

Measurements of unitarity triangle angles: experimental status and perspectives

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for the Belle and Belle II collaborations

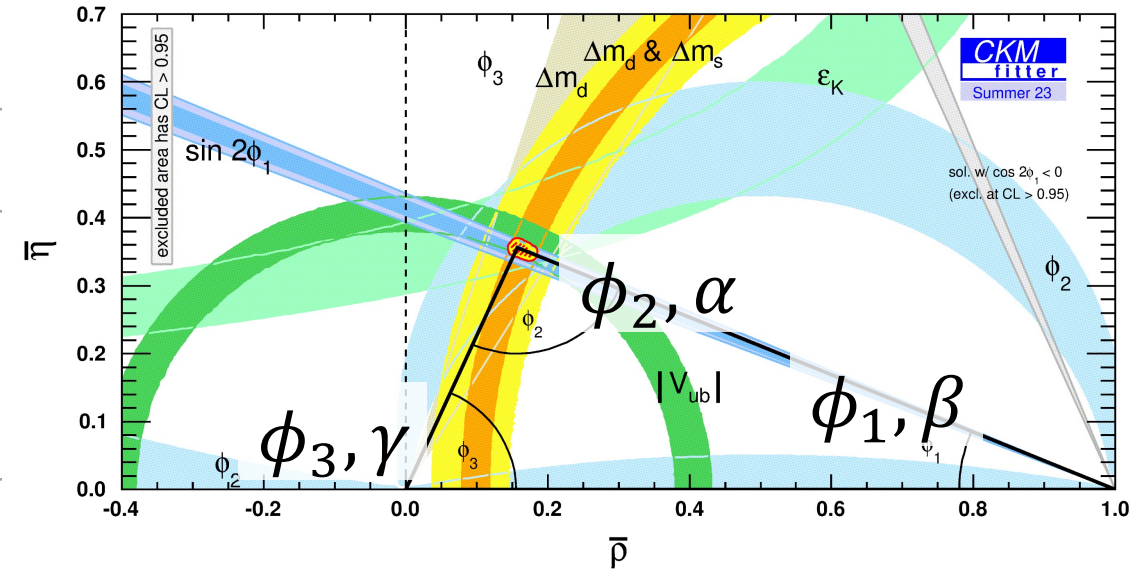
with materials from the LHCb, CMS, and ATLAS experiments

CKM angles are probes of BSM physics

CPV phases in b -quark transitions

Angle	Definition	World Average
$\phi_1 = \beta$	$\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$	$[22.84^{+0.33}_{-0.30}]^\circ$
$\phi_2 = \alpha$	$\arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$	$[86.2^{+3.9}_{-3.5}]^\circ$
$\phi_3 = \gamma$	$\arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$	$[65.9^{+3.3}_{-3.5}]^\circ$

From CKM Fitter; UTfit reports similar values



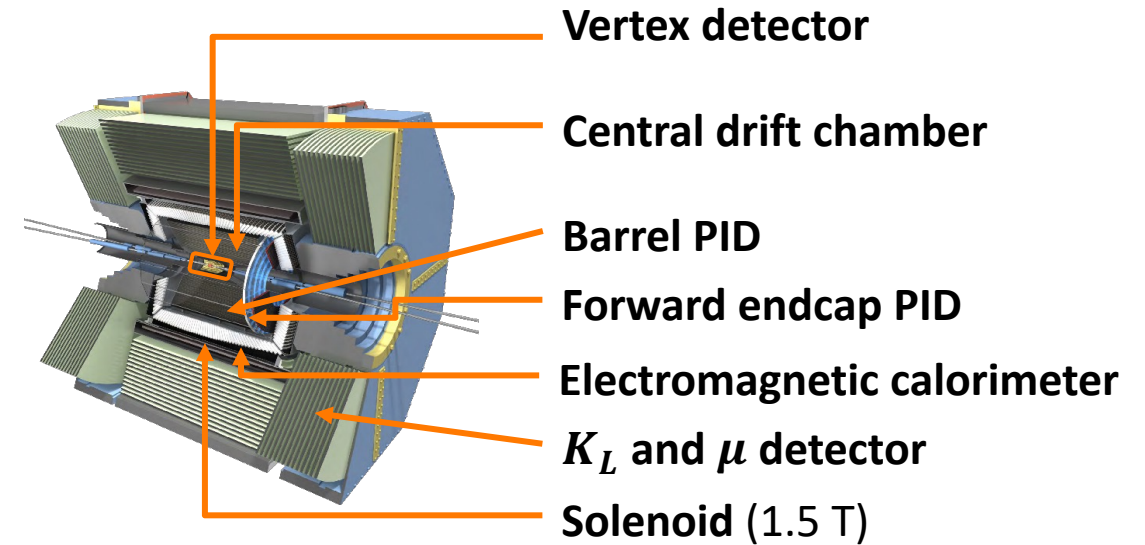
CKM angles provide constraints on BSM physics through unitarity tests

- ϕ_3 and sides: reliable SM reference
- ϕ_1 (from tree-level decays), ϕ_2 , and Δm_d : can be shifted by potential BSM in $B^0\bar{B}^0$ mixing
- BSM in decay amplitude can shift ϕ_1^{eff} in loop-dominated decays from value observed in trees

The instruments

B factory experiment (Belle II)

- **Coherent $B\bar{B}$** production at **low background** from e^+e^- collisions at 10.58 GeV
- Kinematically constrained environment for studying B , D , τ , ...
- Unique reach on decays with π^0



Hadron collider – forward (LHCb)

- **High-statistics incoherent $b\bar{b}$** production.
- Higher cross-section for all kinds of flavored hadrons and large boost in forward region
- Excellent vertexing, tracking, and PID detectors
- Large backgrounds

→ **Outstanding for decays into charged particles only**

Hadron collider – central (CMS/ATLAS)

- **General purpose** detectors that exploit excellent tracking and muon detectors for B -physics opportunities
- Higher collision frequency than LHCb, but also larger pile-up than LHCb

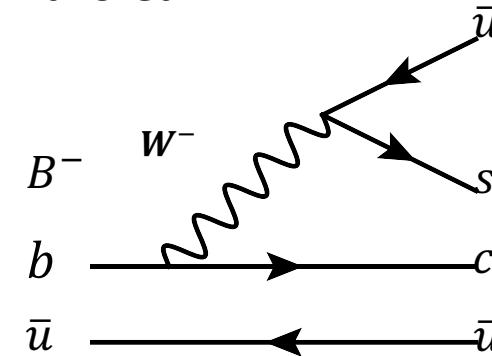
ϕ_3 - the SM reference

ϕ_3 - why and how

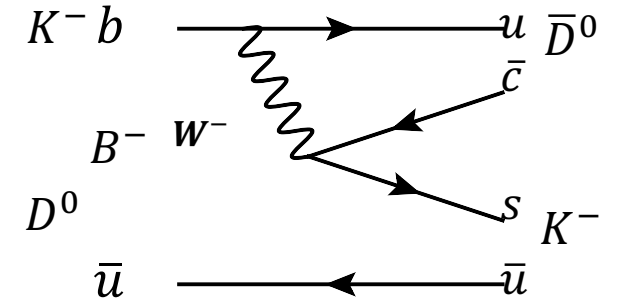
$\arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ from CPV in interfering-tree
 $b \rightarrow u\bar{c}s$ and $b \rightarrow c\bar{u}s$ decay amplitudes

- Ratio of decay amplitudes determines ϕ_3
- **A very reliable SM reference**
(10^{-7} theoretical uncertainty)

