Theoretical progresses on beautiful baryonic CP violation

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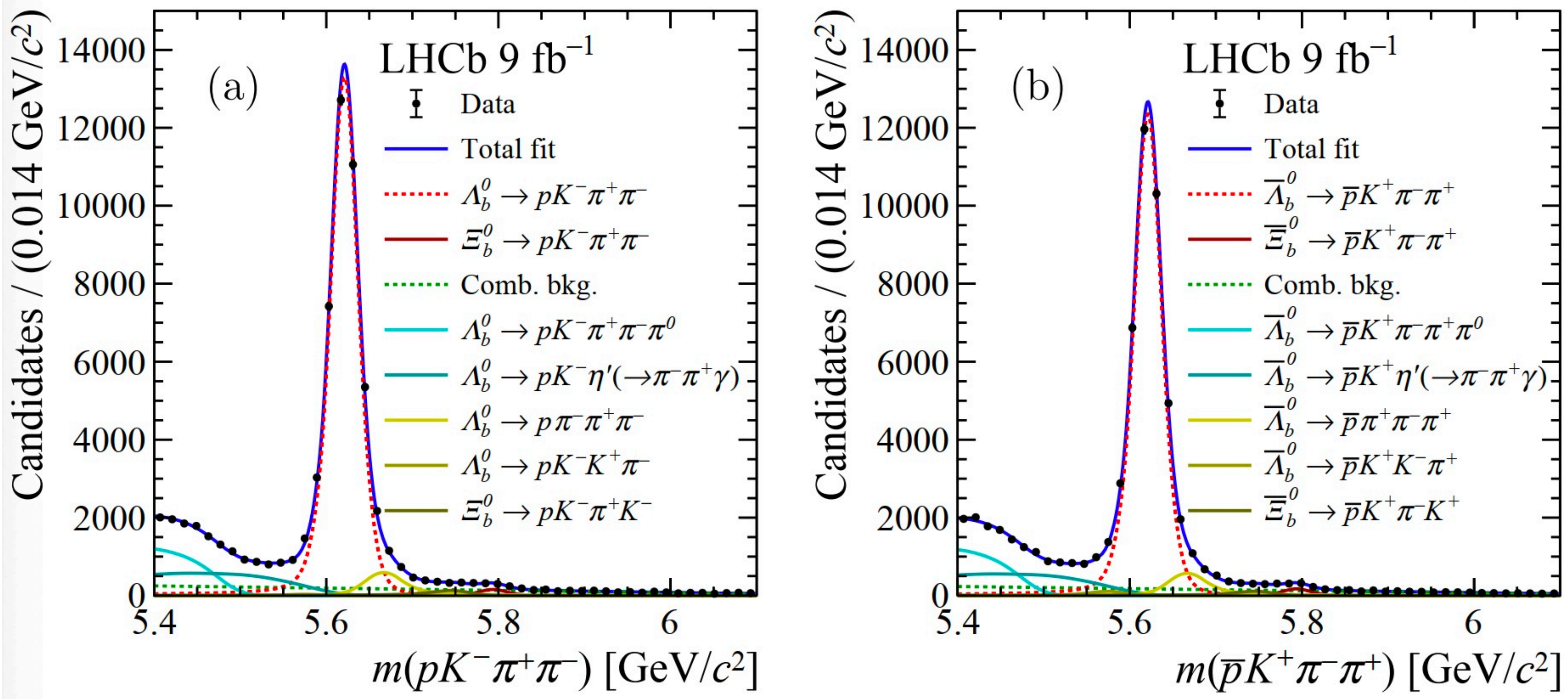
Discovery of baryonic CP violation

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

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

$$5.2\ \sigma$$



Congratulations to the LHCb colleagues!

[LHCb, 2503.16954, submitted to Nature]

Outline

- ❖ **Theoretical studies before the baryonic CP violation discovery**
  - ➡ Theoretical prediction
  - ➡ Observable construction
- ❖ **Theoretical studies after the baryonic CP violation discovery**
  - ➡ Understand the underlying dynamics
  - ➡ New platform of the CKM test

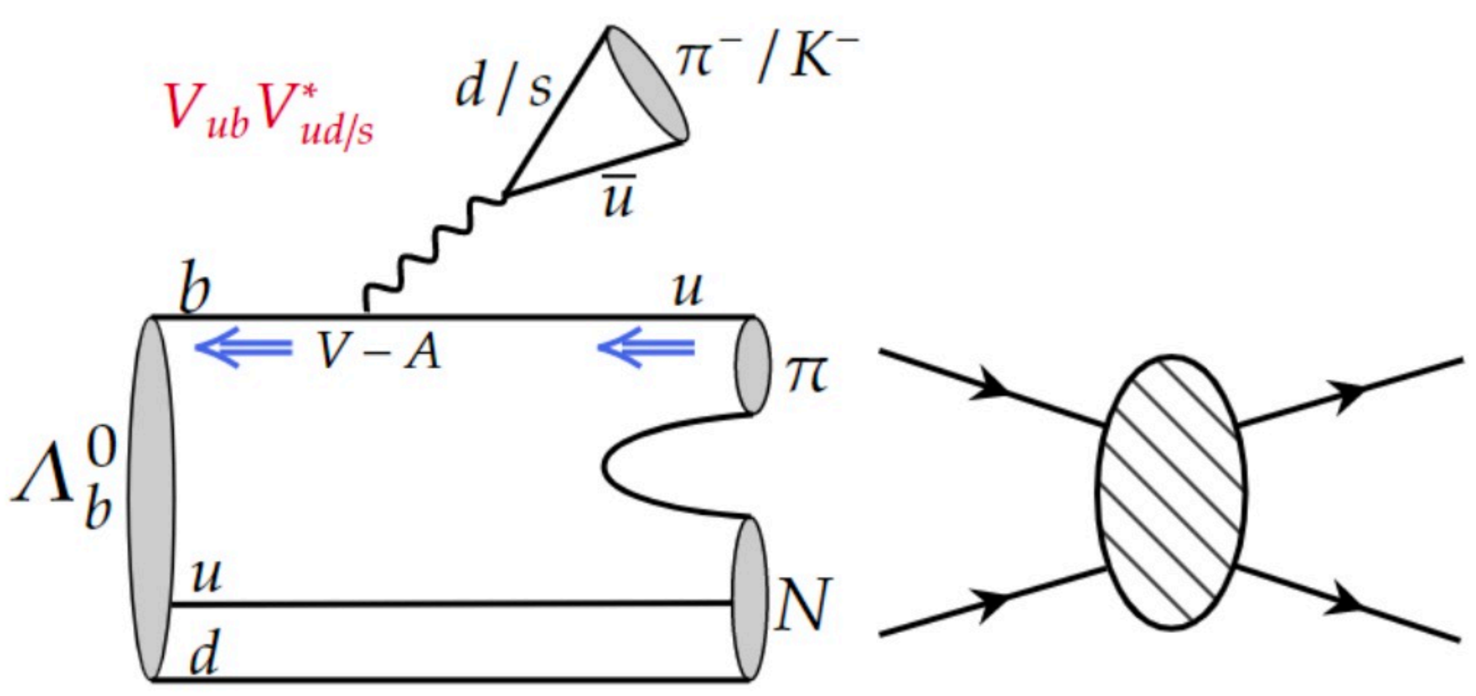
Before the baryonic CP violation discovery

