B-lifetime and time-dependent CP-violation measurement at Belle II

Thibaud Humair, on behalf of the Belle II collaboration
thumair@mpp.mpg.de

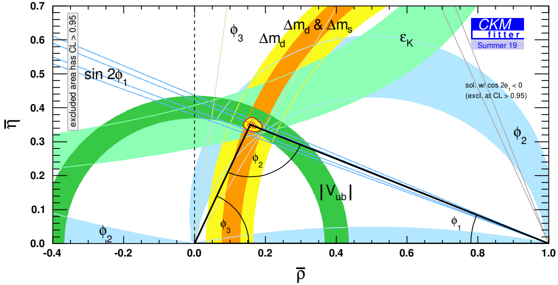
Beauty 2020, Tokyo IPMU

MAX-PLANCK-INSTITUT
FÜR PHYSIK

22nd September, 2020

Status of $\sin 2\phi_1$ measurements

In the SM, CP violation arises via non-zero phase in CKM matrix...
... or equivalently: CKM triangle has non-zero area;
Over-constraining the CKM triangle by measuring its sides and angles provides a stringent precision test of the Standard Model.

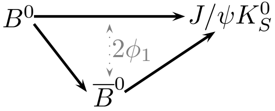


Today: focus on Belle II's preparation for precision measurement of $\sin 2\phi_1$

- World average: $\sin 2\phi_1 = 0.699 \pm 0.017$ (HFLAV2019)
- Result using full Belle dataset: $\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012$ (PRL108(2012)171802)
- Final aim at Belle II: reduce uncertainty by factor ~ 5 to reach $\sim 0.5\%$ precision.

CP violation in interference between mixing and decay

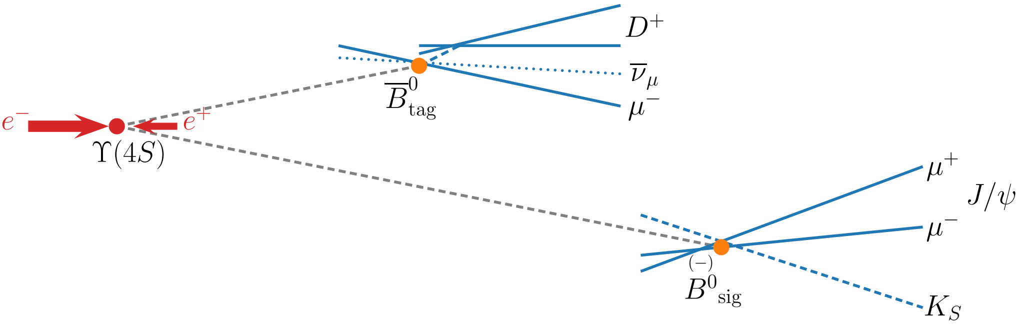
CKM parameter ϕ_1 is accessible using B^0 decays to CP-eigenstates such as $J/\psi K_S^0$;



Measure asymmetry between number of $B^0 \to J/\psi K_S^0$ and $\overline{B}^0 \to J/\psi K_S^0$ decays as a function of the B^0 decay time.

$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{\mathcal{B}(\overline{B}^0 \to J/\psi K_S^0)(t) - \mathcal{B}(B^0 \to J/\psi K_S^0)(t)}{\mathcal{B}(\overline{B}^0 \to J/\psi K_S^0)(t) + \mathcal{B}(B^0 \to J/\psi K_S^0)(t)} = \sin(2\phi_1)\sin(\Delta m_d t)$$

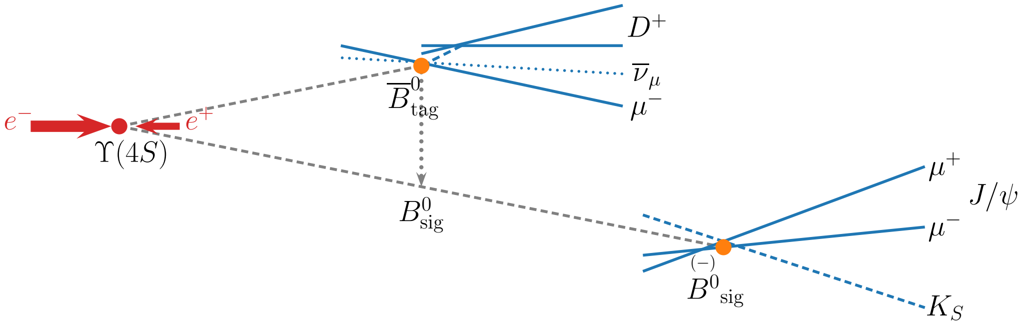
Time dependent CP violation at the B factories



