Nov. 29th, 2022 – Belle II Physics Week in Valencia, Spain

$B^0 \to \tau^+\tau^-$ with hadronic FEI

Optimizing cuts with MVA FBDT

Belle II

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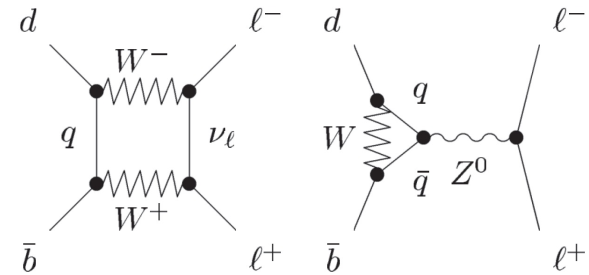
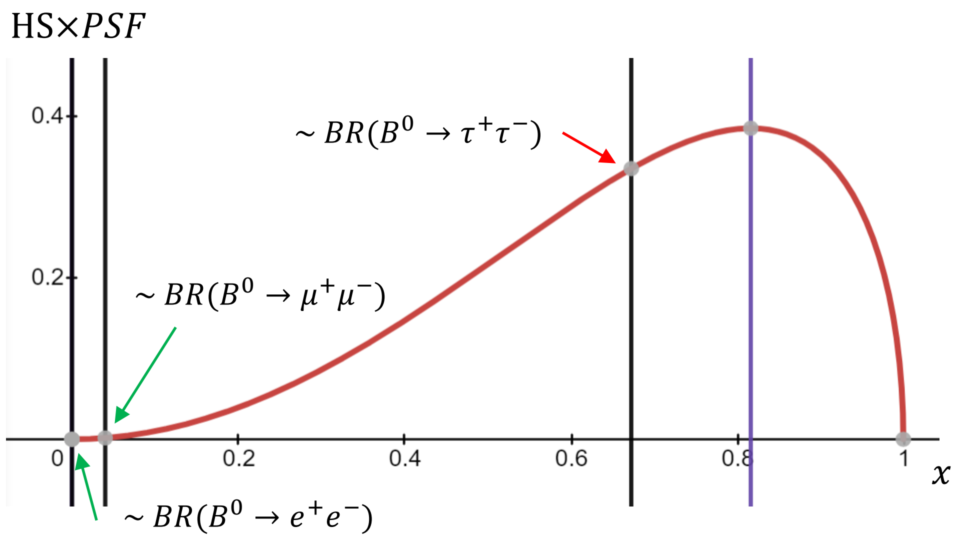
Theoretical calculation with the Effective Field Theory (SM prediction)

$$\mathcal{B}(B^0 \to \ell^+\ell^-) = \frac{G_F^4 M_W^4 M_B^3}{8\pi^5 \Gamma_B} \cdot \underbrace{f_B^2}_{\text{Decay constant}} \cdot \underbrace{|V_{tb}^* V_{td}|^2}_{\text{CKM elements}} \cdot \underbrace{\frac{4m_\ell^2}{M_B^2}}_{\substack{\text{Helicity suppression} \\ \text{(HS)}}} \cdot \underbrace{\sqrt{1 - \frac{4m_\ell^2}{M_B^2}}}_{\substack{\text{Phase space factor} \\ \text{(PSF)}}} \cdot |C_A(\mu)|^2$$



Standard Model Box and Penguin Diagram of $B^0 \to \ell^+\ell^-$



- For $B \to \tau\tau$, ***BR*** is **much higher** because of its **large mass**
  - However, it is **hard** to deal with because
    - τ cannot be detected directly by the detector
    - Sub-decay modes have missing particle
  - **No observation** yet.
- For $B \to \mu\mu$, ***BR*** is **100** times smaller,
  - but muons can be identified with detector level, so it is relatively **easier** to deal with.
- For $B \to ee$, ***BR*** is too small to measure.