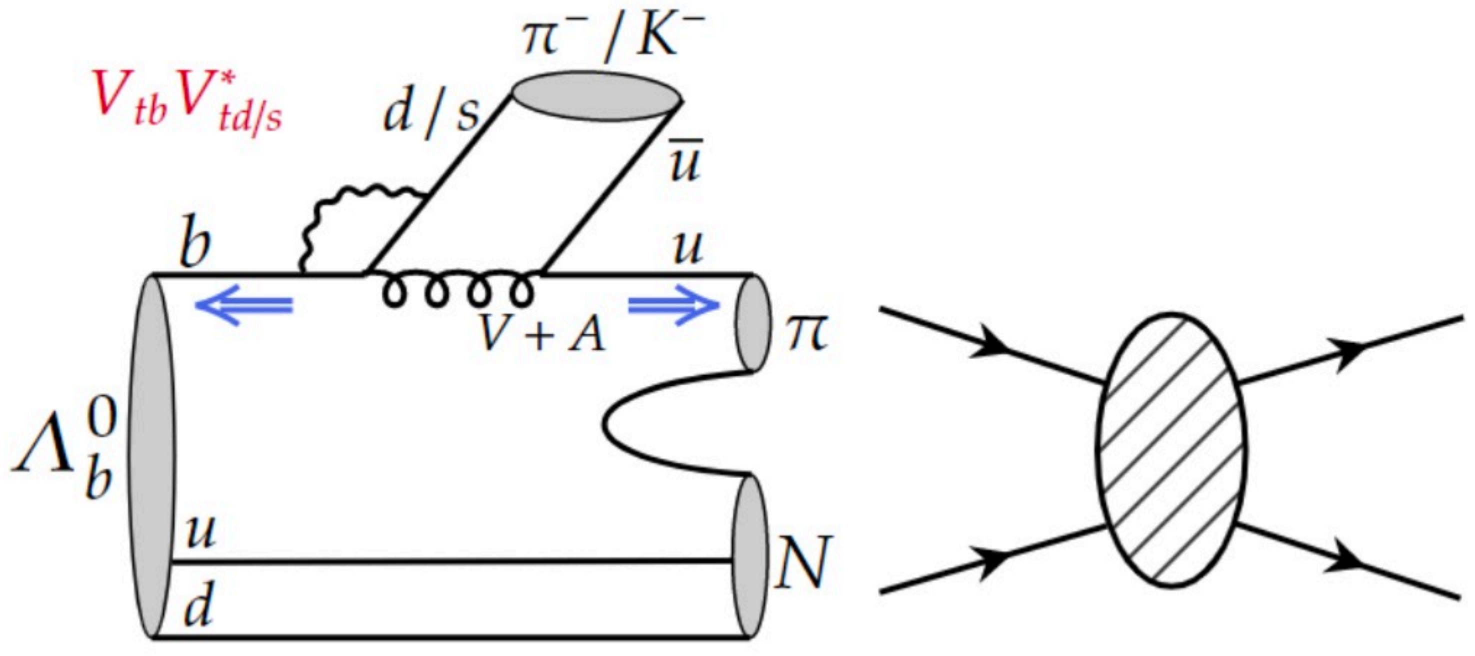
Theoretical prediction

❖ **Final-state $N\pi$ scattering** for $\Lambda_b \to K^-(p\pi^+\pi^-)$

See Fu-Sheng's talk

➡ Strong phases extracted from data





Prediction

decay processes	Scenarios	global CPV
	S1	5.9%
$\Lambda_b^0 \to (\Delta^{++}\pi^-)K^-$	S2	5.8%
$m_{N\pi} \in$ [1.2, 1.9] GeV	S3	5.6%

[Wang,Yu, CPC, 2407.04110]

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

Measurement

[LHCb, 2503.16954, submitted to Nature]

Theoretical prediction

- ❖ **Generalized Factorization Approach** [Hsiao,Liu,Geng,Yu, …]
- ❖ **QCD Factorization** (diquark) [Ke,Wei,…]
- ❖ **Perturbative QCD** [Li,Yu,Zhou …]
- ❖ **Final-state interaction** [Duan,Li,Lu,Wang,Yu, …]
- ❖ **Symmetry analysis** [He,Wang,Wang,Xing, …]

