Measurement of time-dependent CP violation at Belle and Belle II

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Outline

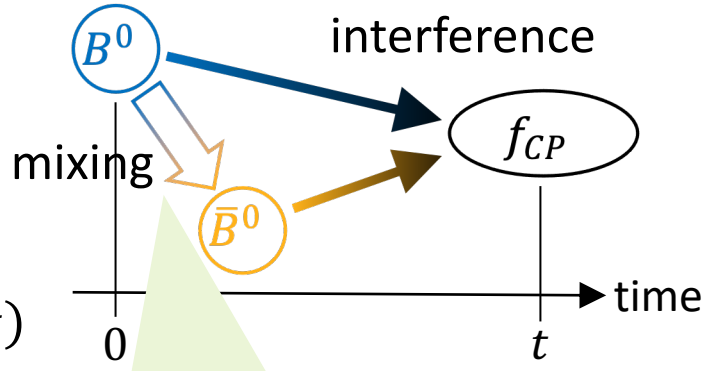
- Introduction
- Achievements in Belle
- Results from Belle II
  - $\sin 2\phi_1$ measurement with GFlaT
  - $\sin 2\phi_1^{\mathrm{eff}}$ measurement in $B^0 \to \eta' K_S^0$
  - S measurement in $B^0 \to K_S^0 \pi^0 \gamma$
  - Other results (Moriond 2023)
- Summary and Prospects

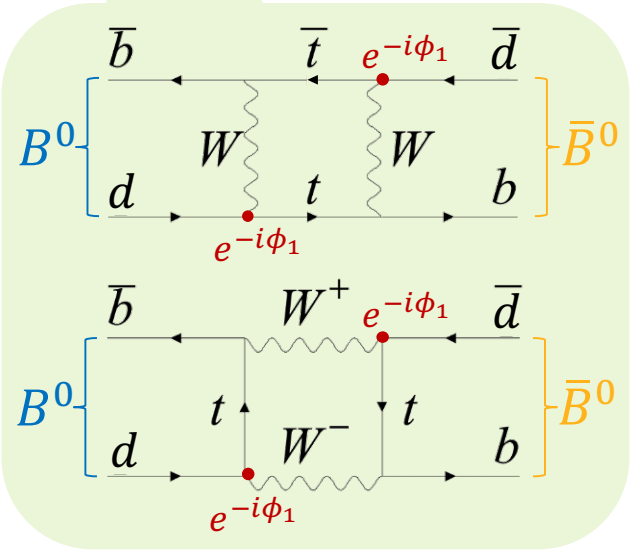
Mixing-induced CP-violation

- B^0-$\bar{B}^0$ mixing via box diagrams
  - $\arg(V_{td}V_{tb}^*)^2 \cong -2\phi_1$
    → Time-dependent CP-violation (TDCPV)

$$\frac{\Gamma(\bar{B}^0 \to f_{CP};t) - \Gamma(B^0 \to f_{CP};t)}{\Gamma(\bar{B}^0 \to f_{CP};t) + \Gamma(B^0 \to f_{CP};t)} = S \cdot \sin(\Delta m_d \cdot t) - \overbrace{C}^{C=-A} \cdot \cos(\Delta m_d \cdot t)$$

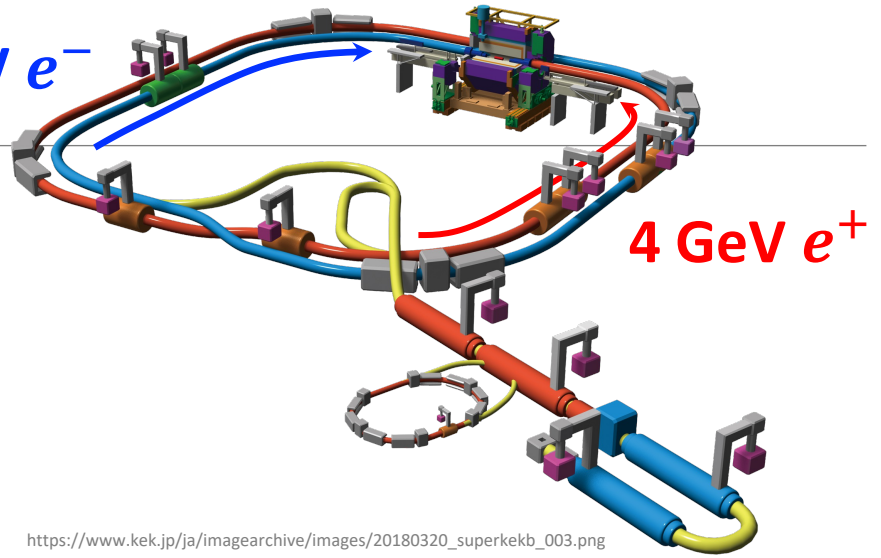
Δm_d: mass difference of B^0 mass eigenstates





  - If no phase in decay → $\underline{\boldsymbol{S = -\xi_{CP} \sin 2\phi_1}}$
    - ξ_{CP}: CP eigenvalue
  - S in loop-suppressed decays is sensitive to CP violation in BSM
    → $\underline{\boldsymbol{S = -\xi_{CP} \sin 2\phi_1^{\mathrm{eff}}}}$

SuperKEKB/Belle II

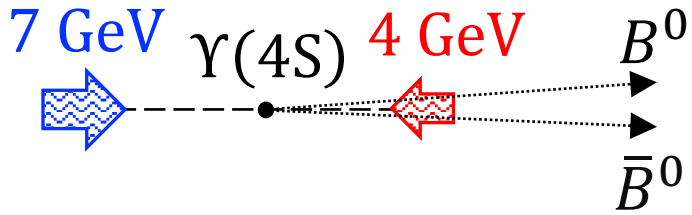


https://www.kek.jp/ja/imagearchive/images/20180320_superkekb_003.png

SuperKEKB (KEK, Tsukuba, Japan)

asymmetric energy collision

$\beta\gamma = 0.29, \sqrt{s} = 10.58$ GeV



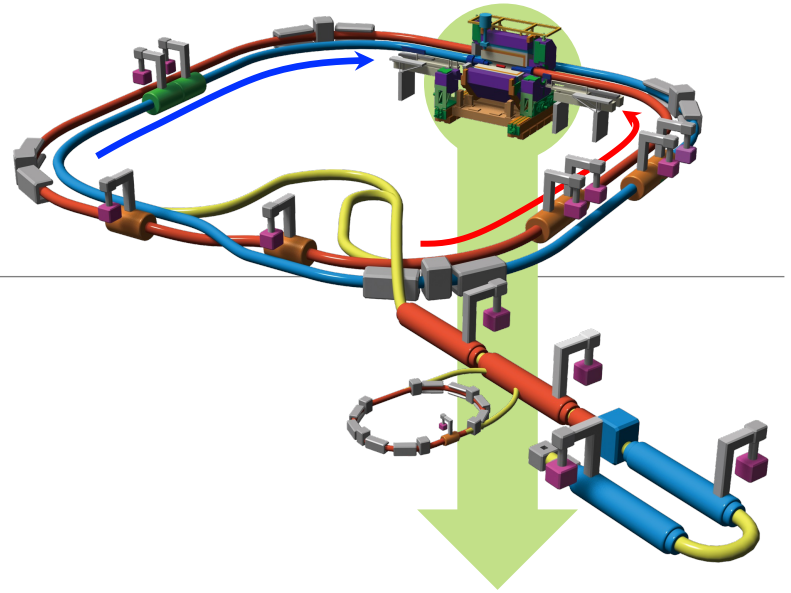
$B^0, \bar{B}^0$: nearly rest at center-of-mass frame

→ known initial 4-momentum

	KEKB/Belle	SuperKEKB/Belle II	
		achieved	target
$\mathcal{L}_{\mathrm{peak}}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.1×10^{34}	**4.7×10^{34} world record**	$\sim6\times10^{35}$
$\mathcal{L}_{\mathrm{int}}$ $[\mathrm{fb}^{-1}]$	1,004 ($711_{\Upsilon(4S)}$)	**424** (**$362_{\Upsilon(4S)}$**)	50,000
$N(B\overline{B})_{\Upsilon(4S)}$	772×10^6	**387×10^6**	$\sim5\times10^{10}$

