Time-dependent CPV measurements at Belle II

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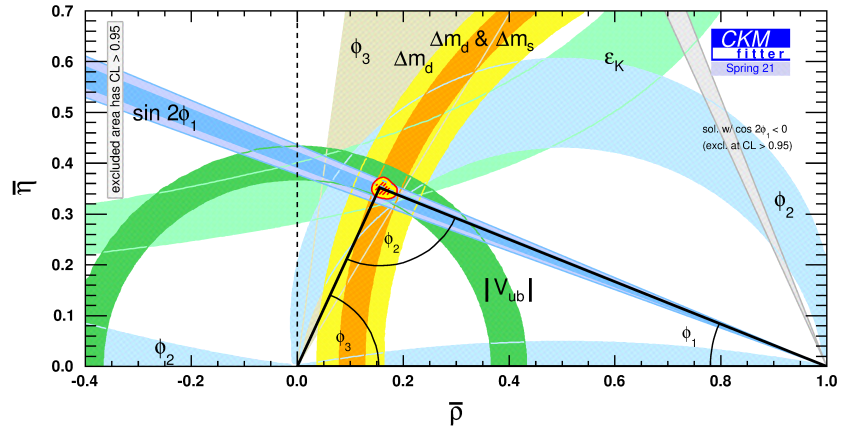
Motivation

- Flavor physics: Measurements of CKM angles (ϕ_1, ϕ_2, ϕ_3) to test SM

- Flavor changing neutral current
  $b \to s$ penguin transitions
  $\to$ Highly sensitive to non-SM particles
  $\to$ Probing the effective value of $\sin(2\phi_1 \equiv 2\beta)$
- Exp. challenges: low $\mathscr{B}(10^{-5})$, flavor tagging, poor decay time resolution (K^0_S, π^0)

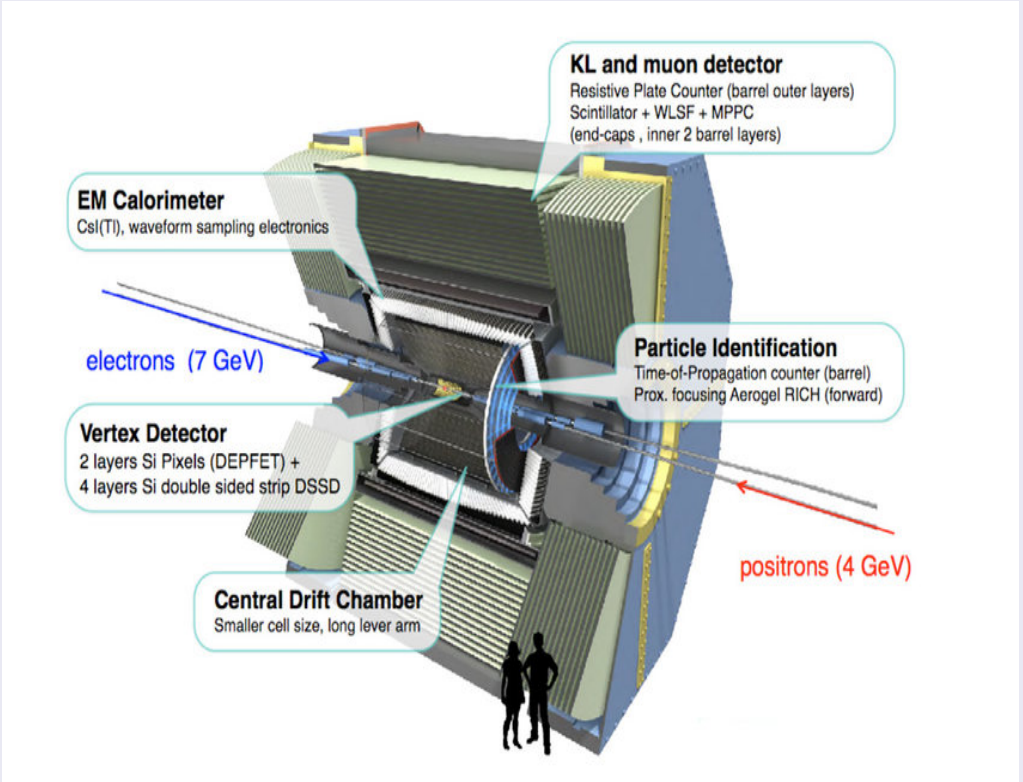


Today's focus

- Lifetime and mixing benchmark in $B \to D^*\pi$
- $\sin(2\phi_1)$ measurement
  $\to$in Cabibbo favoured $(J/\psi K^0_S)$ and suppressed $(K^0_S\pi^0,\ 3K^0_S,\ \phi K^0_S)$

