Direct CP violation measurement of decay $B^0 \to K^0_S \pi^0$

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B2Kspi0 Analysis Slice

Outline

Motivation

- The $K\pi$ isospin sum rule:

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

- $B^0 \to K^0_S\pi^0$ provides the essential neutral-mode input for this sum rule.
- This analysis targets simultaneous extraction of $\mathcal{B}(B^0 \to K^0_S\pi^0)$ and $\mathcal{A}_{CP}$ using combined Belle + Belle II data.

Status Update (since June 2026)

- **Belle II (Kpm)**
  - 3D fit updated: CSMVA > 0.5, single-ARGUS continuum M'_{bc}, dedicated rbin3/6 continuum shapes.
  - **ToyMC validation completed**: pull check (1000 toys), linearity scan, significance estimation, sensitivity landscape.
  - Flavor tagger: qrTFLAT (14 categories in 7 $|qr|$ bins).
- **Belle — Kpm B2BII**
  - Preselection, π^0 MVA, K^0_S and CSMVA optimized.
  - 3D fit with qrGNN flavor tagging, direct KDE $B\bar{B}$ shapes.
  - Closure test passed.

Outline

Belle II Preselection and Selection

Category	Selection conditions
γ reconstruction	$E_\gamma > 0.10$ GeV (Forward), $E_\gamma > 0.05$ GeV (Backward/Barrel)
π^0 selection	$0.110 < \mathrm{InvM}_{\pi^0} < 0.160$ GeV/c^2, `pi0_mva > 0.40`
K^0_S selection	$0.479 < \mathrm{InvM}_{K^0_S} < 0.517$ GeV/c^2, `lammva > 0.10`, `v0mva > 0.90`
CS suppression	`CSMVA_new > 0.50`
B^0 window	$5.24 < M'_{bc} < 5.295$ GeV/c^2, $\lvert\Delta E\rvert < 0.30$ GeV

- Key change: CSMVA cut relaxed from 0.70 to **0.50** —increases signal efficiency while ToyMC validates fit robustness.

3D Fit PDF Model

- Fit observables: $M'_{bc} \in [5.24,\ 5.295]\ \mathrm{GeV}/c^2$, $\Delta E \in [-0.30,\ 0.30]\ \mathrm{GeV}$, $\mathrm{CSOmu} \in [0.0,\ 1.0]$.
- Simultaneous fit in 14 flavor-tag categories (7 $|qr|$ bins $\times$ $q = \pm 1$).

Component	**Observable**	**PDF**
Signal	M'_{bc}	Crystal Ball + Gaussian
Signal	ΔE	Double Crystal Ball
Signal	CSOmu	1st-order polynomial
Continuum $q\bar{q}$	M'_{bc}	Single ARGUS (shared across r-bins)
Continuum $q\bar{q}$	ΔE	2nd-order Bernstein (dedicated rbin3/6)
Continuum $q\bar{q}$	CSOmu	Sum of two exponentials (dedicated rbin3/6)
Generic $B\bar{B}$	$(M'_{bc}, \Delta E)$	2D KDE (`RooNDKeysPdf`)
Generic $B\bar{B}$	CSOmu	1st-order polynomial

- Background mode: **free r-bin** —continuum yields float per r-bin, $B\bar{B}$ total yield floats with fixed r-bin fractions.

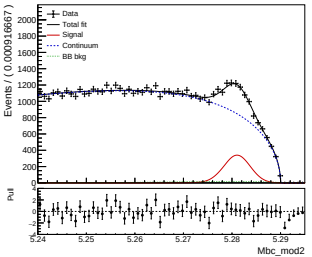
Cut Flow (16rd MC, CSMVA > 0.5)