data used in analysis

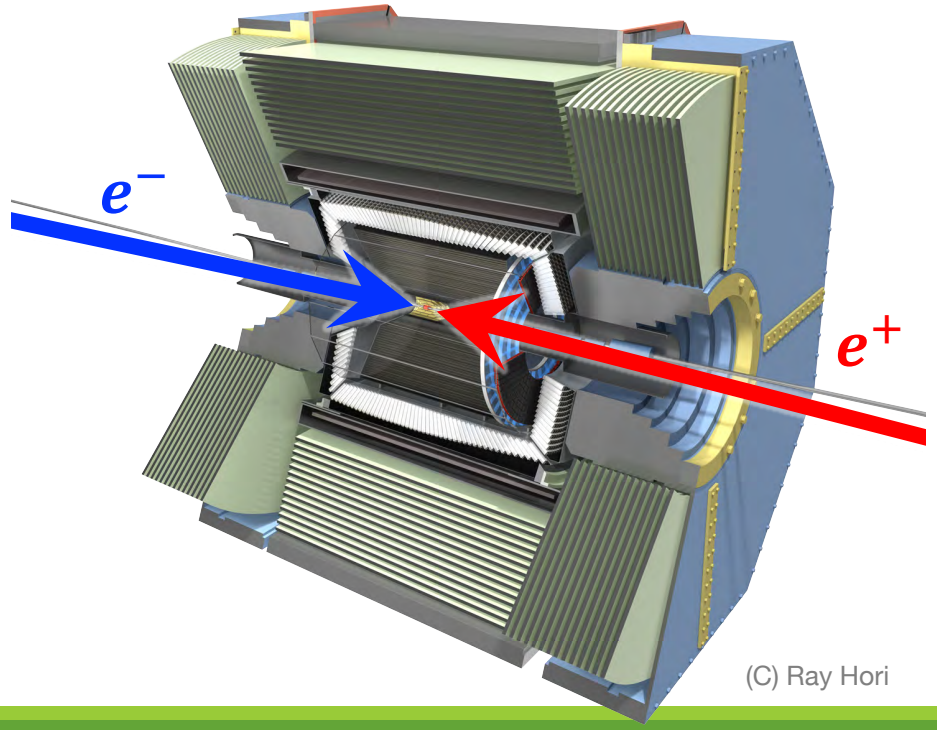
SuperKEKB/Belle II



Belle II detector

multi-purpose complex of 7 detectors

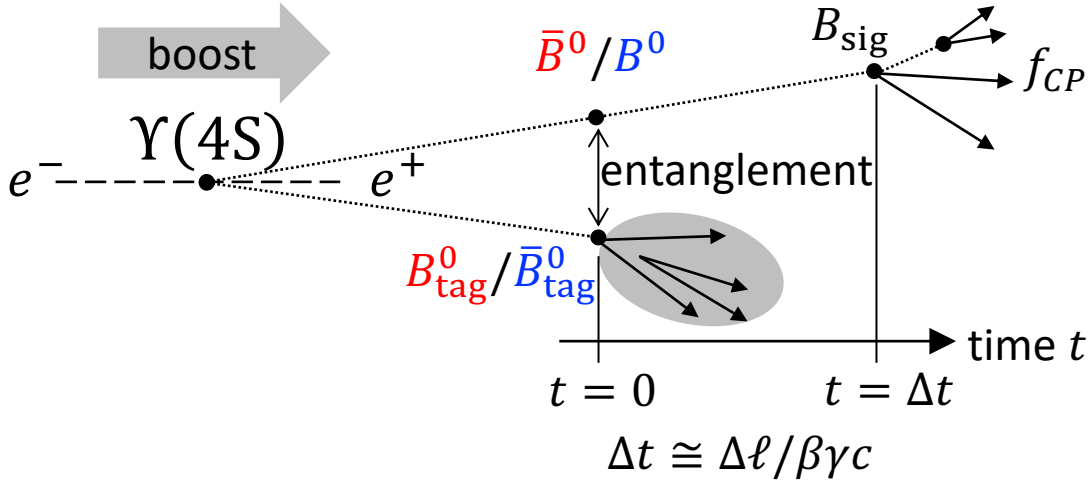
from inner to outer	
silicon pixel	vertex position ($\sigma_\ell \gtrsim 20\ \mu m$)
silicon strip	vertex position, tracking, dE/dx
drift chamber	tracking, momentum, dE/dx
Cherenkov (quartz / aerogel)	identify K/π
electromagnetic calorimeter	detect γ & measure energy
RPC & scintillator	detect K_L^0 & identify μ



(C) Ray Hori

TDCPV measurements at Belle and Belle II

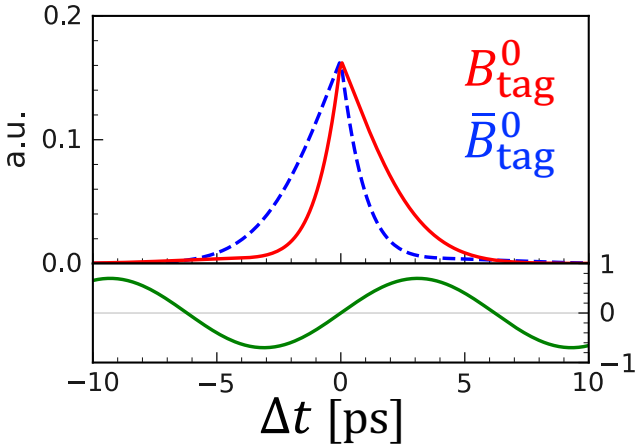
1. Reconstruct $B_{\rm sig} \to f_{CP}$
2. Identify $B^0_{\rm tag}/\bar{B}^0_{\rm tag}$ from decay products
   - flavor $q = +1/-1$
3. Meaure $\Delta t \cong \Delta\ell/\beta\gamma c$
   - $\Delta\ell$: decay vertices distance, $\langle\Delta\ell\rangle \sim 130\ \mu$m
   - Lorentz boost $\beta\gamma = 0.29$ from beam measurement
4. Fit S, C to $\{\Delta t, q\}$



$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q \cdot [S \cdot \sin(\Delta m \Delta t) - C \cdot \cos(\Delta m \Delta t)]\}$$

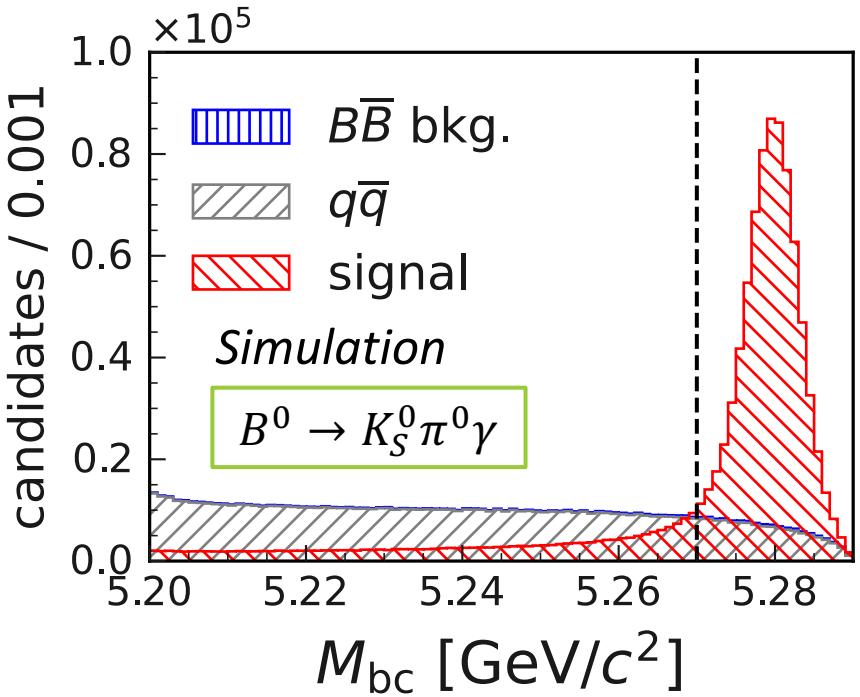
CP-asymmetry

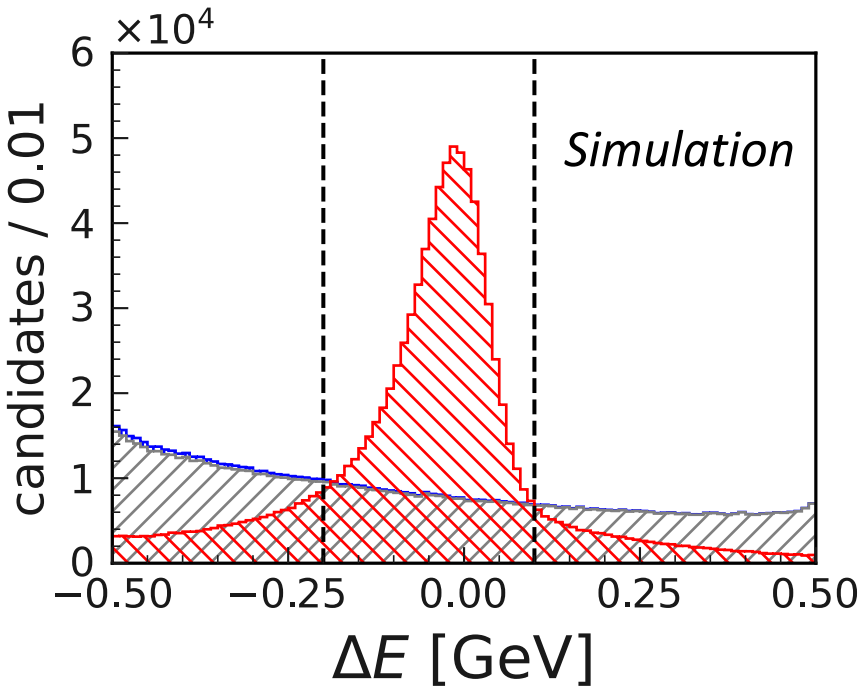
$$a_{CP} = \frac{N(\bar{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}$$



B_{sig} reconstruction w/ beam energy

- Use well-measured beam collision energy $\sqrt{s}$
  - Invariant mass:
    $M_{\mathrm{bc}} = \sqrt{s/4 - p_B^{*2}}$
  - Energy residual:
    $\Delta E = E_B^* - \sqrt{s}/2$



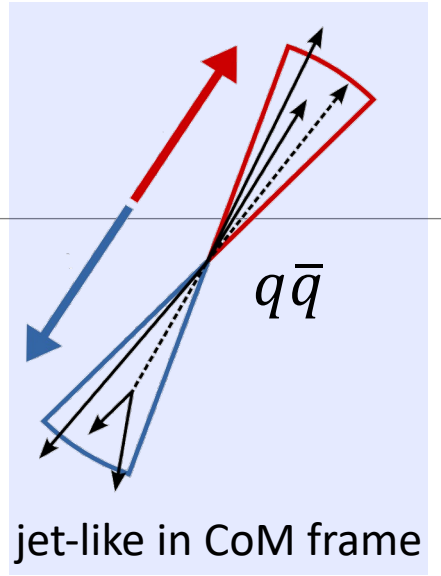


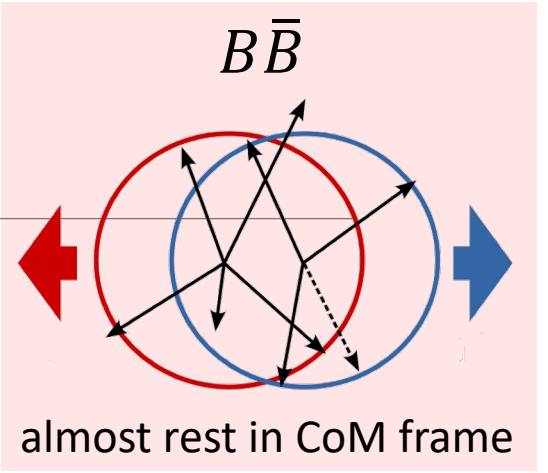
Background suppression

- "continuum" light-quark ($q\bar{q}$) production
  - $O(10^6)$ higher event rate than signal
    - signal: rare B decays

