CPV & Rare decay of B meson at Belle II

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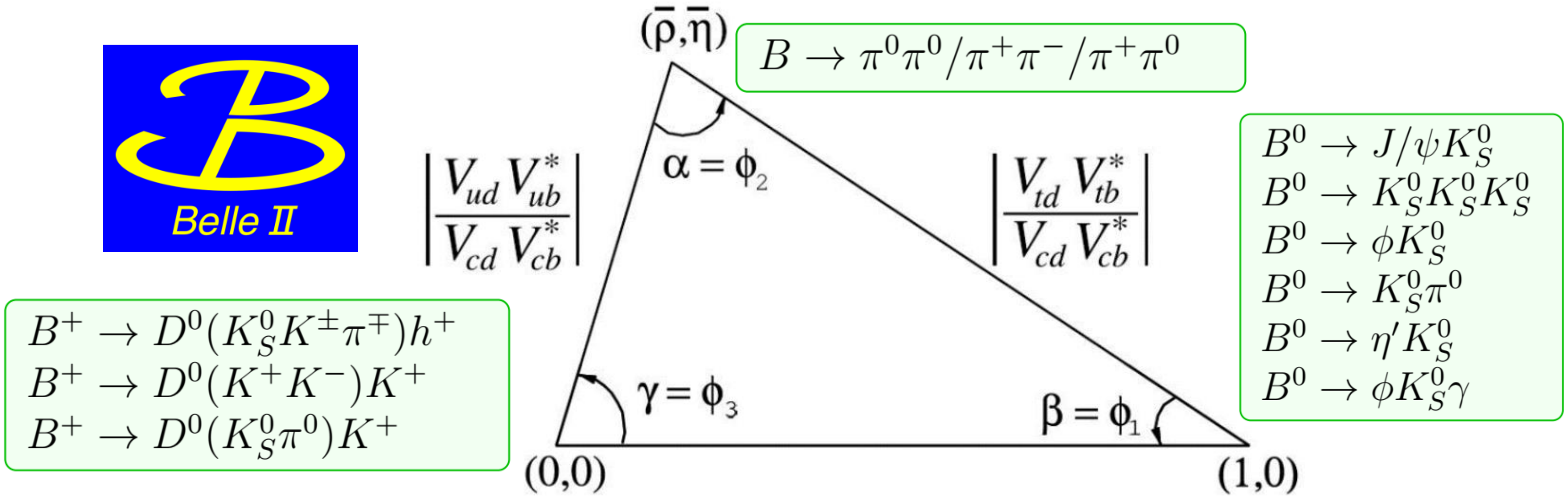
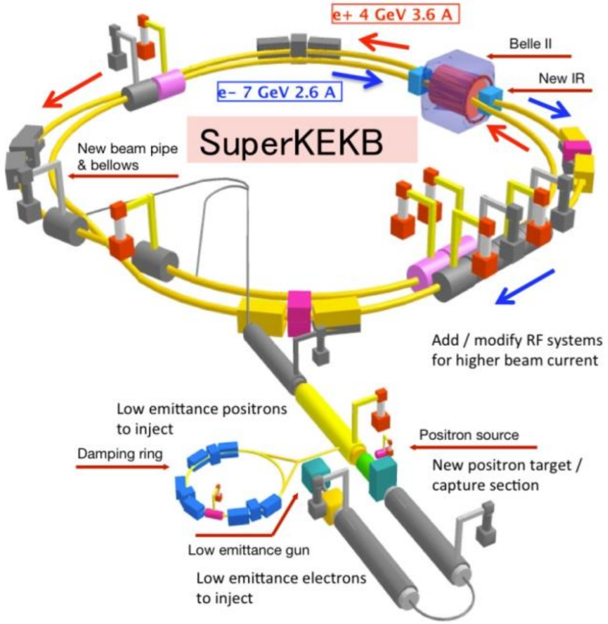
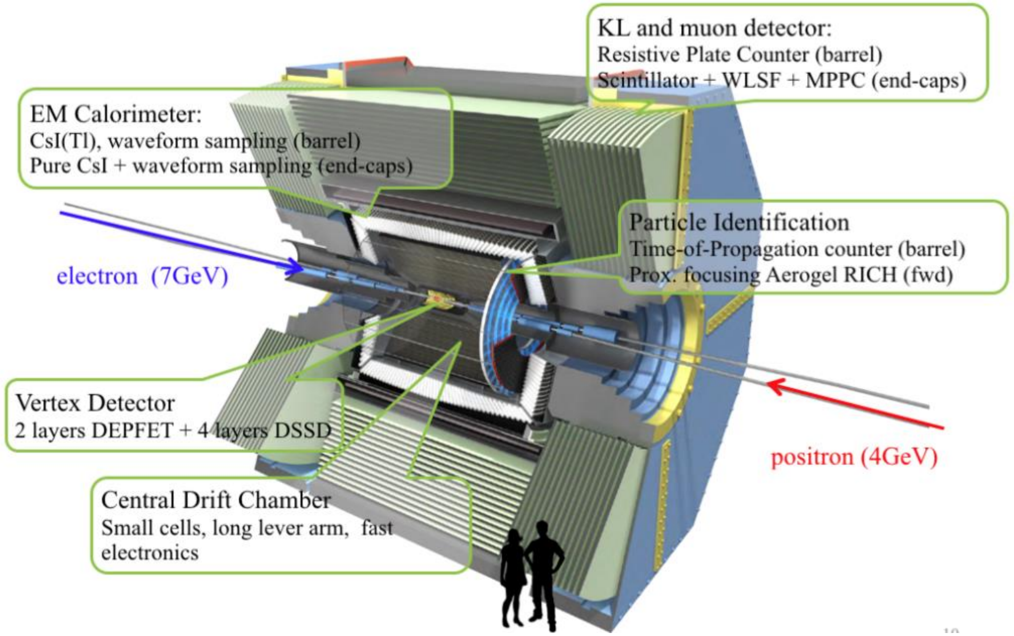
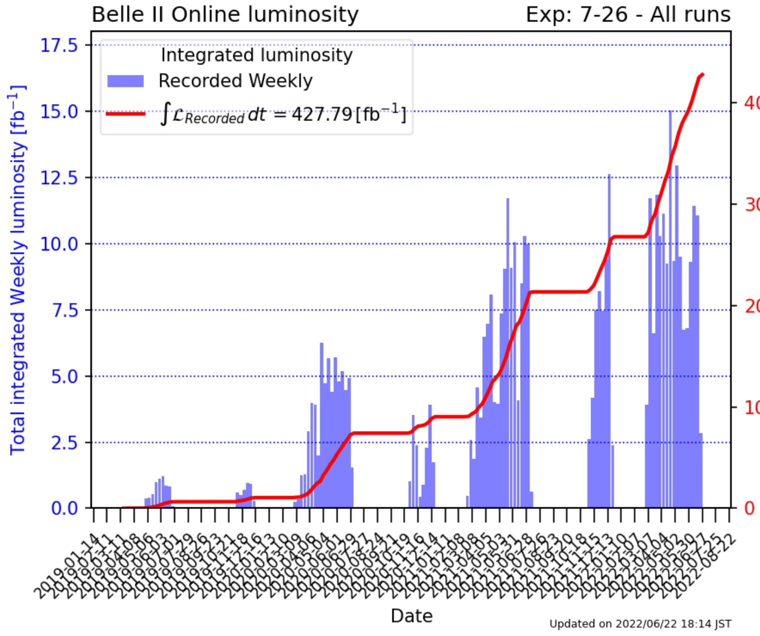


“重味物理前沿论坛研讨会”，2023.11.25，武汉

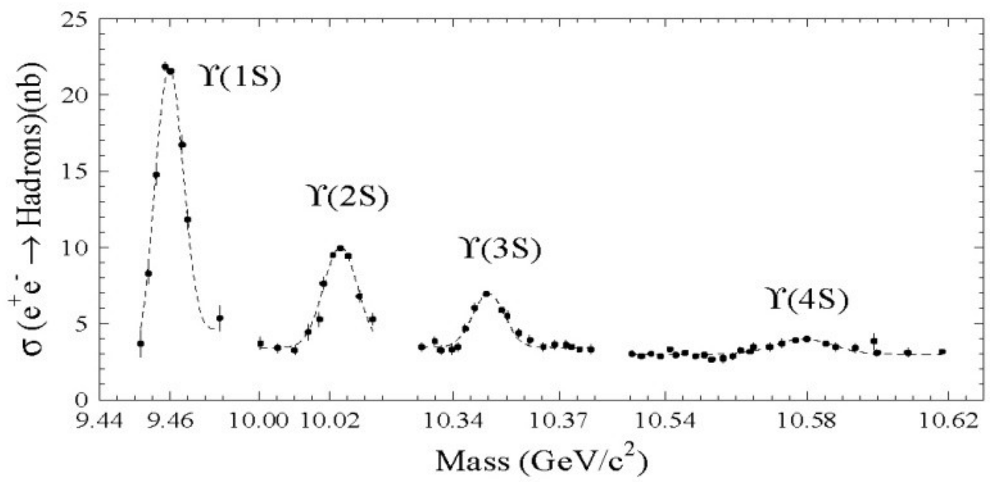
SuperKEKB & Belle II







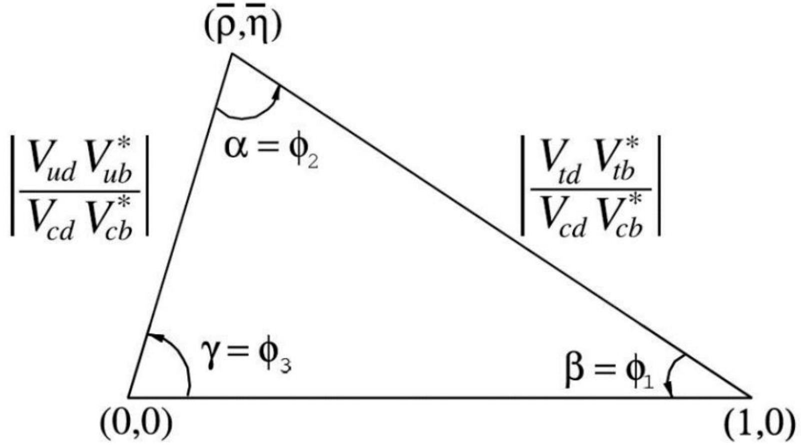
- **Asymmetric e^+e^- collider @ Tsukuba, Japan**
- **Achieved luminosity: 4.7×10^{34} cm^{-2} s^{-1}**
  - ✓ **Target: 6.5×10^{35} cm^{-2} s^{-1}**
- **Target data sample: 50 ab^{-1}**
- **Belle II collects 428 fb^{-1} data sets**
  - ✓ **~ BaBar; ~ half of Belle**



CKM matrix and unitarity triangle

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- **CKM matrix: quarks mixing matrix**
- **Wolfenstein parametrization: A， ρ， η & λ = $|V_{us}|$**
  - ✓ **η: source of CP violation in SM**
- **CKM unitarity ⇒ six unitarity triangle**
  - ✓ $\mathbf{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$
- **CKM unitarity test by angle & sides of CKM triangle**
  - ✓ **Angles: CP violation measurement in B decays**
  - ✓ **Sides: Branching fractions or mixing frequencies**
- **Precise measurements of Unitarity Triangle provides an interesting test for CKM mechanics, and a searching for New Physics.**



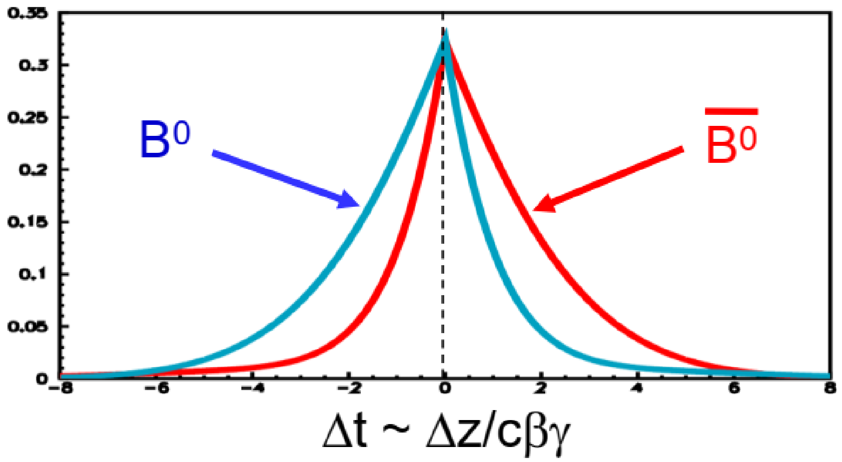
$$\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Time dependent CP violation