Favored



Suppressed

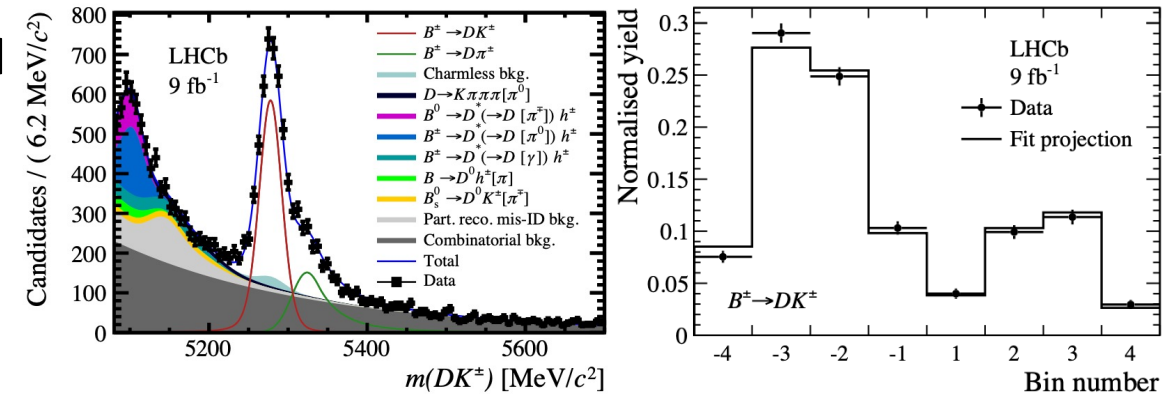


General procedure

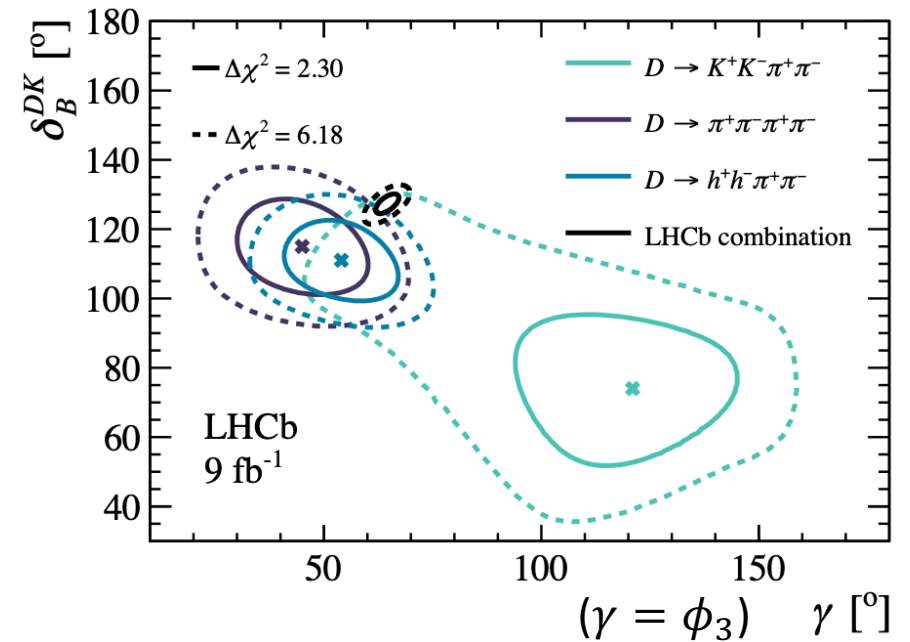
- Use $B_{(s)} \rightarrow D\pi, D_{(s)}K$ decays, and use differences between B and $\bar{B}$ yields to constraint CPV observables
- Extract signal from mass fits, and measure direct CPV parameters
- Extract ϕ_3 from fit to CPV observables combined with external inputs (strong phase difference, ratio of favored and suppressed decay amplitude).
- Challenges: small signals with peaking backgrounds, multi-body D decay treatment.
- Combine results from different methods into coherent determination

An example: $B^0 \rightarrow D(\rightarrow h' h' \pi^+ \pi^-) h^\pm$ at LHCb [arXiv:2509.15139](https://arxiv.org/abs/2509.15139)

- Dataset: 9 fb^{-1}
- Challenge: four-body D decay, requiring a five-dimensional representation
- New 2×4 **binning scheme** based on amplitude model, optimized for sensitivity to γ
- Charge and bin integrated signal extraction using $m(Dh^\pm)$
- Simultaneous CPV parameter extraction from all bins
- $\phi_3 = (52.6^{+8.5}_{-6.4})^\circ$ among the most precise ϕ_3 determination



- Another highlight: time-dependent CPV in $B_S^0 \rightarrow D_s K$ ([JHEP03\(2025\)139](https://arxiv.org/abs/2509.15139))
- Improve ϕ_3 precision from B_S^0 side



ϕ_3 current status

LHCb: $(64.6 \pm 2.8)^\circ$

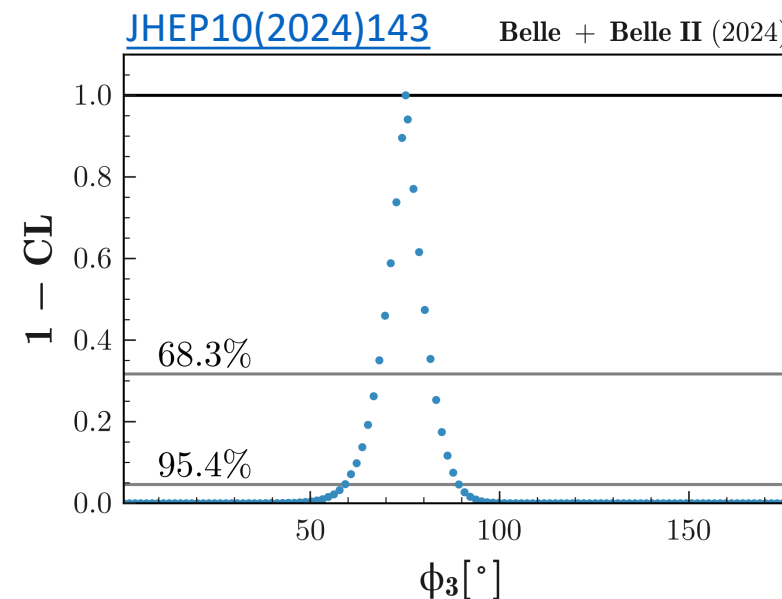
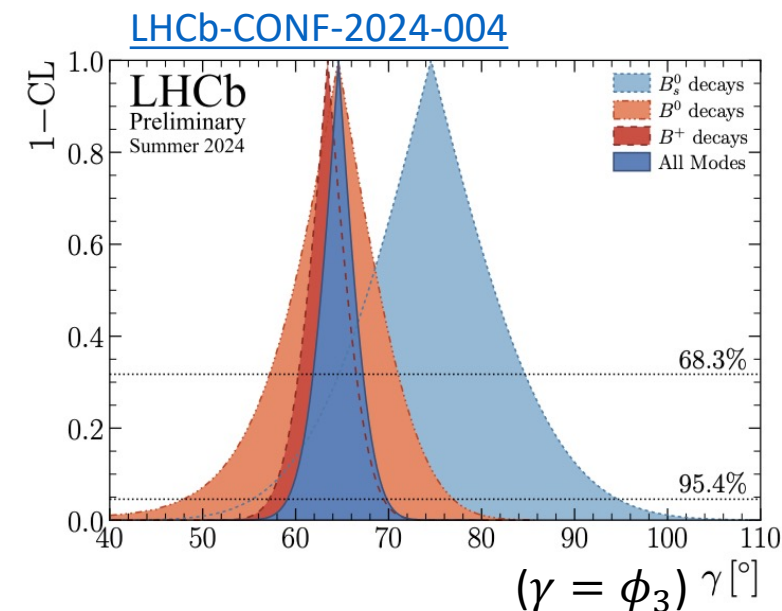
- Combination of 19 channels for B^0 , B^+ , B_s decays, and charm mixing and CPV parameters
- Post 2024 summer results not included yet

Belle + Belle II : $(75.2 \pm 7.6)^\circ$

- Combination of 16 channels, B^+ modes only
- First Belle + Belle II combination

LHCb leads precision thanks to large samples

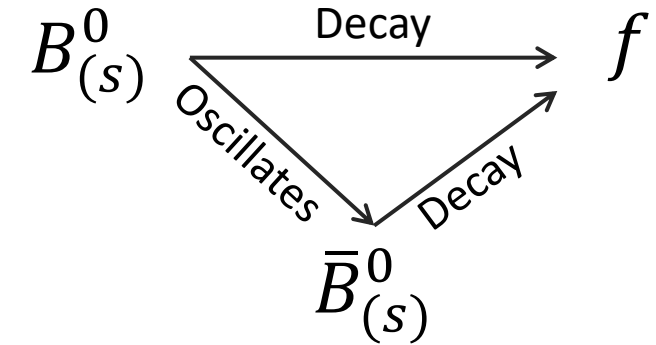
Comparison between Belle II and LHCb systematic uncertainties might be informative in the long term



