Inclusive B decays with $\eta$ mesons and other flavor puzzles at Belle and Belle II

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The Standard Model

- The Standard Model of particle physics:
  - Describes the known fundamental matter particles:
    - Quarks
    - Leptons
  - And interactions between them (mediated by gauge bosons):
    - Electromagnetic
      - Photon (γ) – couples to electrically charged particles.
    - Strong
      - Gluons – couple to quarks (and other gluons).
    - Weak
      - W, Z – couple to quarks and leptons
Beyond the Standard Model?

• Standard Model is “frustratingly successful.”
  – Have we found the last missing piece?
• But it has distinct flaws, just a few examples:
  – Our universe displays a wildly asymmetric ratio of matter to antimatter:
    • “The degree of asymmetry predicted ... is ten orders of magnitude too small.”
    – Standard model has no dark matter candidate.
• So we expect something must lie beyond.
Searches for New Physics

Produce and observe new particles or phenomenon directly.

Use cosmic rays to search for new particles or probe energies beyond those available at colliders.

Observe processes that are extremely rare or forbidden in Standard Model.
**B Factories**

- **B mesons can be produced through the process:**
  \[
  e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B}
  \]
  > 96%

- **B factories are colliders tuned to operate at the energy of the \( \Upsilon(4S) \):**
  - CESR accelerator / CLEO detector
    - Cornell – New York
  - PEP-II accelerator / BaBar detector
    - SLAC - California
  - **KEKB accelerator / Belle detector**
    - KEK – Tsukuba, Japan
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Measuring CPV at Asymmetric $B$ Factories

Primary physics goal of the $B$ factories:
- Measure CP violation in $B$ meson system, confirm the KM mechanism of CP violation...

Search for time dependent decay asymmetries:

Belle
- $8.0 \text{ GeV } e^-, 3.5 \text{ GeV } e^+$
- $\beta \gamma = 0.42$

BaBar
- $9.0 \text{ GeV } e^-, 3.1 \text{ GeV } e^+$
- $\beta \gamma = 0.56$
Success in Time Dependent CPV

CKM verified to ~10%!

A great success, but $B$ factories have much broader physics program.
Charmless Decays of the $b$ Quark

- Bottom quark is second most massive.
  - Many decay channels, many potential measurements.

- Decays to charm can happen at tree level:

- Decays to strange include loops:

Hadrons, Exclusive/Inclusive Decays

- Standard Model Lagrangian describes interactions at quark level, but we only observe quarks bound into hadrons.
  - Baryons (three quarks)
    - e.g., neutron (udd), proton (uud)
  - Mesons (quark-antiquark)
    - e.g., B mesons: \( B^+ = u \bar{b}, \ B^0 = d \bar{b}, \ \bar{B}^0 = \bar{d} \ b, \ B^- = \bar{u} \ b, \)
    - D mesons: \( D^+ = c \bar{d}, \ D^0 = c \bar{u}, \ \bar{D}^0 = \bar{c} \ u, \ D^- = \bar{c} \ d, \)
    - Kaons: \( K^+ = u \bar{s}, \ K^0 = d \bar{s}, \ \bar{K}^0 = \bar{d} \ s, \ K^- = \bar{u} \ s, \)

Quark level process...
→ “Straightforward” theoretical treatment.
Hadrons, Exclusive/Inclusive Decays

• Diagrams so far have included quarks, but we only observe quarks bound into hadrons.

  – Baryons (three quarks)
    • e.g., neutron (udd), proton (uud)
  – Mesons (quark-antiquark)
    • e.g., B mesons: $B^+ = u \bar{b}$, $B^0 = d \bar{b}$, $\bar{B}^0 = \bar{d} b$, $B^- = \bar{u} b$,
    D mesons: $D^+ = c \bar{d}$, $D^0 = c \bar{u}$, $\bar{D}^0 = \bar{c} u$, $D^- = \bar{c} d$,
    Kaons: $K^+ = u \bar{s}$, $K^0 = d \bar{s}$, $\bar{K}^0 = \bar{d} s$, $K^- = \bar{u} s$,

Exclusive process – all hadrons identified explicitly.
  ➔ Experimentally accessible.
  ➔ Hadronization process introduces significant theoretical uncertainties.
Hadrons, Exclusive/Inclusive Decays

