Recent results on hadronic decays and CP violation at Belle II

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On behalf of the Belle II Collaboration

Contents

Introduction : CKM matrix, Belle II experiment

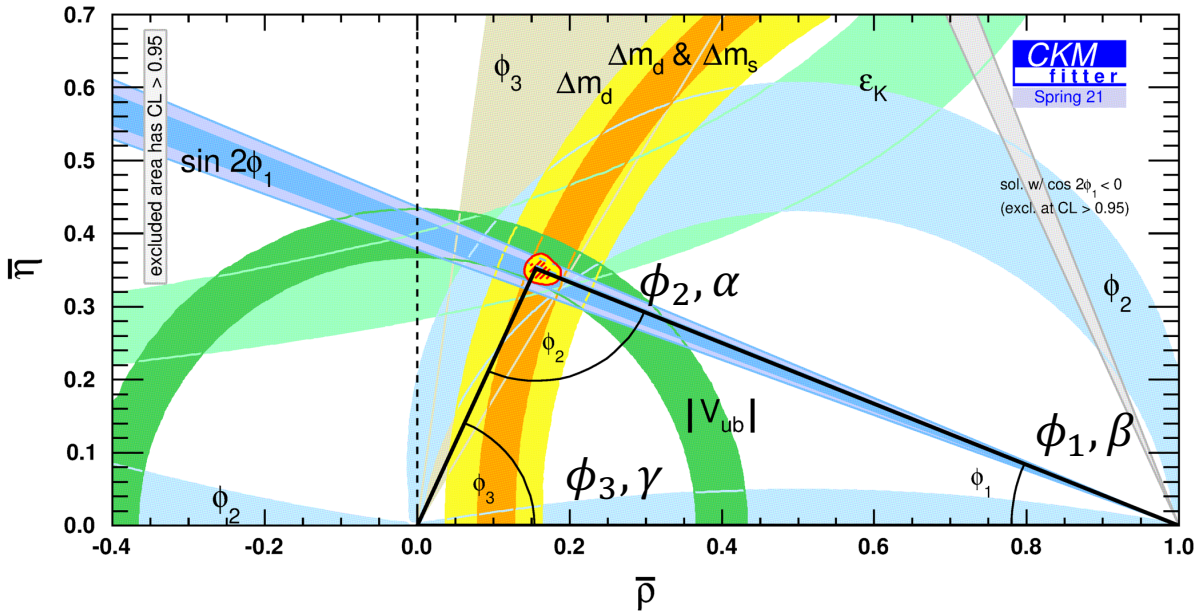
ϕ_1, β result : $B^0 \to J/\Psi K_s^0, K_S^0\, K_S^0 K_S^0$

ϕ_2, α result : $B \to \pi^+\pi^0,\ \pi^0\pi^0, \rho^+\rho^0, \rho^+\rho^-$

ϕ_3, γ result : $B^+ \to D(K_s^0 h^+ h^-)h^+$

Introduction

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



CKM Matrix

- Coupling of flavor-changing weak interaction of quark.
- 3 mixing angle + 1 CP-violating (complex) phase.
- Kobayashi-Maskawa model successfully described the flavor structure of the quark using it.

Unitarity triangle

- Unitarity of the CKM matrix
  → Unitarity Triangle.
- Tested by previous experiments and confirmed.

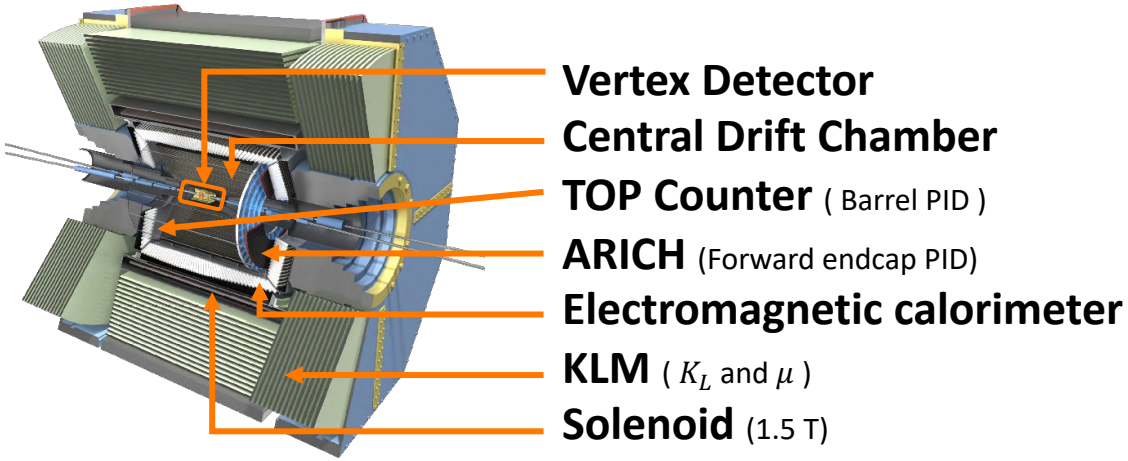
Improve the precision to search physics beyond the standard model in B decay!

