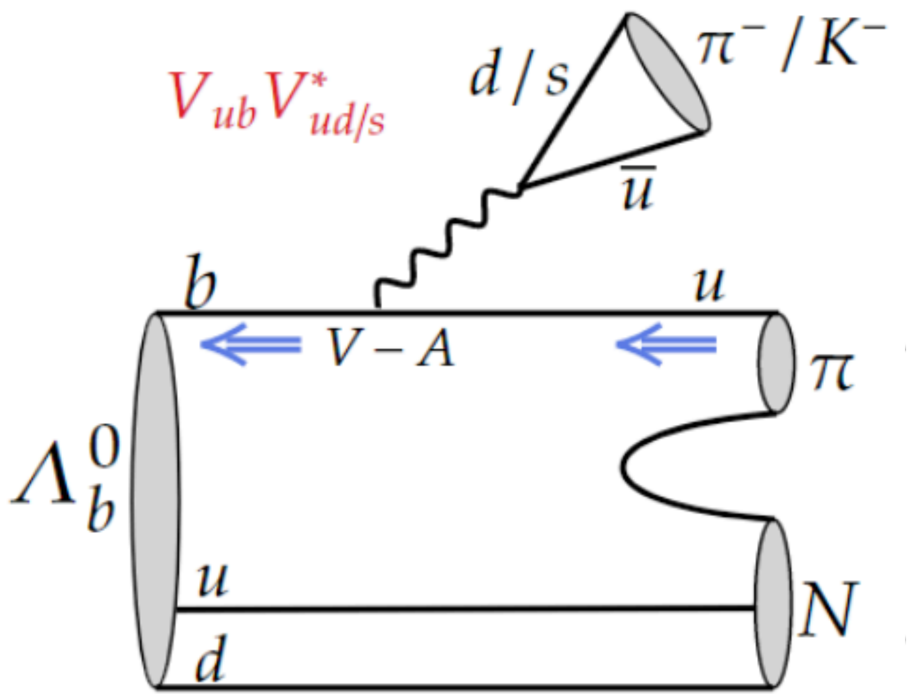
- In the heavy quark expansion,

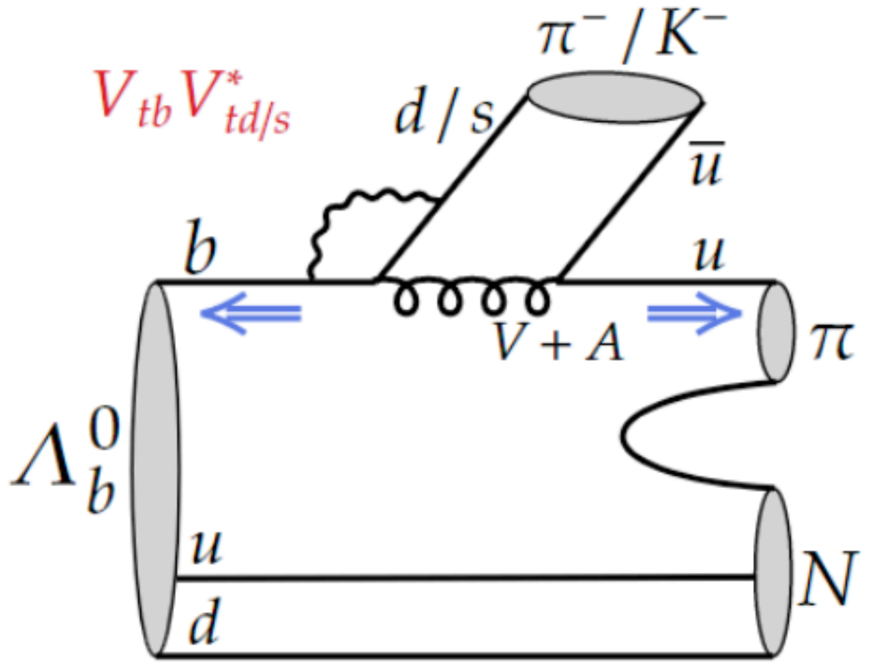
$$\left|\frac{C}{T}\right| \sim \left|\frac{E}{T}\right| \sim O\left(\frac{\Lambda_{\rm QCD}}{m_Q}\right) \qquad \left|\frac{B}{C}\right| \sim O\left(\frac{\Lambda_{\rm QCD}}{m_Q}\right)$$

