

Selection Studies for the Search of $B_s^0 \rightarrow \tau^+ \tau^-$ Decay at LHCb using Run 3 Data

TSM – Winter 2025/2026

Presenter: **Lai Gui**

Supervisor: **Rita De Sousa Ataíde Da Silva**

Responsible Professor: **Prof. Frédéric Blanc**

Introduction

- Why $B_s^0 \rightarrow \tau^+ \tau^-$?
- Aim of the Project
- Signal and Backgrounds

Analysis: Combinatorial Background

- $\Delta m_{B_s^0}$ Cut
- BDT

Analysis: Physics Background

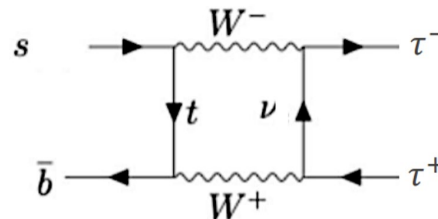
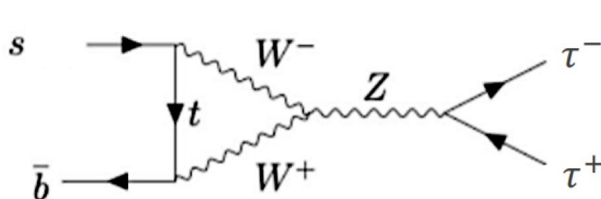
- Applying Existing Selection
- 6π Invariant Mass Cut

Conclusion

Introduction

Why $B_s^0 \rightarrow \tau^+ \tau^-$?

- FCNC (Flavour Changing Neutral Current) process, involving loops



- SM prediction highly suppressed

$$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) \stackrel{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7}$$

hence precise measurement is sensitive to new physics

- Search performed on LHCb Run 1 data, but signal not observed; an upper limit set:

$$\text{LHCb Run 1: } \mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-) < 3.6 \times 10^{-3} \text{ at 95\% CL } \text{[1]}$$

- **Aim:** Perform selection studies for the search of this decay using **LHCb Run 3 data**, where we have **improved reconstruction** and **higher statistics**

Number of Signal Events

- Calculation of signal & total event number

Calculation conditions

- $b\bar{b}$ pair production cross section in the LHCb acceptance range of $2 < \eta < 5$ for 13 TeV (Run 2): $1.543 \times 10^{11} \text{ fb}$ [1]
- In Run 3, beam energy **13** \rightarrow **13.6 TeV**. $b\bar{b}$ production cross section roughly increase linearly with energy
- f_s (fraction hadronising to B_s^0) is about **10.5%** [2]
- Standard model predicts branching ratio for $B_s^0 \rightarrow \tau^+ \tau^-$: 7.7×10^{-7}
- $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ branching ratio \sim **9.31%**
- HLT2 efficiency for signal selection: **1.7%**

Integrated Luminosities

Data sample analysed:

block 7 & 8: **1.172 fb⁻¹**

2024:

9.56 fb⁻¹

Data Sample	Number of Signal Events Produced	Number of Signal Events after HLT2 selection
Block 7 & 8	133.08	2.26
2024	1272.25	21.63

[1] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **118**, 052002 (2017)

[2] J. Meija (CMS Collaboration), *EPJ Web Conf.* **316**, 04003 (2025)

- Data selected with a dedicated HLT2 line:

Sample	Number of Events after HLT2 selection
SS Data	8,481,222 (blocks 7 & 8)
OS Data	12,963,547 (blocks 7 & 8)
MC Signal	4,772 (2M generated)
$B^0 \rightarrow (D^- \rightarrow \pi^- \pi^+ \pi^- \pi^0) \pi^+ \pi^- \pi^+$ (MC Physics Background)	3,104 (2M generated)

- Finish the BDT to suppress combinatorial background using SS Data as the proxy (previous result: test AUC of **0.932**; **0.70%** background efficiency at **60%** signal efficiency)
- Have a first look at one possible physics background

We're looking for $B_s^0 \rightarrow \tau \tau \rightarrow 6 \pi$

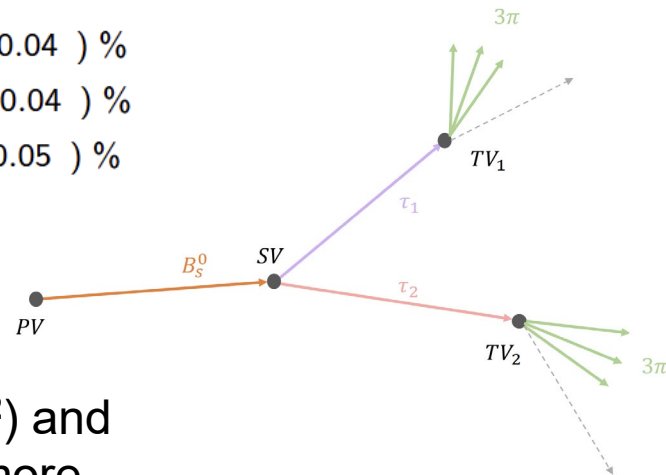
- Relatively small branching ratio than leptonic decays

$$\tau^- \rightarrow \begin{cases} \mu^- \bar{\nu}_\mu \nu_\tau & [g] \quad (17.37 \pm 0.04) \% \\ e^- \bar{\nu}_e \nu_\tau & [g] \quad (17.85 \pm 0.04) \% \\ \pi^- \pi^+ \pi^- \nu_\tau & (9.31 \pm 0.05) \% \end{cases}$$

but the 3-particle vertex offers better geometric constraints.

