# The Belle II Experiment


Hannah Wakeling

Supervisor: Prof. S. Robertson

McGill



## Abstract

Belle II is a particle detector in Japan which studies the decay daughters from collisions of high energy electrons and their antimatter counterparts, positrons. A B meson - predominantly produced at Belle II - decaying to a $D^{(*)}$ meson, a τ lepton and a τ neutrino *could* indicate that new physics exists beyond the current Standard Model of particle physics as recent measurements of this decay showed a deviation from the expected decay rate. This could lead to the uncovering of either a new, unmeasured particle, or - even more optimistically - a whole new realm of particles. The Belle II Collaboration aims to further this hunt for new physics through measuring this decay with the highest amount of B meson data ever collected in order to confirm whether or not new physics has been observed.


## Introduction

Previous $B$ factory success culminated in the 2008 Nobel prize in physics through experimental confirmation of the theory that simultaneously explained the matter/antimatter asymmetries in particle interactions and predicted the 3rd generation of fundamental particles.

*So why another $B$ factory?*

- Belle II aims to:
  1. reach a new intensity frontier
     - Target Instantaneous Luminosity: $\mathbf{L_{peak} = 8x10^{35}\ cm^{-2}s^{-1}}$.
     - Target Integrated Luminosity: $\mathbf{L_{int} > 50\ ab^{-1}}$. ($\sim\mathcal{O}(10^2)$ larger than Belle + BABAR)
  2. look for new physics (NP) in decays of heavy flavour particles
  3. search for new exotic states (X, Y, Z, … )

- $e^-$ and $e^+$ are collided **asymmetrically** at 7 and 4 GeV at the SuperKEKB particle accelerator.
- The beam energies were chosen due to the $\Upsilon(4S)$ resonance, seen in Figure 1. It decays predominantly to large numbers of $B$-anti-$B$ meson pairs, hence the facility is known as a $B$ factory.
- The Belle II detector is designed to find **New Physics** beyond the Standard Model (SM) of

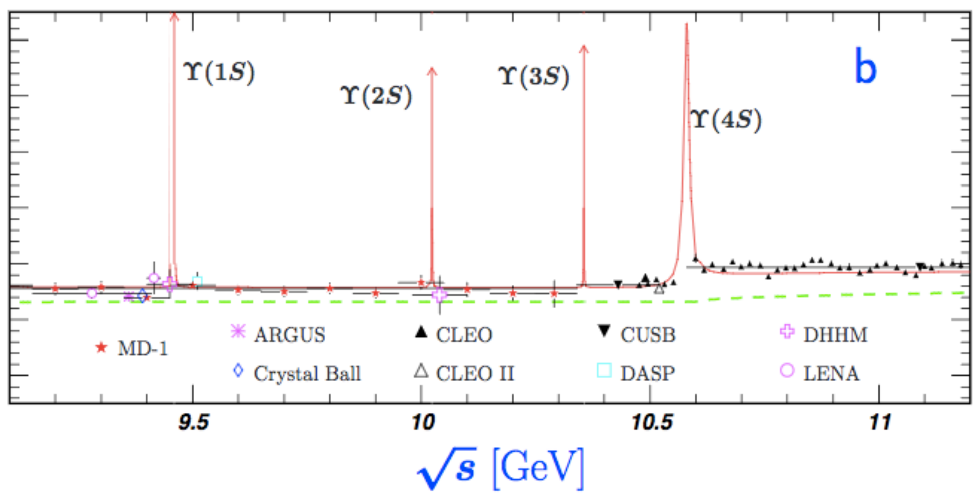


Figure 1: The Upsilon resonances. Y(4S) is the resonance produced at Belle II.

