Measurements of hadronic B decay rates at Belle and Belle II

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on behalf of Belle and Belle II collaborations

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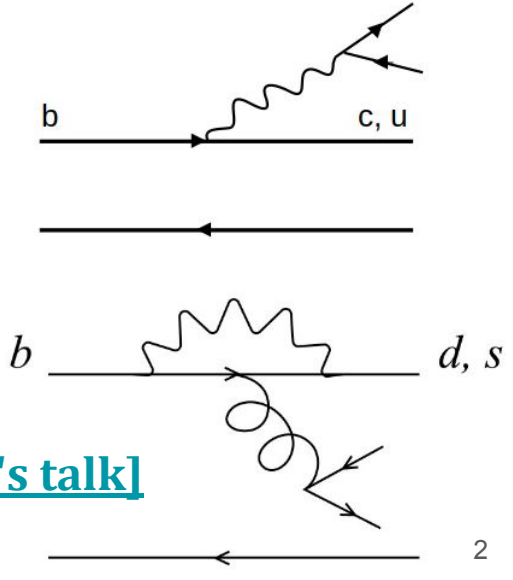
Hadronic B decays

- **Goal : probe indirectly the SM via weak interactions of quarks**
- **387M (Belle II)** and **772M (Belle) BB** pairs to accomplish world's best results.
- **B to hadronic** decays via **b → c,u tree** or **b → d, s penguins**

Talk focuses on improvement of our knowledge on B decays, measure parameters related to CKM angles :

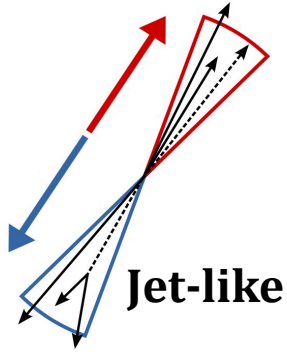
- $B^+ \to D^0\rho(770)^+$
- $B \to D^{(*)}K^-K^{(*)0}$
- $B^0 \to \omega\omega$
- **First Belle+Belle II combination of ϕ_3 measurements**
- $B^0 \to \pi^0\pi^0$ **towards ϕ_2 measurement** [Yu Nakazawa's talk]

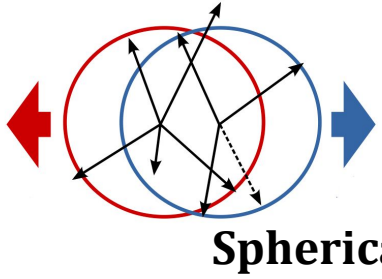


Analysis workflow

- **Υ(4S) decays → BB̄ 96%** of the time, **background** from **$e^+ e^- \to q\bar{q}$** events.
- **Event selection**: final state particle with good track selection, particle ID criteria etc.
- **Reconstruction** : forming B meson using final state particles.
- **Background reduction** : event-shape variables to suppress background etc.
- **Fit** : to extract the signal events.
- **Systematic uncertainties** : toy MC and control sample studies.