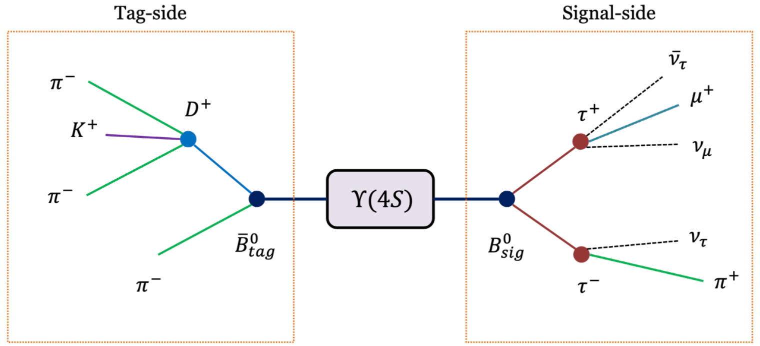
Beyond the Standard Model (BSM)

Theory		Branching fraction	Free parameters (for Enhancement)
SM prediction		$(2.22 \pm 0.19)\times 10^{-8}$ (2014)	-
BSM	2HDM	It can be several orders of magnitude higher	$tan\beta, M_{H^+}$
	Leptoquark		$\frac{\lvert\lambda^{33}\lambda^{13*}\rvert}{M_S^2}$

- Free parameters of BSM models make it possible to expect **enhancement** in the **rare** decay modes.
- The study of $B^0 \to \tau^+\tau^-$ can help to **constraint free parameters** of BSM models
- **Better Theory!**