Leibovich, Ligeti, Stewart, Wise, 2004

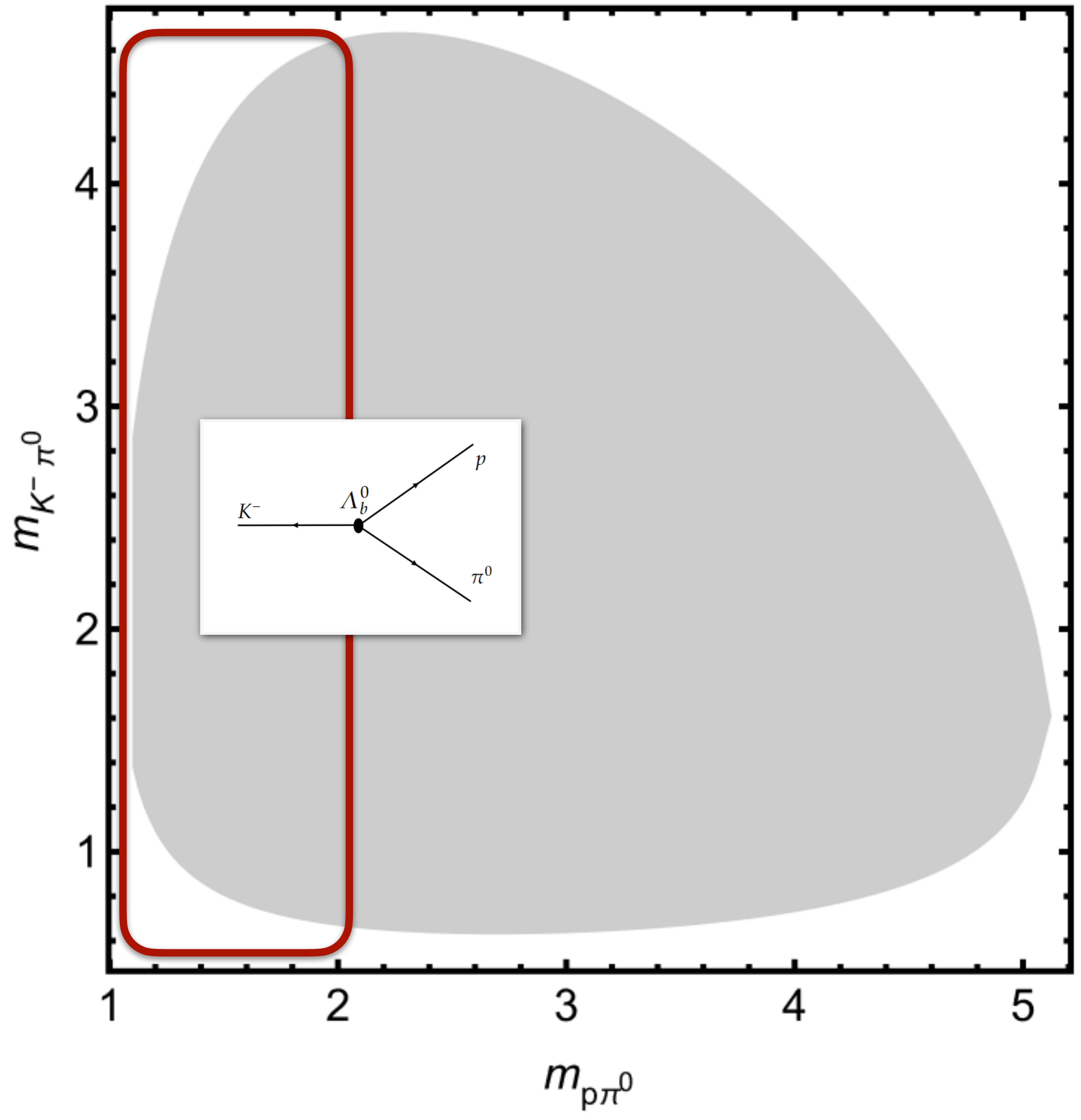


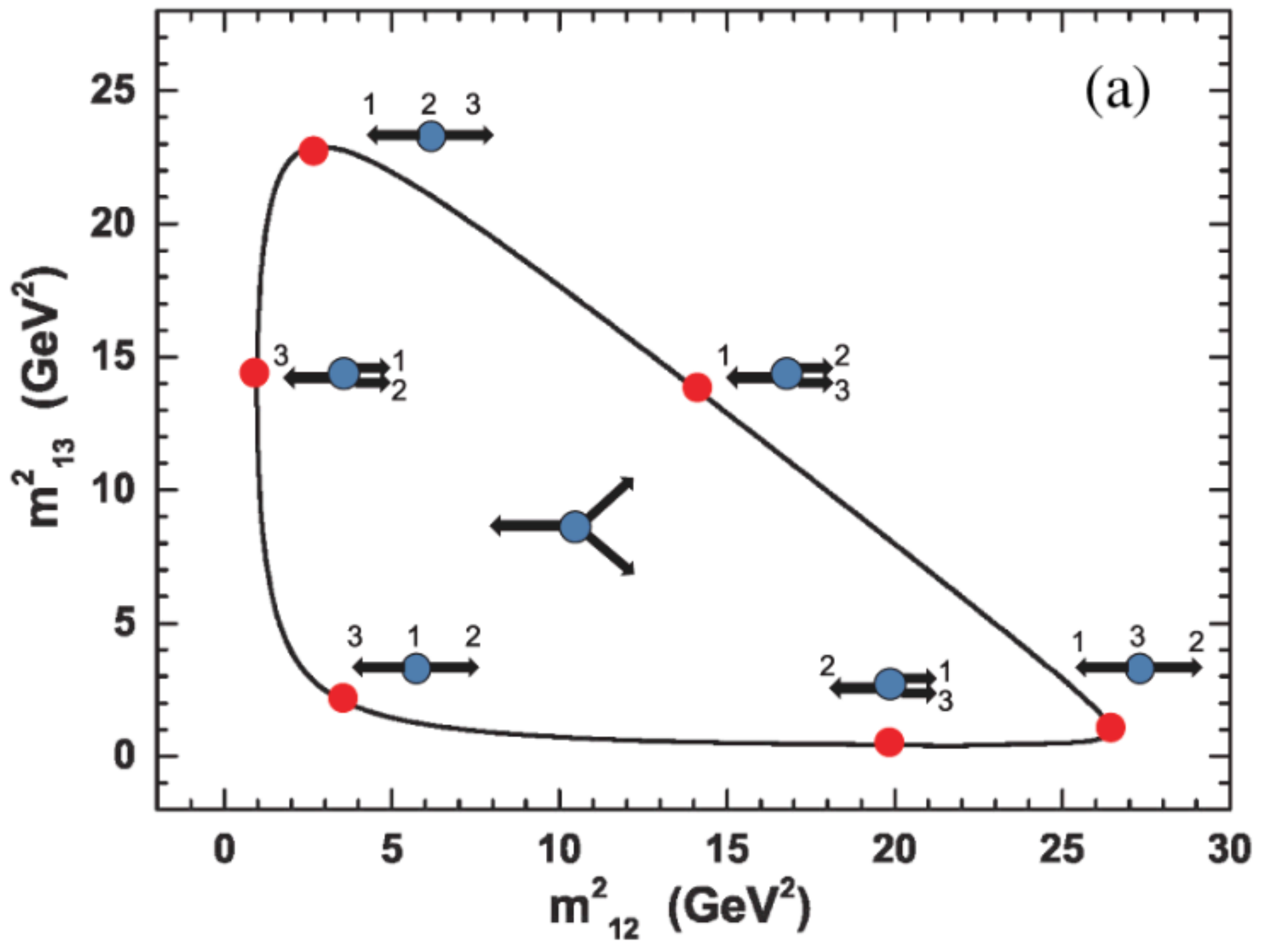
- So we only consider the color-favored emitted tree diagram and corresponding penguin diagram.





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





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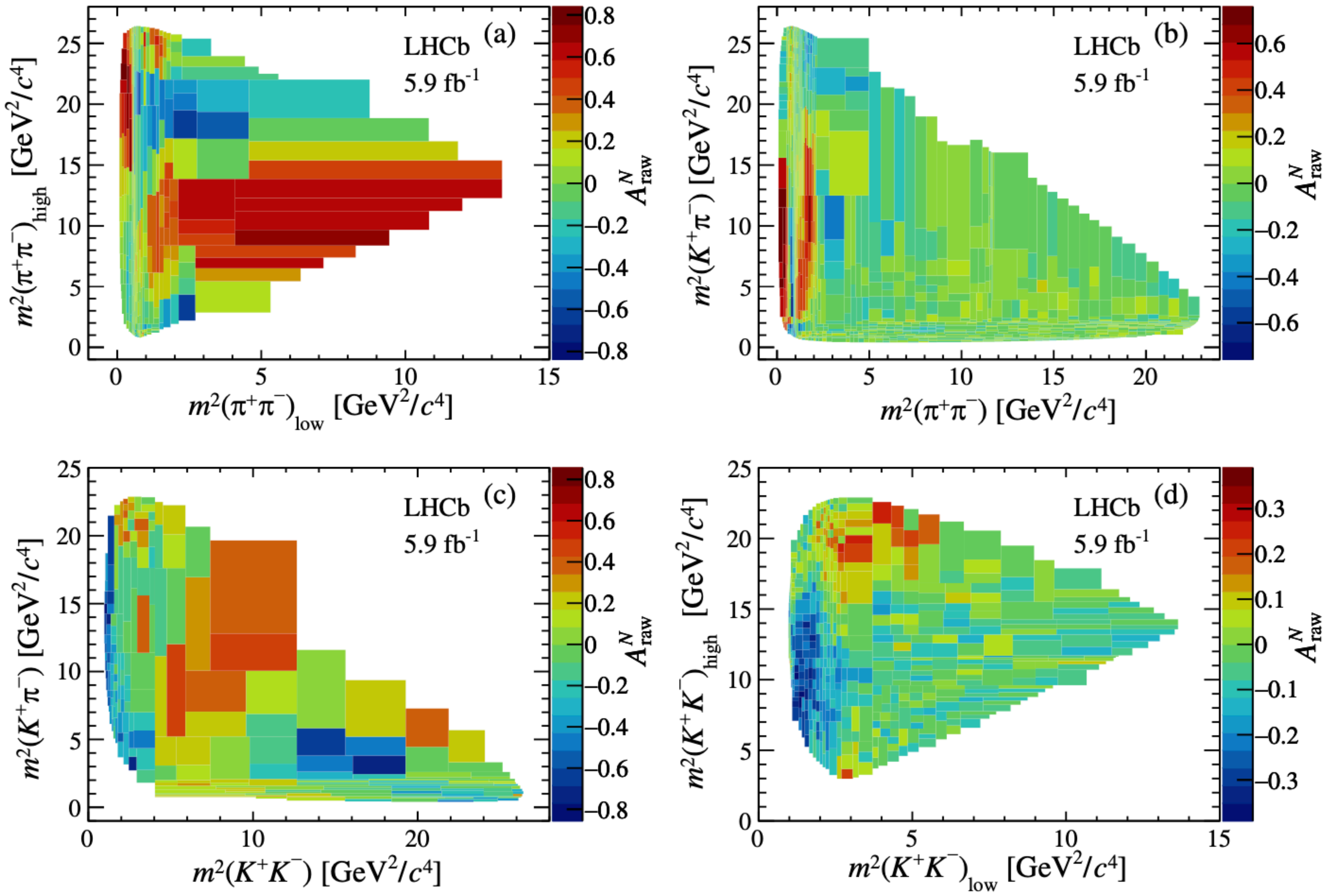
CPV in three-body decays of B mesons