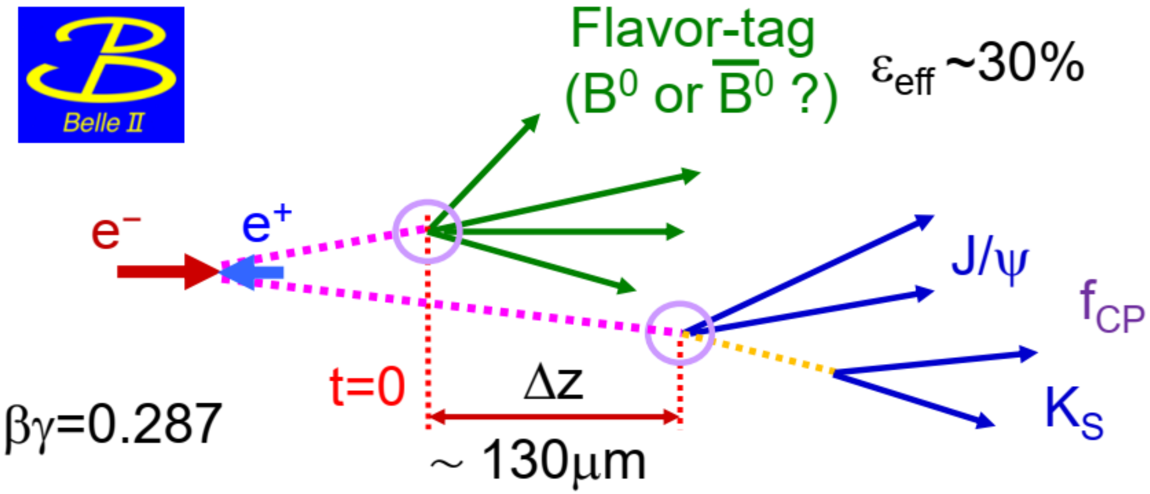
- **B^0 and $\bar{B}^0$ decay to a common CP eigenstate f_{CP}**
- **For CP eigenstate, time dependent decay rate**
  - ✓ **$\mathcal{A}_{CP}$: mixing induced CPV, $\mathcal{A}_{CP} = 0$ @ SM**
  - ✓ **$\mathcal{S}_{CP}$: direct CPV, $\mathcal{S}_{CP} = -\eta_{CP}\sin(2\phi_1)$ @ SM**
  - ✓ **q = -1 for B^0; q = +1 for $\bar{B}^0$**
  - ✓ **τ_{B^0} & Δm_d: B^0 lifetime; B^0-$\bar{B}^0$ oscillation frequency**



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

$$\mathcal{A} = \frac{\Gamma(\bar{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\bar{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$

CP asymmetry



- **Δt measurement ← Δz measurement**
  - ✓ **Good vertex resolution 15 μm**
  - ✓ **Coherent $B^0\bar{B}^0$ pairs**
  - ✓ **High B tagging efficiency**
  - ✓ **Enhanced resolution by small beam size**

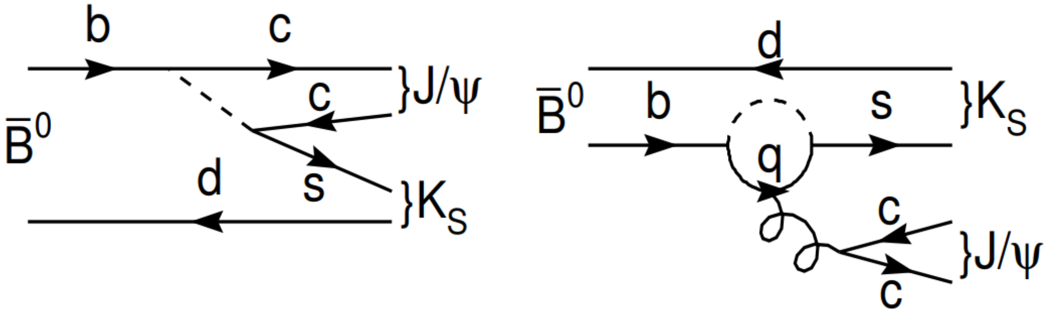
CKM triangle angle ϕ_1/β @ $B^0 \to J/\psi K_S^0$

- Golden channel for $\sin(2\phi_1)$ measurement
  - ✓ Relatively high branching fraction
  - ✓ Low background, ~ 99% purity
  - ✓ Tree-level contribution dominates
  - ✓ Small penguin pollution, $\mathcal{S}_{CP} = \sin(2\phi_1)$ approximation better than 2%
- Fit background-subtracted Δt distribution for $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$

$$\mathcal{S}_{CP} = 0.720 \pm 0.062(stat) \pm 0.016(syst)$$
$$\mathcal{A}_{CP} = 0.094 \pm 0.044(stat)^{+0.042}_{-0.017}(syst)$$

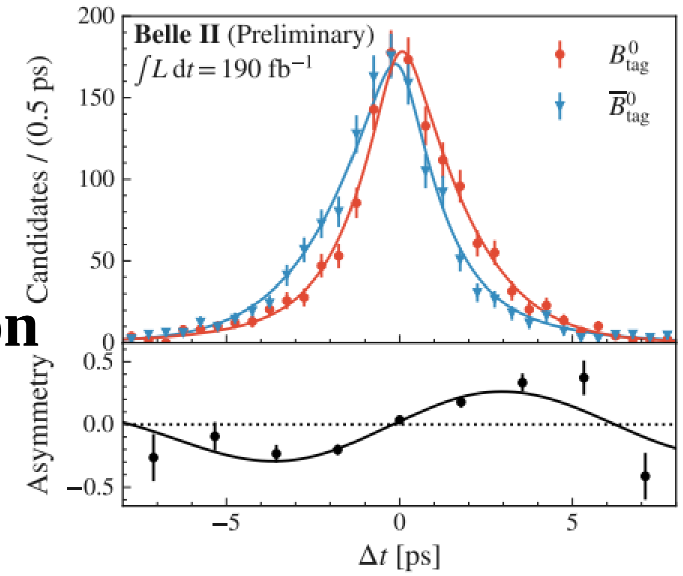
- New flavor tagger GFlaT: ~ 8%reduction in statistical uncertainty

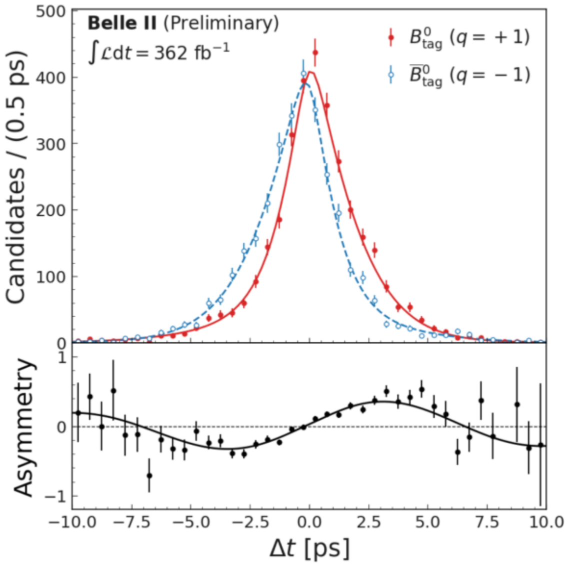
$$\mathcal{S}_{CP} = 0.724 \pm 0.035(stat) \pm 0.014(syst)$$
$$\mathcal{A}_{CP} = 0.035 \pm 0.026(stat) \pm 0.012(syst)$$



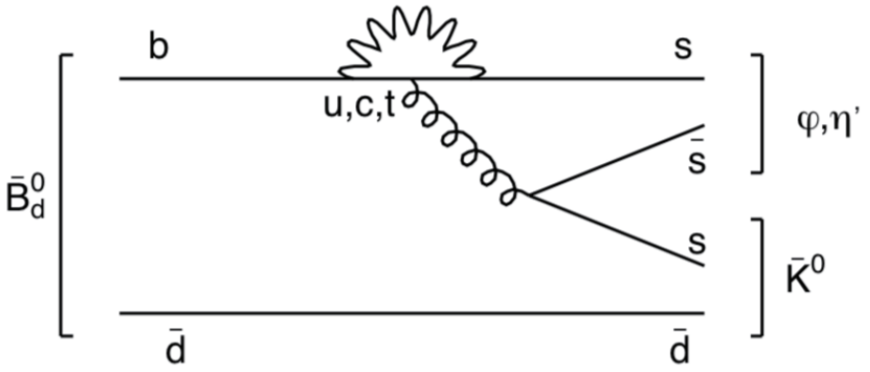
arXiv:2302.12898

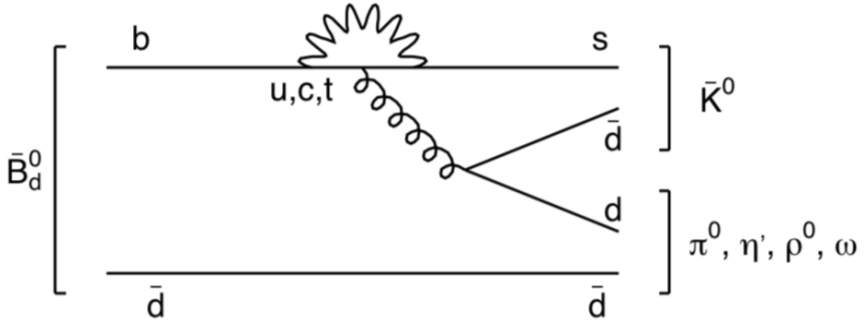
Sample	$N_{\rm evts}$	$p_{\rm sig}(\%)$	$\varepsilon_{\rm sig}(\%)$	S_{CP}	A_{CP}
$B^0 \to J/\psi K_S^0$	2755	98.6	40.6	0.720 ± 0.062	0.094 ± 0.044
$B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0$	1615	99.2	47.6	0.776 ± 0.078	0.042 ± 0.057
$B^0 \to J/\psi(\to e^+e^-)K_S^0$	1140	98.0	33.6	0.676 ± 0.093	0.185 ± 0.068



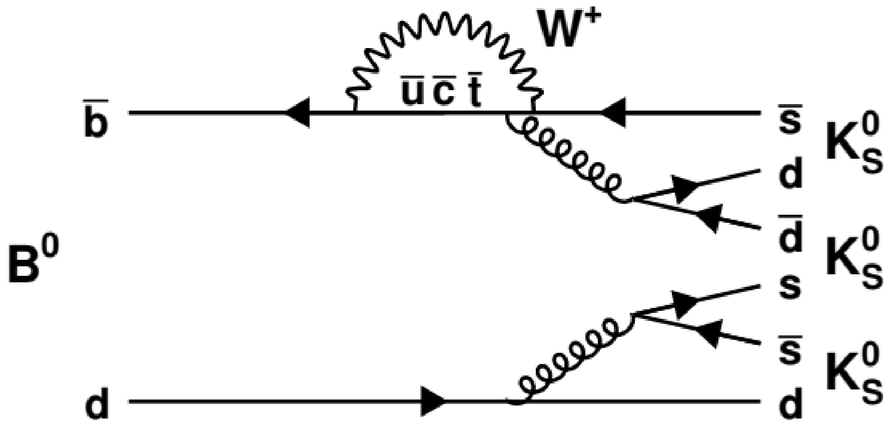


CPV @ $b \longrightarrow sq\bar{q}$ $(q = d, s)$



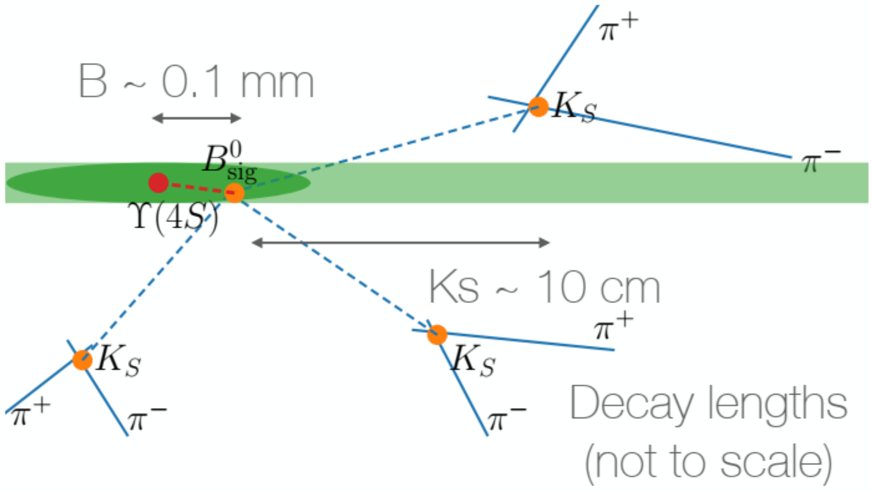


- **Gluonic penguin modes: sensitive to interfering non-SM physics**
- **CP-even state $3K_S^0$:**
  - ✓ **@ SM: $\mathcal{S}_{CP} \approx -\sin(2\phi_1)$ & $\mathcal{A}_{CP} = 0$**
  - ✓ **Deviation of $\mathcal{S}_{CP}$: 0.02 with uncertainty smaller than 0.01**
- **The deviation indicate either large sub-leading amplitudes or non-SM physics**



