INVESTIGATION OF LEPTON FLAVOUR VIOLATION IN HIGGS BOSON DECAYS AT THE FCC-HH: SIMULATION PROCESS AND MACHINE LEARNING APPROACH

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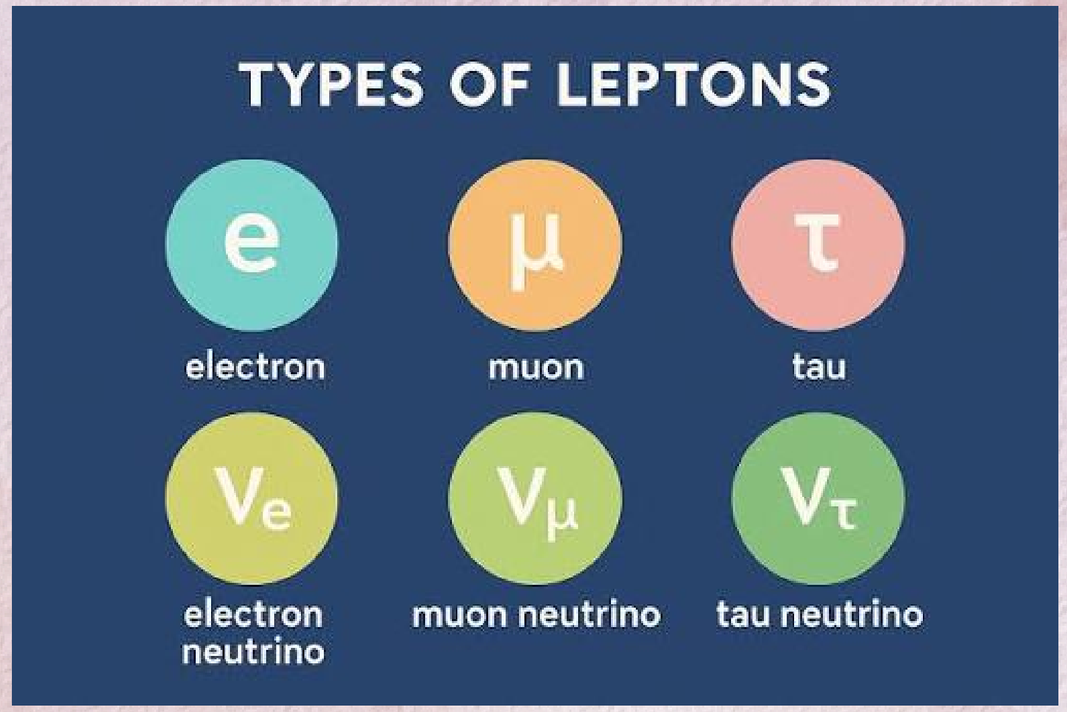
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WHAT IS LEPTON FLAVOUR VIOLATION?

Lepton Flavor Violation (LFV) is the transition between different lepton generations—electrons, muons, and taus—without conserving individual lepton family numbers. While the Standard Model strictly conserves flavor in the charged lepton sector, neutrino oscillations have confirmed that flavor violation occurs among neutral leptons. Within the Standard Model framework, Charged Lepton Flavor Violation (cLFV) processes are heavily suppressed by tiny neutrino masses, rendering them practically unobservable. Consequently, observing any cLFV decay, such as the $H \to e\tau$ channel, would provide direct evidence of Beyond the Standard Model physics.