SuperKEKB and Belle II detector

- Asymmetric collider: e^- of 7 GeV with e^+ of 4 GeV
  $\rightarrow$ clean experimental environment
- World-record peak luminosity: $4.7 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
- New tracking system and improved vertexing
- Improved particle identification



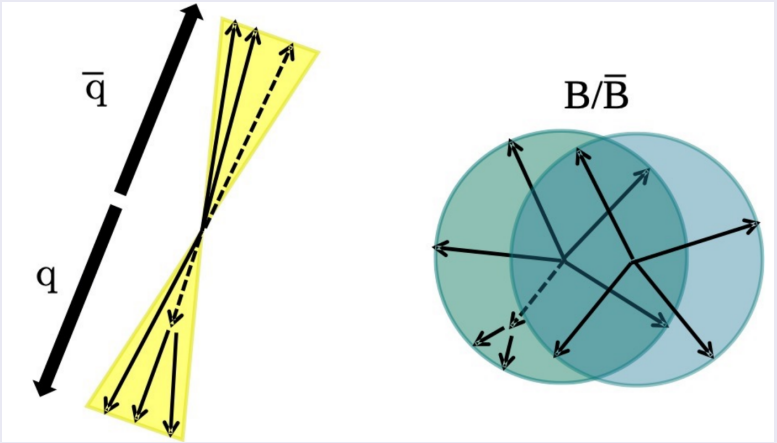
Current status:

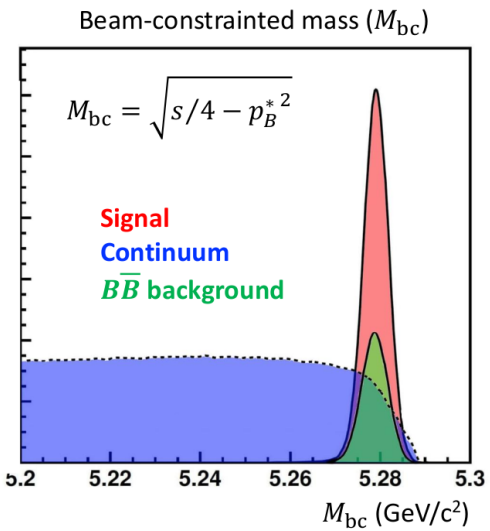
- 362 fb^{-1} $\Upsilon(4S)$ resonance data are collected so far
- LS1 upgrade ongoing and Run 2 will begin in Dec 2023

Signal extraction

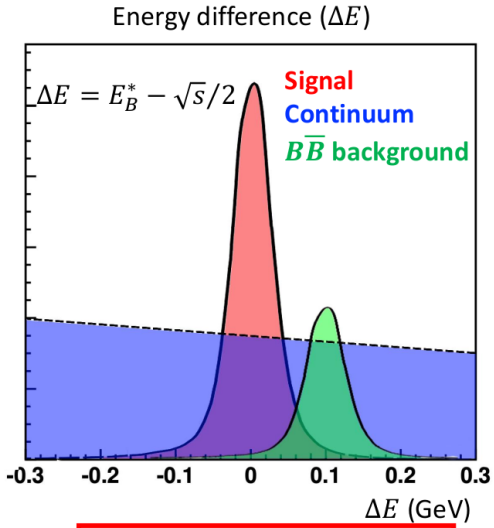
Suppress $10^5\times$ larger $q\bar{q}$ (continuum) background

- Combine several topological variables in multivariate techniques
- $q\bar{q}$ background rejection: $\approx 93-99\%$
  signal retention: $\approx 80-90\%$





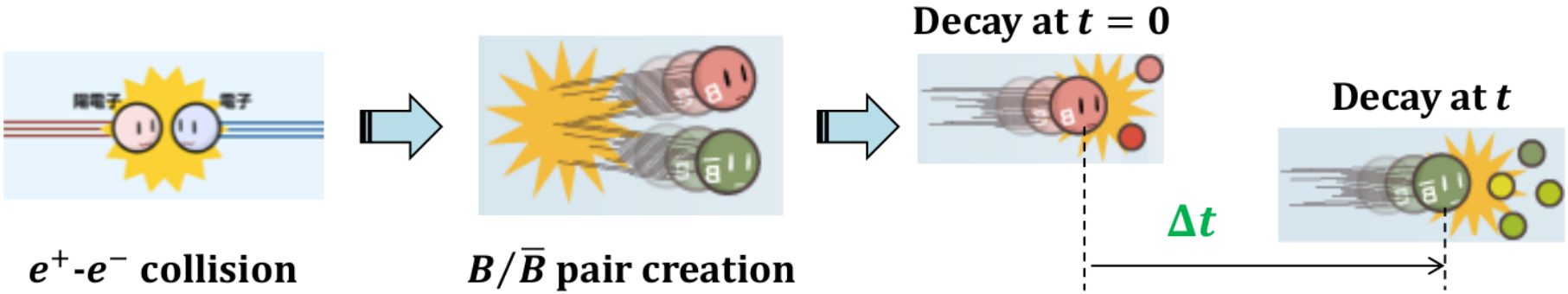
Separate $B\bar{B}$ events from $q\bar{q}$ background



