First Look at CKM Parameters from Early Belle II Data

Pablo Goldenzweig

ICNFP 2019
Crete, Greece
21 - 29 August 2019
The Need for Belle II

Strong evidence that physics beyond the SM exists:

- Temperature fluctuations of cosmic background radiation and rotation curves from spiral galaxies indicate existence of Dark Matter.

- $CP$ violation predicted by the CKM matrix is several orders of magnitudes too small to account for the observed matter anti-matter asymmetry in the universe.

Intensity Frontier Experiments:

Indirect search of New Physics through quantum effects.

Belle II produces large quantities of $b$ quarks for such searches.

For $e^+e^- \rightarrow \tau^+\tau^-$, e.g., F. Tenchini @Flavor2019
Physics of an $e^+e^-$ B Factory

- Collide $e^+$ and $e^-$ at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.
Physics of an $e^+e^- B$ Factory

- Collide $e^+$ and $e^-$ at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.
- $\Upsilon(4S)$ decays to $B^+B^-$ and $B^0\bar{B}^0$ 96% of the time.

\[
\begin{align*}
  &\xrightarrow{\text{anti-B meson}} \ Upsilon(4S) \xleftarrow{\text{B meson}} \\
  &\xrightarrow{\text{b\bar{b}}} \xleftarrow{\text{b\bar{b}}} \\
  &\xrightarrow{\text{light quark}} \xleftarrow{\text{light quark}} \\
  &\xrightarrow{\text{heavy b-quark}} \xleftarrow{\text{heavy anti-b quark}} \\
  &\xleftarrow{\text{Fragmentation into two B mesons}} \\
\end{align*}
\]
Physics of an $e^+e^- B$ Factory

- Collide $e^+$ and $e^-$ at $\sqrt{s} = 10.58$ GeV to create $\Upsilon(4S)$ resonance.
- $\Upsilon(4S)$ decays to $B^+B^-$ and $B^0\bar{B}^0$ 96% of the time.
- Reconstruct $B$ mesons from final state particles in detector.
Broad program to search for New Physics in $B$, $D$ and $\tau$ decays

- **New $CP$ violating phases?**
  \[ \Rightarrow \text{CPV in } B \text{ and } D \text{ decays.} \]

- **Signatures of charged Higgs bosons or leptoquarks?**
  \[ \Rightarrow B^+ \to \ell^+ \nu \text{ and } D^{(*)\tau\nu} \text{ decays.} \]

- **Right-handed currents from new physics?**
  \[ \Rightarrow \text{Photon polarization in radiative decays.} \]

- **New physics in flavor changing neutral current transitions?**
  \[ \Rightarrow \text{Electroweak penguin decays } b \to s\ell^+\ell^-, s\nu\bar{\nu}. \]

- **Exotic tetraquark, pentaquark and hybrid QCD states?**

- **Hidden dark sector accessible from $B$ decays?**
The weak interaction couples different generations of quarks

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix}
= 
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

Weak Eigenstates
CKM Matrix
Mass Eigenstates

The value of the CKM matrix elements are not predicted by the SM and must be determined by experiment.
The weak interaction couples different generations of quarks

\[
\begin{pmatrix}
  d' \\
s' \\
b'
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
s \\
b
\end{pmatrix}
\]

Weak Eigenstates \quad \text{CKM Matrix} \quad \text{Mass Eigenstates}

Unitarity implies: \( V_{CKM} V_{CKM}^\dagger = I \)

\( V_{id} V_{ib}^* = 0 \) represents the orthogonality condition between the first and third column of \( V_{CKM} \).

\textit{All lengths involve } b \text{ decays.}

The angles can be written in terms of CKM matrix elements as:

\[
\begin{align*}
\phi_1 &= \arg \left( -\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right), \\
\phi_2 &= \arg \left( -\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right), \\
\phi_3 &= \arg \left( -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)
\end{align*}
\]
• Global CKM fit: 68% CL.
• $CP$ conserving: $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $B^+ \rightarrow \tau^+ \nu_\tau$.
• $CP$ violating: $\sin 2\phi_1$, $\phi_2$, $\phi_3$, $\epsilon_K$.
• Tree: $\phi_3(DK)$, $\phi_2$ from Isospin analysis.
• Loop.
Global CKM fit: 68% CL.

