Prospects for rare B decays at Belle II

Sam Cunliffe

on behalf of the Belle II radiative and electroweak penguin physics group

APS DPF meeting, FNAL, 31 July - 4 August 2017
This talk

Why rare B decays?

The next generation B-factory
- SuperKEKB
- Belle II

Prospects at Belle II
- Inclusive analyses in general, and $B \rightarrow X_{s,d} \gamma$
- Lepton (non) universality
- $B \rightarrow K^{(*)} \nu \nu$
- $B_{(s)} \rightarrow \tau \tau$; $B \rightarrow K^{(*)} \tau \tau$

Conclusions
This talk

Why rare B decays?

The next generation B-factory
- SuperKEKB
- Belle II

Prospects at Belle II
- Inclusive analyses in general, and $B \rightarrow X_{s,d}\gamma$
- Lepton (non) universality
- $B \rightarrow K^{(*)}\nu\nu$
- $B_{(s)} \rightarrow \tau\tau$; $B \rightarrow K^{(*)}\tau\tau$

Conclusions
Why rare B decays?

\[ b \rightarrow s \ell \ell, \ell = e, \mu, \tau \nu \]

\[ b \rightarrow (s,d) \gamma \]
Why rare B decays?

\[ b \rightarrow s \ell \ell \quad \ell = e, \mu, \tau \]

\[ b \rightarrow (s,d)\gamma \]
Why rare B decays?
Why rare B decays?

SUSY

$\tilde{g}$

$\tilde{H}^0$

$\ell$

$b$  $s$
Why rare B decays?

extended electroweak sector
Why rare B decays?

extended electroweak sector
Why rare B decays?

**Wilson Coefficient**, $C_i$
model-independent coupling in the effective field theory of b quark transitions. Paired with an operator, $\mathcal{O}_i$.

- Consists of a SM bit and a new physics bit: $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$.
- $C_9$, $C_{10}$: vector and axial vector Wilson Coefficients.
- $C_7$: radiative photon Wilson Coefficient.
We've heard from LHCb. Hopefully this slide does not steal their thunder.

Stay tuned after lunch to hear from Belle (S. Sandilya)
Third Prize

Belle II is Gaining Momentum

Installation work in the inner parts of the Belle II detector is ongoing.

Markus Friedl
HEPHY Vienna

The next generation B factory

Photo: Markus Freidl
**SuperKEKB**
Second generation B factory

- **×40** higher luminosity than KEKB
  - Smaller $\beta^*$ (×20)
  - Higher current (×2)

\[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB \]

4GeV positron ring

**collision point**

electron ring 7GeV

**electron-positron linear accelerator**

positron damping ring
SuperKEKB
Second generation B factory

*40 higher luminosity than KEKB
- Smaller $\beta^*$ ($\times 20$)
- Higher current ($\times 2$)

$\text{e}^+\text{e}^- \rightarrow \Upsilon(4S) \rightarrow \text{BB}$

Photo: @belle2collab
Belle II
The detector

e^- @ 7GeV

30°

133°

17°

e^+ @ 4GeV

“Backward” direction

“Forward” direction
Belle II
The detector
Belle II
Interaction point region

new
Two layers of DEPFET high granularity pixel detector

new (larger)
Silicon vertex detector
double sided Si microstrips

new (larger)
Drift chamber tracking
wires in 50:50 He:C\textsubscript{2}H\textsubscript{6}
Belle II
The detector

- **new Barrel PID**
  - quartz bars totally internally reflect Cherenkov photons

- **new** Endcap PID:
  - Aerogel RICH

- **Magnet**
  - 1.5T

- **Electromagnetic calorimeter**
  - CsI(Tl) crystals... **new readout**

- **$K_L$ and muon detectors**
  - Resistive plate chambers + **(new) scintillator** w/ iron flux return
So when do you start taking data?

Right now: cosmics

Commissioning $e^+e^-$ collisions, w/o vertex detector ~February 2018

Target dataset: 50 ab$^{-1}$

'Belle dataset: ~0.7 ab$^{-1}$ @ Y(4S)

'Run 1' Full physics data w/ vertex detector ~January 2019

Integrated luminosity (ab$^{-1}$)

Peak luminosity (cm$^{-2}$s$^{-1}$)
So when do you start taking data?