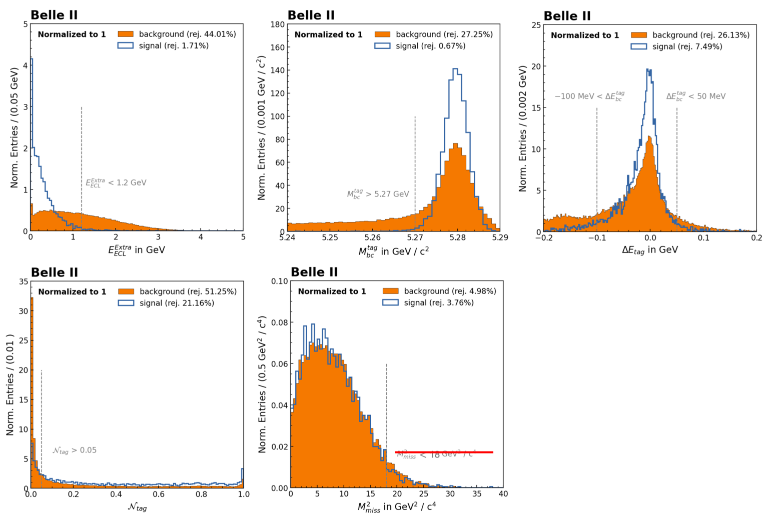
Workflow

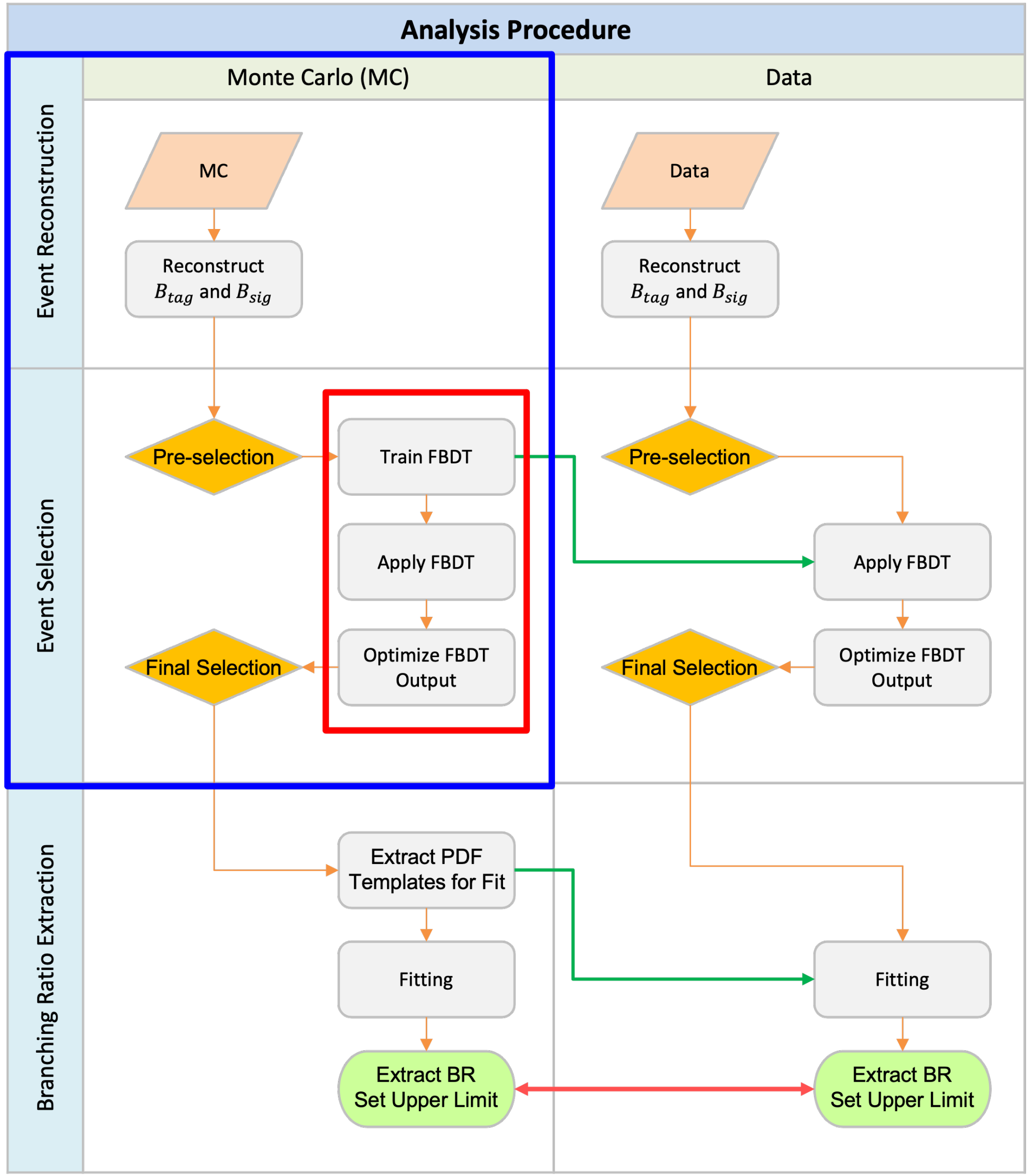
hadronic FEI (B_{tag} Reconstruction)



Pre-selection

Cut	Signal rejection in %	Background rejection in %
$E_{ECL}^{Extra} < 1.2$ GeV	1.71 (99/5788)	44.01 (120849/274604)
$M_{bc}^{tag} > 5.27$ GeV/c²	0.67 (38/5689)	27.25 (41897/153755)
-100 MeV $< \Delta E_{tag} < 50$ MeV	7.49 (423/5651)	26.13 (29228/111858)
$\mathcal{N}_{tag} > 0.05$	21.16 (1106/5228)	51.25 (42349/82630)
~~$M_{miss}^2 < 18$ (GeV/c²)²~~	~~3.76 (155/4122)~~	~~4.98 (2005/40281)~~
Total	~~31.46 (1821/5788)~~	~~86.06 (236328/274604)~~