Probing BSM using mixing

The idea

Decay rate difference between $B_{(s)}^0$ and $\bar{B}_{(s)}^0$ oscillates with time due to interference between direct decay and decay following mixing



$$\frac{\Gamma(\bar{B}_{(s)}^0 \rightarrow f) - \Gamma(B_{(s)}^0 \rightarrow f)}{\Gamma(\bar{B}_{(s)}^0 \rightarrow f) + \Gamma(B_{(s)}^0 \rightarrow f)} = \frac{B_s^0 - C \cos \Delta m_d \Delta t + S \sin \Delta m_d \Delta t}{B_s^0 \frac{S \sin(\Delta m_s t) - C \cos(\Delta m_s t)}{\cosh(\Delta \Gamma_s t/2) + A^{\Delta \Gamma} \sinh(\Delta \Gamma_s t/2)}}, \quad C = 0, \quad S = \sin 2\phi_1$$

$S = \eta_f \sin \phi_s$

Key observable is mixing-induced CP violation asymmetry S :

- Departure from indirect determination from global unitarity fit may indicate BSM
- Differences between S measured in different decays may indicate BSM

Essential ingredients for time-dependent CPV

Flavor tagging: need to know the flavor at a certain time to understand if there was oscillation

Belle II

- Quantum entangled $B\bar{B}$ helps flavor tagging

GNN-based algorithm using all **charged particles** in rest-of-event [PhysRevD.110.012001](#)

- Effective tagging efficiency = **$(37.40 \pm 0.56)\%$**

Hadron collider

- Use particles from b quark pair produced with signal (**opposite side**), or charge correlations between fragmentation products and signal (**same side**)
- **Input particles.** LHCb: μ, e, K , and π . ATLAS, CMS: μ, e , and b -jets (no π and K)
- Effective tagging efficiency = **$4 - 6\%$** at LHCb depending on the decays
- **Inclusive** algorithm using Deep Sets recently developed ([arXiv:2508.20180](#)); 20% fractional improvement

Decay-time measurement: Need to measure time precisely to sample the modulation

Belle II

$\sigma(z)$ 20 μm with $\beta\gamma = 0.28$ boost implies $\sigma(\Delta t) = 1$ ps

Hadron collider

Similar vertex resolution as Belle II, but much larger boost achieves **$\sigma(t) \simeq 60$ fs** at LHCb.

Similar resolution in CMS/ATLAS

Mixing phase golden channels

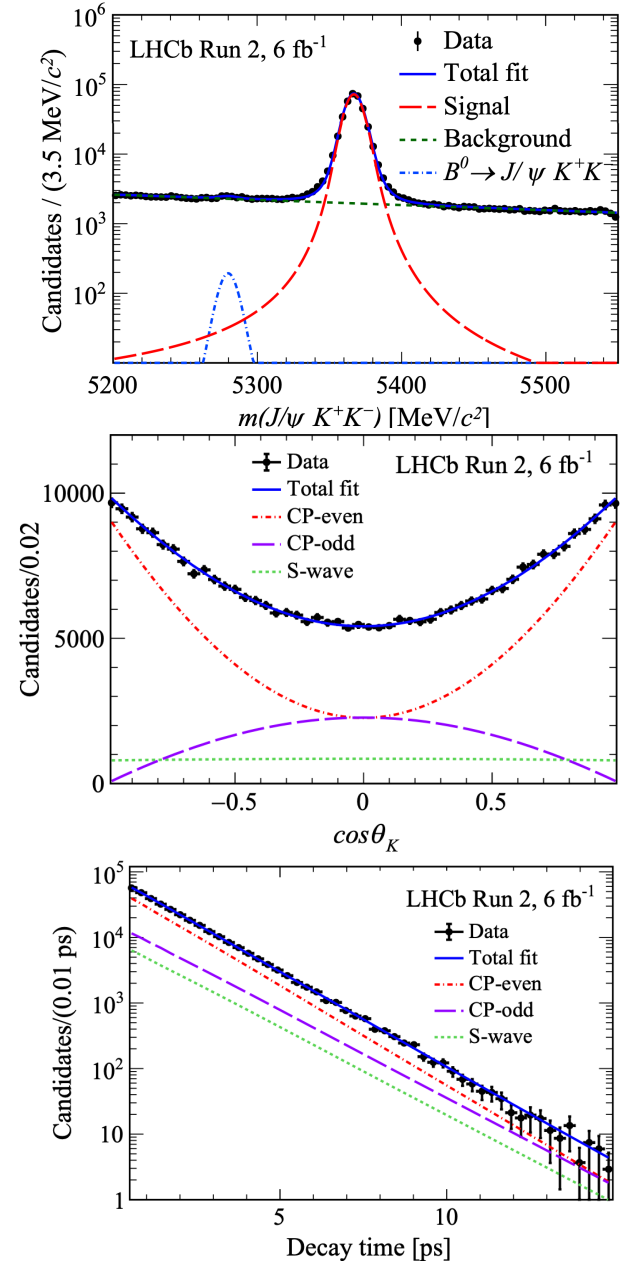
$\phi_s: B_s^0 \rightarrow J/\psi K^+ K^-$ at LHCb

- LHCb Run 2 dataset (6 fb^{-1})
- Challenges: separation of CP -even and CP -odd decays
- $J/\psi(\rightarrow \mu^+ \mu^-, e^+ e^-) K^+ K^-$, $\psi(2S)(\rightarrow \mu^+ \mu^-) K^+ K^-$
- Signal extraction from B invariant mass
 - **350k** signals in total
- Fit to angular variables to separate CP -even, CP -odd, and S-wave (background)

$$\phi_s = -0.039 \pm 0.022 \pm 0.006 \text{ rad}$$

$$\Delta\Gamma_s = 0.845 \pm 0.0044 \pm 0.0024 \text{ ps}^{-1}$$

Most precise in the world



$\phi_s: B_s^0 \rightarrow J/\psi \phi$ at CMS

- 2017 – 2018 dataset: 96.5 fb^{-1}
- Challenge: flavor tagging without PID detectors
- Signal extraction from $m(B_s) \rightarrow 28\text{k}$ signals
- Angular and decay-time analysis similar to LHCb

Improved flavor tagging

- By addition of **same-side**, use of jet charge, and NN
- **Tagging efficiency: $(5.59 \pm 0.02)\%$**
- New dedicated trigger for opposite side muon

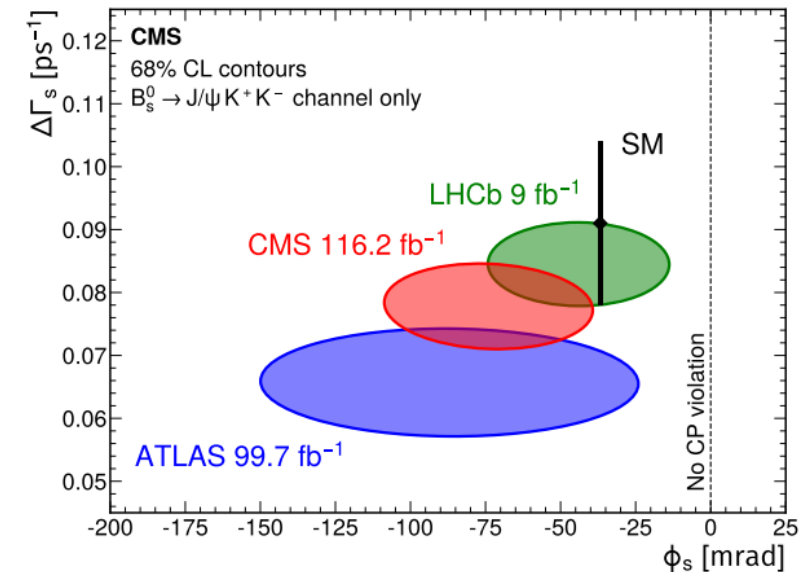
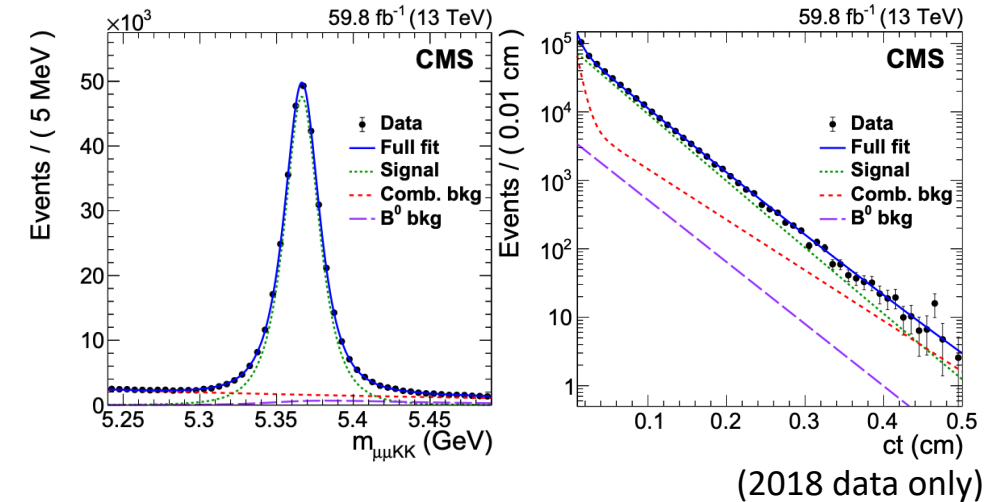
$$\phi_s = (-0.073 \pm 0.023 \pm 0.007) \text{ rad}$$

$$\Delta\Gamma_s = 0.114 \pm 0.014 \pm 0.007$$

(2x better than previous analysis with the **same dataset** ([arXiv:2007.02434](https://arxiv.org/abs/2007.02434)))