- Also the decay occurs through a_1 ($1230 \text{ MeV}/c^2$) and ρ^0 ($775.26 \text{ MeV}/c^2$) resonances, which allows more precise kinematic constraint.

$$\tau^- \rightarrow (a_1^- \rightarrow (\rho^0 \rightarrow \pi^+ \pi^-) \pi^-) \nu_\tau$$



- Combinatorial Background

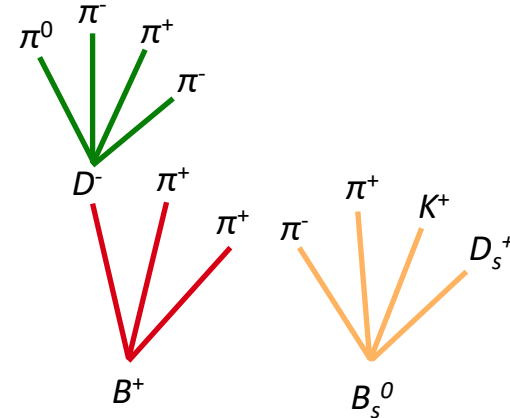
6 π from different decay mothers
(not necessarily from 2τ from B_s^0)

Also could be K misidentified as π

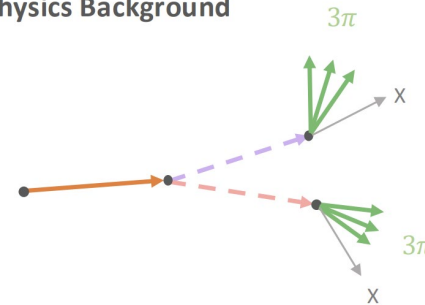
- Physics Background

6 π from B_s^0 / B^0 that mimic the signal signature
(e.g. $D_s^+ D_s^-$)

Combinatorial Background



Physics Background



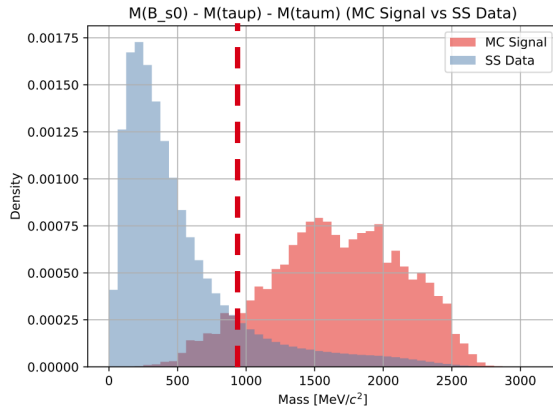
Ex: $B_s^0 \rightarrow D_s^+ D_s^-$

Analysis: Selection Design to Suppress Combinatorial Background

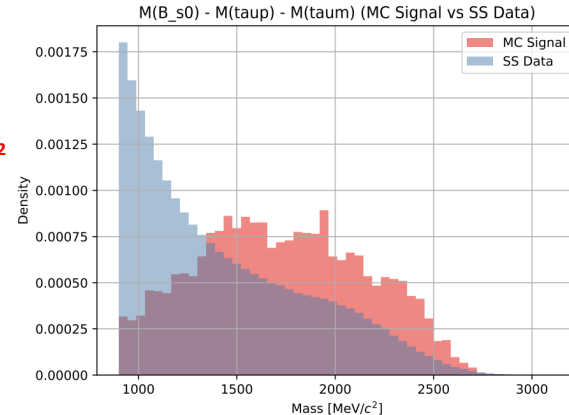
$\Delta m_{B_S^0}$ Cut

$$\Delta m_{B_S^0} = m_{B_S^0} - m_{\tau^+} - m_{\tau^-}$$

where $\left\{ \begin{array}{l} m_{B_S^0} \text{ is the overall invariant mass for the } 6\pi \text{ system,} \\ m_{\tau^\pm} \text{ are for the } 3\pi \text{ from each of the } \tau^\pm \text{ candidates} \end{array} \right.$



Applying cut at 900 MeV/c²



	Events before cut	Events after cut	Efficiencies
MC Signal	4772	4415	92.52%
SS Data	8481222	1234561	14.56%
OS Data	12963547	1791389	13.82%

BDT: Kinematic Variables

Variable Names	Descriptions
<code>pv_tau_angle_deg</code>	Angle between $PV \rightarrow TV$ directions
<code>min_log10_one_minus_OWNPV_DIRA</code>	Minimum of $\log_{10}(1 - \text{DIRA})$ between two τ
<code>taup_three_pi_mass,</code> <code>taum_three_pi_mass</code>	3π invariant mass corresponding to each of the τ candidate
<code>min_log10_BPV_IPCHI2</code>	Minimum of $\log_{10}(\text{IP } \chi^2)$ between two τ
<code>taup_min_rho_mass_diff,</code> <code>taum_min_rho_mass_diff</code>	Min of $ m_{\pi\pi} - m_{\rho} $ among opposite sign $\pi\pi$ pairs for each τ
<code>min_prod_probnn_pi</code>	Minimum of the product of the three π probabilities (PROBNN_PI) between two τ
<code>tau_end_vertex_distance</code>	Distance between τ^+ and τ^- decay vertices

BDT: Isolation Variables

Variable Names	Descriptions
B_s0_VTXISO_OneTrack_NParts	Number of tracks compatible of forming a primary vertex
B_s0_VTXISO_OneTrack_Smallest_DELTACHI2_MASS	The mass of the track with smallest $\Delta\chi^2$ when added to the primary vertex reconstruction
B_s0_HEAD_NC_BIso10_Range_PT	Range of P_T of tracks in the neutral cone region
B_s0_HEAD_CC_BIso05_PASY	Charged-cone PASY variable: $\frac{p_{head}-p_{cone}}{p_{head}+p_{cone}}$
B_s0_VTXISO_OneTrack_Sum_CHI2_DCHI2	Sum of the smallest χ^2 and the smallest $\Delta\chi^2$ when adding tracks to the primary vertex reconstruction

Compared to the previous work:

1. Changed kinematic variable

`max_rho_mass_diff`: Max of $(m_{\pi\pi} - m_{\rho})$



`min_rho_mass_diff`: Min of $|m_{\pi\pi} - m_{\rho}|$

This effectively eliminated the correlation with 3π mass

2. Added new isolation variables

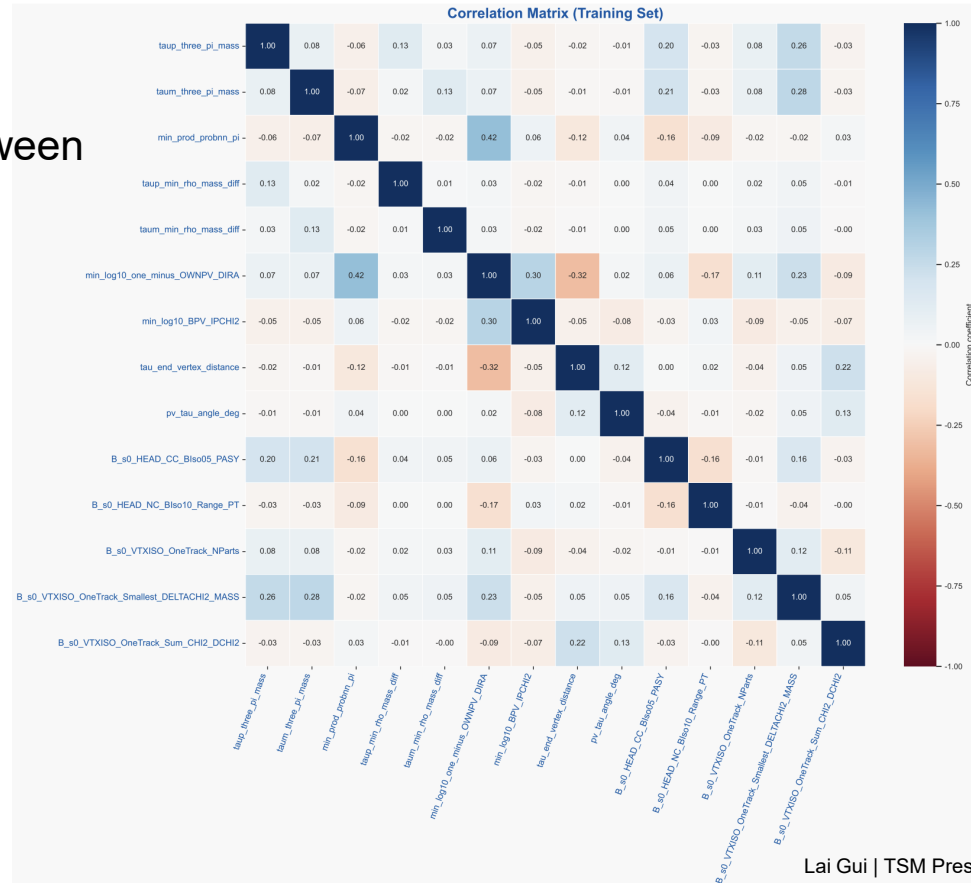
`B_s0_VTXISO_OneTrack_Smallest_DELTACHI2_MASS`

`B_s0_VTXISO_OneTrack_Sum_CHI2_DCHI2`

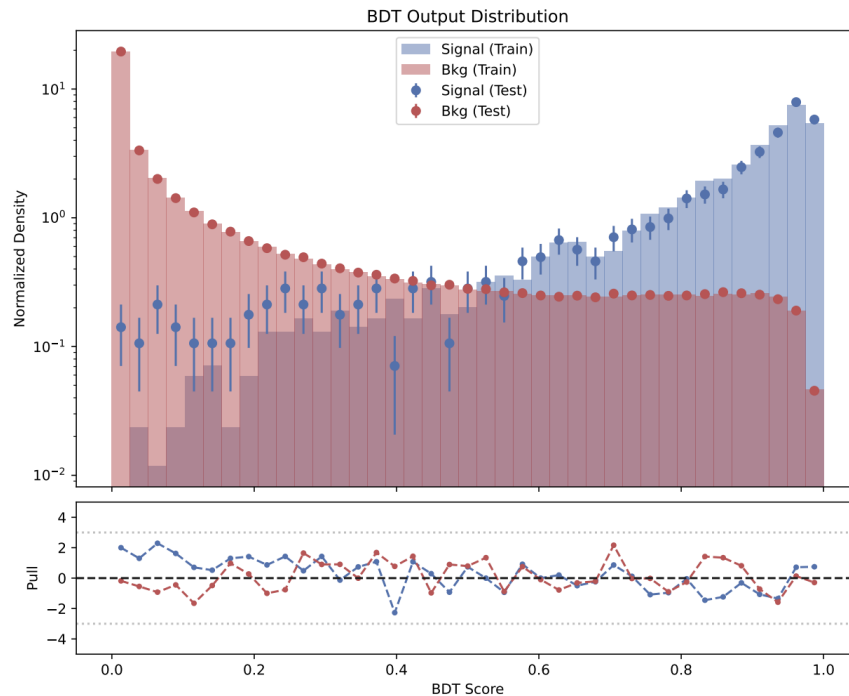
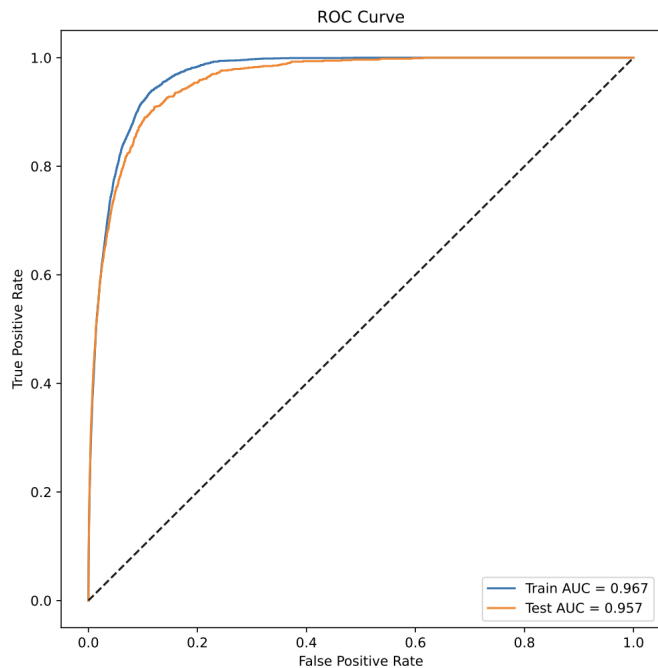
which contains NaN values that were not previously implemented