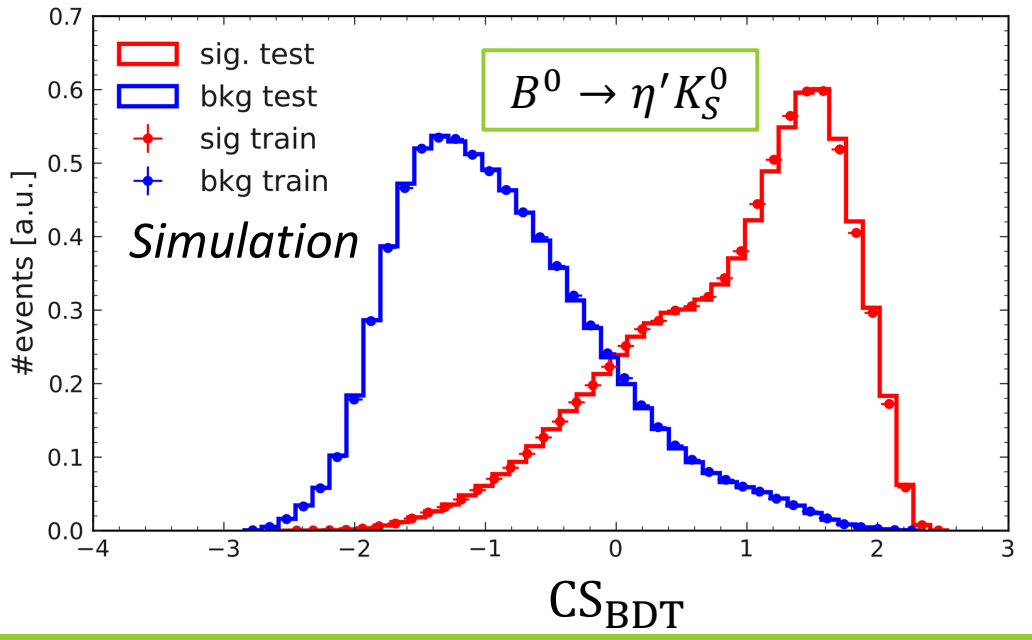
  → dominant source of background

- Continuum suppression (CS)
  - Use boosted decision tree (BDT) for event classification
  - Input event-shape observables
  - Train signal vs. $q\bar{q}$





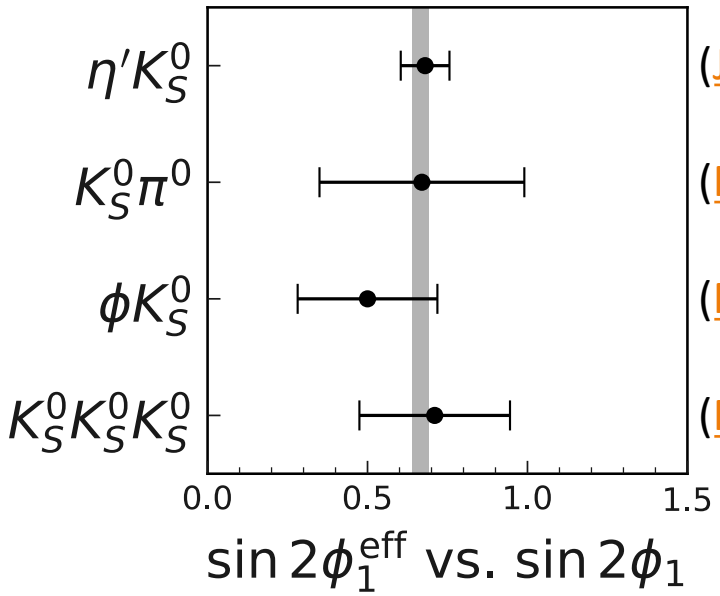
https://b2-master.belle2.org/software/development/sphinx/_images/continuum_without_labels.png



Achievements in Belle

- $\sin 2\phi_1$
  - $0.667 \pm 0.023 \pm 0.012$ (PRL108(2012)171802)
    - $\tau_{B^0} = 1.534 \pm 0.008 \pm 0.010$ ps, $\Delta m_d = 0.511 \pm 0.005 \pm 0.006$ ps^{-1} (PRD71(2005)079903)

- $\sin 2\phi_1^{\mathrm{eff}}$ in gluonic penguins



(JHEP10(2014)165)

(PRD81(2010)011101)

(PRL98(2007)031802)

(PRD103(2021)032003)

- S in radiative penguin
  - $S_{K^{*0}\gamma} = -0.32^{+0.36}_{-0.33} \pm 0.05$ (PRD74(2006)111104)

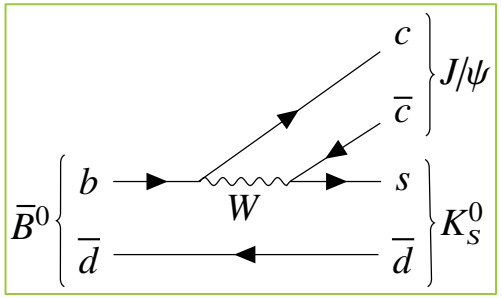
etc.

Belle II is now capable of updating these results!

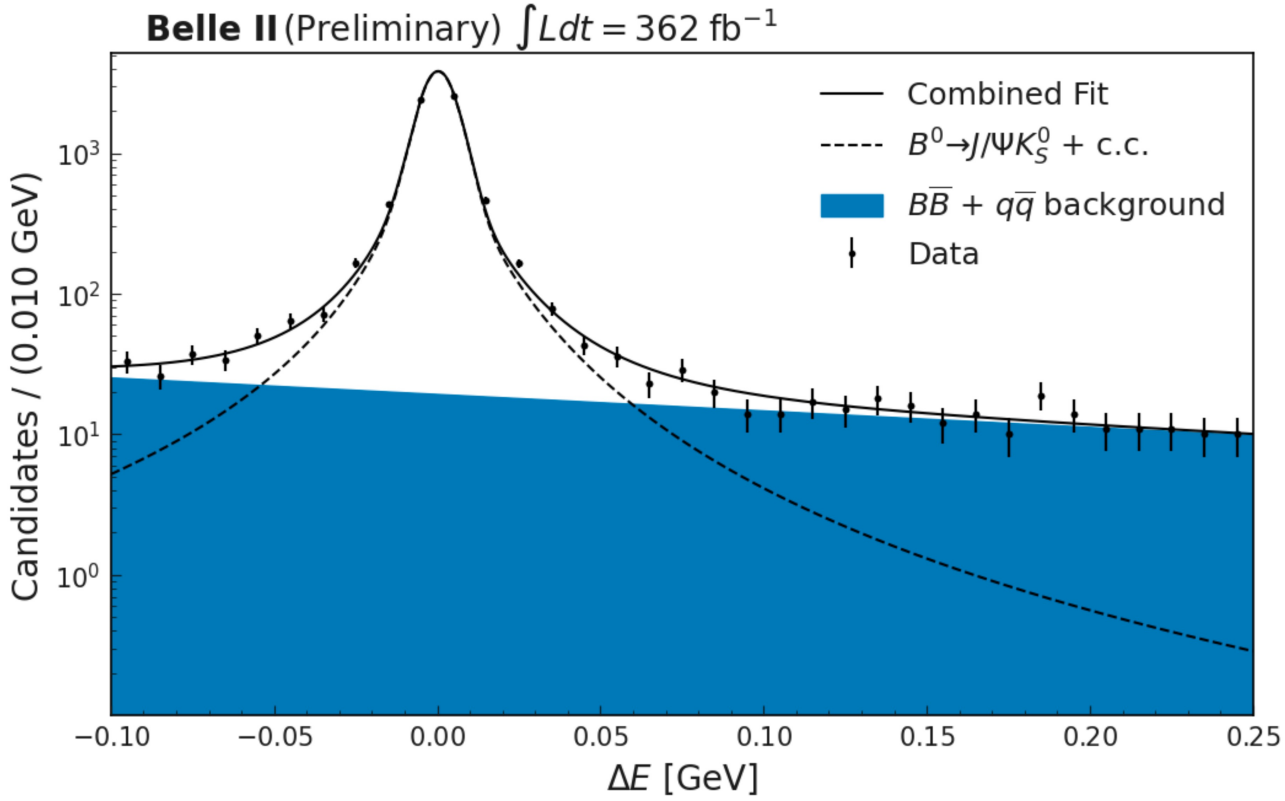
Results from Belle II

$\sin 2\phi_1$ measurement

- TDCPV in $B^0 \to J/\psi\, K_S^0$



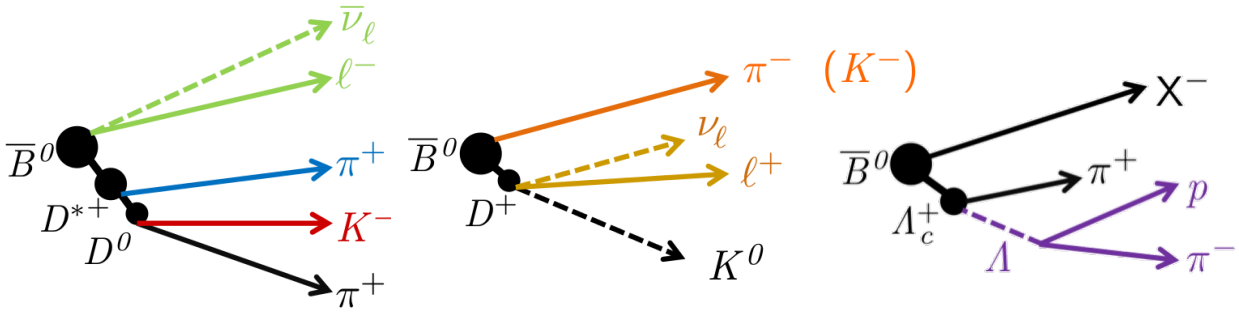
- $b \to c\bar{c}s$: tree-level w/o phase
  → $S = \sin 2\phi_1$
- Experimentally clean signature
  - signal & background separated by fitting ΔE
  - signal yield: 6373 ± 84
- New flavor tagger *GFlaT* is used



