$B_s \to \tau^+\tau^-$ Physics at Future Z Factories

Ánuar Sifuentes Name

uxtzj@student.kit.edu

Supervisor: Xunwu Zuo

Master's Thesis Update – April 2025

Introduction

Karlsruhe Institute of Technology

Why Study B Meson Decays to Taus at FCC-ee?

$$B_c^+ \rightarrow \tau^+ \nu_\tau$$
$$B^+ \rightarrow \tau^+ \nu_\tau$$
$$B_s \rightarrow \tau^+ \tau^-$$

Motivation

- Anomalies in semileptonic decays:

R_K and R_D ratios show tensions with SM

- **τ channels** interesting because due to strong coupling to New Physics (NP) like:

• Leptoquarks

• Two-Higgs-Doublet Models 2HDMs

• Light Higgs Boson $h \to \tau\ \tau$

- FCC-ee has **clean environment and high luminosity**

	Experimental	SM Prediction	Comments
R_K	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01 [4]	$m^2_{\ell\ell} \in [1.0, 6.0]\mathrm{GeV}^2$, via $B^\pm$.
R_{K^*}	$0.69^{+0.12}_{-0.09}$	0.996 ± 0.002 [5]	$m^2_{\ell\ell} \in [1.1, 6.0]\mathrm{GeV}^2$, via B^0.
R_D	0.340 ± 0.030	0.299 ± 0.003	B^0 and $B^\pm$ combined.
R_{D^*}	0.295 ± 0.014	0.258 ± 0.005	B^0 and $B^\pm$ combined.
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	0.25-0.28 [3]	

Table 1: B-meson anomalies
Credit: arXiv:2012.00665 **[hep-ph]**

Why focus on $B_s \to \tau^+\tau^-$

- SM prediction: very suppressed → ideal to spot New Physics
- $B_s \to \tau^+\tau^-$ Analysis cannot be done in LHC at the moment

→ **FCC may have the first chance to observe this decay**

- Main challenge: Identification of both tau particles in B_s decay
- Potential extensions:
  - Lepton Flavor Violation: $B_s \to \tau^\pm \mu^\mp$, $B_s \to \tau^\pm e^\mp$
  - Exotic decays: h (light Higgs) → $\tau^+ \tau^-$

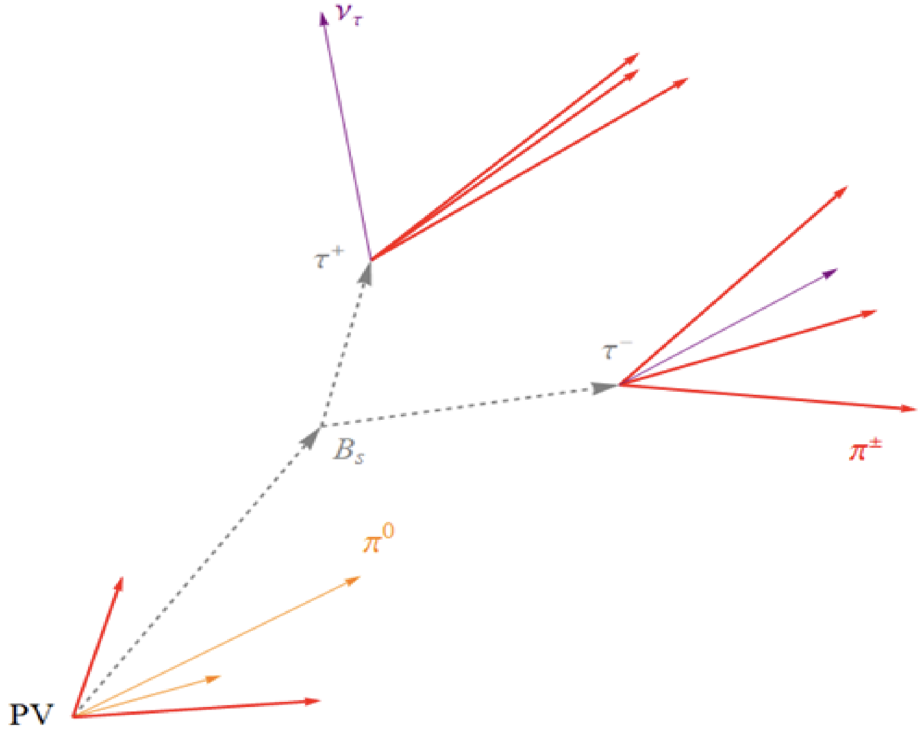

Figure 1: Schematic pictures of $B_s \to \tau^+ \tau^-$
Credit: arXiv:2012.00665 **[hep-ph]**