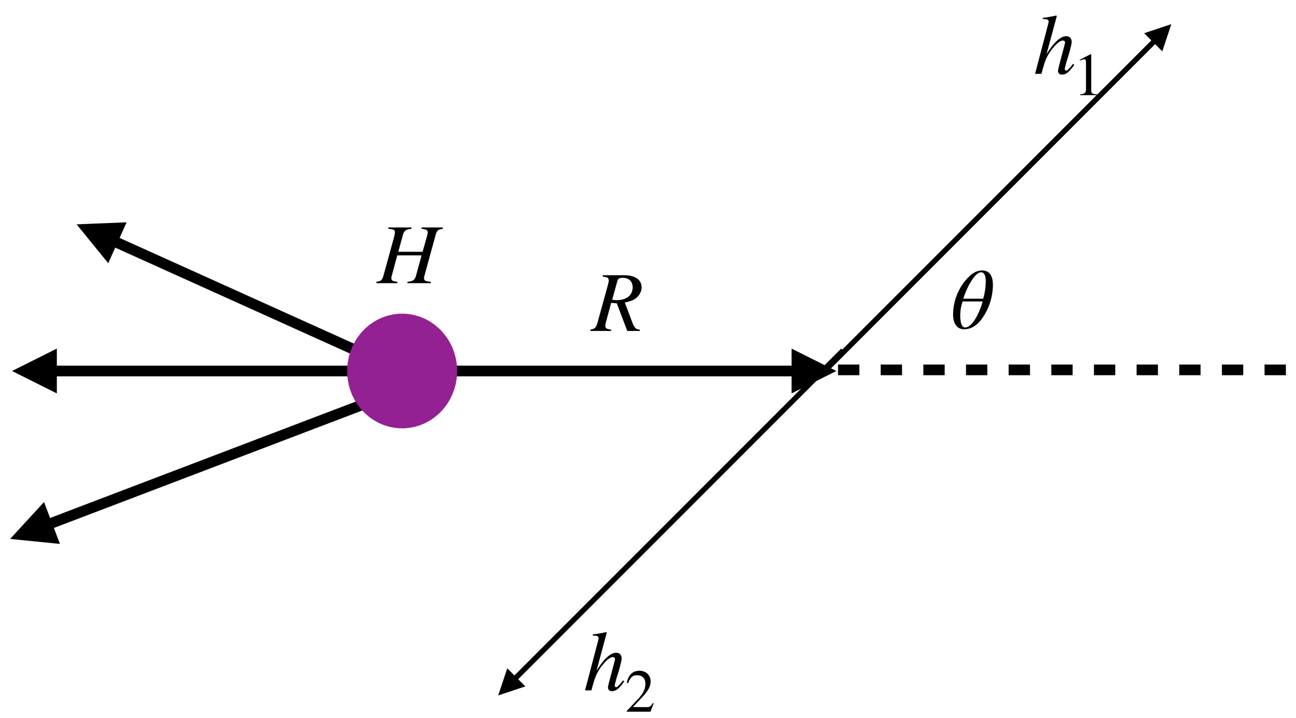
See Fu-Sheng’s talk

Observable construction

❖ **Partial-wave CP asymmetry**: In multi-body ($n \geq 3$) decays $H \to R\ldots \to h_1 h_2 \ldots,$ decay width can be expanded with the Legendre's polynomials, and the partial wave CP asymmetry is hereby defined

$$\overline{|\mathcal{M}|^2} \propto \sum_{j=0}^{\infty} w^{(j)} P_j(c_{\theta_1^*}), \quad \Rightarrow \quad A_{CP}^{(j)} \equiv \frac{w^{(j)} - \bar{w}^{(j)}}{w^{(j)} + \bar{w}^{(j)}}$$

θ_1^* : angle between h_1 and H in the $h_1 h_2$ rest frame



❖ It has at least the following advantages:

1. Combine information in each bins in Dalitz plots

2. Different resonances R may induce interferences with <u>large relative strong phases</u>

[Zhang, Guo, et al, 2103.11335, 2208.13411, 2209.13196]

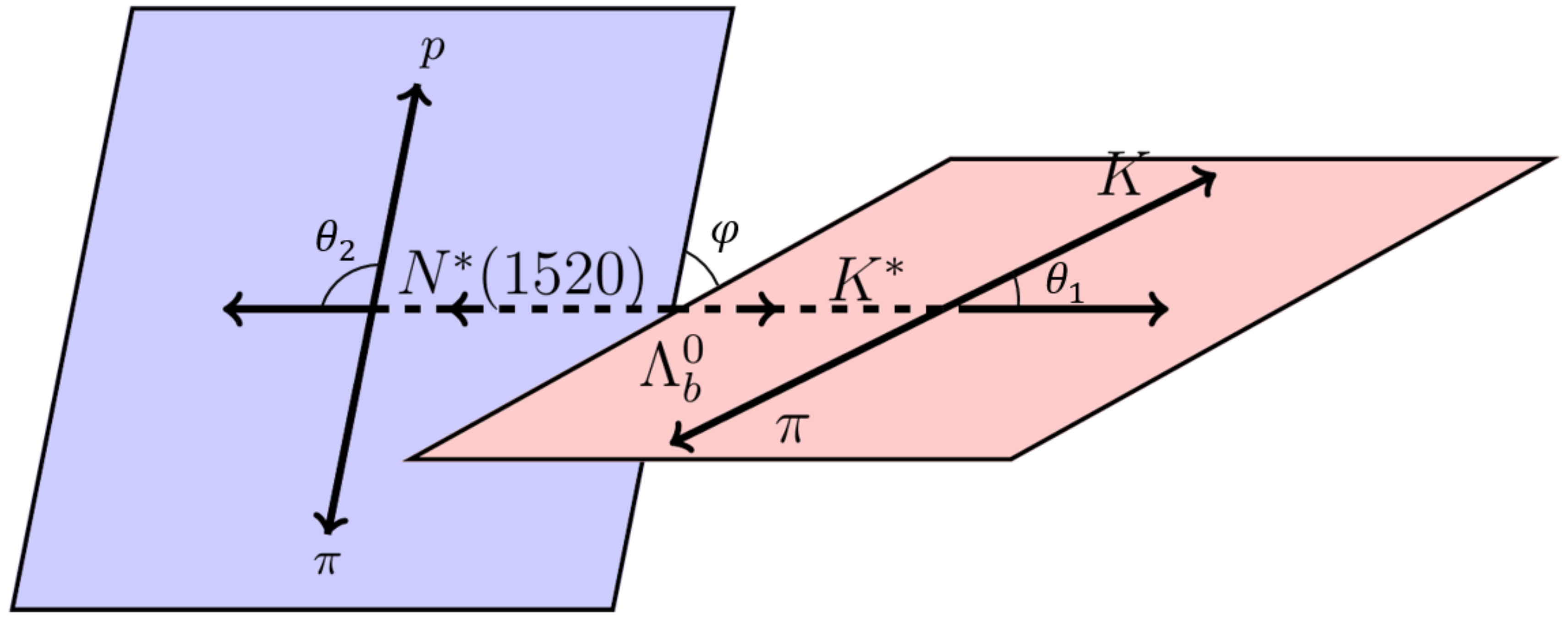
Observable construction

❖ **Complementary T-odd and T-even CP asymmetries** (generalization of α, β, γ):

➡ Measured by weight-function expectation

➡ Dependence on cosine and sine of strong phases

See Prof. Li's talk



$$\frac{d\Gamma}{dc_1\, dc_2\, d\varphi} \propto \mathrm{s}_1^2\mathrm{s}_2^2\left(\left|\mathcal{H}_{+1,+\frac{3}{2}}\right|^2+\left|\mathcal{H}_{-1,-\frac{3}{2}}\right|^2\right)$$
$$+\,\mathrm{s}_1^2\left(\frac{1}{3}+\mathrm{c}_2^2\right)\left(\left|\mathcal{H}_{+1,+\frac{1}{2}}\right|^2+\left|\mathcal{H}_{-1,-\frac{1}{2}}\right|^2\right)$$
$$+\,2\mathrm{c}_1^2\left(\frac{1}{3}+\mathrm{c}_2^2\right)\left(\left|\mathcal{H}_{0,-\frac{1}{2}}\right|^2+\left|\mathcal{H}_{0,+\frac{1}{2}}\right|^2\right)$$

$\sin 2\varphi s_1 s_2 \rightarrow$ $$-\frac{\mathrm{s}_1^2\mathrm{s}_2^2}{\sqrt{3}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}}+\mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin 2\varphi$$

$\cos 2\varphi s_1 s_2 \rightarrow$ $$+\frac{\mathrm{s}_1^2\mathrm{s}_2^2}{\sqrt{3}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}}+\mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos 2\varphi$$

