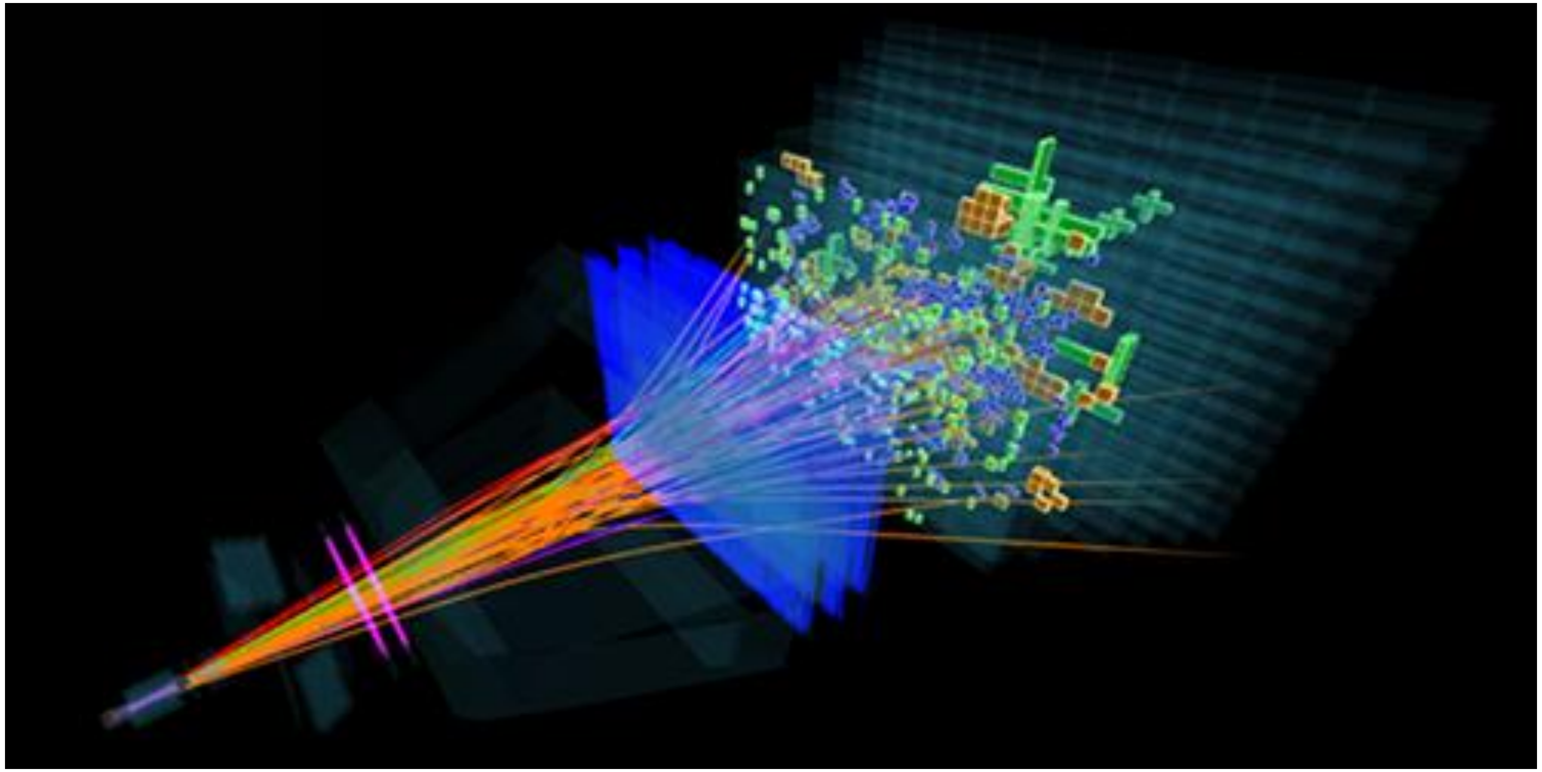
Search for Charmed Baryon Decays with Lepton Flavour Violation at LHCb



Paolo Minhas, Timur Knyazev

Supervisor: prof. dr hab. Mariusz Witek

Motivation & Context

Why do we exist?

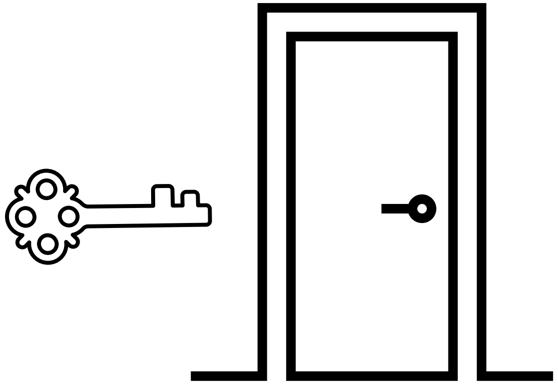
Why do we exist?

- Baryogenesis – explains why there is more matter than antimatter.

- CP Violation – one of the fundamental sources of baryogenesis.

What is the connection?

Decay that we are about to study



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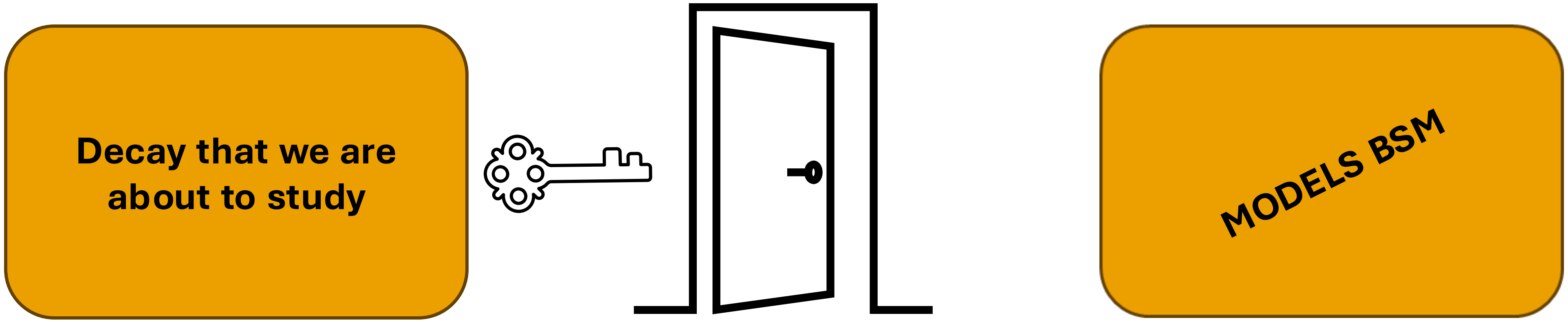
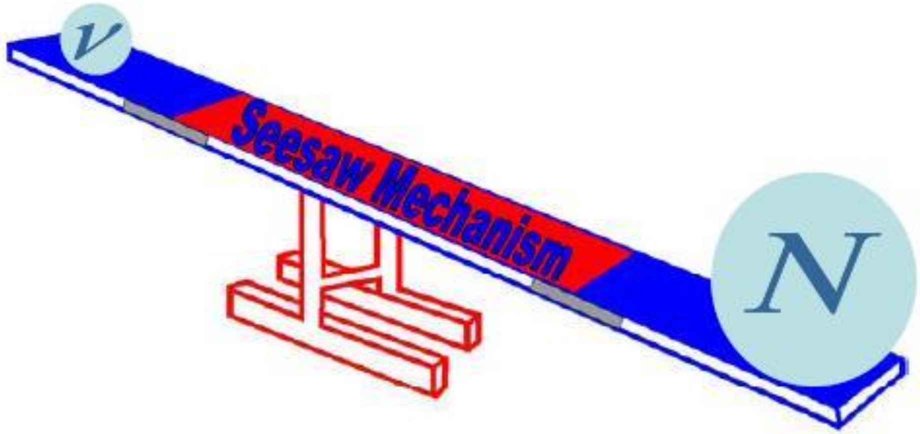


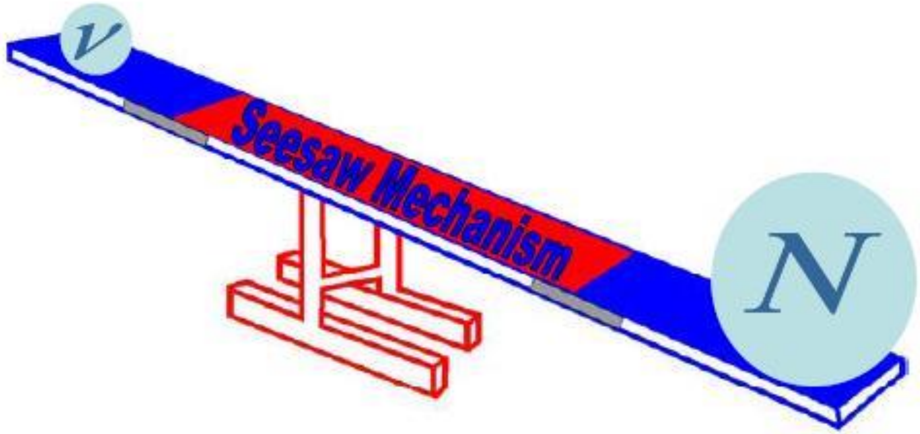
The Seesaw Mechanism

- Explanation of the tiny neutrino masses by introduction of heavy right-handed neutrinos.
- LFV effects are tiny in the Standard Model.



LFV decay: $\mu \rightarrow e\,\gamma$.

Branching ratios (BR) on the order of 10^{-54}.



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IN THE SEESAW MODEL THEY CAN LEAD TO OBSERVABLE DECAYS LIKE:

$$\Lambda_c^+ \rightarrow p\, e\, \mu$$

The Decay of Interest

$$\Lambda_c^+ \to p\ e\ \mu$$

- Forbidden in the Standard Model framework.
- Predicted by models extending Standard Model.