MOTIVATION

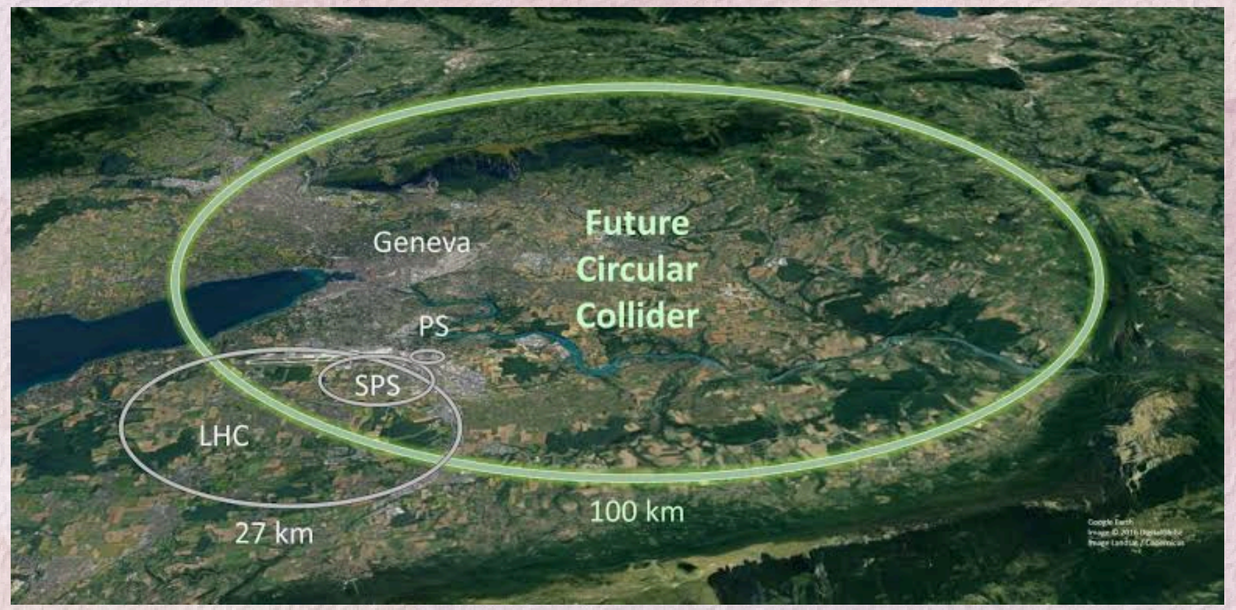
Neutrinos



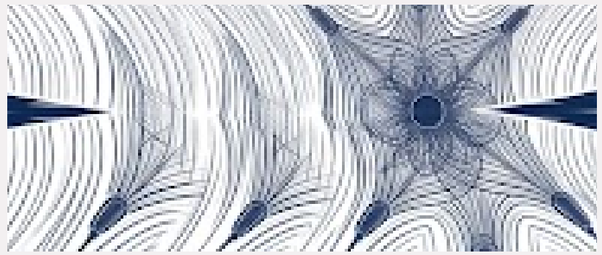
Although the Standard Model predicts flavor conservation in the charged lepton sector, neutrino oscillations—demonstrated by the Super-Kamiokande and SNO experiments—revealed that this conservation is violated in the neutral sector. This discovery makes Charged Lepton Flavor Violation (cLFV) processes in Higgs boson decays to charged leptons a primary target for Beyond the Standard Model physics searches. Planned at CERN with a center-of-mass energy of 100 TeV, the Future Circular Collider (FCC-hh) provides unprecedented statistical potential for probing these rare processes.

WHAT IS FCC-HH?

The Future Circular Collider hadron-hadron (FCC-hh)—where "hh" designates hadron-hadron collisions, primarily between protons—is a proposed post-LHC facility designed to operate within an approximately 91 to 100 km circumference tunnel at CERN. Operating at a target center-of-mass energy of 100 TeV, it is planned to extend the energy and integrated luminosity reach beyond the High-Luminosity LHC. This high-energy environment serves as a framework for direct searches for heavy hypothetical states, high-precision Standard Model measurements, and the evaluation of rare processes within Beyond the Standard Model physics.

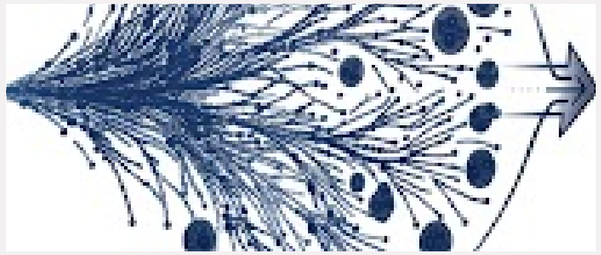


SIMULATION PROCESS



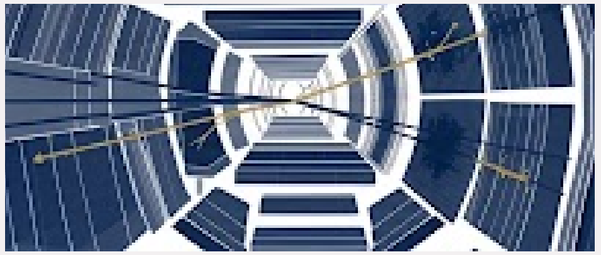
MadGraph5_aMC@NLO

Generates events at the parton level by performing matrix element calculations of collision processes.