$\sin \varphi c_1 c_2 \rightarrow$ $$-\frac{4\mathrm{s}_1\mathrm{c}_1\mathrm{s}_2\mathrm{c}_2}{\sqrt{6}}\mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}}+\mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\sin\varphi$$

$\cos \varphi c_1 c_2 \rightarrow$ $$+\frac{4\mathrm{s}_1\mathrm{c}_1\mathrm{s}_2\mathrm{c}_2}{\sqrt{6}}\mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}}+\mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right)\cos\varphi$$

$\boxed{\cos\delta_s \text{ vs } \sin\delta_s}$

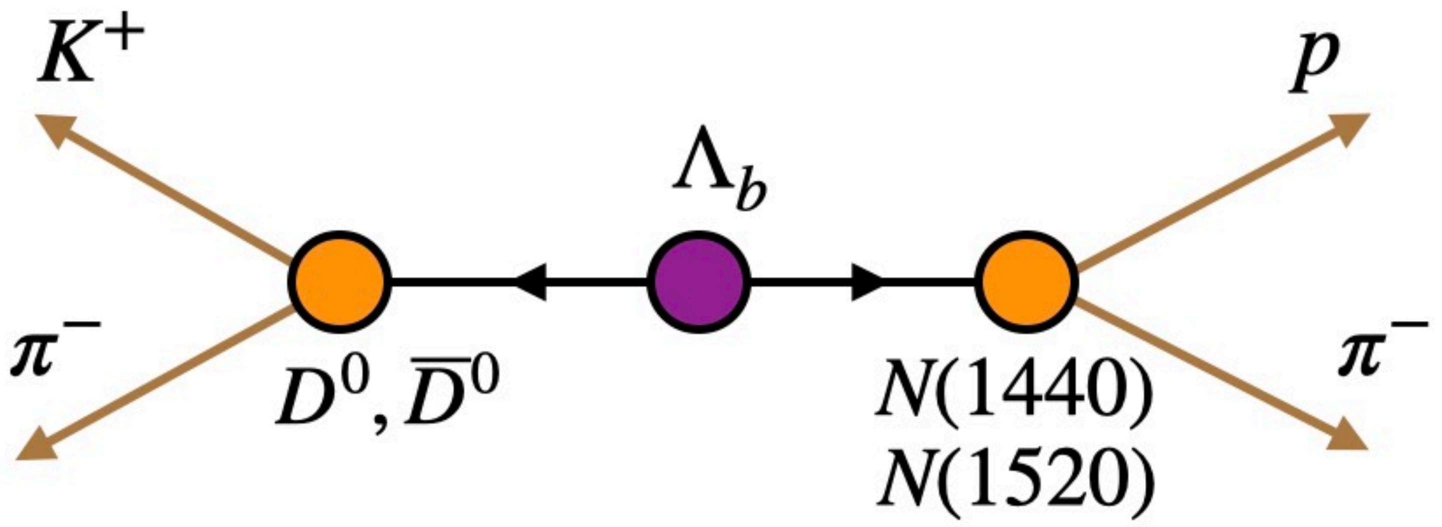
[Wang, **QQ**, Yu, 2211.07332, 2411.18323]

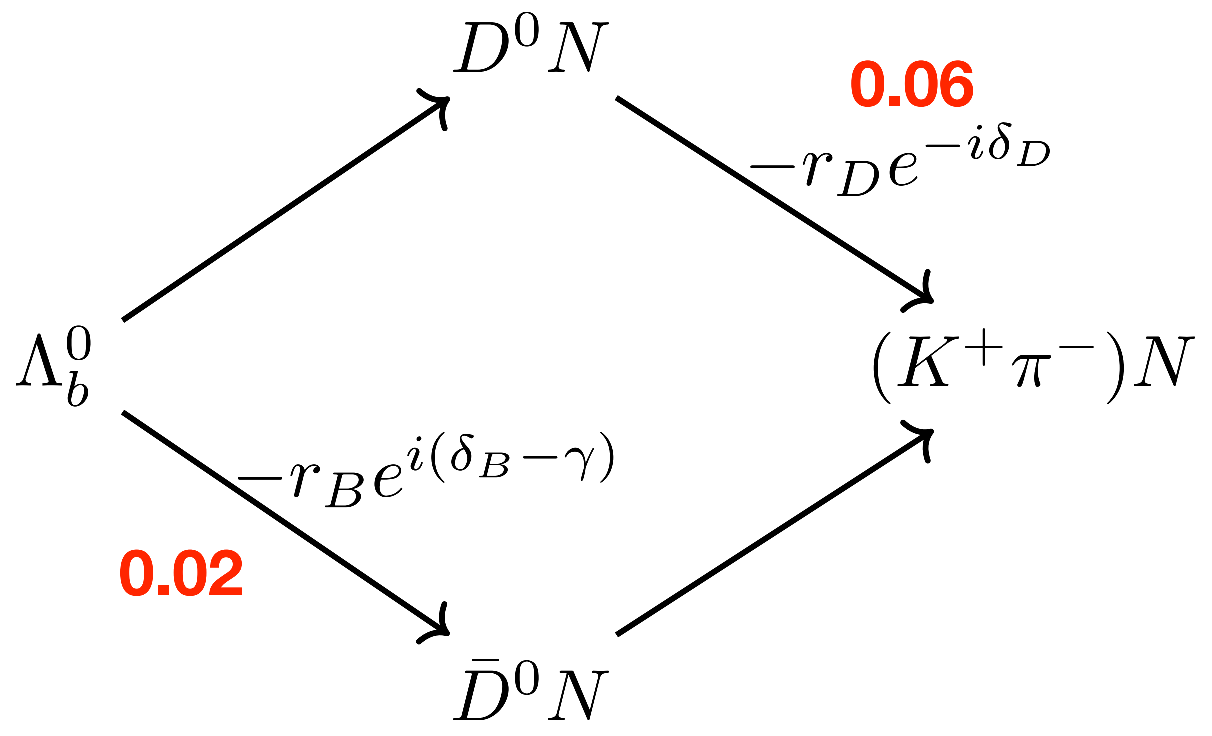
Possible large CP violation in $\Lambda_b \to DN \to (K^+\pi^-)(p\pi^-)$

❖ **Interferences** by two groups of intermediate states [Shen,Wang,**QQ**,PRDL, 2309.09854]

➡ D^0 & $\bar{D}^0$ interference: **large weak phase** γ (comparable magnitude)

➡ $N(1440)$ & $N(1520)$ interference: **diverse strong phases** in different kinematic regions