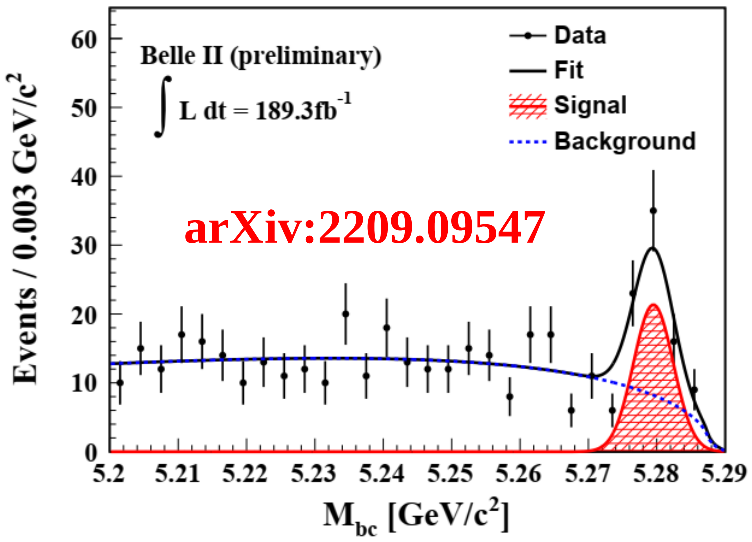
CPV @ $B^0 \to K_S^0 K_S^0 K_S^0$

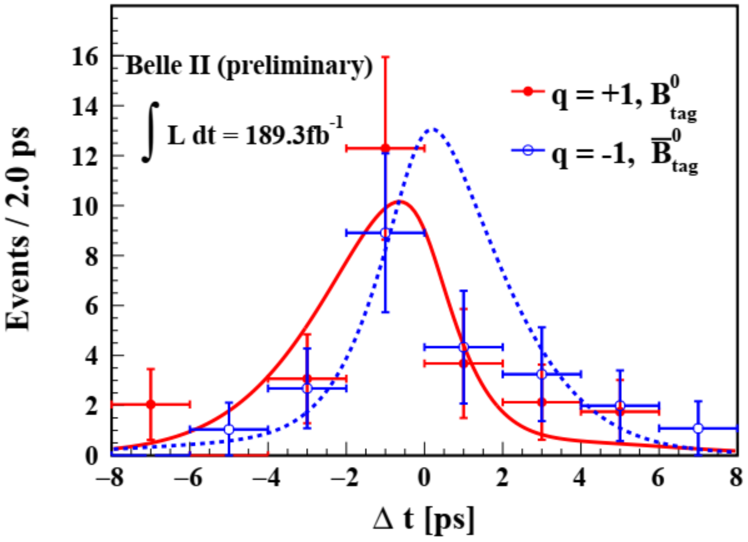
- B vertex challenge: no prompt tracks from B
  - ✓ Trajectories and profile of interaction point
- Two BDT classifiers:
  - ✓ Reduce fake K_S^0 contribution
  - ✓ Reduce continuum $q\bar{q}$ backgrouds
- The results are consistent with that of Belle & BaBar

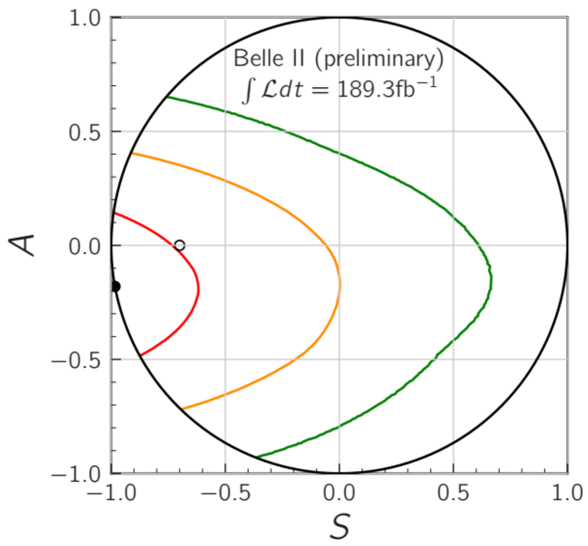


$$\mathcal{S} = -1.86\ ^{+0.91}_{-0.46}\ (\text{stat}) \pm 0.09\ (\text{syst})$$

$$\mathcal{A} = -0.22\ ^{+0.30}_{-0.27}\ (\text{stat}) \pm 0.04\ (\text{syst})$$

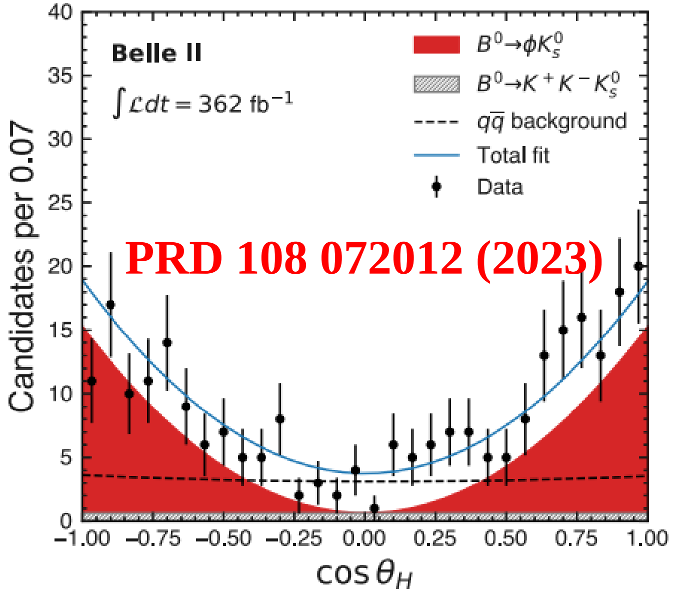


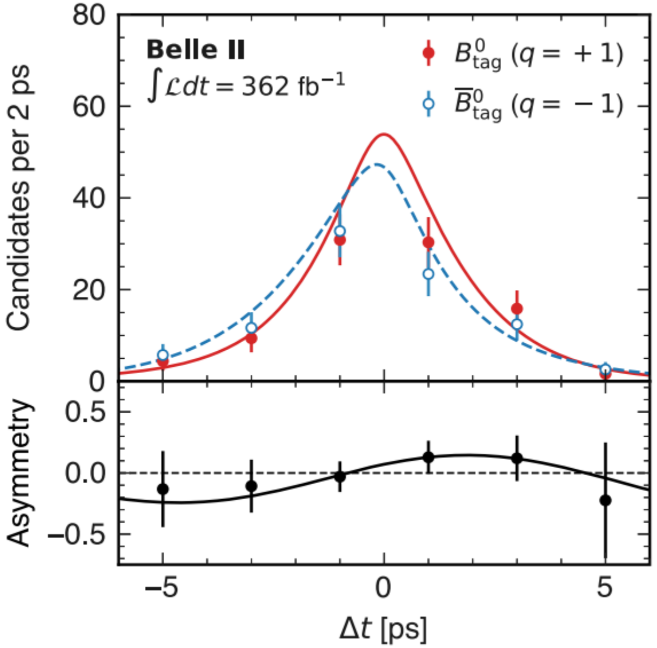




CPV @ $B^0 \leftrightarrow \phi K_S^0$

- Clean experimental signature
  - ✓ Similar Δt resolution as $B^0 \to J/\psi\, K_S^0$
- A BDT classifier for continuum $q\bar{q}$ backgrouds
- Dilution from non-resonant decays with opposite CP
  - ✓ Non-resonant $B^0 \to K^+K^-K_S^0$ disentangled in $\cos\theta_H$
- 162 ± 17 $B^0 \to \phi K_S^0$ events





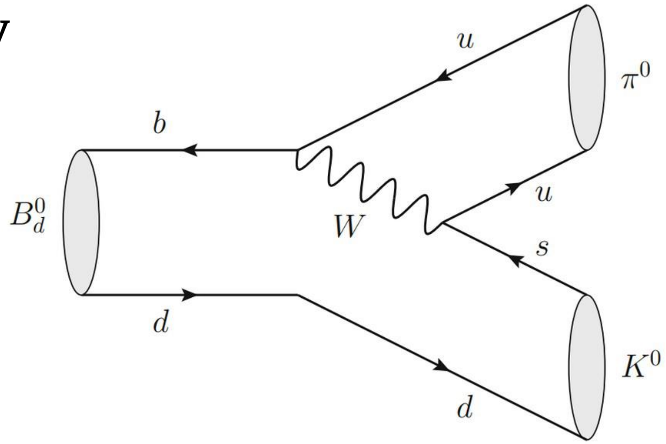
	$N(B\bar{B})$	$\mathcal{S}_{CP}$	$\mathcal{A}_{CP}$
Belle II	387 M	$0.54 \pm 0.26^{+0.06}_{-0.08}$	$0.31 \pm 0.20 \pm 0.05$
Belle	657 M	$0.90^{+0.09}_{-0.19}$	$0.04 \pm 0.20 \pm 0.10 \pm 0.02$
BaBar	470 M	$0.66 \pm 0.17 \pm 0.07$	$0.05 \pm 0.18 \pm 0.05$
HFLAV		$0.74^{+0.11}_{-0.13}$	0.01 ± 0.14

- Similar $\mathcal{A}_{CP}$ uncertainty with smaller data set

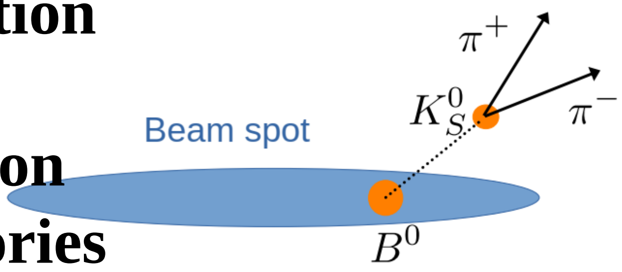
CPV @ $B^0 \to K^0_S\pi^0$

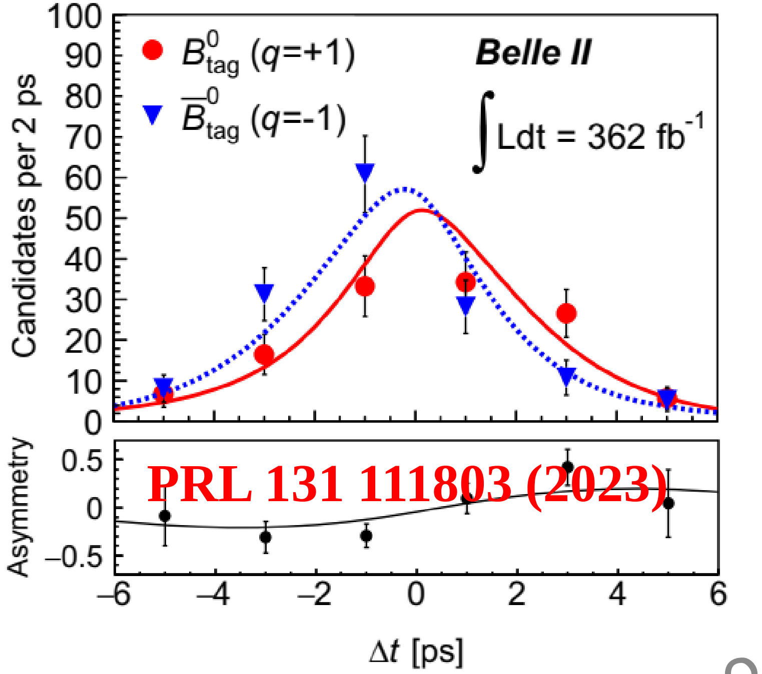
- Isospin symmetry, SM null test with O(1%) theory uncertainty
  - ✓ $I_{K\pi}$: 10% experimental uncertainty dominant $B^0 \to K^0_S\pi^0$

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



- $b \to sd\bar{d}$ with color & CKM-suppressed $b \to su\bar{u}$
  - ✓ Introduce an extra weak phase, shift s_{CP} from $\sin(2\phi_1)$
- Challenge: Decay vertex reconstruction
  - ✓ K^0_S reconstruction & vertexing
  - ✓ High purity & efficient π^0 selection
- $B^0 \to K^0_S\pi^0$ accessible at e^+e^- B factories
- Consistent results with less (60%-80%) luminosity



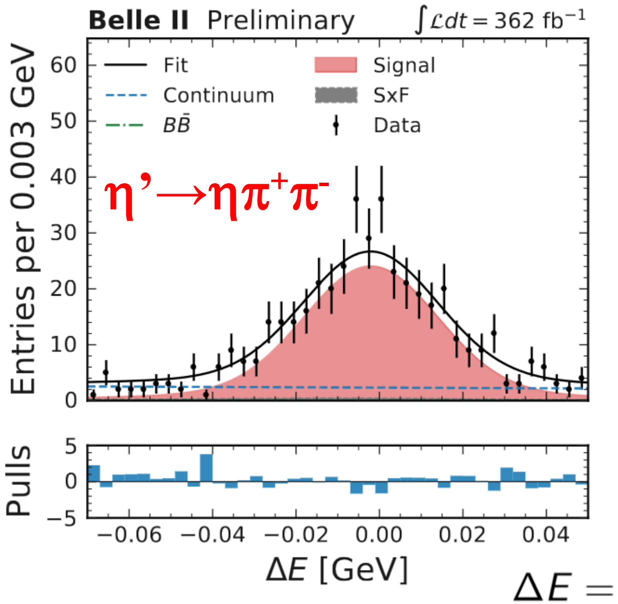


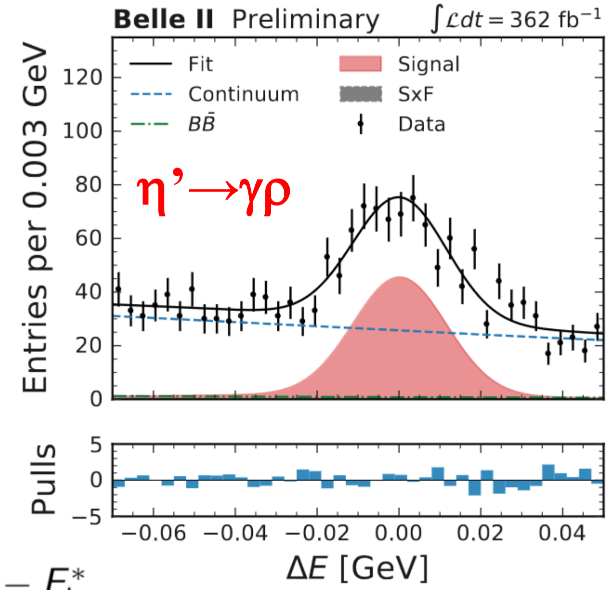
	$N(B\bar{B})$	S_{CP}	$\mathcal{A}_{CP}$
Belle II	387 M	$0.75^{+0.20}_{-0.23} \pm 0.04$	$0.04^{+0.14}_{-0.15} \pm 0.05$
Belle	657 M	$0.67 \pm 0.31 \pm 0.08$	$0.14 \pm 0.13 \pm 0.06$
BaBar	467 M	$0.55 \pm 0.20 \pm 0.03$	$0.13 \pm 0.13 \pm 0.03$
HFLAV		0.57 ± 0.17	0.01 ± 0.10