PYTHIA 8

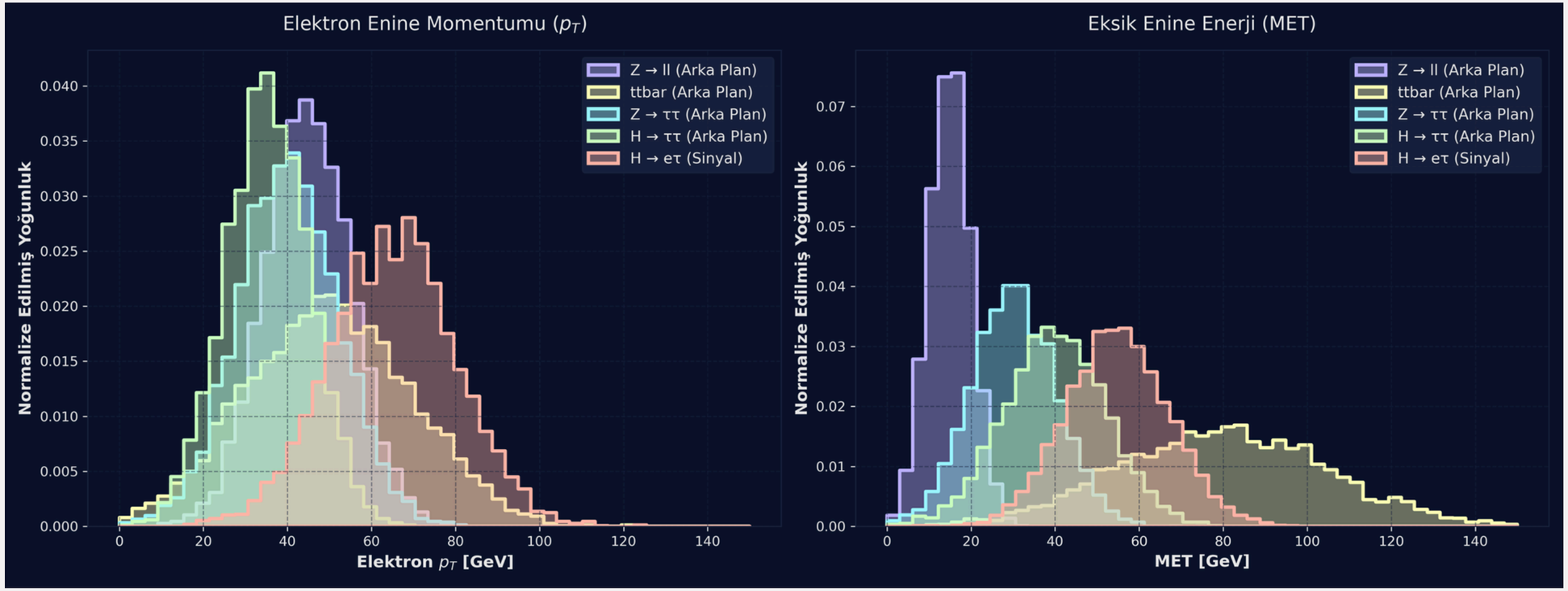
Models the high-energy scatterings of produced partons, parton shower simulations, hadronization processes, and decays of unstable particles.



DELPHES

Provides fast simulation of particle tracking, detector energy responses, and object reconstruction based on FCC-hh detector card parameters.

KINEMATICS


Elektron Enine Momentumu (p_T)
Normalize Edilmiş Yoğunluk
Elektron p_T [GeV]
Z → ll (Arka Plan)
ttbar (Arka Plan)
Z → ττ (Arka Plan)
H → ττ (Arka Plan)
H → eτ (Sinyal)
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0
20
40
60
80
100
120
140
Eksik Enine Enerji (MET)
Normalize Edilmiş Yoğunluk
MET [GeV]
Z → ll (Arka Plan)
ttbar (Arka Plan)
Z → ττ (Arka Plan)
H → ττ (Arka Plan)
H → eτ (Sinyal)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0
20
40
60
80
100
120
140

CUTS & DNN MODEL

Pre-selection Criteria (Kinematic Cuts)

Event Topology: Events are required to contain at least one electron (e-) and one hadronically decaying tau lepton (τh) with the highest transverse momentum {TauTag} == 1).
Transverse Momentum: A kinematic cut of pT > 25GeV is applied to both the leading electron and the hadronic tau lepton.
Pseudorapidity: Restricted according to detector acceptance limits: η < 2.5 for electrons and η < 2.3 for hadronic taus.
b-Jet Veto: To suppress background processes, events are required to have zero b-tagged jets ({BTag_Count} == 0).