Analysis Strategy

Similar Analyses

Target	Year	Author	Exp.	Paper	Note	Method	MVA (amount of signal MC)	Signal Extracting Variables (#)
$B^0 \to \tau^+\tau^-$	2016	M. Ziegler	Belle	-	BN-1390	Hadronic FR, **BDT-based**	BDT for Continuum BG (1) BDT for each signal channel (6) 10 M (training) / 5 M (testing) Each channel: 15 M, 90 M in total	E_{ECL} (1)
$B^0 \to \tau^+\tau^-$	2006	BaBar Collaboration	BaBar	PRL	-	Hadronic full recon., Cut-based	-	m_{ES} (1) (M_{bc}^{tag} in Belle language)
$B^+ \to K^+\tau^\pm\ell^\mp$	2022	S. Watanuki	Belle (B1-635)	Submitted to PRL	BN-1576	Hadronic FEI, **BDT-based**	FBDT for $B\bar{B}$ (4 channels) (4) FBDT for $q\bar{q}$ (4 channels) (4) 5 times 5.2 M, total 26 M	M_{recoil} (1) ($= m_\tau$)
$B \to X\tau\nu$	2022	H. Junkerkalefeld	Belle II	-	B2N-PH-2021-042	Hadronic FEI, **BDT-based**	BDT for $q\bar{q}$ vs. $B\bar{B}$ (1)	M_{miss}^2, p_ℓ^* (2)
$B \to X_s\nu\bar{\nu}$	2022	Junewoo Park	Belle II	-	B2N-PH-2022-028	Hadronic FEI, **BDT-based**	FBDT for Sig. vs Bkg. (1) Total 140 M	FBDT output (1)
$B^+ \to K^+\nu\bar{\nu}$	2020	F. Dattola	Belle II (B2-004)	PRL	B2N-PH-2020-057	Inclusive tagging, **BDT-based**	Special BDTs for Inclusive tagging: BDT_1 and BDT_2 (2)	kaon p_T, BDT_2 output (2)
$B \to X_c\ell\nu_\ell$	2021	M. Welsch	Belle II (B2-006)	Submitted to PRD	B2N-PH-2021-002	Hadronic FEI, Cut-based	-	q^2 (1) $(= (p_\ell + p_\nu)^2$ $= (p_B - p_X)^2)$
$B^0 \to \ell^\pm\tau^\mp$	2020	Kyungho Kim	Belle	PhD. Thesis	BN-1531	SL FEI, TMVA MLP	MLP for each signal channel (4) 2 M (training) / 18 M (Testing) Each channel: 20 M, 80 M in total	p_ℓ^* (1)

This Analysis **VS.**

$B^0 \to \tau^+\tau^-$	-	**Cheolhun Kim**	Belle II	-	-	Hadronic FEI, **BDT-based**	**BDT for Continuum BG (1) ?** **BDT for each signal channel (6) ?**	**E_{ECL} (1) ?**

MVA: Should be decided

- ***How many BDTs?***
  - Case 1: 1 BDT
    - Signal MC vs. Background MC (1 BDT)
  - Case 2: 6 BDTs
    - Signal MC (6 sub-decay channels) vs. Background MC (6 BDTs)
  - Case 3: 2 BDTs
    - Signal MC vs. Continuum MC (1 BDT)
    - Signal MC vs. Generic MC (1 BDT)
  - Case 4: 7 BDTs
    - Signal MC vs. Continuum MC (1 BDT)
    - Signal MC (6 sub-decay channels) vs. Generic MC (6 BDTs)
  - Case 5: 12 BDTs
    - Signal MC (6 sub-decay channels) vs. Continuum MC (6 BDT)
    - Signal MC (6 sub-decay channels) vs. Generic MC (6 BDTs)
  - etc.

Name	τ decay modes
e^+e^-	$\tau \to e\nu_e\nu_\tau$, $\tau \to e\nu_e\nu_\tau$
$e^\pm\mu^\mp$	$\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$
$e^\pm\pi^\mp$	$\tau \to e\nu_e\nu_\tau$, $\tau \to \pi\nu_\tau$
$\mu^+\mu^-$	$\tau \to \mu\nu_\mu\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$
$\mu^\pm\pi^\mp$	$\tau \to \mu\nu_\mu\nu_\tau$, $\tau \to \pi\nu_\tau$
$\pi^+\pi^-$	$\tau \to \pi\nu_\tau$, $\tau \to \pi\nu_\tau$

$B^0 \to \tau^+\tau^-$ sub-decay channels

- ***How many samples are for each BDTs?***

- ***BASF2 Internal MVA package vs. External package***
  - ex) BASF2 Internal MVA package FBDT option vs. Thomas Keck's external FBDT