Dealing with background events

	Properties	Decay Mode	BR
$\tau^\pm$	$m = 1.777\text{GeV}$	$\pi^\pm\pi^\pm\pi^\mp\nu$	9.3%
	$L = 87.0\mu\text{m}$	$\pi^\pm\pi^\pm\pi^\mp\pi^0\nu$	4.6%
$D_s^\pm$	$m = 1.968\text{GeV}$	$\tau^\pm\nu$	5.5%
	$L = 151\mu\text{m}$	$\pi^\pm\pi^\pm\pi^\mp$	1.1%
		$\pi^\pm\pi^\pm\pi^\mp\pi^0$	0.6%
		$\pi^\pm\pi^\pm\pi^\mp 2\pi^0$	4.6%
		$\pi^\pm\pi^\pm\pi^\mp K_S^0$	0.3%
		$\pi^\pm\pi^\pm\pi^\mp\phi$	1.2%
$D^\pm$	$m = 1.870\text{GeV}$	$\tau^\pm\nu$	$< 0.12\%$
	$L = 311\mu\text{m}$	$\pi^\pm\pi^\pm\pi^\mp$	0.31%
		$\pi^\pm\pi^\pm\pi^\mp\pi^0$	1.1%
		$\pi^\pm\pi^\pm\pi^\mp K_S^0$	3.0%

Table 2: Invariant mass and mean decay length (L) of $\tau^\pm$ leptons and charged D mesons
Credit: arXiv:2012.00665 **[hep-ph]**

- $D_s^\pm$ and $D^\pm$ are **main backgrounds (bkg)**
- They can mimic $\tau^\pm$ decays, they also decay in 3 pions
- **Lifetime and mean decay Length is similar**
- combination of preselection:

1. vertex displacement
2. geometric angle ΔΩ

- Isolation variables
- Resonance reconstruction (ρ^0 and a_1)

What Has Been Done Before Bu and Bc Decays

Analysis on $\mathbf{B_c^+} \rightarrow \boldsymbol{\tau^+\nu_\tau}\ \boldsymbol{and}\ \mathbf{B^+} \longrightarrow \boldsymbol{\tau^+\nu_\tau}$

Simulation and samples

- Events simulated using :
- PYTHIA8
- EvtGen
- DELPHES + IDEA detector card
- Campaign: Major Monte Carlo (MC) production efforts for the FCC-ee project.:
- Winter 2023 samples
- Spring 2021 samples
- Samples include
- **Inclusive**: Z→ bb, cc, qq; incluisive decay of every particle
- **Exclusive**: Specific B meson decay chains