Belle II experiment

Belle II experiment

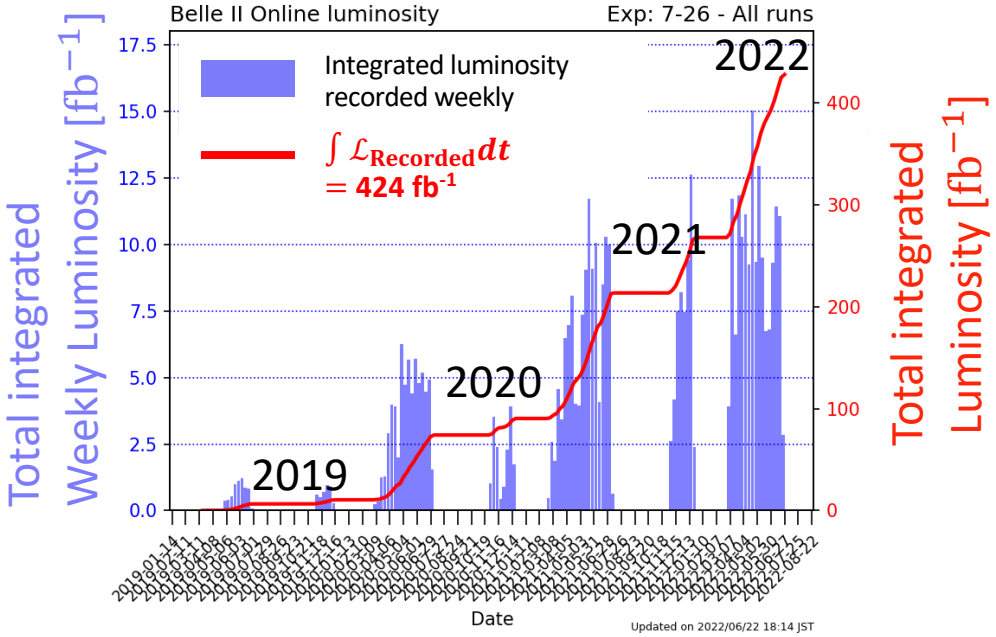
- High luminosity e^-e^+collider experiment at a center of mass energy of 10.58 GeV.
- Target integral Luminosity : $\mathbf{50\ ab^{-1}}$
- Target peak luminosity : $\mathbf{6\times10^{35}cm^{-2}s^{-1}}$

Belle II detector



Status of Belle II

- Integrated $\mathbf{424\ fb^{-1}}$ ($\Upsilon(4S)$: $363 fb^{-1}$)
- Achieved Peak luminosity $\mathbf{4.7\times10^{34}cm^{-2}s^{-1}}$ World-best, **2x higher** than Belle.



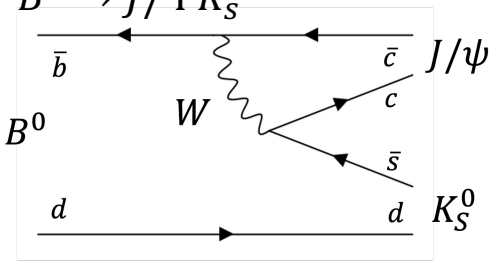
Belle II can measure CKM more precisely and explore the physics beyond the standard model!

ϕ_1, β Measurement

$$\phi_1,\ \beta = \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb})]$$

Time-dependent CPV

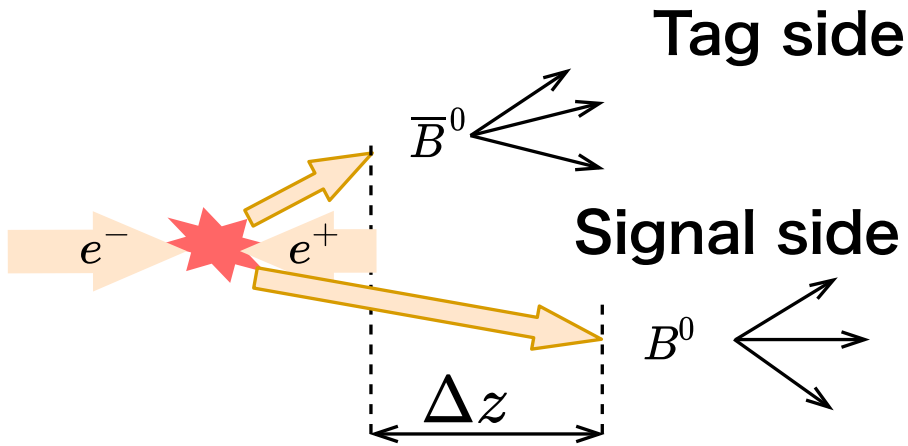
$B^0 \to J/\Psi K_S^0$



$$\frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} = A \cos \Delta m_d \Delta t + S \sin \Delta m_d \Delta t$$

$A = 0$ (Direct CPV)

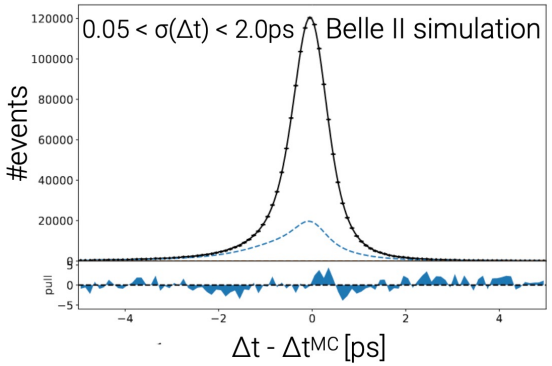
$S = \sin 2\phi_1$ (indirect CPV (mixing))



Δz: Distance of the decay vertex of two B^0

Δt measurement

ICHEP 2022



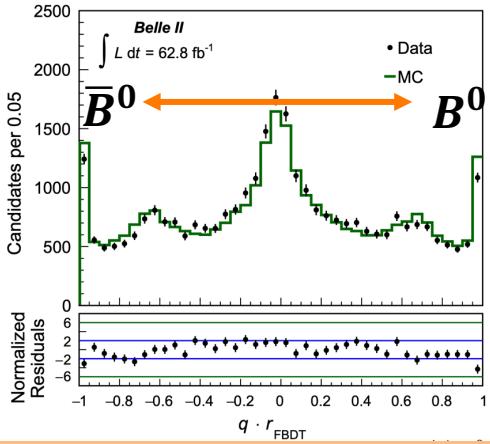
$B\bar{B}$ is boosted ($\beta\gamma = 0.28$)

$\Delta z \to \Delta t$

- Add Pixel detector to improve the resolution.
- Prepared resolution function.

