Mixing and mixing related CP violation in the B system

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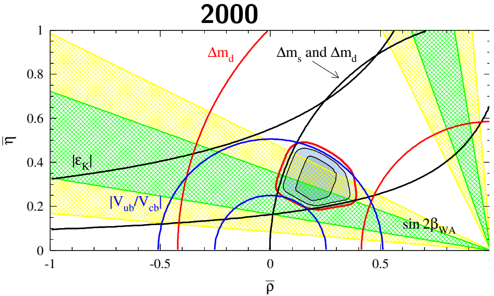
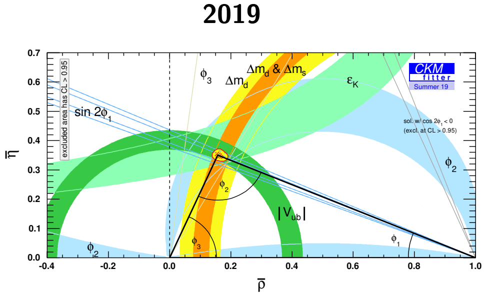
CKM measurements at the B factories

Using CPV measurements with B mesons, Belle and Babar experimentally established the CKM structure of the Standard Model.

After 20 years of Flavour Physics at the B factories and the LHC, CKM triangle known to good precision, but still space for $\mathcal{O}(15\%)$ New Physics contribution.





Belle II will collect a dataset $\sim 50\times$ the size of Belle's and will be able to improve CKM measurements significantly.

Today: recent Belle and Belle II measurements related to the angle ϕ_1 (β), accessible with time-dependent (TD) analyses

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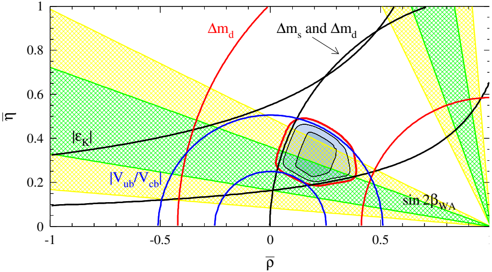
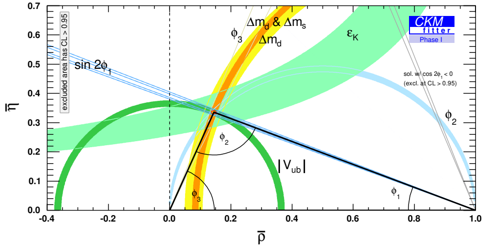
2000



2030?



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Today: recent Belle and Belle II measurements related to the angle ϕ_1 (β), accessible with time-dependent (TD) analyses

CP violation in interference between mixing and decay

CKM parameter ϕ_1 is accessible using B^0 decays to certain CP-eigenstates f_{CP}:

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & \arrow[d, phantom, "\phi_{\mathrm{mix}}"] & f_{\mathrm{CP}} \\ & \overline{B}^0 \arrow[ur] & \end{tikzcd}$$

Measure asymmetry between number of $B^0 \to f_{\mathrm{CP}}$ and $\overline{B}^0 \to f_{\mathrm{CP}}$ decays as a function of the B^0 decay time t.

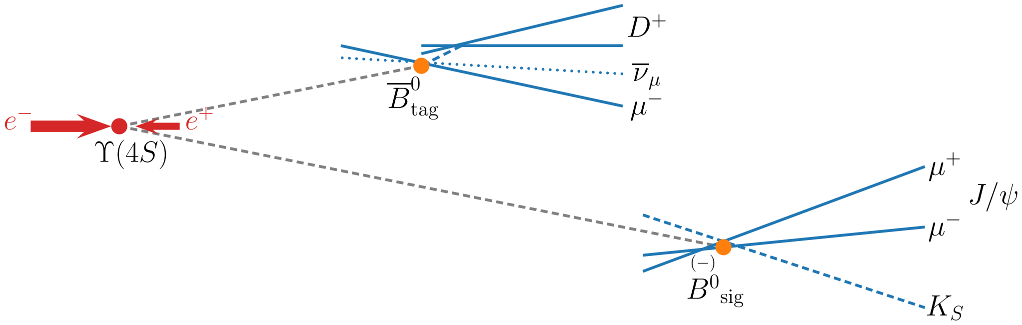
$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{\mathcal{B}(\overline{B}^0 \to f_{\mathrm{CP}})(t) - \mathcal{B}(B^0 \to f_{\mathrm{CP}})(t)}{\mathcal{B}(\overline{B}^0 \to f_{\mathrm{CP}})(t) + \mathcal{B}(B^0 \to f_{\mathrm{CP}})(t)} = S \sin(\Delta m_d t) + A \cos(\Delta m_d t)$$

