TDCPV overview

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Belle II

MAX-PLANCK-INSTITUT
FÜR PHYSIK

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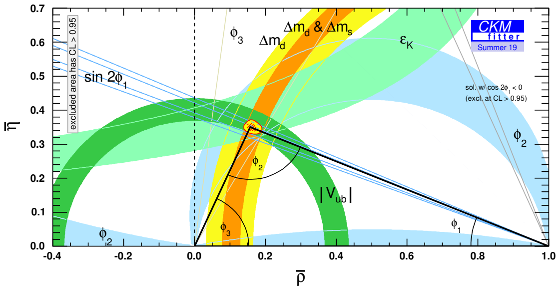
Status of $\sin 2\phi_1$ measurements

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.



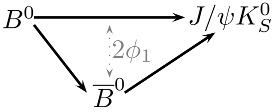
This talk: focus on measurements sensitive to $\sin 2\phi_1$:

- 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 5-10 to reach $\sim 0.5\%$ precision.

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

CP violation in interference between mixing and decay

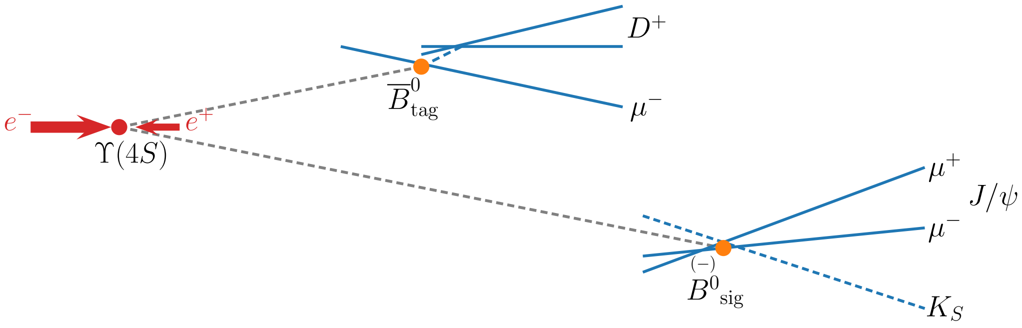
CKM parameter ϕ_1 is accessible using B^0 decays to CP-eigenstates such as $J/\psi K^0_S$;



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

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

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 $\Delta t = \Delta z/\beta\gamma$ measurement;
3. Good flavour tagging performance.

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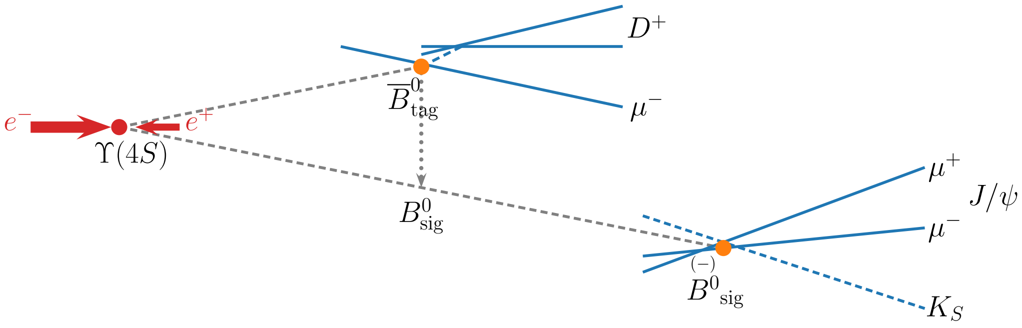