• Diagrams so far have included quarks, but we only observe quarks bound into hadrons.
  – Baryons (three quarks)
    • e.g., neutron (udd), proton (uud)
  – Mesons (quark-antiquark)
    • e.g., B mesons: \( B^+ = u\bar{b}, \overline{B}^0 = d\bar{b}, B^0 = \overline{d}b, B^- = \overline{u}b, \)
    D mesons: \( D^+ = c\bar{d}, D^0 = c\bar{u}, \overline{D}^0 = \overline{c}u, D^- = \overline{c}d, \)
    Kaons: \( K^+ = u\bar{s}, K^0 = d\bar{s}, \overline{K}^0 = \overline{d}s, K^- = \overline{u}s, \)

\[ W \]

\[ \bar{u}, \bar{d} \]

\[ B \]

\[ \frac{s}{s} \]

\[ \eta' \]

\[ (X_s = K, K^*, \text{etc.}) \]

Inclusive or semi-inclusive process

⇒ Experimentally: effectively measure over many final states.
⇒ Potentially reduced theoretical errors.
\[ B \rightarrow X_s \eta' \] and \[ B \rightarrow X_s \eta \]

- **1998**: The CLEO collaboration measures the inclusive process \( B \rightarrow X_s \eta' \)
  - Mass spectrum and branching fraction were both considered surprising:
    - Peaking at high \( X_s \) mass.
    - Anomalously high (in a relative sense...):
      \[
      B(B \rightarrow X_s \eta') = (6.2 \pm 1.6^{+1.3}_{-2.0}) \times 10^{-4}
      \]
  - Confirmed in 2003 by CLEO, 2004 BaBar: \( B = (4.2 \pm 0.9) \times 10^{-4} \) (world average)
  - There was significant debate over whether new physics was required to explain this result.
    - Attributed to a special property of the \( \eta' \) meson, “QCD anomaly.”
      [Atwood, Soni: hep-ph/9704357]
    - Despite name, this is actually Standard Model physics.
    - To date, no conclusive explanation.
    - \( \eta \) and \( \eta' \) mesons mix!

\( \Rightarrow \) Measure this at Belle, but exchange for \( \eta' \) for \( \eta \) to help favor or rule out explanations.
Belle Experiment

SC solenoid
1.5T

CsI(Tl)
16$X_0$

TOF counter

Aerogel Cerenkov cnt.
n=1.015~1.030

3.5 GeV $e^+$

8 GeV $e^-$

Central Drift Chamber
small cell +He/C$_2$H$_6$

μ / $K_L$ detection
14/15 lyr. RPC+Fe

Si vtx. det.
3/4 lyr. DSSD
This analysis uses 657 M BB pairs (605 fb$^{-1}$), out of a total of 772 M.

> 1 ab$^{-1}$

**On resonance:**
- $Y(5S)$: 121 fb$^{-1}$
- $Y(4S)$: 711 fb$^{-1}$
- $Y(3S)$: 3 fb$^{-1}$
- $Y(2S)$: 24 fb$^{-1}$
- $Y(1S)$: 6 fb$^{-1}$

**Off resonance/scan:**
- $\sim 100$ fb$^{-1}$

$\sim 550$ fb$^{-1}$

**On resonance:**
- $Y(4S)$: 433 fb$^{-1}$
- $Y(3S)$: 30 fb$^{-1}$
- $Y(2S)$: 14 fb$^{-1}$

**Off resonance:**
- $\sim 54$ fb$^{-1}$
Measuring $B \rightarrow X_s \eta$ at Belle

• $\eta$ is reconstructed through $\eta \rightarrow \gamma \gamma$
  – We look for pairs of photons that have energies consistent with coming from an $\eta$.

• The $X_s$ state is anything with a net strangeness of 1.
  – We only look for the following decays (pseudo-inclusive):

\[
\begin{align*}
B^+ & \rightarrow K^+ (\pi^0) \eta \\
B^+ & \rightarrow K_S^0 \pi^+ (\pi^0) \eta \\
B^+ & \rightarrow K^+ \pi^+ \pi^- (\pi^0) \eta \\
B^+ & \rightarrow K_S^0 \pi^+ \pi^- \pi^+ (\pi^0) \eta \\
B^+ & \rightarrow K^+ \pi^+ \pi^- \pi^+ \pi^- \eta \\
\end{align*}
\]

  – Efficiency becomes too low to make others worth measuring.
  – Because we don’t measure all possible modes, we have to make an efficiency correction to account for these “missing” modes.
**B Meson Reconstruction: \(M_{bc} & \Delta E\)**

- **Beam-constrained mass:**
  
  \[
  M_{bc} = \sqrt{(E_{\text{beam}}^*)^2 - |p_B^*|^2}
  \]

  (or \(M_{\text{ES}}\))

  - Peaks at \(B\) mass for correctly reconstructed B mesons.
  - Using known beam energy gives improved resolution relative to measuring invariant mass of B candidate directly.

