# Electron Identifcation using Machine Learning in the MPD Experiment at NICA

Sudhir Pandurang Rode for the MPD Collaboration

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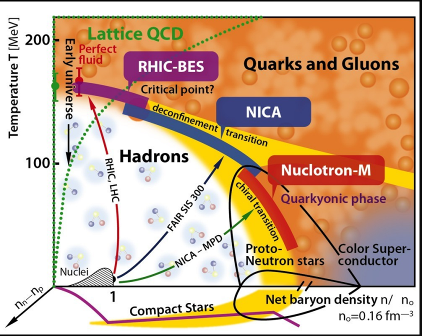
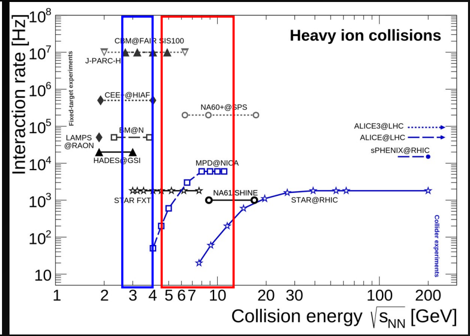
# Heavy-ion collisions

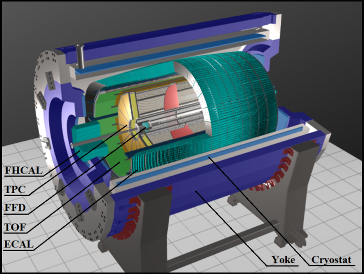
FXT CLD Nucl. Phys. A982 (2019) 163-169

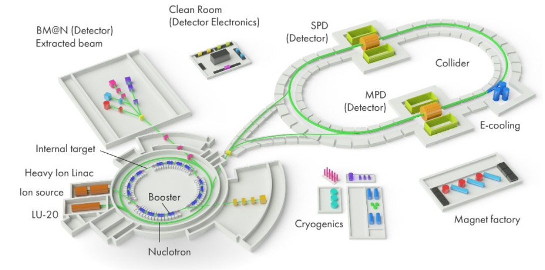



- Smooth crossover at $\mu_B \approx 0 \leftarrow$ Early universe like conditions.
- Explore high $\mu_B$ matter $\rightarrow$ Critical end point and 1st order phase transition.
- Similar net baryon density expected as in the core of neutron stars.
- MPD and BM@N $\rightarrow$ QCD matter study at these densities.
- Various experiments, such as NA61/Shine, STAR-BES and CBM in similar beam energy range.

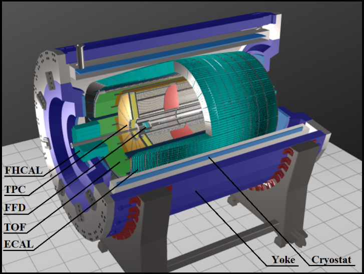
# Multi-Purpose Detector (MPD) experiment at NICA

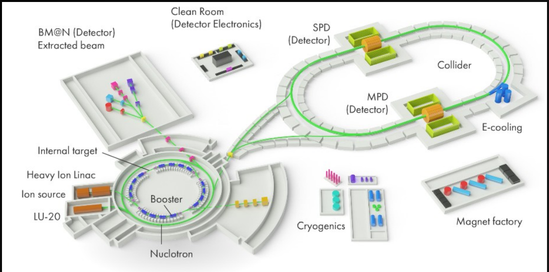



- Nuclotron-based Ion Collider fAcility (NICA) is a megascience project approaching its full commissioning.
- MPD is a flagship experiment at NICA: starting operations in 2026.
- Modes of operation:
  - Collider mode: two beams, $\sqrt{s_{\mathrm{NN}}}$ = 4-11 GeV $\rightarrow$ Xe+Xe/Bi+Bi at $\sqrt{s_{\mathrm{NN}}} \approx$ 7 GeV, $\approx$ 50 Hz at start-up
  - Fixed-target mode: one beam + thin wire ( 50 $\mu$m), $\sqrt{s_{\mathrm{NN}}}$ = 2.4-3.5 GeV $\rightarrow$ Xe/Bi+W/Au at $\sqrt{s_{\mathrm{NN}}} \approx$ 3 GeV, $\approx$ kHz at start-up