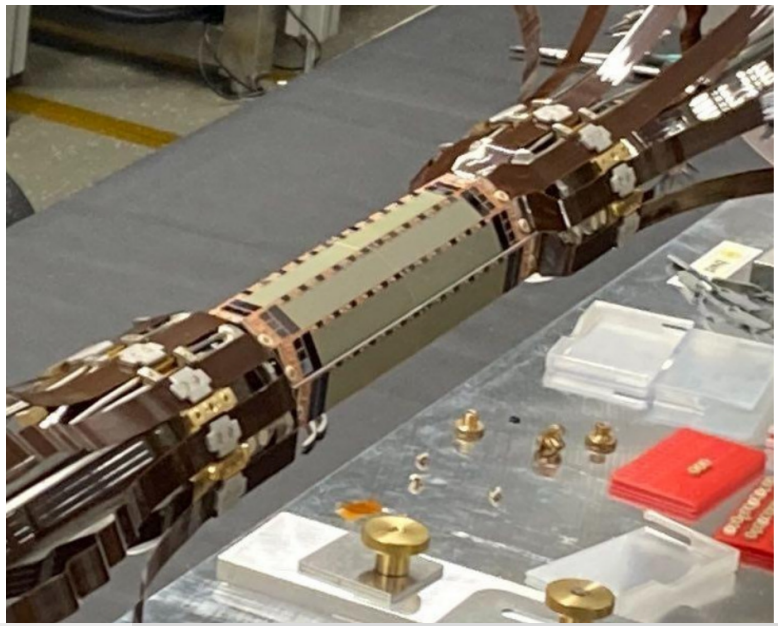
Separate signal events from $B\bar{B}$, $q\bar{q}$ background