Flavor tagging

Eur. Phys. J. C (2022) **82**: 283

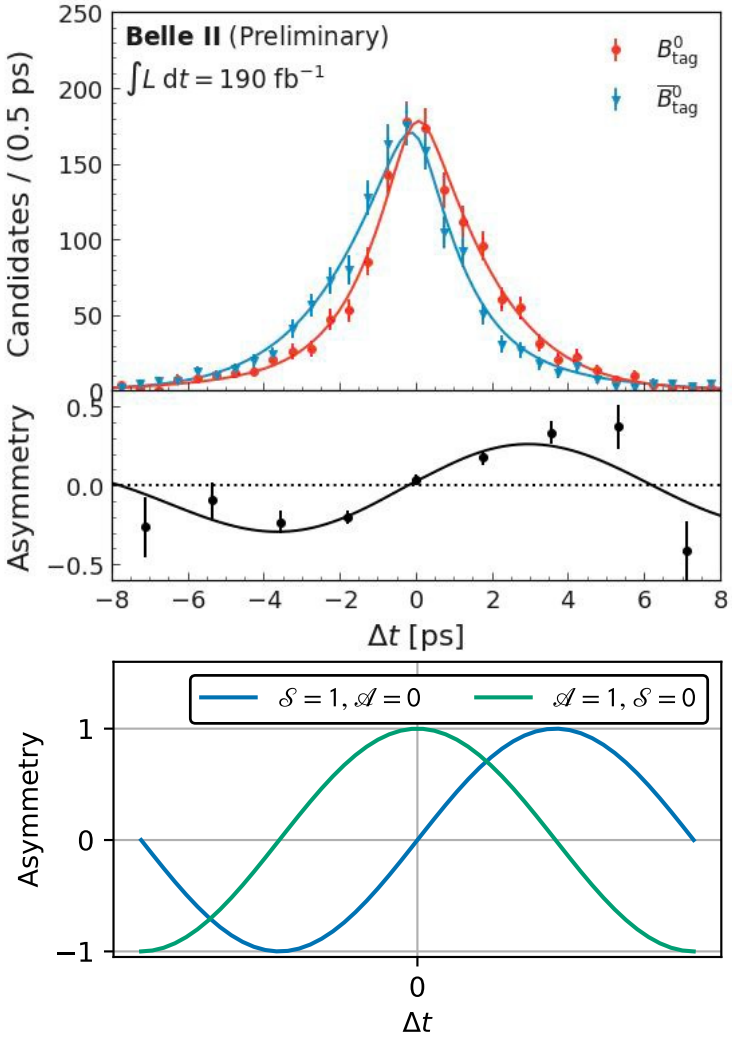


Identify the flavor of signal using tag side decay

- $\epsilon_{eff} = 30.0 \pm 1.2(\text{stat}) \pm 0.4(\text{syst})\ \%$
- Data-MC is consistent.

Comparable with best performance in Belle

$B^0 \to J/\Psi K_S^0$ results (ICHEP 2022)



Golden mode to measure ϕ_1, β

	Belle II $189\ \mathrm{fb}^{-1}$	Belle full data (10.1103/PhysRevLett.108.171802)
S_{CP}	$0.720 \pm 0.062(\mathrm{stat}) \pm 0.016(\mathrm{syst})$	$0.670 \pm 0.029(\mathrm{stat}) \pm 0.013(\mathrm{syst})$
A_{CP}	$0.09 \pm 0.044(\mathrm{stat})^{+0.042}_{-0.017}(\mathrm{syst})$	$-0.015 \pm 0.021(\mathrm{stat})^{+0.045}_{-0.023}(\mathrm{syst})$

Consistent with previous results.

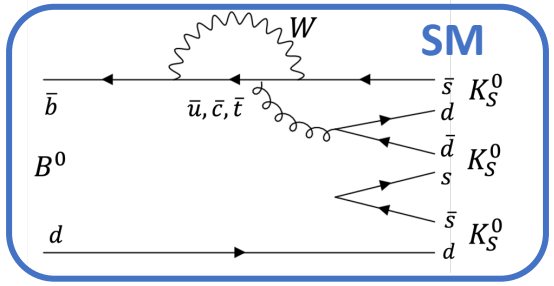
→ **Resolution function and flavor tagging is working well.**

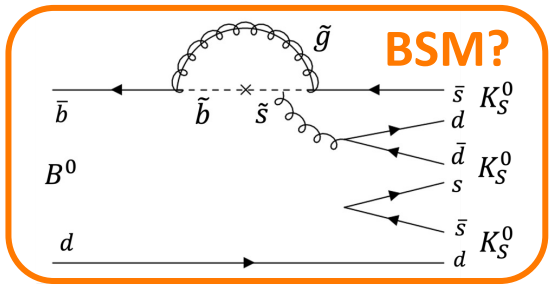
Ready to provide more precise results!

