Search for lepton flavour violation with $B^0 \to \tau\ell$ ($\ell = e, \mu$) at Belle II

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Lepton Flavour Violation (LFV)

Flavour Mixing in the SM

- Quark flavour mixing described by CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Neutral lepton (neutrino) flavour mixing described by PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{\mu 1} & U_{\tau 1} \\ U_{e2} & U_{\mu 2} & U_{\tau 2} \\ U_{e3} & U_{\mu 3} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Charged lepton flavour mixing must occur due to electroweak couplings between neutral and charged leptons

  $\rightarrow$ However CLFV processes dominated by scale of neutrino masses

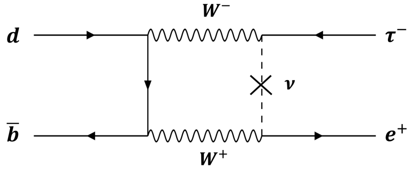
  $\rightarrow$ CLFV in the SM has BFs beyond future experimental sensitivities e.g.

$$\mathcal{B}(\mu \rightarrow e\gamma)_{\mathrm{SM}} \sim \mathcal{O}(10^{-54})$$

Observation of a CLFV decay is unambiguous evidence of new physics!

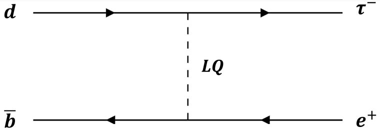
The $B^0 \to \tau\ell$ Decay

In the SM, $B^0 \to \tau\ell$ can only occur through neutrino oscillations ($\times$)



Vector Leptoquarks

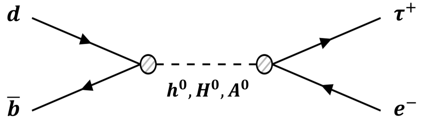
A. D. Smirnov (2018)
arXiv:1801.02895v2



$$\mathcal{B}(B^0 \to e\tau)_{\mathrm{LQ}} = 1.6 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu\tau)_{\mathrm{LQ}} = 4.4 \times 10^{-9}$$

MSSM

A. Dedes, J. Ellis and M. Raidal (2002)
arXiv:hep-ph/0209207v1



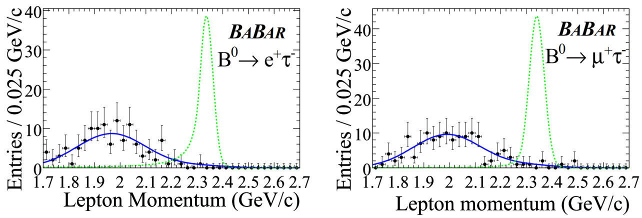
$$\mathcal{B}(B^0 \to \ell\tau)_{\mathrm{MSSM}} \sim \mathcal{O}(10^{-10})$$

Past Searches

Past Searches: world best limit on BF set by Belle (LHCb) for $\ell = e\ (\mu)$ mode

	CLEO (2004)	**BaBar (2007)**	**LHCb (2019)**	**Belle (2021)**
Sample size	9.2 fb^{-1}	342 fb^{-1}	3 fb^{-1}	711 fb^{-1}
$N_{B\overline{B}}$	9.6×10^6	378×10^6	?	772×10^6
$\mathcal{B}^{\mathrm{UL}}(B^0 \to e^\pm \tau^\mp)$	$< 1.1 \times 10^{-4}$	$< 2.8 \times 10^{-5}$	-	$< 1.6 \times 10^{-5}$
$\mathcal{B}^{\mathrm{UL}}(B^0 \to \mu^\pm \tau^\mp)$	$< 3.8 \times 10^{-5}$	$< 2.2 \times 10^{-5}$	$< 1.2 \times 10^{-5}$	$< 1.5 \times 10^{-5}$

- BaBar
  Hadronic B_{tag} reconstruction + fit to signal lepton momentum in B_{sig} frame (p_ℓ^B)



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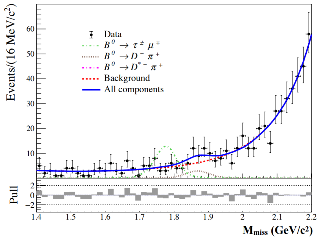
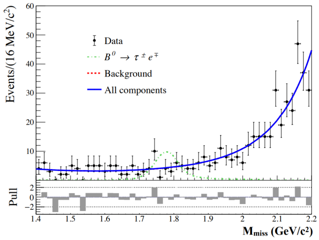
- Belle

  Hadronic B_{tag} reconstruction + do not reconstruct τ in specific channels (inclusive), instead fit to the missing mass which is peaked at m_τ