Three main ingredients are necessary for precise ϕ_1 measurement in a B factory environment:

1. Large dataset, $\mathcal{B}(B^0 \to J/\psi(\ell^+\ell^-)K^0_S(\pi^+\pi^-)) \approx 3.6 \times 10^{-5}$;
2. Precise decay-time difference Δt measurement;
3. Good flavour tagging performance.

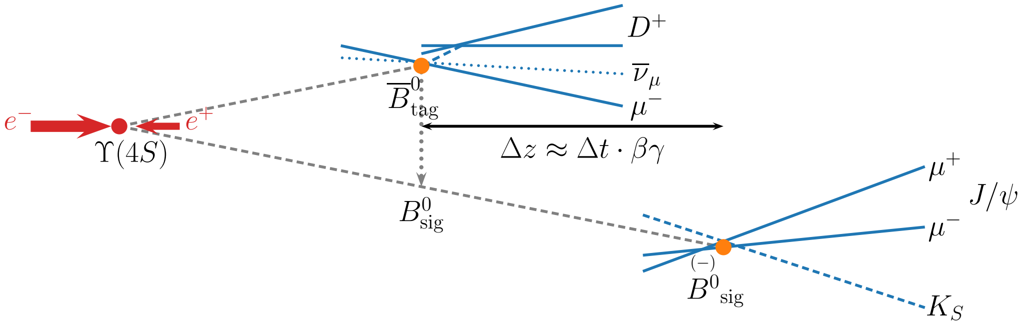
Time dependent CP violation at the B factories



Three main ingredients are necessary for precise ϕ_1 measurement in a B factory environment:

1. Large dataset, $\mathcal{B}(B^0 \to J/\psi(\ell^+\ell^-)K^0_S(\pi^+\pi^-)) \approx 3.6 \times 10^{-5}$;
2. Precise decay-time difference Δt measurement;
3. Good flavour tagging performance.

Time dependent CP violation at the B factories



Three main ingredients are necessary for precise ϕ_1 measurement in a B factory environment:

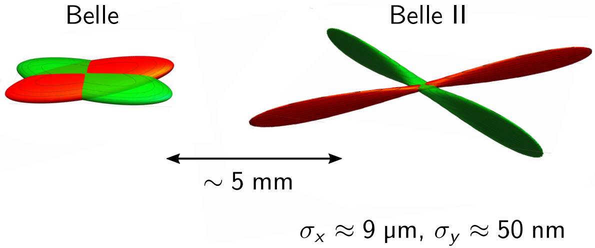
1. Large dataset, $\mathcal{B}(B^0 \to J/\psi(\ell^+\ell^-)K^0_S(\pi^+\pi^-)) \approx 3.6 \times 10^{-5}$;
2. Precise decay-time difference Δt measurement;
3. Good flavour tagging performance.

Achieving high luminosity at Belle II

Belle II will achieve a very high luminosity using so-called nano-beam scheme.

Final Belle II goal wrt Belle:

- $40\times$ peak luminosity (6×10^{35} cm^{-2}s^{-1});
- $50\times$ integrated luminosity (50 ab^{-1}).



So far achieved:

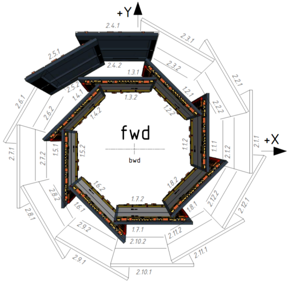
- Peak luminosity:
  2.4×10^{34} cm^{-2}s^{-1}, world record!
- Integrated luminosity for physics data recorded between February 2019 and July 2020:
  74.1 fb^{-1} ($\sim 1/10$ of Belle)

Boost and Δt precision

Belle II has a reduced boost compared to Belle:

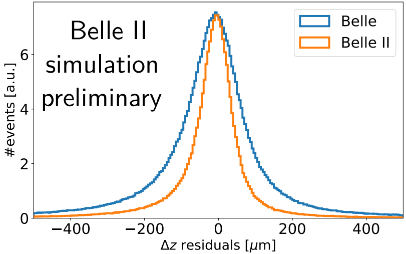
$$\beta\gamma = 0.43 \longrightarrow \beta\gamma = 0.29$$

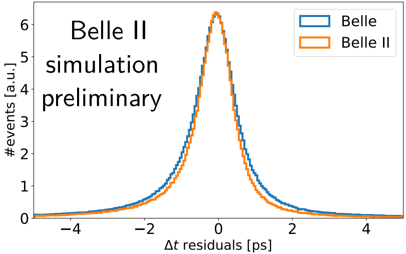
$\Rightarrow$ added a two-layer pixel detector directly around the beam pipe (radius ≈ 1.8 cm) to recover precision on Δt.



Second layer partially installed. One layer is currently enough as the machine needs time to ramp up to the nominal luminosity.

Simulation studies show the precision on Δt should be comparable to that of Belle:





Lifetime measurement

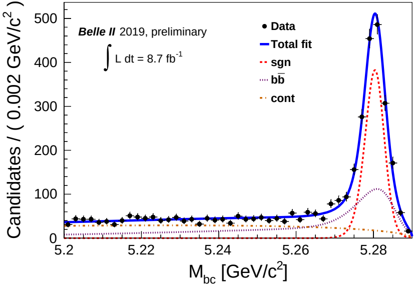
arXiv:2005.07507

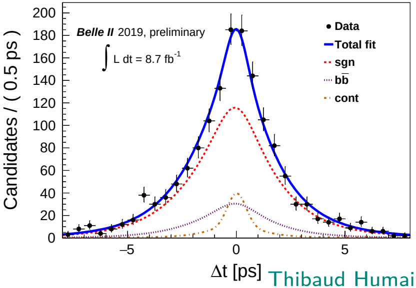
B^0 lifetime measured using 2019 data (8.7 fb^{-1}). Important test of Belle II time measurement capabilities with real data.

- Use hadronic B^0 decays: $B^0 \to D^{(*)-}\pi^+$ and $B^0 \to D^{(*)-}\rho^+$;
- Select events based on PID, kinematic and event shape variables;
- Perform kinematic fit to extract signal fraction; shown here: fit to $M_{bc} = \sqrt{E^2_{beam} - p^2_B}$
- Perform fit to the Δt distribution to extract lifetime;

Result:

$$\tau_{B^0} = 1.48 \pm 0.28 \pm 0.06 \;\; \text{ps}$$





Flavour tagger performance

Flavour tagger performance characterised by

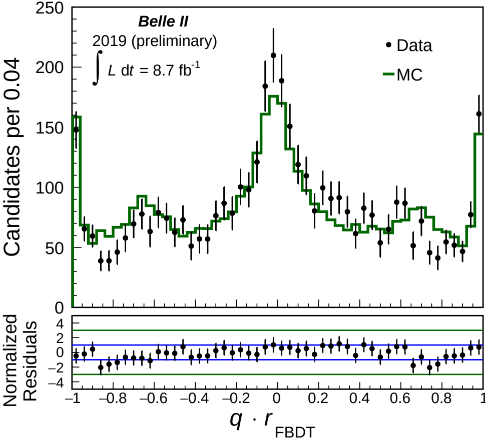
- wrong tag fraction w;
- effective efficiency $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} \cdot (1 - 2w)^2$.

w is measured with 2019 data, time-integrated:

- Reconstruct signal in flavour specific $B^0 \to D^{(*)-} h^+$ final states;
- Measure asymmetry between mixed/unmixed events:

$$\frac{N(B\overline{B}) - N(BB, \overline{BB})}{N(B\overline{B}) + N(BB, \overline{BB})} = (1-2w)(1-2\chi_d)$$

(χ_d mixing prob from PDG)



($r_{\text{FBDT}} \approx 1 - 2w$)

Find ε_{eff} compatible with Belle:

Belle: $\varepsilon_{\text{eff}} = (30.1 \pm 0.4)\%$, Belle II: $\boldsymbol{\varepsilon_{\text{eff}} = (33.8 \pm 3.9)\%}$

Belle II first time-dependent CPV measurement

Using 8.7 fb^{-1} of data, could show that Belle II performs well in measuring decay time and in flavour tagging.
$\Rightarrow$ use 34.6 fb^{-1} to perform first time-dependent CPV measurement.