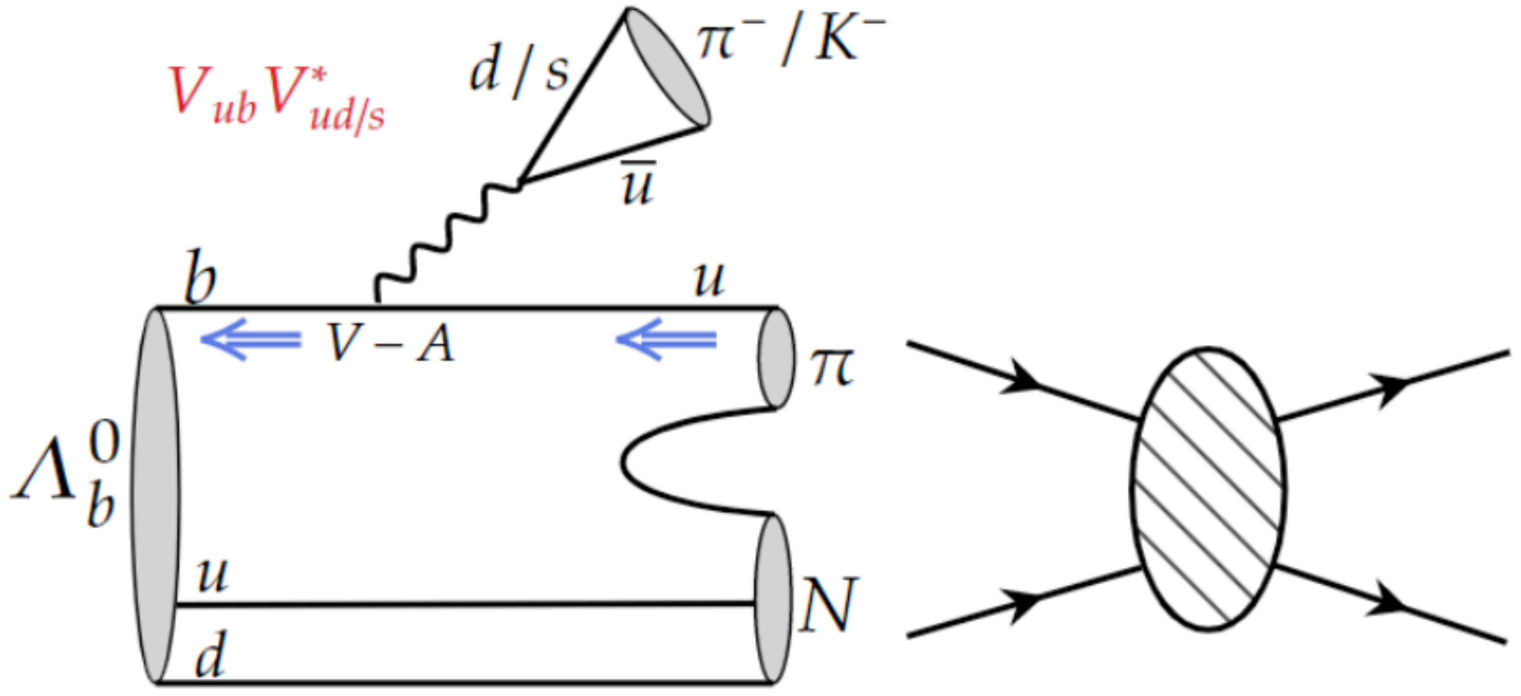
LHCb, 2206.07622

CPV from $N\pi$ scatterings

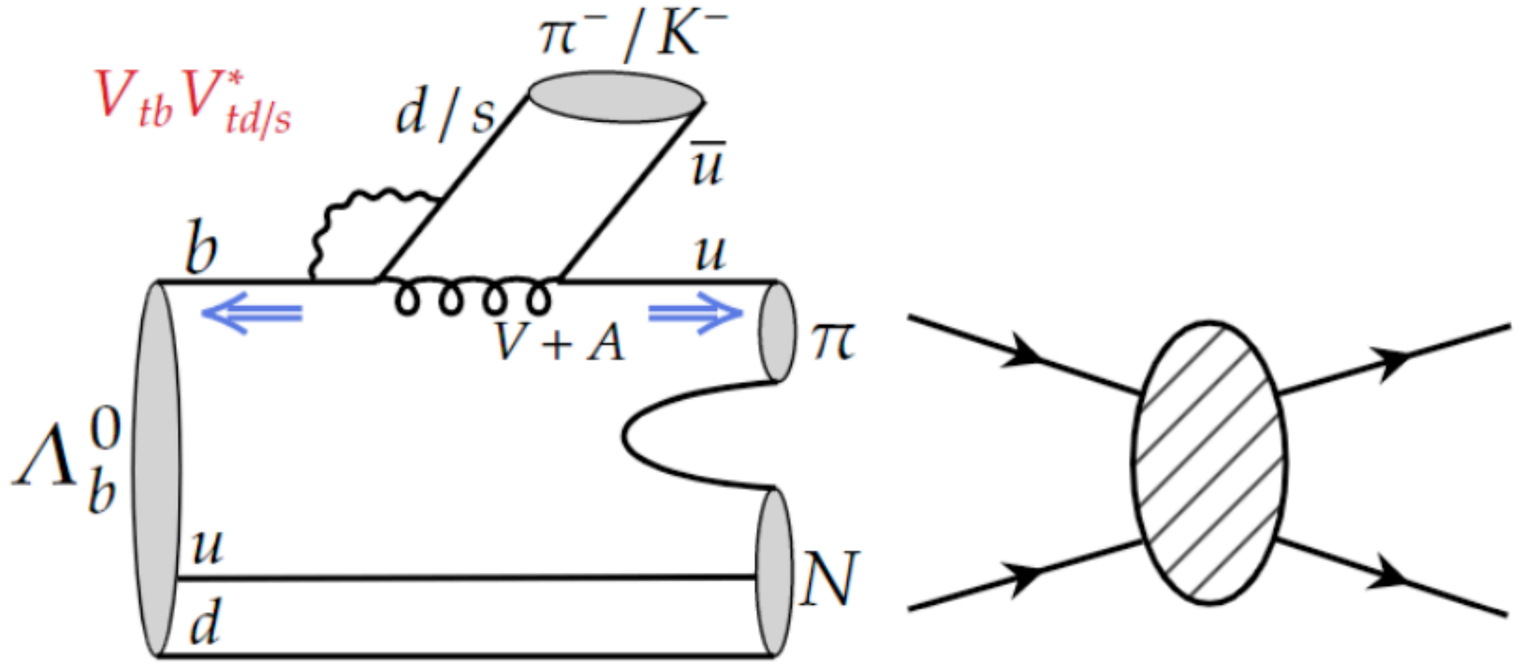
: $\mathcal{S}^{1/2}\mathcal{A}_0$

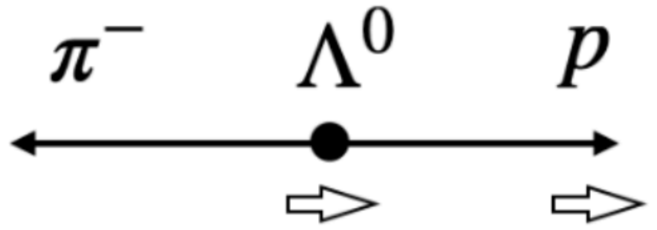
$$\mathcal{A}(\Lambda^0 \to p\pi^-) = \bar{u}_p(S + P\gamma_5)u_\Lambda$$

- Tree:

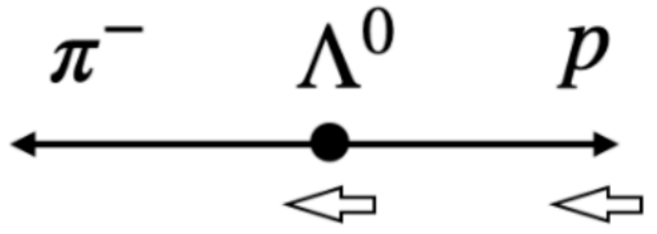


- Penguin:





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



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

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

- 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

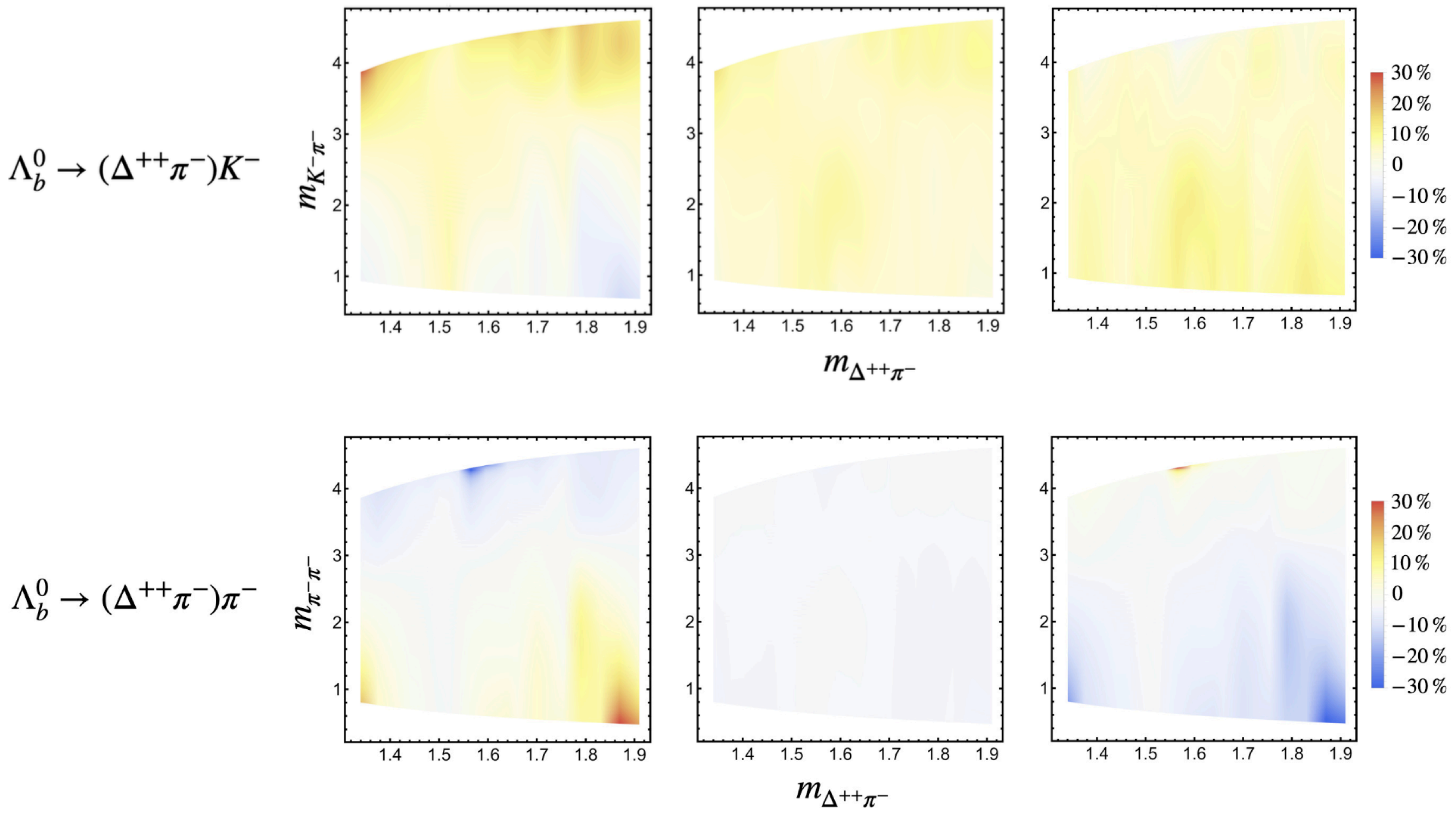
J.P.Wang, **FSY**, CPC48,101002(2024)

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%.

