



Theoretical Time to Distinguish Special Nuclear Materials in Different Scenarios through MPRC-ToF based MST

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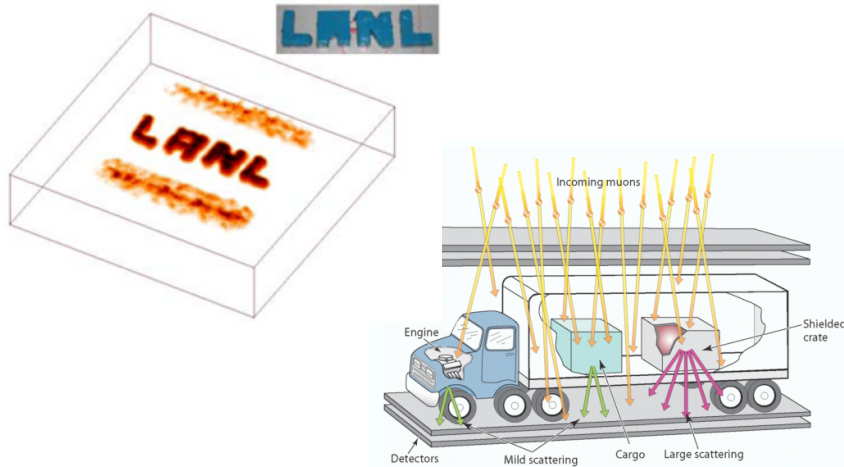
XVII Conferences on Resistive Plate Chambers and Related Detectors, Santiago de Compostela

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12-9-2024



- **Research Background**
- **Other's Work**
- **Simulation Work**
- **Results&Analysis**
- **Future Work**
- **Summary**



■ Muon Scattering Tomography(MST)

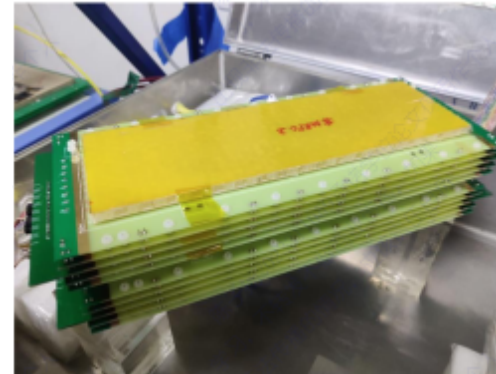
Detailed Imaging

Rapid Detection

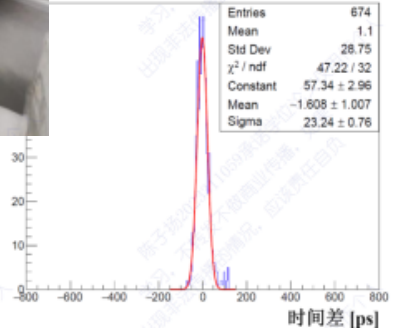
Highly valued these days

- Muon scattering angles reflect certain material's Z number
- But also are influenced by muon energy

➔ Momentum information counts



$$\frac{23.24}{\sqrt{2}} \approx 16.43ps$$



■ MRPC-TOF

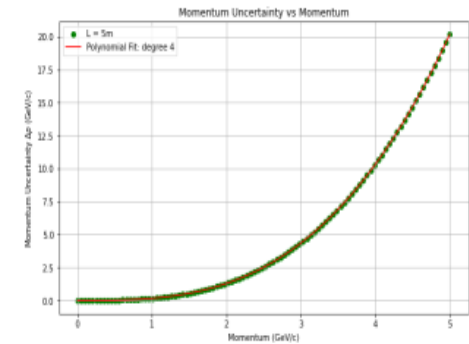
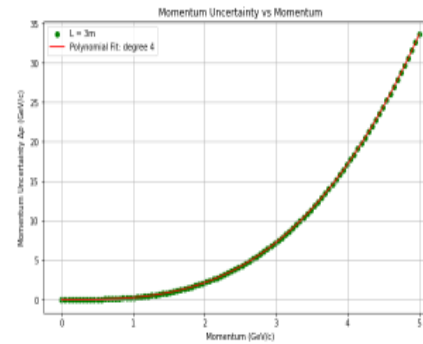
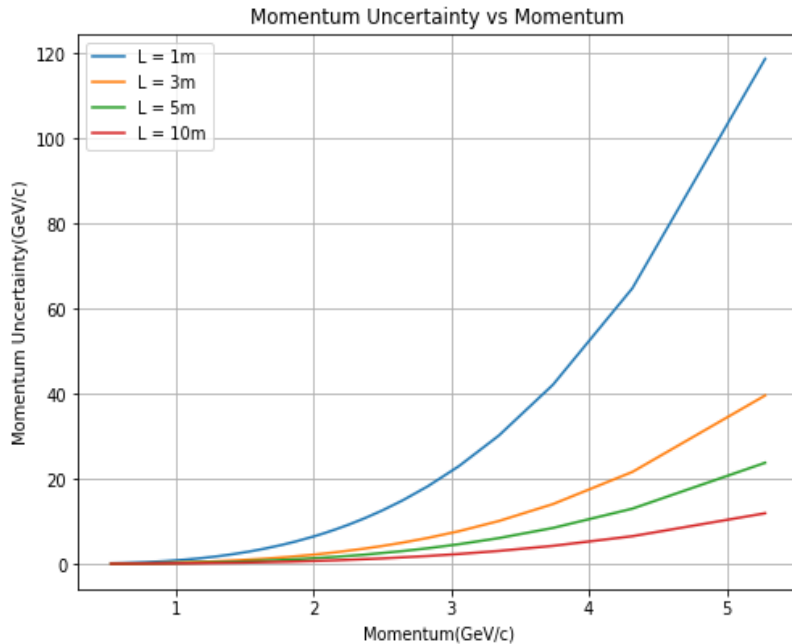
Advantages:

- Excellent time resolution < 20ps
- Large sensitive area
- Stable performance
- ➔ Make up for absence of momentum information in traditional MST



Simulated MRPC-TOF's Performance

Time resolution of simulated MRPC: 30ps

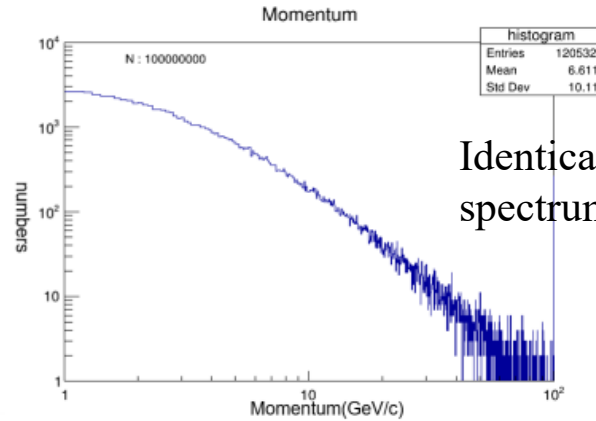
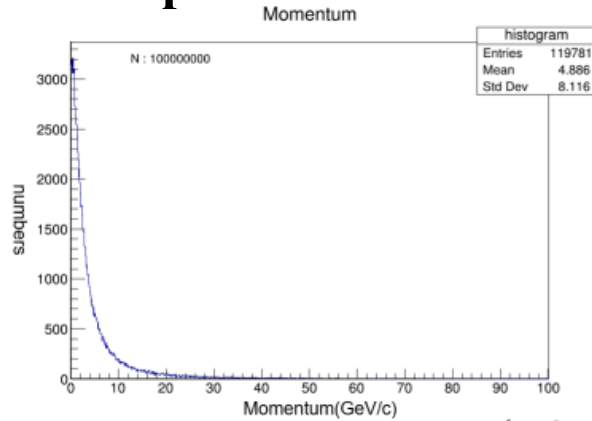


★ The larger the muon energy, the greater the uncertainty. When the TOF spacing is 3m, the uncertainty reaches 60% when the muon energy reaches **1.5GeV(35.83%)**. When 5m, the value will be **2GeV(44.73%)**.

