Machine Learning BSM Searches at the Fermilab SBN Program

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The Higgs Portal – *The Model*

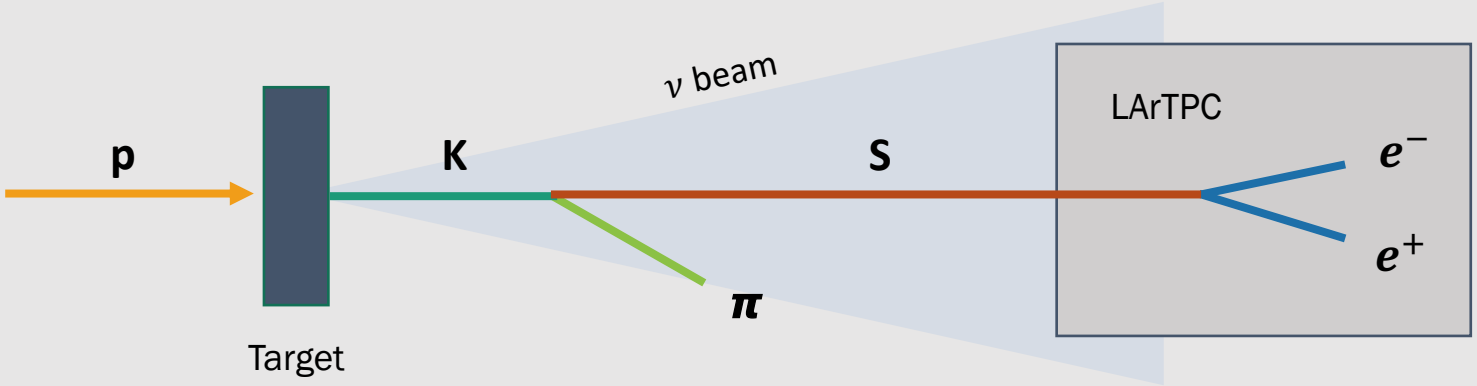
- S mixes with the Higgs boson, and provides an avenue by which Dark Matter can couple to the SM
- Two parameters: m_S, θ_S
- Production: $K \rightarrow \pi S$
- Decay: $S \rightarrow e^- e^+, \mu^- \mu^+, \pi^- \pi^+$

The Higgs Portal – *Sensitivity at Fermilab SBN Program*

Conveniently…

- Neutrino beams produce many kaons, &
- The excellent particle identification abilities of Liquid Argon Time Projection Chambers (LArTPC's) make distinguishing these rare signal events from background feasible

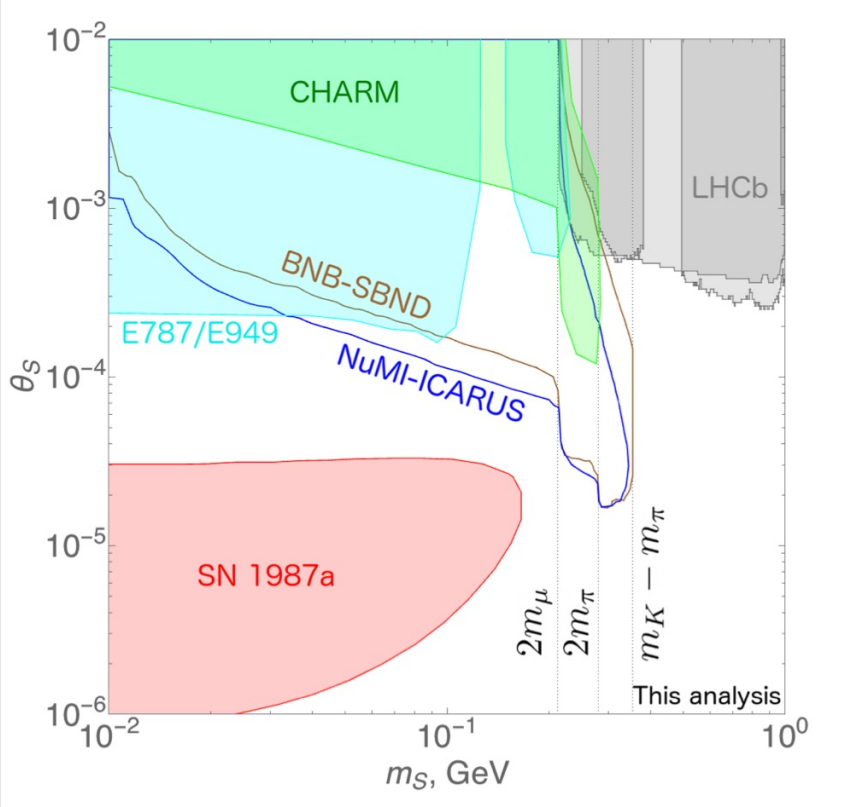
→ The Higgs Portal Model is testable at current and near-term neutrino experiments!