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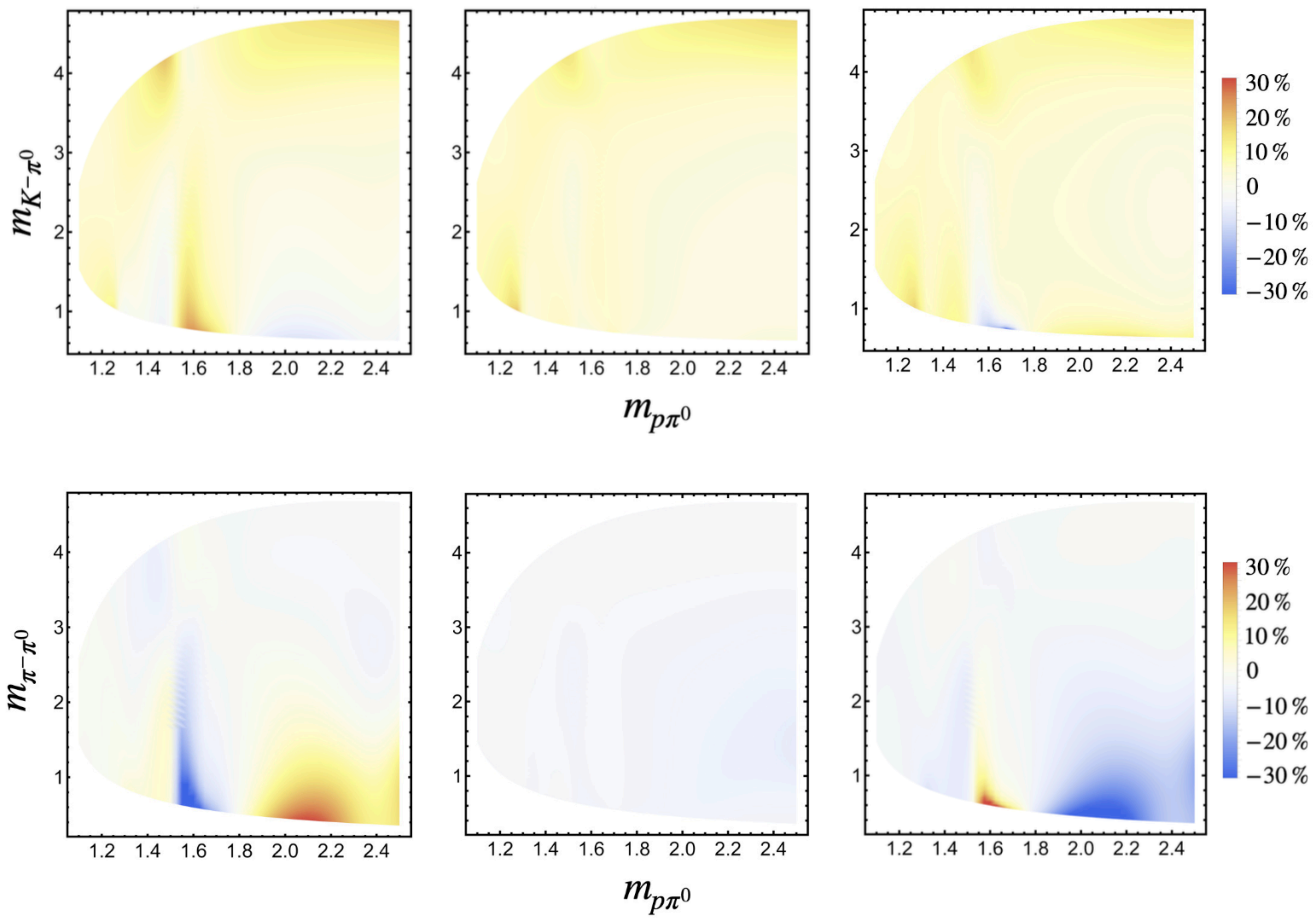
CPV from $N\pi$ scatterings