Purpose of the Project

Search for LFV in Λ_c^+ decays using LHCb data.

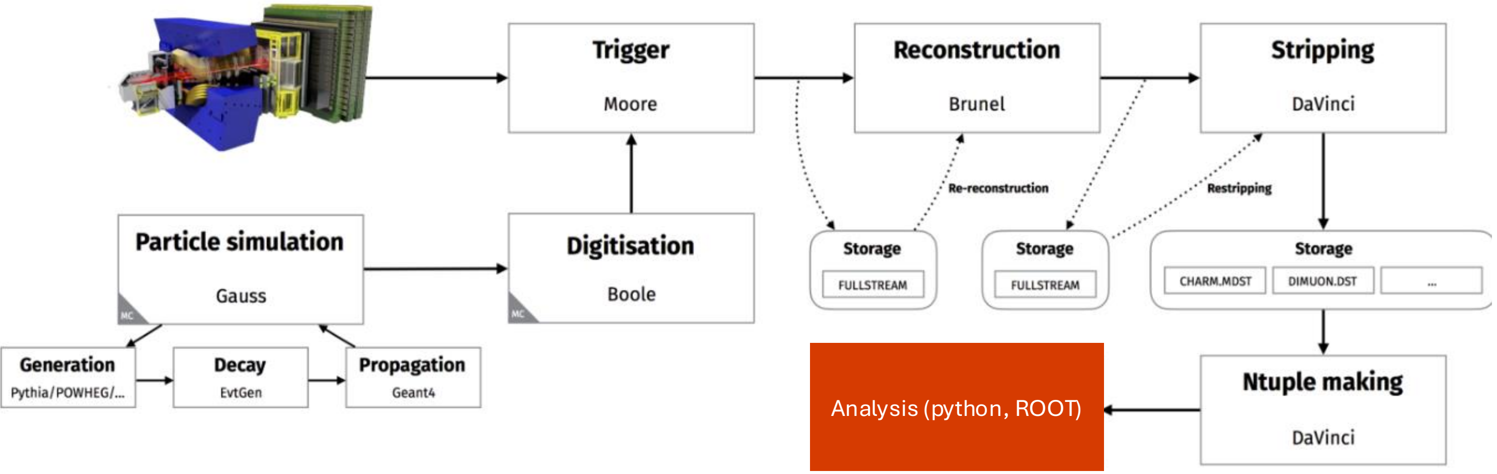
Develop ML-based event selection.

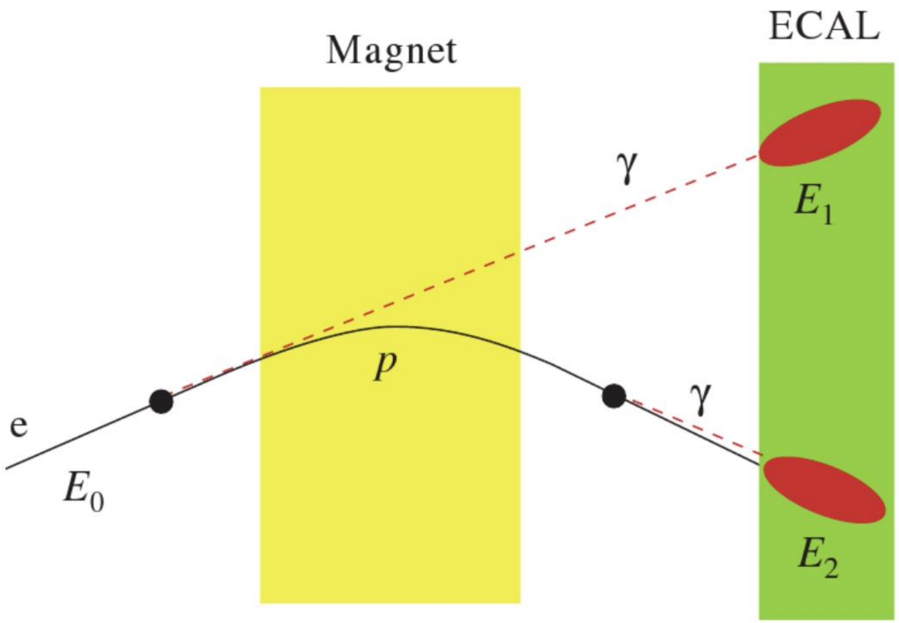
Optimize background suppression.

Estimate upper limits for the signal.

M. Dudek (2023)

Data and Tools





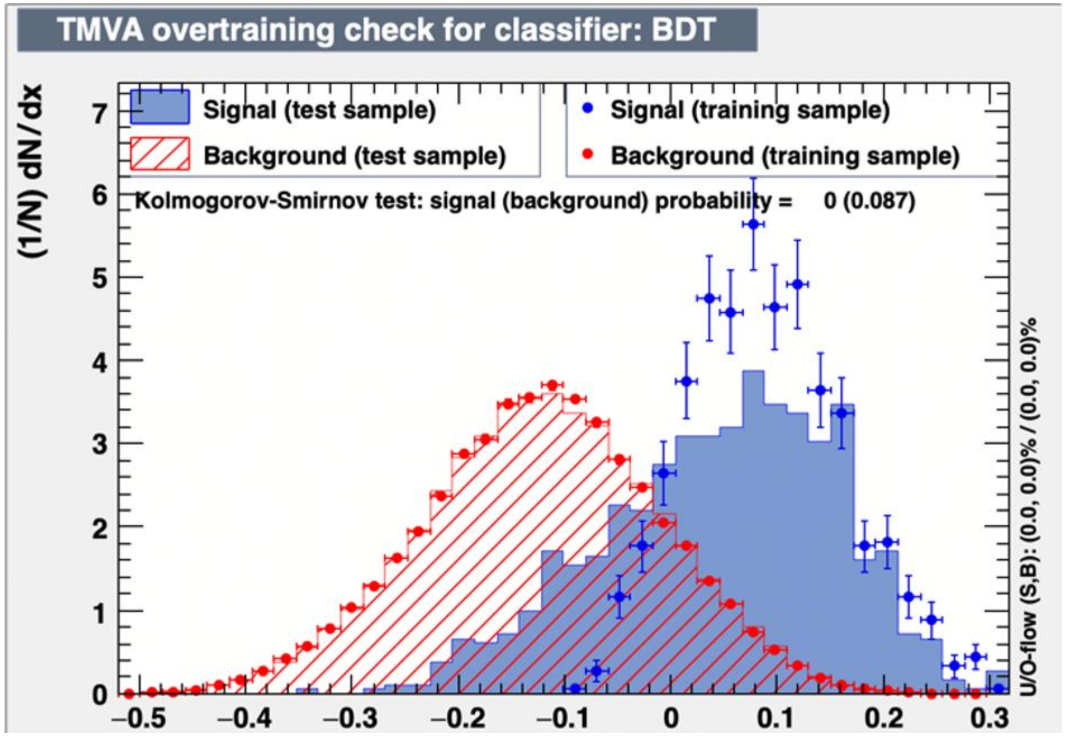
The data has been pre-processed

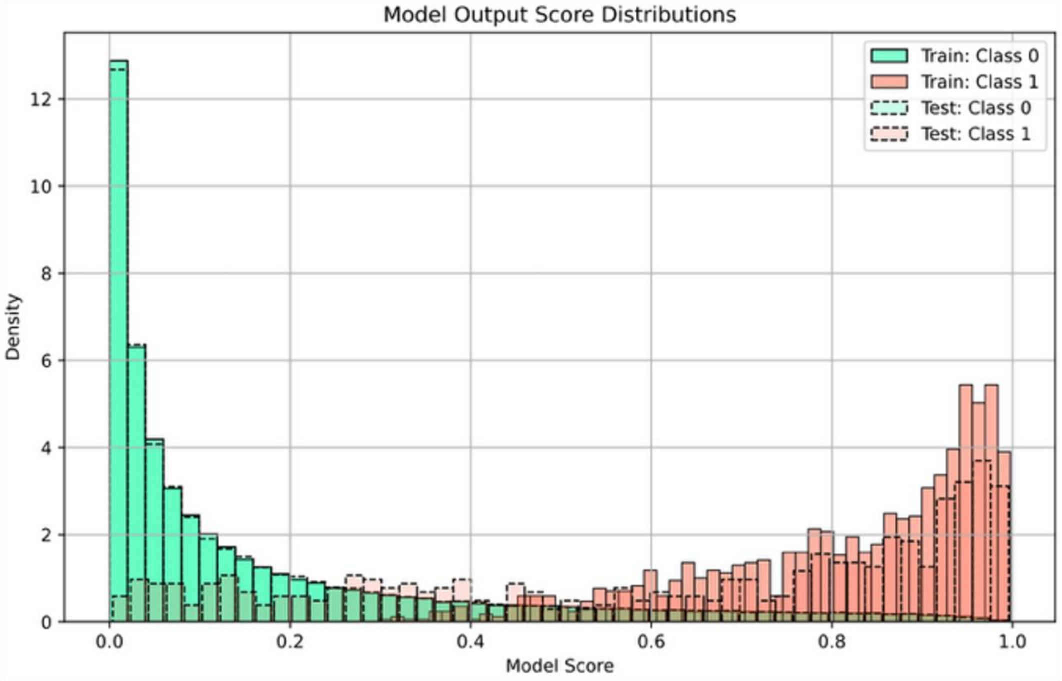
The data is in ntuple format, with 675 different variables

There is Montecarlo (MC) simulated signal, and real LHCb data for background

We use machine learning to sort signal from background

MC signal root ntuple file has 1,727 events compared to 214,977 background data events



