58th Rencontres de Moriond
Electroweak Interactions & Unified Theories
27 March, 2024

Measurements of $B \to K\pi$ and $B \to \pi\pi$ Branching Fractions and CP Asymmetries at Belle II

Shu-Ping Lin*
On behalf of the Belle II collaboration

* lin@pd.infn.it — University of Padova and INFN

Motivation

$\mathscr{B}_X = \Gamma(B \to X)/\Gamma_B$

$$\mathscr{A}^X_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}) - \Gamma(B \to X)}{\Gamma(\bar{B} \to \bar{X}) + \Gamma(B \to X)}$$

- **$B \to K\pi$: isospin sum rule**

$$I_{K\pi} = \mathscr{A}_{K^+\pi^-} + \mathscr{A}_{K^0\pi^+} \cdot \frac{\mathscr{B}_{K^0\pi^+}}{\mathscr{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathscr{A}_{K^+\pi^0} \cdot \frac{\mathscr{B}_{K^+\pi^0}}{\mathscr{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathscr{A}_{K^0\pi^0} \cdot \frac{\mathscr{B}_{K^0\pi^0}}{\mathscr{B}_{K^+\pi^-}} \approx 0$$

  - Exactly zero in the limit of isospin symmetry and no EW penguins
    - O(1%) theoretical precision; O(10%) experimental precision, driven by $\mathscr{A}_{K^0\pi^0}$
  - Sensitive probe of non-SM physics entering the decay amplitudes in the gluonic penguin loop
  - All final states are measured: $B^0 \to K^+\pi^-,\ B^+ \to K^0_S\pi^+,\ B^+ \to K^+\pi^0,\ B^0 \to K^0_S\pi^0$

Ideal for Belle II

- **$B \to \pi\pi$: towards CKM angle α/ϕ_2**

$$\phi_2 = \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right)$$

Least precisely known angle

  - Combined information of $B^0 \to \pi^+\pi^-,\ B^+ \to \pi^+\pi^0,\ B^0 \to \pi^0\pi^0$ to reduce hadronic uncertainties exploiting isospin symmetry

Analysis Strategy

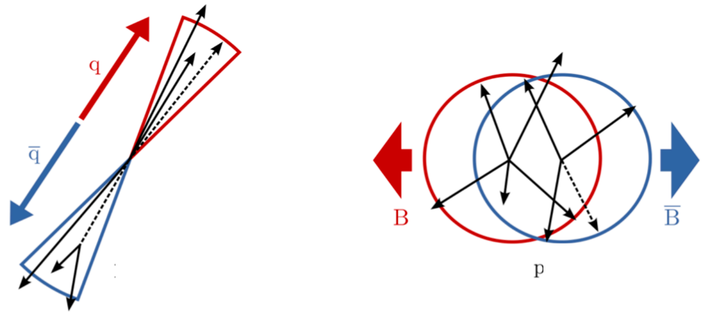
- Reconstruct the decays in 362 fb^{-1} with similar selections
- Continuum suppression (CS) for each channel
  - Suppress $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$
  - MVA trained with **event shape variables**
- 2D fit $(\Delta E, C')$ to measure the BF and CP asymmetries
  - Difference in the reconstructed and expected B energy

    $$\Delta E = E_B^* - \sqrt{s}/2$$

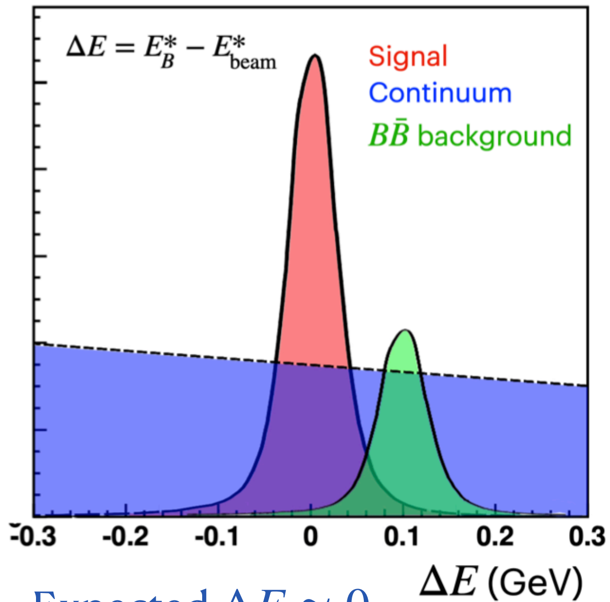
  - Transformed CS output classifier C'