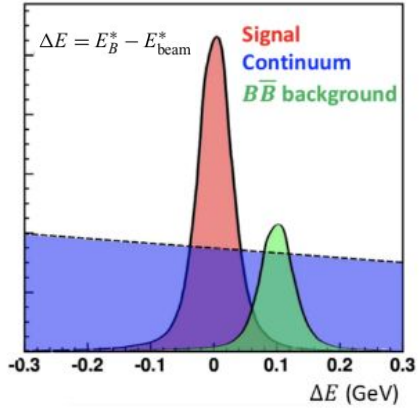
Event Topology

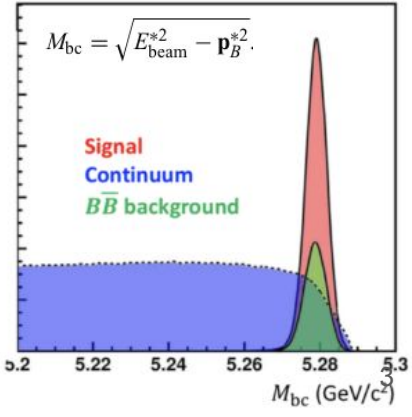




Difference between expected and observed B energy

Invariant B mass with energy replaced by beam energy

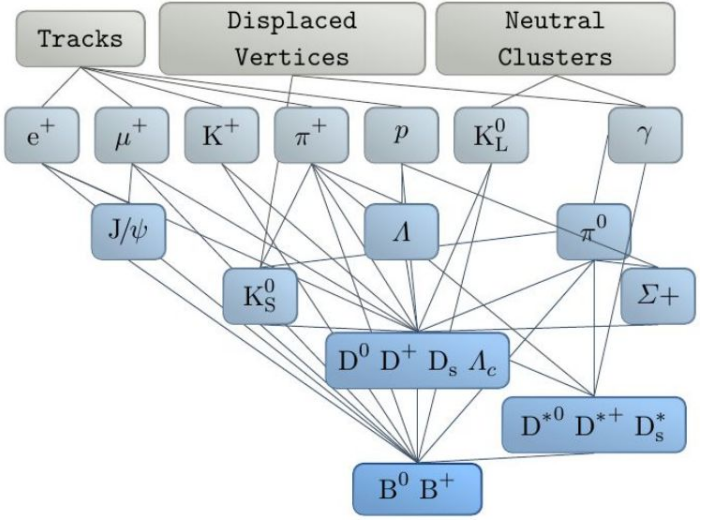


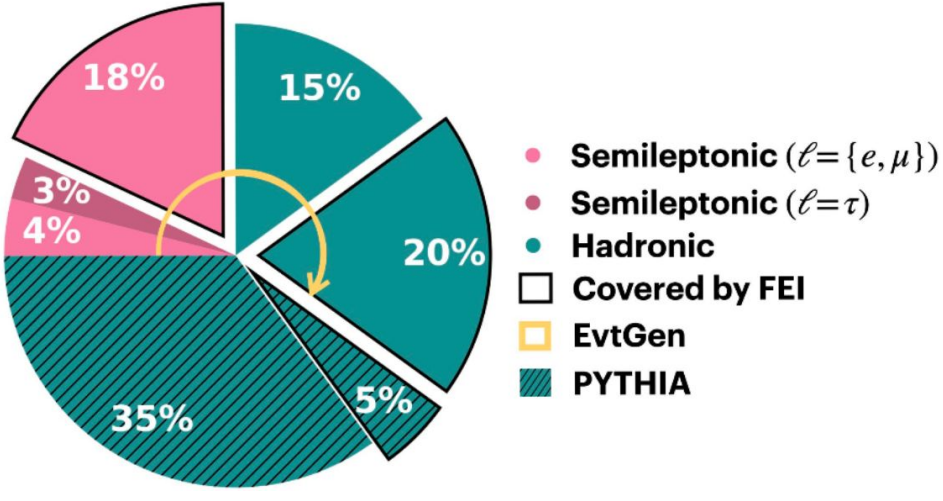


Improve B decay knowledge

- Hadronic decays of B-mesons account for **~75%** of the total branching fraction
- But it's largely **unknown (~50%)**
- Measurements with small data sets ~ **large uncertainties**
- Important to improve **hadronic B-tagging**

Tagging algorithm (**FEI**)





- **Hadronic B tagging:** best purity and you get the B momentum vector
- BDT for each decay trained on simulation [$\mathbf{B\to D^{(*)}\, n\pi\ m\pi^0}$]
- Important for decays with **missing energy** [Meihong's talk]

