Hadronic B decays at Belle and Belle II

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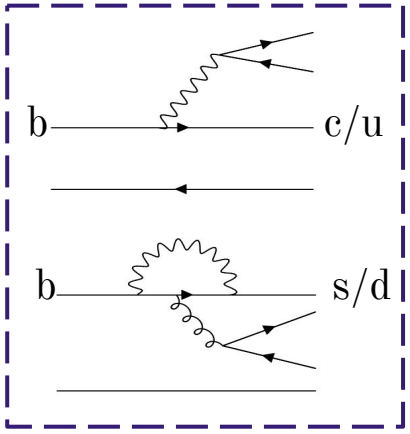
on behalf of the Belle II collaboration

PPC 2024, Parallel Session

B→ Hadronic

- Dominated by the b → c trees.
- Hadronic decays of B-mesons account for ~75% of the total branching fraction.

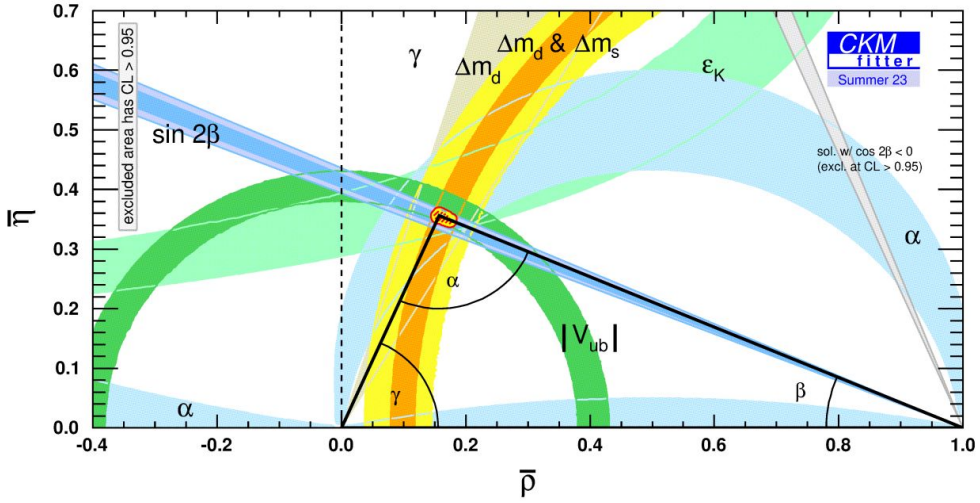


For today:

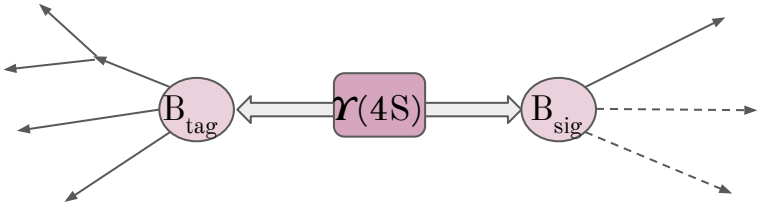
- $B^- \to D^0\rho(770)^{--}$
- $B \to D^{(*)}KK_S$
- Belle + Belle II combined measurement of ϕ_3
- $B\to \pi^0\pi^0$: towards ϕ_2

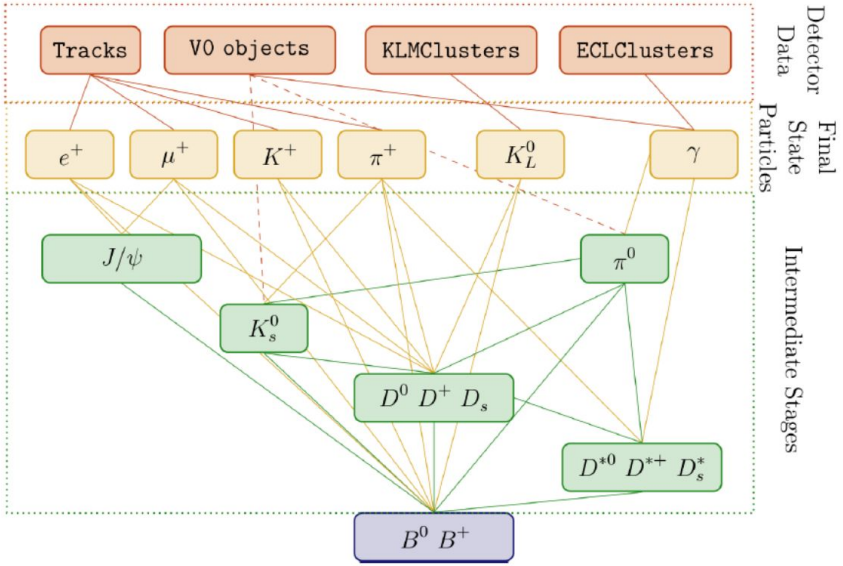
Probe the SM:

- over-constrain CKM triangle
  ϕ_1/β: via time-dependent analysis of e.g. $J/\psi K_S$
  ϕ_2/α: via isospin analysis of $B\to\rho\rho$, $B\to\pi\pi$
  ϕ_3/γ: via $B^-\to Dh^-$, $B^-\to D^*K^-$
- via isospin sum rules