Use signal $B^0 \to J/\psi K_S$ with $J/\psi \to \mu^+\mu^-,\ e^+e^-$ to measure

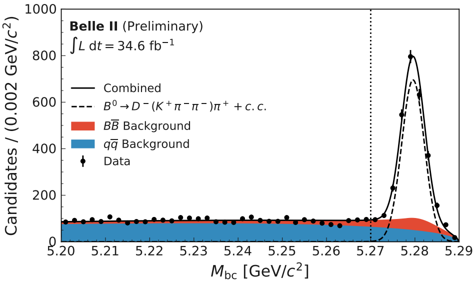
$$a_{\mathrm{CP}}(\Delta t) = \frac{N(B^0_{\text{tag}}) - N(\overline{B}^0_{\text{tag}})}{N(B^0_{\text{tag}}) + N(\overline{B}^0_{\text{tag}})}(\Delta t) = \sin(2\phi_1)\sin(\Delta m_d \Delta t)(1-2w) * \mathcal{R}(\Delta t),$$

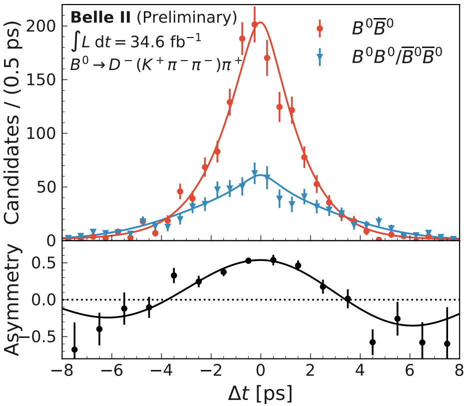
where a_{CP} is the raw asymmetry and $\mathcal{R}$ the Δt resolution function.

w is extracted by performing a time-dependent measurement of the mixing probability using $B^0 \to D^-\pi^+$ as flavour specific signal:

$$p_{\text{mix}}(\Delta t) = \frac{N(B\overline{B}) - N(BB, \overline{BB})}{N(B\overline{B}) + N(BB, \overline{BB})}(\Delta t) = \cos(\Delta m_d \Delta t)(1-2w) * \mathcal{R}(\Delta t)$$

Time-dependent mixing result

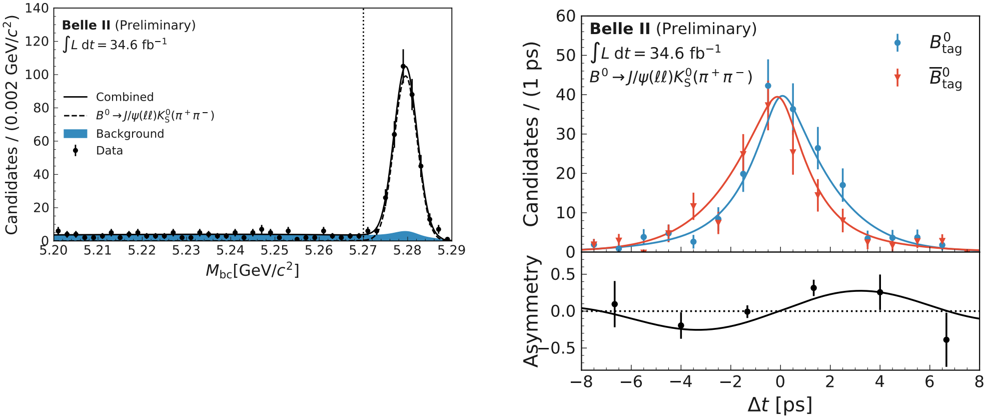




$$\mathbf{\Delta m_d = (0.531 \pm 0.046\ (stat.) \pm 0.013\ (syst.))\ ps^{-1}}$$

Compatible with PDG: $\Delta m_d = (0.5065 \pm 0.0019)\ \text{ps}^{-1}$.

