CPV and entanglement in b-baryons

Flavor and spin; entanglement and weak phase

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Based on 2605.09682

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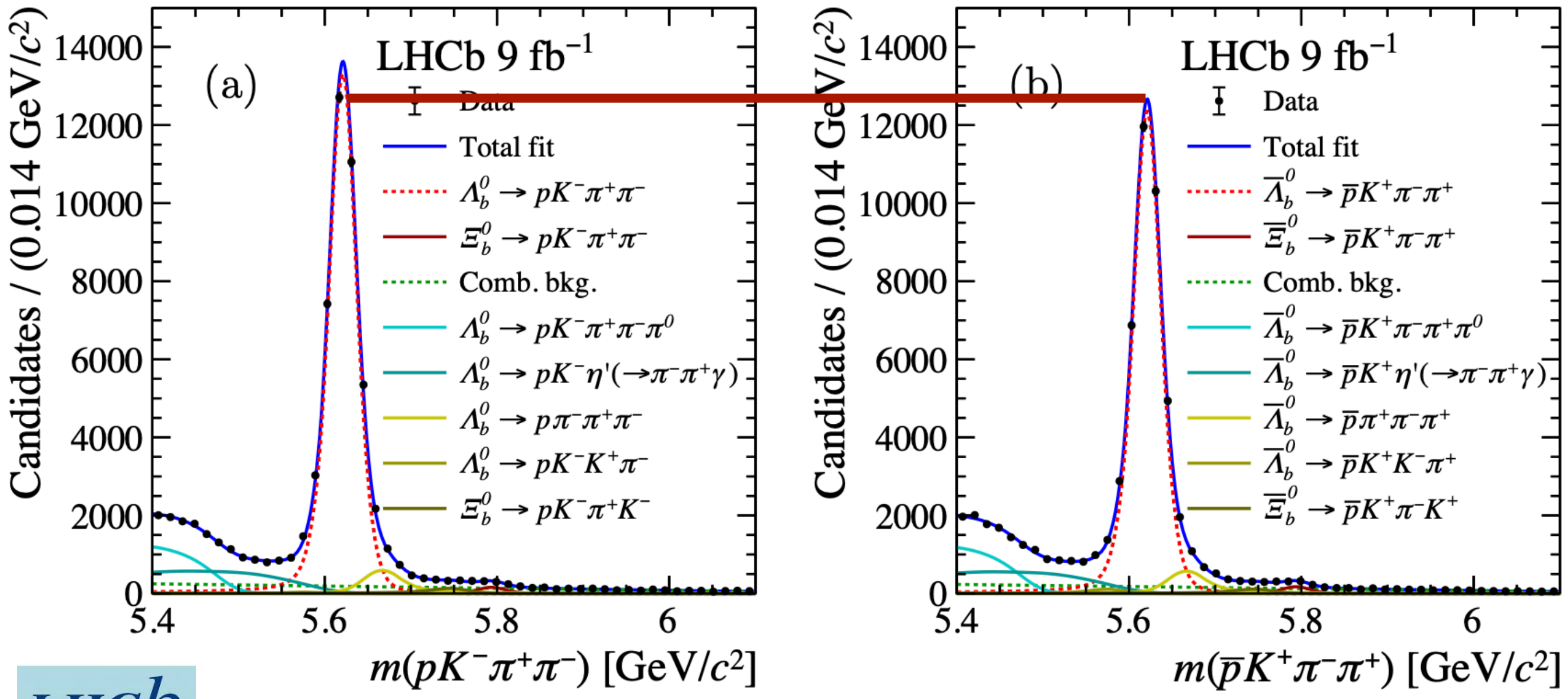
• Overview

The first evidence for CPV above 5σ was established:

$$A_{CP} = (2.45 \pm 0.46 \pm 0.10)\,\%$$



Nature, [2503.16954]

Overview

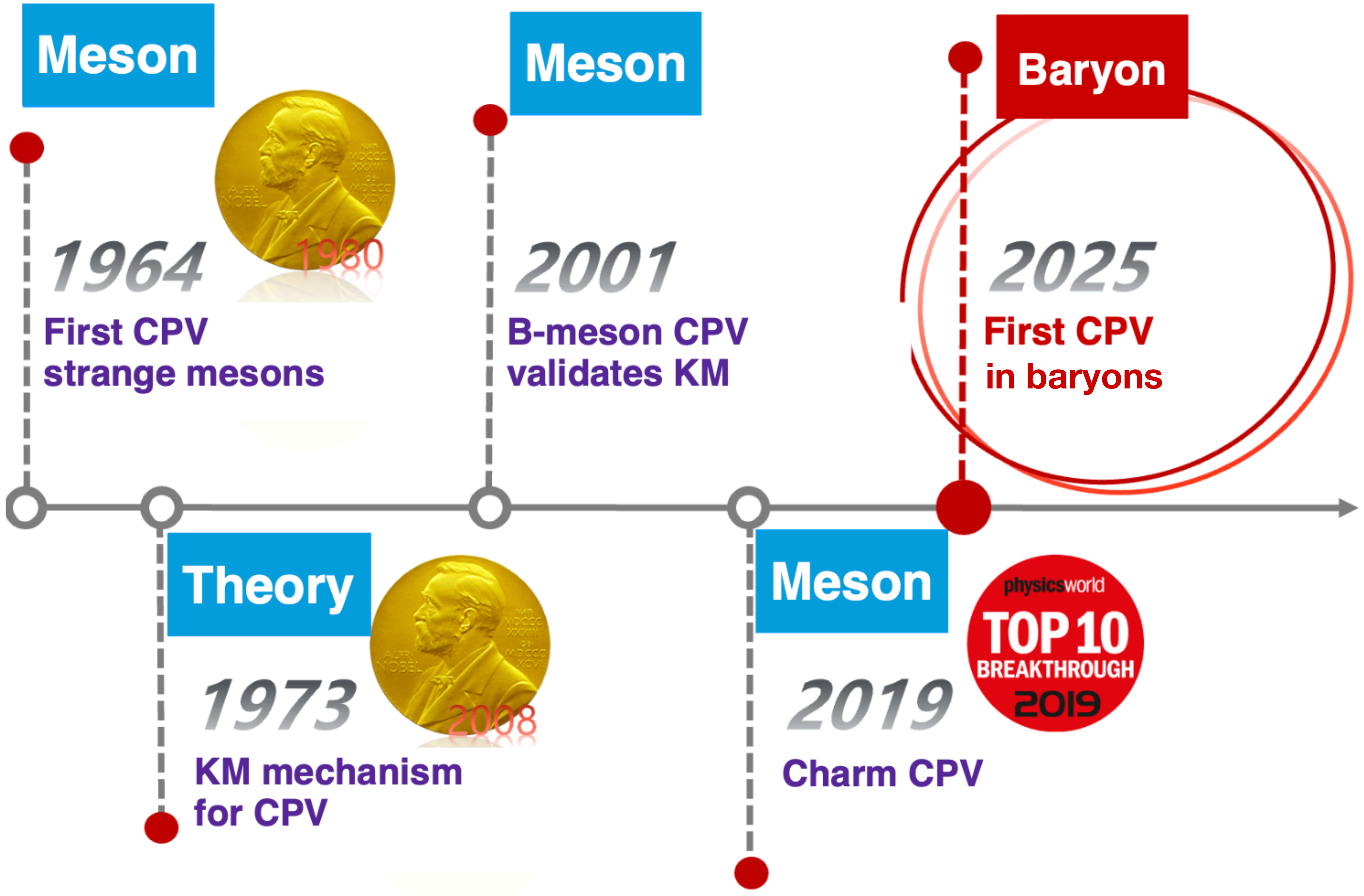


Figure from Fu-Sheng Yu

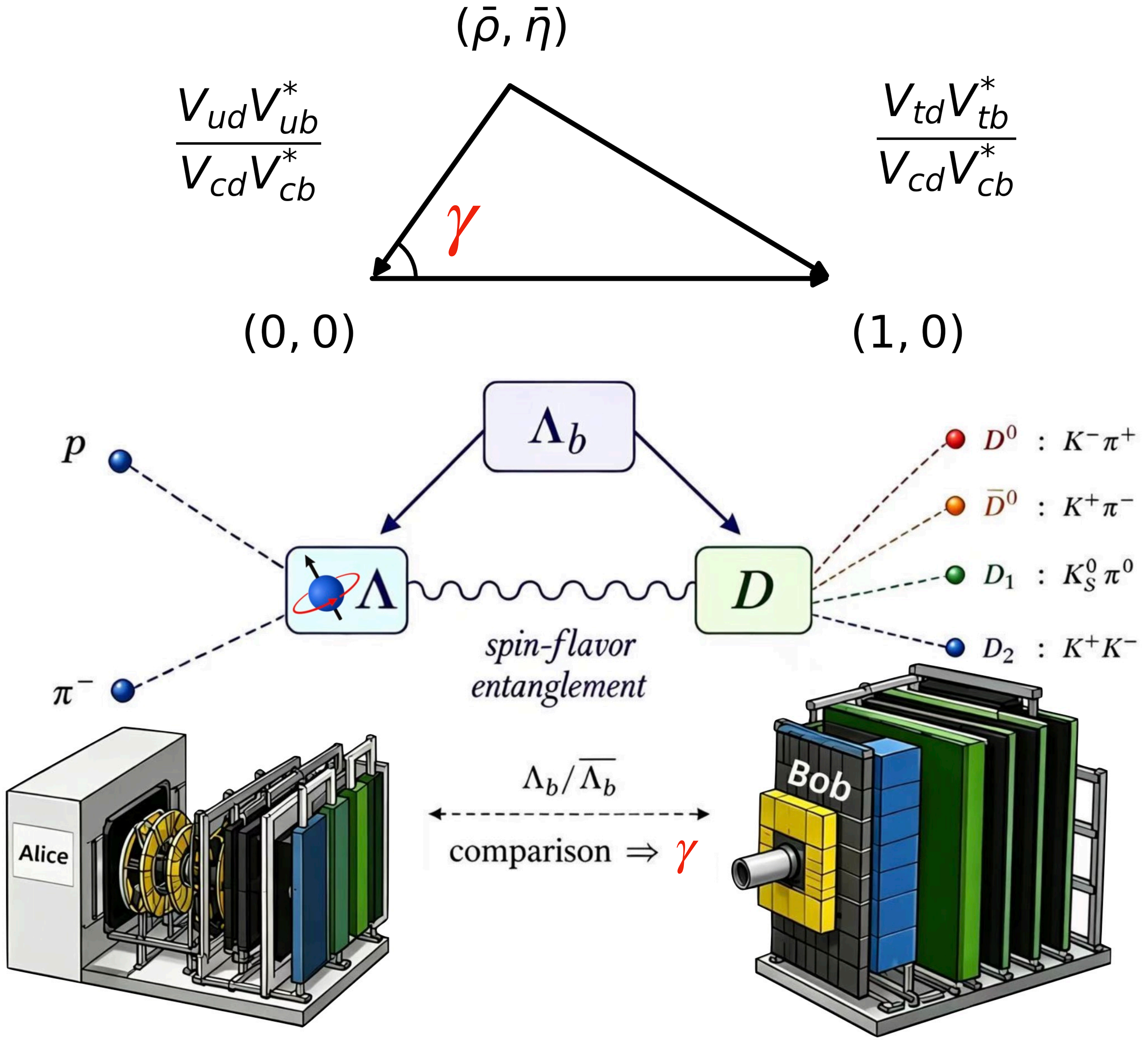
$$A_{CP}(B_s^0 \to \pi^+ K^-) = (22.4 \pm 1.2)\,\%$$

Mode/selection	$A_{CP}(\%)$
$\Lambda_b \to pK^-\pi^+\pi^-$	$2.45 \pm 0.46 \pm 0.10$
$\Lambda_b \to pK^-$	$-1.1 \pm 0.7 \pm 0.4$
$\Lambda_b \to p\pi^-$	$0.2 \pm 0.8 \pm 0.4$
$\Lambda_b \to pK_S^0\pi^-$	$3.4 \pm 1.9 \pm 0.9$
$\Lambda_b \to pK^*(892)^-$	$-0.6 \pm 4.0 \pm 1.9$
$\Lambda_b \to \Lambda K^+K^-$	$8.3 \pm 2.3 \pm 1.6$
$\Lambda_b \to N^*K$	$16.5 \pm 4.8 \pm 1.7$
$\Lambda_b \to \Lambda K^+\pi^-$	$-11.8 \pm 4.5 \pm 2.1$
$\Lambda_b \to \Lambda\pi^+\pi^-$	$-1.3 \pm 5.3 \pm 1.8$
$\Xi_b^0 \to \Lambda K^-\pi^+$	$27 \pm 12 \pm 5$
$\Lambda_b \to J/\psi p\pi^-$	$4.31 \pm 1.06 \pm 0.28$

[2503.16954; 2412.13958; 2508.17836; 2411.15441; 2509.16103]

• Overview

- **Why** is b-baryon CPV much **smaller** than B-meson CPV?
- **Where** should one search for **large** CPV?
- **What** is **new**?
- **How** does it help us **understand** the SM?



