Multilayer SND (Scattering & Neutrino Detector) optimization for statistical analysis of tau-neutrino events using detector response

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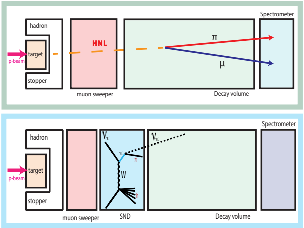
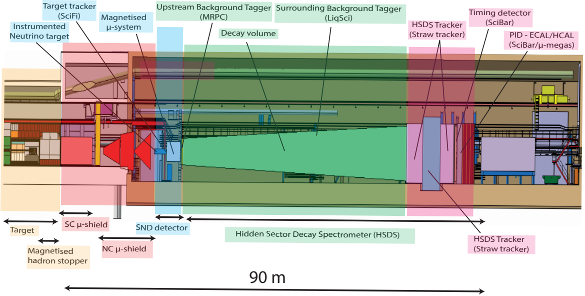
Search for Hidden Particles (SHiP)

- **SHiP** is a recently approved intensity-frontier experiment aiming to search for hidden particles with mass up to $O(10)$ GeV and extremely weak couplings, down to 10^{-10}.
- FIP decay search in background-free environment and LDM scattering
- Rich program at the Scattering & Neutrino Detector (SND): search for Light Dark Matter (LDM) & neutrino interaction physics with unique access to τ neutrino
  - Original Proposal (2013): Developed for new cavern ECN4
  - Refined Proposal (2023): Adaptation to existing ECN3 facility





SHiP experimental techniques: Decay & Scattering

Sensitivity is determined by three key factors:

- **Yields** (protons on target)
- **Acceptance** (including lifetime and angular acceptance)
- **Background level**

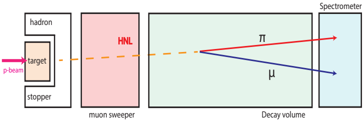
An exhaustive search require "model-independent" detector configuration, which should enable:

- Comprehensive reconstruction and identification of both fully and partially reconstructible modes
- Sensitivity to partially reconstructed modes
  - Distinguish between different models.
  - Assess the compatibility of the observed signal with theoretical predictions.

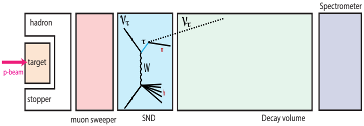
	Physics model	Final state
	SUSY neutralino	$\ell^\pm\pi^\mp,\ \ell^\pm K^\mp,\ \ell^\pm\rho^\mp, \ell^+\ell^-\nu$
	Dark photons	$\ell^+\ell^-, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$
	Dark scalars	$\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$
	ALP (fermion coupling)	$\ell^+\ell^-, 3\pi, \eta\pi\pi, q\bar{q}$
HSDS	ALP (gluon coupling)	$\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$
	HNL	$\ell^+\ell'^-\nu, \pi l, \rho l, \pi^0\nu, q\bar{q}'l$
	Axino	$\ell^+\ell^-\nu$
	ALP (photon coupling)	$\gamma\gamma$
	SUSY sgoldstino	$\gamma\gamma, \ell^+\ell^-, 2\pi, 2K$
	LDM	electron, proton, hadronic shower
SND	$\nu_\tau,\ \bar{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production $(\nu_e, \nu_\mu, \nu_\tau)$	$D_s^\pm,\ D^\pm,\ D^0,\ \overline{D^0},\ \Lambda_c^+,\ \overline{\Lambda_c}^-$

- 4×10^{19} protons on target per year currently available in the SPS
  - $\sim 2 \times 10^{17}$ charmed hadrons (> 10 times the yield at HL-LHC)
  - $\sim 2 \times 10^{12}$ beauty hadrons
  - $\sim 2 \times 10^{15}$ tau leptons
  - $\mathcal{O}(10^{20})$ photons above 100 MeV
  - $3500\ \nu_\tau + \bar{\nu}_\tau$ per year, and $2 \times 10^5\ \nu_e + \bar{\nu}_e / 7 \times 10^5\ \nu_\mu + \bar{\nu}_\mu$ regardless of target design