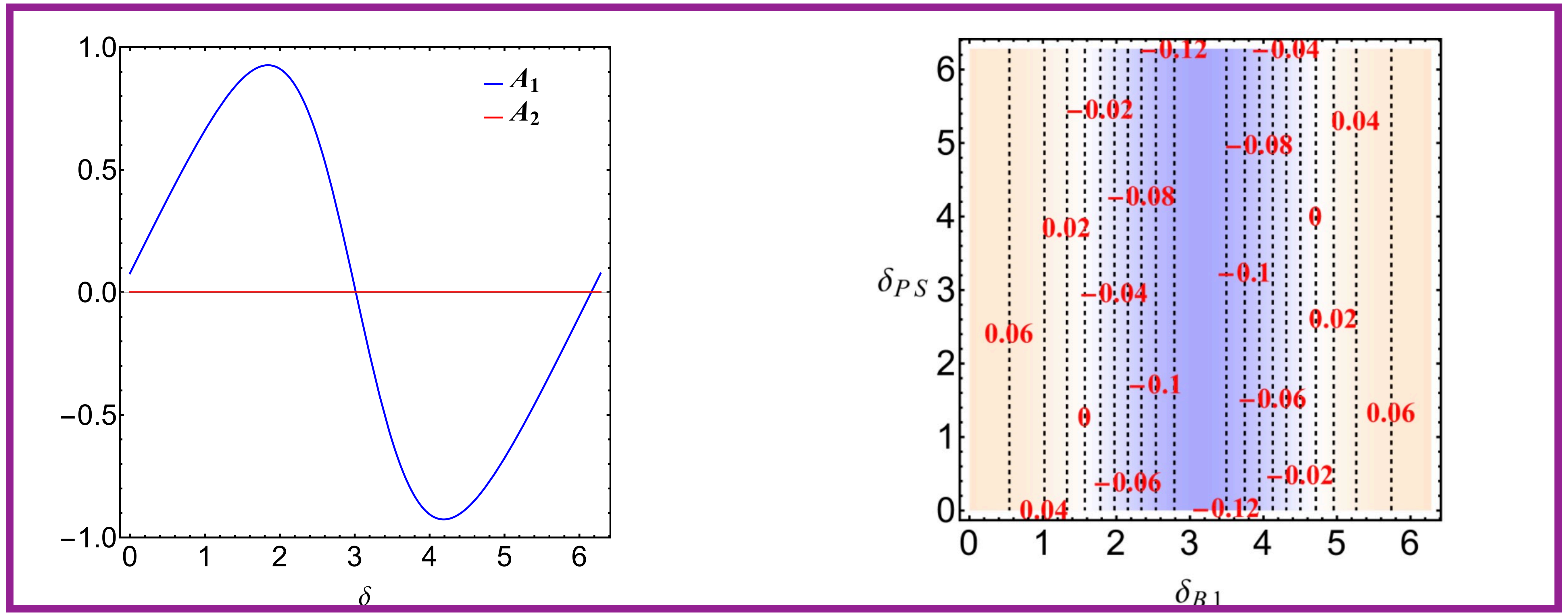


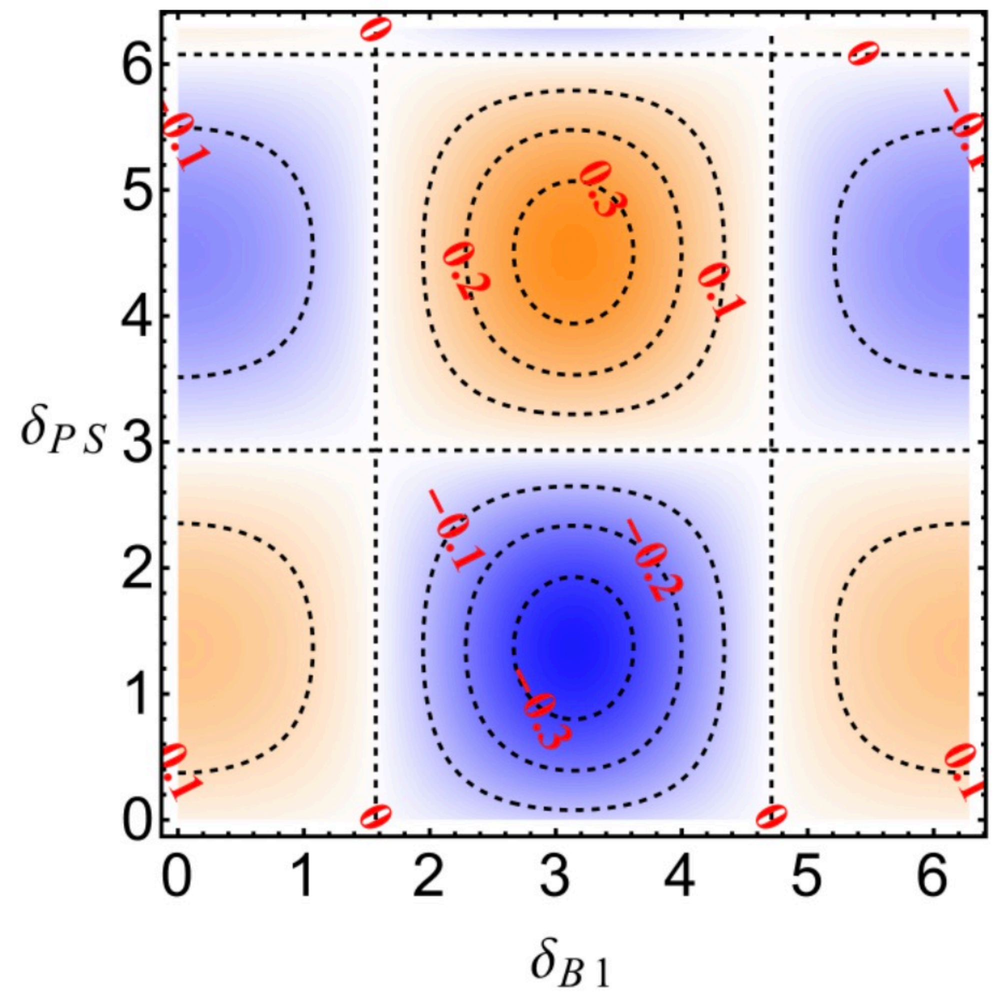


$$A_2 \equiv \frac{\int_{-1}^{1} \mathrm{sgn}[\cos\theta] \cdot \mathcal{N}(\theta)\, \mathrm{d}\cos\theta}{\int_{-1}^{1} \mathcal{D}(\theta)\, \mathrm{d}\cos\theta}$$

