Charm and beauty hadron decays at Belle and Belle II

Justin Skorupa, on behalf of the Belle II collaboration

LLWI 2024, Lake Louise

2024.02.21

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Belle II

Outline

Charm Decays:

- CP violation in charm
- Charm flavor tagging

Hadronic *B* Decays:

- Hadronic *B* decays as tool for semileptonic *B* decays
- Determination of CKM angle ϕ_3/γ and ϕ_2/α
- SM Null Tests

Disclaimer

Too many results to fit all into this presentation

Search for $B^- \to \Xi_c^0 \overline{\Lambda}_c^-$	2401.04807	Belle
Measurements of $B^0 \to \omega\omega$	2401.04646	Belle
Search for $D^0 \to p\ell$	PRD 109, L031101 (2024)	Belle
Evidence of $B^0 \to p\Sigma\pi^-$	PRD 108, 052011 (2023)	Belle
Search for CP violation in $D^+_{(s)} \to K^+K^-\pi^+\pi^0$, $D^+_{(s)} \to K^+\pi^-\pi^+\pi^0$, and $D^+ \to K^-\pi^+\pi^+\pi^0$ decays	2305.12806	Belle
Search for CP violation in $D^+_{(s)} \to K^+K^0_S h^+h^-$ and observation of $D^+_{(s)} \to K^+K^-K^0_S\pi^+$	PRD 108, L111102 (2023)	Belle
Search for $B_s \to \pi^0\pi^0$	PRD 107, L051101 (2023)	Belle
Study of $B^+ \to p\bar{n}\pi^0$	2211.11251	Belle
Determination of the CKM angle ϕ_3 from a combination of Belle + Belle II results		Belle + Belle II
BF and CP violation in $B^+ \to D_D K^+$ with $D \to K^0_S K^+\pi^-$	JHEP 09 2023, 146 (2023)	Belle + Belle II
BF and CP violation in $B^+ \to D_{CP\pm}K^+$	2308.05048	Belle + Belle II
Precise measurement of the D^+_s lifetime	PRL 131, 171803 (2023)	Belle II
BF and CP violation for $B \to K\pi$ and $B \to \pi\pi$	PRD 109, 012001 (2024)	Belle II
Observation of $B \to D^{(*)}K^-K^0_S$	2305.01321	Belle II
Novel method for charm flavor tagging	PRD 107, 112010 (2023)	Belle II

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Too many results to fit all into this presentation

Japanese dish: *Okonomiyaki*; *okonomi* "as you wish"

Presenting my own heavily biased *okonomiyaki* of charm and beauty results

CP violation in charm

Triple product asymmetries

PRD 108, L111102 (2023)

B Factories are also charm factories 1.3 M $c\bar{c}$ events per 1 fb^{-1} (1.1 M for $B\bar{B}$)

Search for CP-violation in $D^+_{(s)} \to K^+ K^0_S h^+ h^-$ at Belle

Measure asymmetry in triple products

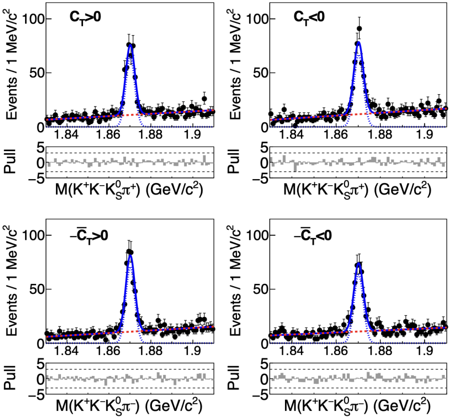
$C_T = v_1 \cdot (v_2 \times v_3)$

$$A_T = \frac{\Gamma(C_T>0)-\Gamma(C_T<0)}{\Gamma(C_T>0)+\Gamma(C_T<0)}; \quad \overline{A}_T = \frac{\Gamma(-\overline{C}_T>0)-\Gamma(-\overline{C}_T<0)}{\Gamma(-\overline{C}_T>0)+\Gamma(-\overline{C}_T<0)}$$