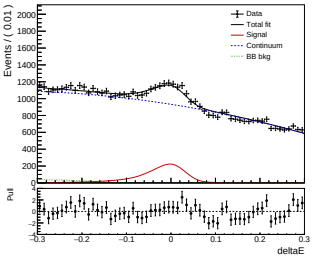
Stage	N_{sig}	ϵ **[%]**	N_{cont}	N_{BB}	**SCF [%]**
Reconstruction	1,413,639	70.68	4,574,057	6,892	6.90
Preselection	1,053,628	52.68	721,221	1,319	2.56
$\pi^0 + K_S^0$ MVA	905,314	45.27	165,529	376	0.93
CSMVA > 0.5	764,251	38.21	22,294	327	0.98
Best candidate	763,317	38.17	22,138	314	1.10

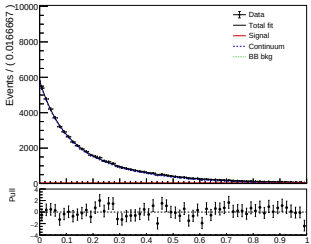
- **BCS strategy**: composite — max pi0 MVA + min rank χ^2 + max Ks v0mva (correct selection: 78.7%).
- **CSMVA cut**: 0.5 — reduces continuum background by $\sim 7\times$ while retaining 84% of pre-CS signal.

3D Fit Result (CSMVA > 0.5, qrTFLAT)

- $\varepsilon_{3D} = (38.17 \pm 0.03)\%$
- $N_{\text{sig}}^{\text{tot}} = 2535 \pm 69$
- $N_{\text{cont}}^{\text{tot}} = 53990 \pm 240$
- $N_{BB}^{\text{tot}} = 509 \pm 60$
- $\boxed{\mathcal{A}_{CP} = -0.006 \pm 0.058}$







Outline

ToyMC Workflow Overview

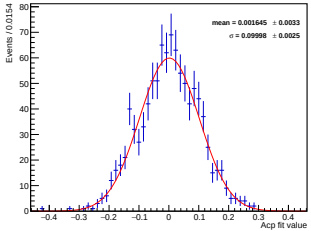
- **Setup**: 700 fb^{-1}, qrTFLAT tagger, single-ARGUS continuum M'_{bc} shape.
- **Generation**: 7 $|qr|$ bins $\times$ $q\pm = 14$ categories; flavor-tag parameters from signal MC; Poisson count fluctuations.
- **Fitting**: fixedShape mode, floating continuum r-bin yields, floating total $B\bar{B}$ yield with fixed r-bin fractions.
- **Four studies** completed:
  1. **Pull check** (1000 toys): bias and pull-width closure.
  2. **Linearity scan**: $A_{CP} \in [-1, 1]$ (11 points) and $N_{\mathrm{sig}} \in [0.70, 1.30]\times$ nominal (17 points).
  3. **Sensitivity landscape**: expected $\sigma(A_{CP})$ from 500 fb^{-1} to 50 ab^{-1}.

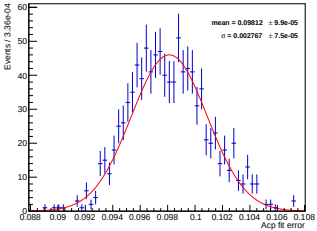
Pull Check: Fit Results (1000 Toys)

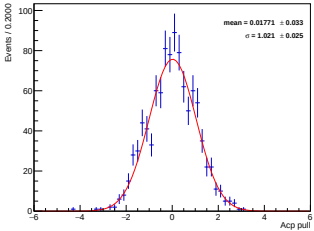
Observable	Pull Mean $\pm$ Error	Pull Sigma $\pm$ Error
A_{CP}	$+0.018 \pm 0.033$	1.021 ± 0.025
$N_{\mathrm{sig}}^{\mathrm{tot}}$	$+0.006 \pm 0.032$	0.961 ± 0.022

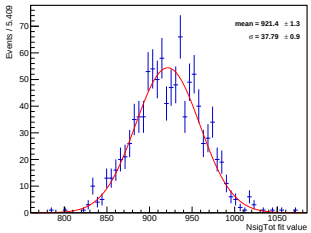
- All 1000/1000 toys passed good-toy criteria (status=0, covQual=3).
- A_{CP} and $N_{\mathrm{sig}}^{\mathrm{tot}}$ are the primary physics observables —both show no significant bias.