- **Energy Difference:**
  
  \[
  \Delta E = E_B^* - E_{\text{beam}}^*
  \]

  - Peaks at 0 for correct B candidates.
Candidate Selection

• With so many modes reconstructed, there are many combinations of particles that can make a $B$ candidate.
  – We choose the best candidate as the one with the lowest $\chi^2 = \chi^2_{\text{vtx}} + \chi^2_{\Delta E}$
    • Vertex fit of charged tracks – tracks should come from interaction point.
    • True $B$ candidates should have $\Delta E \sim 0$

  ➔ This biases the $\Delta E$ distribution, so we do not use it for fitting later.

• We can check the effectiveness of candidate selection by looking at “migration” between modes (or between masses)...

8/28/2012
Candidate Selection

Mass Migration Matrix

Generated $X_s$ Mass (GeV/c$^2$) vs. Reconstructed $X_s$ Mass (GeV/c$^2$)

Fraction fitted ($10^{-5}$)
We have many competing processes that can fake our signal:

\[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \]

**Biggest challenges:**
- The largest charm and rare backgrounds are not well measured, so we must estimate them from data.
- Efficiency relies on assumptions about the \( X_s \) and “missing” modes that we must validate in data.

**Strategy:**
- **Suppress/veto** backgrounds as much as is practical.
- **Estimate** what remains and model it into a fitting procedure.
Continuum Suppression

- Cross section to produce $q\bar{q}$ is about 3 times as large as that to produce $\Upsilon(4S)$. 
Continuum Suppression

• Continuum events:
  - Light quarks produced back-to-back.
  - Jets of hadrons along quark momentum vectors.

• BB events:
  - B pair produced at threshold, each B is nearly at rest.
  - Decay products isotropic.
Continuum Suppression

- Continuum events:
  - Light quarks produced back-to-back.
  - Jets of hadrons along quark momentum vectors.

- BB events:
  - B pair produced at threshold, each B is nearly at rest.
  - Decay products isotropic.

Suppress continuum based on:
- Linear discriminant formed from Fox-Wolfram moments:
  \[ H_l = \sum_{i,j} \frac{|\overrightarrow{p_i}| |\overrightarrow{p_j}|}{s} P_l(\cos \phi_{ij}) \]
- Distance between reconstructed B pairs, \( \Delta z \)
- Cosine of B flight direction: \( \cos \theta_B \)
- Combine all into a likelihood ratio.
Suppresses 99.5% of continuum, retains 34% signal.

*Cut value varies by event quality. A typical value is shown.
Generic \((b \rightarrow c)\) Peaking Backgrounds

Identify common \(b \rightarrow c\) backgrounds from MC. Look for them explicitly in our signal events and “veto” the event if we see something consistent with them:

\[
\begin{align*}
+ D^0 & \rightarrow K n \pi (\pi^0) \text{ vetoes} \\
+ D^\pm & \rightarrow K n \pi (\pi^0) \text{ vetoes} \\
+ \eta_c & \rightarrow \eta \pi^+ \pi^- \text{ veto} \\
+ D_s & \rightarrow \eta \pi \text{ veto} \\
+ D^0 & \rightarrow \eta K_s 
\end{align*}
\]
Fitting Procedure

- The number of signal events is determined with 1-dimensional fits to $M_{bc}$ distributions in bins of $X_s$ mass. Fit components:
  - Signal – Gaussian
  - Continuum – ARGUS function ($t \sqrt{1 - t^2} e^{\alpha(1-t^2)}$)
  - BB backgrounds – divided into 5 components:
    \[
    \begin{align*}
    B^0 & \rightarrow \bar{D}^0 \eta \\
    B^0 & \rightarrow \bar{D}^{*0} \eta \\
    B^+ & \rightarrow D^{(*)-} \pi^+ \eta \\
    B^0 & \rightarrow \bar{D}^{(*)0} \pi^+ \eta \\
    \end{align*}
    \]
  - Rare backgrounds are small. Expected contributions are checked against sidebands, subtracted after fit.
Veto Window Calibration

- MC normalizations need adjustment.
  - Most challenging for poorly measured $D^{(*)} (\pi) \eta$ decays.
  - We use previous Belle measurements for $D \eta$, $D^* \eta$.
  - $D^{(*)} \pi \eta$ is not measured. Calibrated from data with $\chi^2$

\[ \chi^2 = \sum_i \left( \frac{N_{MC}^i - N_{data}^i}{\sqrt{N_{data}^i}} \right)^2 \]

<table>
<thead>
<tr>
<th>Background mode</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \bar{D}^0 \eta$</td>
<td>1.07</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^{*0} \eta$</td>
<td>0.79</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^- \pi^+ \eta$</td>
<td>0.00</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^{*-} \pi^+ \eta$</td>
<td>0.00</td>
</tr>
<tr>
<td>$B^+ \rightarrow \bar{D}^0 \pi^+ \eta$</td>
<td>0.39</td>
</tr>
<tr>
<td>$B^+ \rightarrow \bar{D}^{*0} \pi^+ \eta$</td>
<td>0.39</td>
</tr>
<tr>
<td>Other $b \rightarrow c$ decays</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Veto Window $M_{bc}$ Distributions (Post-Calibration)
Fits to Data

- Perform fitting procedure on full data sample...