Going for time-dependent analysis

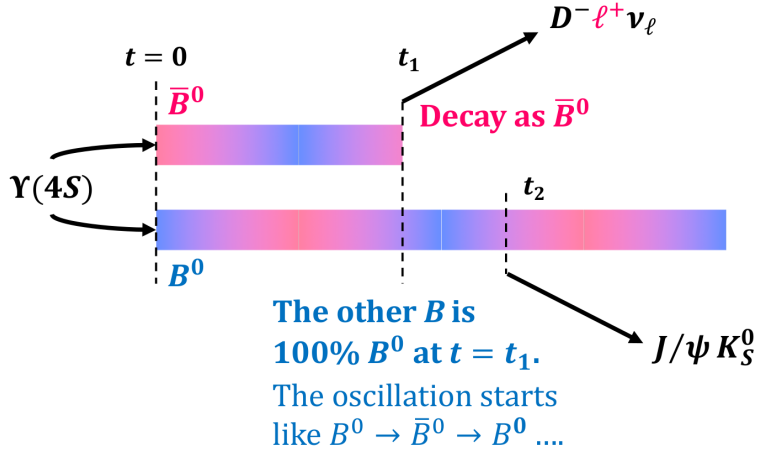
- $B^0\bar{B}^0$ coherent state

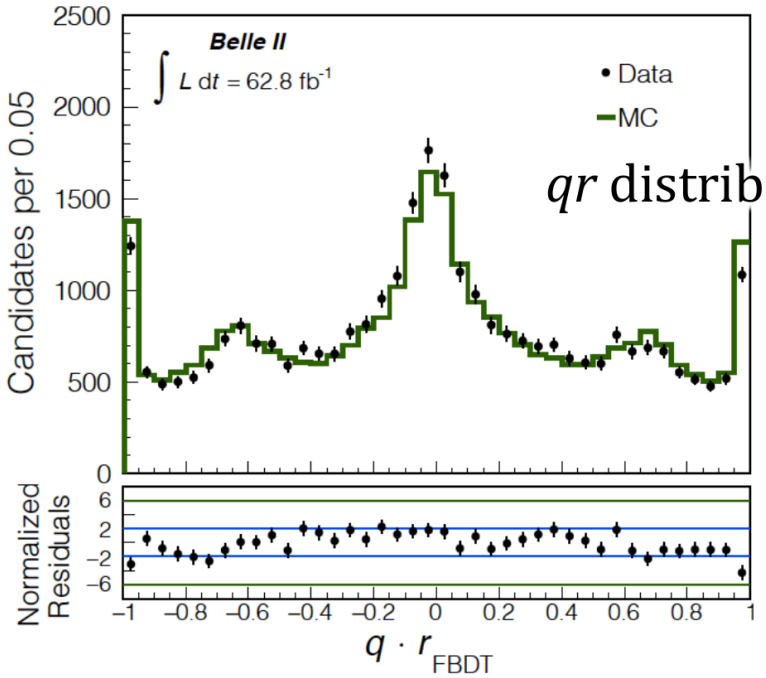


- Belle: ($\beta\gamma = 0.43$, $\Delta z \approx 200\mu m$)
  $\rightarrow$ Belle II: ($\beta\gamma = 0.29$, $\Delta z \approx 130\mu m$)
- Pixel detector installed to compensate reduced boost
- Improved Δt resolution using precise beam-spot profile of nano-beam scheme



Flavor tagging





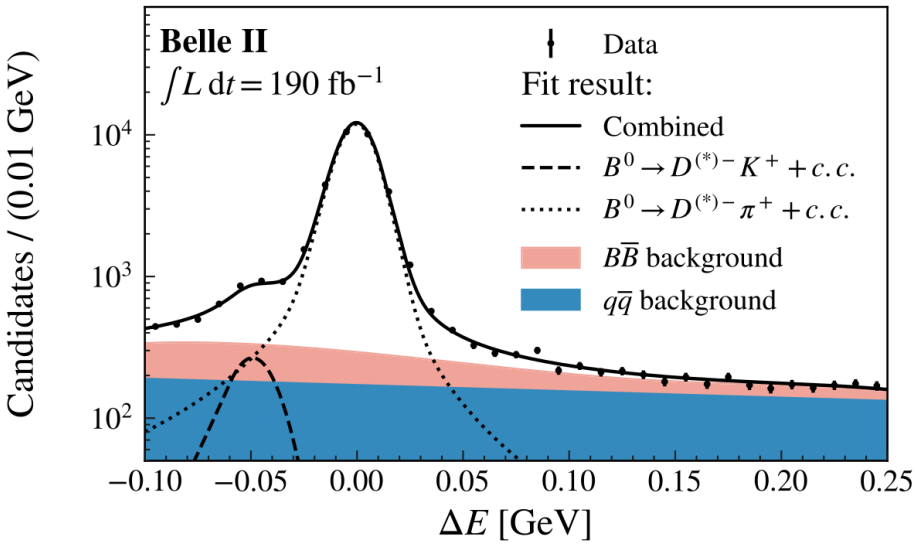
qr distribution

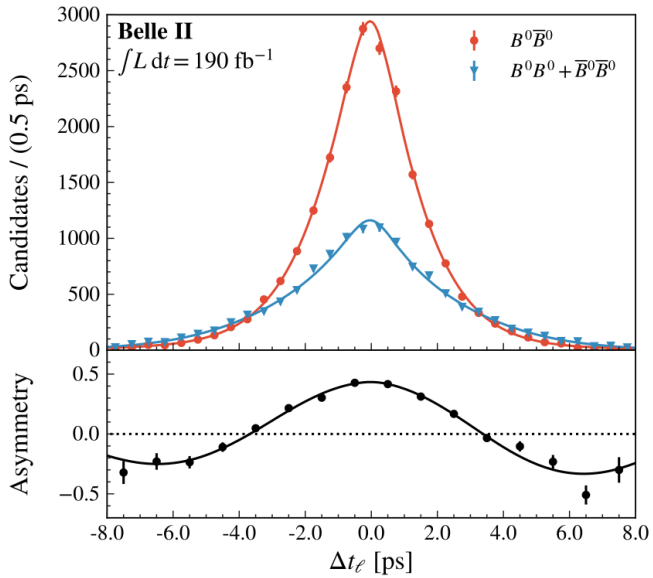
- Category-based FT uses input: kinematic, track hit and PID information
- $q = +1$ for B^0 tag and $q = -1$ for $\bar{B}^0$ tag
- Wrong tagging probability $w = \frac{1-r}{2}$
- Tagging efficiency $= (30.0 \pm 1.3)\%$
- New powerful Graph Neural Network based FT is close to release