    (probability integral transformation)

  - Determine $\mathscr{A}_{CP}$ by measuring $B/\bar{B}$ yields using the charge of B or a **flavour-tagging algorithm** [Eur. Phys. J. C 82, 283 (2022)]
- Correct for data-simulation discrepancy using abundant control channels



Continuum $\qquad B\bar{B}$



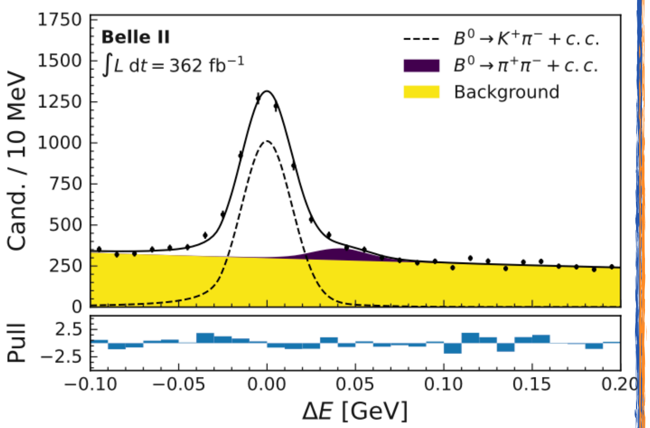
Expected $\Delta E \approx 0$

Result — ΔE fits

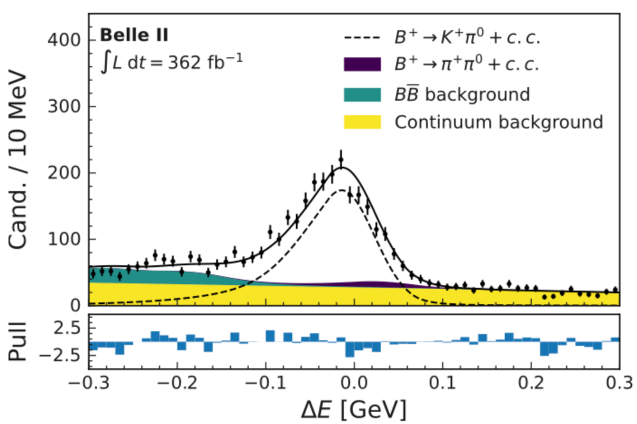
$362\ \mathrm{fb}^{-1}$

Phys. Rev. D 109, 012001 (2024)