Will discuss two types of TD measurements with different purposes:

With tree level decays: *e.g.* $B^0 \to J/\psi K_S$ to measure ϕ_1 precisely
$\Rightarrow$ in SM, $A = 0$ and $S = \sin 2\phi_1$

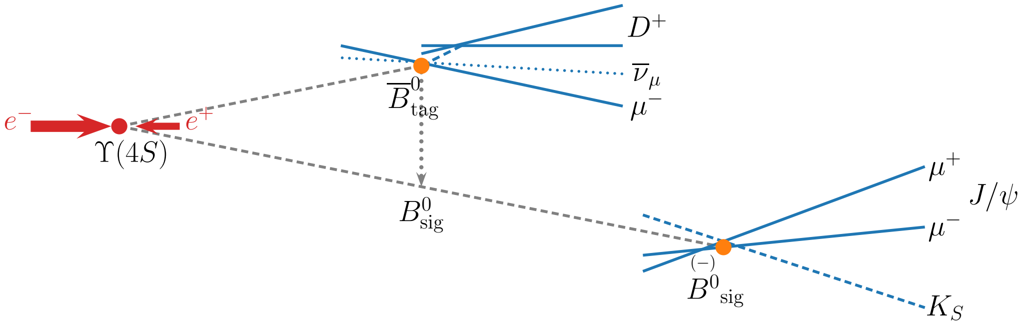
With penguin decays: *e.g.* $B^0 \to \phi K_S$ or $B^0 \to \eta' K_S$. Rare, so sensitive to NP
$\Rightarrow$ A, S could be significantly shifted from SM expectation

Time-dependent CP violation at the B factories



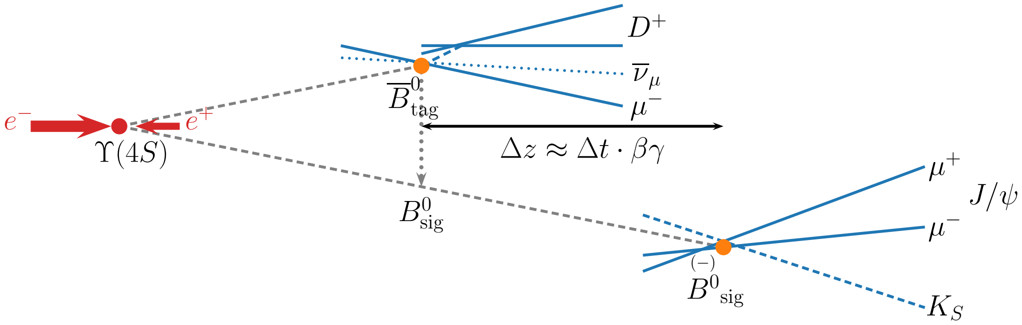
- Only two Bs are produced in e^+e^- collisions and fly along the slide boost direction;

Time-dependent CP violation at the B factories



- Only two Bs are produced in e^+e^- collisions and fly along the slide boost direction;
- When the tag B decays, the signal B has opposite flavour;

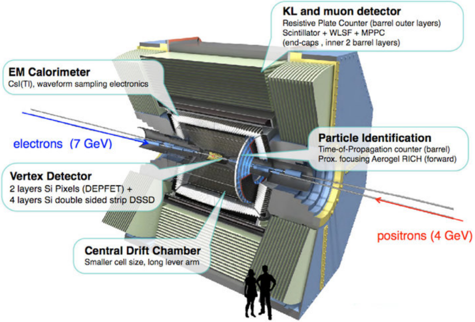
Time-dependent CP violation at the B factories



- Only two Bs are produced in e^+e^- collisions and fly along the slide boost direction;
- When the tag B decays, the signal B has opposite flavour;
- Time between flavour tagging and decay determined from the distance between tag and signal vertices.