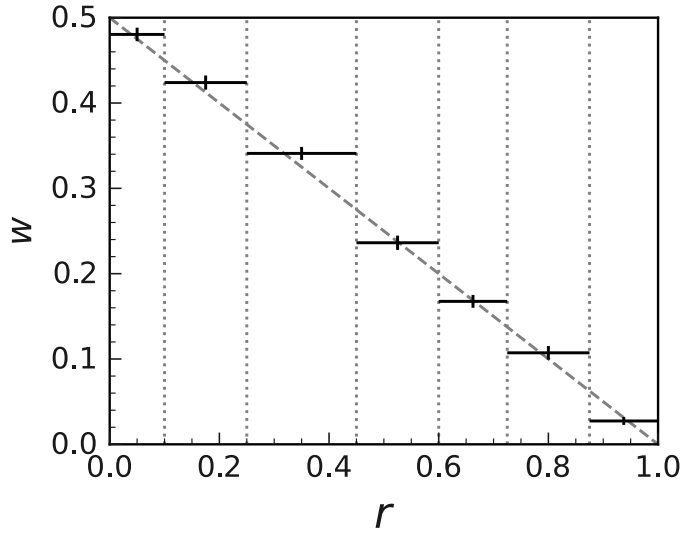
$B^0_{\rm tag}/\bar{B}^0_{\rm tag}$ identification

- (Conventional) Flavor tagger
  - Train BDT for each flavor-specific decay product
    - $\ell^{\pm}$, $K^{\pm}$, slow $\pi^{\pm}$, etc.
    - training sample: B^0 vs. $\bar{B}^0$
  - 13 category-based BDT outputs are merged to $q \cdot r$ in another BDT
    - dilution factor $r = 0/1$: flavor unknown/determined
  - Evaluate wrong tag fraction w & its q-asymmetry Δw in the slice of r
    - measured in large-statistic flavor-specific $B \to D^{(*)\pm} h^{\mp}$ channel
    - confirm $r = 1 - 2w$

    → considered in PDF



https://software.belle2.org/development/sphinx/_images/newFlavorTaggerCategories.png



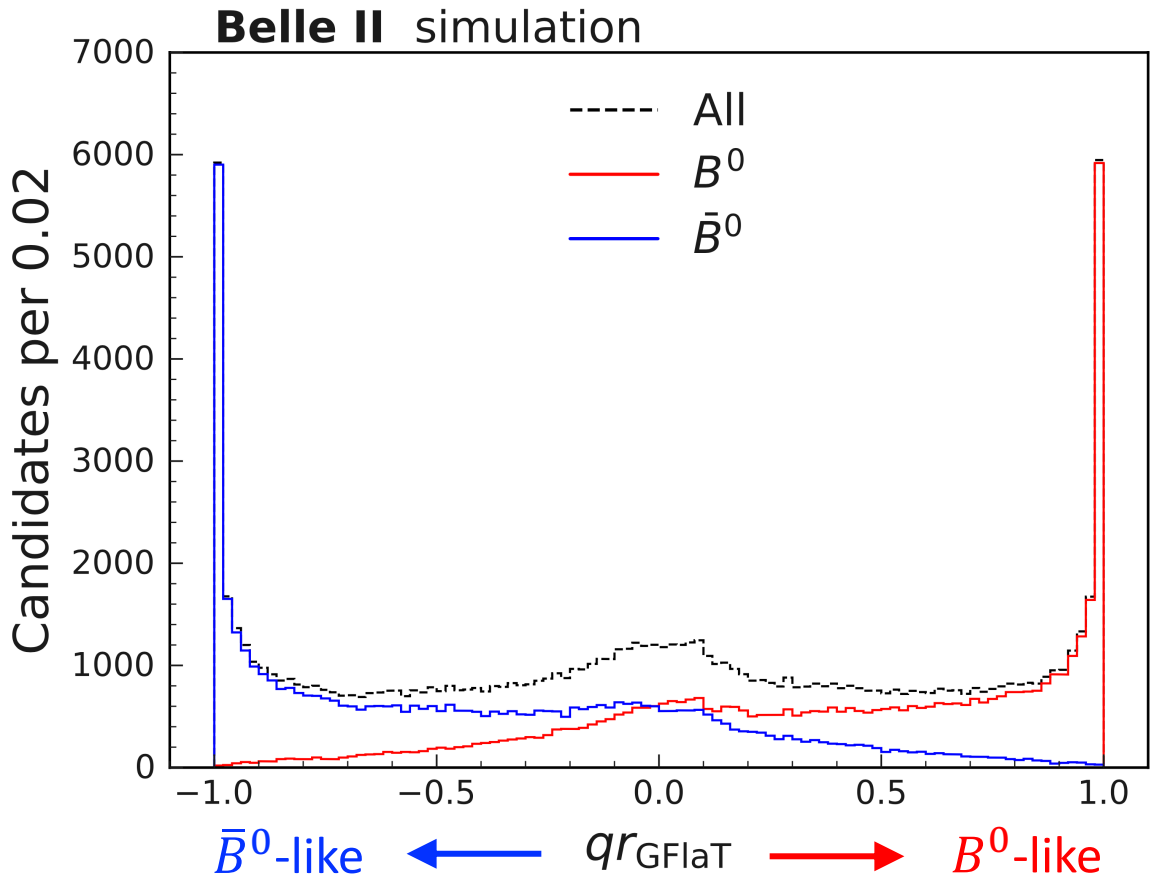
GFlaT: GNN flavor tagger

- Motivation
  - Category-based BDT does not consider relations b/w particles
    - e.g., $B^0 \to K^- X$ fakes $\bar{B}^0 \to D^0/D^+ \to K^-$ chain
- Graph Neural Network
  - Node = particle, Edge = relation

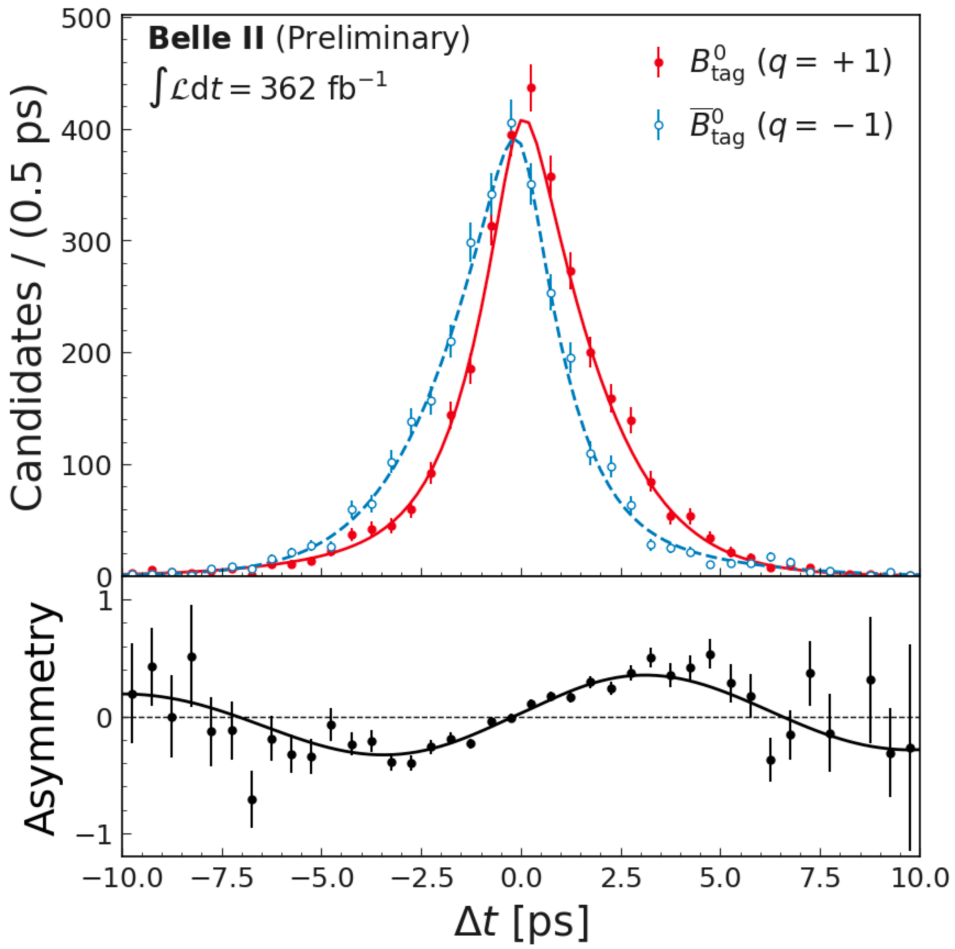
    → Utilize characteristics of relations
    - e.g., prompt/secondary K^- can be distinguished
  - Effective tagging efficiency in data:

    $(31.68 \pm 0.45 \pm 0.41)\%$

    → $(37.40 \pm 0.43 \pm 0.34)\%$ 18% gain
    - c.f. $28.8 \pm 0.6\%$ in Belle



TDCPV in $B^0 \to J/\psi\, K_S^0$



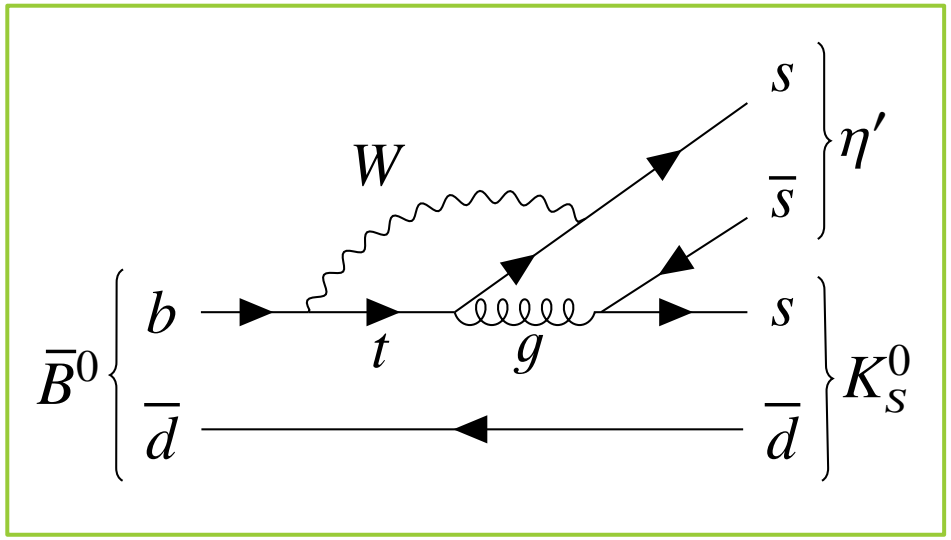
- τ_{B^0} and Δm_d (PRD107(2023)9,L091102)
  - Measured in $B^0 \to D^{(*)-}\pi^+$
  - $\tau_{B^0} = 1.499 \pm 0.013 \pm 0.008$ ps
  - $\Delta m_d = 0.516 \pm 0.008 \pm 0.005$ ps^{-1}
- S and C fit
  - Δt resolution considered in PDF
  - remove background from the fit (sFit)
  - $S = 0.724 \pm 0.035 \pm 0.014$
  - $C = 0.035 \pm 0.026 \pm 0.012$
    - HFLAV: $S = 0.695 \pm 0.019$ $C = 0.000 \pm 0.020$
    - LHCb: $S = 0.716 \pm 0.015$ $C = 0.012 \pm 0.012$

