Measurements of ϕ_1 (β) at Belle II

and related decay-time-dependent analyses

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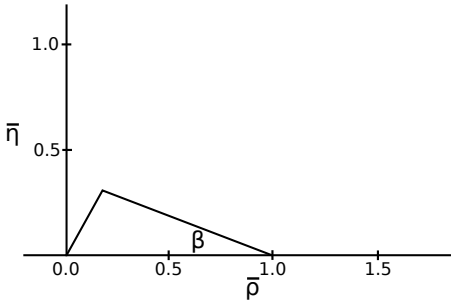
KEK-FF, KEK

9 February 2023

CKM angle β and establishment of the CKM triangle



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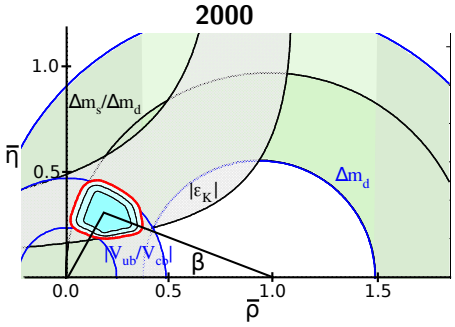

CKM angle β and establishment of the CKM triangle

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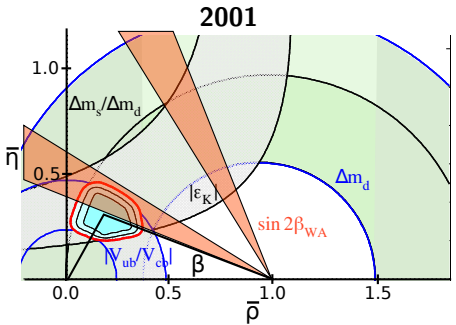
$\Rightarrow$ Nobel Prize to Kobayashi and Maskawa in 2008.



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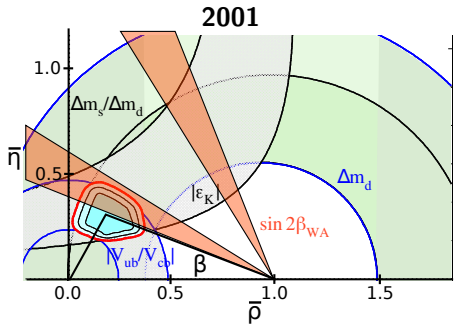
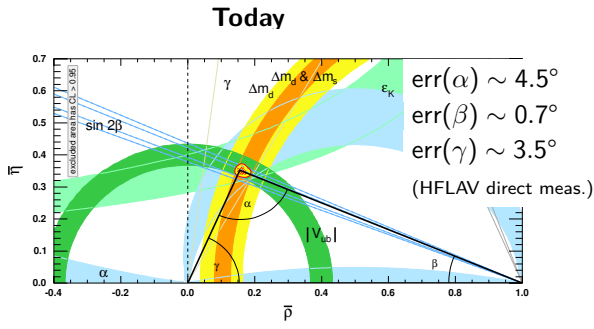
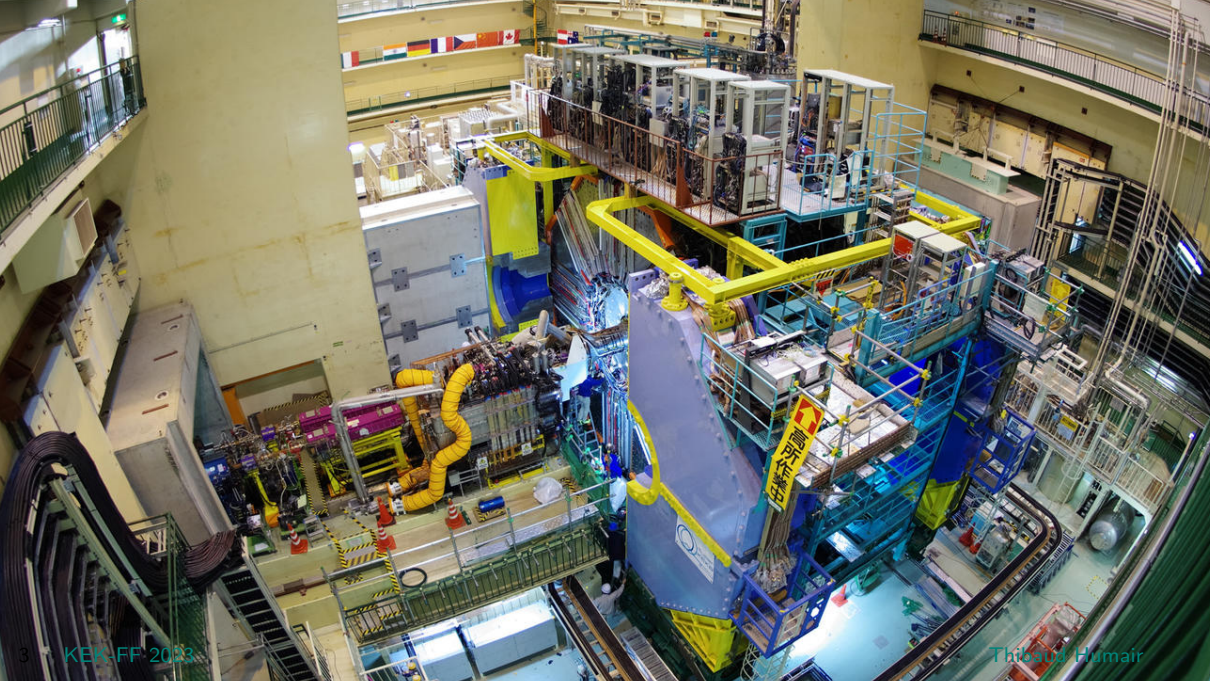