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- BaBar - hadronic B_{tag} reconstruction + fit to signal lepton momentum in B_{sig} frame (p_ℓ^B) $\to$ *reconstruction efficiency* = 0.027% (0.032%) for $\ell = \mu$ ($\ell = e$)
- Belle - hadronic B_{tag} reconstruction + do not reconstruct τ in specific channels (inclusive), instead fit to the missing mass which is peaked at m_τ $\to$ *reconstruction efficiency* = 0.11% (0.098%) for $\ell = \mu$ ($\ell = e$)

Our Approach: hadronic B_{tag} reconstruction using the FEI + reconstruction of the τ $\to$ different fitting regions for leptonic (p_ℓ^B) and hadronic (p_ℓ^B, ΔE_τ) τ modes

$$\Delta E_\tau = \sum_i E_{\pi_i} + p_\nu - 1.777\ \mathrm{GeV} \qquad (\text{in } \tau \text{ frame})$$

τ Reconstruction and Cross-Feed

Exclusive τ Reconstruction: $\sim$ 92% of the τ branching fraction reconstructed

- **Leptonic Modes** are $e\nu\nu$, $\mu\nu\nu$
- **Hadronic Modes** are $h\nu$, $h\pi^0\nu$, $h\pi^0\pi^0\nu$, $hhh\nu$ ($h = \pi, K$)

$B^0 \to e^+\tau^-$ Mode

Generated	Reconstructed π	$\pi\pi^0$	$\pi\pi^0\pi^0$	$\pi\pi\pi$
π	6793	246	28	12
$\pi\pi^0$	4590	10160	1901	170
$\pi\pi^0\pi^0$	479	2007	2857	59
$\pi\pi\pi$	1501	898	317	3775

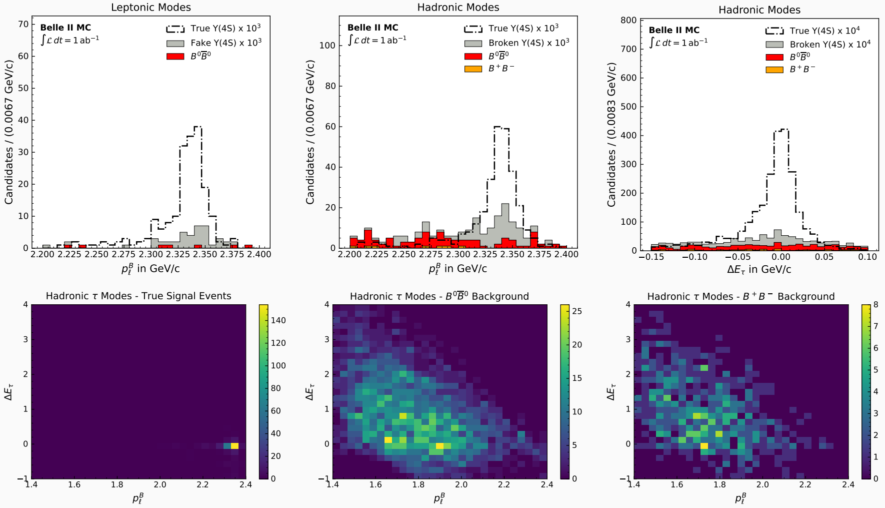
$B^0 \to \mu^+\tau^-$ Mode

Generated	Reconstructed π	$\pi\pi^0$	$\pi\pi^0\pi^0$	$\pi\pi\pi$
π	7650	254	23	8
$\pi\pi^0$	5228	11553	1942	173
$\pi\pi^0\pi^0$	586	2274	3086	63
$\pi\pi\pi$	1698	960	401	4301

Highlighted issues:

- Lost one π^0
- Lost at least one π track
- Incorrectly added one π^0

Signal Regions - $B^0 \to e^+\tau^-$ Mode



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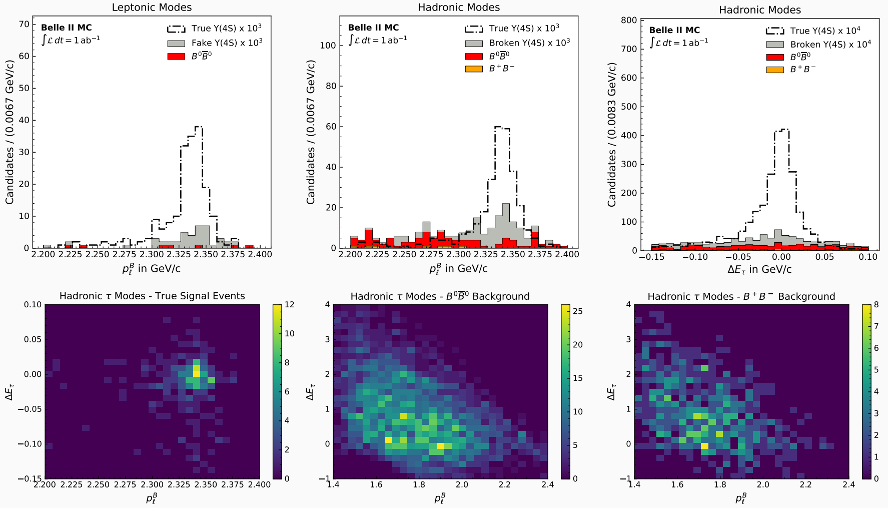