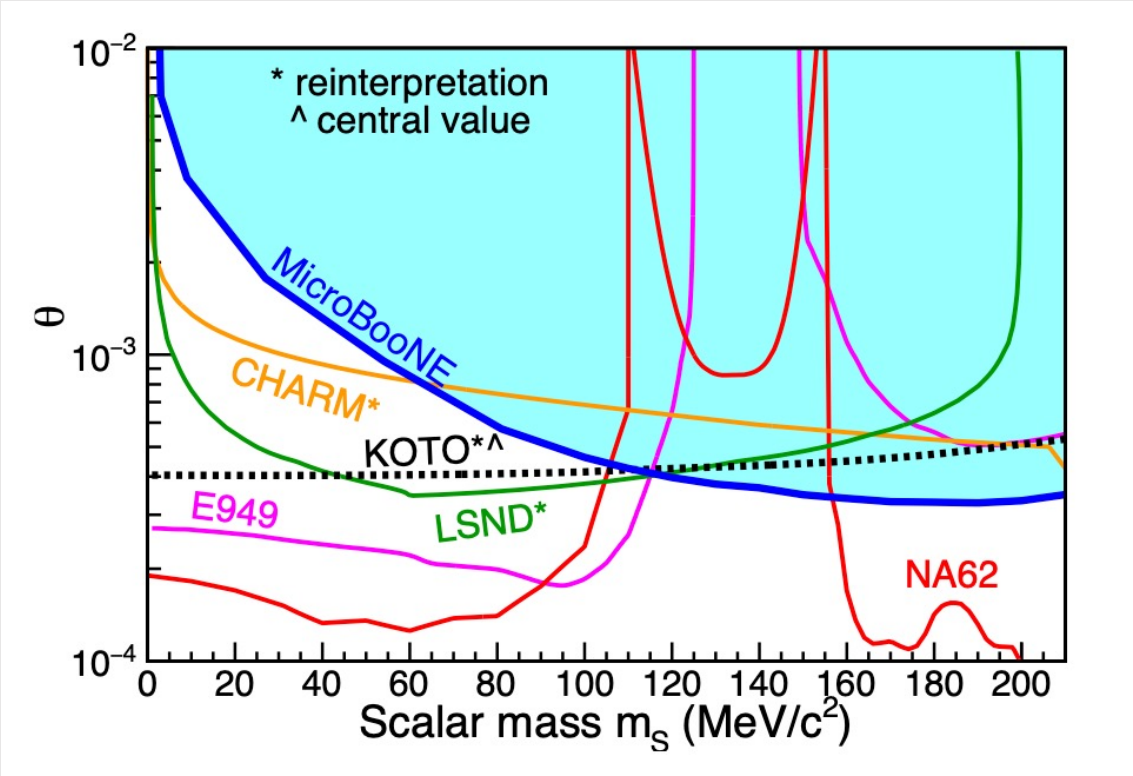
The Higgs Portal – *Sensitivity at Fermilab SBN Program*

Batell, Berger, Ismail (2019)
arXiv:1909.11670

- 2σ sensitivity to 5 signal events $m_S = \mathcal{O}(100\ \mathrm{MeV})$ demonstrated for ICARUS detector with w/ NuMI beam



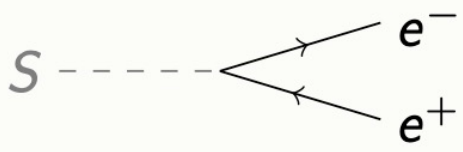
The Higgs Portal –
The Search is Happening Now!