## The Belle II Detector

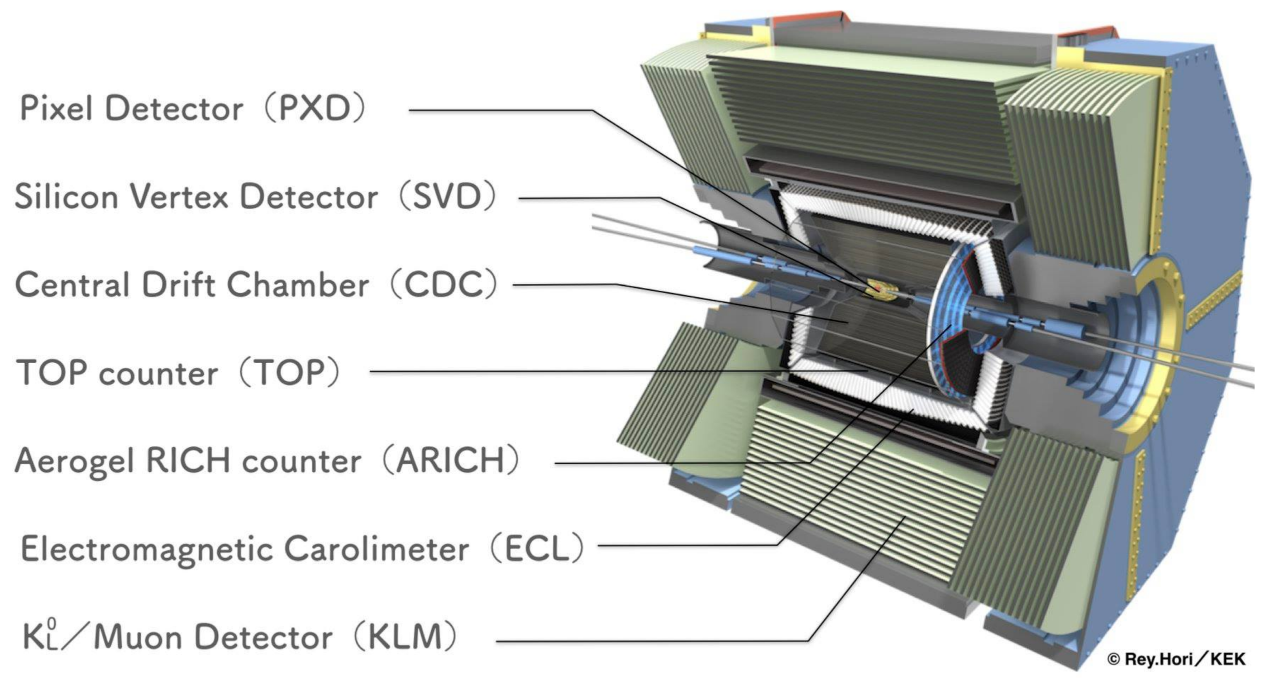


Figure 2: A schematic of the Belle II detector.

- SuperKEKB/Belle II started taking data in March 2018 with 'Phase 2' (without the SVD and PXD), and has now commenced 'Phase 3' (with the SVD and PXD).
- The Belle II Collaboration contains over 900 members from 26 different countries and is still growing!

## Missing Energy at the Belle II Detector

- Missing energy (i.e. $\nu$s) will allow us to probe for signs of physics beyond the Standard Model.
- Anomalies have already been observed in data.
- The luminosity at Belle II significantly improves the precision on measurements of $B$ and $D$ mesons and the $\tau$ lepton decays and should be able to resolve these observed anomalies!
- However $B$ decays with missing energy are limited in their available kinetic information.
- To identify the signal decay one has to exclusively reconstruct one of the $B$ meson decays (the 'tagged $B$' or $B_{\text{tag}}$).
- This constrains the 4-momentum and the flavour of the other $B$ ('signal $B$' or $B_{\text{sig}}$)

  i.e. whether it was constructed from a *b* quark or an anti-*b* quark.

