Flavor-Spin Entanglement and the Weak Phase Extraction in $\Lambda_b \to \Lambda D$

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Based on 2605.09682

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Introduction

Entanglement means correlations of the full system cannot be factorized into independent subsystem states:

separable

$$|\psi\rangle = |0\rangle_A \otimes |0\rangle_B$$

non-separable

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B\right)$$

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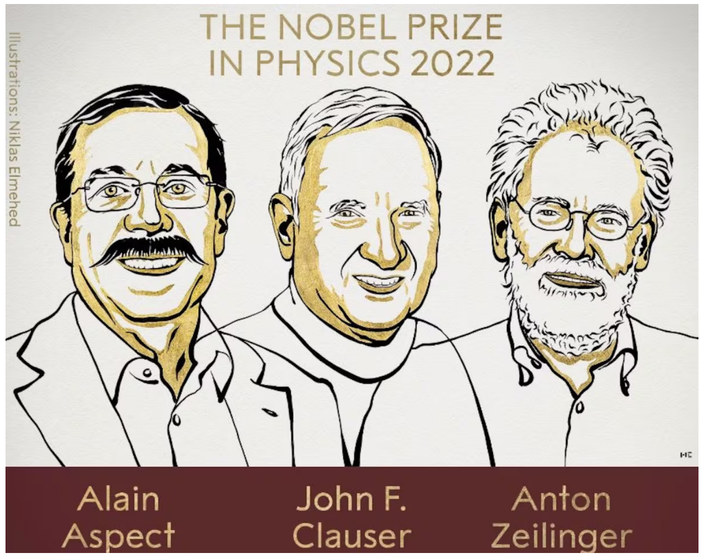
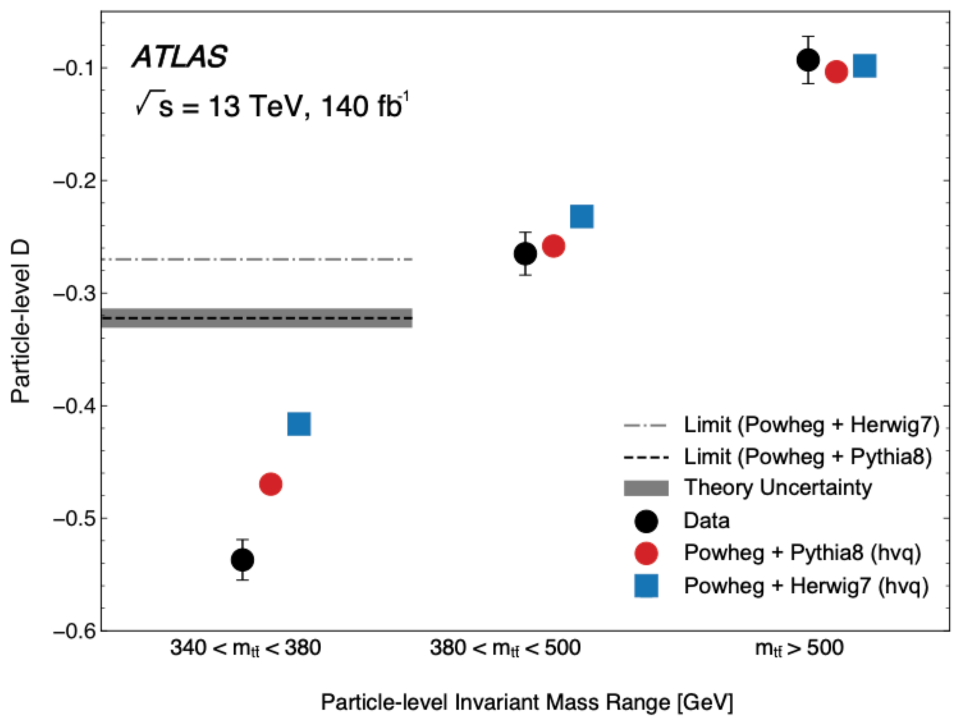
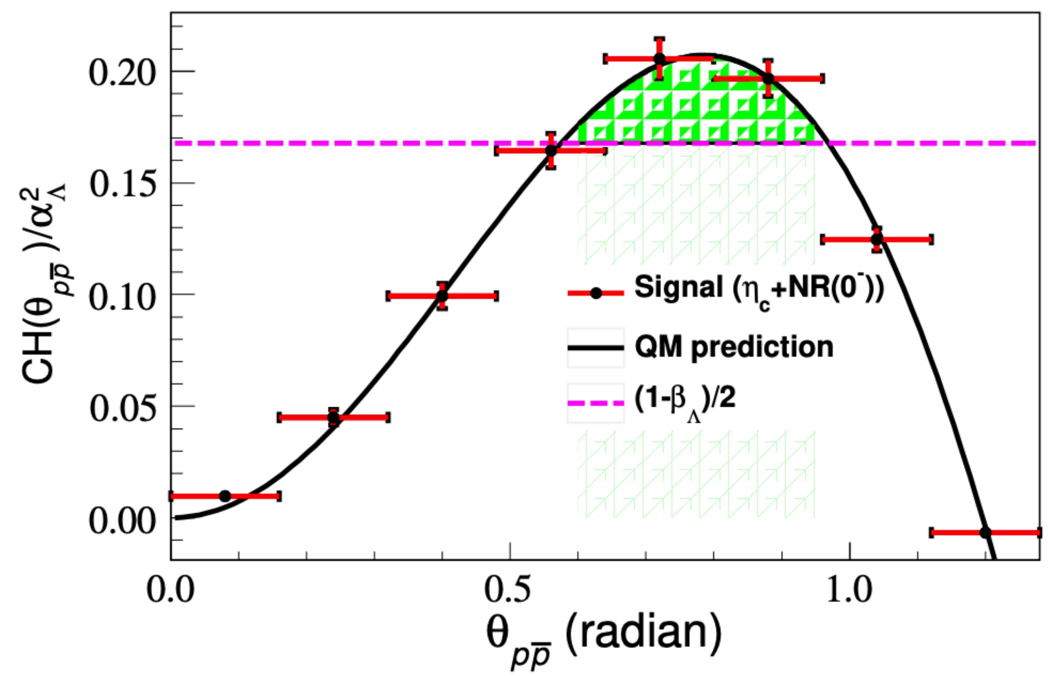


