Everything of baryon CPV

Why? What? When?

于福升

兰州大学

4th LHCb workshop @ Yantai, 2024.7.30

Outline

1. Why baryon CPV? Motivation

2. Why not yet observed for baryon CPV?

3. What process and When to observe baryon CPV?

   ✓New proposal: $N\pi$ rescatterings

Outline

1. **Why baryon CPV? Motivation**
2. Why not yet observed for baryon CPV?
3. What process and When to observe baryon CPV?
   - ✓New proposal: $N\pi$ rescatterings

CP violation

- Particle physics: study symmetries and symmetry breakings.
- Charge-Parity symmetry violation (**CPV**) is the key problem of flavor physics,

  See the logo of LHCb and Peilian's talk on LHCb review.

- Belle and BABAR observed direct CPV in 2004,

  => KM mechanism wan the Nobel Prize in 2008.

- Workshops of flavor physics: FPCP, CKM, HFCPV.
- The only one phase in the 18 SM parameters.

History of CP violation

- 1956, Parity violation in weak interaction
- 1964, Observation of CP violation in Kaon
- 1973, Kobayashi-Maskawa mechanism
- 2004, Observation of direct CPV in B meson
- 2019, Observation of direct CPV in D meson

physicsworld
TOP 10
BREAKTHROUGH
2019

History of CP violation

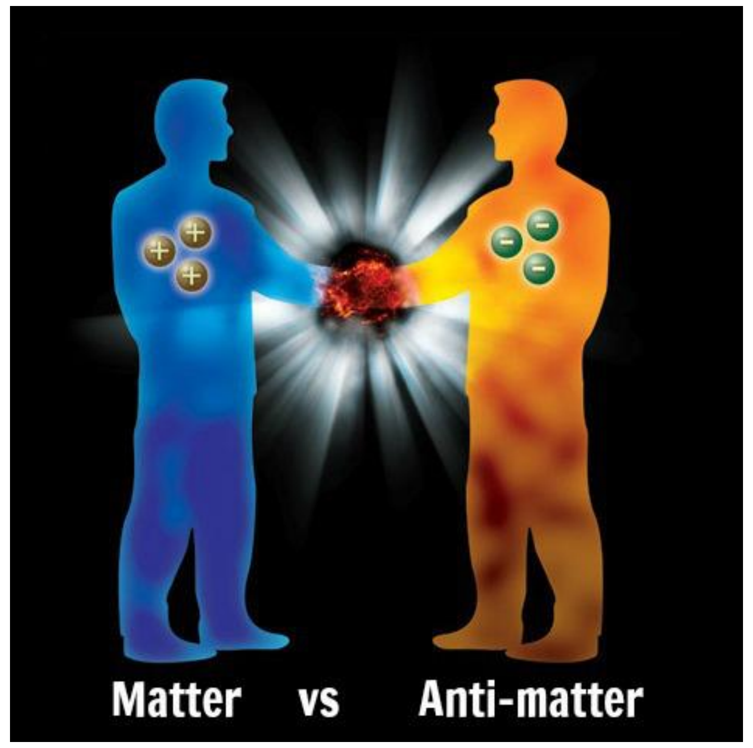
- 1956, Parity violation in weak interaction
- 1964, Observation of CP violation in Kaon
- 1973, Kobayashi-Maskawa mechanism
- 2004, Observation of direct CPV in B meson
- 2019, Observation of direct CPV in D meson

physicsworld
TOP 10
BREAKTHROUGH
2019

- **CPV of baryon? Never established! Why? What? When?**

CP violation in baryons

- Sakharov conditions for **matter-antimatter asymmetry of the Universe**:
  1) **baryon** number violation
  2) C and **CP violation**
  3) out of thermal equilibrium



- **CPV: SM < BAU. => new source of CPV, NP**
- **The visible universe is mainly made of baryons.**
- **It is of great significance to search for baryon CPV.**

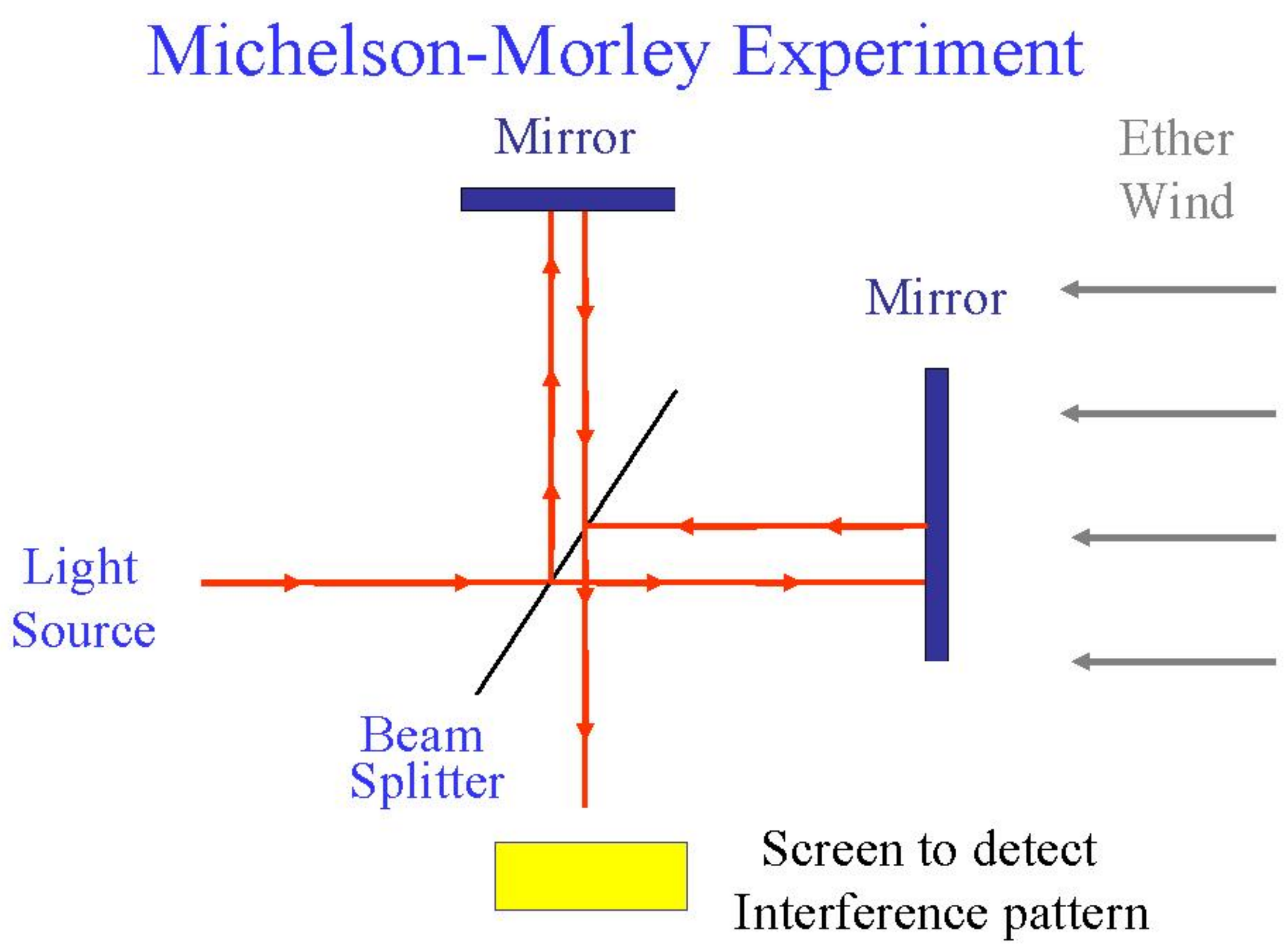
To be or not to be: Whether CPV of baryon is from SM?

- Not sure until observation !

- 1865, Maxwell electromagnetic (EM) theory
- 1887, Herz successfully observed EM waves
- 1887, Michelson-Morley failed to find the Ether

- **Precise test of the SM is important, in particular when something is not established.**

- Theoretical prediction and experimental searches



First American winner of Nobel Prize

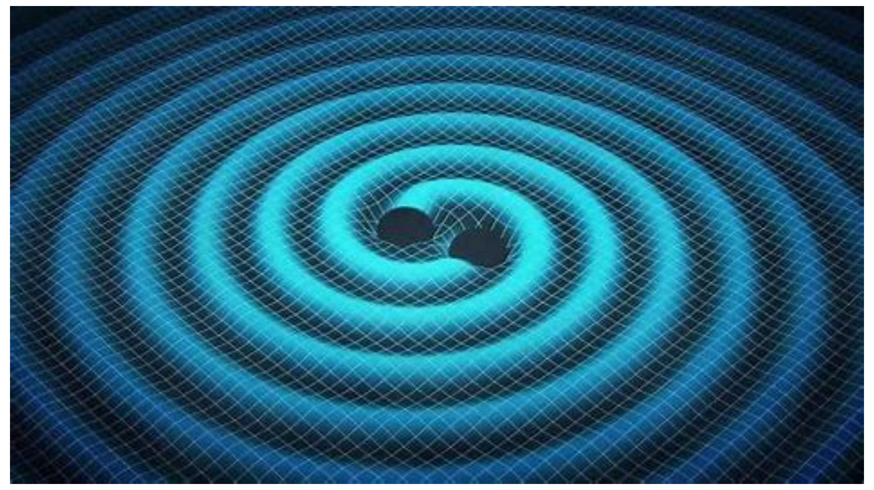
New horizon

•Observation of gravitational waves

=> not only confirm the General Relativity,

=> but also open the Multi-messenger era of

cosmology.