$A_T \neq 0$ also due to final state interaction

Define $a_{CP}^{T\text{-odd}} = 0.5(A_T - \overline{A}_T)$ to remove this effect

Mode	$N(D^+_{(s)})$	$a_{CP}^{T\text{-odd}}$ (%)
$D^+ \to K^+ K^0_S \pi^+ \pi^-$	18632 ± 214	$(0.34 \pm 0.87 \pm 0.32)$
$D^+_s \to K^+ K^0_S \pi^+ \pi^-$	70080 ± 676	$(-0.46 \pm 0.63 \pm 0.38)$
$D^+ \to K^+ K^- K^0_S \pi^+$	1425 ± 44	$(-3.34 \pm 2.66 \pm 0.35)$

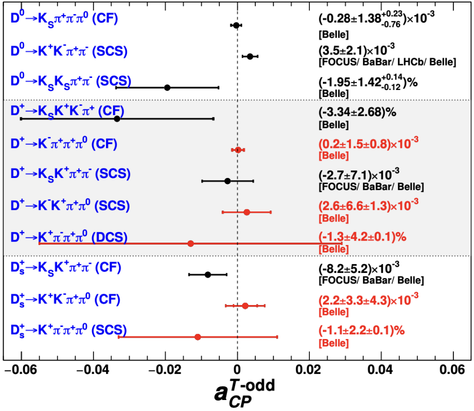


$\Rightarrow$ All results consistent with no CP-violation

Triple product asymmetries

2305.12806

Using same approach as before: Search for T-violation in $D^+_{(s)} \to K^+K^-\pi^+\pi^0$, $D^+_{(s)} \to K^+\pi^-\pi^+\pi^0$, and $D^+ \to K^-\pi^+\pi^+\pi^0$ decays at Belle



$\Rightarrow$ First measurements for these decays; All results consistent with no CP-violation

Charm flavor tagging

Charm Flavor Tagging

PRD 107, 112010 (2023)

Need to know D^0 flavor for *CP*-violation measurments

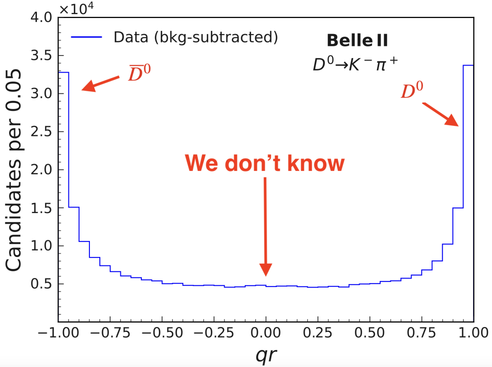
Since 1977, achieved by exclusively reconstruction $D^{*+} \to D^0\pi^+$

$\Rightarrow$ Clean sample **but** low efficiency

New approach: Train BDT based on kinematic and particle identification information from opposite side c (inspired by b flavor tagging)

$$\epsilon = (47.91 \pm 0.07(\text{stat}) \pm 0.51(\text{syst}))\%$$

- Doubles sample size compared to old method



Hadronic *B* decays as tool for semileptonic *B* decays

Measurment of $B \to D^{(*)} K^- K_S^0$

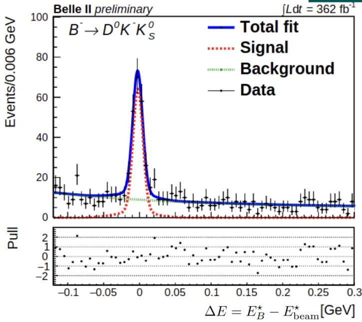
2305.01321

Roughly 30% of B $\to$ hadron decays are not measured

$\Rightarrow$ Limits performance of the hadronic tag

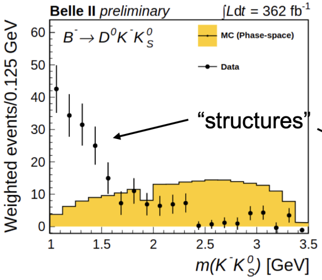
Total BF of $B \to D^{(*)} K^{(*)} K^{(*)}$ could be up to 6%, but only 0.3% is known + High purity

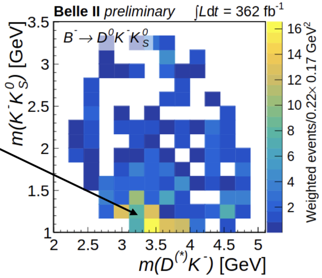
$\Rightarrow$ Candidates to be included in hadronic tag



$$\mathcal{B}(B^- \to D^0 K^- K_S^0) = (1.89 \pm 0.16 \pm 0.10) \times 10^{-4}$$
$$\mathcal{B}(\overline{B}^0 \to D^+ K^- K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4}$$
$$\mathcal{B}(B^- \to D^{*0} K^- K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4}$$
$$\mathcal{B}(\overline{B}^0 \to D^{*+} K^- K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4}$$