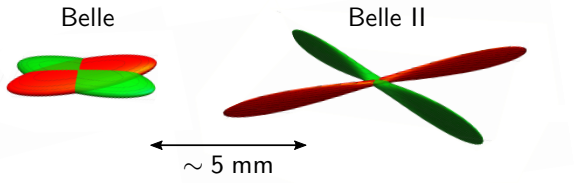
Today: β and other CKM angles have become a precision test of the SM, β best known angle
Central aim at Belle II: push β-related measurements to ultimate precision.



Belle II and SuperKEK-B

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

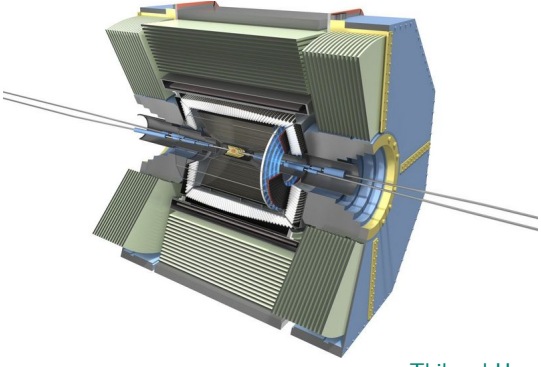
- Goal: $L = 6 \times 10^{35}$ cm$^{-2}s^{-1}$ ($30\times$ Belle)
- Achieved: 4.7×10^{34} cm$^{-2}s^{-1}$ ($2\times$ Belle)



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

$\Rightarrow$ Enhanced K/π separation

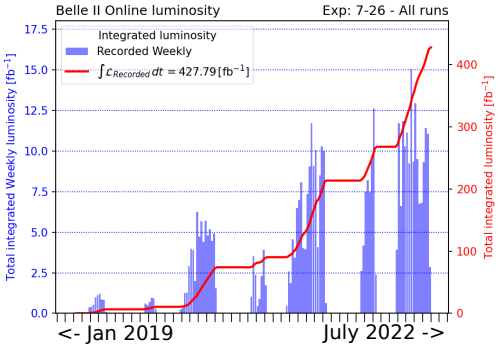
$\Rightarrow$ Improved vertex resolution (more later...)



Data taking status

- 360 fb^{-1} on tape $\sim$ 400 M $B\bar{B}$ pairs
  $\sim$ Babar and 1/2 Belle
- Now in shutdown till $\sim$end 2023
  $\Rightarrow$ machine improvements
  $\Rightarrow$ installation of complete pixel detector

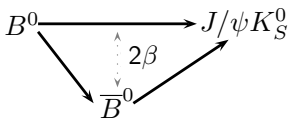
Today: results on 190 fb^{-1} of data or less



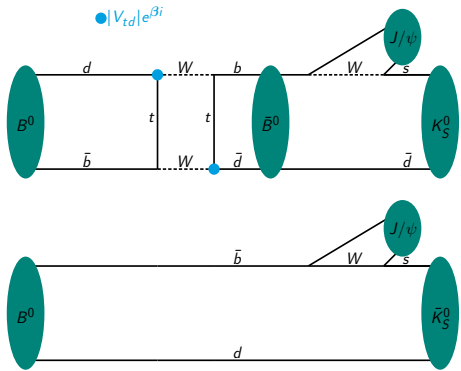
CP-violation in interference between mixing and decay

$\beta \approx$ phase of V_{td}

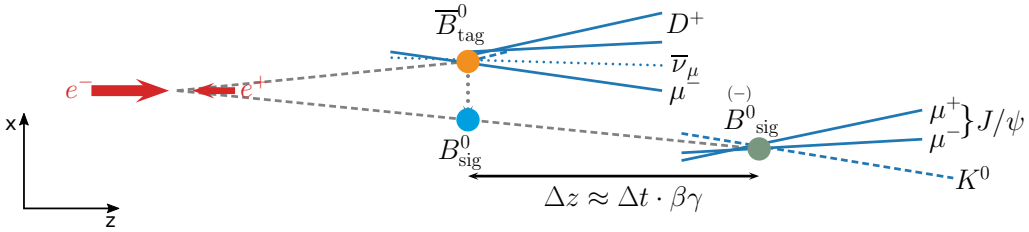
CP-violation occurs with B^0 or $\bar{B}^0$ decays to *CP*-eigenstates:



The decay $B^0 \to J/\psi K_S^0$ allows to measure the CKM angle β with low uncertainty: golden mode at Belle II.