Model Input Features

Kinematics & Spatial: Electron p_T, Tau p_T, Electron η, Tau η, ΔR, ΔΦ
Identification & Tracking: Iso_e, d_0, mass_τ
Event-Level & Reconstruction: MET, H_T, N_jet, m_vis, m_T

```python
plt.style.use('dark_background')
sns.set_palette("husl")

INPUT_CSV  = "../DNN_Feature_Data/LFV_DNN_Features_Combined.csv"

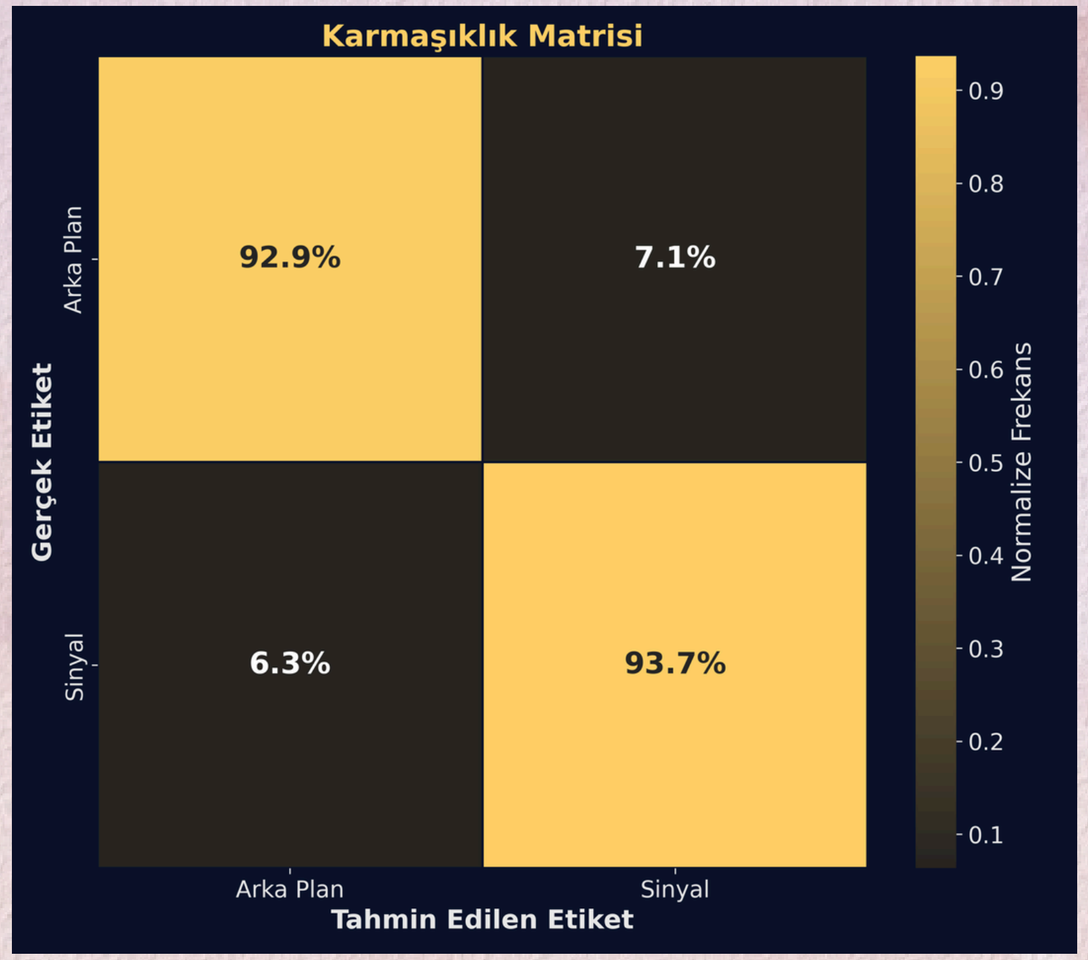
OUTPUT_DIR = "Model_Performans_Sonuclari"
MODEL_DIR  = os.path.join(OUTPUT_DIR, "model")

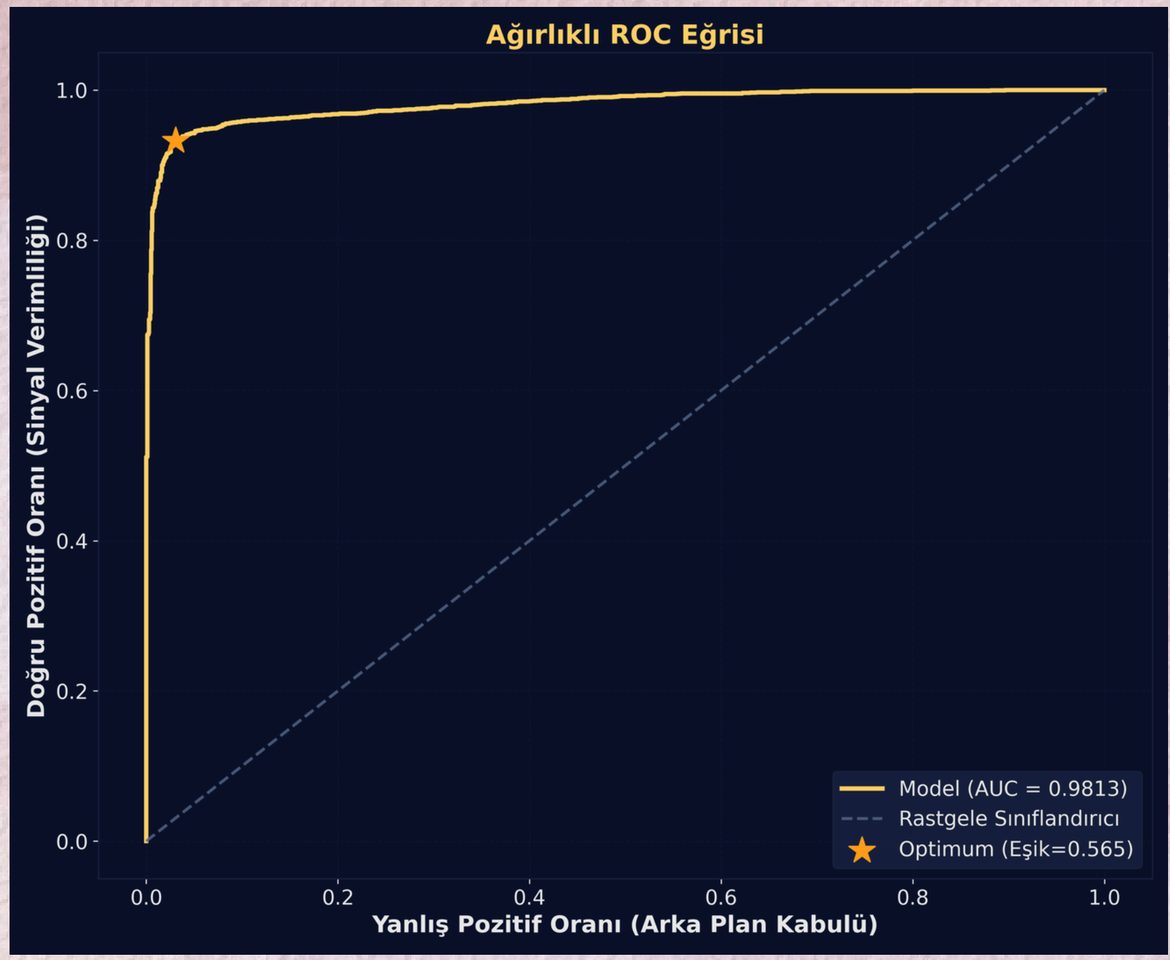
for directory in [OUTPUT_DIR, MODEL_DIR]:
    os.makedirs(directory, exist_ok=True)
```

