Measurements of unitarity triangle angles: experimental status and perspectives

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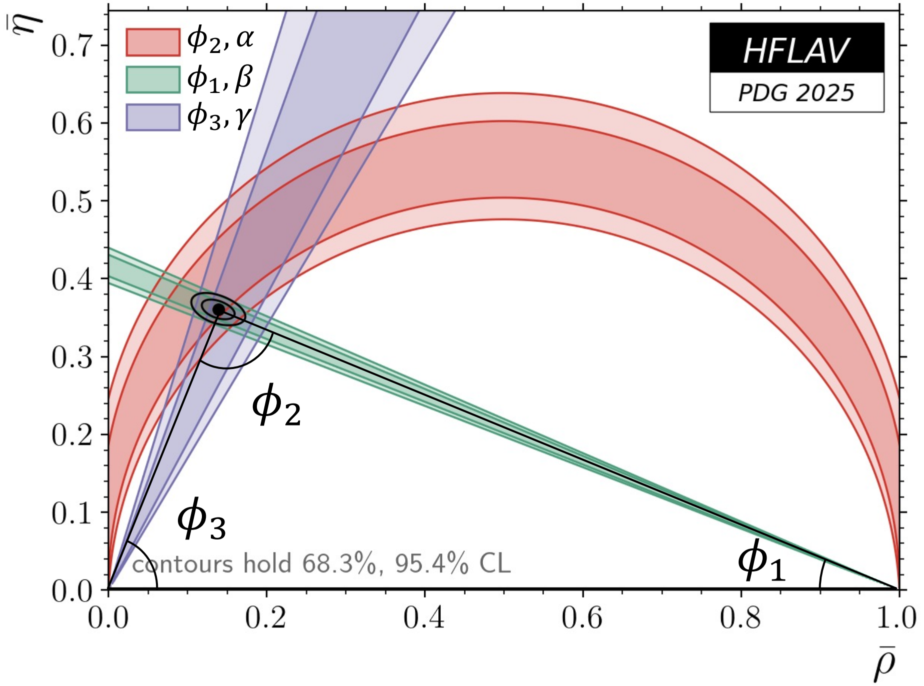
for the Belle and Belle II collaborations
with materials from the LHCb, CMS, and ATLAS experiments

CKM angles are probes of BSM physics

CPV phases in b-quark transitions

Angle	Definition	World average
$\phi_1 = \beta$	$\arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$	$[22.63^{+0.45}_{-0.44}]^\circ$
$\phi_2 = \alpha$	$\arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$	$[86.2^{+3.7}_{-3.0}]^\circ$
$\phi_3 = \gamma$	$\arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$	$[65.9^{+2.7}_{-2.8}]^\circ$

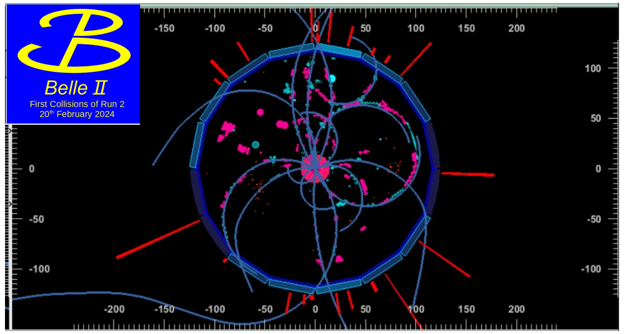
From HFLAV. CKM fitter and UTfit report similar values

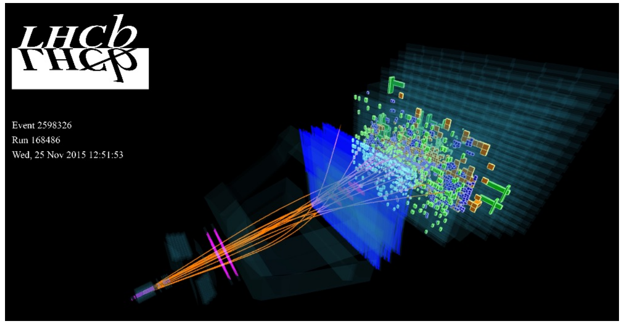


CKM angles provide constraints on BSM physics through unitarity tests

- ϕ_3 and sides: reliable SM references
- 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 amplitudes can shift ϕ_1^{eff} in loop-dominated decays from value observed in trees

The instruments





B factory experiments (Belle II)

- **Coherent $B\overline{B}$** 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's

Hadron collider – forward (LHCb)

- **High-statistics incoherent $b\overline{b}$** production from $O(10)$ TeV pp collisions
- 1000x higher cross-sections for **all kinds of flavored hadrons** and large boost in forward region
- Excellent vertexing, tracking, and PID detectors
- Large backgrounds

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

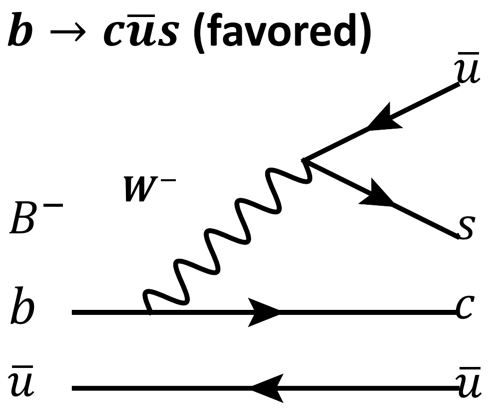
→ Outstanding for decays into charged particles only

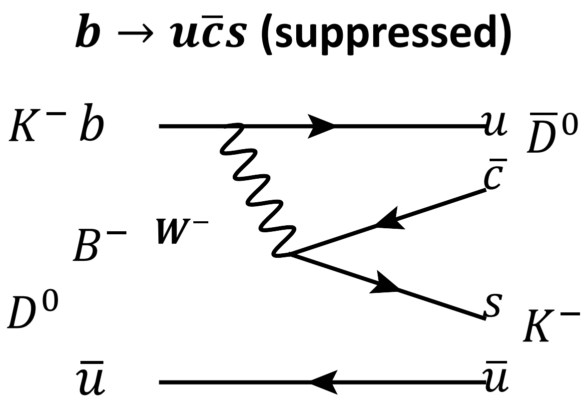
ϕ_3 - the SM reference

ϕ_3 - why and how

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

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





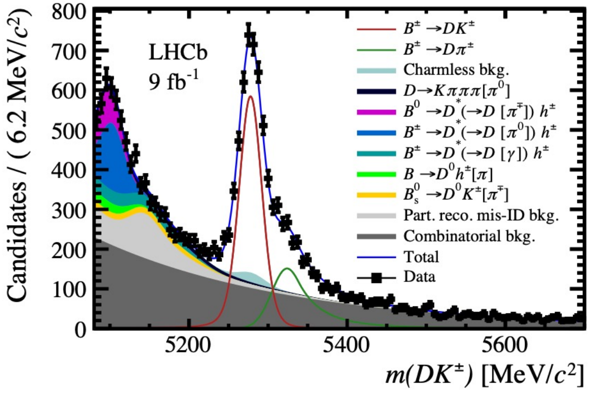
Typical analysis

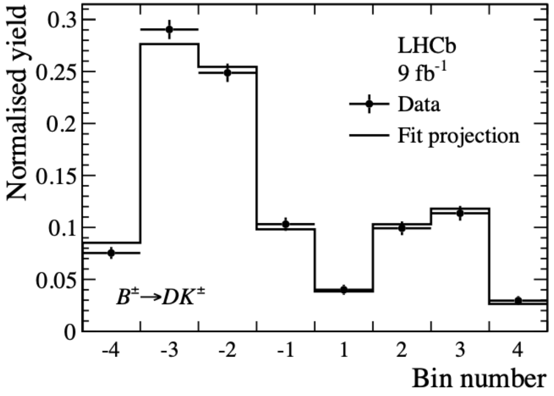
- Use $B^0_{(s)} \to D_{(s)}K$ decays picking $D_{(s)}$ decays that maximize interference
- Extract signal from mass fits, and measure CPV from B vs $\bar{B}$ yield differences
- Extract ϕ_3 from fit to CPV observables combined with external inputs (strong-phase differences, ratio between favored and suppressed decay amplitudes).
- Challenges: small signals with peaking backgrounds, multi-body D decay treatment.
- **Combine results** from different methods into coherent ϕ_3 determination

