Time-dependent *CP*-violation and charmless decays

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Moriond EW 2022, La Thuile

Belle II

MAX-PLANCK-INSTITUT FÜR PHYSIK

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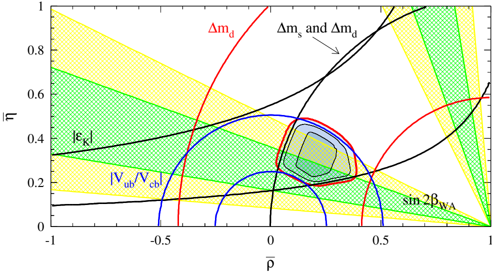
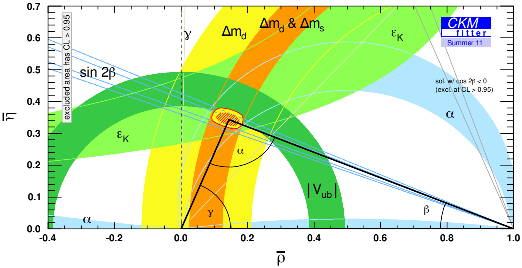
CP-violation from the perspective of Belle II

BaBar and Belle collected data between 1999 and 2010. Using CP-violation measurements with B mesons, they experimentally established the CKM structure of the SM.

2000



2011 (pre LHCb)



Belle II will collect a dataset much larger than Belle's, will be able to:

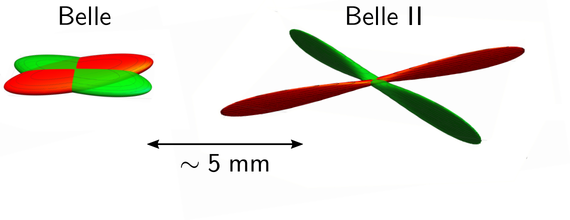
- Refine measurements of the CKM triangle;
- More generally, put the SM at test using CP-violation.

Main strength of B factories vs LHC: clean environment with constrained kinematics
$\Rightarrow$ can analyse a wider range of B decays, in particular with neutrals (π^0, γ, K_L...)

Belle II and SuperKEKB

SuperKEKB e^+e^- collider achieves higher instant luminosity using so-called nano beam scheme.

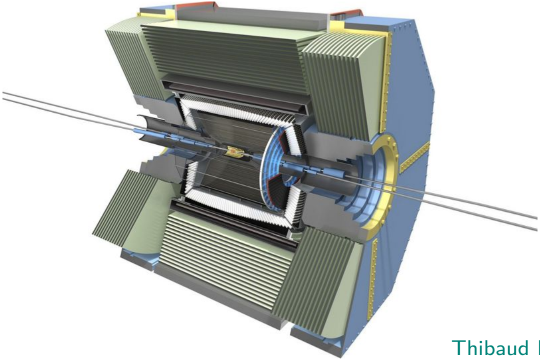
- Goal: $L = 6 \times 10^{35}$ cm$^{-2}s^{-1}$ (30$\times$ Belle)
- Achieved: 3.8×10^{34} cm$^{-2}s^{-1}$ World record!



Belle II: all sub-detectors underwent a major upgrade from Belle, improving performance in spite of higher beam background, *e.g.*:

⇒ Enhanced K/π separation

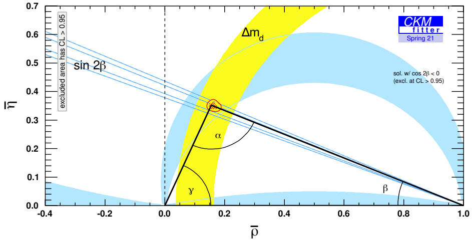
⇒ Improved vertex resolution (more later...)



Outline

Today: 4 Belle II brand new measurements related to CKM studies or *CP*-violation, using 190 fb^{-1} of Belle II data collected until November 2021 ($1/4^{\mathrm{th}}$ of Belle dataset).