GFlaT reduces statistical uncertainty by ~8%

$\sin 2\phi_1^{\mathrm{eff}}$ measurement in $B^0 \to \eta' K_S^0$

- $B^0 \to \eta' K_S^0$
  - $b \to sq\overline{q}$: loop-suppressed transition

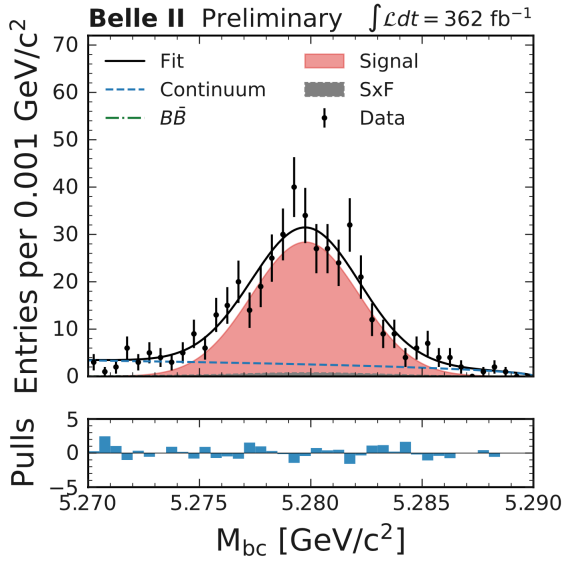
    → Deviation of $S = \sin 2\phi_1^{\mathrm{eff}}$ from $\sin 2\phi_1$ indicates BSM effect
  - relatively high BF w.r.t. other gluonic penguins

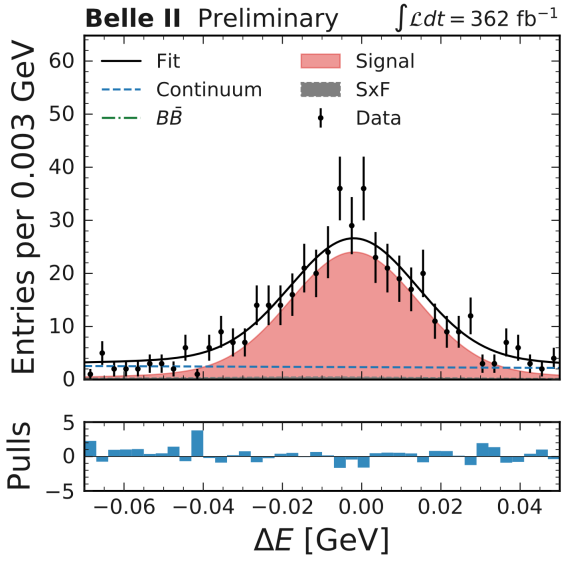


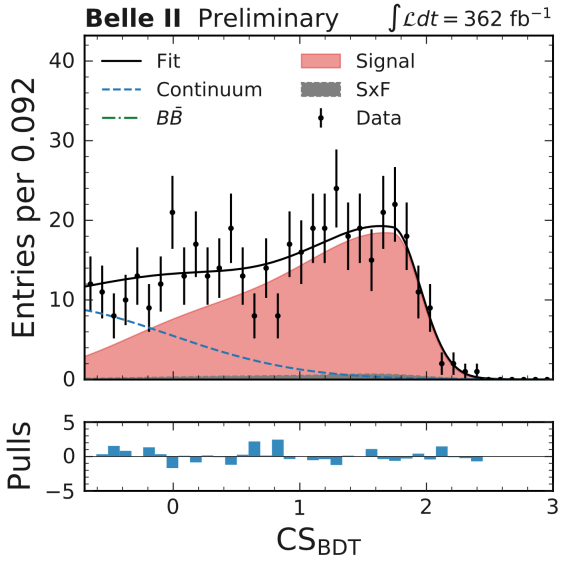
$B^0 \to \eta' K_S^0$ event reconstruction

- Reconstruct 2 sub-channels
  - $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$
  - $\eta' \to \rho(\pi^+\pi^-)\gamma$
- Signal & background separation
  - High backgrounds from $q\bar{q}$ events
    - random combination of tracks
  - Fit $M_{\mathrm{bc}}, \Delta E, \mathrm{CS}_{\mathrm{BDT}}$ (3-dimensional)

$\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$
signal yield: 358 ± 20







$B^0 \to \eta' K_S^0$ event reconstruction

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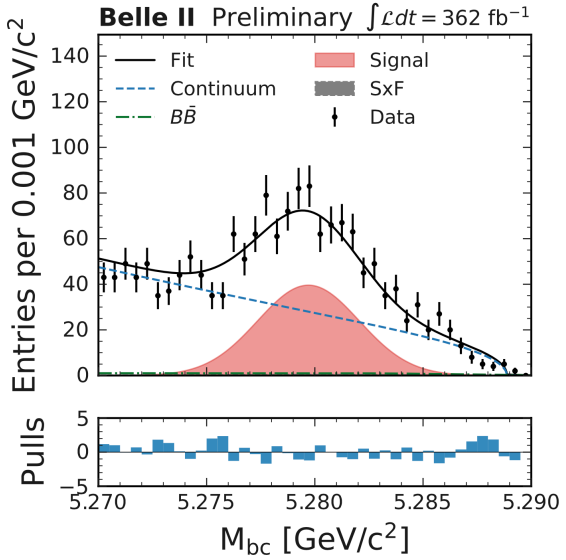
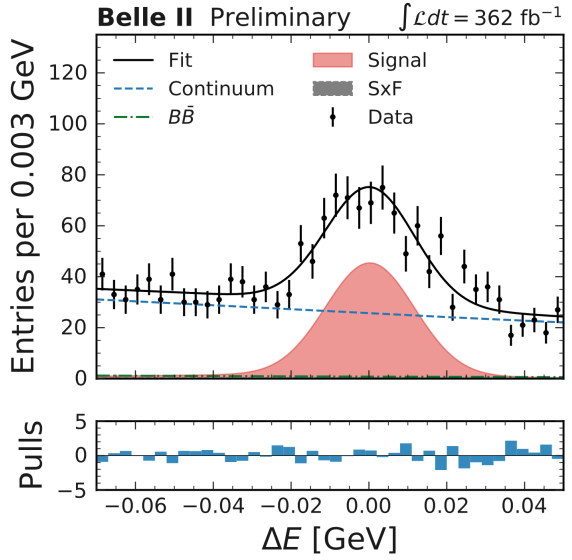
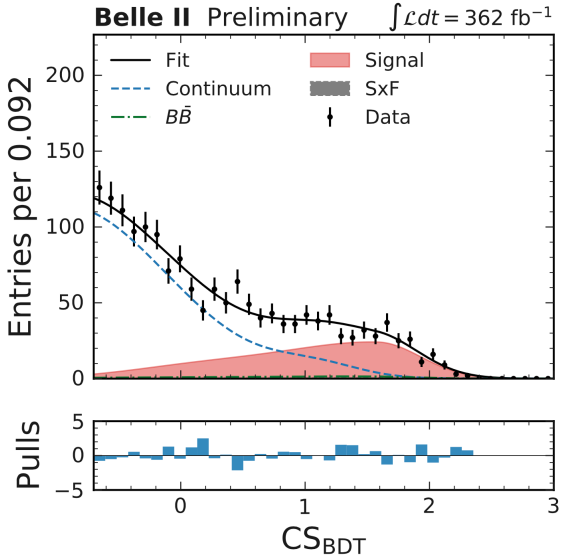
  - High backgrounds from $q\bar{q}$ events
    - random combination of tracks
  - Fit $M_{\mathrm{bc}}, \Delta E, \mathrm{CS}_{\mathrm{BDT}}$ (3-dimensional)