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

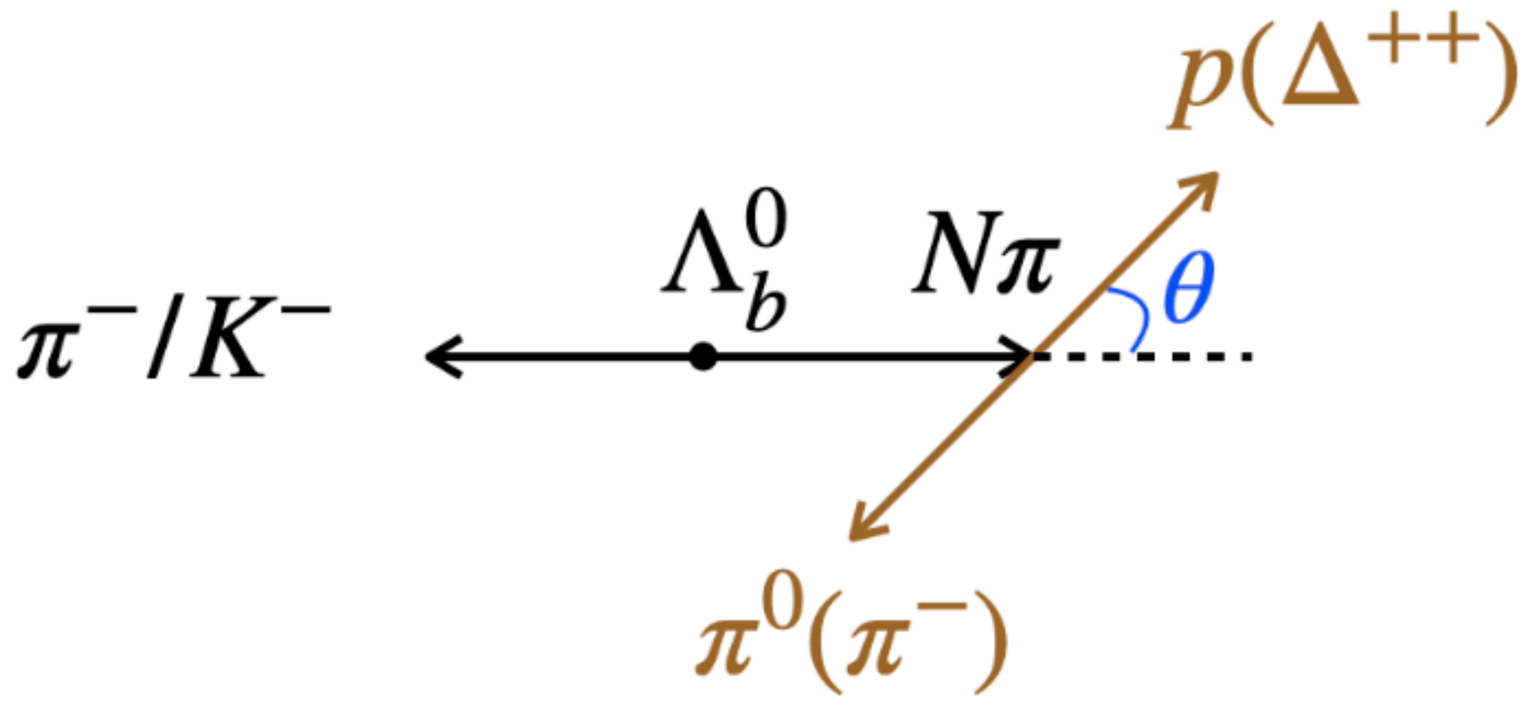
$\Lambda_b^0 \to (p\pi^0)\pi^-$



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

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

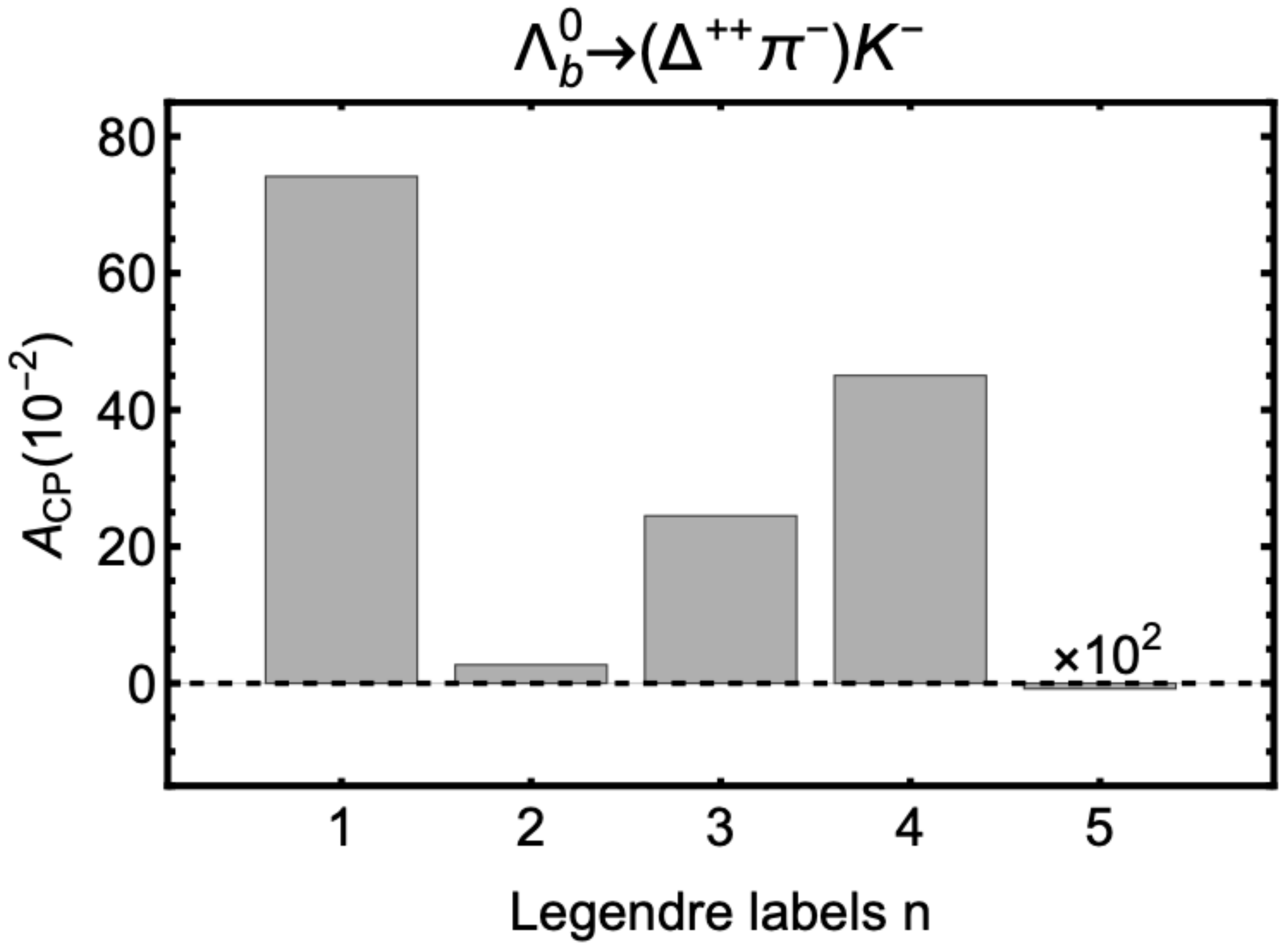
CPV of Legendre moments