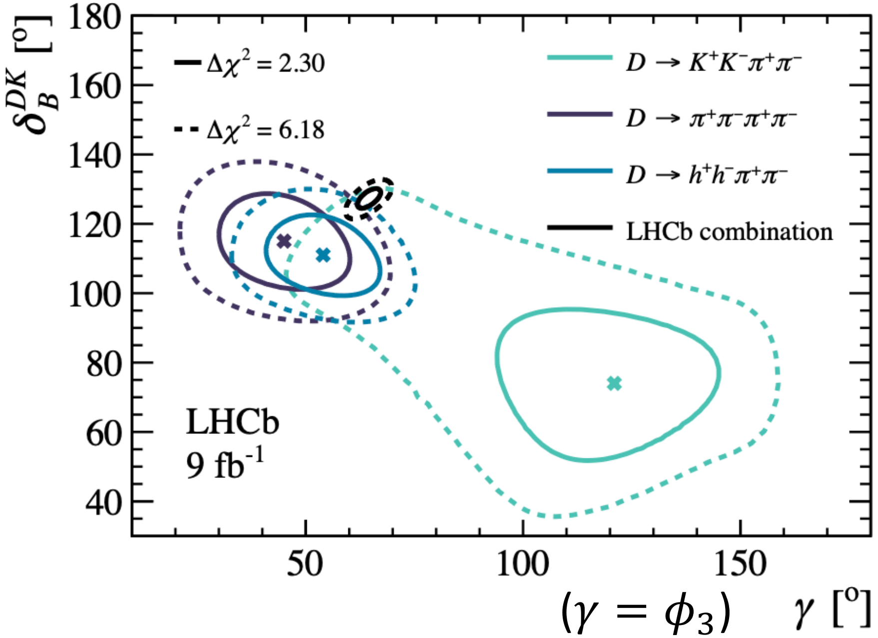
An example: $B^0 \to D(\to h'h'\pi^+\pi^-)h^\pm$ at LHCb

arXiv:2509.15139

- Dataset: 2011-2012 ($3\ \mathrm{fb}^{-1}$), 2015-2018($6\ \mathrm{fb}^{-1}$)
- Challenge: four-body D^+ decay, requiring **a five-dimensional representation**
- $2{\times}4$ binning scheme based on amplitude model, **optimized for sensitivity to ϕ_3**
- Charge and bin integrated signal extraction using m($Dh^\pm$)→ Extracted 13k decays
- Simultaneous CPV extraction from all bins
- $\boldsymbol{\phi_3 = (52.6^{+8.5}_{-6.4})^\circ}$: among the most precise determination







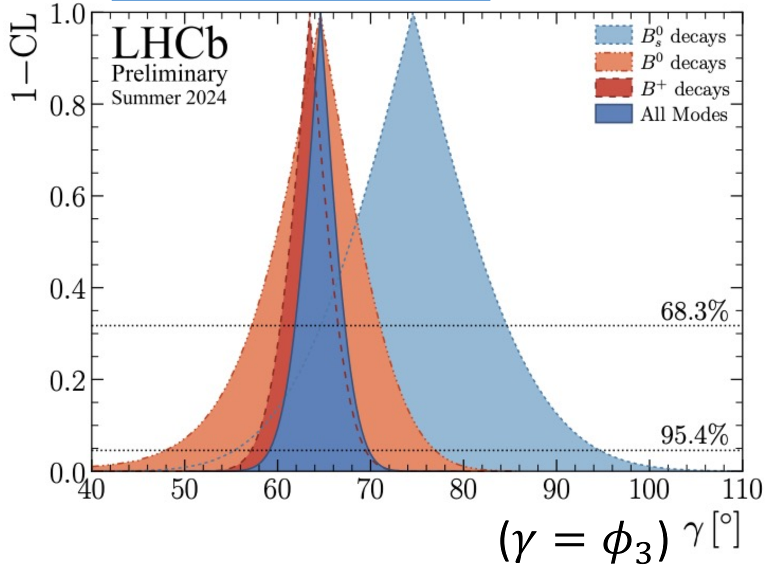
Another highlight: time-dependent CPV in $B_s^0 \to D_sK$: $\phi_3 = 81^{+12\circ}_{-11}$ (JHEP03(2025)139)
Improve ϕ_3 precision from B_s^0 side

ϕ_3 current status

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

- 2011-2012 (3 fb^{-1}) 2015-2018 (6 fb^{-1})
- Combination of 19 channels from B^0, B^+, B_s^0 decays, along with charm mixing and CPV parameters
- Post 2024 summer results not included yet

LHCb-CONF-2024-004

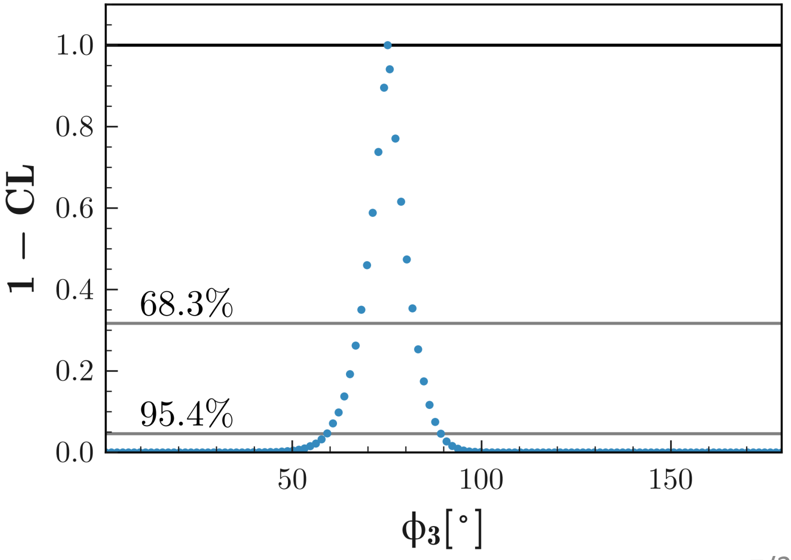


$(\gamma = \phi_3)$

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

- Belle 711 fb^{-1}, Belle II 362 fb^{-1}
- Combination of 16 channels, B^+ modes only
- First Belle + Belle II combination

JHEP10(2024)143



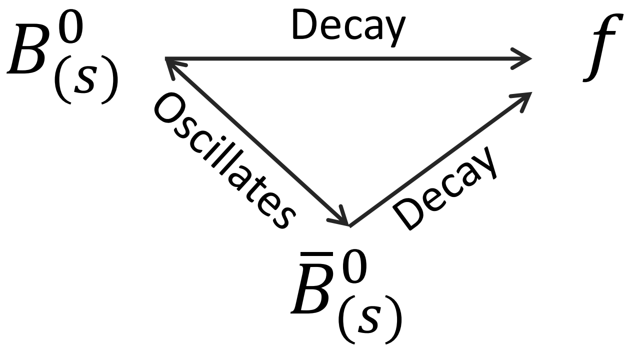
LHCb leads precision thanks to large samples

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

Probing BSM using $B^0_{(s)}$ mixing

The idea

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



$$\frac{\Gamma(\bar{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\bar{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to f)} =$$