Time-dependent CP-violation result



$$\mathbf{\sin(2\phi_1) = \ 0.55 \ \pm \ 0.21\ (stat.) \ \pm \ 0.04\ (syst.)}$$

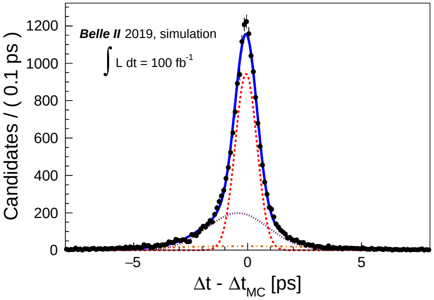
Belle II already able to see first 2.7 σ hint for time-dependent CPV!

Towards precision measurements

The Belle II measurements presented so far show that the detector performs well and as expected.
$\Rightarrow$ next step is to get ready for precision measurements!

This involves:

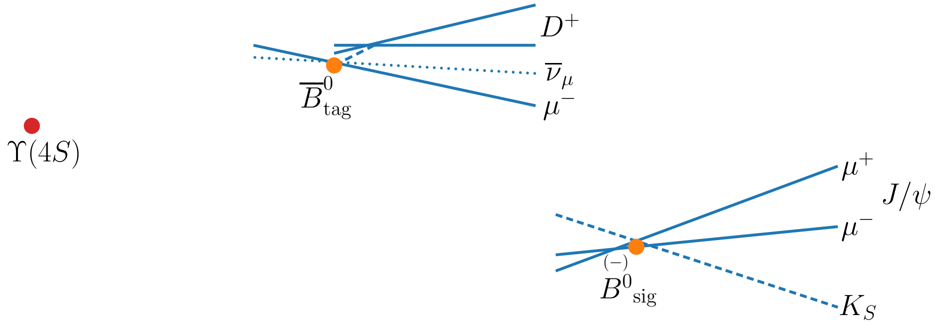
- Refining description of the Δt resolution. So far simple 1D model is used, a more complex parametric model can be used to reduce detector-related systematics;
- Adding other modes, i.e. $\psi(2S)K_S$, $J/\psi K_L$, $J/\psi K^*(K_S\pi^0)$, etc;
- Improving vertex resolution;
- ...



Beam spot constraint

Time-dependent measurements can benefit from the small beamspot.

- Measure beam spot size and position using $ee \to \mu\mu$ events;
- Use momentum conservation to constrain B^0_{tag} vertex.

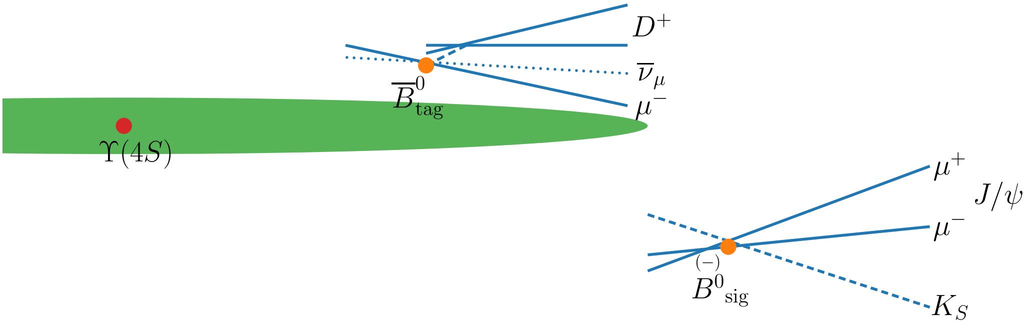


Will be utilised in future analyses to improve Δt resolution.

Beam spot constraint

Time-dependent measurements can benefit from the small beamspot.

- Measure beam spot size and position using $ee \to \mu\mu$ events;
- Use momentum conservation to constrain $B^0_{\rm tag}$ vertex.

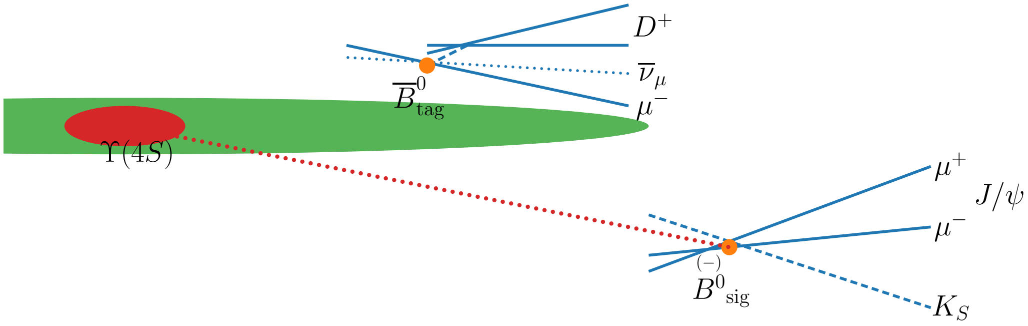


Will be utilised in future analyses to improve Δt resolution.

