Physics Prospects of Super KEKB and Belle II

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History of Successes from B Factories

• Belle and BaBar have made a wide variety of achievements over ~10 year running period:
  – CKM measurements of:
    • Matrix elements
    • Unitary triangle angles
    - CKM is correct to ~first order
  – Direct CP violation:
    • B → K π
  – New hadronic states:
    • X,Y,Z mesons
  – Rare probes of new physics:
    • b → s γ
    • b → s ℓ⁺ ℓ⁻

• Belle II at SuperKEKB provides a unique opportunity to constrain and search for new physics at the intensity frontier, in a complimentary way to LHC.
Belle II @ SuperKEKB: Toward 50 ab$^{-1}$

- **Belle II / Super KEKB** timeline:
  - Expect to begin operation in 2014.
  - Collect ~50 ab$^{-1}$ by 2020-2021.

- **Physics Prospects**:
  - What can we do with 50 ab$^{-1}$ of data? (...and what can we do along the way?)
  - How are super B factory measurements complementary to those at LHC?

- **Selected physics topics, examples of**:
  - Modes with missing energy: $B \rightarrow \tau \nu$
  - Direct CP violation: $B \rightarrow K \pi$
  - Mixing-induced CP violation: $b \rightarrow s \gamma$

*Details of SuperKEKB / Belle II detector covered in previous talk (H. Nakayama)
• At Belle II, B’s are produced by: 
  \[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \]
  – One B meson (“tag” B) can be reconstructed in a common decay.
    • Fully reconstructed: e.g., \( B \rightarrow D^{(*)}\pi \), \( B \rightarrow D^{(*)}\rho \), ...
    • Partially reconstructed: e.g., semileptonically
  – Allows determination of “signal” B flavor, charge, momentum.
    • Particles associated with “tag” B can be removed from event.
      \( \Rightarrow \) Allows searches for modes with missing energy.
Missing Energy Modes: $B^{-} \rightarrow \tau^{-} \nu$

- Tension between the global CKM fit and $B(B \rightarrow \tau \nu)$:

![Graph showing tension between the global CKM fit and $B(B \rightarrow \tau \nu)$]

- Better measurement of $B \rightarrow \tau \nu$ may reveal source of the tension.
  
  - Tag-side information vital when $\geq 2 \nu'$s in final state! Signal is seen as zero excess $E_{ECL}$.

Example w/ semileptonic tag, 657M BB

$B(B^{-} \rightarrow \tau^{-} \bar{\nu}_{\tau}) = (1.54^{+0.38}_{-0.37}(stat)^{+0.29}_{-0.31}(syst)) \times 10^{-4}$

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Nishimura - Physics Prospects of Super KEKB / Belle II
B → τν at Belle II

• Also sensitive to new physics:
  • In type-II Two-Higgs Doublet Model (THDM), the SM branching fraction of $B^{-} \rightarrow \tau^{-} \nu$ is modified:

  $$\mathcal{B}(B^{-} \rightarrow \tau^{-} \bar{\nu}_{\tau}) = \mathcal{B}_{SM}(B^{-} \rightarrow \tau^{-} \bar{\nu}_{\tau}) \left[ 1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right]$$

Belle II discovery region with 5 ab$^{-1}$
  • Assumes improvements in theory values:
    • 5% $|V_{ub}|$ error
    • 5% $f_B$ error

5 σ discovery region

current 95% exclusion
B → τ ν at Belle II

- Also sensitive to new physics:
  - In type-II Two-Higgs Doublet Model (THDM), the SM branching fraction of $B^- \rightarrow \tau^- \nu$ is modified:

  $$\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = \mathcal{B}_{\text{SM}}(B^- \rightarrow \tau^- \bar{\nu}_\tau) \left[ 1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right]$$

  Belle II discovery region with 50 ab$^{-1}$

- Assumes improvements in theory values:
  - 2.5% $|V_{ub}|$ error
  - 2.5% $f_B$ error

*Does not yet account for improvements in full-recon efficiency. Recently work suggests $\mathcal{O}(2x)$ improvements.
Direct CP Violation: $B \rightarrow K \pi$

- Puzzle of direct CP violation in $K \pi$:
  - Difference in DCPV in charged/neutral $B$ decays:
    \[ \Delta A \equiv A_{K^\pm \pi^0} - A_{K^\pm \pi^\mp} = +0.164 \pm 0.037 \]
    
- If the only diagrams are:
  then we expect $\Delta A = 0$
  - Missing diagrams?
  - Hadronic interactions?
  \[ \Rightarrow \] These result in large theoretical uncertainty...

