First measurement of mixing-induced *CPV* in $B^0 \to \pi^0\pi^0$ and new results on *B/D CPV* at Belle and Belle II

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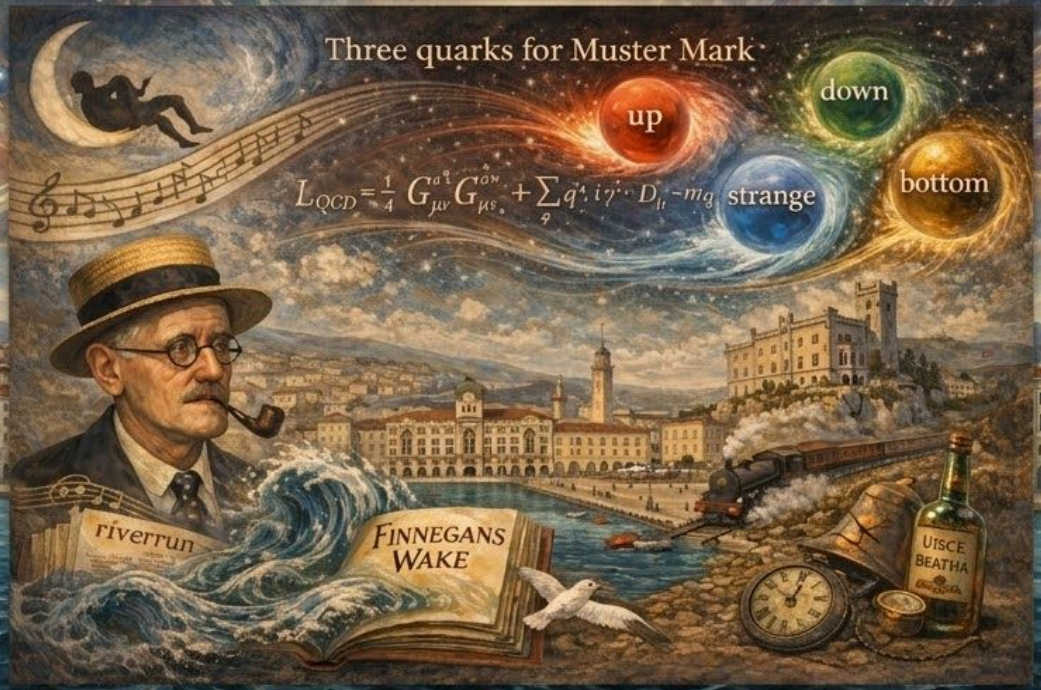
on behalf of the Belle and Belle II Collaborations

Moriond EW
March 16, 2026



INFN TRIESTE

Belle II

Today: new results since last Moriond

Mixing-induced CPV in radiative $B^0 \to K_S \pi^+ \pi^- \gamma$ decay

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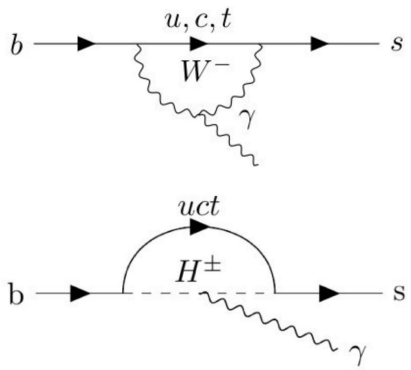
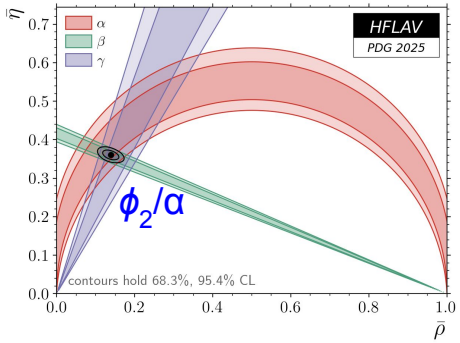


World first mixing-induced CPV in $B^0 \to \pi^0 \pi^0$

Using quantum entanglement in $B^0\bar{B}^0$ system

New for Moriond 2026



In addition, direct CPV in $D^0 \to \pi^0 \pi^0$, $D^0 \to \pi^+ \pi^- \pi^0$, $D^+ \to \pi^+ \pi^0$

Belle II experiment

- Near-threshold production of quantum correlated $B^0\bar{B}^0$ pairs at SuperKEKB asymmetric e^+e^- collider
- *B, D,* and τ factory
- Small μm-level size interaction region
- Instantaneous luminosity record of 5.1 x 10^{34} cm^{-2} s^{-1} (twice higher than KEKB)

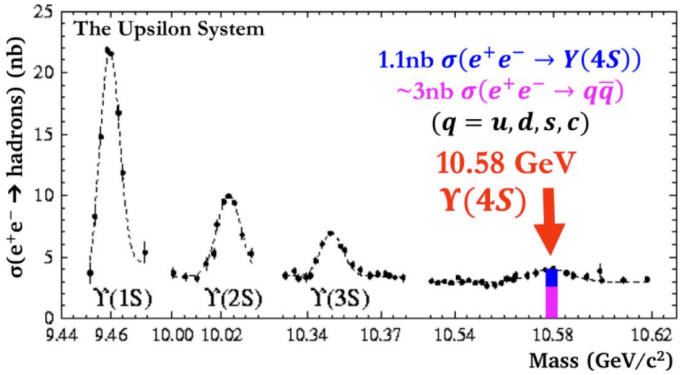
Belle II integrated **365 fb^{-1} (2019 - 2022)** and 200 fb^{-1} (2024 –) at the Y(4S)

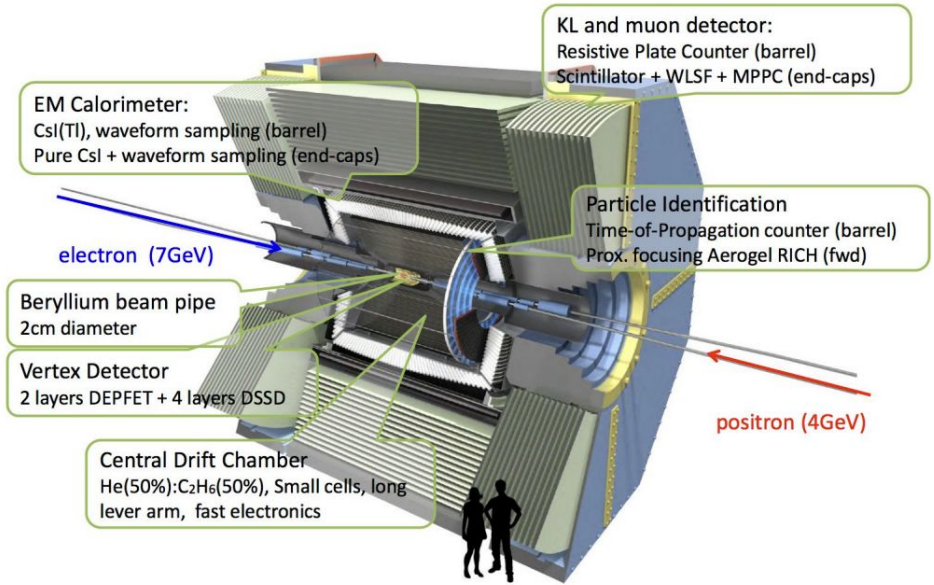
Compare with 710 fb^{-1} at Belle in 1999 - 2011

4π spectrometer with PID and em. calorimeter

Good reconstruction of tracks and neutrals.

