Search for Heavy Neutral Leptons with LHCb

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Neutrinos in the Standard Model

Experimental observations which cannot be explained by the Standard Model (SM) and require a minimal extension:

1. **Neutrino masses**

   → seesaw mechanism

2. **Baryon asymmetry of the Universe**

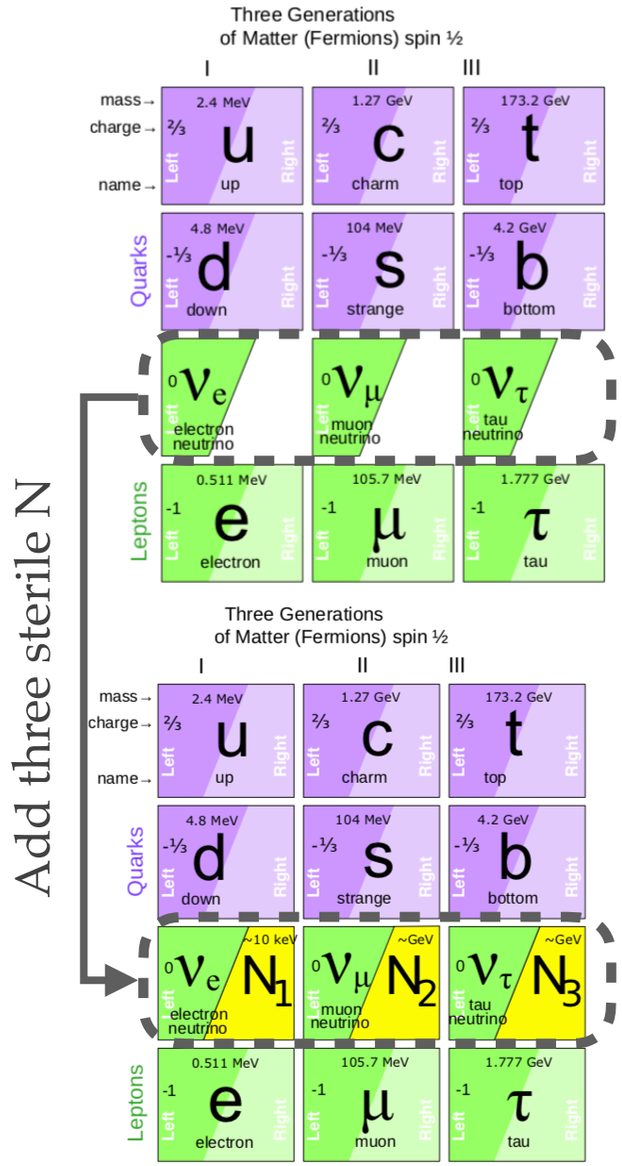
   → degenerate N_2 and N_3 (mass ~ 1 to ~10^2 GeV) could lead to significant increase of CP violation

3. **Dark matter**

   → lightest N_1 (a few keV)

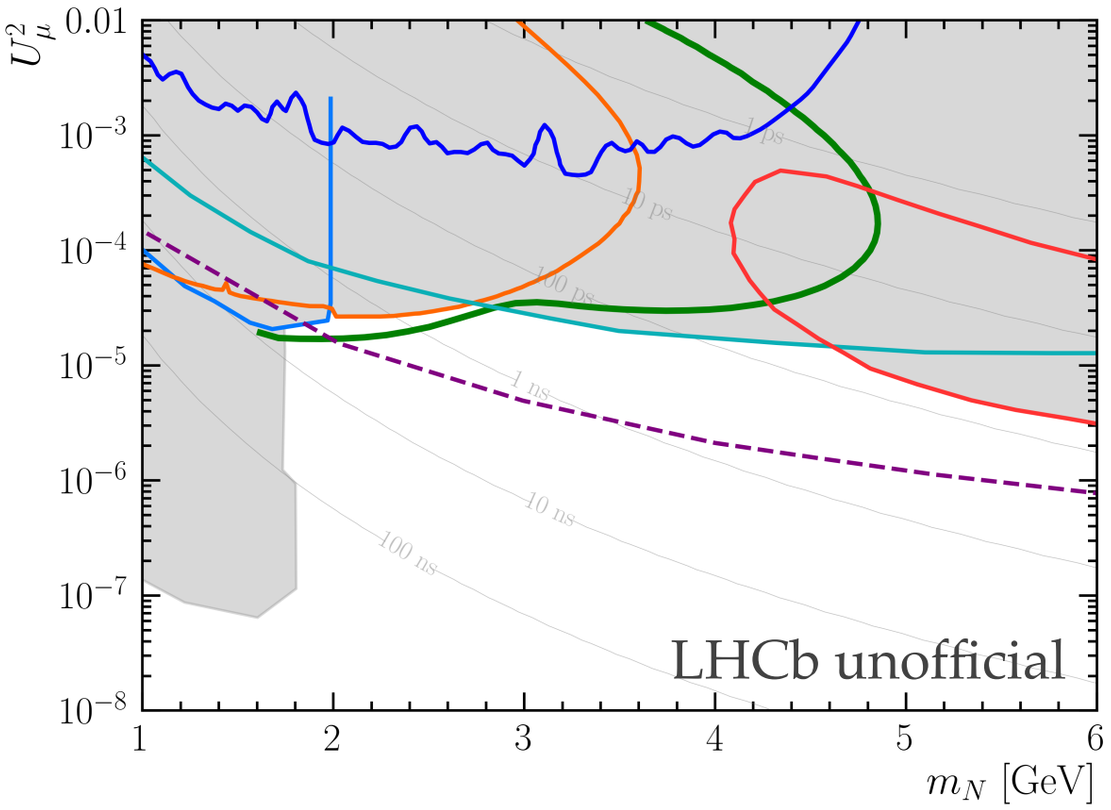
These and other evidences require new physics beyond the SM

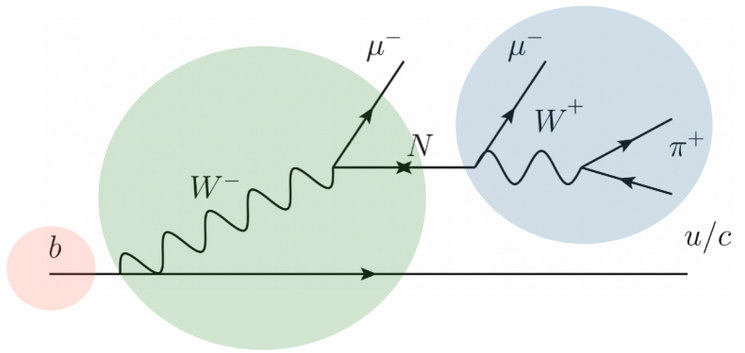
- Extension to the *νMSM* (neutrino Minimal Standard Model) by addition of heavy neutral leptons (HNLs), which are right-handed massive neutrinos



Where to look for?

- HNLs coupling U_μ^2 as a function of m_N
- Parameter U_μ^2 gives HNL mixing with SM neutrino (flavour μ)

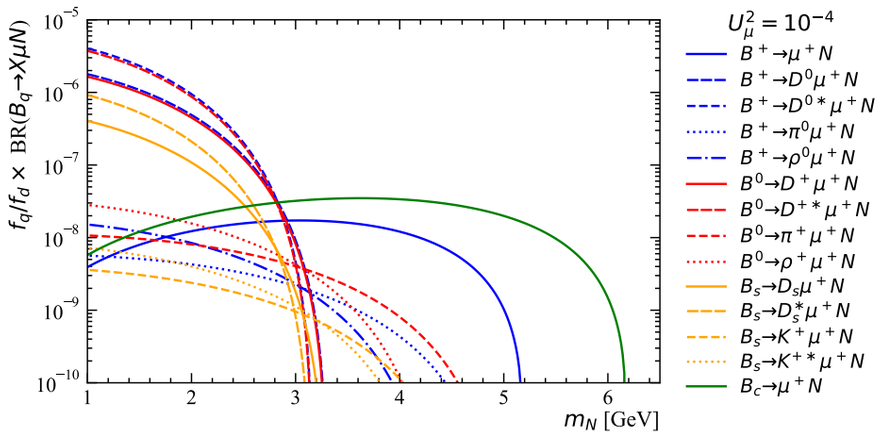




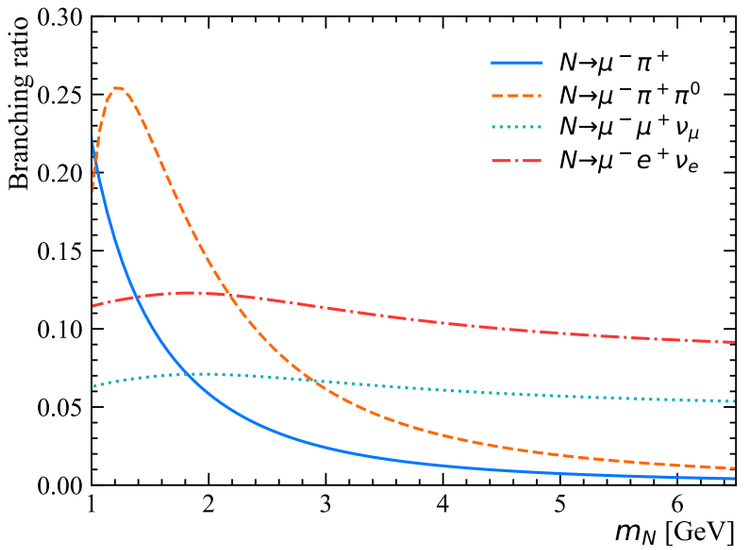
- Production of $b\bar{b}$ quarks

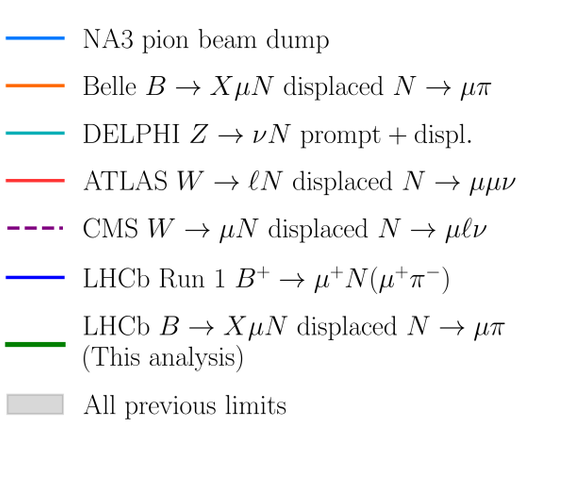
$$N_{\text{decays}} = \mathscr{L} \cdot \frac{\sigma_{pp\to B^\pm X}}{\epsilon_{pp\to B^\pm X}} \cdot \frac{f_q}{f_u} \cdot \text{BR}(B_q \to X\mu^+ N) \cdot \text{BR}(N \to \mu^+\pi^-) \cdot \varepsilon_{\text{FV}} \cdot \varepsilon_{\text{Reco}} \cdot \varepsilon_{\text{MVA}}$$