Each data point corresponds to one fit

\[ B \rightarrow K^* \eta \]

\[ B \rightarrow K^{*}(1430) \eta \]
Branching Fraction Calculation

- Branching fraction in each $X_s$ mass bin defined as:

$$B(B \rightarrow X_s \eta) = \frac{N^i_{\text{sig}} - N^i_{\text{BB}} - N^i_{X_s \eta}}{2N_{\text{BB}} e_\gamma}$$

- $N^i_{\text{BB}}$ is the total number of BB pairs.
- $N^i_{\text{sig}}$ is the total number of expected rare backgrounds.
- $M_{X_s}$ is the mass of $X_s$.
- $e_\gamma$ is the reconstruction efficiency (left).
- $\epsilon$ represents correction factors between data/MC.
- $r$ represents correction factors in the $\eta \rightarrow \gamma \gamma$ mode.
- Correct for only reconstructing $\eta$ in the $\gamma \gamma$ mode.
- Correct by subtracting small number of expected rare backgrounds.
### Systematic Uncertainties on Signal Yields

#### Contributions from PDF shapes / normalizations
- Any value that was fixed in the fit is varied to study how yields change.

#### Rare background subtractions
- Varyed and effect on yield is tabulated.

All significantly smaller than the statistical uncertainties.

<table>
<thead>
<tr>
<th>$X_s$ Mass range (GeV/$c^2$)</th>
<th>Fit yield</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 - 0.6</td>
<td>60.2 ± 12.4</td>
<td>5.7</td>
</tr>
<tr>
<td>0.6 - 0.8</td>
<td>15.3 ± 8.8</td>
<td>1.9</td>
</tr>
<tr>
<td>0.8 - 1.0</td>
<td>250.0 ± 19.2</td>
<td>14.0</td>
</tr>
<tr>
<td>1.0 - 1.2</td>
<td>84.2 ± 13.8</td>
<td>6.6</td>
</tr>
<tr>
<td>1.2 - 1.4</td>
<td>146.2 ± 17.2</td>
<td>9.2</td>
</tr>
<tr>
<td>1.4 - 1.6</td>
<td>137.0 ± 17.6</td>
<td>8.1</td>
</tr>
<tr>
<td>1.6 - 1.8</td>
<td>127.7 ± 18.4</td>
<td>7.2</td>
</tr>
<tr>
<td>1.8 - 2.0</td>
<td>64.2 ± 17.8</td>
<td>3.5</td>
</tr>
<tr>
<td>2.0 - 2.2</td>
<td>85.7 ± 18.4</td>
<td>4.6</td>
</tr>
<tr>
<td>2.2 - 2.4</td>
<td>48.6 ± 17.9</td>
<td>2.7</td>
</tr>
<tr>
<td>2.4 - 2.6</td>
<td>34.8 ± 12.5</td>
<td>2.7</td>
</tr>
<tr>
<td>0.4 - 2.6</td>
<td>1054 ± 54</td>
<td>23</td>
</tr>
<tr>
<td>1.8 - 2.6</td>
<td>233 ± 34</td>
<td>7</td>
</tr>
</tbody>
</table>
Other Systematic Uncertainties

\[ B(B \rightarrow X_s \eta)_i = \frac{N^i_{\text{sig}} - N^i_{X_s \gamma} - N^i_{X_d \eta} - N^i_{X_s \eta'}}{2N_{B B} \epsilon_i r_i B(\eta \rightarrow \gamma \gamma)} \]

- Include uncertainties from:
  - \( N_{BB} \): 1.4%
  - \( B(\eta \rightarrow \gamma \gamma) \): < 1%
  - \( r_i \):
    - \( \eta \) recon. : 2.7%
    - qq suppression: 3.7%
    - Candidate selection: <1%
    - Other reconstructions, particle ID, & tracking (see table)