- *CP* asymmetry in $B^+ \to \rho^+ \rho^0$ (α)
- B^0 lifetime and oscillation frequency
- *CP* asymmetry with $B^0 \to K_S \pi^0$
- $B^0 \to K_S \pi^0 \gamma$ branching fraction



Measurements related to CKM angle γ covered later by Riccardo Manfredi.

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

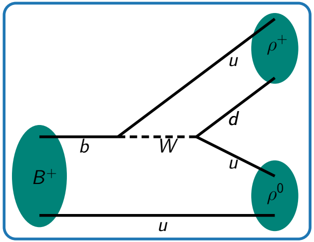
Can access CKM angle α using combination of three decays:

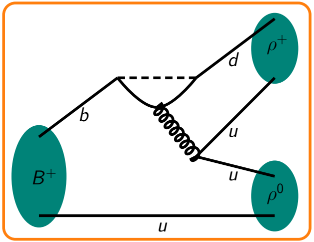
$$B^+ \to \rho^+(\to \pi^+\pi^0)\rho^0(\pi^+\pi^-),\ B^0 \to \rho^0\rho^0,\ B^0 \to \rho^+\rho^-$$

Belle II is a unique place to measure all three!

To do that, measure direct CP-asymmetry in decays where ρ^+ and ρ^0 are longitudinally polarised, need:

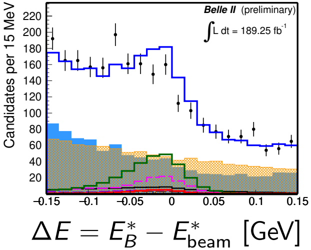
1) Longitudinal polarization fraction f_L;
   $\Rightarrow$ Get it from distribution of helicity angles of the π^+s
2) Asymmetry in rate $B^+ \to \rho^+\rho^0$ vs $B^- \to \rho^-\rho^0$
   $\Rightarrow$ Direct CP-violation from interference between tree and penguin





New $B^+ \to \rho^+\rho^0$ angular analysis

- Large background from $e^+e^- \to u\bar{u},\ d\bar{d},\ c\bar{c},\ s\bar{s}$.
- ⇒ Reduced with multavariate algorithm
- 6D template fit taking correlations into account
- ⇒ Templates from MC, calibrated using control channels
- Instrumental asymmetry measured with $D^+ \to K^0_S\pi^+$:
- ⇒ $A_{\text{det}} = 0.0040 \pm 0.0048$



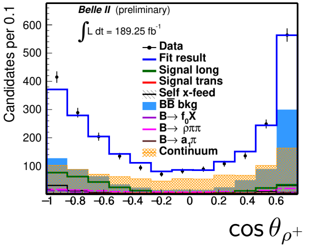
Result compatible with previous measurements:

$$A_{\text{CP}} = -0.069 \pm 0.068\ (\text{stat.}) \pm 0.060\ (\text{syst.})$$

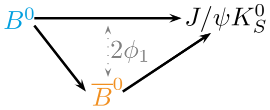
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = \left(23.2^{+2.2}_{-2.1}\ (\text{stat.}) \pm 2.7\ (\text{syst.})\right) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033}\ (\text{stat.}) \pm 0.027\ (\text{syst.})$$

World average: $A_{\text{CP}} = -0.05 \pm 0.05$



Time-dependent analyses

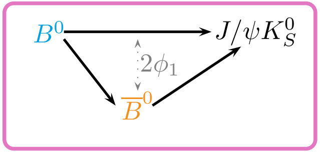


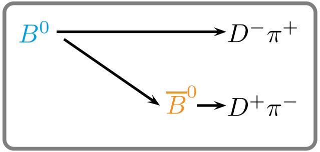
***CP*-asymmetry in interference between mixing and decay:**

$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{N(B^0 \to f_{\mathrm{CP}}) - N(\overline{B}^0 \to f_{\mathrm{CP}})}{N(B^0 \to f_{\mathrm{CP}}) + N(\overline{B}^0 \to f_{\mathrm{CP}})}(t) = (S_{\mathrm{CP}} \sin(\Delta m_d t) + A_{\mathrm{CP}} \cos(\Delta m_d t))$$

with S_{CP}: time-dependent asymmetry and A_{CP}: direct CP-asymmetry.