→ During the simulation, to characterize the uncertainty, muons with **lower energies** follow **Gaussian distribution** with true value as μ , corresponding uncertainty calculated by formula as σ , and muons with higher energies were assumed to be **uniformly distributed(3~5GeV)**.



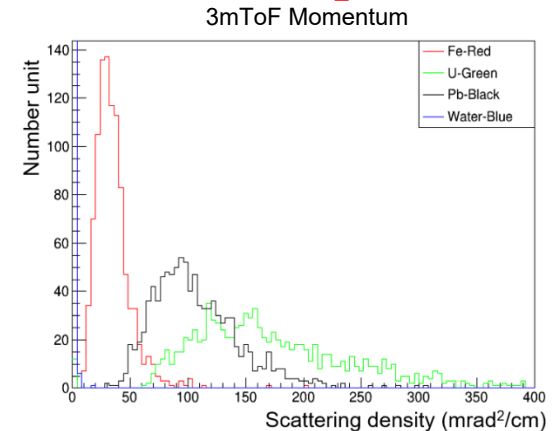
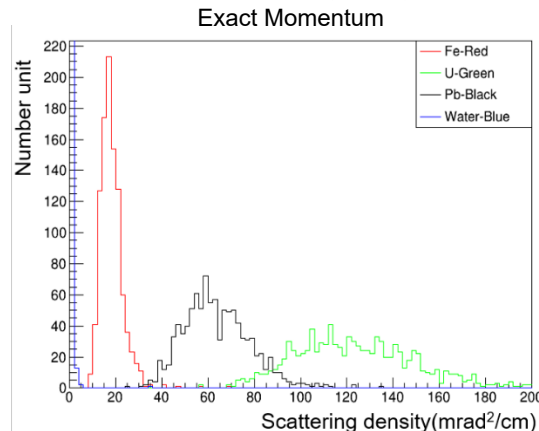
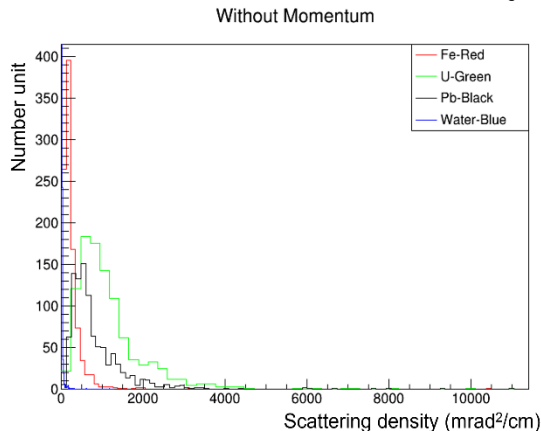
Cosmic Muon Spectrum



Identical to real cosmic muon spectrum

Bugaev/Reyna Model: $\Phi_B(p) = A_B p^{- (a_3 y^3 + a_2 y^2 + a_1 y + a_0)}$ $\Phi_R(p, \theta) = \cos^3(\theta) \Phi_B(p \cos \theta)$ $y = \log_{10} p$

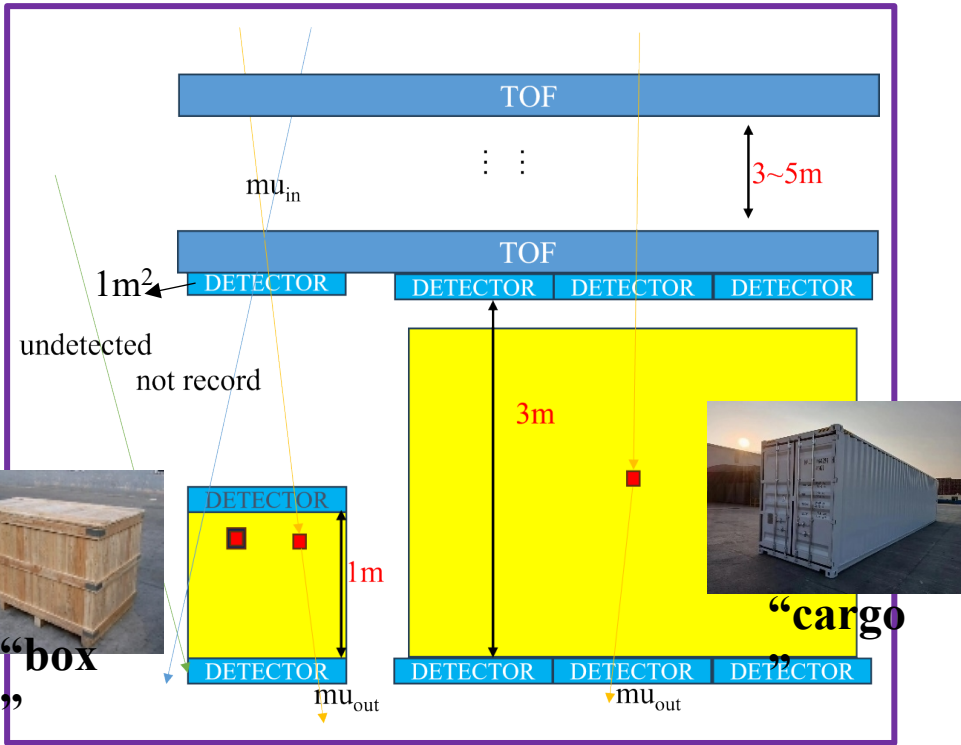
Discrimination ability of MRPC-ToF(3m) of 4 materials **60s exposure time**



Compared to the case without momentum, using an MRPC-TOF with a 3-meter spacing to obtain muon momentum can achieve better material discrimination ability.



Simulated Scenarios and relevant conditions based on GEANT4

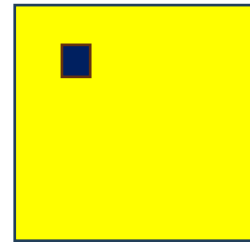
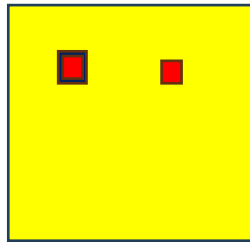


- ★ Sensitive area each detector: 1m^2
- ★ Volumes:
 - small volume: “box” model height: 1m
 - large volume: “cargo” model height: 2.6m
- ★ Filling materials(Background):
 - (“heavy” → up to weight limit)
 - Wood, Fe
- ★ Exposure time:
 - 30s, 45s, 60s, 120s(only for cargo)
 - (assuming flux: $10,000\text{ min}^{-1}\text{m}^{-2}$)
- ★ Materials inside volumes:
 - (All randomly placed)
 - U block (10cm cube) \longleftrightarrow comparison empty
 - U block shielded by Pb(1, 2, 5cm) \updownarrow comparison
 - Pb block(same size)

★ Geometrical acceptance(GA):
 3m length between 2 detectors → 18.8%
 1m length between 2 detectors → 45.2%



■ Classification Task



Unsafe case tagged “**true**”

Safe case tagged “**false**”

If U block **true**, then empty case **false**;

↕ *Never appear together*

If shielded U block **true**, then Pb block of equal size **false**.

What should a classifier(simulated MST) do:
confirm true cases are true; false cases are false.