Mixing and lifetime measurement

- 33 k $B^0 \to D^{*+} h^-$ events used
- Fit ΔE and continuum background discriminator output (C_{out}) to determine signal events
- Background subtracted Δt fitted to determine Δm_d and τ_{B^0}

Phys. Rev. D 107, L091102





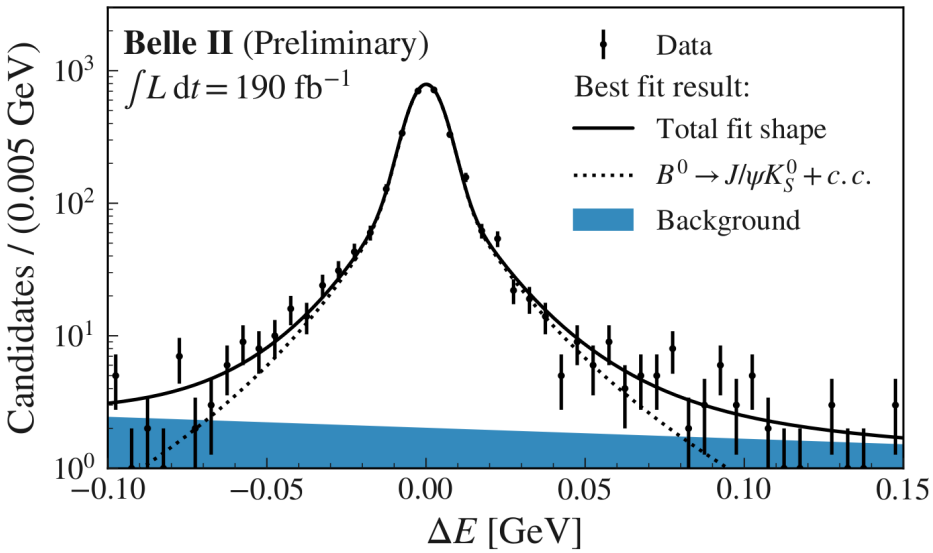
$\tau_{B^0} = 1.499 \pm 0.013(stat) \pm 0.008(syst)\text{ps}, \Delta m_d = 0.516 \pm 0.008(stat) \pm 0.005(syst)\text{ps}^{-1}$

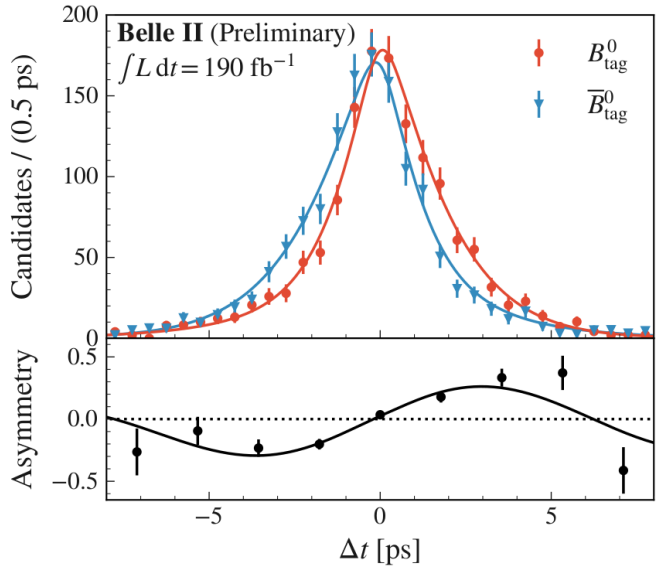
Benchmark for time-dependent measurements

Measurement of $\sin 2\phi_1$ in $B^0 \to J/\psi K^0_S$

- Utilize validated framework to $J/\psi K^0_S$ sample (3k events)
- Fit ΔE to determine signal events
- Background subtracted Δt fitted to measure CP parameters
- Flavor tagger and some resolution function parameters are taken from $B^0 \to D^{*-} h^+$

