Measurement of the CP violating asymmetry in $B^0 \rightarrow \phi K_s^0$
Recap: CKM matrix and CP violation

- Within Standard Model (SM)
  - CKM matrix:
    - Coupling strength among quarks
      \[
      V_{\text{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix}
      V_{ud} & V_{us} & V_{ub} \\
      V_{cd} & V_{cs} & V_{cb} \\
      V_{td} & V_{ts} & V_{tb}
      \end{pmatrix}
      \]
    - One irreducible CP-violating phase factor
  - Unitary triangle:
    - Graphical representation of parameter relations
- CP-violation: fundamental asymmetry between matter vs antimatter
  - Phase factor from SM: magnitudes too small compared to observed
  - Search for contributions from New Physics (NP) beyond SM

Review first day of workshop for more details

Credit: prof Soeren Prell’s talk yesterday
CP violation and measurement of $\phi_1$

- CP violation manifests in:
  - **Mixing:** $B^0 \leftrightarrow \bar{B}^0$ oscillation
    - Asymmetry in the transition
  - **Decay:** $B^0 \rightarrow \phi K_S^0$ vs $\bar{B}^0 \rightarrow \phi K_S^0$
    - Asymmetry in the decays
  - **Interference** between mixing and decay
    - Time-dependent CP asymmetry contains $\sin 2\phi_1$

Measure $\phi_1$ through $A_{CP} = \frac{\Gamma_B(t) - \Gamma_{\bar{B}}(t)}{\Gamma_B(t) + \Gamma_{\bar{B}}(t)}$

Credit: prof Soeren Prell's talk yesterday
Measure $\phi_1$ through $A_{CP} = \frac{\Gamma_B(t) - \Gamma_{\bar{B}}(t)}{\Gamma_B(t) + \Gamma_{\bar{B}}(t)}$

Tree level: golden mode $B^0 \rightarrow J/\psi K^0$

Most precise measurement of $\phi_1$

Free from New Physics

Penguin pollution can be constrained by other channels

Penguin loop: this channel $B^0 \rightarrow \phi K^0_S$

Suppressed in Standard Model

Can be modified by New Physics models
Roadmap: CPV measurement of $B^0 \rightarrow \phi K^0_S$

➤ Principle:

➤ $e^+e^- \rightarrow \Upsilon(4S)$: moves in lab frame

➤ $\Upsilon(4S) \rightarrow B^0\bar{B}^0$: one side decays first

➤ Example shows tag side decays first

➤ First stage:

➤ Reconstruct CP side decay

➤ Second stage:

➤ Obtain vertex positions on CP and tag sides

➤ Third stage:

➤ Obtain $\Delta t$ distribution with flavor tagging

$\beta\gamma = 0.284$

$\Delta z = \beta \gamma c \Delta t$

$\Delta t = t_{CP} - t_{tag}$

$<\Delta z> \sim 130 \mu m$ at Belle II
Reconstruct CP side \((B^0 \rightarrow \phi K^0_S)\)

- Daughter decays: \(\phi \rightarrow K^+K^-\) and \(K^0_S \rightarrow \pi^+\pi^-\)
- Forming \(K^0_S\) candidates:
  - Directly detected tracks from \(\pi^+\) and \(\pi^-\)
  - Converge 2 tracks back to a decay vertex
- Energy-momentum conservation
  - \((E_{K^0_S}, \vec{p}_{K^0_S}) = (E_{\pi_1}, \vec{p}_{\pi_1}) + (E_{\pi_2}, \vec{p}_{\pi_2})\)
  - \(m_{reco} = \sqrt{E^2 - (\vec{p})^2}\)
- Expected: invariant mass \(m_{K^0_S}\)
- Double-Gaussian functions: finite resolution of detectors
- Combinatorial backgrounds: results of wrong track combinations

\[\begin{align*}
\phi & \rightarrow K^+K^- \\
K^0_S & \rightarrow \pi^+\pi^- \\
\end{align*}\]
Selection cuts on daughters

- Objective: keep signal & reject background
  - Cuts: put requirements on candidates
- Figure of merit $S / \sqrt{S + B}$
  - Optimize on MC files
- Final selections:
  - $K_S^0 \rightarrow \pi^+ \pi^-$ cuts:
    - chiProb of vertex fitting $> 0$, kinematic updates on daughters
    - “goodBelleKshort”
  - $\phi \rightarrow K^+ K^-$ cuts:
    - chiProb of vertex fitting $> 0$, kinematic updates on daughters
    - Tracks: ‘kaonID$>0.05$ and nCDCHits$>0$ and inCDCAcceptance’
    - (More details on cuts in backup)
Reconstruct $B^0 \to \phi K^0_S$:

Kinematic constrains in B-factories:

- $e^+ e^-$ beam 4-momentum very well-measured

Variables to reconstruct:

- Beam-energy constrained mass

$$M_{bc} = \sqrt{E^*_{beam}^2 - p_B^*}$$

- Energy difference

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

Similar to $m_{reco} = \sqrt{E^2 - (\vec{p})^2}$; also $p_B^*$ could be larger than $E^*_{beam}$ to weed out wrong candidates.
MC sample: 1/ab of BBbar and qqbar

Preselection:
- Vertex fit, chiProb>0, no daughter kinematics update

In addition to cuts on \( \phi \) and \( K_S^0 \)
- \( 3\sigma \) (tail) mass window on \( \phi \) and \( K_S^0 \)
- \( 5.2 < M_{bc} < 5.3 \), \( |\Delta E| < 0.2 \)
  - Single candidate: multiplicity<1.004
  - Best candidate based on chiProb

Signal and background components
- Signal: visible peak
- Background: dominated by qqbar (“continuum”)
B⁰ selection cuts

- Bkg dominated by continuum
  - Part 1: Tighten |ΔE| < 0.02
  - Part 2: continuum suppression
“Fancy” $B^0$ selection cuts

- Continuum suppression with BDT
- Training samples
  - Signal MC
- Continuum with $|\Delta E| < 0.2$
- To increase statistics

Validation of var distr

Comprehensive introduction: https://indico.belle2.org/event/5/sessions/10/attachments/85/122/Continuum_suppression_lecture_V2.pdf
“Fancy” $B^0$ selection cuts

- Continuum suppression with BDT
- Training samples
  - Signal MC
- Continuum with $|\Delta E| < 0.2$
  - To increase statistics

Comprehensive introduction: https://indico.belle2.org/event/5/sessions/10/attachments/85/122/Continuum_suppression_lecture_V2.pdf
» Eventually will move to multi-variable fit

» This fit: $M_{bc}$ only

» Fix signal resolution to MC

» Fix Argus shape to MC

RooRealVar::nsig = 509.478 +/- 28.9847  L(0 - 300000) 35bins

RooRealVar::nsig = 34.9189 +/- 7.6694  L(0 - 300000) 20bins
Future steps

➤ Address peaking background
➤ Fit to multiple variables
  ➤ $M_{bc}$, $\Delta E$, BDT response, $\Delta t$...
➤ Measurement of $\phi_1$
Thank you for your attention!

FUN FACT: Ex-particle-physicists make the worst biologists.
Backup slides to follow...
Outline of this talk

➤ Principle of measurement
  ➤ Review of CKM matrix and CP violation
  ➤ Measurement of $\phi_1$ in Unitary Triangle

➤ Reconstructions and selections
  ➤ Daughter particles $\phi$ and $K^0_S$
    ➤ $B^0 \rightarrow \phi K^0_S$ candidates

➤ BDT training and variable validation
  ➤ Widen $\Delta E$ for larger training sample
  ➤ Sideband validation between MC and data

➤ Future plans
Asymmetric energy:
- Moves in the lab frame
- One side decays first
- (Example shows tag side first)

\[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0 \]
To reconstruct $B^0 \rightarrow \phi K_S^0$:

- In B-factories: $e^+ e^-$ beam 4-momentum very well-measured

Variables to reconstruct:

- Beam-energy constrained mass

$$M_{bc} = \sqrt{E_{beam}^* - p_B^*}$$

- Energy difference

$$\Delta E = E_B^* - E_{beam}^*$$

// Mbc and deltaE

double particleMbc(const Particle* part)
{
  FCmsLabTransform T;
  TLorentzVector vec = T.rotateLabToCms() * part->get4Vector();
  double E = T.getCMSEnergy() / 2;
  double m2 = E * E - vec.Vect().Mag2();
  double mbc = m2 >= 0 ? sqrt(m2) : std::numeric_limits<double>::quiet_NaN();
  return mbc;
}

double particleDeltaE(const Particle* part)
{
  FCmsLabTransform T;
  TLorentzVector vec = T.rotateLabToCms() * part->get4Vector();
  return vec.E() - T.getCMSEnergy() / 2;
}
Phi and Kshort cuts on SigMC

- $\phi$: where $\mu \pm 3\sigma$ window = (1.004, 1.034) GeV

<table>
<thead>
<tr>
<th>Require $p \geq 1.8$</th>
<th>Rel eff (acc)</th>
<th>Abs eff (acc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>numMatched</td>
<td>$\frac{N\text{this and all cuts above}}{N\text{all cuts above}}$</td>
<td>$\frac{N\text{this and all cuts above}}{N\text{all generated}}$</td>
</tr>
<tr>
<td>pre-vtx</td>
<td>85.9%</td>
<td>85.9%</td>
</tr>
<tr>
<td>Other ana cuts</td>
<td>74.8%</td>
<td>64.2%</td>
</tr>
<tr>
<td>3sigma window</td>
<td>90.5%</td>
<td>58.1%</td>
</tr>
</tbody>
</table>