- Production of N in b decays



- Exclusive decay of $N \to \mu pi$

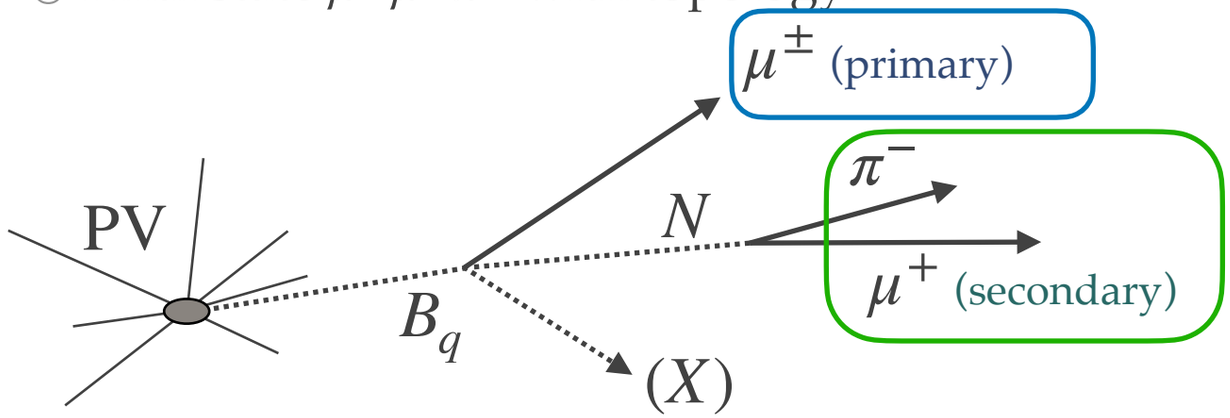




Analysis strategy

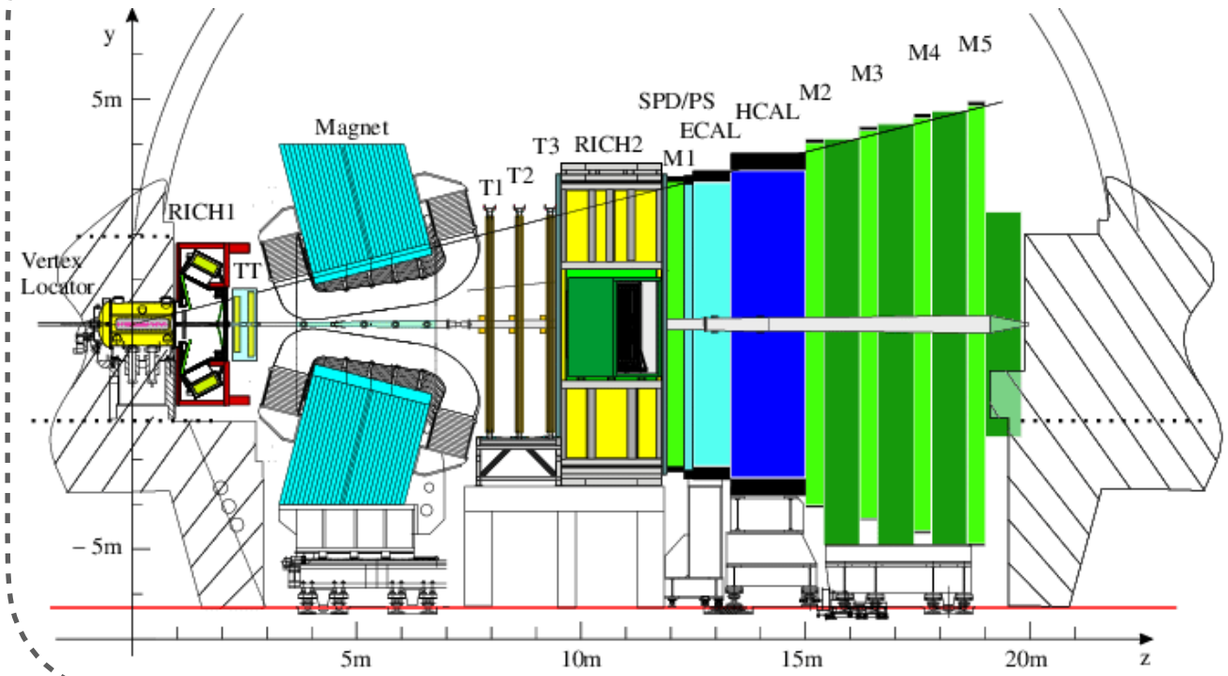
- Search heavy neutral leptons (N) in B decays
  - N mass between 1.5 and 6 GeV
  - Lifetimes in range 10-1000 ps
  - Lower (higher) m_N dominated by D (W) decays
- Focus for now on $N \to \mu^+\pi^-$ decay
  - Simpler analysis, lower background
  - Plan to do partially reconstructed N decays ($N \to \mu^-\pi^+\pi^0$, $N \to \ell^-\ell'^+\nu$) in the future

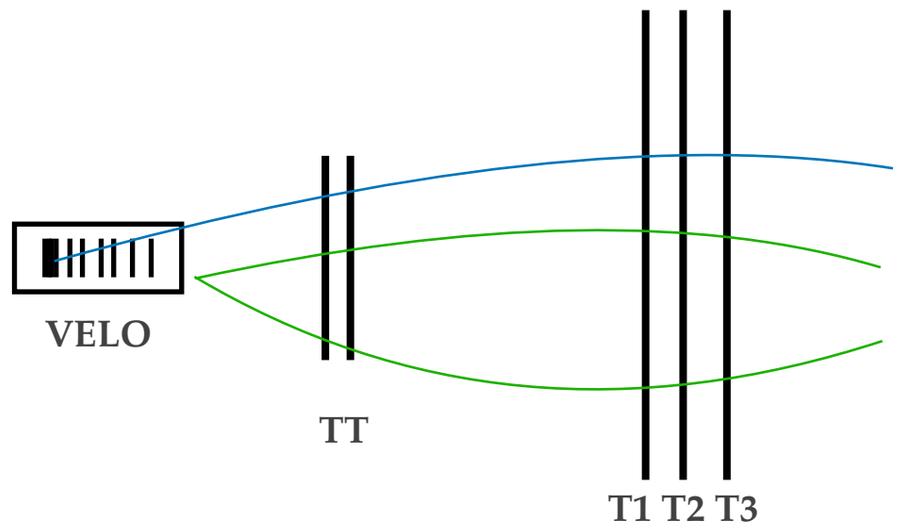
- Final state $\mu^\pm\mu^+\pi^-$ with topology:



- Considering both $\mu^+\mu^+$ (SS) and $\mu^-\mu^+$ (OS)

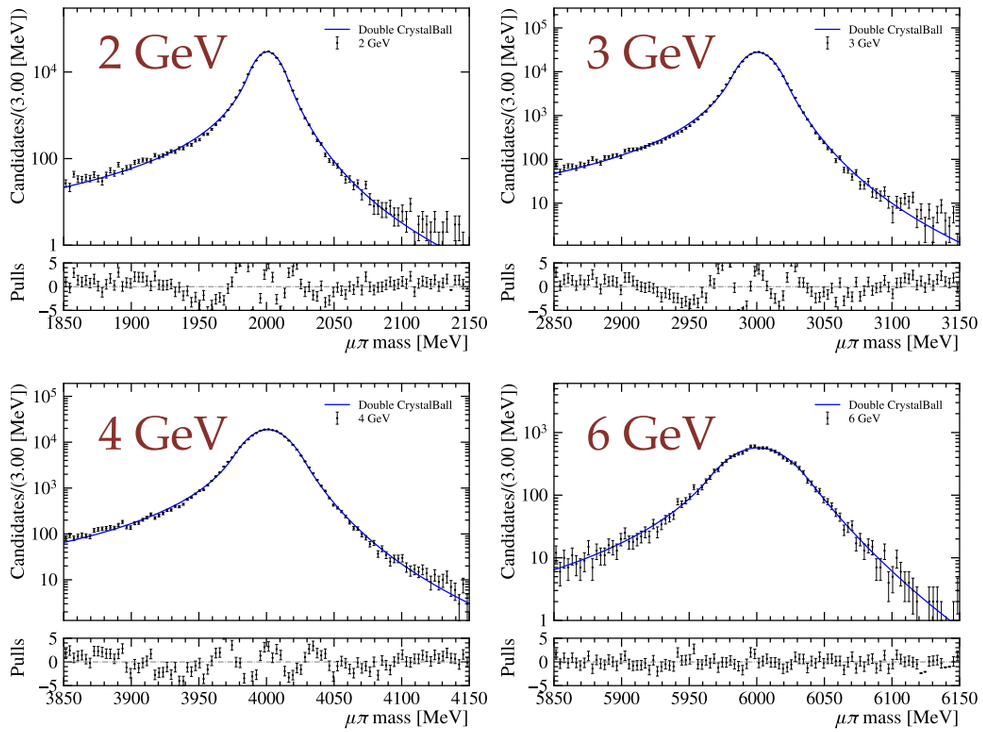
Large Hadron Collider Beauty (LHCb)

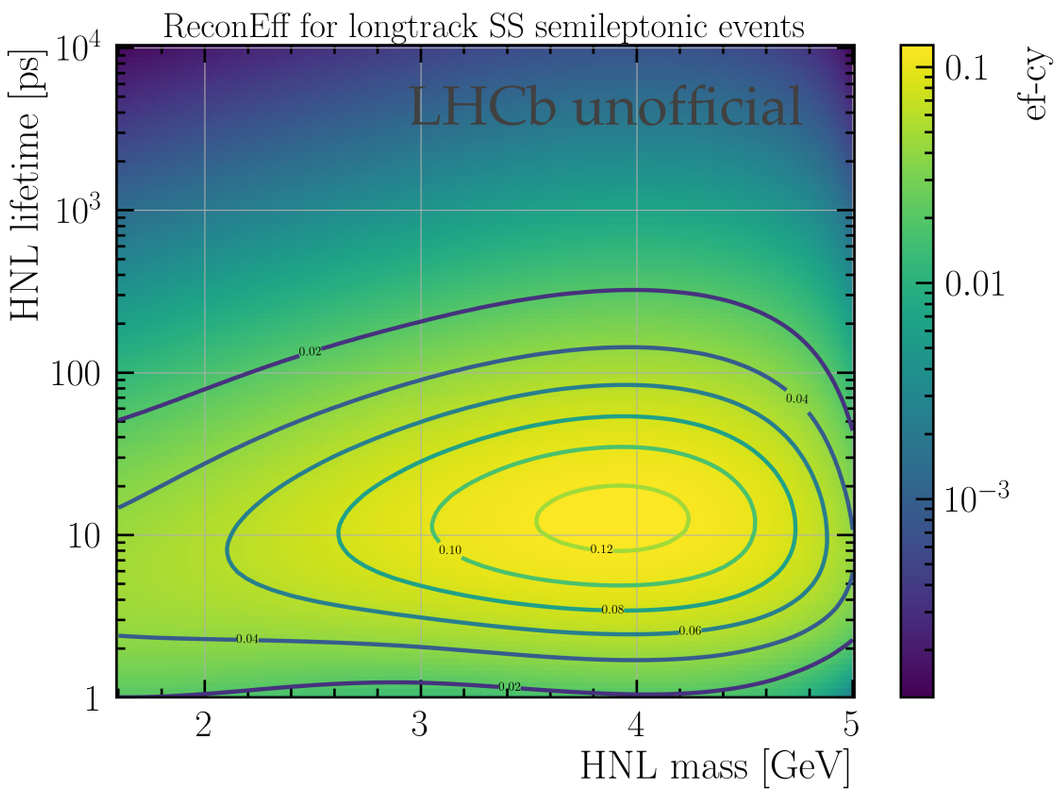


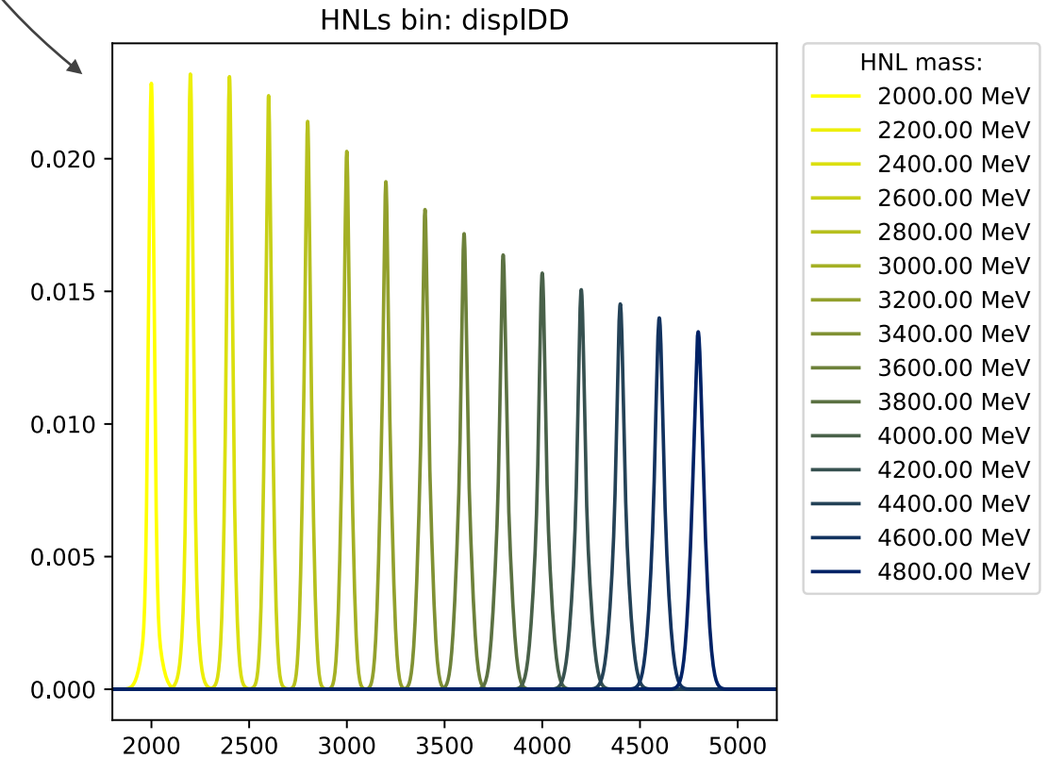


Signal mass shape and efficiency from the MC simulation

- Limited number of MC samples in mass - lifetime space (m_N, τ_N)
- PDFs are interpolated between all points
- The signal efficiency is interpolated to cover 2D m_N, τ_N search space