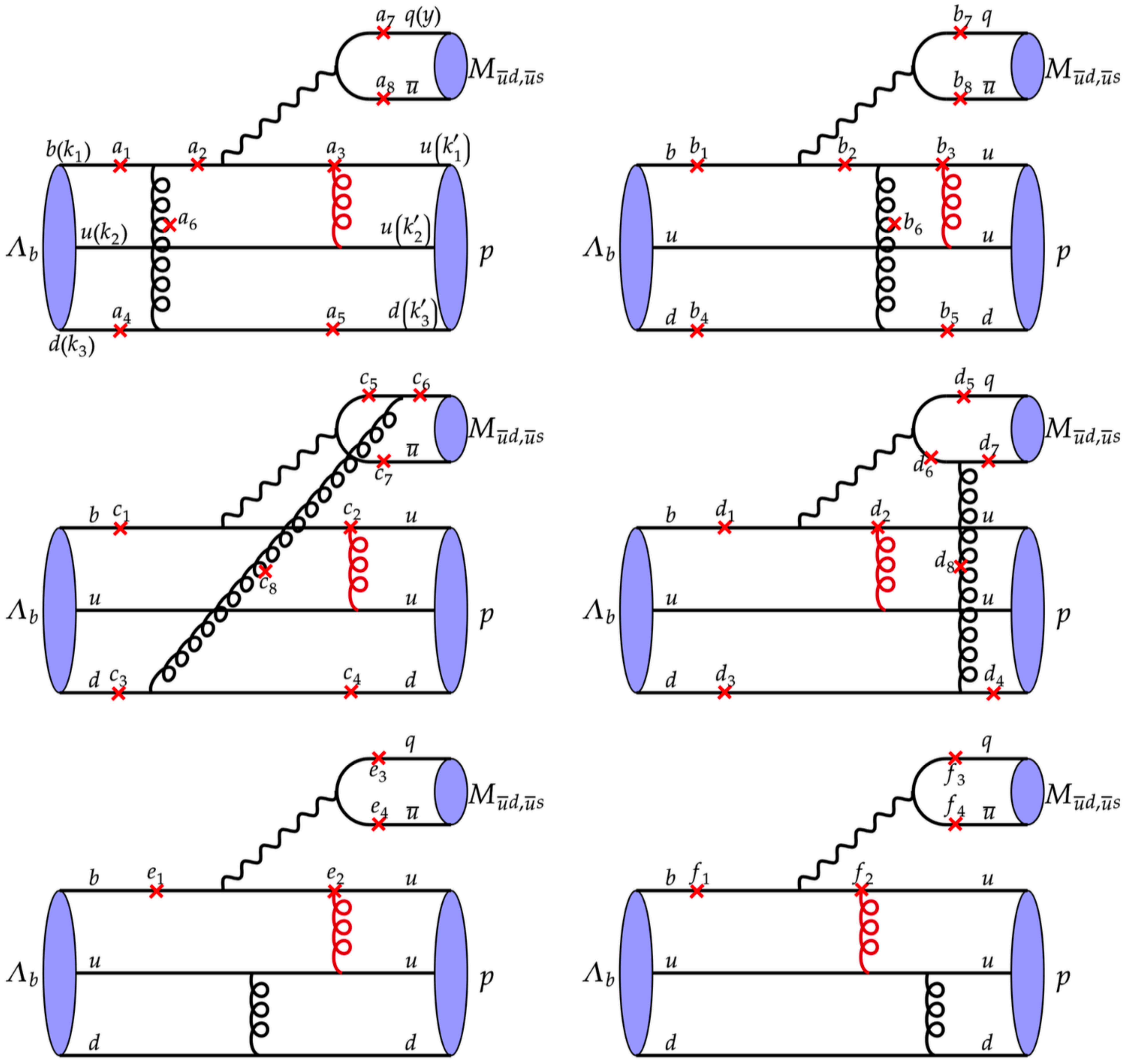
• Why small CPV in Λ_b?

- Perturbative contributions require at least ***two*** hard gluons.

- A full QCDF/SCET-type factorization theorem for nonleptonic b-baryon decays is still **missing**.

- Currently, only calculations based on k_T factorization exist.

- Numerical results in this part shall be regarded as **pQCD benchmark** with assumed endpoint behavior and LCDAs.



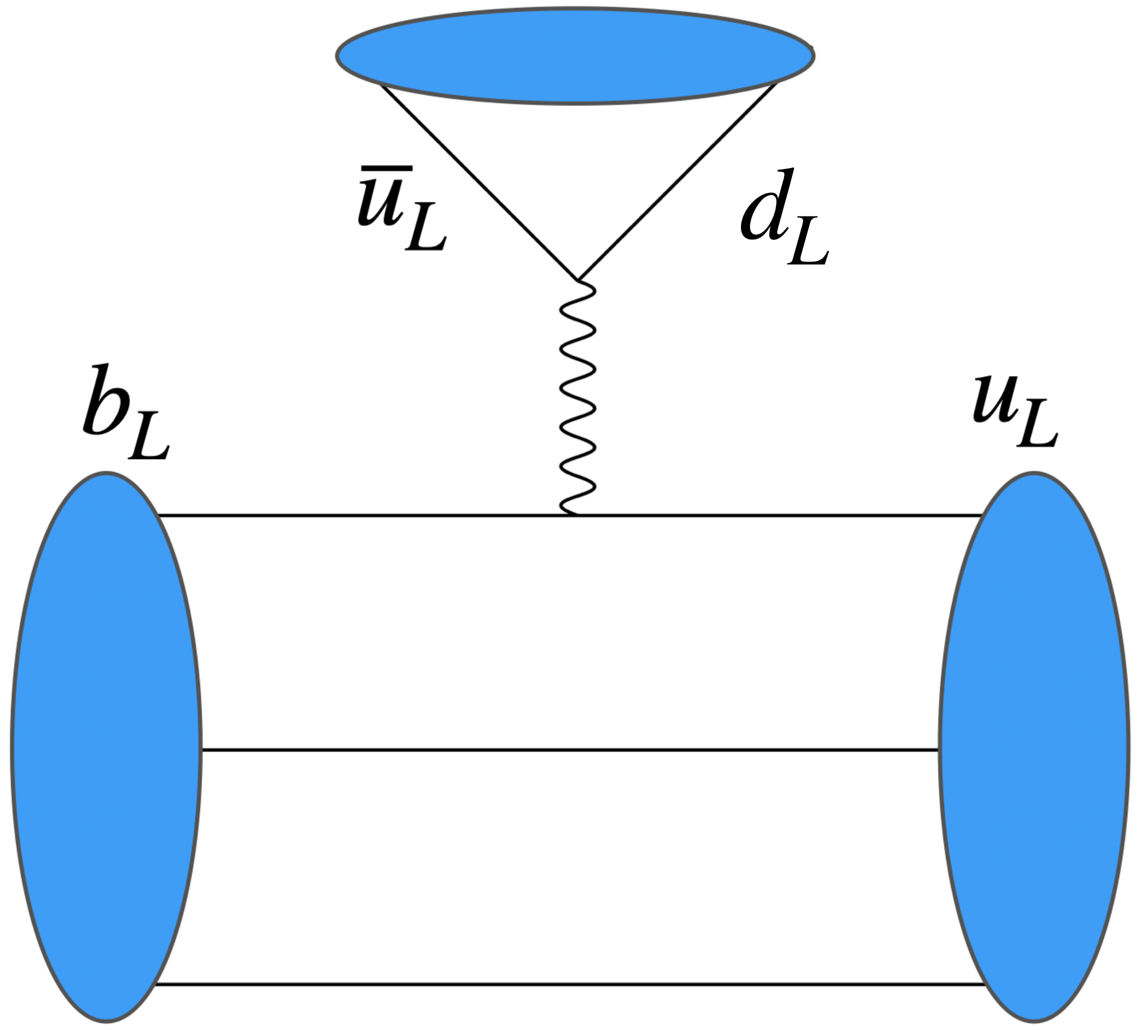
[2506.07197]

Why small CPV in Λ_b?

- Two dominant operators in $\Lambda_b \to p\pi^-$ with $\lambda_q = V_{qb}V^*_{qd}$
- In the naive factorization:

$$h_{\pm}^{O_1} \propto c_1\lambda_u e^{i\delta^1_\pm}\left[(m_{\Lambda_b}+m_p)f_0 \mp (m_{\Lambda_b}-m_p)g_0\right].$$

$$h_{\pm}^{O_6} \propto -c_6\lambda_t e^{i\delta^6_\pm}R_\pi\left[(m_{\Lambda_b}+m_p)f_0 \pm (m_{\Lambda_b}-m_p)g_0\right].$$



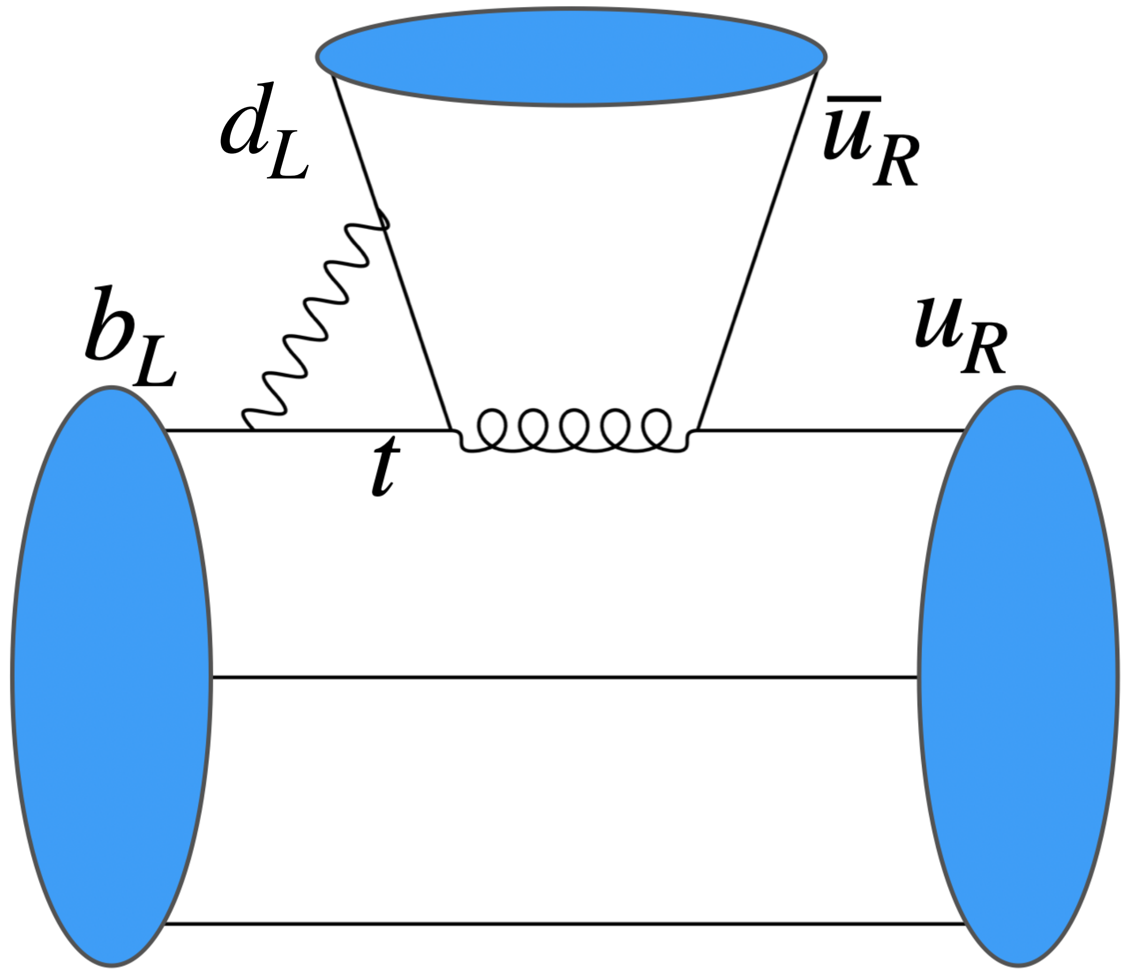
$$\mathscr{H}_{\text{Tree}} \ni \lambda_u c_1 \left(\bar{u}_L\gamma_\mu b_L\right)\left(\bar{d}_L\gamma^\mu u_L\right)$$

- Lattice-QCD input: Detmold-Lehner-Meinel [1503.01421]

$$f_0(m_\pi^2) = 0.16 \pm 0.05, \quad g_0(m_\pi^2) = 0.19 \pm 0.04.$$

$$\left|h_+^{\text{Tree}}\right|^2 : \left|h_-^{\text{Tree}}\right|^2 \simeq (0.01 \pm 0.06) : 1$$

$$\left|h_+^{\text{Penguin}}\right|^2 : \left|h_-^{\text{Penguin}}\right|^2 \simeq 1 : (0.29 \pm 0.13)$$



$$\mathscr{H}_{\text{Penguin}} \ni \lambda_t c_6 \left[2(\bar{u}_R b_L)(\bar{d}_L u_R)\right]$$

* *left-handed $O_{3,4}$ included*

• Why small CPV in Λ_b?