- $CP$ conserving: $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $B^+ \to \tau^+ \nu_\tau$.
- $CP$ violating: $\sin 2\phi_1$, $\phi_2$, $\phi_3$, $\epsilon_k$.
- Tree: $\phi_3(DK)$, $\phi_2$ from Isospin analysis.
- Loop.
- Global CKM fit: 68% CL.
- CP conserving: $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $B^+ \rightarrow \tau^+ \nu_\tau$.
- CP violating: $\sin 2\phi_1$, $\phi_2$, $\phi_3$, $\epsilon_k$.
- Tree: $\phi_3(DK)$, $\phi_2$ from Isospin analysis.
- Loop.
Global CKM fit: 68% CL.
- $CP$ conserving: $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $B^+ \to \tau^+\nu_\tau$.
- $CP$ violating: $\sin 2\phi_1$, $\phi_2$, $\phi_3$, $\epsilon_k$.
- Tree: $\phi_3(DK)$, $\phi_2$ from Isospin analysis.
- Loop.
Global CKM fit: 68% CL.

- $CP$ conserving: $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $B^+ \rightarrow \tau^+ \nu_\tau$.
- $CP$ violating: $\sin 2\phi_1$, $\phi_2$, $\phi_3$, $\epsilon_K$.
- Tree: $\phi_3(DK)$, $\phi_2$ from Isospin analysis.
- Loop.
CKM Fits

- Global CKM fit: 68% CL.
- $CP$ conserving: $|V_{ub}|/|V_{cb}|$, $\Delta m_d$, $\Delta m_s$, $B^+ \rightarrow \tau^+ \nu_\tau$.
- $CP$ violating: $\sin 2\phi_1$, $\phi_2$, $\phi_3$, $\epsilon_k$.
- Tree: $\phi_3(DK)$, $\phi_2$ from Isospin analysis.
- Loop. ⇒ Still room for corrections from NP at $O(0.1)$.
Lesson from Flavor

Unwise to assume 0.1% is “good enough” in flavor.

1962: “A special search at Dubna was carried out by E. Okonov and his group. They have not found a single $K_L \rightarrow \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al, JETP 1962). At that stage the search was terminated by administration of the Lab. The group was unlucky.” L.B. Okun, “Spacetime and vacuum as seen from Moscow” (2002)

1964: Cronin & Fitch observed 45 $K_L \rightarrow 2\pi$ decays (out of 22,700 Kaon decays) a long distance from the production point: $\mathcal{B}(K_L \rightarrow 2\pi) = 2 \times 10^{-3}$. PRL 13 138 (1964)
Intensity Frontier: *SuperKEKB Accelerator*

Upgrade to achieve **40x peak $\mathcal{L}$ under 20x bkgd**

$$\mathcal{L} = \frac{\gamma_{e\pm}}{2e} \left( 1 + \frac{\sigma_{y}^{*}}{\sigma_{x}^{*}} \right) \left( \frac{I_{e\pm} \xi_{y}^{e\pm}}{\beta_{y}^{*}} \right) \left( \frac{R_{L}}{R_{\xi_{y}}} \right)$$

Doubling the beam currents.

Reduction in the beam size by 1/20 at the IP.
Upgrade to achieve 40x peak $\mathcal{L}$ under 20x bkgd

$$\mathcal{L} = \frac{\gamma e \pm \sigma_y^*}{2e r_e} \left( 1 + \frac{\sigma_x^*}{\sigma_y^*} \right) \left( \frac{I_e \pm \xi_y^*}{\beta_y^*} \right) \left( \frac{R_L}{R_{\xi_y}} \right)$$

Doubling the beam currents.

Reduction in the beam size by 1/20 at the IP.
Intensity Frontier: *SuperKEKB Accelerator*

Upgrade to achieve **40x peak $\mathcal{L}$** under 20x bkgd

\[
\mathcal{L} = \frac{\gamma e \pm \sigma_r}{2e \gamma} \left(1 + \frac{\sigma_y}{\sigma_x}\right) \left(\frac{I_e \pm \xi_y e}{\beta_y}\right) \left(\frac{R_L}{R_{\xi_y}}\right)
\]

Doubling the beam currents.

Reduction in the beam size by 1/20 at the IP.
$\mathcal{L}_{\text{Inst.}} = 1.2 \times 10^{34}$ (peak)

Results shown today are from a sub-set of this data
First $B\bar{B}$ Event in Phase 3
CP Violation Measurements

\[ P(\Delta t, q) = e^{-|\Delta t|/\tau_{B^0}} \frac{1}{\tau_{B^0}} \left[ 1 + q (A_{CP} \cos \Delta m_d \Delta t + S_{CP} \sin \Delta m_d \Delta t) \right] \]
**CP Violation Measurements**

- **CPV in mixing**
  - $|B\rangle \neq |\bar{B}\rangle$

- **Direct CPV in Decay**
  - $|B\rangle \neq |B\rangle$
  - $|\bar{B}\rangle \neq |\bar{f}\rangle$