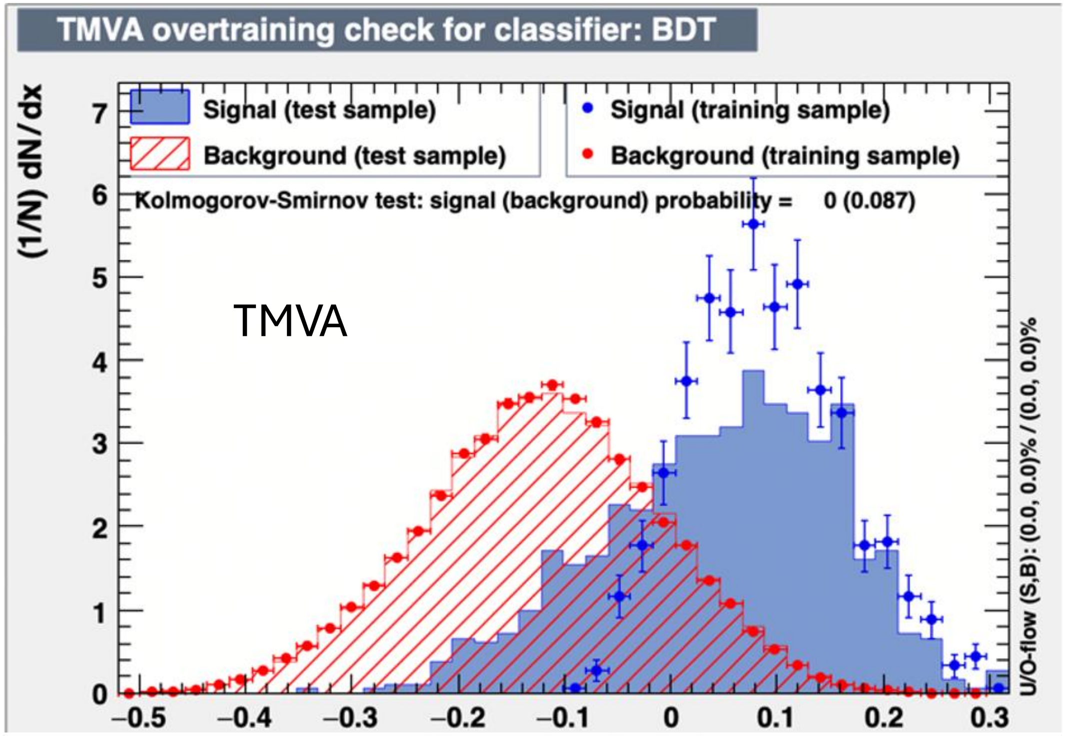


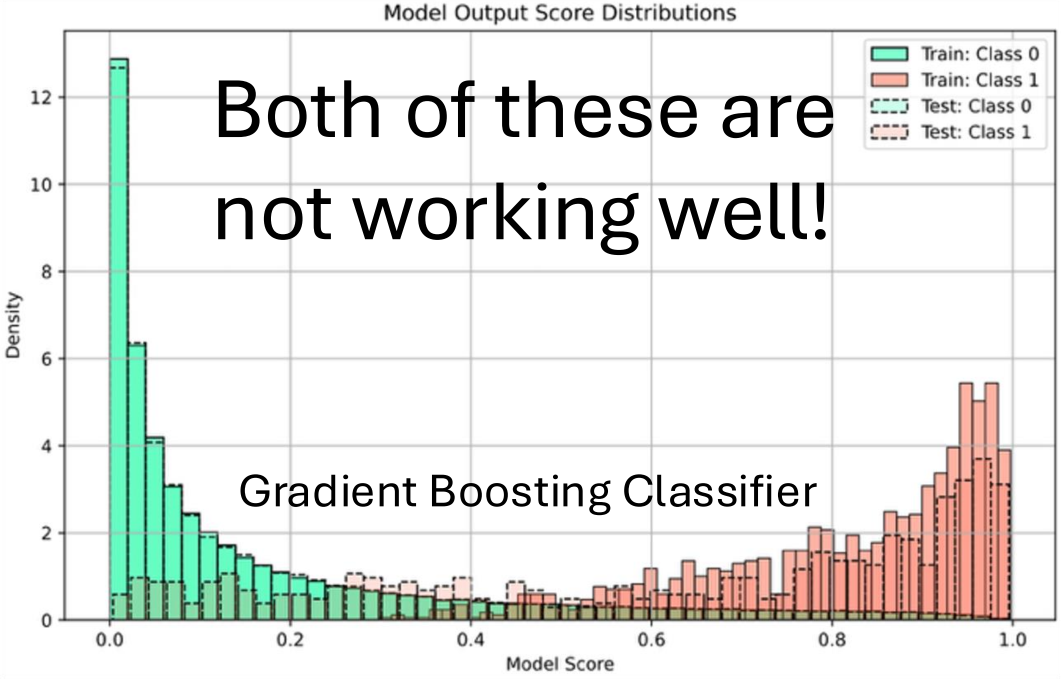
ROOT or Python?

We can easily analyse the ntuple in ROOT using the toolkit for multivariate analysis (TMVA)

We can convert ntuples into dataframes with pandas and analyse using python

We can use scikit learn, xgboost or one of the many other machine learning libraries





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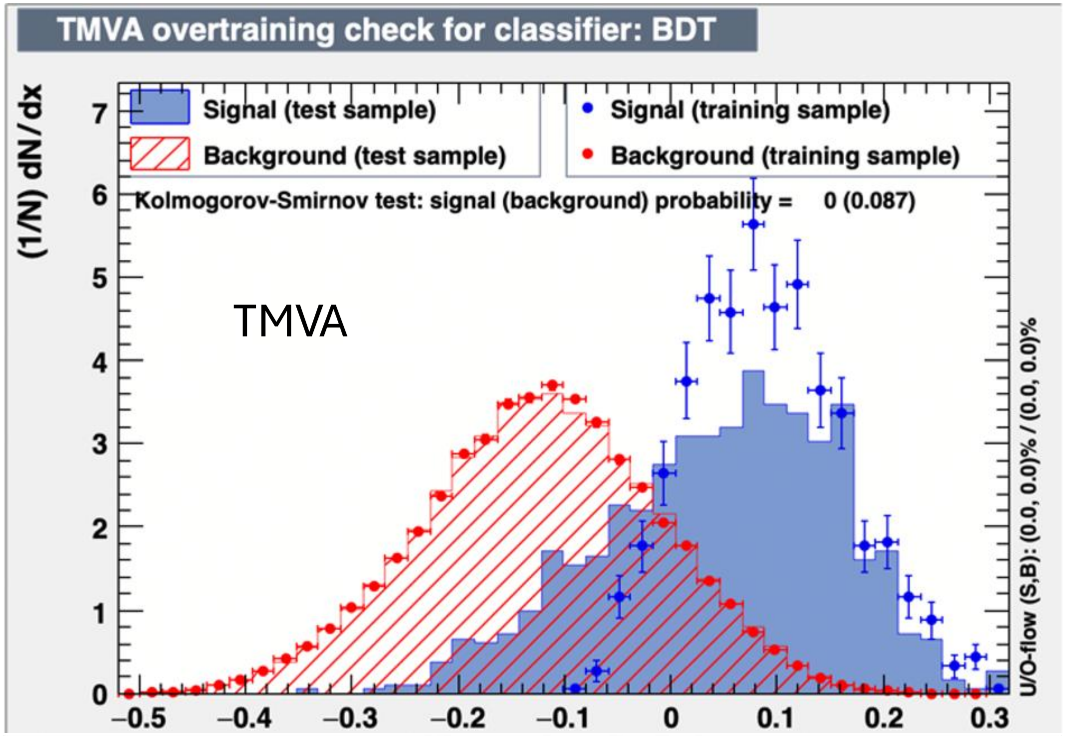