3 first observations

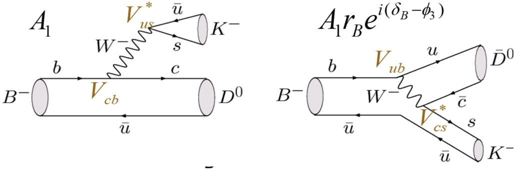


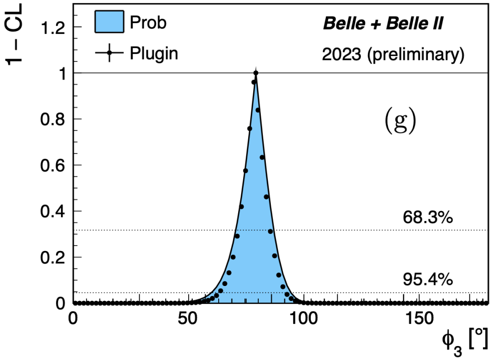


Determination of CKM angle ϕ_3/γ and ϕ_2/α

Determination of CKM angle ϕ_3/γ

- phase between $b \to u$ and $b \to c$ transitions
- tree level only, negligible theory uncertainty
- Several Belle + Belle II measurments:
  - $D \to K_S^0 hh$ [JHEP 02 (2022) 063]
  - $D \to K_S^0 K\pi$ [2306.02940]
  - $D \to K_S^0 \pi^0, KK$ [2308.05048]
- **New** determination of γ using only Belle and Belle II measurments: $\gamma = (78.6 \pm 7.3)^\circ$



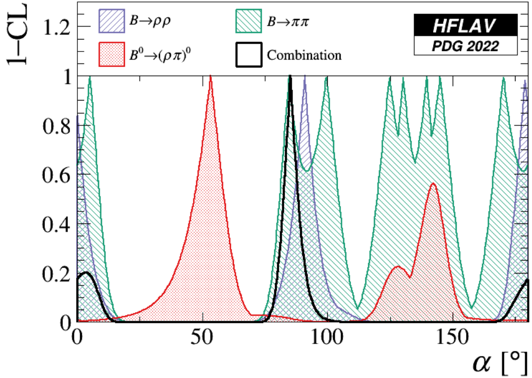


Towards CKM angle ϕ_2/α

Least well known angle of CKM triangle

Accessible in tree level $B^0 \to \pi^+\pi^-$ transitions but sizable loop level contribution introduces shift

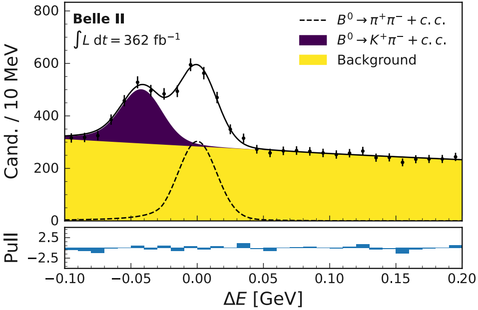
Remove shift using $\mathcal{B}$ and $\mathcal{A}^{\text{CP}}$ of isospin related $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$

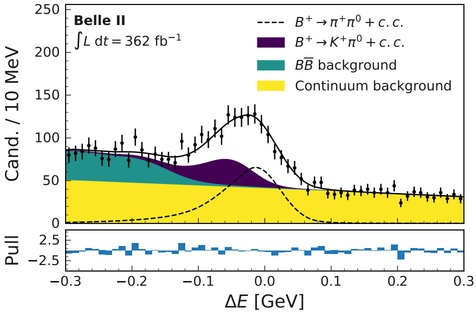


Belle II is a unique place to measure all involved decays!

