BEGINNING AN ANALYSIS OF $B^0 \rightarrow \omega K_S^0$: BACKGROUND, GOALS, AND FIRST INSIGHTS

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Belle II

- Why Charmless B Decays?
- Decay Mechanism and Diagrams
- Belle Measurements and Motivation
- Continuum Suppression
- Flavor Tagging and CPV Parameters
- Current Status and Signal MC
- Summary and Outlook

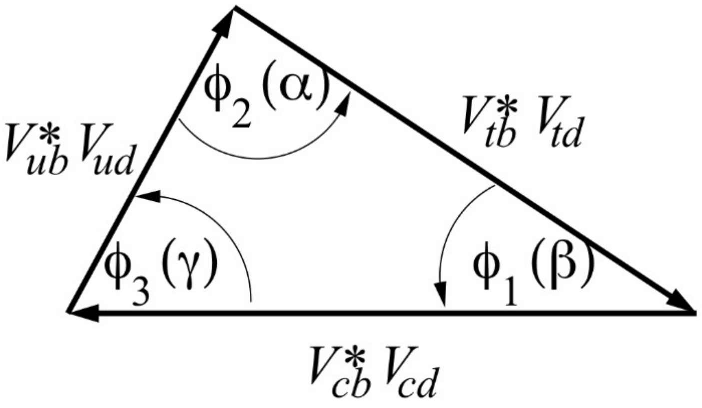
Outline

WHY STUDY CHARMLESS B DECAYS?

- **CP violation** arises from a single irreducible phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix
- Essential for addressing the origin of the matter–antimatter asymmetry in the universe
- **Charmless B decays** (e.g.$B^0 \to \omega K_S^0$) are sensitive to new physics
- Contribution from **loop-level (penguin) diagrams**
- Penguin amplitudes can reveal contributions from beyond the Standard Model

$$V_{CKM} \equiv \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix}$$

$$(VV^\dagger)_{ij} = (V^\dagger V)_{ij} = \delta_{ij}, \quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

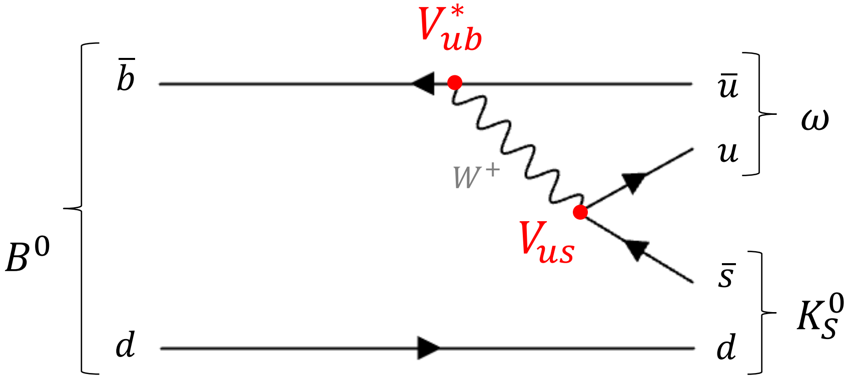


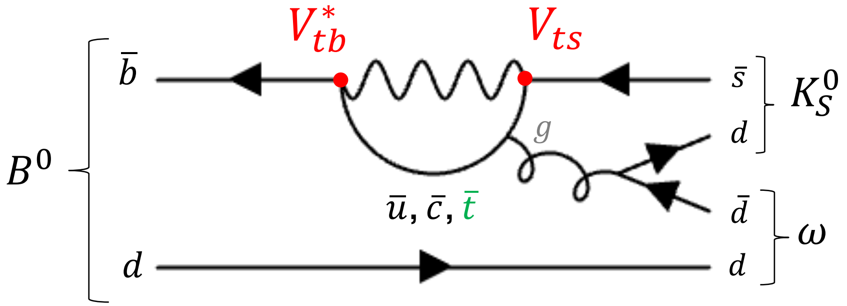
DECAY MECHANISM AND DIAGRAMS

- **Branching fraction:** $\mathcal{B}\left(B^0 \to \omega K_S^0\right) = 4.5{\times}10^{-6}$ (Belle 2014)
- In $B^0 \to \omega K_S^0$ interference between **color suppressed** and **doubly Cabibbo suppressed** tree level and **penguin** amplitudes which may lead to **new physics** and measurable CP asymmetry.
- sensitive to the interior angle of the unitarity triangle

$$\phi_1(\beta) = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$$

- The CKM phase ϕ_1 is accessible experimentally through interference between the direct decay of a B meson and $B^0\overline{B^0}$ mixing followed by a decay into the same final state.