$B^0 \to K^0_S K^0_S K^0_S$ arXiv:2209.09547

$B^0 \to K^0_S K^0_S K^0_S$

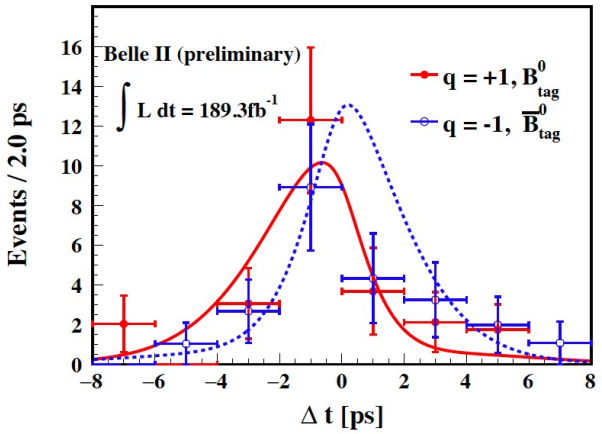
$S = -\sin 2\phi_1 + \Delta S$, $A = \Delta A$

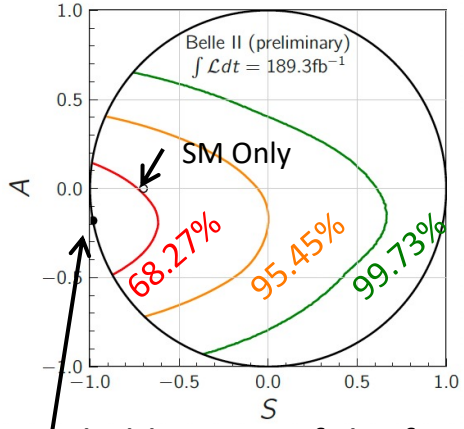




Penguin decay→ sensitive mode to BSM

	Belle II 189 fb^{-1}	Belle full data (10.1103/PhysRevD.103.032003)
S_{CP}	$-1.86^{+0.91}_{-0.46}(\text{stat}) \pm 0.09(\text{syst})$	$0.710 \pm 0.23(\text{stat}) \pm 0.05(\text{syst})$
A_{CP}	$0.094^{+0.30}_{-0.27}(\text{stat}) \pm 0.04(\text{syst})$	$0.12 \pm 0.15(\text{stat}) \pm 0.05(\text{syst})$





most probable point of the fit

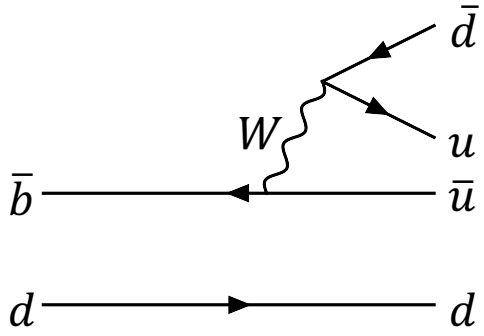
Consistent with SM and Belle, statistically limited.

Analysis with 363 fb^{-1} is ongoing

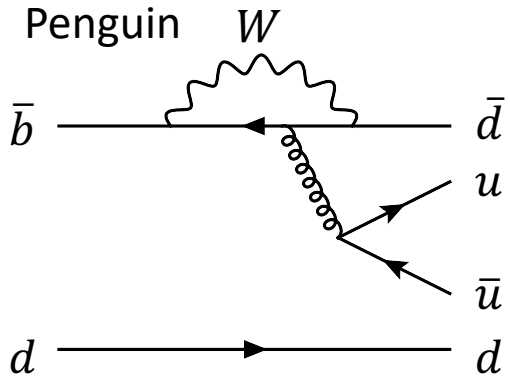
ϕ_2, α Measurement

$$\phi_2,\ \alpha = \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$$

Tree



Penguin



$$\frac{\Gamma(\bar{B}^0\to f)-\Gamma(B^0\to f)}{\Gamma(\bar{B}^0\to f)+\Gamma(B^0\to f)} = \boldsymbol{A}\ cos\,\Delta m_d\Delta t\ + \boldsymbol{S}\ sin\,\Delta m_d\Delta t$$

Using $b \to u$ tree decays (ex. $B^0 \to \pi^+\pi^-$),

$\boldsymbol{S = \sin(2\phi_2 + 2\Delta\phi_2)}$

$\boldsymbol{A \neq 0}$

S is polluted by the interference between tree and penguin, and direct CPV appears.

Isospin analysis

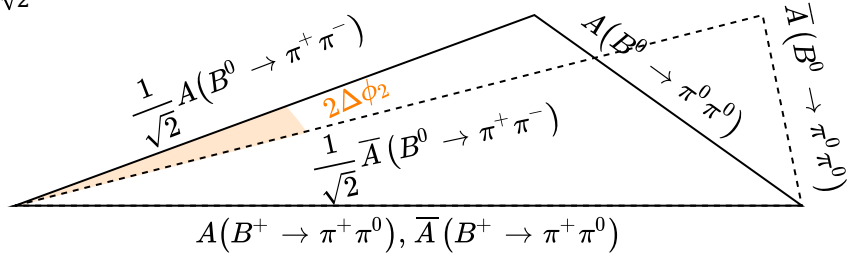
Isospin relations

	Tree	Penguin
$\pi^+\pi^-$	○	○
$\pi^+\pi^0$	○	×
$\pi^0\pi^0$	△ (color suppressed)	○

Granou-London isospin relations

$$\frac{1}{\sqrt{2}}A(B^0\to\pi^+\pi^-) - A(B^0\to\pi^0\pi^0) = A(B^+\to\pi^+\pi^0)$$

$$\frac{1}{\sqrt{2}}\bar{A}(B^0\to\pi^+\pi^-) - \bar{A}(B^0\to\pi^0\pi^0) = \bar{A}(B^+\to\pi^+\pi^0)$$