Time-dependent analyses at Belle II: *CP*-asymmetries



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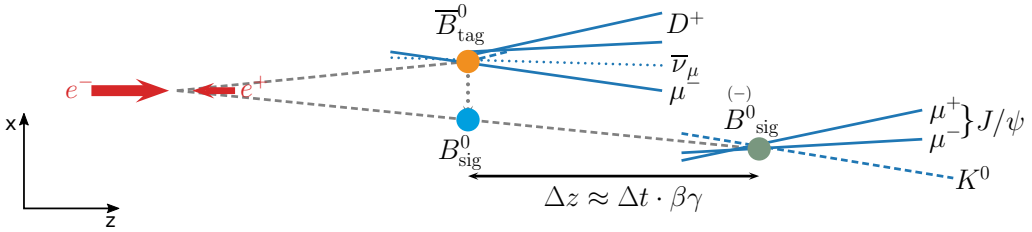

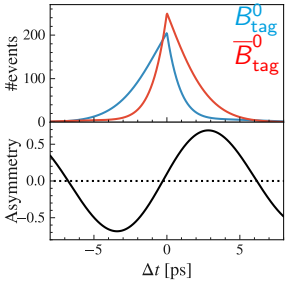

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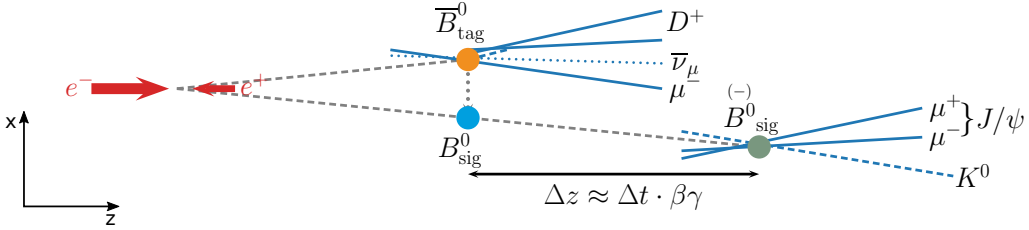

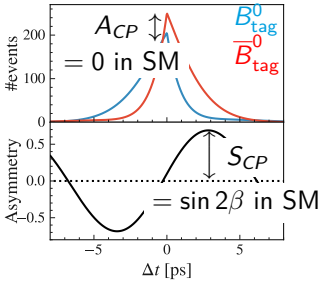

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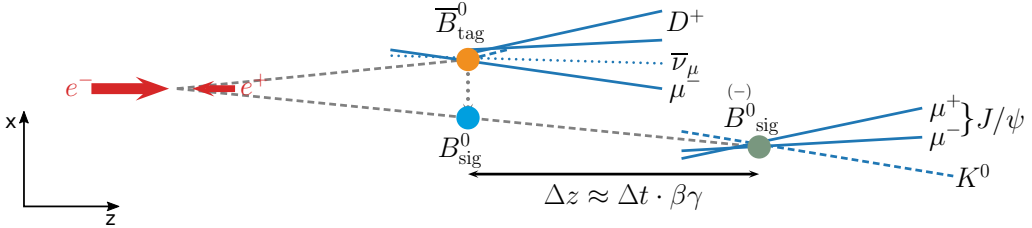

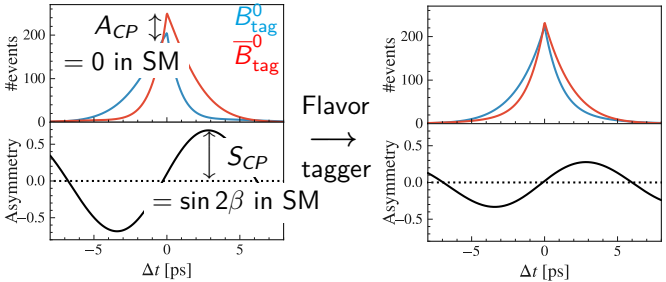

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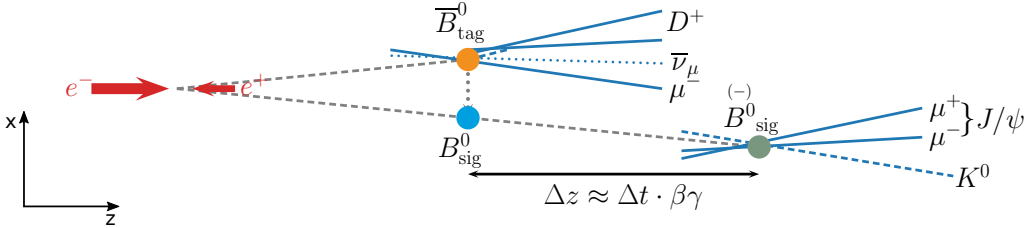