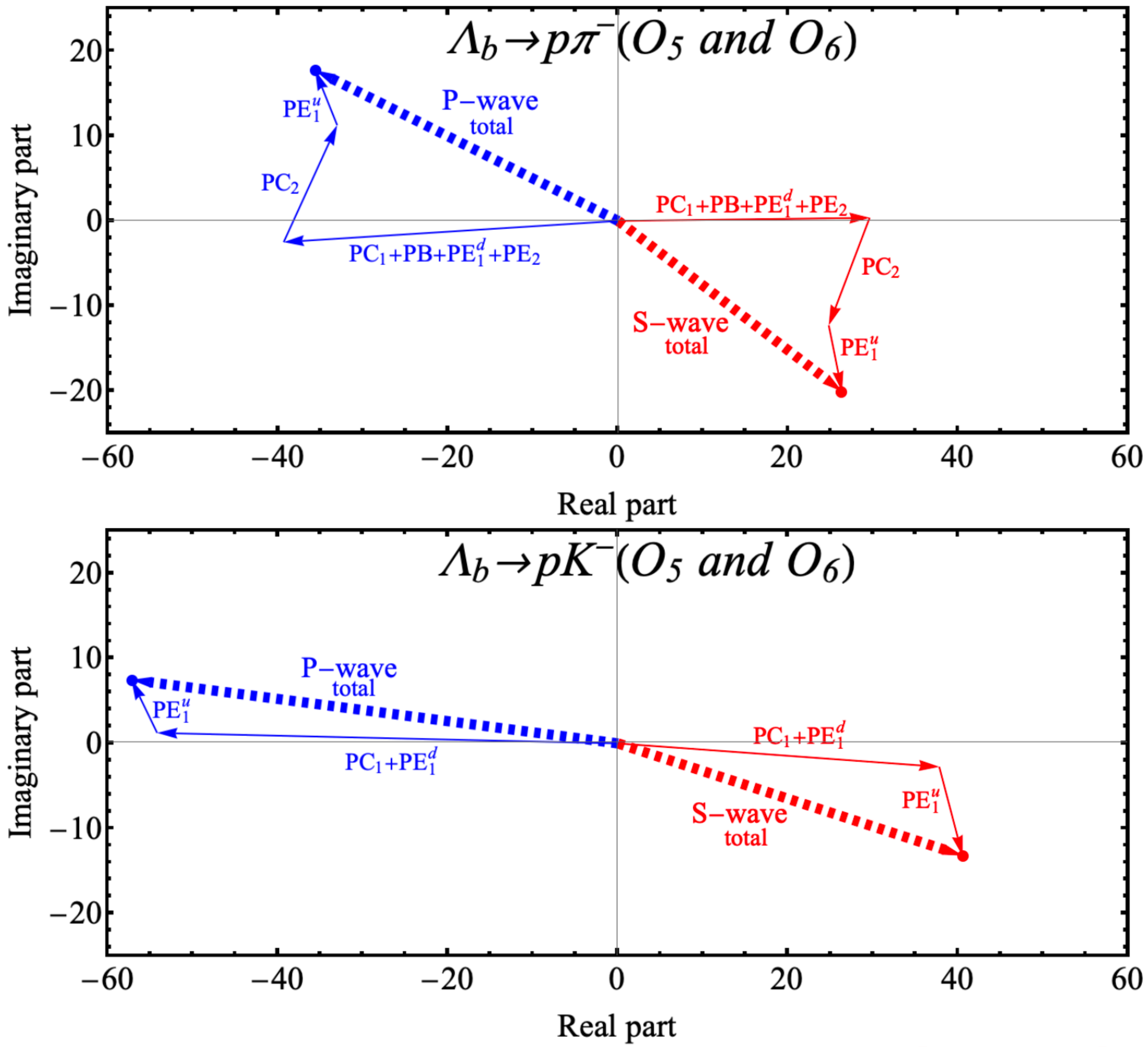
- $V_{ub}V_{ud}^*$ and $V_{tb}V_{td}^*$ do ***not**** interfere in $|h_-|^2$, $|h_+|^2$.

  * *approximately*

➡ Effects of weak phases are ***gone*** in A_{CP} and α_{CP}!

$$A_{CP} = \frac{|h_+|^2 + |h_-|^2 - |\bar{h}_+|^2 - |\bar{h}_-|^2}{|h_+|^2 + |h_-|^2 + |\bar{h}_+|^2 + |\bar{h}_-|^2}.$$

$$\alpha = \frac{|h_+|^2 - |h_-|^2}{|h_+|^2 + |h_-|^2},$$



*$S \approx P$ for O_1

[2506.07197]

- Equivalently, A_{CP} **cancels** between S and P waves.
- In pQCD calculations, $\delta_-^1 \approx \delta_-^6$ further suppresses CPV.

[2111.02091, 2506.07197]

Where should one search for large CPV?

- $V_{ub}V_{ud}^*$ and $V_{tb}V_{td}^*$ do ***not**** interfere in $|h_-|^2$, $|h_+|^2$.

** approximately*

➡ Effects of weak phases are ***gone*** in A_{CP} and α_{CP}!

- However, they strongly ***interfere*** in β .

$$\beta = \frac{2\mathrm{Im}(h_+^* h_-)}{|h_+|^2 + |h_-|^2}, \quad \gamma = \frac{2\mathrm{Re}(h_+^* h_-)}{|h_+|^2 + |h_-|^2}.$$

***not weak phase*

- Bad news: β and γ are difficult to measure.

Observable	$\Lambda_b \to p\pi^-$	$\Lambda_b \to pK^-$
$\mathcal{B}(10^{-6})$	$3.34^{+2.90}_{-1.71}$	$2.83^{+3.33}_{-1.59}$
$A_{CP}(\%)$	$5.0^{+2.0}_{-3.2}$	$-6.0^{+2.4}_{-1.7}$
$\alpha_{CP}(\%)$	$2.0^{+1.4}_{-2.0}$	$4.0^{+3.2}_{-3.9}$
$\beta_{CP}(\%)$	$22.0^{+7.6}_{-5.2}$	$-44.0^{+8.4}_{-4.1}$
$\gamma_{CP}(\%)$	$11.0^{+4.8}_{-5.7}$	$2.0^{+6.7}_{-5.1}$

[2506.07197]

• Where should one search for large CPV?

- Decay distributions with **sequential** decays:

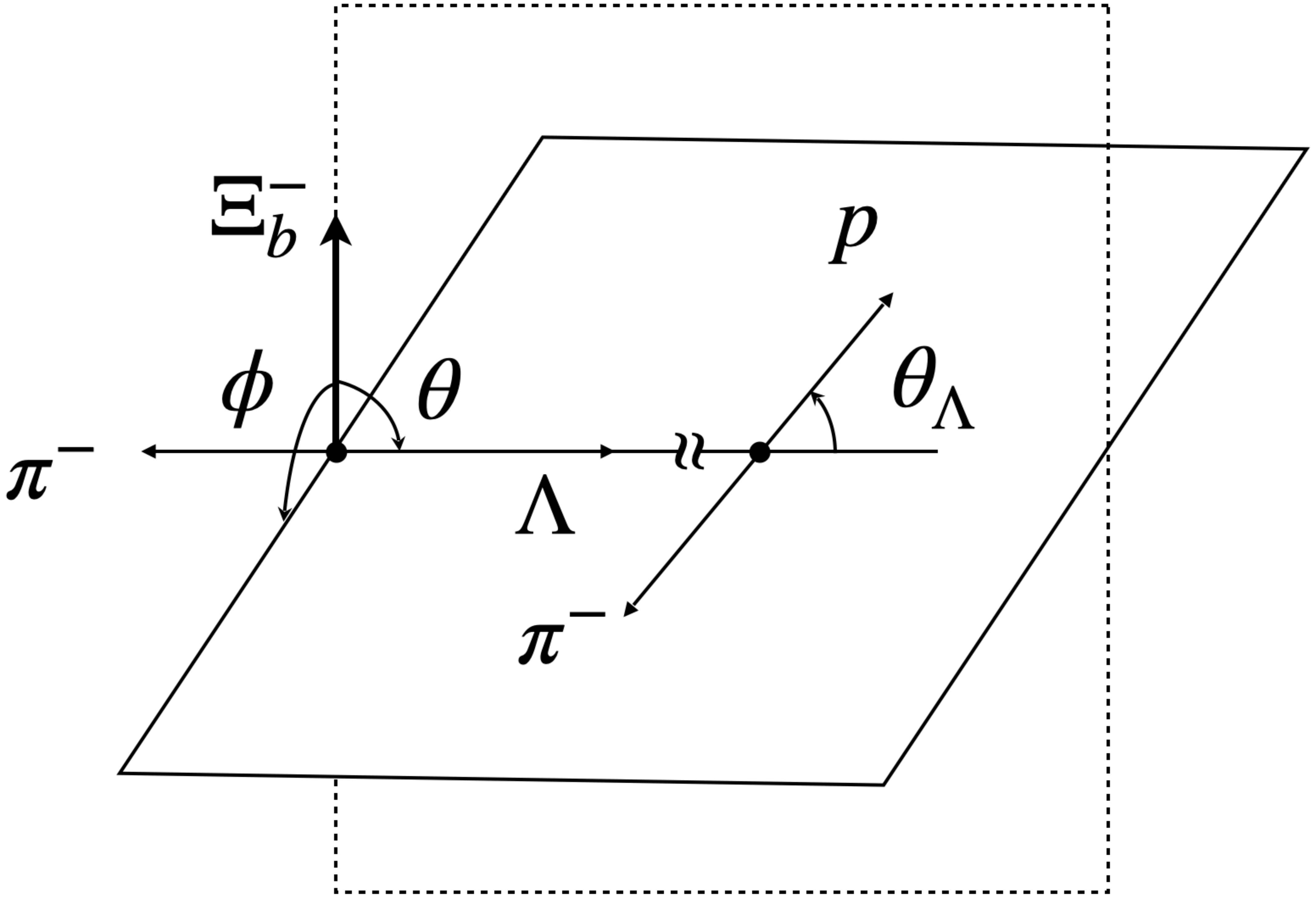
$$\mathscr{D}(\Omega) \ni \frac{1}{8\pi} P_b \alpha_\Lambda \beta \sin\phi \sin\theta \sin\theta_\Lambda$$

- **Triple product asymmetries**:

$$TPA = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

$$TPA(\pi^-) \simeq 0.7\,\% \left(\frac{P_b}{0.10}\right)\left(\frac{\alpha_\Lambda}{0.75}\right)\left(\frac{\beta_{CP}}{0.25}\right).$$

$$TPA(K^-) \simeq -1.2\,\% \left(\frac{P_b}{0.10}\right)\left(\frac{\alpha_\Lambda}{0.75}\right)\left(\frac{\beta_{CP}}{-0.40}\right).$$



[2111.02091]

Where? What's new and how it helps?