The Belle and Belle II detectors

Although all sub-detectors underwent a major upgrade switching from Belle to Belle II, the general layout of the detectors look similar:



- **Tracking**: drift chamber
- **Vertexing**: 4 layer silicon strip detector (+ 2 layer pixel at Belle II)
- **PID**: EM calorimeter (also for π^0/γ detection), Cherenkov counters (also TOF at Belle), and dE/dx from drift chamber;
- $\boldsymbol{\mu/K_L}$: outer part of the detector to differentiate μ's and K_L's.

Outline

Between 1999 and 2010, the Belle detector collected 711 fb^{-1} of data at the $\Upsilon(4S)$ resonance
$\Rightarrow$ 772 mio $B\overline{B}$ pairs
Using the full Belle dataset, get

$$\sin 2\phi_1 = 0.667 \pm 0.023 \pm 0.012 \; (\textit{PRL}108(2012)171802)$$

Final aim at Belle II: reduce uncertainty by factor ~ 5 to reach $\sim 0.5\%$ precision. Systematic uncertainties will have to be tackled!

Today, one recent Belle measurement:

- $B^0 \to K_S K_S K_S$ TD analysis;

After that: highlights from Belle II in the preparation for precision time-dependent measurements.

Belle

$B^0 \to K_S K_S K_S$ TD analysis

$B^0 \to K_S K_S K_S$: purpose and selection

PRD103,032003(2021)

Purpose:

$B^0 \to K_S K_S K_S$ is mediated by a penguin transition

$\Rightarrow$ rare and sensitive to NP.

In SM, expect:

- $A = 0$ as tree diagram negligible wrt penguin;
- $S = -\sin(2\phi_1) \approx -0.70$ (opposite of $B^0 \to J/\psi K_S$).

Reconstruction and selection:

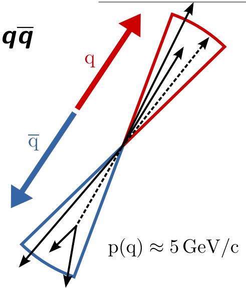
Reconstruct $K_S \to \pi^+\pi^-$ and use Neural Network (NN) to suppress bkg with $\pi^+\pi^-$ not from K_S.

Remaining bkg: almost exclusively continuum $e^+e^- \to q\overline{q}$ ($q = u, d, c, s$)

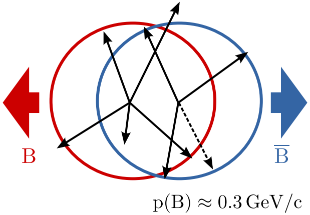
$\Rightarrow$ train an event-shape based NN to suppress it.

Main idea: In CoM, $q\overline{q}$ is jet-like and $B\overline{B}$ spherical.

$q\overline{q}$



$B\overline{B}$



$B^0 \to K_S K_S K_S$: fit for signal fraction

PRD103,032003(2021)

Perform 3D fit to extract signal/bkg fractions:

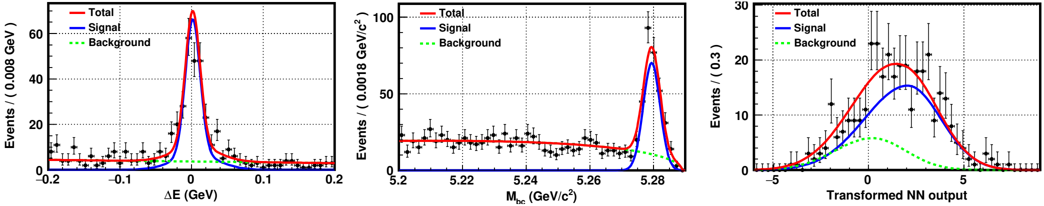
1) Energy difference $\Delta E \equiv E^*(B^0) - E_{\text{CMS}}/2$

$\Rightarrow$ Width dominated by momentum resolution

2) beam energy-constrained mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{CMS}}/2)^2 - p^*(B^0)^2}$

$\Rightarrow$ Width dominated by beam energy resolution

3) $q\bar{q}$ Neural Network output.