Excellent vertex resolution thanks to pixel detector





Direct *CP* violation in charm

- LHCb observes nonzero *CPV* in $\pi^+ \pi^-$ and $K^+ K^-$. *Origin investigated through CPV in isospin-related final states*
- Belle II provides key input in final states with π^0 *or* K^0 such as charm's golden channel $D^+ \to \pi^+ \pi^0$
- All measurements based on 2019 - 2022 Belle II sample: 365 fb^{-1} (on-resonance) plus 63 fb^{-1} (off-resonance) – half of Belle sample

$D^+ \to \pi^+ \pi^0$ Phys.Rev.D 112 (2025) 3

$A_{CP} = (-1.8 \pm 0.9 \pm 0.1)$ %

Comparable precision with world best (LHCb)

$D^0 \to \pi^0 \pi^0$ Phys.Rev.D 112 (2025) 1

$A_{CP} = (0.30 \pm 0.72 \pm 0.20)$ %

Comparable precision with world best (Belle)

$D^0 \to K_S K_S$ Phys.Rev.D 112 (2025) 1

$A_{CP} = (-0.6 \pm 1.1 \pm 0.6)$ %

World best precision

$D^0 \to \pi^+ \pi^- \pi^0$ arXiv:2510.21224

$A_{CP} = (0.29 \pm 0.27 \pm 0.13)$ %

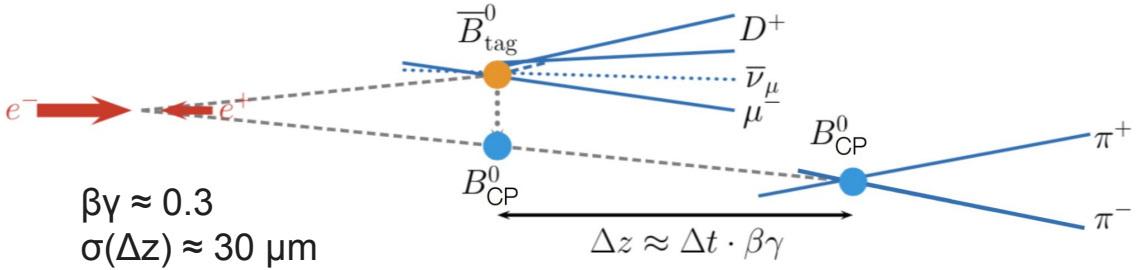
34% more precise than world best (BaBar)

Consistency with *CP* symmetry:
few permil to 1% precision constrains possible BSM

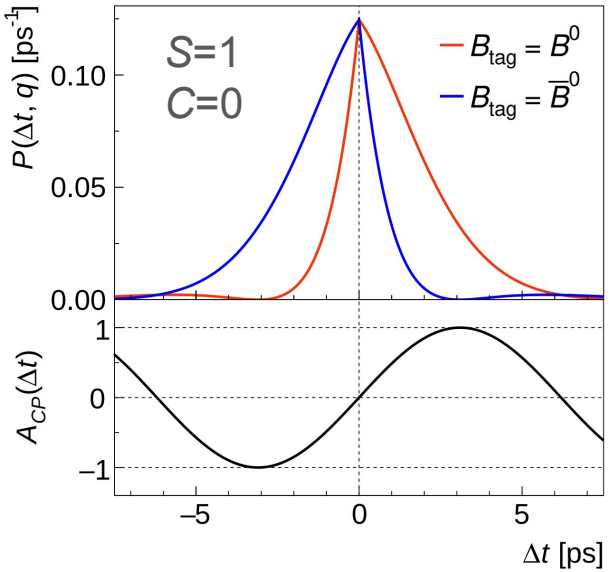
Decay-time-dependent *CPV* at *B* factories

- Asymmetric energy $e^+e^- \rightarrow Y(4S) \rightarrow B^0_{CP}\, B^0_{tag}$
- *B* mesons produced at ~rest in CM, get boosted in lab and evolve coherently until one decays
- B^0_{CP} decays to *CP* eigenstate of interest
- B^0_{tag} decays generically: statistical algorithm determine its flavor (B^0 or $\overline{B}^0$) and therefore the signal flavor (thanks to quantum entanglement)
- Interplay between decay time and flavor probes *CP*

$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{P}(\Delta t, +1) - \mathcal{P}(\Delta t, -1)}{\mathcal{P}(\Delta t, +1) + \mathcal{P}(\Delta t, -1)} = S \sin \Delta m \Delta t - C \cos \Delta m \Delta t$$



βγ ≈ 0.3
σ(Δz) ≈ 30 μm
σ(Δt) ≈ 0.6 ps



Δt = t_{CP} - t_{tag} derived from decay vertices of both *B* mesons

Time-dependent *CP* asymmetry in $B^0 \to K_S \pi^+ \pi^- \gamma$

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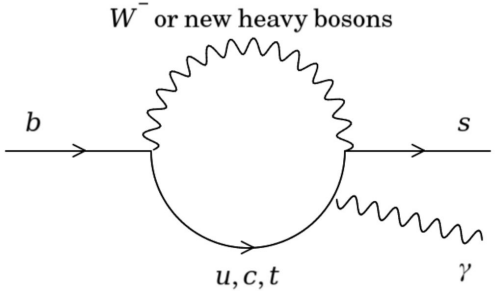
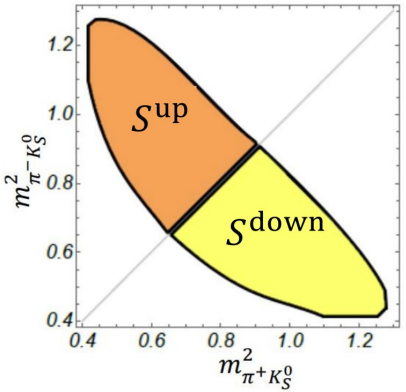
- SM suppresses (by m_s/m_b) right-handed photon polarisation in $b \to s\gamma$. No alternative decay path means no interference. Hence ~null mixing-induced *CP* violation, S ≈ 0
- BSM can generate right-handed photon, leading to nonzero S due to interference between left- and right-handed currents
- Determine *CPV* parameters S and C from time-dependent analysis
- Challenges: background suppression and proper modeling of decay-time-difference resolution (depends on instrumental and reconstruction effects of two vertices)
- Following *JHEP* 09 (2019) 034 S and C also measured separately in two halves of the Dalitz plane for better constraints in the C_7/C_7' plane of BSM Wilson coefficients