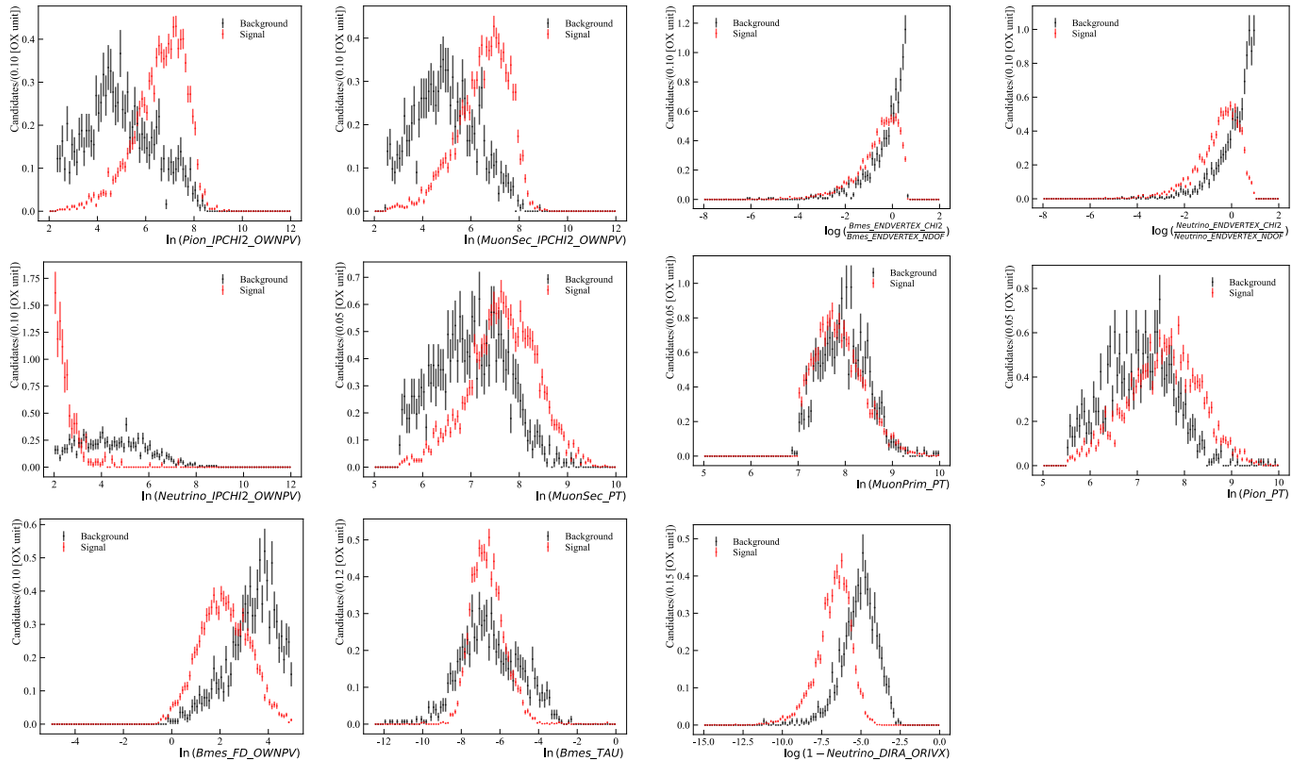




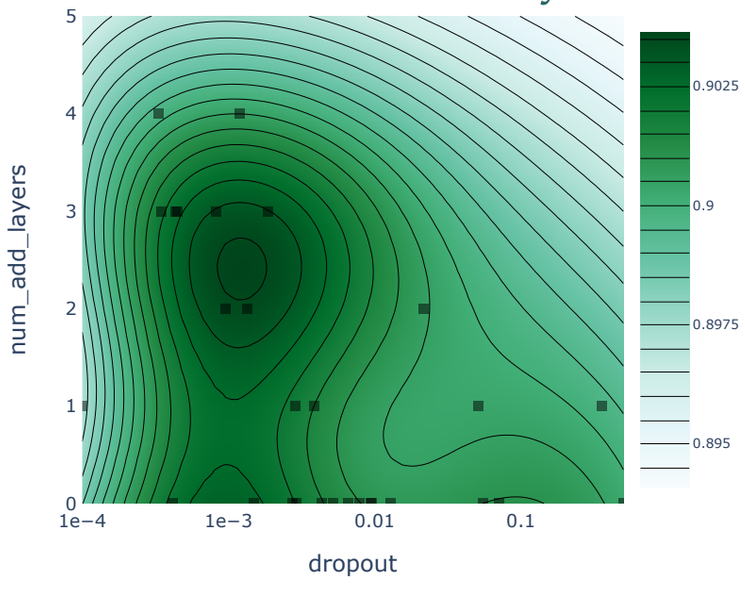
Multivariate analysis against combinatorial background

- Parametrised m_N as one of the input features to the classifier, as described in arXiv:1601.07913
  - True HNL mass of background sampled randomly from signal distribution
  - Given feature doesn't bring any discrimination power
  - Improved interpolated performance at intermediate mass values.
- NN hyper-parameters optimisation using Bayesian optimisation with Gaussian process