arXiv:1311.6666 [hep-ex]

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DECAY DESCRIPTION

- **Decay Chain:**
  - $B^0 \rightarrow \omega K_S^0$
  - $\omega \rightarrow \pi^+\pi^-\pi^0$
  - $K_S^0 \rightarrow \pi^+\pi^-$
  - $\pi^0 \rightarrow \gamma\gamma$

Event Selection:

- Track quality cuts: $|dz| < 4.0$ cm $dr < 0.4$ cm
- Mass Windows: $\left|M_{\pi\pi} - m_{K_S^0}\right| < 16\text{MeV}/c^2$, $\left|M_{\gamma\gamma} - m_{\pi^0}\right| < 16\text{MeV}/c^2$, $|M_{3\pi} - m_\omega| < 50\text{MeV}/c^2$
- π^0 reconstruction: $E_\gamma > 50\text{MeV}$ in the ECL barrel region

  $E_\gamma > 100\text{MeV}$ in the ECL end cap regions
- Additional selection criteria: $M_{\text{bc}} > 5.25\, GeV/c^2$, $-0.15\text{GeV} < \Delta E < 0.1\text{GeV}$

- **Previously measured by Belle (2014):** final data sample $772{\times}10^{+6}$ $B\bar{B}$ pair

$$\boxed{\mathcal{B} = \left(4.5 \pm 0.4\,(stat) \pm 0.3\,(syst)\right){\times}10^{-6}}$$

- **First evidence of CP violation in $B^0 \rightarrow \omega K_S^0$ decay channel at the level of 3.1σ.**
  - Mixing-induced CP violation: $\boxed{\mathcal{S} = -0.36 \pm 0.19\,(stat) \pm 0.05\,(syst)}$
  - Direct CP violation: $\boxed{\mathcal{A} = +0.91 \pm 0.32\,(stat) \pm 0.05\,(syst)}$

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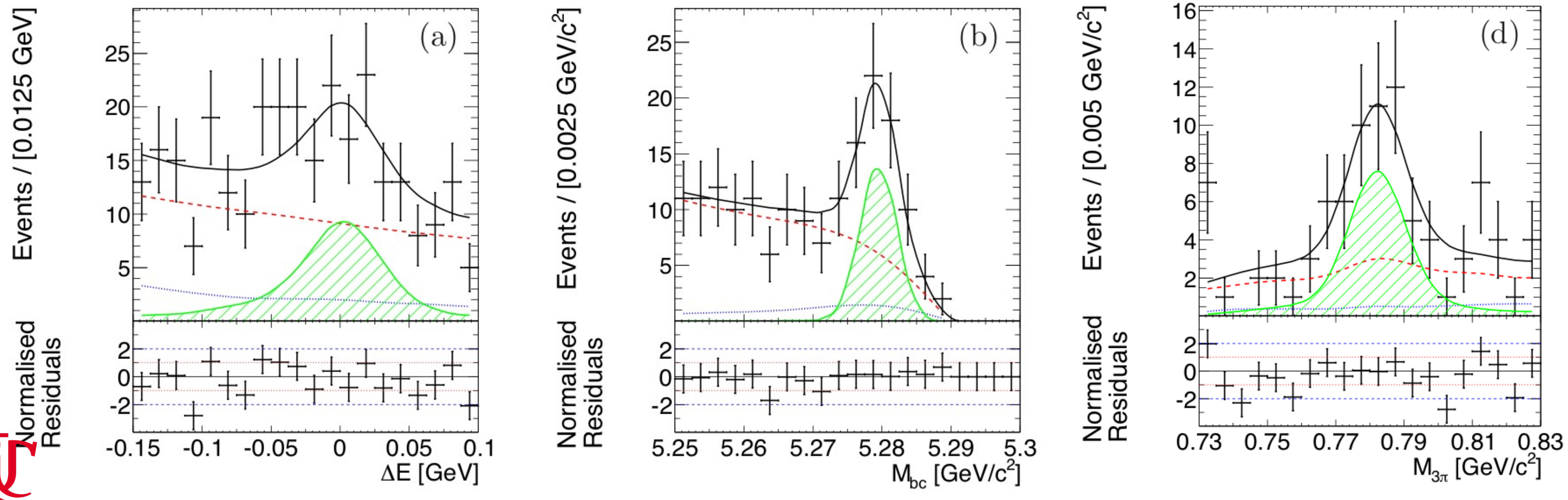
BELLE RESULTS