- $K^0_S$: where $\mu \pm 3\sigma$ window = (0.483, 0.513) GeV

<table>
<thead>
<tr>
<th>Require $p \geq 1.8$</th>
<th>Rel eff (acc)</th>
<th>Abs eff (acc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>numMatched</td>
<td>$\frac{N\text{this and all cuts above}}{N\text{all cuts above}}$</td>
<td>$\frac{N\text{this and all cuts above}}{N\text{all generated}}$</td>
</tr>
<tr>
<td>pre-vtx</td>
<td>75.6%</td>
<td>75.6%</td>
</tr>
<tr>
<td>Other ana cuts</td>
<td>89.6%</td>
<td>67.8%</td>
</tr>
<tr>
<td>3sigma window</td>
<td>98.3%</td>
<td>66.6%</td>
</tr>
</tbody>
</table>

Signal MC events with B0 candidates

<table>
<thead>
<tr>
<th>numEvts with candidates</th>
<th>Rel eff (acc)</th>
<th>Abs eff (acc)</th>
<th>Abs eff (ind)</th>
</tr>
</thead>
<tbody>
<tr>
<td>numMatched</td>
<td>$\frac{N\text{this and all cuts above}}{N\text{all cuts above}}$</td>
<td>$\frac{N\text{this and all cuts above}}{N\text{all generated}}$</td>
<td>$\frac{N\text{this cut alone}}{N\text{all generated}}$</td>
</tr>
<tr>
<td>phi_ana_cuts</td>
<td>67.4%</td>
<td>67.4%</td>
<td>67.4%</td>
</tr>
<tr>
<td>phi_3sigma</td>
<td>88.0%</td>
<td>59.3%</td>
<td>90.4%</td>
</tr>
<tr>
<td>Ks_ana_cuts</td>
<td>78.7%</td>
<td>46.7%</td>
<td>74.0%</td>
</tr>
<tr>
<td>Ks_3sigma</td>
<td>97.1%</td>
<td>45.3%</td>
<td>87.7%</td>
</tr>
</tbody>
</table>
Decay vertex vector (particleDX, particleDY, particleDZ) defined in:
https://stash.desy.de/projects/B2/repos/software/browse/analysis/variables/include/VertexVariables.h#117

Momentum vector (particlePX, particlePY, particlePZ) defined in:
https://stash.desy.de/projects/B2/repos/software/browse/analysis/variables/src/Variables.cc#76
## Performance in ±3σ region

### Significance and Purity

- **Significance** = \( S / \sqrt{S+B} \)
- **Purity** = \( S / (S+B) \)

<table>
<thead>
<tr>
<th>Cut Condition</th>
<th>KS:2trk</th>
<th>KS:merged</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No cut</strong></td>
<td>123</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td><strong>SigLxy &gt; 3</strong></td>
<td>162</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>0.78</td>
</tr>
<tr>
<td><strong>SigLxy&gt;3 confL&gt;0.1%</strong></td>
<td>167</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td><strong>goodBelleKs</strong></td>
<td>168</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>0.97</td>
<td>0.97</td>
</tr>
</tbody>
</table>

- **confL > 0.1%** (Default)

### Data Points

- **SigLxy > 3**
  - 162: 0.80
  - 167: 0.78
- **SigLxy>3 confL>0.1%**
  - 167: 0.90
  - 173: 0.89
- **goodBelleKs**
  - 168: 0.97
  - 175: 0.97

### Additional Notes

- Combo 200k MC13a unskimmed mDST
- Estimated integrated luminosity 42 pb\(^{-1}\)
- "mixed", "charged", "uubar", "ddbar", "ssbar", "ccbar"

### Diagrams

- Graphs showing distributions for different cuts and conditions.
## Performance in ±3σ region

<table>
<thead>
<tr>
<th>Total signal (fitted)</th>
<th>Total Background (fitted)</th>
<th>KS:2trk</th>
<th>KS:merged</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No cut</strong></td>
<td></td>
<td>34,241 (92.4%)</td>
<td>37,049 (ref)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>43,214 (92.4%)</td>
<td>46,762 (ref)</td>
</tr>
<tr>
<td><strong>SigLxy &gt; 3</strong></td>
<td></td>
<td>32,738 (88.4%)</td>
<td>35,774 (96.5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8,195 (17.5%)</td>
<td>10,082 (21.6%)</td>
</tr>
<tr>
<td><strong>SigLxy &gt; 3</strong></td>
<td>confL &gt; 0.1%</td>
<td>30,755 (83.0%)</td>
<td>33,712 (91.0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,197 (6.8%)</td>
<td>4,341 (9.3%)</td>
</tr>
<tr>
<td></td>
<td>(Default)</td>
<td>28,849 (77.9%)</td>
<td>31,763 (85.7%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>809 (1.7%)</td>
<td>1,044 (2.2%)</td>
</tr>
<tr>
<td><strong>goodBelleKs</strong></td>
<td></td>
<td>27,607 (74.5%)</td>
<td>30,426 (82.1%)</td>
</tr>
<tr>
<td></td>
<td>confL &gt; 0.1%</td>
<td>633 (1.4%)</td>
<td>836 (1.8%)</td>
</tr>
</tbody>
</table>