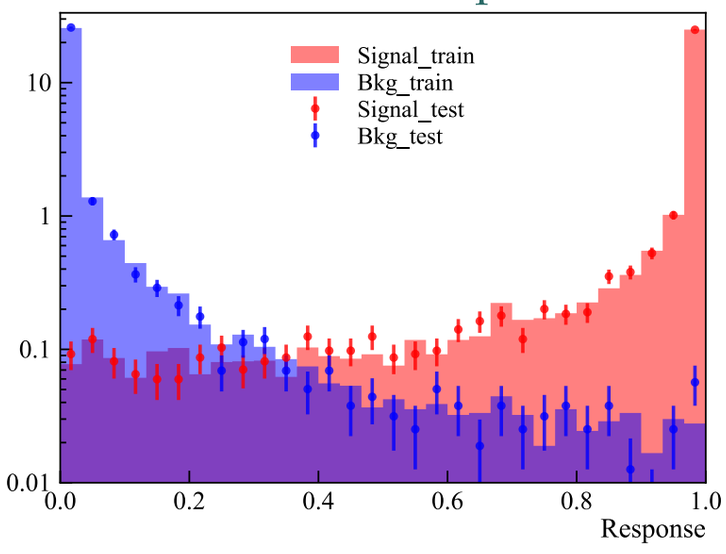
- Classifier features



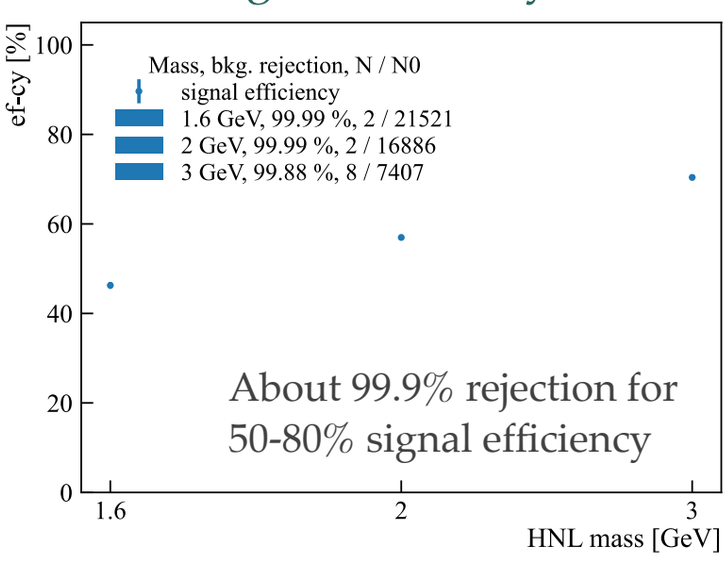
Balanced accuracy



Classifier response



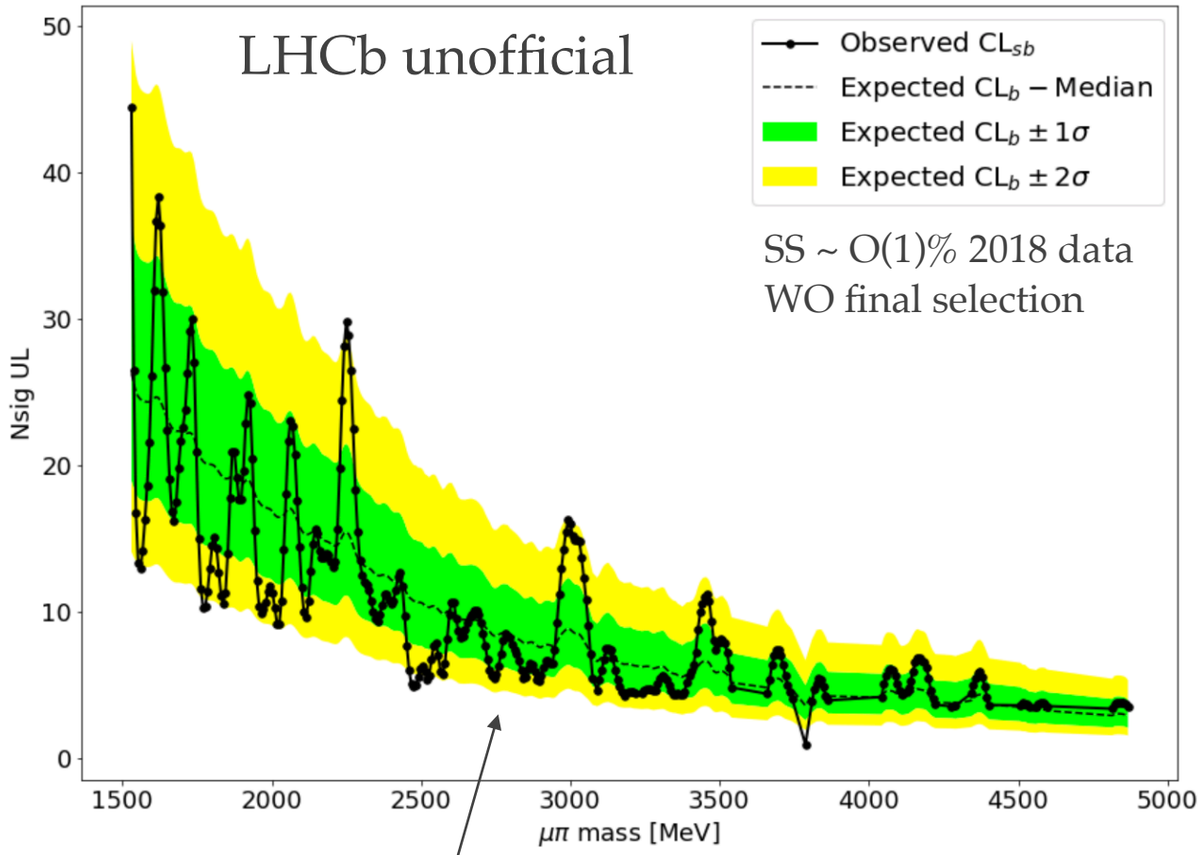
Signal efficiency

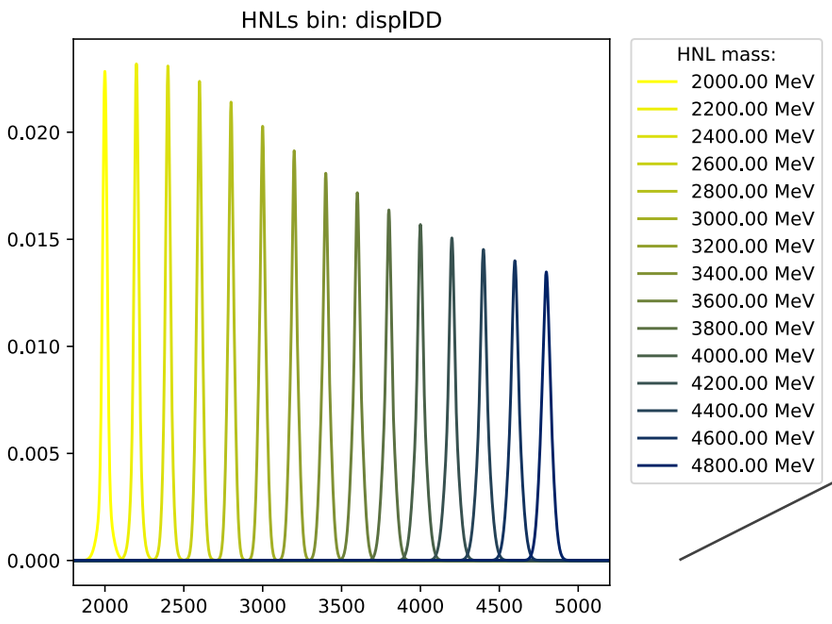


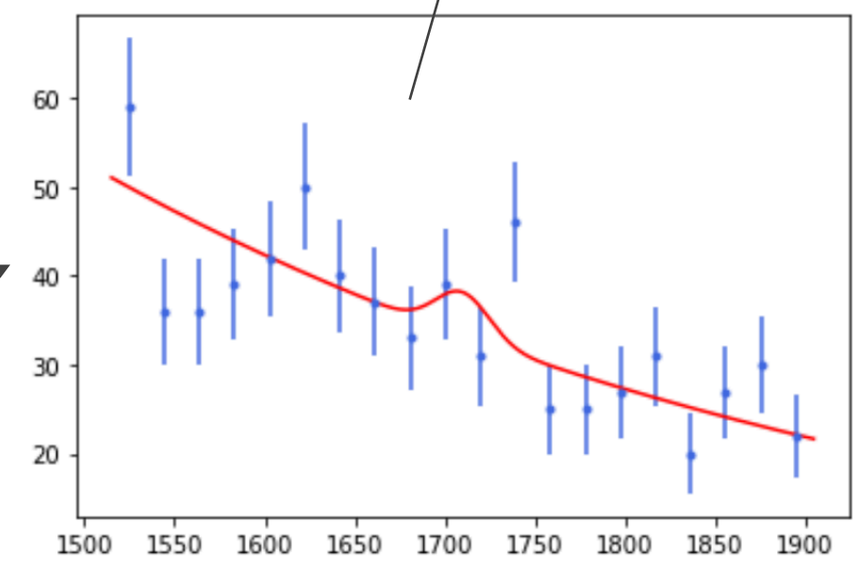
Fit and Upper Limit setting strategy

Scan over range of $m_{\mu\pi}$:

- Look at a specific mass hypothesis
- Define search window (depends on σ_N, taken from simulation)
- Fit S+B and test to B only
- Using expo/linear as a background pdf
- Signal shape is interpolated for each scan point

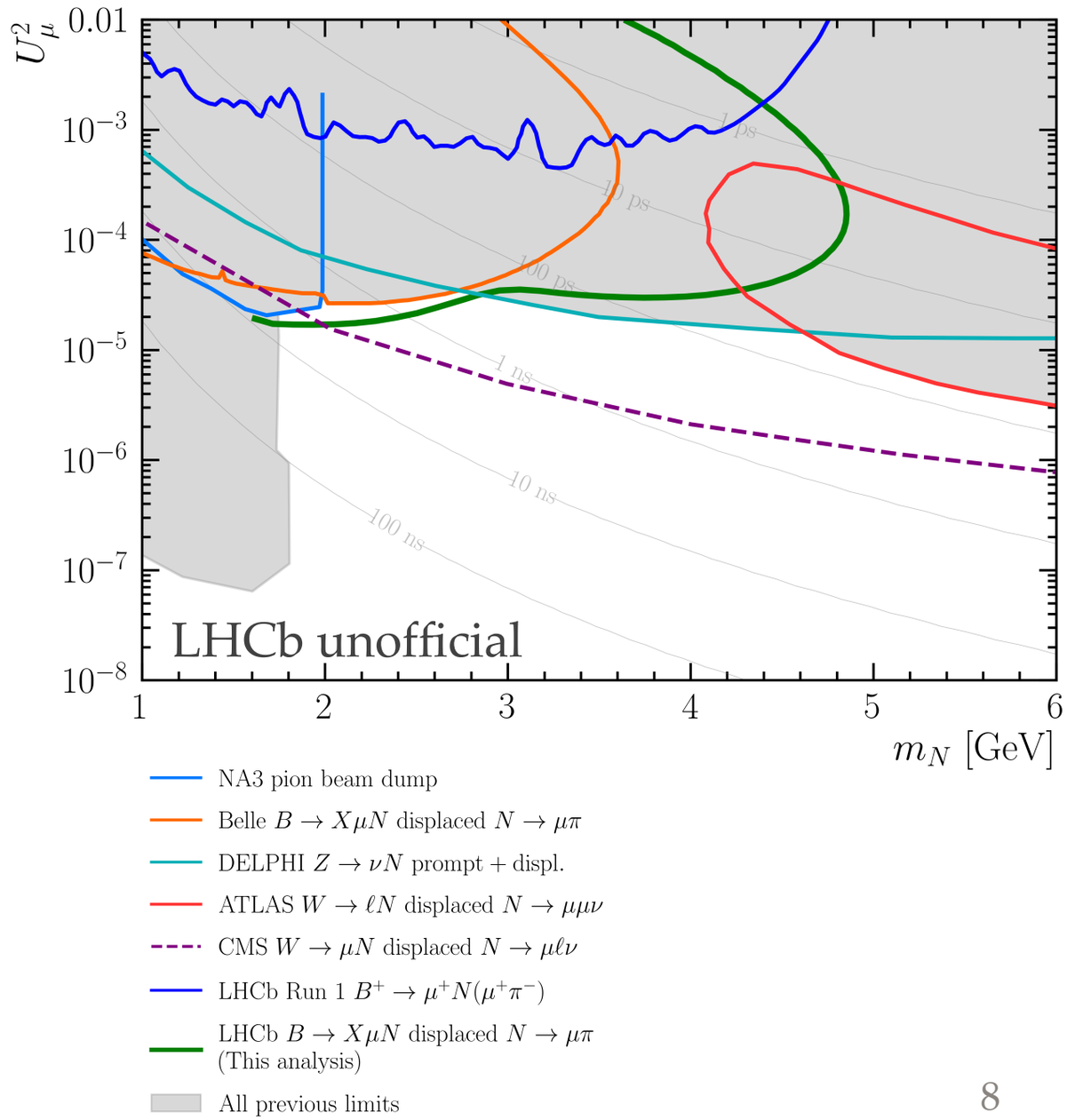






Conclusions

- Clear strategy for HNL search in B decays
- Full efficiency modelling in place
  - RapidSim for gen-level fiducial volume
  - Full MC interpolated in m_N and τ_N for reco eff-cy
- Neural network with excellent performance
  - Reduces combinatorial background by factor 10^3
- Zero-bkg limits are encouraging
  - More than one order of magnitude lower in U_μ^2 than previous LHCb result

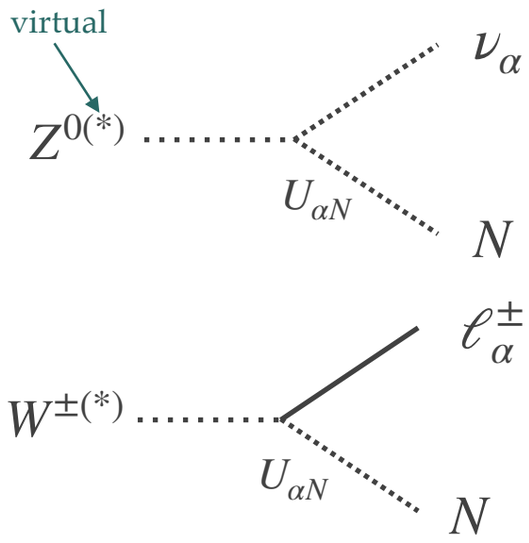


BACKUP

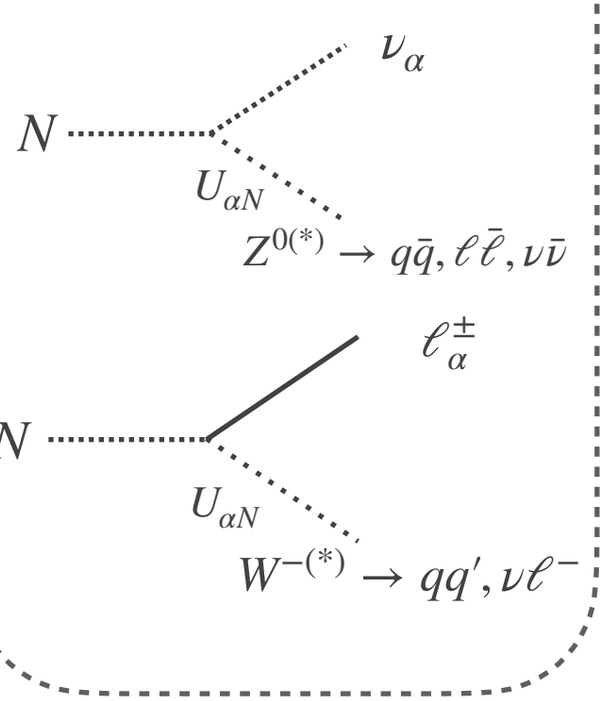
HNLs in the νMSM

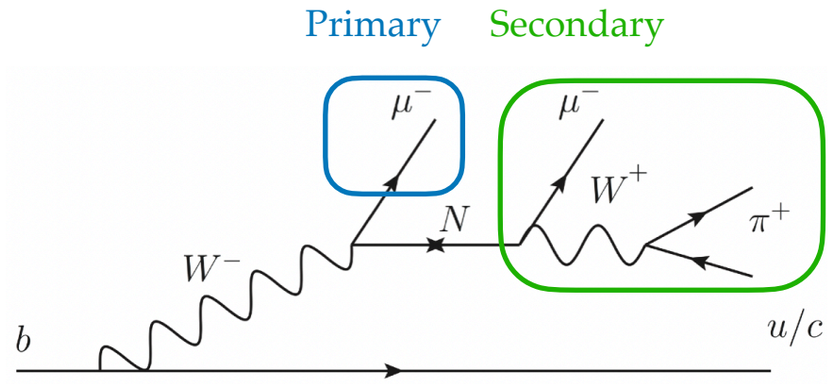
Production:

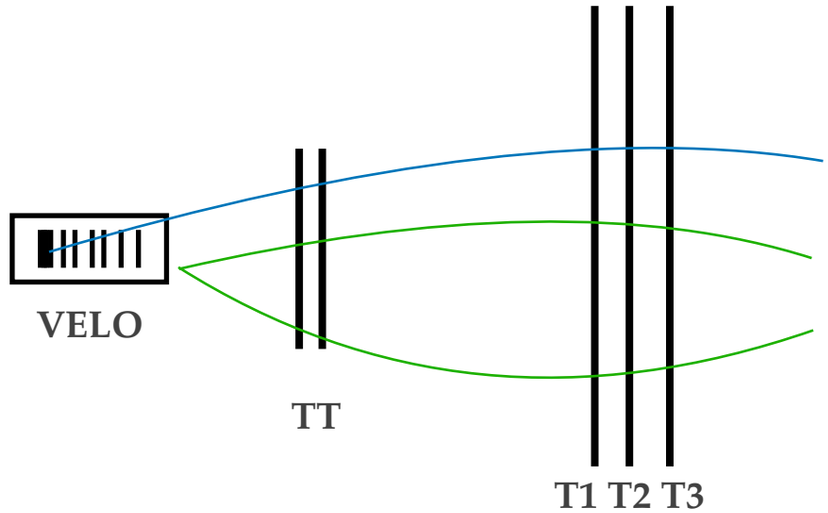
just as SM neutrino



Decay:





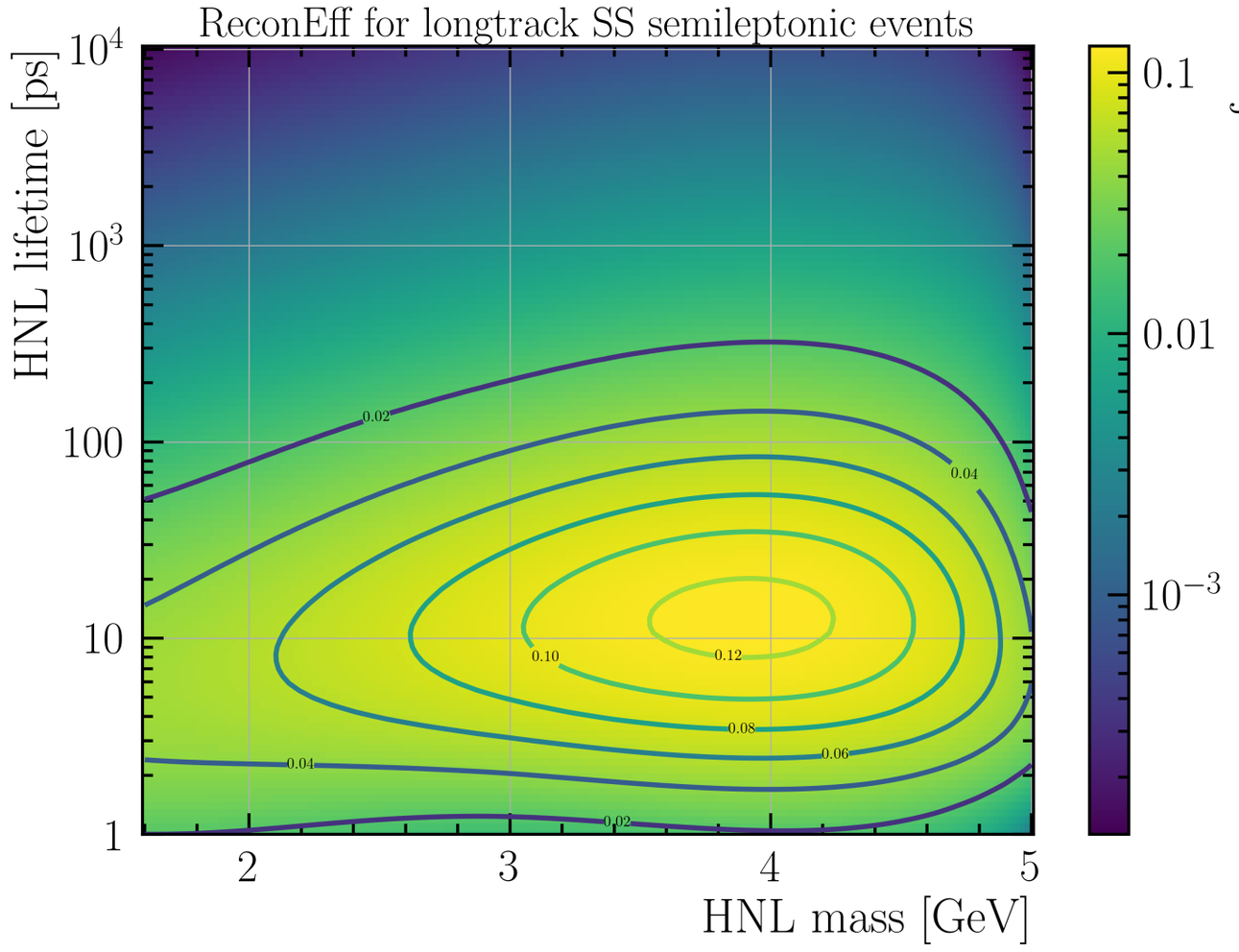


- Could be visible in charged final states
- Parameter $U_{\alpha N}^2$ gives HNL mixing with SM neutrino (flavour α)
- N lifetime $\tau \propto |U_{\alpha N}|^{-2} m^{-5}$

Reconstruction efficiency

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{FV}} \cdot \varepsilon_{\text{Reco}} \cdot \varepsilon_{\text{MVA}}$$

- Reco efficiency (after FV)
  - Taken from LHCb MC
  - Modelled as function of m_N and τ_N:
    - τ_N by reweighting decay time
    - m_N interpolation assuming smooth behaviour
- $3 \times 3 \times 2$ categories:
  - Semilept, B_u leptonic, B_c leptonic
  - Prompt, displ-long, displ.downstream
  - Same/opposite sign muons (SS/OS)



Neural network

- Trained MVA classifier to suppress combinatorial background
- Separated training for leptonic/semilept, SS/OS, prompt/displaced/downstream
- Signal sample:
  - Full MC with all mass points
  - Lifetime of the training sample is reweighed to populate corresponding category
- Background sample:
  - Data from sidebands of $m(\mu\mu\pi)$
- The list of features is the same for all categories

  $\log_{10}(1 - DIRA(N))$,

  $\log_{10}\left(\chi^2_{vtx}(N)/\mathrm{dof}\right)$, $\log_{10}\left(\chi^2_{vtx}(B_q)/\mathrm{dof}\right)$,

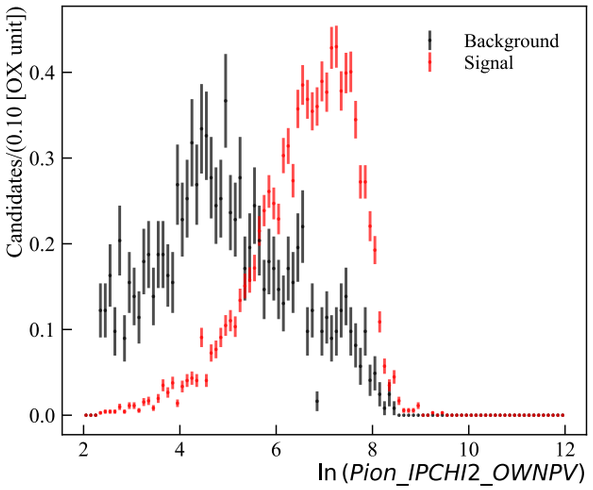
  $\ln \chi^2_{IP}(\pi)$, $\ln \chi^2_{IP}(\mu_{sec})$, $\ln \chi^2_{IP}(N)$,

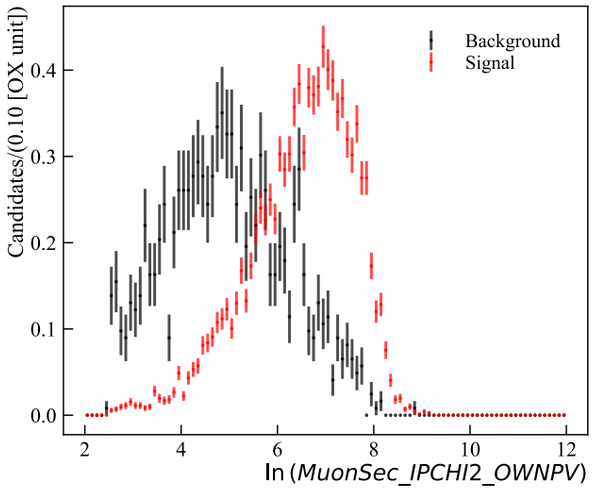
  $\ln p_T(\pi)$, $\ln p_T(\mu_{sec})$, $\ln p_T(\mu_{prim})$,

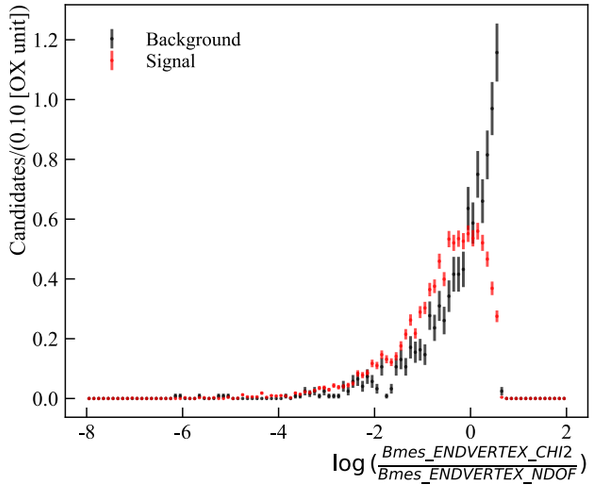
  $\ln FD(B_q)$, $\ln \tau(B_q)$,

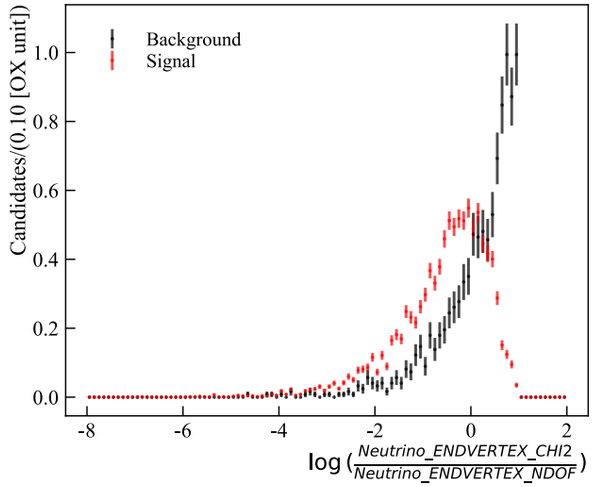
  m_N^{true}
- Leptonic category additionally includes $\log_{10}(1 - DIRA(B_q))$ since the $\vec{p}$ of the B_q is reconstructed

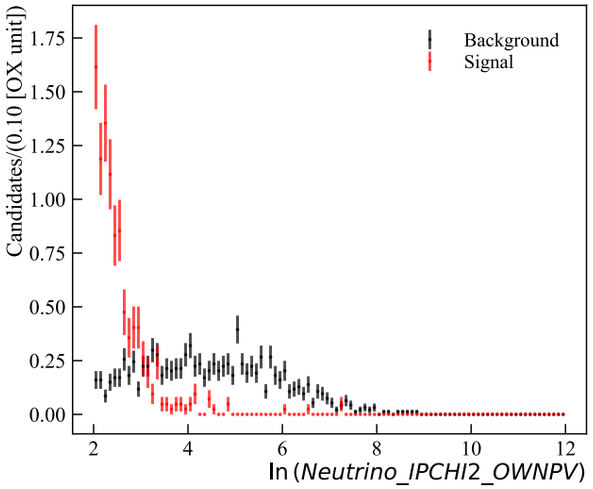
Training features (semilept, SS, Downstream)