arXiv:2302.12898

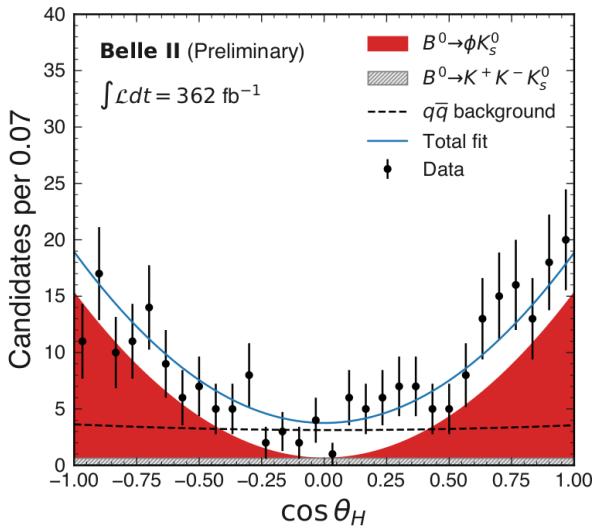


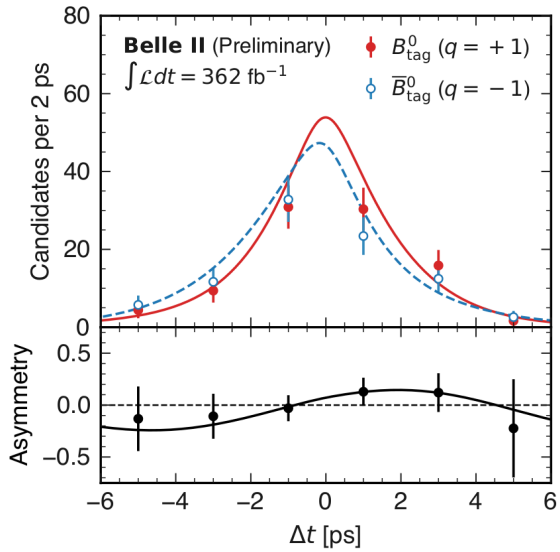


$A_{CP} = 0.094 \pm 0.044(stat)^{+0.042}_{-0.017}(syst), S_{CP} = 0.720 \pm 0.062(stat) \pm 0.016(syst)$

Measurement in $B^0 \to \phi K^0_S$

- Clean experimental access to probe $\Delta S_{CP} \equiv S_{CP}^{b\to sq\bar{q}} - \sin 2\phi_1$, with similar Δt resolution function as $J/\psi K^0_S$
- Fit signal-extraction variables Δt, M_{bc}, C_{out} and $\cos\theta_H$
- Nonresonant background coming from $B^0 \to K^+K^-K^0_S$ separated using $\cos\theta_H$





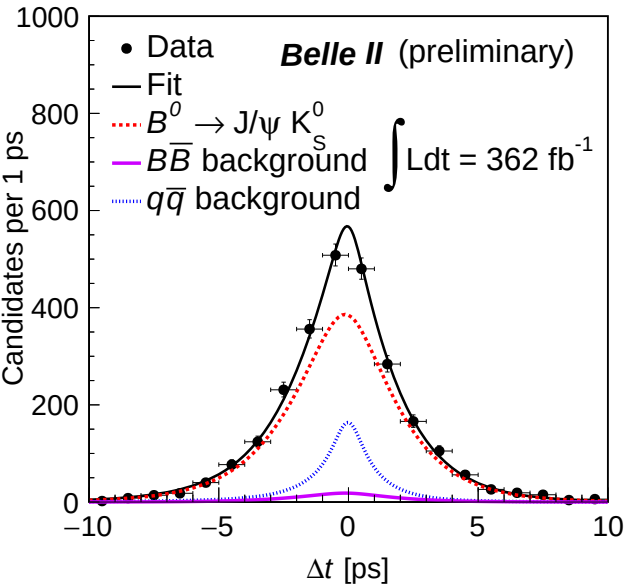
$A_{CP} = 0.31 \pm 0.20(stat) \pm 0.05(syst), S_{CP} = 0.54 \pm 0.26(stat)^{+0.06}_{-0.08}(syst)$