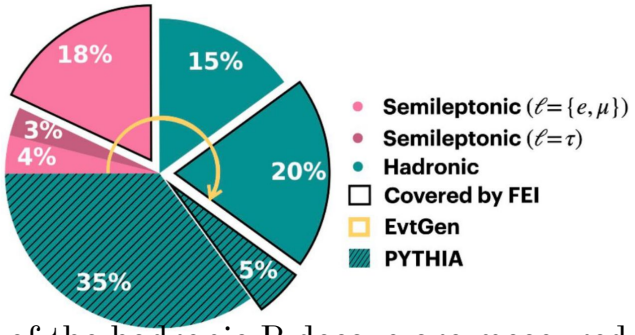


Hadronic Tagging





- Missing energy modes need tagging.
- Hadronic tagging has high purity as well as gives direction of B.
- But large data-MC discrepancy in several channels



- Only half of the hadronic B decays are measured.
- PYTHIA generates the other half in MC.
- Most measurements are performed with small data sets.

Improving FEI efficiency → More DATA in hand

Tagging techniques

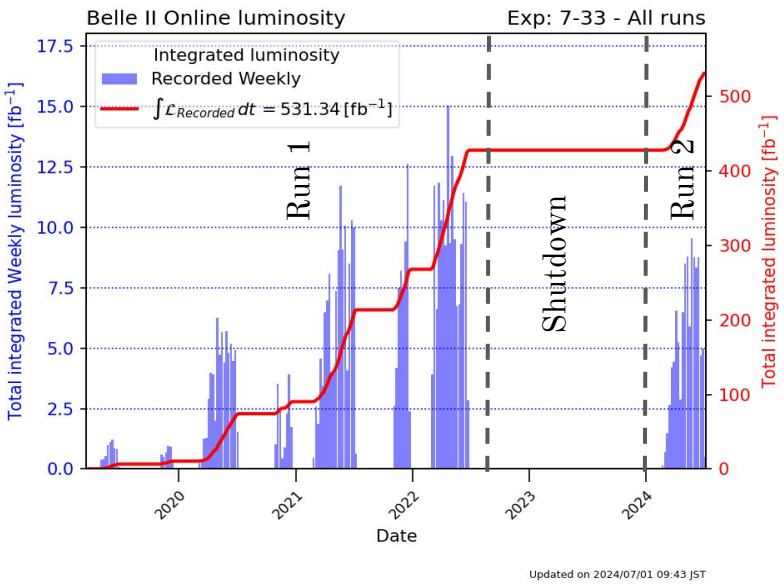
Purity ⟷ Efficiency

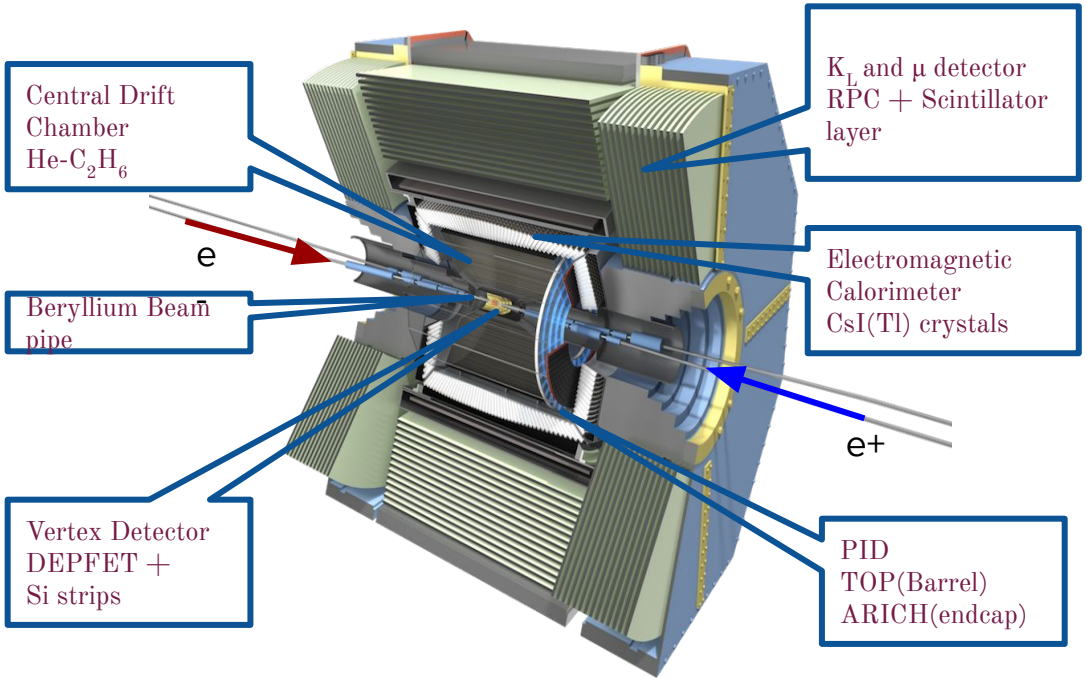
Inclusive	**Semileptonic**	**Hadronic**
$B \to$ anything	$B \to D^{(*)}\ell\nu_\ell$	$B \to$ hadrons
$\epsilon \approx \mathcal{O}(100\%)$	$\epsilon \approx \mathcal{O}(1\%)$	$\epsilon \approx \mathcal{O}(0.1\%)$