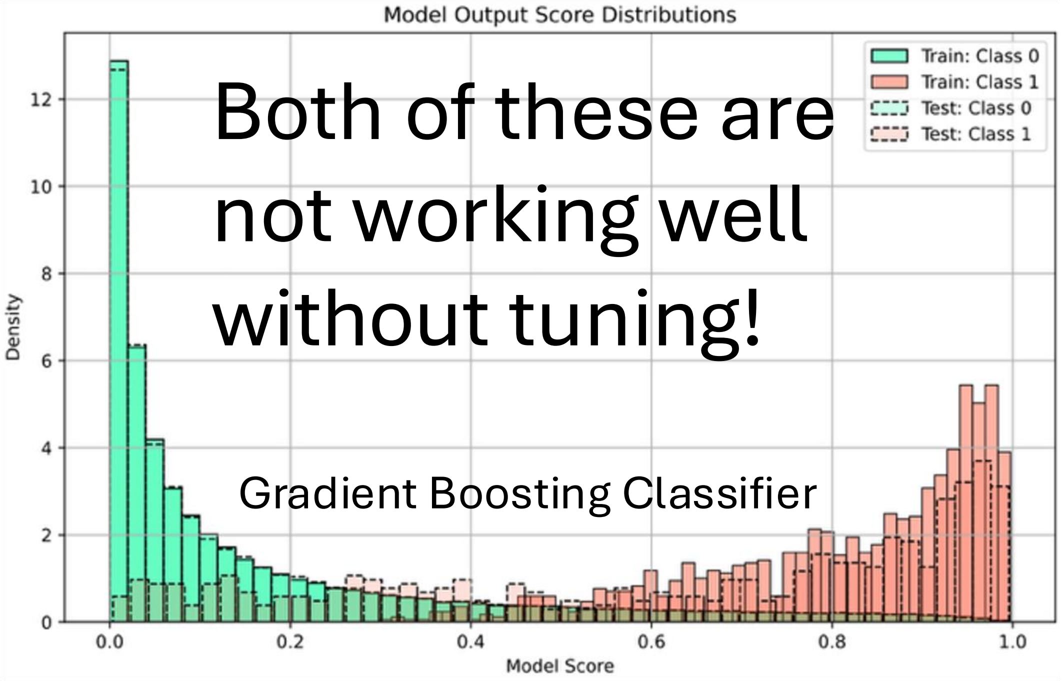

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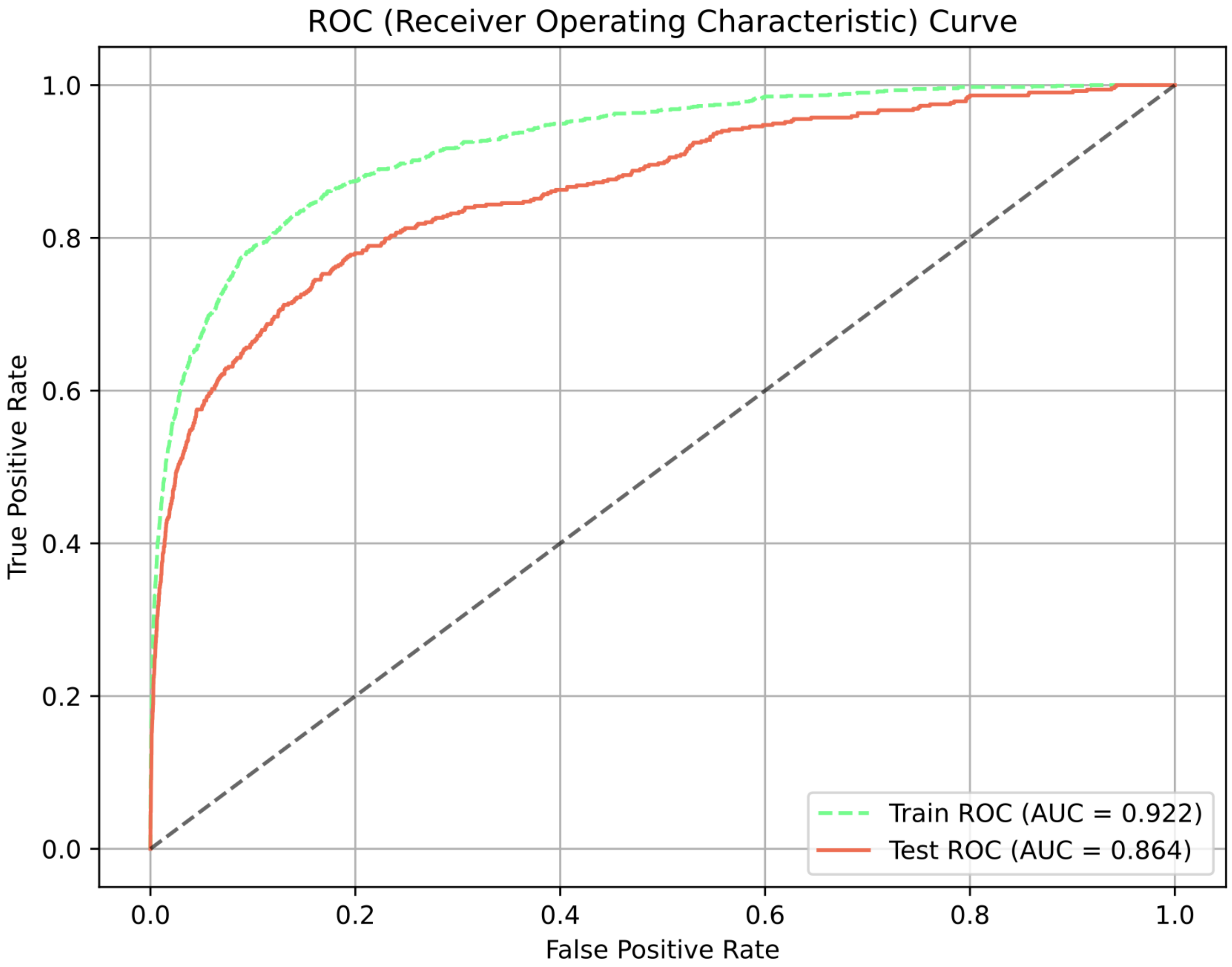
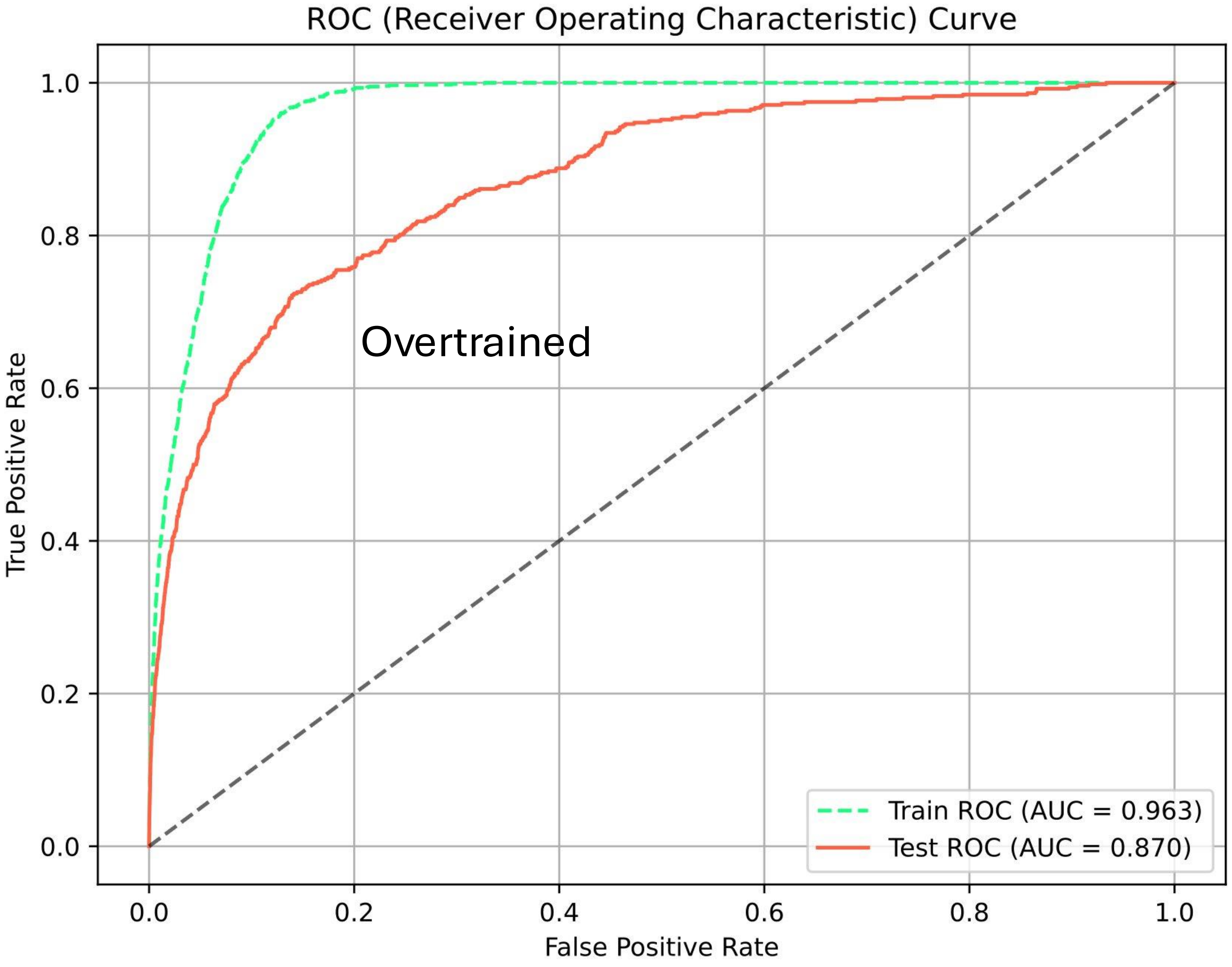
Optimisation & Overtraining



- n_estimators=100
- max_depth=3
- learning_rate=0.1
- min_child_rate=10
- use_label_encoder=False
- eval_metric='logloss'
- random_state=42