<table>
<thead>
<tr>
<th>( M_{X_s} ) (GeV/c^2)</th>
<th>( K^0_S ) (( \pm % ))</th>
<th>( \pi^0 ) (( \pm % ))</th>
<th>( \pi^\pm ) (( \pm % ))</th>
<th>( K^\pm ) (( \pm % ))</th>
<th>Tracking (( \pm % ))</th>
<th>Total (( \pm % ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4–0.6</td>
<td>1.08</td>
<td>0.00</td>
<td>0.00</td>
<td>0.74</td>
<td>0.77</td>
<td>5.07</td>
</tr>
<tr>
<td>0.6–0.8</td>
<td>1.07</td>
<td>0.40</td>
<td>0.37</td>
<td>0.70</td>
<td>1.60</td>
<td>5.29</td>
</tr>
<tr>
<td>0.8–1.0</td>
<td>1.08</td>
<td>0.38</td>
<td>0.38</td>
<td>0.72</td>
<td>1.81</td>
<td>5.36</td>
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<tr>
<td>1.0–1.2</td>
<td>1.06</td>
<td>0.57</td>
<td>0.49</td>
<td>0.76</td>
<td>2.04</td>
<td>5.47</td>
</tr>
<tr>
<td>1.2–1.4</td>
<td>1.03</td>
<td>0.65</td>
<td>0.59</td>
<td>0.80</td>
<td>2.35</td>
<td>5.61</td>
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<tr>
<td>1.4–1.6</td>
<td>1.02</td>
<td>0.70</td>
<td>0.68</td>
<td>0.84</td>
<td>2.62</td>
<td>5.74</td>
</tr>
<tr>
<td>1.6–1.8</td>
<td>1.01</td>
<td>0.74</td>
<td>0.78</td>
<td>0.87</td>
<td>2.92</td>
<td>5.91</td>
</tr>
<tr>
<td>1.8–2.0</td>
<td>0.92</td>
<td>0.62</td>
<td>0.92</td>
<td>0.88</td>
<td>3.25</td>
<td>6.07</td>
</tr>
<tr>
<td>2.0–2.2</td>
<td>0.96</td>
<td>0.72</td>
<td>0.93</td>
<td>0.92</td>
<td>3.20</td>
<td>6.07</td>
</tr>
<tr>
<td>2.2–2.4</td>
<td>0.95</td>
<td>0.75</td>
<td>0.97</td>
<td>0.95</td>
<td>3.31</td>
<td>6.14</td>
</tr>
<tr>
<td>2.4–2.6</td>
<td>0.89</td>
<td>0.76</td>
<td>0.98</td>
<td>0.97</td>
<td>3.40</td>
<td>6.19</td>
</tr>
</tbody>
</table>

- Most are studied using independent control samples.
- Again, these are all smaller than statistical errors.
Modeling Systematics

- Dominant for this measurement!
- Studied three models:
  - Flat $X_s$ mass, QCD anomaly-like, three body $b \rightarrow (u,d) s \eta$
  - Efficiency does not change dramatically!
  - ...but all models use PYTHIA for fragmentation of $X_s$ into hadrons.
\( X_s \) Fragmentation (PYTHIA)

- Repeat fits in sub-categories & compare expected mode distributions in PYTHIA MC to data:

\[
\text{Consistent within errors except for deficit of modes with a } \pi^0.\]
\( \Xs \) Fragmentation, \( \pi^0 \) Deficit

- Fraction of modes with a \( \pi^0 \) is studied in data and MC.
- Can calculate a reweighted efficiency and compare with that calculated from MC \( \rightarrow \) assign a systematic error.
Fraction of modes with a $\pi^0$ is studied in data and MC.

Can calculate a reweighted efficiency and compare with that calculated from MC → assign a systematic error.

Total from modeling errors:

<table>
<thead>
<tr>
<th>$M_{X_s}$ (GeV/$c^2$)</th>
<th>Mass migration (±%)</th>
<th>Missing modes (±%)</th>
<th>PYTHIA (+%)</th>
<th>PYTHIA (-%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4–0.6</td>
<td>0.70</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>±0.70</td>
</tr>
<tr>
<td>0.6–0.8</td>
<td>2.20</td>
<td>0.07</td>
<td>9.62</td>
<td>0.00</td>
<td>+9.87</td>
</tr>
<tr>
<td>0.8–1.0</td>
<td>2.82</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>±2.85</td>
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<tr>
<td>1.0–1.2</td>
<td>3.06</td>
<td>3.63</td>
<td>0.00</td>
<td>18.26</td>
<td>+4.75</td>
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<tr>
<td>1.2–1.4</td>
<td>4.54</td>
<td>4.47</td>
<td>0.00</td>
<td>2.64</td>
<td>+6.37</td>
</tr>
<tr>
<td>1.4–1.6</td>
<td>5.68</td>
<td>7.25</td>
<td>0.00</td>
<td>9.56</td>
<td>+9.21</td>
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<tr>
<td>1.6–1.8</td>
<td>5.30</td>
<td>10.24</td>
<td>0.00</td>
<td>18.39</td>
<td>+13.28</td>
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<tr>
<td>1.8–2.0</td>
<td>7.01</td>
<td>13.21</td>
<td>0.00</td>
<td>27.99</td>
<td>+21.70</td>
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<tr>
<td>2.0–2.2</td>
<td>5.76</td>
<td>16.33</td>
<td>0.00</td>
<td>10.85</td>
<td>+31.74</td>
</tr>
<tr>
<td>2.2–2.4</td>
<td>8.46</td>
<td>18.89</td>
<td>0.00</td>
<td>33.40</td>
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<tr>
<td>2.4–2.6</td>
<td>7.35</td>
<td>21.06</td>
<td>0.00</td>
<td>37.37</td>
<td>+22.31</td>
</tr>
</tbody>
</table>
Final Results and Implications