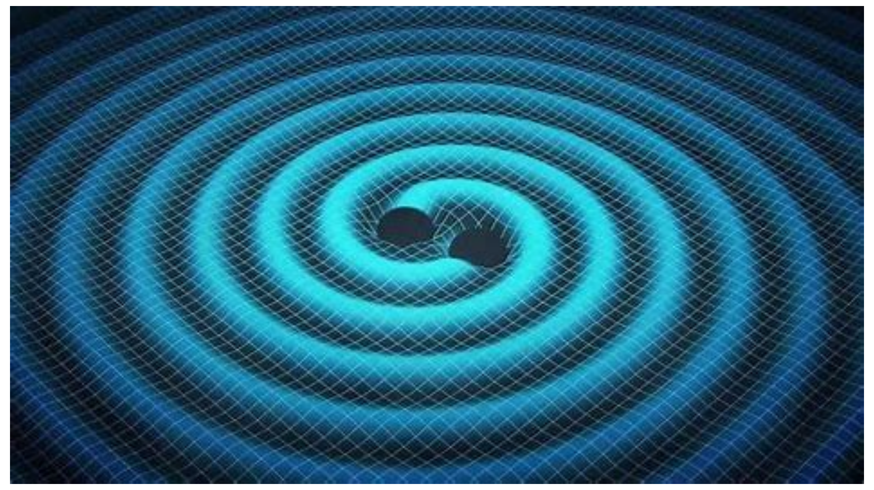


New horizon

•Observation of gravitational waves

=> not only confirm the General Relativity,

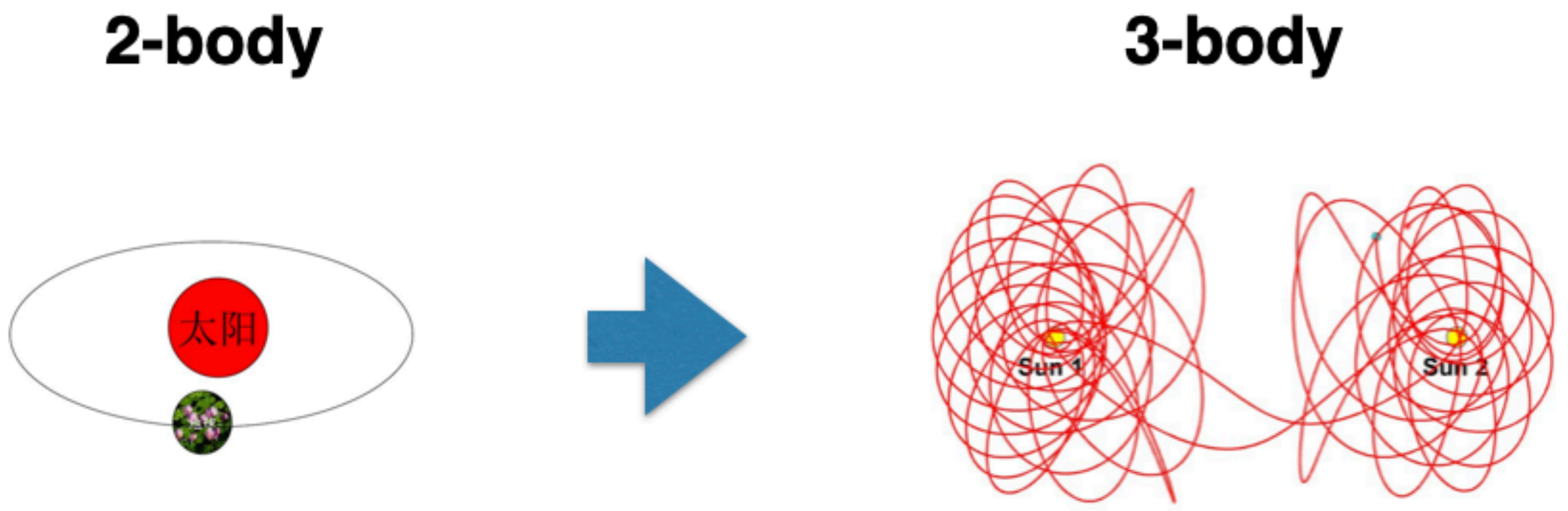
=> but also open the Multi-messenger era of cosmology.



•Meson -> Baryon : More is different.

•New QCD dynamics: exclusive baryon.

•New challenges and opportunities.



Outline

1. Why baryon CPV? Motivation

2. Why not yet observed for baryon CPV?

3. What process and When to observe baryon CPV?

✓New proposal: $N\pi$ rescatterings

Puzzle & Opportunities

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

Puzzle & Opportunities

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

- Precision of baryon CPV measurements has reached the order **1%** [LHCb, '18]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\,\%$$

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

$$A_{CP}(\overline{B}^0 \to \pi^+\pi^-) = (31.1 \pm 3.0)\,\%\,, \quad A_{CP}(\overline{B}^0 \to \pi^+K^-) = (8.36 \pm 0.32)\,\%$$

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

Puzzle & Opportunities

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

- Precision of baryon CPV measurements has reached the order **1%** [LHCb, '18]

$$A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%\,, \quad A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\,\%$$

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

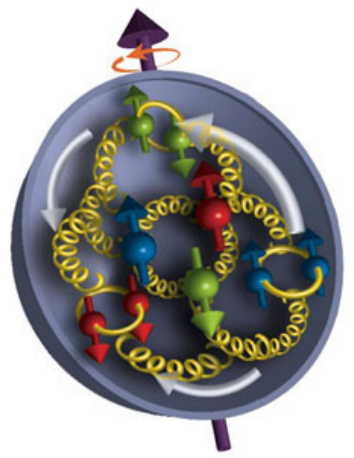
$$A_{CP}(\overline{B}^0 \to \pi^+\pi^-) = (31.1 \pm 3.0)\,\%\,, \quad A_{CP}(\overline{B}^0 \to \pi^+K^-) = (8.36 \pm 0.32)\,\%$$

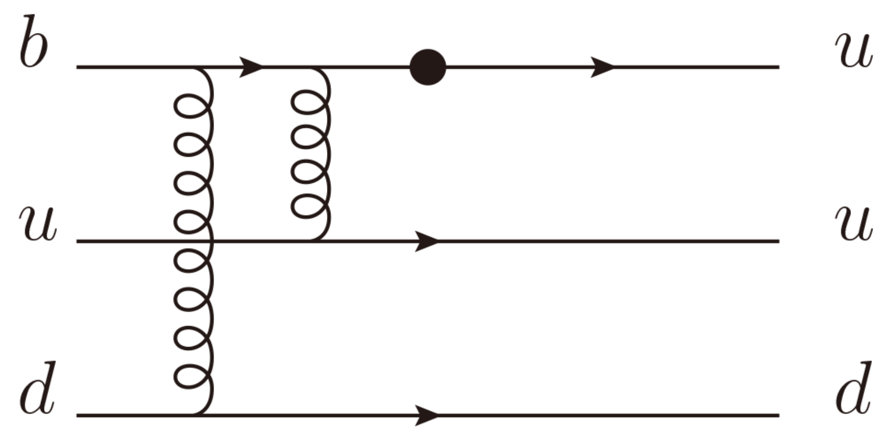
- **It can be expected that CPV in b-baryons might be observed soon !!**

- **Puzzle: why not yet observed for baryon CPV? What difference of dynamics?**

Different dynamics of baryon decays

- **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]

Λ_b decays 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, when consider high-twist LCDAs, results are consistent with LatticeQCD. [J.J.Han, Y.Li, H.n.Li, Y.L.Shen, Z.J.Xiao, FSY, 2022]

	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

- In 2024, it can be understood why CPV of b-baryon decays is so small by PQCD [J.X.Yu, J.J.Han, Y.Li, H.n.Li, Z.J.Xiao, FSY, 2024]