- Combo 200k MC13a unskimmed mDST
  - Estimated integrated luminosity 42 pb⁻¹
  - “mixed”, “charged”, “uubar”, “ddbar”, “ssbar”, “ccbar”
<table>
<thead>
<tr>
<th>Total signal (fitted)</th>
<th>KS:2trk</th>
<th>KS:merged</th>
<th>Significance = S/sqrt(S+B)</th>
<th>KS:2trk</th>
<th>KS:merged</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>34,241 (92.4%)</td>
<td>37,049 (ref)</td>
<td>123</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>43,214 (92.4%)</td>
<td>46,762 (ref)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SigLxy &gt; 3</td>
<td>32,738 (88.4%)</td>
<td>35,774 (96.5%)</td>
<td>162</td>
<td>0.80</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>8,195 (17.5%)</td>
<td>10,082 (21.6%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SigLxy &gt; 3</td>
<td>30,755 (83.0%)</td>
<td>33,712 (91.0%)</td>
<td>167</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>confL &gt; 0.1%</td>
<td>3,197 (6.8%)</td>
<td>4,341 (9.3%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>goodBelleKs</td>
<td>28,849 (77.9%)</td>
<td>31,763 (85.7%)</td>
<td>168</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>809 (1.7%)</td>
<td>1,044 (2.2%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>goodBelleKs</td>
<td>27,607 (74.5%)</td>
<td>30,426 (82.1%)</td>
<td>164</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>confL &gt; 0.1%</td>
<td>633 (1.4%)</td>
<td>836 (1.8%)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example shows SigLxy > 3 and confL > 0.1%
Golden mode for $\phi_1$

- $\phi_1$ most precisely by $B^0 \rightarrow J/\psi K^0$ via $b \rightarrow c\bar{c}s$
- Interference between mixing and decay: $A_{CP} = \frac{\Gamma_B(t) - \Gamma_{\bar{B}}(t)}{\Gamma_B(t) + \Gamma_{\bar{B}}(t)}$
  - Tree level:
    - $A = 0; S = -\sin 2\phi_1$ in absence of loop
    - Free from New Physics
  - Penguin loop:
    - Suppressed in Standard Model
    - Can be modified by New Physics models
    - Contains “Penguin pollution”
      $$S_{J/\psi K_S^0} \equiv \sin \phi_d + \Delta S_{J/\psi K_S^0} \equiv \sin(\phi_d + \delta \phi_{J/\psi K_S^0})$$
The channel \( B \rightarrow J/\psi \pi^0 \)

- \( \phi_1 \) most precisely by \( B^0 \rightarrow J/\psi K^0 \) via \( b \rightarrow c\bar{c}s \)
- \( B \rightarrow J/\psi \pi^0 \) proceeds via \( b \rightarrow c\bar{c}d \): Cabbibo suppressed
  - Tree level: also color suppressed
    - \( A = 0; \ S = - \sin 2\phi_1 \) in absence of loop
    - Same weak phase as \( b \rightarrow c\bar{c}s \)
  - Penguin loop:
    - (Highly) suppressed in Standard Model
    - Can be modified by New Physics models
    - Shift values of \( A \) and \( S \)
    - Constrain “penguin pollution” for \( B^0 \rightarrow J/\psi K^0 \)
Variables used in BDTG

foxWolframR1 foxWolframR2 foxWolframR3 foxWolframR4
harmonicMomentThrust1 harmonicMomentThrust2 harmonicMomentThrust3 harmonicMomentThrust4
cleoConeThrust0 cleoConeThrust1 cleoConeThrust2 cleoConeThrust3 cleoConeThrust4 cleoConeThrust5 cleoConeThrust6 cleoConeThrust7 cleoConeThrust8
thrustAxisCosTheta
KSFWVariables(hso00) KSFWVariables(hso02) KSFWVariables(hso04) KSFWVariables(hso10) KSFWVariables(hso12) KSFWVariables(hso14) KSFWVariables(hso20) KSFWVariables(hso22) KSFWVariables(hso24) KSFWVariables(hoo1) KSFWVariables(hoo2) KSFWVariables(hoo3) KSFWVariables(hoo4) KSFWVariables(et) KSFWVariables(mm2)
M(\phi) cosineHelicityAngle(\phi) [To suppress non-resonant K+K-K0]

No significant improvement by including some other variables