Branching fraction of $B^+ \to D^0\rho(770)^+$ at Belle II

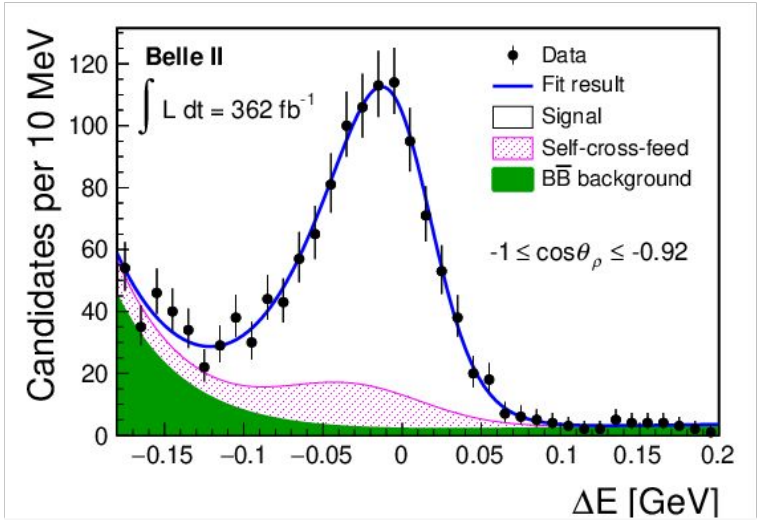
Test heavy-quark limit and factorisation models [Nucl. Phys. B 591, 313 (2000)]

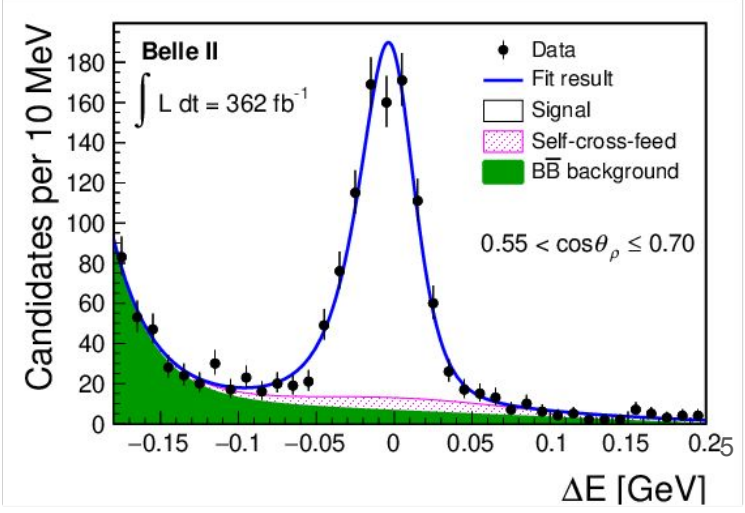
WA BF : **(1.35 ± 0.18)%** driven by CLEO measurement with large uncertainty **(14%)** CLEO, PRD 50, 43 (1994)

Signal extracted from **fit to ΔE**

Challenge: separate $B^+ \to D^0\rho^+(\to\pi^+\pi^0)$ **resonant** and $B^+ \to D^0\pi^+\pi^0$ **non-resonant** component.
— Fit performed in bins of **helicity angle ($\cos\theta_\rho$)**

θρ : angle between π momentum and direction opposite to B momentum in ρ rest frame.