New observables:
- $S^+ = S^{\mathrm{up}} + S^{\mathrm{down}}$
- $S^- = S^{\mathrm{up}} - S^{\mathrm{down}}$

Full amplitude analysis also ongoing, see Sahil talk in evening

$B^0 \to K_S \pi^+ \pi^- \gamma$ analysis outline

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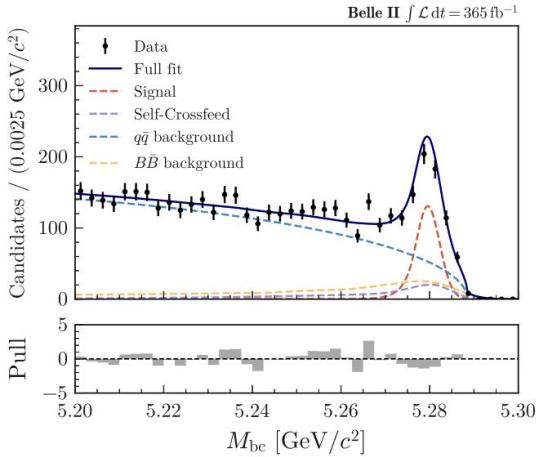
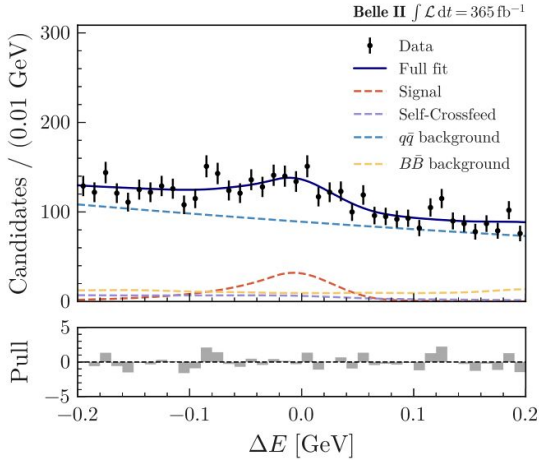
- Combined analysis of Belle (711 fb^{-1}) and Belle II (365 fb^{-1}) data
- Dominant background from light quarks - suppressed by BDT
- Three-dimensional maximum likelihood fit in
  - the ‘classic’ *B*-factory observables M_{bc} and ΔE (to separate signal from background)
  - and Δt (to determine time evolution)

Signal yields
Belle: 475 ± 31
Belle II: 350 ± 23



Invariant B^0 mass with beam energy replacing B^0 energy
(in CM frame)



Difference between observed B^0 energy and beam energy
(in CM frame)

$B^0 \to K_S \pi^+ \pi^- \gamma$ results

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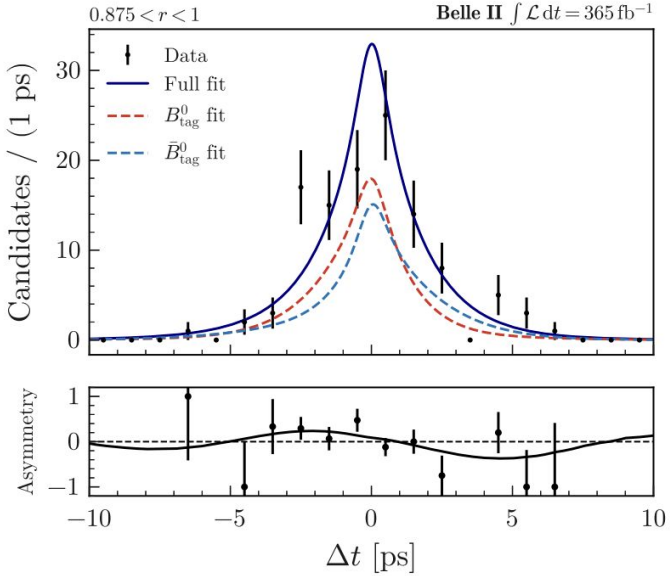
- Δt spectrum modeled as convolution of physics distribution with resolution function (from $B \to D\pi$ decays)
- Over Belle, Belle II benefits from better K_S efficiency and more powerful graph-NN flavor tagging ($\varepsilon_{\text{BelleII}} = 37\%$ vs $\varepsilon_{\text{Belle}} = 30\%$)



Belle

$$C = -0.04 \pm 0.11 \pm 0.07$$
$$S = -0.18 \pm 0.17 \pm 0.08$$

Belle II

$$C = -0.29 \pm 0.13 \pm 0.05$$
$$S = -0.36 \pm 0.16 \pm 0.06$$

Combined

$$C = -0.17 \pm 0.09 \pm 0.04$$
$$S = -0.29 \pm 0.11 \pm 0.05$$

$$S^+ = -0.57 \pm 0.23 \pm 0.10$$
$$S^- = 0.31 \pm 0.24 \pm 0.05$$

Compare to previous results

BaBar PRD93 (2015): S = 0.14 ± 0.25 ± 0.03 (426 fb^{-1})
Belle PRL101 (2008): S = 0.09 ± 0.27 ± 0.07 (605 fb^{-1})

Most precise S in any $b \to s\,\gamma$ transition. Belle II uncertainty similar to Belle but with half data.

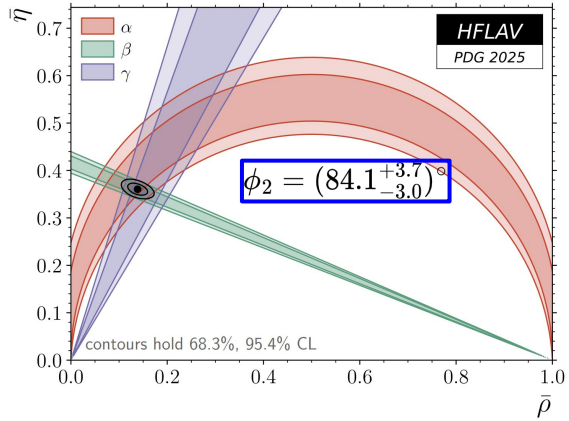
New for Moriond 2026!