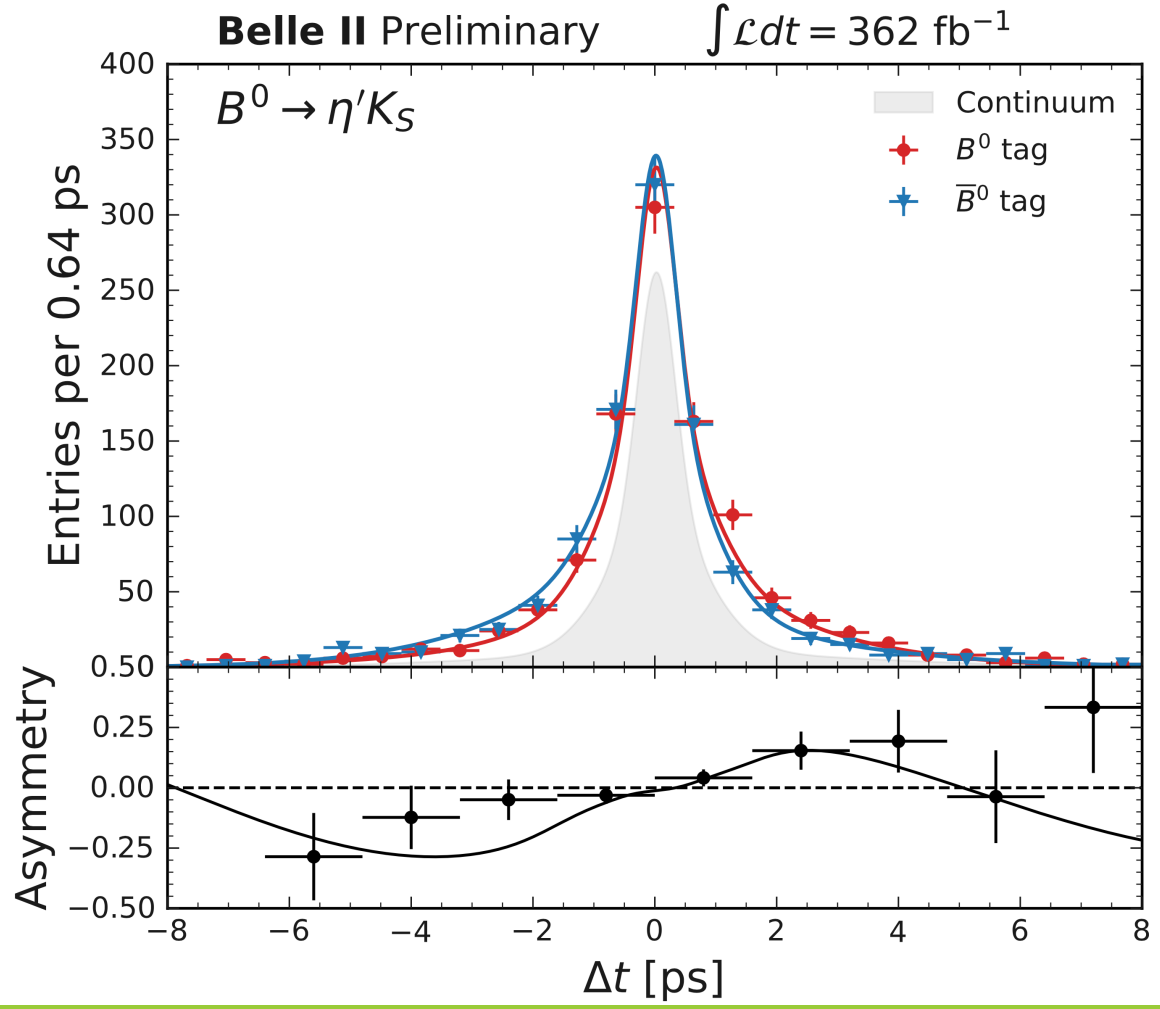
$\eta' \to \rho(\pi^+\pi^-)\gamma$
signal yield: 471 ± 29







TDCPV in $B^0 \to \eta' K_S^0$



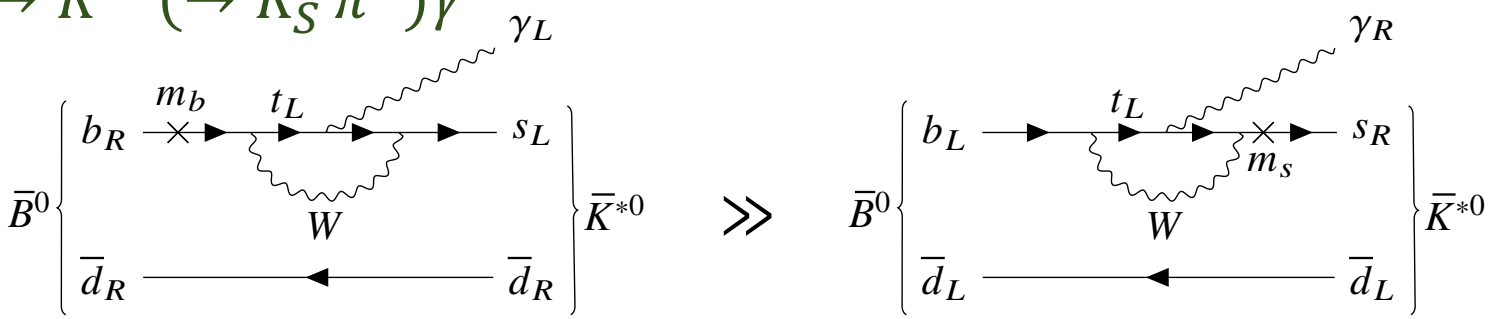
- S and C fit
  - Background Δt shape taken from sideband
    → considered in PDF
  - Validated in $B^\pm \to \eta' K^\pm$
  - Background-included asymmetry shown

  - $S = \quad 0.67 \pm 0.10 \pm 0.04$
  - $C = -0.19 \pm 0.08 \pm 0.03$
    - HFLAV: $S = 0.63 \pm 0.06$ $C = -0.05 \pm 0.04$
    - Cross-checked in $\eta' \to \eta(\pi^+\pi^-\pi^0)\pi^+\pi^-$ sub-channel

Unique at Belle II

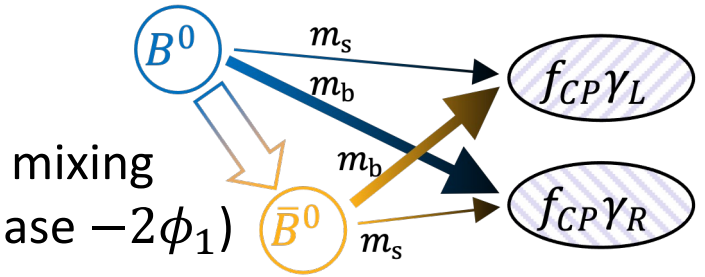
S measurement in $B^0 \to K_S^0\pi^0\gamma$

- S in $B^0 \to K^{*0}(\to K_S^0\pi^0)\gamma$



* In charge conjugate, helicity and polarization flip

- polarization constraints flavor
- ***O*(0.01)** in SM ↔ ***O*(0.1)** possible in BSM
- analyze in 2 channels:
  exclusive $K^{*0}\gamma$ / inclusive $K_S^0\pi^0\gamma$
  - $M_{K_S^0\pi^0} \in (0.8,1.0)\ \mathrm{GeV}/c^2$ for $K^{*0}\gamma$
  - rest of the region in $[0.6,1.8]\ \mathrm{GeV}/c^2$ for $K_S^0\pi^0\gamma$



mixing
(phase $-2\phi_1$)