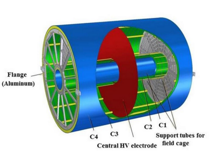
# Multi-Purpose Detector (MPD) experiment at NICA

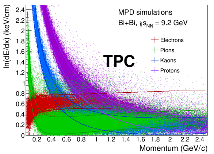



- Strategy: High luminosity scans in energy and system size to measure different signals.
- Advantages: Same apparatus for scans with benefits of collider geometry.
  - maximum phase space, correlated systematic effects for different systems and energies.
- Sub-systems with modern technologies: TPC, TOF, ECal, FFD, FHCal.
- Suitable for dilepton measurements: e+e- pairs.

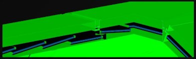
# MPD sub-systems

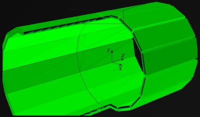


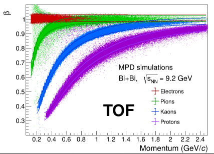



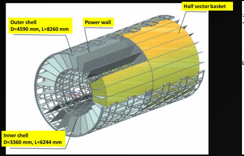

- 3D tracking with dE/dx measurement (accuracy of 6-7%) and 1-3% momentum resolution.
- 24+ ROC and 100+ % FE cards ready.
- HV/leakage tests – ongoing
- TPC + ECAL cooling systems under commissioning

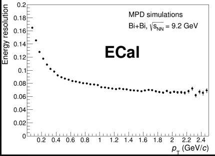
- All 28 (100%) TOF modules are assembled, tested, stored and ready for installation and Spare modules in production.
- Designed Time and coordinate resolution of ≈ 80 ps and ≈ 0.5 cm, respectively.
- Better PID perfomance is achieved when combined with TPC.








- Full configuration: 50 half-sectors in full azimuth (25 full sectors).
- Measures deposited energy from 10 MeV to a few GeV with resolution of about 7% at 1 GeV.
- 45 half-sectors to be ready by October, the rest depends on WLS fiber supply

**Ready for commisioning by end of the year.**

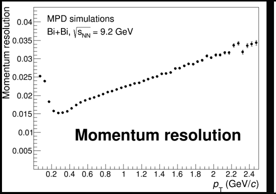
# Particle Identification (PID) in Heavy-Ion Experiment

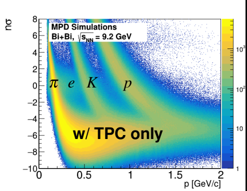
- PID is a crucial step in the physics analysis of the experimental data.
- It enables detailed study of the produced identified particles, their spectra, and yields.
- PID helps explore different phenomena such as, chemical equilibrium, strangeness enhancement, and collective flow of various species.
- It allows disentangling complex particle production mechanisms.

**Such a crucial step requires excellent detector performance!**

# Track reconstruction and Particle Identification (PID)

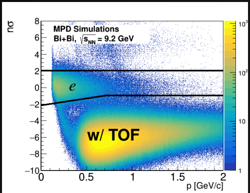
- MPD has excellent track reconstruction and particle identification capabilities.

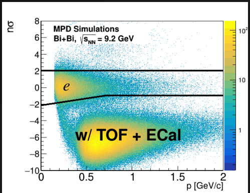



- TPC measures $<\mathrm{dE}/\mathrm{dX}>$and momentum with resolution of about 6-7$\%$ and 1-3$\%$, respectively.