Time-dependent analyses





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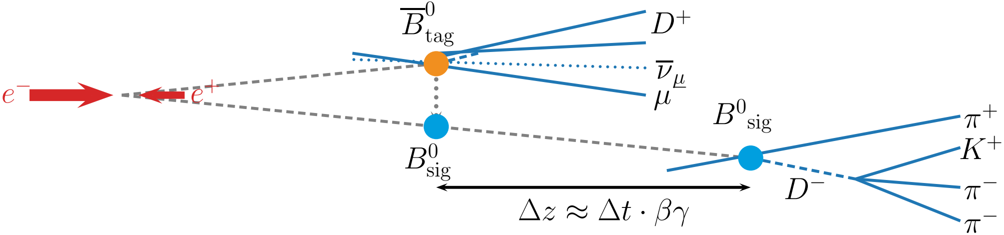
B^0-$\overline{B}^0$ mixing:

$$\mathrm{mix}(t) = \frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)}(t) = \cos(\Delta m_d t)$$

with Δm_d the oscillation frequency.

Time-dependent analyses at the B factories



Critical for good time-dependent measurements:

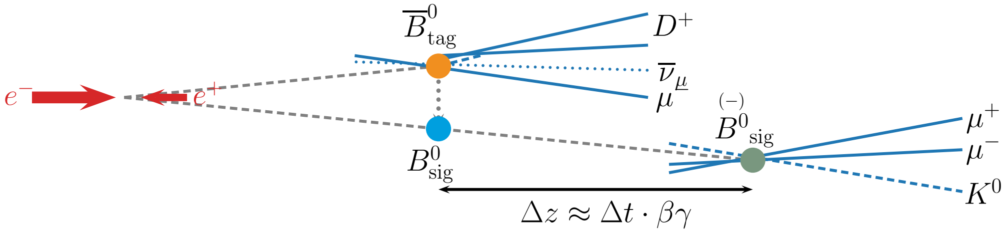
- Good vertex resolution
- High tagging efficiency ε_{tag}

Belle II: $\varepsilon_{\text{tag}} = (30.0 \pm 1.3)\%$
Belle : $\varepsilon_{\text{tag}} = (30.1 \pm 0.4)\%$

arXiv:2110.00790

Today: precision oscillation frequency and lifetime measurement.

Time-dependent analyses at the B factories



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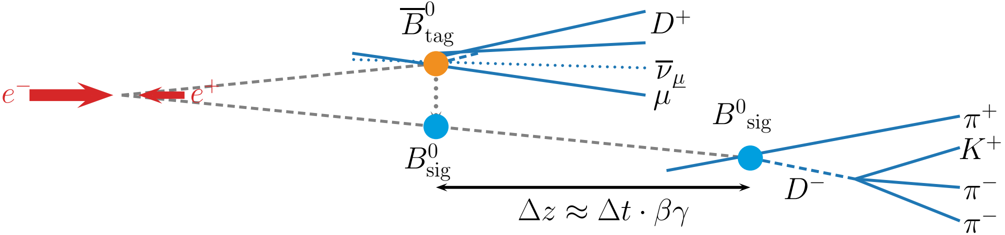
Today: precision oscillation frequency and lifetime measurement.

Also a crucial foundation for flagship measurement of $S_{\text{CP}} = \sin 2\beta$ with $B^0 \to J/\psi K_S$, which uses $10\times$ smaller dataset.