Visible decay to SM particles

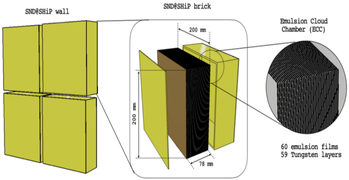


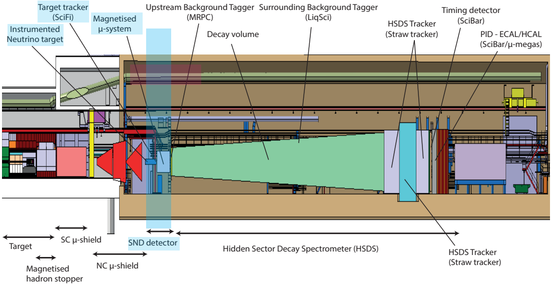
Scattering off atomic electrons and nuclei

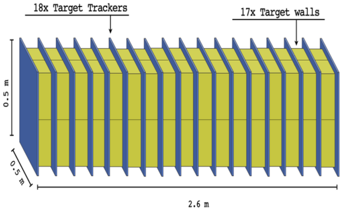


Scattering & Neutrino Detector (SND)

- Original design based on **nuclear emulsions**: DONuT / OPERA / **SND@LHC**
- Emulsion Cloud Chamber (ECC) bricks
- Target Tracker (TT): 18 layers of SciFi
- μ spectrometer: Drift tubes (4 stations)
  - Air core dipole magnet: 1 T

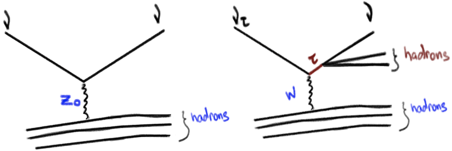




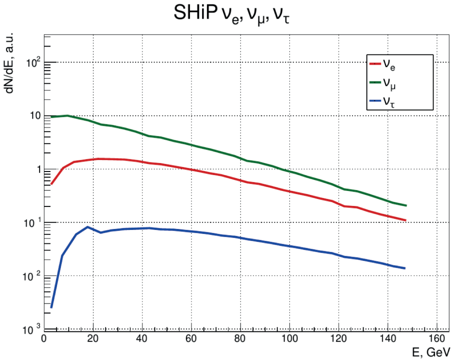


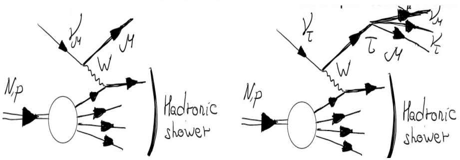
The task

- We need to classify the two signals from these processes:
  - **NCDIS** $\nu_\mu \rightarrow$ hadrons
  - **CCDIS** $\nu_\mu \rightarrow \mu +$ hadrons
  - **CCDIS** $\nu_\tau \rightarrow \tau +$ hadrons (hadronic & leptonic τ decay modes)



Neutrino spectra were taken from the SHiP experiment and used as a GENIE input. Detector response was performed using Geant4.

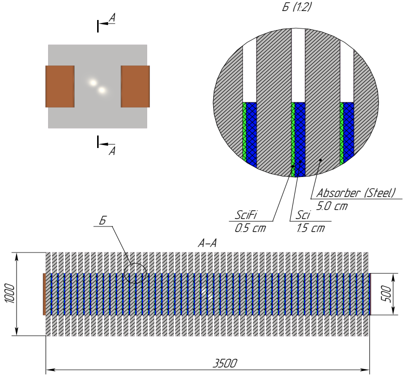




Detector concept

- **Absorber:**
  - Material: Fe (5 cm, 2 cm)
  - Magnetic field: 1.7 Tesla along the y-axis
- **Tracker:**
  - Fibres: ∅ 250 μm SciFi
- **Scintillator:**
  - Endep Scint layers