Correlation Matrix

- Indicates dependency between features
- Correlation observed:
 - **PROBNN vs DIRA**
- Overall good dissociation



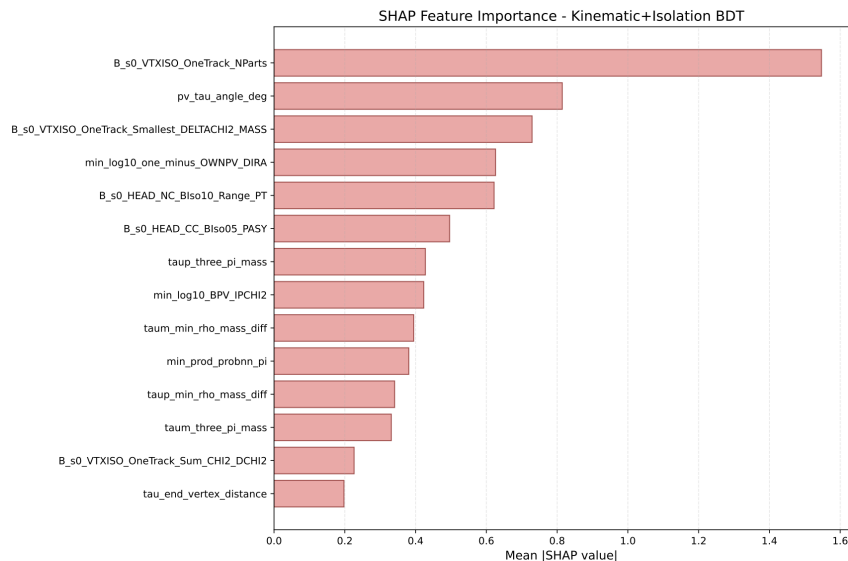
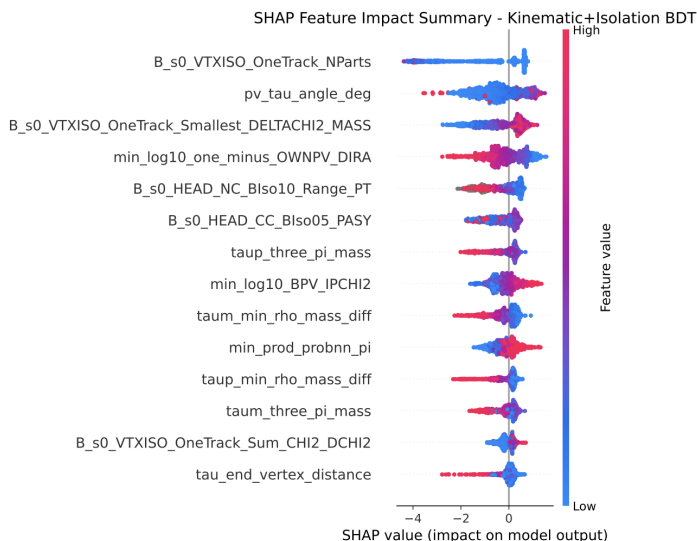
BDT Training Results



- Test AUC score improved from previous **0.932** to **0.957**
- No significant overtraining gap

BDT Training Results

- **SHAP values:**
Correlation between feature value and its impact on the model training
- **SHAP-based Feature importance:**
Measures average impact of each feature on final output scores
Computed by testing all feature combinations, capturing feature correlations



- Previously with $\Delta m_{B_S^0}$ cut:

Sample	Efficiency after $\Delta m_{B_S^0}$ cut
MC Signal	92.52%
SS Data	13.82%

- After BDT cut at different thresholds, overall efficiencies:

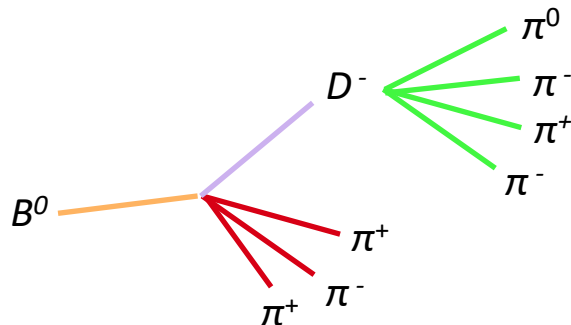
BDT Threshold	MC Signal Efficiency	SS Data Efficiency
0.7290	70.06%	0.74%
0.7820	65.12%	0.58%
0.8230	60.00%	0.46%
0.8610	55.06%	0.35%
0.8880	50.11%	0.26%

