An introduction to the Belle II detector/experiment

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Introduction

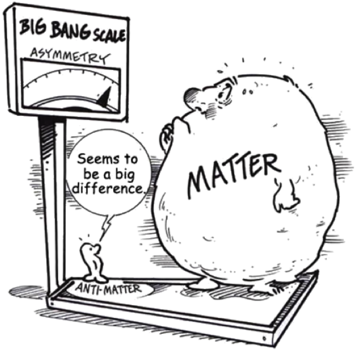
The Standard Model (SM) fails to describe key observations from cosmology:

- No dark matter candidate
- No explanation for matter-antimatter asymmetry

$\Rightarrow$ Motivates searches for non-SM physics

Belle II searches at the **intensity frontier**

- Generate $B\overline{B}$ pairs over and over again
- Measure their decay extremely precisely
- Observation of new particles/forces by deviations from the SM expectation



$B\overline{B}$ Pair Production

$B\overline{B}$ production at the **SuperKEKB** accelerator:

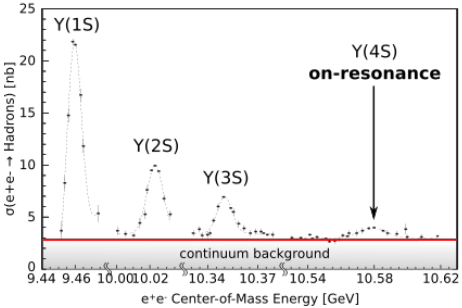
e^+e^- collision at 10.58 GeV

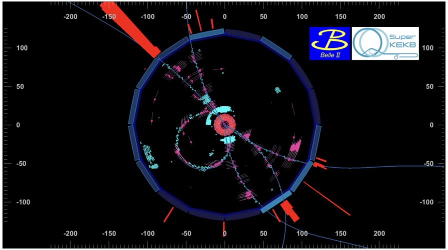
- $\Upsilon(4S)$ resonance (bound $b\overline{b}$ state)

$\approx$ 4 background events per signal event

96% of $\Upsilon(4S)$ decay into $B(b, u/d)\overline{B}$ pairs and nothing else

no heavier $B\overline{B}$ pairs allowed $(b, s/c)$



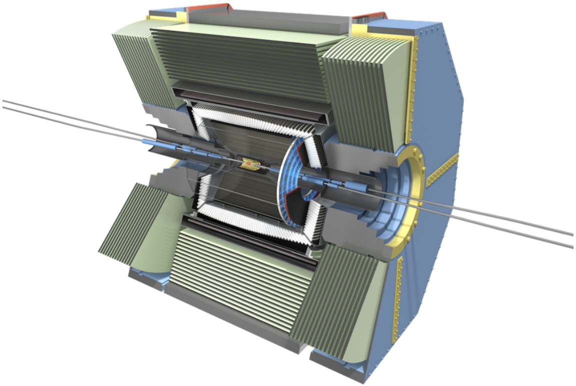


$B\overline{B}$ Pair Detection

Belle II: general purpose detector situated at the interaction point of SuperKEKB

$B\overline{B}$ pairs produced (almost) at rest $\Rightarrow$ spherical event shape $\rightarrow$ 4π detector

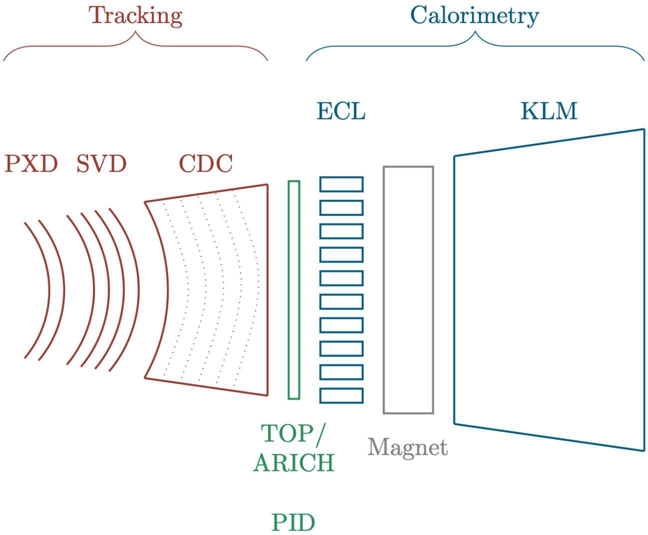
know the beam energy and
can measure all decay particles
$\Rightarrow$ Precise knowledge of kinematics
$\Rightarrow$ Good neutral reconstruction
$\Rightarrow$ If one B is reconstructed all tracks/energy clusters have to belong to the other B



Operation:

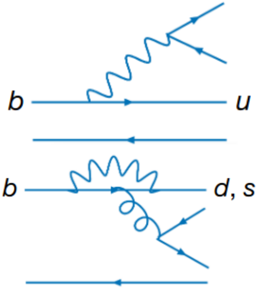
- Recorded: 387 million $B\overline{B}$ pairs until 2022

Belle II Detector Schematically



Non-Leptonic Charmless B Decays

- Hadronic B decays, where $b \to u, d, s$ but not $b \to c$
- Cabbibo-suppressed $b \to u$ tree-level diagram
- Non-negligible contribution from $b \to d, s$ loop-level diagrams
  $\Rightarrow$ Sensitive to non-SM physics



Searches for non-SM physics at the intensity frontier:

$$f_{\mathrm{Exp}} \pm \delta_{\mathrm{Exp}} = f_{\mathrm{SM}} \pm \delta_{\mathrm{SM}} + f_{\mathrm{BSM}} \pm \delta_{\mathrm{BSM}}$$

- QCD effects make theory calculation difficult

Iso-spin sum-rule

Combination of isospin-related decays cancels theoretical and experimental uncertainties, and provides a test for non-SM physics:

$$I_{K\pi} = \mathcal{A}^{\mathrm{CP}}_{K^+\pi^-} + \mathcal{A}^{\mathrm{CP}}_{K^0\pi^+} \frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0} \frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^0\pi^0} \frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

Theoretical precision: $\mathcal{O}(0.01)$, Experimental precision: $\mathcal{O}(0.1)$

- Direct CP asymmetry $\mathcal{A}^{\mathrm{CP}}_{K^0\pi^+}$: Rate of $B^+ \to K^0\pi^+$ vs rate of $B^- \to K^0\pi^-$
- Branching fraction $\mathcal{B}_{K^0\pi^+}$: Rate of $B^+ \to K^0\pi^+$ plus rate of $B^- \to K^0\pi^-$

Belle II is a unique place to measure all involved decays!

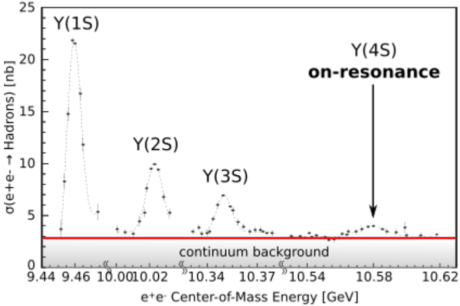
Analysis Overview

- **Reconstruction**: Combine final state particles from tracks (K^+, π^-) and energy clusters not associated with a track (π^0) to B candidates
- **Selection**: Apply selection to suppress background
- **Fit**: Extract models from simulation for signal and remaining background, fit to experimental data and evaluate physics quantities
- **Systematic Uncertainties**: Estimation of systematic uncertainties

Reconstruction and Selection

- Reconstruct charged particles (K^+, π^-) from tracks and energy clusters not associated with a track (π^0) and obtain momentum and energy
- Combine them in kinematic fits to reconstruct B candidates according to decay topology
  $\Rightarrow B \rightarrow K^0(\rightarrow K_S^0 \rightarrow \pi^+\pi^-)\ \pi^+$
  $\Rightarrow B \rightarrow K^+\pi^0(\rightarrow \gamma\gamma)$
  $\Rightarrow B \rightarrow \pi^+\pi^0(\rightarrow \gamma\gamma)$
- Impose selection criteria
  $\Rightarrow$ Detector acceptance
  $\Rightarrow$ Reconstructed energy and mass
  $\Rightarrow$ Reconstruct track as pion or kaon based on response of PID system

Selection Cont'd

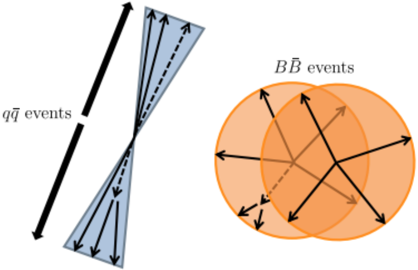


Exp. challenges: $\mathcal{B} \approx \mathcal{O}(10^{-5})$

$\Rightarrow$ large contribution from $e^+e^- \rightarrow q\bar{q}$ (continuum background)

Exploit different event topologies to suppress continuum background

$\Rightarrow$ Train machine learning algorithm on discriminating event shape variables



Fit $B^0 \to K^0\pi^+$

After selection, background remains

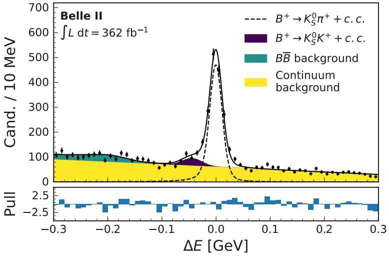
$\Rightarrow$ Perform fit of sample composition to estimate signal and background contribution