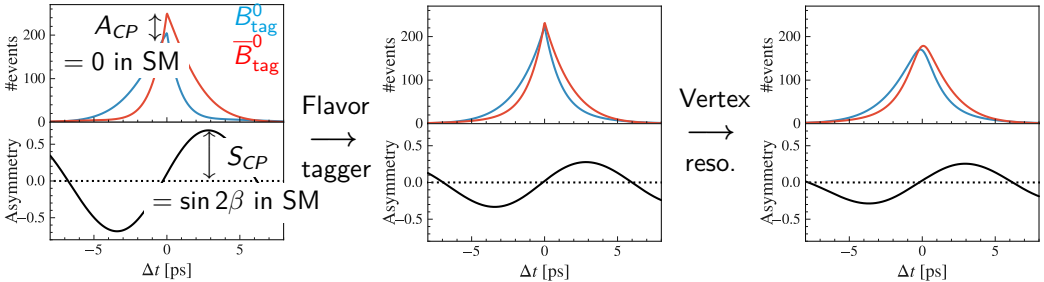

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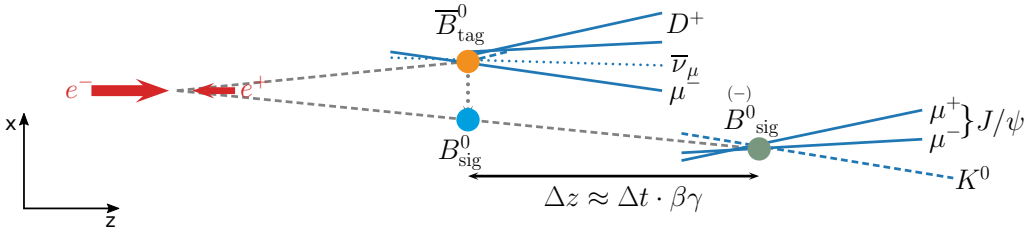
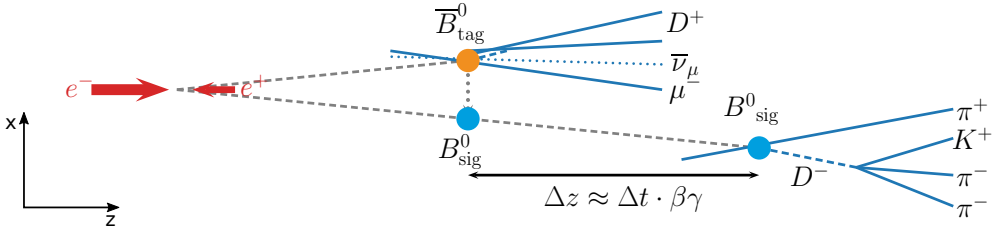


Time-dependent analyses at Belle II: flavour oscillations



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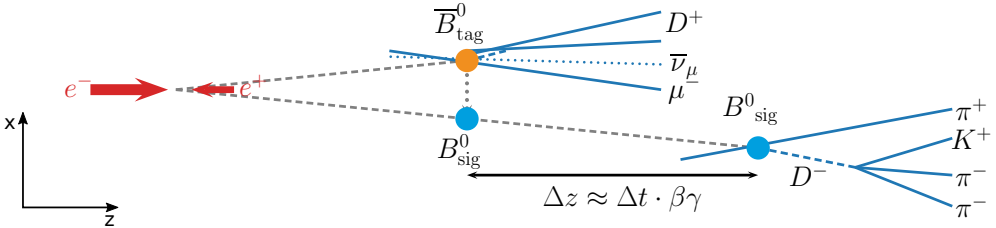

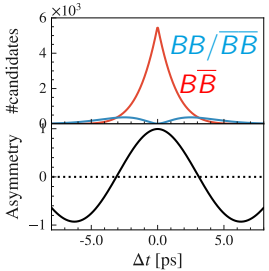

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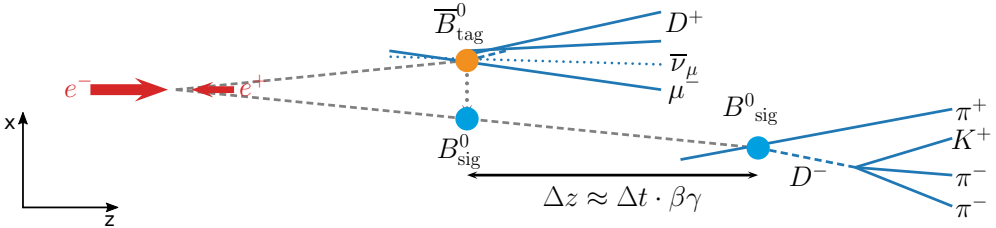

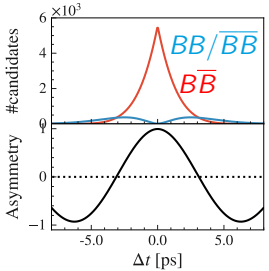

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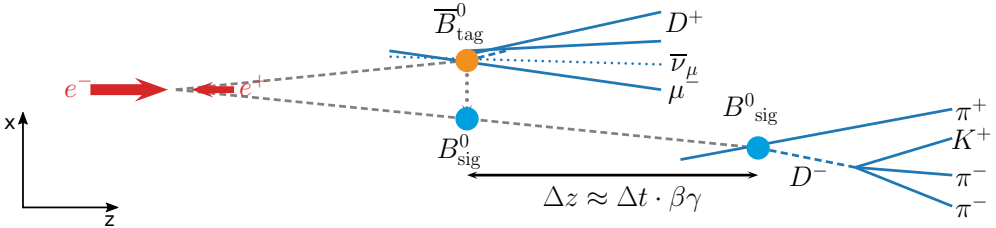