- Right now: cosmics

- Target dataset: 50 ab⁻¹

- Commissioning e⁺e⁻ collisions, w/o vertex detector ~February 2018

- 'Run 1': Full physics data w/ vertex detector ~January 2019

- Belle dataset: ~0.7 ab⁻¹ @ Y(4S)

- A nice rule of thumb: 1.1×10⁹ Y(4S)→BB per ab⁻¹; 1M[BB]/fb⁻¹; 1G[BB]/ab⁻¹
This talk

- Why rare B decays?
- The next generation B-factory
  - SuperKEKB
  - Belle II
- Prospects at Belle II
  - Inclusive analyses in general, and $B \to X_{s,d} \gamma$
  - Lepton (non) universality
  - $B \to K(\ast)\nu\nu$
  - $B_{(s)}\to\tau\tau$; $B \to K(\ast)\tau\tau$
- Conclusions
1. Fully inclusive

- Exploit clean decay environment at Belle II c.f. LHCb.
- Can be fully hadronic tag (have full event information)
- ...or semi-leptonic tag (don't have full event information)

2. Sum-of-exclusives

- Reconstruct, the 'X' from many exclusive decays:
  \( X_s \rightarrow K n \pi, 3K m \pi, K \eta m \pi \) (\( n>1, m \geq 1 \)).
- Specify flavour if X (\( X_s \) or \( X_d \)).
- Know flavour of B.
- Know isospin.

| Tag                | FR\(^2\) @ Belle | FEI @ Belle MC | FEI @ Belle II MC |
|--------------------|------------------|----------------|-------------------|
| Hadronic \( B^+ \) | 0.28 %           | 0.49 %         | 0.61 %            |
| Semileptonic \( B^+ \) | 0.67 %       | 1.42 %         | 1.45 %            |
| Hadronic \( B^{+0} \) | 0.18 %         | 0.33 %         | 0.34 %            |
| Semileptonic \( B^0 \) | 0.63 %       | 1.33 %         | 1.25 %            |
Inclusive analysis strategies

1. Fully inclusive

- Exploit clean decay environment at Belle II
- Can be used in exclusive decays
  (have full event information)
- ...or semi exclusive (don't have full event)

| Tag | Hadronic $B^+$ | Semileptonic $B^+$ |
|-----|----------------|-------------------|
| Hadronic $B^+$ | 0.67 % | 1.42 % |
| Semileptonic $B^+$ | 0.18 % | 0.33 % |
| Hadronic $B^+$ | 0.18 % | 0.33 % |
| Semileptonic $B^+$ | 0.63 % | 1.33 % |

2. Sum-of-exclusives

- Reconstruct the 'X' from many exclusive decays
- Know flavour of $B$
- Specify flavour if $X$ (either $K^0$, $D^0$, or $X_d$)

![Diagram showing inclusive analysis strategies](image)
**B → X_{s,d}γ**

- **Belle II 'golden channel'.**
  - High yield. Usually good S/B ratio.

- **Sub-percent level** uncertainties for $A_{CP}$, $\Delta A_{CP}$, Isospin asymmetry ($\Delta_{0+}$) w/ 50ab$^{-1}$

- **Percent level** uncertainties for branching fraction, and time-dependent CPV ($S_{CP}$), and $|V_{td}/V_{ts}|$

---

### Table 1.1: Observables accessible in analysis with hadronic tagging, since the momentum of B to Belle II instead systematic uncertainties will dominate at Belle due to the limited number of events at Belle II, can be directly measured with a fully-inclusive analysis. With lepton tagging, the branching ratio measurement can be used to reduce the uncertainty. The hadronic tagging provides a straightforward method tagging.

| reco. method         | tagging | effi.   | $S/B$  | $q$ | $p_B$ | $A_{CP}$ | $\Delta_{0+}$ | $\Delta A_{CP}$ |
|----------------------|---------|---------|--------|-----|-------|----------|---------------|-----------------|
| sum-of-exclusive     | none    | high    | moderate | $s$ or $d$ | yes  | yes  | yes  | yes            |
| fully-inclusive      | had. $B$| very low| very good| $s$ and $d$ | yes  | yes  | yes  | yes            |
|                      | SL $B$  | very low| very good| $s$ and $d$ | no   | yes  | yes  | yes            |
|                      | L       | moderate| good     | $s$ and $d$ | no   | yes  | no   | no             |
|                      | none    | very high| very bad | $s$ and $d$ | no   | no   | no   | no             |

---

The photon spectrum in the lepton tagging analysis. The branching ratio measurement with the sum-of-exclusive method has compared to the fully-inclusive method. BaBar measured the branching ratio of $B$-meson momentum with hadronic tagging, can be used to reduce the latter source of uncertainty by dedicated studies of the cluster shape in the calorimeter. A possible to reduce this uncertainty by dedicated measurements. At Belle II it should be possible to reduce this uncertainty by dedicated measurements. At Belle II it should be possible to reduce this uncertainty by dedicated measurements.
B→X_{s,d}γ

- **Belle II 'golden channel'.**
  - High yield. Usually good S/B ratio.