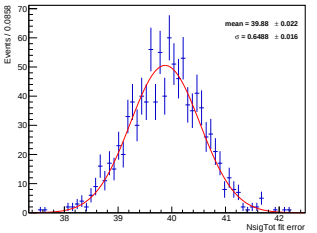
Pull Check: Figures

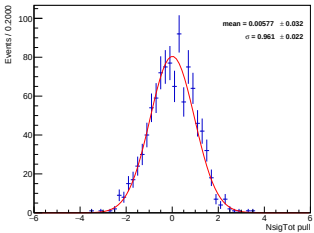












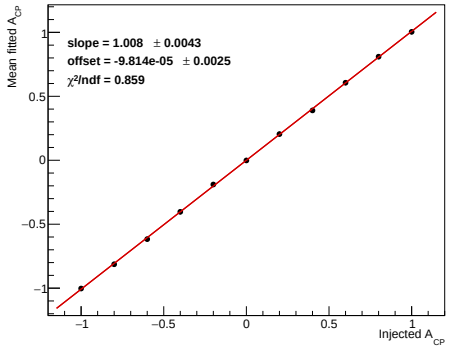
Linearity Scan: A_{CP} and $N_{\mathrm{sig}}^{\mathrm{tot}}$

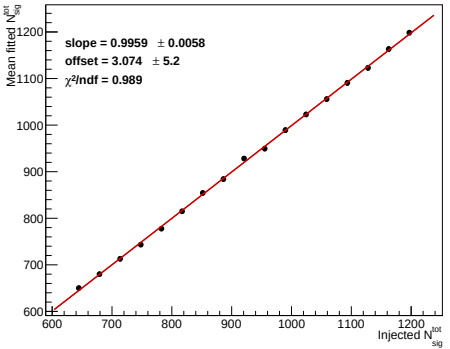
- A_{CP} **linearity**: 11 injection points from -1.0 to $+1.0$, 100 toys each.
- N_{sig} **linearity**: 17 points from $0.70\times$ to $1.30\times$ nominal, 100 toys each.

Scan	**Intercept**	**Slope**	χ^2/ndf	**Conclusion**
A_{CP} linearity	$(-0.01 \pm 0.25) \times 10^{-2}$	1.008 ± 0.004	0.86	slope consistent with 1
N_{sig} linearity	3.1 ± 5.2	0.996 ± 0.006	0.99	slope consistent with 1

- Both slopes are consistent with 1 and intercepts with 0 —no injection-dependent bias observed.

Linearity Scan: Figures





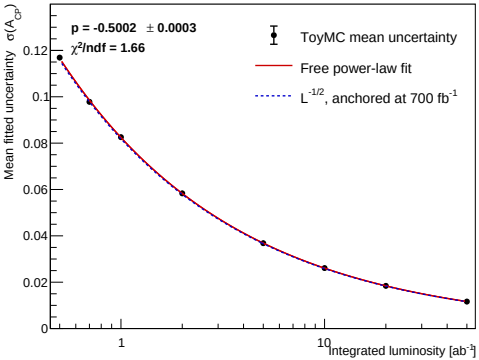
A_{CP} Sensitivity vs. Luminosity

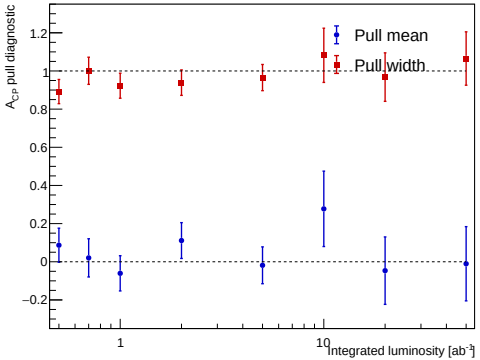
- 8 scan points from 500 fb^{-1} to 50 ab^{-1}, $A_{CP} = 0$ injection.
- Yields scale linearly with luminosity; statistical uncertainties only.