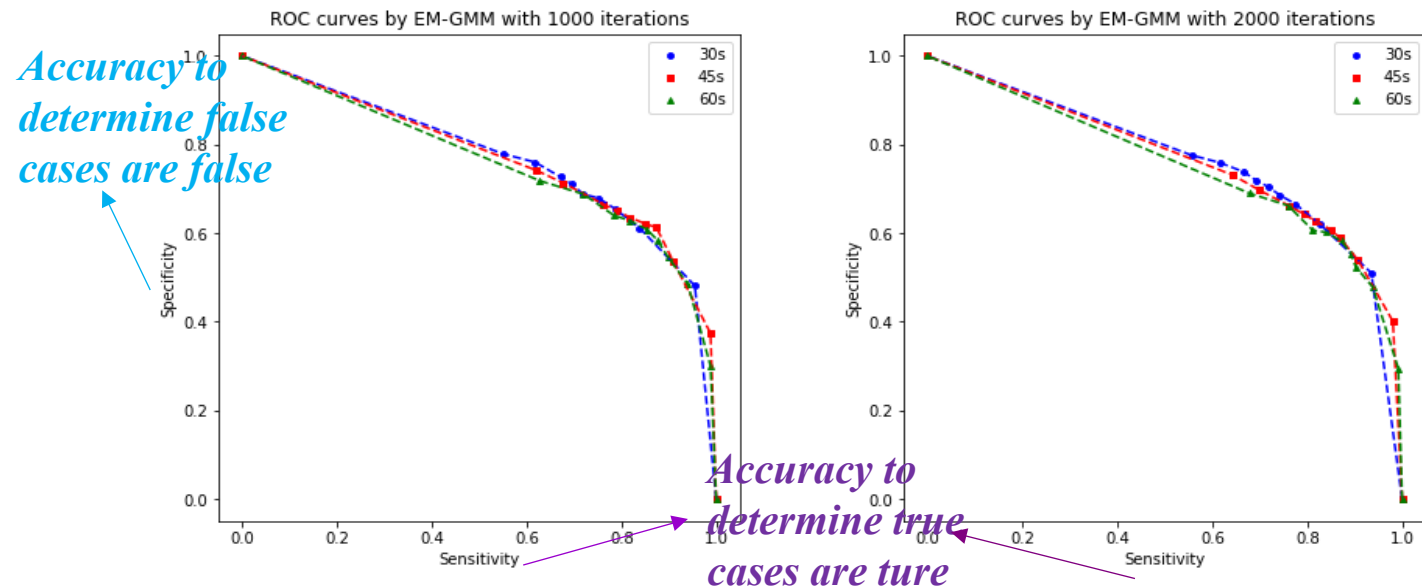


Data Analysis Methods:

- Unsupervised method: EM-GMM → prior data training not required
(Expectation Maximization of Gaussian Mixture Models)
- Supervised methods(next page)

ROC Curve Results of EM-GMM(exact momentum):

Why EM-GMM: Since the scattering angles of muon follow 1 Gaussian distribution after passing through 1 specific material. For mixed materials, the distribution of the muon's scattering angles will become a mixture of Gaussian distributions.



45.2% GA



Wood "box"

- U block (10cm cube) ↑ Scenario of each result will be shown on slides

No Significant difference can be observed.

Accuracy at optimal working point: ~73% → unsatisfactory

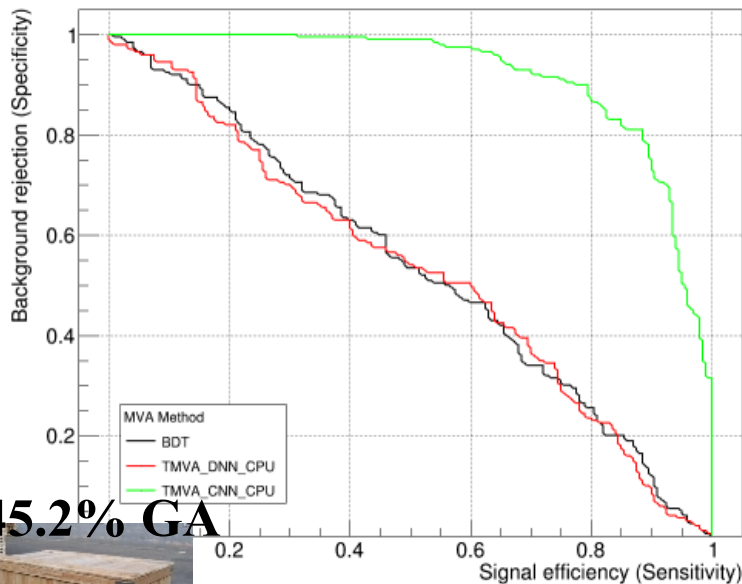
Supervised Methods:

- BDT(Boosted Decision Trees)
- DNN(Deep Neural Network)
- CNN(Convolution Neural Network)

⇒ ROOT TMVA toolkit

30s exposure with exact momentum:

Signal efficiency vs. Background rejection

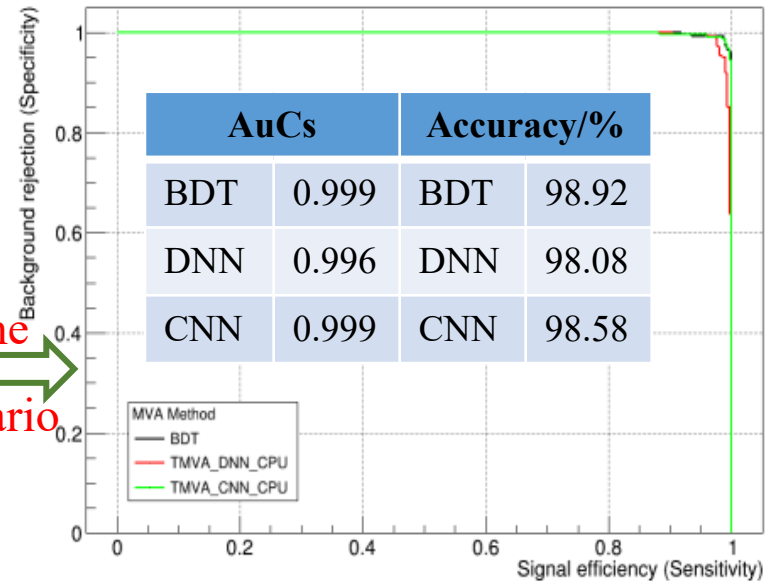


45.2% GA



Wood
4U block (10cm
cube)

Signal efficiency vs. Background rejection



Same Scenario

Raw Data Enhancement



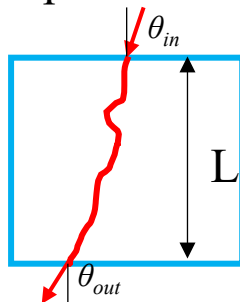
Not good

Much Better



■ Data Enhancement:

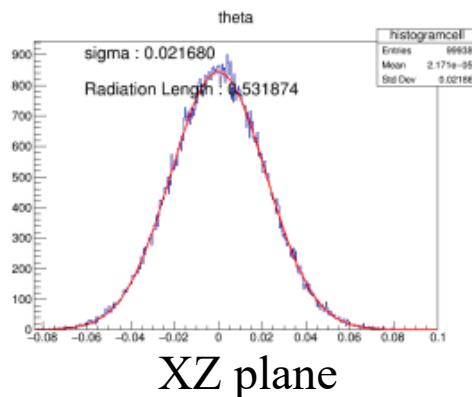
- Length correction: Muon's path is always longer than material's thickness.



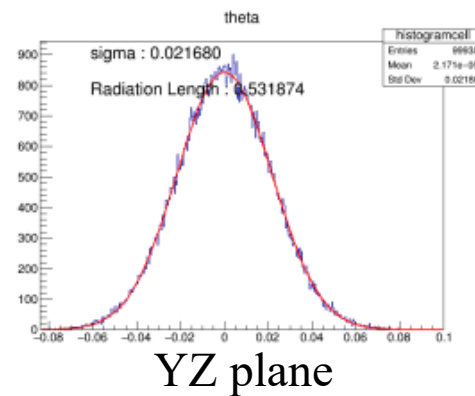
$$\sigma_{\theta} = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{\frac{L}{L_0}} \left[1 + 0.038 \ln \left(\frac{L}{L_0} \right) \right]$$

$$L_{\text{pass}} \approx L / \cos \theta_{\text{in}}$$

- 2-D Combination: Muon scattering angle's distribution on both planes follows Gaussian distribution. 2D's information is more sufficient.