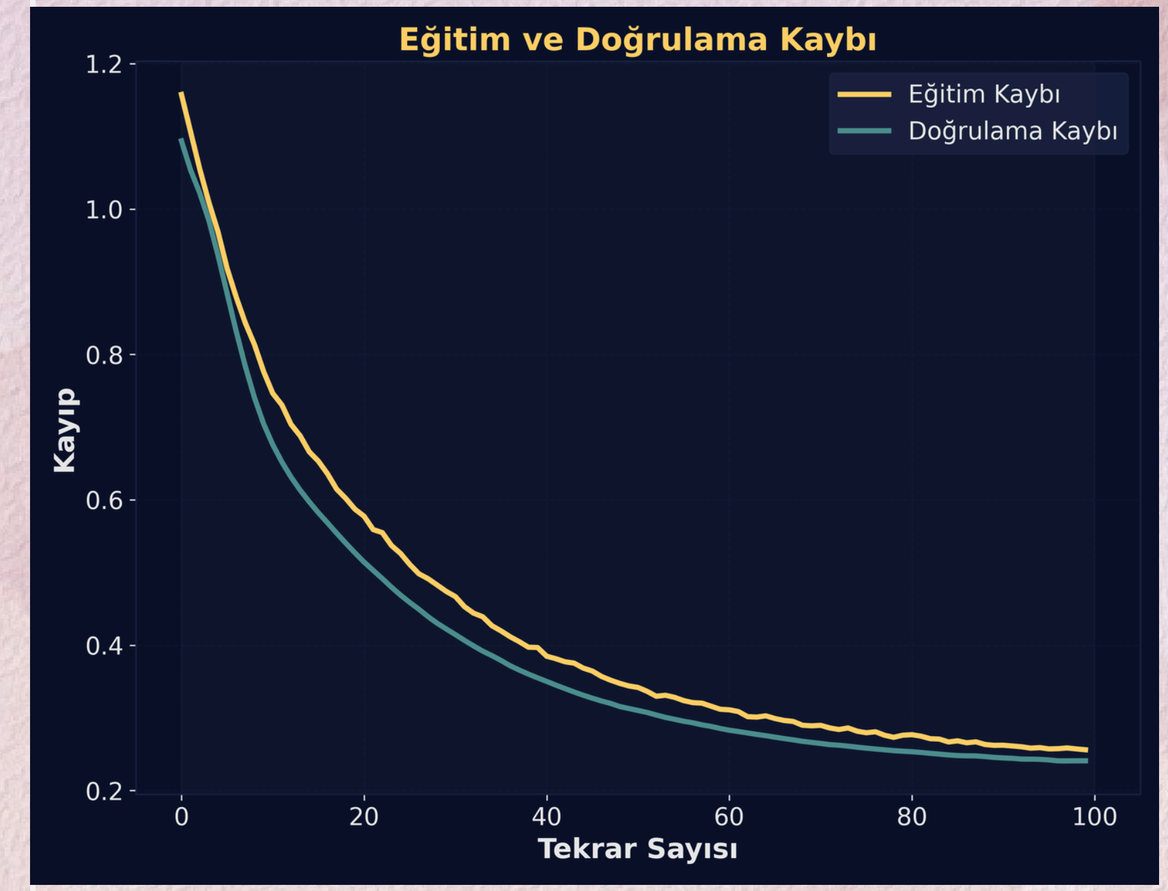
```python
RANDOM_STATE      = 42
TEST_SIZE         = 0.2
VALIDATION_SPLIT  = 0.2
BATCH_SIZE        = 1024
MAX_EPOCHS        = 100
LEARNING_RATE     = 0.0005
LABEL_SMOOTHING   = 0.05
N_KFOLD           = 5

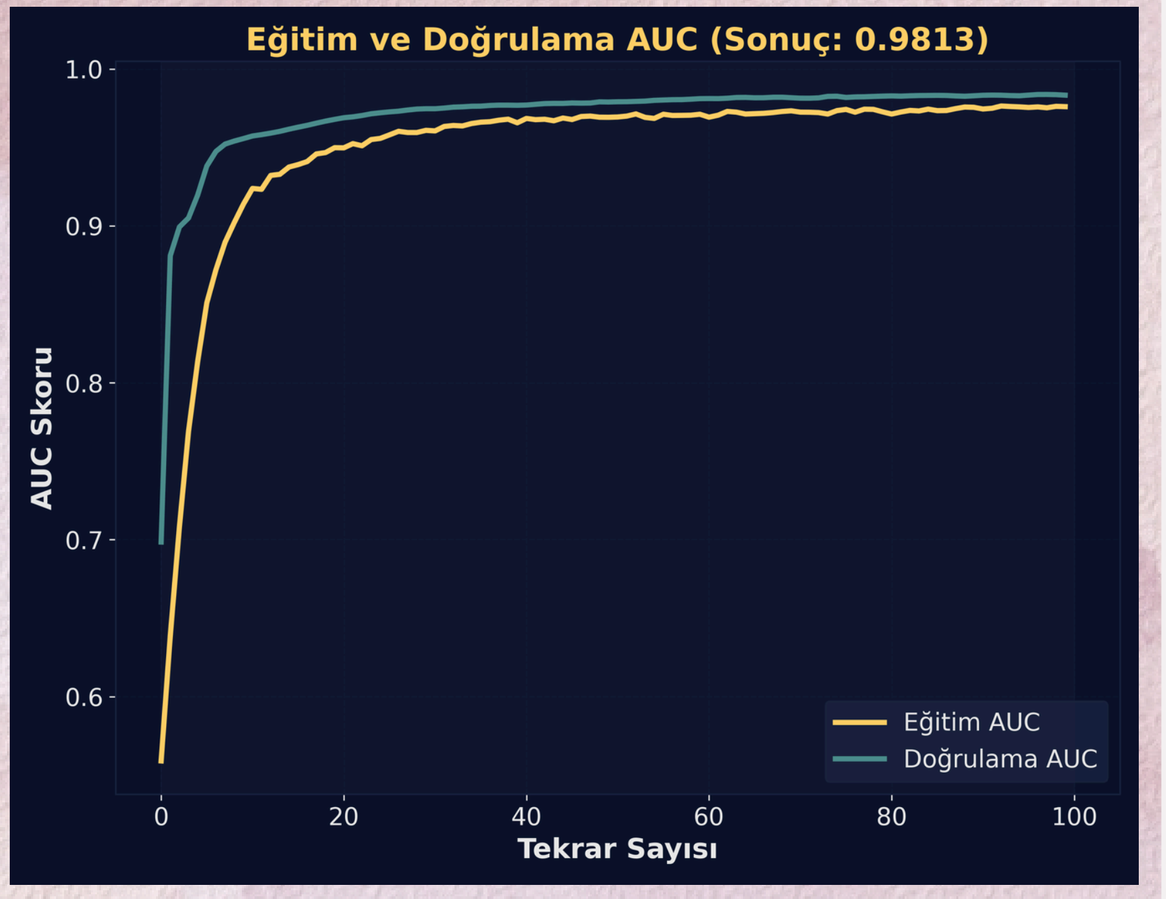
np.random.seed(RANDOM_STATE)
tf.random.set_seed(RANDOM_STATE)
```