$\boldsymbol{B^0}$ $-C\,cos\,\Delta m_d \Delta t \; + S\,sin\,\Delta m_d \Delta t$ $\quad C = 0,$ $\quad \boldsymbol{S = \sin 2\phi_1}$

$\boldsymbol{B^0_s}$ $\dfrac{S\sin(\Delta m_s t) - C\cos(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) + A^{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)},$ $\quad S = \eta_f \sin \boldsymbol{\phi_s}$

Δm and $\Delta\Gamma$: mass and width differences between B mass eigenstates

Key observable is mixing-induced CP violation asymmetry $\boldsymbol{S}$:
→ Departure from indirect determination based on 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 $(\mathbf{37.40 \pm 0.56})\%$

LHCb/ATLAS/CMS

- Use $\mu, e, K,\ \pi$ and photons (LHCb), or μ, e, and b-jets (ATLAS/CMS) from b quark pair-produced with signal (**opposite side**), or charge correlations between fragmentation products and signal (**same side**)
- Effective tagging efficiency 6% at LHCb/CMS and 2% at ATLAS depending on the decays
- Reaching **7.2 – 7.8%** with recent Deep Sets inclusive algorithm (arXiv:2508.20180)

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 $\sigma(\Delta t) \approx 1$ ps

Hadron collider

Relevant vertex resolution 20 μm with Belle II, but much larger boost achieves $\boldsymbol{\sigma(t) \approx 50\ \mathrm{fs}}$ at LHCb.
Similar resolution $(80 - 100\ \mathrm{fs})$ in CMS/ATLAS

Mixing phase golden channels

ϕ_s: $B_s^0 \to \psi K^+ K^-$ at LHCb

PhysRevLett.132.051802

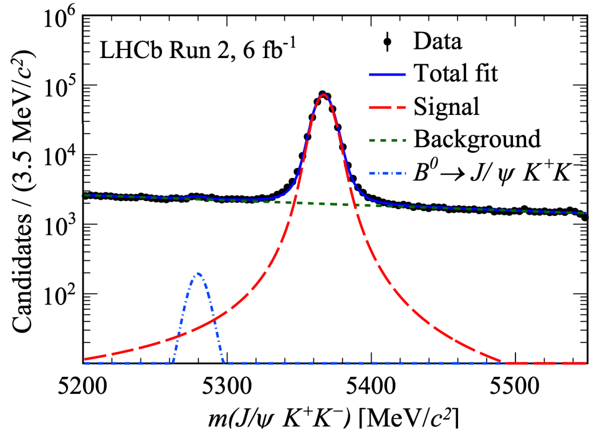
- 2015-2018 dataset (6 fb^{-1})
- $J/\psi(\to \mu^+\mu^-, e^+e^-)K^+K^-, \psi(2S)(\to \mu^+\mu^-)K^+K^-$ at $m(KK) \approx m(\phi)$
- Signal extraction from B invariant mass
  → **350k** decays in total
- Challenges: separation of CP-even and CP-odd decays
- Fit to angular variables to separate CP-even, CP-odd, and S-wave

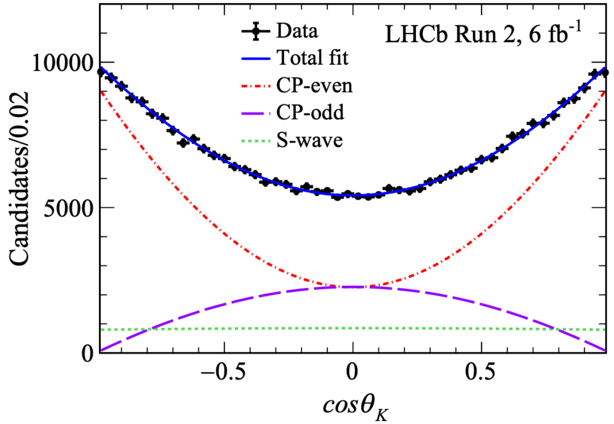
$\boldsymbol{\phi_s = -0.039 \pm 0.022 \pm 0.006}$ **rad**

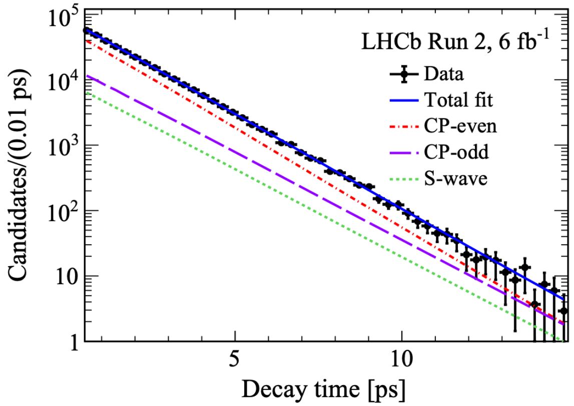
$\boldsymbol{\Delta\Gamma_s = 0.845 \pm 0.0044 \pm 0.0024\ \text{ps}^{-1}}$

LHCb combination: $\boldsymbol{\phi_s = -0.031 \pm 0.018}$ **rad**

Most precise in the world

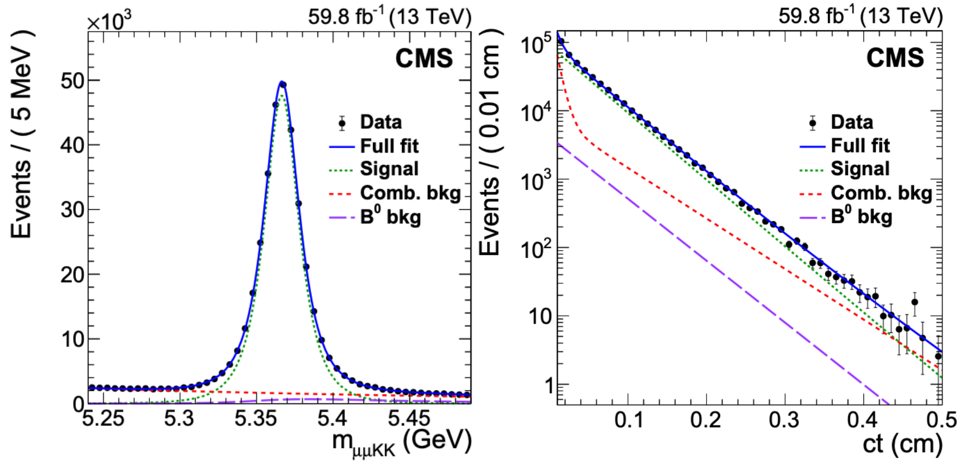






ϕ_s: $B_s^0 \to J/\psi\phi$ at CMS

- 2017 – 2018 dataset: 96.5 fb^{-1}
- $J/\psi(\to \mu^+\mu^-)K^+K^-$
- Challenge: flavor tagging without PID
- Signal extraction from $m(B_s)$→ 28k decays
- Angular and decay-time analysis similar to LHCb



(2018 data only)

Improved flavor tagging

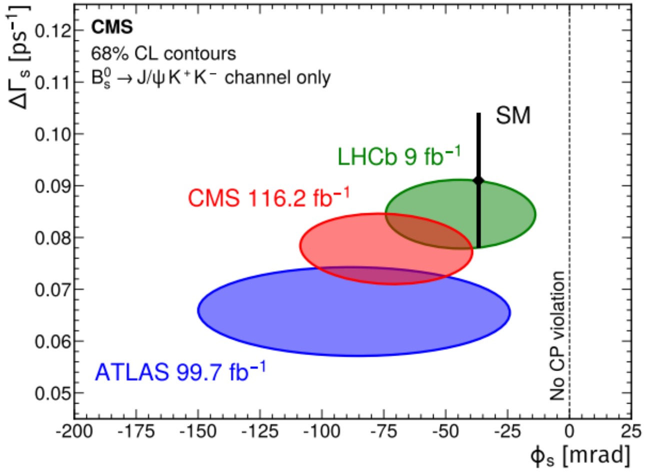
- Addition of **same-side**, use of jet charge, and NN
- New dedicated trigger for opposite side muon