Optimisation & Overtraining



- n_estimators=**100**
- max_depth=3
- learning_rate=0.1
- #subsample=0.5
- #**scale_pos_weight**=np.sum(y_train == 0) / np.sum(y_train == 1)
- **min_child_rate=10**
- use_label_encoder=False
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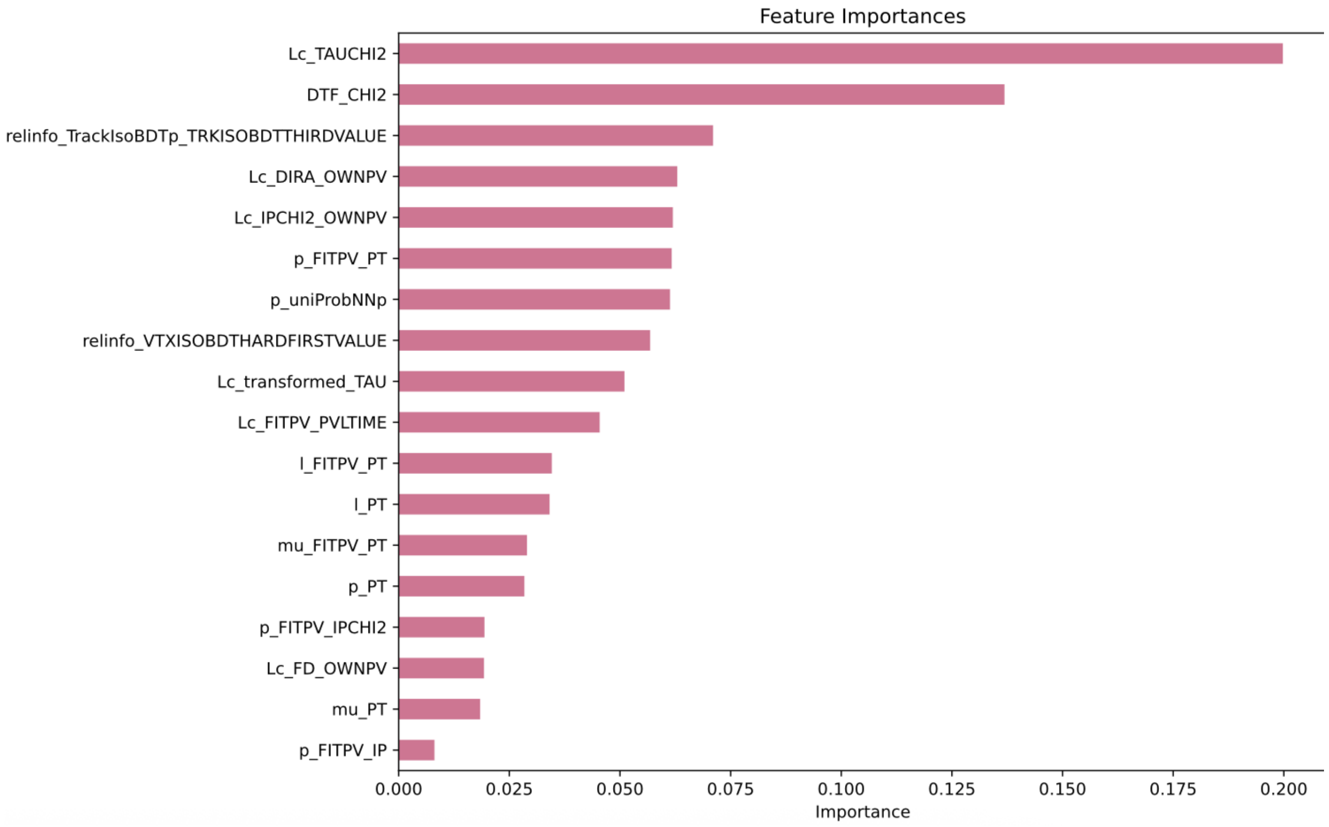
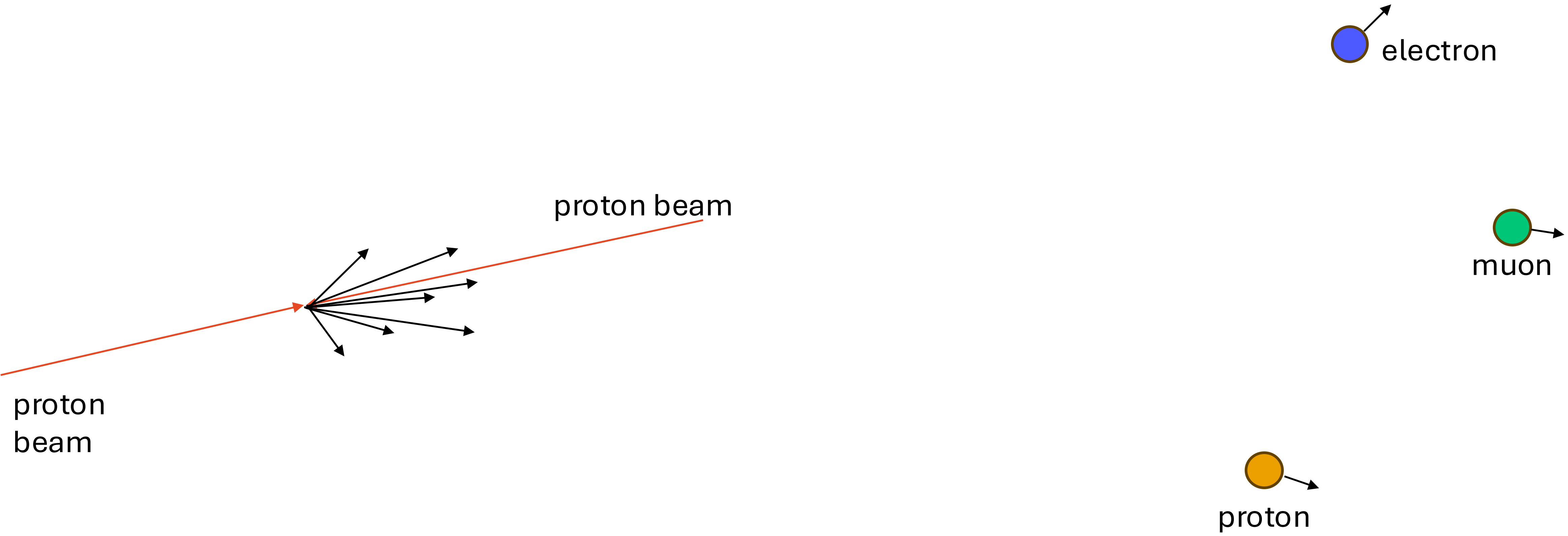
Optimisation & Overtraining



- Thinking about the physics – which do the variables mean?
- We use a preliminary model to select which variables are most 'useful' from a list of 36 already calculated
- We shortlist the 18 best, then use these to tune a second model
- Hyperparameters of the second model are more selective
- We train the model on the signal and data then use it on the reference channel as well (the p mu mu final state with phi excitation)

Variables



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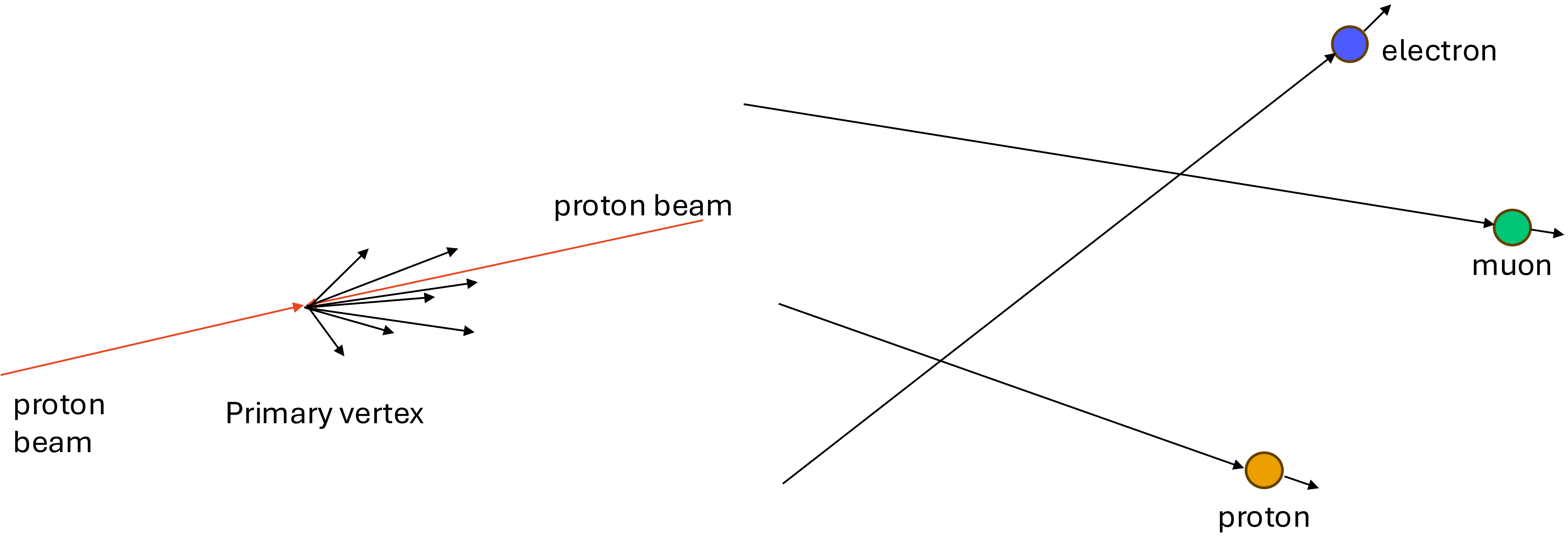
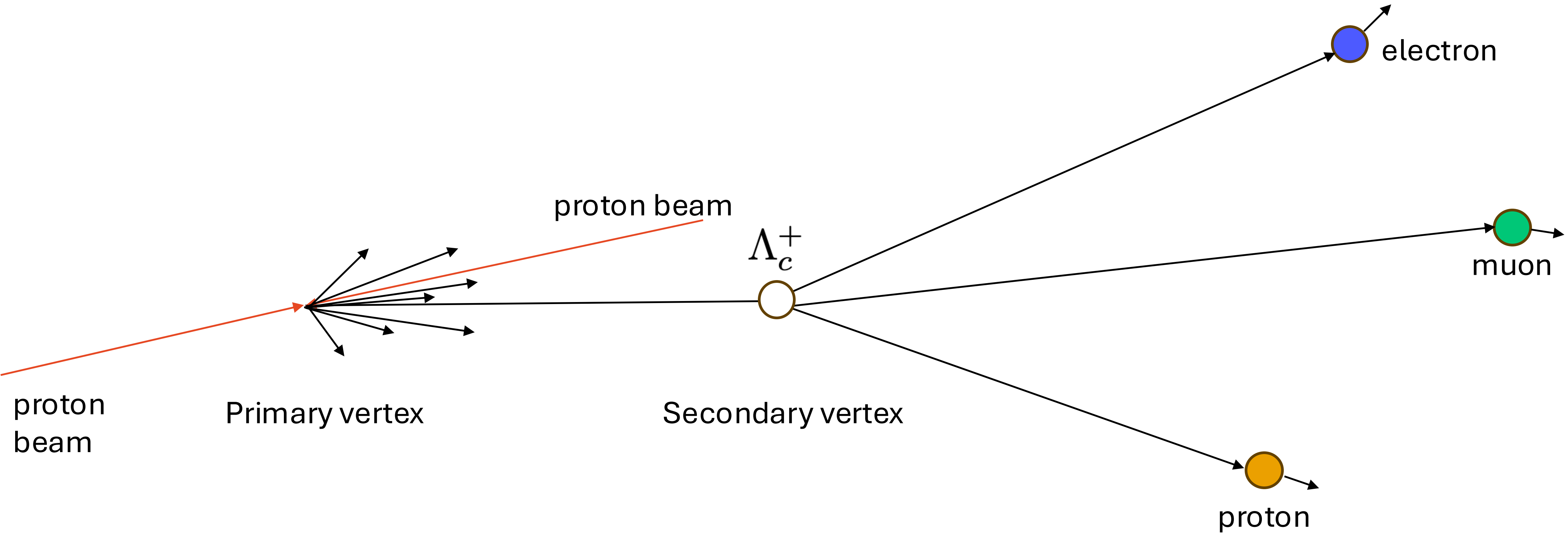