Negative helicity dominates

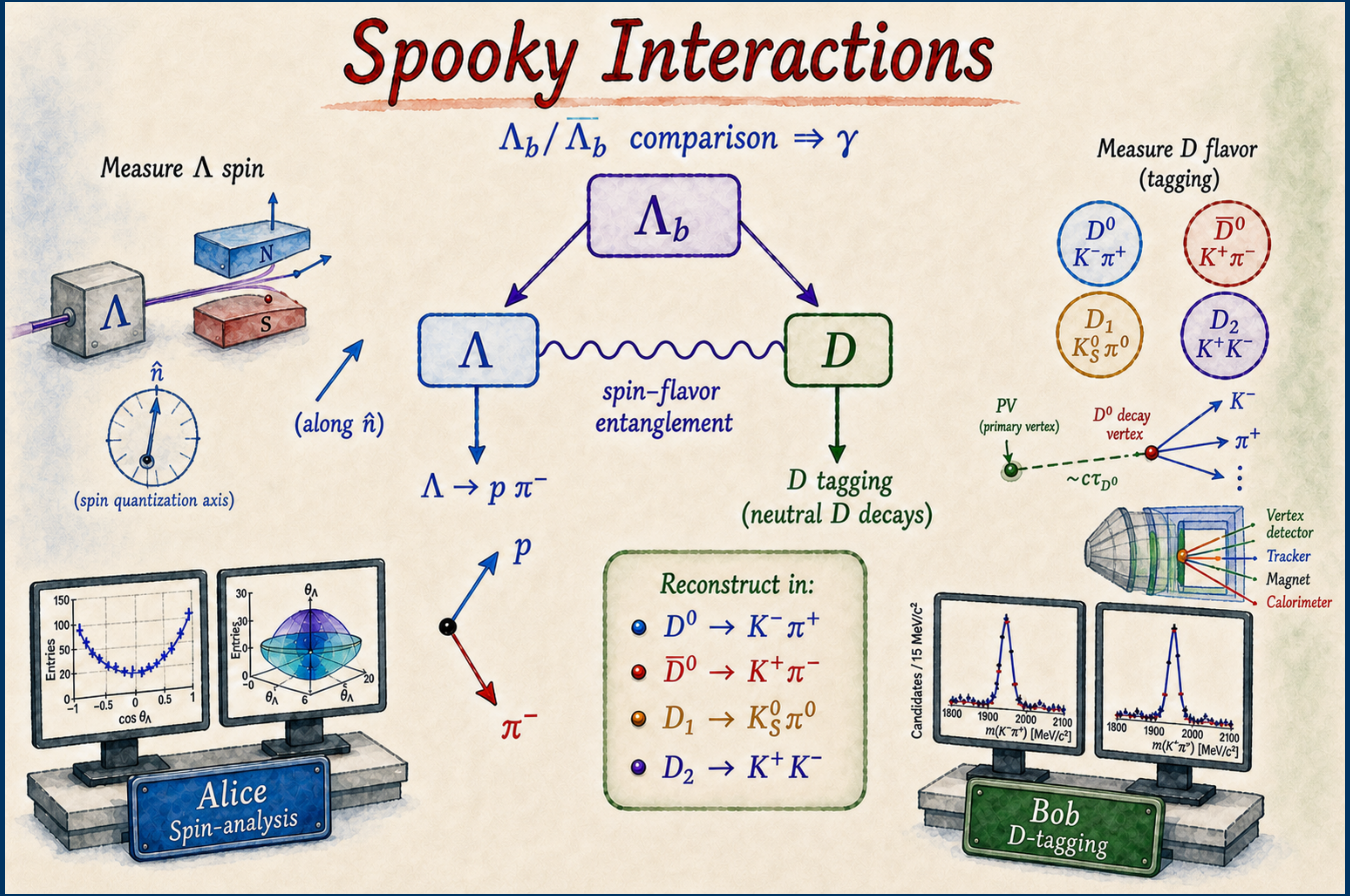
↓

Large interference & CPV

New entanglement

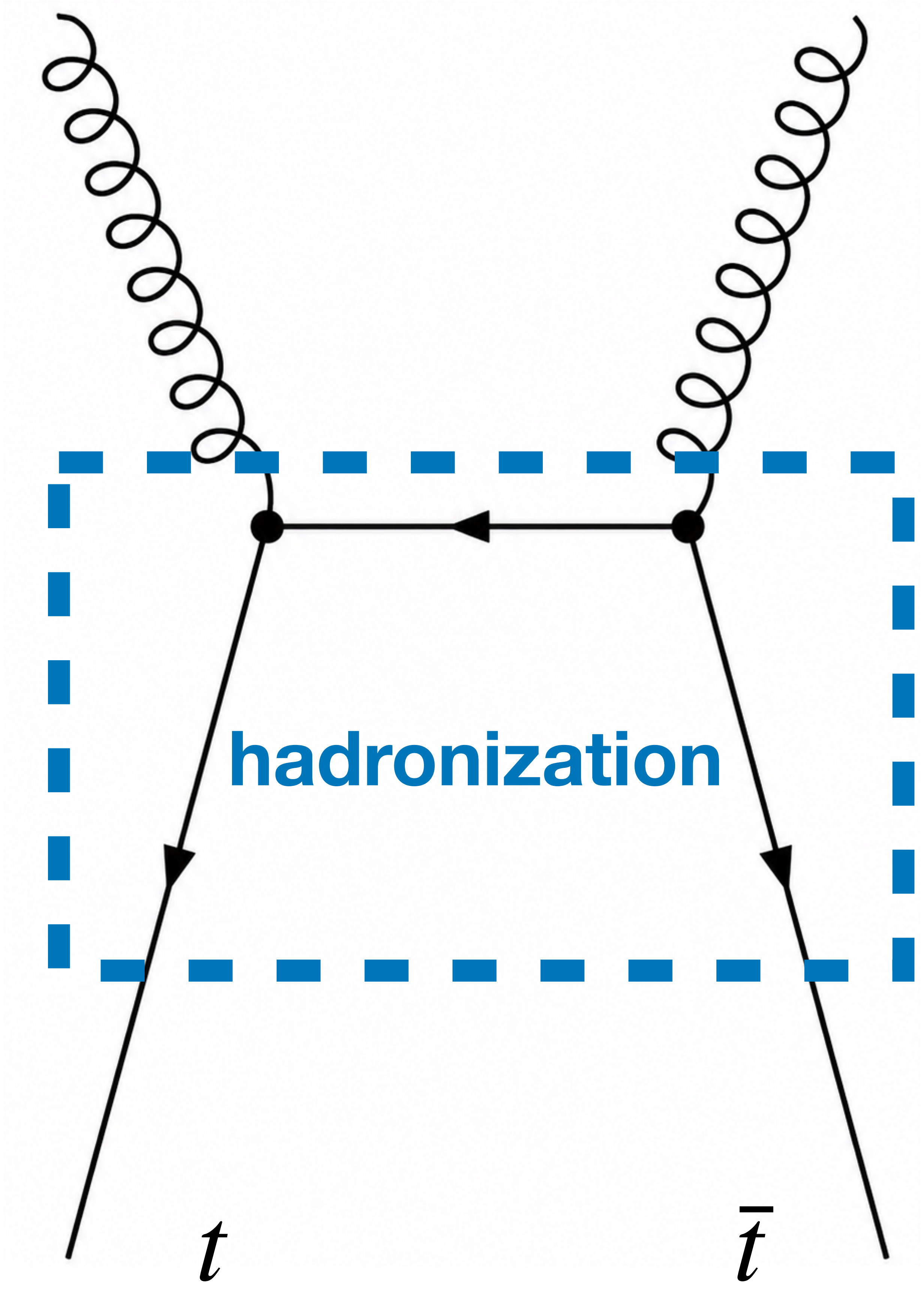
↓

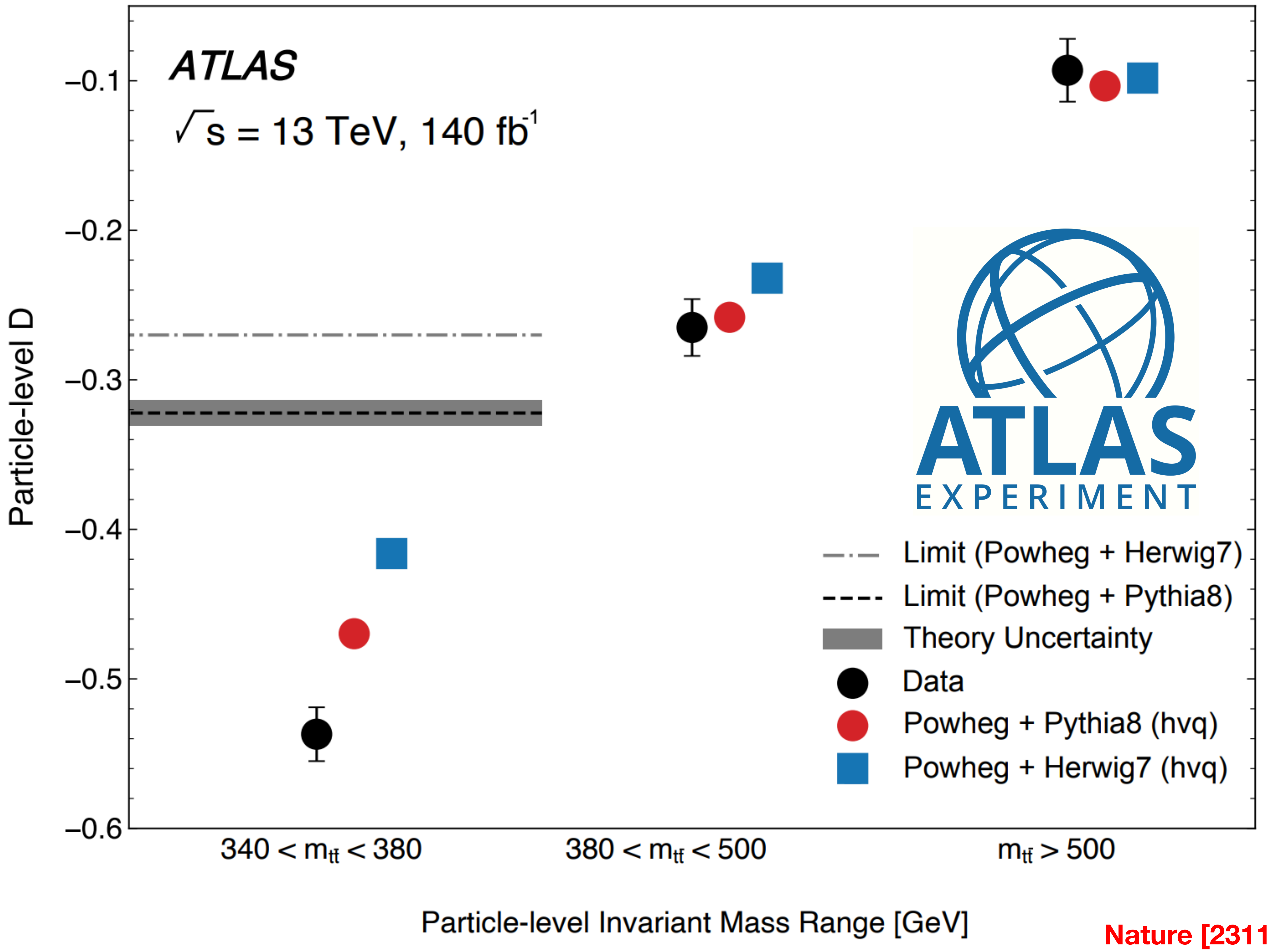
$\sigma_\gamma^{-1} \propto$ size of entanglements



• Applications in high energy physics

$t\bar{t}$ entanglement, signaling toponium-like hadronization





Nature [2311.07288]

Where should one search for large CPV?

- The effective Hamiltonian reads:

$$\mathscr{H}_{\overline{D}^0} \ni V_{ub}V_{cs}^*(\bar{u}b)_L(\bar{s}c)_L$$

$$\mathscr{H}_{D^0} \ni V_{cb}V_{us}^*(\bar{c}b)_L(\bar{s}u)_L$$

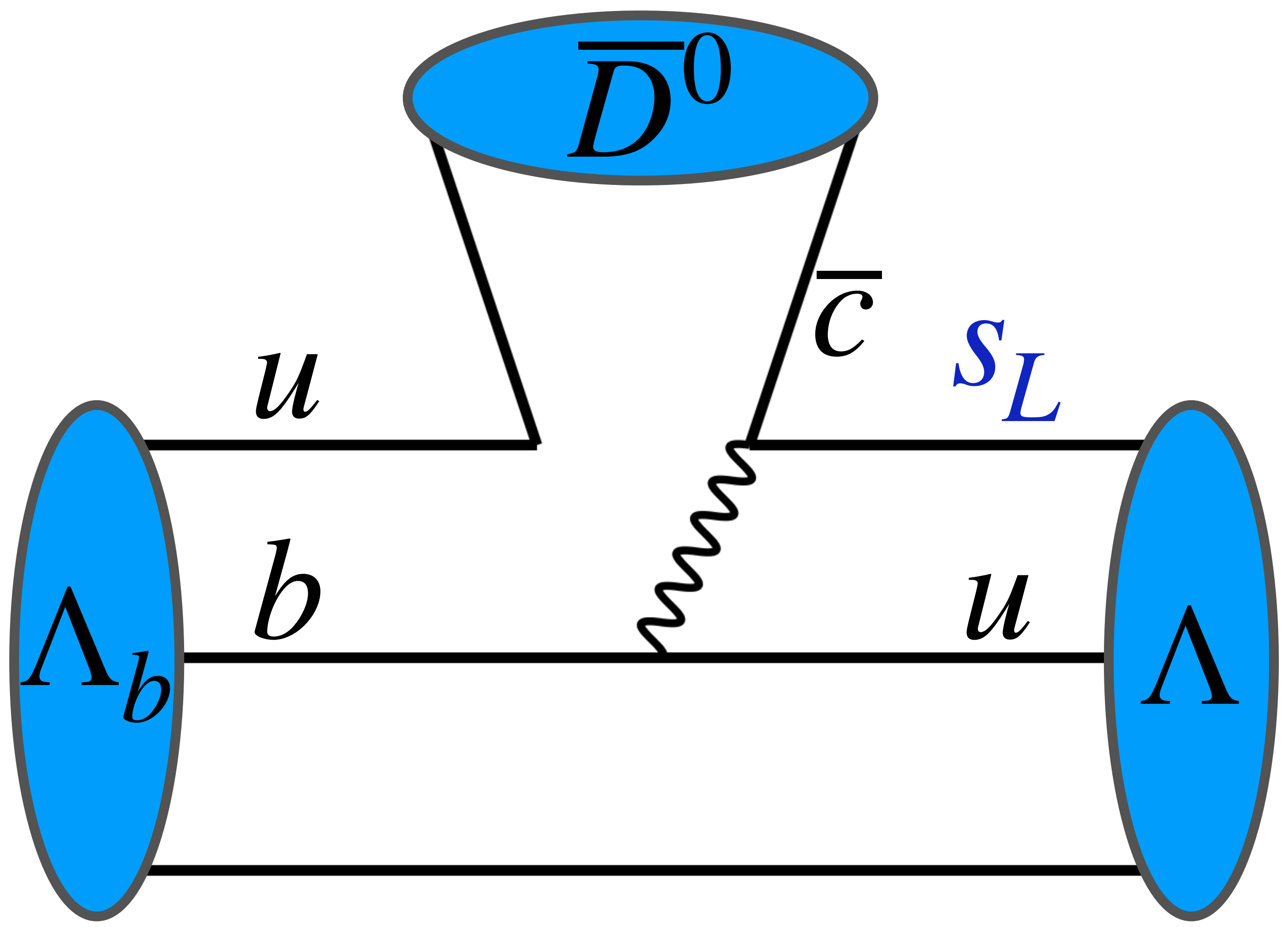
- Since $\vec{s}_\Lambda \approx \vec{s}_s$, the helicity suppression of the CKM interference is nearly absent.

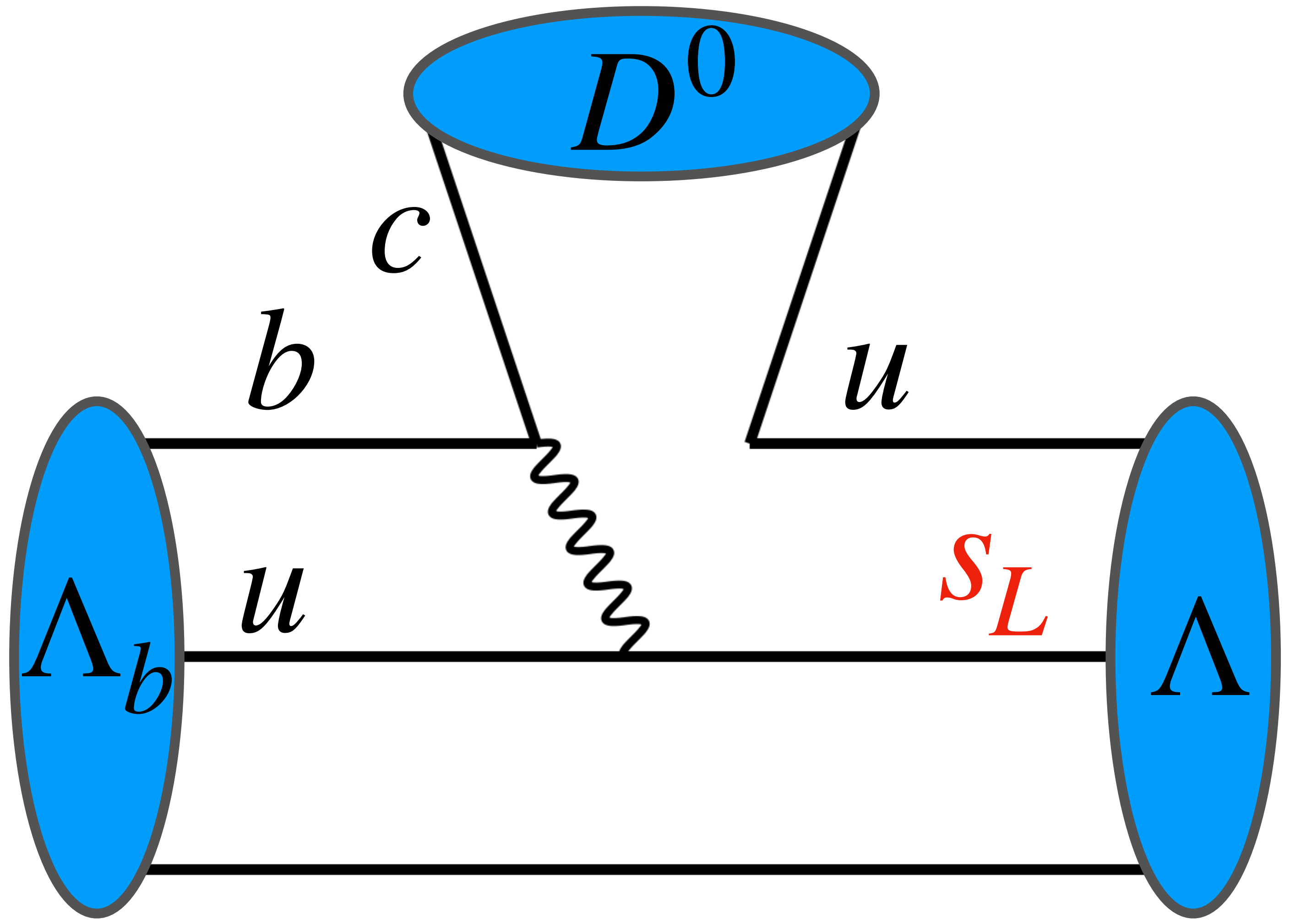
$$D_{1,2} = \frac{1}{\sqrt{2}}\left(D^0 \pm \overline{D}^0\right)$$