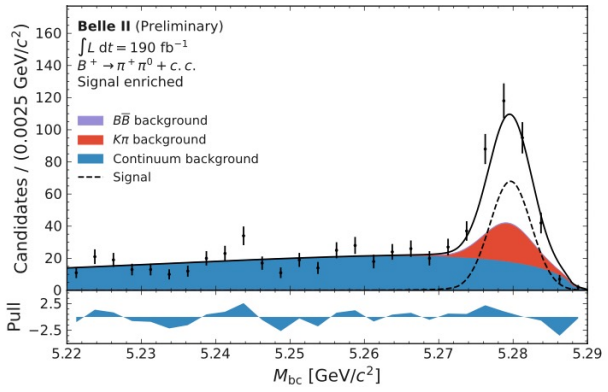
Observables to measure ϕ_2

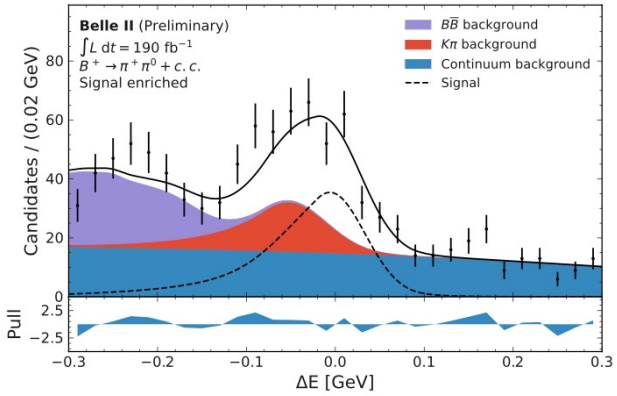
$\pi^+\pi^-$	BF, S,A
$\pi^+\pi^0$	BF, A
$\pi^0\pi^0$	BF, A

$\Delta\phi_2$ can be subtracted using this relationship

$B \to \pi\pi$ Results

$\pi^+\pi^0$ arXiv:2209.05154

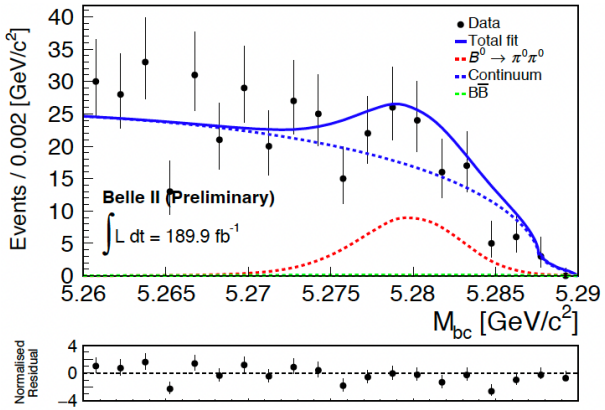


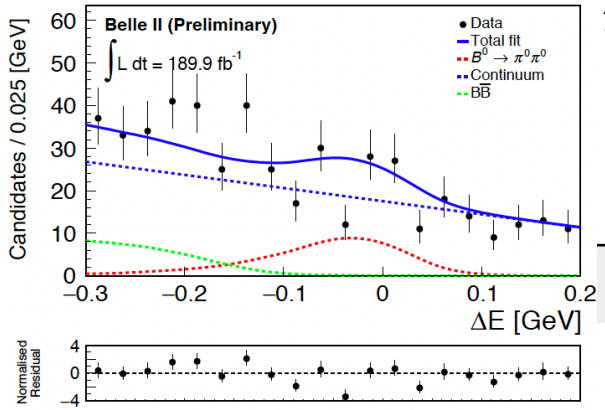


Fitting: 3D ($M_{bc}, \Delta E$, continuum suppression (CS))
Systematic uncertainty: comes from the control sample size

	Belle II 189 fb^{-1}	Belle full data (10.1103/PhysRevD.87.031103)
$\mathcal{B}$	$(6.12 \pm 0.53 \pm 0.53)\times10^{-6}$	$(5.86 \pm 0.26 \pm 0.38)\times10^{-6}$
A_{CP}	$-0.085 \pm 0.085 \pm 0.019$	$0.25 \pm 0.043 \pm 0.007$

$\pi^0\pi^0$ ICHEP 2022





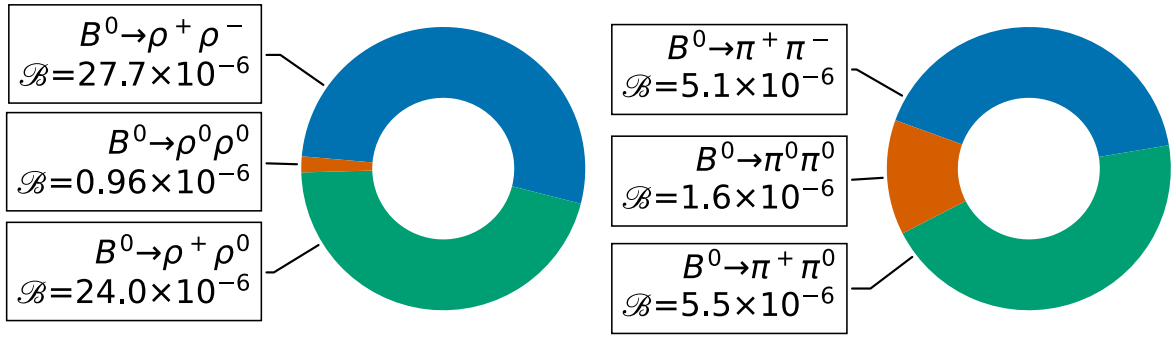
$\pi^0 \to \gamma\gamma$ has a lot of background → **developed MVA**
Fitting : 3D ($M_{bc}, \Delta E$, CS) in 7 flavor tagging bin