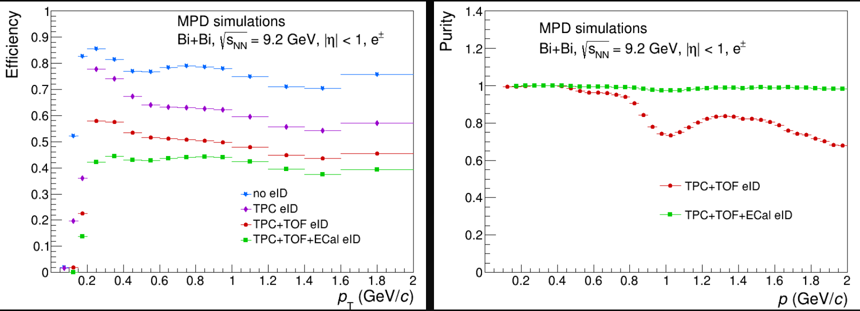
- TPC alone is not enough to achieve pure electron sample.
- TOF complements with purity about 80$\%$ beyond p = 1 GeV/c.
- Addition of ECal allow even better electron-hadron separation.




**The purity improves significantly with ECal!**

# Electron reconstruction efficiency and Purity



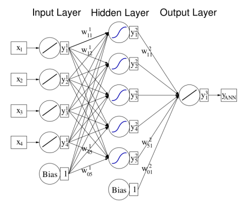

- With TOF, the purity reaches about 80% and the efficiency of about 50% is achieved.
- The purity can reach up to 100% with the help of ECal along with nearly 45% efficiency: exceptional electron-hadron separation above $p \gtrsim 0.8$ GeV/c.

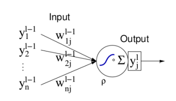
**Still, the loss of efficiency using traditional cuts method is significant! $\rightarrow$ need a better way to improve this.**

# PID using Machine Learning

- Machine learning has been used for the identification of various particles for some time now.
- This approach can help in improving the electron identification efficiency $\rightarrow$ S/B and significance in dielectron analysis.
- Procedure:
  - Preparation of the data sample, generally, two samples, one for training (50$\%$) and other is for validation (50$\%$) $\rightarrow$ Actual proportion of Signal (electrons) and Background (hadrons).
  - Selection of the discriminating variables.
  - Training model on the sample and validation with testing sample.
- There are many models/classifiers available in TMVA package which used in this study $\rightarrow$ for instance, Multi-Layer Perceptron (MLP) and Boosted Decision Tree (BDT).
- Only studies with MLP and BDT are shown in this presentation.

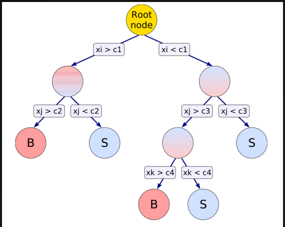
# Neural Network and Decision Tree[1]




- **MLP:** Neurons that learn patterns in data, organized in layers with direct connections from one layer to the next.
- Neuron response functions map inputs to outputs.
- Good at finding complex patterns in data.
- Needs lots of trial-and-error to set up properly

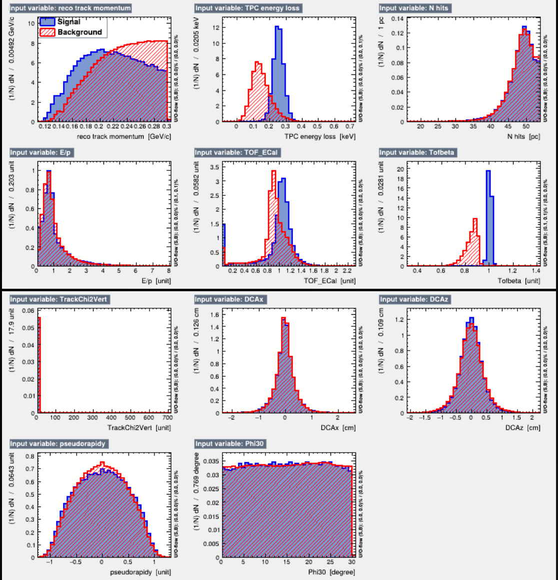
- **BDT:** Simple model making predictions via step-by-step "if-then" rules
- Turns weak trees into strong predictors through sequential error correction
- Robust performance on structured data
- Training speed scales with number of trees




- Classififcation between signal and background is carried out by training models to learn a decision boundary based on discriminating variables.