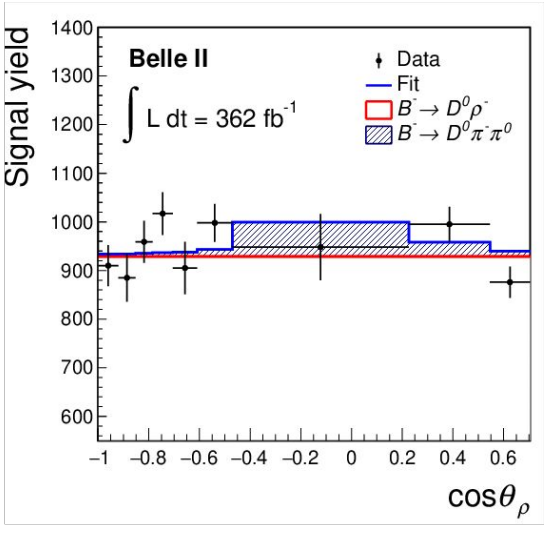


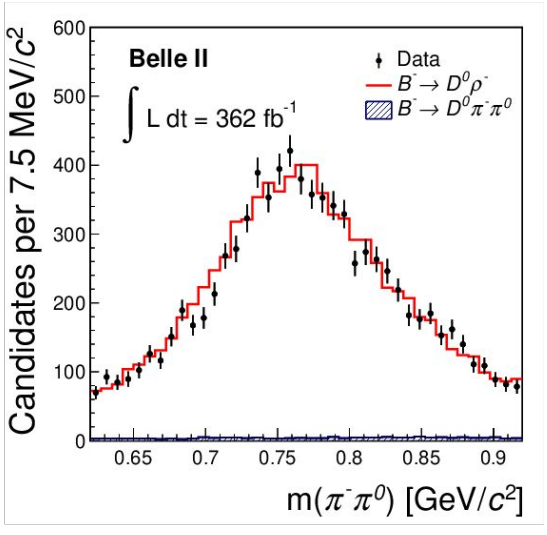


Branching fraction of $B^+ \to D^0\rho(770)^+$ at Belle II

Template fit in $\cos\theta_\rho$

- **Non-uniform binning** : flat $\cos\theta_\rho$ distribution for $\mathbf{B \to D\rho}$
- **Less than 2 %** contribution of $\mathbf{B^+ \to D^0\pi^+\pi^0}$ s-wave component





$$\mathcal{B}(B^+ \to D^0\rho^+) = (0.94 \pm 0.02 \pm 0.05)\ \%$$

- **World's best result with more than 2x improvement in precision**
- Factorisation test: in agreement with prediction, improved precision
- Systematically limited by uncertainty on π^0 efficiency

PhysRevD.109.L111103

$B \to D^{(*)} K^{-} K^{(*)0}_{(S)}$ and $B \to D^{(*)} D_s^{-}$ at Belle II

B → DKK: largely unexplored sector

➢ **Few % of B** branching fraction expected

➢ Only **0.28 %** measured so far

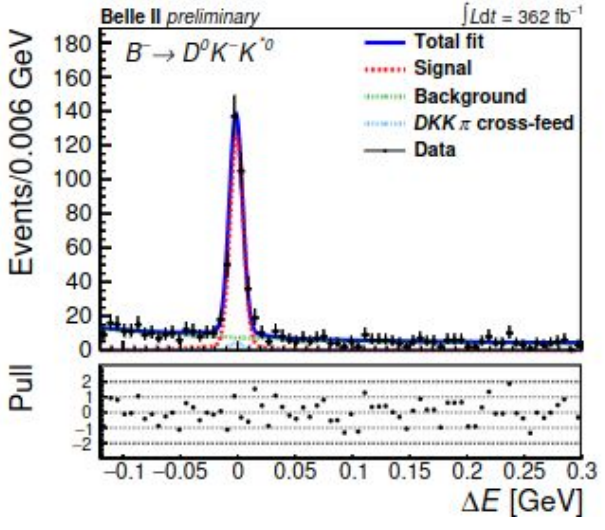
- **Challenge:** estimate **non-resonant**