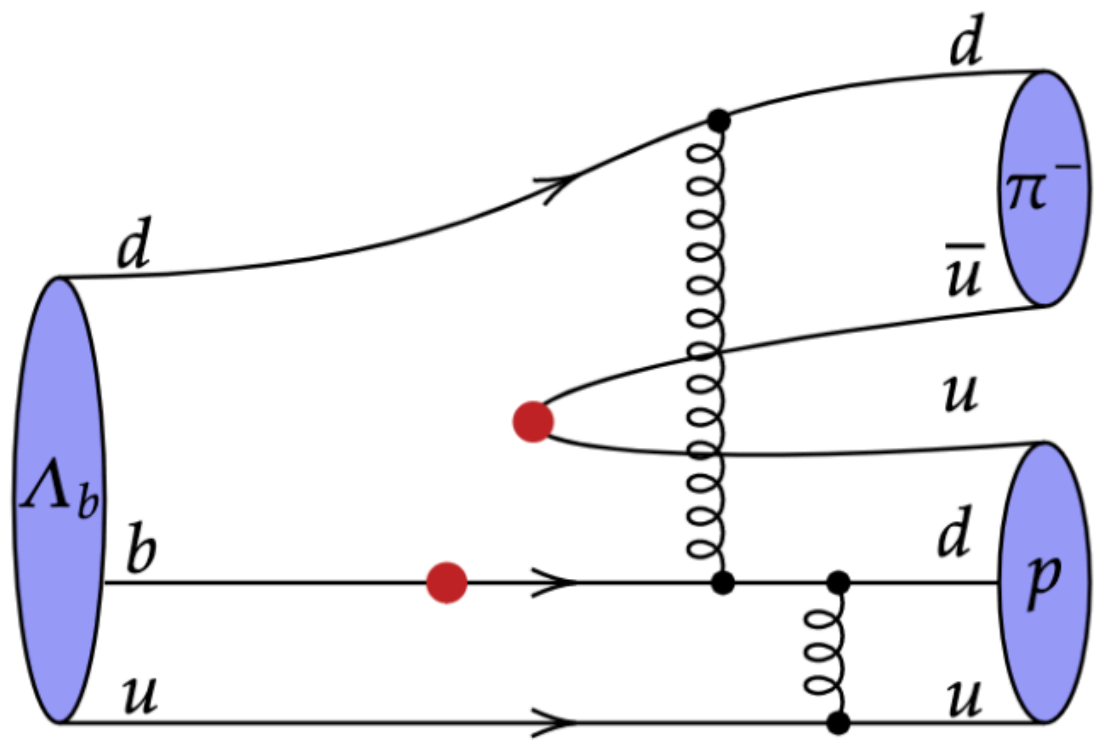
$$A_{CP}^{\rm th}(\Lambda_b^0 \to p\pi^-) = (4.1^{+0.8+1.2+1.2}_{-0.3-0.7-0.8})\,\%\,, \quad A_{CP}^{\rm th}(\Lambda_b^0 \to pK^-) = (-5.8^{+1.2+1.4+1.3}_{-0.2-3.7-1.2})\,\%$$

$$A_{CP}^{\rm exp}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%\,, \quad A_{CP}^{\rm exp}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.0)\,\%$$

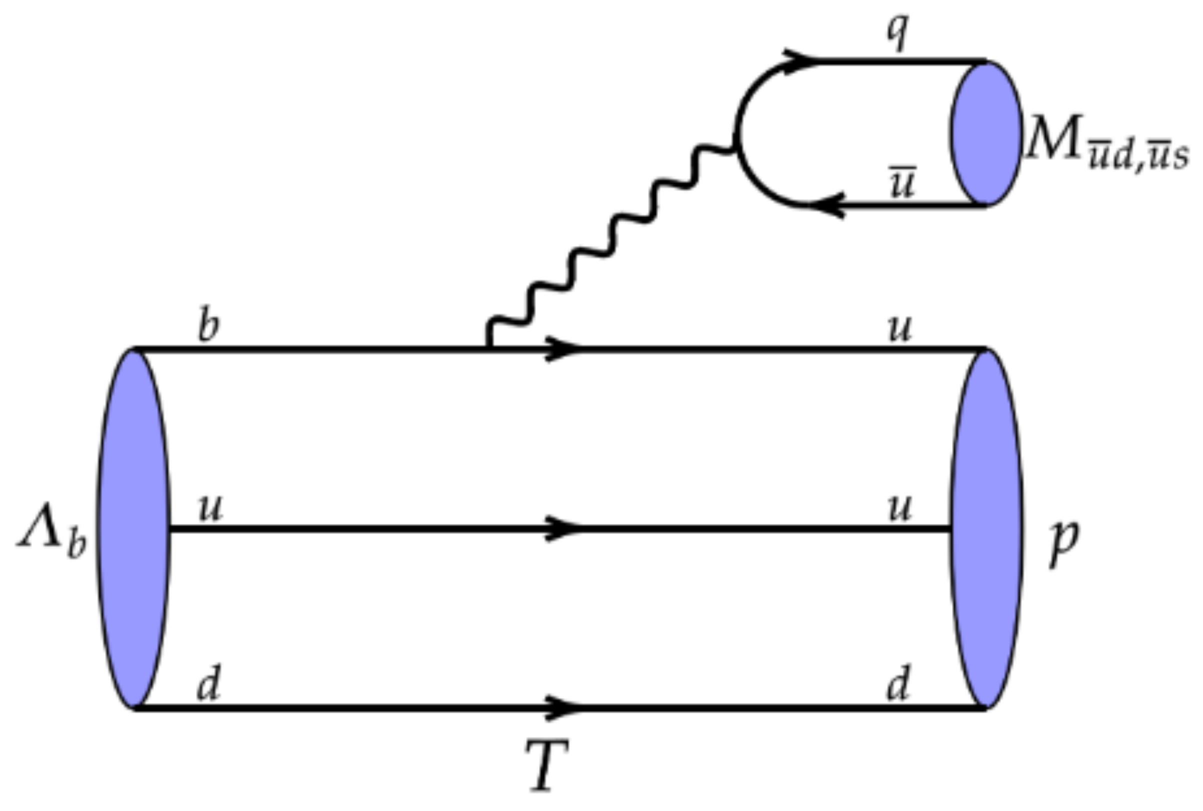
CPV cancelled between S- and P-waves

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

penguin:



tree:



$\bar{u}_p \cdots (1-\gamma_5) u_{\Lambda_b}$

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

$$\Lambda_b \to p\pi^- \;:\; A_{CP}^S = 15\,\%\,,\quad A_{CP}^P = -\,7\,\%\,,\quad A_{CP}^{\rm tot} = (4.1^{+0.8+1.2+1.2}_{-0.3-0.7-0.8})\,\%$$

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

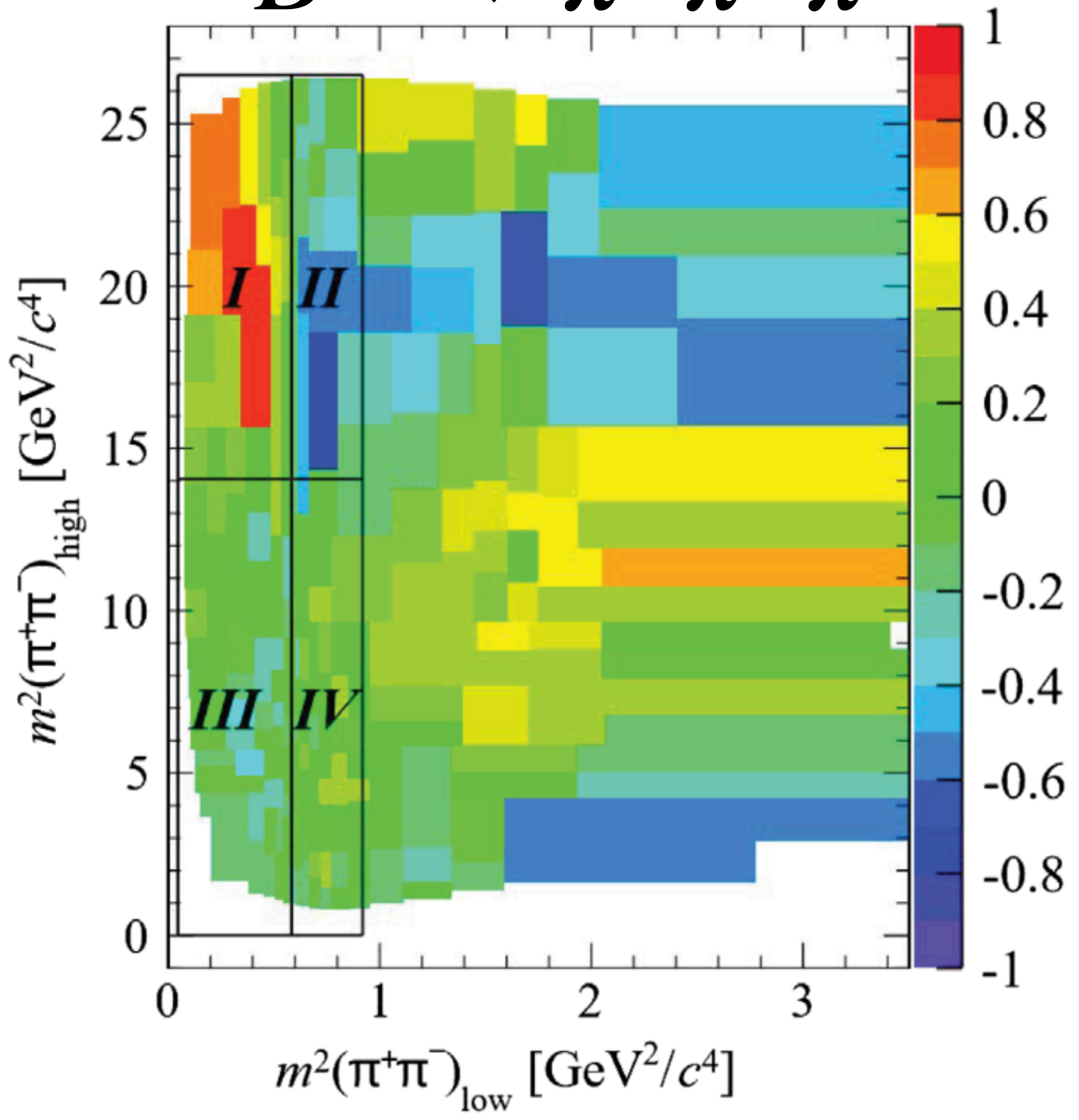
Multi-body decays

- More resonances, more partial waves, thus more chances.
- 3σ evidence in $\Lambda_b \to p\pi\pi\pi$ [LHCb, 2016]. But not observation until now.
- Total CPV of multi-body decays are usually $\leq 10\,\%$, due to the CPT theorem and thus identical lifetimes of particle and anti-particle.
- But **regional CPV could be very large.**