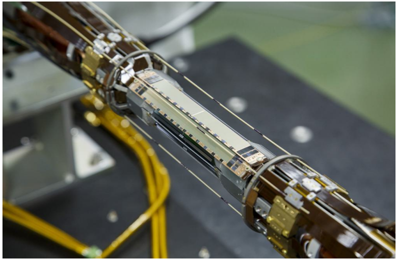
Time-dependent *CP*-violation at the *B* factories



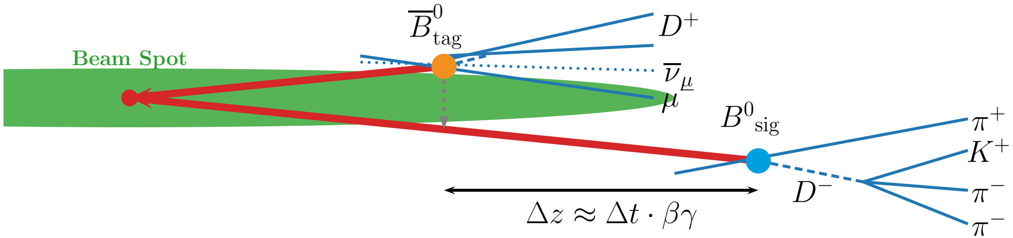
New beam scheme means reduced boost wrt Belle:

$$\beta\gamma = 0.43 \longrightarrow \beta\gamma = 0.29$$
$$\Delta z \approx 200\ \mu\text{m} \longrightarrow \Delta z \approx 130\ \mu\text{m}$$

$\Rightarrow$ added a pixel detector directly around the beam pipe (radius $\approx$ 1.4 cm) to recover precision on Δt.



Time-dependent *CP*-violation at the *B* factories



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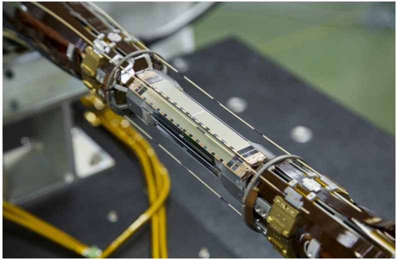
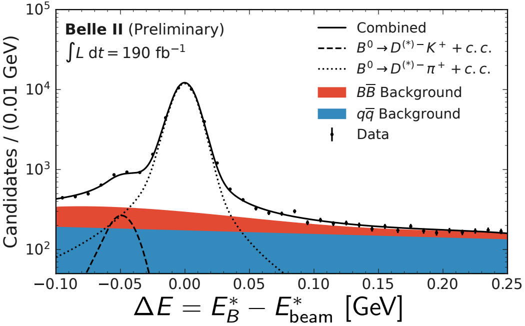
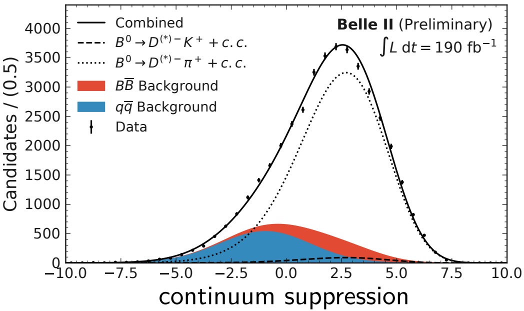


Use beam spot profile to increase precision on vertex fit
$\Rightarrow$ new beam scheme means smaller beam spot and stronger constraint

New mixing and lifetime measurement: backgrounds





Use $\sim 40k$ decays reconstructed from hadronic $B^0 \to D^{(*)-}\pi^+/K^+$ modes.

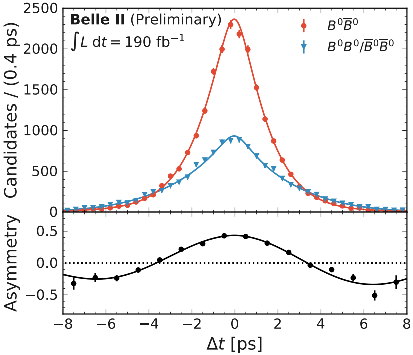
2 backgrounds: $e^+e^- \to q\overline{q}$ and misreconstructed $e^+e^- \to B\overline{B}$
Discriminate signal and backgrounds using ΔE and event-shape multivariate classifier.