[1] ***Disclaimer:*** **I am not an expert on Machine Learning. This is just for information.**

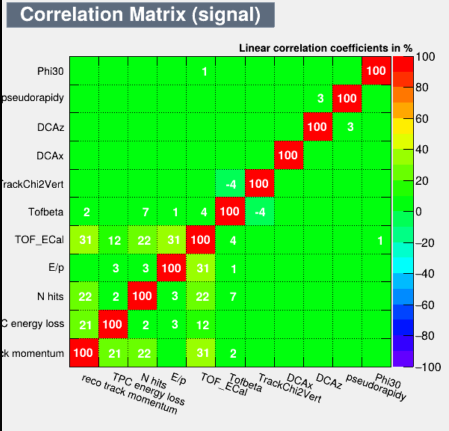
# Input variables

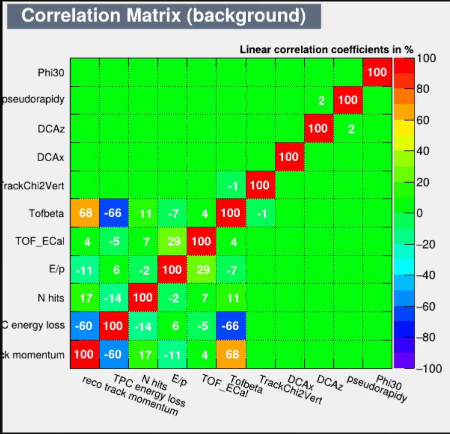



Following discriminant variables are fed to the ML models:

- Momentum
- dEdX
- No of Hits
- E/p
- Velocity, $\beta$ measured in the TOF and ECal
- Track chi2 to vertex
- DCAx
- DCAz
- Pseudorapidity ($\eta$)
- Azimuthal angle ($\phi$)

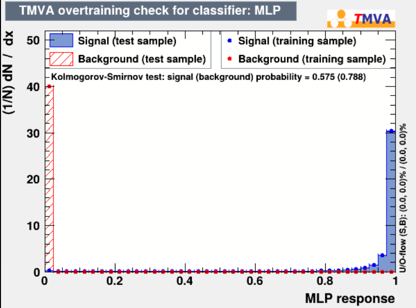
# Correlation matrices: $e^{\pm}$ (Signal) and hadrons (Bkg)

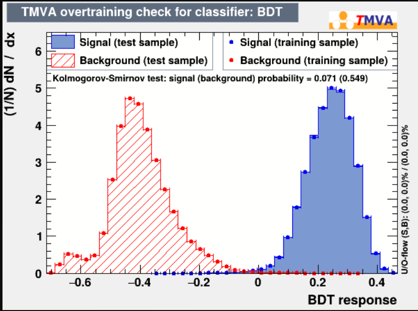



- Almost all variables for signal are uncorrelated.
- In case of background, there is (anti-)correlation between some variables, for instance, dEdx and Tofbeta.

# Momentum integrated training



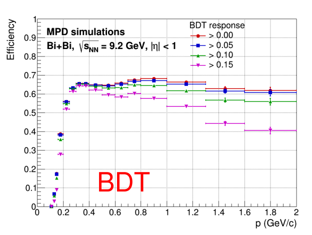



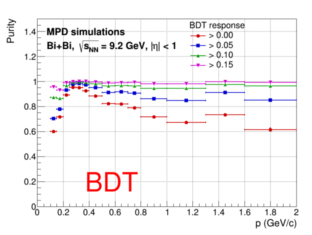

- The training was performed well.
- Overtraining test carried out using Kolmogorov Smirnov test[2] $\rightarrow$ suggested no overtraining.

[2] provides a $p$-value equal to the statistical probability that two samples are drawn from the same distribution. The smaller the $p$, the greater the overtraining. As a rule of thumb, it is recommended to try to reduce overtraining if $p < 0.01$, especially if the separation is visibly poorer for the testing samples than for the training samples.