electron
proton beam
muon
proton
beam
Primary vertex
proton

Variables



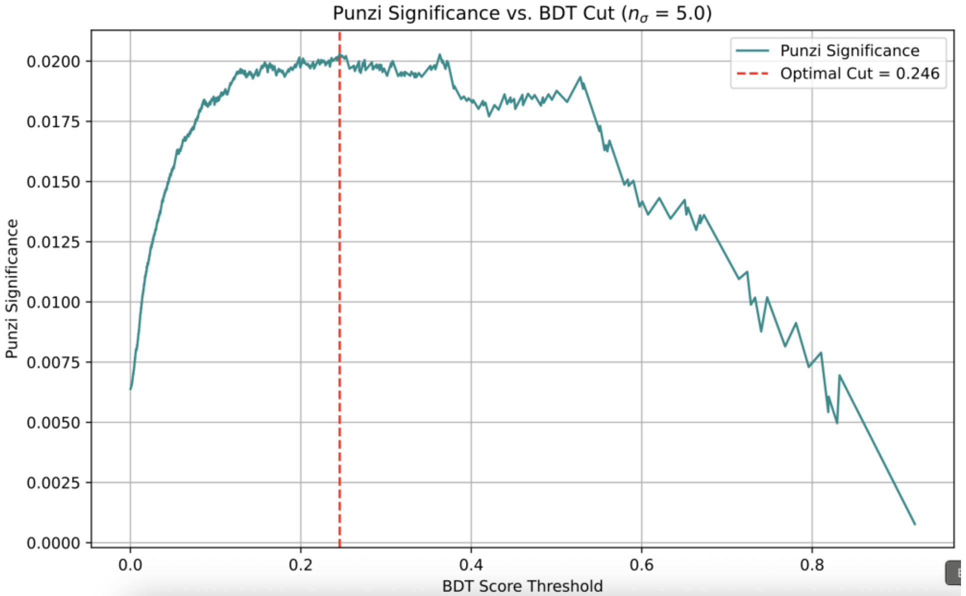
Lc_TAUCHI2, DTF_CHI2
Measures how accurately the secondary vertex points to the primary vertex in time and topology

G. Punzi (2003)

Punzi's Figure of Merit & Cuts

$$\frac{\epsilon(t)}{\frac{a}{2} + \sqrt{B(t)}}$$

ϵ is the efficiency
a is the significance (5σ)
$B(t)$ is background



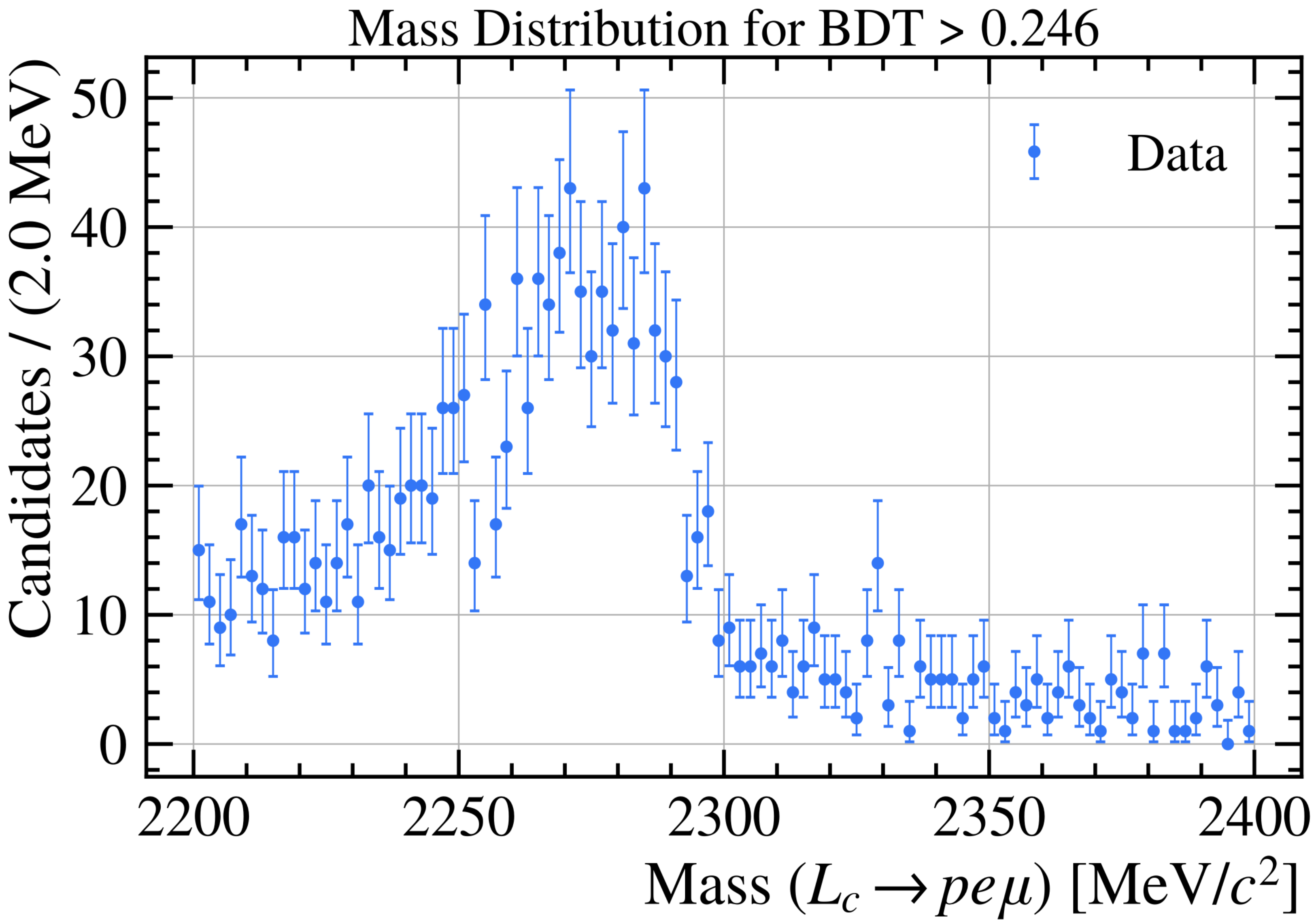
We need to use a standardised method to cut background using the BDT score

We use the Punzi Figure of Merit (FoM) to optimize selection to achive the best sensitivity for our measurement