CPV @ $B^0 \to \eta' K^0_S$

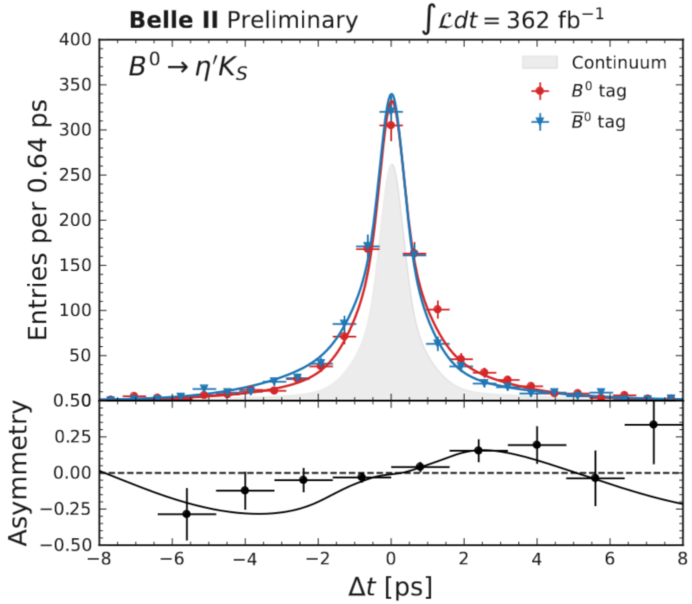
- $b \to s$ penguin process
- Relatively high BF w.r.t. other gluonic penguins
- High background form continuum $q\bar{q}$
- η’ modes: η(2γ)p$^+\pi^-$ & γ ρ($\pi^+\pi^-$)
  - ✓ $\eta' \to \eta\pi^+\pi^-$ mode: 358 ± 20 event
  - ✓ $\eta' \to \gamma\rho$ mode: 471 ± 29 event
- Consistent results with Belle & BaBar

	N($B\bar{B}$)	$\mathcal{S}_{CP}$	$\mathcal{A}_{CP}$
Belle II	387 M	$0.67 \pm 0.10 \pm 0.04$	$0.19 \pm 0.08 \pm 0.03$
Belle	657 M	$0.68 \pm 0.07 \pm 0.03$	$0.03 \pm 0.05 \pm 0.03$
BaBar	467 M	$0.57 \pm 0.08 \pm 0.02$	$0.08 \pm 0.06 \pm 0.02$
HFLAV		0.63 ± 0.06	0.05 ± 0.04



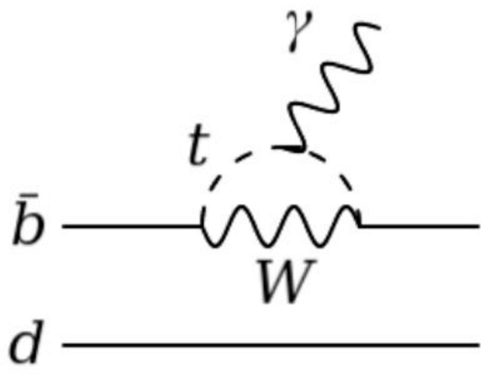


$\Delta E = E^*_B - E^*_{\text{beam}}$

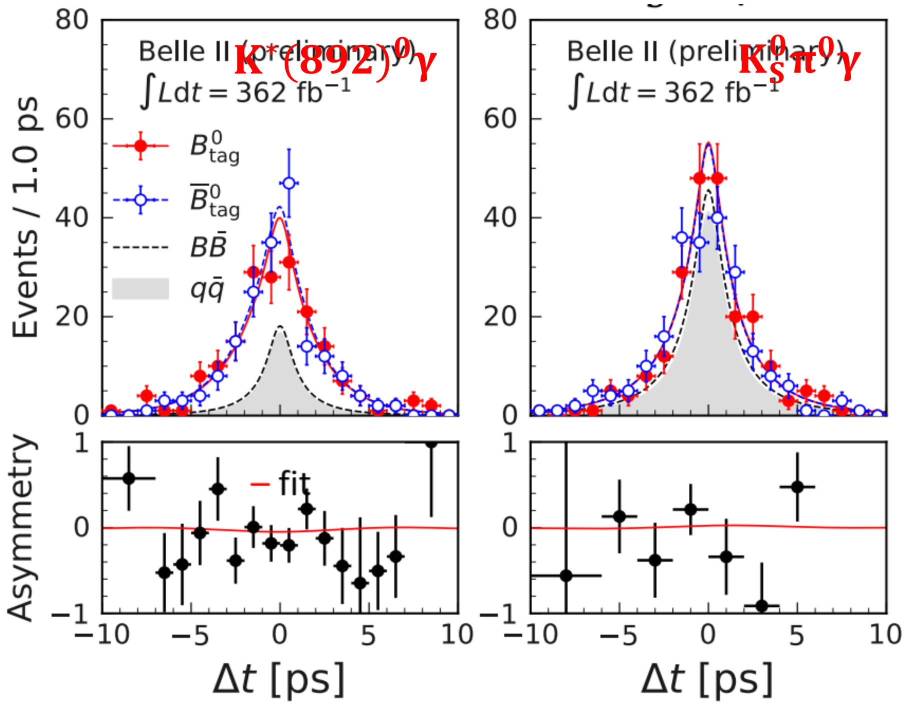


Radiative penguins @ $B^0 \to K_S^0\pi^0\gamma$

- **SM: b → s γ forbidden @ tree level, loop contribution**
- **Polarization of photon constrains flavor**
  - ✓ **@ SM: $\mathcal{S}_{CP}$ helicity suppressed, $\mathcal{S}_{CP} = 0.035 \pm 0.017$**
- **New physics could contribute into $\mathcal{S}_{CP}$ significantly**
- **Challenge: no prompt tracks, reconstruct decay vertex**
  - ✓ **from K_S^0 using beam spot constraint**
- **$B^0 \to K_S^0\pi^0\gamma$ accessible at e^+e^- B factories**
- **Two M(Kπ) region:**
  - ✓ **K*(892) [0.8, 1.0]GeV, and rest of [0.6, 1.8]GeV**
- **Most precise results to date**

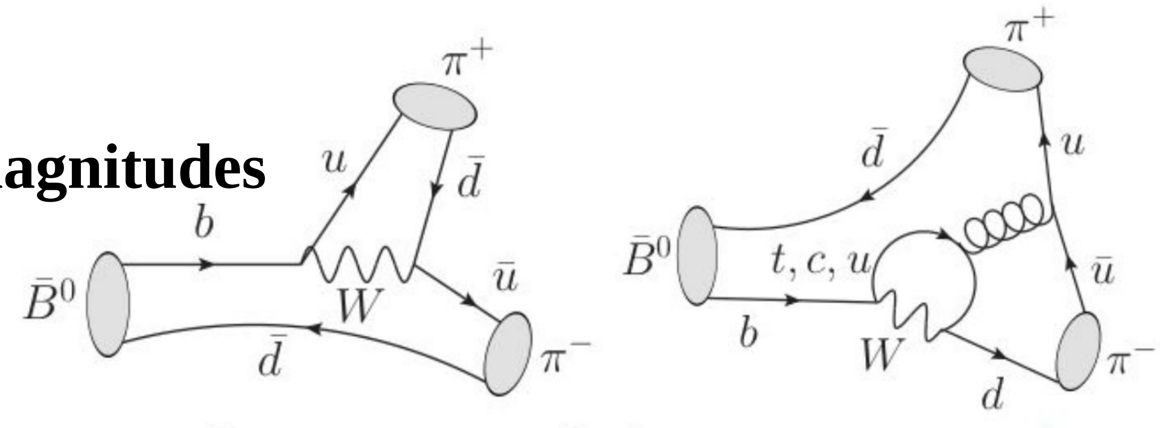


	N(BB̄)	Mode	$\mathcal{S}_{CP}$	$\mathcal{A}_{CP}$
Belle II	387 M	$K^*(892)^0\gamma$	$0.00^{+0.27}_{-0.26} \pm 0.03$	$0.10 \pm 0.13 \pm 0.03$
HFLAV		$K^*(892)^0\gamma$	-0.16 ± 0.22	-0.04 ± 0.14
Belle II	387 M	$K_S^0\pi^0\gamma$	$0.04^{+0.45}_{-0.44} \pm 0.10$	$-0.06 \pm 0.25 \pm 0.08$
Belle	657 M	$K_S^0\pi^0\gamma$	0.50 ± 0.68	0.20 ± 0.39



CKM angle ϕ_2/α @ $b \longrightarrow d u \bar{u}$

- **CKM angle ϕ_2/α with most poor precision**
  - ✓ **HFLAV: $\phi_2 = (85.2^{+4.8}_{-4.3})^{o}$**
- **Tree & penguin amplitudes have similar magnitudes**
- **Penguin pollution complicates extraction**
  - ✓ $\phi_2^{\text{eff}} = \phi_2 + 2\Delta\phi_2$
  - ✓ **Introduce hadronic uncertainty**
- **Isospin relation to disentangle tree and penguin contributions**
  - ✓ **Using Br and CP asymmetry $\mathcal{A}$**

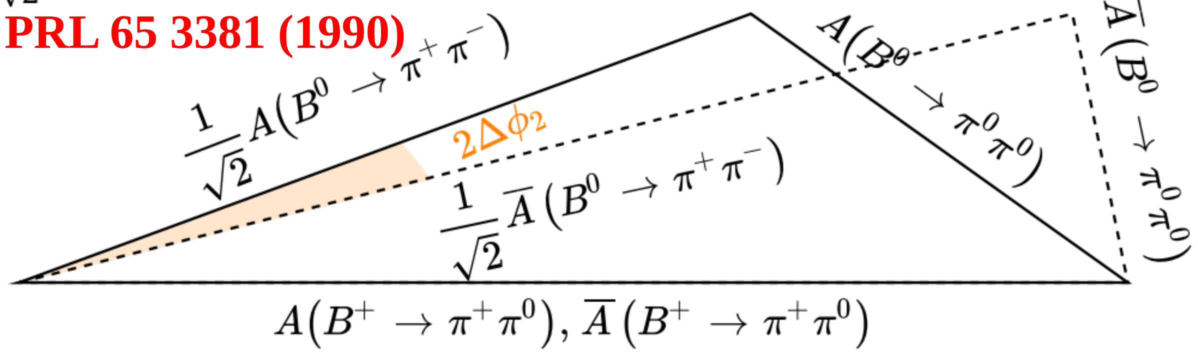


$$\frac{1}{\sqrt{2}}A(B^0 \to \pi^+\pi^-) - A(B^0 \to \pi^0\pi^0) = A(B^+ \to \pi^+\pi^0)$$

$$\frac{1}{\sqrt{2}}\bar{A}(B^0 \to \pi^+\pi^-) - \bar{A}(B^0 \to \pi^0\pi^0) = \bar{A}(B^+ \to \pi^+\pi^0)$$

PRL 65 3381 (1990)

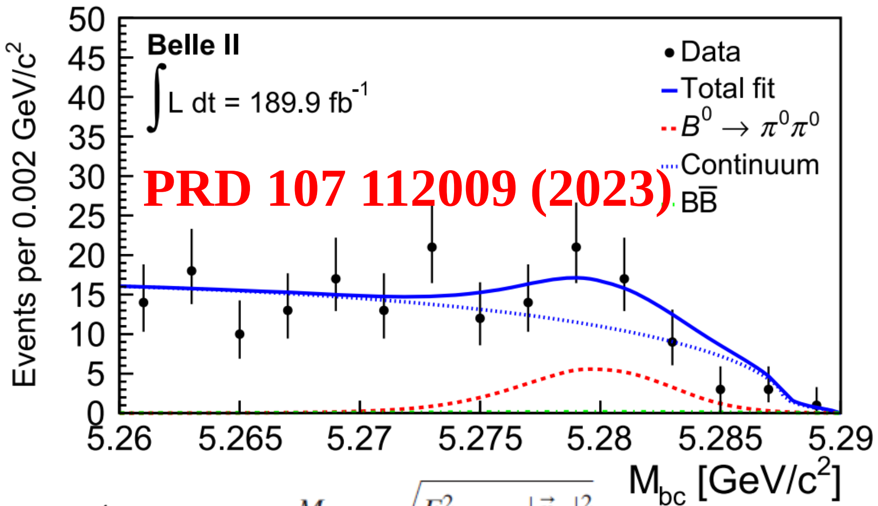
Mode	Tree	Penguin
$\pi^+\pi^-$	✔	✔
$\pi^+\pi^0$	✔	✘
$\pi^0\pi^0$	*suppressed*	✔



$B \to \pi\pi$ results

- $B^0 \to \pi^0\pi^0$ mode
  - ✓ constrain penguin component
- A BDT classifier to suppress non-signal photon
- A BDT classifier for continuum $q\bar{q}$ backgrouds
- Br & CP asymmetry by fitting
  - ✓ achieve Belle Br precision, using only 1/3 of dataset