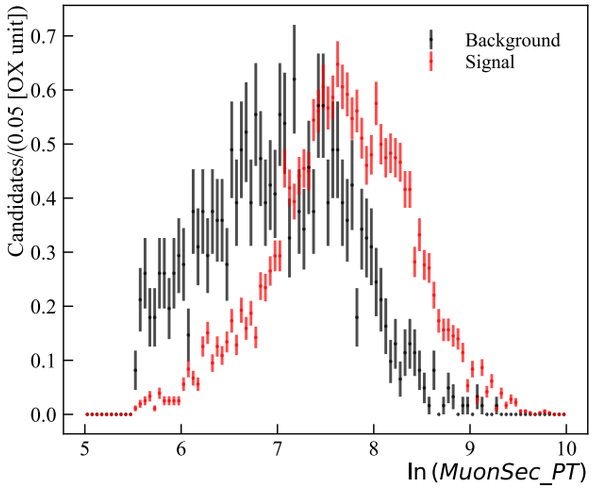


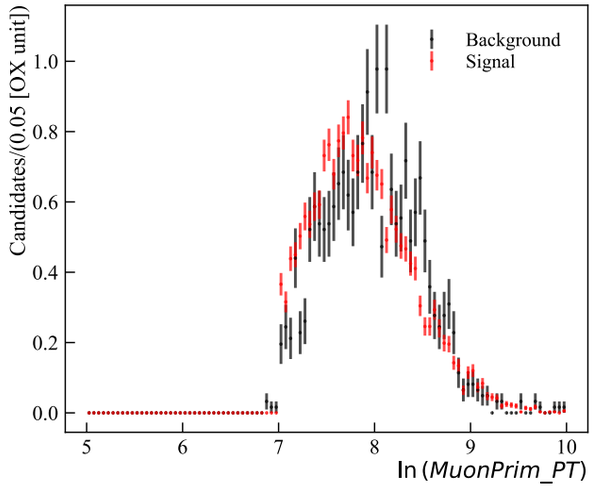


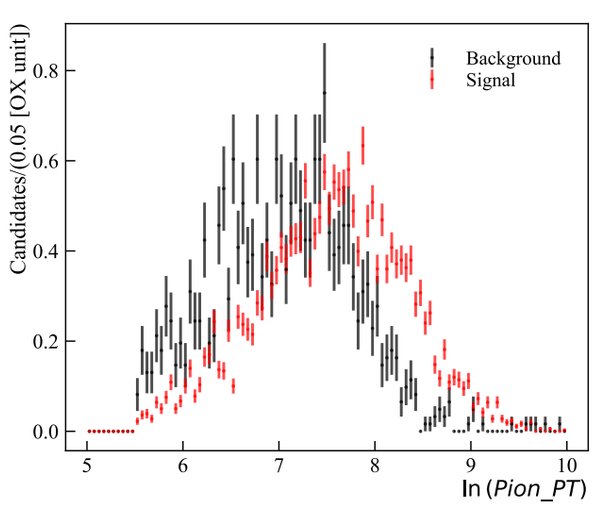


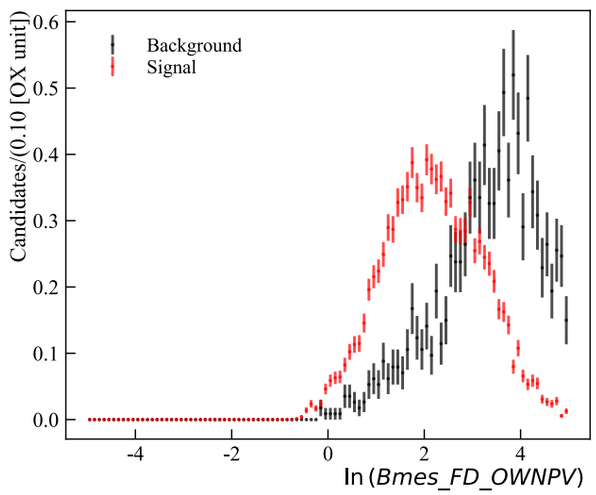


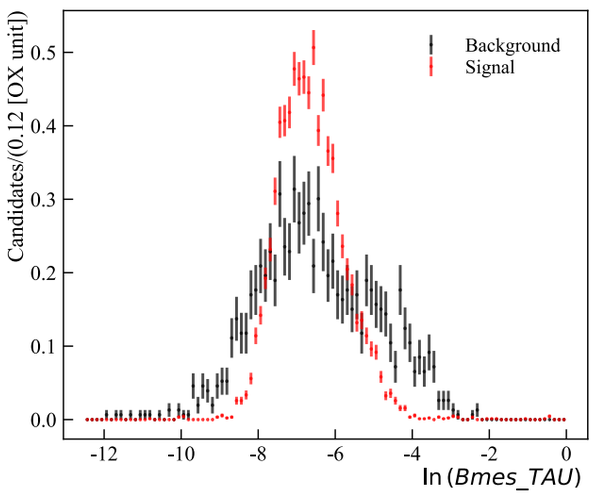


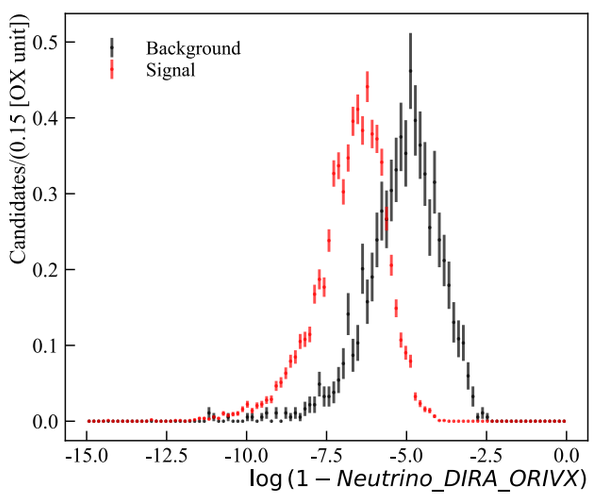






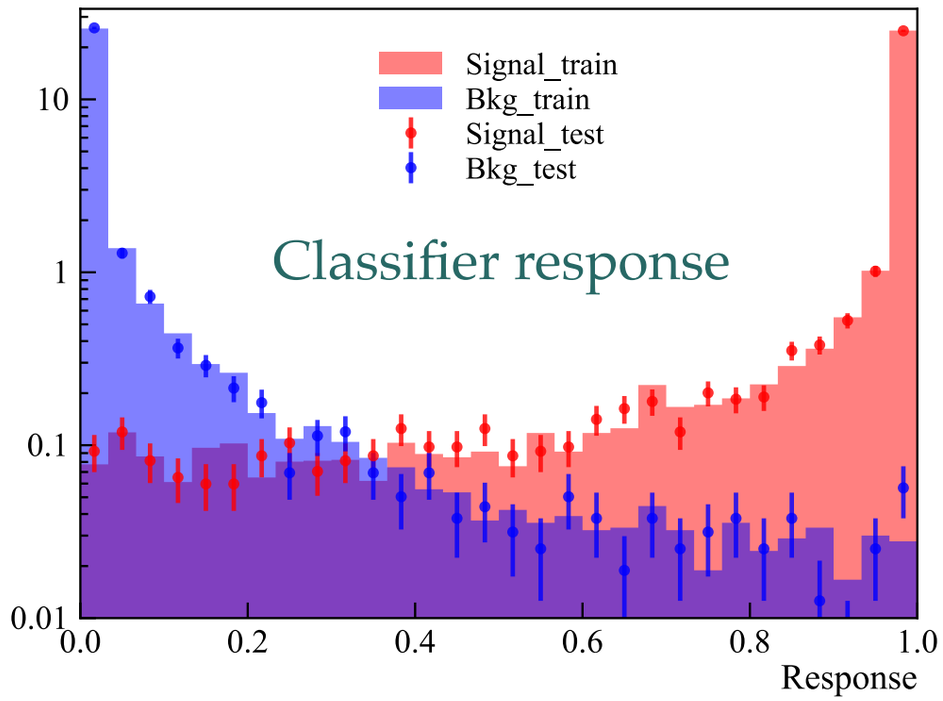




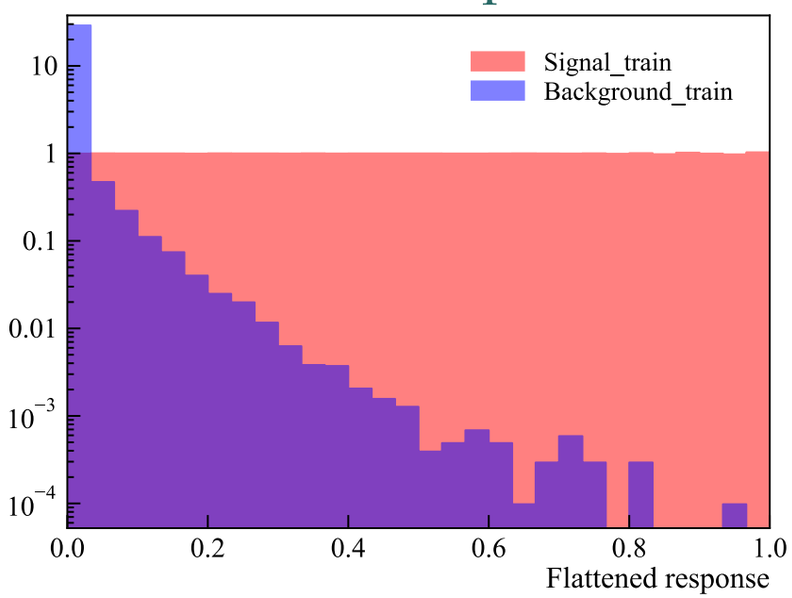


NN optimisation and performance

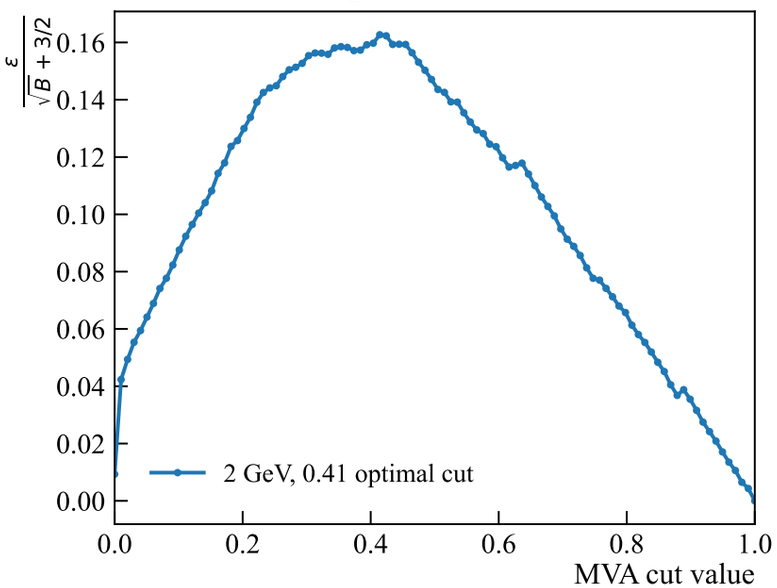
- MVA cut optimised with f.o.m. $= \dfrac{\varepsilon}{\sqrt{B} + 3/2}$ for optimal m_N^{true} of the search bin
  - ε is the signal efficiency from MC
  - B is the background yield in a $\pm 2\sigma_m$ window under the peak of the $\mu\pi$ spectrum ($\mu\mu\pi$ sideband scaled to the signal region)
- Example for **semilept / SS / displ.long** category
  - Relevant only at $m_N \leq 3$ GeV
  - **Optimal m_N = 2 GeV (strongest expected limit)**
  - About 99.9% rejection for 50-80% signal efficiency
  - Expect about O(10) bkg events under signal peak