Belle II

- Asymmetric e^-e^+ collisions at $\Upsilon(4S)$ resonance.
- $\Upsilon(4S)$--> BB : 2B's and nothing else.
- 1.1×10^9 $B\bar{B}$ pairs per ab^{-1}

➢ clean environment
➢ excellent neutral reconstruction





Analysis

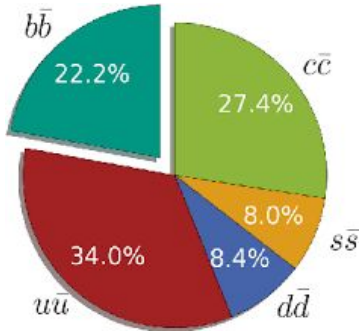
1. Reconstruction
- Start with final state particles
- Form a B candidate

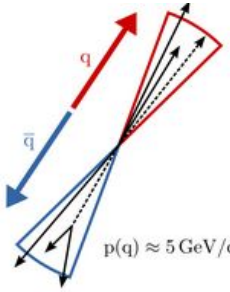
2. Selection
- Background suppression
- Mostly continuum background

3. Modelling + Fit
- Model using simulation
- fit to data to extract physics quantities

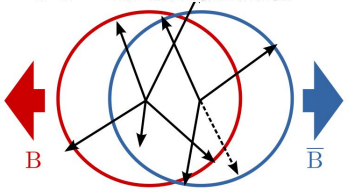
4. Systematic uncertainties
- toy studies + control modes