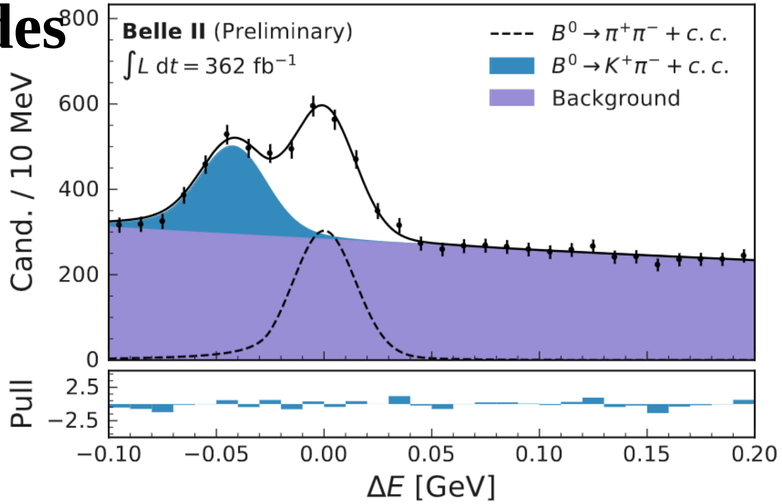
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$
$$\mathcal{A}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

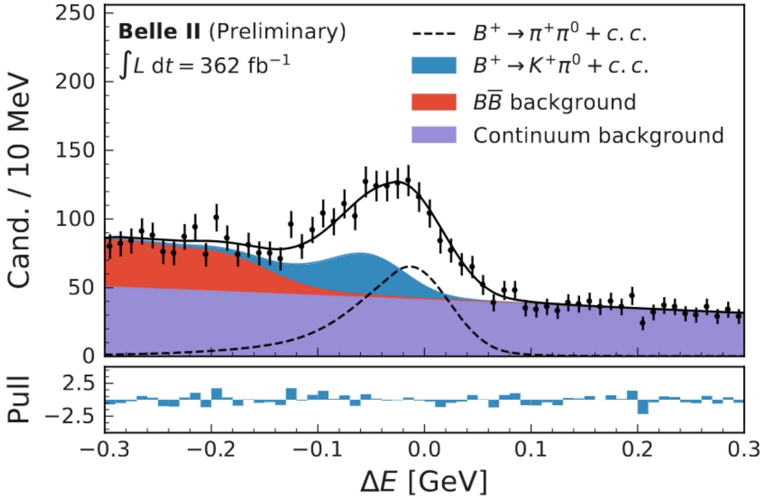


$$M_{\rm bc} = \sqrt{E^2_{\rm beam} - |\vec{p}_B|^2}$$

- $B^0 \to \pi^+\pi^-$ & $B^+ \to \pi^+\pi^0$ modes
  - ✓ Updated with 362 fb^{-1} data
- World best Br of $B^0 \to \pi^+\pi^-$

$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$
$$\mathcal{B}(B^+ \to \pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.27) \times 10^{-6}$$
$$\mathcal{A}(B^+ \to \pi^+\pi^0) = -0.081 \pm 0.054 \pm 0.008$$



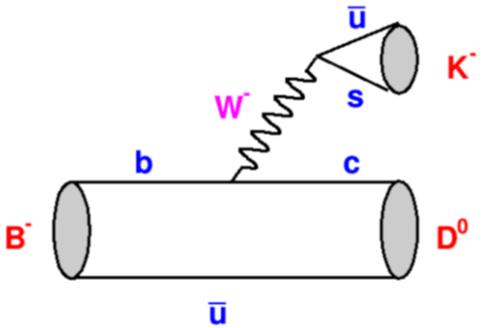


A new constraint to ϕ_2/α from $\pi\pi$ analysis ?

CKM angle ϕ_3/γ

- ϕ_3/γ: using interference $b \to c\bar{u}s$ & $b \to u\bar{c}s$

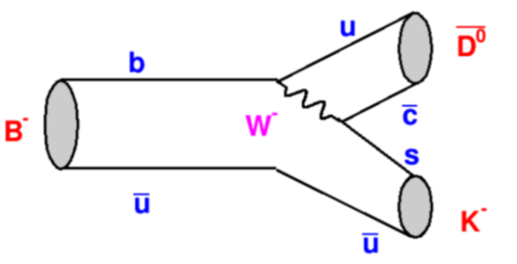
$$\frac{A_{sup}(B^- \to \bar{D}K^-)}{A_{fav}(B^- \to DK^-)} = r_B\ e^{i(\delta_B-\phi_3)}$$



colour allowed

$B^- \to D^0 K^- \approx V_{cb}V_{us}^*$

A_1

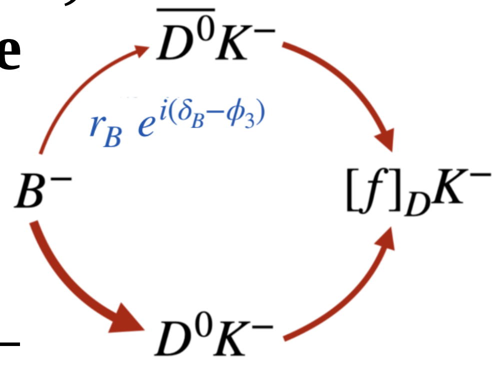


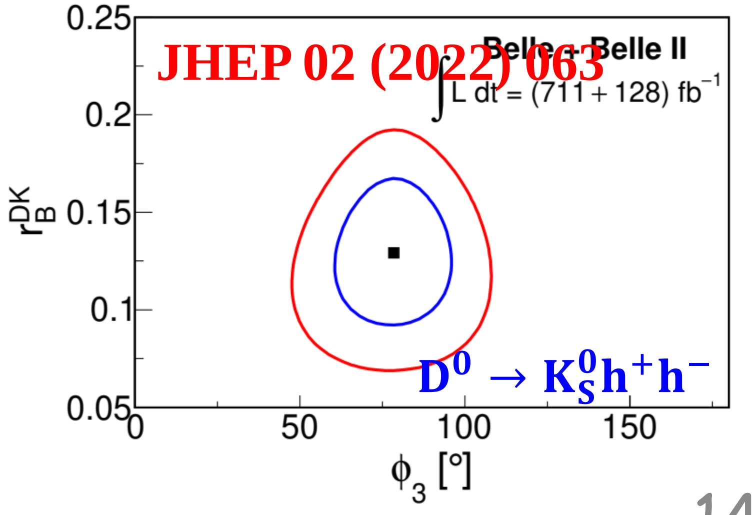
colour suppressed

$B^- \to \bar{D}^0 K^- \approx V_{ub}V_{cs}^*$

$A_1 r_B e^{i(\delta_B-\phi_3)}$

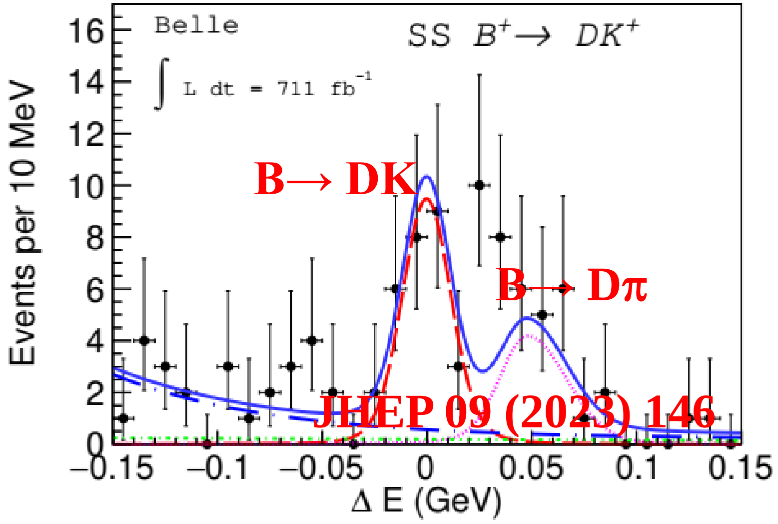
- Only tree contributions, theoretically clean
- Direct measurement $\phi_3 = (66.2^{+3.4}_{-3.2})^o$
  - ✓ indirect measurement $\phi_3 = (63.4 \pm 0.9)^o$
- Amplitude ratio r_B and strong phase δ_B are mode dependent
  - ✓ Sensitivity depend on modes
- Approaches: different D final states
  - ✓ Self-conjugate final states $D \to K_S^0 h^+ h^-$
    Belle + Belle II: $\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^o$
  - ✓ Cabibbo suppressed decays $D \to K_S^0 K^\pm \pi^\mp$
  - ✓ CP eigenstates $D \to K^+K^-$, $K_S^0 \pi^0$





CKM angle ϕ_3/γ @ $D \to K^0_S K^{\pm}\pi^{\mp}$

- $B^{\pm} \to Dh^{\pm}$ ($h = K, \pi$) with $D \to K^0_S K^{\pm}\pi^{\mp}$
  - ✓ Decay type m = SS: B & K @ D, same sign
  - ✓ Decay type m = OS: B & K @ D, opposite sign
- Four CP asymmetries and three Br ratios
  - ✓ Model-independent information on ϕ_3/γ
- First Belle & Belle II result from this channel
- Consistent with LHCb, but not competitive



$$\mathcal{A}_m^{Dh} \equiv \frac{N_m^{Dh^-} - N_m^{Dh^+}}{N_m^{Dh^-} + N_m^{Dh^+}}$$

$$\mathcal{R}_m^{DK/D\pi} \equiv \frac{N_m^{DK^-} + N_m^{DK^+}}{N_m^{D\pi^-} + N_m^{D\pi^+}}$$

$$\mathcal{R}_{\mathrm{SS/OS}}^{D\pi} \equiv \frac{N_{\mathrm{SS}}^{D\pi^-} + N_{\mathrm{SS}}^{D\pi^+}}{N_{\mathrm{OS}}^{D\pi^-} + N_{\mathrm{OS}}^{D\pi^+}}$$

$$\mathcal{A}_{\mathrm{SS}}^{DK} = \frac{2r_B^{DK} r_D \kappa_D \sin(\delta_B^{DK} - \delta_D)\sin\phi_3}{1 + (r_B^{DK})^2 r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} - \delta_D)\cos\phi_3},$$

$$\mathcal{A}_{\mathrm{OS}}^{DK} = \frac{2r_B^{DK} r_D \kappa_D \sin(\delta_B^{DK} + \delta_D)\sin\phi_3}{(r_B^{DK})^2 + r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} + \delta_D)\cos\phi_3},$$

$$\mathcal{A}_{\mathrm{SS}}^{D\pi} = \frac{2r_B^{D\pi} r_D \kappa_D \sin(\delta_B^{D\pi} - \delta_D)\sin\phi_3}{1 + (r_B^{D\pi})^2 r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} - \delta_D)\cos\phi_3},$$

$$\mathcal{A}_{\mathrm{OS}}^{D\pi} = \frac{2r_B^{D\pi} r_D \kappa_D \sin(\delta_B^{D\pi} + \delta_D)\sin\phi_3}{(r_B^{D\pi})^2 + r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} + \delta_D)\cos\phi_3}.$$

$$\mathcal{R}_{\mathrm{SS}}^{DK/D\pi} = R\frac{1 + (r_B^{DK})^2 r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} - \delta_D)\cos\phi_3}{1 + (r_B^{D\pi})^2 r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} - \delta_D)\cos\phi_3},$$

$$\mathcal{R}_{\mathrm{OS}}^{DK/D\pi} = R\frac{(r_B^{DK})^2 + r_D^2 + 2r_B^{DK} r_D \kappa_D \cos(\delta_B^{DK} + \delta_D)\cos\phi_3}{(r_B^{D\pi})^2 + r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} + \delta_D)\cos\phi_3},$$

$$\mathcal{R}_{\mathrm{SS/OS}}^{D\pi} = \frac{1 + (r_B^{D\pi})^2 r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} - \delta_D)\cos\phi_3}{(r_B^{D\pi})^2 + r_D^2 + 2r_B^{D\pi} r_D \kappa_D \cos(\delta_B^{D\pi} + \delta_D)\cos\phi_3},$$

$$A_{\mathrm{SS}}^{DK} = -0.089 \pm 0.091 \pm 0.011,$$
$$A_{\mathrm{OS}}^{DK} = 0.109 \pm 0.133 \pm 0.013,$$
$$A_{\mathrm{SS}}^{D\pi} = 0.018 \pm 0.026 \pm 0.009,$$
$$A_{\mathrm{OS}}^{D\pi} = -0.028 \pm 0.031 \pm 0.009,$$
$$R_{\mathrm{SS}}^{DK/D\pi} = 0.122 \pm 0.012 \pm 0.004,$$
$$R_{\mathrm{OS}}^{DK/D\pi} = 0.093 \pm 0.013 \pm 0.003,$$
$$R_{\mathrm{SS/OS}}^{D\pi} = 1.428 \pm 0.057 \pm 0.002,$$

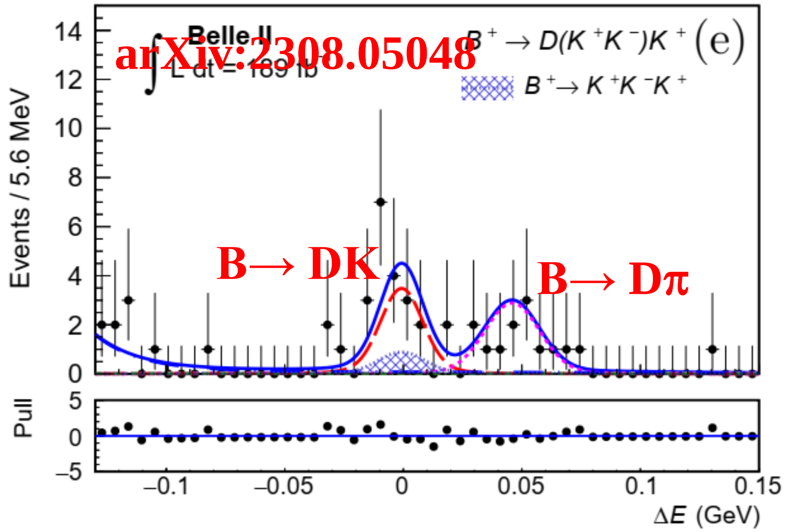
CKM angle ϕ_3/γ @ $D \to K^+K^-$ & $K_S^0\pi^0$