1. Subtract backgrounds from sidebands (sWeights) to obtain background-free signal sample.
2. Fit background-subtracted Δt distribution, with a model taking into account wrong-tag fraction and finite vertex resolution

New mixing and lifetime measurement: result

Result compatible with world average:

$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})\ \text{ps},$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat.}) \pm 0.005\,(\text{syst.})\ \text{ps}^{-1}.$$



Compared to Belle and BaBar's best measurement:

- Slightly worse stat. uncertainty because not using $B^0 \to D^{*-}\ell^+\nu$ modes yet.
- better alignment and background systematics.
- comparable resolution modelling systematics.

Milestone in Belle II program: we are fully ready for time dependent analyses!

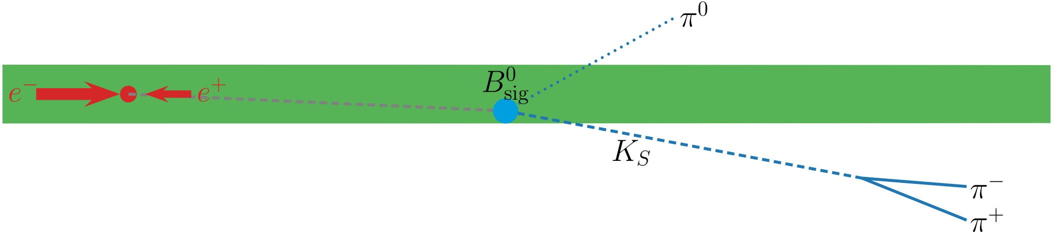
Next steps: τ, Δm_d with $B^0 \to D^{*-}\ell^+\nu$ and competitive $\sin 2\beta$ measurement.

$B^0 \to K_S \pi^0$ and $K\pi$ puzzle

$B \to K\pi$ decay are rare, therefore sensitive to New Physics. In particular, long-standing discrepancy in Isospin sum rule:[1]

$$2A_{\mathrm{CP}}(B^0 \to K^+\pi^-) + 1.3A_{\mathrm{CP}}(B^+ \to K_S\pi^+) - 1.2A_{\mathrm{CP}}(B^+ \to K^+\pi^0) - A_{\mathrm{CP}}(B^0 \to K_S\pi^0) \approx 0$$

Uncertainty on this null test dominated by $A_{\mathrm{CP}}(B^0 \to K_S\pi^0)$, only feasible at Belle II.



Need good performance with neutrals and beam spot constraint.

[1] More accurate formula takes into account branching fractions and lifetimes

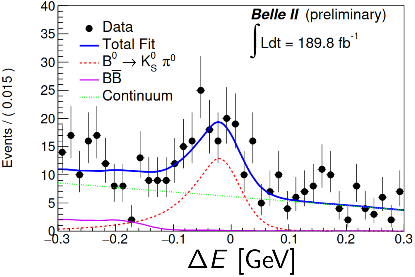
New $K_S\pi^0$ $A_{\rm CP}$ measurement

Perform 4D fit (including Δt and ΔE)

Use $B^0 \to J/\psi(\mu^+\mu^-)K_S$ to calibrate Δt shapes

Wrong-tag fraction measured from mixing measurement

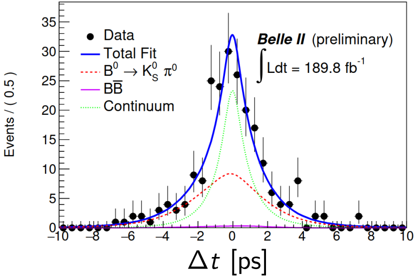
Constrain $S_{\rm CP}$ using previous measurements to maximise precision on $A_{\rm CP}$.



Result:

$$A_{\rm CP} = -0.41^{+0.30}_{-0.32}\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$

$$\mathcal{B} = (11.0 \pm 1.2\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-6}$$



World average: $A_{\rm CP} = 0.00 \pm 0.13$.