Time-dependent CPV in $B^0 \to \pi^0 \pi^0$

The issue with $B^0 \to \pi^0 \pi^0$

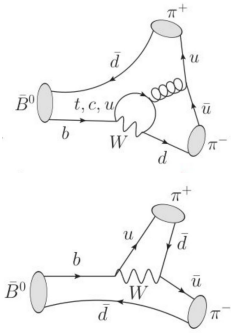
New for Moriond 2026!

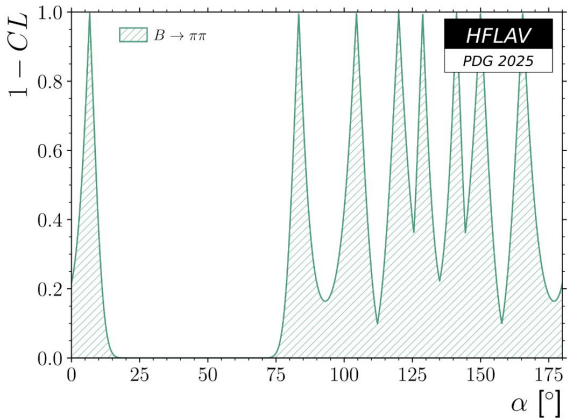
- ϕ_2/α the least known angle of the Unitarity Triangle
- Missing *S* measurement in $B^0 \to \pi^0\pi^0$ leads to 8-fold ambiguity in ϕ_2 determination from $B \to \pi\,\pi$
- 99% of $B^0 \to \pi^0\pi^0$ decays lead to **4-photon vertexless** final state.
- Standard t-dependent *CPV* analysis impossible with current samples



The physics of B factories (2014)

$B \to \pi\pi$ system is complicated by the need to measure time-dependent *CP* asymmetry of the all-neutral final state decay of B^0 mesons to $\pi^0\pi^0$. This is not possible at the present level of statistics, although high luminosity super flavor factory may be able to constrain the decay vertex of the $B^0 \to \pi^0\pi^0$ candidate using Dalitz decays of one or both π^0 mesons, or events where one or more photons convert in the detector material. The situation is further exac-





Belle II physics book (2018)

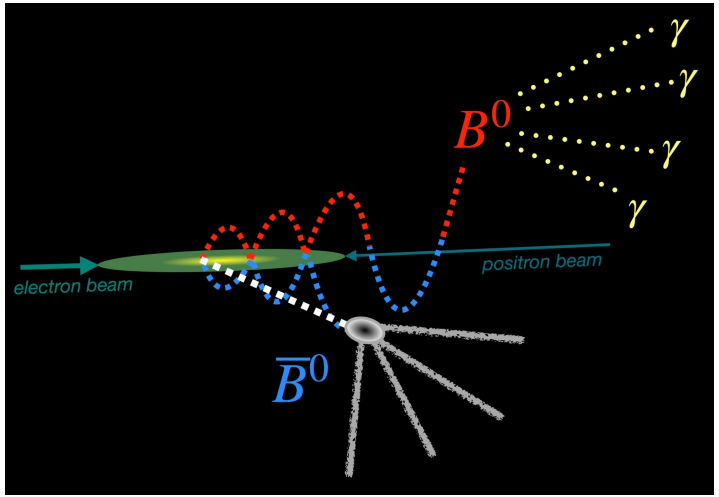
$B^0 \to \pi^0\pi^0$. At present, there is not enough data to perform a time-dependent *CP*-analysis of the decay mode $B \to \pi^0\pi^0$. Neutral pions decay to about (98.823 ± 0.034)% [88] into two photons, and, without external photon conversion $\gamma \to e^+ e^-$, they do not provide information to reconstruct the vertex of the B^0. Also the fraction of useful Dalitz decays

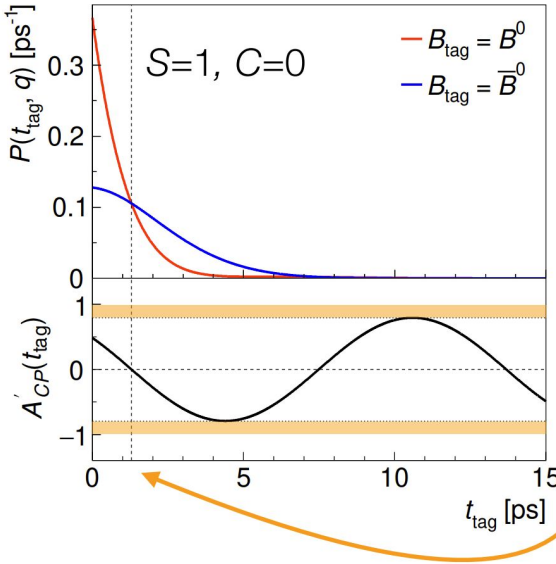
Getting B_{CP} vertex requires 20 times more data than now available

Any other option?

New for Moriond 2026!

Thanks to $B^0\overline{B}^0$ quantum entanglement, time-dependent flavour asymmetry arises even when measuring a single decay time, such as the tag-B meson decay time t_{tag}, instead of $\Delta t = t_{CP} - t_{tag}$ Phys.Rev.D 112 (2025) 3





$$\mathcal{A}'_{CP}(t_{tag}) = S' \sin \Delta m(t_{tag} - t_0) - C' \cos \Delta m(t_{tag} - t_0)$$

$$S' = -\frac{S}{\sqrt{1+(\tau\Delta m)^2}} \approx \mathbf{-0.8\ S}$$

$$C' = \frac{C}{\sqrt{1+(\tau\Delta m)^2}} \approx \mathbf{0.8\ C}$$

$$t_0 = \frac{1}{\Delta m}\arctan(\Delta m\tau) \approx \mathbf{1.3\ ps}$$

Mixing-induced CPV can be measured without signal vertex

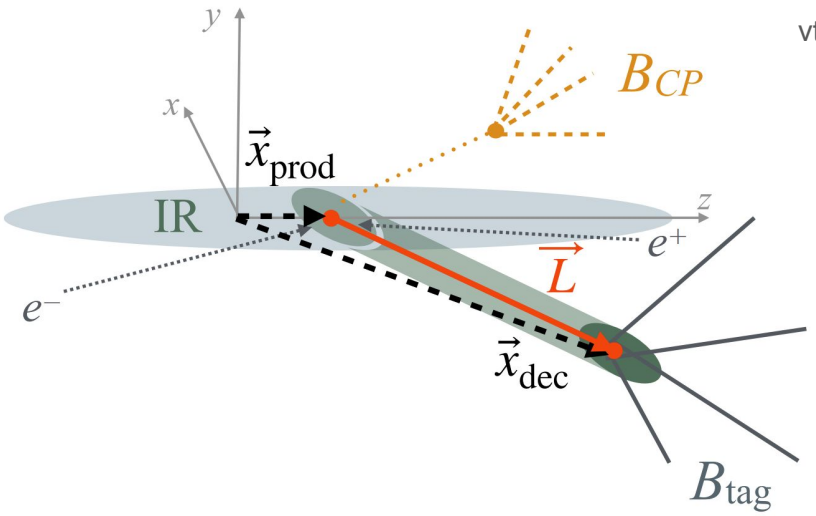
….but t_{tag} resolution is crucial

Uniquely accessible to Belle II

New for Moriond 2026!