Mode	$\mathcal{B}(10^{-5})$	A_{CP}	α_{CP}	β_{CP}	γ_{CP}
ΛD^0	$3.1^{+1.8}_{-0.8}$	0	0	0	0
$\Lambda\overline{D}^0$	$2.3^{+1.1}_{-0.7}$	0	0	0	0
ΛD_1	$1.9^{+1.1}_{-0.4}$	$(-44^{+10}_{-3})\%$	$(3^{+2}_{-1})\%$	$(12^{+5}_{-5})\%$	$(8^{+5}_{-3})\%$
ΛD_2	$3.5^{+1.9}_{-1.0}$	$(72^{+4}_{-14})\%$	$(-11^{+6}_{-6})\%$	$(-25^{+11}_{-9})\%$	$(-18^{+6}_{-9})\%$

pQCD, [2604.17877]

- Numerical results alone are ***not*** the whole story.





Gronau–London–Wyler method in B mesons.

[hep-ph/9612433]

What is new?

- The final state lives in $\mathscr{H}_{\text{flavor}} \otimes \mathscr{H}_{\text{spin}}$

$$|D\Lambda\rangle = \frac{1}{\mathcal{N}}\left[e^{-i\gamma}|\overline{D}^0\rangle \otimes \chi_{\overline{D}} + |D^0\rangle \otimes \chi_D\right],$$

* χ_D and $\chi_{\overline{D}}$ are the Λ helicity spinors.

$$\chi_{\overline{D}} = \begin{pmatrix} S_{\overline{D}^0} + P_{\overline{D}^0} \\ S_{\overline{D}^0} - P_{\overline{D}^0} \end{pmatrix}, \qquad \chi_D = \begin{pmatrix} S_{D^0} + P_{D^0} \\ S_{D^0} - P_{D^0} \end{pmatrix}. \qquad \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \left|\lambda = \frac{1}{2}\right\rangle, \quad \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \left|\lambda = -\frac{1}{2}\right\rangle$$

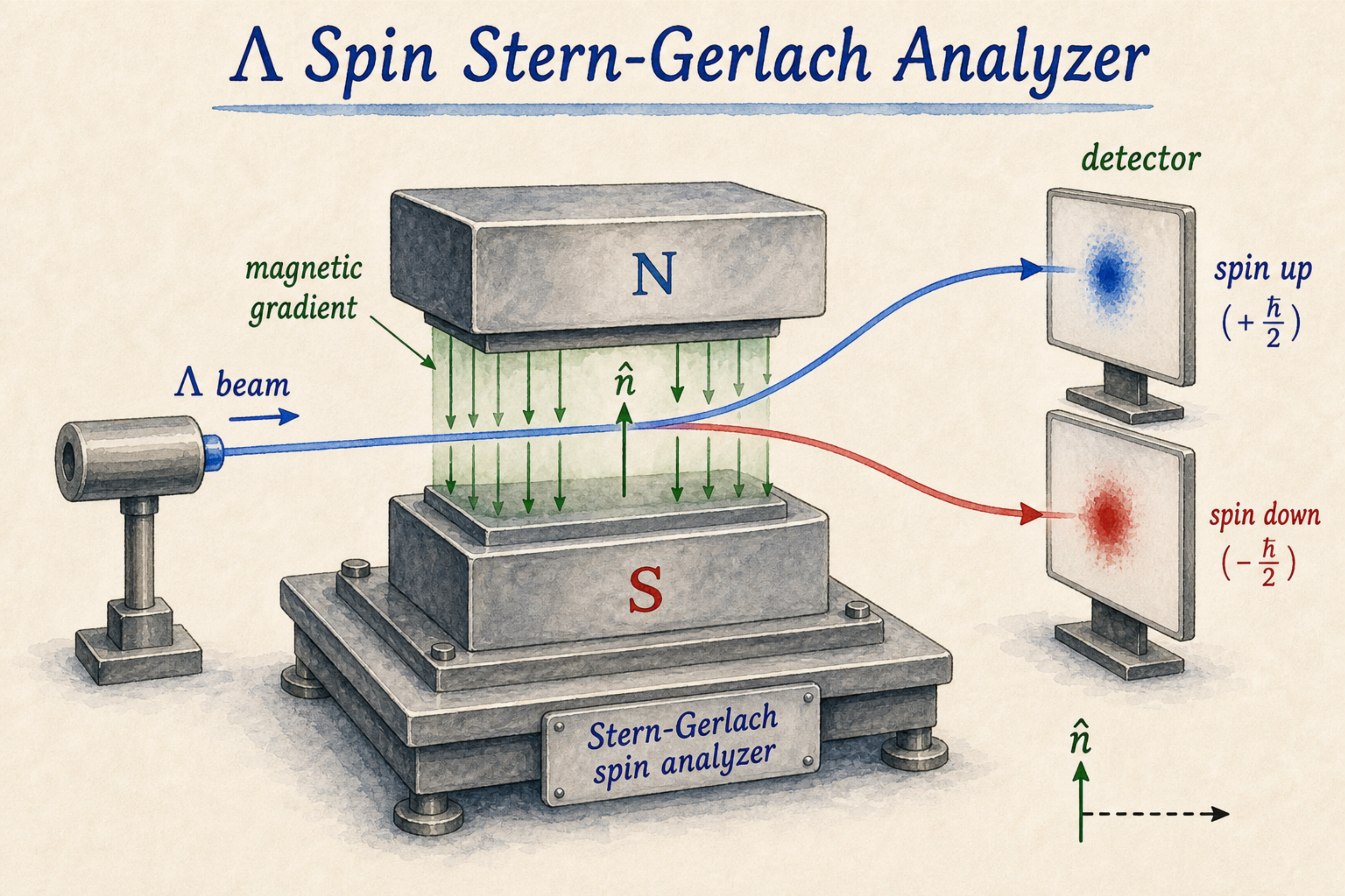
- The spinors live in the helicity basis of

$$|\lambda\rangle = \frac{1}{2\pi}\int d\Omega\, |\vec{k}, \lambda; \Lambda D\rangle\, e^{iJ_z\phi} d^{1/2}_{J_z\lambda}(\theta)\,.$$

$$\hat{\alpha} = 2\hat{k}\cdot\vec{s}, \quad \hat{\beta} = 2\left(\vec{J}\times\hat{k}\right)\cdot\vec{s}, \quad \hat{\gamma} = 2\left(\vec{J} - \hat{k}\,\hat{k}\cdot\vec{J}\right)\cdot\vec{s},$$

$$\hat{\alpha} \to \sigma_z, \quad \hat{\beta} \to -\sigma_y, \quad \hat{\gamma} \to \sigma_x, \quad \langle\hat{\alpha}\rangle_D = \alpha_D \quad \text{e.t.c..}$$

- Lee-Yang parameters act as helicity generators.



In memory of J. G. Körner, Mainz

What is new?

- The final state lives in $\mathscr{H}_{\text{flavor}} \otimes \mathscr{H}_{\text{spin}}$

$$|D\Lambda\rangle = \frac{1}{\mathcal{N}}\left[e^{-i\gamma}|\overline{D}^0\rangle \otimes \chi_{\overline{D}} + |D^0\rangle \otimes \chi_D\right],$$

- The D flavors form an $SU(2)$ Hilbert space:

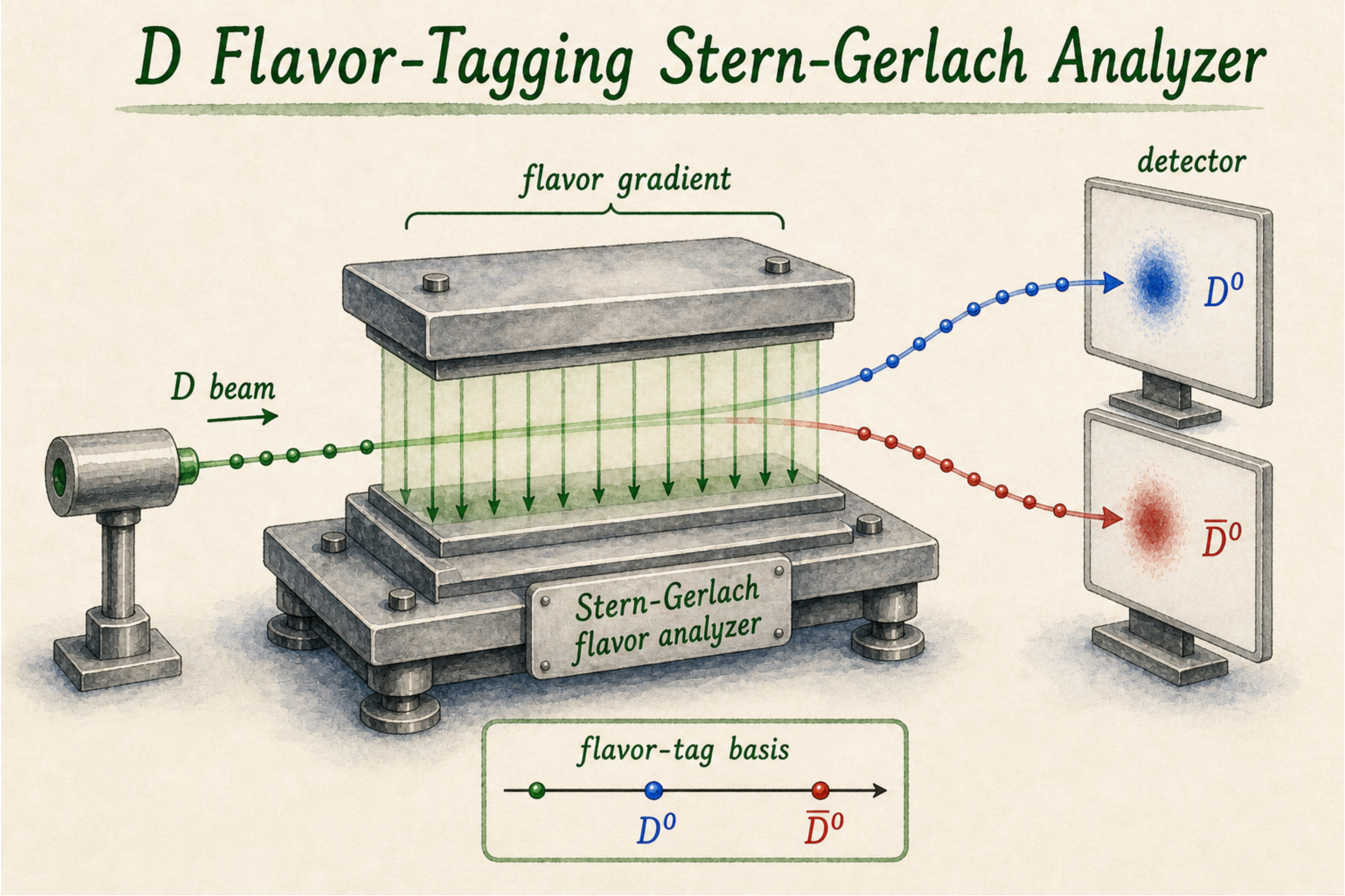
$$\hat{O}_F = \left|\overline{D}^0\right\rangle\left\langle\overline{D}^0\right| - \left|D^0\right\rangle\left\langle D^0\right|.$$