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

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

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



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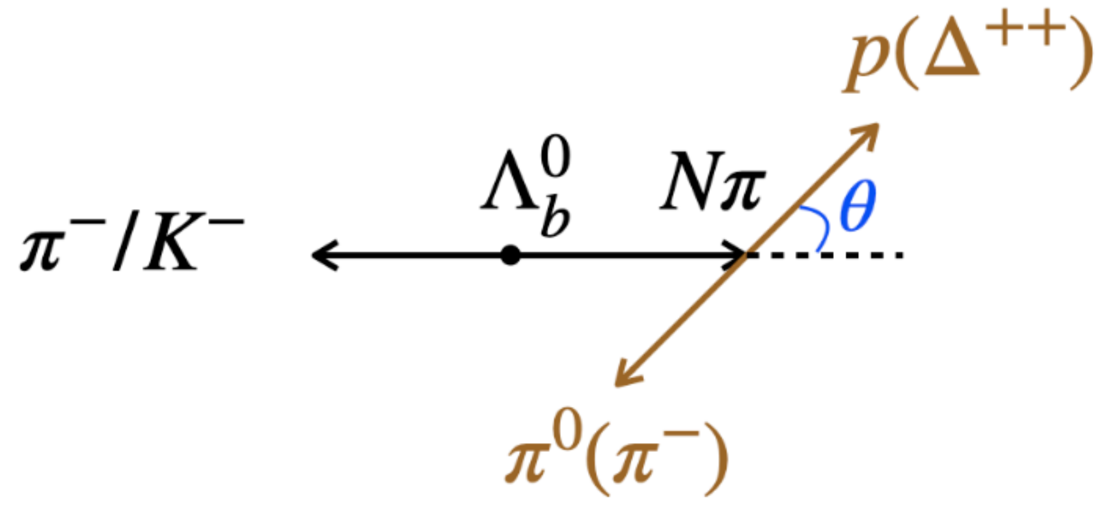
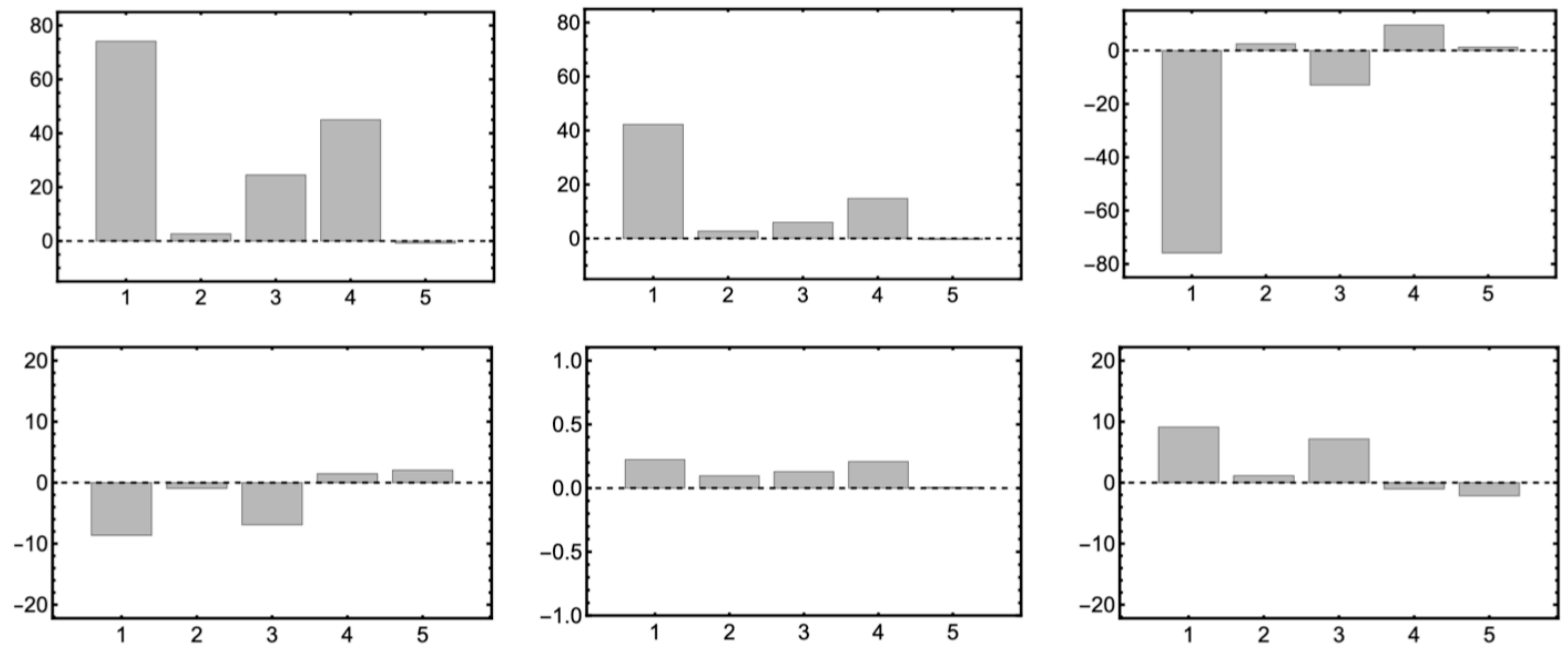
CPV of Legendre moments