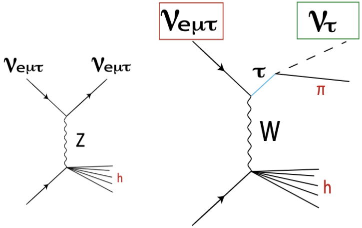
1 (3) cm × 1 (3) cm × 1.5 cm (xyz) (Poly)

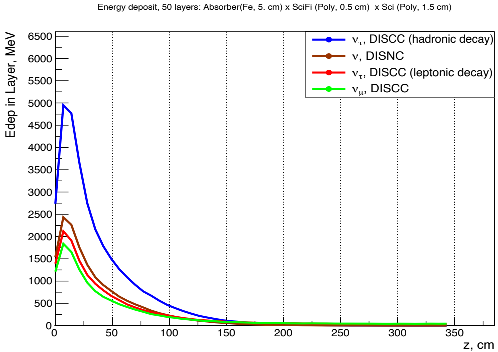


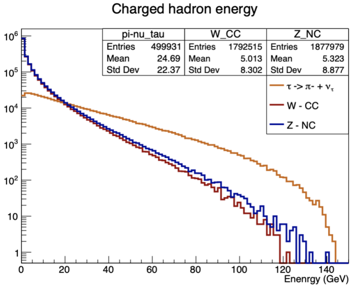
#	Name	Quantity
1	Magnetic absorber (GO Steel)	50
2	Sci	50
3	SciFi	50
4	Current Coil	2

Longitudinal shower profile for CCDIS ν_τ & NCDIS ν_μ

- **Charged current (hadronic decay):**
  - Hadrons from τ decay are more energetic.
- **Neutral current and charged current (leptonic decay):**
  - Hadrons initiated by Z slightly energetic than hadrons from W.

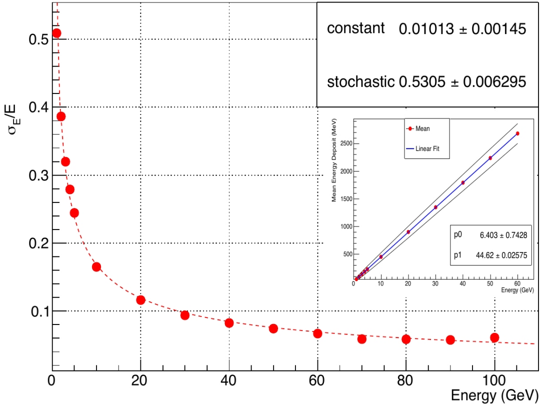


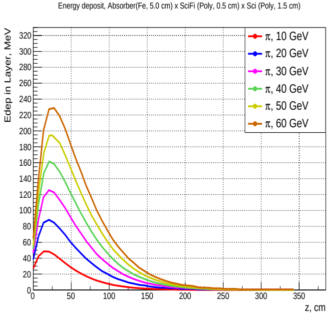




Energy resolution

- **Incoming particles**: π, e
- Particles momentum range: **1-100 GeV/c**



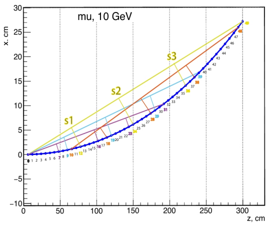


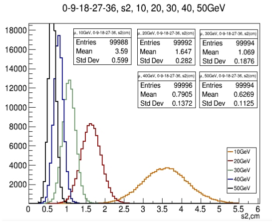
- for electrons: $\frac{\sigma_E}{E} \sim \frac{33\%}{\sqrt{E}}$
- for pions : $\frac{\sigma_E}{E} \sim \frac{53\%}{\sqrt{E}}$