- **CPV in the interference between mixing and decay**
  - $|B\rangle \rightarrow |f_{CP}\rangle$

\[
\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q (A_{CP} \cos \Delta m_d \Delta t + S_{CP} \sin \Delta m_d \Delta t)]
\]

**Key ingredients:**

- Vertex position measurement.
- $B$ meson flavor tagging.

\[
\Delta z = \beta \gamma \Delta t
\]
**CP Violation Measurements**

- **CPV in mixing**
- **Direct CPV in Decay**
- **CPV in the interference between mixing and decay**

\[
P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 + q \left( A_{CP} \cos \Delta m_d \Delta t + S_{CP} \sin \Delta m_d \Delta t \right) \right]
\]

**Key ingredients:**
- Vertex position measurement.
- \( B \) meson flavor tagging.
$CP$ Violation Measurements

$CPV$ in mixing

$B \neq \bar{B}$

Direct $CPV$ in Decay

$|B\rangle \xrightarrow{A_{CP}} |f\rangle$

$|\bar{B}\rangle \xrightarrow{S_{CP}} |f_{CP}\rangle$

$CPV$ in the interference between mixing and decay

$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q(A_{CP} \cos \Delta m_d \Delta t + S_{CP} \sin \Delta m_d \Delta t)]$

Key ingredients:

- Vertex position measurement.
- $B$ meson flavor tagging.
PXD mounted on beam pipe

- 1\textsuperscript{st} pixel layer at $r = 14\text{mm}$ to IP.
  [Belle at $r = 20\text{mm}$]

  *Improves vertex resolution along z-axis.*

- Larger SVD w/outer layer at $r = 135\text{mm}$.
  [Belle at $r = 88\text{mm}$]

  *Higher fraction of $K_S'$ with vertex hits improves vertex resolution.*
**$D^0$ Lifetime Measurement:** $D^{*+} \rightarrow [D^0 \rightarrow K^- \pi^+] \pi^+$

Requires the reconstruction of 2 vertices:

1) **$D^0$ decay vertex** from $K$ and $\pi$ daughters.
2) **$D^0$ production point** from the reconstructed $D^0$ momentum and crossing of $\pi_s$.

⇒ Calculate $D^0$ decay length: $L_{\text{dec}} = (\mathbf{r}_{\text{decay}} - \mathbf{r}_{\text{production}}) \cdot \hat{\mathbf{P}}_D$.

⇒ $t_{\text{flight}} = \frac{m_D L_{\text{dec}}}{c p_D}$.
**D^0 Lifetime Measurement:**  \( D^{*+} \rightarrow [D^0 \rightarrow K^- \pi^+] \pi^+ \)

\[ \tau_{D^0} = (380 \pm 40) \text{ fs} \]

Clear demonstration of the combined performance of the PXD and SVD

\[ \tau_{D^0}^{PDG} = (410.1 \pm 1.5) \text{ fs} \]
Flavor Tagging

- $\bar{B}^0$
- $D^{*+}$
- $D^0$
- $\nu_\ell$
- $\ell^-$
- $\pi^+$
- $\ell^+$
- $K^-$
- $\pi^-$
- $X^-$
- $\Lambda_c^+$
- $\bar{K}^0$
- $\Lambda$

Tracks → KLMClusters → ECLClusters

- Electron
- Int. El.
- Muon
- Int. Muon
- Kin. Lepton
- Int. Kin. Lep.
- Kaon
- Kaon-Pion
- Slow Pion
- FSC
- Maximum P
- Fast Hadron
- Lambda

$q \cdot r$

$q_{\text{cand}} \cdot y_{\text{cat}}$

$e$

$\mu$

$K$

$\pi$

$p$

$\Lambda$

$\rho$

$\omega$

$\phi$

$\Delta$

$\Omega$

$\Sigma$

$\Xi$

$\eta$

$\eta'$
Flavor Tagging

- Total expected tagging efficiency:
  $\Sigma \epsilon_i \times (1 - 2\omega_i)^2 = (37.16 \pm 0.03)\%$.
  [30 – 33% @ Belle, BABAR]

- Dilution factor $r$ due to mistag $\omega$:
  $r = 1 - 2\omega \Rightarrow$ 
  $A_{CP}^{obs} = (1 - 2\omega) \cdot A_{CP}$
Belle II Prospects for $\phi_1$

Most precisely measured UT parameter: $\phi_1^\text{CKM Fitter} = \left(22.51^{+0.55}_{-0.40}\right)^\circ$.