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

- **Dynamics is important. Search for large regional CPV**

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



- S- & P-wave interference, $f_0(500) - \rho(770)$

Outline

1. Why baryon CPV? Motivation

2. Why not yet observed for baryon CPV?

3. **What process and When to observe baryon CPV?**

✓**New proposal: $N\pi$ rescatterings**

Multi-body decays of Λ_b

- For first observation of baryon CPV, it must be multi-body decays of Λ_b.
- Advantage: more resonances, more chances for large CPV
- Disadvantage: Too many resonances, and with large uncertainties

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

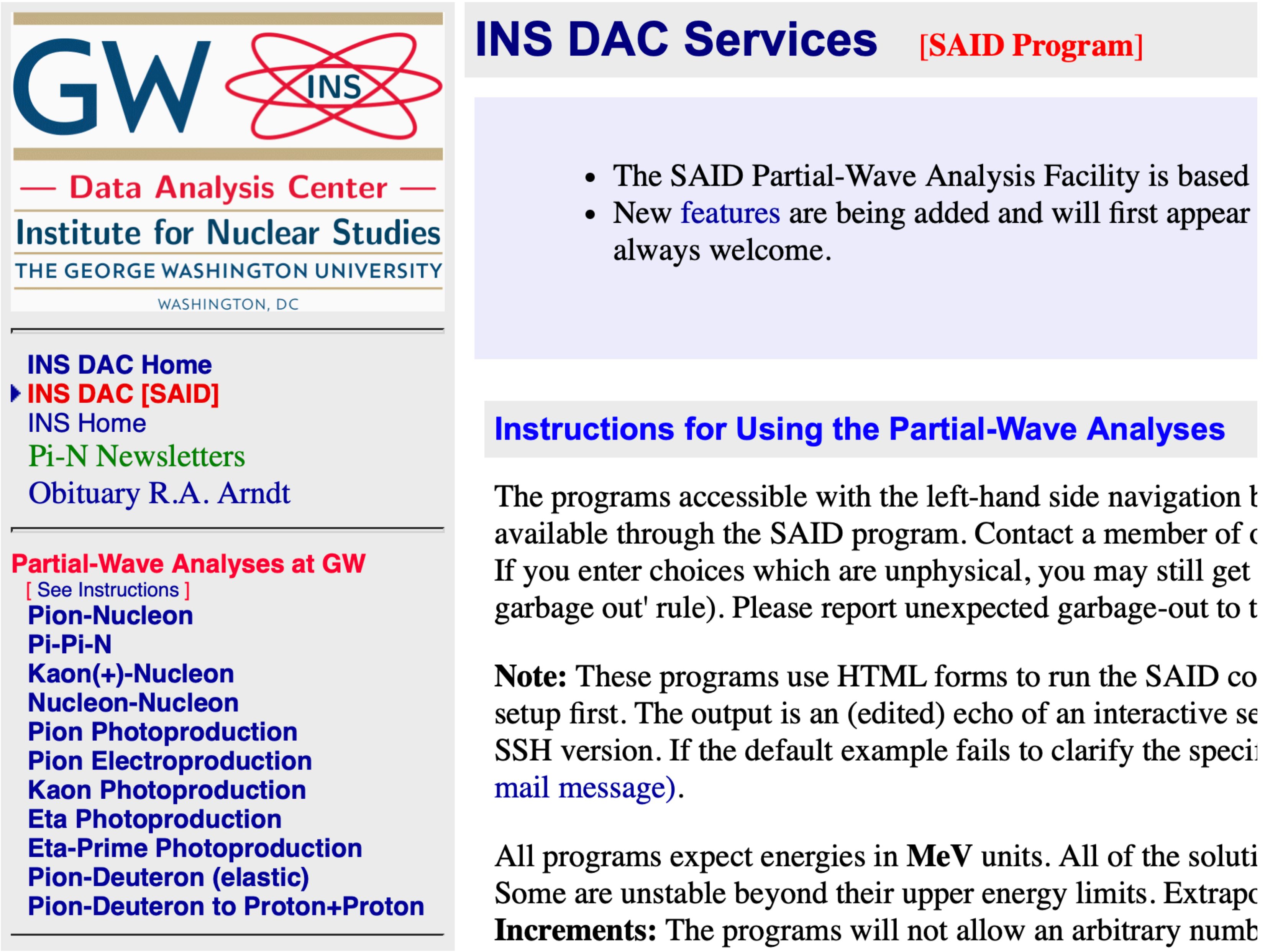
$N(1700)$ BREIT-WIGNER MASS	1650 to 1800 ($\approx$ 1720) MeV
$N(1700)$ BREIT-WIGNER WIDTH	100 to 300 ($\approx$ 200) MeV
$N(1710)$ BREIT-WIGNER MASS	1680 to 1740 ($\approx$ 1710) MeV
$N(1710)$ BREIT-WIGNER WIDTH	80 to 200 ($\approx$ 140) MeV
$N(1720)$ BREIT-WIGNER MASS	1680 to 1750 ($\approx$ 1720)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