t_{tag} resolution mostly function of

- B_{tag} vertex resolution
- Beam spot size

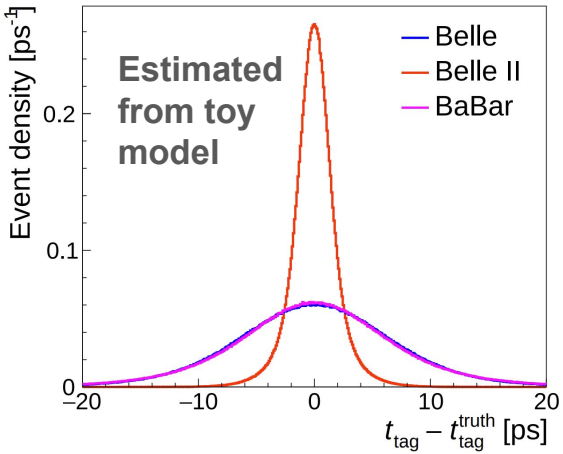


Momenta of beams

IP size

vtx resolution

	Belle II	Belle	BaBar
e^- (e^+) beam energy [GeV]	7.0 (4.0)	8.0 (3.5)	9.0 (3.0)
Beam energy spread [MeV]	5.45	5.36	4.63
Crossing angle [mrad]	83	22	0
Interaction region x width [μm]	13	70	148
Interaction region y width [μm]	0.2	1.0	6.9
Interaction region z width [μm]	350	6000	15150
B_{tag} vertex x-y resolution [μm]	30	80	80
B_{tag} vertex z resolution [μm]	30	100	125



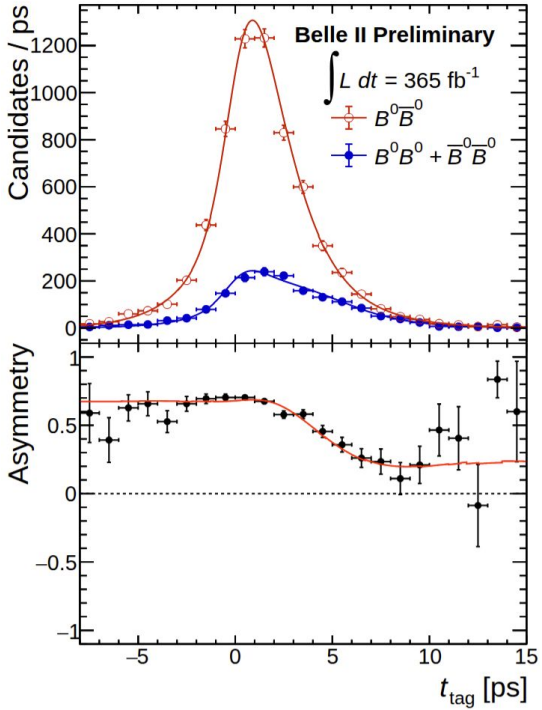
Belle II has reasonable (1.5 ps) t_{tag} resolution

Belle/Babar resolution of 6 ps hindered any *S* ambition

t_{tag} resolution from $B^0 \to D^- \pi^+$ data

New for Moriond 2026!

- Reconstruction of B_{tag} decay time tested on 36 000 flavor-specific $B^0 \to D^- \pi^+$ decays
- t_{tag} resolution differs between simulation and data. Take shape from simulation and adjust parameters on data.
- Validate through measurement of B^0-$\bar{B}^0$ oscillation frequency and B^0 lifetime based only on B_{tag} vertex (a first!)



Results

$\Delta m_d = (0.512 \pm 0.011)$ ps^{-1}
$\tau(B) = (1.509 \pm 0.026)$ ps

Compare with conventional Δt
Phys. Rev. D 107 (2023)

$\Delta m_d = (0.516 \pm 0.009)$ ps^{-1}
$\tau(B) = (1.499 \pm 0.015)$ ps

Quantum entanglement unveils B^0-$\bar{B}^0$ oscillations even when looking at single decay time only

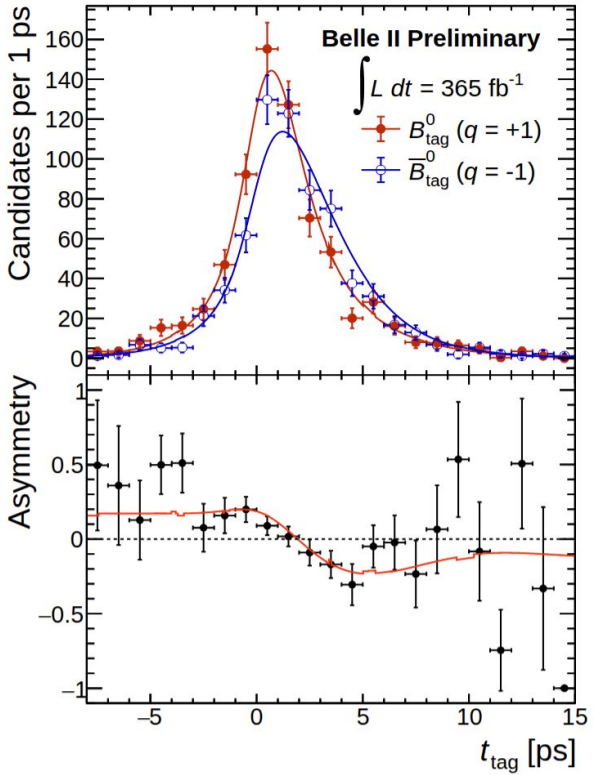
Validation on $B^0 \to J/\psi\, K_S$ decays

New for Moriond 2026!