Challenges: small BR, high backgrounds, neutrals

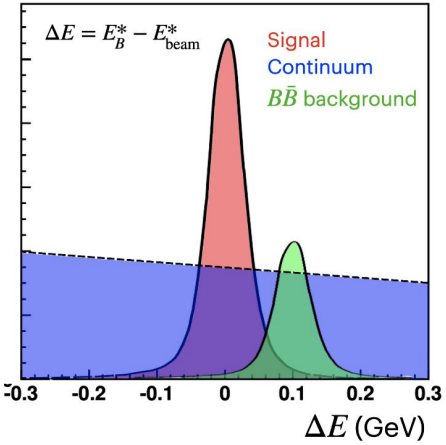


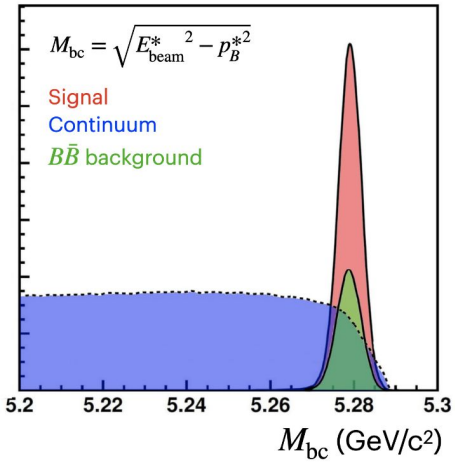


$e^+e^- \to q\bar{q}$ $(q \in \{u, d, s, c\})$



$e^+e^- \to \Upsilon(4S) \to B\overline{B}$





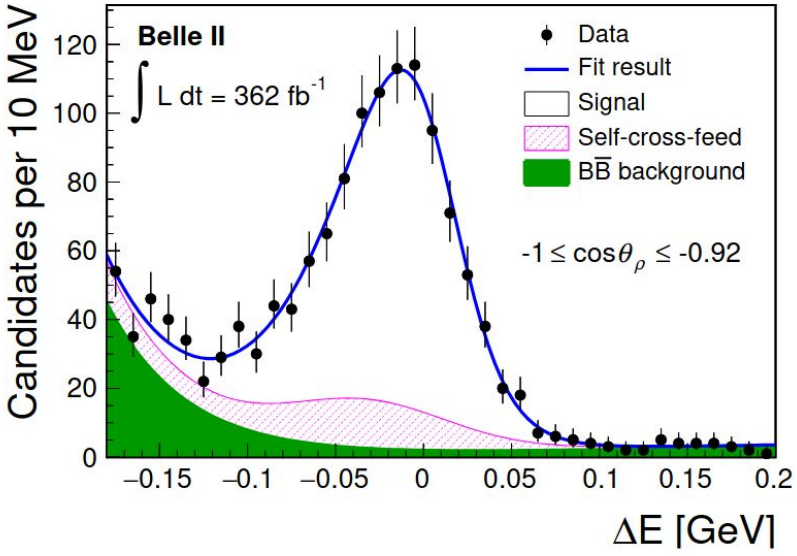
Improving knowledge on B decays

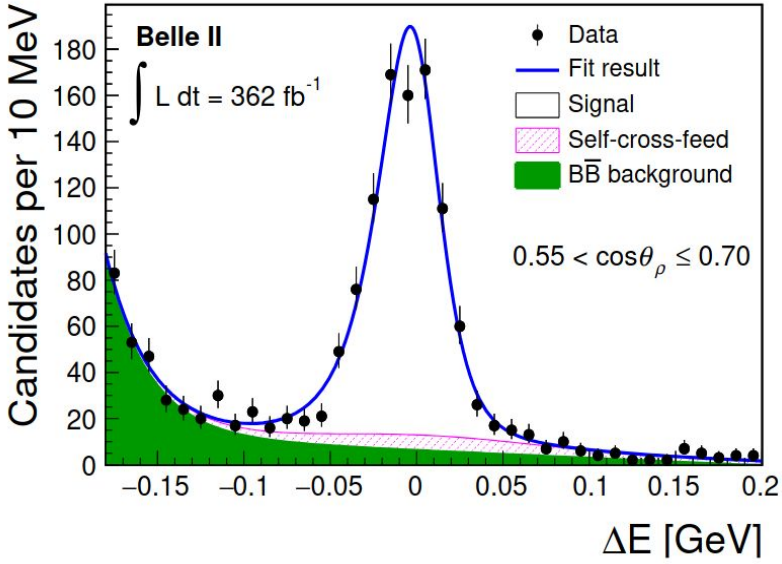
$B^- \to D^0\rho(770)^-$

[Phys. Rev. D 109, L111103]

- PDG measurement- (1.35±0.18)% by CLEO(1994) with 0.9fb-1, which includes large uncertainty
- $B^- \to D^0\rho^-$, $B^0 \to D^+\rho^-$, and $B^0 \to D^0\rho^0$ provides tests of calculations of hadronic decay rates based on the heavy-quark limit and factorization models.

Needs to account: Contamination from non-resonant component $B^- \to D^0\pi\pi^0$ contribution in ΔE.





- Signal Extraction- unbinned maximum likelihood fit to ΔE distribution

Solution: Perform fit in bins of $\cos\theta_\rho$ (θ_ρ the angle between the π^- momentum and the direction opposite to the B^- momentum in the ρ^- rest frame)

$B^- \to D^0\rho(770)^-$

[Phys. Rev. D 109, L111103]

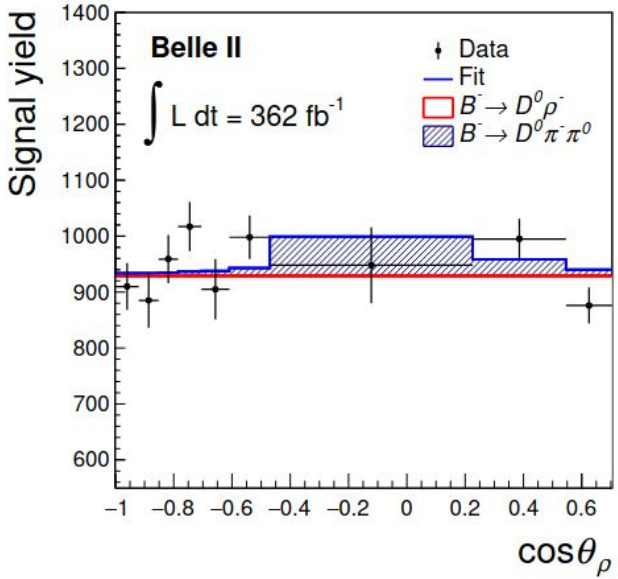
Template fit to distribution $\cos\theta_\rho$:

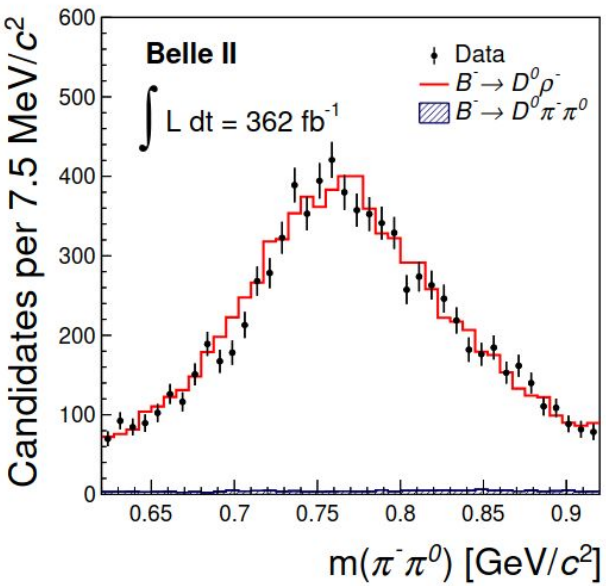
- non-uniform binning: flat distribution for $B^-\to D^0\rho^-$
- $\cos\theta_\rho < 0.7$: to suppress decays $B^- \to D^{**}\pi$
- $\sim(1.9\pm1.8)\%$ contribution of $B^-\to D^0\pi\pi^0$

$$\mathcal{B}(B^- \to D^0\rho^-) = (0.939\pm0.021\ \pm0.050)\%$$

2× better precision!!