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

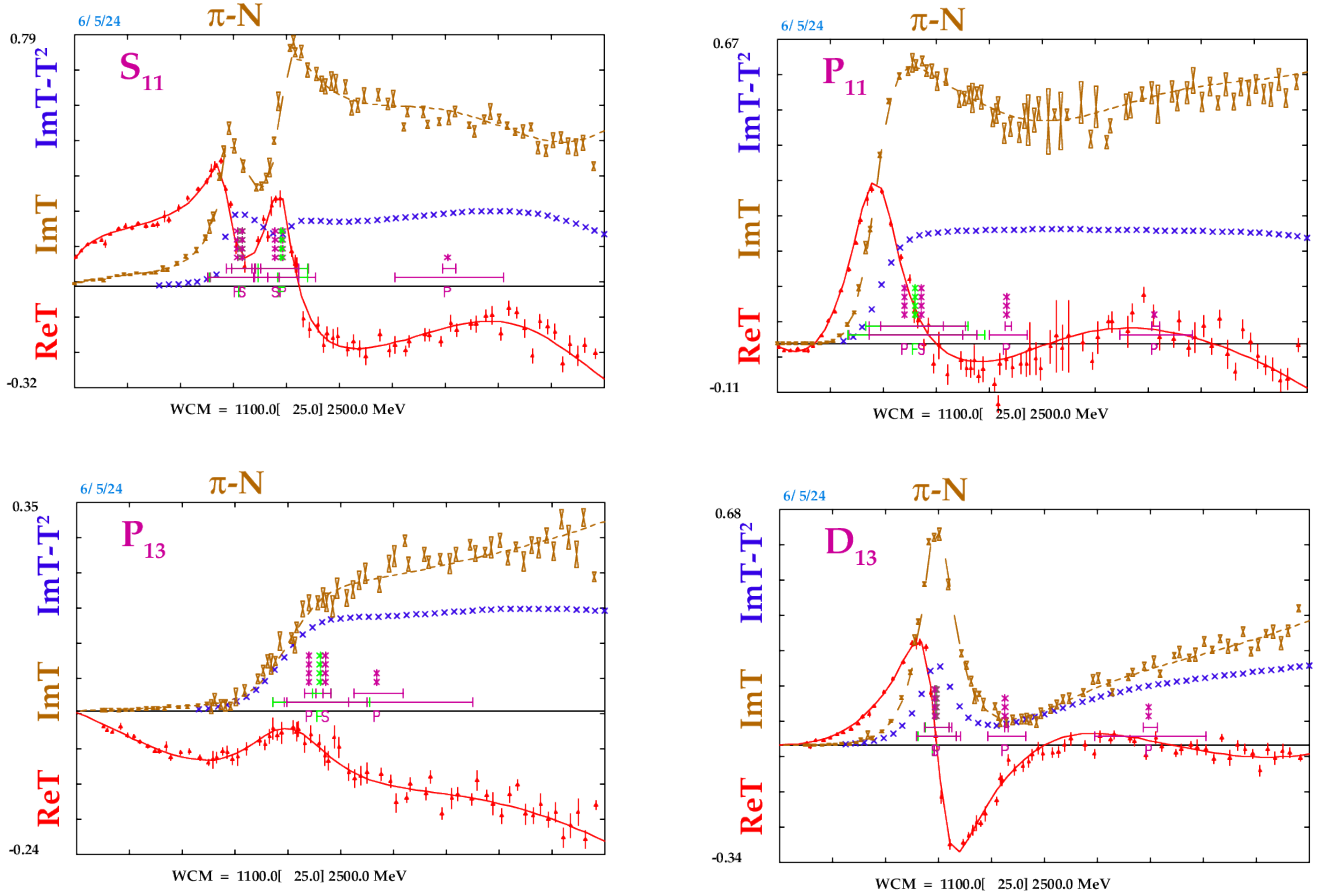
$N\pi$ scatterings

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

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



$N\pi \rightarrow N\pi$



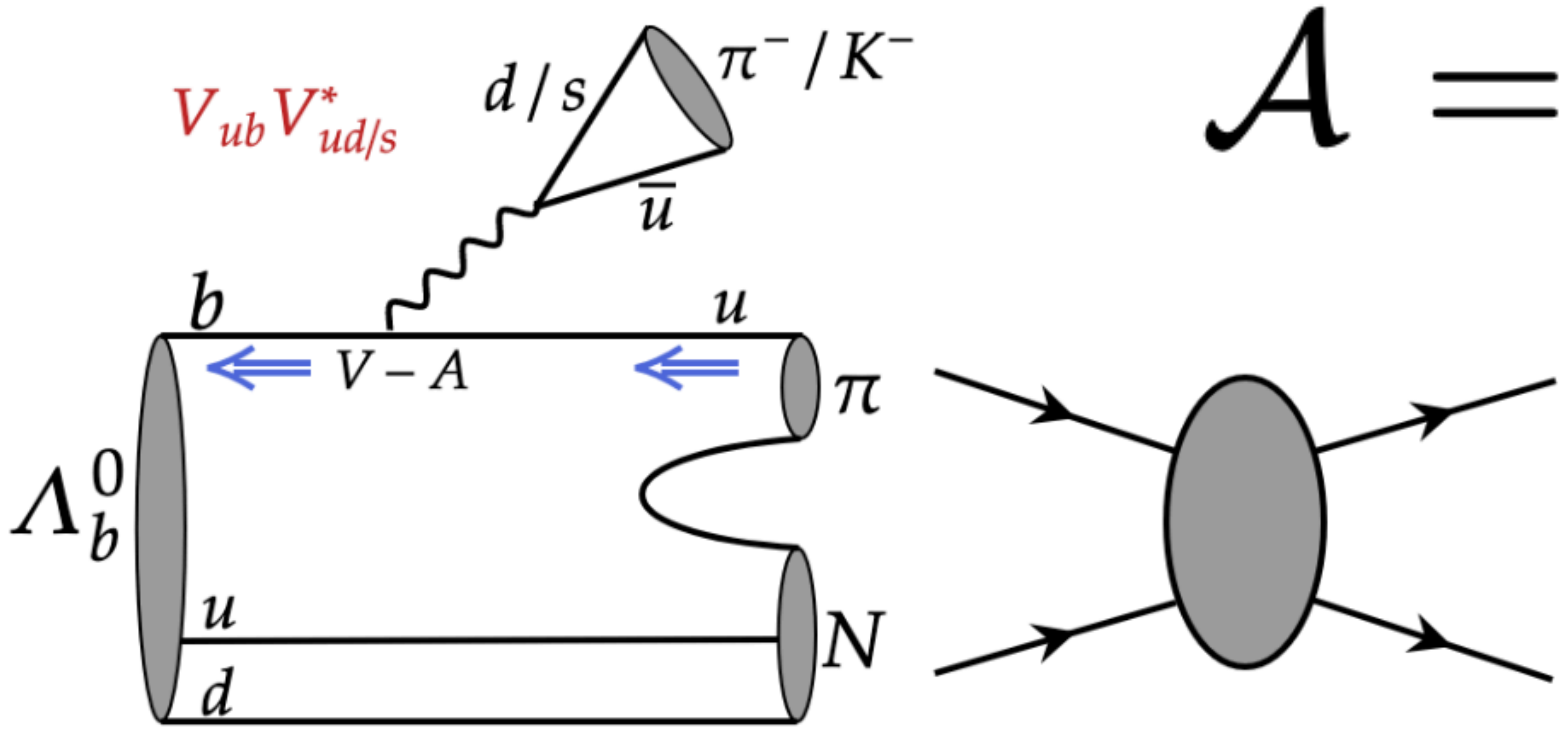
- Partial-wave amplitudes with strong phases!

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

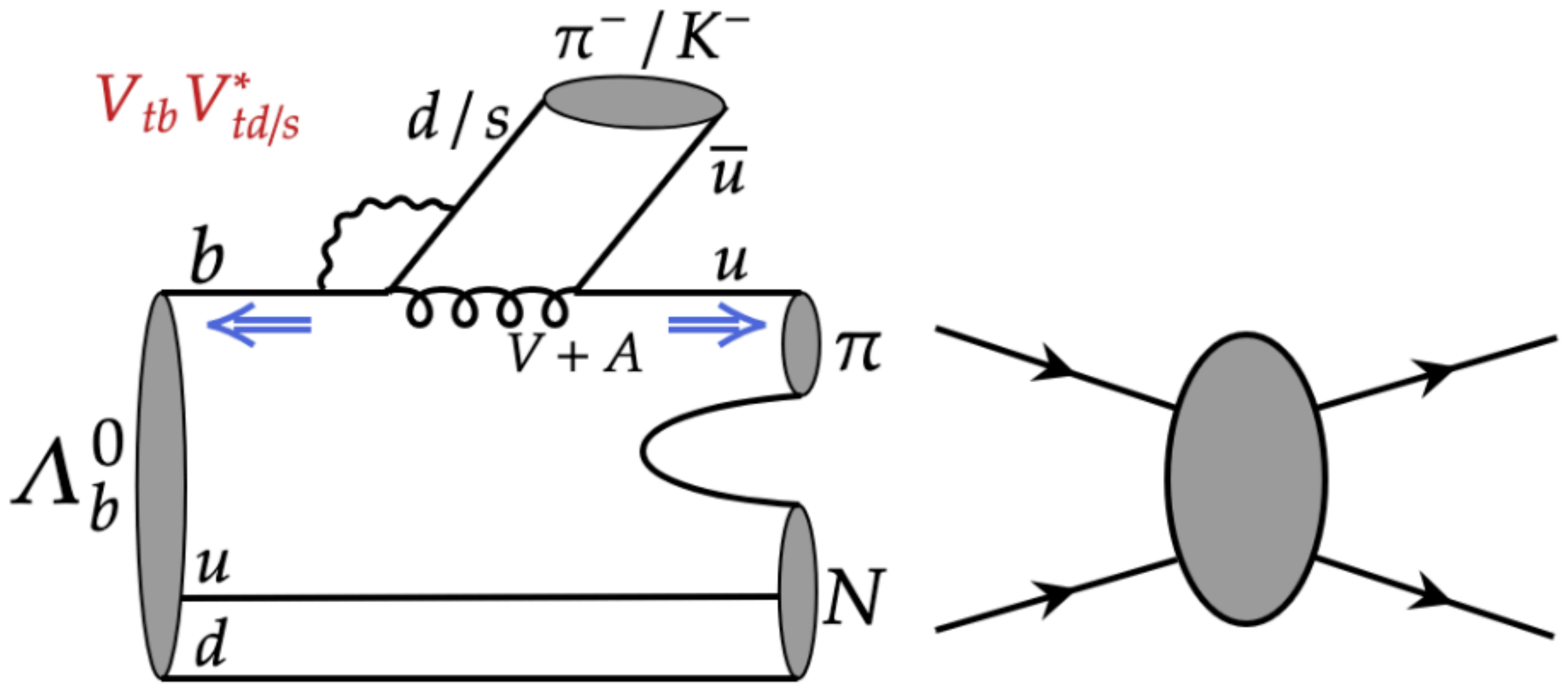
CPV from $N\pi$ scatterings

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

- Tree:



- Penguin:



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

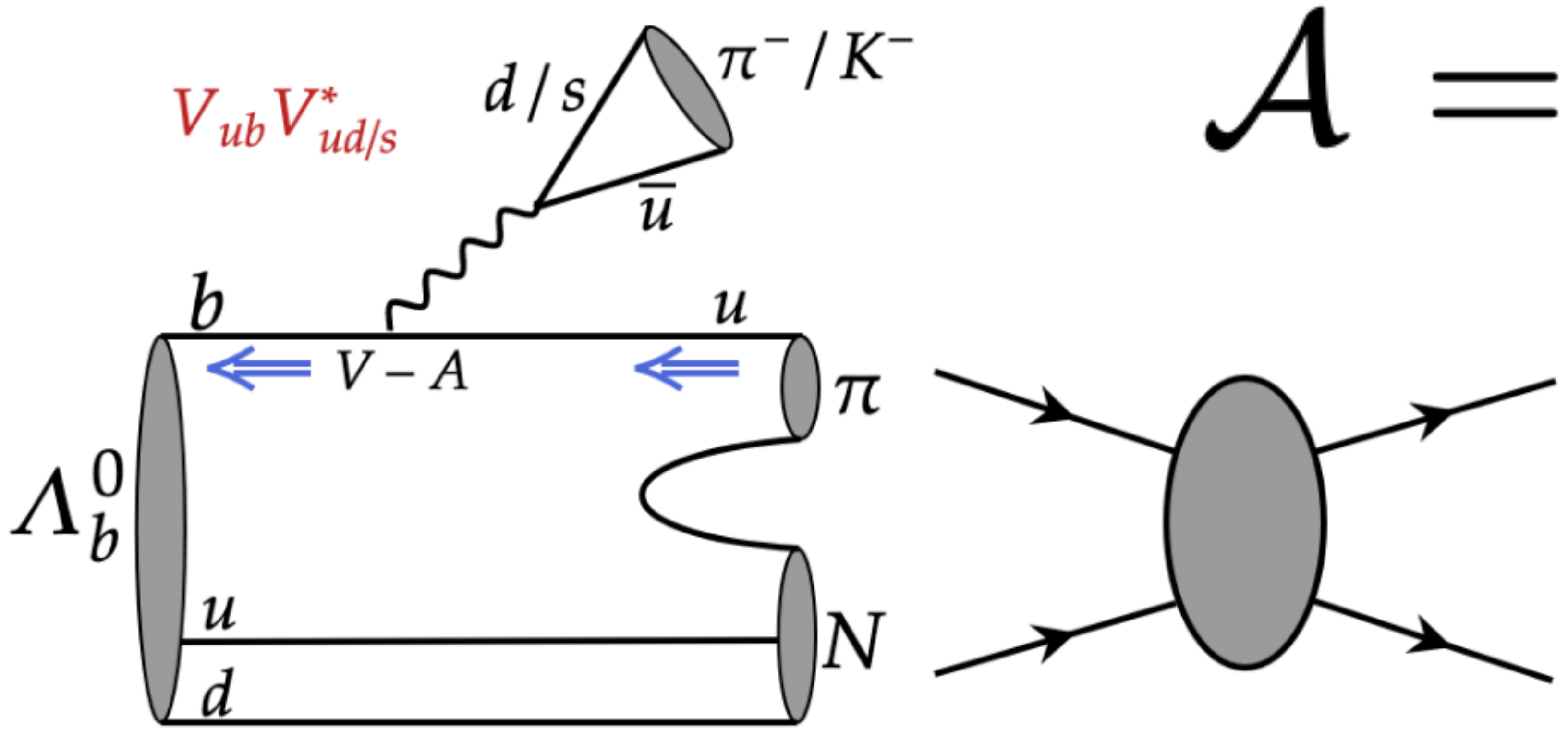
- weak phase
- strong phase

J.P.Wang, FSY, 2407.04110

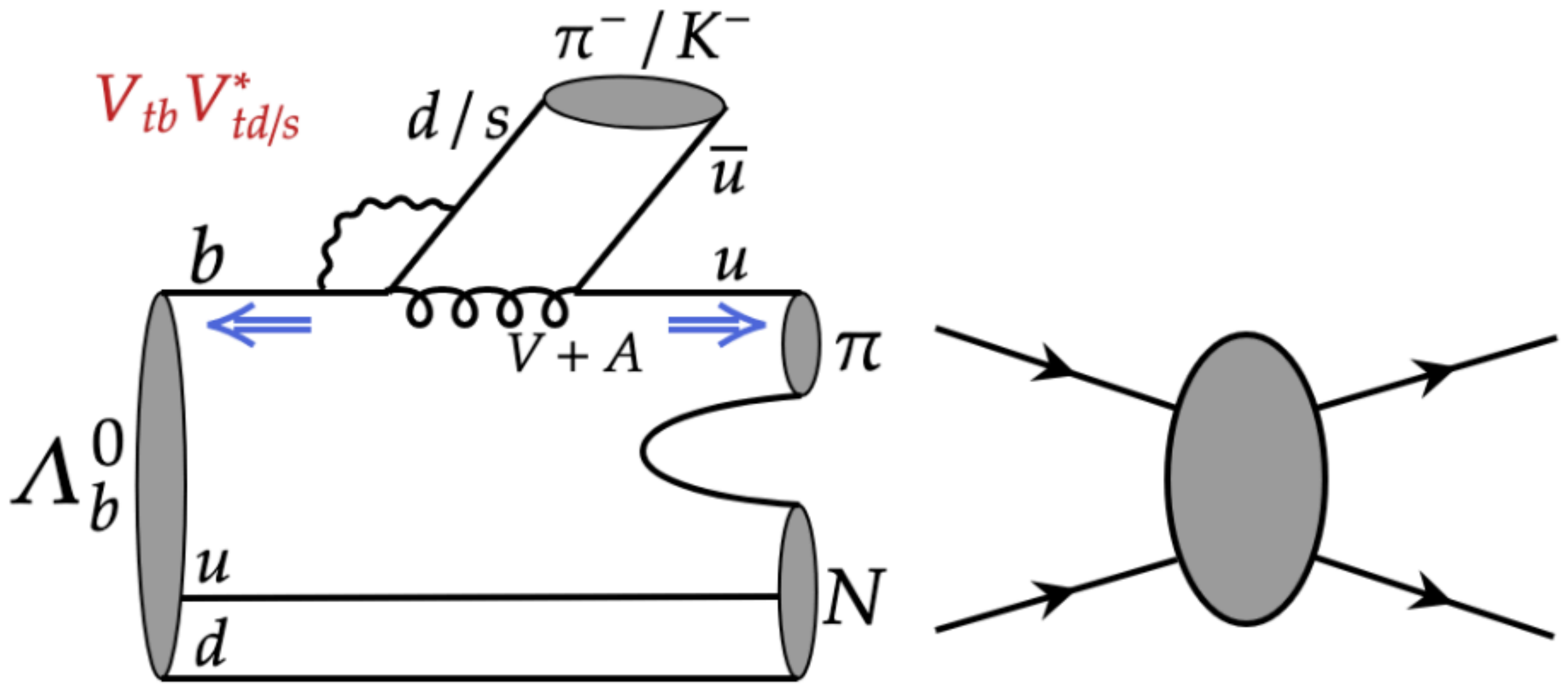
CPV from $N\pi$ scatterings

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

- Tree:



- Penguin:



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

- Different chirality

➡ different helicity

➡ different partial waves

➡ PWA interference

➡ difference of strong phases

➡ **CPV**

J.P.Wang, FSY, 2407.04110

CPV from $N\pi$ scatterings

- Suggestions: processes

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

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

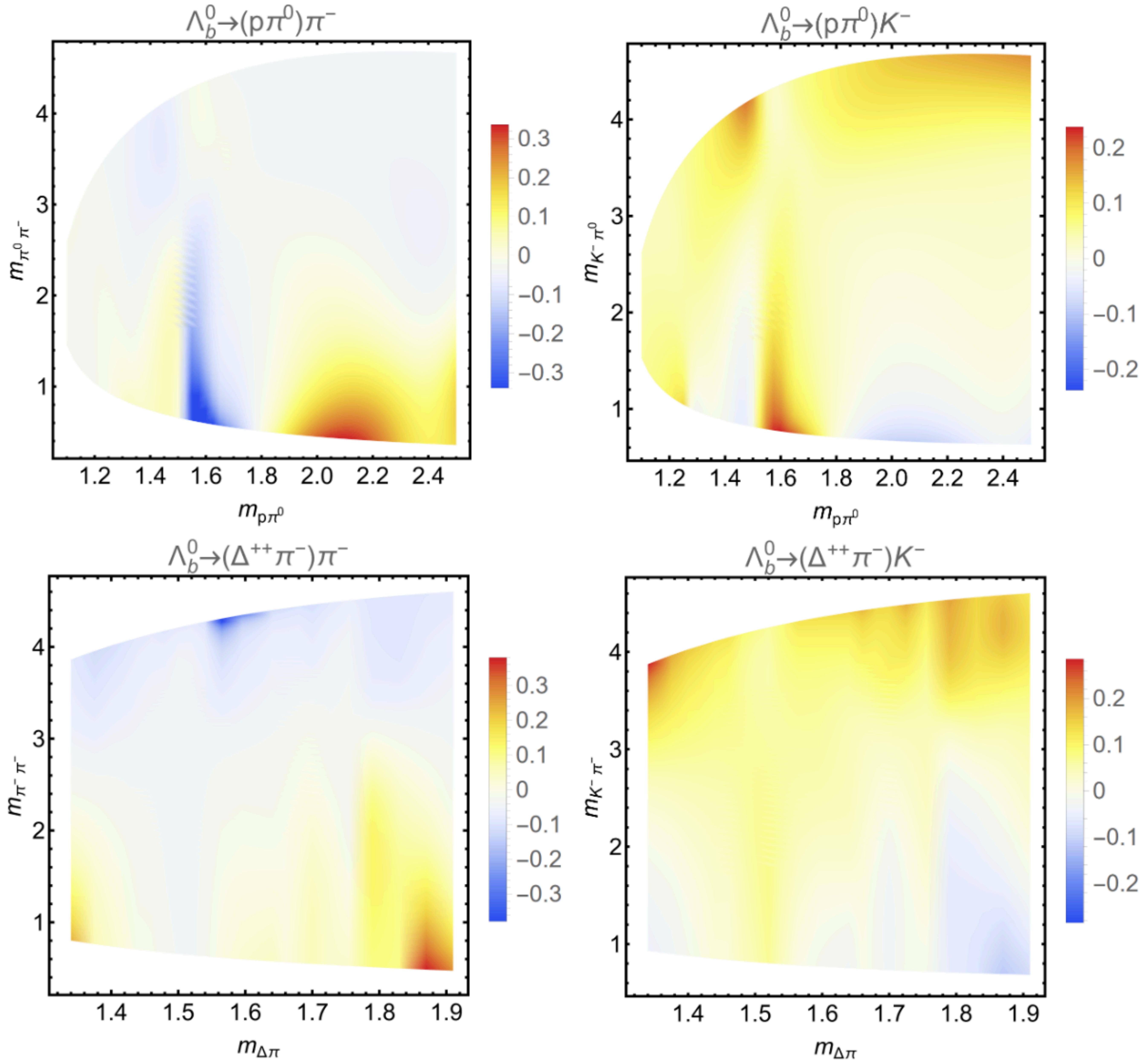
$$(N\pi \to p\pi\pi): \quad \Lambda_b^0 \to (p\pi^+\pi^-)\pi^-, \quad (p\pi^+\pi^-)K^-$$