- $B^\pm \to DK^\pm$ decay
  - ✓ $D \to K^+K^-$ (CP even) & $D \to K_S^0\pi^0$ (CP odd)
- Neglect small effects of D^0-$\bar{D}^0$ mixing and CP violation in D^0 decay

$$\mathcal{R}_{CP\pm} = \frac{\mathcal{Br}(B^- \to D_{CP\pm}K^-) + \mathcal{Br}(B^+ \to D_{CP\pm}K^+)}{\mathcal{Br}(B^- \to D_{\text{flav}}K^-) + \mathcal{Br}(B^+ \to D_{\text{flav}}K^+)} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\phi_3$$

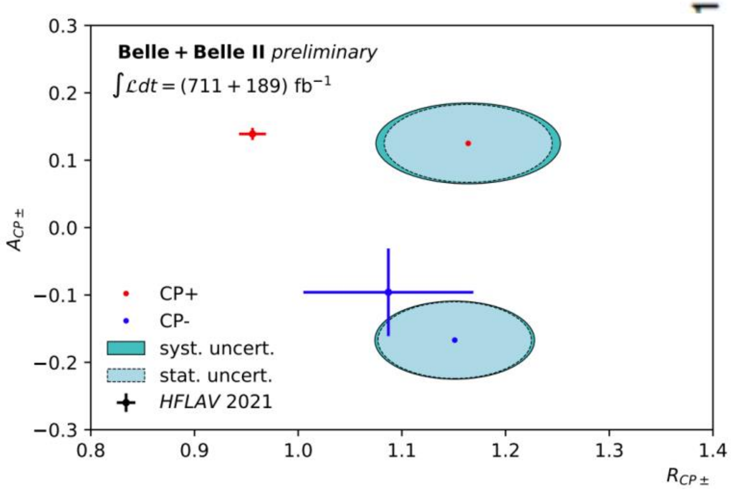
$$\mathcal{A}_{CP\pm} \equiv \frac{\Gamma(B^- \to D_{CP\pm}K^-) - \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)} = \pm 2r_B \sin\delta_B \sin\phi_3/\mathcal{R}_{CP\pm}$$

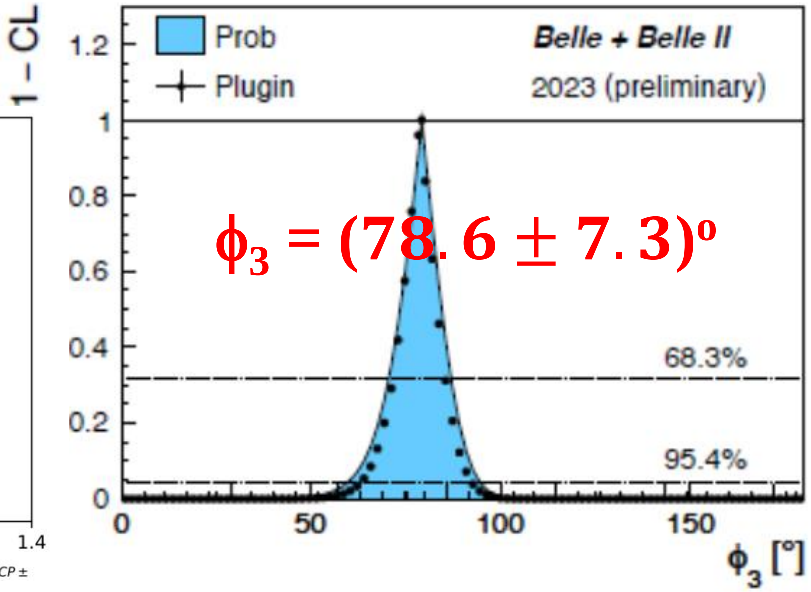
$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$
$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$
$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%,$$



- $\mathcal{A}_{CP+} \neq \mathcal{A}_{CP-}$: 3.5σ evidence
- Consistent results, but no competitive
- Combined ϕ_3 @ Belle & Belle II

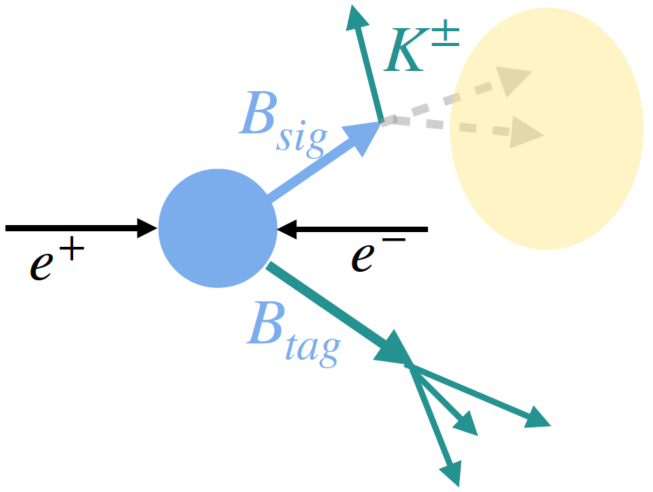
$\phi_3 = (66.2^{+3.4}_{-3.6})^o$

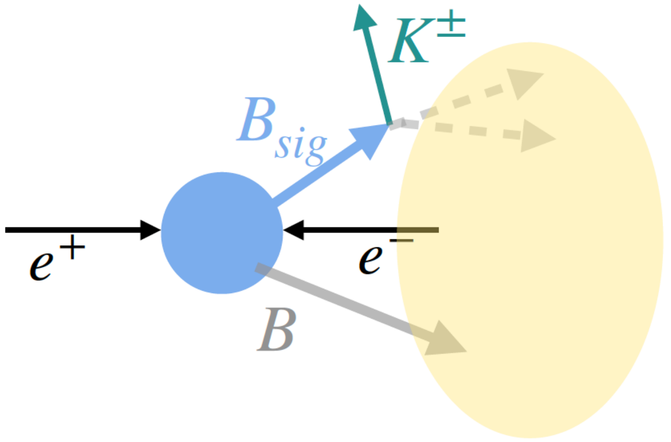


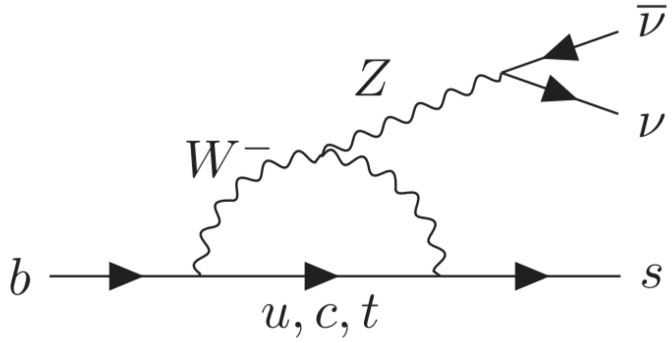


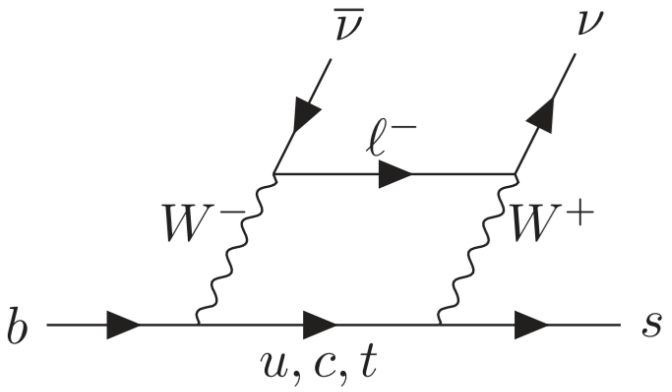
Rare $B^+ \to K^+\nu\bar{\nu}$ @ SM

- $B^+ \to K^+\nu\bar{\nu}$: flavor-changing neutral current
  - ✓ suppressed by GIM mechanism
  - ✓ @ SM: $Br(B^+ \to K^+\nu\bar{\nu}) = (5.58\pm0.37)\times10^{-6}$
- extensions beyond SM: substantially rate increase
- Very challenging experimentally
  - ✓ Low Br, high background contributions
  - ✓ 3-body kinematics, no good kinematic variable to fit
- Unique for e^+e^- colliders
- Hadronic B-tagging vs. inclusive B-tagging
  - ✓ Reconstruct signal B final state