+



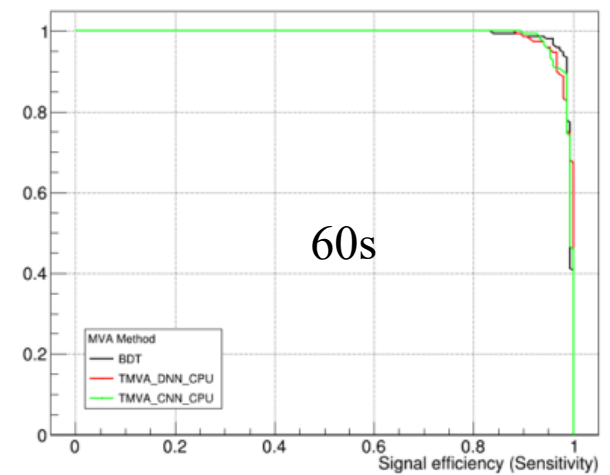
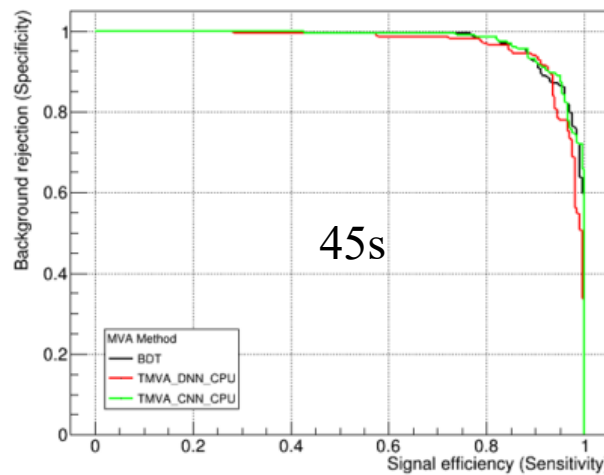
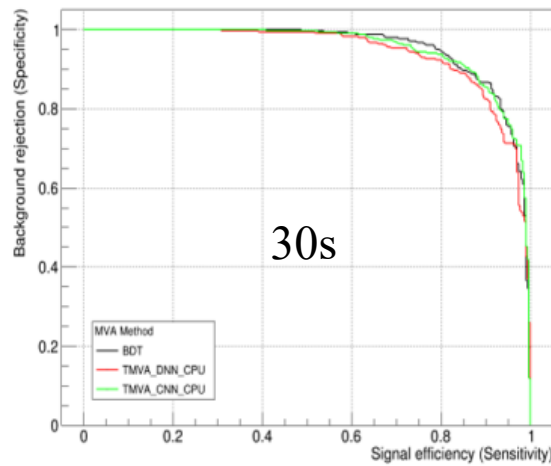
- Angle weight(Dimensionality reduction): angles which count more got bigger weights **11**

ROC Curves of MRPC-TOF:

Signal efficiency vs. Background rejection

Signal efficiency vs. Background rejection

Signal efficiency vs. Background rejection



Same data under **3m MRPC-TOF momentum** uncertainty can achieve relatively good results

45.2% GA



Wood "box"

■ U block (10cm cube)

AuCs		Method		
		BDT	CNN	DNN
time/s	30	0.956	0.954	0.944
	45	0.976	0.978	0.967
	60	0.992	0.991	0.991

Accuracy/%		Method		
		BDT	CNN	DNN
time/s	30	88.58	89.08	86.08
	45	91.5	92.75	91
	60	96.75	96.08	94.58

For boxes similar to the model, the accuracy of detecting a 10cm length U-block within **45s** can reach **92%**.
If the time is extended to **60s**, it can reach **96%**.

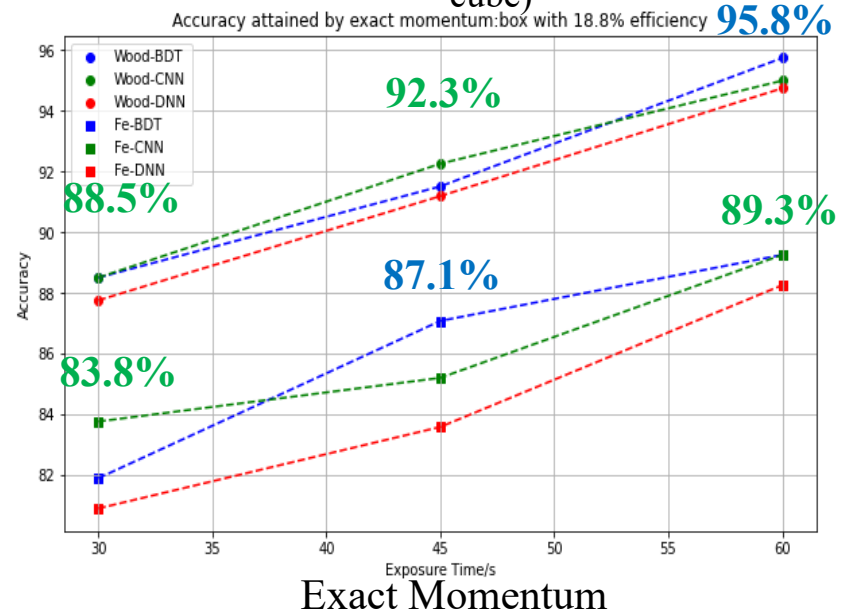
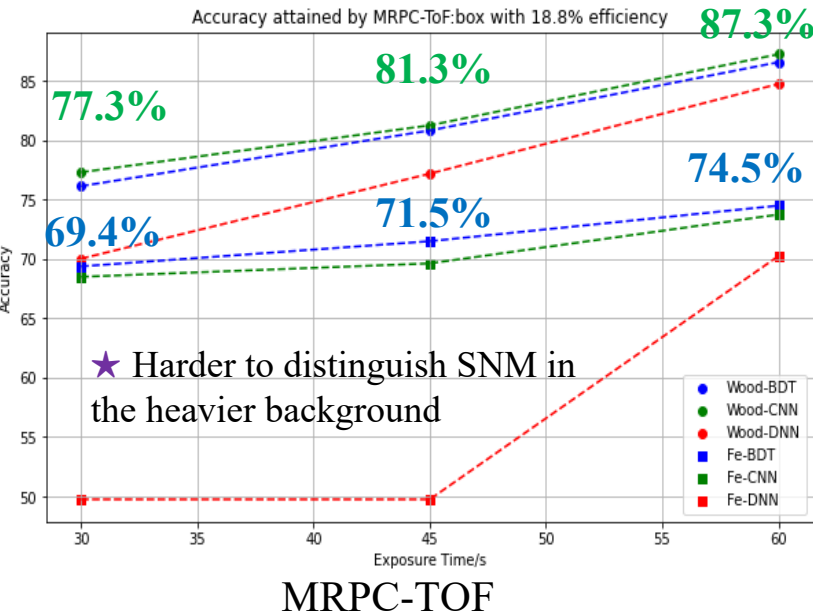
18.8% GA



Results of MRPC-TOF with smaller GA:

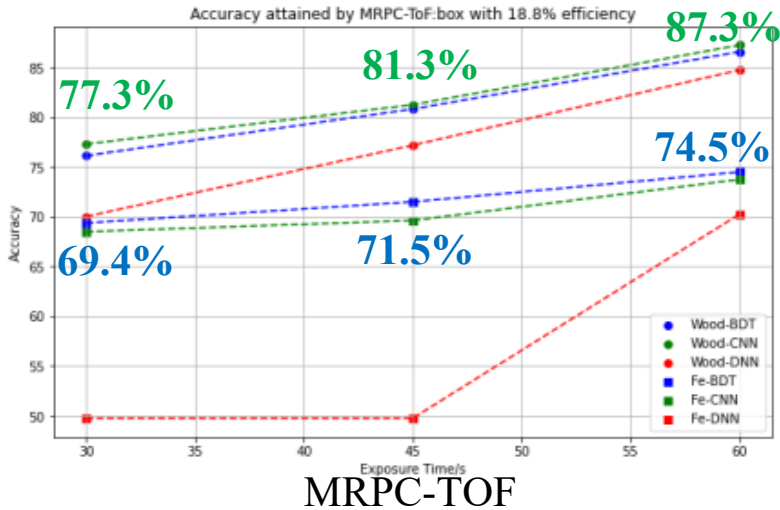
Geometrical acceptance 18.8% (30s,45s,60s) :

All annotated numbers represent the best results of the three classifiers. ■ U block (10cm cube)



The more difficult the simulated scenario, the greater the loss on accuracy caused by the momentum information, further highlighting the importance of momentum in MST.