We chose the cut to maximize FoM

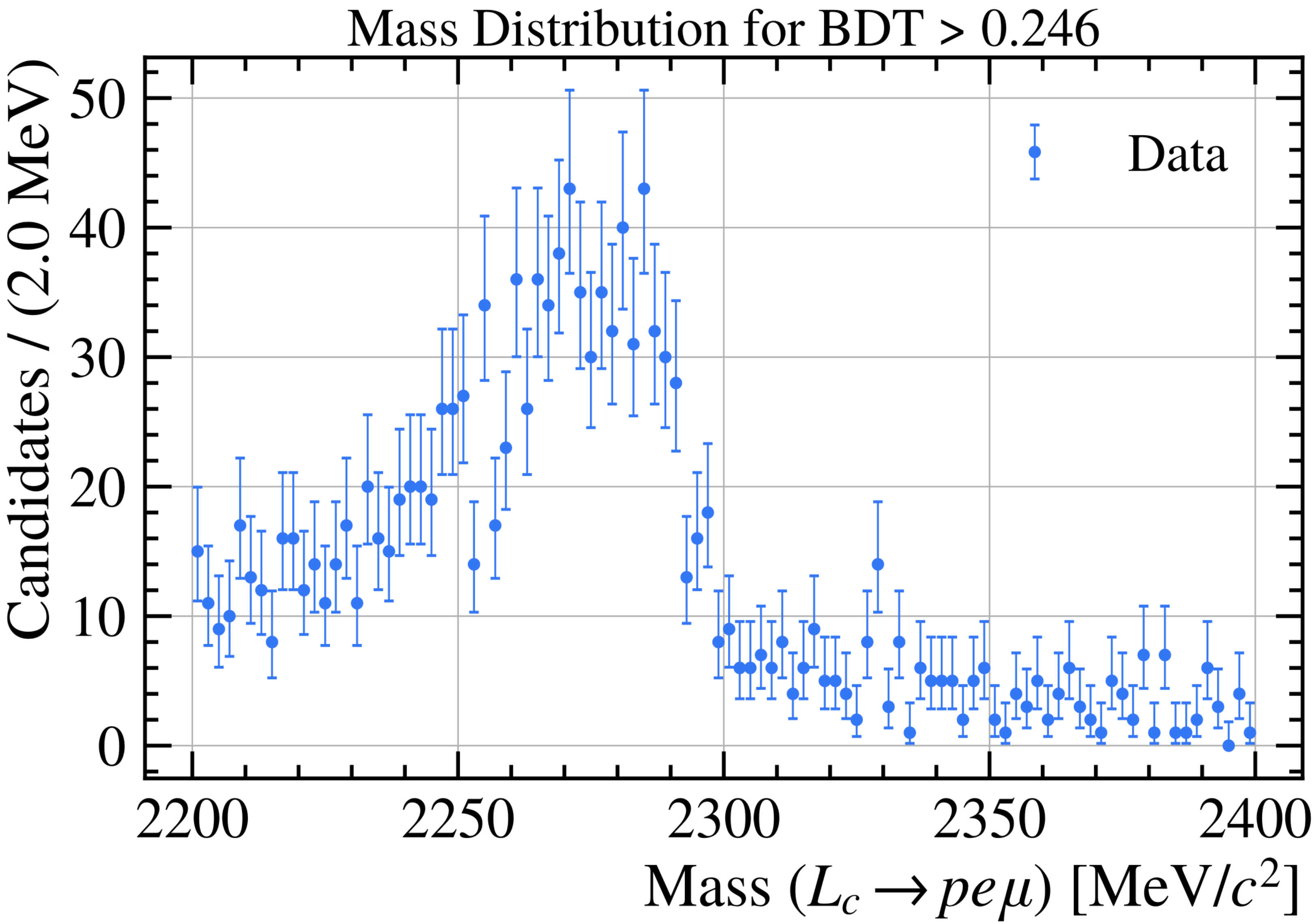
This cut was made at 0.246

Invariant Mass



Zfit (python)

Invariant Mass



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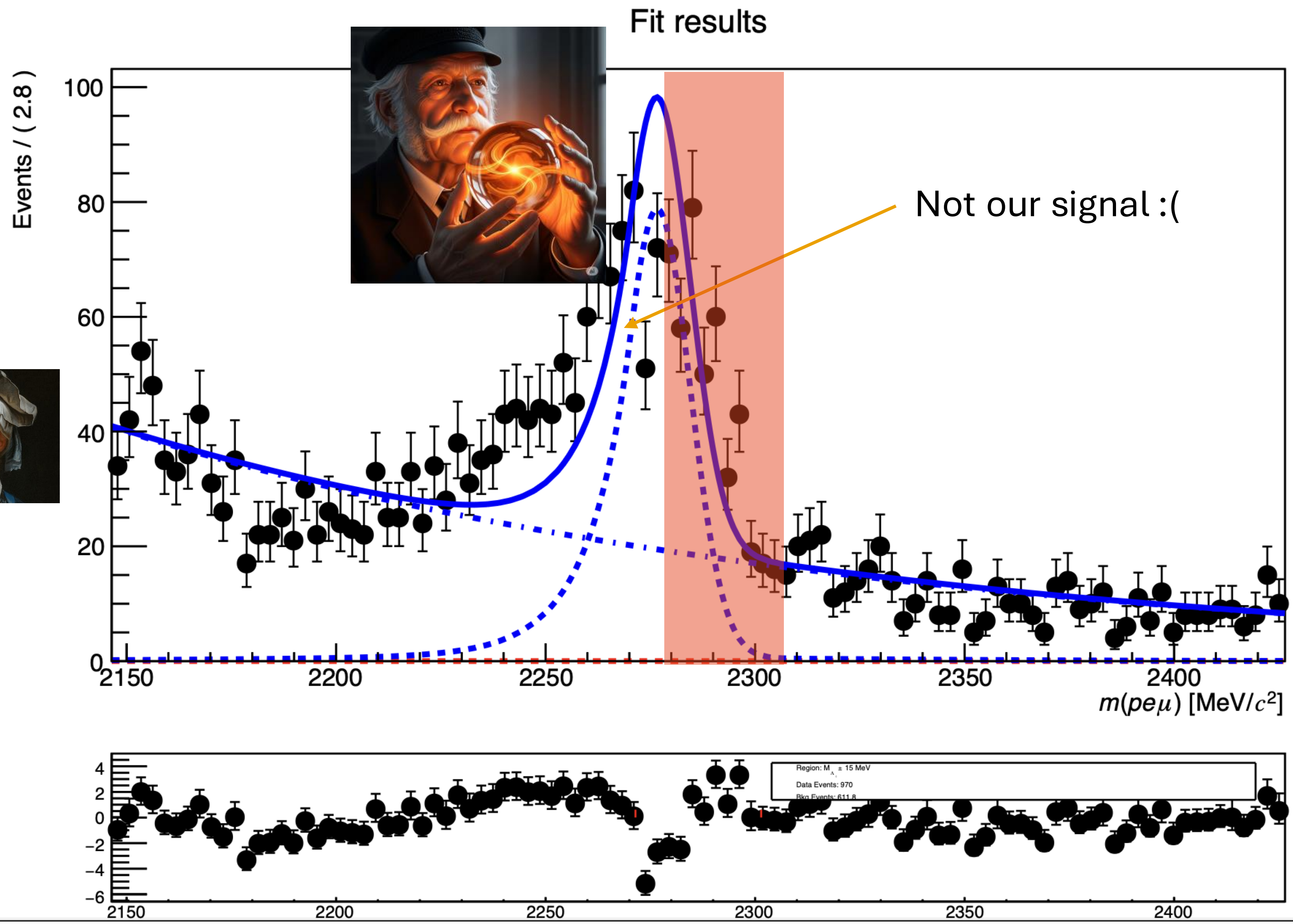
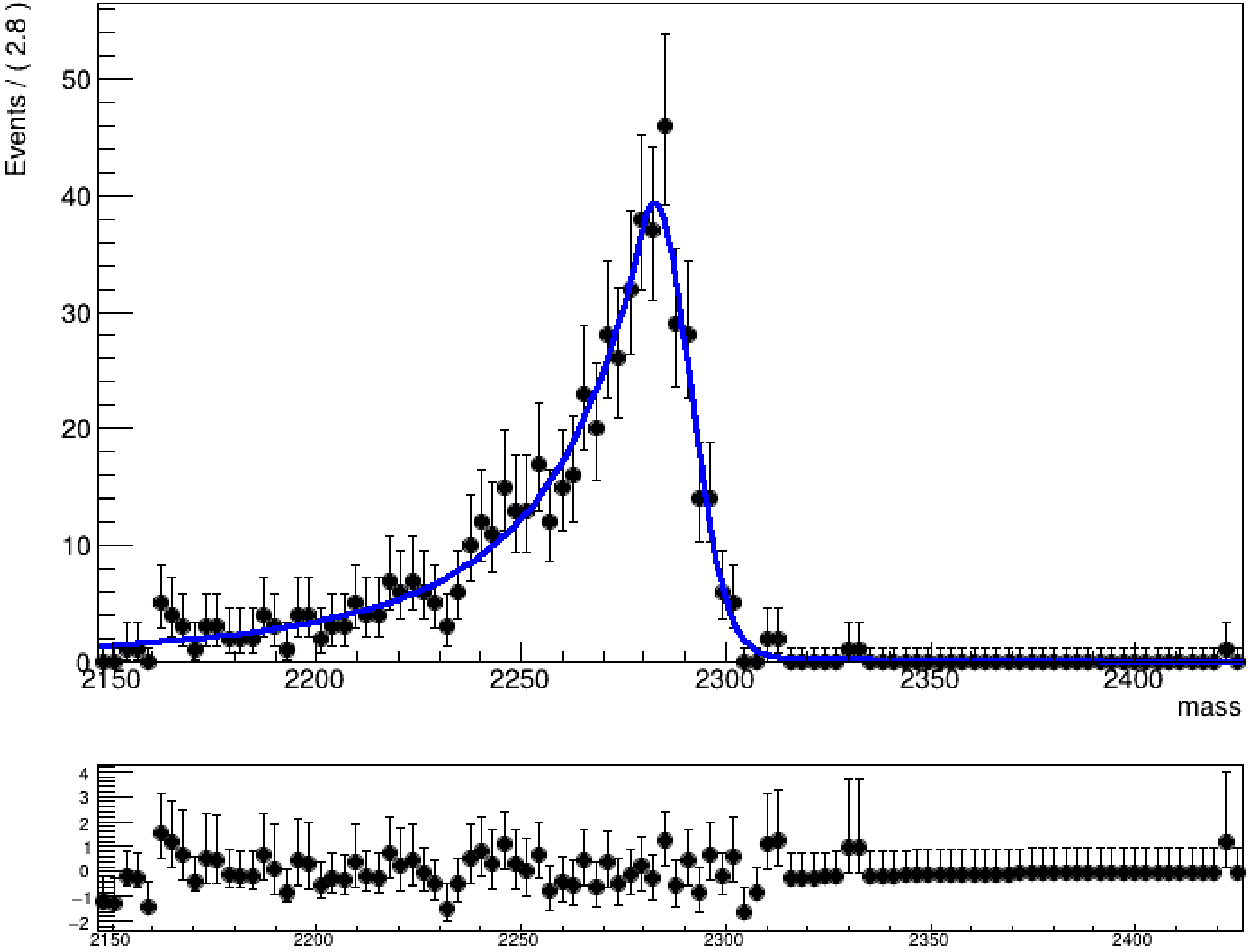