- 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

Dalitz CPV from $N\pi$ scatterings

- 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



Global CPV from $N\pi$ scatterings

$N\pi$ scatterings	decay processes	global CPV	CPV of $\cos\theta < 0$	CPV of $\cos\theta > 0$
$N\pi \to \Delta^{++}\pi^-$	$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$	5.9%	8.0%	3.6%
$m_{N\pi} \in [1.2, 1.9]\mathrm{GeV}$	$\Lambda_b^0 \to (\Delta^{++}\pi^-)\pi^-$	-4.1%	-5.4%	-2.4%
$N\pi \to p\pi^0$	$\Lambda_b^0 \to (p\pi^0)K^-$	5.8%	8.2%	2.7%
$m_{N\pi} \in [1.1, 2.5]\mathrm{GeV}$	$\Lambda_b^0 \to (p\pi^0)\pi^-$	-3.9%	-3.9%	-3.7%

J.P.Wang, FSY, 2407.04110

CPV of Legendre moments

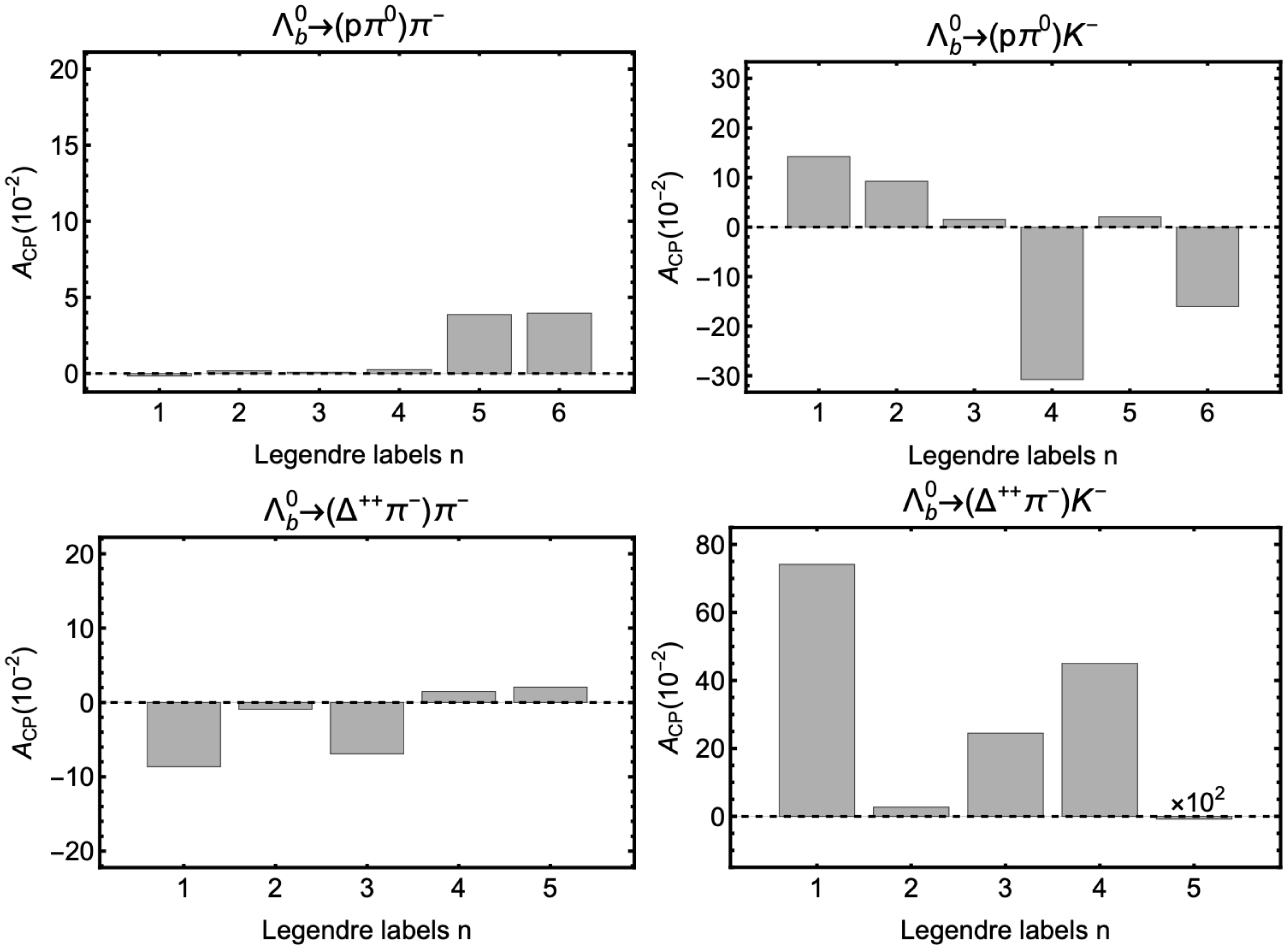
$$\frac{d\Gamma}{d\cos\theta} \propto \sum_{n=0} \mathcal{L}_n P_n(\cos\theta)$$

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

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

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

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



Summary and outlook

- Baryon CPV is a new horizon of heavy flavor physics.
- We propose a new CPV mechanism from $N\pi$ scatterings
- Large CPV could be observed soon.
- $N\pi$ scatterings can be used in amplitude analysis.

Thank you!

$\Lambda_b \to p\pi^-$	$\|S\|$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\|P\|$	$\phi(P)^\circ$	Real(P)	Imag(P)
T_f	705.23	0.00	705.23	-0.00	999.83	0.00	999.83	-0.00
T_{nf}	59.39	-96.19	-6.40	-59.04	261.83	-98.04	-36.63	-259.26
C'	28.67	154.23	-25.82	12.46	41.12	177.74	-41.09	1.62
E_2	68.37	-143.60	-55.03	-40.57	74.29	122.16	-39.55	62.89
B	9.98	87.19	0.49	9.97	12.75	-115.34	-5.45	-11.52
Tree	623.26	-7.11	618.47	-77.19	901.03	-13.23	877.10	-206.27
$P_f^{C_1}$	58.38	0.00	58.38	0.00	2.90	0.00	2.90	0.00
$P_{nf}^{C_1}$	1.35	-109.77	-0.46	-1.27	10.71	-97.31	-1.36	-10.62
P^{C_2}	13.23	-115.55	-5.71	-11.94	15.15	69.75	5.24	14.21
$P^{E_1^u}$	8.92	-88.28	0.27	-8.91	8.59	112.64	-3.31	7.93
P^B	1.38	-43.29	1.00	-0.95	1.27	-177.04	-1.27	-0.07
$P^{E_1^d} + P^{E_2}$	3.55	-103.32	-0.82	-3.46	2.13	5.67	2.12	0.21
Penguin	58.97	-26.74	52.67	-26.53	12.44	69.67	4.32	11.67