	Belle II 189 fb^{-1}	Belle full data (10.1103/PhysRevD.96.032007)
$\mathcal{B}$	$(1.27 \pm 0.25 \pm 0.18)\times10^{-6}$	$(1.31 \pm 0.19 \pm 0.19)\times10^{-6}$
A_{CP}	$0.14 \pm 0.46 \pm 0.007$	$0.14 \pm 0.36 \pm 0.01$

Both are consistent with Belle results, $\pi\pi$ analysis is ready to give a new constraint to ϕ_2

ϕ_2, α Measurement by $B \to \rho\rho$ channel

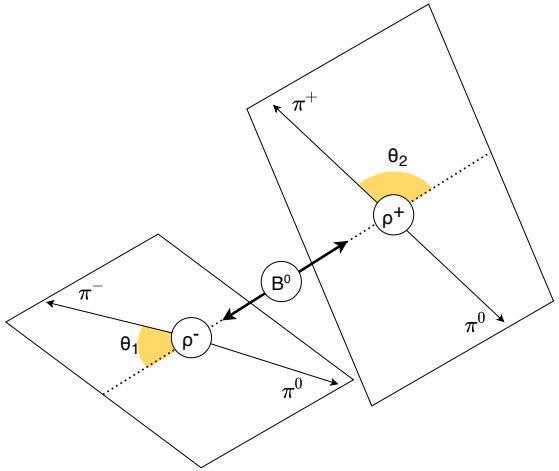
Penguin contribution in $\pi\pi$ and $\rho\rho$



Smaller $\mathcal{B}$ of $\rho^0\rho^0$ → Smaller Penguin pollution

Smaller $\Delta\phi_2$ → Improved precision

Challenge in $\rho\rho$ analysis



Polarization of P→VV decay

Longitudinal	CP-Even
Transverse	CP-Even + CP-odd

Only longitudinal can be used in ϕ_2 measurement

Measure longitudinal polarization from angular analysis

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_{\rho^+} d\cos\theta_{\rho^-}} = \frac{9}{4}\left(f_L \cos^2\theta_{\rho^+} \cos^2\theta_{\rho^-} + (1-f_L)\frac{1}{4}\sin^2\theta_{\rho^+} \sin^2\theta_{\rho^-}\right)$$

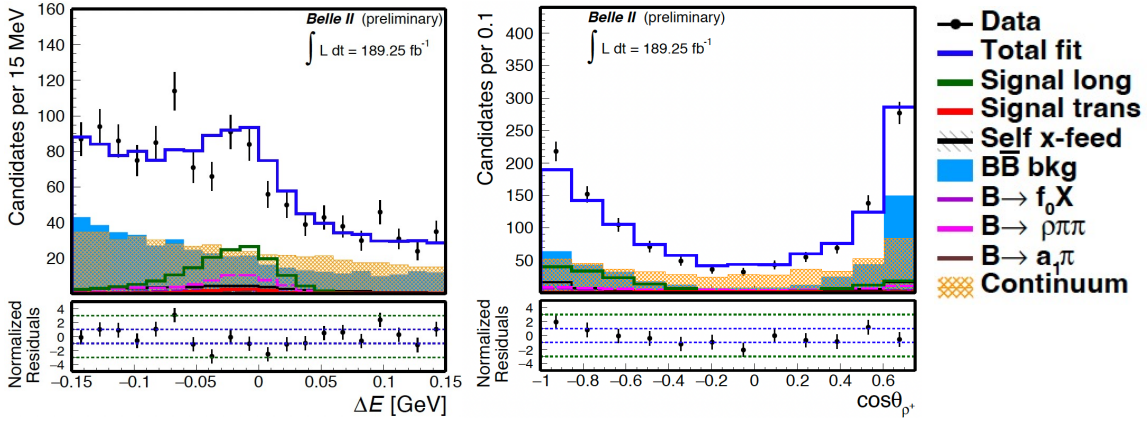
Observables to measure ϕ_2

$\rho^+\rho^-$	BF, S,A, f_L
$\rho^+\rho^0$	BF, A, f_L
$\rho^0\rho^0$	BF, A, f_L

$\rho\rho$ analysis is more complicated, but has better sensitivity to ϕ_2

$B \to \rho\rho$ results

$\rho^+\rho^0$ arXiv:2206.12362

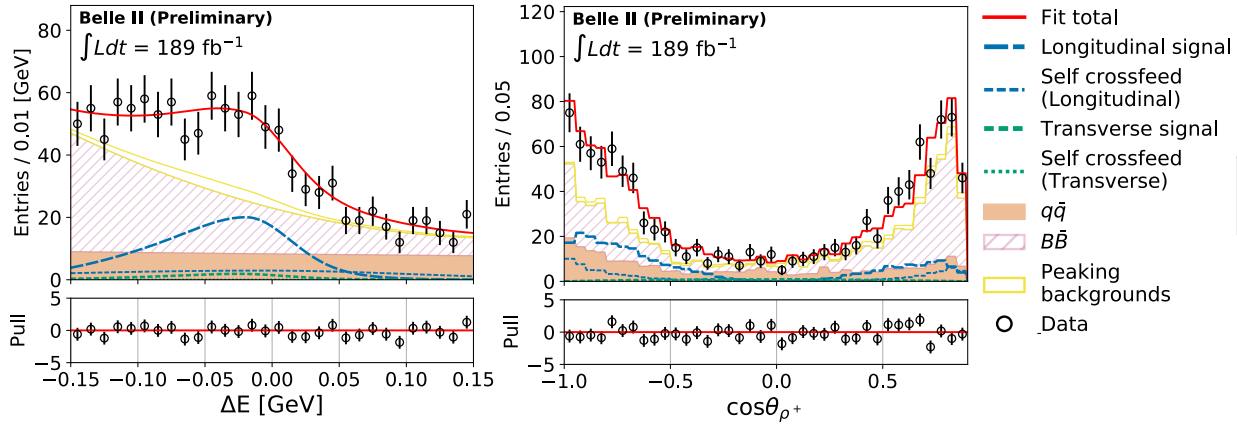


Fitting: 6D fit (ΔE, CS, m_ρ, $\cos\theta_\rho$)