Fit finds 258 ± 17 signal candidates with purity $\approx 74\%$ in the signal region ($M_{\text{bc}} > 5.27$ GeV and $|\Delta E| < 0.1$ GeV).

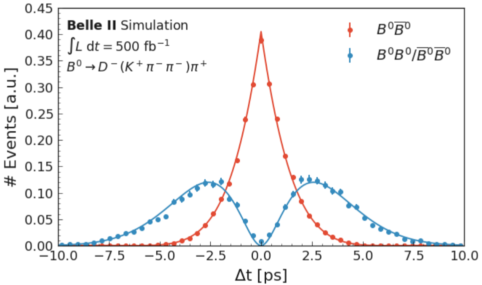
These events are then then used for the TD fit...

Experimental effects in time-dependent measurements

When measuring the CP asymmetry, have to take into account two experimental effects:

- asymmetry is diluted by the wrong-tag-fraction w,
- Δt distribution smeared out by resolution function $\mathcal{R}$

w and some of the resolution function parameters are extracted by performing a time-dependent measurement of the mixing probability using abundant $B^0 \to D^- h^+$ decays as flavour specific signal:



MC Truth

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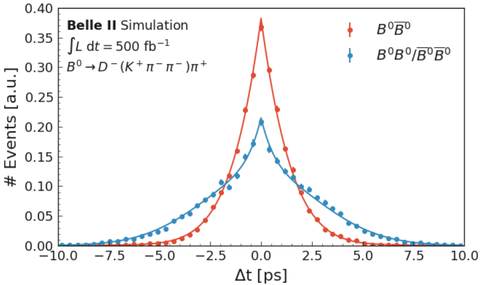

$w \approx\ 20\%$

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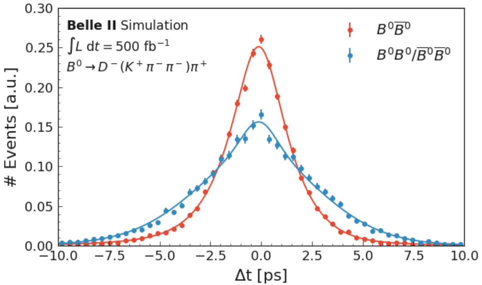


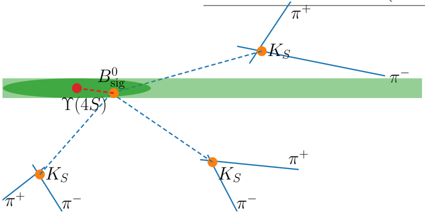
$w \approx$ 20% and $\mathcal{R}$

$B^0 \to K_S K_S K_S$: time-dependent fit

PRD103,032003(2021)

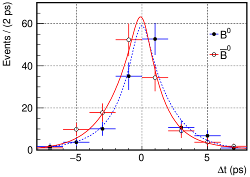
At Belle, B^0 fly ~ 200 μm and $K_S \sim 1$ cm, so:

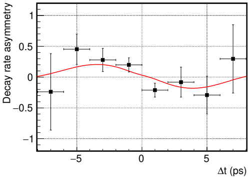
1. Use only K_S from two pions with hits in the vertex detector;
2. Use constraint that B^0 flies along the boost direction.