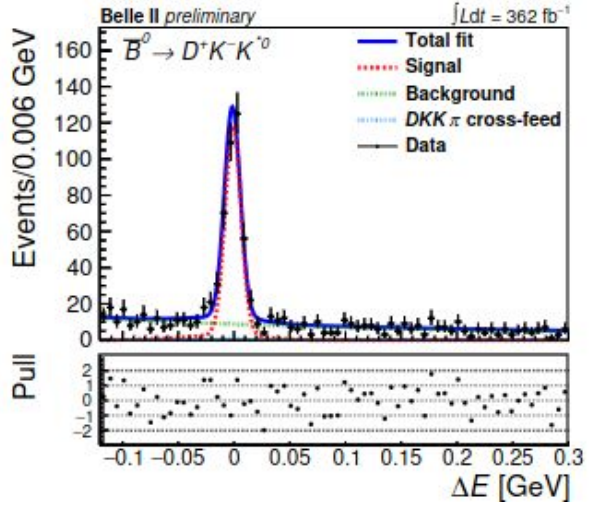
  $B \to DK^{-}K^{+}\pi$ modes in K^{*}

- Signal extracted from **fit to ΔE**

- Subtract background, and look at **invariant**

  mass and **Dalitz** distributions



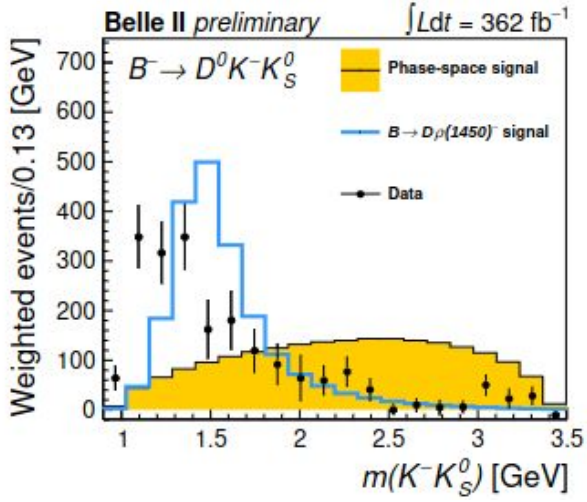


$B \to D^{(*)} K^- K_{(S)}^{(*)0}$ and $B \to D^{(*)} D_s^-$ at Belle II

- Efficiency correction applied in the plane **m[$D^{(*)}K^-$]** and **m[$K^- K_{(S)}^{(*)0}$]**
- Extraction of bkg-subtracted and efficiency corrected invariant mass and helicity
- Dominant transitions $\mathbf{J^P = 1^{-/+}}$
- **$B \to D^{(*)} D_s (\to KK^{(*)})$** are used as control modes

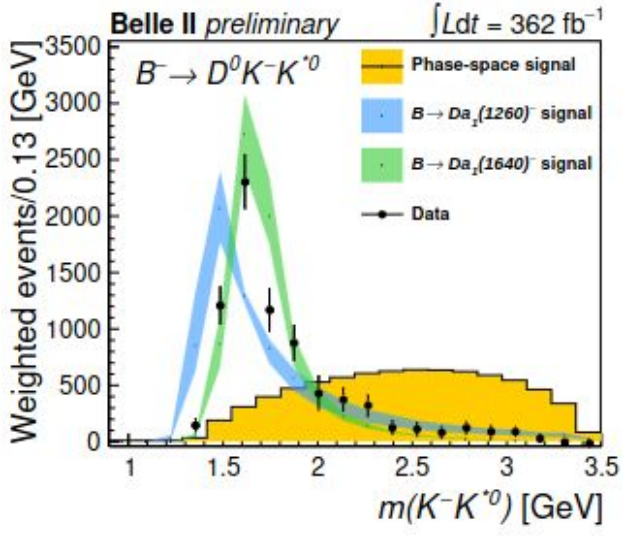
$J^P = 1^-$

(ρ)



$J^P = 1^+$

(a_1)



$B \to D^{(*)} K^- K_{(S)}^{(*)0}$ and $B \to D^{(*)} D_s^-$ at Belle II

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

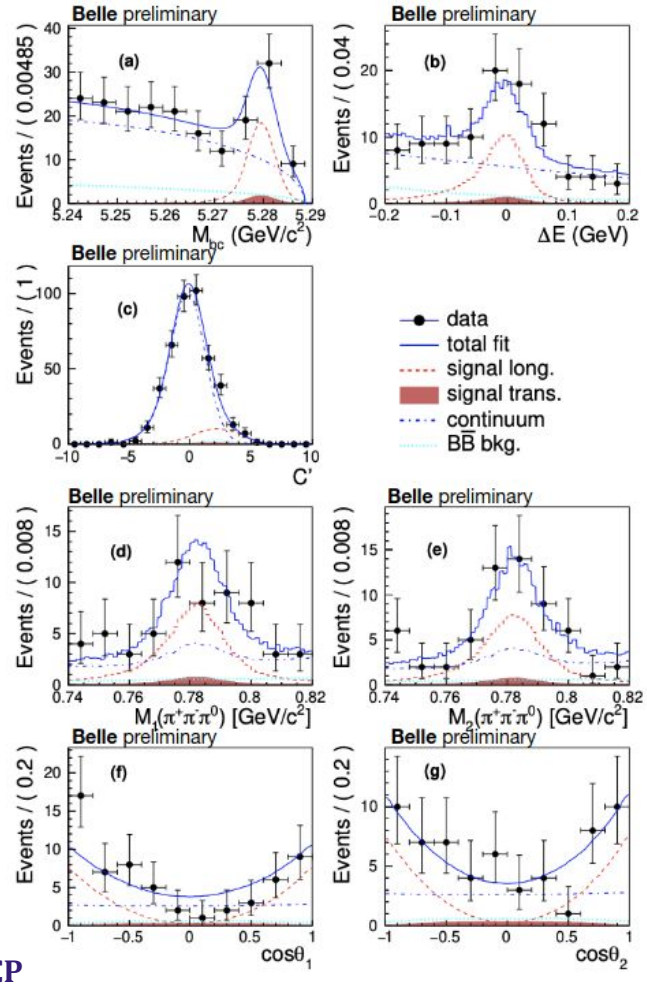
Total 12 channels, first observation for 3 channels
World's best precision for the rest