Quick Note On Background For Leptonic SR

Three Categories

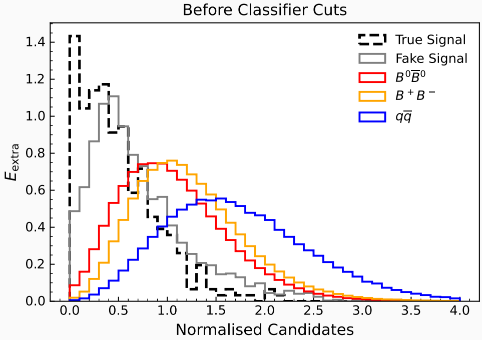
1. Two true leptons e.g. $B \to D(\to K_L^0 \ell \nu)\ell \nu$
2. One or more fake leptons due to mis-id e.g. $B \to \pi \ell \nu$
3. J/ψ decays e.g. $B \to J/\psi(\to ee)K_L^0$

E_{extra} For Leptonic SR

Idea: add 2$^{\mathrm{nd}}$ fitting variable for leptonic τ modes

Candidate Variable

- E_{extra} which is the **residual energy** in the electromagnetic calorimeter
- **Signal events** should peak at 0 due to correct reconstruction
- **Background events** peak at higher values



Signal distribution broadens due to:

- **Beam background**
- **Fake photons** e.g. hadronic split-offs, clustering failures

Remove these from E_{extra}

$\rightarrow$ signal and background is easier to distinguish

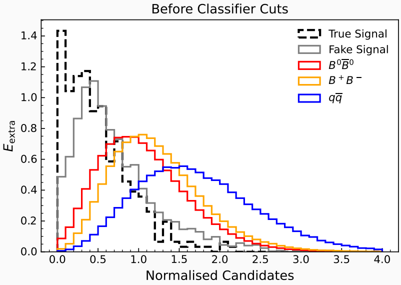
E_{extra} Clean-Up MVAs

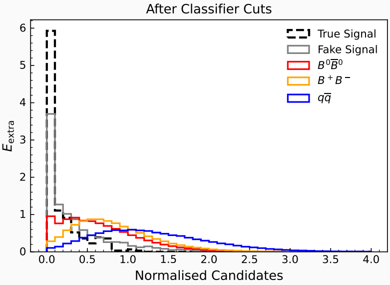
Beam Background BDT Features

- **Energy**, **timing** and **polar angle** of the cluster
- Output of a separate MVA that characterises **cluster shapes**
- Output of a separate MVA that uses **pulse-shape information** from activated ECL crystals, where class 0 = hadronic showers and class 1 = electromagnetic showers

Fake Photon BDT Features - all the beam background BDT features plus

- Distance between the cluster and its **nearest track**





Summary

E_{extra} MVAs Summary

- Improve E_{extra} for use as either selection cut or fitting variable
- MVAs used by many analyses, e.g. $B \to K\nu\nu$, $R(D^*)$, $B \to \mu\nu$, $B \to \tau\nu$
- Methodology can be used for other detectors with crystal calorimeters with near-4π coverage e.g. BES-III, KLOE

$B^0 \to \ell\tau$ Future

- Nearing the pointy end of analysis - finalising and checking fitting procedure + calculating systematics
- Upper limit measurement coming soon...

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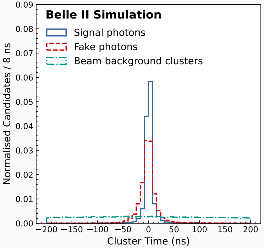

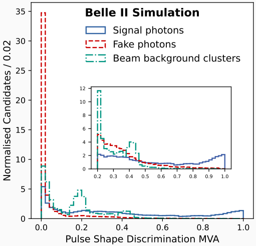

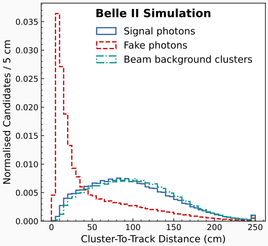

Classifier Performance

The optimal hyperparameters were chosen using **holdout** with results below:

	# Trees	Max Depth	Shrinkage	Test AUC Score
Beam Background BDT	100	3	0.1	0.998
Fake Photon BDT	300	3	0.1	0.944

Output of beam background/fake photon BDT gives **probability of being class 1** i.e. the cluster originating from a signal photon