Time dependent fit returns:

$$S = -0.71 \pm 0.23\,(\text{stat.}) \pm 0.05\,(\text{syst.}),$$
$$A = \quad 0.12 \pm 0.16\,(\text{stat.}) \pm 0.05\,(\text{syst.}).$$





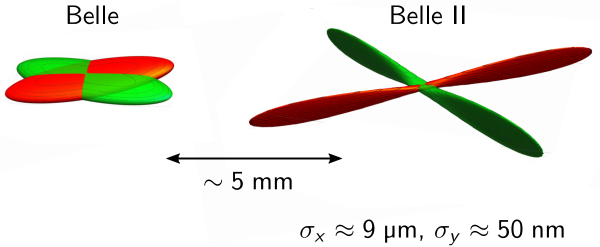
Result compatible with SM expectation and 2.5 σ away from "no CPV" hypothesis.
$\Rightarrow$ large room for improvement with this mode and other penguin modes with Belle II in future

Belle II

Recent results and prospects

Achieving high luminosity at Belle II

Upgraded collider SuperKEKB provide very high luminosity to Belle II using so-called nano-beam scheme.



Final Belle II goal wrt Belle:

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

So far achieved:

- Peak luminosity:
  3.1×10^{34} cm^{-2}s^{-1}, world record!
- Integrated luminosity recorded between February 2019 and November 2021:
  220 fb^{-1} ($\sim$ 30% of Belle)

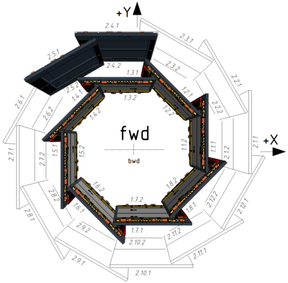
Higher luminosity means higher beam background $\Rightarrow$ Sub-detectors were upgraded from Belle to cope with that (some more detail later in the talk)

Boost and Δt precision

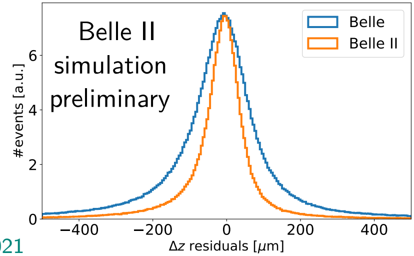
New beam scheme means Belle II has a reduced boost wrt Belle:

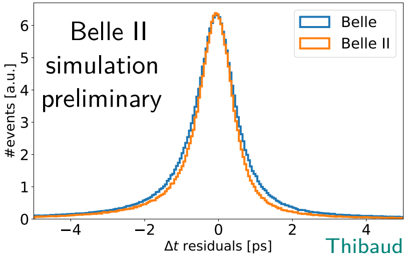
$$\beta\gamma = 0.43 \longrightarrow \beta\gamma = 0.29$$

$\Rightarrow$ added a two-layer pixel detector directly around the beam pipe (radius $\approx$ 1.4 cm) to recover precision on Δt.
Pixels (and not strips) used because of high bkg close to beam.



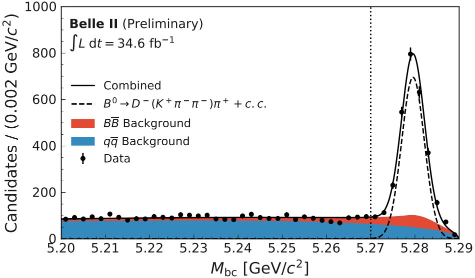
Second layer partially installed. One layer is currently enough as the machine needs time to ramp up to the nominal luminosity.
Simulation studies show the precision on Δt should be comparable to that of Belle:

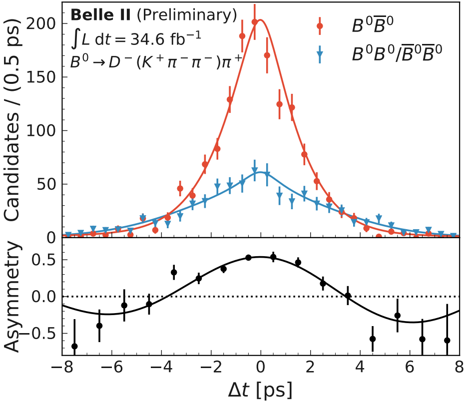




Time-dependent mixing result

Using 34.6 fb^{-1} Belle II performed mixing frequency measurement using $B^0 \to D^- \pi^+$.