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



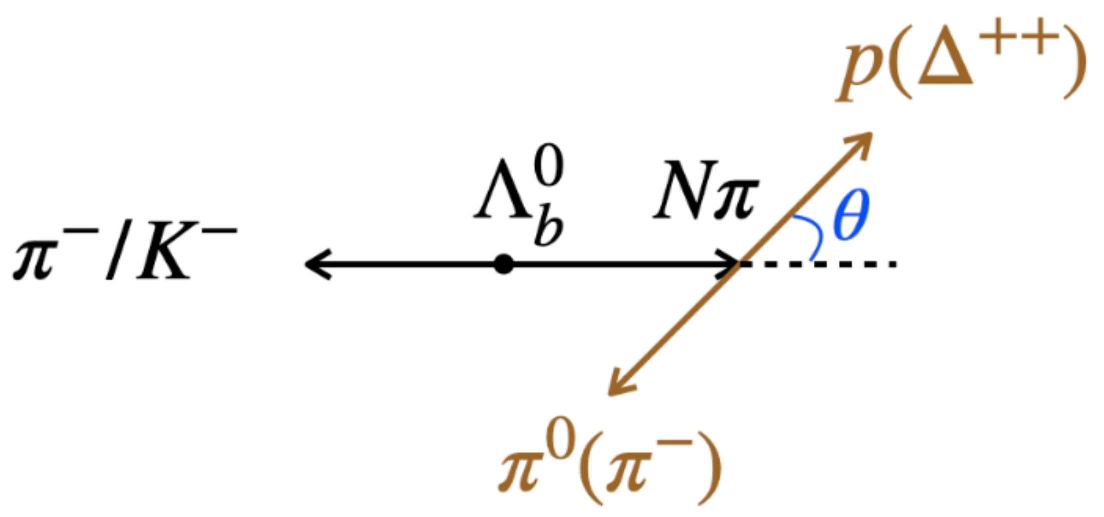
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$

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



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



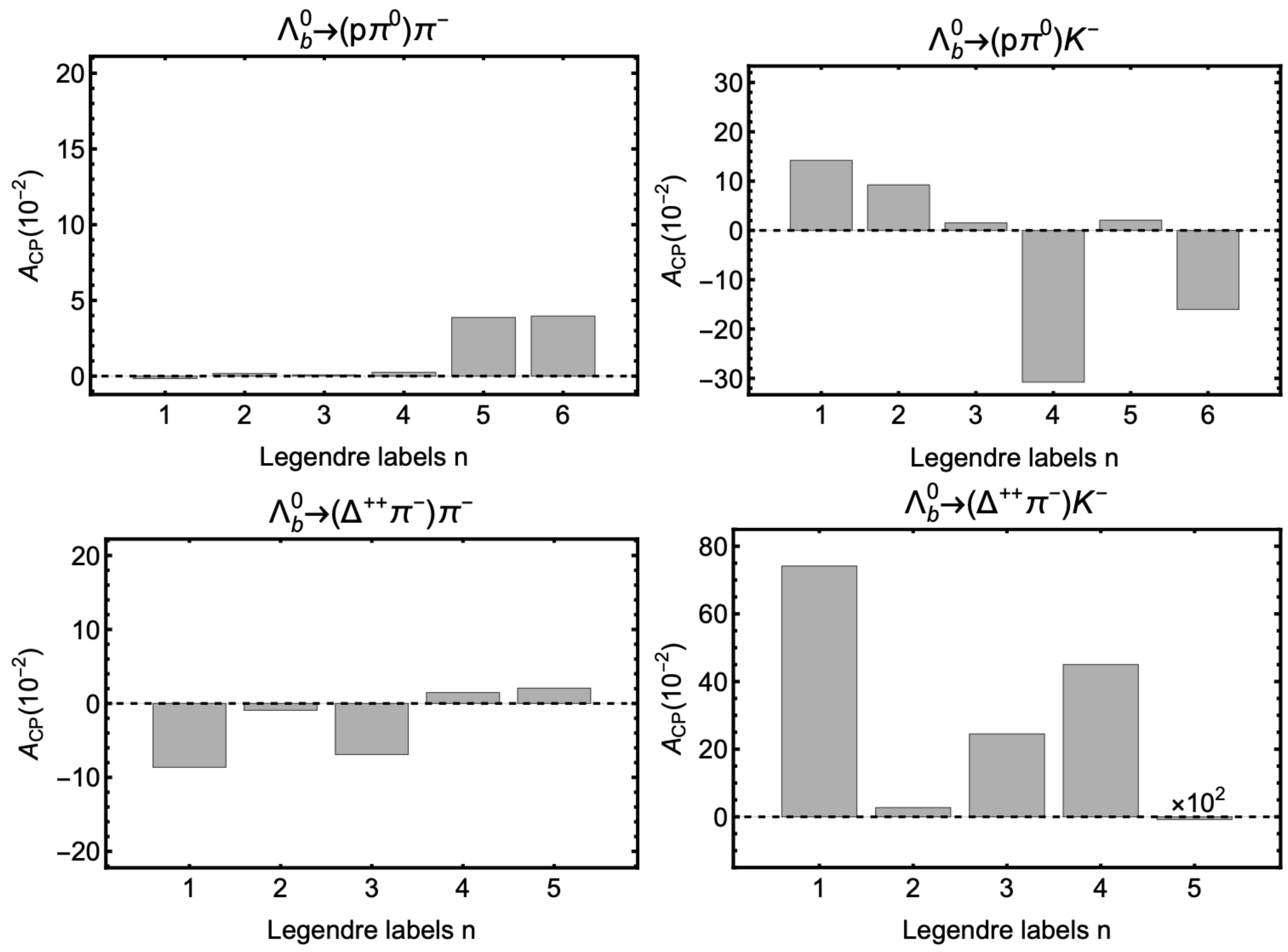
$$\frac{d\Gamma}{d\cos\theta} \propto \sum_{n=0} \mathcal{L}_n P_n(\cos\theta)$$