Luminosity	**Mean** $\sigma(A_{CP})$	N_{toys}
500 fb^{-1}	0.117	100
700 fb^{-1}	0.098	100
1 ab^{-1}	0.083	100
2 ab^{-1}	0.058	100
5 ab^{-1}	0.037	100
10 ab^{-1}	0.026	30
20 ab^{-1}	0.018	30
50 ab^{-1}	0.012	30

- Power-law fit: $\sigma(A_{CP}) = 0.0985 \times (L/700\ \mathrm{fb}^{-1})^{-0.5002}$, $\chi^2/\mathrm{ndf} = 1.66$.

A_{CP} Sensitivity Figures





ToyMC Summary

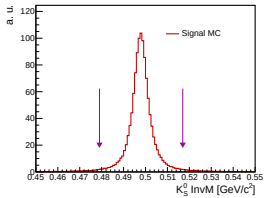
- **Linearity**: A_{CP} and $N_{\mathrm{sig}}^{\mathrm{tot}}$ both show perfect linear response (slopes $= 1.008 \pm 0.004$ and 0.996 ± 0.006).
- **Sensitivity**: $\sigma(A_{CP}) \propto 1/\sqrt{L}$ validated from 500 fb^{-1} to 50 ab^{-1}.
- **Conclusion**: The 3D $q \cdot r$-binned simultaneous fit model passes all ToyMC validation tests. The fit is ready for data unblinding (pending Collaboration approval).

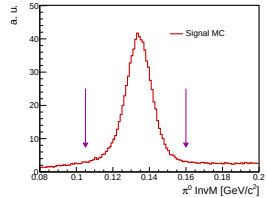
Outline

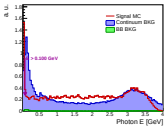
Belle B2BII: Dataset and Preselection

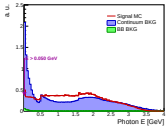
- **Signal MC**: 2×10^6 events.
- **Generic MC**: 2 streams (charged + mixed), scaled to $2\times$ Belle data.
- **Rare MC**: $50\times$ data size.
- **Belle data**: $\sim 711\ \mathrm{fb}^{-1}$.

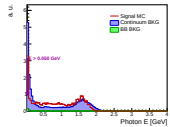
Category	Selection
γ reco	$E_\gamma > 0.10$ (Fwd), $E_\gamma > 0.05$ GeV (Bwd/Barrel)
π^0	$0.100 < \mathrm{InvM}_{\pi^0} < 0.160\ \mathrm{GeV}/c^2$
K^0_S	$0.479 < \mathrm{InvM}_{K^0_S} < 0.517\ \mathrm{GeV}/c^2$
B^0 window	$5.24 < M_{bc} < 5.30\ \mathrm{GeV}/c^2$, $\lvert\Delta E\rvert < 0.30$ GeV







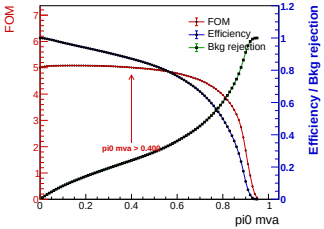


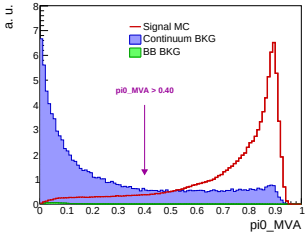


Belle π^0 MVA Training and Optimization

- **Classifier**: FastBDT.
- **Inputs**: π^0 InvM, daughterAngle, chiProb; $\gamma_{1,2}$ beamBackgroundSuppression, fakePhotonSuppression; E_{low}, E_{high}.
- **FOM**: $N_S/\sqrt{N_S+N_B}$.