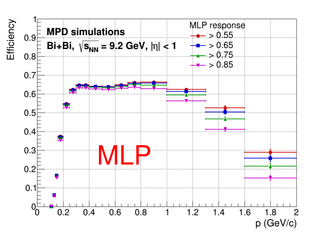
# Momentum integrated training

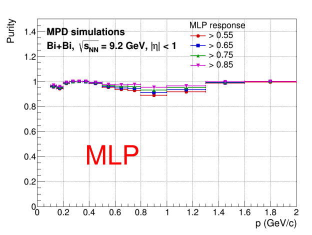
- Both BDT and MLP are not able to perform better at high momenta.



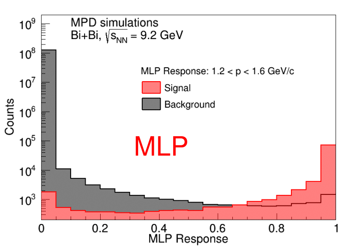

- Efficiency drops at high momenta.

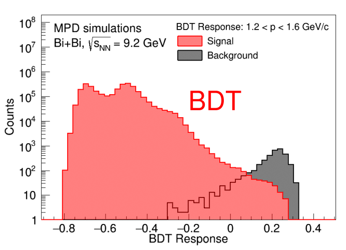


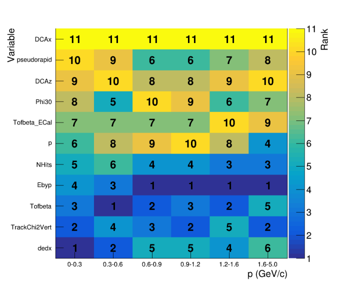



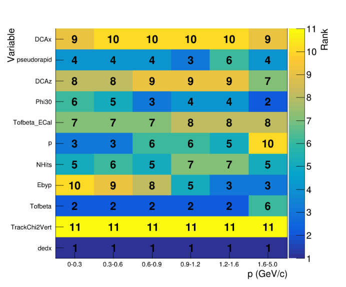

**Momentum differential training may improve the classification at high momentum.**

# Momentum differential training



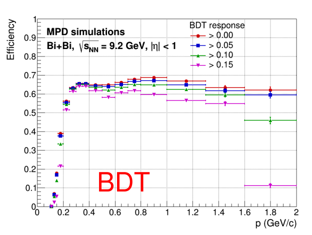



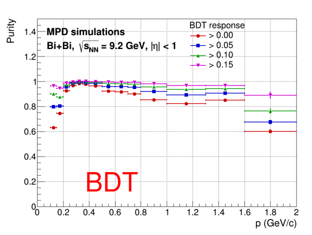




- Samples were trained in various momentum intervals.
- Classifier-dependent sensitivity to input variables at higher momenta.

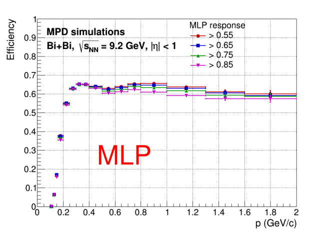
# Momentum differential training

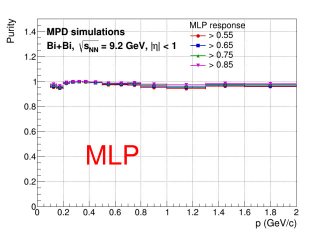
- BDT still seems to be less effective at high momenta compared to MLP.



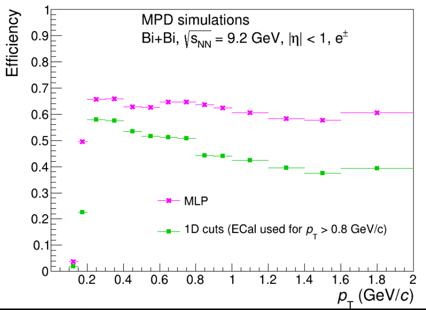

- MLP perform better and provide p-independent efficiency and purity.