Tree-dominated $b \to c\bar{c}s$ golden mode $B^0 \to J/\psi K_S^0$. $A_{CP} = 0$, $S_{CP} = \sin(2\phi_1)$:

- Theoretically and exp. precise.
- Expected total uncertainty $\delta\phi_1 \lesssim 0.1^\circ$ w/50ab$^{-1}$. 

![Diagram of $B^0 \to J/\psi K_S$ decay]
Belle II Prospects for $\phi_1$

Most precisely measured UT parameter: $\phi_1^{\text{CKM Fitter}} = \left(22.51^{+0.55}_{-0.40}\right)^\circ$.

Tree-dominated $b \to c\bar{c}s$ golden mode $B^0 \to J/\psi K^0_S$, $A_{CP} = 0$, $S_{CP} = \sin(2\phi_1)$:
- Theoretically and exp. precise.
- Expected total uncertainty $\delta\phi_1 \lesssim 0.1^\circ$ w/50ab$^{-1}$.
- First $J/\psi K^0_S$ peak ($N = 26.9 \pm 5.2$) with Belle II. $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$
Belle II Prospects for $\phi_1$

Most precisely measured UT parameter: $\phi_1^{\text{CKM Fitter}} = (22.51^{+0.55}_{-0.40})^\circ$.

Tree-dominated $b \to c\bar{c}s$ golden mode

$B^0 \to J/\psi K^0_S$ $A_{CP} = 0$, $S_{CP} = \sin(2\phi_1)$:

- Theoretically and exp. precise.
- Expected total uncertainty $\delta \phi_1 \lesssim 0.1^\circ$ w/50ab$^{-1}$.
- First $J/\psi K_S^0$ peak ($N = 26.9 \pm 5.2$) with Belle II. $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$

- $CP$ asymmetry projection @50ab$^{-1}$.
Belle II Prospects for $\phi_1$

Most precisely measured UT parameter: $\phi_1^{\text{CKM Fitter}} = \left(22.51^{+0.55}_{-0.40}\right)^\circ$.

Tree-dominated $b \to c\bar{c}s$ golden mode $B^0 \to J/\psi K^0_S$, $A_{CP} = 0$, $S_{CP} = \sin(2\phi_1)$:
- Theoretically and exp. precise.
- Expected total uncertainty $\delta\phi_1 \lesssim 0.1^\circ$ w/50ab$^{-1}$.
- First $J/\psi K^0_S$ peak ($N = 26.9 \pm 5.2$) with Belle II. $M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}$
- $CP$ asymmetry projection @50ab$^{-1}$.

- Gluonic-penguin-dominated $b \to q\bar{q}s$
  
- Sensitive to NP in loop
  
- $\Leftarrow$ NP would be discovered

(e.g. $\eta' K^0_S$ w/o competition from LHCb)
Current precision: $\phi_2^{\text{CKM Fitter}} = (91.6^{+1.7}_{-1.1})^\circ$.

- Sizeable penguin contribution:

$$A_{CP} \neq 0, \quad S_{CP} = \sqrt{1 - A_{CP}^2 \sin(2(\phi_2 + \Delta \phi_2))}$$
Belle II Prospects for $\phi_2$

Current precision: $\phi_2^{\text{CKM Fitter}} = \left(91.6^{+1.7}_{-1.1}\right)^\circ$.

- Sizeable penguin contribution:
  \[ A_{CP} \neq 0, \quad S_{CP} = \sqrt{1 - A_{CP}^2 \sin(2(\phi_2 + \Delta\phi_2))} \]

- Penguin pollution can be estimated using $SU(2)$ Isospin analysis to $B \to \pi\pi, \rho\rho$.

  *PRL 65, 3381 (1990)*
Belle II Prospects for $\phi_2$

Current precision: $\phi_2^{\text{CKM Fitter}} = (91.6^{+1.7}_{-1.1})^\circ$.

- Sizeable penguin contribution:
  
  $A_{CP} \neq 0, \ S_{CP} = \sqrt{1 - A_{CP}^2 \sin(2(\phi_2 + \Delta \phi_2))}$

- Penguin pollution can be estimated using $SU(2)$ Isospin analysis to $B \to \pi\pi, \rho\rho$.
  
  PRL 65, 3381 (1990)

- $S_{\pi^0 \pi^0}$ never measured.

  Challenge: $B^0$ decay vertex reconstructed based on $\gamma$ conversion and Dalitz $\pi^0$ decays with IP-tube constraint.
Belle II Prospects for $\phi_2$

Current precision: $\phi_{2}^{\text{CKM Fitter}} = (91.6^{+1.7}_{-1.1})^\circ$.