MVA: My first trial

- ***How many BDTs?***
  - **Case 1: 1 BDT**
    - **Signal MC vs. Background MC (1 BDT)**
  - Case 2: 6 BDTs
    - Signal MC (6 sub-decay channels) vs. Background MC (6 BDTs)
  - Case 3: 2 BDTs
    - Signal MC vs. Continuum MC (1 BDT)
    - Signal MC vs. Generic MC (1 BDT)
  - Case 4: 7 BDTs
    - Signal MC vs. Continuum MC (1 BDT)
    - Signal MC (6 sub-decay channels) vs. Generic MC (6 BDTs)
  - Case 5: 12 BDTs
    - Signal MC (6 sub-decay channels) vs. Continuum MC (6 BDT)
    - Signal MC (6 sub-decay channels) vs. Generic MC (6 BDTs)
  - etc.

Signal (MC14)
$B^0 \to \tau\tau$, 20 M (0.2 / 0.8) BGx0: 4 M / BGx1: 16 M ⇒ **16 M** (hadronic FEI skimmed)
Background (MC14)
※ Skim: **SkimM14ri_ax1** (hadronic FEI skimmed) Generic $B^0\bar{B}^0$ (mixed): **~ 900 fb^{-1}** B^+B^- (charged): **~ 900 fb^{-1}** Continuum u,d,s,c (each): **~ 1000 fb^{-1}**

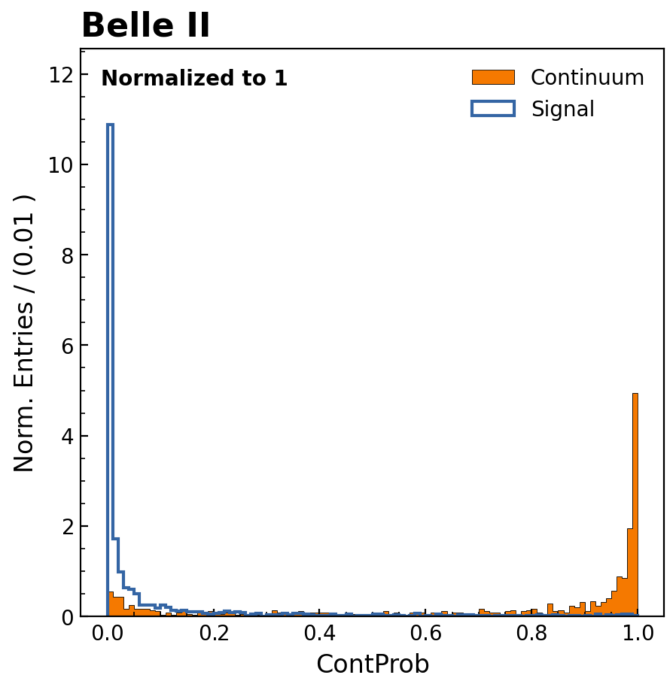
MC Sample Information

- ***How many samples are for each BDTs?***
  - **MC14 (Train : Test = 5 : 5)**
    - Signal MC: **8 M / 8 M**
    - Generic MC: **450 fb^{-1} / 450 fb^{-1}**
    - Continuum MC: **500 fb^{-1} / 500 fb^{-1}**

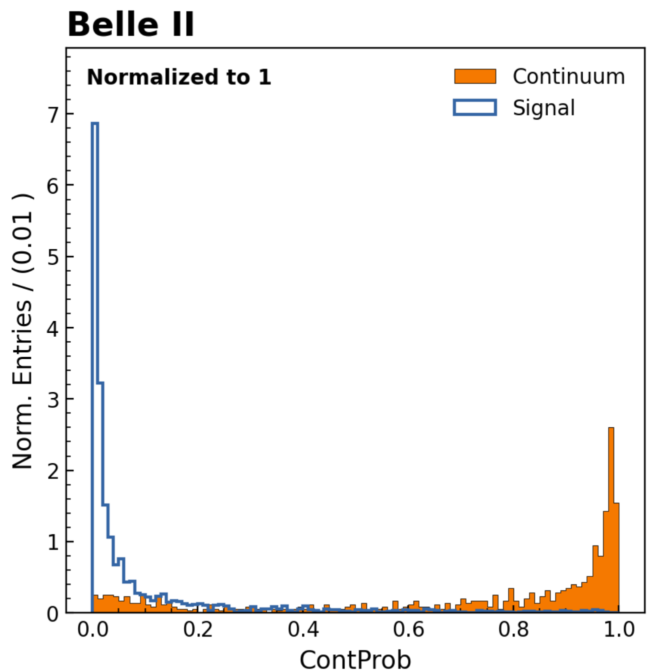
- ***BASF2 Internal MVA package vs. External package***
  - ex) **BASF2 Internal MVA package FBDT option** vs. Thomas Keck's external FBDT