Towards CKM angle ϕ_2/α

PRD 109, 012001 (2024)





$\mathcal{B} = (5.83 \pm 0.33(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-6}$

$\mathcal{A}^{\text{CP}} = 0.081 \pm 0.54(\text{stat}) \pm 0.008(\text{syst})$

$\mathcal{B} = (5.10 \pm 0.29(\text{stat}) \pm 0.32 \ (\text{syst})) \times 10^{-6}$

World best result for BF of $B^0 \to \pi^+\pi^-$

Result of $\mathcal{B}$ $B^+ \to \pi^+\pi^0$ limited by π^0 systematic

SM Null Tests

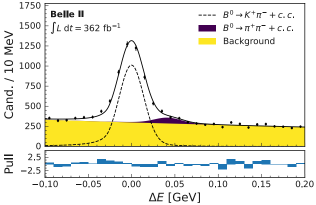
Isospin sum-rule

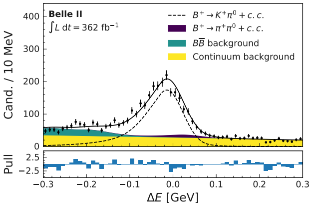
PRD 109, 012001 (2024)

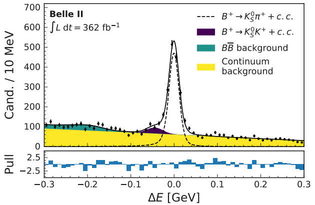
Combination of $B \to K\pi$ decays offers SM null test [Phys.Lett.B 627 (2005) 82-88]:

$$\mathcal{A}^{CP}_{K^+\pi^-} + \mathcal{A}^{CP}_{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{CP}_{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{CP}_{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

Theoretical precision: $\mathcal{O}(0.01)$, Experimental precision: $\mathcal{O}(0.1)$







$\mathcal{A}^{CP} = (-7.2 \pm 1.9\ \text{(stat)} \pm 0.7\,\text{(syst)})\%$
$\mathcal{B} = (20.67 \pm 0.37\,\text{(stat)} \pm 0.6\,\text{(syst)}) \times 10^{-6}$

$\mathcal{A}^{CP} = (1.3 \pm 2.7\ \text{(stat)} \pm 0.5\ \text{(syst)})\%$
$\mathcal{B} = (14.21 \pm 0.38\,\text{(stat)} \pm 0.85\,\text{(syst)}) \times 10^{-6}$

$\mathcal{A}^{CP} = (4.6 \pm 2.9\ \text{(stat)} \pm 0.7\ \text{(syst)})\%$
$\mathcal{B} = (24.40 \pm 0.71\,\text{(stat)} \pm 0.86\,\text{(syst)}) \times 10^{-6}$

Understanding of K^0_S and π^0 systematic at 2% and 5%

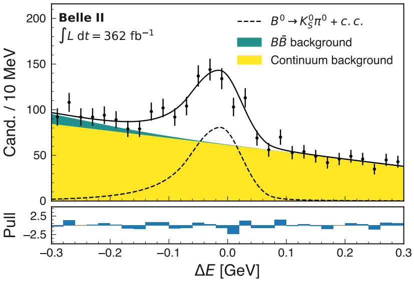
Isospin sum-rule

PRD 109, 012001 (2024)

Two analyses of $B^0 \to K_S^0\pi^0$ one time-dependent [PRL 131, 111803 (2023)] and one time-integrated. Both are combined to enhance sensitivity.

$$\mathcal{A}^{CP} = -0.01 \pm 0.12\,(\text{stat}) \pm 0.05\,(\text{syst})$$
$$\mathcal{B} = (10.50 \pm 0.62\,(\text{stat}) \pm 0.67\,(\text{syst})) \times 10^{-6}$$

World's best result on $\mathcal{A}^{CP}$



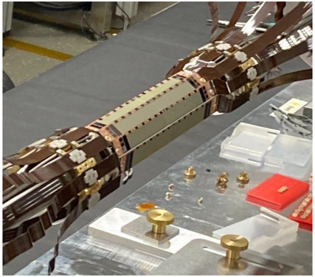
Putting all together for the null test:

$$-0.03 \pm 0.13 \pm 0.05$$

Competitive with world average -0.13 ± 0.11

Conclusion

Belle is still providing exciting results both standalone and also in combined Belle + Belle II analyses



Belle II is improving its tools

- Development of new tools using novel ideas
- (Re)measurements to improve hadronic tagging

Belle II isospin sum-rule result and input measurements for ϕ_2/α already on par with world average

$\Rightarrow$ Sum-rule result is statistically limited, input from Belle II crucial to enhance sensitivity