\[ \mathcal{B} = 26.1 \pm 3.0^{+1.9}_{-2.1}(\text{stat})^{+4.0}_{-7.1}(\text{syst})(\text{model}) \times 10^{-5} \]

**Belle** \( B \rightarrow X_s \eta \)

PRL 105, 19803 (2010).

**Uncertainties:**
- Black – statistical
- Red – + systematic
- Blue – + modeling

\[ \mathcal{B} = (4.2 \pm 0.9) \times 10^{-4} \text{ (world average)} \]

- Similar shape between \( X_s \eta \) and \( X_s \eta' \) disfavors previous explanations based on special features of the \( \eta' \).

- Unfortunately, there still is no definitive conclusion.
  - Theoretical side: not much work has been done on this topic recently.
    - A study by Chay, Kim, Leibovich, Zupan [arXiv:0708.2466] suggested this measurement would be useful to pin down contributions to both modes, but no follow-ups yet.
  - Experimental side: uncertainties are still large.
Future Measurements?

- Especially at large $X_s$ mass, the statistical uncertainties are very high.
  → Increase statistics significantly ($\sqrt{N}$)
- Modeling uncertainties rely on measuring what was in the $X_s$.

\[ B = 26.1 \pm 3.0 \text{(stat)}^{+1.9}_{-2.1} \text{(syst)}^{+4.0}_{-7.1} \text{(model)} \times 10^{-5} \]

Uncertainties:
- Black: statistical
- Red: + systematic (in quadrature)
- Blue: + modeling (in quadrature)

- Some backgrounds were from bad particle identification.
  $\pi^+\pi^-\eta$ can look very similar to $K^+\pi^-\eta$ if the $\pi^+$ is misidentified.
  → Improve the detector performance.

- Again, higher statistics would allow more detailed comparisons, lead to more reliable models.
Other Future Measurements

- Improving precision on CKM picture, search for deviations:

- Continue a varied flavor physics program; explore existing tensions...

As some tensions ease...

...and provide powerful constraints on NP models.
Complementary to LHC Searches

- Previous examples include modes with missing energy.
- $B \to \tau \nu$; $B \to D^{(*)} \tau \nu$
  - Multiple neutrinos! Significant missing energy.
- These are very challenging experimentally...
  - Rely on clean $e^+e^-$ environment and detector hermeticity.

- Fully reconstruct "tag" $B$ to determine "signal" $B$ flavor, charge, momentum.

$\Rightarrow$ B factories are uniquely suited for such measurements!
Upgrading KEKB and Belle

- Increased luminosity:
  - ~10-20x higher backgrounds, rad. damage
  - Increased trigger rates (0.5 ➔ 200 kHz).
- Need to maintain or improve on existing performance.

➡ Significant detector upgrades!

Belle event with increased background overlaid.
Use nano-beam scheme developed by P. Raimondi for SuperB

\[ L = \frac{\gamma}{2e} \left( \frac{I_{\pm \pm}}{I_{\pm \pm}^*} \right) \left( \frac{\sigma_x^*}{\sigma_x} \right) \left( \frac{R_L}{R_y} \right) = 8 \times 10^{35} \text{ cm}^2 \text{ s}^{-1} \]

(w/o crab)

22 mrad

Vertical beta function reduction
\( \beta_y^* 5.9 \text{ mm} \rightarrow 0.3 \text{ mm} \)

Beam current increase.