MVA: Status

- **[Done]** Testing Code with a small amount of MC sample
  - **[Done]** BASF2 Internal MVA FBDT
  - **[Done]** Thomas Keck's External MVA FBDT



Internal FBDT



External FBDT

- **[Ongoing]** For all MC sample
  - **[Done]** gbasf2 test
  - The first trial (previous slide)
    - A job submitting script
    - Plot result
    - Testing GridSearch for determining Hyper Parameters

Plan

- Complete the ***first trial***
  - Signal MC vs. Background MC (1 BDT)

- Further trials
  - ***Decide BDT strategy***

- Decide the amount of ***MC15 signal sample*** for production
  - Ask production & FEI skim (WG1 DP/Skim Liaison)
    - ex) 20 M for each 6 sub-decay modes (Total 120 M) ?
      - ex) 10 M for training / 10 M for testing (5 : 5)
      - ex) 16 M for training / 4 M for testing (8 : 2)

- Decide a signal extracting variable
  - ex) A variable (or variables) shows the best separating power
    - E_{ECL} ?

Name	τ decay modes
e^+e^-	$\tau \to e\nu_e\nu_\tau,\ \tau \to e\nu_e\nu_\tau$
$e^\pm\mu^\mp$	$\tau \to e\nu_e\nu_\tau,\ \tau \to \mu\nu_\mu\nu_\tau$
$e^\pm\pi^\mp$	$\tau \to e\nu_e\nu_\tau,\ \tau \to \pi\nu_\tau$
$\mu^+\mu^-$	$\tau \to \mu\nu_\mu\nu_\tau,\ \tau \to \mu\nu_\mu\nu_\tau$
$\mu^\pm\pi^\mp$	$\tau \to \mu\nu_\mu\nu_\tau,\ \tau \to \pi\nu_\tau$
$\pi^+\pi^-$	$\tau \to \pi\nu_\tau,\ \tau \to \pi\nu_\tau$

$B^0 \to \tau^+\tau^-$ sub-decay channels

Backup

Backup

Motivation: Physics / Theory

$B^0 \to ll$ Branching fraction: SM prediction and measurement

	SM prediction	Measurement		
		Detector	Upper Limit	Measurement
$B^0 \to e^+e^-$	$(2.48 \pm 0.21)\times10^{-15}$ [1] (2014)	LHCb	2.5×10^{-9} [2] (2020) (90 % CL) 3.0×10^{-9} [2] (2020) (95 % CL)	-
$B^0 \to \mu^+\mu^-$	$(1.06 \pm 0.09)\times10^{-10}$ [1] (2014)	ATLAS	2.1×10^{-10} [3] (2019) (95 % CL)	$(-0.19 \pm 0.16)\times10^{-9}$ [3] (2019)
		LHCb	3.4×10^{-10} [4] (2017) (95 % CL)	$(0.15^{+0.12}_{-0.10}{}^{+0.02}_{-0.01})\times10^{-9}$ [4] (2017)
$\boldsymbol{B^0 \to \tau^+\tau^-}$	?!! $(2.22 \pm 0.19)\times10^{-8}$ [1] (2014)	LHCb	1.6×10^{-3} [5] (2017) (90 % CL) 2.1×10^{-3} [5] (2017) (95 % CL)	-
		Belle (Not published, Expired, Not official)	-	?!! $(4.39^{+0.80}_{-.083} \pm 0.45)\times10^{-3}$ [6] (2016)
		BABAR	4.1×10^{-3} [7] (2006) (90 % CL)	-