Selection	Sig eff. [%]	Bkg rej. [%]
π^0 MVA > 0.4	87.14 ± 0.04	24.11 ± 0.11
CSMVA > 0.5	75.2 (relative)	92.7

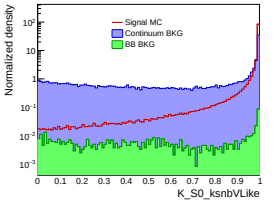


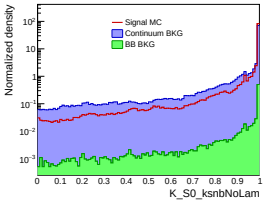


Belle K^0_S KsNB Selection

- **Selector**: Belle KsNB (`ksnbVLike`, `ksnbNoLam`).
- Replaces deprecated `goodBelleKshort`.
- **FOM**: $N_S/\sqrt{N_S+N_B}$, scaled to $711\ \mathrm{fb}^{-1}$.
- Each variable scanned independently over $[0,1]$.

Variable	Cut
`ksnbVLike`	> 0.90
`ksnbNoLam`	> 0.90

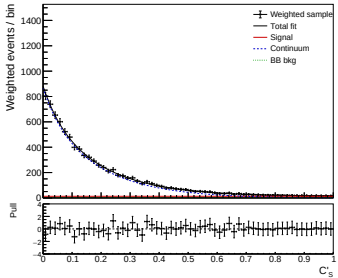


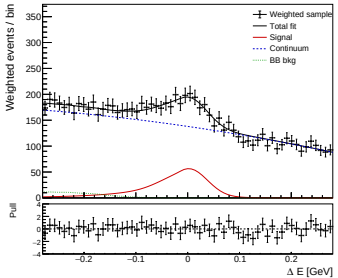


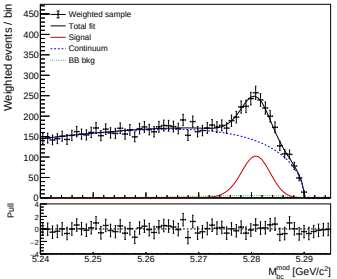
Kpm B2BII: FBDT vs. qrGNN Flavor Tag

- luminosity: $711\,\mathrm{fb}^{-1}$
- qrGNN gives $\sim 7\%$ improvement in $\sigma(A_{CP})$ over FBDT.

Observable	**FBDT**	**qrGNN**
N_{sig} (closure)	782 ± 35	777 ± 35
A_{CP}	-0.037 ± 0.117	-0.024 ± 0.109







Summary

- **Belle II Kpm —ToyMC phase complete**:
  - 3D $q{\cdot}r$-binned fit (qrTFLAT, CSMVA > 0.5) returns $\mathcal{A}_{CP} = -0.006 \pm 0.058$ and $N_{\rm sig}^{\rm tot} = 2535 \pm 69$ for 16rdMC sample.
  - ToyMC pull, linearity, significance, and sensitivity all pass validation.
  - $\sigma(A_{CP}) \approx 0.098$ at $700\ \mathrm{fb}^{-1}$, follows $1/\sqrt{L}$ scaling.
- **Kpm B2BII (Belle) — fit framework in place**:
  - Preselection, π^0 MVA, K_S^0 selection, and CSMVA optimized.
  - 3D fit with qrGNN, KDE $B\bar{B}$ shape, r-bin-dependent continuum modeling.
  - Closure test passed; CSMVA optimization and ToyMC are next.
- **Next steps**:
  - Systematics evaluation for Belle II (detector acceptance, flavor-tag calibration, shape uncertainties).
  - Belle CSMVA optimization and ToyMC.
  - Combined Belle + Belle II result preparation.

Thank you for your attention!