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

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

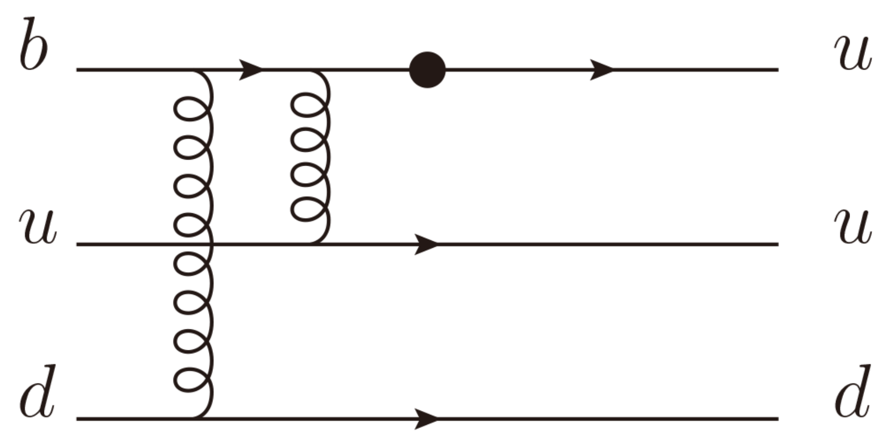
$\Lambda_b^0 \to (p\pi^0)K^-$:

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



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

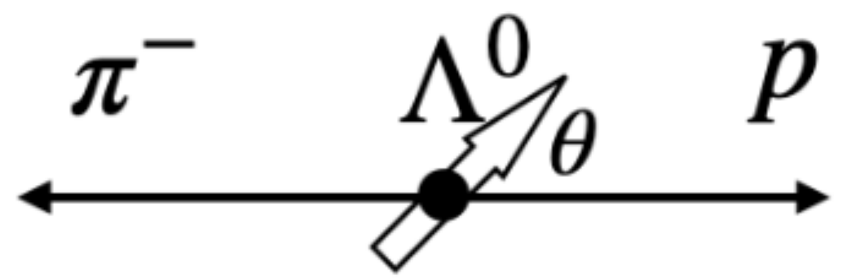
2. **Non-perturbative inputs**

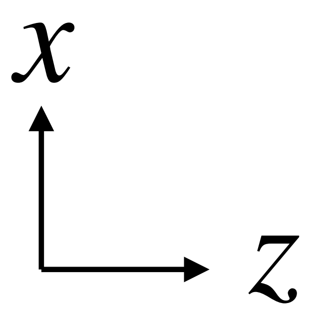
- Theoretical uncertainties are dominated by the non-perturbative input parameters, such as the light-cone distribution amplitudes (LCDA) of baryons and di-hadrons.
- Form factors of $\Lambda_b \to (N\pi)$

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

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

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

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

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

Lee-Yang parameter, or decay asymmetry parameter

CPV of Polarizations

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

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

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

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

$$a^{\alpha}_{CP} \propto [r_s \sin(\delta_{p,p} - \delta_{s,t}) - r_p \sin(\delta_{p,t} - \delta_{s,p})] \sin \Delta\phi$$

$$a^{\beta}_{CP} \propto [r_p \cos(\delta_{p,t} - \delta_{s,p}) - r_s \cos(\delta_{p,p} - \delta_{s,t})] \sin \Delta\phi$$

$$a^{\gamma}_{CP} \propto [|S_t||S_p| \sin(\delta_{s,t} - \delta_{s,p}) - |P_t||P_p| \sin(\delta_{p,t} - \delta_{p,p})] \sin \Delta\phi$$

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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, $UQ_-U^\dagger = Q_-$

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

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

complimentary

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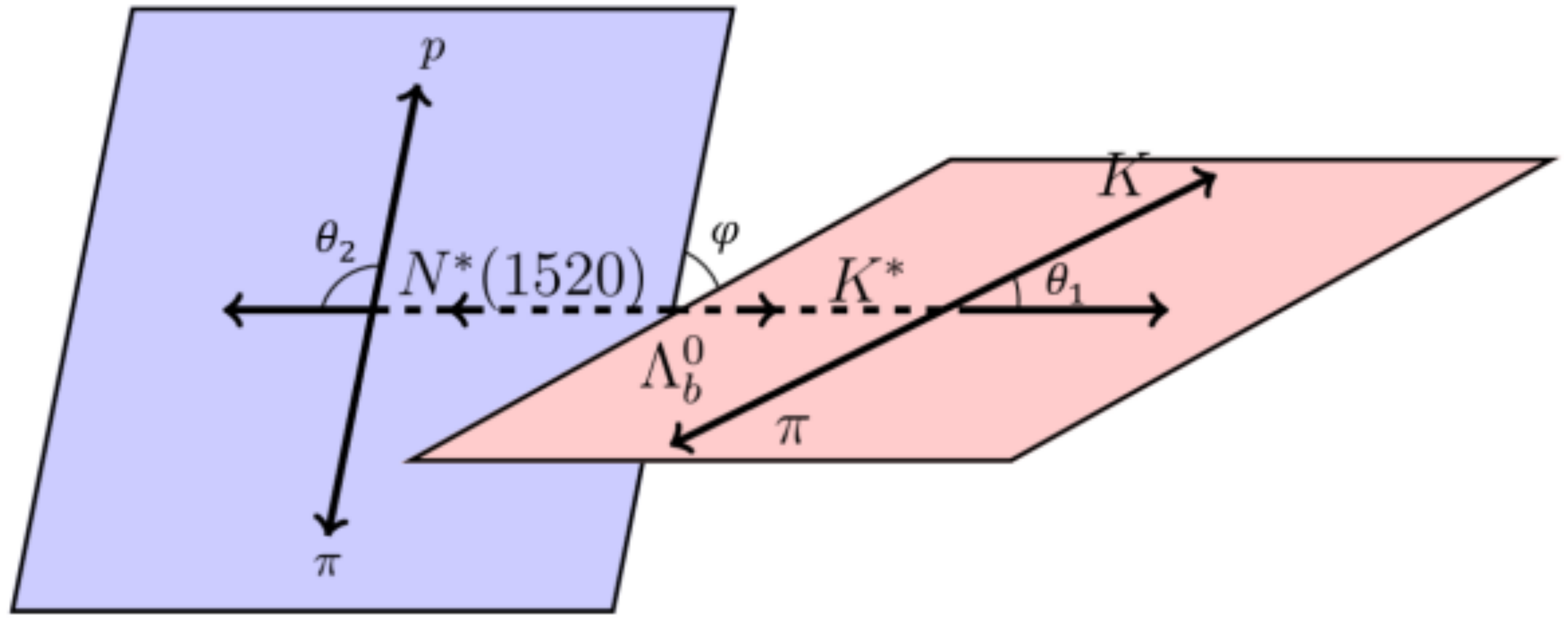
Angular distributions

$$\frac{d\Gamma}{dc_1\,dc_2\,d\varphi} \propto -\frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi$$
$$+\frac{s_1^2 s_2^2}{\sqrt{3}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi$$
$$-\frac{4s_1c_1s_2c_2}{\sqrt{6}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi$$
$$+\frac{4s_1c_1s_2c_2}{\sqrt{6}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi$$



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

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

- 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.