- Signal extracted via 2D fit in $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$ and $\Delta E = E_B - E_{beam}$
- Clean clustering of signal candidates near expected region
- Signal region is clearly defined nearby: $M_{bc} > 5.27\ GeV/c^2$ and $-0.04\ GeV < \Delta E < 0.03\ GeV$
- Green hatched curves show the $B^0 \rightarrow\ \omega K_S^0$ signal component, dashed red curves indicate the $q\bar{q}$ background, and blue dotted curves show the $B\bar{B}$ background component.



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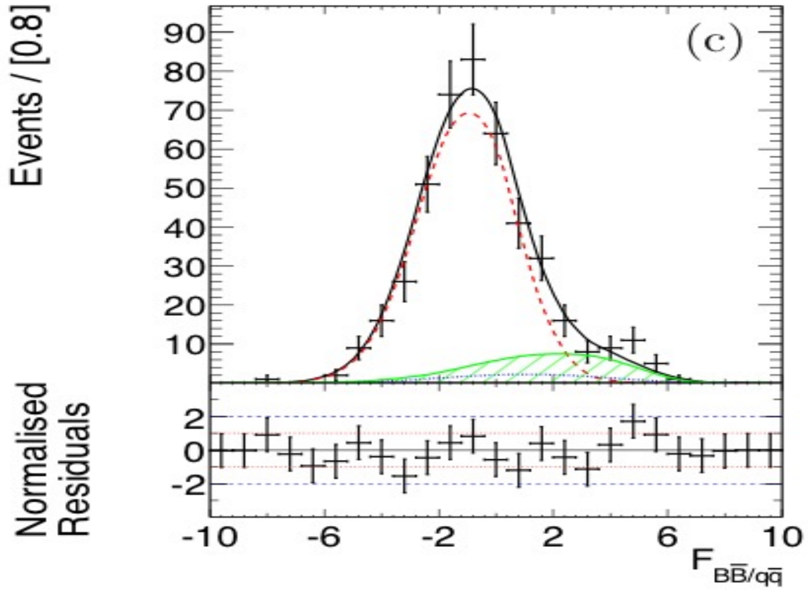
CONTINUUM SUPPRESSION: BELLE-I

- **The Challenge:**
  - Dominant background in e^+e^- comes from $e^+e^- \rightarrow q\bar{q}$ (continuum) events, where $q = u, d, s, c$.
- **Discrimination Techniques:**
  - To suppress this background, multivariate analysis (MVA) tools are employed.
  - Belle uses a modified Fox-Wolfram moments to differentiate between signal and continuum.
  - The likelihood ratio from this discriminant can be transformed into a Gaussian-like distribution, $\mathcal{F}_{B\bar{B}/q\bar{q}} = \log\frac{\mathcal{L}_{B\bar{B}/q\bar{q}}-0.2}{1-\mathcal{L}_{B\bar{B}/q\bar{q}}}$.
  - Further improvement comes from incorporating the polar angle of the B meson candidate in the CMS, which follows a $1 - cos^2\theta_B$ distribution for $B\bar{B}$ events and is flat for continuum.
- **Impact:** A loose selection of $L_{B\bar{B}/q\bar{q}}$ can reduce $q\bar{q}$ background by 62% with a signal efficiency of 94%.



Distribution of the continuum suppression variable ($\mathcal{F}_{B\bar{B}/q\bar{q}}$) for (Belle 2014 data, signal-enhanced region). The green hatched curve is signal, dashed red is $q\bar{q}$ background, and blue dotted is $B\bar{B}$ background.