Table. Recent & Best values of Branching fraction $B^0 \to \ell\ell$

[1] Christoph Bobeth et al., "$B_{s,d} \to l^+l^-$ in the Standard Model with Reduced Theoretical Uncertainty", PRL (2014)

[2] R. Aaij et al., "Search for Rare Decay $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$", LHCb Collaboration, PRL (2020)

[3] M. Aaboud et al., "Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector", ATLAS collaboration, JHEP (2019)

[4] R. Aaij et al., "Measurement of the $B_s^0 \to \mu^+\mu^-$ Branching Fraction and Effective Lifetime and Search for $B^0 \to \mu^+\mu^-$ Decays", LHCb Collaboration (2017)

[5] R. Aaij et al, "Search for the Decays $B_s^0 \to \tau^+\tau^-$ and $B^0 \to \tau^+\tau^-$", LHCb collaboration, PRL (2017)

[6] M. Ziegler, "Search for the rare decay $B^0 \to \tau^+\tau^-$ with Belle", Belle collaboration, Belle Note (BN-1390) (2016)

[7] B. Aubert et al, "Search for the Rare Decay $B^0 \to \tau^+\tau^-$ at BABAR", BABAR collaboration, PRL (2006)

[8] A.M. Sirunyan et al., "Measurement of properties of $B_s^0 \to \mu^+\mu^-$ decays and search for $B^0 \to \mu^+\mu^-$ with the CMS experiment", CMS collaboration, JHEP (2020)

$B_s^0 \to ll$ Branching fraction: SM prediction and measurement

	SM prediction	Measurement		
		Detector	Upper Limit	Measurement
$B_s^0 \to e^+e^-$	$(8.54 \pm 0.55)\times10^{-14}$ [1] (2014)	LHCb	9.4×10^{-9} [2] (2020) (90 % CL) 11.2×10^{-9} [2] (2020) (95 % CL)	-
$B_s^0 \to \mu^+\mu^-$	$(3.65 \pm 0.23)\times10^{-9}$ [1] (2014) √	CMS	-	$(2.9 \pm 0.6 \pm 0.4)\times10^{-9}$ [8] (2020) √
		ATLAS	-	$(2.8^{+0.8}_{-0.7})\times10^{-9}$ [3] (2019)
		LHCb	-	$(3.0 \pm 0.6^{+0.3}_{-0.2})\times10^{-9}$ [4] (2017)
$B_s^0 \to \tau^+\tau^-$	$(7.73 \pm 0.49)\times10^{-7}$ [1] (2014)	LHCb	5.2×10^{-3} [5] (2017) (90 % CL) 6.8×10^{-3} [5] (2017) (95 % CL)	-

Table. Recent & Best values of Branching fraction $B_s^0 \to \ell\ell$

[1] Christoph Bobeth et al., "$B_{s,d} \to l^+l^-$ in the Standard Model with Reduced Theoretical Uncertainty", PRL (2014)
[2] R. Aaij et al., "Search for Rare Decay $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$", LHCb Collaboration, PRL (2020)
[3] M. Aaboud et al., "Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector", ATLAS collaboration, JHEP (2019)
[4] R. Aaij et al., "Measurement of the $B_s^0 \to \mu^+\mu^-$ Branching Fraction and Effective Lifetime and Search for $B^0 \to \mu^+\mu^-$ Decays", LHCb Collaboration (2017)
[5] R. Aaij et al, "Search for the Decays $B_s^0 \to \tau^+\tau^-$ and $B^0 \to \tau^+\tau^-$", LHCb collaboration, PRL (2017)
[6] M. Ziegler, "Search for the rare decay $B^0 \to \tau^+\tau^-$ with Belle", Belle collaboration, Belle Note (BN-1390) (2016)
[7] B. Aubert et al, "Search for the Rare Decay $B^0 \to \tau^+\tau^-$ at BABAR", BABAR collaboration, PRL (2006)
[8] A.M. Sirunyan et al., "Measurement of properties of $B_s^0 \to \mu^+\mu^-$ decays and search for $B^0 \to \mu^+\mu^-$ with the CMS experiment", CMS collaboration, JHEP (2020)