People in hep-ph are seriously thinking about entanglement *at colliders* in recent years.

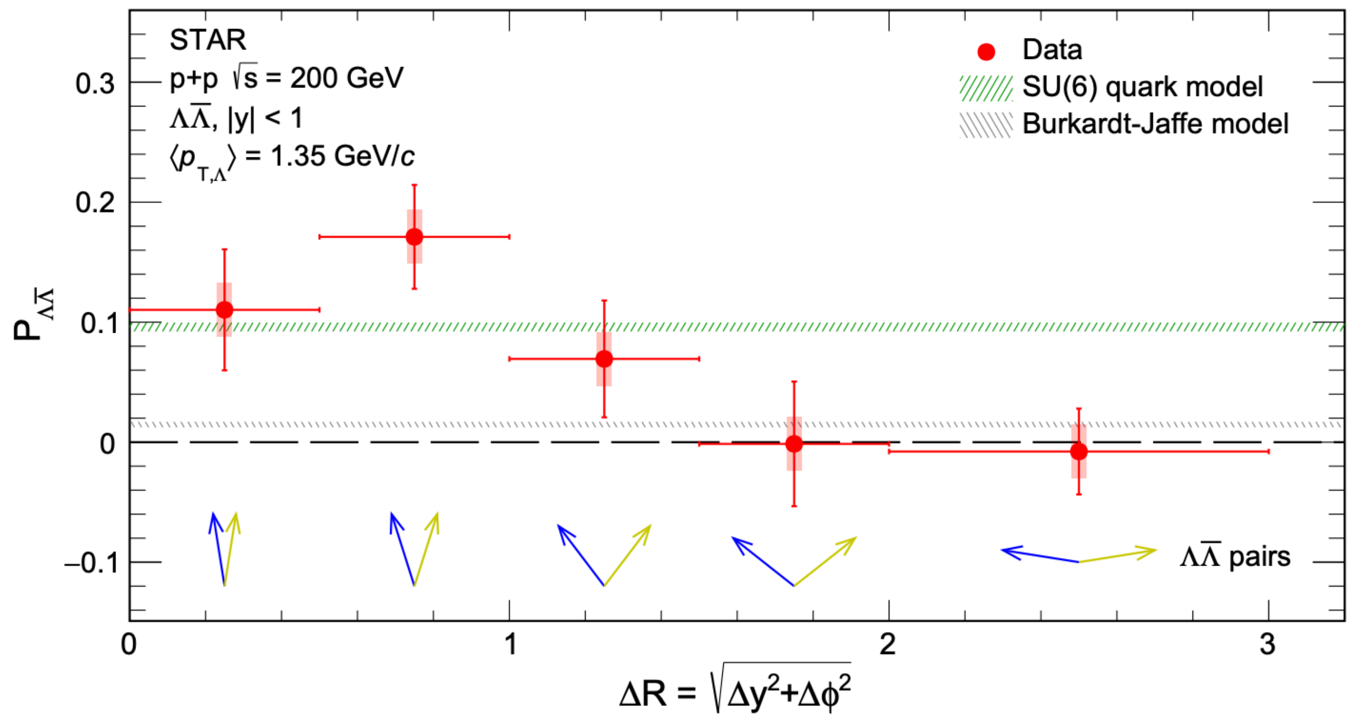
Introduction



ATLAS, Nature, 2024



BESIII, Nature Commun., 2025



STAR, Nature, 2026

Introduction

Including photons, all these examples discussed above are measuring the *spin-spin* correlations of the final state particle pairs. At colliders, the main focus is on the spin-spin correlation of the fermion pair at final states.

Spin correlation
(joint angular distribution)

$$\rho = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i B_i^{+} s^i \otimes \boldsymbol{I}_2 + \sum_j B_j^{-} \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

Polarization of the subsystem
(Decay distribution)

Introduction

A second example is *flavor-flavor* correlations in neutral meson-antimeson systems, examples include B_d^0, B_s^0, D^0, K^0

$$\rho_f = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i b_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j b_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

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The propagating mass eigenstates are different from decaying states, the latter of which are CP-tagged. ρ_f can thus be fully reconstructed from the CP-tagged decaying channels.

	$B_s^0 \bar{B}_s^0$	$K^0 \bar{K}^0$
Quantum discord	0.58 ± 0.10	0.617 ± 0.003
Concurrence	0.69 ± 0.15	0.701 ± 0.003
Steerability variable	0.48 ± 0.07	0.4818 ± 0.0017
Bell variable	0.1856 ± 0.0015	0.187 ± 0.004
Conditional entropy	-0.16 ± 0.31	-0.154 ± 0.007
SSRE (magic)	0.38 ± 0.15	0.389 ± 0.003

Kun Cheng, Tao Han, Matthew Low, Tong Arthur Wu, PRL 2026

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Q2: If so, what is the physical importance?