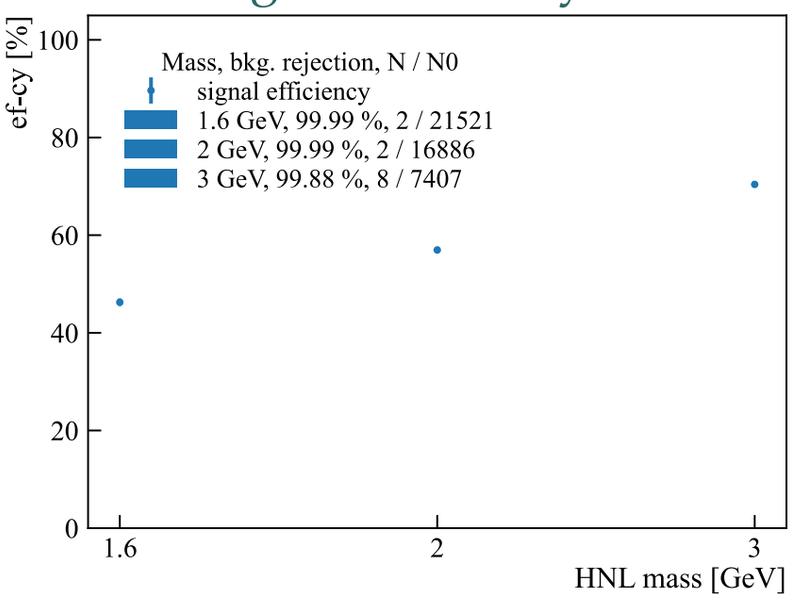
Flattened response



Cut optimisation

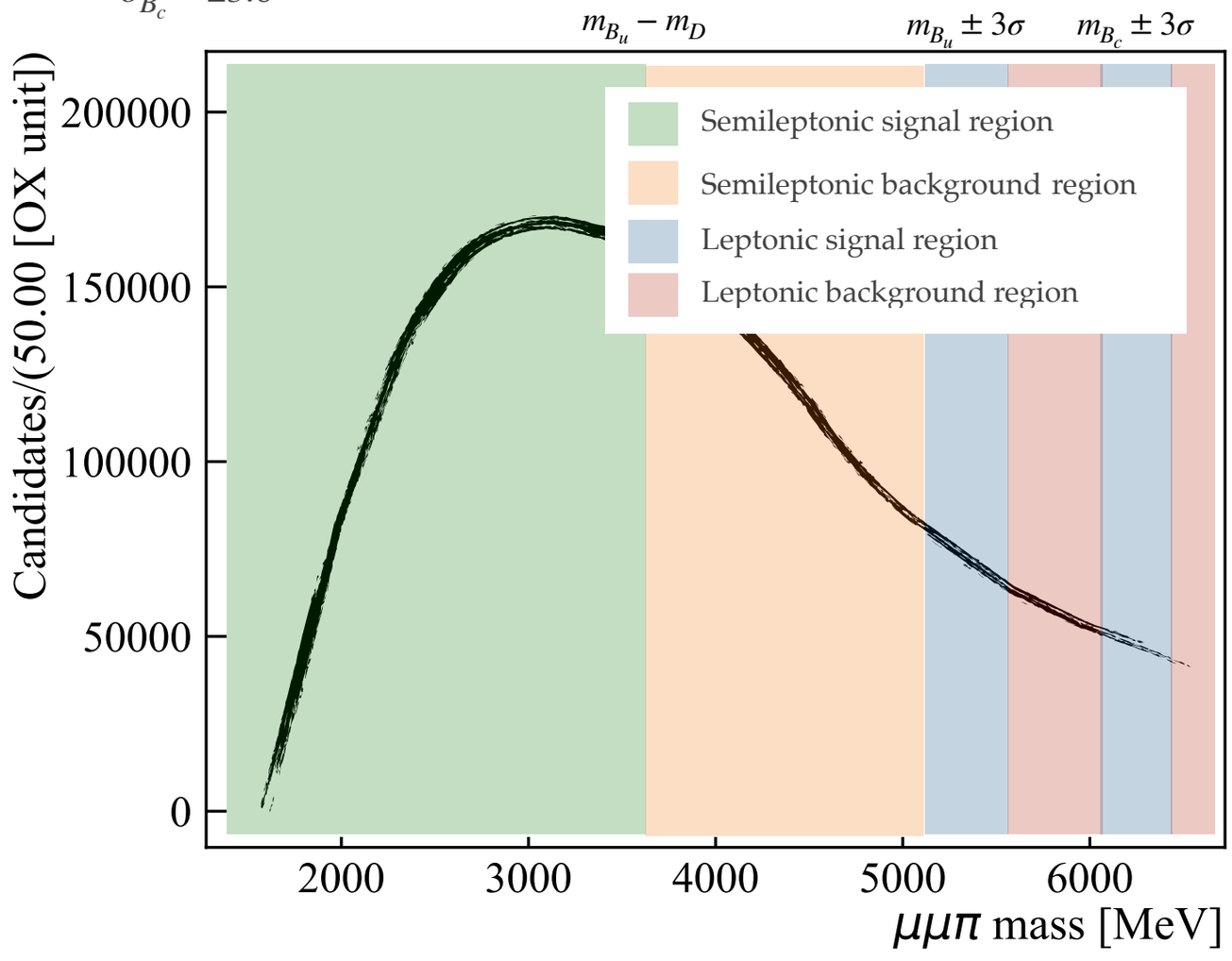


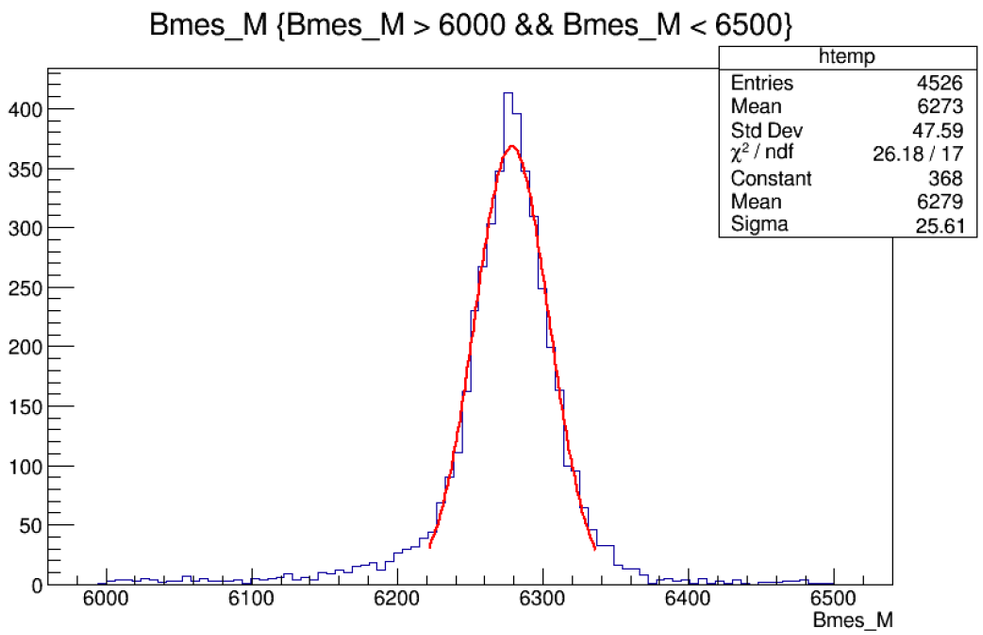
Signal efficiency

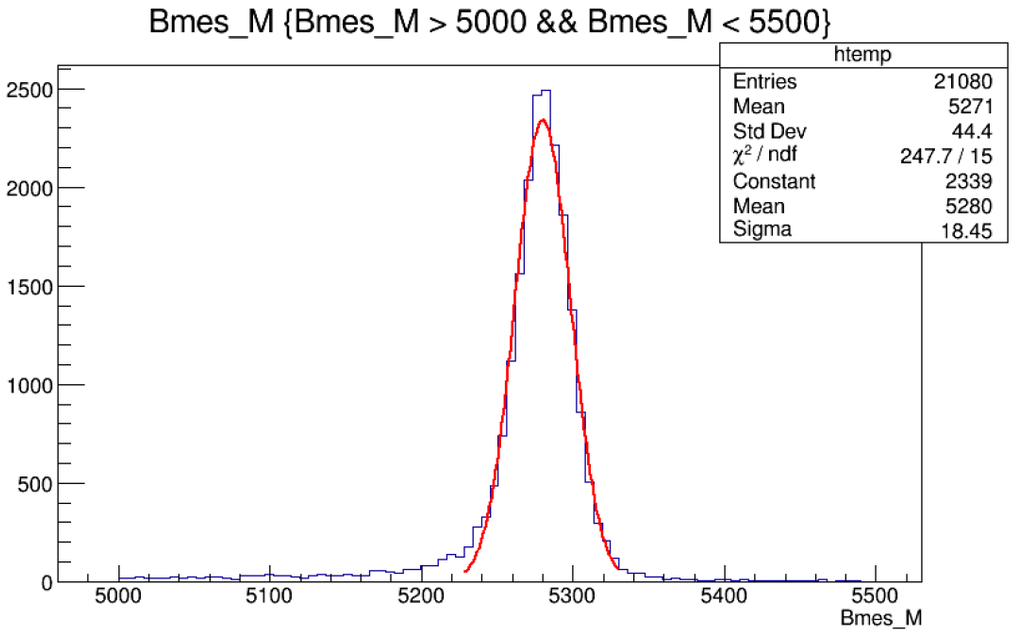


Signal / background regions

- Leptonic bkg region == $[m_{B_u} + 3\sigma_{B_u}, m_{B_c} - 3\sigma_{B_c}] \cup [m_{B_c} + 3\sigma_{B_c},\ 6500MeV]$
- Semileptonic bkg region == $[m_{B_u} - m_D, m_{B_u} - 3\sigma_{B_u}]$
- Take
  - $\sigma_{B_u} = 18.5$
  - $\sigma_{B_c} = 25.6$