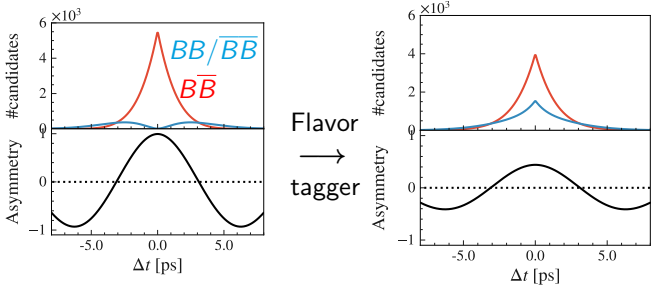

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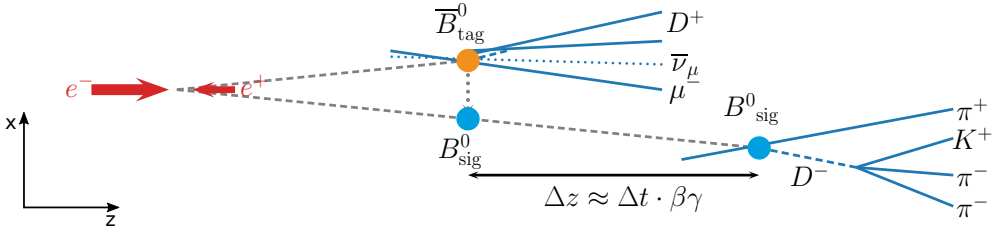
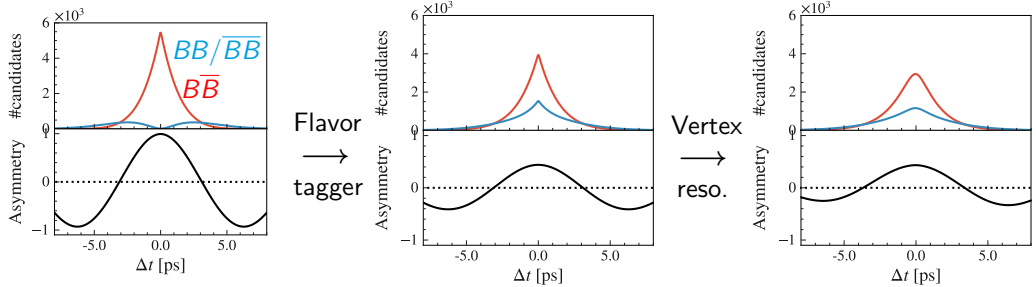
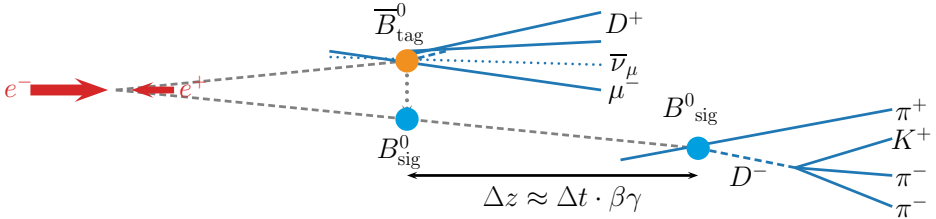




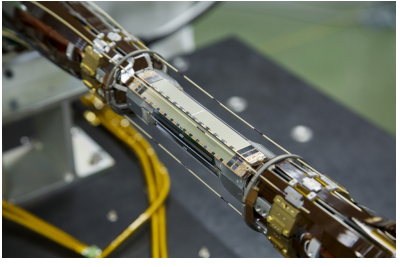
Time-dependent analyses at Belle II: vertex resolution



Time measurement is a fundamental ingredient!
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.



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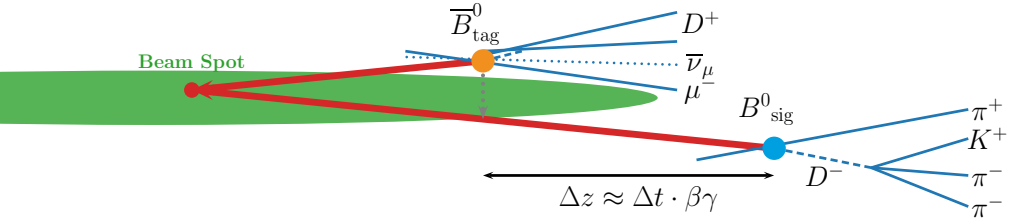

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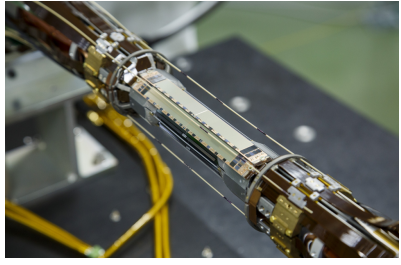
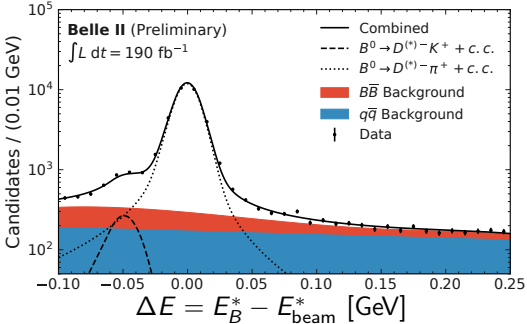
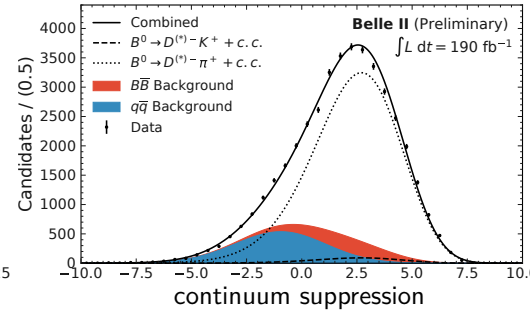


Use beam spot profile to increase precision on vertex fit
$\Rightarrow$ new beam scheme means smaller beam spot and stronger constraint

Oscillation frequency measurement: background treatment





Use $\sim 35k$ hadronic $B^0 \to D^{(*)-}\pi^+/K^+$ decays in 190 fb^{-1} of data.