	Belle II 189 fb^{-1}	BaBar (10.1103/PhysRevLett.102.141802)
$\mathcal{B}$	$(23.2^{+2.2}_{-2.1} \pm 2.7)\times10^{-6}$	$(23.7 \pm 1.4 \pm 1.4)\times10^{-6}$
A_{CP}	$-0.069 \pm 0.068 \pm 0.060$	$-0.054 \pm 0.055 \pm 0.010$
f_L	$0.943^{+0.035}_{-0.033} \pm 0.027$	$0.950 \pm 0.015 \pm 0.006$

Analysis with 363fb^{-1} is ongoing

$\rho^+\rho^-$ arXiv:2208.03554



$\pi^0 \to \gamma\gamma$ has a lot of background → **developed MVA**

Fitting: 6D fit (ΔE, CS, m_ρ, $\cos\theta_\rho$)

	Belle II 189 fb^{-1}	Belle (Phys. Rev. D **94**, 099903 (2016))
$\mathcal{B}$	$(26.7 \pm 2.8 \pm 2.8)\times10^{-6}$	$(28.3 \pm 1.5 \pm 1.5)\times10^{-6}$
f_L	$0.956 \pm 0.035 \pm 0.033$	$0.988 \pm 0.012 \pm 0.023$

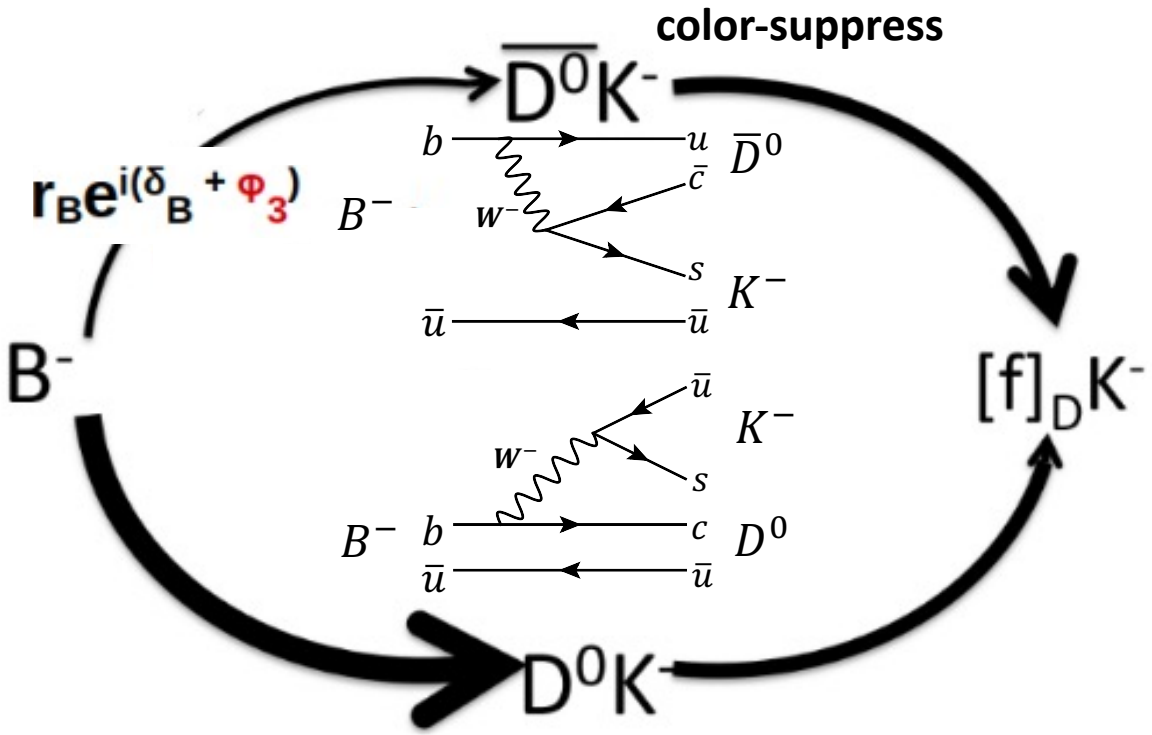
Analysis with 363fb^{-1} + time-dependent CPV is ongoing

Ready to do first ϕ_2 measurement with $\rho\rho$

ϕ_3, γ measurement

$$\phi_3, \gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$$

will appear in CPV parameter of $b \to u\bar{c}s$ and $b \to c\bar{u}s$ tree decay interference.



$$A_{B^-} = A_D + r_B e^{i(\delta_B - \phi_3)} \bar{A}_D$$
$$A_{B^+} = \bar{A}_D + r_B e^{i(\delta_B + \phi_3)} A_D$$