Beam spot constraint

Time-dependent measurements can benefit from the small beamspot.

- Measure beam spot size and position using $ee \to \mu\mu$ events;
- Use momentum conservation to constrain B^0_{tag} vertex.

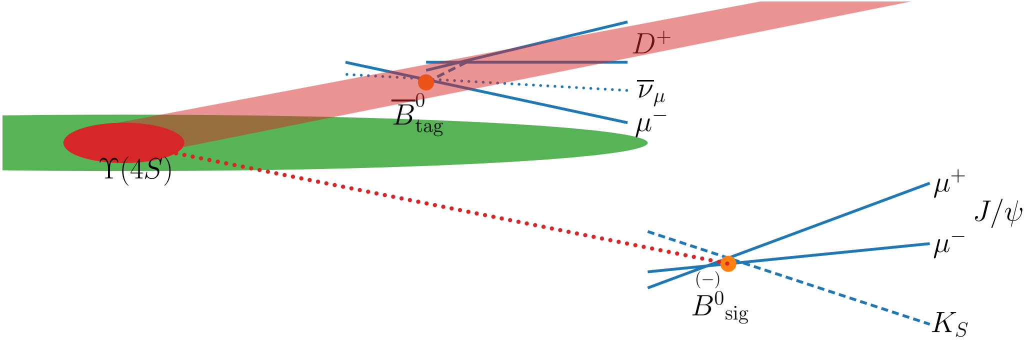


Will be utilised in future analyses to improve Δt resolution.

Beam spot constraint

Time-dependent measurements can benefit from the small beamspot.

- Measure beam spot size and position using $ee \to \mu\mu$ events;
- Use momentum conservation to constrain B^0_{tag} vertex.



Will be utilised in future analyses to improve Δt resolution.

Charmless modes

arXiv:2008.03873, BELLE2-NOTE-PL-2020-003

Analyses of charmless B^0 decays interesting:

small branching-fraction $\Rightarrow$ potentially sensitive to NP

Look for differences wrt $J/\psi K_S$ mode in TDCPV analysis.

Full analyses require more data, but some work started:

$\boldsymbol{B^0 \to \eta' K_S}$ **:**

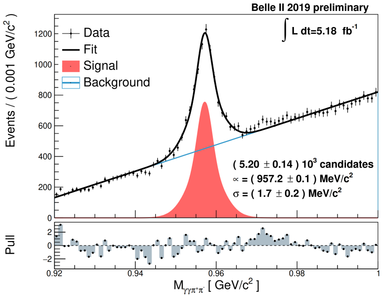
- Rediscovery of the $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ decay.

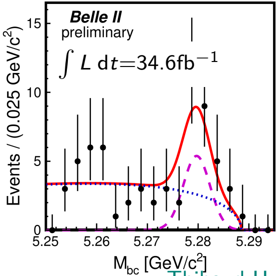
$\boldsymbol{B^0 \to \phi(K^+K^-)K^{(*)0}}$ **:**

- Used multivariate selection to rediscover this mode;
- Fitted K^+K^- helicity angle to isolate ϕ (P-wave);

$\rightarrow$ necessary for time dependent study as P- and S-wave have difference CP eigenvalues.

(See Yun-Tsung Lai's talk for more detail)





Conclusions and outlook

Using up to 34.6 fb^{-1} of data (out of 74.1 fb^{-1} recorded), Belle II has shown:

- Good vertex resolution and ability to measure B lifetime;
- Good flavour tagging performance;
- Ability to perform complete time-dependent CPV analyses.

We are now accumulating more data and improving our analysis techniques to:

- Perform precision measurements of the flavour parameters;
- Analyse rare modes sensitive to New Physics.

So far Belle II performs nominally in all aspects of TDCPV analyses.
Getting ready for the ultimate precision!