Combination with the 8 TeV analysis: $(-0.074 \pm 0.023) \text{ mrad}$

→ **First evidence** for CPV with 3.2σ significance



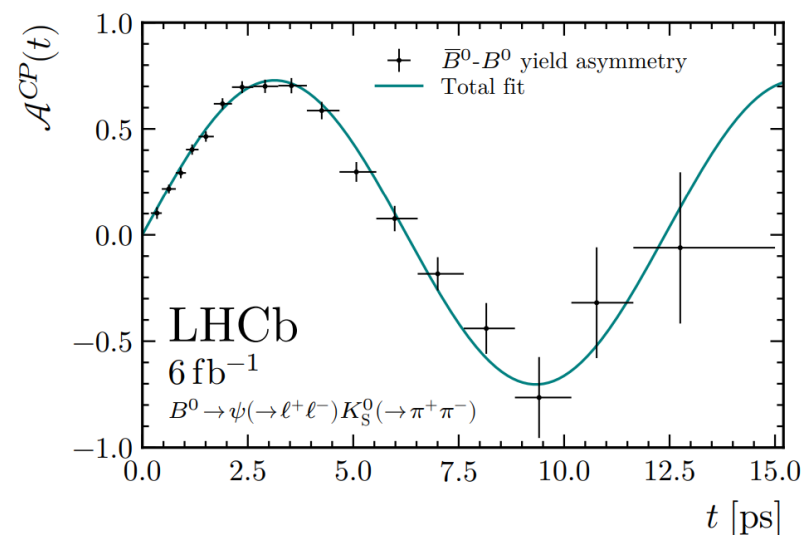
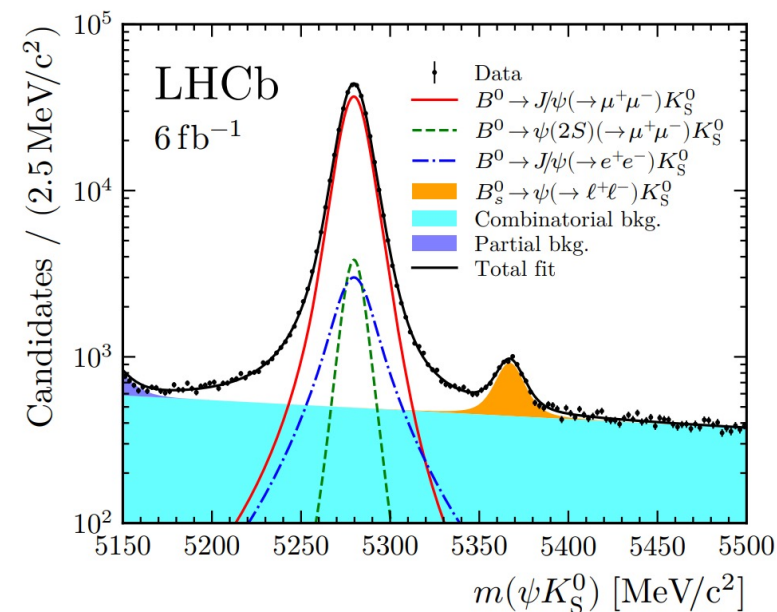
$\phi_1: B^0 \rightarrow \psi K_S^0$ at LHCb

- Run2 (6 fb^{-1}) dataset
- $J/\psi(\rightarrow \mu\mu, ee)K_S^0$ and $\psi(\rightarrow \mu\mu)K_S^0$
- Challenges: calibration of flavor tagging and resolution
- Signal extraction from $m(\psi K_S^0)$
→ Obtain **373k events of large signals** in total

$$S = 0.717 \pm 0.013 \pm 0.008$$

$$C = 0.008 \pm 0.012 \pm 0.003$$

World's best result.



$\phi_1: B^0 \rightarrow J/\psi K_S^0$ at Belle II

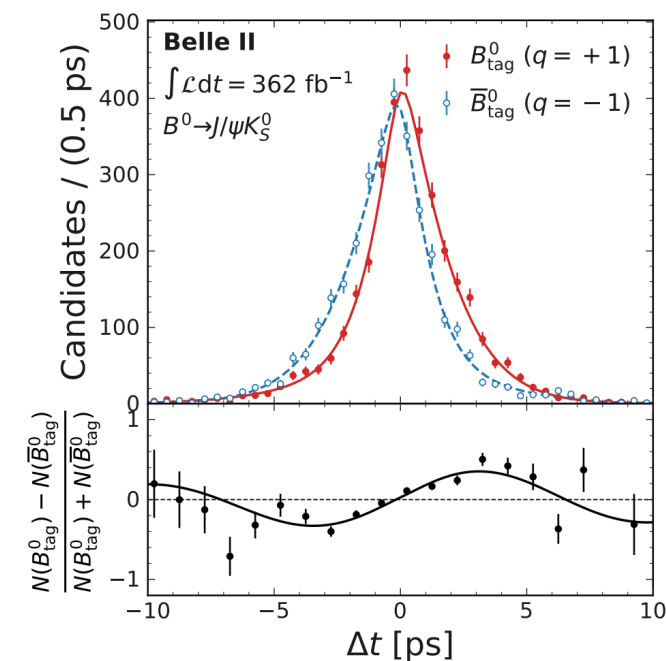
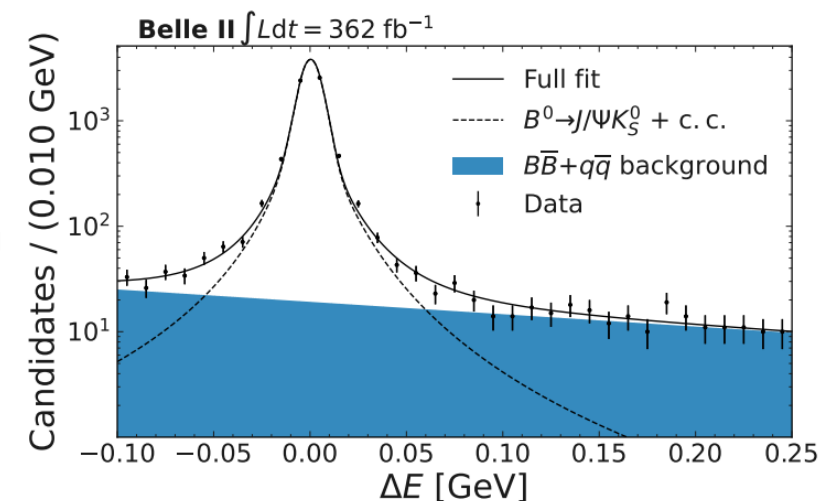
- Dataset: 362 fb^{-1}
- Data-driven Δt resolution and flavor tagging calibration from the mixing fit to $B^0 \rightarrow D^{(*)-} \pi^+$
- Signal extraction from $\Delta E \rightarrow 6.4\text{k}$ signals
- **New flavor tagging** algorithm (FBDT $\rightarrow$ GNN).
- **30%** fractional improvement in effective tagging efficiency

First results:

$$S = 0.724 \pm 0.035 \pm 0.009$$

$$C = -0.035 \pm 0.026 \pm 0.029$$

Aim for precision competitive with LHCb
with future larger datasets



Combined measurement of both mixing phases at LHCb

[JHEP01\(2025\)061](#)