- Choice of BDT Threshold of **0.823** made for ~ 60% overall signal efficiency

Analysis: Physics Background

$B^0 \rightarrow D 3\pi$

$$B^0 \rightarrow (D^- \rightarrow \pi^- \pi^+ \pi^- \pi^0) \pi^+ \pi^- \pi^+$$



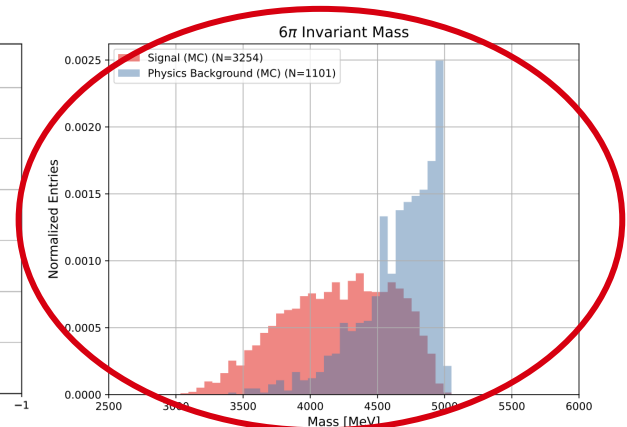
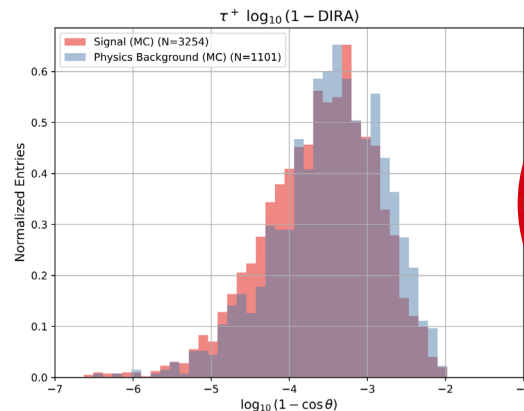
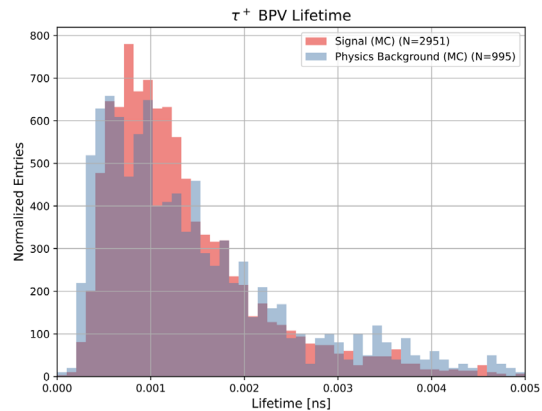
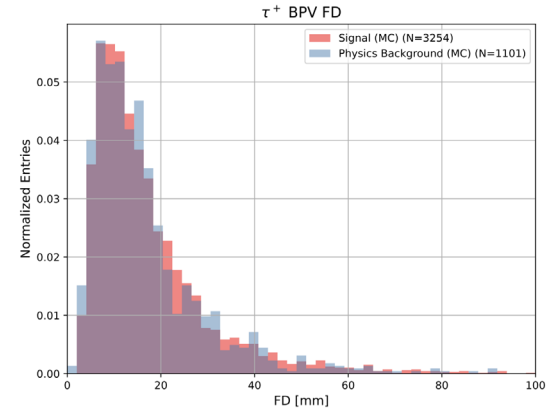
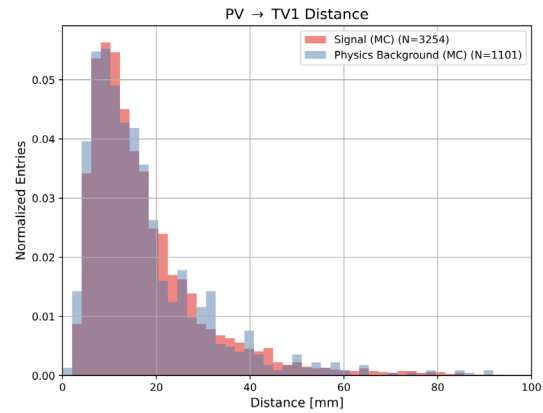
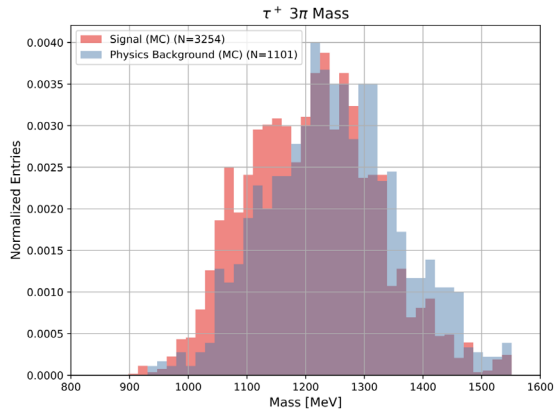
- where D^- can decay through $\pi^0 + a_1^-$ resonance, then $a_1^- \rightarrow \rho^0 + \pi^-$, which very much mimics the process of τ decay
- Branching Ratio $\sim 7.0 \times 10^{-5}$ (more prominent than signal's 7.7×10^{-7})

- Perform BDT selection with the model trained to suppress combinatorial background, with a threshold set at **0.8230** for 60% total signal efficiency

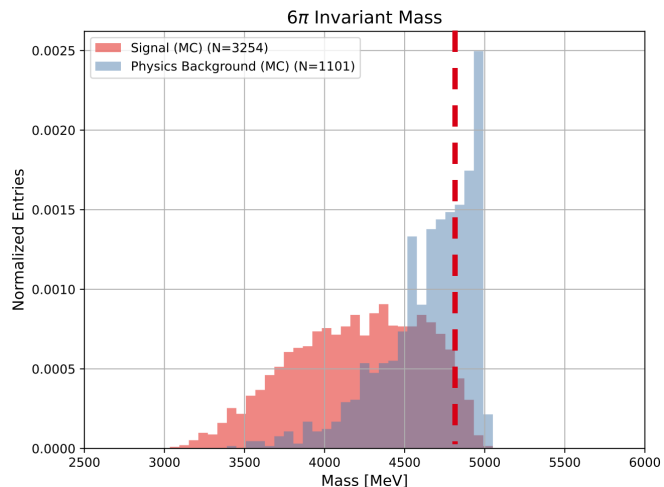
Selection Efficiencies	MC Signal	$B^0 \rightarrow (D^- \rightarrow \pi^- \pi^+ \pi^- \pi^0) \pi^+ \pi^- \pi^+$
Delta B_s^0 mass cut	92.52%	95.81%
Delta B_s^0 mass cut + BDT	68.19%	35.47%

- The BDT is less effective in suppressing this physics background (**35.47%**) than combinatorial background (**0.46%**)

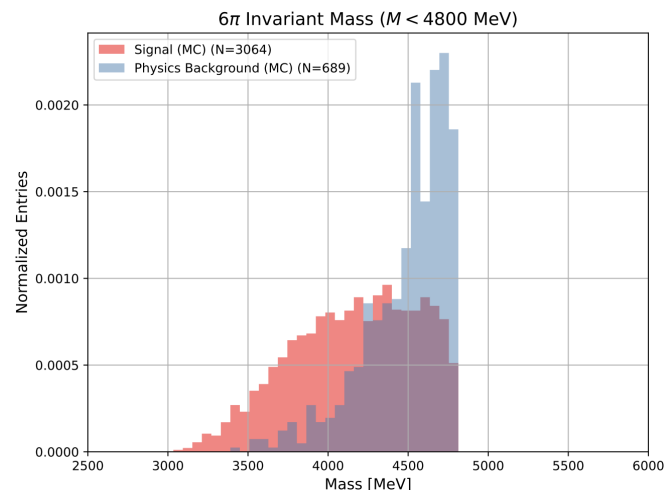
Kinematic Variables



6 π invariant mass cut



Applying cut at 4800 MeV



Selection Efficiencies	MC Signal	$B^0 \rightarrow (D^- \rightarrow \pi^- \pi^+ \pi^- \pi^0) \pi^+ \pi^- \pi^+$
6 π invariant mass cut	94.16%	62.58%
Overall efficiency	64.21%	22.20%