■ “box” model with 2 geometrical acceptance
Geometrical acceptance 18.8% (30s,45s,60s) :



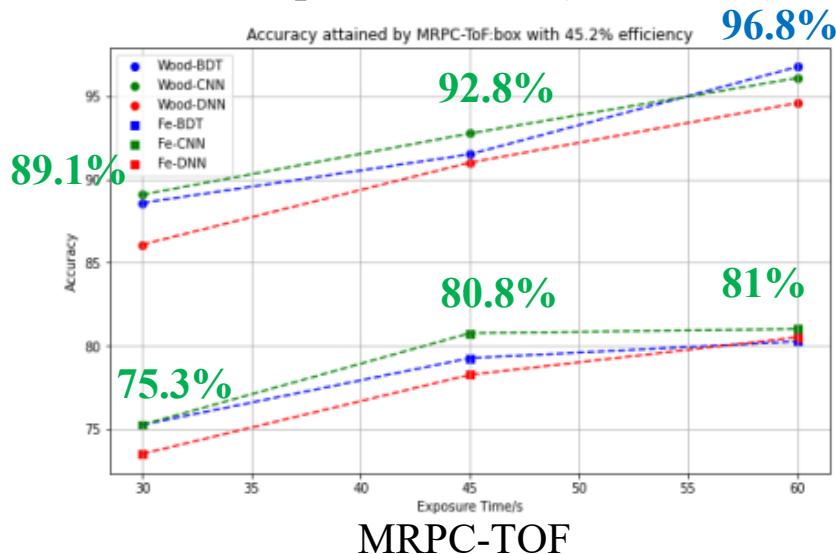
“box”

■ U block (10cm cube)

★ Geometrical Acceptance greatly influences the accuracy.

OBVIOUS!

■ Geometrical acceptance 45.2% (30s,45s,60s) :



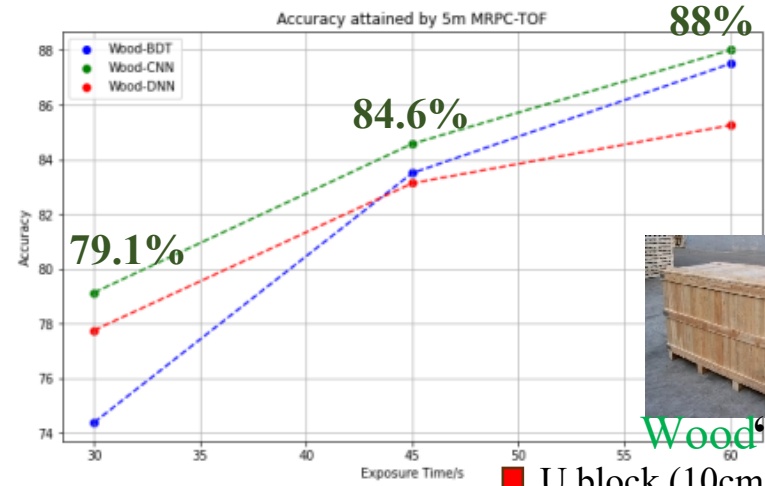
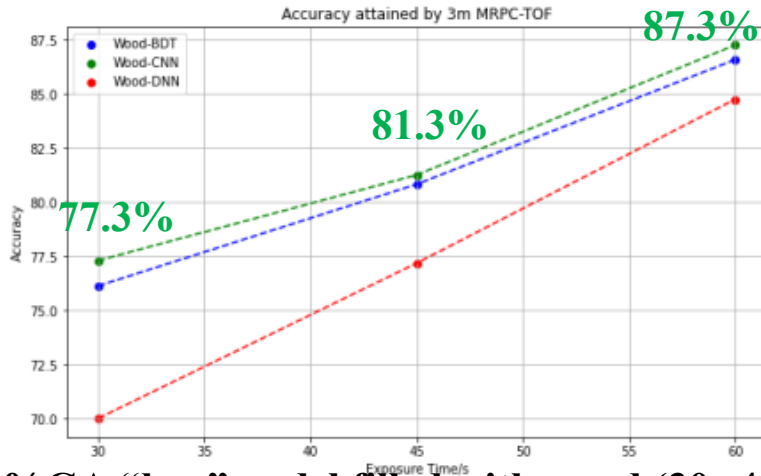
But not conflict with the exposure time:

1. It is more closely related to hardware
2. The geometrical acceptance increase the muon amount by increasing the solid angle.
3. Muons with bigger incident angles can be captured.



3m TOF → 5m TOF

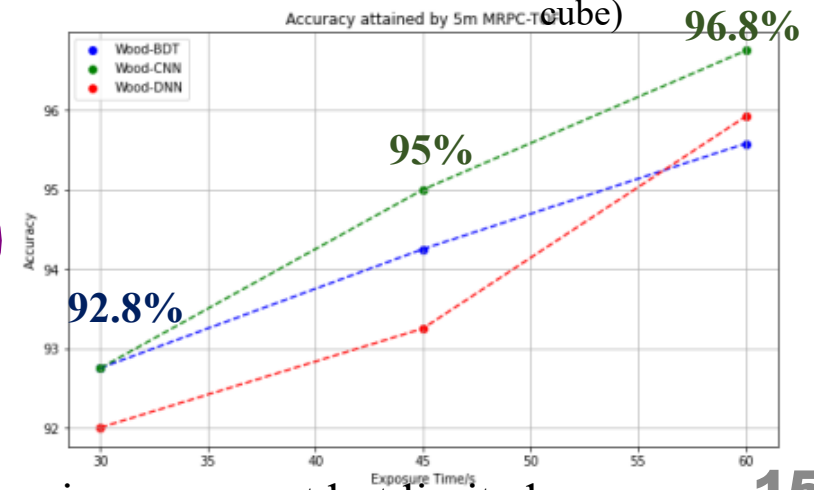
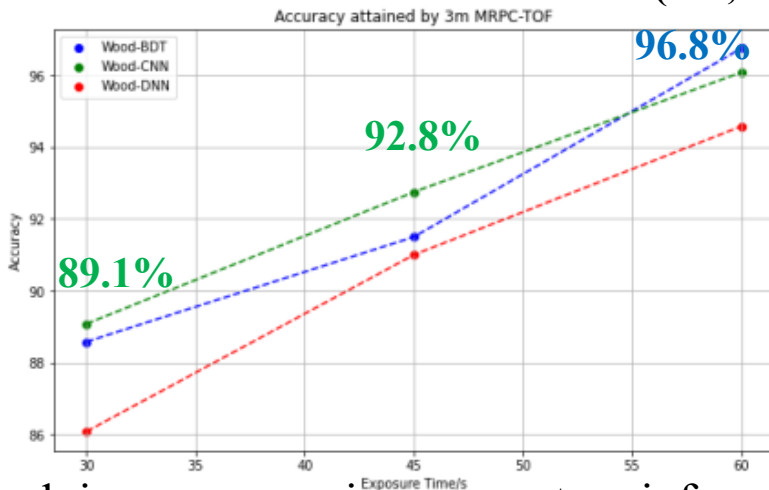
18.8%GA “box” model filled with wood(30s,45s,60s):