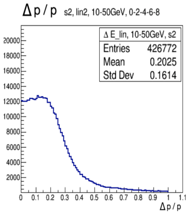
Energy deposit collected in Scint layers

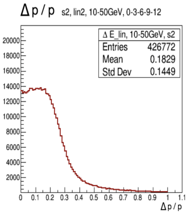
Particle (muon) momentum reconstruction

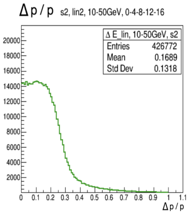
- We determine **sagitta** to use the dependences of these parameters on the kinetic energy of the muon
- The trajectory parameters, **S1**, **S2**, **S3** are calculated as "distances from a point to a line"
- If the functions p = f(s) for a limited range of **10-30 GeV** are used, the most accurate determination of the muon momentum of $\sim$ **12%** is obtained
- If the functions p = f(s) for **10-50 GeV** are used, a determination of the muon momentum with an accuracy of $\sim$ **14-15%** is obtained





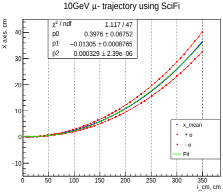


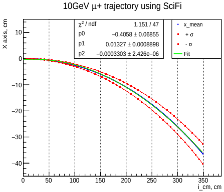


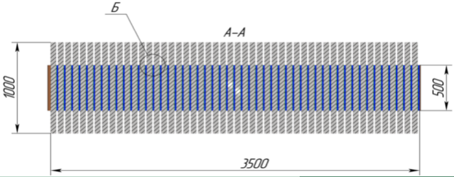


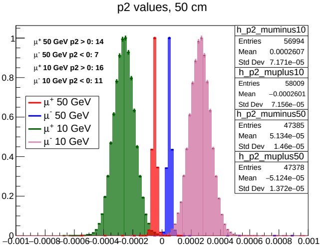
Particle (muon) charge reconstruction

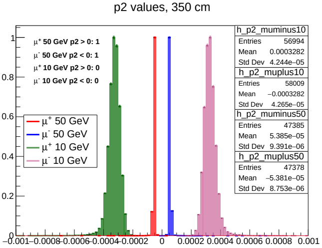
- Determine charge: the sign of the fitted **parabolic coefficient p2** to decide whether the muon is
  - μ^+: $p_2 < 0$
  - μ^-: $p_2 > 0$





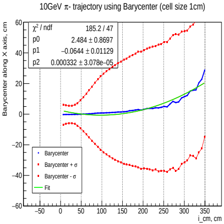


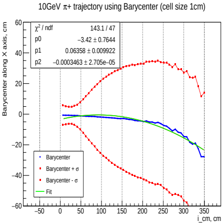


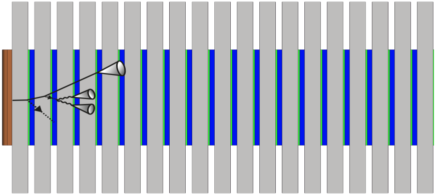


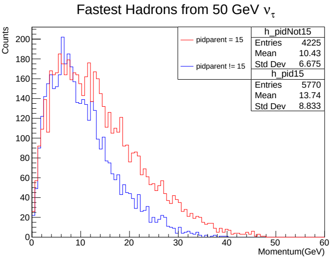
Particle (pion) momentum reconstruction

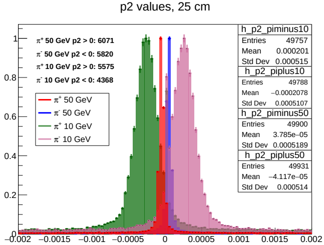
- Based on **the fastest hadron track charge**, determine whether the tau neutrino is ν_τ or $\bar{\nu}_\tau$
- Momentum reconstruction for **hadrons** using SciFi information in process
- Trajectory for **hadrons** using only Scint layers information





