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Machine Learning Techniques to Probe Heavy Neutral leptons in the electron channel at FCC-ee (Brief Summary)

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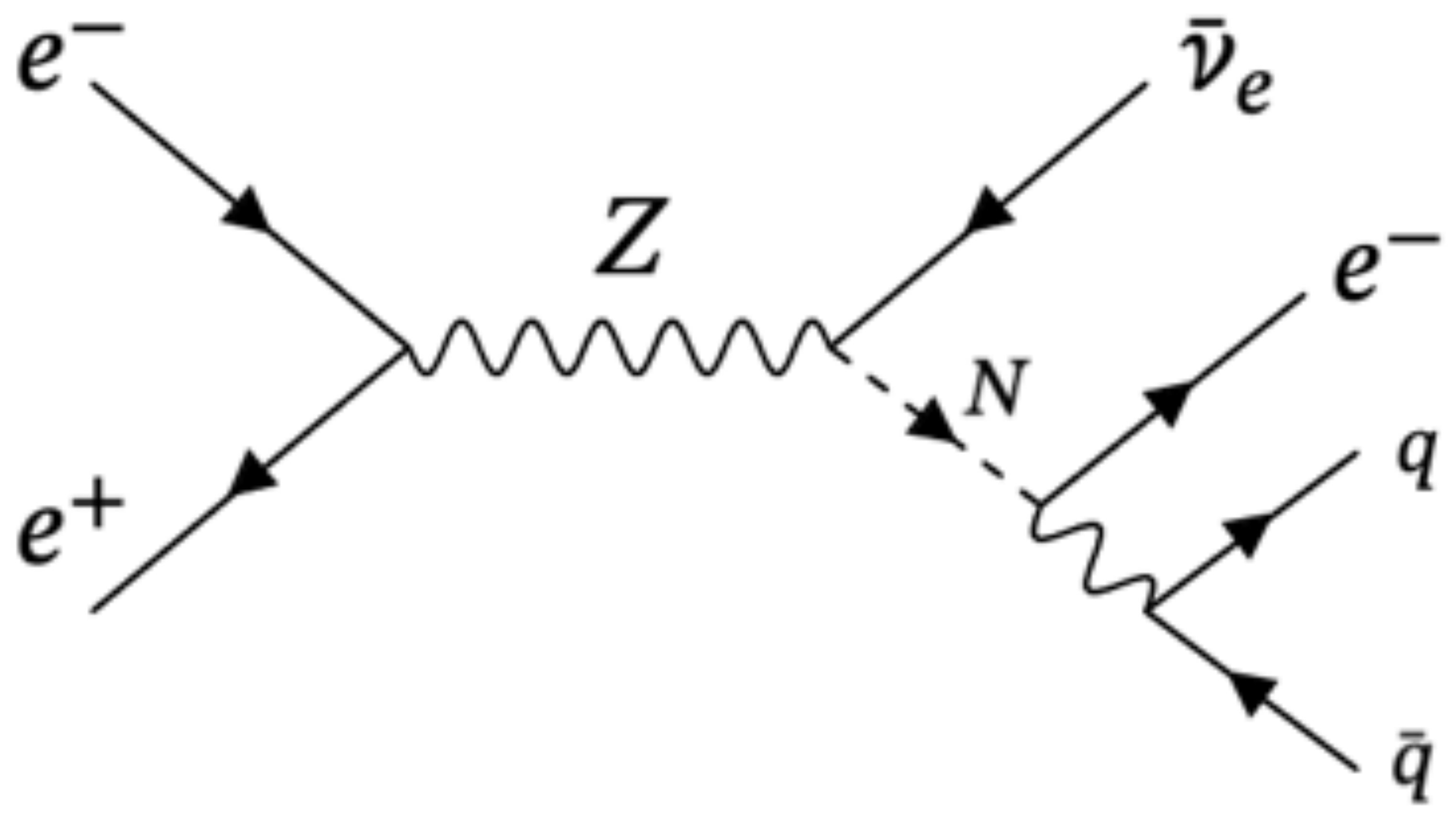
Introduction

- **Low-scale** inverse seesaw mechanism enables the search for heavy right-handed neutrinos with Yukawa couplings $O(10^{-6})$ in the mass range of **10** to **100 GeV**