Wood “box”

■ U block (10cm cube)

45.2%GA “box” model filled with wood (30s,45s,60s) :

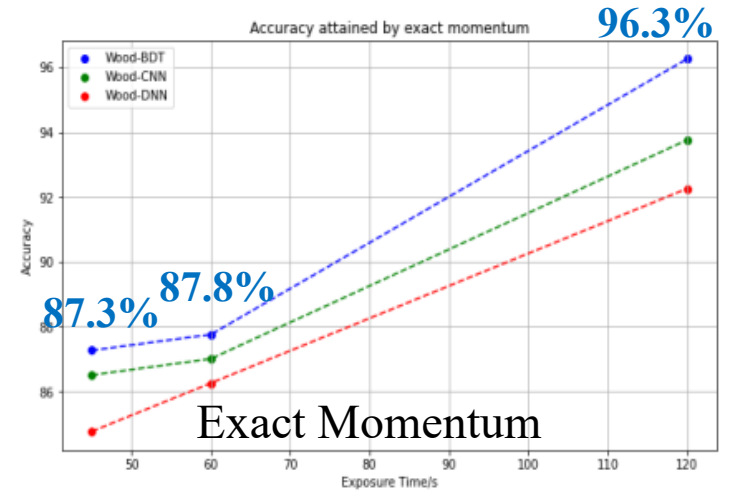
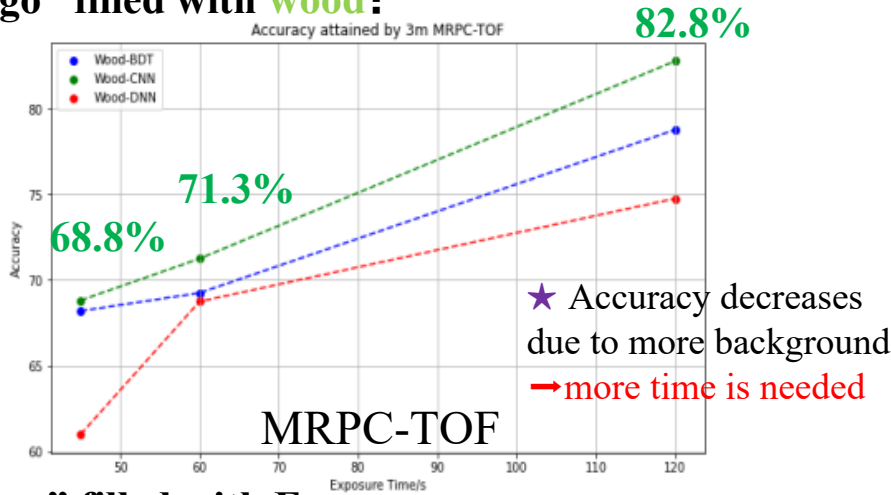


Applying more precise momentum information brings improvement but limited.



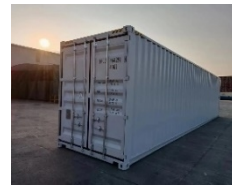
Results of Supervised Methods: "cargo" model(45s,60s,120s)

"cargo" filled with wood:



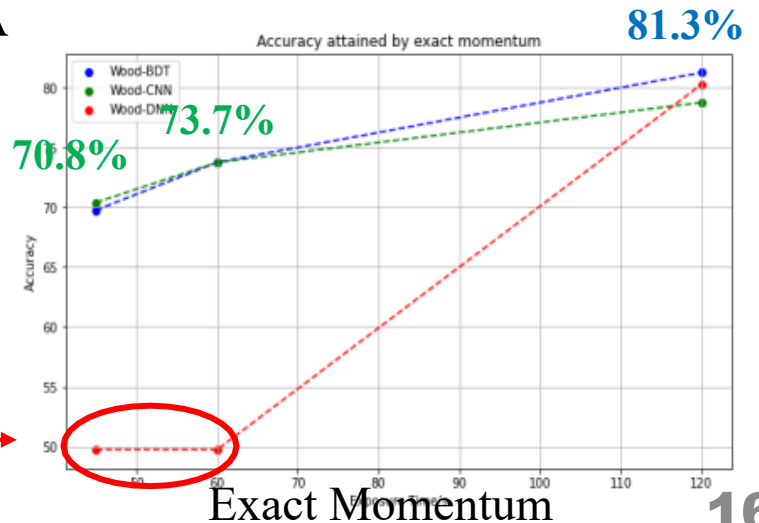
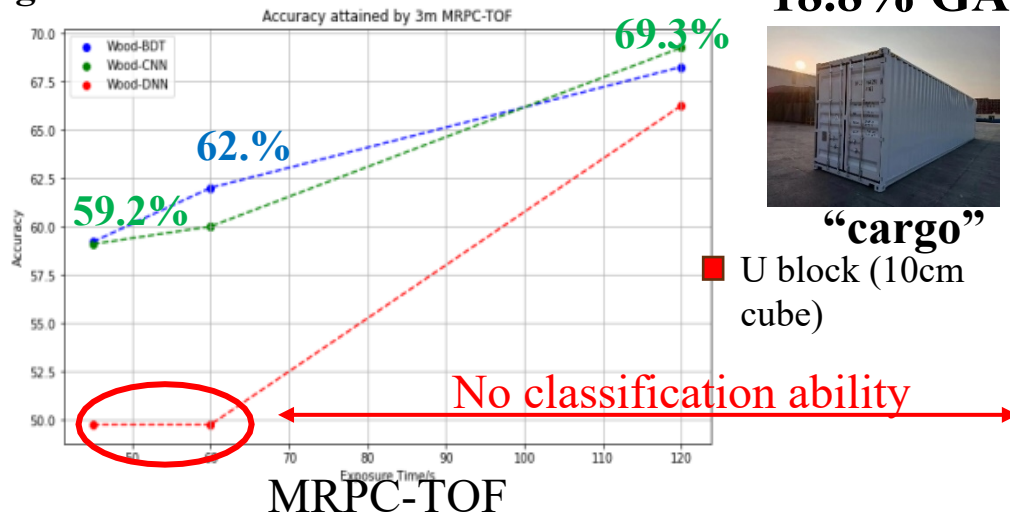
"cargo" filled with Fe:

18.8% GA



"cargo"

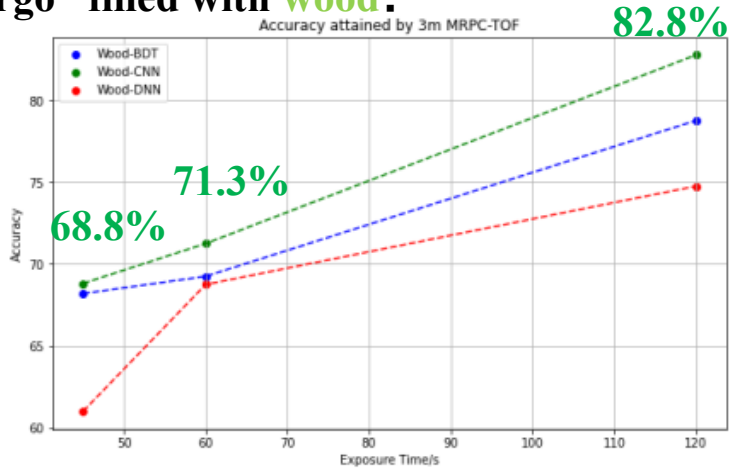
■ U block (10cm cube)





Results of Supervised Methods: "cargo" model 3m TOF → 5m TOF (45s, 60s, 120s)