Event selection strategy

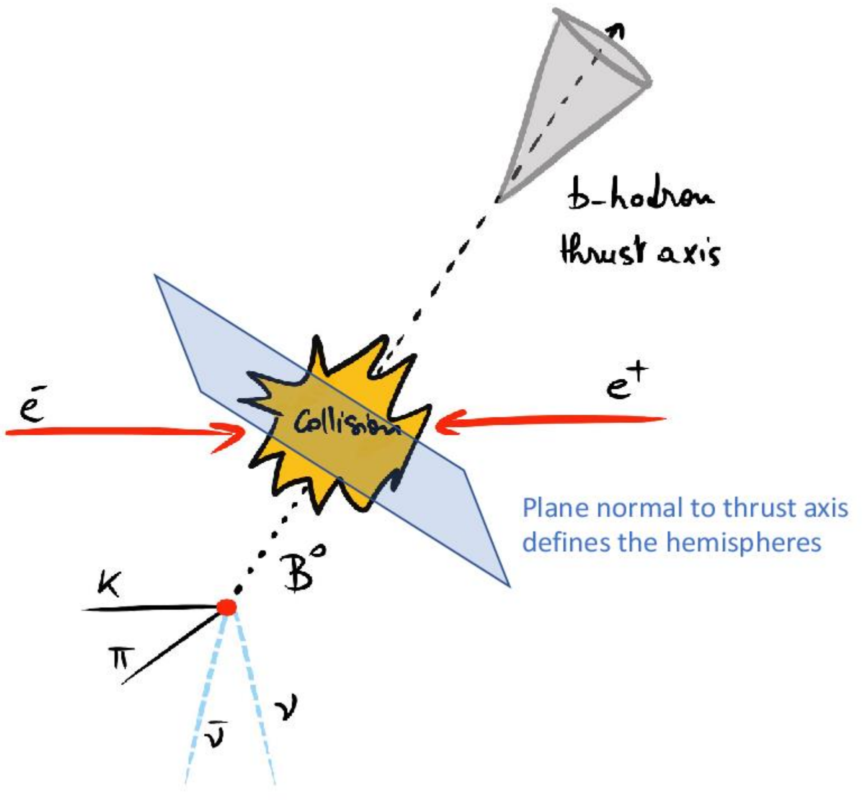

Figure 2: Representation of thrust axis (not our decay)
Credit: Rivière et al. (2024) – *Prospects for searches of $b \to s\, \nu\, \bar{\nu}$* at FCC-ee [ResearchGate link]

- The two b-quarks can be split into two hemispheres
  → **Thrust axis**
- Signal decays involve missing energy from neutrinos
  → **Energy imbalance**
- Bkg have more balanced energy distributions
- Preselection removes obvious background

Tau reconstruction

Karlsruhe Institute of Technology

- Events must have a candidate tau vertex:
  - Candidate is chosen as the **3π vertex** with the smallest vertex fit χ^2 in the signal hemisphere.
  - have an invariant mass below that of the τ lepton
  - have at least one m(π+π−) combination within the range 0.6–1.0 GeV
- Look for **3 pion system**
  - Reconstruct the **mass and number of 3 pion candidates** in the event
- Reconstruct invariant mass of intermediate resonances
  - **$a_1^{\pm}$ and ρ_0 mesons** in the τ decay chain.

$$\tau^+ \longrightarrow \pi^+ \pi^+ \pi^- \nu_\tau$$

Boosted Decision Trees

- **XGBoost-based BDTs** to separate signal from background.
- **BDT1**: General Background Rejection, uses event-level features:
  - Energy balance; Number of tracks; Vertex properties
- Achieved excellent separation in Bu/Bc analyses:
  - ROC Area = 0.983
- **BDT2**: Signal Type classification
- Distinguishes B_c^+, B^+ **and background**
- Uses more refinded methods:
  - **3π system**: mass, thrust angle, multiplicity
  - **Vertex info**: impact parameter, PV mass
  - **D meson tagging**
- Performance
  - AUC (Bc vs non-Bc): **0.921**
  - AUC (Bu vs non-Bu): **0.886**