- Validation by measuring mixing-induced CPV in 6000 $B^0 \to J/\psi\, K_S$ decays – golden sin $2\phi_1$ mode
- Based on classic Belle II sin $2\phi_1$ measurement (Phys.Rev.D 110 (2024) 1), but ignoring signal vertex
- Results consistent with conventional Δt measurement (and known values) – 3x larger uncertainties

Novel t-tag method
S = 0.84 ± 0.10
C = -0.06 ± 0.03

Conventional Δt method
S = 0.72 ± 0.04
C = -0.04 ± 0.03



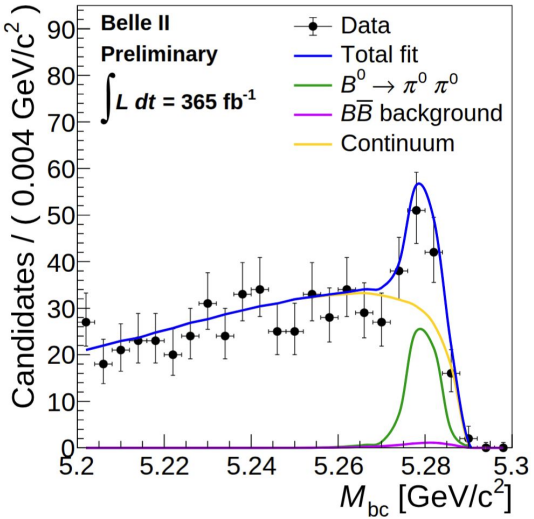
First measurement of mixing-induced CPV without signal decay vertex - it works!

Now onto $B^0 \to \pi^0\pi^0$

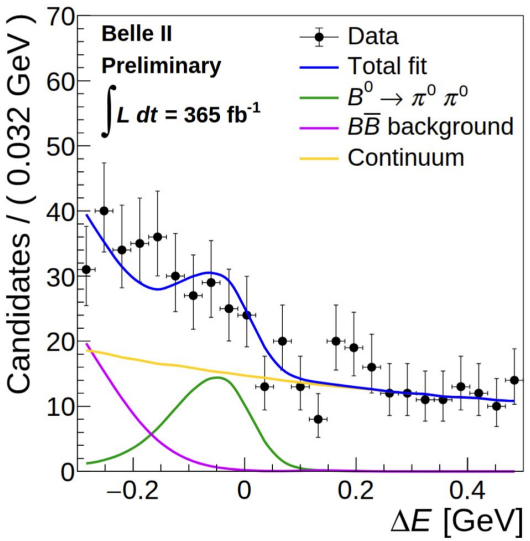
New for Moriond 2026!

- BDT suppresses four-photon bckg from $e^+e^- \to qq\bar{q}$, which is 100x higher than signal
- Irreducible, signal-sized BBbar background (86% from $B^+ \to \rho^+\pi^0$)
- Parameters S and C from fit to
  - Beam-constrained B^0 mass (M_{bc}),
  - Energy difference (ΔE),
  - Continuum suppression discriminator
  - Wrong flavor-tag fraction
  - B_{tag} decay time
  - B_{tag} decay-time uncertainty

Beam-constrained B^0 mass



B^0 energy wrt the beam



171 ± 24 signal decays
(compare with 154 at BaBar and 74 at Belle)

Results

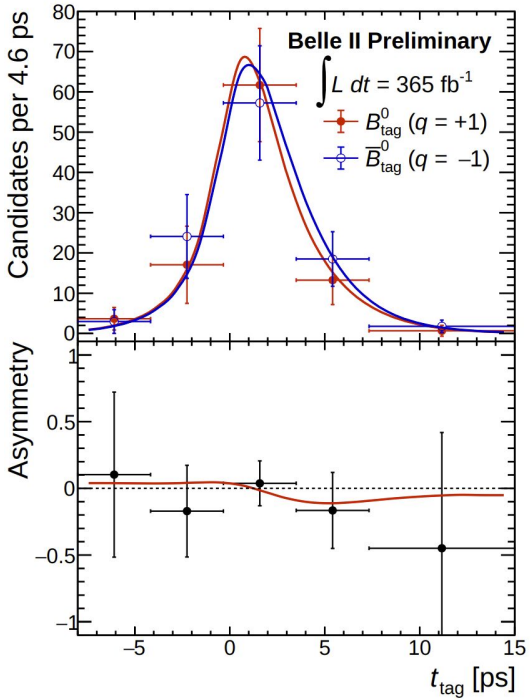
New for Moriond 2026!

$$S_{00} = 0.61^{+0.75}_{-0.79}\,(\text{stat}) \pm 0.11\,(\text{syst}),$$
$$C_{00} = 0.05 \pm 0.28\,(\text{stat}) \pm 0.07\,(\text{syst}).$$

Novel approach, along with SKEKB compact interaction region and pixel detector, enable measurement of mixing induced *CP* violation in $B^0 \to \pi^0\pi^0$

Would require 20x more data with conventional approach

Precision limited by sample size. Large margins of improvement



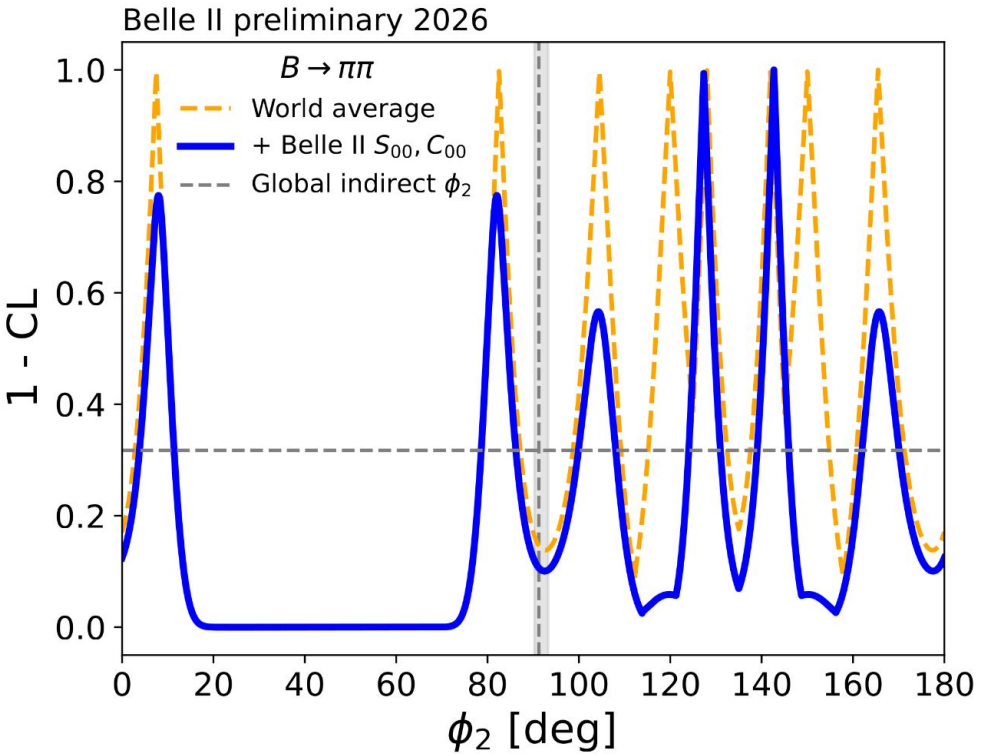
Mixing induced CPV in $B^0 \to \pi^0\,\pi^0$ measured for the first time