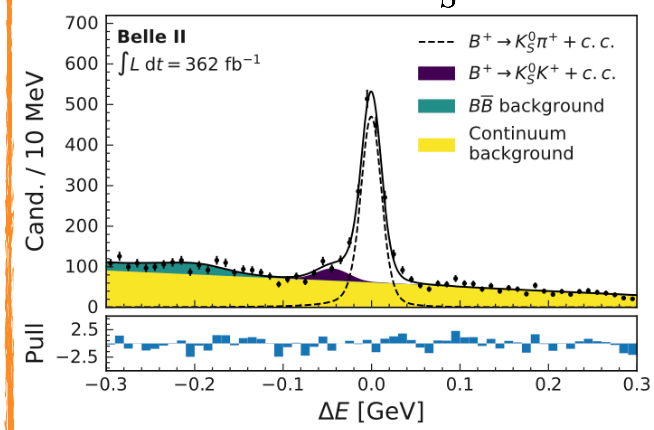
3900 $B^0 \to K^+\pi^-$



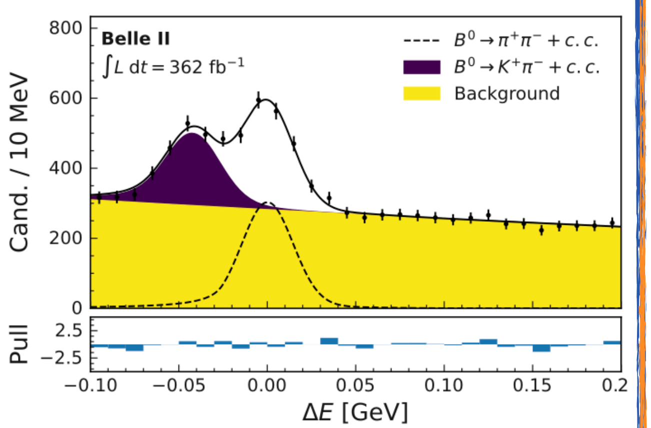
2000 $B^+ \to K^+\pi^0$



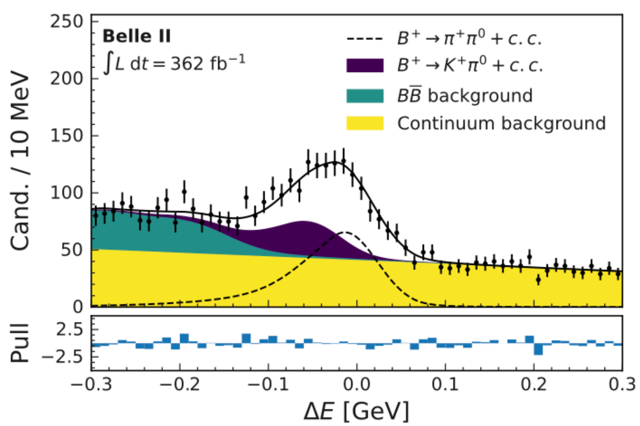
1500 $B^+ \to K_S^0\pi^+$



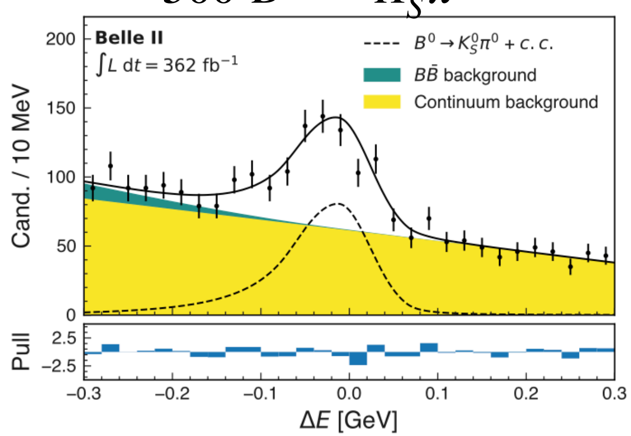
1200 $B^0 \to \pi^+\pi^-$



800 $B^+ \to \pi^+\pi^0$



500 $B^0 \to K_S^0\pi^0$



Simultaneous fit

Simultaneous fit

Result

$362\ \mathrm{fb}^{-1}$

Phys. Rev. D 109, 012001 (2024)