Systematically limited by π^0 reconstruction efficiency





Factorization test : In agreement with prediction

$B \to D^{(*)} K K^{(*)0}_{(S)}$ and $B \to D^{(*)} D^{-}_{s}$

[J. High Energ. Phys. **2024**, 206]

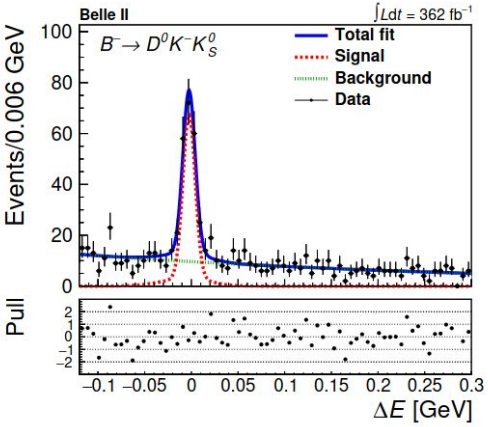
$B \to DK^{-}K$ decays make up a few percent of the overall hadronic branching fraction

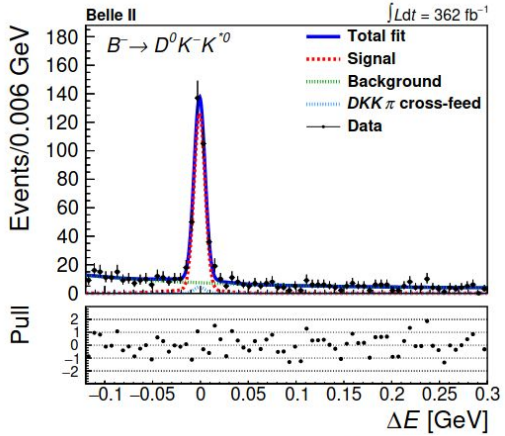
- Only a small amount of them are well measured.
- Serves as inputs for simulations and tagging techniques.
- Possibility of $B \to DX^{-}(\to K^{-}K)$, with an intermediate resonance X^{-} that decays strongly,

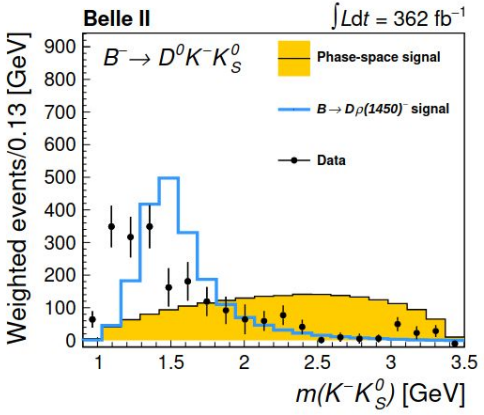
Challenge: bkg from non-resonant $B \to DK^{-}K\pi$

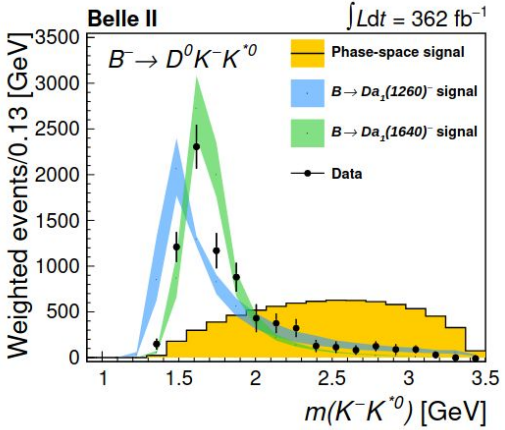
Modes in K* modes→ fit to $M(K\pi)$

- Signal Extraction: fit ΔE distribution
- BFs extracted applying an efficiency correction in the plane $M(D^{(*)}K_S^{(*)0}, M(K^{-}K_S^{(*)0})$
- Extraction of bkg-subtracted and efficiency-corrected invariant mass and helicity angles.
- $J^P = 1^{-/+}$ dominant transitions







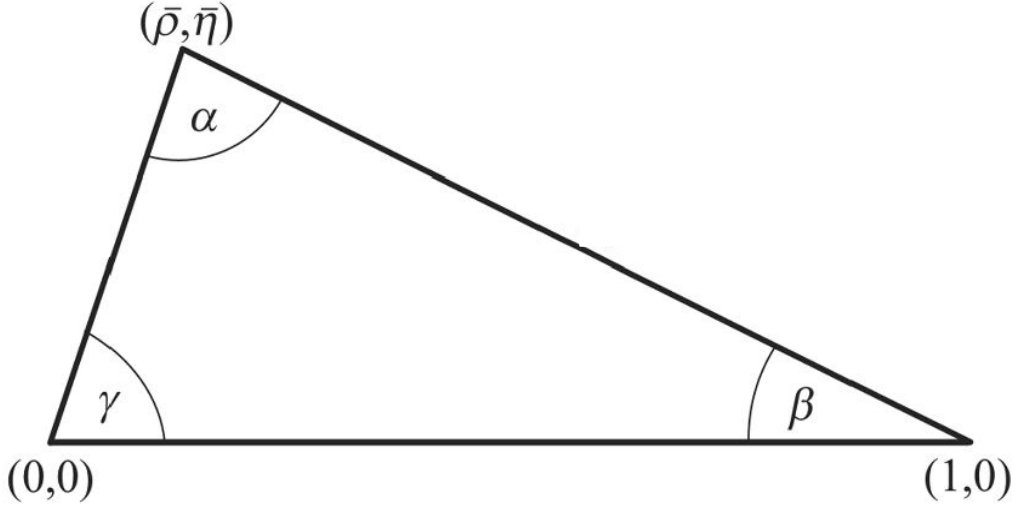


$B \to D^{(*)} K K^{(*)0}_{(S)}$ and $B \to D^{(*)} D^{-}_{s}$

[J. High Energ. Phys. **2024**, 206]