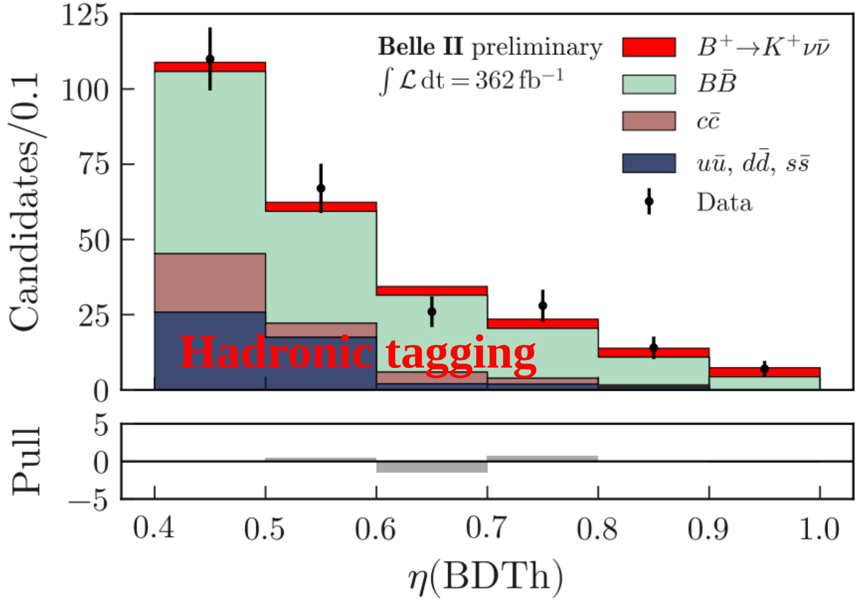


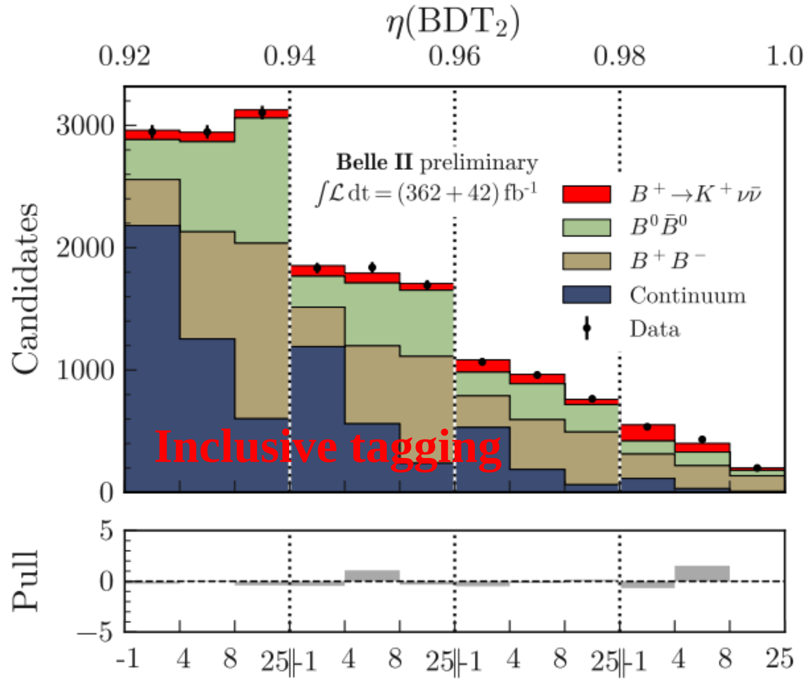




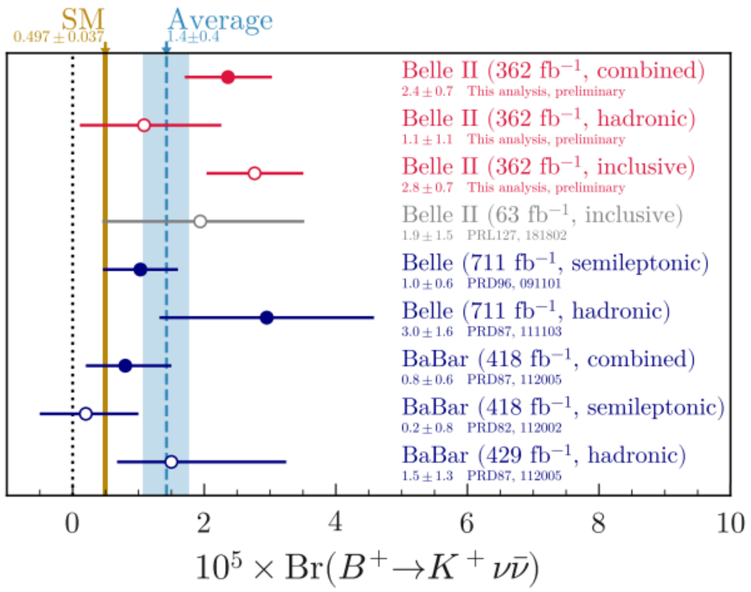


$B^+ \to K^+\nu\bar{\nu}$ @ SM

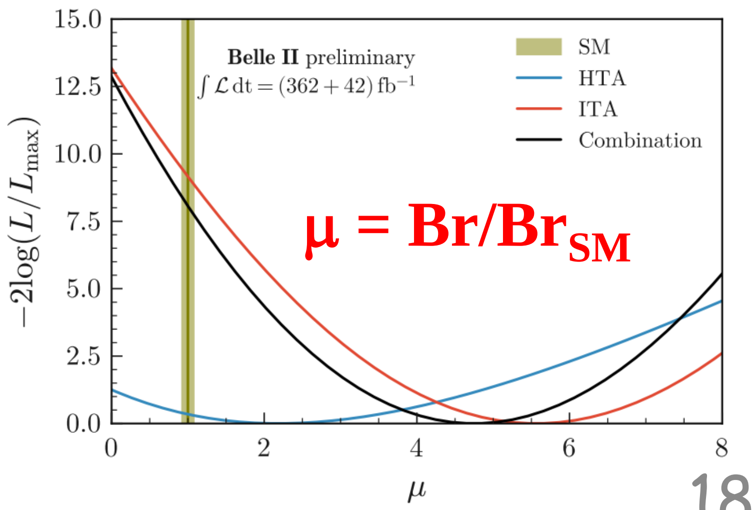




$$q^2_{rec} = s/4 + M_K^2 c^4 - \sqrt{s} E_K^* c$$



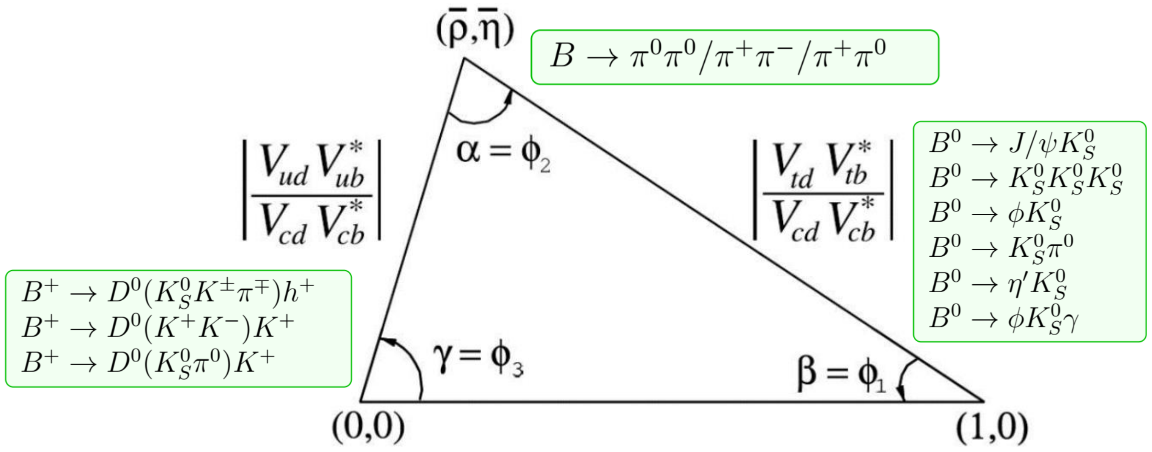
Method	Br($\times 10^{-5}$)	$\mu = Br/Br_{SM}$
Hadronic	$1.1^{+0.9}_{-0.8}(stat)^{+0.8}_{-0.5}(sys)$	$2.2 \pm 2.3(stat)^{+1.6}_{-0.7}(sys)$
Inclusive	$2.8 \pm 0.5(stat) \pm 0.5(sys)$	$5.6 \pm 1.1(stat)^{+1.1}_{-0.9}(syst)$
Combine	$2.4 \pm 0.5(stat)^{+0.5}_{-0.4}(sys)$	$4.7 \pm 1.0(stat) \pm 0.9(syst)$



- **First evidence for $B^+ \to K^+\upsilon\bar{\upsilon}$: 3.5σ from null, 2.6σ from SM**

Summary and outlook

- Belle II collects **428 fb^{-1}** data, comparable to BaBar data, about half of Belle data
- Robust program to measure CKM angle $\phi_1/\phi_2/\phi_3$ @ B decays
  - ✓ Unique/competitive @ performance of neutral particles
  - ✓ CPV @ rare(penguin) decay, profiting from clean event topology
- Belle II prospects
  - ✓ More data: restart data taking this winter
  - ✓ Better control: software (GFlaT) & hardware (new pixel vertex detector modules)



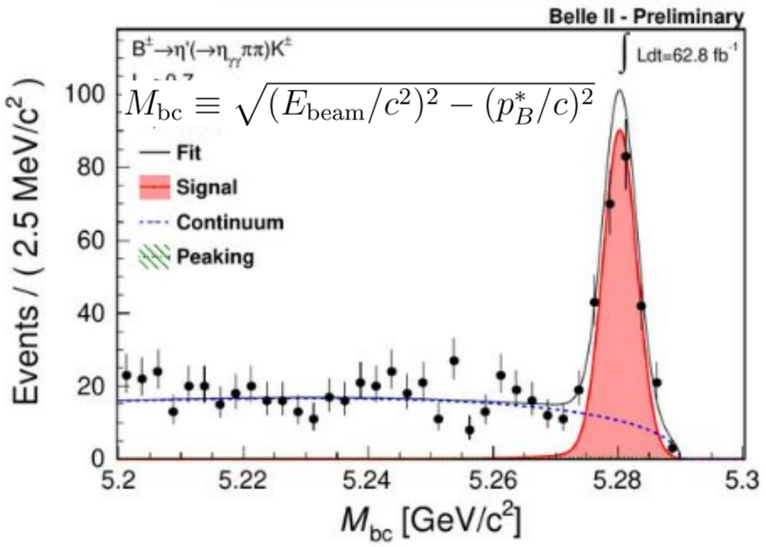
arXiv:2203.11349

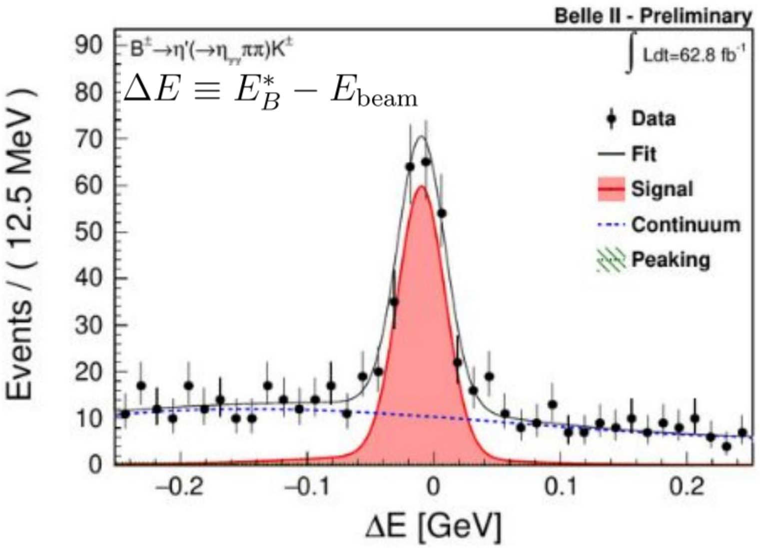
Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%	$< 1\%$
$S_{CP}(B \to \eta' K_S^0)$	0.08	0.03	0.015	0.007
$A_{CP}(B \to \pi^0 K_S^0)$	0.15	0.07	0.025	0.018
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035	0.015

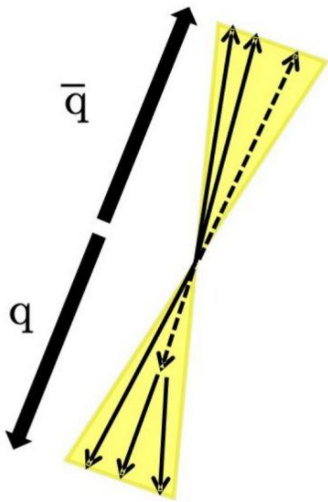
B-factory variables

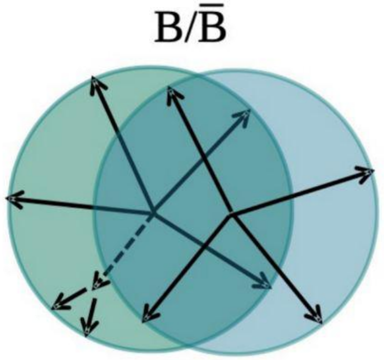
- Beam-constrained mass M_{bc} & energy discrepancy ΔE separating signal from backgrounds, with knowledge of beam energy
- Dominant background from $e^+e^- \to q\bar{q}(q = u, d, c, s)$
  - ✓ Jet-like vs. spherically symmetric event topology
  - ✓ A BDT-classifier to reduce continuum $q\bar{q}$ background

Process @ Υ(4S)	σ (nb)
$e^+e^- \to b\bar{b}$	1.1
$e^+e^- \to c\bar{c}$	1.3
$e^+e^- \to q\bar{q}(q = u, d, s)$	2.1
$e^+e^- \to \tau\bar{\tau}$	0.93









GNN flavor tagger (GFLat)

- New flavor tagger based on graph neural network
- Use interrelation between particles
- Gain 18% relative tagging efficiency compared to Category-based flavor tagger (CB FT)

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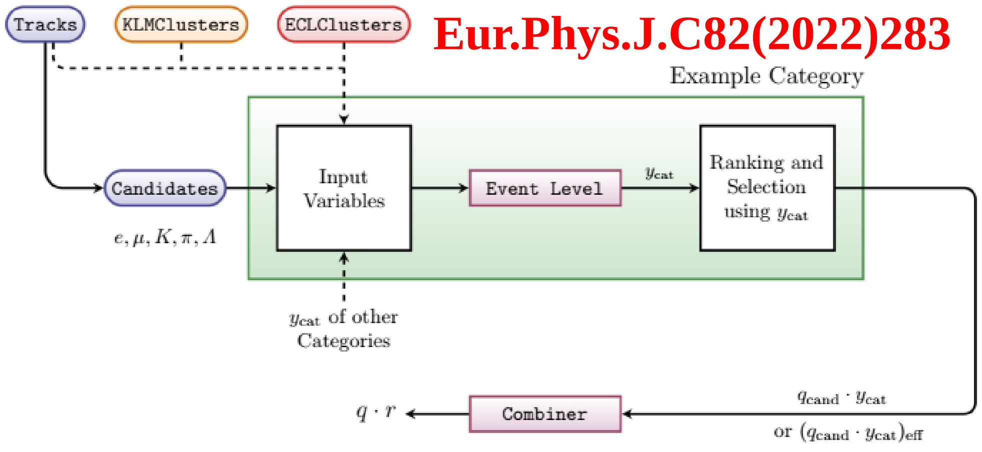
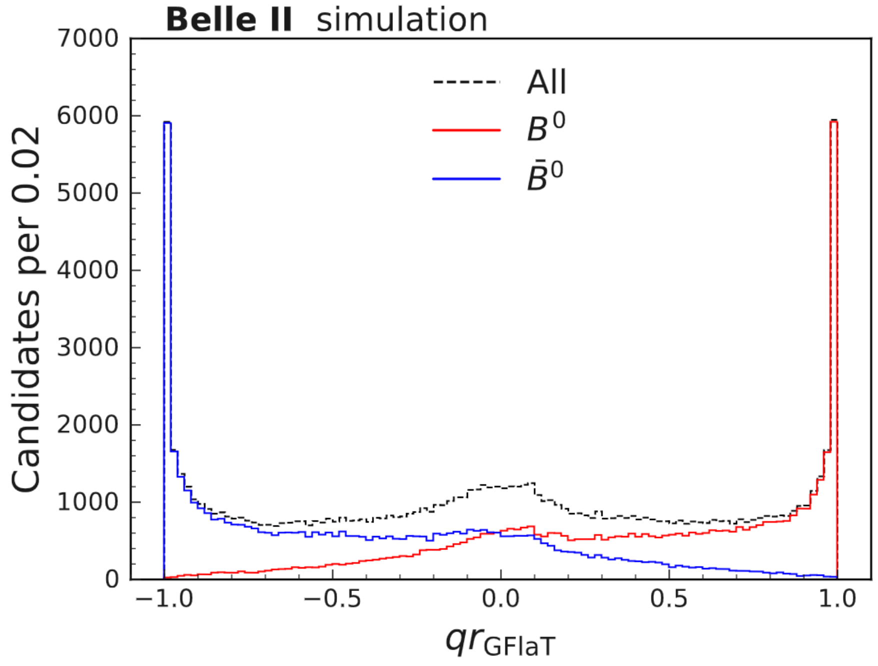
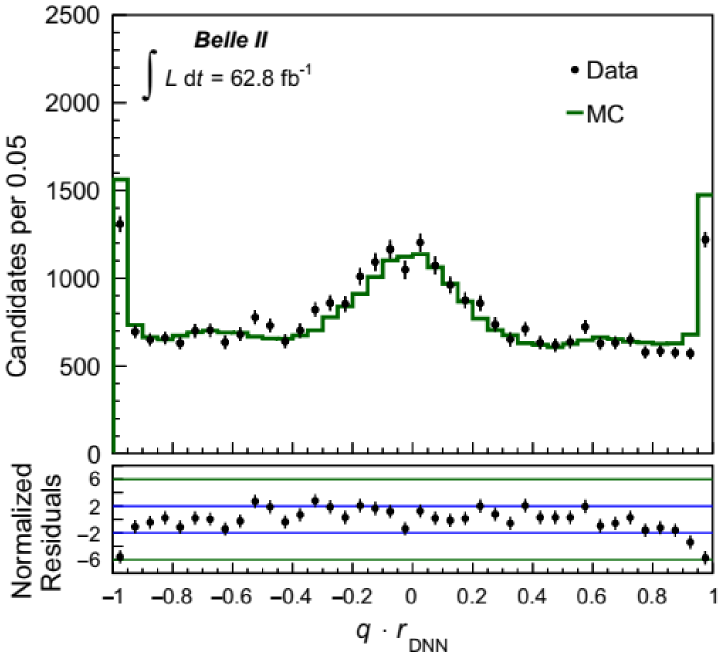