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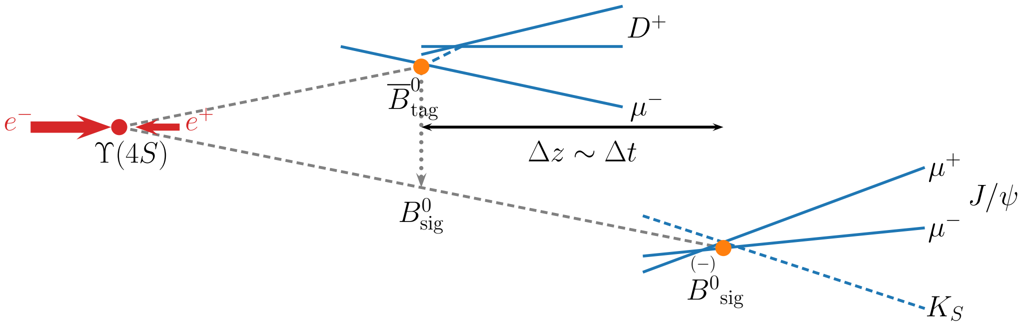

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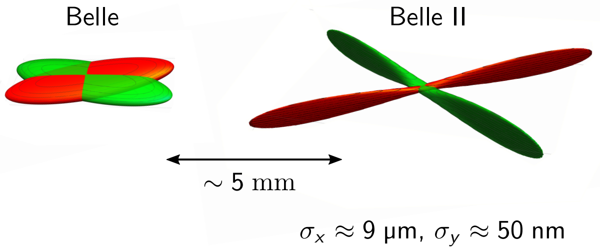
Achieving high luminosity at Belle II

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

Final Belle II goal wrt Belle:

- 40× peak luminosity ($8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$);
- 50× integrated luminosity ($50\ \mathrm{ab}^{-1}$).



So far achieved:

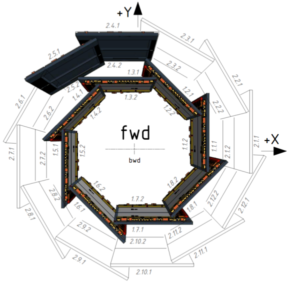
- Integrated luminosity for physics data recorded between February 2019 and July 2020: 74.1 fb^{-1} ($\sim 1/10$ of Belle)
- Today focus on time dependent measurements using part of this dataset.

Boost and Δt precision

Belle II has a reduced boost compared to Belle:

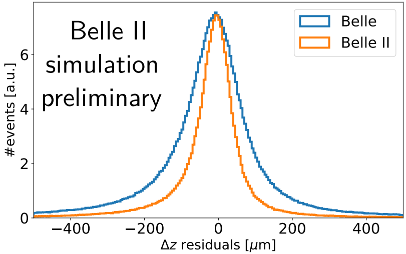
$$\beta\gamma = 0.43 \longrightarrow \beta\gamma = 0.29$$

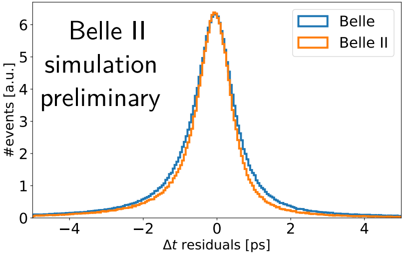
$\Rightarrow$ added a two-layer pixel detector to recover precision on Δt.



Second layer not yet fully installed but 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

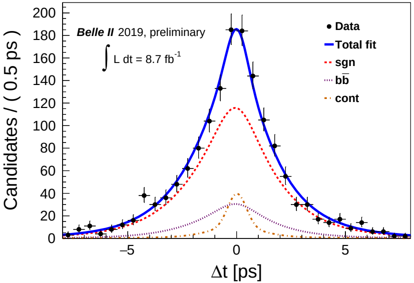
arXiv:2005.07507

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

- Use hadronic B^0 decays: $B^0 \to D^{(*)-}\pi^+$ and $B^0 \to D^{(*)-}\rho^+$;
- Perform fit to the Δt distribution to extract lifetime;

Result:

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



Flavour tagger performance

arXiv:2008.02707

Flavour tagger performance characterised by

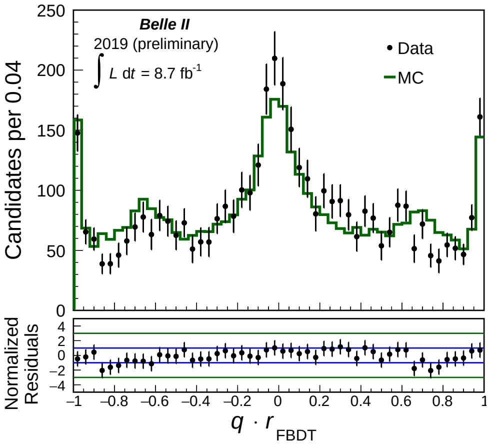
- wrong tag fraction w;
- effective efficiency $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} \cdot (1 - 2w)^2$.

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:

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

(χ_d mixing prob from PDG)



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

Dedicated talk by Justin on Tuesday.

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

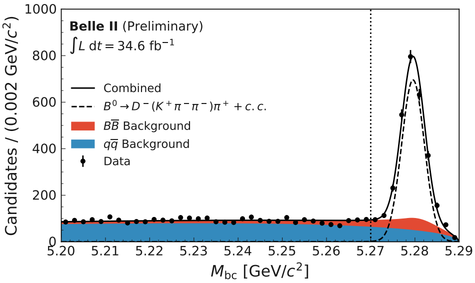
$$a_{\mathrm{CP}}(\Delta t) = \frac{N(B^0_{\mathrm{tag}}) - N(\overline{B}^0_{\mathrm{tag}})}{N(B^0_{\mathrm{tag}}) + N(\overline{B}^0_{\mathrm{tag}})}(\Delta t) = \sin(2\phi_1)\sin(\Delta m_d \Delta t)(1-2w) * \mathcal{R}(\Delta t),$$

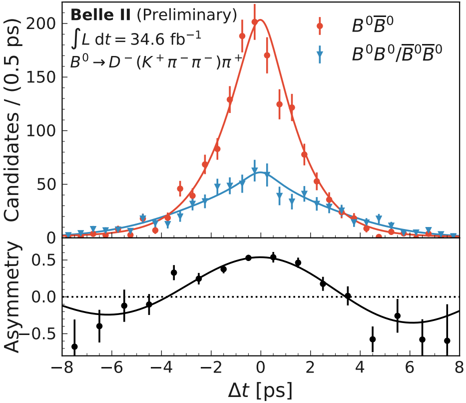
where a_{CP} is the raw asymmetry and $\mathcal{R}$ the Δt resolution function.

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

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

Time-dependent mixing result

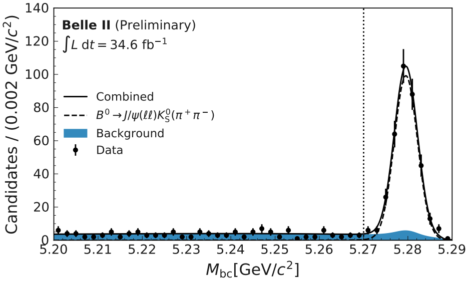


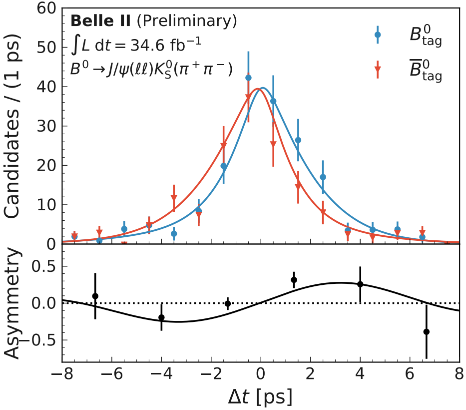


$$\boldsymbol{\Delta m_d = (0.531 \pm 0.046\,(\mathrm{stat}) \pm 0.013\,(\mathrm{syst}))\ \mathrm{ps}^{-1}}$$

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

Time-dependent CP-violation result





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

2.7 σ evidence for time-dependent CPV!