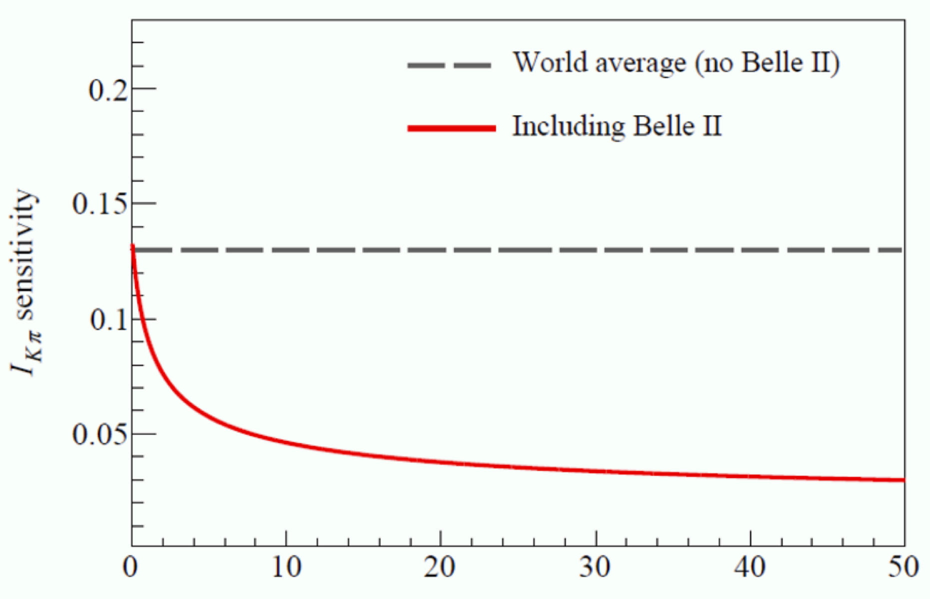
Decay	$\mathcal{B}\ [10^{-6}]$	$\mathcal{A}_{CP}$
$B^0 \to K^+\pi^-$	$20.67 \pm 0.37 \pm 0.62$	$-0.072 \pm 0.019 \pm 0.007$
$B^+ \to K^+\pi^0$	$13.93 \pm 0.38 \pm 0.71$	$0.013 \pm 0.027 \pm 0.005$
$B^+ \to K^0\pi^+$	$24.37 \pm 0.71 \pm 0.86$	$0.046 \pm 0.029 \pm 0.007$
$B^0 \to K^0\pi^0$	$10.73 \pm 0.63 \pm 0.62$	$-0.01 \pm 0.12 \pm 0.04$
$B^0 \to \pi^+\pi^-$	$5.83 \pm 0.22 \pm 0.17$	$\cdots$
$B^+ \to \pi^+\pi^0$	$5.10 \pm 0.29 \pm 0.27$	$-0.081 \pm 0.054 \pm 0.008$

- $B^0 \to K_S^0\pi^0$ result from a combined analysis with *Phys. Rev. Lett. 131, 111803 (2023)*
- Branching fractions are limited by **systematic uncertainties** except for $B^0 \to K_S^0\pi^0$ and $B \to \pi\pi$

  Major systematic uncertainties: π^0 efficiency, B^+/B^0 production ratio, $N_{B\bar{B}}$, K_S^0 efficiency
- Asymmetries limited by **statistical uncertainties**
- $\boxed{I_{K\pi} = -0.03 \pm 0.13 \pm 0.04}$ (world average: 0.13 ± 0.11)

Summary

- Measured branching fractions and CP asymmetries for the rare decays: $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$, $B^+ \to K^+\pi^0$, $B^+ \to \pi^+\pi^0$, $B^+ \to K_S^0\pi^+$, $B \to K_S^0\pi^0$
- Obtained a sum rule test for $B \to K\pi$ decays compatible with SM expectation
- Results competitive and in agreement with world best measurements
- The sum rule test is limited by the statistical uncertainty of $B^0 \to K^0\pi^0$ CP asymmetry