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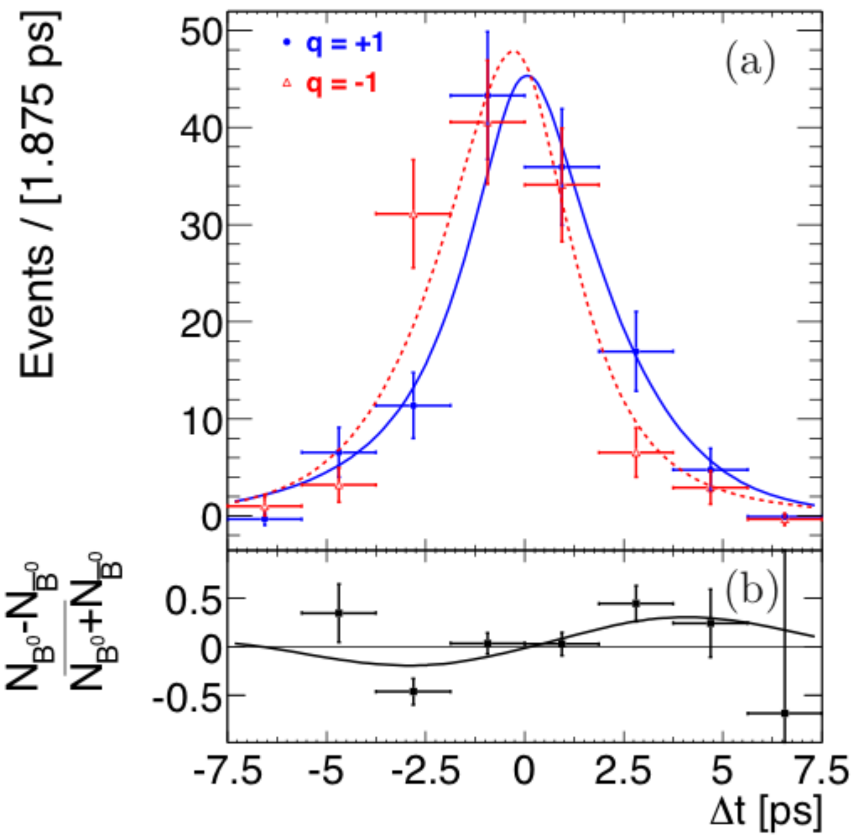
TIME-DEPENDENT CP VIOLATION & FLAVOR TAGGING

- The probability of a B meson having a flavor content q at some time and decaying to such a CP eigenstate after a time Δt is:

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

$\mathcal{A}$ (direct CP violation) and $\mathcal{S}$ (mixing-induced CP violation).

- **Time Difference (Δt) Measurement:**
  - Δt is the proper time interval between the decays of the reconstructed B meson (B^0_{Rec}) and the tag-side B meson (B^0_{Tag}).
  - It's approximated from the displacement in z between their decay vertices: $\Delta t \simeq \Delta z/\beta\gamma c$.
- **Flavor Tagging:**
  - The flavor of B^0_{Tag} is determined from tracks and photons not used in B^0_{Rec} reconstruction.
  - Tagging information includes the flavor $q = +1 (B^0)$ and -1 ($\bar{B}^0$) and flavor tag quality (r), ranging from 0 (no discrimination) to 1 (unambiguous assignment).



Background-subtracted time-dependent fit results (a) shows the Δt distribution for B^0 and $\bar{B}^0$ tags. (b) shows the asymmetry $N_{B^0} - N_{\bar{B}^0}/N_{B^0} + N_{\bar{B}^0}$as a function of Δt, used to extract the CP violation parameters.

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CURRENT STATUS – SIGNAL MC BELLE-II

- Successfully generated and processed a dedicated Monte Carlo sample for $B^0 \to \omega K_S^0$ decays.
- This simulation is crucial for understanding detector response and optimizing event selection. Basic selection applied: PID, kinematic cuts
- **Reconstruction Progress:**
  - Working on implementing the reconstruction chain for the final state particles: π^+, π^-, π^0, and photons.
  - dr < 0.5 and abs(dz) < 4.0 and thetaInCDCAcceptance
  - $\pi^\pm$: Binary PID: $\mathcal{L}_\pi/(\mathcal{L}_\pi + \mathcal{L}_K) > 0.4$
  - π^0 : stdPi0s: eff60_May2020 / E_γ>50 Mev → barrel & E_γ>100 Mev → caps regions / Momentum of π^0 > 210 Mev/c
  - Mass Windows: $720\ Mev < M_{\omega \to \pi^+\pi^-\pi^0} < 840\ Mev$ / $472\ Mev < M_{K_S^0 \to \pi^+\pi^-} < 524\ Mev$ / $115\ Mev < M_{\pi^0} < 150\ Mev$

Mode: $B^0 \to \omega K_S^0$	**Efficiency (ϵ)**
BelleII signal MC	$10.9\ \% \pm 0.031\%$
Belle SVD2	14.5%

  - Further optimization of selection criteria based on MC performance.