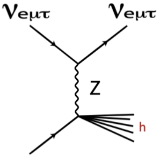


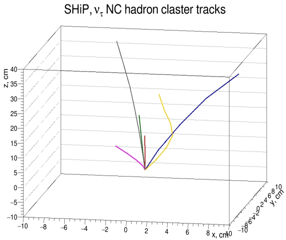


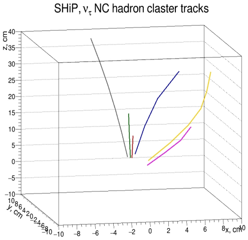


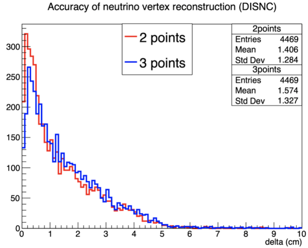
Neutrino vertex reconstruction

- **To reconstract the vertex**, we extrapolate our tracks by a linear function
- Each track segment is crossed in pairs, then the average sum of the distance to the center of the segment that connects the crossed lines is taken
- In the actual configuration of the detector there is **no zero point**, there are only track points starting from **z=5cm**





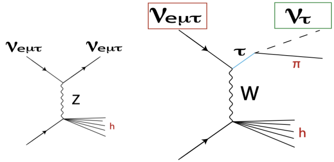




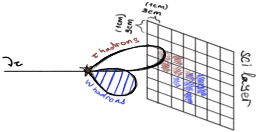
Conclusion: vertex reconstruction accuracy using SciFi layers $\sim$ **0.1 cm**

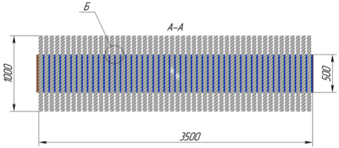
CCDIS ν_τ (hadronic decay) & NCDIS ν_μ

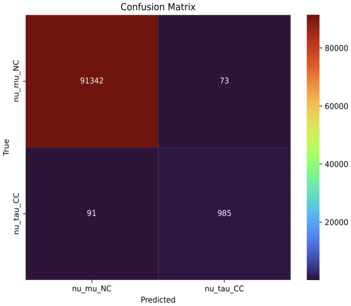
- **16 Scint layers** (out of 50 layers)
  - Energy deposition
  - Energy of hadron cluster
  - Shower CoG in XY plane
  - Shower width in XY plane
- **in total: 81 parameter**



The less diagonal the matrix, the better the classification

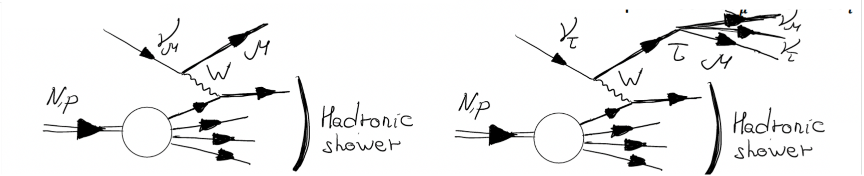






Parameters describing close parts (layers) of the detector are correlated

CCDIS ν_τ (leptonic decay) & CCDIS ν_μ Reasonable cuts on the data



- Non-trivial problem due to:
  - High-imbalanceness of the classes (300:1);
  - overlaping feature distributions.
- The cut on the angle btw P_μ and P_{hadr} should be applied:

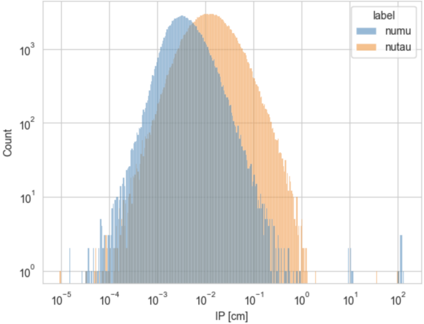
$$\alpha < \arctan \frac{\text{Det. transverse length / 2}}{\text{Det. longitudinal length / 2}} \simeq 10 \text{ degr.} \text{ — rejects 70\% of the data}$$