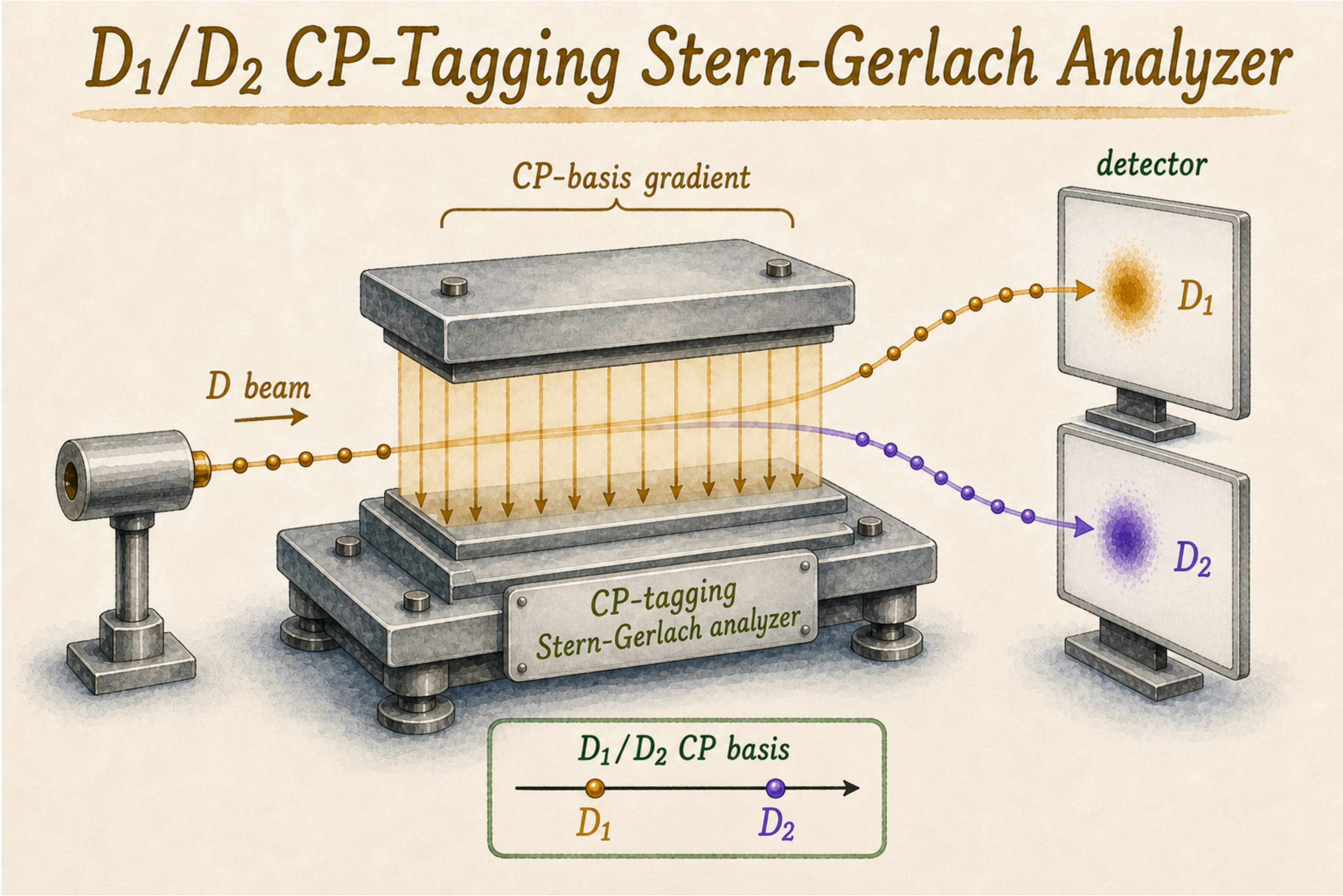
$$\hat{O}_{12} = |D_1\rangle\langle D_1| - |D_2\rangle\langle D_2| = |D^0\rangle\langle\overline{D}^0| + |\overline{D}^0\rangle\langle D^0|.$$

- They define σ_z and σ_x in the flavor space.

- However, the y direction of the D-flavor is not measurable as

$$D_{y,\pm} = \frac{1}{\sqrt{2}}\left(D^0 \pm i\overline{D}^0\right)$$ is ***not*** accessible.





Thought experiment: active flavor detection

What is new?

- The size of the entanglement is given by

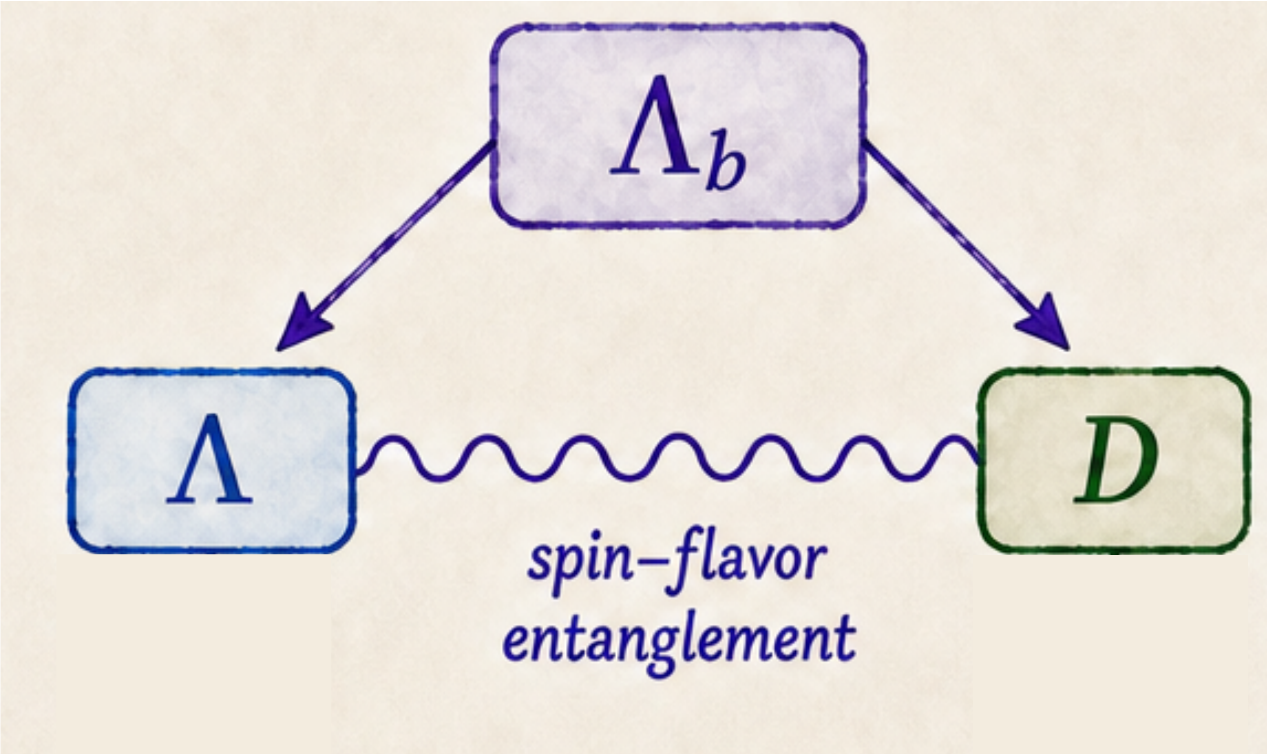
$$\mathscr{C} = \left[\frac{1-R_F^2}{2}\left(1-\alpha_{\overline{D}^0}\alpha_{D^0}-\beta_{\overline{D}^0}\beta_{D^0}-\gamma_{\overline{D}^0}\gamma_{D^0}\right)\right]^{1/2}, \quad R_F = \frac{\Gamma_{\overline{D}^0}-\Gamma_{D^0}}{\Gamma_{\overline{D}^0}+\Gamma_{D^0}}.$$

- The necessary and sufficient condition for entanglement is

$$\mathscr{C} \neq 0 \quad \Longleftrightarrow \quad R_F^2 \neq 1 \quad \text{and} \quad \xi_{\overline{D}^0} \neq \xi_{D^0}, \quad \text{for } \xi = \alpha, \beta, \gamma$$

- For instance, to prove $\mathscr{C}$ is nonzero, it suffices to show $R_F^2 \neq 1$ and $\alpha_{D^0} \neq \alpha_{\overline{D}^0}$.

Λ helicity depends on the D flavor tag, and vice versa.



• What is new?

- The size of the entanglement is given by

$$\mathscr{C} = \left[\frac{1-R_F^2}{2} \left(1 - \alpha_{\overline{D}^0}\alpha_{D^0} - \beta_{\overline{D}^0}\beta_{D^0} - \gamma_{\overline{D}^0}\gamma_{D^0}\right) \right]^{1/2}, \quad R_F = \frac{\Gamma_{\overline{D}^0} - \Gamma_{D^0}}{\Gamma_{\overline{D}^0} + \Gamma_{D^0}}.$$

- The transverse spins β_D and γ_D are more difficult to measure, and we give the bounds

$$\mathscr{C}_{\min,\max} = \frac{2}{\Gamma_{\overline{D}^0} + \Gamma_{D^0}} \left[\Gamma_{\overline{D}^0}\Gamma_{D^0} - \frac{\left(\Gamma_{D_1} - \Gamma_{D_2}\right)^2}{4} - \frac{\left(I_+ \pm I_-\right)^2}{4} \right]^{1/2},$$

$$I_\pm = \left[\Gamma_{\overline{D}^0}\Gamma_{D^0}(1 \pm \alpha_{\overline{D}^0})(1 \pm \alpha_{D^0}) - \frac{\left[\Gamma_{D_1}(1 \pm \alpha_{D_1}) - \Gamma_{D_2}(1 \pm \alpha_{D_2})\right]^2}{4} \right]^{1/2}.$$

- A nonzero $\mathscr{C}_{\min}$ would provide the **first** lower bound on the **size** of **spin-flavor entanglement**.

How it helps?

- Since there is no CPV in flavor-tagged modes $(D^0, \overline{D}^0)$, we have that $\overline{\mathscr{C}} = \mathscr{C}$ for $\overline{\Lambda}_b \to \overline{\Lambda} D$.

$$|D\overline{\Lambda}\rangle = \frac{1}{\mathcal{N}}\left[|\overline{D}^0\rangle \otimes \sigma_x \chi_D + e^{i\gamma}|D^0\rangle \otimes \sigma_x \chi_{\overline{D}}\right],$$

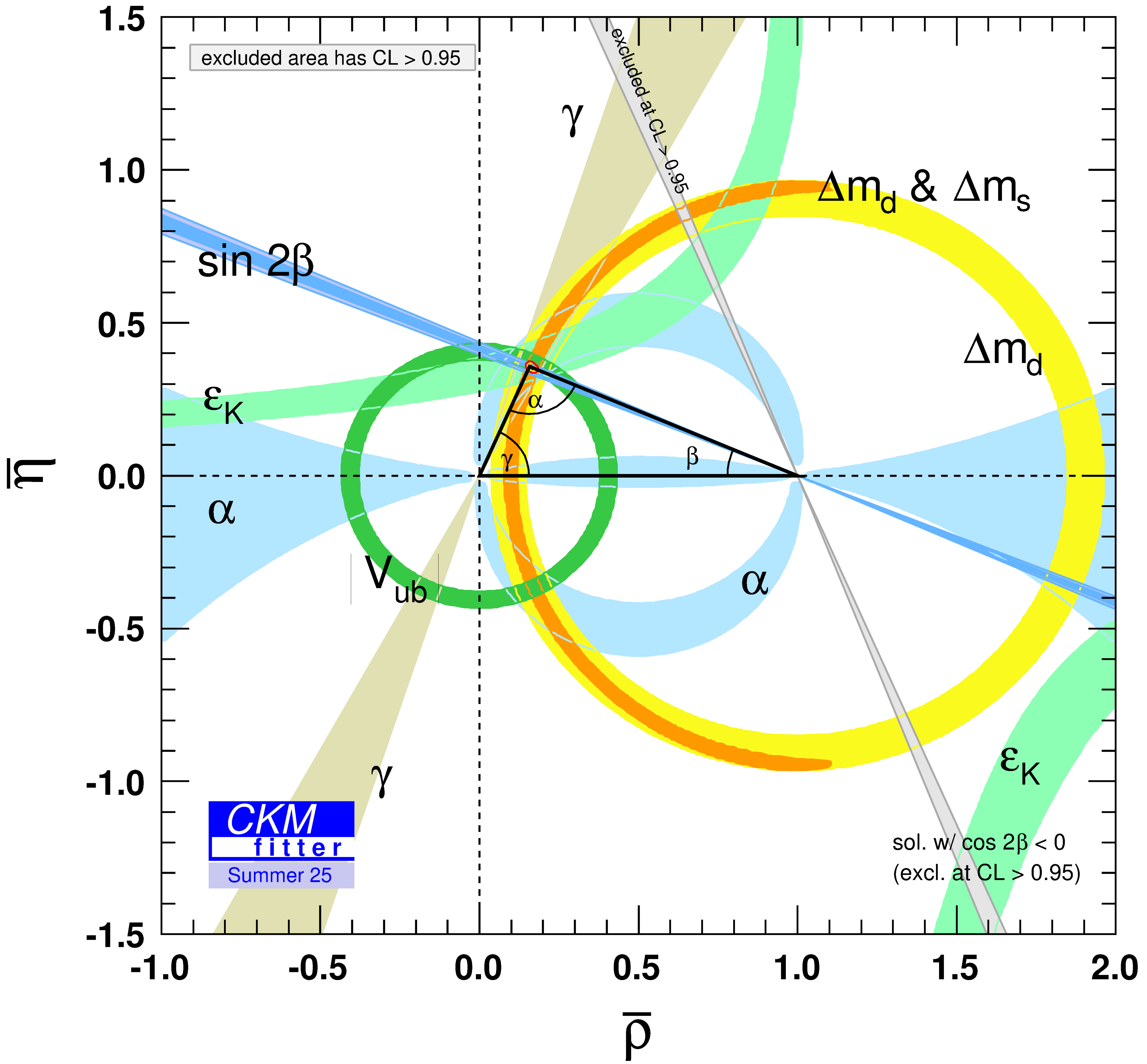
to be compared with

$$|D\Lambda\rangle = \frac{1}{\mathcal{N}}\left[e^{-i\gamma}|\overline{D}^0\rangle \otimes \chi_{\overline{D}} + |D^0\rangle \otimes \chi_D\right].$$

- Question: how to measure γ ?

$$\gamma = \frac{1}{2}\arg\left[\frac{\left(z_{\overline{D}^0} - z_{D_{1,2}}\right)\left(\bar{z}_{D^0} - \bar{z}_{D_{1,2}}\right)}{\left(z_{D^0} - z_{D_{1,2}}\right)\left(\bar{z}_{\overline{D}^0} - \bar{z}_{D_{1,2}}\right)}\right],$$

Projective coordinates of χ_D : $\quad z_D = \dfrac{\alpha_D + i\beta_D}{1 + \gamma_D}$.