Backup

ToyMC: $q \cdot r$ Category Construction

$$N_{\mathrm{sig}}^{i,q} = \frac{1}{2} N_{\mathrm{sig}}^{\mathrm{tot}} \epsilon_i \Big[1 - q\Delta\omega_i + q\mu_i(1 - 2\omega_i) + \big(q(1 - 2\omega_i) + \mu_i(1 - q\Delta\omega_i)\big)(1 - 2\chi_d)\mathcal{A}_{CP} \Big].$$

$$N_{\mathrm{cont}}^{i,q} = \frac{1}{2} N_{\mathrm{cont},i}^{\mathrm{tot}},$$

- $i = 0, \ldots, 6$ labels the $|qr|$ bin; $q = \pm 1$ is the tag-sign category.
- Signal yield controlled by $(\epsilon_i, \omega_i, \Delta\omega_i, \mu_i, \chi_d, \mathcal{A}_{CP})$.
- Continuum and $B\bar{B}$ yields float per r bin, split symmetrically in q.

ToyMC: $|qr|$ Bin Definitions

r-bin	$\|qr\|$ **range**
rbin0	$[0.000, 0.100)$
rbin1	$[0.100, 0.250)$
rbin2	$[0.250, 0.500)$
rbin3	$[0.500, 0.625)$
rbin4	$[0.625, 0.750)$
rbin5	$[0.750, 0.875)$
rbin6	$[0.875, 1.000]$

- Each r-bin is further split into $q > 0$ and $q < 0$ categories —14 categories total.
- Larger $|qr|$ bins (rbin5, rbin6) carry more flavor-tagging power for A_{CP}.

Belle II: Flavor-Tag Parameters (qrTFLAT)

- Flavor tagger: `qrTFLAT` (nominal).
- Parameters extracted from signal MC in the 3D fit region (CSMVA > 0.5).

Bin	$\lvert qr\rvert$ range	ϵ_i	ω_i	$\Delta\omega_i$	μ_i
0	$[0.000, 0.100)$	0.0992	0.4751	0.0006	-0.0025
1	$[0.100, 0.250)$	0.1241	0.4144	-0.0009	0.0028
2	$[0.250, 0.500)$	0.1716	0.3196	-0.0106	0.0100
3	$[0.500, 0.625)$	0.0808	0.2250	-0.0002	0.0043
4	$[0.625, 0.750)$	0.0820	0.1644	0.0116	-0.0078
5	$[0.750, 0.875)$	0.0957	0.1001	0.0053	-0.0049
6	$[0.875, 1.000]$	0.3465	0.0249	0.0014	-0.0097

- High r-bin6 fraction (34.7%) and low mistag (2.5%) provides strong A_{CP} sensitivity.

ToyMC Pull Check: Full Results Table

Observable	N toys	Fit Mean	Fit Err (RMS)	Pull Mean	Pull Sigma
A_{CP}	1000	$+0.0016$	0.0981 (0.003)	$+0.018$	1.02
N_{sig}	1000	921.4	39.9 (0.65)	$+0.006$	0.96
N_{cont}	1000	19555	142.3 (0.51)	-0.021	1.05
N_{BB}	1000	183.3	14.9 (0.67)	-0.103	2.21

- Input yields: $N_{\mathrm{sig}} = 920.74$, $N_{\mathrm{cont}} = 19559.40$, $N_{BB} = 184.45$.
- Good-toy criterion: status=0, covQual=3, finite positive errors, finite pulls.
- 100% toy retention —no fit failures in the nominal pull ensemble.

ToyMC Sensitivity: Power-Law Fit

- Fit function: $\sigma(A_{CP}) = C \times (L/700\ \mathrm{fb}^{-1})^{p}$.
- Free fit: $C = 0.09852 \pm 0.00011$, $p = -0.50022 \pm 0.00033$, $\chi^2/\mathrm{ndf} = 9.98/6 = 1.66$.
- Exponent consistent with purely statistical $1/\sqrt{L}$ scaling: no systematics floor visible at this stage.

Detector	$\sigma(A_{CP})$ **at 50** ab^{-1}
Belle II (this study)	~ 0.012

- At Belle II target luminosity, statistical precision reaches $\sim 1.2\%$ on A_{CP}.
- This is purely statistical —realistic systematics will set a precision floor well above this value.