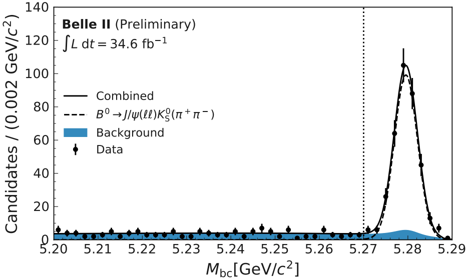
$$\boldsymbol{\Delta m_d = (0.531 \pm 0.046\ (\text{stat.}) \pm 0.013\ (\text{syst.}))\ \text{ps}^{-1}}$$

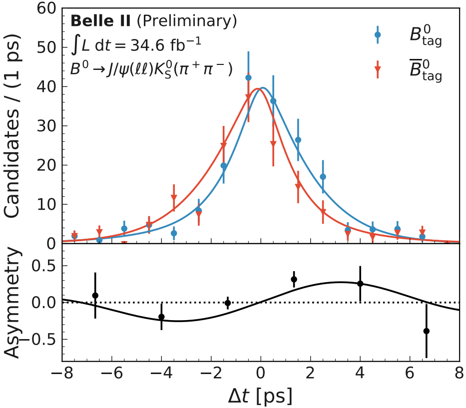
Compatible with PDG: $\Delta m_d = (0.5065 \pm 0.0019)\ \text{ps}^{-1}$.

Time-dependent CP-violation result

BELLE2-NOTE-PL-2020-011

Using the same data, Belle II performed the first Time-Dependent analysis using $B^0 \to J/\psi K_S$.





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

Good early demonstration that Belle II can perform TD analyses.

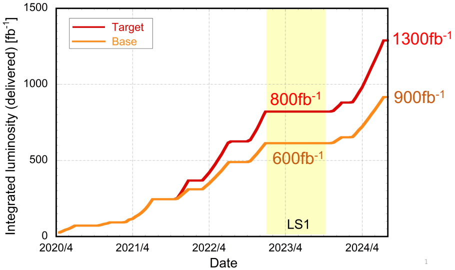
Belle II data taken so far

It's just the beginning!

Not yet enough data to be competitive with Belle with ϕ_1-related measurement, but getting ready for precision measurements.

Outline of the rest of the talk:

- Flavour tagger performance;
- D lifetime measurement;
- $B^0 \to J/\psi K_L$ reconstruction;
- $B^0 \to \eta' K_S$ branching fraction.



Flavour tagger performance

Flavour tagger performance characterised by

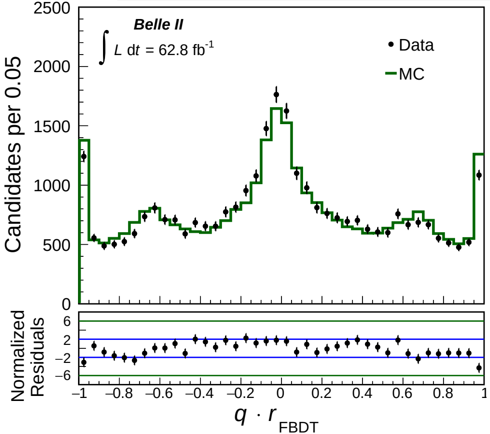
- wrong tag fraction w;
- effective efficiency $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} \cdot (1-2w)^2$.

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:

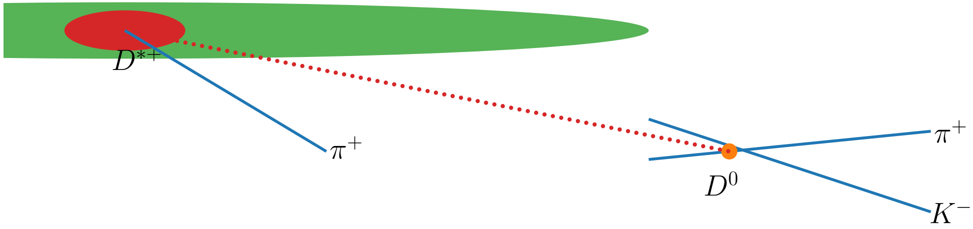
Belle: $\varepsilon_{\text{eff}} = (30.1 \pm 0.4)\%$, Belle II: $\boldsymbol{\varepsilon_{\text{eff}} = (30.0 \pm 1.3)\%}$

Algorithm being improved at the moment.