• How it helps?

- We choose the basis:

$$\chi_{\overline{D}} = \begin{pmatrix} u' \\ 0 \end{pmatrix}, \qquad \chi_D = \begin{pmatrix} u \\ v \end{pmatrix},$$

- We find :

$$\sigma_\gamma \simeq \frac{1}{\mathscr{C}} \left[\frac{1}{\sigma^2_{\delta_u}} + \frac{1}{f^2_{\text{br}}(R_F, \mathscr{C})(\sigma_{\delta_v})^2} + \frac{\Delta_{\text{corr}}}{\sigma_{\delta_u}\sigma_{\delta_v}} \right]^{-1/2}$$

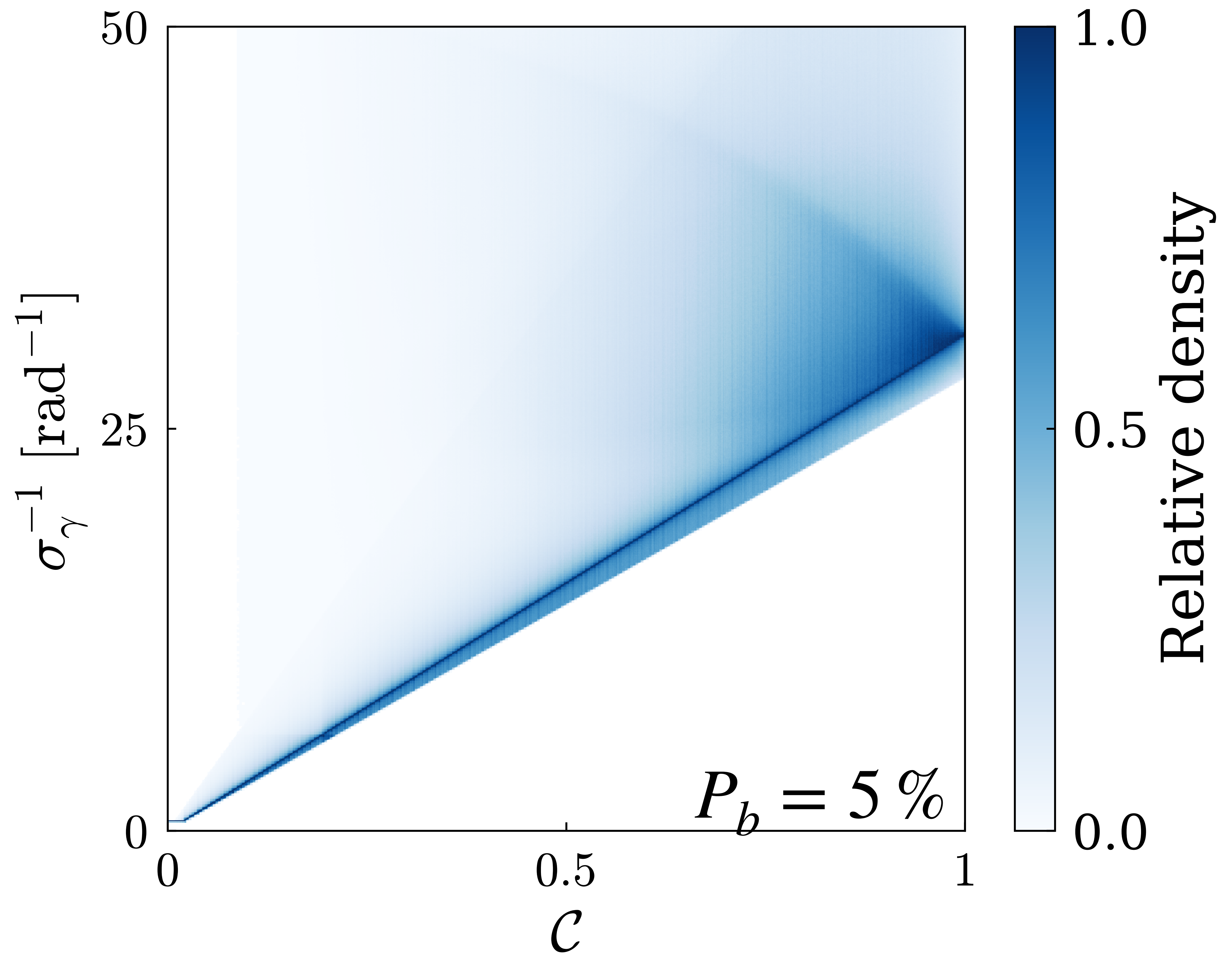
Related to phase uncertainty of u

Related to phase uncertainty of v

- With pQCD input: ***optimistic*** statistical uncertainties

$\sigma_\gamma \simeq (0.6^\circ)/P_b$ — Λ_b

$\gamma = (66.3^{+0.7}_{-1.9})^\circ$ — B-meson



Observable-level sensitivity scan with random hadronic amplitudes, using LHCb Run-3 yields.

• Final remarks on nonlocal entanglement/Bell tests

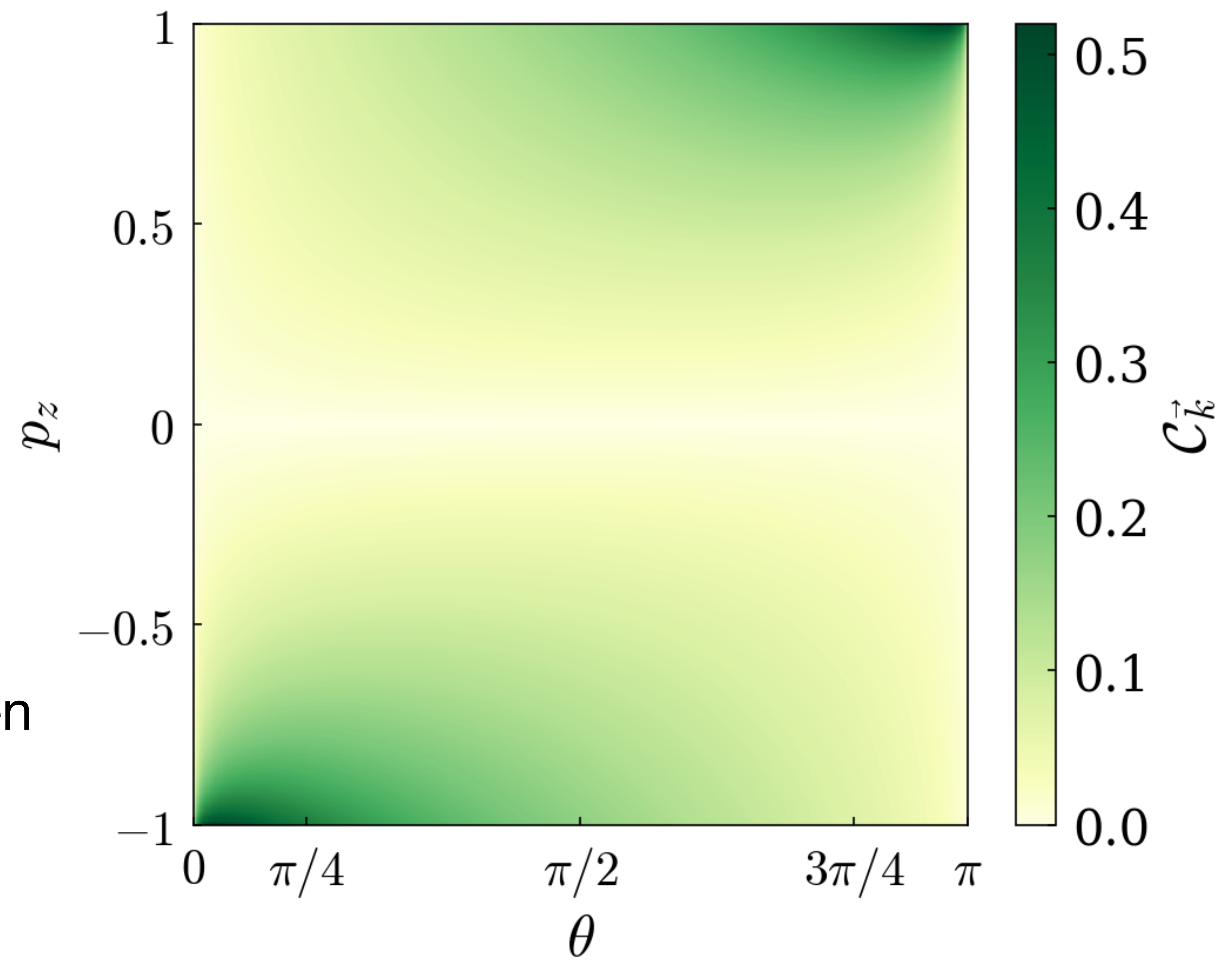
- The partial decay width is promoted to a 2×2 matrix to unify the description of D.

$$\frac{\partial^2 \Gamma}{\partial \cos\theta \, \partial\phi} = \frac{|\vec{k}|}{64\pi^2 m_{\Lambda_b}^2}\left[N\left(1 + P_b \cos\theta\, \vec{s}\cdot\hat{r}\right) + P_b \boldsymbol{\alpha} \cos\theta + \boldsymbol{\alpha}\, \vec{s}\cdot\hat{r} + P_b \boldsymbol{\beta} \sin\theta\, \vec{s}\cdot\hat{\phi} - P_b \boldsymbol{\gamma} \sin\theta\, \vec{s}\cdot\hat{\theta}\right]$$

$$\boldsymbol{\alpha} = \begin{pmatrix} 2\mathrm{Re}(S^*_{\overline{D}^0} P_{\overline{D}^0}) & P_{\overline{D}^0} S^*_{D^0} + S_{\overline{D}^0} P^*_{D^0} \\ P_{D^0} S^*_{\overline{D}^0} + S_{D^0} P^*_{\overline{D}^0} & 2\mathrm{Re}(S^*_{D^0} P_{D^0}) \end{pmatrix}$$

$$= \frac{1}{2}\mathrm{Tr}\,(\boldsymbol{\alpha}) + \vec{\alpha}\cdot\vec{\sigma}$$

- Collider Bell tests are ***not*** loophole-free: ***without freely*** chosen measurement directions and timings, local hidden variables can mimic the observed correlations.



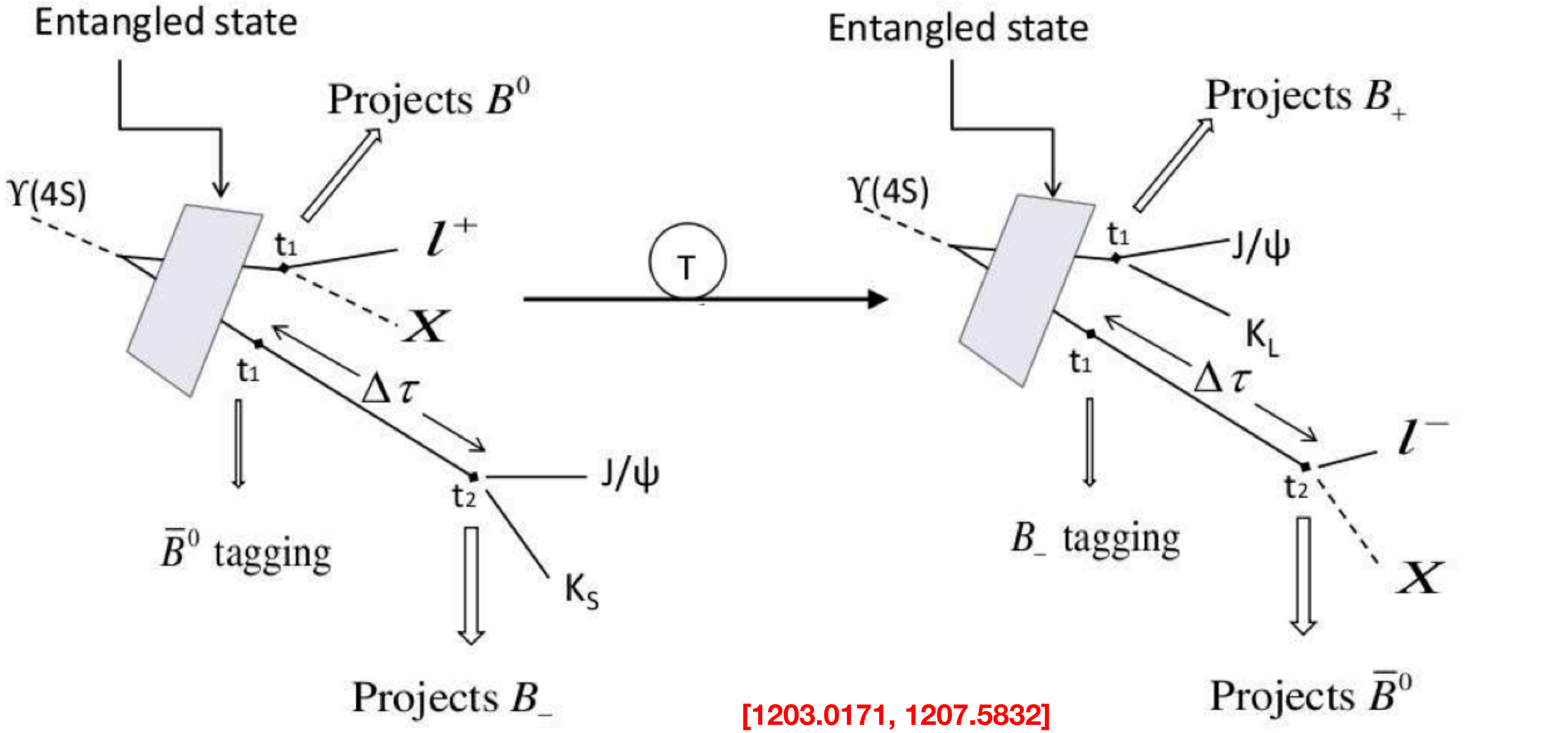
Der Mensch kann tun, was er will, aber er kann nicht wollen, was er will. — Schopenhauer