BDT Input Variables: Continuum Suppression

#	Variables
1	"R2"
2	"thrustBm"
3	"thrustOm"
4	"cosTBTO"
5	"cosTBz"
6	"KSFWVariables(et)"
7	"KSFWVariables(mm2)"
8	"KSFWVariables(hso00)"
9	"KSFWVariables(hso02)"
10	"KSFWVariables(hso04)"
11	"KSFWVariables(hso10)"
12	"KSFWVariables(hso12)"
13	"KSFWVariables(hso14)"
14	"KSFWVariables(hso20)"
15	"KSFWVariables(hso22)"

#	Variables
16	"KSFWVariables(hso24)"
17	"KSFWVariables(hoo0)"
18	"KSFWVariables(hoo1)"
19	"KSFWVariables(hoo2)"
20	"KSFWVariables(hoo3)"
21	"KSFWVariables(hoo4)"
22	"CleoConeCS(1)"
23	"CleoConeCS(2)"
24	"CleoConeCS(3)"
25	"CleoConeCS(4)"
26	"CleoConeCS(5)"
27	"CleoConeCS(6)"
28	"CleoConeCS(7)"
29	"CleoConeCS(8)"
30	"CleoConeCS(9)"

BDT Input Variables: BN-1390 (Belle, $B^0 \to \tau^+\tau^-$)

Table 6.5.: Input variables of the neural nets.

	Variable	Short description
Lab. frame	$p_{T,i}$	Transverse momentum of B_{sig} daughters
	E_i	Energy of B_{sig} daughters
	$\cos\theta_i$	Polar angle of B_{sig} daughters
	$\cos\theta_{0\triangleleft 1}$	Angle between B_{sig} daughters
	A_{01}	Momentum asymmetry of B_{sig} daughters
	$M(B_{sig})$	Reconstructed mass of B_{sig}
	p_T	Reconstructed transverse momentum of B_{sig}
	M^2_{miss}	Squared missing mass of the event
	$\lvert\vec{p}_{miss}\rvert$	Absolute value of the missing momentum in the event
	$\lvert\vec{p}_{T,miss}\rvert$	Absolute value of the transverse component of the missing momentum in the event
	d_{IP}	Distance of B_{sig} vertex and IP
	$\Sigma(d_{IP})$	Significance of d_{IP}
B_{sig} rest frame	$\lvert\vec{p}^*_i\rvert$	Absolute value of the momentum of B_{sig} daughters
	$\cos\theta^*_{0\triangleleft 1}$	Angle between B_{sig} daughters
	$\cos\theta^*_{\tau\triangleleft\pi}$	Angle between τ and B_{sig} daughter with π hypothesis
	$\cos\theta_{hel,0}$	Angle between daughter 0 and the reconstructed momentum of B_{sig}

※ $B^0 \to \tau^+\tau^-$, BN-1390, M. Ziegler (2016)

Previous talks

2021

- 2021.09.14. 25th EWP Meeting
  - https://indico.belle2.org/event/5190/#5-b0-tautau
- 2021.12.02. Leptonic Subgroup Meeting
  - https://indico.belle2.org/event/5728/#3-b0-to-tau-tau-analysis-statu

2022

- 2022.01.20. WG1 pre-session, 41st B2GM
  - https://indico.belle2.org/event/6017/#20-b0-to-tau-tau
- 2022.05.31. WG1 pre-session, 42nd B2GM
  - https://indico.belle2.org/event/6930/#sc-2-14-b-tau-tau
- 2022.Aug.04. Leptonic subgroup meeting
  - https://indico.belle2.org/event/7366/#7-b-to-tau-tau-preselection
- 2022.Oct.05. WG1 pre-session, 43rd B2GM
  - https://indico.belle2.org/event/7826/#sc-1-29-b-tau-tau