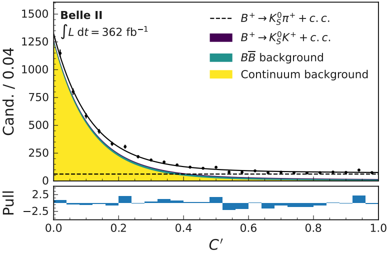
$\Rightarrow$ 2D fit in $\Delta E = E_B^* - E_{\text{beam}}^*$ and MVA output

$\Rightarrow$ Fit models extracted on simulated data

$\Rightarrow$ 11 free parameter (signal and background yield, and background shape)

$$\mathcal{A}^{\text{CP}} = \quad (4.6 \pm 2.9 \;\; (\text{stat}) \pm 0.7 \;\; (\text{syst}))\,\%$$
$$\mathcal{B} \quad = (24.37 \pm 0.71 \; (\text{stat}) \pm 0.86\,(\text{syst})) \times 10^{-6}$$





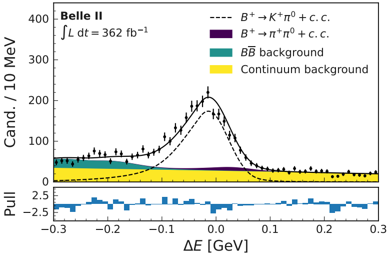
Fit $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$

After selection, background remains

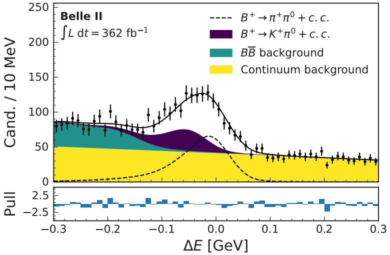
$\Rightarrow$ Similar fit to previous slide

$\Rightarrow$ Samples are fitted simultaneously to properly account for cross feed

$\Rightarrow$ π^0 energy leakage in calorimeter, broadens signal ΔE peaks



$$\mathcal{A}^{CP}_{K^+\pi^0} = (1.3 \pm 2.7\ \text{(stat)} \pm 0.5\ \text{(syst)})\%$$
$$\mathcal{B}_{K^+\pi^0} = (13.93 \pm 0.38\ \text{(stat)} \pm 0.71\ \text{(syst)}) \times 10^{-6}$$
$$\mathcal{A}^{CP}_{\pi^+\pi^0} = (-8.1 \pm 5.4\ \text{(stat)} \pm 0.8\ \text{(syst)})\%$$
$$\mathcal{B}_{\pi^+\pi^0} = (5.10 \pm 0.29\ \text{(stat)} \pm 0.27\ \text{(syst)}) \times 10^{-6}$$



Systematic Uncertainties

Branching fraction

Source	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K^0_S\pi^+$
Tracking	0.2	0.2	0.7
$N_{B\bar{B}}$	1.5	1.5	1.5
f^{+0}	2.4	2.4	2.4
π^0 efficiency	3.8	3.8	-
K^0_S efficiency	-	-	2.0
CS efficiency	0.7	0.7	0.5
PID correction	0.1	0.2	-
ΔE shift and scale	1.2	2.0	0.3
$K\pi$ signal model	0.1	<0.1	<0.1
$\pi\pi$ signal model	<0.1	<0.1	-
$K\pi$ CF model	<0.1	0.1	-
$\pi\pi$ CF model	<0.1	0.1	-
$K^0_S K^+$ model	-	-	0.1
$B\bar{B}$ model	0.3	0.5	<0.1
$q\bar{q}$ flavor model	-	-	-
Multiple candidates	1.0	0.3	0.1
Total	5.1	5.2	3.6
Stat uncert.	2.8	5.1	2.9

Direct CP violation

Source	$B^0 \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K^0_S\pi^+$
ΔE shift and scale	0.001	0.002	0.001
$K^0_S K^+$ model	-	-	0.001
Fitting bias	-	0.007	0.006
Instrumental asymmetry	0.005	0.004	0.004
Total	0.005	0.008	0.007
Stat uncert.	0.027	0.054	0.029

Iso-spin sum-rule

Iso-spin sum-rule provides null test of standard model:

$$I_{K\pi} = \mathcal{A}^{\mathrm{CP}}_{K^+\pi^-} + \mathcal{A}^{\mathrm{CP}}_{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

Combining measurements with Belle II results for other decays:

$$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$$

Competitive with world average -0.13 ± 0.11

Conclusion

Test of the iso-spin sum-rule is still statistically limited

Belle II is providing competitive results with its current data set (half of Belle, equivalent to BaBar)

$\Rightarrow$ Usage of machine learning

$\Rightarrow$ Better π^0 reconstruction

More to come:

$\Rightarrow$ Dataset used here 387 million $B\overline{B}$ pairs

$\Rightarrow$ Belle II aims to collect $>$ 50000 million $B\overline{B}$ pairs