Impact on ϕ_2

Reduces 8-fold ambiguity in $B \to \pi\pi$ ϕ_2 determination to 6 solutions

Allowed 68% CL interval shrunk by **40%**

CKM-like ϕ_2 solutions from ππ and ρρ are consistent and have similar uncertainty of ~ ± 5 deg



Conclusions

25 years after first *B*-factories, *CP* violation remains decisive indirect probe for many generic SM extensions

Belle II exploiting unique *CPV* capabilities in *B/D* decays into π^0, γ, K_S

- Leading precision in golden $D^+ \to \pi^+ \pi^0$ and $D^0 \to \pi^+ \pi^- \pi^0$
- Combined Belle/Belle II time-dependent *CPV* of $B^0 \to K_S \pi^+ \pi^- \gamma$ yields most precise mixing-induced *CPV* in $b \to s \gamma$
- World first mixing-induced *CPV* in vertexless $B^0 \to \pi^0 \pi^0$ channel
  - Enabled by novel method based on quantum correlation, compact SuperKEKB interaction region, and Belle II pixel detector.
  - 40% reduction in 68% CL range for ϕ_2 from $B \to \pi\pi$ decays: would require 20x more data with conventional methods

Backup

Idea of single-time CPV pioneered by Andrew Foland

- The single-time time-dependent CPV measurement was first proposed by A. Foland from CLEO in 1999 and at Belle II we rediscovered it 26 years later
- The main motivation was possible t_{CP}-based sin 2β measurement in $B^0 \to J/\psi\, K_S$ at CLEO
- Possibility for t_{tag}-based measurement of α in $B^0 \to \pi^0\pi^0$ was also mentioned although this channel had not been discovered yet

PHYSICAL REVIEW D, VOLUME 60, 111301

Measurement of *CP* violation at the $\Upsilon(4S)$ without time ordering or Δt

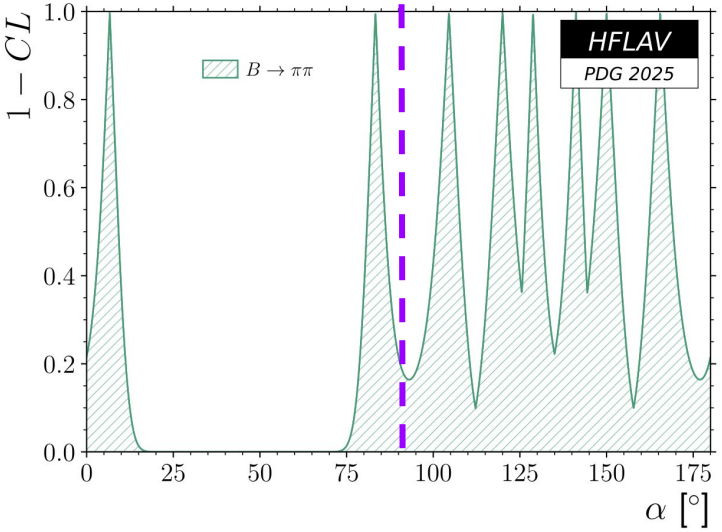
Andrew D. Foland
Cornell University, Ithaca, New York 14853
(Received 17 June 1999; published 8 November 1999)

I derive the expressions for the CP-violating asymmetry arising from interference between mixed and direct decays in the $\Upsilon(4S)$ system, for the case in which only one of the B decay times is observed, integrating over the decay time of the other B. I observe that neither the difference of the decay times Δt, nor even their time ordering, need be detected. A technique for measurement of the CP-violating weak decay parameter $\sin 2\beta$ is described which exploits this observation. [S0556-2821(99)50521-3]

In 1999 the technology was not mature enough for this method.
Thanks to Belle II we can use it now.

Determination of the CKM angle ϕ_2/α

B→*ππ:* Suspected golden channel (since ~1990)



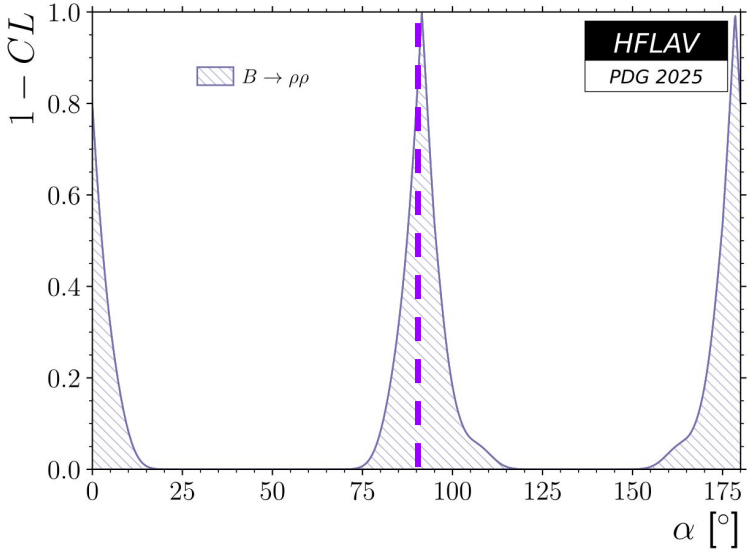
SM prediction:

$\alpha = (91.1^{+1.4}_{-0.8})^\circ$

Measured:

$(84.1^{+3.7}_{-3.0})^\circ$

B→ρρ*:* New sheriff in town (since ~2004)



Gronau, London, Phys.Rev.Lett. 65 (1990)