- **Sub-percent level** uncertainties for $A_{\text{CP}}$, $\Delta A_{\text{CP}}$, Isospin asymmetry ($\Delta_0^+$) w/ 50ab$^{-1}$

- **Percent level** uncertainties for branching fraction, and time-dependent CPV ($S_{\text{CP}}$), and $|V_{td}/V_{ts}|$

---

**Reco. Method**

| reco. method       | tagging         | effi.   | $S/B$    | $q$ | $p_B$ | $A_{\text{CP}}$ | $\Delta_0^+$ | $\Delta A_{\text{CP}}$ |
|--------------------|-----------------|---------|----------|-----|-------|-----------------|--------------|---------------------|
| sum-of-exclusive   | none            | high    | moderate | $s$ or $d$ | yes  | yes  | yes  | yes  |
| fully-inclusive    | had. $B$        | very low| very good| $s$ and $d$ | yes  | yes  | yes  | yes  |
|                    | SL $B$          | very low| very good| $s$ and $d$ | no   | yes  | yes  | yes  |
|                    | L               | moderate| good     | $s$ and $d$ | no   | yes  | no   | no   |
|                    | none            | very high| very bad | $s$ and $d$ | no   | no   | no   | no   |

---

S Cunliffe (PNNL) | Rare B decays and prospects at Belle II

2 August 2017 | 11
B → X_{s,d} γ

- **Belle II 'golden channel'.**
  - High yield. Usually good S/B ratio.

- **Sub-percent level** uncertainties for $A_{\text{CP}}$, $\Delta A_{\text{CP}}$, Isospin asymmetry ($\Delta_0^+$) w/ 50ab$^{-1}$

- **Percent level** uncertainties for branching fraction, and time-dependent CPV ($S_{\text{CP}}$), and $|V_{td}/V_{ts}|$

| reco. method     | tagging | effi.   | $S/B$    | $q$  | $p_B$ | $A_{\text{CP}}$ | $\Delta_0^+$ | $\Delta A_{\text{CP}}$ |
|------------------|---------|---------|---------|-----|-------|----------------|-------------|------------------------|
| sum-of-exclusive | none    | high    | moderate| $s$ or $d$ | yes | yes | yes | yes | yes |
| fully-inclusive  | had. $B$| very low| very good| $s$ and $d$ | yes | yes | yes | yes | yes |
|                  | SL $B$  | very low| very good| $s$ and $d$ | no  | yes | yes | yes | yes |
|                  | L       | moderate| good     | $s$ and $d$ | no  | yes | no  | no  | no  |
|                  | none    | very high| very bad | $s$ and $d$ | no  | no  | no  | no  | no  |
Lepton (non) universality; $b \to s \ell \ell$

- Not a Belle II golden channel (silver, bronze?).
- Independent verification strongly desired, since this is a hot topic.
- Ratio built from inclusive decays "$R_{X_s}$" only[?] possible at Belle II.
- Better electron recovery at Belle II than LHCb.

**Prospects Belle II**

- $R_K$, $R_{K^*}$, $R_{X_s}$
- Electron and muon modes have similar efficiency
- Sensitive to both low $q^2$ and high $q^2$ ($q^2 > 14.4$ GeV$^2$)
- The errors reach to $\approx 2\%$ for all $K$, $K^*$ and $X_s$ modes
- Lepton ID systematics is about $\pm 0.4\%$ at Belle II
Not a Belle II golden channel (silver, bronze?).

Independent verification strongly desired, since this is a hot topic.

Ratio built from inclusive decays "R_{Xs}" only possible at Belle II.