Overall 40x higher luminosity!
**SuperKEKB**

- Colliding bunches
- New superconducting /permanent final focusing quads near the IP

- TiN-coated beam pipe with antechambers
- Replace short dipoles with longer ones (LER)
- Redesign the lattices of HER & LER to squeeze the emittance

- Low emittance positrons to inject
- Damping ring
- Positron source
- New positron target / capture section

- New beam pipe & bellows
- Low emittance gun
- Low emittance electrons to inject

- New IR
- Add / modify RF systems for higher beam current

- L=8·10^{35} s^{-1} cm^{-2}

- x 40 Gain in Luminosity

8/28/2012
The Belle II Detector

CsI(Tl) EM calorimeter: waveform sampling electronics, pure CsI for end-caps

4 layers DSSD → 2 layers PXD (DEPFET) + 4 layers DSSD

Central Drift Chamber: smaller cell size, long lever arm

7.4 m

3.3 m

1.5 m

RPC $\mu$ & $K_L$ counter: scintillator + Si-PM for end-caps

Time-of-Flight, Aerogel Cherenkov Counter → Time-of-Propagation counter (barrel), proximity focusing Aerogel RICH (forward)

K/π Identification at Belle & BaBar
Detection of Internally Reflected Cherenkov Light

- Charged particles of same momentum but different mass (e.g., $K^\pm$ and $\pi^\pm$) emit Cherenkov light at different angles.
  - Momentum measured by curvature of the particle through tracking.
- Detect the emitted photons in 2+ dimensions ($x,y,t$)
- BaBar DIRC as a model:

The larger the expansion region, the better the $x$-$y$ image...
A **large volume (>1m)** may be required for acceptable performance.

\[ \theta_c = \cos \left( \frac{1}{n\beta} \right) \]

Quartz: $n = 1.471$ ($\lambda=390\text{nm}$)
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Left: Simulation w/ 2 m expansion volume, 2 GeV K/$\pi$
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![Simulation w/ 2 m expansion volume, 2 GeV K/π](image)

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Belle Before/After Upgrade

Upgrade Barrel PID Volume

Aerogel Cerenkov Counter (ACC)

Time-of-Flight (TOF) System
Time-of-Propagation (TOP) Counter

- Work at bar end, measure x,t, not y ➔ compact!

\[ \text{e.g., NIM A, 494, 430-435 (2002)} \]

\[ \text{90°, 2GeV} \]

\[ \text{Red - Pion} \]

\[ \text{Blue - Kaon} \]

(Peaks offset by \( \sim 200 \) ps)
Simulation Studies

• Independent simulations:
  – Belle Geant3 + standalone code (Nagoya)
  – Standalone Geant4 (Hawaii)
  – Standalone code (Ljubljana)
  – Recently, full Belle II Geant4 simulation.

• All utilize a $\Delta \log(\text{Likelihood})$ approach to determine particle classification.
  – PDFs are defined in x,y, and t
  – Geant-based versions take probability distribution functions from simulated events.
    ➔ Extremely time consuming to generate the PDFs, but can include all the effects (scattering, ionization, delta-rays, etc.) that Geant can provide.
  – $\Delta \log(\text{Likelihood})$ in Ljubljana code utilizes analytical expressions for the likelihood functions.
Adding Imaging to the TOP?

• To improve the performance (and ease burden on precision timing):
  – Explored a few geometries and photodetectors.
  – Fine pixelization with Geiger-mode APDs.
  – Adding optics elements to backward end of detector.

• Many studies were killed before they could be fully explored:
  • MPPCs are too susceptible to neutron damage.
  • Extra optics required modifications to the calorimeter.
Nominal Belle II iTOP Design

• Relatively small expansion volume.
• Advantages of the iTOP option, relative to two-bar TOP:
  – Less dependent on how well we can synchronize our timing with the collision time for each event (nominally we would like ~25 ps).
  – Less sensitive to timing resolution of single detected photons.
  – Readout was easier to implement (single location for readout modules).
  – No alignment issues between forward and backward blocks.

**Single bar option (iTOP)**
- \( L_{\text{bar}} \sim 2600 \text{mm} \)
- \( L_{\text{expansion}} \sim 100 \text{ mm} \)

**Two bar option**
- \( L_{\text{backward}} \sim 1850 \text{mm} \)
- \( L_{\text{forward}} \sim 750 \text{ mm} \)
Detector and Electronics Requirements

• Photodetectors:
  – Excellent single $\gamma$ timing resolution (< 100 ps).
  – Must work in magnetic field.
  ➔ Hamamatsu SL-10 micro-channel plate photomultiplier tubes (MCP-PMTs)

• Electronics:
  – Fit in the very compact space.
  – Utilize excellent timing resolution of the MCP-PMTs.
  – Accommodate $\sim$5 $\mu$s Belle II trigger latency.
  – Provide information on all photons to Belle II trigger system.
  – No dead time at single pixel hit rates of $\sim$100 kHz.


\[ \sigma_{TTS} \approx 31 \text{ ps} \]
Waveform Sampling

e.g., 8-channel IRS2, designed by Gary Varner (UH)

Switched capacitor array sampling

Tiny stored charge: $1\text{mV} \sim 100e^-$

Example MCP-PMT waveform:

- Multi-gigasample per second waveform digitization.
  - Voltages are stored in analog form, using a switched capacitor array.
  - Analog storage memory is 32k samples deep to accommodate trigger latency.
  - Digitization of analog memory occurs when a L1 trigger is received.
  - Allows for full record of the event, and many signal processing possibilities.
Caveats of Waveform Sampling

• More data than you might often want!
  – It’s nice to have waveforms as a diagnostic tool...