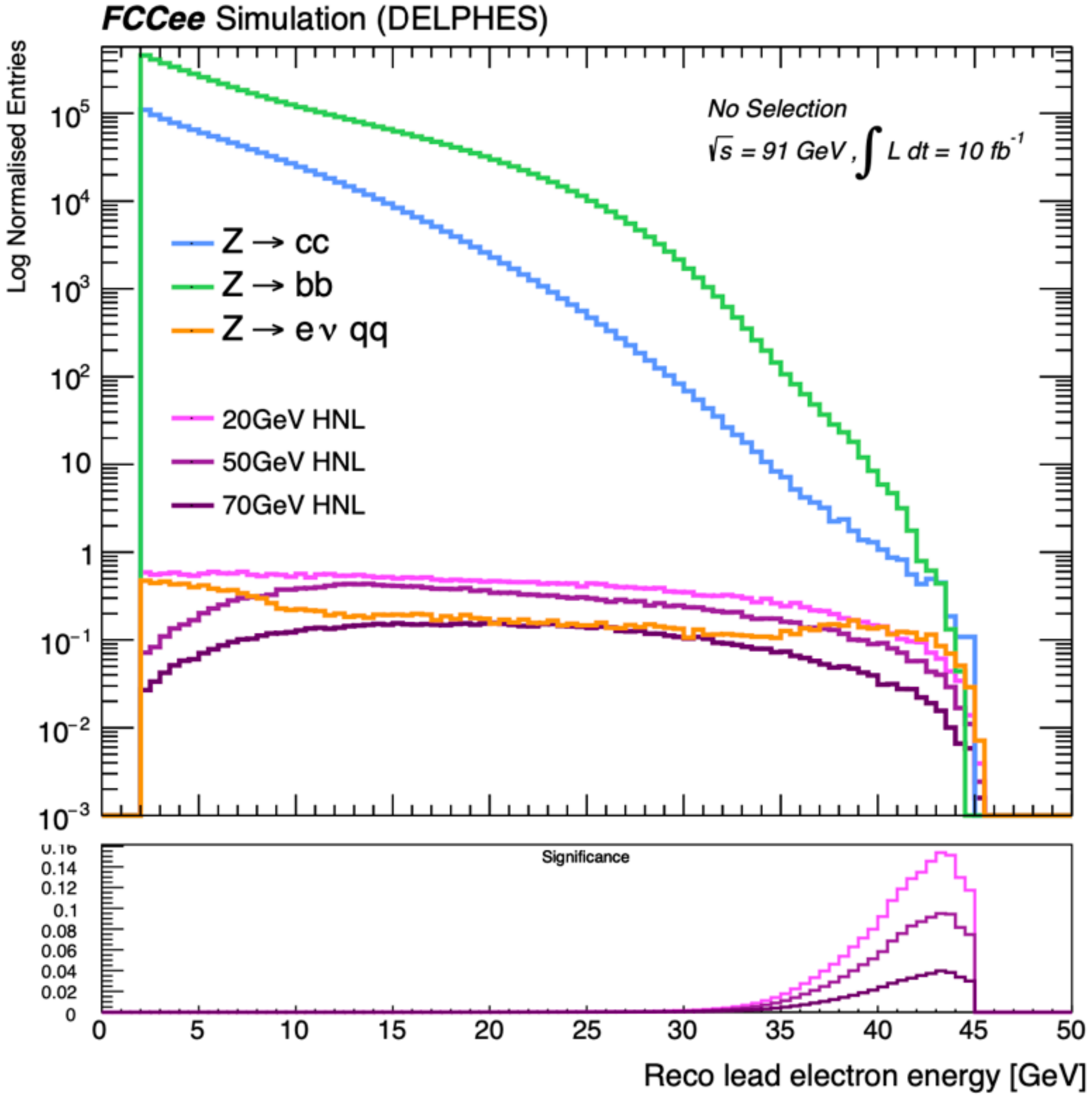
- Our analysis focuses on **the electron final state with two jets,** investigating the (pseudo-) **Dirac** HNL model between **10-80 GeV** with mixing angles between $10^{-4} < |U_{eN}|^2 < 10^{-10}$



Background Processes

◉ **Three dominant SM background processes considered:**

- Z→bb, cc or Z→4 body final state (instead of heavier quark final states like Z→ττ)
- The 4-body bkg and all signal samples are privately generated using MadGraph



Process	σ(pb)	Monte-Carlo events	Production $\mathcal{L}$ (fb^{-1})
$Z \to b\bar{b}$	6.65×10^3	4.39×10^8	6.60×10^1
$Z \to c\bar{c}$	5.22×10^3	4.98×10^8	1.15×10^2
$Z \to$ 4body	1.40×10^{-2}	1.00×10^5	7.14×10^3