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A1: It's natural to propose spin-flavor entanglement — but we have to prove that the flavor space lives in e.g. $SU(2)_f$

Q2: If so, what is the physical importance?

A2: As we will argue in the following, spin-flavor entanglement provides a new paradigm for precision SM tests.

Spin-flavor entanglement in $\Lambda_b \to \Lambda D$

Spin-flavor entanglement in $\Lambda_b \to \Lambda D$

We propose the spin-flavor entanglement: the spin of Λ entangles with the flavor of D, where $D = D_1, D_2, D^0, \overline{D}^0$

To see this, we define the Lee-Yang operators as

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

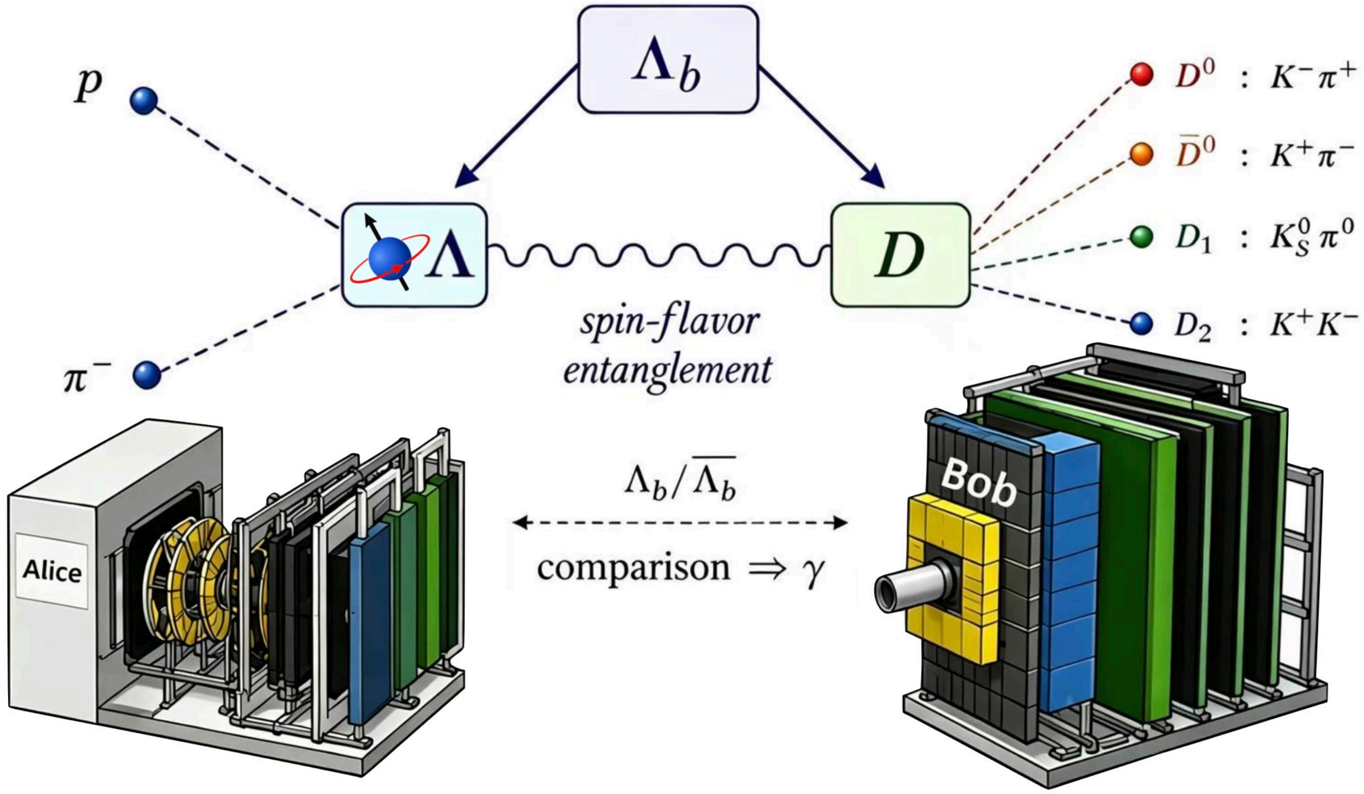
$\hat{k}$: direction of Λ in the rest frame of Λ_b
$\vec{s}$: spin of Λ
$\vec{J}$: total angular momentum

It's then easy to check that $\hat{\alpha} \to \sigma_z$, $\hat{\beta} \to -\sigma_y$, $\hat{\gamma} \to \sigma_x$ such that the *D flavors span the $SU(2)_f$ Hilbert space*:

$$\hat{O}_F = |\overline{D}^0\rangle\langle\overline{D}^0| - |D^0\rangle\langle D^0| = \sigma_z, \qquad \hat{O}_{12} = |D_1\rangle\langle D_1| - |D_2\rangle\langle D_2| = \sigma_x$$

Spin-flavor entanglement in $\Lambda_b \to \Lambda D$

Schematically,



$$\rho_{sf} = \frac{1}{4}\left(\boldsymbol{I}_4 + \sum_i B_i^+ s^i \otimes \boldsymbol{I}_2 + \sum_j b_j^- \boldsymbol{I}_2 \otimes s^j + \sum_{i,j} C_{ij} s^i \otimes s^j\right)$$