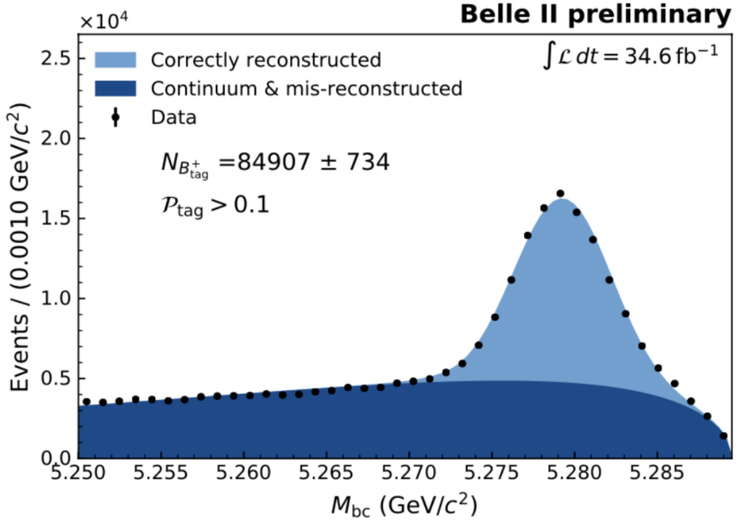
CB FT:	$\epsilon_{tag} = (31.68 \pm 0.45 \pm 0.41)\%$
GFlaT:	$\epsilon_{tag} = (37.40 \pm 0.43 \pm 0.34)\%$

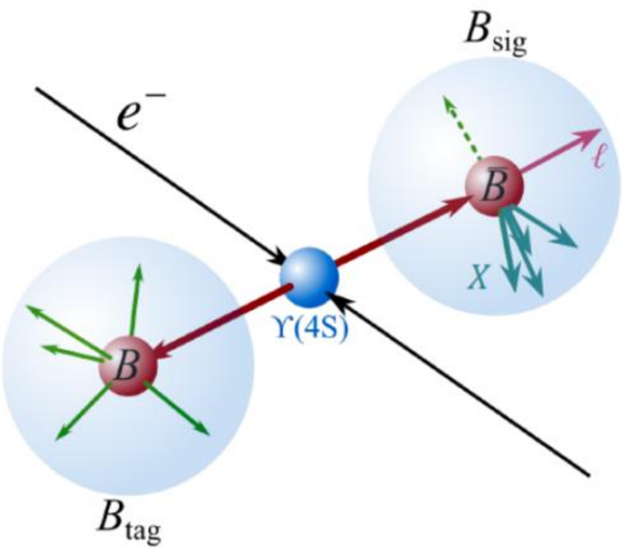




B-tagging: Full event interpretation (FEI)

- Hadronic vs. semi-leptonic tagging
- FEI algorithm for B-tagging
  - ✓ Hierarchical reconstruction of 10^4 B decay chains
  - ✓ Machine learning: ~ 200 BDTs trained with MC
- FEI output
  - ✓ List of tag candidates
  - ✓ A probability to have correct reconstruction





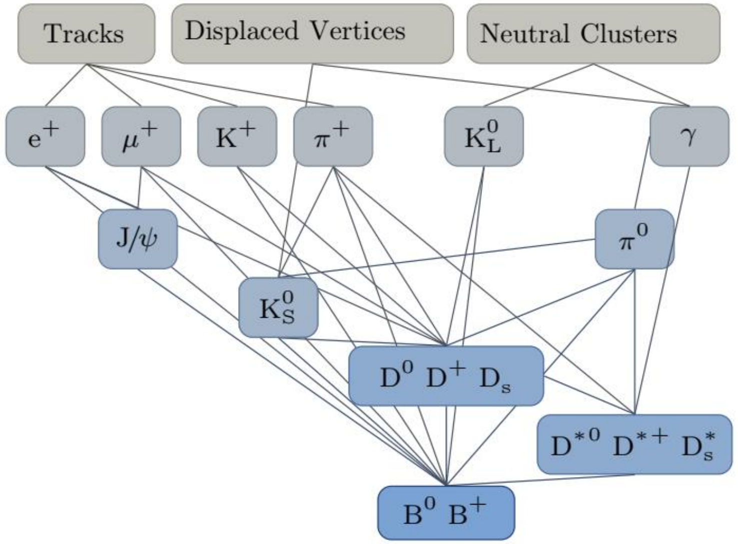
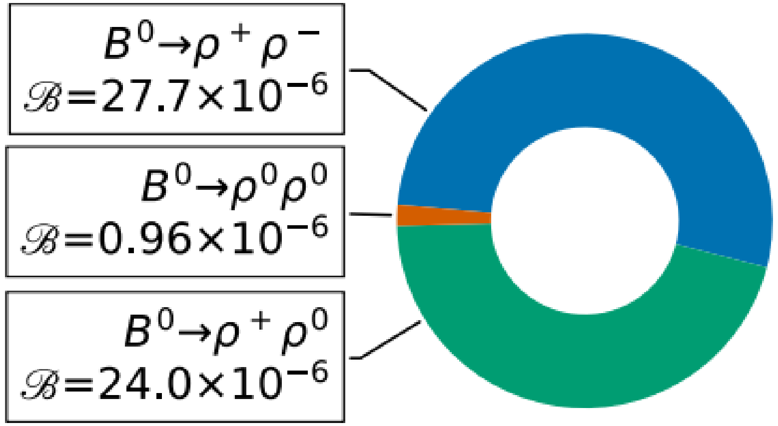
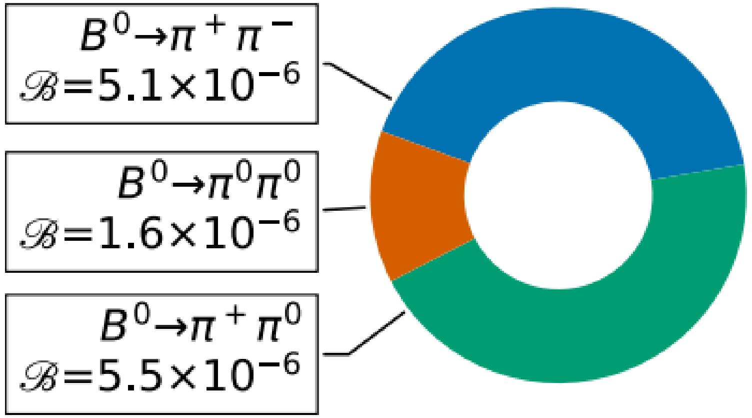


Table 1 Summary of the maximum tag-side efficiency of the Full Event Interpretation and for the previously used exclusive tagging algorithms **Comp. Soft. Big Sci 3 6 (2019)**

	$B^{\pm}$ (%)	B^0 (%)
Hadronic		
FEI with FR channels	0.53	0.33
FEI	0.76	0.46
FR	0.28	0.18
SER	0.4	0.2
Semileptonic		
FEI	1.80	2.04
FR	0.31	0.34
SER	0.3	0.6

CKM angle ϕ_2/α @ $B \to \rho\rho$



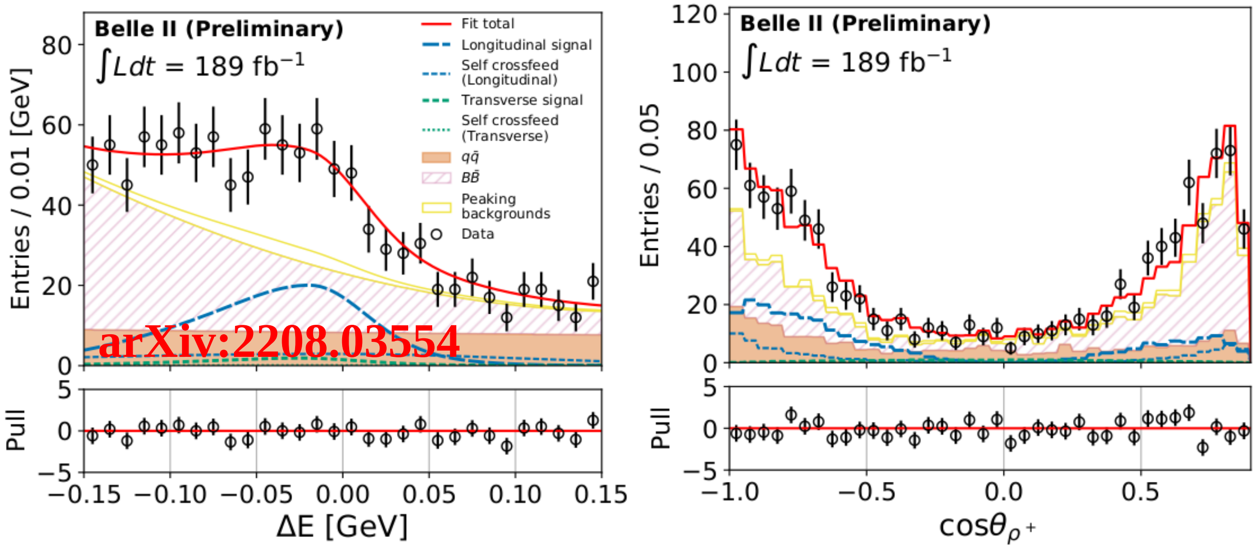


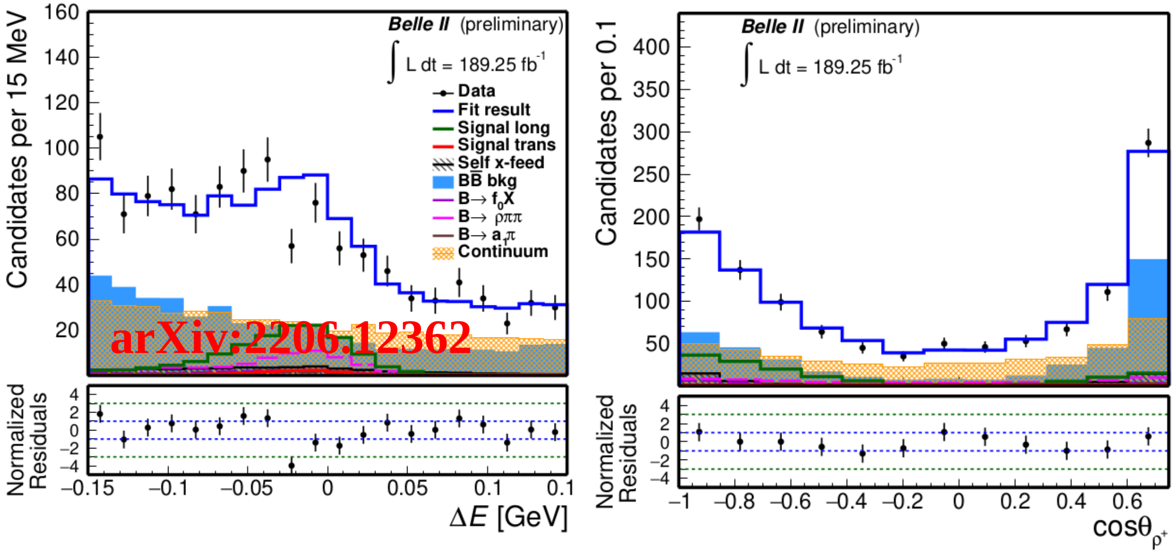
- **Smaller Br of $B^0 \to \pi^0\pi^0$**
  - ✓ **Smaller penguin pollution**
  - ✓ **Smaller $\Delta\phi_2 \to$ improved ϕ_2 precision**
- **Polarization of $P \to VV$ decay** $\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_{\rho^+}\,d\cos\theta_{\rho^-}} = \frac{9}{4}\left(f_L\cos^2\theta_{\rho^+}\cos^2\theta_{\rho^-} + (1-f_L)\frac{1}{4}\sin^2\theta_{\rho^+}\sin^2\theta_{\rho^-}\right)$
  - ✓ **Longitudinal: Cp-even; Transversal: CP-even + CP-odd**
  - ✓ **Only longitudinal polarization f_L for ϕ_2 measurement**
- **Angular analysis to disentangle longitudinal & Transversal polarization**
- **Complicated $\rho\rho$ analysis has better sensitivity to ϕ_2**

$B \to \rho\rho$ results

- **Broad width doesn't provide good signal-background separation**
- **Non-negligible contribution from peaking backgrounds**
- **Extract Br, f_L and CP asymmetry**

extension to full sample promising





$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (2.67 \pm 0.28 \pm 0.28) \times 10^{-5}$$

$$f_L = 0.956 \pm 0.035 \pm 0.033$$

extension to full sample promising

$$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

$$\mathcal{A}_{CP} = -0.069 \pm 0.068 \pm 0.060$$