2 backgrounds: $e^+e^- \to q\overline{q}$ and misreconstructed $e^+e^- \to B\overline{B}$

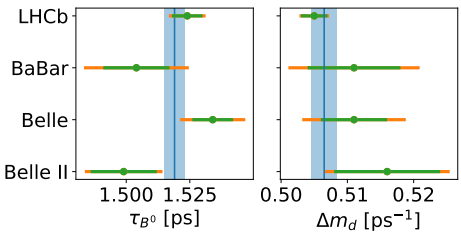
1. Fit ΔE and the classifier output based on event topology variables
2. Subtract backgrounds from sidebands (sWeights) to obtain background-free Δt distribution

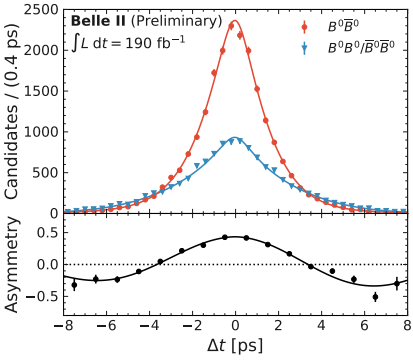
$\Rightarrow$ fit Δt distribution to extract Δm_d and τ_{B^0}

Oscillation frequency measurement: result

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

Comparison with world average:





Best determination of Δm_d from LHCb.

Milestone in Belle II program: not only an input to the CKM fit, but precise validation of the whole machinery for time-dependent measurements!

Oscillation frequency measurement: detector response

Tagging power:

$\varepsilon_{\text{tag}} = \mathbf{29.9 \pm 0.6\%}$ ($\sim$ 5-7% at LHCb & $29.8 \pm 0.4\%$ at Belle)

- Improvement already seen with new data processing: $\varepsilon_{\text{tag}} = 31.7 \pm 0.4\%$ (stat)
- Further improvement possible with improved PID & MVA techniques

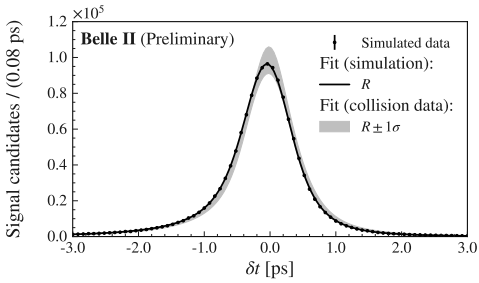
Resolution:

Δt resolution model takes into account:

- Vertex resolution
- Smearing due to secondary D mesons in B_{tag} decay $\Rightarrow$ yield main systematic

$\Rightarrow$ similar resolution than Belle in spite of reduced boost

Good control of the detector's alignment yield a reasonably small systematic

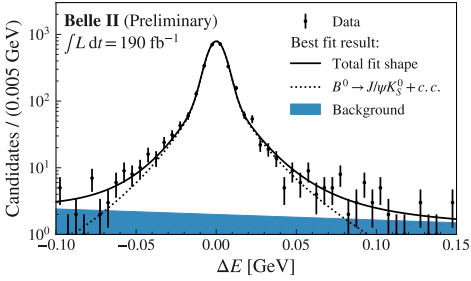


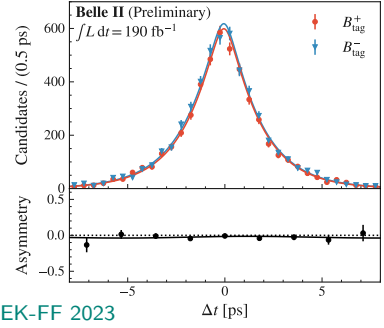
Measurement of the CKM angle β

Machinery ready for measurement of β

Reconstruct 2755 $B^0 \to J/\psi K_S$ with $J/\psi \to ee$ and $J/\psi \to \mu\mu$

Sample 98.6% pure





Extra cross-checks: check measurements with $B^+ \to J/\psi K^+$, where no CPV is expected

$$S_{CP} = 0.016 \pm 0.029(\text{stat})$$

$$A_{CP} = 0.021 \pm 0.021(\text{stat})$$

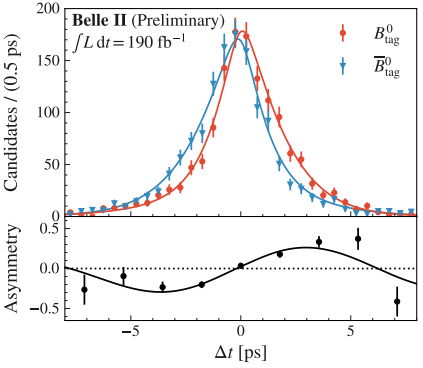
Measurement of the CKM angle β: result

First Belle II measurement of β:

$$\sin 2\beta = S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044(\text{stat}) {}^{+0.042}_{-0.017}(\text{syst})$$

Corresponds to $\beta = (23.0 \pm 2.6(\text{stat}) \pm 0.7(\text{syst}))^\circ$

World average (PDG): $(21.9 \pm 0.7)^\circ$



Belle ($c\bar{c}K_S$, $J/\psi K_L$):

$$S_{CP} = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst})$$
$$A_{CP} = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})$$

PRL108,171802(2012)

LHCb ($\psi(2S)K_S$, $J/\psi K_S$ with 3/fb):

$$S_{CP} = 0.760 \pm 0.034(\text{stat} \oplus \text{syst})$$
$$A_{CP} = -0.017 \pm 0.029(\text{stat} \oplus \text{syst})$$