- Effective in suppressing this specific physics background

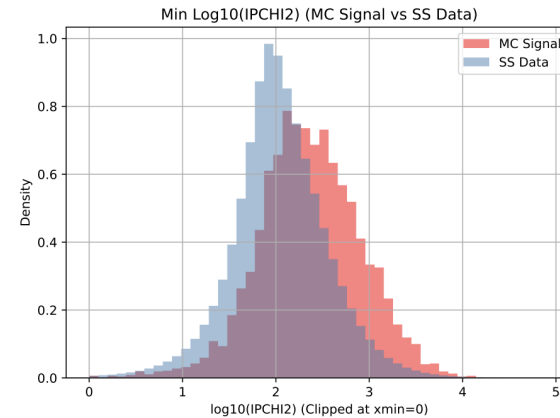
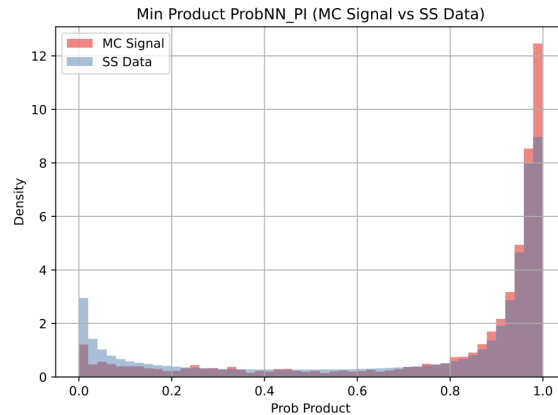
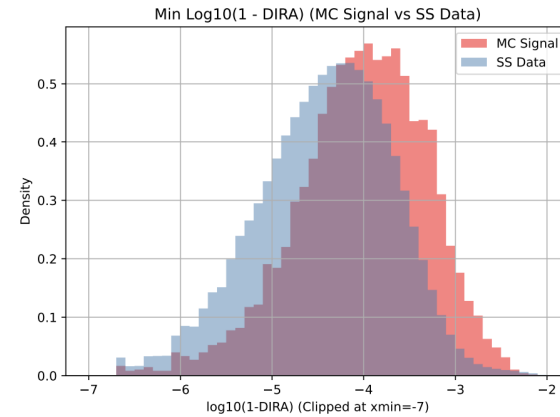
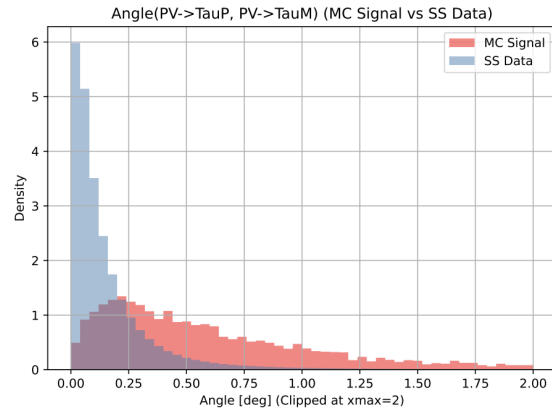
Conclusion

- Expected number of signal events in the sample analysed is low (**2.26**). HLT2 of 2025 has higher efficiency, which will improve this.
- Modified BDT increases effectiveness in background rejection. The combinatorial background efficiency decreased from **0.70%** to **0.46%** at signal efficiency **~60%**.
- First study on one physics background is performed; the BDT trained for combinatorial background is less effective in suppressing physical background (**35.47%**)
- Potential kinematic variable cuts help with its suppression. An efficiency of **22.20%** is achieved for this physics background at **64.21%** signal efficiency.
- Future study can attempt training BDT using the physics background. Also similar study can be performed on other physics background channels.

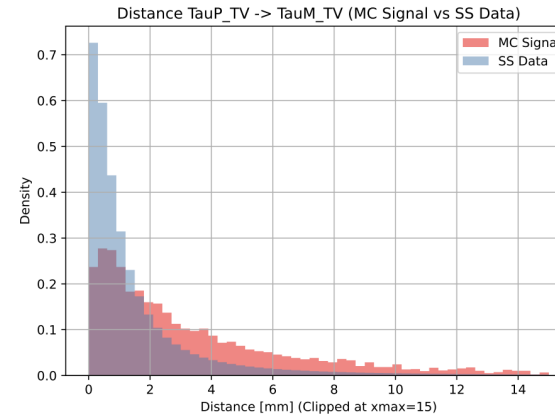
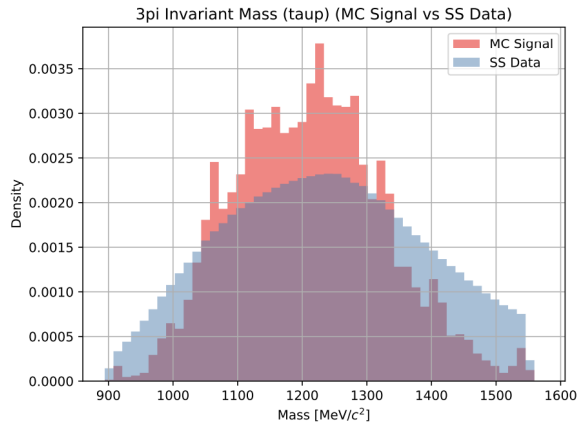
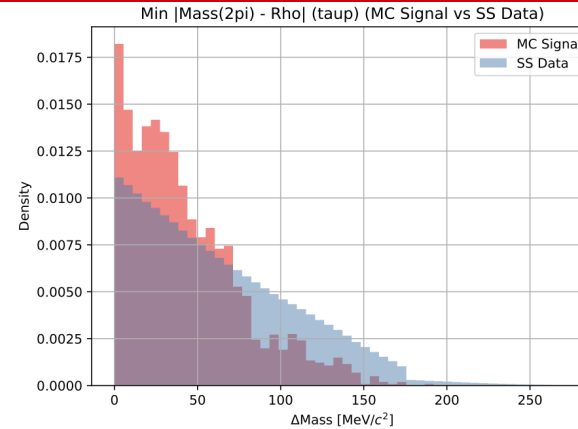
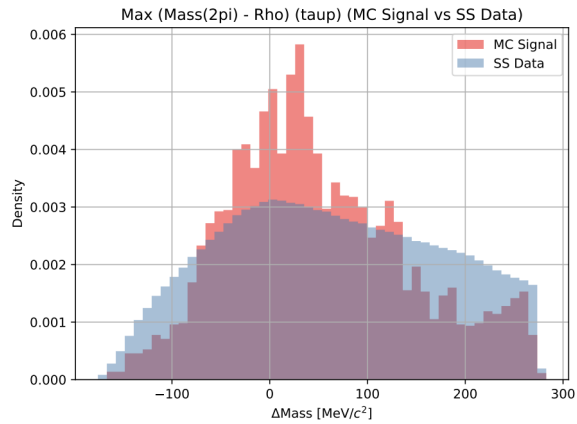
*Thank
you!*