B_i^+: spin polarization vector of Λ

b_j^-: flavor polarization vector of D

C_{ij}: spin-flavor correlations

Spin-flavor entanglement in $\Lambda_b \to \Lambda D$

The full density matrix can be computed by promoting the partial waves to 2-row vectors

$$\mathscr{M} = i\,\bar{u}\left(\boldsymbol{S} - \frac{\boldsymbol{P}}{\kappa}\gamma_5\right)u_b \qquad\qquad \boldsymbol{S} = (S_{\overline{D}^0}, S_{D^0})^T, \qquad \boldsymbol{P} = (P_{\overline{D}^0}, P_{D^0})^T$$

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

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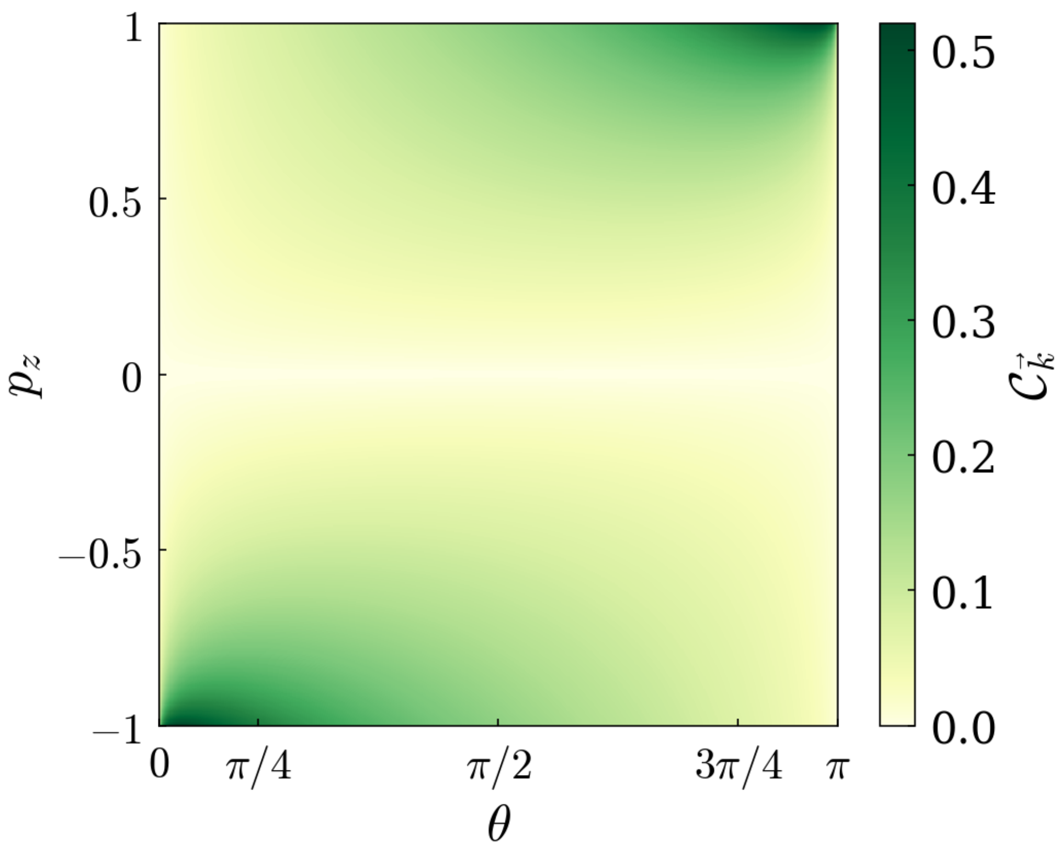
These partial waves can be computed, for example, using pQCD



Zhou Rui, Zhi-Tian Zou, Ya Li, Ying Li, 2604.17877

Large p_z and $\theta = 0, \pi \Leftrightarrow$ large entanglement

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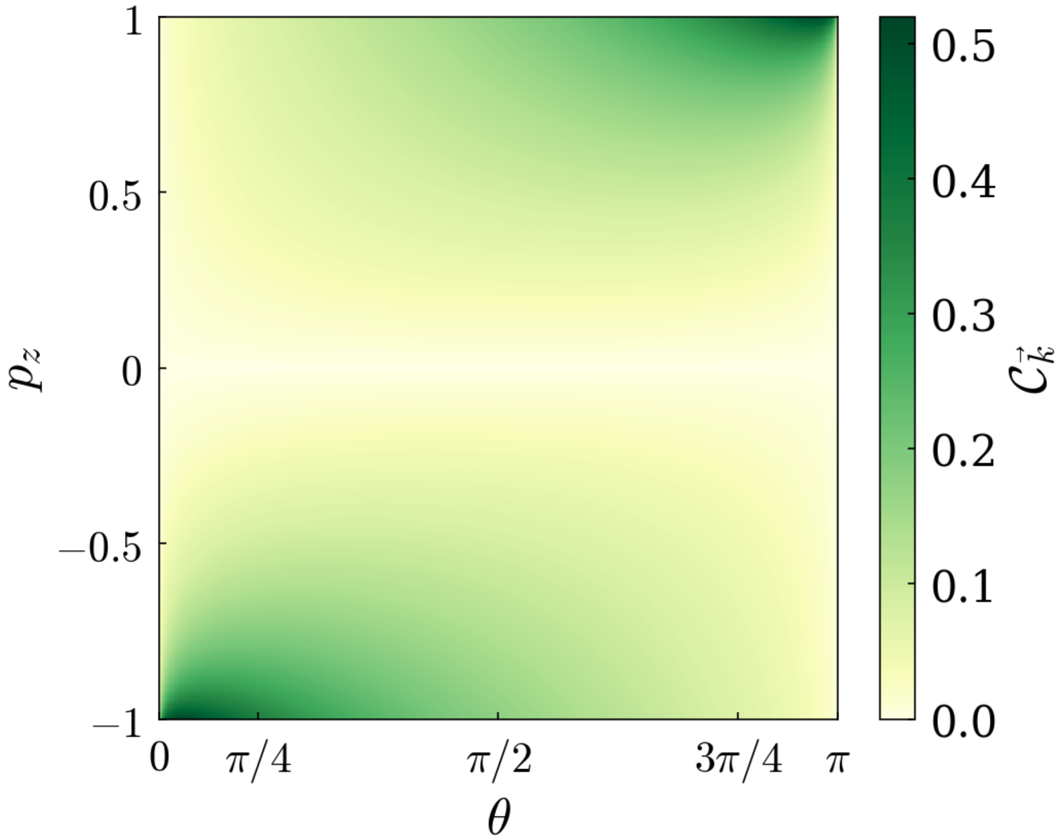