→ **Tagging efficiency: $(5.59 \pm 0.02)\%$**

$\boldsymbol{\phi_s = -0.073 \pm 0.023 \pm 0.007}$ **rad**

$\boldsymbol{\Delta\Gamma_s = 0.114 \pm 0.014 \pm 0.007\ \text{ps}^{-1}}$

(2x better than previous analysis with the **same dataset** (arXiv:2007.02434)

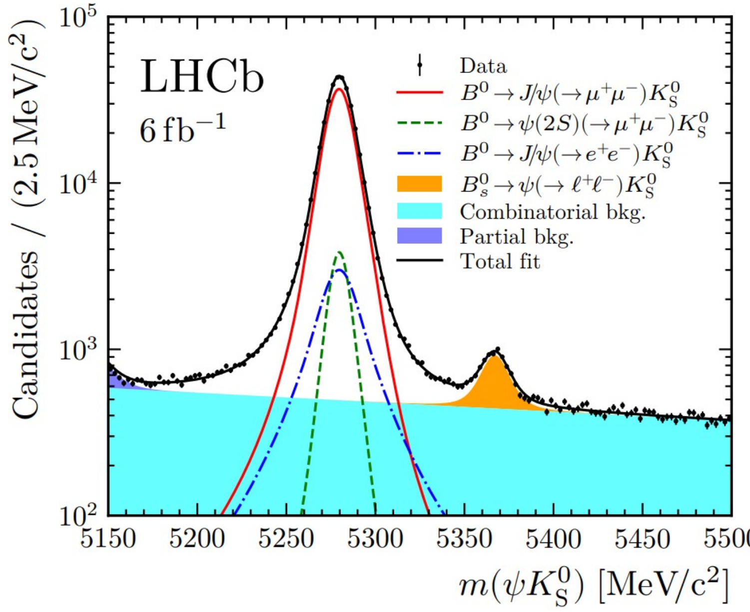


Combination with the 8 TeV analysis: $\boldsymbol{(-0.074 \pm 0.023)}$ **mrad**

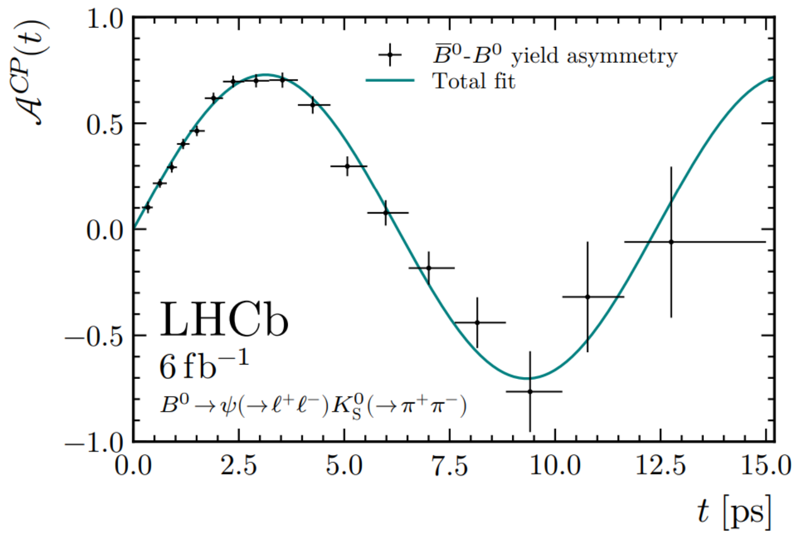
→ **First evidence** for CPV (3.2σ significance)

ϕ_1: $B^0 \rightarrow \psi K_s^0$ at LHCb

- 2017 – 2018 dataset: 6 fb^{-1}
- $J/\psi(\rightarrow \mu\mu, ee)K_s^0$ and $\psi(\rightarrow \mu\mu)K_s^0$
- Challenges: calibration of flavor tagging and resolution
- Signal extraction from B^0 mass
  →Large signal of **373k decays**
- Major systematic uncertainties:
  $\Delta\Gamma_d$ uncertainty and flavor tagger parameters calibrated through $B^0 \rightarrow J/\psi K^{*0}$



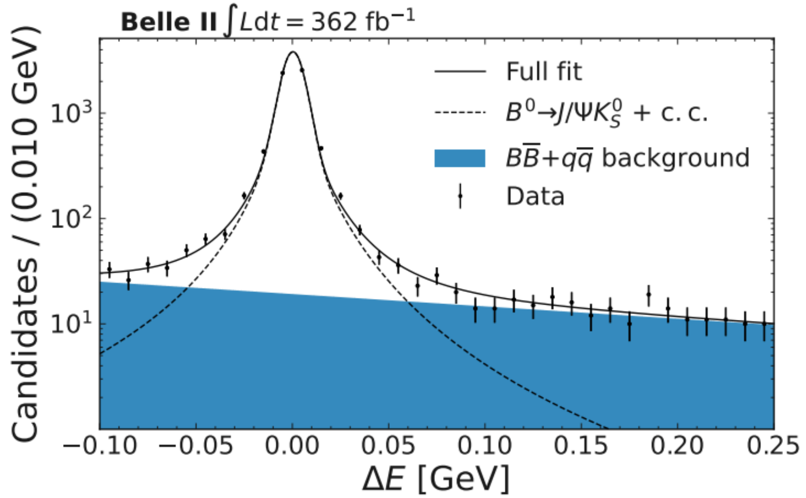
$S = +0.717 \pm 0.013 \pm 0.008$
$C = +0.008 \pm 0.012 \pm 0.003$
World's best result.



ϕ_1: $B^0 \to J/\psi K_s^0$ at Belle II

PhysRevD.110.012001

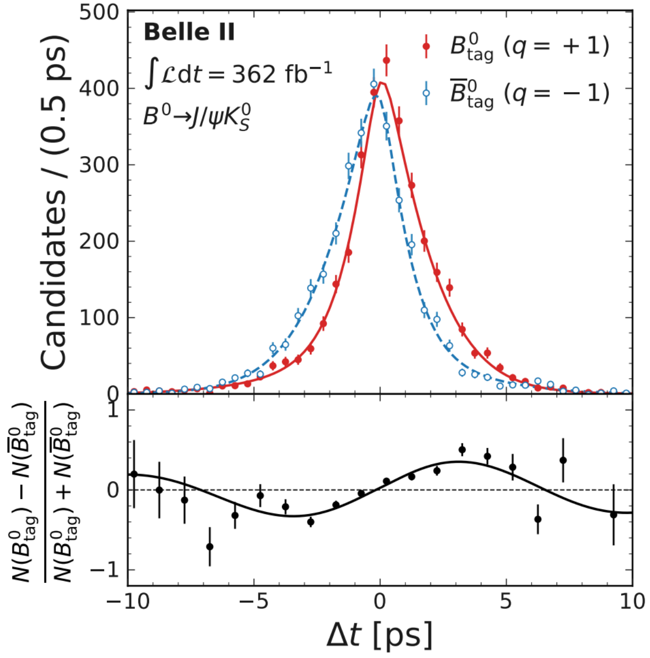
- 2019-2022 dataset: 362 fb^{-1}
- Data-driven Δt resolution and flavor tagging calibration
- Signal extraction from $\Delta E \rightarrow$ 6.4k decays
- **New flavor tagging** algorithm
- **30%** fractional improvement in effective tagging efficiency



First results:

$\boldsymbol{S = +0.724 \pm 0.035 \pm 0.009}$

$\boldsymbol{C = -0.035 \pm 0.026 \pm 0.029}$



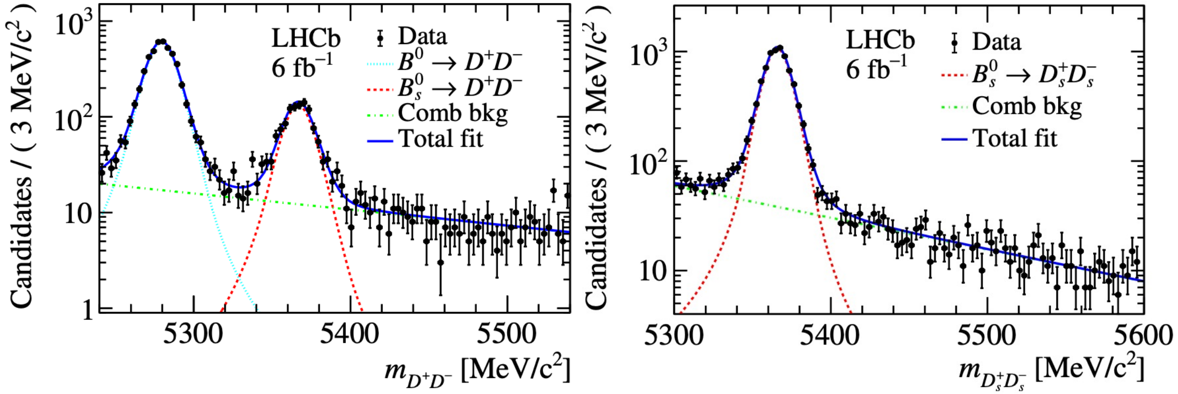
Aim for precision competitive with LHCb with future larger datasets

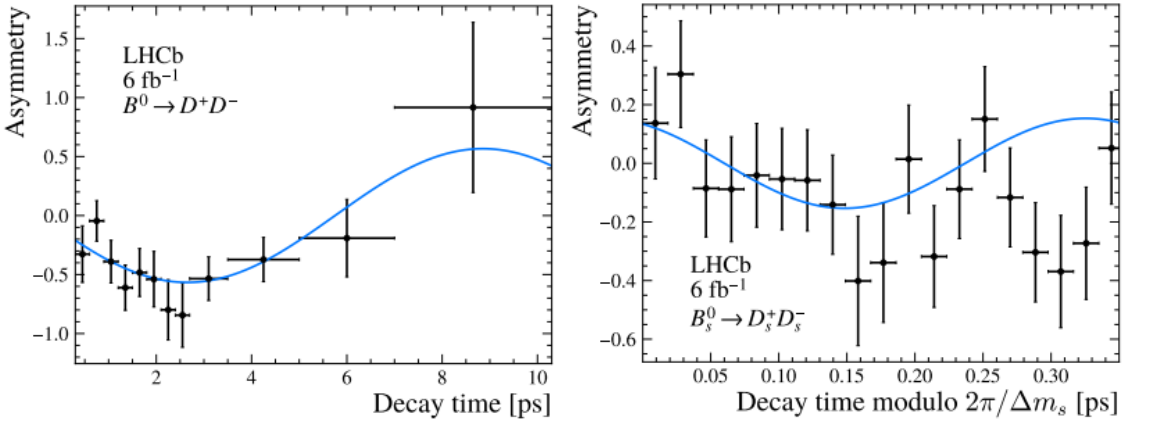
Combined measurement of both mixing phases at LHCb

JHEP01(2025)061

- Use $B^0 \rightarrow D^+D^-$ for $\boldsymbol{\phi_1}$ combined with$B_s^0 \rightarrow D_s^+D_s^-$ for $\boldsymbol{\phi_s}$ which are dominated by trees
- CPV parameters in B^0 and B_s^0 constrain each other loops through U-spin symmetry
- 2015-2018 dataset: 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^0 decays
- Decay-time fit as in $B_s^0 \rightarrow J/\psi KK$
- Combine with Run1 results,
  $S_{D^+D^-} = -0.549 \pm 0.085 \pm 0.015$
  $C_{D^+D^-} = +0.162 \pm 0.088 \pm 0.009$
  $\phi_s = -0.086 \pm 0.106 \pm 0.028$ rad
  Most precise $B_{(s)} \rightarrow D_{(s)}D_{(s)}$ result.

$\boldsymbol{B^0 \rightarrow D^+D^-}$ $\boldsymbol{B_s^0 \rightarrow D_s^+D_s^-}$





Beyond trees

ϕ_1: $B^0 \to J/\psi\pi^0$

PhysRevD.111.012011

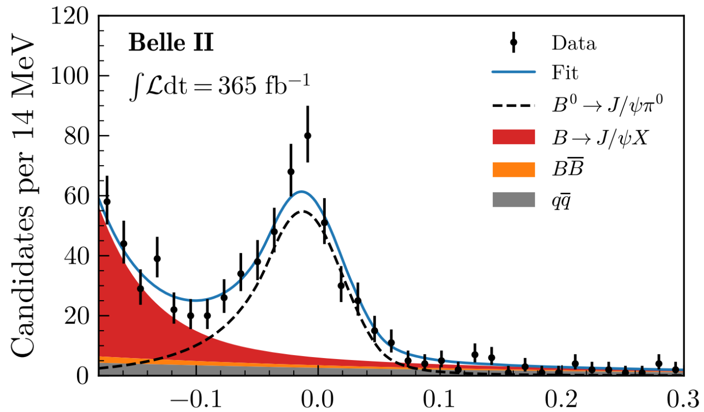
- Loop contribution can bias S of $J/\psi K_S^0$
- In preparation for future precision measurements, start considering loop pollution
- 2019-2022 dataset: 365 fb^{-1}
- Signal extraction from ΔE and $m(J/\psi)$. → 392 decays
- Challenges: low branching fractions, **π^0 background**
  → Improved $ee \to q\bar{q}$ suppression with MVA, π^0 selection
- Similar analysis as $J/\psi K_S^0$

$\boldsymbol{S = -0.88 \pm 0.17 \pm 0.03}$

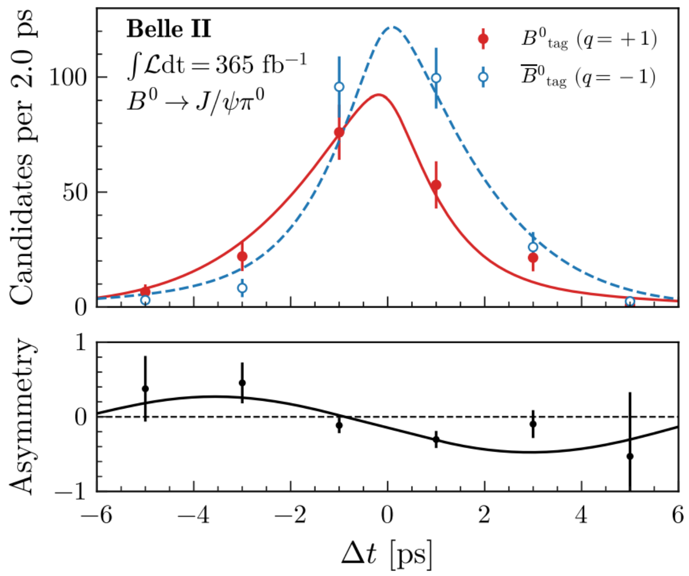
$\boldsymbol{C = +0.13 \pm 0.12 \pm 0.03}$

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

Most precise in the world.