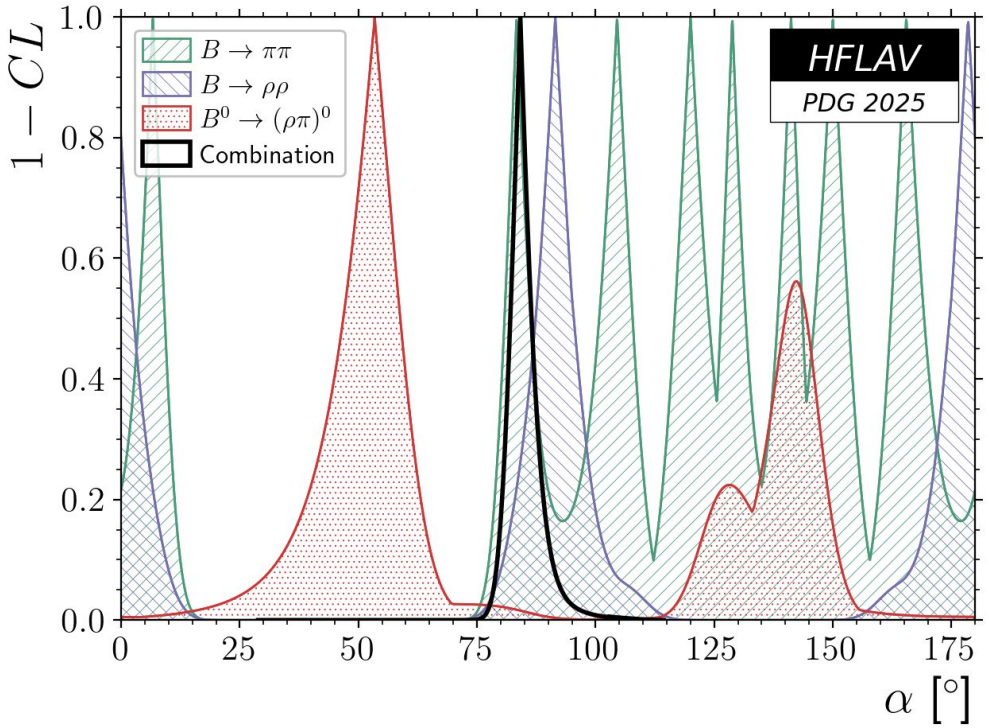
Falk at al., Phys.Rev.D 69 (2004)

Can Belle II make *ππ* better?

Determination of the CKM angle ϕ_2/α: All modes

The rho-rho peak is just between the two pi-pi peaks

But the rho-pi pushes the result to the left pi-pi peak



Measurement of t_{tag}

The t_{tag} measurement at *B* factories exploits:

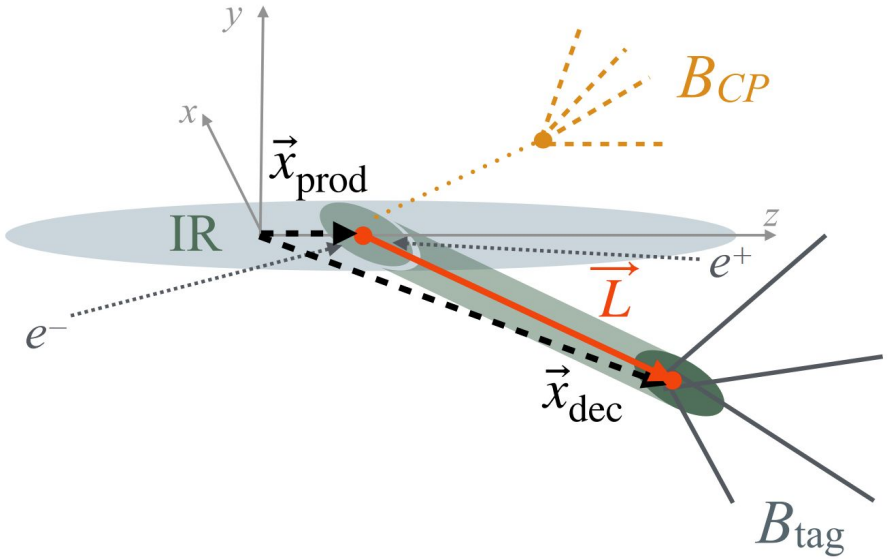
- The spatial distribution of the B_{tag} production point
  ("beam spot" measured in ee→μμ)
- B_{tag} decay point (=vertex)
- The knowledge of the B_{tag} momentum which is calculated from the B_{sig} momentum using momentum conservation

Vertex fit with beam spot and B_{tag} momentum constraint:

$$\chi^2 = (\vec{x}_{\rm prod} - \vec{x}_{\rm IR})^T V_{\rm IR}^{-1} (\vec{x}_{\rm prod} - \vec{x}_{\rm IR}) + (\vec{x}_{\rm dec} - \vec{x}_{B_{\rm tag}})^T V_{B_{\rm tag}}^{-1} (\vec{x}_{\rm dec} - \vec{x}_{B_{\rm tag}})$$

$$\vec{x}_{\rm dec} = \vec{x}_{\rm prod} + \frac{t_{\rm tag}}{m_B} \vec{p}_{\rm tag}$$

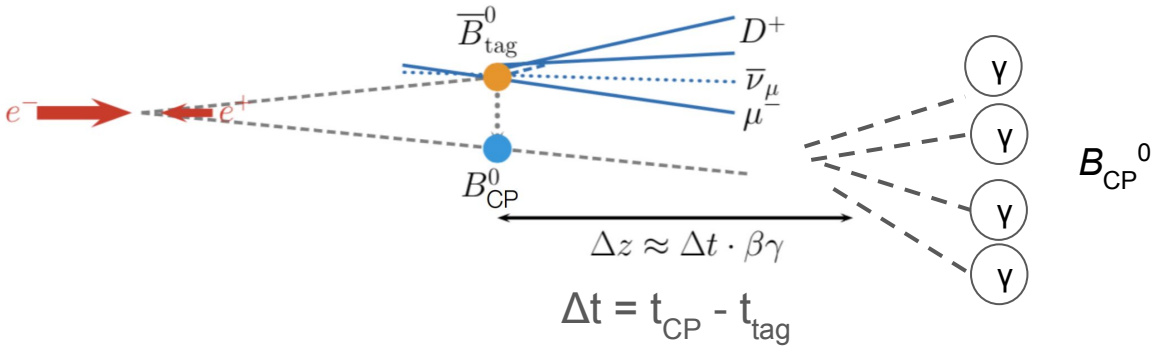
$$t_{\rm tag} = m_B \frac{\vec{L} \cdot \vec{p}_{\rm tag}}{|p_{\rm tag}|^2}$$



Determination of both t_{tag} and its uncertainty, exploiting all information we have

$B^0 \to \pi^0 \pi^0$: a decay without signal vertex

Signal final state comprised of 4 photons from two π^0 decays



$\Delta z = z_{CP} - z_{tag}$ cannot be measured → $\Delta t = \beta\gamma\, \Delta z$ cannot be measured → ? → *S* cannot be measured

First measurement of mixing-induced *CPV* in $B^0 \to \pi^0\pi^0$ and new results on *B*/*D CPV* at Belle and Belle II

Radek Žlebčík (INFN Trieste)

on behalf of the Belle and Belle II Collaborations

Moriond EW
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