❖ Global or regional large CP violation

Direct CP violation





After the baryonic CP violation discovery

Understand the underlying dynamics

❖ **Model-dependent calculation**

➡ Practical to apply

➡ Grasp the key issue easily

➡ Applicable to specific situation

➡ Randomly improve

➡ At most loyal to standard model, never discovery new physics

❖ **Model-independent calculation**

➡ Difficult to perform

➡ Key issue requires more efforts

➡ Widely applicable

➡ Systematical to improve

➡ Necessary for precision test of the standard model

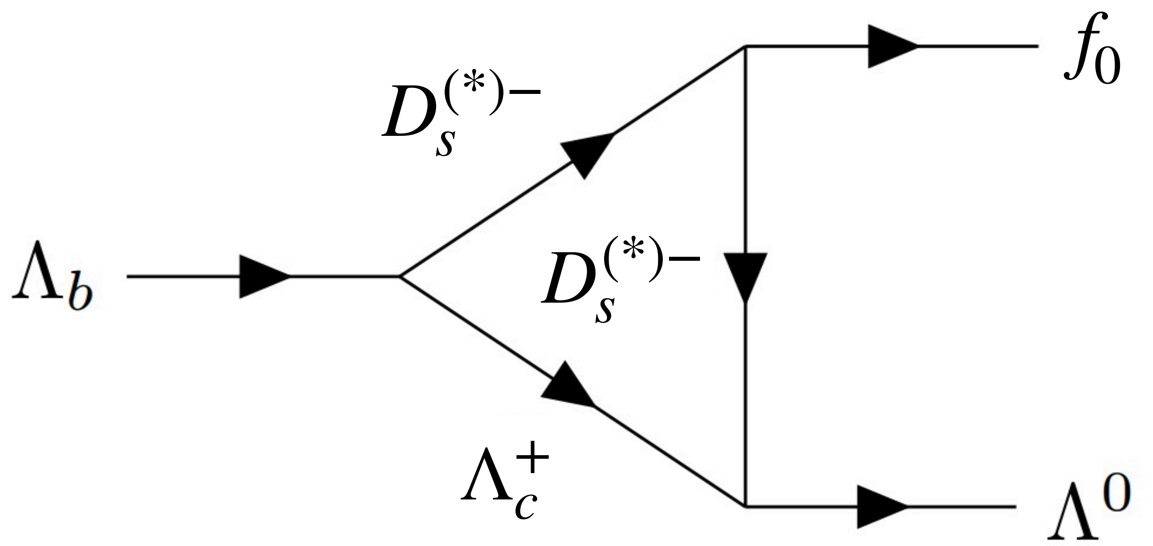
Confront data to optimize.

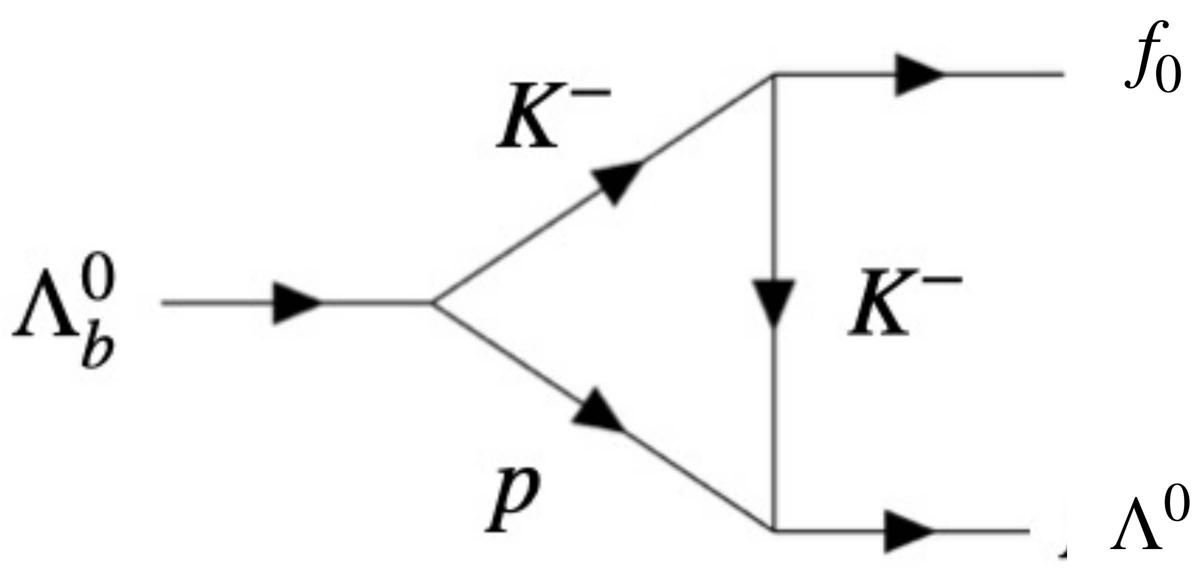
See Fu-Sheng's talk

Understand the underlying dynamics

❖ **Final-state interaction** for $\Lambda_b \to pK^-\pi^+\pi^-$ **Preliminary!**