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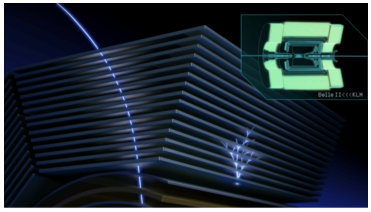
β at Belle II: next steps

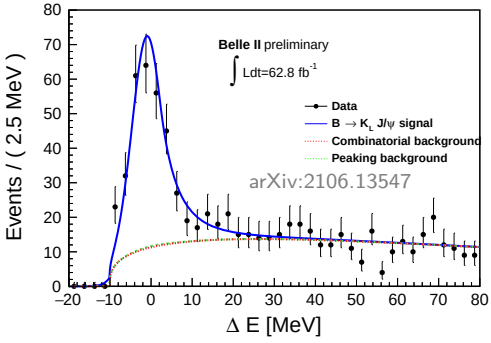
Updated measurement in preparation:

- Using all available data (2× more)
- Using $B^0 \to J/\psi K_L$ mode (2× more)

Belle II ability to detect $B^0 \to J/\psi K_L$ already demonstrated.

Improve statistical power and reduces systematics related to CP violation in B_{tag} decays.
$\Rightarrow$ dominant systematic on A_{CP}





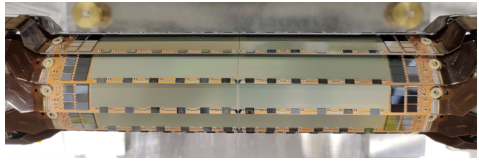
The future of β at Belle II

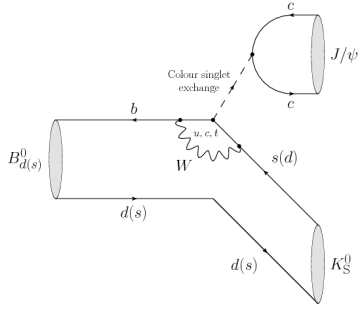
Challenges to improve β measurement below 0.5° (with 5 ab^{-1}):

Vertex resolution:

With increased beam background at high lumi, need to keep vertex resolution under control:

- No significant degradation seen so far
- Full 2 layer PXD detector will be installed in near future $\Rightarrow$ no degradation of the resolution expected before $\sim$ 2027 (half design lumi)
- Further improvement envisaged in later future





Penguin pollution:

- Penguin pollution: expected to be $\mathcal{O}(1°)$

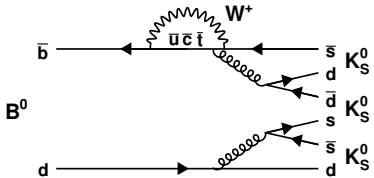
$\Rightarrow$ Can be controlled with penguin-enhanced modes: $B_s \to J/\psi K^0_S$ (LHCb), $B^0 \to J/\psi \pi^0$

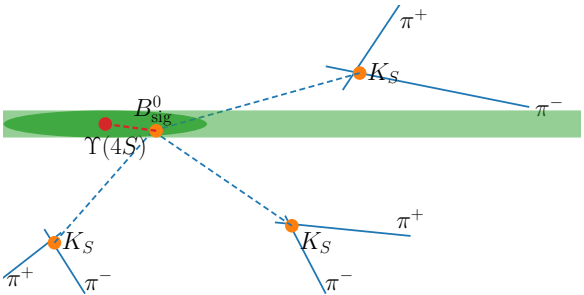
Synergy between theory/LHCb/Belle II needed!

Time-dependent CPV with penguins: $B^0 \to K^0_S K^0_S K^0_S$

New Physics expected to have larger impact in these decays that are suppressed in the SM

Check if A_{CP} & S_{CP} deviate from SM expectation in modes with clean theory prediction





$B^0 \to K^0_S K^0_S K^0_S$:

- Gluonic penguin
- No track coming from signal B

$\Rightarrow$ Challenging vertex reconstruction

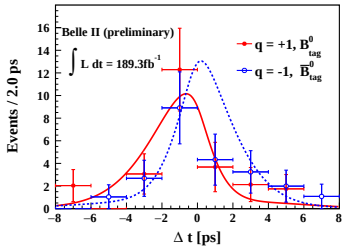
$B^0 \to K^0_S K^0_S K^0_S$: Belle II results and prospects

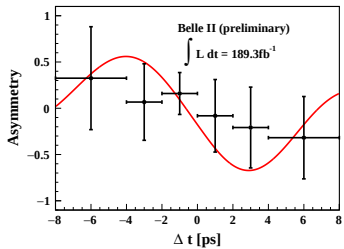
Reconstruct 102 signal events, half of which have vertex information (other half only used to get direct asymmetry)

$$S_{CP} = -1.86^{+0.91}_{-0.46}(\text{stat}) \pm 0.09(\text{syst})$$
$$A_{CP} = -0.22^{+0.30}_{-0.27}(\text{stat}) \pm 0.04(\text{syst})$$

Expectation: $S_{CP} = -\sin 2\beta = -0.7$, $A_{CP} = 0.0$
Good proof of principle for TD analyses with neutrals.

Analysis with full data and improved K^0_S reco ongoing.
Expected to reach similar precision as wolrd's best result from Belle PRD103.032003 where 270 events are seen.