Random State: 42
Test Size: 0.2
Validation Split: 0.2
Batch Size: 1024
Max Epochs: 100
Learning Rate: 0.0005
Label Smoothing: 0.05
K-Fold Cross-Validation: 5 folds
Hidden Layers: 4 layers (64, 32, 16, and 8 neurons, respectively)
Activation Functions: ReLU for hidden layers, Sigmoid for the output layer


Karmaşıklık Matrisi
92.9%
7.1%
6.3%
93.7%
Arka Plan
Sinyal
Gerçek Etiket
Arka Plan
Sinyal
Tahmin Edilen Etiket
Normalize Frekans
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1


Ağırlıklı ROC Eğrisi
Doğru Pozitif Oranı (Sinyal Verimliliği)
Yanlış Pozitif Oranı (Arka Plan Kabulü)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Model (AUC = 0.9813)
Rastgele Sınıflandırıcı
Optimum (Eşik=0.565)


Eğitim ve Doğrulama Kaybı
Eğitim Kaybı
Doğrulama Kaybı
Kayıp
Tekrar Sayısı
1.2
1.0
0.8
0.6
0.4
0.2
0
20
40
60
80
100


Eğitim ve Doğrulama AUC (Sonuç: 0.9813)
Eğitim AUC
Doğrulama AUC
AUC Skoru
Tekrar Sayısı
1.0
0.9
0.8
0.7
0.6
0
20
40
60
80
100

LITERATURE REVIEW

Boyarkin et al.: Theoretical branching ratios were calculated two orders of magnitude below experimental limits, highlighting the need for high-statistics colliders.

Herrero-García et al. (UV Completions): One-loop neutrino models were excluded due to excessive signal suppression, demonstrating that Zee and Left-Right Symmetric Models can reach targeted signals.

Herrero-García (LHC Run 2): Single-loop models were ruled out, identifying Zee and Left-Right Symmetric Models as primary viable candidates at lower energies.

CMS Collaboration (2015, Run 1): A 2.4-sigma excess was observed over background, establishing the first direct upper limit on the decay branching ratio.