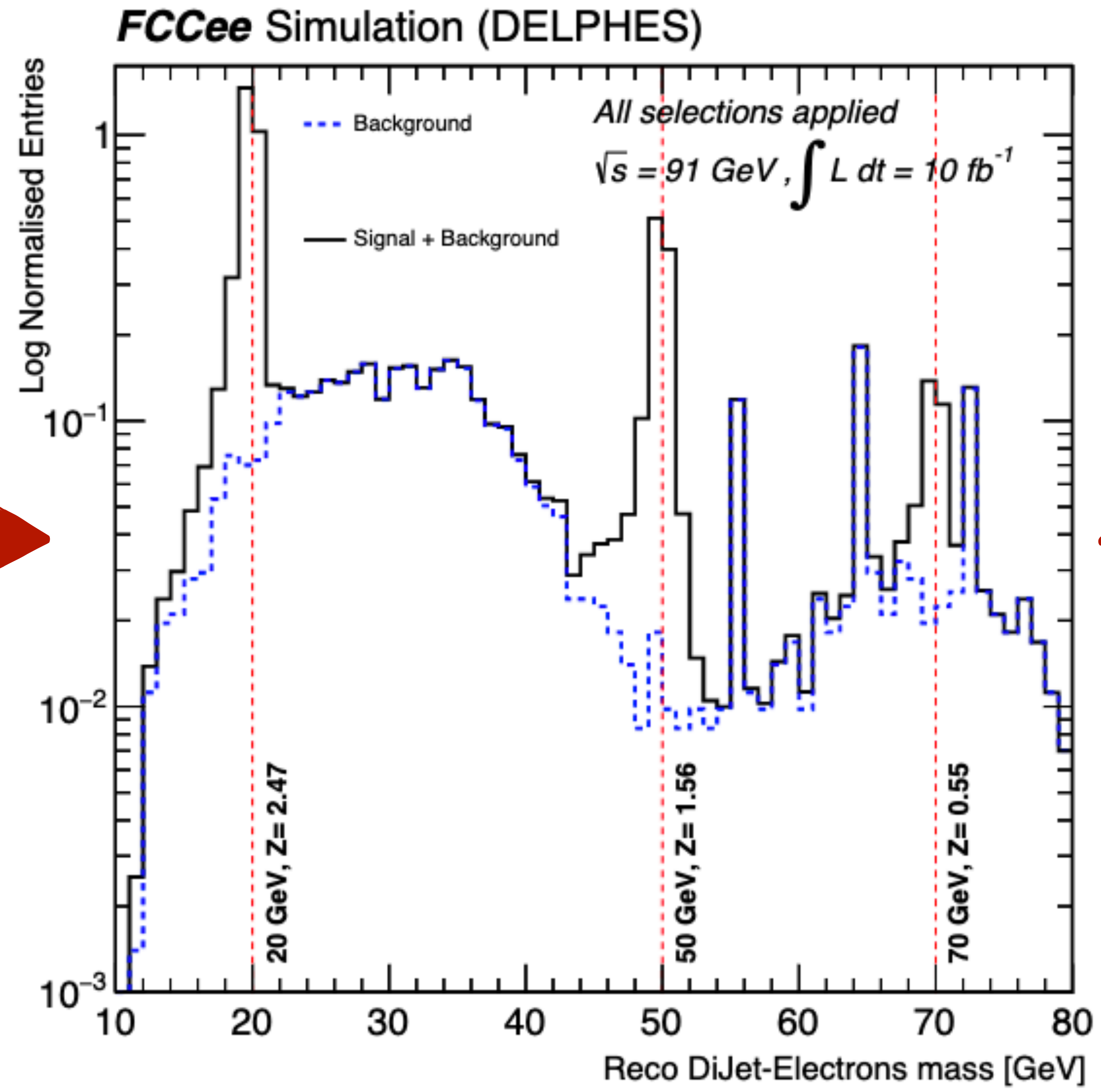
Limited MC statistics for central backgrounds; the analysis is conducted at **10 fb^{-1}** and scaled to **150 ab^{-1}** for the final result