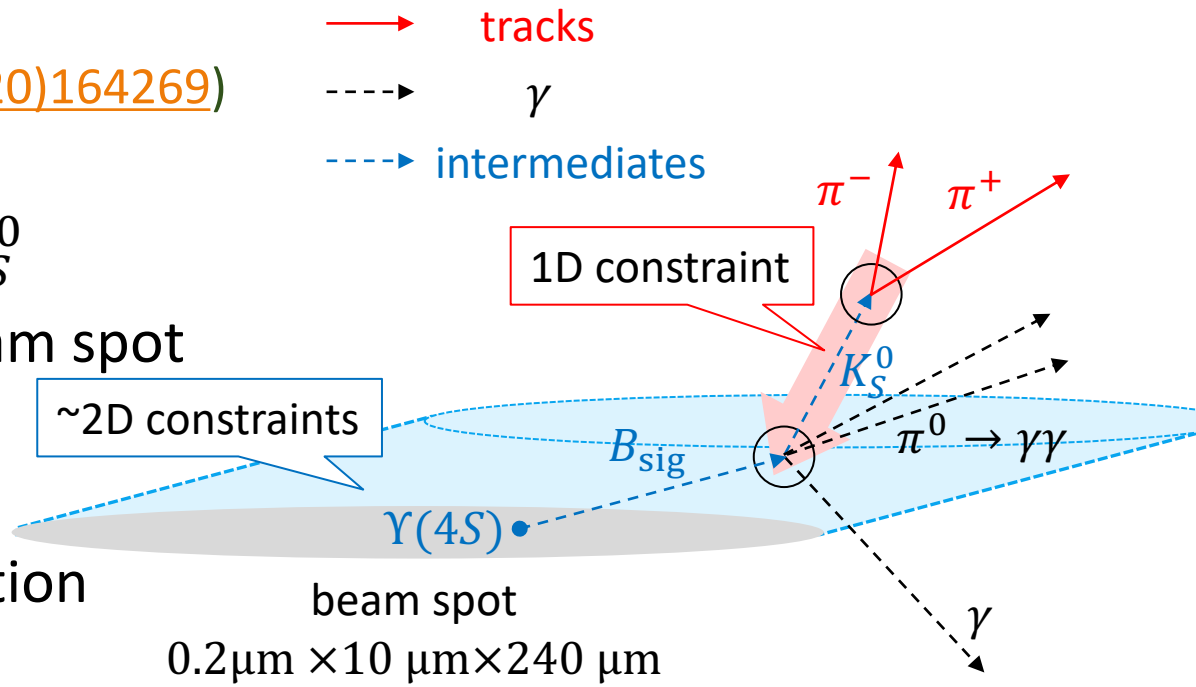
interference suppressed

$$S \cong -2\frac{m_s}{m_b}\sin 2\phi_1$$

0.04

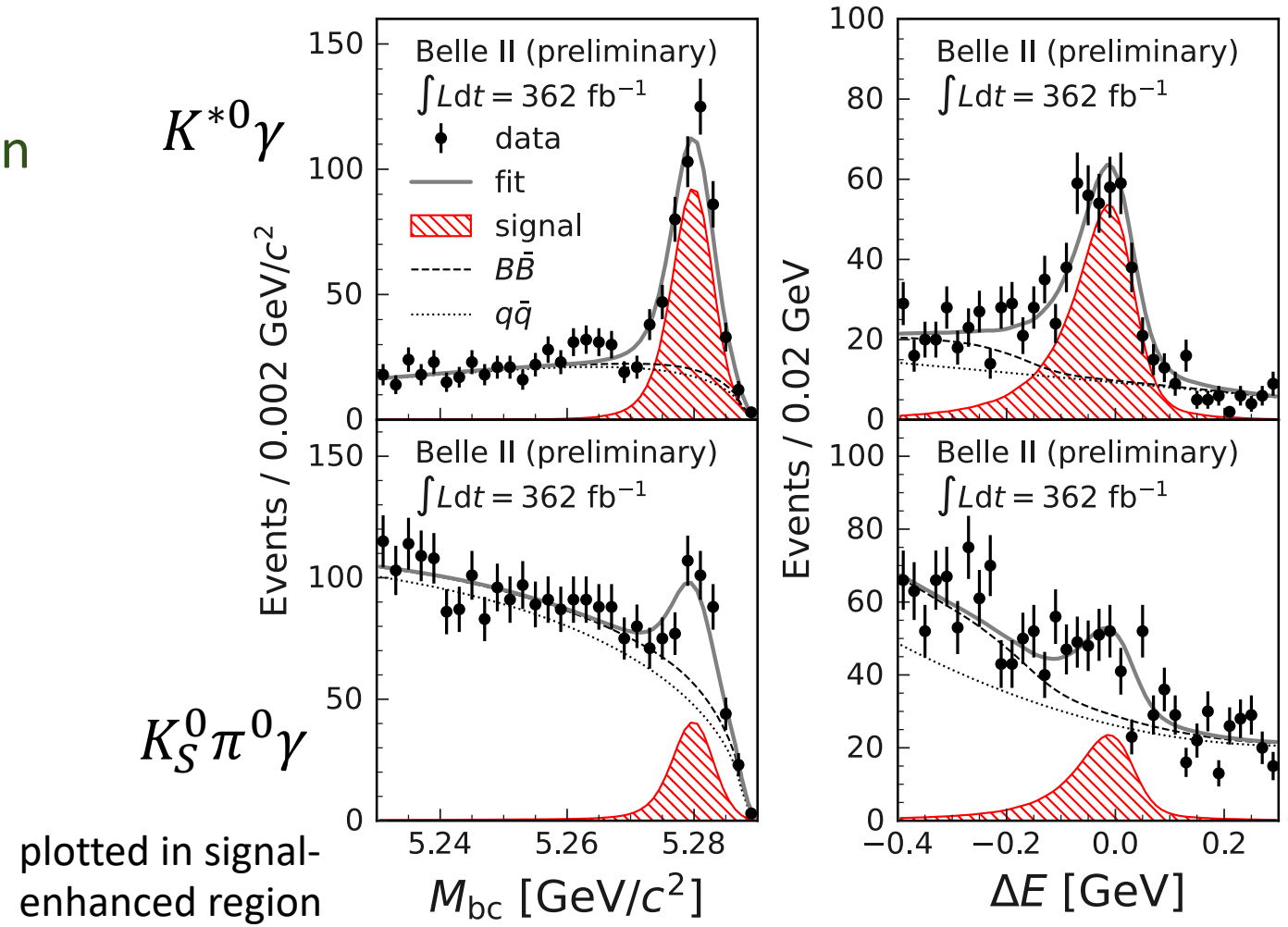
$B^0 \to K_S^0 \pi^0 \gamma$ vertex reconstruction

- Vertex fit w/o prompt tracks (NIMA976(2020)164269)
  - Unique at Belle II
  - $B_{\rm sig}$ vertex reconstructed only from K_S^0
  - Constrain $B_{\rm sig}$ production point to beam spot
    - measured in $e^+e^- \to \mu^+\mu^-$ events
  - Candidates w/ poor vertex reconstruction used in a time-integrated way
    - improve precision of C

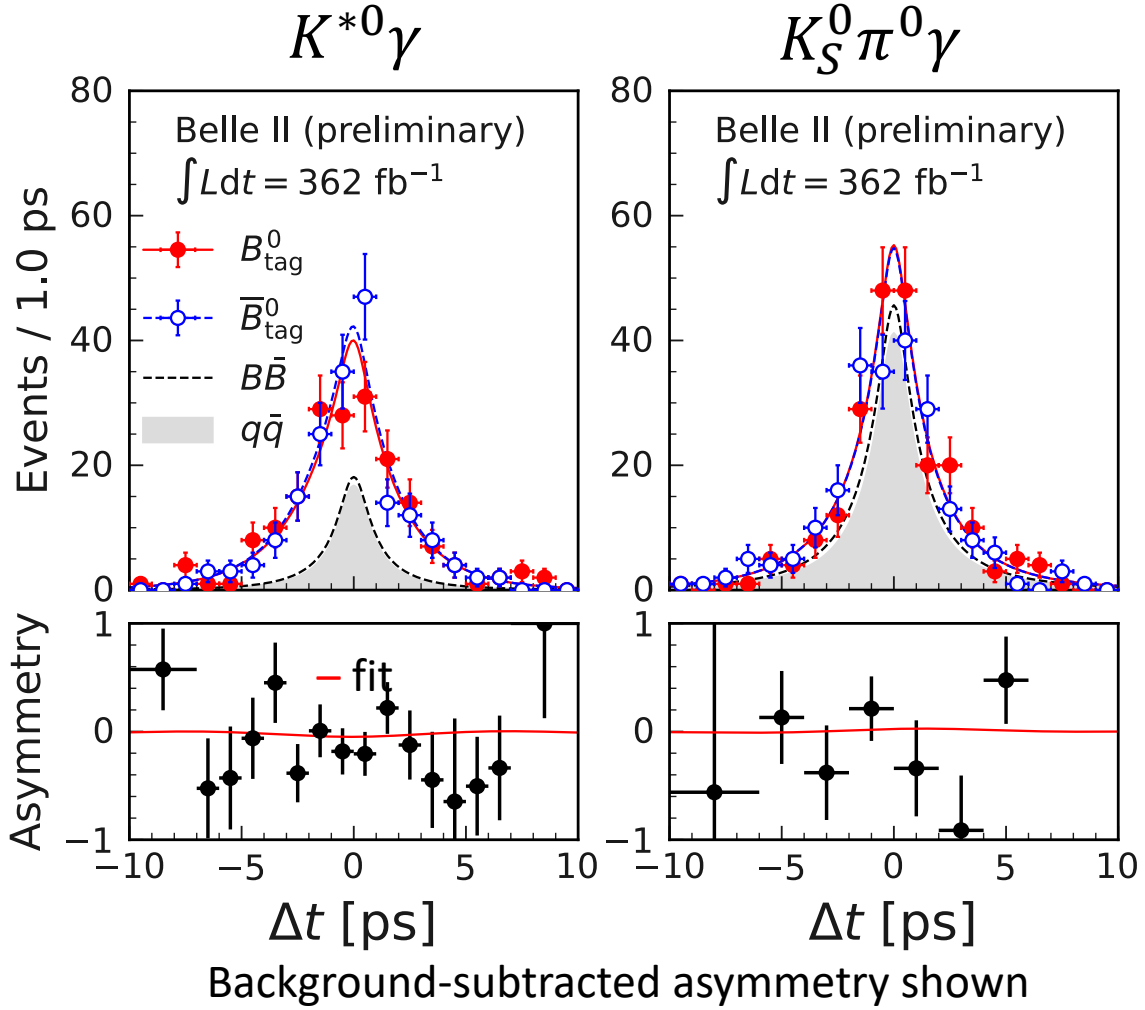


$B^0 \to K_S^0 \pi^0 \gamma$ signal reconstruction

- signal & background separation
  - 2D-fit to M_{bc} and ΔE
  - classify 3 components
    - signal, $B\overline{B}$ background, $q\overline{q}$
  - Signal yield:
    $385 \pm 24\ (K^{*0}\gamma)$
    $171 \pm 23\ (K_S^0 \pi^0 \gamma)$



TDCPV in $B^0 \to K_S^0 \pi^0 \gamma$

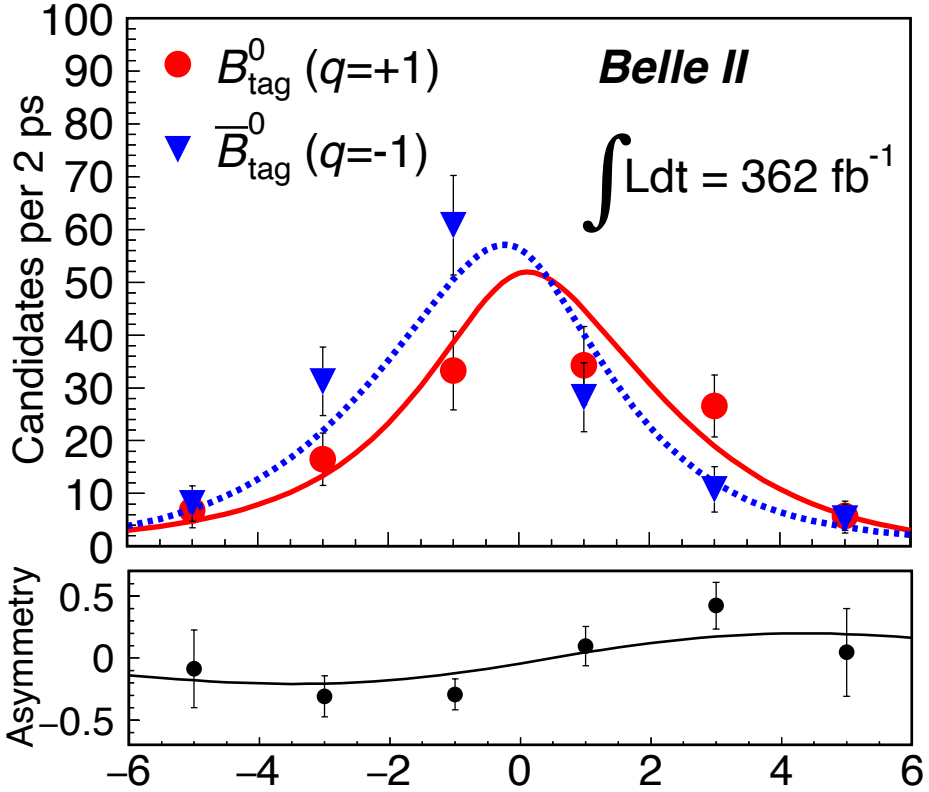


Background-subtracted asymmetry shown

- TDCPV parameters in $K^{*0}\gamma$ channel
  - $S = 0.00^{+0.27}_{-0.26} \pm 0.03$
  - $C = 0.10 \pm 0.13 \pm 0.03$
    - HFLAV: $S = -0.16 \pm 0.22$ $C = -0.04 \pm 0.14$
- TDCPV parameters in $K_S^0\pi^0\gamma$ channel
  - $S = \quad 0.04^{+0.45}_{-0.44} \pm 0.10$
  - $C = -0.06 \pm 0.25 \pm 0.08$
    - Belle (2006): $S = 0.50 \pm 0.68$ $C = 0.20 \pm 0.39$

Most precise result to date!