Similar uncertainty on A_{CP} despite using smaller dataset wrt Belle/BaBar

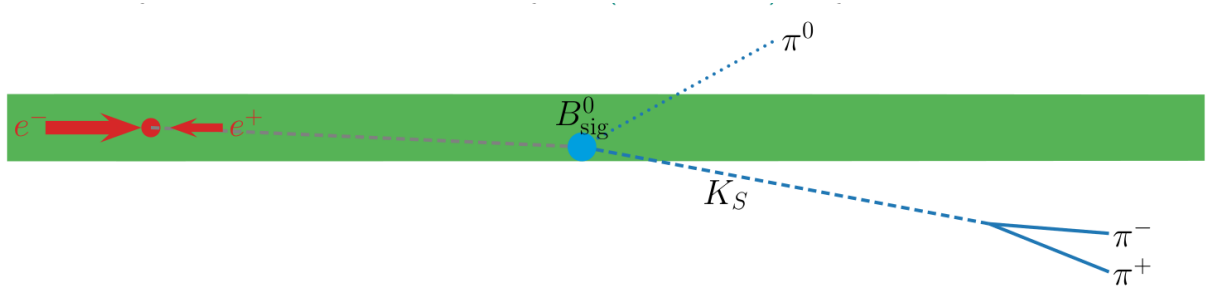
Measurement in $B^0 \to K^0_S \pi^0$

- Challenge: No primary charged particles to vertex, poor decay time resolution, need good performance with neutrals
- Fit signal-extraction variables ΔE, M_{bc}, Δt, and C_{out} in bins of flavor-identification quality
- Poor Δt resolution events also used to increase the precision on A_{CP}
- Validate on $B^0 \to J/\psi K^0_S$ with K^0_S only vertex

Belle II is the key player

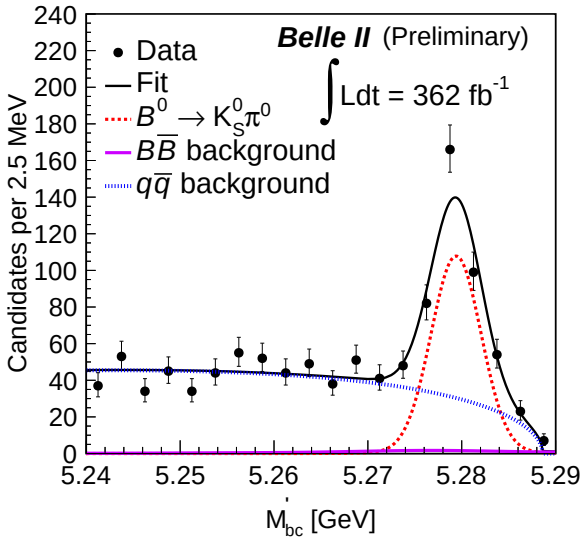


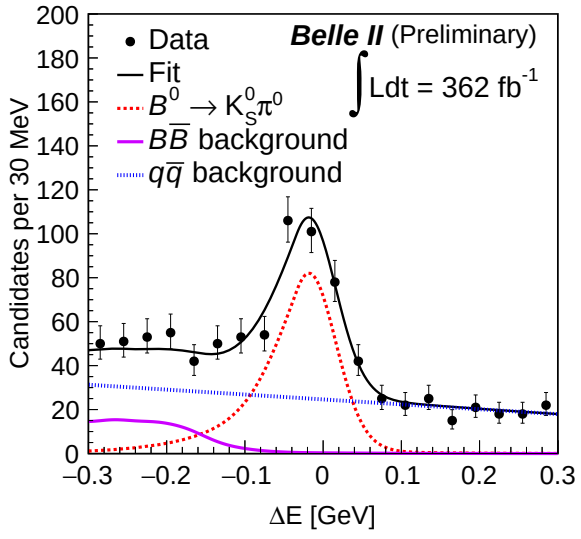
$\tau_{B^0} = 1.46 \pm 0.05$ ps

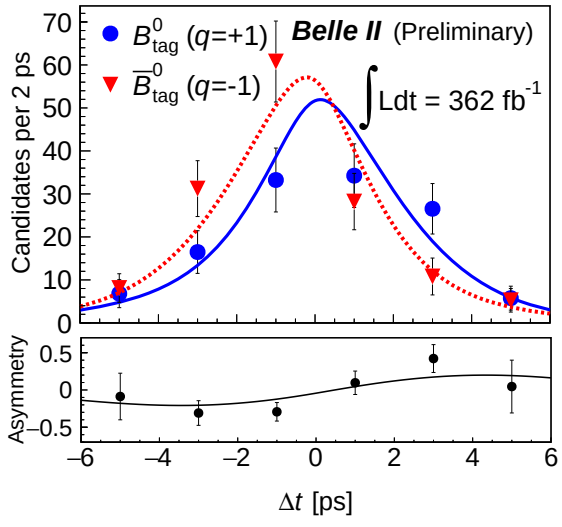


Measurement in $B^0 \to K^0_S\pi^0$

arXiv:2305.07555







Signal yield $=415 \pm 25$

$A_{CP} = 0.04 \pm 0.15(stat) \pm 0.05(syst)$, $S_{CP} = 0.75^{+0.20}_{-0.23}(stat) \pm 0.04(syst)$