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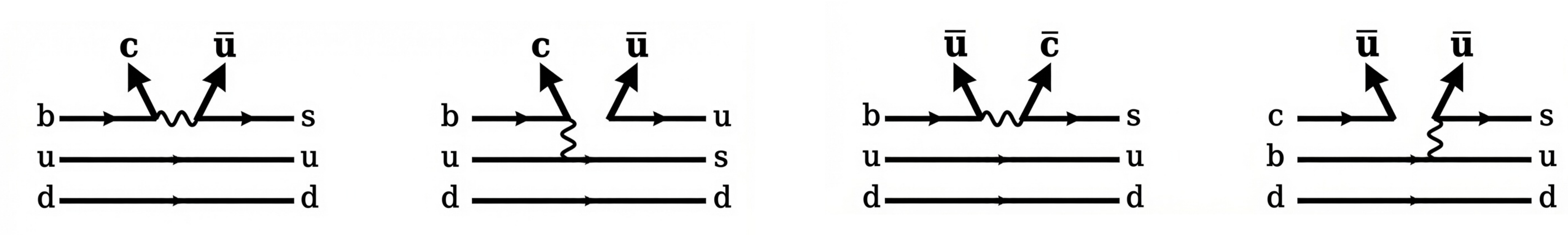
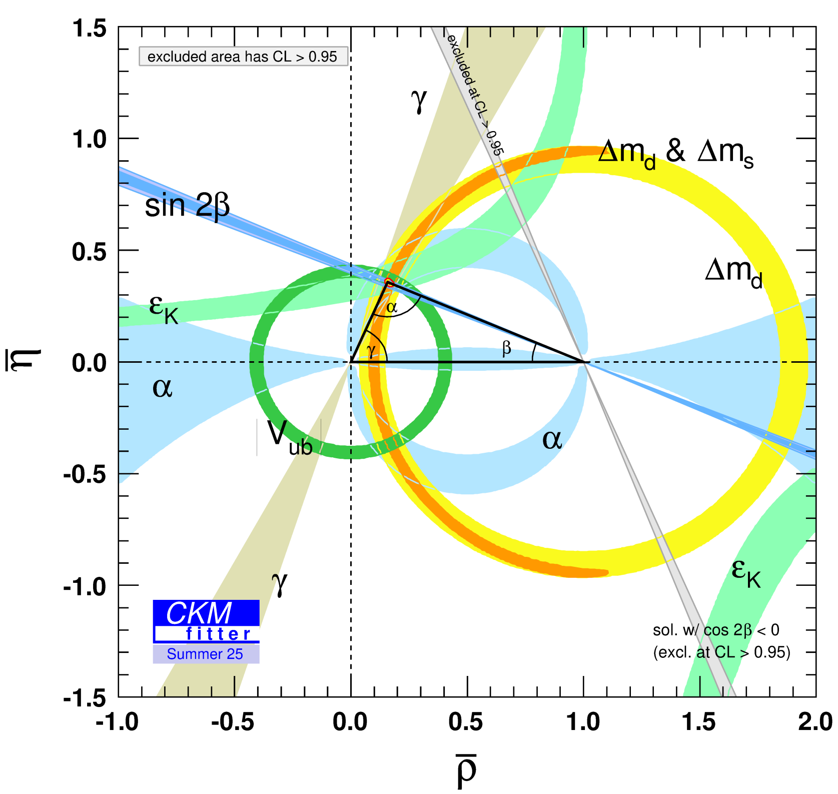
Q: so what?

Spin-flavor entanglement in $\Lambda_b \to \Lambda D$

Firstly, $\Lambda_b \to \Lambda D$ in the SM is induced by the following diagrams



Integrating out the SU(2) gauge bosons, the effective Hamiltonian can be written as



$$\mathscr{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb} V_{us}^* \left[\left(C_1 Q_1^{(c)} + C_2 Q_2^{(c)} \right) + \left| \frac{V_{ub} V_{cs}^*}{V_{cb} V_{us}^*} \right| e^{-i\gamma} \left(C_1 Q_1^{(u)} + C_2 Q_2^{(u)} \right) \right] + h.c.$$

$$Q_1^{(c)} = \left(\bar{c}_\alpha b_\beta\right)_{V-A} \left(\bar{s}_\beta u_\alpha\right)_{V-A}, \qquad Q_2^{(c)} = \left(\bar{c}_\alpha b_\alpha\right)_{V-A} \left(\bar{s}_\beta u_\beta\right)_{V-A}$$

$$Q_1^{(u)} = \left(\bar{u}_\alpha b_\beta\right)_{V-A} \left(\bar{s}_\beta c_\alpha\right)_{V-A}, \qquad Q_2^{(u)} = \left(\bar{u}_\alpha b_\alpha\right)_{V-A} \left(\bar{s}_\beta c_\beta\right)_{V-A}$$