- Use $B^0 \rightarrow D^+ D^-$ for ϕ_1 , $B_s \rightarrow D_s^+ D_s^-$ for ϕ_s which are dominated by tree
- CPV parameters in B^0 and B_s^0 constrain each other loop through U-spin symmetry
- Dataset: LHCb Run 2 (6 fb^{-1})
- Challenge: systematic error from peaking backgrounds
→ Reduced by improved selection
- Fit to mass for signal extraction via *sPlot*.
→ 5.7k B^0 decays, 13k B_s decays

- Decay-time fit as in $B_s \rightarrow J/\psi KK$

- Combine with Run1 results,

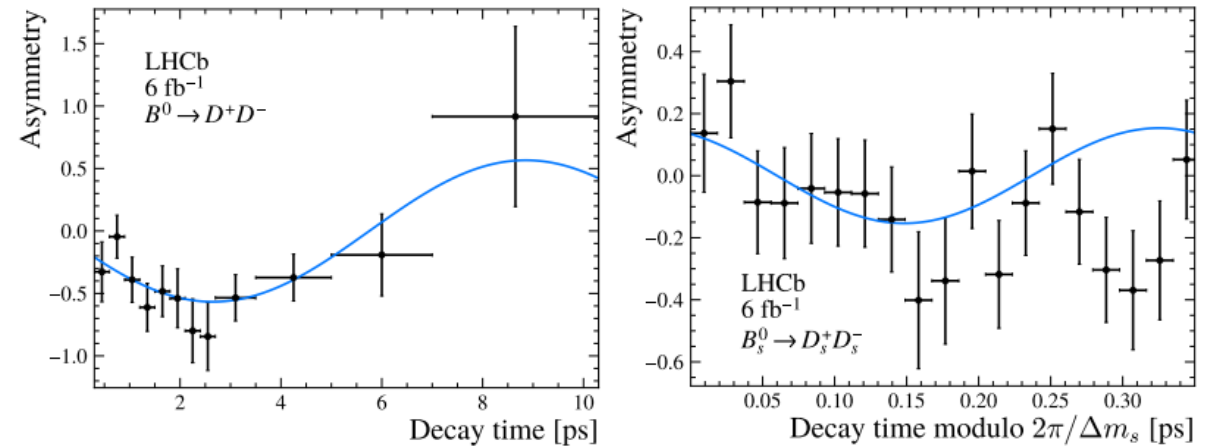
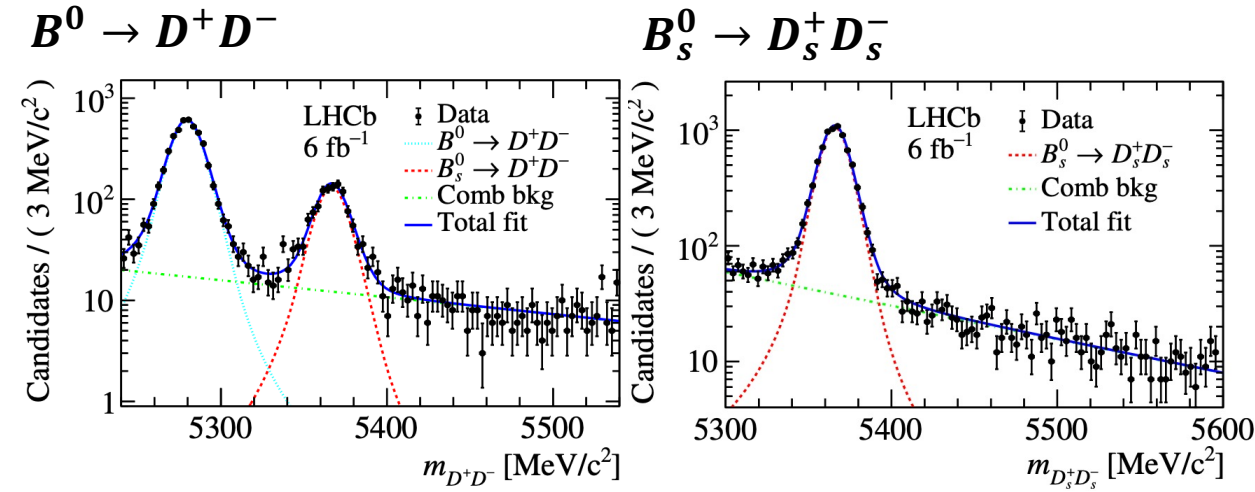
$$S_{D^+ D^-} = -0.549 \pm 0.085 \pm 0.015$$

$$C_{D^+ D^-} = +0.162 \pm 0.088 \pm 0.009$$

$$\phi_s = (-0.086 \pm 0.106 \pm 0.028) \text{ rad}$$

$$|\lambda_{D_s^+ D_s^-}| = 1.054 \pm 0.099 \pm 0.020$$

Most precise $B_{(s)} \rightarrow D_{(s)} D_{(s)}$ result.



Beyond trees

$$\phi_1: B^0 \rightarrow J/\psi \pi^0$$

- Possible loop contribution can shift S of $J/\psi K_S^0$.
- In preparation for future precision measurements, start considering loop pollution
- Dataset: 365 fb^{-1}
- Signal extraction from ΔE and $m(J/\psi)$. $\rightarrow 392$ signals
- Challenges: low branching fractions, π^0 background
 $\rightarrow$ Improved $ee \rightarrow q\bar{q}$ suppression with MVA, π^0 selection
- Similar analysis as $J/\psi K_S^0$

$$S = -0.88 \pm 0.17 \pm 0.03$$

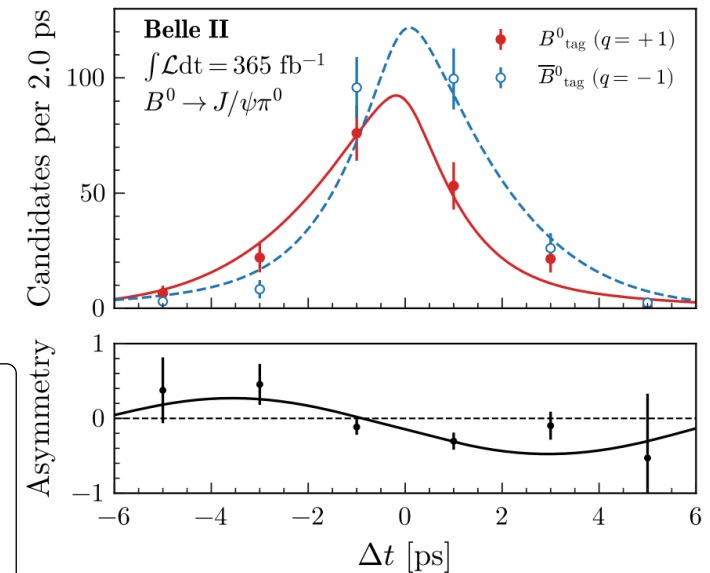
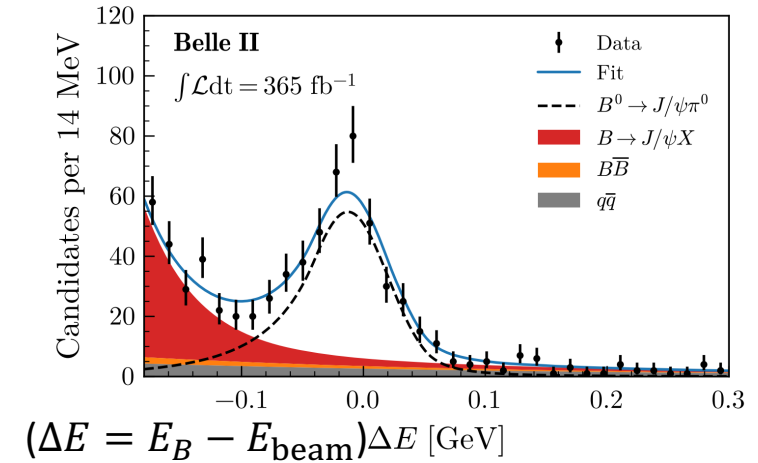
$$C = 0.13 \pm 0.12 \pm 0.03$$

$$\mathcal{B} = (2.02 \pm 0.12 \pm 0.10) \times 10^{-5}$$

Most precise in the world.