$(\Delta E = E_B - E_{\mathrm{beam}})$



Another interesting mode: $B^0 \to J/\psi\omega$ (PhysRevD.111.032012)
- Also useful to understand $J/\psi K_S^0$ loops
- Demonstrate possibility of CPV measurement in this channel

PhysRevD.110.112002

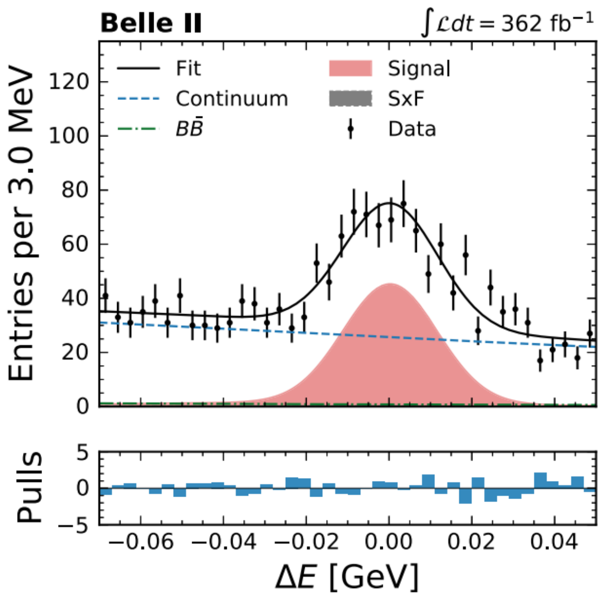
Loops as probes for BSM: $B^0 \to \eta' K_s$

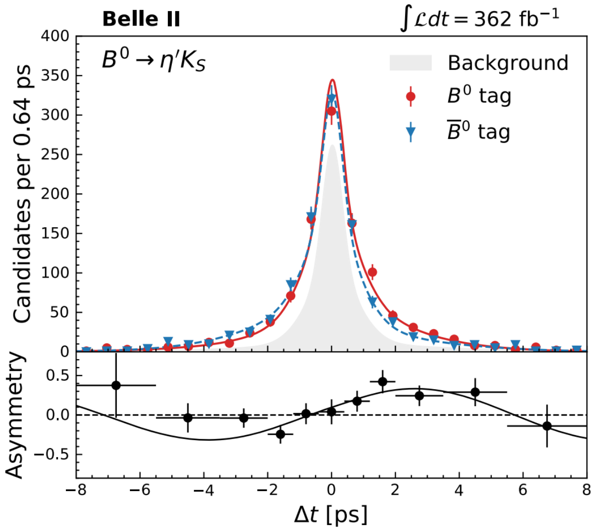
- One of the few remaining golden channels
- Decay dominated by loops: if S differs from ψK_S^0, strong indication of BSM in loops ($|S(\psi K_s) - S(\eta' K_S^0)| < 0.01$)(PLB, 620, 143)
- 2019-2022 dataset: 362 fb^{-1}
- Used $\eta' \to \eta(\to \gamma\gamma)\pi\pi$ and $\eta' \to \rho^0(\to \pi\pi)\gamma$ (**unique to Belle II**)
- Challenges: γ reconstruction, large-background
- Signal extraction from B invariant mass using beam energy, energy difference between measured and beam, and $ee \to qq$ suppression BDT output

  → 829 decays
- $\boldsymbol{C = -0.19 \pm 0.08 \pm 0.03}$
- $\boldsymbol{S = +0.67 \pm 0.10 \pm 0.03}$

  $\leftrightarrow S$ from trees $= 0.710 \pm 0.011$ (world average)

  Comparable precision with Belle and BaBar





ϕ_2: the phase unique to Belle II

ϕ_2: why and how

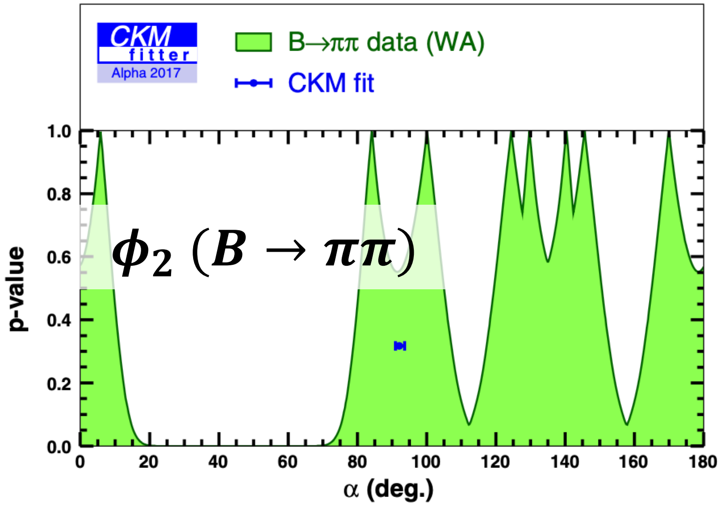
- $S = \sin(2\phi_2)$ from $b \to u$ **tree** amplitude ($B^0 \to \pi^+\pi^-, \rho^+\rho^-$)
- 5%-30% **loops shift S** and C.
- Recover with isospin analysis of $B \to h^+h^-, h^+h^0, h^0h^0$

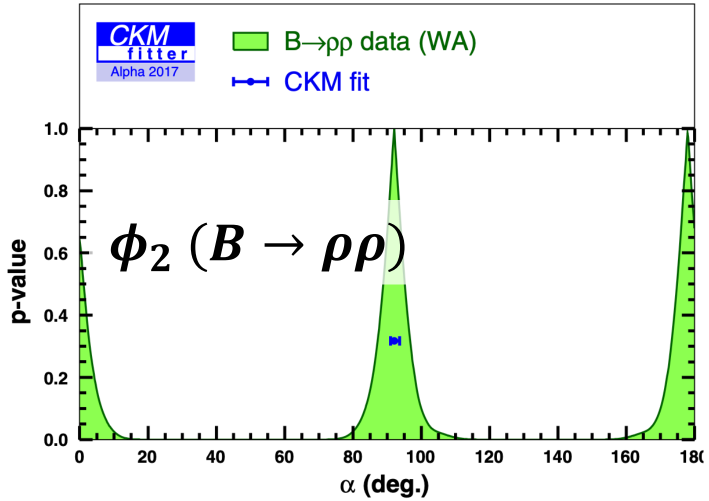
$\rho\rho$ vs $\pi\pi$

- **Uncertainty from loop smaller in $\rho\rho$**
  due to 10x smaller loop in $\rho\rho$
- $\rho\rho$ is spin-0 → spin-1 spin-1 decay. **Angular analysis** needed to separate longitudinal state
- ϕ_2 from $\pi\pi$ less precise due to **multiple solutions because $S(\pi^0\pi^0)$ is missing**, as we cannot measure $\pi^0 \to \gamma\gamma$ vertex
- New promising method to measure $S(\pi^0\pi^0)$→ see Radek's talk