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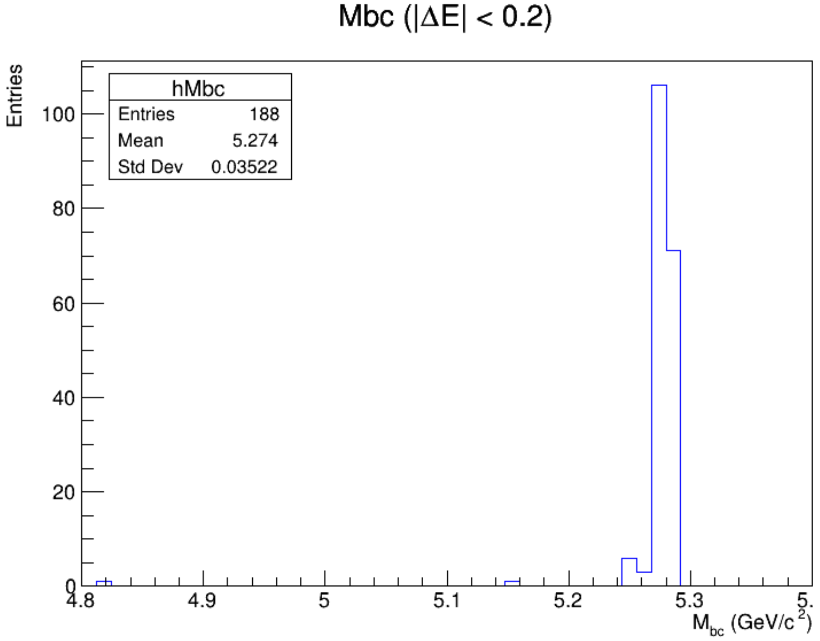
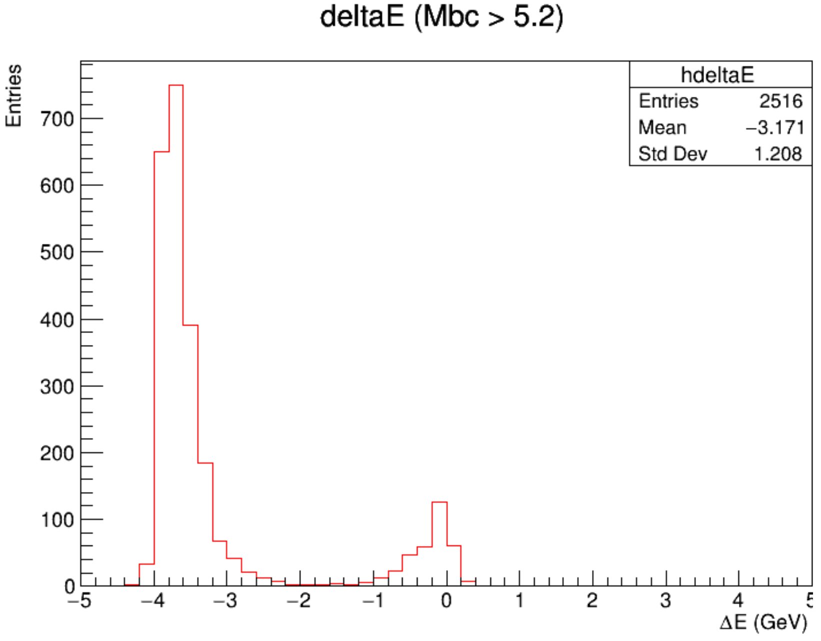
arXiv:2412.19624 [hep-ex]
arXiv:1311.6666 [hep-ex]
arXiv:2401.04646 [hep-ex]