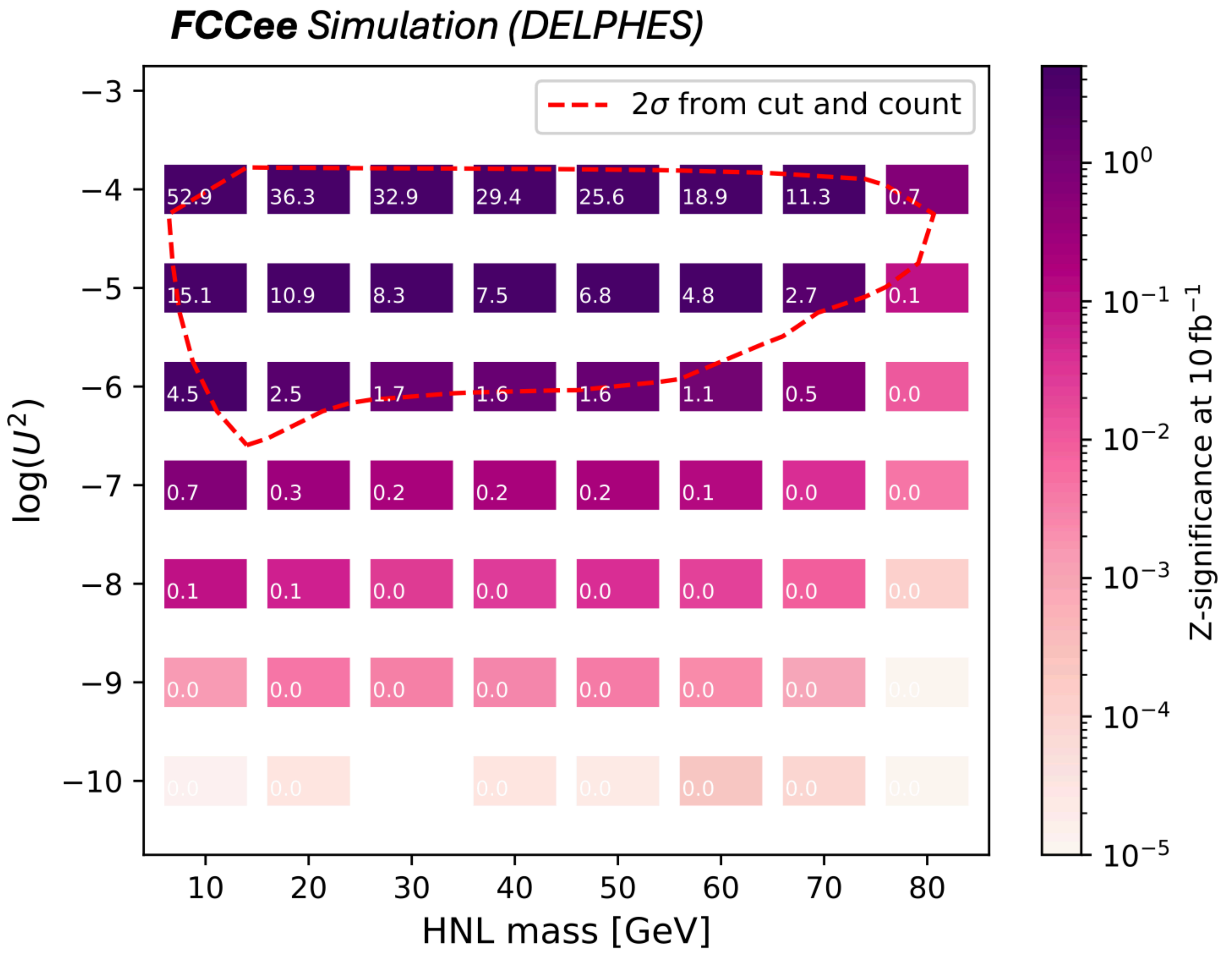
Analysis Methods

◉ Cut and Count Method

- **C&C studies made by D. Moulin (master thesis, 2023) and used as benchmark for optimization**

Variable	Selection
Missing energy	$> 12\,\mathrm{GeV}$
Leading electron energy	$> 35\,\mathrm{GeV}$
3D di-jet Angle	$< 2.4\,\mathrm{rad}$
Di-jet – Electron ΔR	< 3





Significance: $Z = \sqrt{2\left(n \cdot \ln\left[\frac{n\,(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b\,(b+\sigma^2)}\right]\right)}$

Analysis Methods

◉ Machine Learning Method(s)

- Studies made by T. Critchley (master thesis, 2024) trying to increase the sensitivity from the C&C method

✦ BDT Method:

- XGBoost in conjunction with TMVA (binary classification)

✦ DNN Method:

- Keras in Tensorflow with hyperparameter optimization (binary classification)

❖ For both methods:

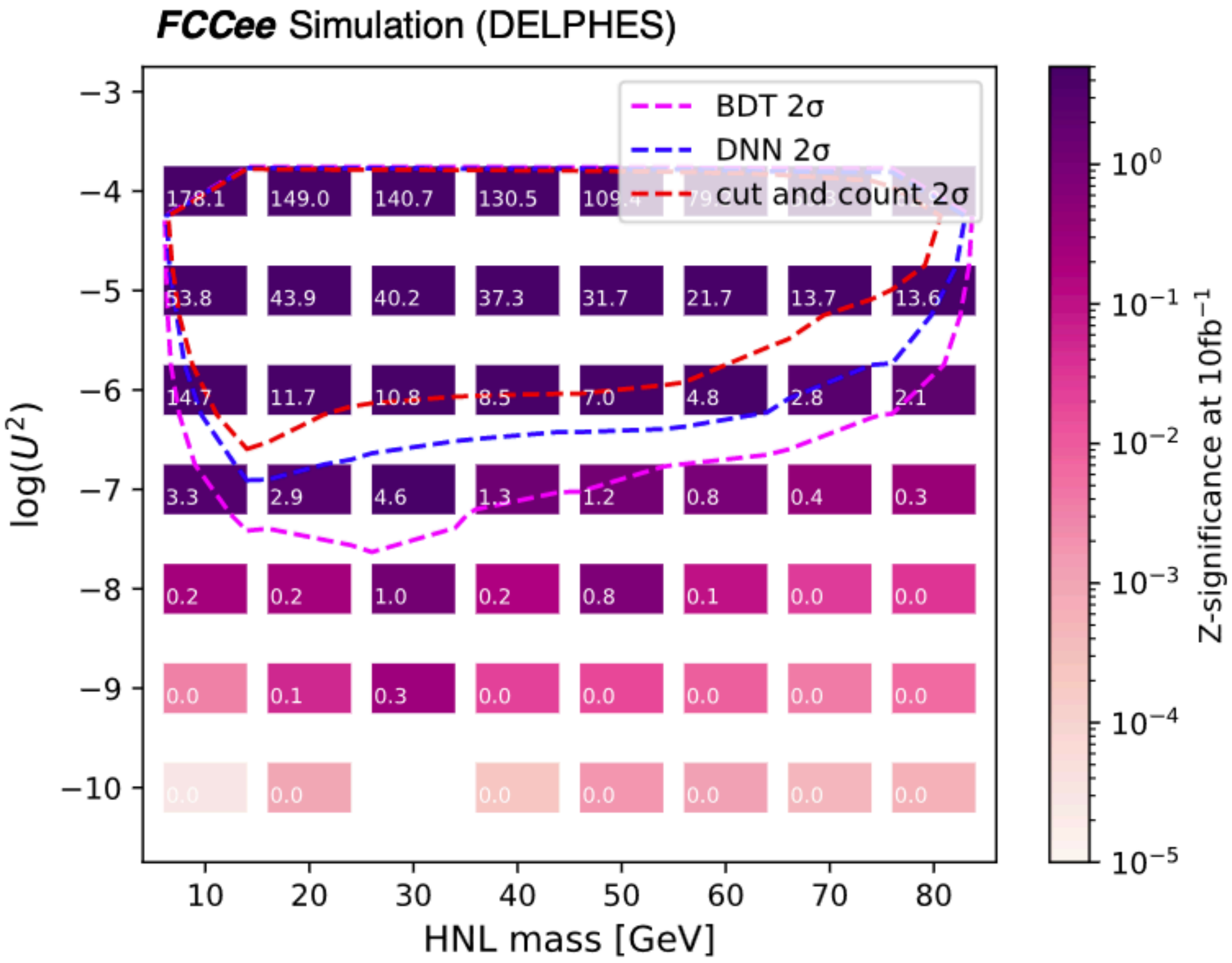
- Individual training for every mass point trying to reach the full sensitivity
- The following variables were used for the training →

Object	Variables
Leading electron	$E, \phi, d_0, \sigma_{d_0}, \Delta R_{ejj}$
Neutrino	E_{miss}, θ
Di-jet system	$\Delta R_{jj}, \phi$
Vertex and tracks	$n_{\text{tracks}}, n_{\text{primary tracks}}, \chi^2_{\text{vertex}}$