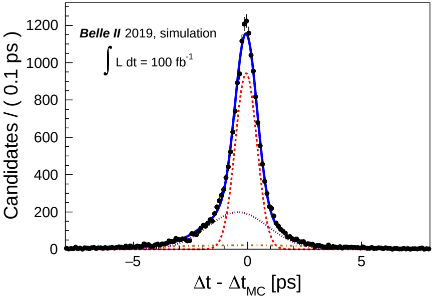
Towards precision measurements

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

With a few 100 fb^{-1}, can produce competitive τ and Δm_d measurements.
$\Rightarrow$ τ and Δm_d next milestone before $\sin 2\phi_1$.

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 (different approaches studied at MPI and Japan);
- Improving flavour tagger performance and precise calibration;
- Improving vertex resolution;
- ...



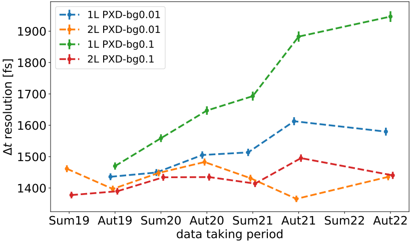
Impact of second PXD layer on Δt

Performed simulation study to assess impact of the 2nd PXD layer on the precision on Δt (MPI+DESY)
Caveat: Old simulation sample was used
$\longrightarrow$ For more precise results, should update beam parameters and background composition...
... but conclusions below unchanged:

- higher background $\Rightarrow$ higher probability to assign wrong PXD hit to track;
- With only one PXD layer, significant loss of performance within $\sim$ 2 years;
- Performance loss can be recovered with 2nd layer;

$\Rightarrow$ 2nd PXD layer crucial for time-dependent analyses in the future;

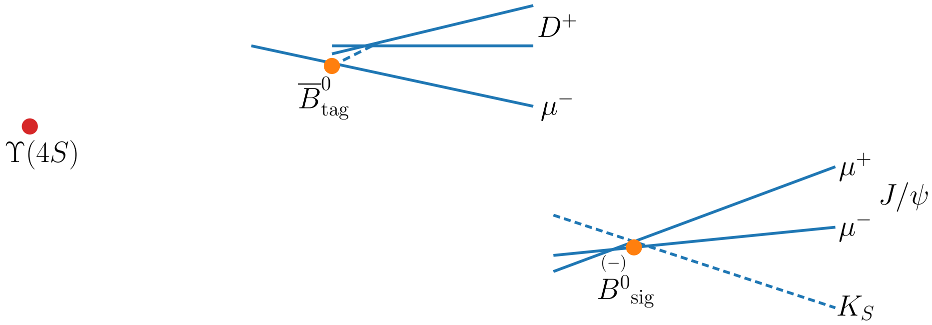
$\Rightarrow$ also crucial to understand how background in the PXD impacts the Δt resolution function.



Beam spot constraint

Time-dependent measurements can benefit from the small beamspot.

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



Work ongoing to implement this constraint for future measurements (MPI, DESY, Prague).

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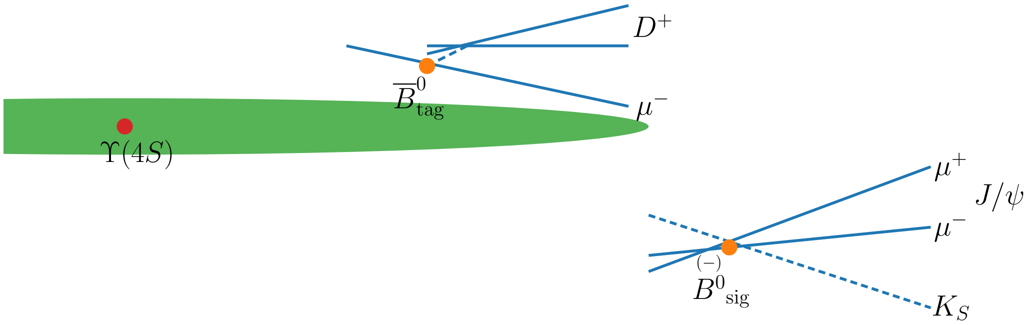