Spin-flavor entanglement in $\Lambda_b \to \Lambda D$

Let's look at the spin-flavor state for $\Lambda_b \to \Lambda D$:

$$\chi_{\overline{D}} = \begin{pmatrix} S_{\overline{D}^0} + P_{\overline{D}^0} \\ S_{\overline{D}^0} - P_{\overline{D}^0} \end{pmatrix}, \quad \chi_D = \begin{pmatrix} S_{D^0} + P_{D^0} \\ S_{D^0} - P_{D^0} \end{pmatrix}$$

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

one can then relate the concurrence of the pure state to the precision of the weak phase γ

Uncertainty
in γ extraction

$$\sigma_\gamma \propto \frac{1}{\mathscr{C}}$$

Concurrence of the
Λ-D system

the proportional is regular for $\mathscr{C} \to 0$ and has to be determined from MC simulation

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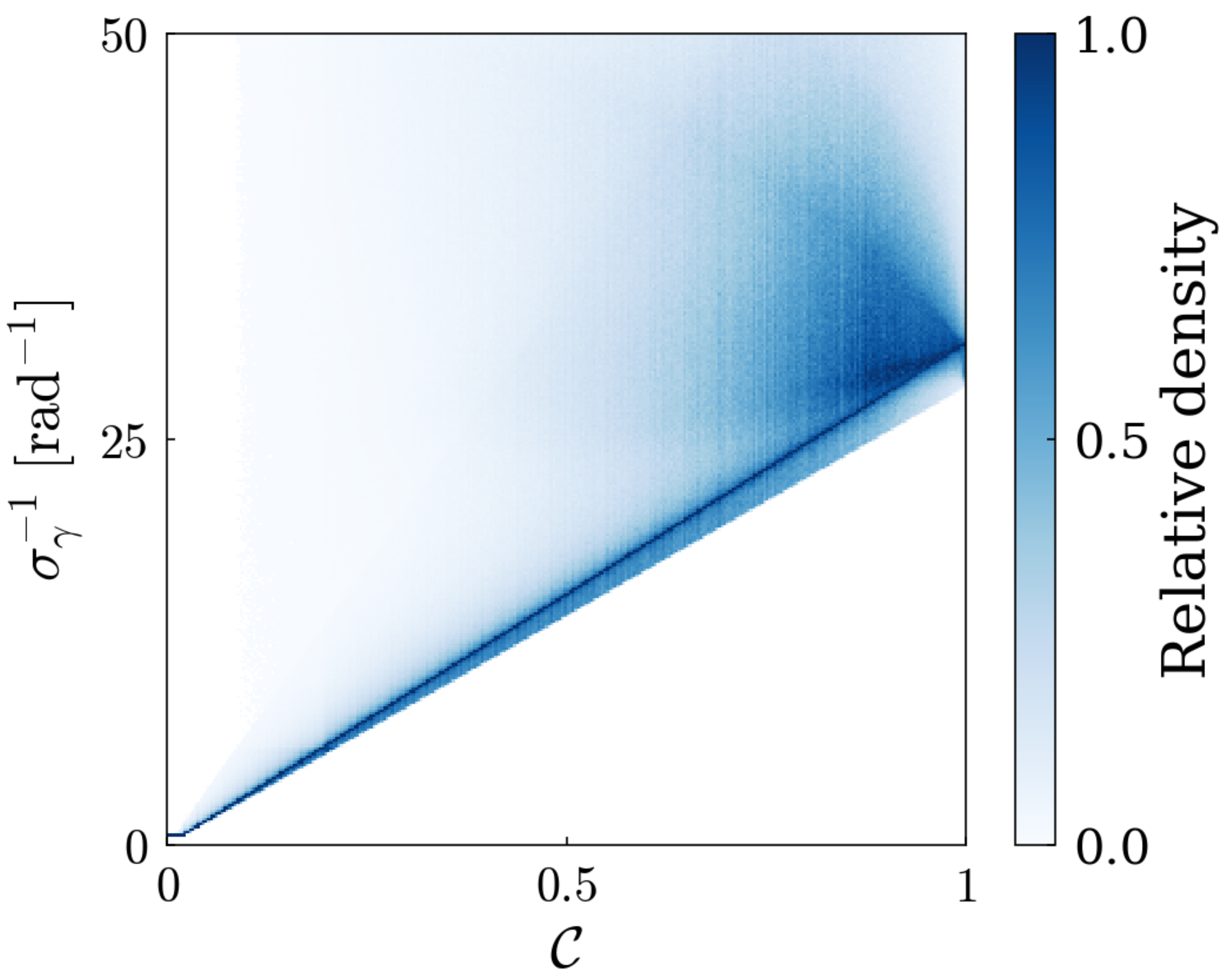