Backup Slides

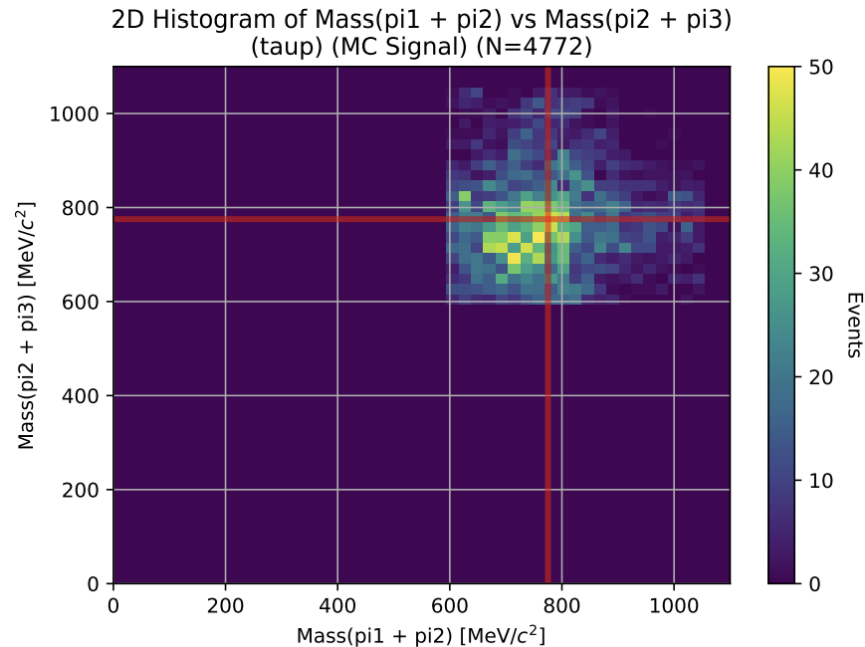
BDT: Kinematic Variable Distributions



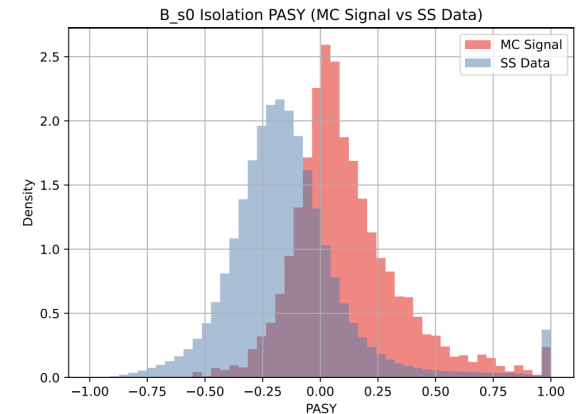
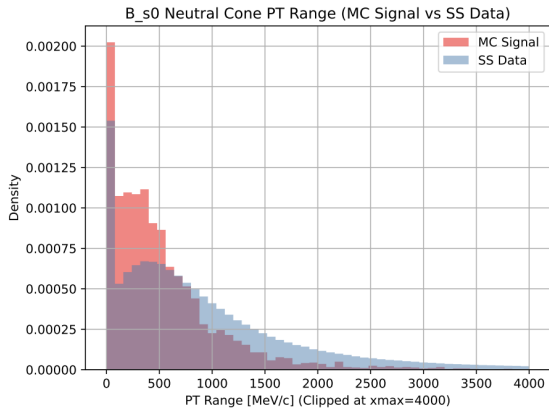
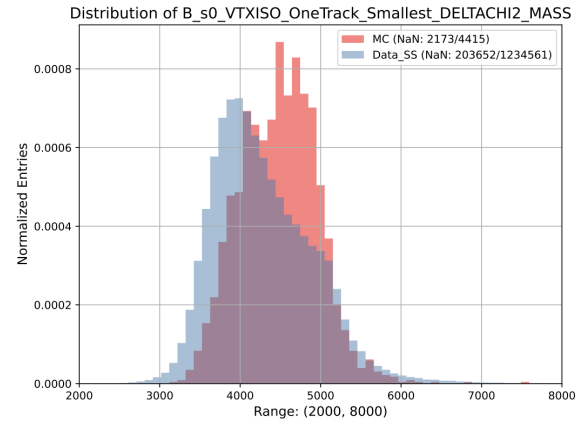
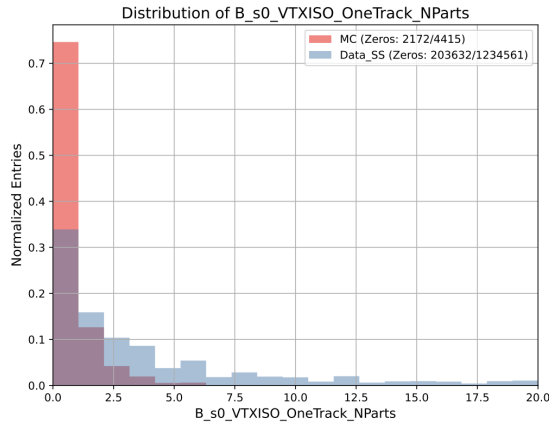
BDT: Kinematic Variable Distributions