B $\rightarrow K \pi$ w/ 535M BB
CPV in $B \rightarrow K \pi$ at Belle II

- However, we can compare to a **model independent** sum rule:

$$A_{\text{CP}}(K^+\pi^-) + A_{\text{CP}}(K^0\pi^+) \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+}$$

$$= A_{\text{CP}}(K^+\pi^0) \frac{2B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} + A_{\text{CP}}(K^0\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)}$$

- This rule is free of the previous theoretical complications.
- Can be represented as a diagonal band:

- **Current situation:**

*Slope determined by branching fractions & lifetimes, fairly precisely known.*
CPV in $B \rightarrow K \pi$ at Belle II

• However, we can compare to a **model independent** sum rule:

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)}$$

  -- This rule is free of the previous theoretical complications.
  -- Can be represented as a diagonal band:

• Current situation:

Shaded region is overlap of $A(K^0\pi^0)$ and $A(K^0\pi^+)$.

Benefits from:
✓ Charged $K/\pi$ ID (TOP counter)
✓ $\pi^0 \rightarrow \gamma \gamma$ efficiency (ECL)
✓ $K_S$ vertexing eff. (increased SVD radius)
✓ ...and of course, statistics

⇒ Belle II is especially well suited to measure the all neutral final state: $K^0\pi^0$
CPV in $B \rightarrow K \pi$ at Belle II

• However, we can compare to a **model independent sum rule**:

\[
A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0) \frac{2B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)}
\]

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Gronau, PLB627, 82 (2005)
Mixing Induced CP Violation in $b \rightarrow s \gamma$

- In SM, photon polarizations in $b \rightarrow s \gamma$ depend on $b$ flavor:
  
  $b \rightarrow s \gamma_L$  
  $\bar{b} \rightarrow s \gamma_R$

- Presence of mixing-induced CP violation would indicate the presence of right handed currents and clear hints of new physics.
  - This type of new physics does not require a new phase.
Time Dependent CPV in $b \rightarrow s \gamma$

• A recent example:
  – Search for TCPV in $B \rightarrow \phi K \gamma$

Belle preliminary, arXiv: 1012.0481
$B \rightarrow \phi K \gamma$ with 772M BB

\[ S(B \rightarrow \phi K \gamma) = +0.74^{+0.72}_{-1.05}(\text{stat})^{+0.10}_{-0.24}(\text{syst}) \]
\[ A(B \rightarrow \phi K \gamma) = +0.35 \pm 0.58(\text{stat})^{+0.23}_{-0.10}(\text{syst}) \]

– Measurements are statistics limited...
  • Also the case for similar modes: $B \rightarrow K_S \pi^0 \gamma$, $B \rightarrow K^* \gamma$
Time Dependent CPV in $b \rightarrow s \gamma$

- Statistics limited for $S(b \rightarrow s \gamma)$ in other modes
Time Dependent CPV in $b \rightarrow s \gamma$

- Example improvements in the error of $S$ as a function of integrated luminosity for:
  - Nonresonant $K_S \pi^0 \gamma$
  - Resonant $K^*0 \gamma$
  - All $K_S \pi^0 \gamma$

- This sensitivity can help distinguish between models...

Belle II projected

✓ Efficiency for $K_S \rightarrow \pi^+ \pi^-$ improves with SVD radius.
Identifying NP at Belle II

Projected with 5 ab$^{-1}$

- Randomly chosen parameter point

--- Current 99% CL on $S(B \to \phi K_S)$

Belle II can identify the nature of NP, in some cases indistinguishable at LHC.
Summary

• Belle II at SuperKEKB will enable a new generation of precision studies in flavor physics.
  – A number of unique opportunities to further constrain SM and search for new physics.

• Significant opportunities both during data collection and with final dataset (50+ ab$^{-1}$).
  – Only a short sampling of modes given here... for more information, see:

Belle II and LHC experiments will be nicely complimentary.
Missing Energy Modes: $B \to K \nu \nu$

- FCNC process:
  - Loops in penguin / box diagrams make $B \to K \nu \nu$ sensitive to new physics.
  - SM prediction [Buchalla, PRD 63, 014015 (2001)]:
    \[ \mathcal{B}(B \to K \nu \nu) = (3.8^{+1.2}_{-0.6}) \times 10^{-6} \]

Current best upper limits by BaBar:

- BaBar analysis w/ 657M BB
  - $\mathcal{B}(B^+ \to K^+ \nu \bar{\nu}) < 1.3 \times 10^{-5}$
  - $\mathcal{B}(B^0 \to K^0 \nu \bar{\nu}) < 5.6 \times 10^{-5}$

$\Rightarrow$ Another mode with two neutrinos: well-suited for B-factory environment.
B $\rightarrow$ K\(^{(\ast)}\) $\nu \nu$ at Belle

\[ \epsilon = \frac{\sqrt{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}}{|(C_L^{\nu})_{SM}|} \]
\[ \eta = \frac{-\Re(C_L^{\nu}C_R^{\nu\ast})}{|C_L^{\nu}|^2 + |C_R^{\nu}|^2} . \]
Figure 5.3: Expected total errors on $\Delta S$ as a function of integrated luminosity.
$B \rightarrow D^* \tau \nu$