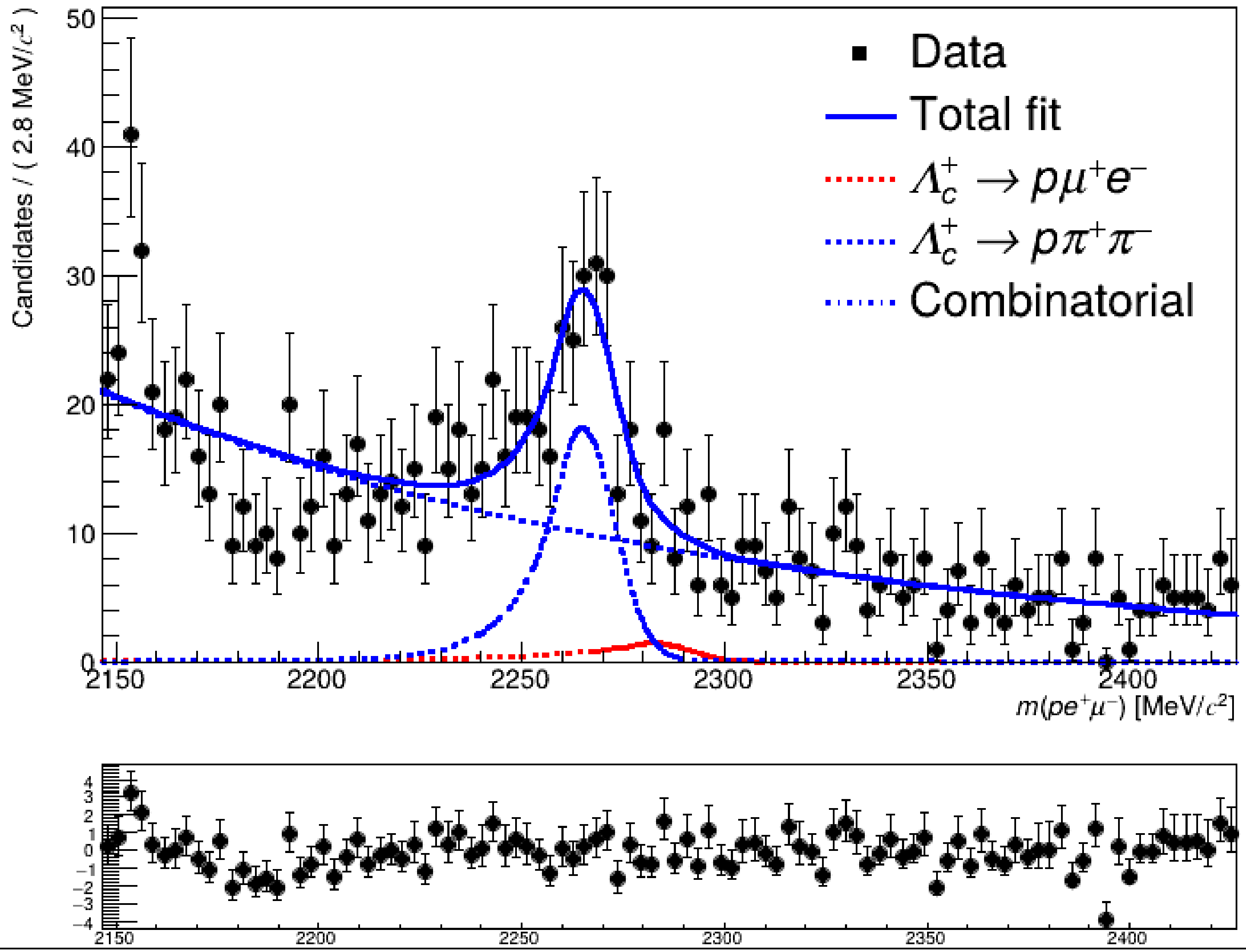
Invariant Mass

Our signal shape from Montecarlo (CB + Gauss)



Roofit (ROOT)

Invariant Mass



Roofit (ROOT)

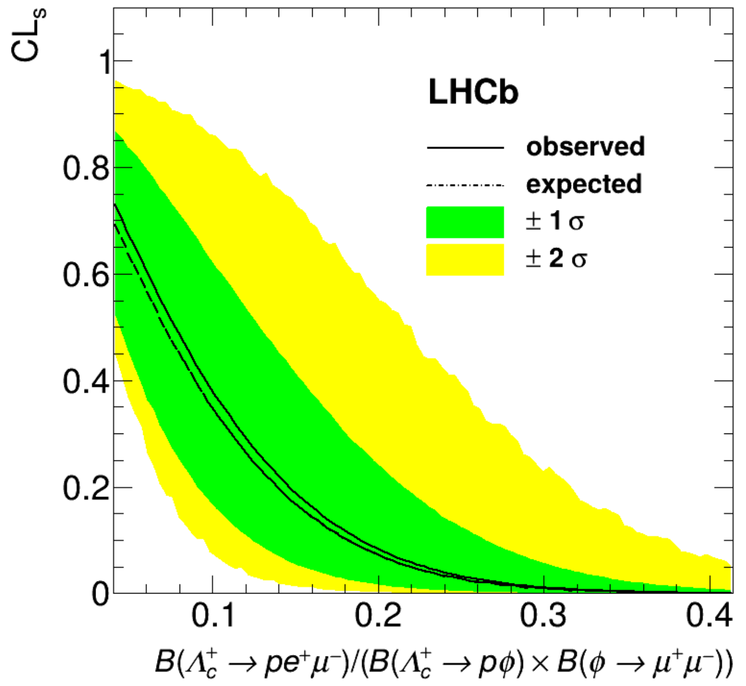
CLs Method

```
int ndata = 256;          // observed data
double nB = 254.579;       // expected background
double nS_min = 0;
double nS_max = 500;
double step = 1;
int ntoys = 10000;
```

```
>>> 90% CL upper limit on nS is approx 28.0
```

CLs method is used to set an upper limit on the signal strength

We scan different signal values and determine the highest one for which CLs remains below 0.10, corresponding to a **90% confidence level.**



Branching Ratio Limit

$$BR_{sig} = \frac{n_{sig}}{n_{ref}} \times \frac{\varepsilon_{ref}}{\varepsilon_{sig}} \times BR_{ref}$$

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Used reference mode: ${\Lambda_c}^+ \rightarrow p\, \mu^+\mu^-$

$$BR\left({\Lambda_c}^+ \rightarrow p\, \varphi\right) = 1.05 \pm 0.14 \times 10^{-3}$$

$$BR(\varphi \rightarrow \mu^+\mu^-) = 2.86 \pm 0.19 \times 10^{-4}$$

Branching Ratio Limit

$$BR_{sig} = \frac{28.0}{354.136} \times \frac{0.000194665}{0.000166151} \times 3.003 \times 10^{-7}$$

$$\approx 2.8 \times 10^{-8}$$

VS

$p e^+ \mu^-$	LF	$<$	9.9	$\times 10^{-6}$	CL=90%
$p e^- \mu^+$	LF	$<$	1.9	$\times 10^{-5}$	CL=90%

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ABOUT 100 TIMES MORE SENSITIVE THAN PDG WEBSITE

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Summary and Outlook

Goal: We searched for the rare decay ${\Lambda_C}^+ \rightarrow p\, e^-\mu^+$ as a potential signal of LFV in the charmed baryon sector.

Method: By using data from LHCb and advanced statistical techniques, including machine learning-based event selection and the CLs method, we set an upper limit on the branching ratio at **90% confidence level**.

Results:

- We achieved an upper limit of 2.8×10^{-8}, which is **about 100 times smaller** than the current PDG limit of 1.9×10^{-5}.
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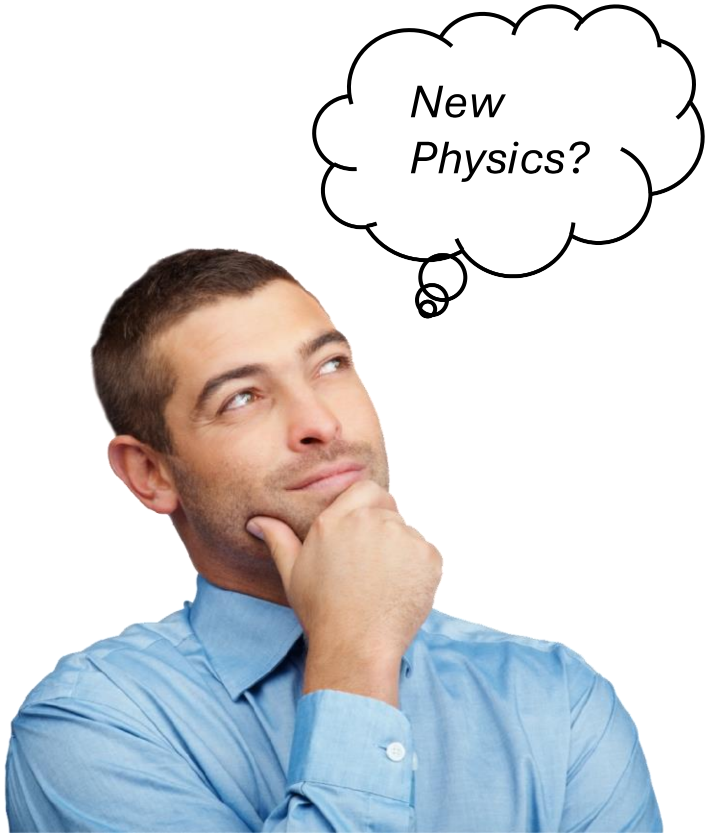

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Thank you

Backup / References

PDG 2024, LHCb publications, TMVA and uproot documentation

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K Mukaida, K Schmitz & M Yamada, Baryon Asymmetry of the Universe from Lepton Flavor Violation, Phys. Rev. Lett. 129 1 011803 (2022)

Malczewski, J. (2023). Acta Physica Polonica B Editorial Office: Search for the Lepton-flavour Violation at the LHCb. *Acta Phys. Pol. B Proc. Suppl.*,.