Another useful mode: $B^0 \rightarrow J/\psi \omega$ ([PhysRevD.111.032012](#))

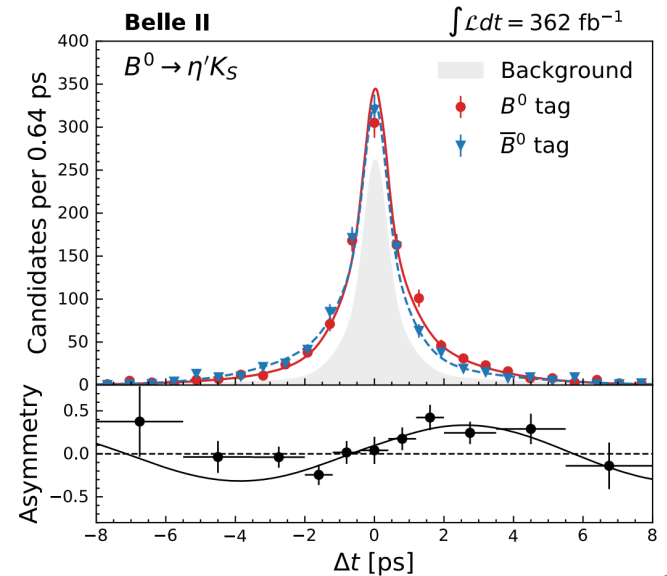
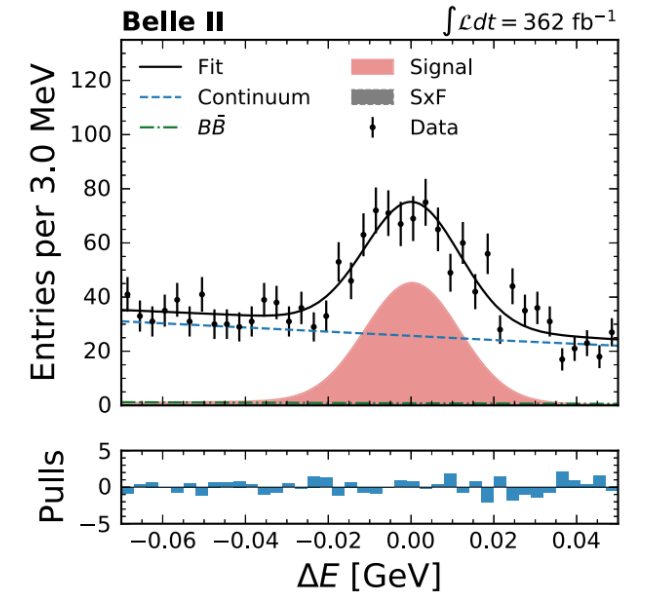
- Also useful to understand $J/\psi K_S^0$ loops
- Demonstrate possibility of CPV measurement in this channel



Loops as probes for BSM: $B^0 \rightarrow \eta' K_s$

- One of the few missing golden channels
- Dominated by loop amplitude
- If S differs from ψK_s^0 , strong indication of BSM in the loop
- Used $\eta' \rightarrow \eta(\rightarrow \gamma\gamma)\pi\pi$ and $\eta' \rightarrow \rho^0(\rightarrow \pi\pi)\gamma$ (**unique to Belle II**)
- Challenges: γ reconstruction, large-background
- Signal extraction by B invariant mass using beam energy, energy difference between measured and beam, and $ee \rightarrow qq$ suppression BDT output
→ 829 signals
- $C = -0.19 \pm 0.08 \pm 0.03$
- $S = +0.67 \pm 0.10 \pm 0.03$
↔ S from trees = 0.710 ± 0.011 (world average)

Comparable precision with Belle and BaBar



ϕ_2 : the phase unique to Belle II

ϕ_2 : why and how

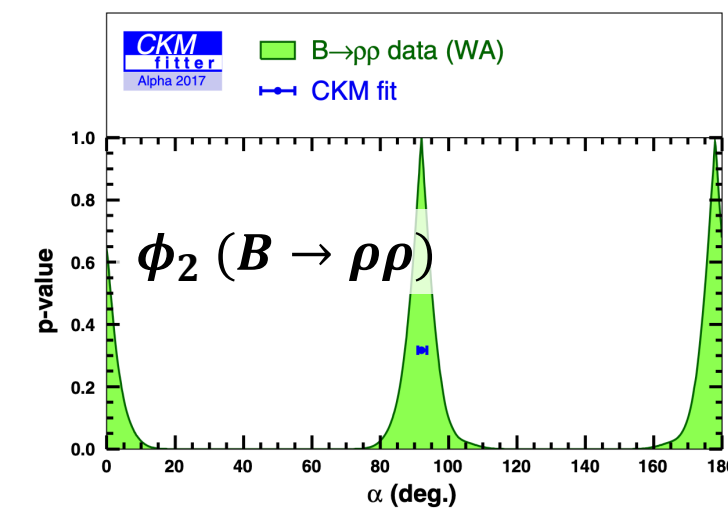
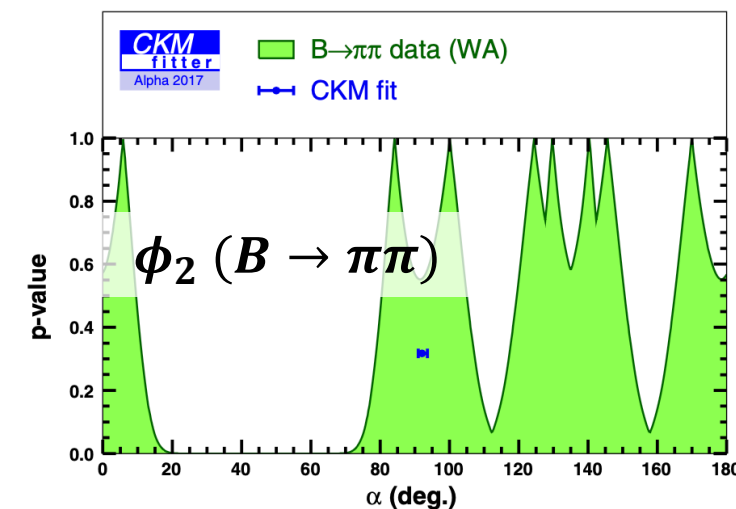
- $S = \sin(2\phi_2)$ in $b \rightarrow u$ tree amplitude ($B^0 \rightarrow \pi^+\pi^-, \rho^+\rho^-$)
- 5%-30% loop shift S and C .
- Correct with isospin analysis of $B \rightarrow h^+h^-, h^+h^0, h^0h^0$ ($h = \pi, \rho$)

$\rho\rho$ vs $\pi\pi$

- Uncertainty from loop smaller in $\rho\rho$ due to 10x smaller loop in $\rho\rho$
- $\rho\rho$ is spin0 $\rightarrow$ spin1 spin1 decay. Angular analysis needed to separate longitudinal state
- $S(\pi^0\pi^0)$ missing because cannot measure $\pi^0 \rightarrow \gamma\gamma$ signal vertex $\rightarrow \pi\pi$ less precise due to multiple solutions
- New promising method to measure $S(\pi^0\pi^0) \rightarrow$ see [Radek's talk](#)

$B \rightarrow \rho\rho$ more precise, but more complicated

Eur. Phys. J. C 77, 574 (2017)