- removing low-energy nucleons from the nucleus fragmentation: fully absorbed in the passive material
- In case of using Impact parameter (IP) of muons w.r.t. to the interaction point:

$$\text{IP} > 0.1 \text{ cm (resolution is 0.1 cm)} \;\; \& \; \text{IP} < 0.6 \text{ cm (remove outliers)}$$

Impact parameter (IP) of muons w.r.t. to the interaction point

- Simulation (5 cm of the passive material). Extrapolation of first 3 points back to the $z = 0$ cm.

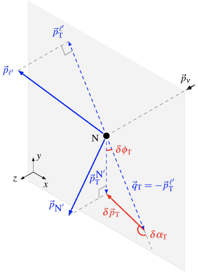


- Multiple scattering of muon/tau also contributes into IP.
- Resolution of the vertex reconstruction is not sufficient to use IP as a parameter in the classification.

$$\text{IP}^{\text{nutau}}_{\text{max}} - \text{IP}^{\text{numu}}_{\text{max}} \simeq 0.007 \text{ cm}$$

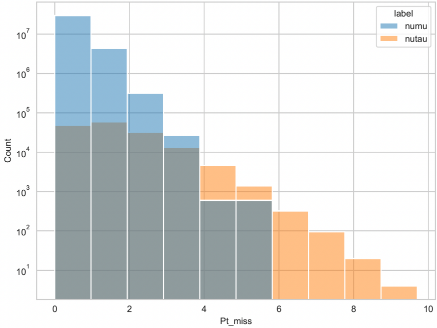
Crucial parameter

- Difference in missing transverse momentum distribution is mostly caused by the neutrinos that carried away momentum.



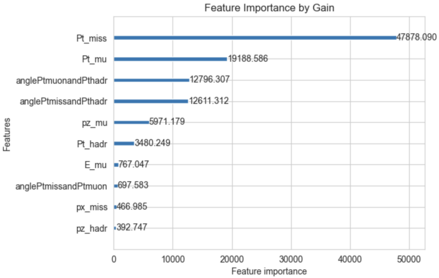
https://arxiv.org/pdf/1512.05748

Cut on the missing P_T is possible but rejects most of the nutau events as well → BDT.



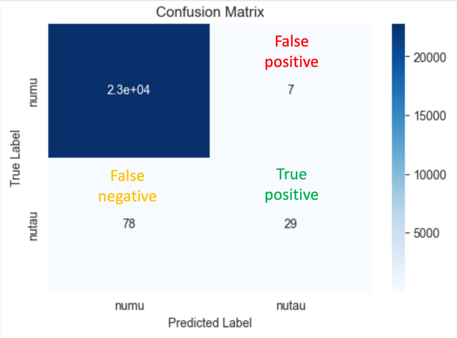
Classification setup of BDT classifier (Lightgbm based)

- Training on 80%, validation on 20% of the data.
- Data is weighted to consider the imbalanceness of the dataset ($w = 1./300$ weights for nutau events instead of $w = 300.$ for numu).
- 18 kinematic parameters used as features (momenta and energies of muons and hadronic showers, and angles btw momenta in the transverse plane).
- Muon momenta and hadronic shower energies are smeared according to the detector resolution.
- Optimization of hyperparameters of BDT using Optuna.