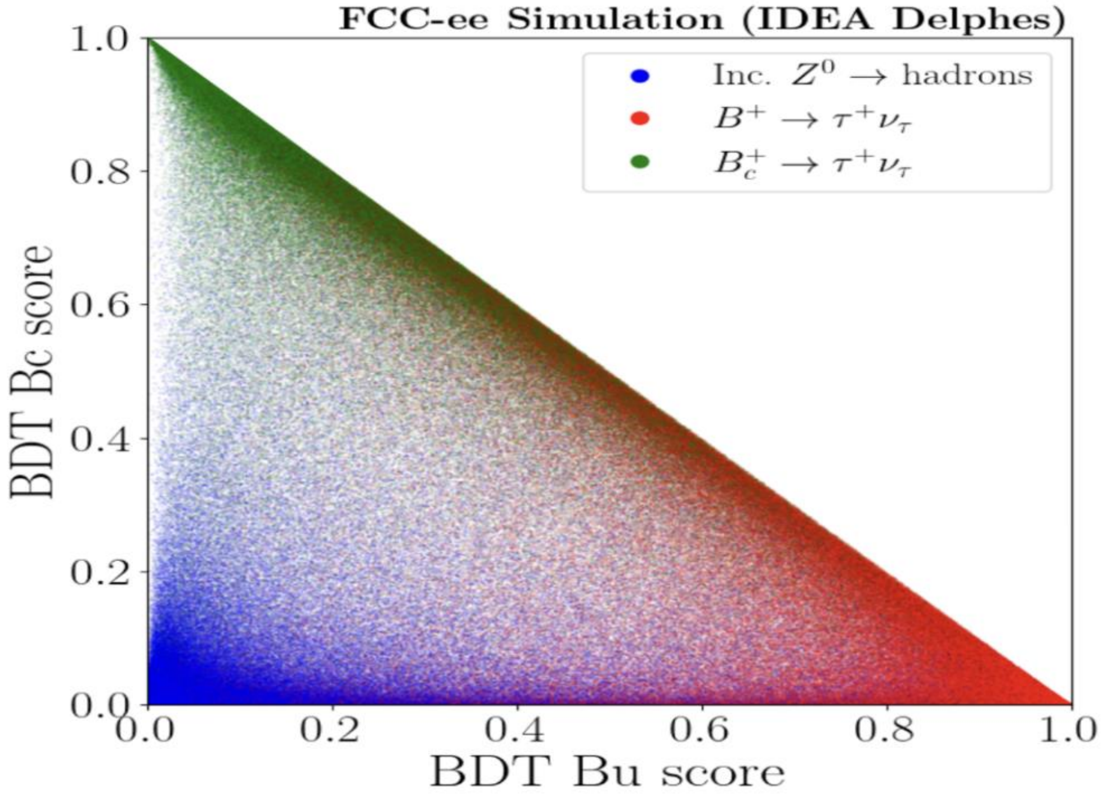

Figure 3:Distribution of second stage BDT output in Bu-Bc plane
Credit: https://arxiv.org/abs/2305.02998

Plans for $B_s \to \tau^+\tau^-$

Analysis Strategy for B_s decays

Analysis strategy

- Two reconstruction methods being studied:
  - **Single jet/cone**: Does the jet structure look like 2 overlapping taus?
  - **Vertex based-method**: Similar to Bu/Bc, but for 2 displaced vertices
- Will train MVAs for:
  - $B_s \rightarrow \tau^+\tau^-$ vs inclusive $Z \rightarrow bb$
- Using isolation, geometry, energy imbalance, and tau reconstruction

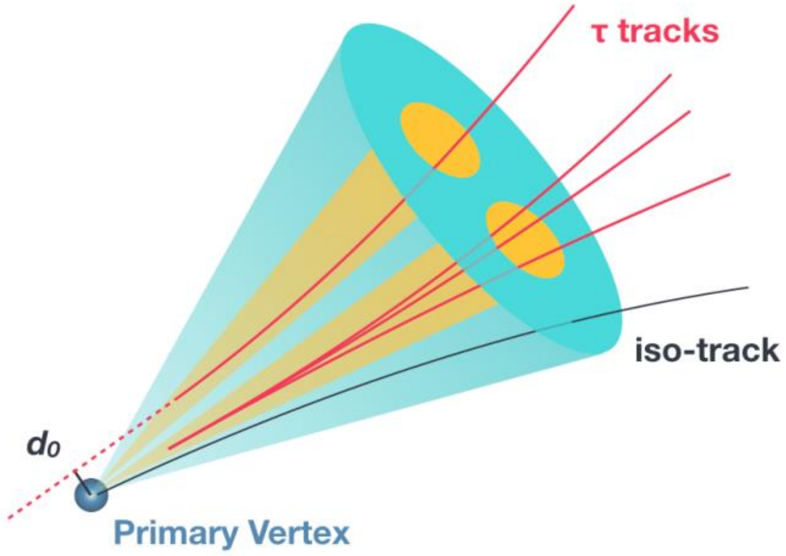

Figure 4: Schematic representation of a di-ττ object
Credit: arXiv:2007.14811CERN-EP-2020-118

Goal and Plan for the study

- Evaluate the potential of FCC-ee to observe rare tau-related B meson decays, in this case $B_s \to \tau^+\tau^-$. (potentially also for $B^0 \to \tau^+ \tau^-$)
- Constrain or reveal New Physics
- **General plan:**
- Understand the physics and relevant decay channels
- Learn about FCC-ee event structure and background sources
- Use machine learning (BDTs) to separate signal from background
- Evaluate how well FCC-ee could measure or constrain these decays

Progress and next steps

Karlsruhe Institute of Technology

What I've done so far:

✅ Studied the relevant decays: **B^+ and $B_c^+ \rightarrow \tau^+\nu_\tau$** (for methodology), and **$B_s \rightarrow \tau^+\tau^-$**

✅ Learned about background processes and their suppression strategies

✅ Understood the role of **BDTs** in separating signals and backgrounds

What comes next:

🔜 **Set up analysis framework** and load FCC-ee bkg samples

🔜 **Set up the 2 reconstruction approaches** and compare results

🔜 Train and evaluate BDTs for **signal–background separation**

🔜 Prepare plots and organize results for internal discussion

Thank you

Questions or feedback are welcome!

Efficiency and Optimization

- In $B_c^+ \, and B^+$ studies optimization is done

  by maximizing: **Purity = S / (S + B)**
- Efficiency is estimated from exclusive simulated decays.
- BDT1 and BDT2 cuts are tuned separately.
- Final cuts chosen to balance signal efficiency and background suppression.
- A 3D efficiency function is evaluated over BDT cut values to find the optimal region