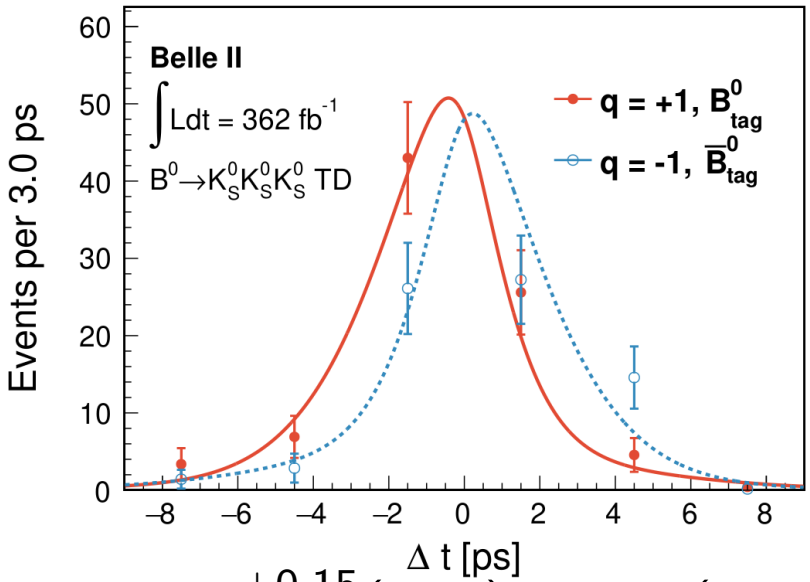
$I_{K\pi}$(with TI analysis) $= -0.03 \pm 0.13 \pm 0.05$ (see Karim's talk)

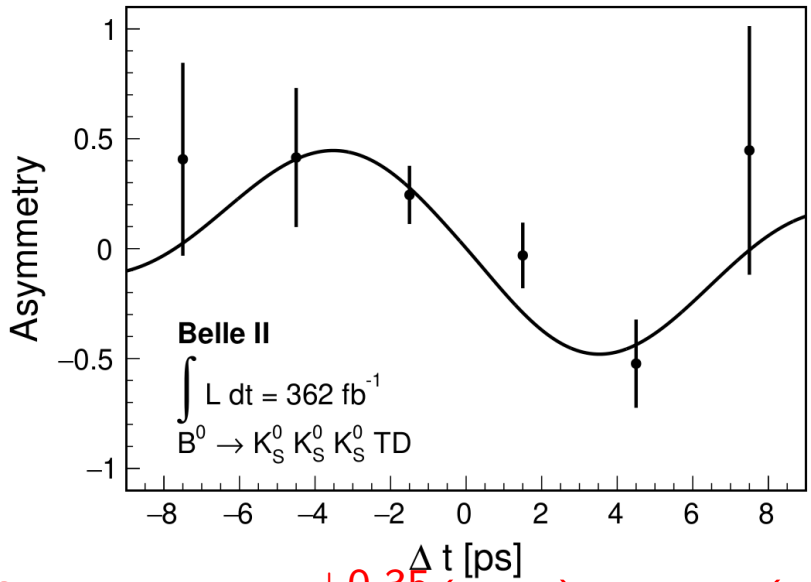
- Improved neutrals reconstruction, continuum suppression and event-by-event resolution of proper times
- Achieve precision comparable with world's best result even with smaller sample!

Measurement in $B^0 \to K^0_S K^0_S K^0_S$

- Similar challenge like $K^0_S \pi^0$: no primary charge track to vertex and poor decay time resolution
- Events are categorized based on Δt resolution
- Good and poor Δt resolution are fitted simultaneously to determine CP parameters

Preliminary





$A_{CP} = 0.07^{+0.15}_{-0.20}(stat) \pm 0.02(syst)$, $S_{CP} = -1.37^{+0.35}_{-0.45}(stat) \pm 0.03(syst)$

Unique channel to Belle II

Conclusion

- Belle II has unique access to channels that offer key tests of the SM
- Precision achieved on the $B^0 \to K^0_S \pi^0$ channel already competitive to world's best measurement
- Precision on $I_{K\pi}$ test comparable to world best result
- Belle II is in a unique position to measure $b \to sq\bar{q}$ transitions, which are sensitive to prove BSM physics through penguin loops

Thank You

Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown

- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- completed transition to new DAQ boards (PCIe40)
- accelerator improvements: injection, non-linear collimators, monitoring
- replacement of aging components
- additional shielding and increased resilience against beam bckg

Currently working on pixel detector installation:
==> shipping to KEK in ~mid March
==> final tests at KEK scheduled in April

On track to resume data taking next winter with new pixel detector [1]