Channel	Yield (K^0_S / K^{*0})	Average ε (K^0_S / K^{*0})	$\mathcal{B}$ [10^{-4}]	
$B^- \to D^0 K^- K^0_S$	209 ± 17	0.098	$1.82 \pm 0.16 \pm 0.08$	
$\bar{B}^0 \to D^+ K^- K^0_S$	105 ± 14	0.048	$0.82 \pm 0.12 \pm 0.05$	First observation
$B^- \to D^{*0} K^- K^0_S$	51 ± 9	0.044	$1.47 \pm 0.27 \pm 0.10$	
$\bar{B}^0 \to D^{*+} K^- K^0_S$	36 ± 7	0.046	$0.91 \pm 0.19 \pm 0.05$	
$B^- \to D^0 K^- K^{*0}$	325 ± 19	0.043	$7.19 \pm 0.45 \pm 0.33$	
$\bar{B}^0 \to D^+ K^- K^{*0}$	385 ± 22	0.021	$7.56 \pm 0.45 \pm 0.38$	3× better precision
$B^- \to D^{*0} K^- K^{*0}$	160 ± 15	0.019	$11.93 \pm 1.14 \pm 0.93$	
$\bar{B}^0 \to D^{*+} K^- K^{*0}$	193 ± 14	0.020	$13.12 \pm 1.21 \pm 0.71$	
$B^- \to D^0 D^-_s$	144 ± 12 / 153 ± 13	0.04 / 0.09	$95 \pm 6 \pm 5$	
$\bar{B}^0 \to D^+ D^-_s$	145 ± 12 / 159 ± 13	0.02 / 0.05	$89 \pm 5 \pm 5$	World's best
$B^- \to D^{*0} D^-_s$	30 ± 6 / 29 ± 7	0.02 / 0.04	$65 \pm 10 \pm 6$	
$\bar{B}^0 \to D^{*+} D^-_s$	43 ± 7 / 37 ± 7	0.02 / 0.04	$83 \pm 10 \pm 6$	

CPV via CKM

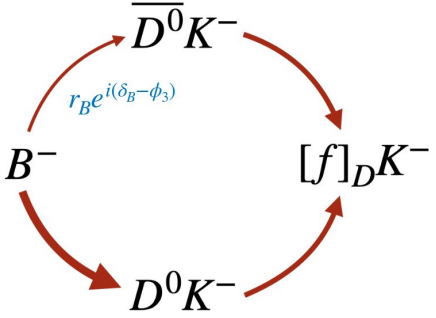


ϕ_3/γ measurement:Belle + Belle II combination

$\phi_3 \equiv \arg\left(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb}\right)$

$$\frac{\mathscr{A}^{\text{suppr.}}\left(B^- \to \overline{D}^0 K^-\right)}{\mathscr{A}^{\text{favor.}}\left(B^- \to D^0 K^-\right)} = r_B e^{i(\delta_B - \phi_3)}$$

[arXiv:2404.12817v2]
Accepted by JHEP



- Tree level decays — no (large) BSM
- Strong constraint on SM

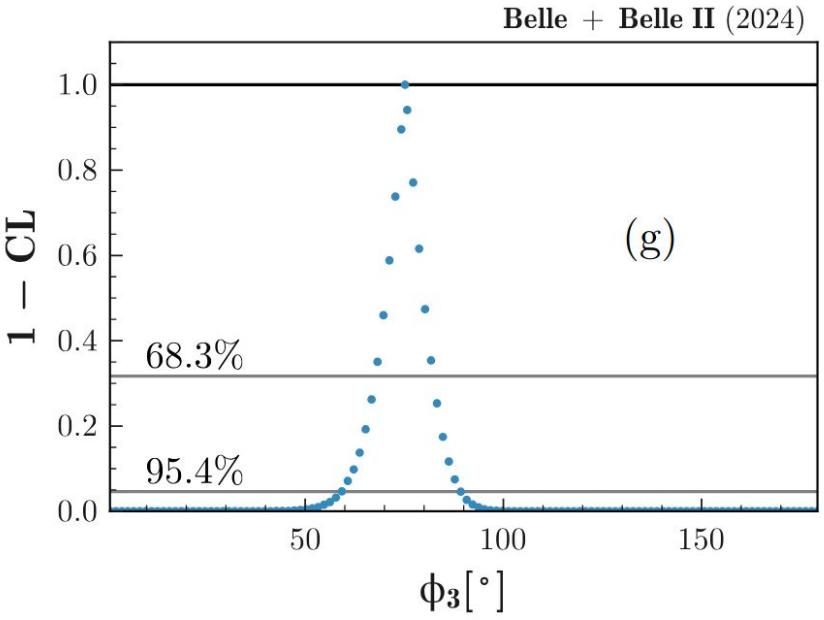
various approaches — different final states:
– Self-conjugate final states
– Cabibbo-suppressed decays ,
– eigenstates
First combination of all Belle and Belle II measurements:
59 input observables, 18 free parameters.