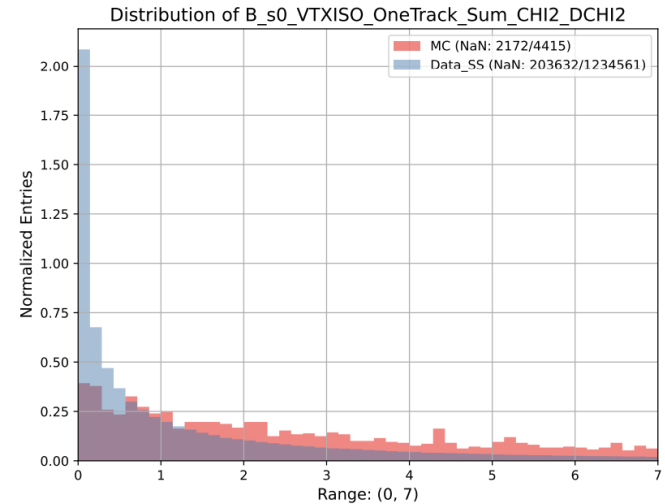
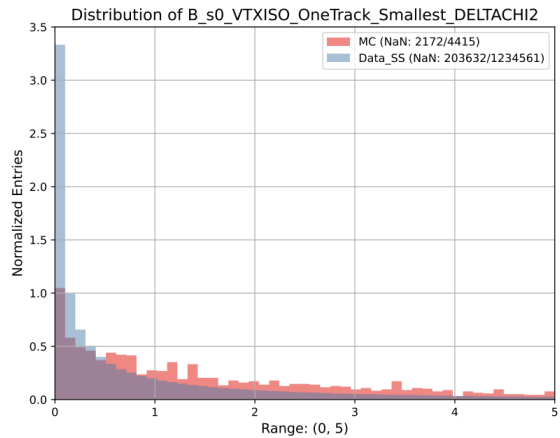
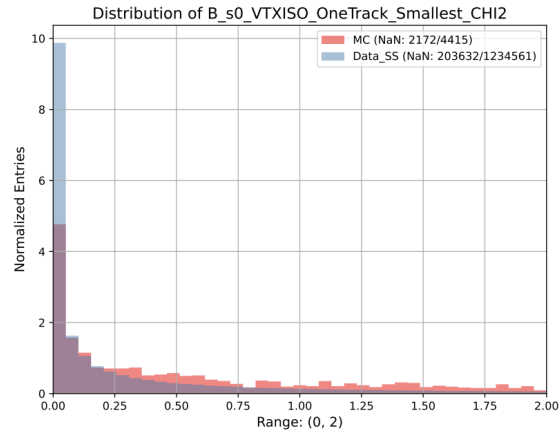
Dalitz Plot for $M_{\pi_1 + \pi_2}$ vs $M_{\pi_2 + \pi_3}$



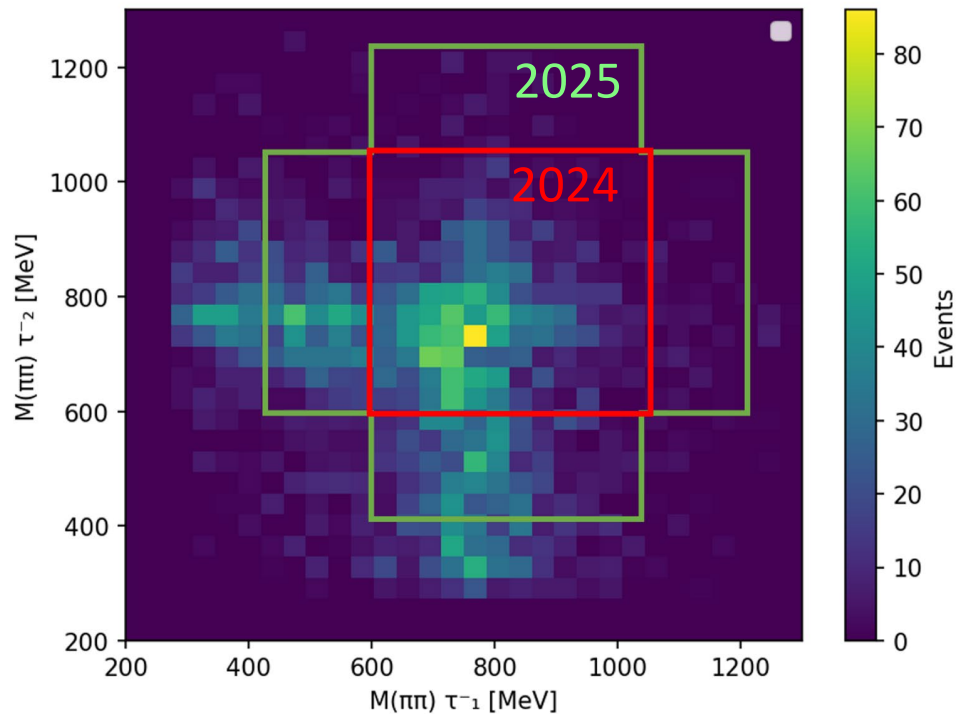
BDT: Isolation Variable Distributions



BDT: Isolation Variable Distributions



Dalitz Plot for HLT2 Selections



- **Punzi FoM** maximises discovery sensitivity:

$$Z_{\text{Punzi}} = \frac{\epsilon_S}{a/2 + \sqrt{B}}$$

- Maximum Punzi occurs at BDT threshold of **0.951**