D lifetime: beam spot constraint

Measurement of D^0 and D^+ lifetimes performed with 72 fb^{-1} data.
Not B physics, but high precision test of Belle II capabilities to perform time-dependent measurements.

D decay time computed from distance between beam spot and D decay vertex:



Compute D decay time from its momentum $\vec{p}$ and flight vector $\vec{d}$:

$$t = \frac{m_D}{p}\left(\vec{d} \cdot \hat{p}\right)$$

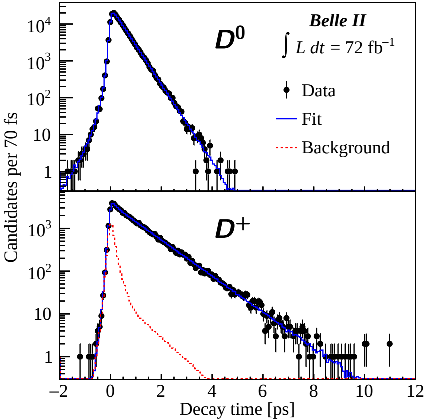
D lifetime: result

Result is the most precise measurement of D^0 and D^+ lifetimes:

$$\tau(D^0) = 410.5 \pm 1.1\,(\text{stat.}) \pm 0.8\,(\text{syst.})\text{ fs},$$
$$\tau(D^+) = 1030.4 \pm 4.7\,(\text{stat.}) \pm 3.1\,(\text{syst.})\text{ fs}.$$

This precise result gives confidence about Belle II performance in:

1. Vertex detector and tracking;
2. Beam spot size measurement (using $ee \to \mu\mu$ events);
3. Detector alignment.



K_L detection and $B^0 \to J/\psi K_L$

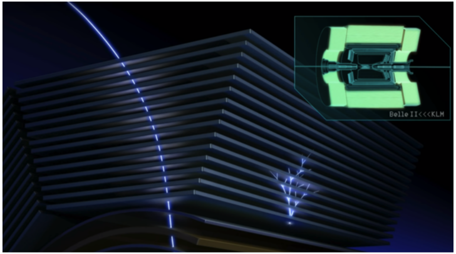
Measuring $\sin(2\phi_1)$ not only with $B^0 \to J/\psi K_S$ but also $B^0 \to J/\psi K_L$ has two advantages:

1. Boost statistics: double the number of signal events (albeit with less good purity)
2. Will help for systematics: $B^0 \to J/\psi K_S$ is CP-odd and $B^0 \to J/\psi K_L$ is CP-even. This can help reduce systematic related to the CP violation on the tag side.

At Belle and Belle II, use KLM detector to detect K_L, *i.e.* alternance of iron plates and flat detectors.

At Belle, detectors were gas based (RPCs).
At Belle II, RPCs would not be able to withstand high flux of neutrons from the beam.
$\Rightarrow$ In the inner layers of the barrel and in the endcaps, RPCs replaced by scintillators.

The KLong and Muon (KLM) Detector System



μ K_L

$\Rightarrow$ important to test Belle II capabilities to reconstruct K_Ls.

$B^0 \to J/\psi K_L$ reconstruction

arXiv:2106.13547

Compute $B^0 \to J/\psi K_L$ candidates' energy using known beam energy and position of the K_L cluster in the KLM.

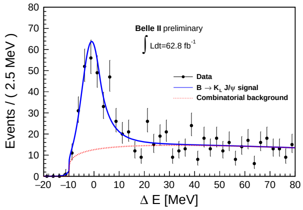
In 62.8 fb^{-1} of Belle II data, find:

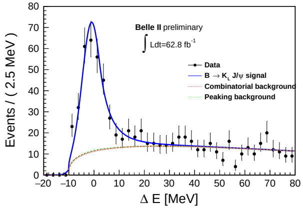
$$N(B^0 \to J/\psi(\mu\mu)K_L) = 267 \pm 21\,(\text{stat.}) \pm 28\,(\text{peaking bkg}),$$
$$N(B^0 \to J/\psi(ee)K_L) = 226 \pm 20\,(\text{stat.}) \pm 31\,(\text{peaking bkg}).$$

Yields and purities comparable to Belle.