Results. Confusion matrix

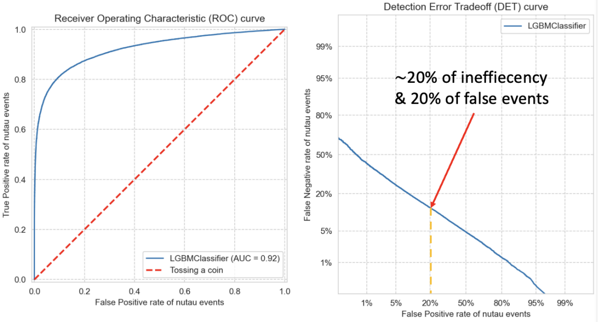
- Confusion matrix **does not show the performance of the classifier for different discriminator threshold** which is crucial for highly-imbalanced problem.
- Maximising True positive (TP) value.
- False negative (FN) value shows the ineffiecency of the classifier (how many nutau were classified incorrectly). Not dangerous for searching for nutau signal.
- False positive (FP) value shows the number of incorrectly classified numu events. Dangerous for searching for nutau signal.



Random test data sampling:
TP/(FP + TP) $= [0.69, 0.94]$ in 95% CI.

Results. ROC-AUC and DET curves

- Varying the discriminator threshold from 0 to 1, one can choose the classifier with the required performance.
- ROC-AUC — tradeoff btw. TP and FP, DET — tradeoff btw. FN (inefficiency) and FP.
- Example: discriminator threshold is chosen with 20% of ineffeciency and 20% of false events.



Thank you!

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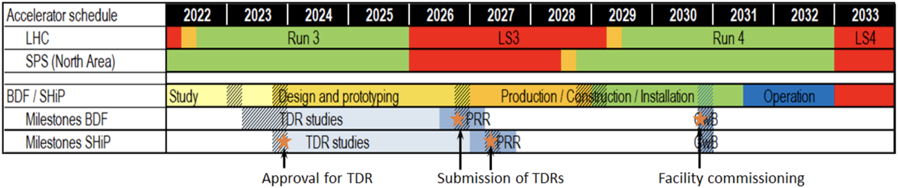
BDF/SHiP preliminary schedule

- Availability of test beams challenging
- Important to start data taking > 1 year before **LS4**



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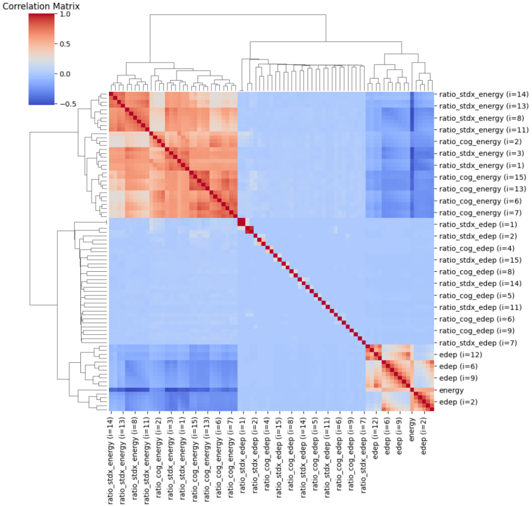
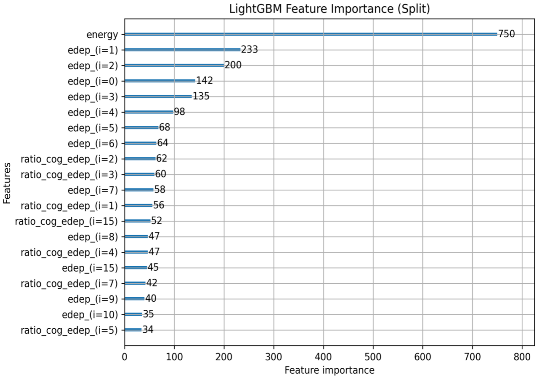
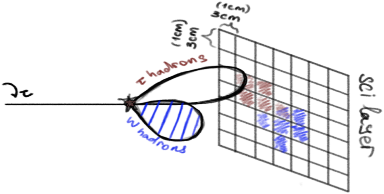


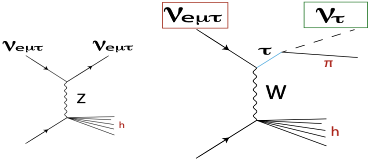
CCDIS ν_τ (hadronic decay) & NCDIS ν_μ

- Most valuable: energy of hadron cluster, energy deposit in layers;
- Split measures how often a feature is used to split the data in decision trees during training, which helps assess the feature's importance in making decisions.