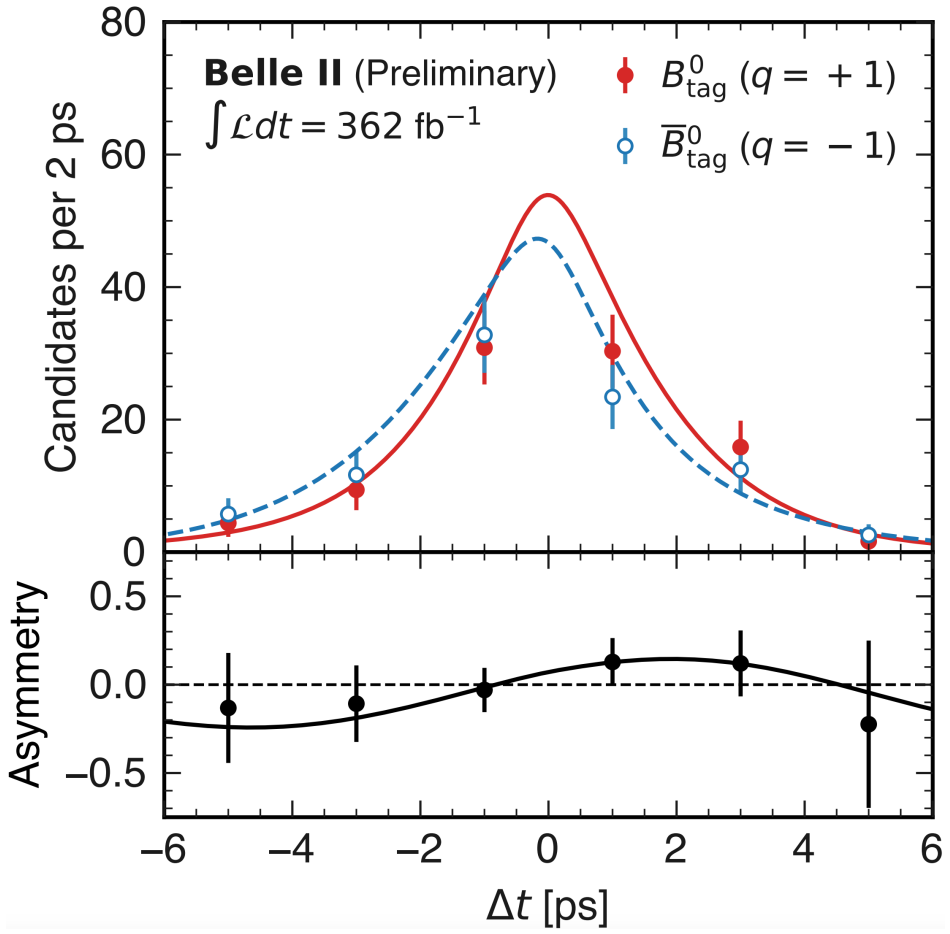
Belle II results in Moriond 2023 (1)



Background subtracted using sPlot

- TDCPV in $B^0 \to K^0_S \pi^0$ (arXiv: 2305.07555)
  - Vertex reconstruction similar to $K^0_S \pi^0 \gamma$
  - Simultaneous fit to $\Delta t, q, M'_{\rm bc}, \Delta E, {\rm CS}_{\rm BDT}$
    - $M'_{\rm bc}, \Delta E, {\rm CS}_{\rm BDT}$ for signal & background separation
    - $M'_{\rm bc} = \sqrt{\left(\sqrt{s}/2 - E^{*2}_{K^0_S}\right)^2 - m^2_{\pi^0}}$
  - Signal yield: 415^{+26}_{-25}
  - $S = \quad 0.75^{+0.20}_{-0.23} \pm 0.04$
  - $C = -0.04 \pm 0.15 \pm 0.05$
    - HFLAV: $S = 0.57 \pm 0.17$ $C = 0.01 \pm 0.10$

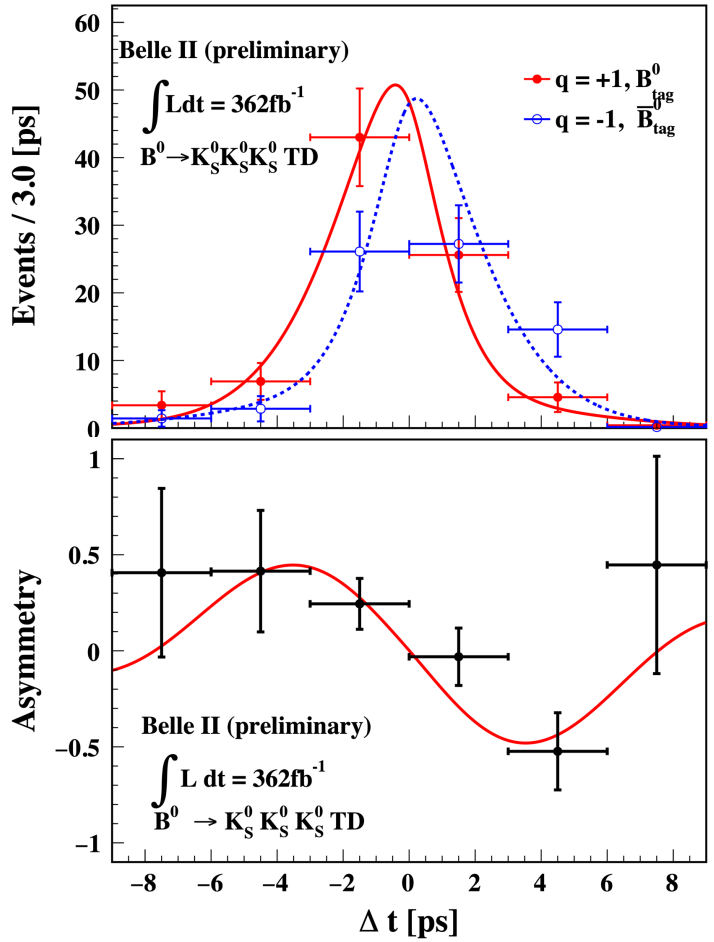
Belle II results in Moriond 2023 (2)



Background subtracted using sPlot

- TDCPV in $B^0 \to \phi K^0_S$ (arXiv: 2307.02802)
  - $\phi \to K^+K^-$
  - Simultaneous fit to $\Delta t, q, M_{\rm bc}, {\rm CS}_{\rm BDT}, \cos\theta_H$
    - $M_{\rm bc}, {\rm CS}_{\rm BDT}, \cos\theta_H$ for signal & background separation
    - θ_H: angle between $\boldsymbol{p}_{B^0}$ and $\boldsymbol{p}_{K^+}$ in the ϕ rest frame
  - Signal yield: 162 ± 17 (resonant)
  - $S = \quad 0.54 \pm 0.26^{+0.06}_{-0.08}$
  - $C = -0.31 \pm 0.20 \pm 0.05$
    - HFLAV: $S = 0.74^{+0.11}_{-0.13}$ $C = 0.01 \pm 0.14$

Belle II results in Moriond 2023 (3)

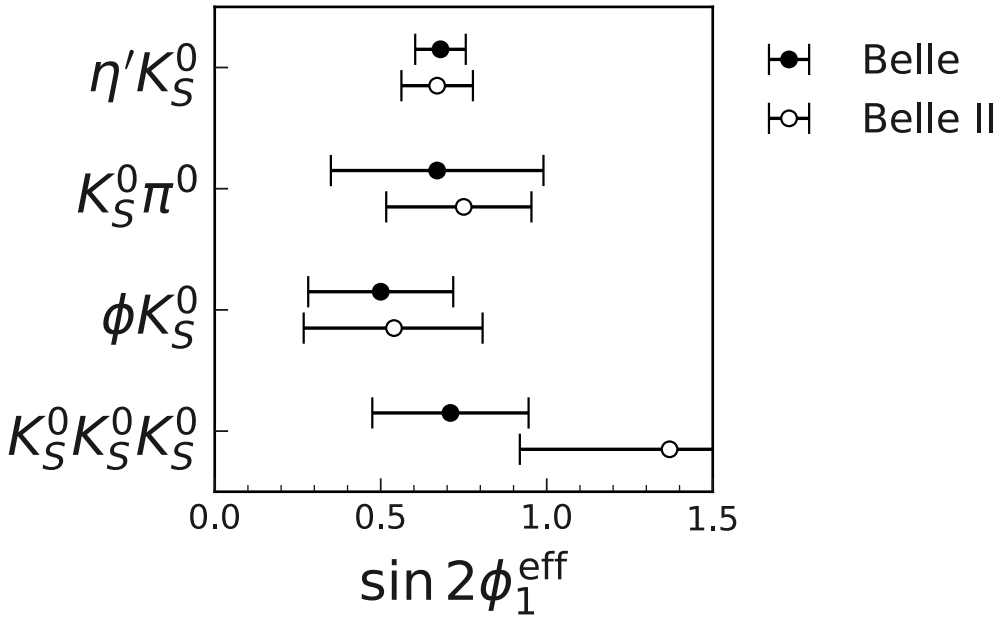


Background subtracted using sPlot

- TDCPV in $B^0 \to K_S^0 K_S^0 K_S^0$
  - Unique vertex reconstruction w/ three displaced vertex
  - Signal & background separated w/ $M_{\mathrm{bc}}, M, \mathrm{CS}_{\mathrm{BDT}}$
  - Signal yield: 220^{+17}_{-16}
  - $S = -1.37^{+0.35}_{-0.45} \pm 0.03$
  - $C = -0.07 \pm 0.20 \pm 0.05$
    - HFLAV: $S = -0.83 \pm 0.17$ $C = -0.15 \pm 0.12$

Summary and Prospects

- Belle II has started to produce time-dependent CP violation results
  - Improved analysis tools
  - Unique and the world's best/world-leading $\sin 2\phi_1^{\mathrm{eff}}$ with smaller dataset
  - Unique and the world's best time-dependent CP violation in $b \to s\gamma$



- Prospects
  - Restart data taking this winter w/ pixel detector fully installed