➡ Strong phases from FSI

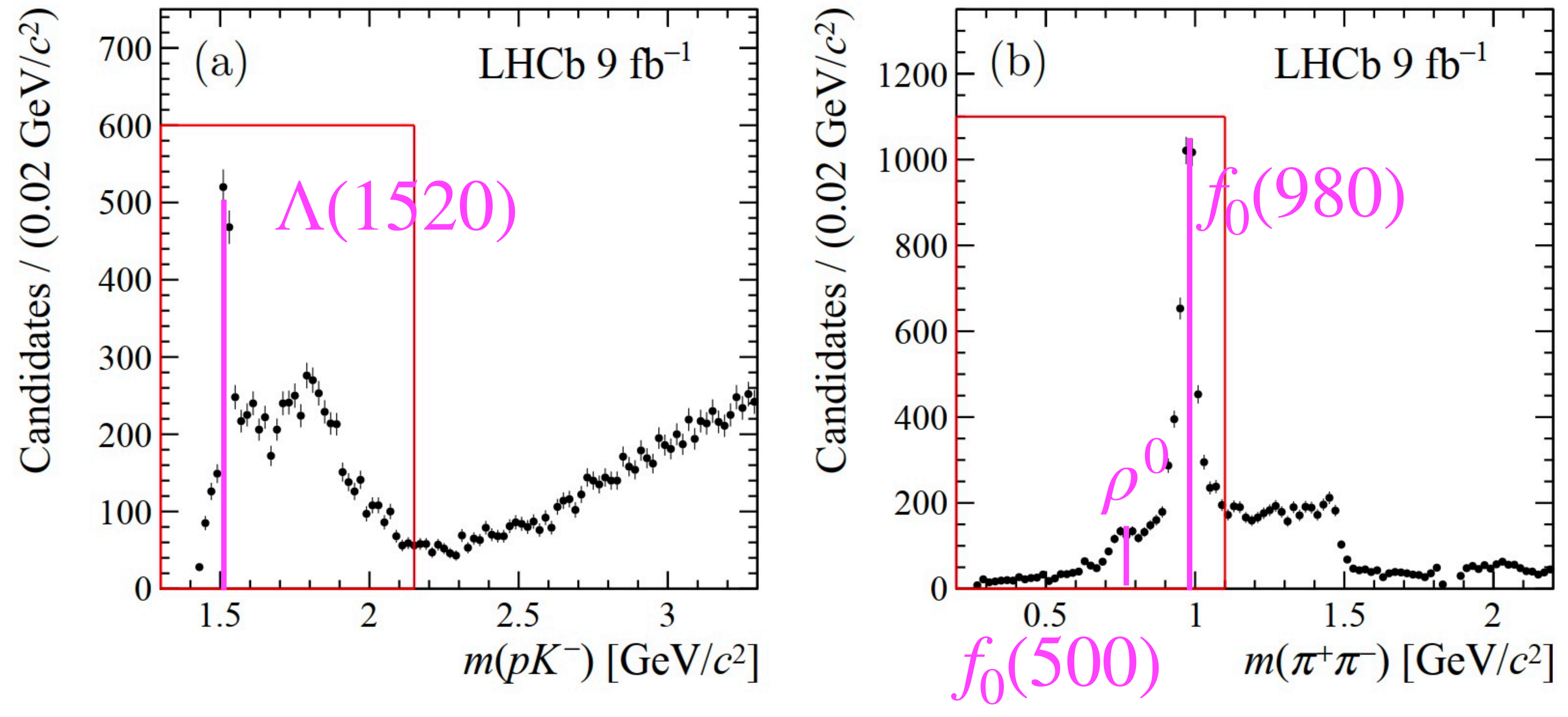




	BR	$A_{\rm CP}$
$\Lambda(1520)f_0(980)$	$6.01^{+6.99}_{-3.47}\times10^{-6}$	$(2.9^{+3.8}_{-1.6})$ %
$\Lambda(1520)\rho^0$	$1.37^{+1.56}_{-0.65}\times10^{-6}$	$(28.2^{+14.5}_{-9.1})$ %
$\Lambda(1520)f_0(500)$	$9.28^{+11.50}_{-5.42}\times10^{-7}$	$(-1.0^{+1.1}_{-0.7})$ %

→ Weighted $A_{\rm CP} \approx 6.6\,\%$

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



[Feng,**QQ**,Shang,Yu, to appear]

[LHCb, 2503.16954, submitted to Nature]

Understand the underlying dynamics

❖ It seems that currently the model-dependent calculation (FSI) is acceptable

❖ With more precise data, it can be improved

❖ But it can never precisely test the CKM mechanism

❖ We need other ways out

Complementary T-odd and T-even CP asymmetry

❖ **General conclusion**: T-odd correlation $Q\_$ induces CPV with cosine dependence on strong phases

$$TQ_- = -Q_- T, \qquad A_{CP}^{Q_-} \equiv \frac{\langle Q_- \rangle - \langle \bar{Q}_- \rangle}{\langle Q_- \rangle + \langle \bar{Q}_- \rangle} \propto \cos\delta_s$$

if it satisfies two conditions: (i) for the final-state basis $\{|\psi_n\rangle$, n =1,2,…}, there is a unitary transformation U, s.t. $UT|\psi_n\rangle = e^{-i\alpha}|\psi_n\rangle$; (2) $UQ_-U^\dagger = Q_-$.

Proof:

$$\begin{aligned}\langle f|Q_-|f\rangle &= \langle i|S^\dagger Q_- S|i\rangle \\ &= \sum_{m,n}\langle\psi_i|S^\dagger|\psi_m\rangle\langle\psi_m|Q_-|\psi_n\rangle\langle\psi_n|S|\psi_i\rangle \\ &= \sum_{m,n} A_m^* A_n \langle\psi_m|Q_-|\psi_n\rangle\ .\end{aligned}$$

$$\begin{aligned}\langle\psi_m|Q_-|\psi_n\rangle &= \langle\psi_m|\mathcal{T}^\dagger\mathcal{T}\,Q_-|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger Q_-\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger\,\mathcal{U}^\dagger\mathcal{U}\,Q_-\,\mathcal{U}^\dagger\mathcal{U}\,\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|\mathcal{T}^\dagger\mathcal{U}^\dagger\,Q_-\,\mathcal{U}\mathcal{T}|\psi_n\rangle^* \\ &= -\langle\psi_m|Q_-|\psi_n\rangle^*\ ,\end{aligned}$$

$$\longrightarrow \quad \langle f|Q_-|f\rangle \ni \mathrm{Im}(A_m^* A_n) \quad \longrightarrow \quad A_{CP}^{Q_-} \propto \sin\delta_w \cos\delta_s$$

$$A_{CP}^{Q_+} \propto \sin\delta_w \sin\delta_s$$

[Wang, **QQ**, Yu, 2211.07332, 2411.18323]

Complementary T-odd and T-even CP asymmetry

- The complementarity helps **reduce** the strong phase dependence

$$\langle\mathcal{O}_+\rangle = \mathcal{R}e(\mathcal{H}_{\lambda_i,\lambda_j}\mathcal{H}^*_{\lambda_m,\lambda_n} + \mathcal{H}_{-\lambda_i,-\lambda_j}\mathcal{H}^*_{-\lambda_m,-\lambda_n})$$
$$\langle\mathcal{O}_-\rangle = \mathcal{I}m(\mathcal{H}_{\lambda_i,\lambda_j}\mathcal{H}^*_{\lambda_m,\lambda_n} + \mathcal{H}_{-\lambda_i,-\lambda_j}\mathcal{H}^*_{-\lambda_m,-\lambda_n})$$

$$\Rightarrow$$

$$\begin{aligned} a_{CP}^{\mathcal{O}_+} \propto & [-H^t_{i,j}H^p_{m,n}\sin(\delta^t_{i,j}-\delta^p_{m,n}) \\ & + H^p_{i,j}H^t_{m,n}\sin(\delta^p_{i,j}-\delta^t_{m,n})]\sin\Delta\phi \\ & + (i,j,m,n \to -i,-j,-m,-n)\ , \\ a_{CP}^{\mathcal{O}_-} \propto & [-H^t_{i,j}H^p_{m,n}\cos(\delta^t_{i,j}-\delta^p_{m,n}) \\ & + H^p_{i,j}H^t_{m,n}\cos(\delta^p_{i,j}-\delta^t_{m,n})]\sin\Delta\phi \\ & + (i,j,m,n \to -i,-j,-m,-n)\ , \end{aligned}$$

Complementary, but not enough.