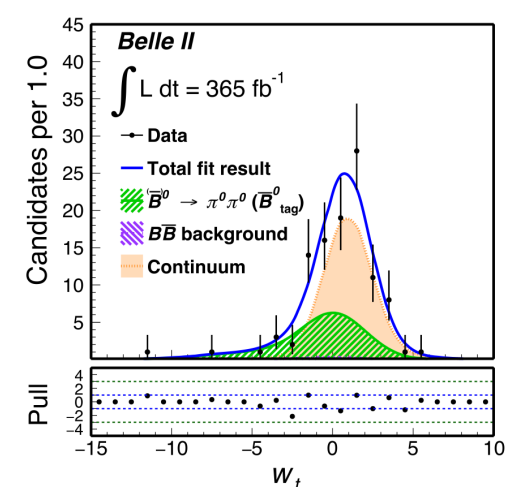
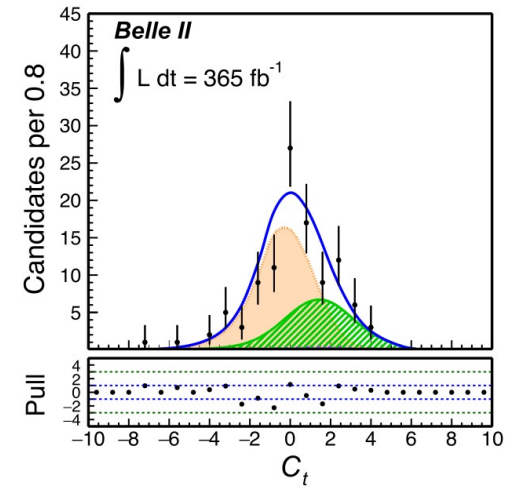
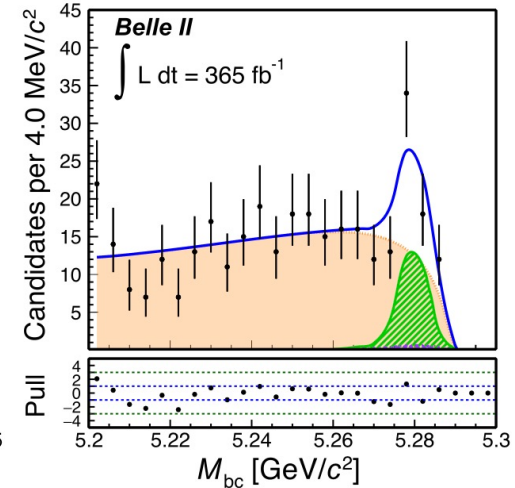
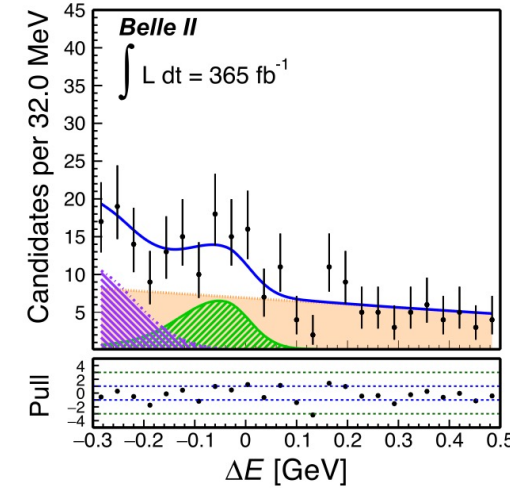


$$B^0 \rightarrow \pi^0 \pi^0$$

$\pi^0 \rightarrow \gamma\gamma$ has a lot of backgrounds.

Only Belle II can measure this

- Dataset: 365 fb^{-1}
- Large $ee \rightarrow qq$ backgrounds is the largest challenge
→ Suppressed it by data-driven BDT
- Signal extraction from B^0 mass, energy difference from beam energy, wrong tagging flavor probability, and continuum suppression
→ 125 signals



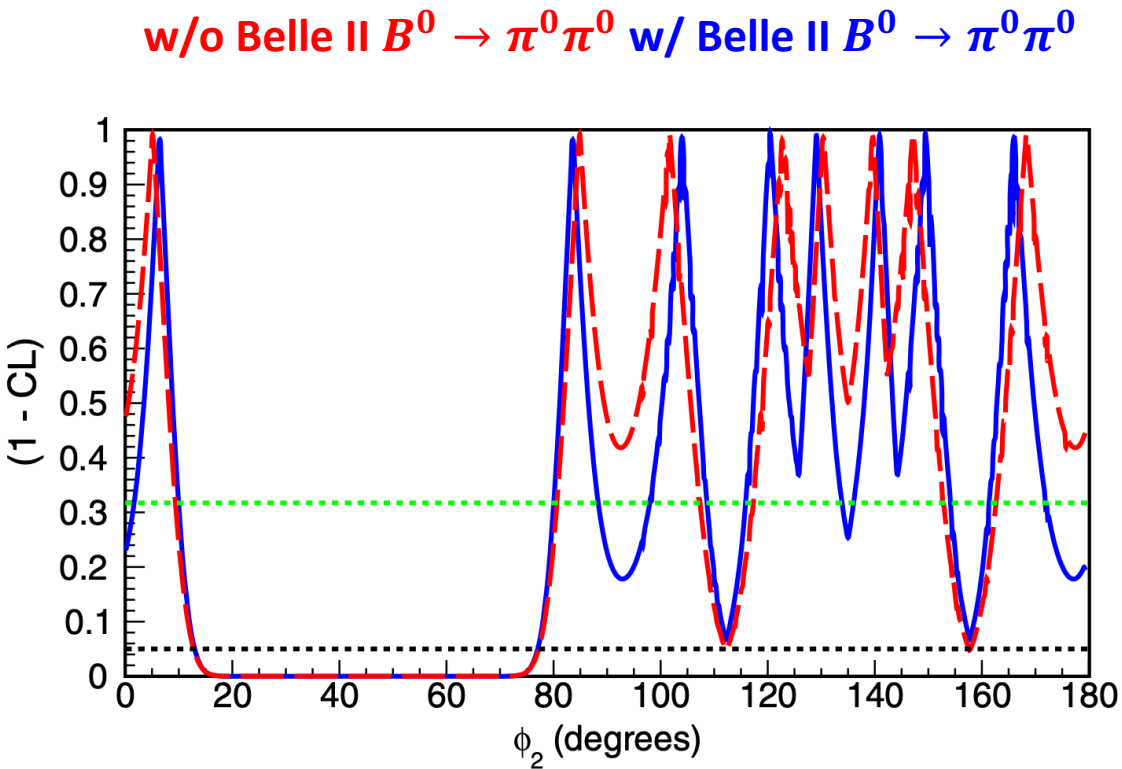
Results and constraint on ϕ_2

	$\mathcal{B}(\times 10^{-6})$	$\mathcal{C}$	$N_{Y(4S)}$
Belle II	$1.25 \pm 0.20 \pm 0.11$	$-0.03 \pm 0.30 \pm 0.04$	387×10^6
Belle	$1.31 \pm 0.19 \pm 0.19$	$-0.14 \pm 0.36 \pm 0.10$	772×10^6
BABAR	$1.83 \pm 0.21 \pm 0.13$	$-0.43 \pm 0.26 \pm 0.05$	383.6×10^6

World-leading or nearly so, despite 50% smaller sample size

30% fractional improvement on ϕ_2 68% CL exclusion interval

Systematic uncertainties dominated by π^0 efficiency, based on $D^{*-} \rightarrow \bar{D}^0(K^+\pi^-\pi^0)\pi^-$
→will improve soon