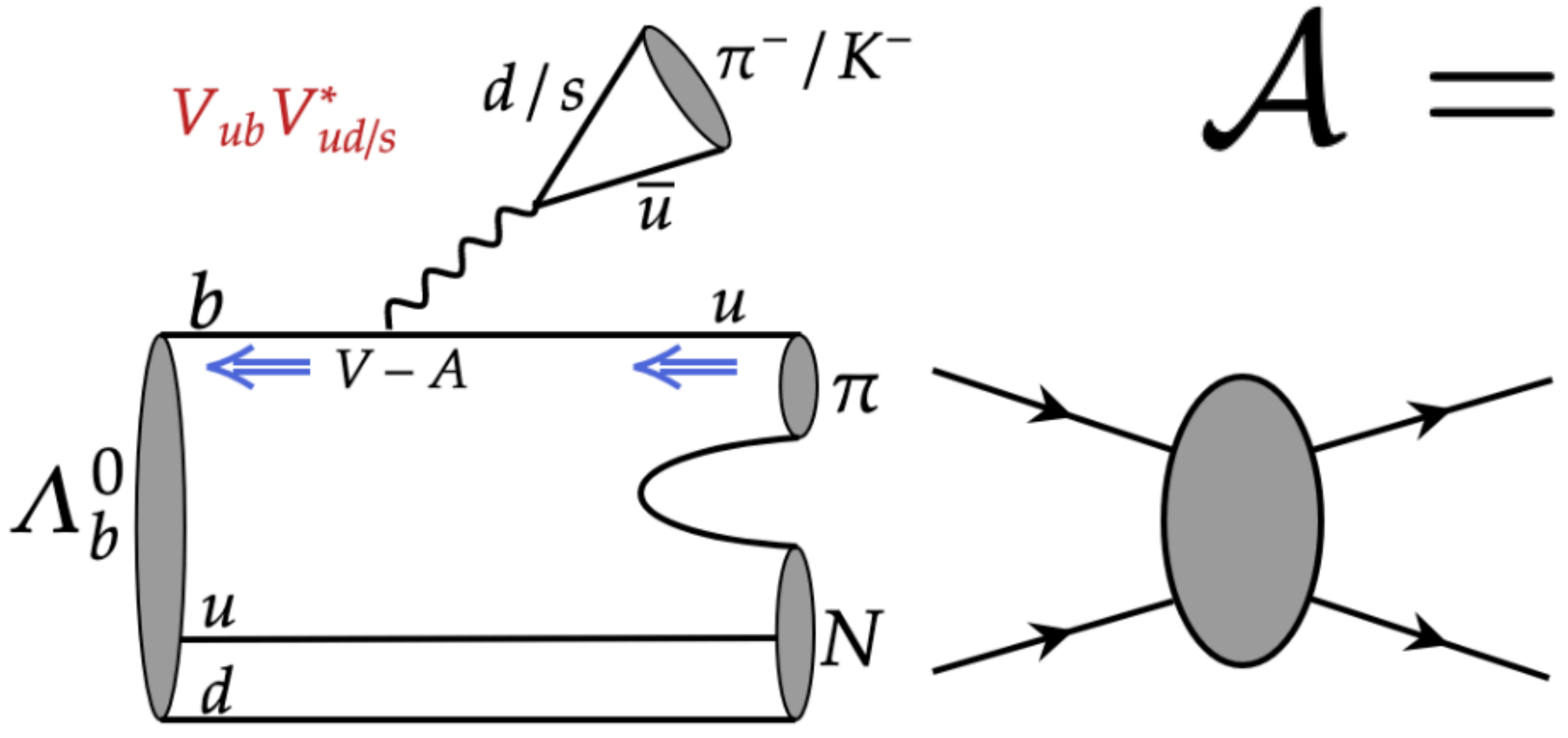
$\Lambda_b \to pK^-$	$\lvert S \rvert$	$\phi(S)^\circ$	Real(S)	Imag(S)	$\lvert P \rvert$	$\phi(P)^\circ$	Real(P)	Imag(P)
T_f	865.26	0.00	865.26	-0.00	1230.27	0.00	1230.27	-0.00
T_{nf}	59.55	-96.39	-6.63	-59.18	346.03	-97.78	-46.84	-342.85
E_2	89.83	-139.95	-68.77	-57.80	81.80	121.73	-43.02	69.57
Tree	798.47	-8.42	789.86	-116.98	1172.70	-13.48	1140.41	-273.27
$P_f^{C_1}$	76.56	0.00	76.56	0.00	3.29	180.00	-3.29	0.00
$P_{nf}^{C_1}$	0.96	-122.66	-0.52	-0.80	14.20	-93.96	-0.98	-14.17
$P^{E_1^u}$	11.73	-90.78	-0.16	-11.73	10.94	114.13	-4.47	9.98
$P^{E_1^d}$	7.33	-96.70	-0.86	-7.28	2.53	52.22	1.55	2.00
Penguin	77.61	-14.79	75.03	-19.81	7.52	-163.11	-7.19	-2.18

CPV from $N\pi$ scatterings

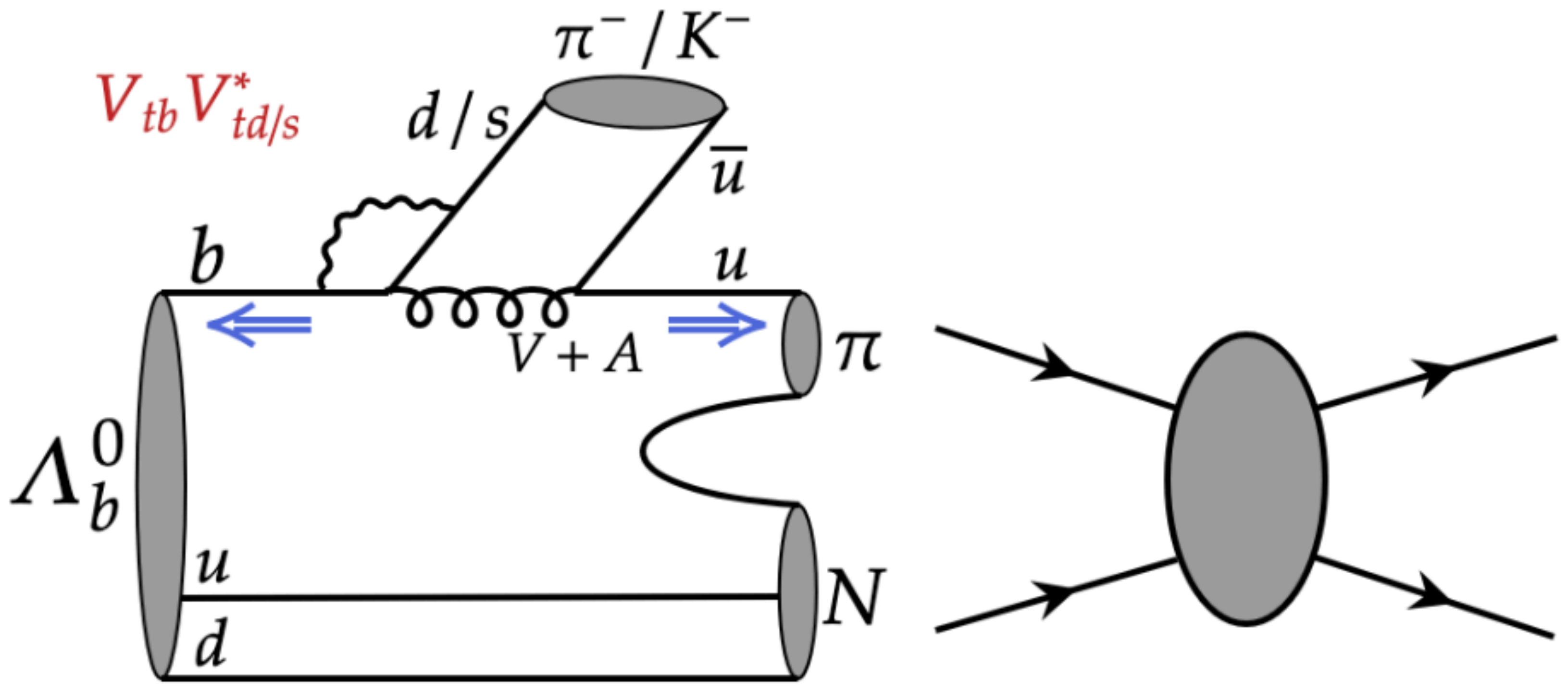
$$\mathcal{A} = \mathcal{S}^{1/2}\mathcal{A}_0$$

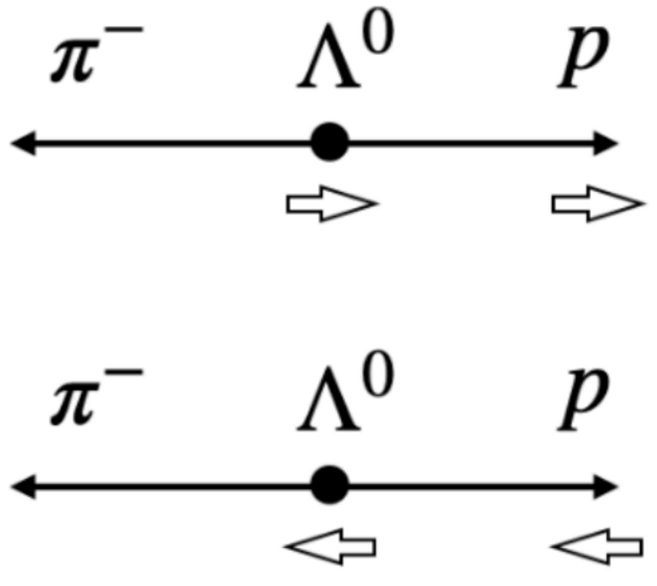
$$\mathcal{A}(\Lambda^0 \to p\pi^-) = \bar{u}_p(S + P\gamma_5)u_\Lambda$$

- 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 from $N\pi \to N\pi$ scattering

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

tree

$$+ a_1\left(-S_{11}g_1^{1/2^-} + P_{11}g_1^{1/2^+} + \ldots\right)(m_{\Lambda_b} + m_{N\pi})\gamma_5\Big]u_{\Lambda_b}$$

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

penguin

$$+\left(-(a_4 + R_\pi a_6)S_{11}g_1^{1/2^-} + (a_4 - R_\pi a_6)P_{11}g_1^{1/2^+} + \ldots\right)(m_{\Lambda_b} + m_{N\pi})\gamma_5\Big]u_{\Lambda_b}$$

$a_1 = 1.016, \; a_4 = -0.021, \; a_6 = -0.032, \; R_\pi = 1.25.$ $\qquad a_4 + R_\pi a_6 = -0.06, \qquad a_4 - R_\pi a_6 = 0.02.$