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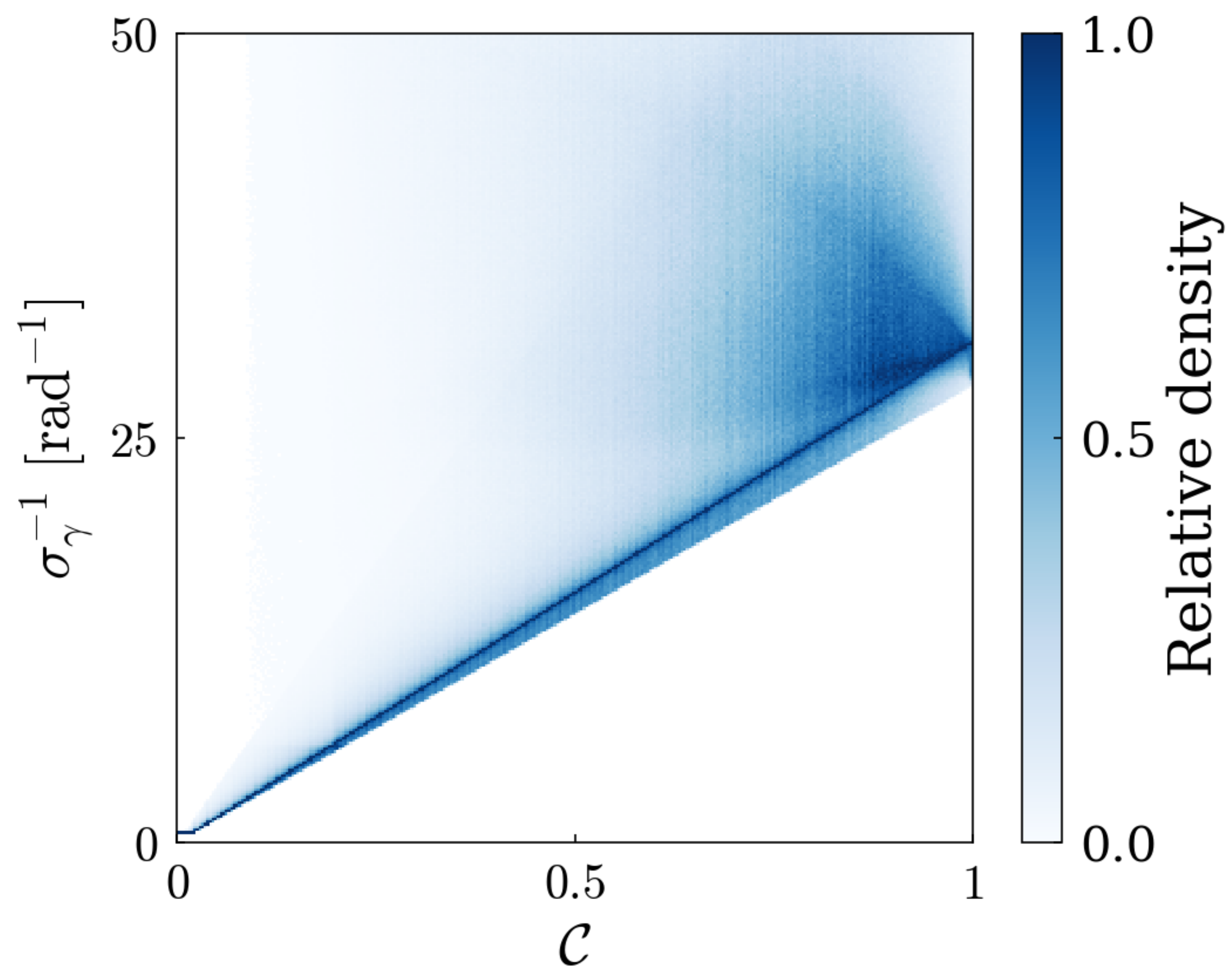
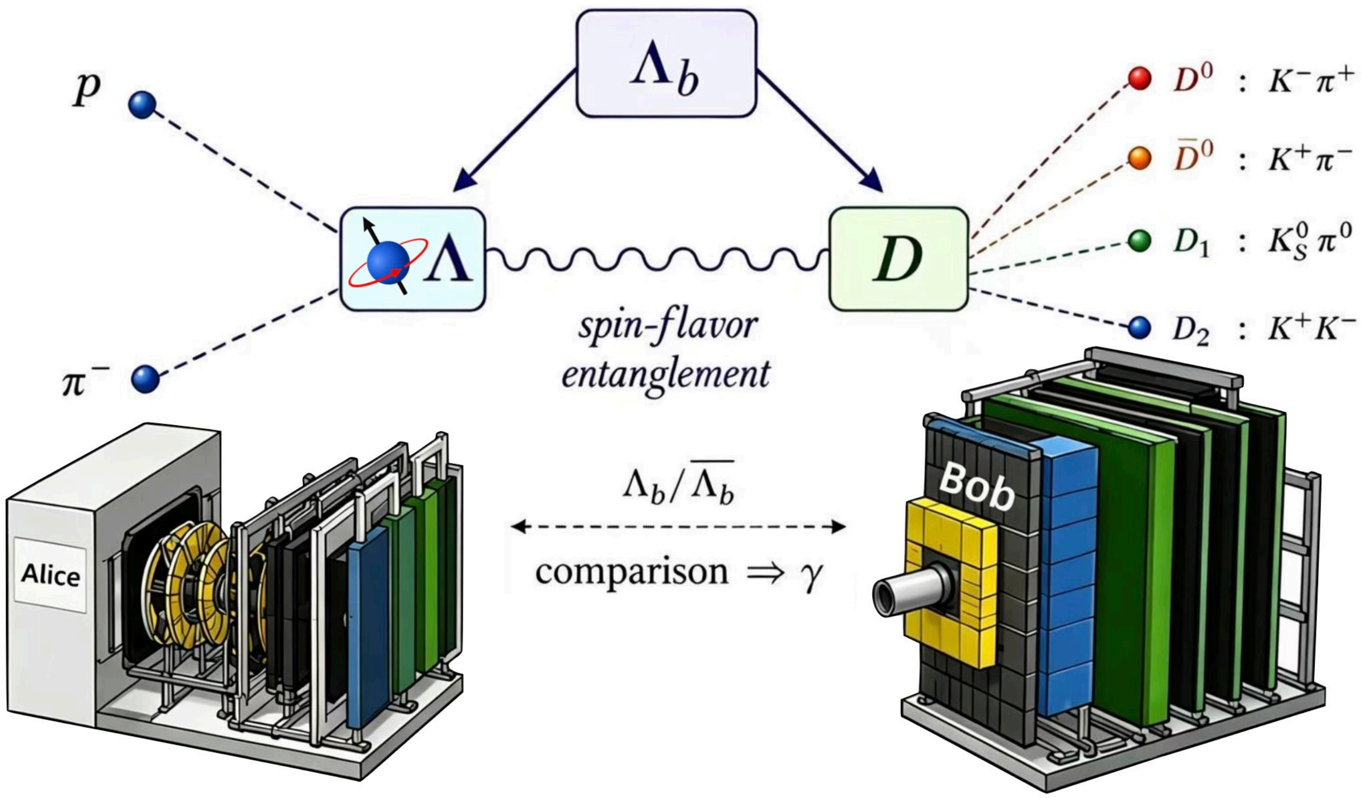