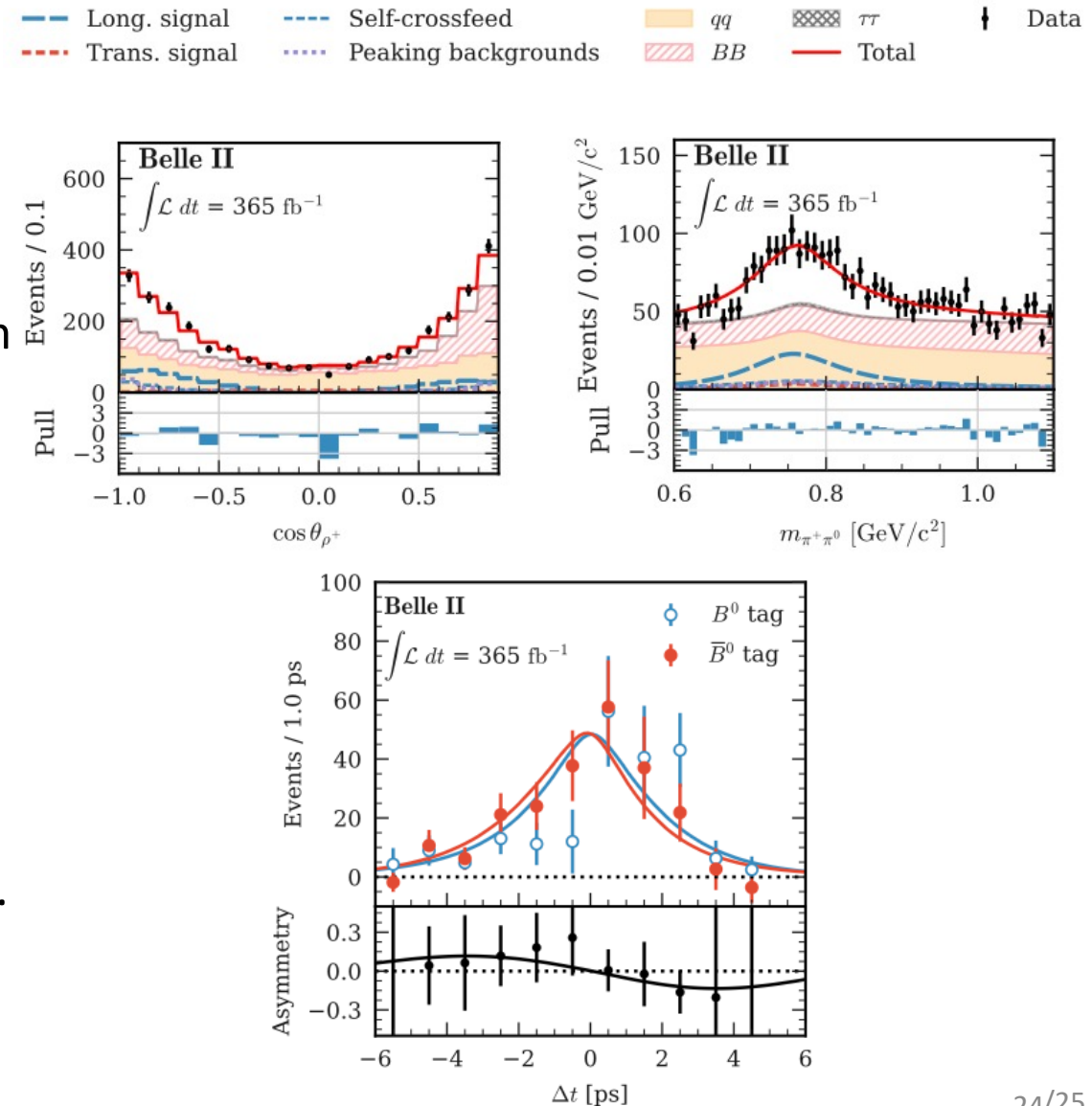
$$B^0 \rightarrow \rho^+ \rho^-$$

- Dataset: 365 fb^{-1}
- Large backgrounds due to large ρ width
→ Neural network-based qq suppression (TabNet)
- Soft π^0 background in $\rho \rightarrow \pi\pi^0$ (**Belle II unique**)
→ Fake photon suppression using cluster shapes
- 6D signal extraction by ΔE , $m_{\pi\pi}$ (signal vs BG), continuum suppression output (signal vs qq), and $\cos \theta$ (polarization)
→ 436 signals
- CPV extraction from decay-time difference

$$S = -0.26 \pm 0.19 \pm 0.08$$

$$C = -0.02 \pm 0.12^{+0.06}_{-0.05}$$

New results with **comparable precision** to prior experiments.



ϕ_2 impact

$B \rightarrow \rho\rho$ world average

$$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$$

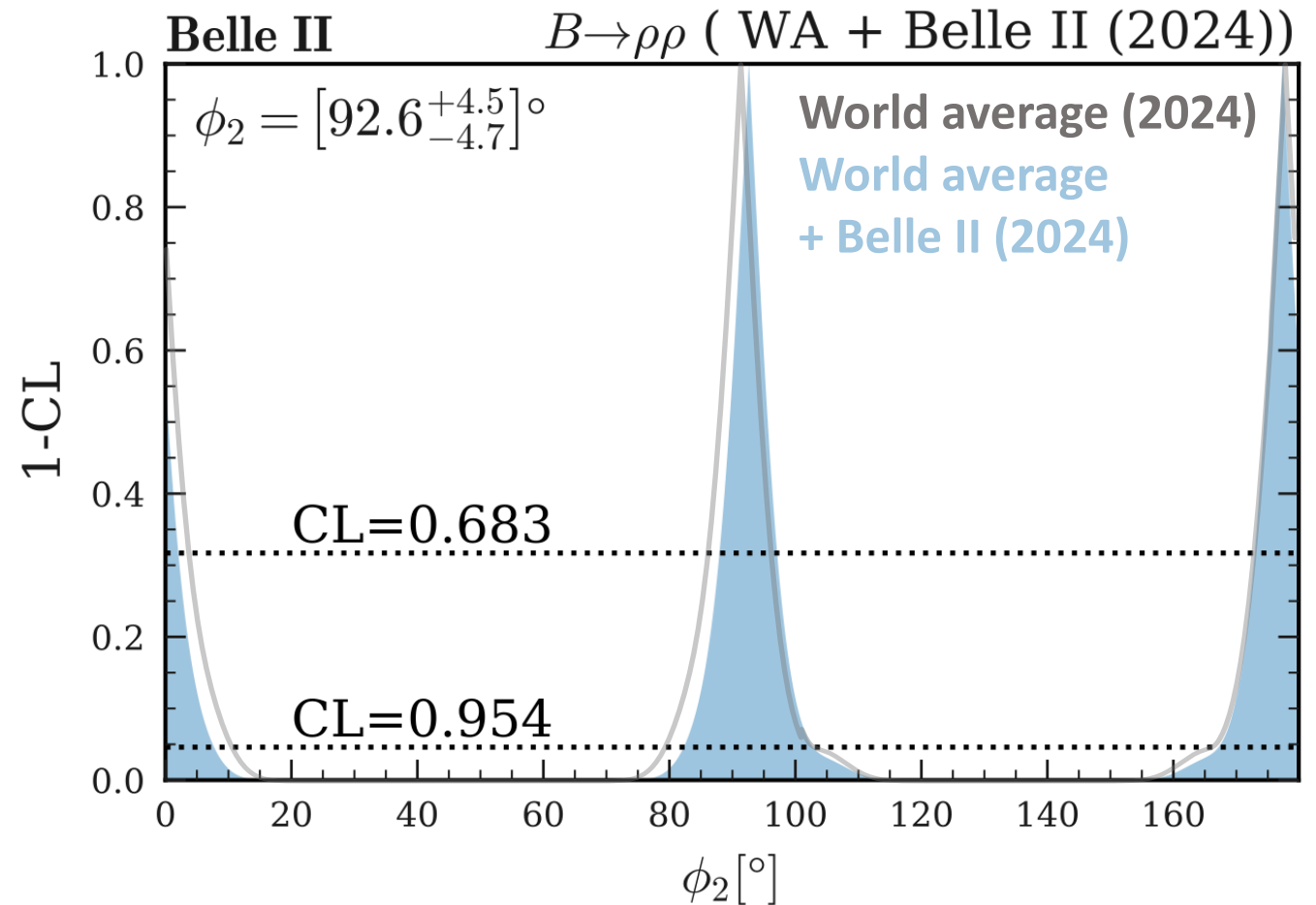
$B \rightarrow \rho\rho$ world average

+ Belle II $\rho^+\rho^-$ results

$$\rightarrow \phi_2 = (92.6^{+4.5}_{-4.7})^\circ$$

10% improvement from Belle II results!

Dominated by S of $\rho^+\rho^-$ and $\rho^0\rho^0$.



Perspectives for coming five years

[arXiv:2503.24346](https://arxiv.org/abs/2503.24346)

[arXiv:1808.10567](https://arxiv.org/abs/1808.10567)

	Belle II $\int \mathcal{L} dt = 5 - 10 \text{ ab}^{-1}$	LHCb, ATLAS, CMS Run 3
ϕ_s	---	0.023 rad $\rightarrow$ 0.008 rad in LHCb, CMS Similar precision at ATLAS $\rightarrow$ Unique to LHC . Stringent SM test by comparison of ϕ_s from tree and loop
ϕ_3	$7.6^\circ \rightarrow 3^\circ$	$2.8^\circ \rightarrow$ 0.8°
ϕ_1	$1.5^\circ \rightarrow 0.46^\circ$	$0.54^\circ \rightarrow$ 0.22° $\rightarrow$ LHCb leading precision, and Belle II will reach similar level on ϕ_1
ϕ_1^{eff}	$\sigma(S(\eta' K_s)) = 0.10 \rightarrow$ 0.029	---
	$\rightarrow$ Stringent SM test by comparison ϕ_1^{eff} from Belle II and ϕ_1 from LHCb + Belle II	
ϕ_2	$4.5^\circ \rightarrow$ 2°	---
	$\rightarrow$ Unique to Belle II . Further improvement by $S(\pi^0 \pi^0)$ with new technique. This might be crucial for UT test after other parameters become precise	

Summary

CKM angles are probes of BSM physics.

ϕ_3

- A reliable SM reference
- LHCb leads precision by its high-statistics data.

ϕ_1

- Mixing-induced phase, most precise angle
- Golden channel is $J/\psi K_S^0$, measured precisely by both Belle + Belle II and LHCb.
- LHCb and CMS highlight: ϕ_S measurement for $B_S^0 \bar{B}_S^0$ mixing

ϕ_2

- The most imprecise angle, need to improve this.
- Many decays require π^0 reconstruction making it unique to Belle II
- New measurements for $\pi^0 \pi^0$ and $\rho^+ \rho^-$ improves the world average by dozens of percent!