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

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





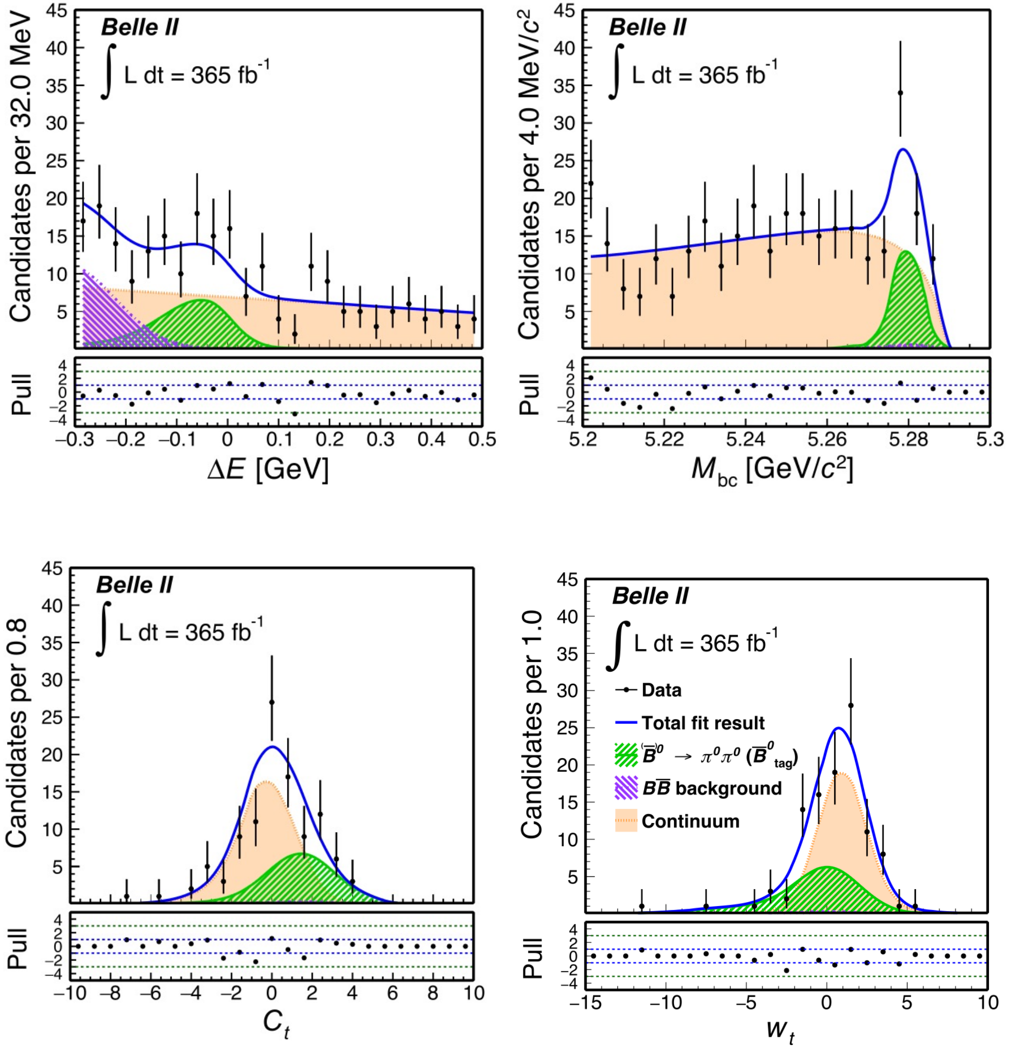
$B^0 \to \pi^0\pi^0$

[PRD 111, L071102 (2025)]

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

Only Belle II can measure this

- 2019-2022 dataset: $365\ \mathrm{fb}^{-1}$
- Large $ee \to qq$ backgrounds is the **main challenge**
  → Suppress it by data-driven BDT
- Signal extraction from B^0 mass, energy difference from beam energy, wrong tagging flavor probability, and continuum suppression
  → 125 decays
- Photon selection, energy calibration validated using $B^+ \to K^+\pi^0$and $B^0 \to \overline{D}^0(\to K^+\pi^-\pi^0)\pi^0$ decays



Results and constraint on ϕ_2

PRD 111, L071102 (2025)

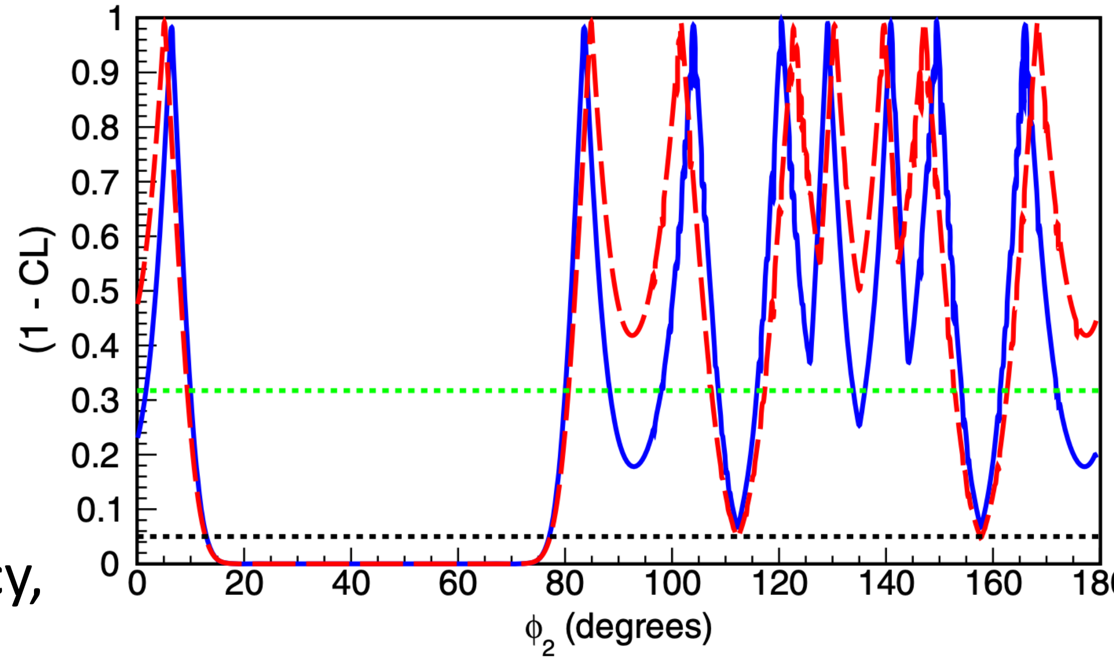
	$\mathcal{B}(\times 10^{-6})$	C	$N_{\Upsilon(4S)}$
Belle II	$1.25 \pm 0.20 \pm 0.11$	$-0.03 \pm 0.30 \pm 0.04$	387×10^6
Belle	$1.31 \pm 0.19 \pm 0.19$	$-0.14 \pm 0.36 \pm 0.10$	772×10^6
BABAR	$1.83 \pm 0.21 \pm 0.13$	$-0.43 \pm 0.26 \pm 0.05$	383.6×10^6

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

30% fractional improvement on 1-sigma ϕ_2 range

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

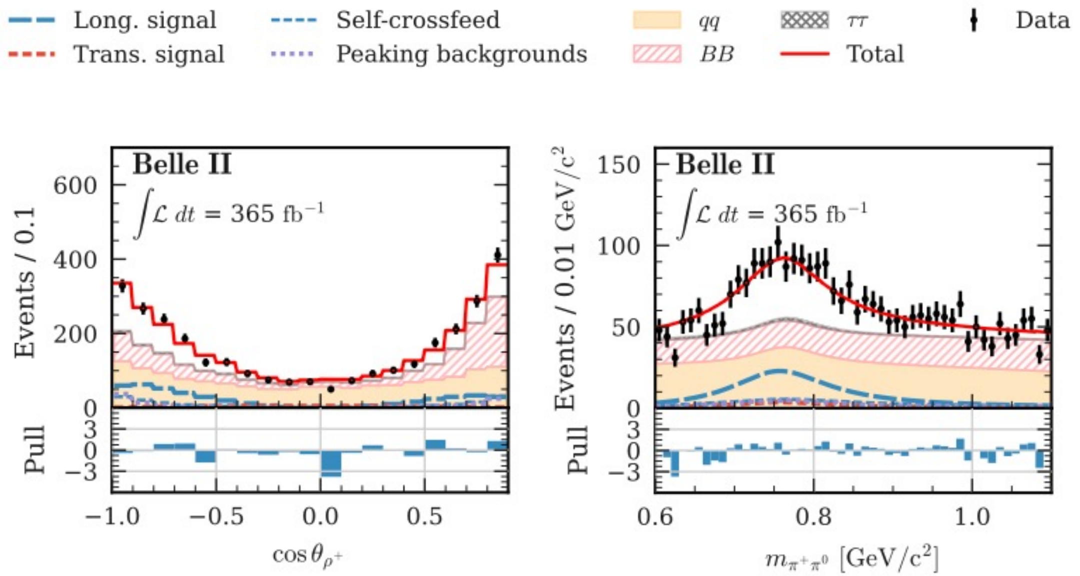
w/o Belle II $B^0 \to \pi^0\pi^0$ w/ Belle II $B^0 \to \pi^0\pi^0$