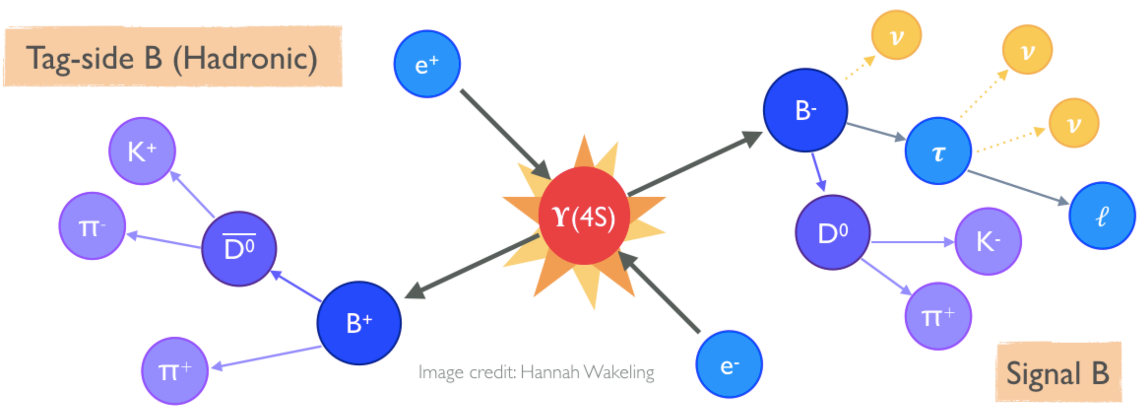


Figure 3: An example decay inside the Belle II detector. The hadronic tag-side $B$ is well defined, whereas the signal $B$ has missing energy.

## Tagging the $B$ meson

- There are two ways we can tag:
  1. **Hadronic tagging**: $B_{\text{tag}}$ is fully reconstructed in numerous hadronic decays.
  2. **Semileptonic tagging**: $B_{\text{tag}}$ is partially reconstructed in semileptonic decays.
- A Belle II specific algorithm, **F**ull **E**vent **I**nterpretation (FEI), **unifies** hadronic and semileptonic tagging.
- It partially recovers missing information and infers strong constraints on our signal candidates by automatically reconstructing the Rest of Event in thousands of exclusive decay channels.
- It combines all of its information into a single 'signal probability' value which allows analysts to chose the highest probability $B_{\text{sig}}$ candidate.

## Rare Decays with Missing Energy at the Belle II Detector

### $B \to \tau\,\nu$

- SM prediction: $\mathscr{Br}$ = (0.77 ± 0.06)x$10^{-4}$.
- Current measurements: $\mathscr{Br}$ = (0.821±0.003)x$10^{-4}$.
- If there is no evidence of NP, it still provides a direct determination of $f_b$ and $|V_{ub}|$.

### $B \to K^{(*)}\,\nu\,\bar{\nu}$

- Flavour changing neutral current prohibited at the tree level in the SM.
- Clean decay to examine and no signal evidence yet.
- Could observe with 18 $ab^{-1}$ of data!

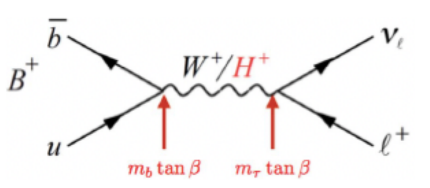

Figure 4: Feynman diagram of the $B \to \tau\,\nu$ decay.

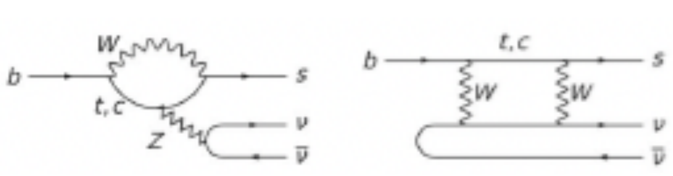

Figure 5: Feynman diagram of the $B \to K^{(*)}\,\nu\,\bar{\nu}$ decay.