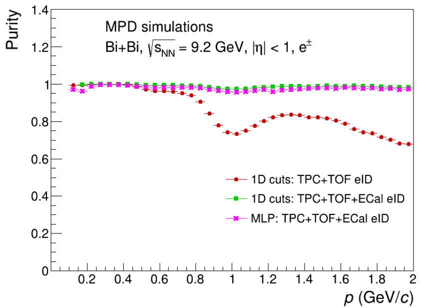



**Momentum differential training helps to separate signal and background effectively, especially, using MLP.**

# Benefit of Machine learning in PID




- Efficiency obtained using neural network i.e. Multi-layer Perceptrons (MLP) shows enhancement in the electron identification performance of the MPD compare traditional 1D selection cuts method.
- Purity has remained almost 100% as in traditional method.
- Black-box nature pose challenges for debugging, Inherit biases from training data, and Systematic uncertainties are harder to quantify.

**Efficiency is improved by 50% above $p_T > 0.8$ GeV/c!**

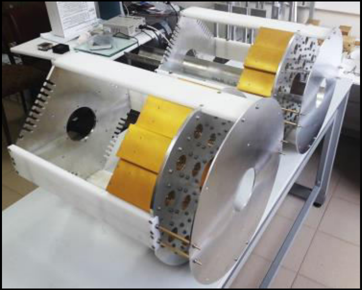
# Conclusions

- All MPD sub-systems are in advanced stage and ready for commissioning by end of the year $\rightarrow$ MPD is expected to begin operations in 2026.
- Particle Identification is an important step in the various physics analyses.
- ECal provides excellent electron-hadron separation: leads to highly pure electron sample.
- Electron Identification efficiency suffers loss due to traditional cut based method.
- Improvement in the electron identification performance is observed using Machine Learning.
- Both MLP and BDT does enhance the efficiency, however, MLP performs better in the high momentum region.

# THANK YOU

# BACK-UP

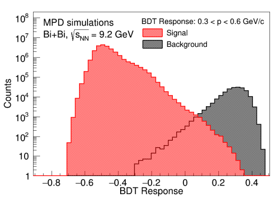
# Forward detectors

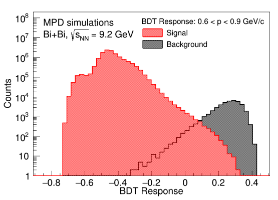


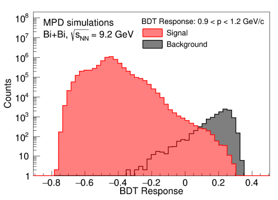
- FFD (Fast Forward Cherenkov Detector): Provides fast triggering of A+A collisions and generates the start-time (T0) pulse generation for the ToF detector with a time resolution better than 50 ps.
- Two FFD detectors at $2.7 < |\eta| < 4.1$
- FHCal (Forward Hadron Calorimeter): Event centrality and reaction plane measurements with potential for event triggering.
- Two FHCAL detectors at $2 < |\eta| < 5$, $\approx$ 1x1 m$^2$ each

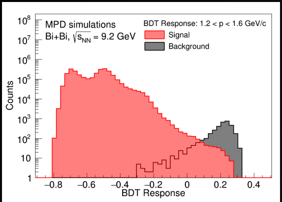
**Ready for installation**

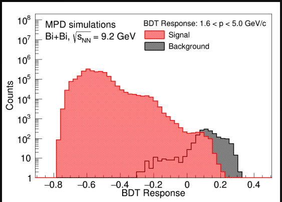
# Momentum dependent training (BDT)

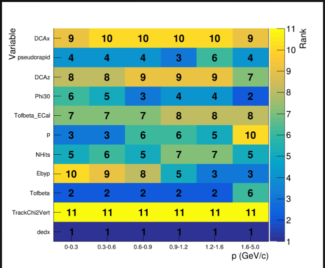


# Momentum dependent training (MLP)