New $B^0 \to K_S^0\pi^0\gamma$ branching fraction measurement

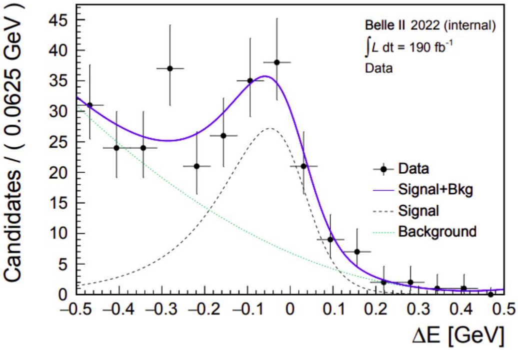
In the SM, γ is RH in $B^0 \to K_S^0\pi^0\gamma$ and LH in $\overline{B}^0 \to K_S^0\pi^0\gamma$
$\Rightarrow$ expect no time-dependent asymmetry in $B^0 \to K_S^0\pi^0\gamma$.
However, can occur in BSM models with different chirality structure.

Belle II unique place where to measure asymmetry.

In preparation for time-dependent analysis, performed branching fraction measurement:

$$\mathcal{B} = (7.3 \pm 1.8\,(\text{stat.}) \pm 1.0\text{ syst}) \times 10^{-6}$$

Compatible with world average
$\mathcal{B} = (7.0 \pm 0.4) \times 10^{-6}$



Conclusions and prospects

Start of a new chapter for Belle II B physics program.

Today:

- Angular CP-violation analysis with $B^+ \to \rho^+\rho^0$;
- Precision time-dependent lifetime and B^0 oscillation frequency measurement;
- Measurements using modes with many neutrals.

To come soon:

- Refined CP-violations analyses with higher statistical power and more decay modes;
- Competitive measurement of CKM angle β.

Looking further into the future: improving analyses techniques, *e.g.*:

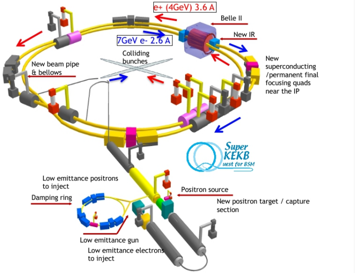
- Dalitz analyses with 3-body charmless modes;
- Improving flavour tagger performance and vertex-related systematics;

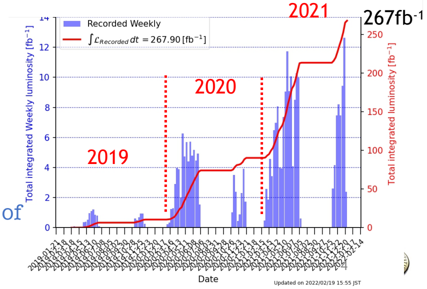
$\Rightarrow$ preparing to attack systematic limit on β.

Backup

The SKB/Belle II program

- Phase 1(2016): no detector, no collision, test the rings
- Phase 2 (2018): first collisions with complete accelerator
  - Incomplete detector: Vertex detector replaced by dedicated background detector (Beast 2)
- Phase 3 (2019-): luminosity run with complete detector
  - Pixel Detector (PXD): layer 1 + only 2 ladders in layer 2
  - Full 4-layers strip detector (SVD)
  - First physics paper appeared in January 2020
- New and difficult accelerator. Additional operational complexity during the pandemic.
- Record peak luminosity $3.81 \times 10^{34} cm^{-2}s^{-1}$.
- Path to reach $2 \times 10^{35} cm^{-2}s^{-1}$ identified.
- Still large factors to reach the target peak luminosity of $6.5 \times 10^{35} cm^{-2}s^{-1}$.





Short term luminosity projections

- Base scenario: conservative extrapolation of SKB parameters from 2021
- Target scenario: extrapolation including possible improvement during LS1
- LS1 starts in summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement work on machine and detector.
- We resume machine operation from fall 2023.
- An International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.