Work ongoing to:

- Boost statistics including neutral clusters from the calo;
- Include this mode to the TD measurement of $\sin 2\phi_1$.





$B^0 \to \eta' K_S$: aim and selection

arXiv:2104.06224

$B^0 \to \eta' K_S$ is penguin-dominated and sensitive to NP. Neutrals in final state make it challenging at the LHC.

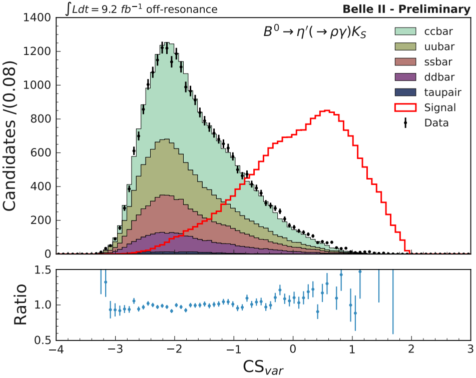
$\Rightarrow$ TD analysis with this mode is a high priority at Belle II.

So far, measured branching fraction with 62.8 fb^{-1} of data.

Reconstruct $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$.

Train a BDT based on event shape variables to suppress continuum background.

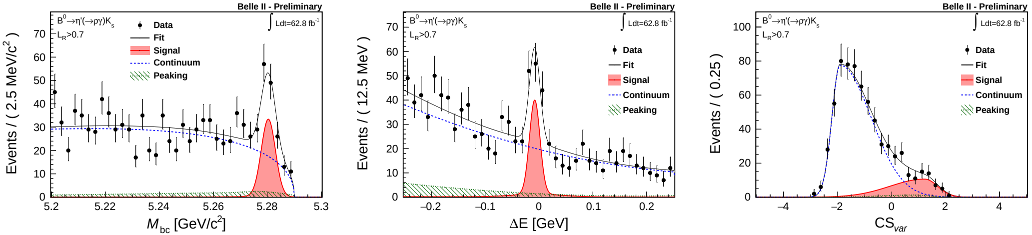
- $\Rightarrow$ BDT validated using off-resonance data
- $\Rightarrow$ Remaining data/MC differences accounted for as systematic uncertainties.



$B^0 \to \eta' K_S$: branching fraction

arXiv:2104.06224

Extract signal yield with a 3D fit to M_{bc}, ΔE, BDT output:



The signal yield per fb^{-1} is larger than a previous Belle analysis (PRL97-061802(2006)), thanks to improved continuum suppression.

PID and tracking efficiencies are extracted using control modes.

Branching fraction result:

$$\mathcal{B}(B^0 \to \eta' K^0) = (63.4 \pm 3.4\,(\mathrm{stat.}) \pm 3.2\,(\mathrm{syst.})) \times 10^{-6}$$

Dominant systematics come from the peaking background and BDT calibration.

Next step: time-dependent CPV analysis!

Conclusion and outlook

With its 711 fb^{-1} dataset, Belle has had a very rich program related to mixing-induced CPV,

- Recent result: time-dependent CP violation analysis with $B^0 \to K_S K_S K_S$.

After collecting 220 fb^{-1} of data, Belle II has shown:

- Ability to perform complete time-dependent CPV analyses;
- Good vertex resolution and ability to measure D lifetime;
- Good flavour tagging performance;
- Good performance with neutrals and re-discovery of penguin modes.

Plan for the direct future at Belle II:

- Measurement of B^0 lifetime and mixing frequency;

$\Rightarrow$ already statistically limited, so good check of time-dependent machinery;

- Time-dependent analyses with penguin and charmless modes;
- Measurement of $\sin 2\phi_1$ with $B \to J/\psi K_S$ and related modes.