B decay	D decay	Method	Data set (Belle + Belle II)[fb^{-1}]	
$B^+ \to Dh^+$	$D \to K^0_S\pi^0, K^-K^+$	GLW	$711+189$	[JHEP 05 212 (2024)]
$B^+ \to Dh^+$	$D \to K^+\pi^-, K^+\pi^-\pi^0$	ADS	$711+0$	[PRL 106 231803 (2011), PRD 88 091104(2013)]
$B^+ \to Dh^+$	$D \to K^0_S K^-\pi^+$	GLS	$711+362$	[JHEP 09 146 (2023)]
$B^+ \to Dh^+$	$D \to K^0_S h^-h^+$	BPGGSZ (m.i.)	$711+128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K^0_S\pi^-\pi^+\pi^0$	BPGGSZ (m.i.)	$711+0$	[JHEP 10 178 (2019)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D \to K^0_S\pi^0, K^0_S\phi, K^0_S\omega, K^-K^+, \pi^-\pi^+$	GLW	210+0	[PRD 73 051106 (2006)]
$B^+ \to D^*K^+$	$D^* \to D\pi^0, D\gamma, D \to K^0_S\pi^-\pi^+$	BPGGSZ (m.d.)	$605+0$	[PRD 81 112002 (2010)]

ϕ_3/γ measurement:Belle + Belle II combination

[arXiv:2404.12817v2]
Accepted by JHEP

Decay	Observable	Value	Source
$D \to K^+\pi^-$	$R_D^{K\pi}$	$(3.44 \pm 0.02) \times 10^{-3}$	HFLAV
	$\delta_D^{K\pi}$	$(191.7 \pm 3.7)°$	
	$r_D^{K\pi}\cos(\delta_D^{K\pi})$	-0.0562 ± 0.0081	BESIII
	$r_D^{K\pi}\sin(\delta_D^{K\pi})$	-0.011 ± 0.012	
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$	0.0441 ± 0.0011	CLEO + LHCb + BESIII
	$\kappa_D^{K\pi\pi^0}$	0.79 ± 0.04	
	$\delta_D^{K\pi\pi^0}$	$(196 \pm 11)°$	
$D^0 - \overline{D}^0$ mixing	x_D	$(0.407 \pm 0.044)\%$	HFLAV
	y_D	$(0.647 \pm 0.024)\%$	
$D \to K^0_S K^-\pi^+$	$(r_D^{K^0_S K\pi})^2$	0.356 ± 0.034	CLEO
	$\kappa_D^{K^0_S K\pi}$	0.94 ± 0.12	
	$\delta_D^{K^0_S K\pi}$	$(-16.6 \pm 18.4)°$	
	$(r_D^{\overline{K}^0_S K\pi})^2$	0.370 ± 0.003	LHCb
$B^+ \to Dh^+$	R_{GLS}	0.0789±0.0027	PDG



$\phi_3 = (75.2 \pm 7.6)°$

[HFLAV]
$\phi_3^{WA}(°) = 66.2^{+3.4}_{-3.6}$

$B^0 \to \pi^0\pi^0$: towards ϕ_2

Tree-level b→uud processes allow extraction of ϕ_2

- Interference with penguin amplitudes
- Statistical limitation due to color suppression in tree diagram

First measurement of $B^0 \to \pi^0\pi^0$ at Belle II

- 4 photons in final state
- Suffers from large background

Update on BF and A_{CP} using full Run-1 statistics with

- new GNN-based flavor tagger
- BDT dedicated for photon selection and qq suppression
- reduction of systematic uncertainties