- Sizeable penguin contribution:
  
  $A_{CP} \neq 0, S_{CP} = \sqrt{1 - A_{CP}^2} \sin(2(\phi_2 + \Delta \phi_2))$

- Penguin pollution can be estimated using $SU(2)$ Isospin analysis to $B \to \pi\pi, \rho\rho$.

  \textbf{PRL 65, 3381 (1990)}

- $S_{\pi^0 \pi^0}$ never measured.

  \textit{Challenge: $B^0$ decay vertex reconstructed based on $\gamma$ conversion and Dalitz $\pi^0$ decays with IP-tube constraint.}

- Expected total uncertainty on $\phi_2$ with the combined inputs from $B \to \pi\pi, \rho\rho$ is $0.6^\circ$. 

Belle II Prospects for $\phi_3$

Current precision: $\phi_3^{\text{CKM Fitter}} = \left(65.81^{+0.99}_{-1.66}\right)$

- The standard candle, along with $|V_{ub}|/|V_{cb}|$: $\phi_3 \approx \text{arg}|V_{ub}^*|$.
- Very precise theoretical prediction of $\delta\phi_3/\phi_3 \sim 10^{-7}$. \textit{JHEP 1401 (2014)}
- Limited by the small $B$ of the processes used in its measurement. \textit{Large experimental gain can be made with Belle II.}
- $b \to c\bar{u}s$ and $b \to u\bar{c}s$ tree amplitudes in $B^\pm$ meson decays to open-charm final states.

$$\frac{A^{\text{suppr.}}(B^- \to D^0 K^-)}{A^{\text{fAVOR.}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$

\textit{Possibility of DCPV in the interference between same final state for $D^0$ and $\bar{D}^0$.}
Belle II Prospects for $\phi_3$

Current precision: $\phi_3^{\text{CKM Fitter}} = (65.81^{+0.99}_{-1.66})$

- The standard candle, along with $|V_{ub}|/|V_{cb}|$: $\phi_3 \approx \text{arg}|V_{ub}^*|$. 
- Very precise theoretical prediction of $\delta \phi_3/\phi_3 \sim 10^{-7}$. \textit{JHEP} 1401 (2014)
- Limited by the small $B$ of the processes used in its measurement. \textit{Large experimental gain can be made with Belle II}.
- $b \to c\bar{u}s$ and $b \to u\bar{c}s$ tree amplitudes in $B^{\pm}$ meson decays to open-charm final states.

$$\frac{A^{\text{suppr.}}(B^- \to D^0 K^-)}{A^{\text{favor.}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$

\textit{Possibility of DCPV in the interference between same final state for $D^0$ and $\bar{D}^0$.}

- Re-discovery of $B^- \to D^0 K^-$. Fit with high-$p$ PID: $N_{DK} = 38 \pm 8 (6\sigma)$.

$\Delta E \equiv E_B - E_{\text{Beam}}$
Belle II Prospects for $\phi_3$

Current precision: $\phi_3^{\text{CKM Fitter}} = (65.81^{+0.99}_{-1.66})$

- The standard candle, along with $|V_{ub}|/|V_{cb}|$: $\phi_3 \approx \text{arg}|V_{ub}^*|$.

- Very precise theoretical prediction of $\delta\phi_3/\phi_3 \sim 10^{-7}$. JHEP 1401 (2014)

- Limited by the small $B$ of the processes used in its measurement. Large experimental gain can be made with Belle II.

- $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ tree amplitudes in $B^\pm$ meson decays to open-charm final states.

- $B^\pm \rightarrow D^0 K^\mp$.

  $A^{\text{suppr.}}(B^- \rightarrow D^0 K^-) / A^{\text{favor.}}(B^- \rightarrow D^0 K^-) = r_B e^{i(\delta_B - \phi_3)}$

  Possibility of DCPV in the interference between same final state for $D^0$ and $\bar{D}^0$.

- Re-discovery of $B^\pm \rightarrow D^0 K^\mp$. Fit with high-$p$ PID: $N_{DK} = 38 \pm 8$ ($6\sigma$).

  $\Delta E \equiv E_B - E_{\text{Beam}}$
Several key $B$ decay channels for measuring CKM elements contain neutrinos in the final state: $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$, $B^+ \to \ell^+ \nu_\ell$.