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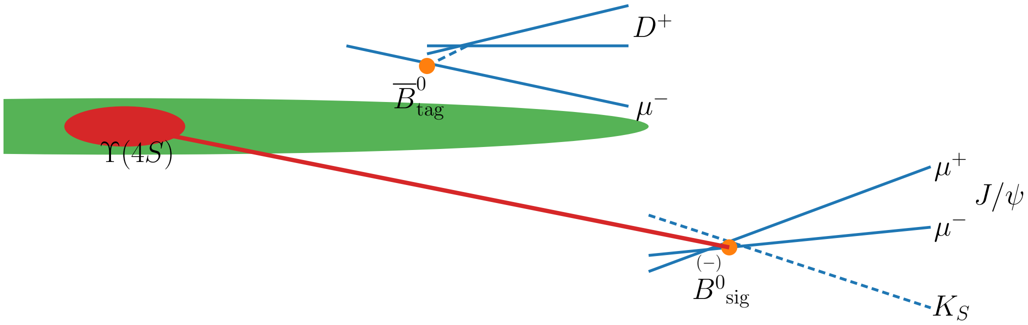

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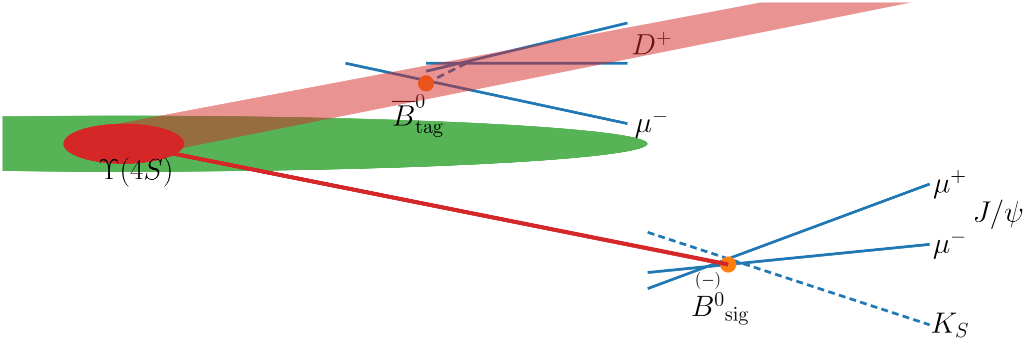

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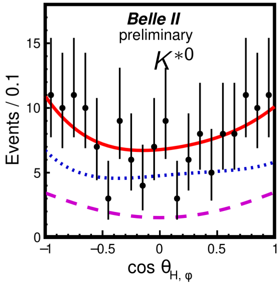
Other modes

So far in the talk, focused on studies with $B \to D^{(*)}h$ and $B^0 \to J/\psi K_S$ modes.
Lot of work is ongoing for time-dependent analyses of other modes, here some examples:

- Semileptonic $B \to D^{(*)}\ell\nu$ for flavour tagger calibration, Δm_d, τ, a_d^{sl} (mostly Japan);
- $B^0 \to J/\psi K_L$ (CP-odd equivalent to $J/\psi K_S$) (Italy);
- $B^0 \to J/\psi K^{*0}(K_S\pi^0)$ contains even and odd amplitudes, TD angular analysis started at MPI;
- Charmless modes (rare so potentially sensitive to New Physics): polarization fraction in $B^0 \to \phi K^*$ in arXiv:2008.03873;
- ...



Conclusions and outlook

Using up to 34.6 fb^{-1} of data, 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.

Work ongoing to:

- Prepare and calibrate tools required for precision time-dependent analyses

  vertex constraint, flavour tagger, etc.
- Prepare analyses of other abundant modes to increase precision on $\sin 2\phi_1$, or rarer modes to look for New Physics.

Important contributions of German groups in these different areas.