Signal extraction by simultaneous fit

- ΔE, Mbc, BDT output (C), transformed wrong tag probability

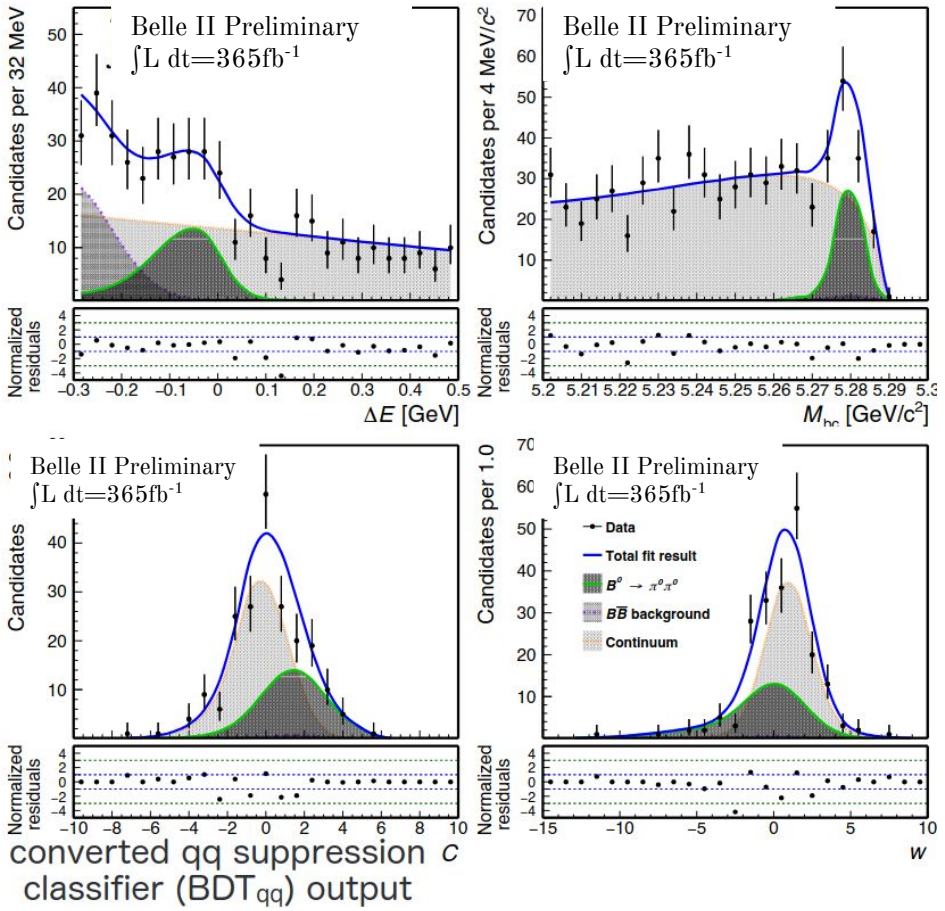
$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$

World's best

$A_{CP}(B^0 \to \pi^0\pi^0) = 0.06 \pm 0.30 \pm 0.06$

Compatible with world averages despite smaller data sample

paper in preparation
189fb^{-1}[Phys. Rev. D 107, 112009]



Summary

- Improve B decay knowledge $B^- \rightarrow D^0\rho^-$, $B \rightarrow DD_S$
- New decay modes observed $B \rightarrow D^{(*)}K^-K_S^{(*)0}$.
- Combining Belle and Belle II measurements to precisely measure ϕ_3
- Progress towards measurement of ϕ_2

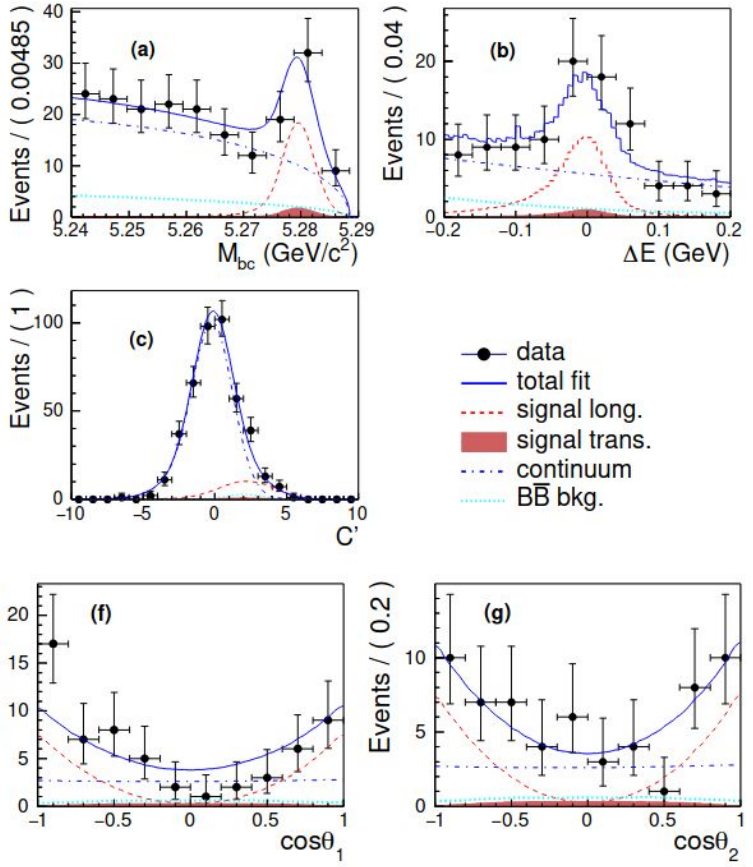
Run 2 started, more luminosity on it's way!

$B^0 \to \omega\omega$

[Phys. Rev. Lett. 133, 081801]

- Rare and never observed decay
- Polarisation (f_L) and direct-CPV parameter A_{CP} useful for $B \to VV$ decays
- BF, f_L and A_{CP} extraction in full Belle dataset
- Bkg suppressed using event-topology information
- Signal extraction from fit to: ΔE, M_{bc}, continuum suppression output, ω invariant masses and cosine of helicity angles of both the ω's

$$\begin{aligned} \mathcal{B} &= (1.53 \pm 0.29 \pm 0.17) \times 10^{-6} \\ f_L &= 0.87 \pm 0.13 \pm 0.13 \\ A_{CP} &= -0.44 \pm 0.43 \pm 0.11\,, \end{aligned}$$



$B \to D^{(*)} K K^{(*)0}_{(s)}$ and $B \to D^{(*)} D^{-}_{s}$

bkg-subtracted and efficiency corrected $m(K^{-}K)$ distributions