Backup

• Applications in high energy physics

First direct observation of T violation in B mesons

$$\Upsilon(4S) \to \frac{1}{\sqrt{2}}\left(B^0\overline{B}^0 - B^0\overline{B}^0\right)$$



[1203.0171, 1207.5832]

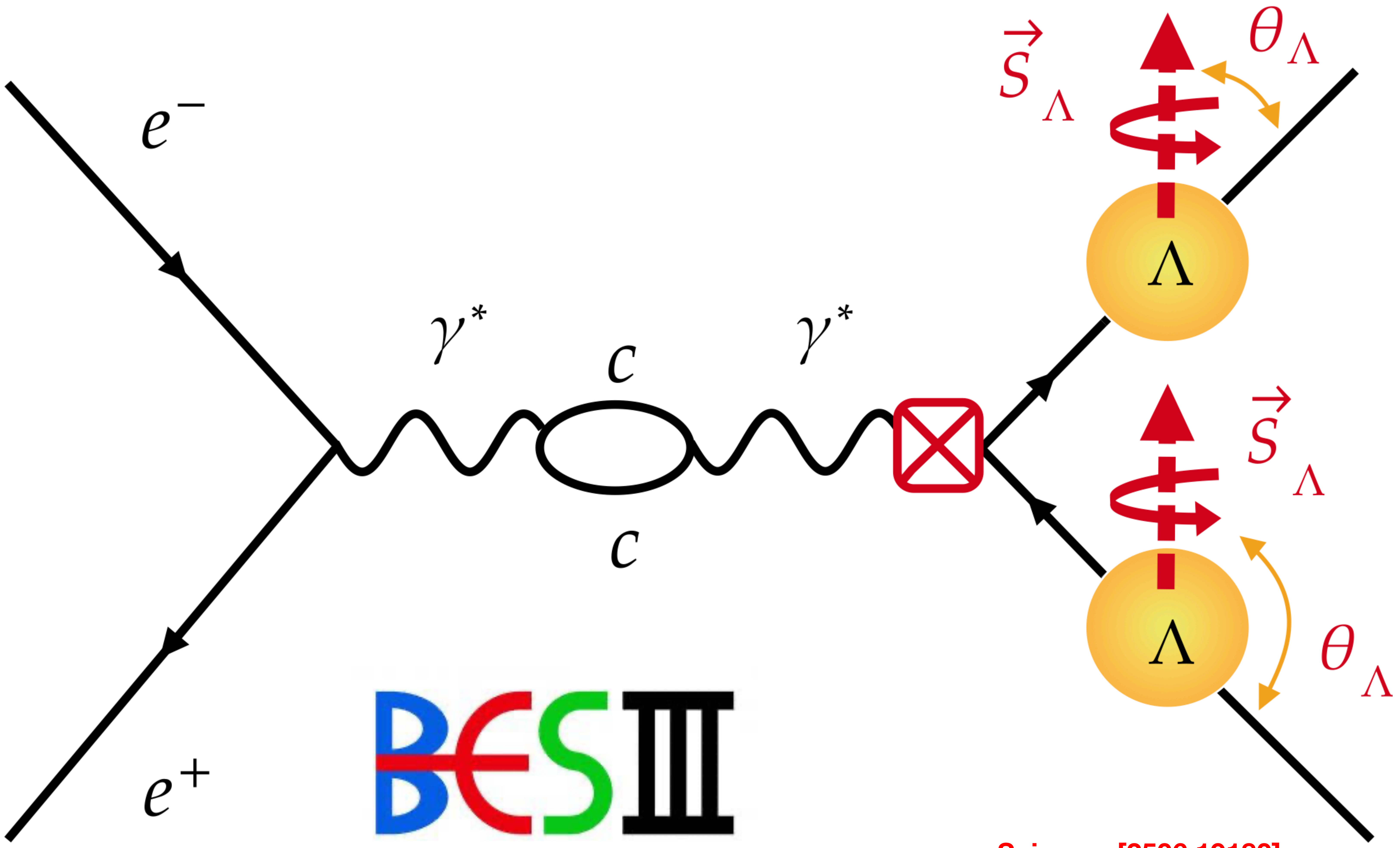
$$\overline{B}^0 \xrightarrow{\Delta\tau} B_-$$

$$B_- \xrightarrow{\Delta\tau} \overline{B}^0$$

BABAR

- **Applications in high energy physics**

Measure hyperon electric dipole moments: $|\psi\rangle \ni |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



BESIII

Science, [2506.19180]

• Where should one search for large CPV?

- ***Maybe,*** the same suppressions hold for the multi-body decays since

$$\mathcal{H}_{\text{Tree}} \ni \lambda_u c_1 \left(\bar{u}_L \gamma_\mu b_L\right)\left(\bar{d}_L \gamma^\mu u_L\right)$$

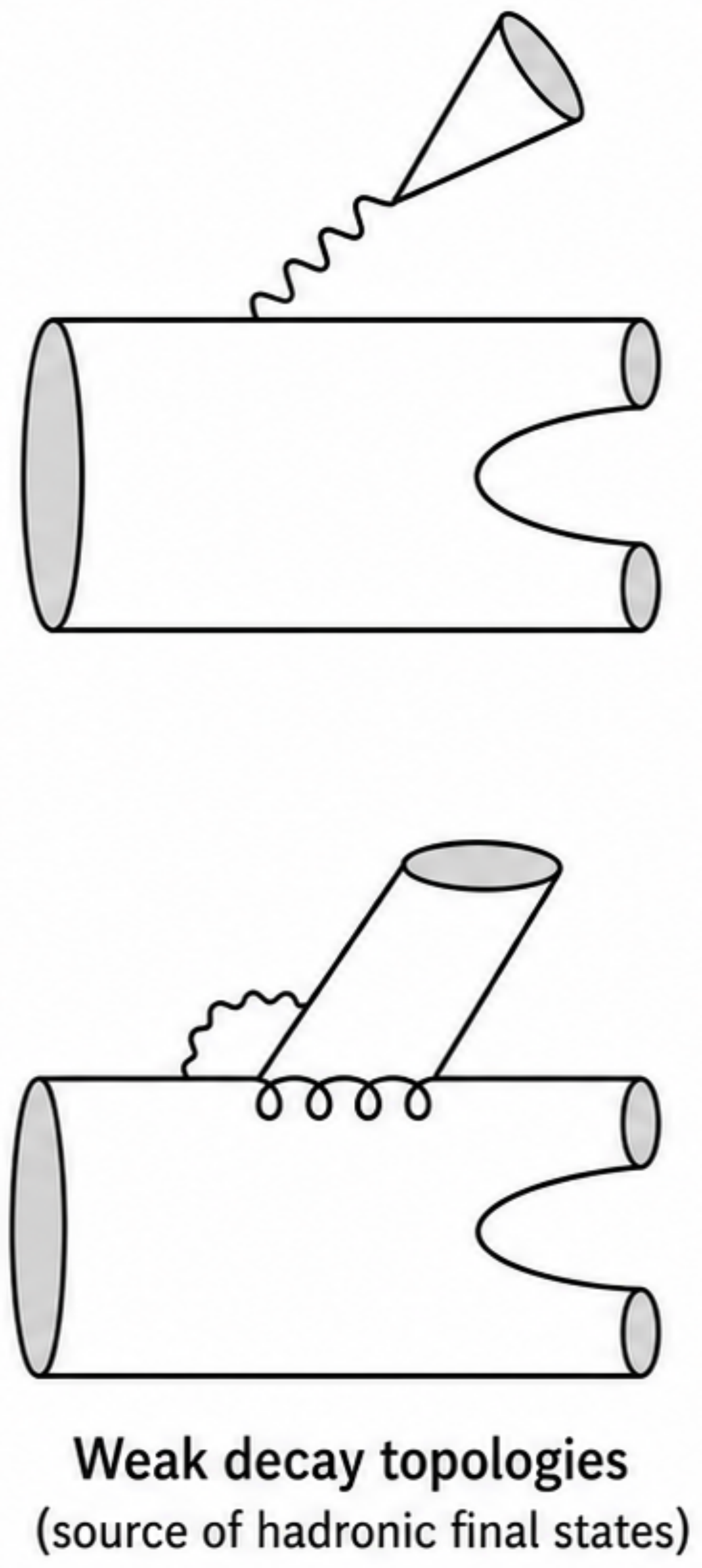
$$\mathcal{H}_{\text{Penguin}} \ni \lambda_t c_6 \left[2(\bar{u}_R b_L)(\bar{d}_L u_R)\right]$$

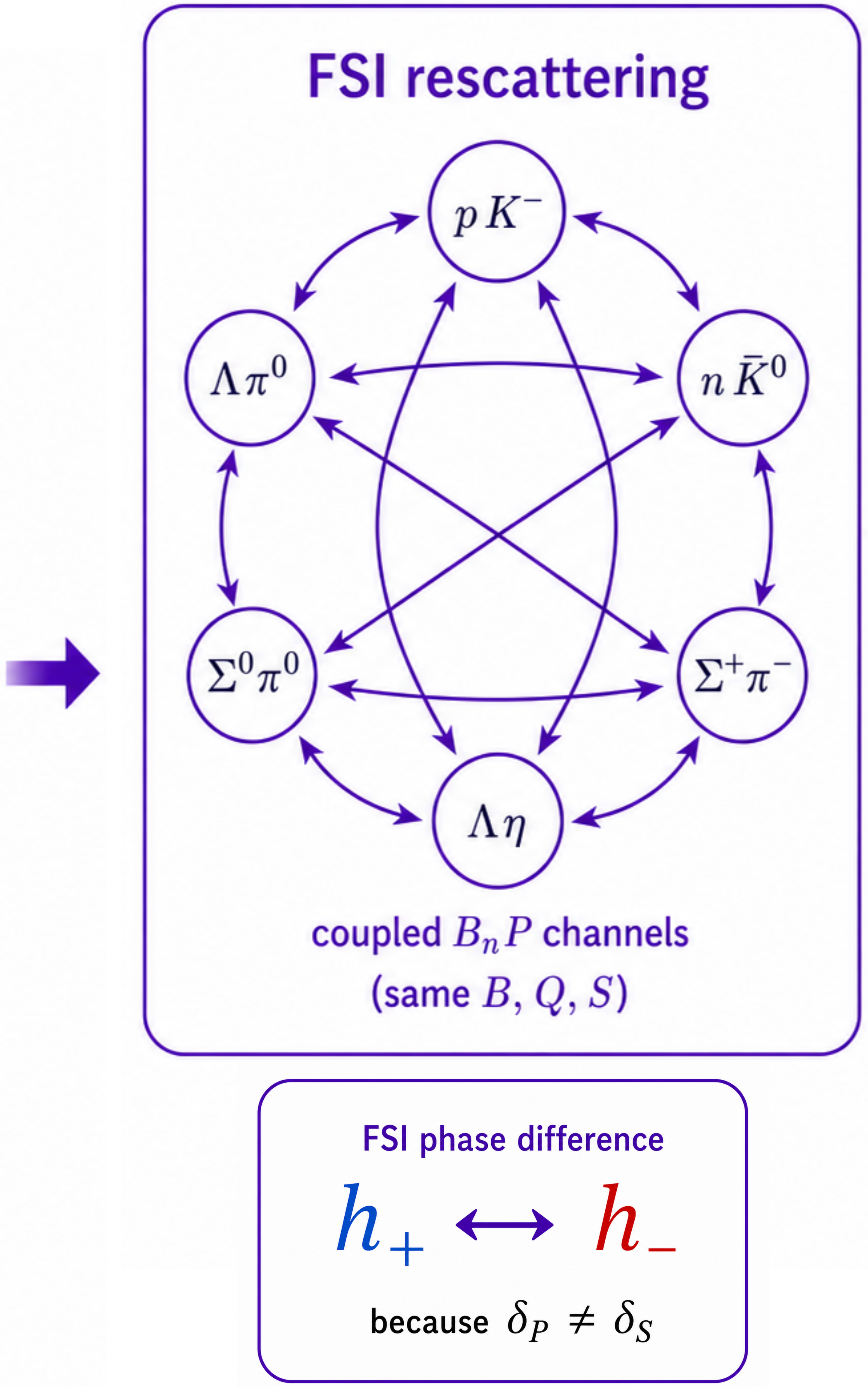
favor different helicities of final-state baryons.

- In the **low-q^2** region, the data show that

$$A_{CP}(\Lambda_b \to N^*(1520)K) = (16.5 \pm 4.8 \pm 1.7)\,\%$$

- For details, see **[2411.15441]**





- Starting with a standard $H_{\text{spin}} \otimes H_{\text{spin}}$ Hilbert space:

$$|\psi\rangle = c_{++}|\uparrow\uparrow\rangle + c_{+-}|\uparrow\downarrow\rangle + c_{-+}|\downarrow\uparrow\rangle + c_{--}|\downarrow\downarrow\rangle .$$

Rotate the bases of the two spins such that

$$|\psi\rangle = \cos\theta|\uparrow\uparrow\rangle + \sin\theta\left(\cos\phi|\downarrow\uparrow\rangle + \sin\phi|\downarrow\downarrow\rangle\right) .$$

$|\psi\rangle$ ***cannot*** be written as a direct product $|\psi\rangle = |\lambda_1\rangle \otimes |\lambda_2\rangle$ if the first and the third terms are nonzero.

Wootters concurrence*:

$$\mathscr{C} = |\langle\psi^*|\sigma_y \otimes \sigma_y|\psi\rangle| = 2\cos\theta\sin\theta\sin\phi$$

$*$ for pure states.