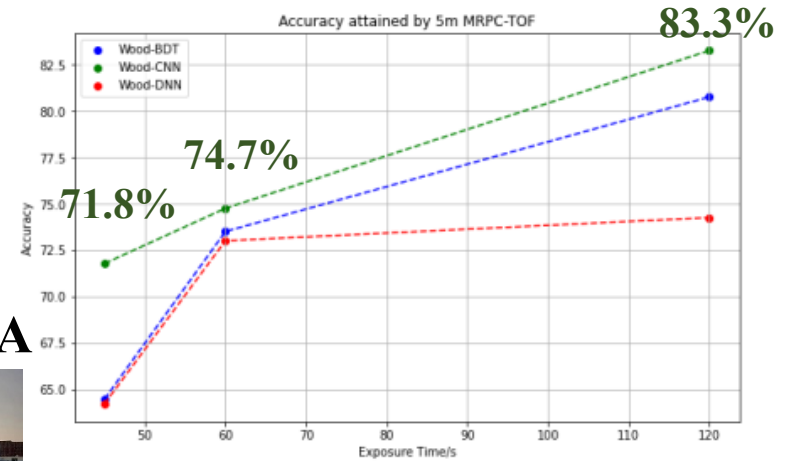
"cargo" filled with **wood**:



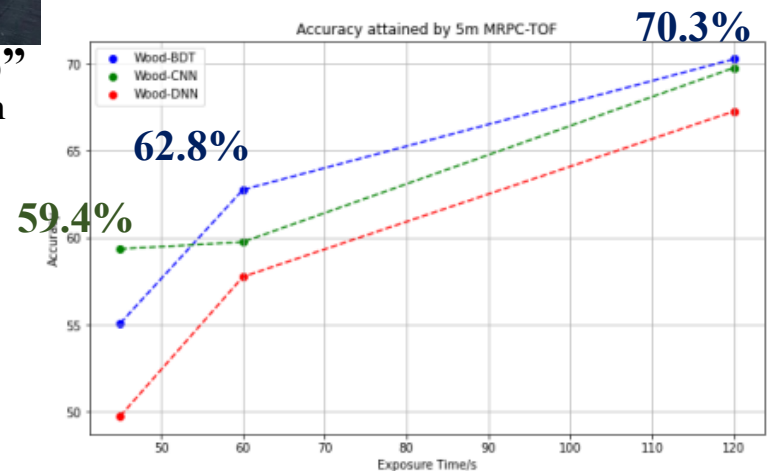
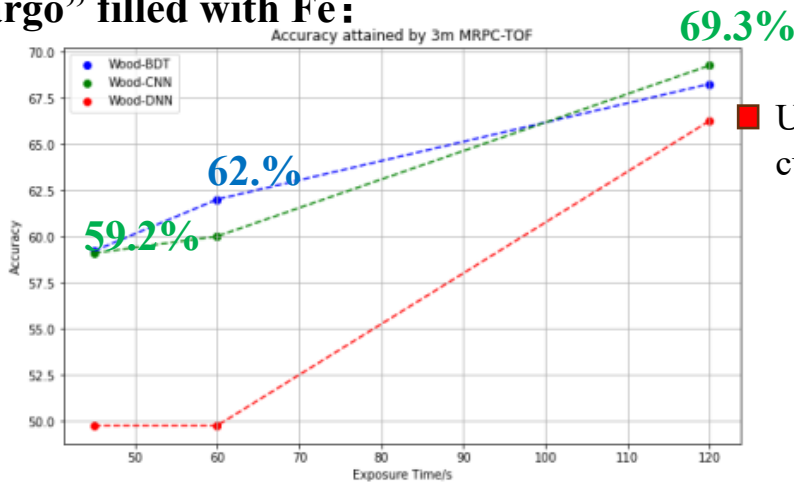
18.8% GA



"cargo"
U block (10cm cube)



"cargo" filled with **Fe**:



Also seemed limited

Shielded condition (30, 45, 60s)

45.2% GA

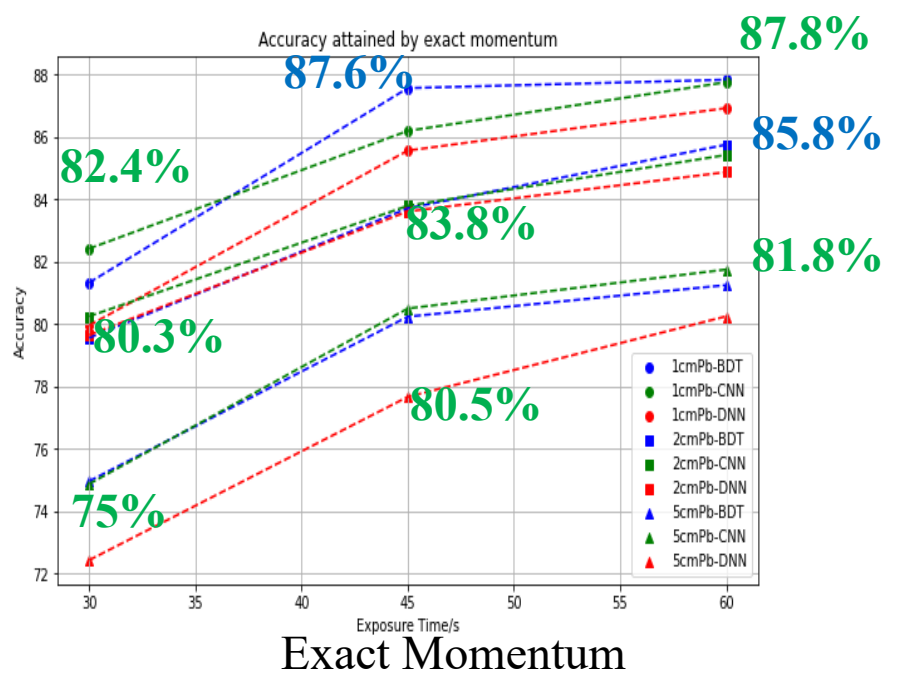
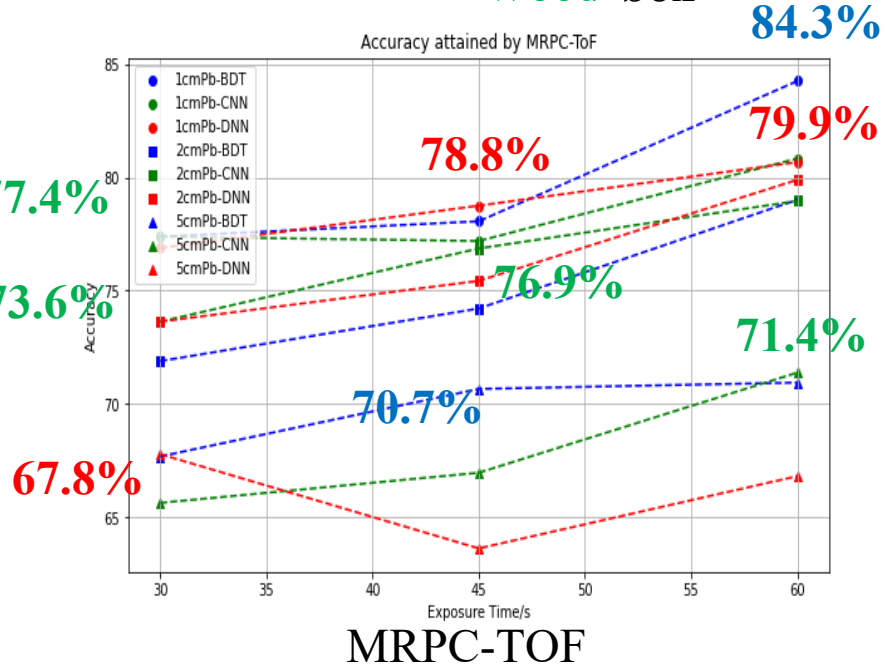
Shielded in "box":



Wood "box"