Lifetime reweighting

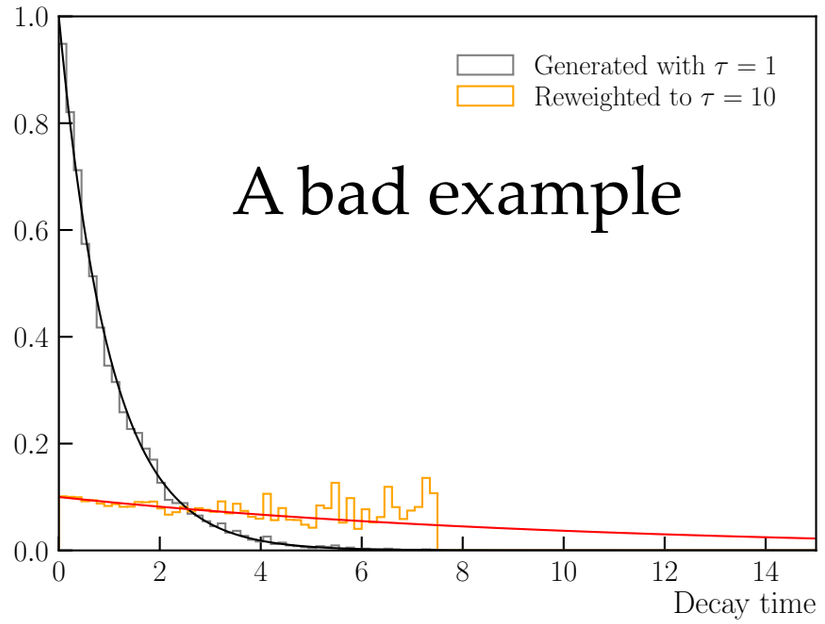
- Can reweight MC to any lifetime with

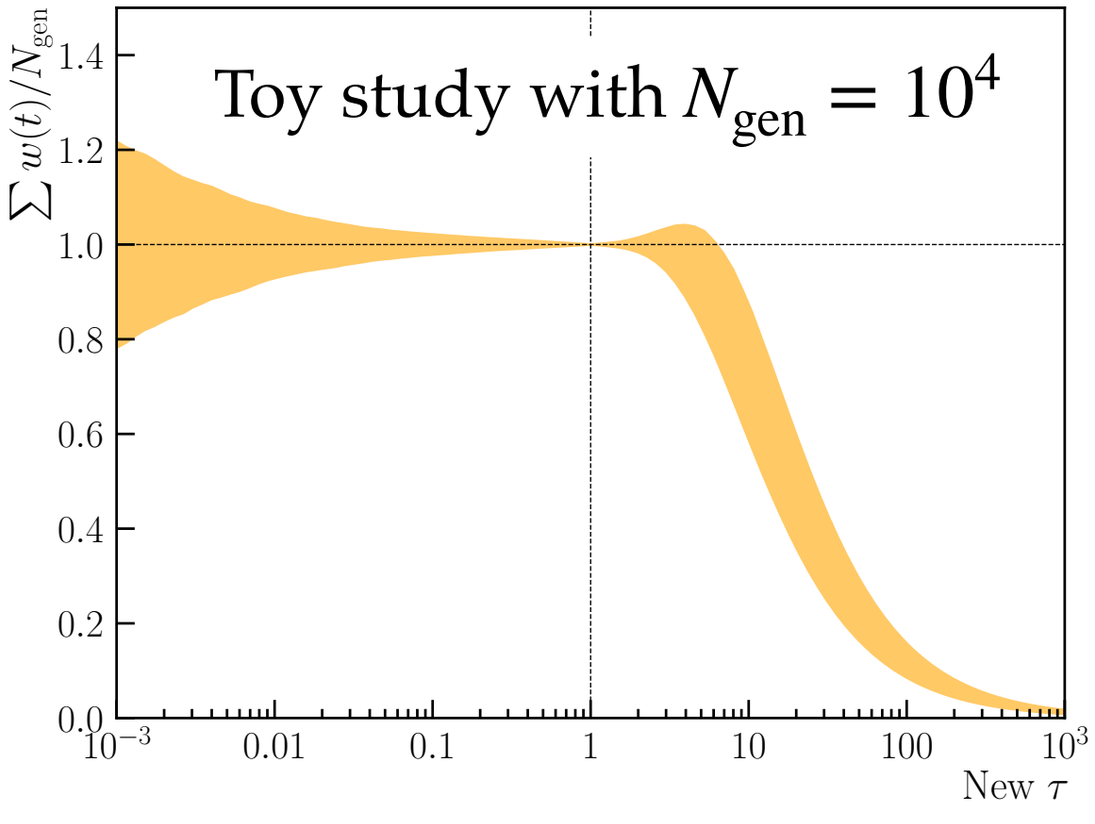
$$w(t) = \frac{\tau_{\text{gen}}}{\tau_{\text{new}}} \frac{\exp(-t/\tau_{\text{new}})}{\exp(-t/\tau_{\text{gen}})}$$

  where the $\frac{\tau_{\text{gen}}}{\tau_{\text{new}}}$ factor insures $\sum w(t) = N_{\text{gen}}$

- However, strictly true only with infinite statistics
  → Get huge biases when $\tau_{\text{new}} > \tau_{\text{gen}}$

- Need to take some care when calculating efficiencies by combining MC samples with different τ_{gen}
  - Cannot reweight to $\tau_{\text{new}} > \tau_{\text{gen}}$ unless τ_{gen} already covers the decay time region of interest
  - Solution: scale down contribution of reconstructed samples with large weights by rescaling $\max(w(t)) = 1$ for each τ_{gen}





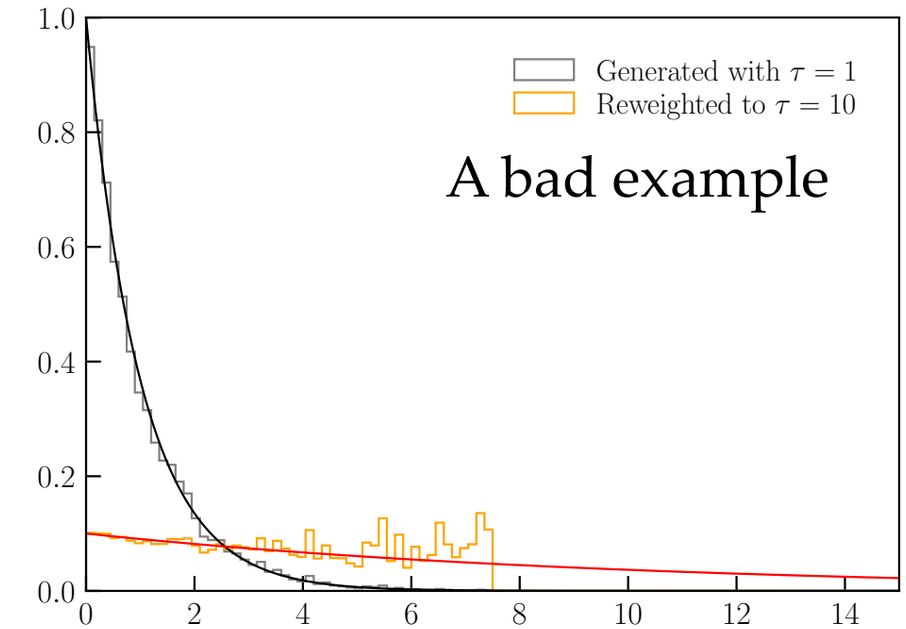
Lifetime reweighting

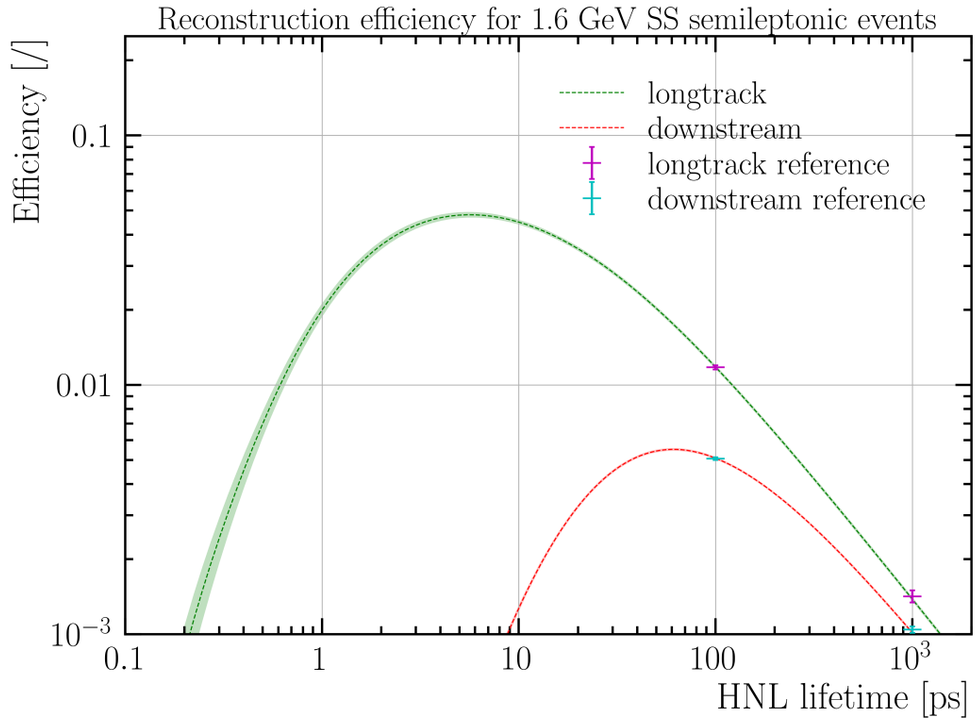
- To cover lifetime space we need MC samples of multiple τ_N
- Can reweight MC to any lifetime with

$$w(t) = \frac{\tau_{\text{gen}}}{\tau_{\text{new}}} \frac{\exp(-t/\tau_{\text{new}})}{\exp(-t/\tau_{\text{gen}})}$$

where the $\frac{\tau_{\text{gen}}}{\tau_{\text{new}}}$ factor insures $\sum w(t) = N_{\text{gen}}$

- However, strictly true only with infinite statistics
  → Get huge biases when $\tau_{\text{new}} > \tau_{\text{gen}}$ unless τ_{gen} already covers the decay time region of interest
- Need to take some care when calculating efficiencies by combining MC samples with different τ_{gen}
- Crosschecked lifetime reweighting with LHCb MC
  - Few generated τ points
    - well covering decay times in VELO + downstream





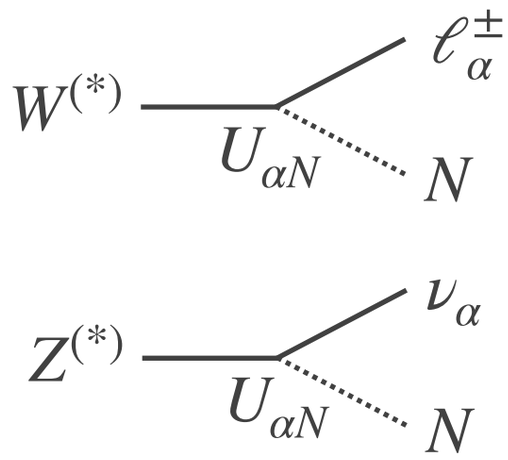
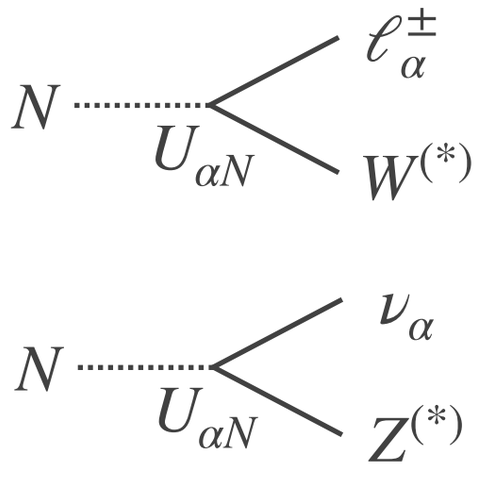
Motivation

- Heavy Neutral Leptons could explain several BSM phenomena:
  - Neutrino oscillations (seesaw mechanism)
  - Baryon asymmetry of the Universe (leptogenesis)
  - Dark matter (lightest sterile neutrino)
- HNL's (N) are singlets with respect to the SM gauge group
  $\mathscr{L}_{\text{Neutrino portal}} = F_\alpha \left(\overline{L}_\alpha \cdot \tilde{H}\right) N + h.c.$
- After EWSB the Higgs v.e.v. provides a mass mixing term between SM neutrinos and HNL

$$\mathscr{L}_{int} = \frac{g}{2\sqrt{2}} W_\mu^+ \overline{N^c} \sum_\alpha U_{\alpha N}^* \gamma^\mu \left(1-\gamma_5\right) \ell_\alpha^- + \frac{g}{4\cos\theta_W} Z_\mu \overline{N^c} \sum_\alpha U_{\alpha N}^* \gamma^\mu \left(1-\gamma_5\right) \nu_\alpha + \text{h.c.}$$

- Parameter $U_{\alpha N}^2$ gives HNL mixing with SM neutrino (flavour α)
  - Production rate is proportional to $U_{\alpha N}^2$
  - HNL lifetime τ is proportional to $U_{\alpha N}^{-2} \cdot m_N^{-5}$
- HNL can be a Majorana or Dirac particle
  $\rightarrow \ell^\pm$ in production and decay can have the same charge!

Production



Decay