$|V_{cb}|$ and $|V_{ub}|$ via Missing Energy Decays

$B$
\[\begin{array}{ccc}
\bar{b} & |V_{cb}| & b \\
\bar{u} & \ell^- & c \\
\end{array}\] $D^{(*)}$

$B^+$
\[\begin{array}{ccc}
\bar{b} & |V_{ub}| & b \\
\bar{u} & W^+ & \ell^+ \\
\end{array}\] $\nu_\ell$

Cannot be directly reconstructed
Several key $B$ decay channels for measuring CKM elements contain neutrinos in the final state: $\bar{B} \rightarrow D^{(*)}\ell\bar{\nu}_\ell$, $B^+ \rightarrow \ell^+\nu_\ell$

$|V_{ub}|$ from inclusive and exclusive semileptonic $B$ decays.

$|V_{ub}|$ from $B^+ \rightarrow \tau^+\nu_\tau$.

$|V_{ub}|/|V_{cb}|$ from $\Lambda_b$ decays.
Several key $B$ decay channels for measuring CKM elements contain neutrinos in the final state: $\bar{B} \to D^{(*)}\ell \bar{\nu}_\ell$, $B^+ \to \ell^+ \nu_\ell$.

Take advantage of experimental setup of $B$-factories:

- $B\bar{B}$ pairs are produced without any additional particles;
- Detectors enclose the interaction region almost hermetically;
- Collision energy (initial state) is precisely known:
  $$p_{e^+} + p_{e^-} = p_B + p_{\bar{B}}.$$
Tagging

- **Inclusive Tag**
  - $\epsilon = \mathcal{O}(100\%)$
  - Consistency of $B_{\text{tag}}$

- **Semileptonic Tag**
  - $\epsilon = \mathcal{O}(1\%)$
  - Knowledge of $B_{\text{tag}}$

- **Hadronic Tag**
  - $\epsilon = \mathcal{O}(0.1\%)$
  - Exact knowledge of $B_{\text{tag}}$
**B Tagging**

**Inclusive Tag**
\[ \epsilon = O(100)\% \]
Consistency of \( B_{\text{tag}} \)

**Semileptonic Tag**
\[ \epsilon = O(1)\% \]
Knowledge of \( B_{\text{tag}} \)

**Hadronic Tag**
\[ \epsilon = O(0.1)\% \]
Exact knowledge of \( B_{\text{tag}} \)

---

**Hierarchical tag-side \( B \)-meson recombination algorithm for Belle II.**
- Utilizes \( O(200) \) decay channels with BDTs trained for each decay.
- Reconstructs \( O(10k) \) unique decay chains in 6 stages.
- 3x higher MC reconstruction efficiency than predecessor algorithm.
2019 Belle II Data $\mathcal{L} = 0.41 \text{ fb}^{-1}$

Tag-side $B^+$ meson classifier output.

Tag-side $B^+$ meson categories.

Exclusive Tagging: The Full Event Interpretation (FEI)

Hierarchical tag-side $B$-meson recombination algorithm for Belle II.

- Utilizes $\mathcal{O}(200)$ decay channels with BDTs trained for each decay.
- Reconstructs $\mathcal{O}(10k)$ unique decay chains in 6 stages.
- 3x higher MC reconstruction efficiency than predecessor algorithm.
Observe $\sim 1729$ fully reconstructed $B$ mesons.

Hierarchical tag-side $B$-meson recombination algorithm for Belle II.

- Utilizes $\mathcal{O}(200)$ decay channels with BDTs trained for each decay.
- Reconstructs $\mathcal{O}(10k)$ unique decay chains in 6 stages.
- 3x higher MC reconstruction efficiency than predecessor algorithm.
First look at $B^0 \to D^{*+} \ell^- \bar{\nu}_\ell$ decays \((\ell = e, \mu)\)

Observed 146 events in untagged sample:
- \(N_{\text{sig}} = 63 \pm 10\) events for \(\ell = \mu\).

\[
\cos \theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*}
\]

\(Y = \text{visible final state system} \ (D^*e)\)
First look at $B^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$ decays \quad (\ell = e, \mu)

Observed 146 events in untagged sample:

- $N_{\text{sig}} = 63 \pm 10$ events for $\ell = \mu$.
- $N_{\text{sig}} = 83 \pm 10$ events for $\ell = e$.

\begin{align*}
\cos \theta_{BY} &= \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*} \\
Y &= \text{visible final state system } (D^* e)
\end{align*}
First look at $B^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays ($\ell = e, \mu$)

Observed 146 events in untagged sample:

- $N_{\text{sig}} = 63 \pm 10$ events for $\ell = \mu$.
- $N_{\text{sig}} = 83 \pm 10$ events for $\ell = e$.