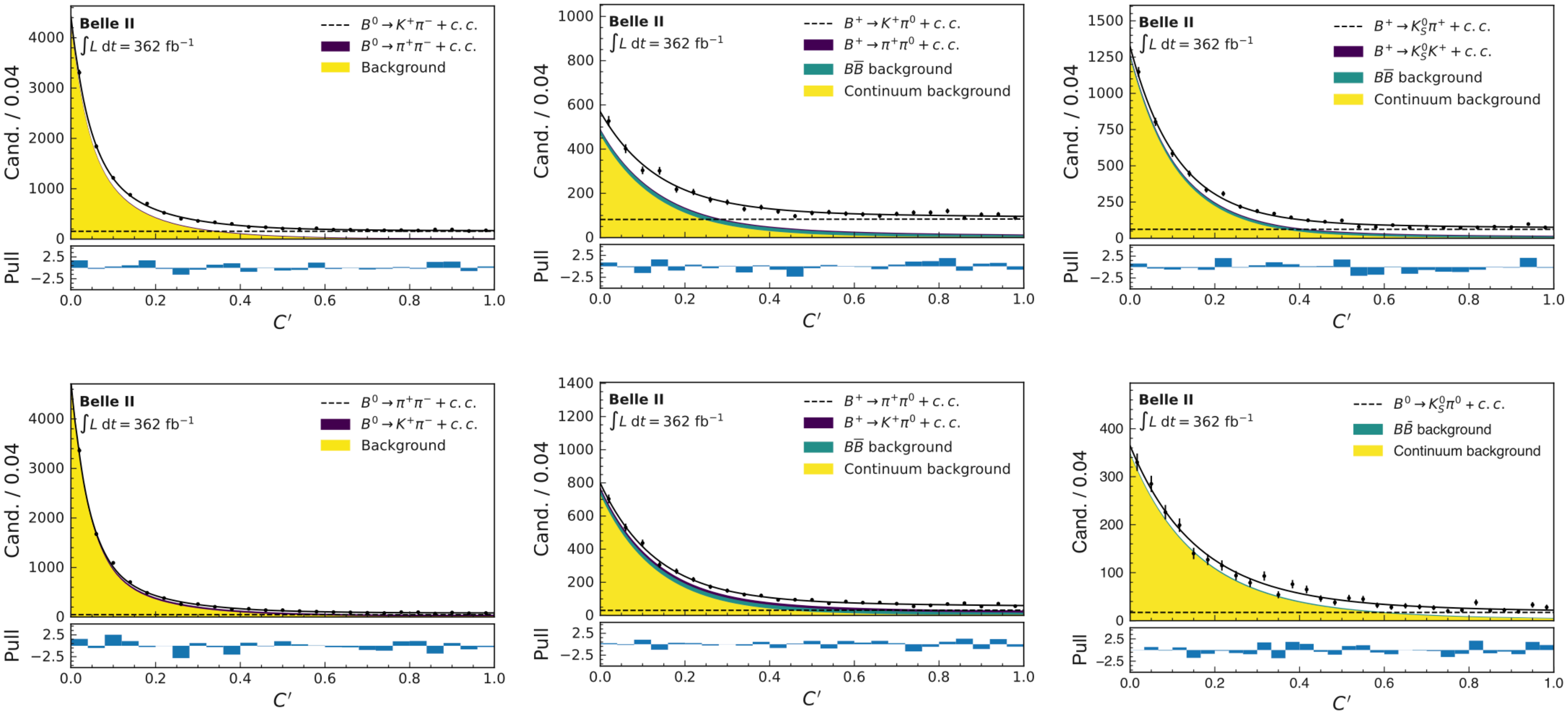


arXiv:2207.06307

Backup

Result — C' fits

$362\ \mathrm{fb}^{-1}$



	$I_{K\pi}$				
PDG	− 0.13	±	0.11		
Belle	− 0.270	±	0.132	±	0.060
Belle II	− 0.03	±	0.13	±	0.04

$K_S^0\pi^0$ correlation with TD analysis
$\mathscr{B}$: 76 %
$\mathscr{A}_{CP}$: 21 %

Systematic Uncertainties

Source [%]	$B^0 \to K^+\pi^-$	$B^0 \to \pi^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K_S^0\pi^+$	$B^0 \to K_S^0\pi^0$
Tracking	0.5	0.5	0.2	0.2	0.7	0.5
$N_{B\bar{B}}$	1.5	1.5	1.5	1.5	1.5	1.5
$f^{+-/00}$	2.5	2.5	2.4	2.4	2.4	2.5
π^0 efficiency			3.8	3.8		3.8
K_S^0 efficiency					2.0	2.0
CS efficiency	0.2	0.2	0.7	0.7	0.5	1.7
PID correction	0.1	0.1	0.1	0.2		
ΔE shift and scale	0.1	0.2	1.2	2.0	0.3	1.7
$K\pi$ signal model	0.1	0.2	0.1	<0.1	<0.1	0.1
$\pi\pi$ signal model	<0.1	0.1	<0.1	<0.1		
$K\pi$ feed-across model	<0.1	0.1	<0.1	0.1		
$\pi\pi$ feed-across model	0.1	0.2	<0.1	0.1		
$K_S^0K^+$ model					0.1	
$B\bar{B}$ model			0.3	0.5	<0.1	0.3
$q\bar{q}$ flavor model						0.9
Multiple candidates	<0.1	< 0.1	1.0	0.3	0.1	0.3
Total	3.0	3.0	5.1	5.2	3.6	5.8