• Example where waveform sampling allowed us to see and filter out a sinusoidal noise source:

• But in the end, we are usually interested in just a couple features (e.g., time and charge).

• Using waveform sampling requires that we take on the burden of the feature extraction.
  – Either in hardware or offline analysis.

\[ 512 \text{ samples} \times 12 \text{ bits} = 768 \text{ bytes} / \gamma \]
Elements of iTOP Electronics

- SCROD-based board stack, ASICs + Spartan-6 FPGA (Hawaii)
- Waveform sampling ASICs (Hawaii)
- Remote programming link (CAT-7)
- Timing/trigger distribution (CAT-7)
- Trigger data by fiberoptic
- Waveform data by fiberoptic
- COPPER Based Readout (KEK)
- DSP_FIN (Hawaii)
- FTSW
- TRG_FIN (Hawaii)
Aside: Flexible Front-end Electronics

- Same electronics can be used for multiple readouts (by changing “front” board).
- For example, same packages are being used to instrument the FDIRC prototype with Jerry Va’vra here at SLAC in a cosmic ray test stand (total 768 channels).
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Other Belle II Upgrades – Endcap PID

Proximity focusing scheme:

Slightly different indices of aerogel stacked ➔ improve Cherenkov angle resolution.

⇒ Excellent PID efficiency over wide momentum range.
• Significant improvement in K/π discrimination:
  – Rare radiative processes:
    • \( B \rightarrow \rho^0 \rightarrow \pi^+\pi^- \gamma \)
    • \( B \rightarrow K^* \rightarrow K^+\pi^- \gamma \)

• Other physics impact: \( K\pi \) CPV puzzle.
  – Naively, for \( K^+\pi^0, K^+\pi^- \) we expect: \( \Delta A = 0 \).
  – Current Belle value (EPS 2011):
    \( \Delta A = +0.112 \pm 0.028 @ 4\sigma \)
  – ...but theoretical uncertainty can be large.

• Model independent sum rule:

\[
\begin{align*}
A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) & = A_{CP}(K^+\pi^0)^2 B(K^0\pi^+) / B(K^+\pi^-) \tau_0 / \tau_+ \\
& = A_{CP}(K^+\pi^0)^2 B(K^0\pi^0) / B(K^+\pi^-) + A_{CP}(K^0\pi^0)^2 B(K^0\pi^0) / B(K^+\pi^-)
\end{align*}
\]

Gronau, PLB627, 82 (2005)
**Improved PID Performance at Belle II**

- Significant improvement in $K/\pi$ discrimination:
  - Rare radiative processes:
    - $B \to \rho^0 \to \pi^+\pi^-\gamma$
    - $B \to K^* \to K^+\pi^-\gamma$
  - Other physics impact: $K\pi$ CPV puzzle.
    - Naively, for $K^+\pi^0$, $K^+\pi^-$ we expect: $\Delta A = 0$.
    - Current Belle value (EPS 2011):
      $\Delta A = +0.112 \pm 0.028 @ 4\sigma$
    - ...but theoretical uncertainty can be large.
- Model independent sum rule:
  $A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{B(K^0\pi^+)}{B(K^+\pi^-)}\frac{\tau_0}{\tau_+}$
  $= A_{CP}(K^+\pi^0)\frac{2B(K^+\pi^0)}{B(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2B(K^0\pi^0)}{B(K^+\pi^-)}$

*Gronau, PLB627, 82 (2005)*
Other Belle II Physics...

Very broad physics program within Belle II!

For many more specific examples, see arXiv:1002.5012: “Physics at Super B Factory”
Closing Remarks

- Super B factories will allow many sensitive searches for new physics.
  - Existing tensions can be fully explored. Others may arise.
- Super KEKB & Belle II are approved by Japanese government.
  - ~400 members from over 60 institutes in 19 countries.
  - Accelerator and detector upgrades are occurring now.
- Planning to collect 50 ab\(^{-1}\) by 2022.
  - Broad physics program, complementary to LHC.