[Wang, **QQ**, Yu, 2211.07332, 2411.18323]

- Note that, even knowing A_i & $\bar{A}_i$, the weak phase is not necessarily determined

4 equations

$$\begin{aligned} A_i &= t_i e^{i\delta^t_i} e^{i\omega^t} + p_i e^{i\delta^p_i} e^{i\omega^p} \\ \bar{A}_i &= t_i e^{i\delta^t_i} e^{-i\omega^t} + p_i e^{i\delta^p_i} e^{-i\omega^p} \end{aligned}$$

6 unknown parameters

- Several channels having **same/different tree/penguin** amplitudes are required

Complementary T-odd and T-even CP asymmetry

- $\Lambda_b \to DN, D\Lambda$ is a good example

[Giri,Mohanta,Khanna,PRD, hep-ph/0112220]
[Zhang,Jiang,Chen,Qian, 2112.12954]
[Shen,Wang,**QQ**,PRDL, 2309.09854]

➡ The $D^0, \bar{D}^0$ amplitudes can be extracted from their decays to $K^-\pi^+, K^+\pi^-, K^+K^-, \pi^+\pi^-$

$$\mathrm{Amp}(\Lambda_b \to \Lambda D^0) = S_1 e^{i\delta_1^S} + P_1 e^{i\delta_1^P} \boldsymbol{\sigma}\cdot\hat{\mathbf{q}}$$

$$\mathrm{Amp}(\bar{\Lambda}_b \to \bar{\Lambda}\overline{D^0}) = \bar{S}_1 e^{i\delta_1^S} + \bar{P}_1 e^{i\delta_1^P} \boldsymbol{\sigma}\cdot\hat{\mathbf{q}}$$

$$\mathrm{Amp}(\Lambda_b \to \Lambda\overline{D^0}) = e^{-i\gamma}\left(S_2 e^{i\delta_2^S} + P_2 e^{i\delta_2^P} \boldsymbol{\sigma}\cdot\hat{\mathbf{q}}\right)$$

$$\mathrm{Amp}(\bar{\Lambda}_b \to \bar{\Lambda} D^0) = e^{i\gamma}\left(\bar{S}_2 e^{i\delta_2^S} + \bar{P}_2 e^{i\delta_2^P} \boldsymbol{\sigma}\cdot\hat{\mathbf{q}}\right)$$

16 equations

10 unknown parameters

It can be used to extract the CKM angle γ.

Prospects

❖ **To find more such sets of channels**

❖ **To find more relations between amplitudes**

➡ Angular distribution —— spatial rotation

➡ Time dependent —— time translation

➡ Hadron invariant mass ——Breit-Wigner?

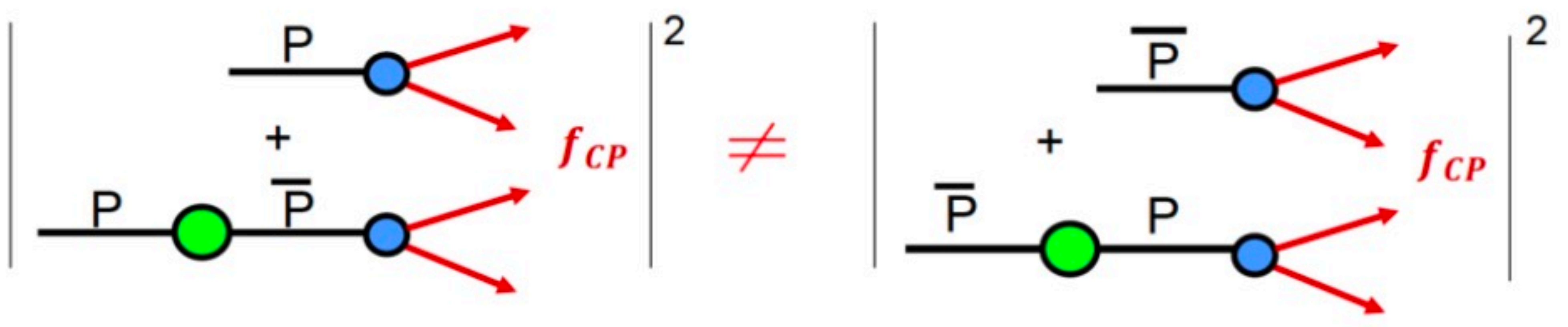
See Zhen-Hua's talk

“Discovery” of a new type of CP violation

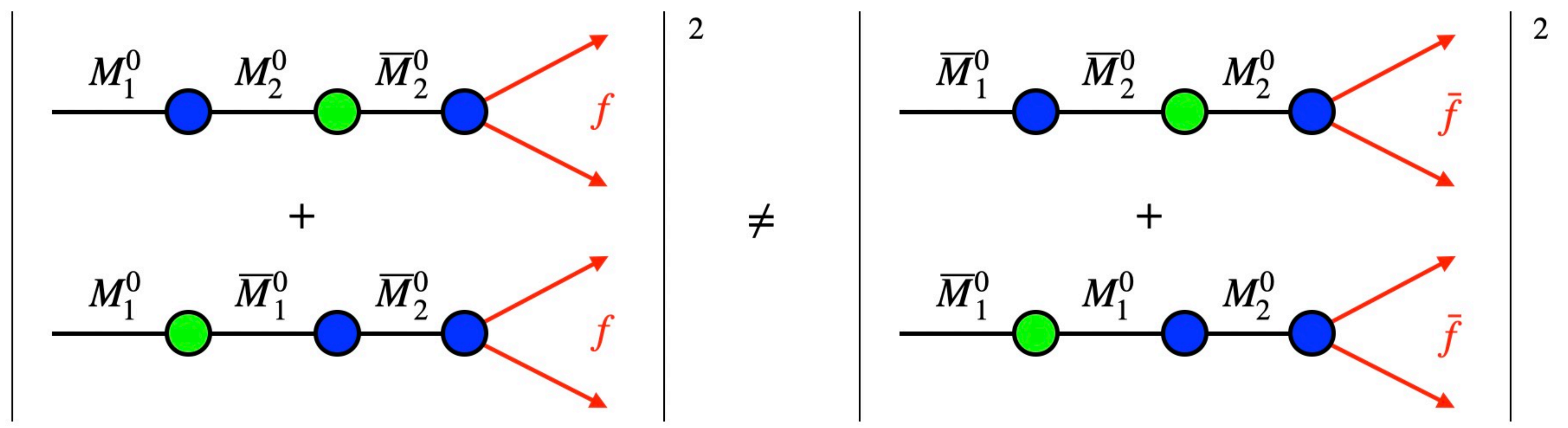
❖ **CP violation in decay**

❖ **CP violation in mixing**

❖ **CP violation in interference between decay & mixing**



❖ **CP violation in interference between mixing & mixing**



[Shen,Song,**QQ**, PRDL, 2301.05848]
[Song,Shen,**QQ**, EPJC, 2403.01904]
[Song,Wang,**QQ**,Li, EPJC, 2501.05689]

Thank you!