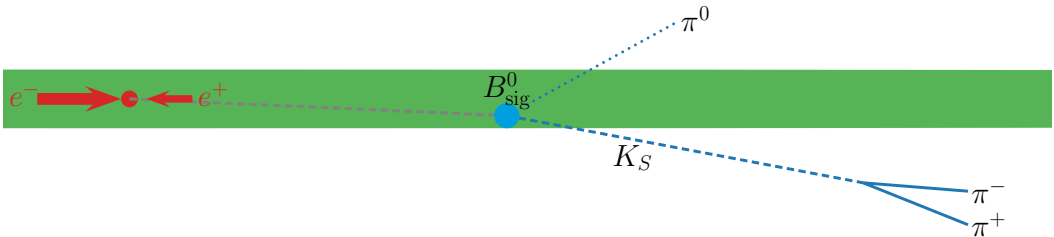
arXiv:2209.0954

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

In SM, $B^0 \to K_S\pi^0$ has $S_{CP} \approx \sin 2\beta$ and $A_{CP} \approx 0$ up to $\mathcal{O}(0.1)$ corrections.

Also, isospin sum-rule precision limited by $A_{CP}(B^0 \to K_S\pi^0)$:

$$2A_{CP}^{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} - A_{CP}^{K^+\pi^-} - A_{CP}^{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} + 2A_{CP}^{K^+\pi^0)}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} \approx 0$$



Need good performance with neutrals and beam spot constraint.

$B^0 \to K_S\pi^0$: Belle II results and prospects

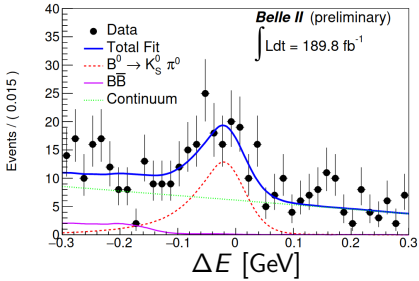
Use $B^0 \to J/\psi(\mu^+\mu^-)K_S$ to calibrate Δt shapes

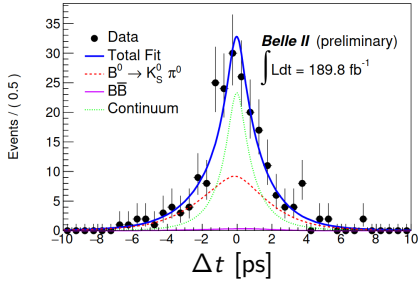
Constrain S_{CP} using previous measurements to maximise precision on A_{CP}.

Result:

$$\mathcal{A}_{\rm CP} = -0.41^{+0.30}_{-0.32}\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$
$$\mathcal{B} = (11.0 \pm 1.2\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-6}$$

Measurement using full 360/fb data in preparation.

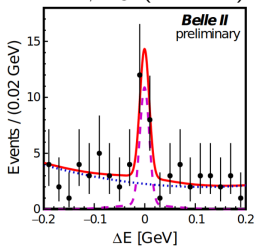




TDCPV in penguins: prospects

Several TD analyses with penguin modes ongoing.
BR measurements already performed with these modes:

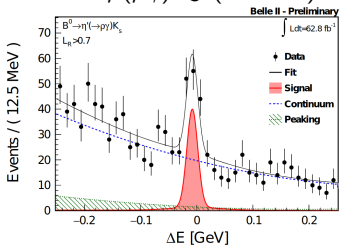
$B^0 \to \phi K_S$ (34 fb^{-1})



$\mathcal{B} = (5.9 \pm 1.8 \pm 0.7) \times 10^{-6}$

arXiv::2008.03873

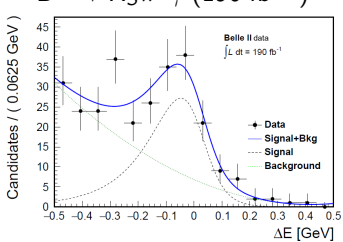
$B^0 \to \eta'(\rho\gamma)K_S$ (63 fb^{-1})



$\mathcal{B} = (59.9^{+5.8}_{-5.5} \pm 2.9) \times 10^{-6}$

arXiv::2104.06224

$B^0 \to K_S\pi^0\gamma$ (190 fb^{-1})



$\mathcal{B} = (7.3 \pm 1.8 \pm 1.0) \times 10^{-6}$

arXiv::2206.08280

The time-dependent analyses profit from Belle II's clean environment and high flavour tagger performance.

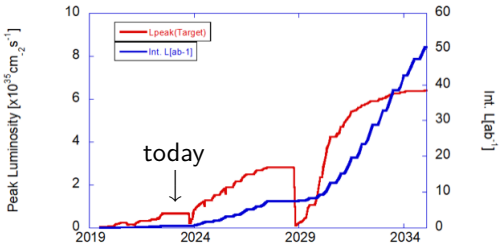
Conclusions and outlook

Belle II detector performs nominally and entered the game of β/ϕ_1-related measurement:

- First β measurement with $B^0 \to J/\psi K_S$;
- Time-dependent analyses with penguins: $B^0 \to K_S K_S K_S$ and $B^0 \to K_S \pi^0$.

It is just the very beginning!

- Have twice as much data on tape;
- $\mathcal{O}(100)\times$ more in a decade



The best is yet to come: many promising results with B factories unique capabilities, *e.g.* analyses with neutrals & very high flavour tagger efficeny.