[arXiv.2406.06277], submitted to JHEP

$B^0 \to \omega\omega$ at Belle

- Rare and never observed decay
- Polarisation (f_L) and direct-CPV parameter A_{CP}
- f_L useful for $B \to VV$ decays
- Using full **Belle dataset (711 fb^{-1})**
- Signal extraction from **7D fit to: ΔE, M_{bc},** continuum suppression**, ω invariant masses** & **cosine of helicity** angles of both the ω's.

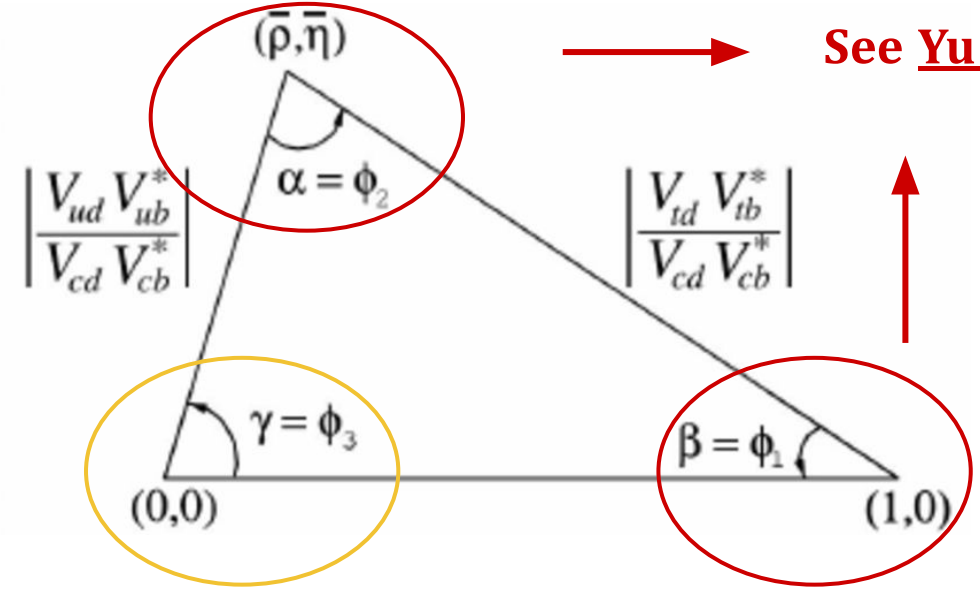
$$\mathcal{B} = (1.53 \pm 0.29 \pm 0.17) \times 10^{-6}$$
$$A_{CP} = -0.44 \pm 0.43 \pm 0.11$$
$$f_L = 0.87 \pm 0.13 \pm 0.13$$



First observation of the decay (7.9σ), no significant A_{CP}

[arXiv.2401.04646], accepted by PRL

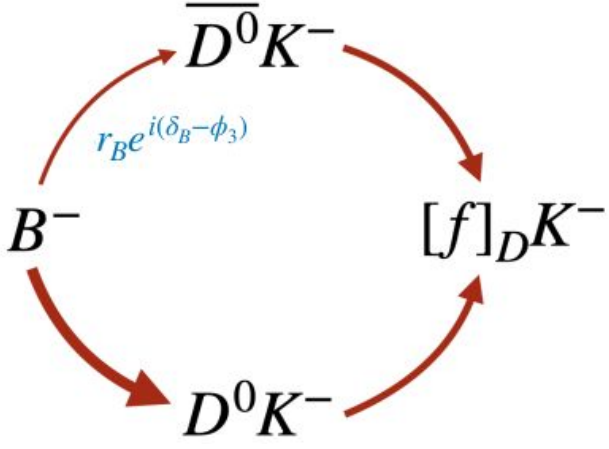
CKM angles



See Yu Nakazawa's talk

First Belle+Belle II combination of ϕ_3 measurements

- **Tree level** decays - strong constraints on SM
- ϕ_3 : phase between **b** → **u** and **b** → **c**
- Interference between two decays to same final state gives access to phase:
- Current WA dominated by LHCb