Branching fraction of $B^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays is a key ingredient in resolving the 3.5$\sigma$ tension in exclusive vs. inclusive measurements of $|V_{cb}|$.

$$\cos \theta_{BY} = \frac{2E_B^*E_Y^* - M_B^2 - m_Y^2}{2p_B^*p_Y^*}$$

$Y = \text{visible final state system} \ (D^*e)$
Summary

Belle II poised to usher in a new era of precision flavor physics with 50 ab$^{-1}$ of data collected at the SuperKEKB accelerator.

- Measurements of CKM parameters will improve very quickly with initial 5-10 ab$^{-1}$.
- Potential for many more exciting results.

Thank you!
Extra material
Expected errors on $|V_{ub}|$ and $|V_{cb}|$.

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle (2017)</th>
<th>5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ incl.</td>
<td>$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8%)$</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$ excl.</td>
<td>$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0%<em>{ex.} \pm 1.4%</em>{th.})$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ incl.</td>
<td>$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0%<em>{ex.} \pm 2.5%</em>{th.})$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$ excl. (WA)</td>
<td>$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5%<em>{ex.} \pm 3.0%</em>{th.})$</td>
</tr>
</tbody>
</table>

Expected errors on several selected observables related to the measurement of time dependent CP violation in $B$ decays and the measurement of the UT angles $\phi_1$ and $\phi_2$.

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle (2017)</th>
<th>5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin 2\phi_1 (B \to J/\psi K^0)$</td>
<td>$0.667 \pm 0.023 \pm 0.012$</td>
<td>0.012</td>
<td>0.005</td>
</tr>
<tr>
<td>$S(B \to \phi K^0)$</td>
<td>$0.90^{+0.09}_{-0.19}$</td>
<td>0.048</td>
<td>0.020</td>
</tr>
<tr>
<td>$S(B \to \eta^\prime K^0)$</td>
<td>$0.68 \pm 0.07 \pm 0.03$</td>
<td>0.032</td>
<td>0.015</td>
</tr>
<tr>
<td>$S(B \to J/\psi \pi^0)$</td>
<td>$-0.65 \pm 0.21 \pm 0.05$</td>
<td>0.079</td>
<td>0.025</td>
</tr>
<tr>
<td>$\phi_2 \ [^\circ]$</td>
<td>$85 \pm 4 \text{ (Belle+BaBar)}$</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>$S(B \to \pi^+ \pi^-)$</td>
<td>$-0.64 \pm 0.08 \pm 0.03$</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>$Br.(B \to \pi^0 \pi^0)$</td>
<td>$(5.04 \pm 0.21 \pm 0.18) \times 10^{-6}$</td>
<td>0.13</td>
<td>0.04</td>
</tr>
<tr>
<td>$S(B \to K^0 \pi^0)$</td>
<td>$-0.11 \pm 0.17$</td>
<td>0.09</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Vertex Detector

Si pixel (2 layers) and strip (4 layers):

- 1\textsuperscript{st} pixel layer at $r = 14\text{mm}$ to IP
  [Belle at $r = 20\text{mm}$]
  Improves vertex resolution along $z$-axis

- Larger SVD w/outer layer at $r = 135\text{mm}$.
  [Belle at $r = 88\text{mm}$]
  Higher fraction of $K_S^+$ with vertex hits improves vertex resolution

Resolution much better than Belle and BaBar

Greater outer radius enhances $K_S$ acceptance

Resolution much better than Belle and BaBar

VXD practice installation
Tracking Detector

Central Drift Chamber:
- $He(50\%) \ C_2H_6(50\%)$.
- Larger outer radius of 1111mm (Belle 863mm) allows for improved $p$ resolution.
- Smaller cells with lower occupancy and capacity for higher hit rate.

Wire configuration

Full readout of the CDC

Single track

Showering event

Simulated track reconstruction efficiency

Stable performance for up to 3x predicted beam BG
Particle Identification

Two RICH systems covering full momentum range
- Barrel: Time of Propagation (TOP) counter (16 modules).
  \[\Rightarrow \text{Measure x-y position of Cherenkov } \gamma \text{'s and their arrival time}.\]
- Forward Endcap: Aerogel Ring Imaging Cherenkov detector (ARICH)
  \[\Rightarrow \text{Proximity focusing with silica aerogel (4}\sigma\text{ separation at } 1 - 3.5 \text{ GeV/c})\]

Average \(\epsilon_K\) vs. \(\pi\) fake rate improved: Fake rate decreases by \(\approx 3\) for the same \(\epsilon\) w.r.t. Belle

The background \(B \to K^* \gamma\) (Belle/Belle II) \(\approx 30x\) more abundant than \(B \to \rho \gamma\).
Electromagnetic Calorimeter

Re-usage of Belle’s CsI(Tl) crystal calorimeter, but with new electronics with 2MHz wave form sampling to compensate for the larger beam-related backgrounds and the long decay time of CsI(Tl) signals.