$r_B \simeq c_f |V_{cs}V_{ub}^*/V_{us}V_{cb}^*| \sim 0.1$

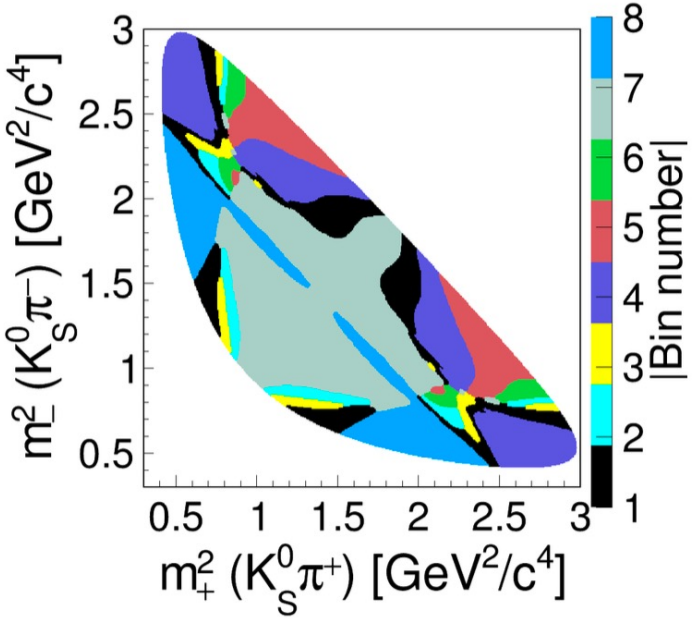
δ_B: strong phase difference

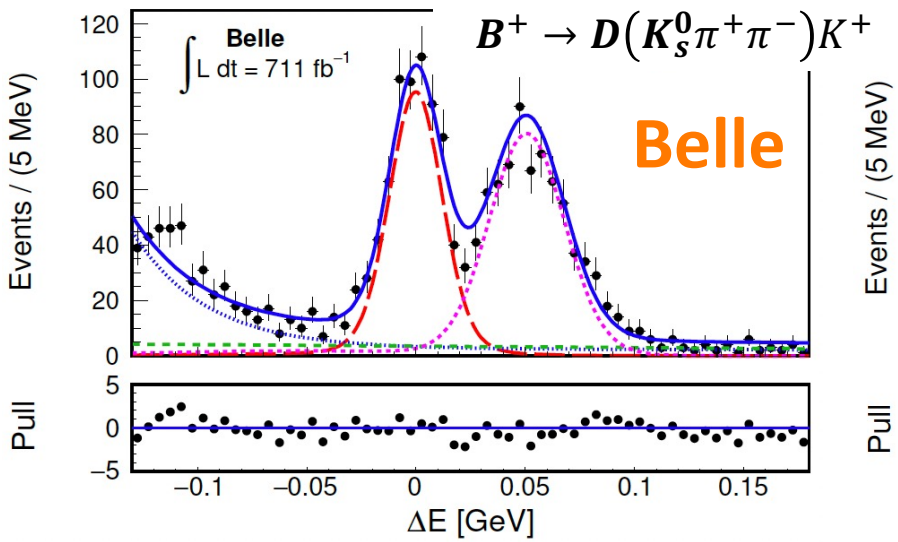
$B^+ \to D\left(K^0_s h^+ h^-\right) h^+$ results(JHEP02(2022)063)

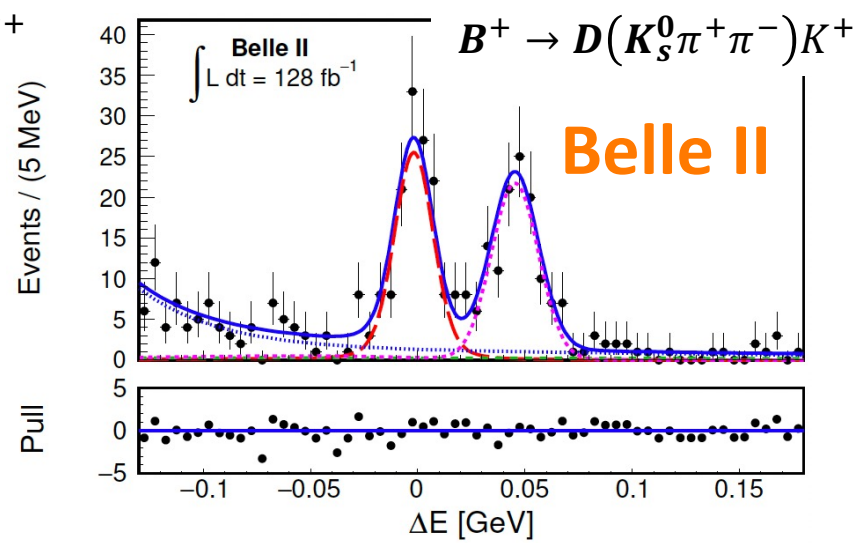
Categorized by D-decay Dalitz plot analysis(model-independent)

Use strong-phase difference parameters by CLEO and BESIII as external inputs.

First Belle+Belle II analysis







$$\phi_3 = (\,78.4 \pm 11.4\,(stat.) \pm 0.5(syst.) \pm 1.0\,(external)\,)$$

Summary

Belle II is in the process of completing the analysis for CKM measurement and showed the capability of higher precision measurement using a larger dataset.

Recent results

ϕ_1, β results

- Time-dependent CPV of $B^0 \to J/\Psi K_s^0, K_S^0\, K_S^0 K_S^0$

ϕ_2,α result

- $\mathcal{B}$ and A of $B \to \pi^+\pi^0,\ \pi^0\pi^0$
- $\mathcal{B}$, A and f_L of $B^+ \to \rho^+\rho^0$
- $\mathcal{B}$ and f_L of $\rho^+\rho^-$

ϕ_3,γ result

- $B^+ \to D(K_s^0 h^+ h^-)h^+$

	Current value and precision	Belle II 5 ab^{-1} precision	Belle II 50 ab^{-1} precision
$\sin 2\phi_1$	0.71 ± 0.09	0.012	0.005
ϕ_2	$85.2^{+4.8}_{-4.3}$	$2°$	$0.6°$
ϕ_3	$65.9^{+3.3}_{-3.5}$	$4.7°$	$1.5°$

arXiv:2203.11349

Belle II is ready to provide more precise result!