Pb block

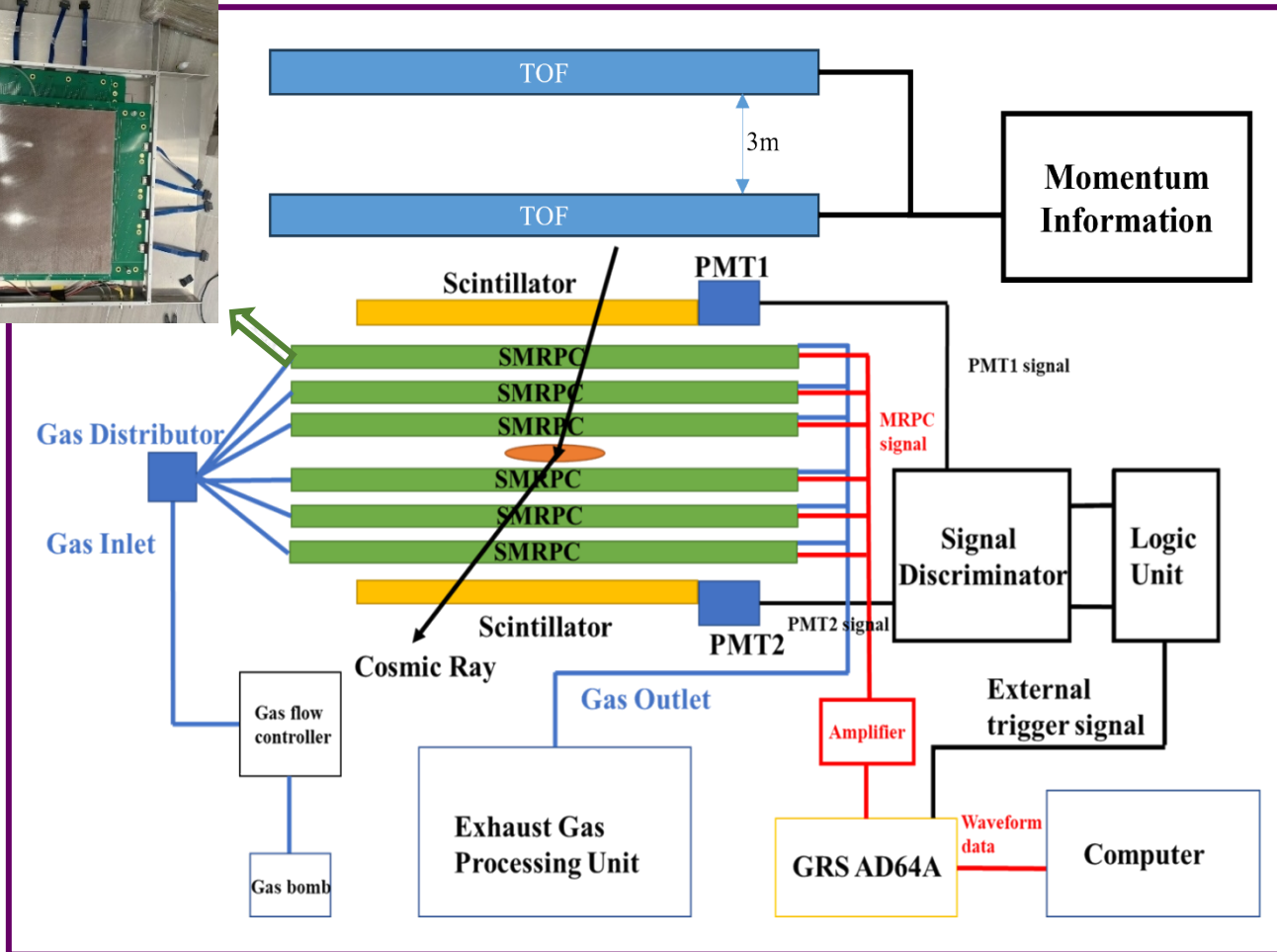
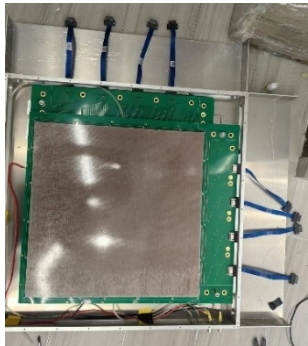
U block shielded by Pb (1cm, 2cm, 5cm)



The results are still not bad within a short period of exposure, indicating that MRPC-ToF has the potential to detect some hidden materials



◆ Combine TOF with our MST → experimental work



Performance Indicators:

Sensitive area: 50cm×50cm

Readout channels: 384

Position resolution: 0.8mm

SMRPC: 6



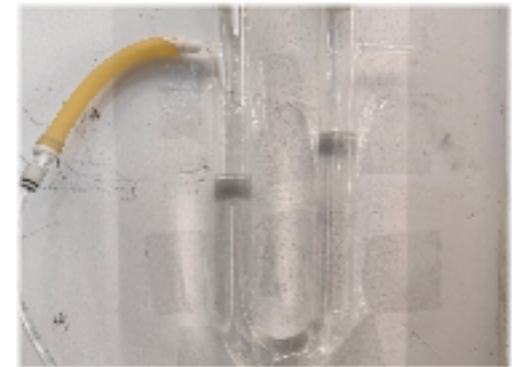
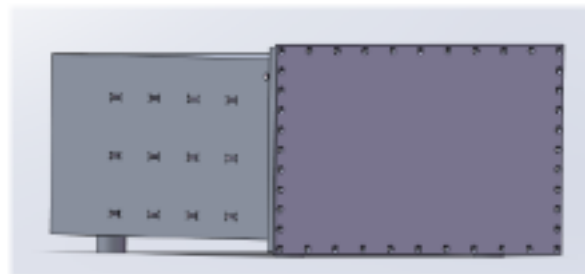
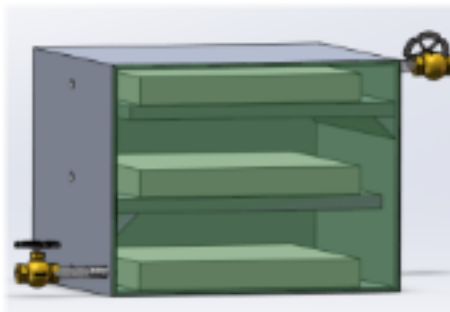
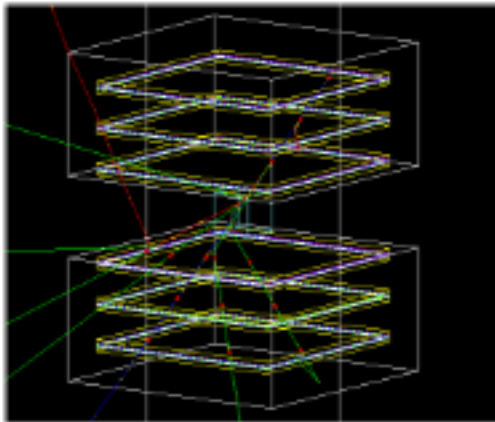
◆ **Combine TOF with our MST → experimental work**



Performance Indicators:
Sensitive area: 50cm×50cm
Readout channels: 384
Position resolution: 0.8mm
SMRPC: 6



◆ Gas Tight MRPC Module



Simple gas tightness test



◆ TOF-MRPC definitely improves the quality of MST

- For small containers, maintaining a relatively low geometrical acceptance for muons with TOF-MRPC momentum estimate, it is possible to achieve a detection accuracy of over **90%** within **45s**. For bigger cargos, over **80%** within **2 min**.
- Applying MRPC-ToF to MST for momentum measurement is highly realistic. For better MST, momentum information is indispensable.
- 3m-TOF is enough, for the case of a small number of muon events, improving the accuracy of momentum measurements has limited benefits.
- If hardware condition allows, improving geometrical acceptance is very beneficial.

CNN and BDT are highly recommended choices for data analysis!



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Thanks For Your Attention!

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Geometrical acceptance 45.2% (30s,45s,60s) :

45.2% GA



“box”

■ U block (10cm cube)