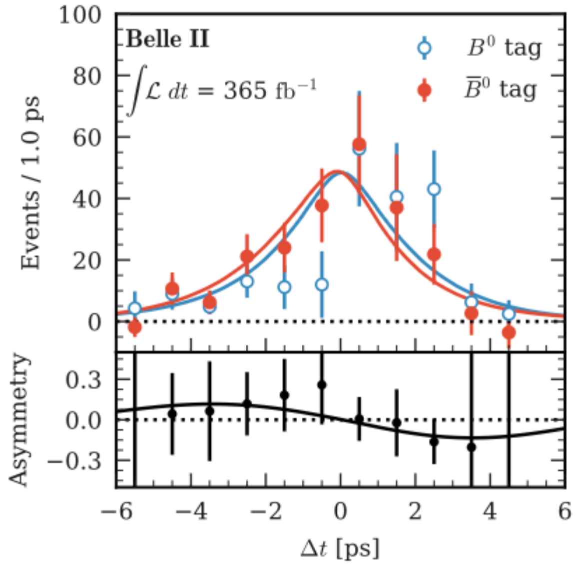


$B^0 \to \rho^+\rho^-$

PRD 111, 092001 (2025)

- 2019-2022 dataset: $365\ \mathrm{fb}^{-1}$
- Large backgrounds due to large ρ width and pion-only final state → Neural network-based qq suppression (TabNet)
- Soft π^0 background in $\rho \to \pi\pi^0$ (**Unique to Belle II**) → 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 decays
- CPV extraction from decay-time difference





$$S = -0.26 \pm 0.19 \pm 0.08$$
$$C = -0.02 \pm 0.12^{+0.06}_{-0.05}$$

Comparable precision to previous experiments.

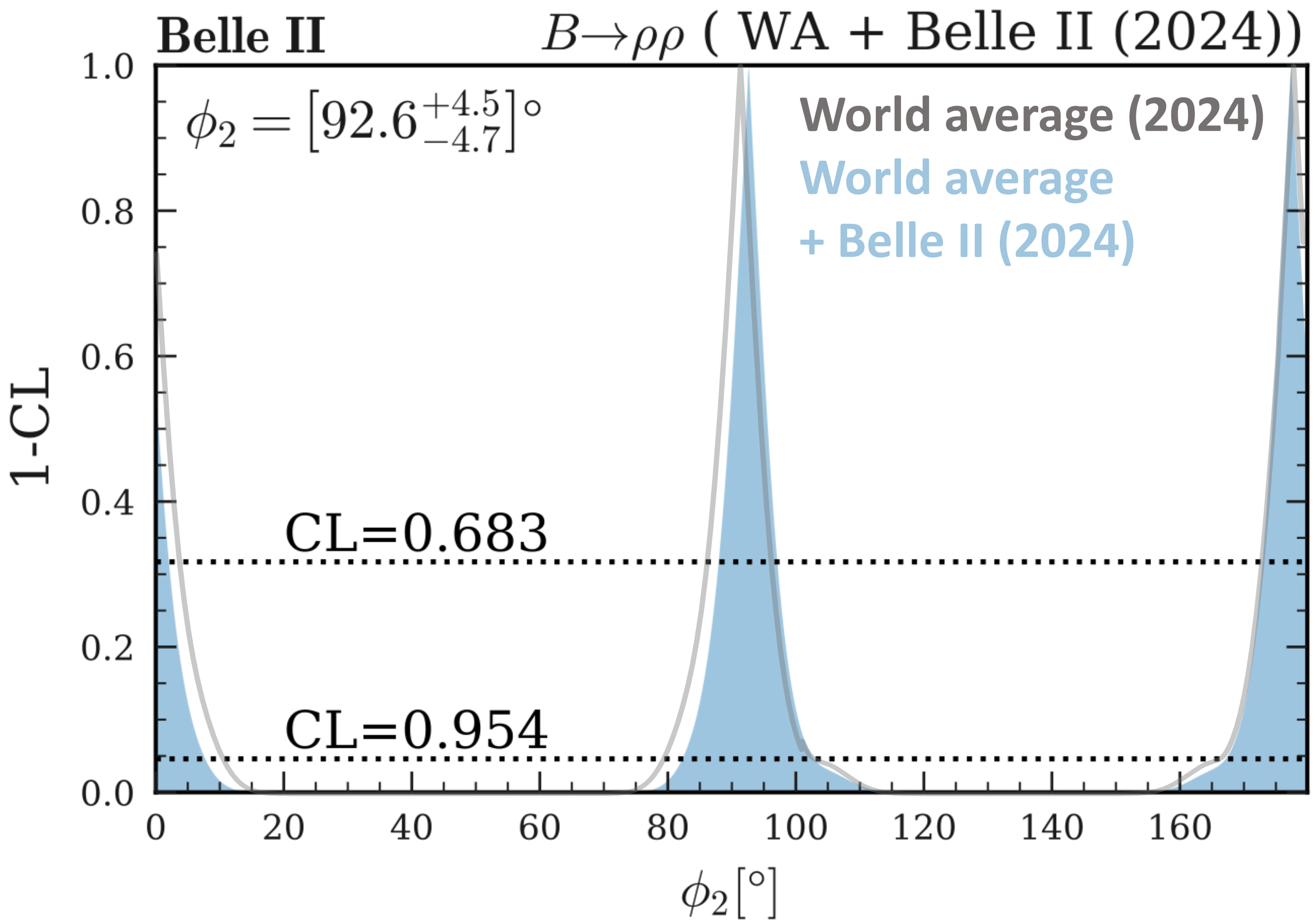
ϕ_2 impact

[PRD 111, 092001 (2025)](PRD 111, 092001 (2025))

$B \rightarrow \rho\rho$ world average
$\phi_2 = \left(91.5^{+4.5}_{-5.4}\right)^\circ$

+ Belle II $\rho^+\rho^-$ results
$\rightarrow \phi_2 = \left(92.6^{+4.5}_{-4.7}\right)^\circ$

10% improvement from Belle II!
Dominated by S of $\rho^+\rho^-$ and $\rho^0\rho^0$.



Perspectives for coming five years

arXiv:2503.24346
arXiv:1808.10567

	Belle II $\int \mathcal{L}\,dt = 5 - 10\ \mathrm{ab}^{-1}$	**LHCb, ATLAS, CMS** Run 3
ϕ_s	---	0.023 rad →0.008 rad in LHCb, CMS Similar precision at ATLAS
	→Unique to LHC. Stringent SM test by comparison of the value from SM	
ϕ_3	$7.6° \rightarrow 3°$	2.8° → **0.8°** (LHCb)
	→ LHCb leading precision.	
ϕ_1	$1.5° \rightarrow 0.46°$	$0.54° \rightarrow \mathbf{0.22°}$ (LHCb)
	→ LHCb leading precision, Belle II may reach similar level on ϕ_1	
ϕ_1^{eff}	$\sigma(S(\eta' K_s)) = 0.10 \rightarrow \mathbf{0.029}$ $\sigma(S(\phi K_s)) = 0.26 \rightarrow \mathbf{0.048}$	---
	→Stringent SM test by comparing ϕ_1^{eff} from Belle II and ϕ_1 from LHCb +Belle II	
ϕ_2	4.5°→2°	---
	→ 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 is a reliable SM reference

- LHCb leads precision due to large samples

ϕ_1 is mixing-induced phase that provides one of the most stringent constraint to BSM in mixing

- $J/\psi K_s^0$ measured precisely LHCb, Belle II may reach similar level in the future
- LHCb and CMS highlight: ϕ_s measurement for $B_s^0\bar{B}_s^0$ mixing

ϕ_2 is the most imprecise angle, may soon limit power of unitarity fits

- 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 10%!