A: the entanglement controls the precision of the weak phase extraction

$\sigma_\gamma \simeq 0.6^\circ$ for $p_z = 1$ vs $\sigma_\gamma \simeq 2^\circ$ from CKMFitter

Summary



1. A new paradigm in γ extraction from spin-flavor entanglement;
2. Focusing on events with maximal spin-flavor entanglement (p_z & $\theta = 0, \pi$) to increase the precision .

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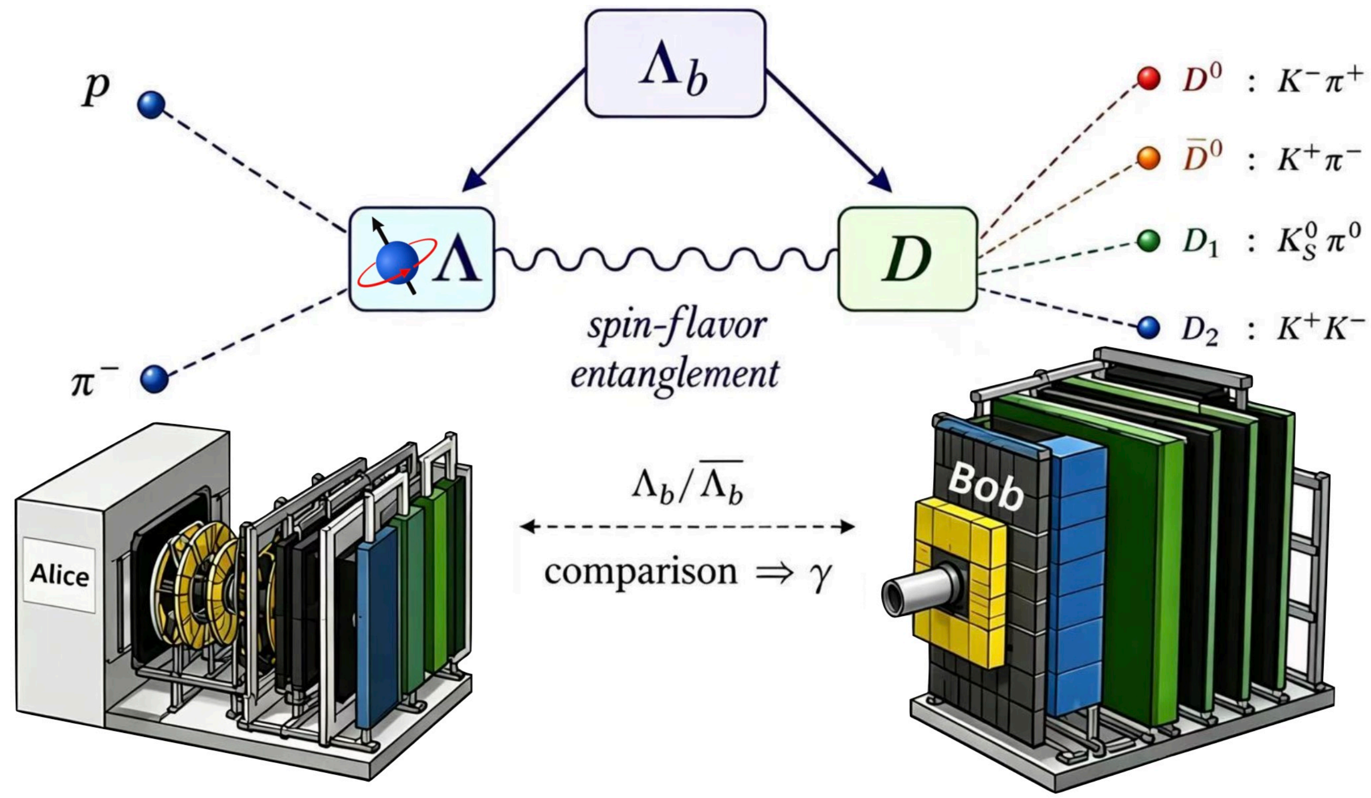

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yddy

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