Sensitivity Comparison

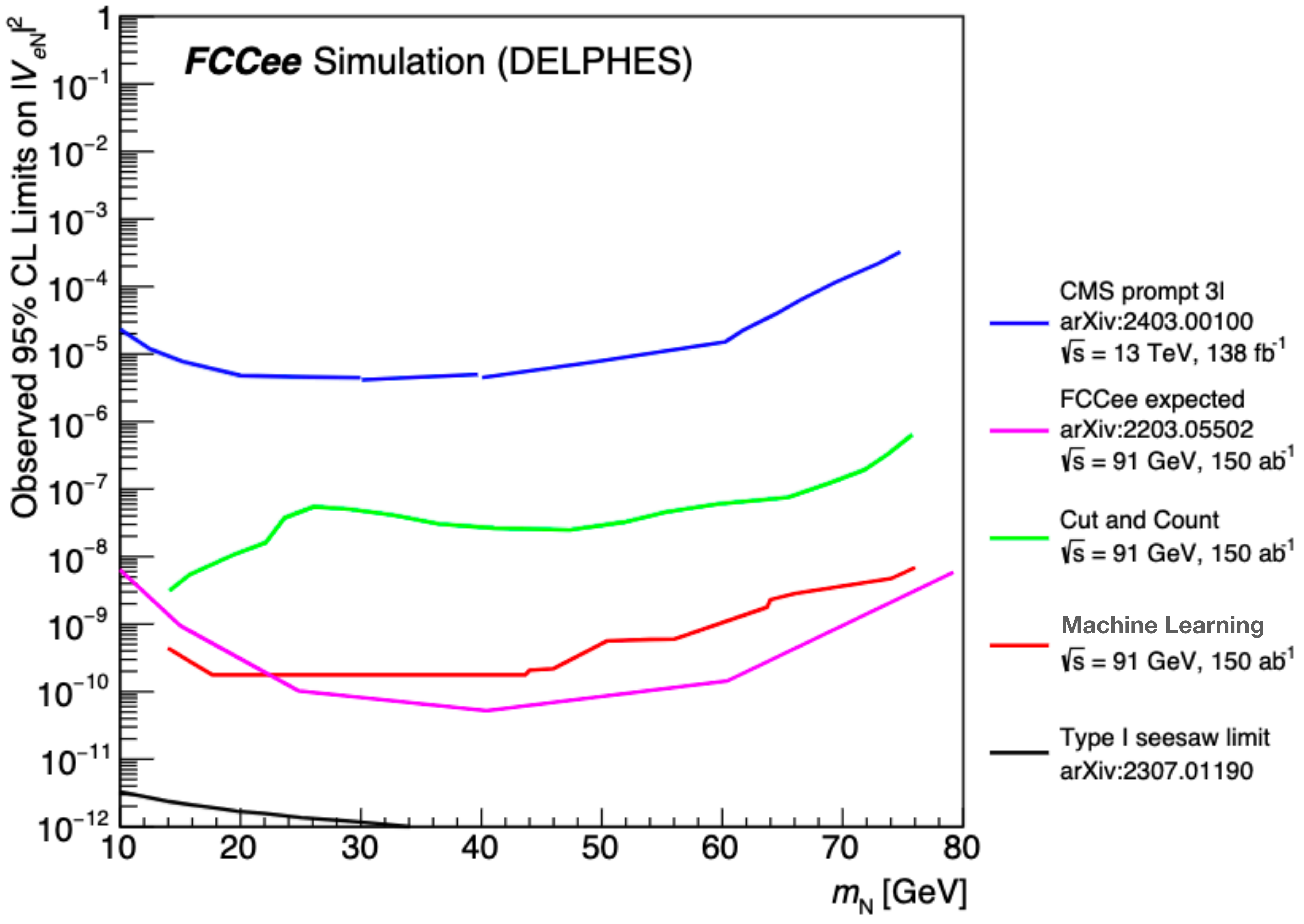
- **BDT model provides ~2 orders of magnitude more sensitivity compared to the C&C method and outpeforms DNN**

- **The (current) DNN approach offers ~1 order of magnitude improvement**
  - Hard to optimize but…
  - …implementing more sophisticated DNN architectures and robust hyperparameter optimization could significantly improve the performance



Summary

*CMS result only for 138 fb-1



- Scaled to 150 ab^{-1} without accounting for uncertainties, the plot **shows broader phase space coverage compared to the C&C**
- Nearing FCC-ee limits with ~50% of the branching ratio; serves as a guide for improvement
- **ML shows strong potential to improve limits**
- **Increasing MC statistics** in the signal region is **essential** for robust analysis