Various approaches - different D final states:

- Self-conjugate final states **D** → $K_S^0 h^+ h^- (\pi^0)$
- Cabibbo-suppressed decays **D** → $K_S^0 K^\pm \pi^\mp$, **D** → $K^+ \pi^- (\pi^0)$
- CP eigenstates **D** → K^+K^-, $K_S^0 \pi^0$

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

WA :

$\phi_3 = (65.9\ ^{+3.3}_{-3.5})^\circ$

HFLAV

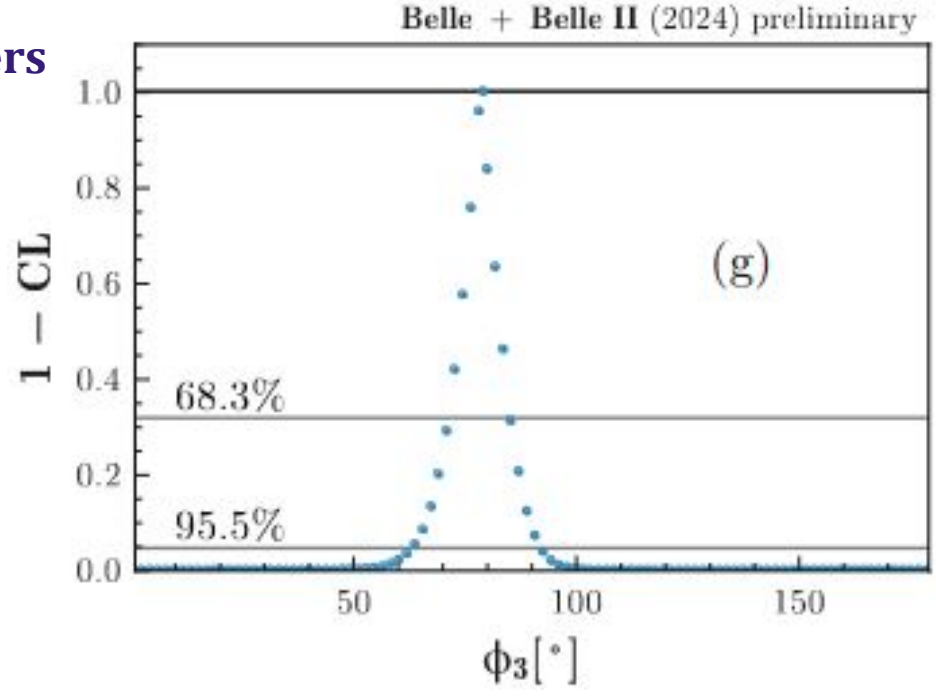
First Belle+Belle II combination of ϕ_3 measurements

60 input observables, 16 free parameters

$$\phi_3 = (78.6^{+7.2}_{-7.3})^\circ$$

First combination of Belle and Belle II measurements.

[arXiv.2404.12817]



Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]

Summary

- **Exploiting the Belle II run 1 data set along with the Belle data set to test SM**
- **Improve the hadronic B tagging with FEI - new measurements**

- Improve B decay knowledge : $B^+ \to D^0 \rho^+$
- Observe new decay channels : $B \to D^{(*)} K^- K_S^0$ and $B^0 \to \omega\omega$
- Measure parameters related to CKM angles : combined ϕ_3 from Belle+Belle II

Many world's best and competitive results with smaller dataset.
Run 2 started, more luminosity is coming!

Stay tuned!!!

$B \to D^{(*)} K^- K_{(S)}^{(*)0}$ and $B \to D^{(*)} D_s^-$ at Belle II

Bkg subtracted and efficiency corrected m[K^-K] distributions