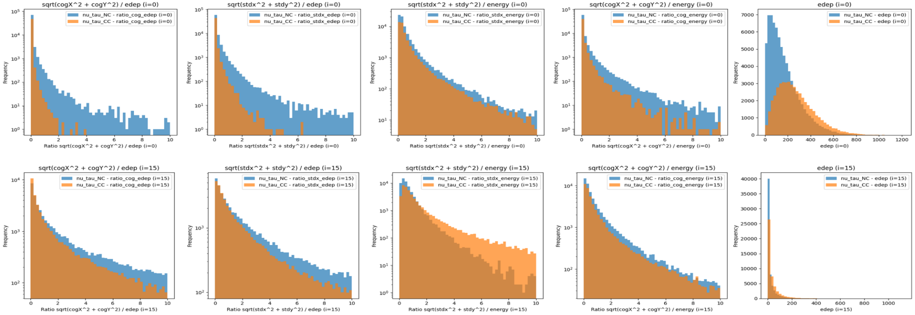


CCDIS ν_τ (hadronic decay) & NCDIS ν_μ





- Parameters (example):



Impact parameter (IP) of muons w.r.t. to the interaction point

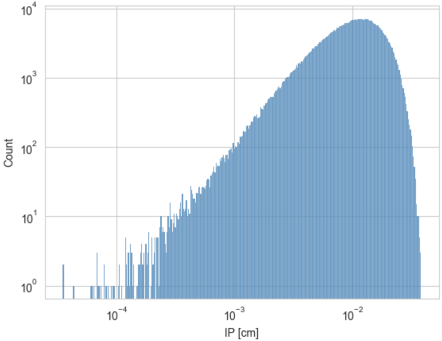
- The difference btw 2 cases is the path before the decay of tau in the nutau case. IP should be larger in this case:

$$\text{IP} = c\gamma\tau\sin(\theta) =$$

$$c\tau\frac{E_\tau}{m_\tau}\sqrt{1-(p_{\tau,z}/P_\tau)^2}$$

- Multiple scattering of muon/tau also contributes into IP.

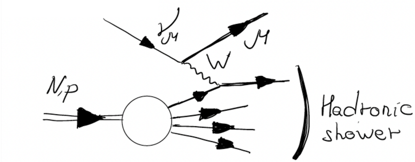
- Theory. Calculate the contribution into IP of muon due to the tau decay for nutau case for (E_τ, θ_τ) in SHiP case.

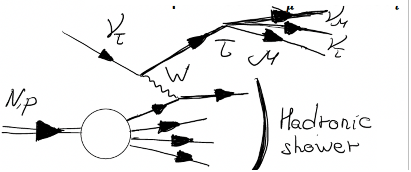


$\text{IP}^\tau_{\text{max}} \sim 10^{-2}$ cm

CCDIS ν_τ (leptonic decay) & CCDIS ν_μ

- Non-trivial problem due to:
  - High-imbalanceness of the classes (300:1);
  - overlaping feature distributions.





Results. ROC-AUC and DET curves

- Varying the discriminator threshold from 0 to 1, one can choose the classifier with the required performance.
- ROC-AUC — tradeoff btw. TP and FP, DET — tradeoff btw. FN (inefficiency) and FP.
- Metrics:
  - True positive rate $= \frac{\text{TP}}{\text{Actual positive}}$ ← Maximising
  - False positive rate $= \frac{\text{FP}}{\text{Actual negative}}$ ← Dangerous
  - False negative rate $= \frac{\text{FN}}{\text{Actual positive}}$ ← Not dangerous