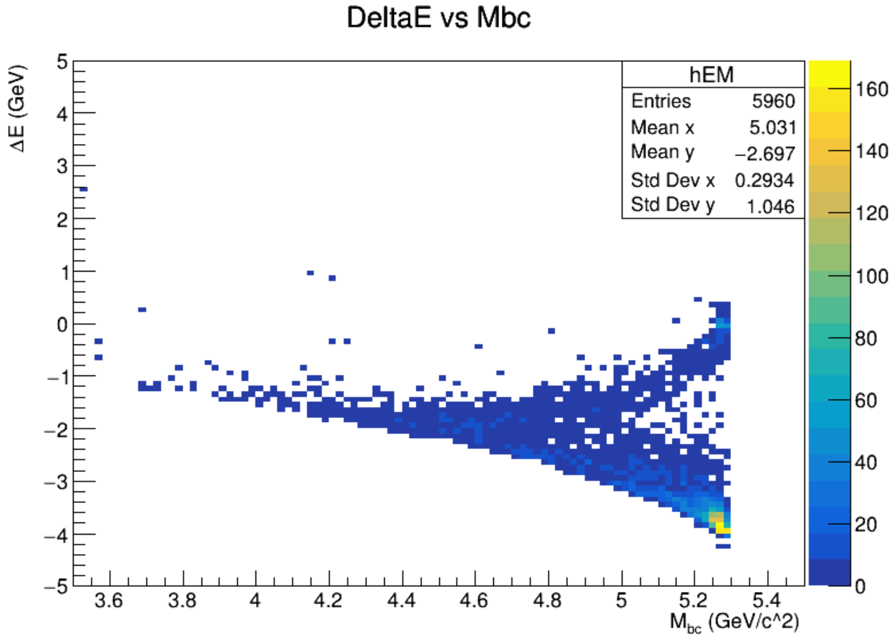
FEW RESULTS AND PLOTS

✓ **signal MC**

- $\boldsymbol{M_{bc}}$ **plot:** shows the Mbc distribution after applying cut $|\Delta E| < 0.2\ GeV$
- $\boldsymbol{\Delta E}$ **plot:** shows the ΔE distribution after applying cut $M_{bc} > 5.2\ GeV$
- $\boldsymbol{\Delta E}$ **vs** $\boldsymbol{M_{bc}}$ **plot:** 2D histogram shows the correlation between ΔE and $\boldsymbol{M_{bc}}$. We see a clear concentration of events in the signal region around the expected $\boldsymbol{M_{bc}}$ and ΔE values.







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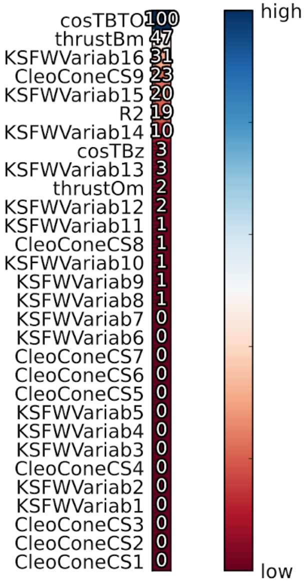
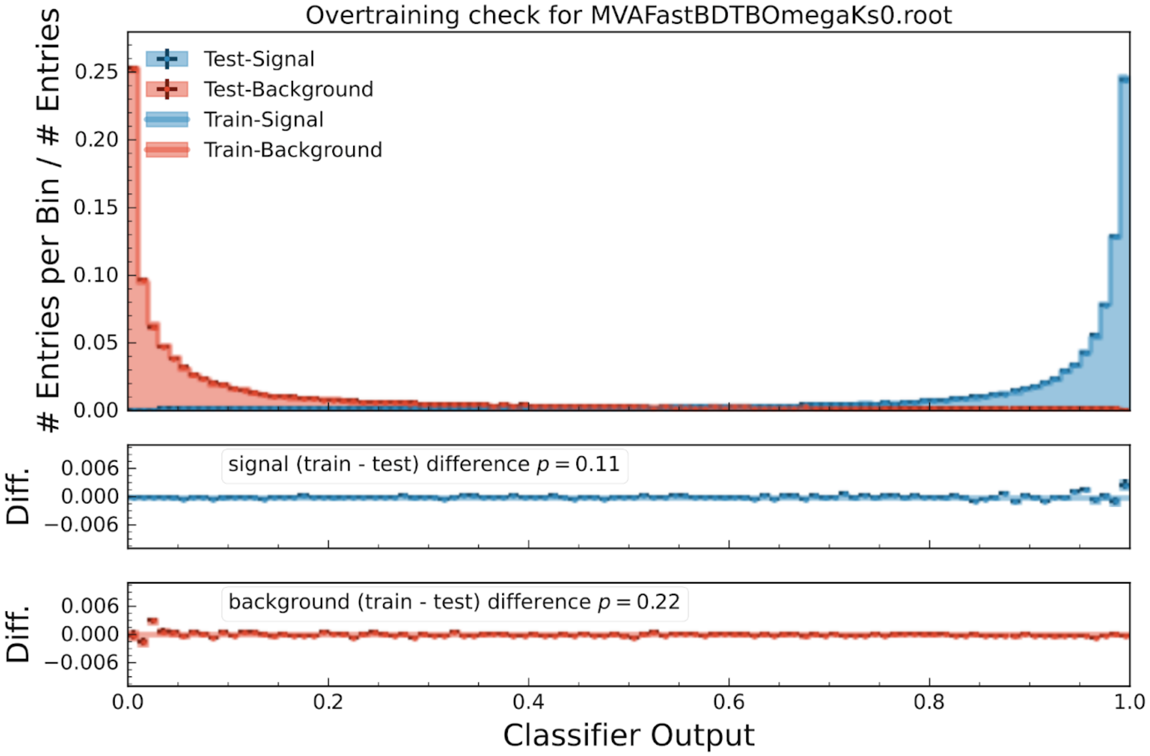
Next steps to improve it:

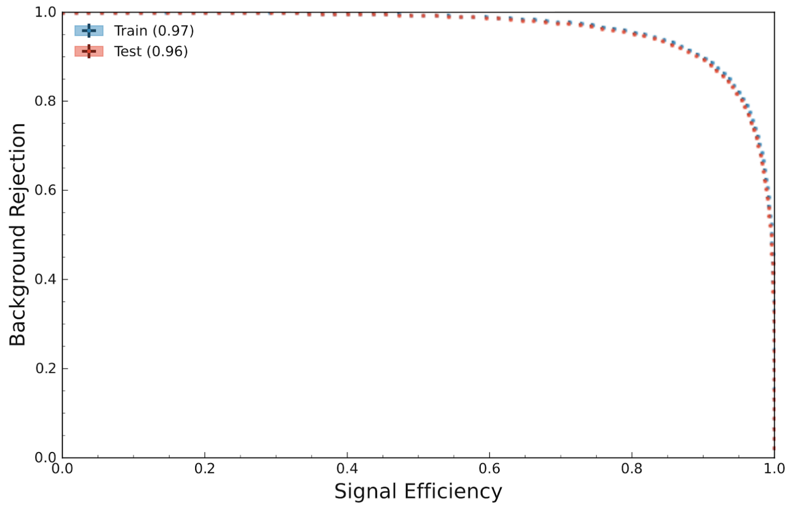
- ❑ optimization of event selection criteria
- ❑ Best Candidate Selection

CONTINUUM BACKGROUND SUPPRESSION BELLE II

- Suppress background from continuum $e^+e^- \rightarrow q\bar{q}$ production, where $q = u, d, s, c$
- Utilize a fast boosted decision tree (FBDT)
- **Key Variables Used in FBDT:**
  - Modified Fox-Wolfram moments / CLEO "cones" / Magnitude of the ROE (Rest of Event) thrust / Cosine of the angle between the thrust axis of B^0_{sig} and the thrust axis of the ROE / Cosine of the angle between the thrust axis of Bsig0 and the beam axis / Polar angle of the Bsig0 momentum in the e+e− center-of-mass system







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SUMMARY AND OUTLOOK

- Charmless B decays, particularly $B^0 \to \ \omega\, K_S^0$, are vital probes for CP violation and potential new physics beyond the Standard Model, due to contribution from penguin.
- Belle's previous measurement provided the first evidence of CP violation in $B^0 \to \ \omega\, K_S^0$ at 3.1 standard deviations, paving the way for Belle II's high-precision measurements.
- My current work involves setting up the full analysis chain, beginning with signal Monte Carlo reconstruction and initial background studies.
- **Goals for Belle II:**
  - Utilize Belle II's enhanced detector performance to achieve greater precision in the measurements of $\mathcal{B}\ (B^0 \to \ \omega\, K_S^0)$, $\mathcal{A}$, and $\mathcal{S}$.
- **Next Steps for My Analysis:**
  - Complete optimization of event selection criteria using full MC samples.
  - Working on Best Candidate Selection
  - Develop and implement advanced background suppression techniques.
  - Working Flavor Tagging and move toward data fit
  - Progress towards extracting results from Belle II collision data.

THANK YOU

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