### $B \to D^{(*)}\,\tau\,\nu$

- Sensitive to physics beyond the SM

$$R_{D^{(*)}} = \frac{\text{Br}(B \to D^{(*)}\tau\nu_\tau)}{\text{Br}(B \to D^{(*)}\ell\nu_\ell)}$$

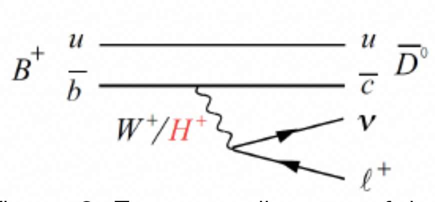

Figure 6: Feynman diagram of the $B \to D^{(*)}\ell\,\nu$ decay.

- SM prediction:
  - $R(D)_{SM}$ = 0.297 ± 0.017
  - $R(D^*)_{SM}$ = 0.252 ± 0.003
- World average for $R(D^{(*)})$ was in ~4.1$\sigma$ deviation from the SM but recent Belle and LHCb results are consistent with SM for $B \to D^*\ell\nu$
- Lepton universality test: electroweak couplings of leptons to gauge bosons independent of flavour?

Before we measure these rare decays, we have to model detector performance and the high backgrounds that are present at Belle II to be able to distinguish signal from background.

## Measuring the $B \to D^{(*)}\ell\nu$ Decay

To measure $R(D^{(*)})$, we need to measure the normalisation mode, $B \to D^{(*)}\ell\nu$.

1. Model the data we expect to take using Monte Carlo
2. Optimise model to determine the signal of the decay.
3. Analyse results and extract branching ratio values.

Belle II aims to have a preliminary measurement of the hadronic $B \to D^{(*)}\ell\nu$ decay by Summer 2020!

Belle 2 could reach 3% sensitivity for $R(D^{(*)})$ at 50$ab^{-1}$!

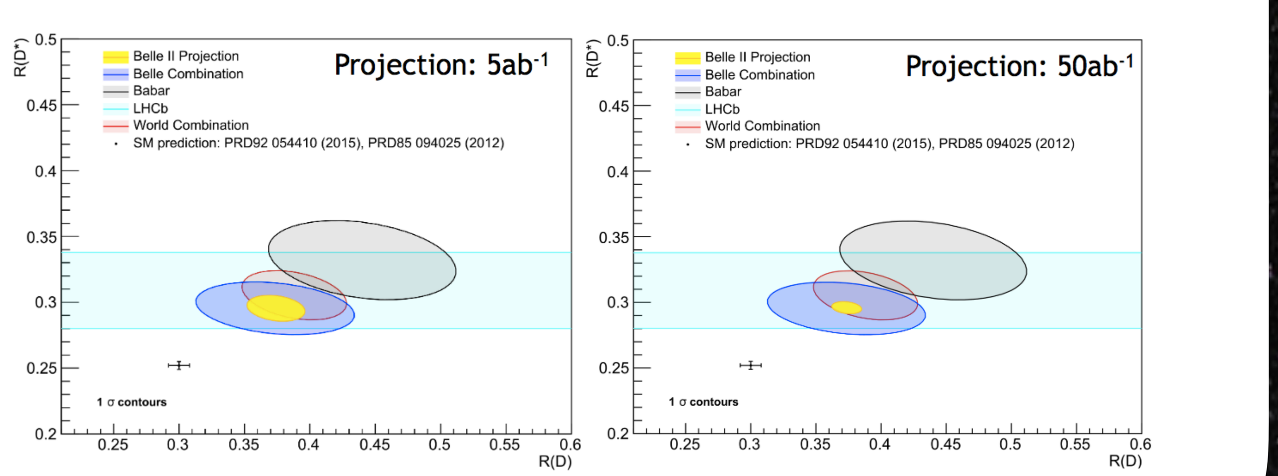


Figure 7: The projection for the R(D) and R(D*) measurement at the Belle II detector with 5 $ab^{-1}$ (left) and 50 $ab^{-1}$ (right)


## References

[1] The Belle II Collaboration: E. Kou *et al*. The Belle II Physics Book. (2018); arXiv: 1808.10567v4 [hep-ex].

[2] Particle Data Group: M. Tanabashi *et al.* Phys. Rev. D 98, 030001 (2018).