CMS Collaboration (2021, Run 2): No significant excess was observed, setting tighter upper limits below a quarter of a percent for tau-related decay modes.

ATLAS Collaboration (2023, Run 2): No significant signal was found, yielding updated upper bounds below zero point two percent for both decay channels.

Arroyo-Ureña et al. (HL-LHC): Projected that while electron-muon and tau-muon channels could reach discovery levels, the electron-tau mode remains inaccessible even at maximum integrated luminosity.

[1] M. A. Arroyo-Ureña *vd.*, "Lepton flavor violation in Higgs boson decays at the HL-LHC," *arXiv preprint* (2025). [arXiv:2511.19337]

[2] ATLAS İşbirliği, "Searches for lepton-flavour-violating decays of the Higgs boson into $e\tau$ and $\mu\tau$ in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector," *JHEP* **07**, 166 (2023). [arXiv:2302.05225]

[3] CMS İşbirliği, "Search for lepton-flavor violating decays of the Higgs boson in the $\mu\tau$ and $e\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Rev. D* **104**, 032013 (2021). [arXiv:2105.03007]

[4] O. M. Boyarkin, G. G. Boyarkina ve D. S. Vasileuskaya, "The Higgs boson decays with the lepton flavor violation," *Int. J. Mod. Phys. A* **33**, 1850103 (2018). [arXiv:1902.04481]

[5] J. Herrero-Garcia, N. Rius ve A. Santamaria, "Higgs lepton flavour violation: UV completions and connection to neutrino masses," *JHEP* **11**, 084 (2016). [arXiv:1605.06091]

[6] CMS İşbirliği, "Search for lepton-flavour-violating decays of the Higgs boson," *Phys. Lett. B* **749**, 337 (2015). [arXiv:1502.07400]

[7] "INSPIRE-HEP Belgesi," https://inspirehep.net/files/56d16b4b5c463e0221e995ee9bf8d61f

CONCLUSION

In this study conducted under FCC-hh conditions, all signal and background Monte Carlo samples were simulated from scratch. The optimized DNN model achieved an AUC score of 0.9813 and a signal selection accuracy of 93.7% on the test dataset, separating signal from dominant Standard Model backgrounds. A literature review spanning past studies up to the High-Luminosity LHC (HL-LHC) indicates that sensitivity to the H->eτ channel remains constrained by center-of-mass energy and low expected branching ratios. In this context, conducting this analysis under FCC-hh conditions could provide enhanced reach to evaluate discovery limits and branching ratio sensitivities for this channel.

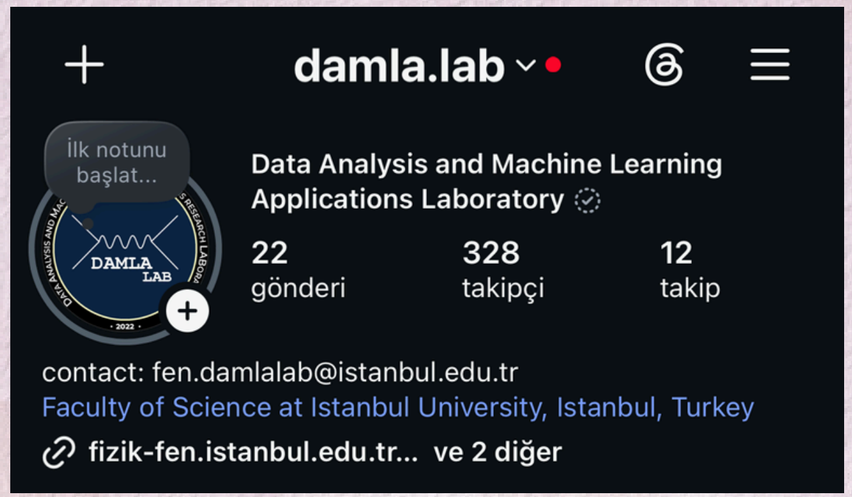
FUTURE PLANS

1. **Monte Carlo Simulations:** Produce consistent 100k-event samples for extended SM background and signal processes.

2. **Theoretical Framework:** Finalize literature review on *(ex. cLFV)* phenomenology and underlying theoretical models *(ex. Froggatt-Nielsen Singlet Model)*. Also, complete the reading articles.

3. Branching ratio calculations and statistical limit extraction.

4. **ML Optimization:** Architecture optimization to boost signal-to-background discrimination.


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THANK YOU

Aleyna Bülbül