⇒ Resolution much better at Belle II

Peak energy resolution in the ECL barrel as a function of true photon energy
Applicable in Belle *and* Belle II analyses within the Belle II analysis software framework:

Allows one to make a benchmark comparison of the tag-side efficiency with the predecessor Belle Full Reconstruction (FR) algorithm.

* Perform physics analysis on Belle data with increased statistics (from the same 711 fb$^{-1}$), *while we await a large Belle II dataset.*
Use the FEI on Belle data to reconstruct several well known semileptonic decays.

\[ \epsilon = \frac{N_{DATA}}{N_{MC}} \]

\[ \epsilon_{charged} = 0.74 \pm 0.05 \quad \epsilon_{neutral} = 0.86 \pm 0.07 \]
Measurements of $D_{CPV}$ in $B^+ \rightarrow K^+\pi^0$ found to be different than $B^0 \rightarrow K^+\pi^-$.

\[ A_{K^+\pi^0} - A_{K^+\pi^0} = 0.112 \pm 0.027 \pm 0.007 \ (4\sigma) \]
The difference could be due to:

- **Neglected diagrams** contributing to $B$ decays (theoretical uncertainty is still large).

\[
K^+ \pi^- : T + P + P_{EW}^C \\
K^+ \pi^0 : T + P + C + P_{EW} + P_{EW}^C + PA
\]

- Some unknown NP effect that violates Isospin.

⇒ **In combination with other $K\pi$ measurements** and with the larger Belle II dataset, strong interaction effects can be controlled and the validity of the SM can be tested in a model-independent way.
Asymmetry (test-of-sum) rule for NP nearly free of theoretical uncertainties, where the SM can be tested by measuring all observables: [PLB 627, 82(2005), PRD 58, 036005(1998)]

\[ I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^0} + \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^+\pi^0} \frac{B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^0\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \]

\[ (I_{K\pi} = -0.0088^{+0.0016}_{-0.0017} + 0.0131) \] [NNLO] PLB 750(2015)348-355

\[ I_{K\pi} = -0.270 \pm 0.132 \pm 0.060 \] [Belle]

- Most demanding measurement is \( K^0\pi^0 \) final state: \( A_{K^0\pi^0} = 0.14 \pm 0.13 \pm 0.06 \). Belle, PRD 81, 011101(R) (2010)

- With Belle II, the uncertainty on \( A_{K^0\pi^0} \) from time-dep. analysis is expected to reach \( \sim 4\% \).

\[ \Rightarrow \text{Sufficient for NP studies} \]
Modified $P_{EW}$ Sector

- Data point is the WA for $A_{K^0 \pi^0}$ and $S_{K^0 \pi^0}$.
- The $A_{K^0 \pi^0}$ value obtained from the sum rule with WA inputs for all other $A_{K \pi}$ and $B(K \pi)$ values.
- Isospin relation involving tighter constraints from CKM angle $\gamma$:
  \[
  \sqrt{2} A_{K^0 \pi^0} + A_{K^+ \pi^0} = - (\hat{T} + \hat{C}) (e^{i\gamma} - q e^{i\phi} e^{i\omega}).
  \]
  EW penguin effects described by
  \[
  q e^{i\phi} e^{i\omega} \equiv - \left( \hat{P}_{EW} + \hat{P}_{EW}^C \right) / (\hat{T} + \hat{C}).
  \]

- Discrepancy can be resolved if:
  $CP$ asymmetries move by $\approx 1\sigma$; $B(K^0 \pi^0)$ moves by $\approx 2.5\sigma$.
- Or NP from EW $Z$ penguins that couple to quarks:
  *Includes models with extra $Z'$ bosons, which can be used to resolve anomalies in $B \to K^{(*)}\ell\ell$ measurements.*
Reducible vs. Irreducible Errors

Reducible

- The systematic uncertainties of the PDF parameters.
- Particle identification requirements.
- The possible CP violation effect in the accompanying $B$ meson decays.
- Vertex resolution.
- $\Delta t$ resolution function parametrization.
- Tag-side interference.

Irreducible

- Uncertainties in the interaction-point profile.
- Dependence on the vertex selection-criteria.
- The effect of detector misalignment.
- Possible bias in the $\Delta Z$ determination.
- $K^\pm \pi^\pm, \pi^0$ detection efficiency.
- Uncertainty in branching fraction measurements.
- Asymmetry of charged particle detection efficiency (in $\Lambda$ measurements).
- Vertex reconstruction uncertainty originating from the SVD mis-alignment (in $S$ measurements).