Source	$B^+ \to K^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K_S^0\pi^+$	$B^0 \to K_S^0\pi^0$
ΔE shift and scale	<0.001	0.001	0.002	0.001	0.003
$K_S^0K^+$ model				0.001	
$B\bar{B}$ background asymmetry					0.026
$q\bar{q}$ background asymmetry					0.024
$q\bar{q}$ flavor model					0.011
Fitting bias			0.007	0.006	
Instrumental asymmetry	0.007	0.005	0.004	0.004	
Total	0.007	0.005	0.008	0.007	0.037

Flavour Tagger (category-based)

- Multivariate methods to determine the flavour of the tag-side B meson in events with a pair of neutral B mesons.
- One of the neutral B decays to a CP eigenstate and the other to a flavour-specific channel.
- Determine the flavour at the time of its decay.
- The different signatures can be grouped into 13 categories.
- Assign flavour $q = \pm 1$ and flavour-tagger quality r for each event.

Categories	Targets
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
KinLepton	e^-
Intermediate KinLepton	ℓ^+
Kaon	K^-
KaonPion	K^-, π^+
SlowPion	π^+
FastHadron	π^-, K^-
MaximumP	ℓ^-, π^-
FSC	ℓ^-, π^+
Lambda	Λ
Total= 13	

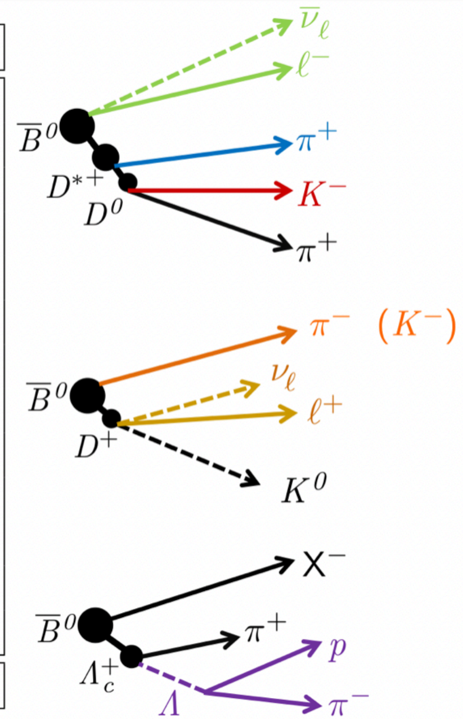


Fig. 6.5 *Underlying decay modes of the flavor tagging categories.*

Time-Dependent $B^0 \to K_S^0 \pi^0$ Analysis

[Phys. Rev. Lett. 131, 111803 (2023)]

$$\mathscr{S}_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

$$\mathscr{C}_{CP} = -0.04^{+0.14}_{-0.15} \pm 0.05$$

- Time-dependent CP asymmetries

$$\mathscr{A}_{CP}(t) = \mathscr{S}_{CP}\sin(\Delta m t) - \mathscr{C}_{CP}\cos(\Delta m t)$$

Mixing-induced asymmetry Direct asymmetry

- Fit $(M_{bc}, \Delta E, C', \Delta t)$ in bins of the flavour tagging quality to extract the CP asymmetries $\mathscr{S}_{CP}$ and $\mathscr{C}_{CP}$
- Validated on $B^0 \to J/\psi K_S^0$ reconstructed without the J/ψ vertex
- Precision competitive with world's best