Better electron recovery at Belle II than LHCb.
Another Belle II 'golden channel'

Observable at Belle II (if SM)
- 10-12% uncertainty w/ 50ab⁻¹

Use full event reconstruction
- Exploit the missing energy + sum of missing 3 momentum in CoM frame $(E^*_{\text{miss}} + cp^*_{\text{miss}})$
\( \mathcal{B}_{(s)} \to \tau \tau; \ B \to K(\ast) \tau \tau \)

- Very challenging to measure at LHCb.
- *Rare + missing energy*: not observable in Belle II assuming SM.
- Limit on branching fraction of \( \mathcal{B} \to K(\ast) \tau \tau \) @ \( 10^{-6} \) with \( 50 \text{ab}^{-1} \).
  - c.f. SM \( 10^{-7} \).
- Limit on branching fraction of \( \mathcal{B} \to \tau \tau \) @ \( 10^{-5} \) with \( 50 \text{ab}^{-1} \).
  - c.f. SM \( 10^{-7} \). Enhanced by LH currents to \( 10^{-6} \).
  - \( B_s \) mode dependent on SuperKEKB running schedule: \( \Upsilon(5S) \to B_s B_s \).
- Interesting case for R&D, tagging improvements, reconstruction improvements. Recall tagging efficiencies \(<2\%\).
- Other interesting possible LFV, LNU searches only possible at Belle II with full event reconstruction: \( B \to (K(\ast))e\tau, \ B \to (K(\ast))\mu\tau. \)
Conclusions

- Commissioning collisions 2018.
- **Full detector physics** data expected to start in 2019.
  - Quickly overtake Belle dataset.
- Target data sample **50ab⁻¹**
  - Roughly 1G[BB pairs] per ab⁻¹ @ Y(4S)

| Decays | Comment |
|--------|---------|
| $B \to X_{s,d} \gamma$ | improve precision |
| $B \to K^{(*)} \nu \nu$ | will observe if SM |
| $B_{(s)} \to \tau \tau$; $B \to K^{(*)} \tau \tau$ | limit if SM, possible in some NP scenarios |
| $B \to X_{\ell \ell}$; $R_{X_s}$ | independent check of LHCb, strong $C_9^{NP}$ constraints |
| $B \to K^{(*)} \ell \ell$; $R_{K,K^*}$ | check of LHCb's indications of LNU |
Conclusions

- **Commissioning collisions** 2018.
- **Full detector physics** data expected to start in 2019.
  - Quickly overtake Belle dataset.
- **Target data sample** **50ab**
  - Roughly 1G[BB pairs] per ab⁻¹ @ Y(4S)

| Decay          | Result                                                                 |
|----------------|------------------------------------------------------------------------|
| B → X_{s,d}γ   | improve precision                                                      |
| B → K(*)νν     | will observe if SM                                                     |
| B_{(s)} → ττ; B → K(*)ττ | limit if SM, possible in some NP scenarios                           |
| B → X_{ll}; R_{X_{s}} | independent check of LHCb, strong C_{9}^{NP} constraints                     |
| B → K(*)ll; R_{K,K*} | check of LHCb's indications of LNU                                  |

S Cunliffe (PNNL) | Rare B decays and prospects at Belle II
2 August 2017 | 15
Extra material
SuperKEKB
Second generation B factory

The Intensity Frontier

Targets:
- Instantaneous luminosity: \(8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}\)
- Integrated luminosity: \(50 \text{ab}^{-1}\) by 2024
Inclusive $b \rightarrow s l l$

- (Obviously) detailed angular analysis not possible in inclusive scheme (hadron fragments).

- Percent level uncertainty for $d B/dq^2$, forward-backward asymmetry of leptons, $A_{FB}$.

Assume $C_9^{NP}$, add Belle II inclusive measurements into exclusion plot.

Will push the 'discrepancy' way into 'observation' land (i.e. <6σ)
B → D(*)τν

- **Percent level** uncertainties on (individual) ratio of branching fractions $B \rightarrow D(*)\tauν$ to $B \rightarrow D(*)\ellν$, $R(D(*))$, and polarisations of $D^*$ and $τ$.
- **Becomes** **systematics limited** before 5ab$^{-1}$.

**FIG. 11:** $B \rightarrow D(*)\tauν$ measurements.

**FIG. 12:** $B \rightarrow D(*)\tauν$ summary.
Current R&D: machine learning
Benchmarking with $B \rightarrow K^* \gamma$

- Improvements seen with TensorFlow neural networks c.f. TMVA
  [https://www.tensorflow.org]

- Becoming industry standard, actively maintained / improved.

- Benchmarking in 'easy' mode: precursor to trying out with more complex analysis (e.g. $B \rightarrow K^{(*)}\tau\tau$).

---

**Belle II** simulation, preliminary

![Graph showing signal efficiency versus background rejection comparison between TensorFlow, Tuned BDT, TMVA-BDT, and TMVA-NN.](image-url)