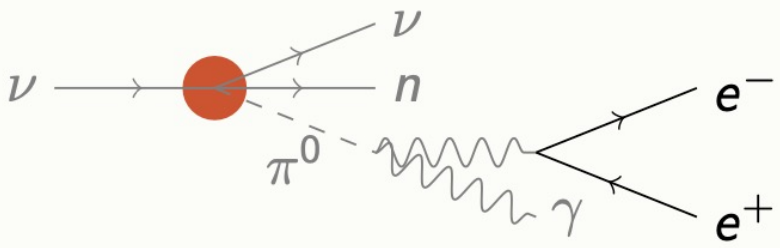
Microboone Collaboration (2021)
arXiv:2106.00568

The Higgs Portal – *Background*

Signal



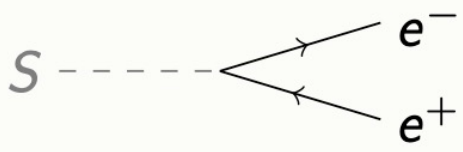
Background



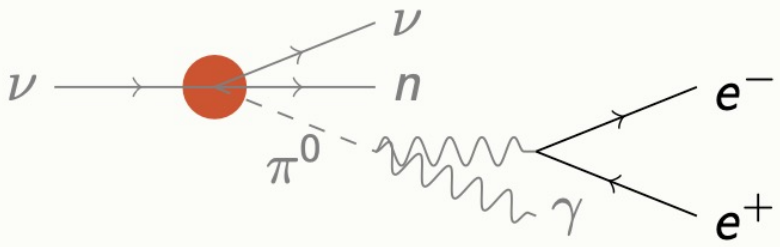
- The lighter the scalar, the more columnated the shower pair and the more it resembles shower conversion.

The Higgs Portal – *Background*

Signal



Background



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Can machine learning be leveraged to discern signal from background?

This Work

Compare sensitivity to Higgs Portal Scalar using traditional cut-and-count analysis vs. convolutional neural network (CNN).

Simulation

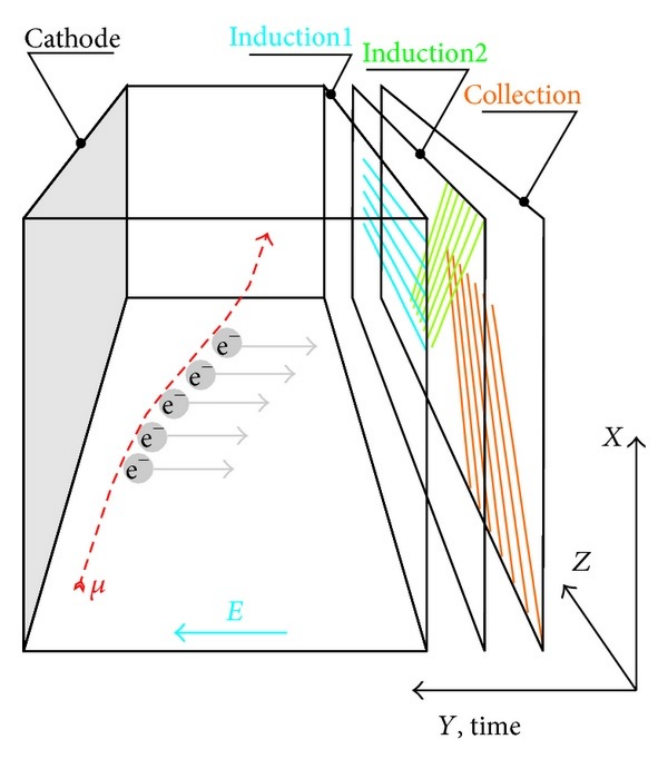
1) Generate 4-momenta
   - Signal: find kaon parents from g4numi ν events, decay to S, propagate to detector, decay to e^+/e^-.
   - Background: 3-5 GeV ν_e events w/ GENIE w/ similar topology to signal

2) Run kinematic variables through Geant4 configured for ^{40}Ar. Save non-zero energy deposits

3) Convert to charge & project onto LArTPC wire planes:

$$Q_{dep} \approx E_{dep}/W_{ion}$$

$$Q_{det} \approx Q_{dep}\frac{A}{1 + k(dE/dx)/|E_{drift}|}$$

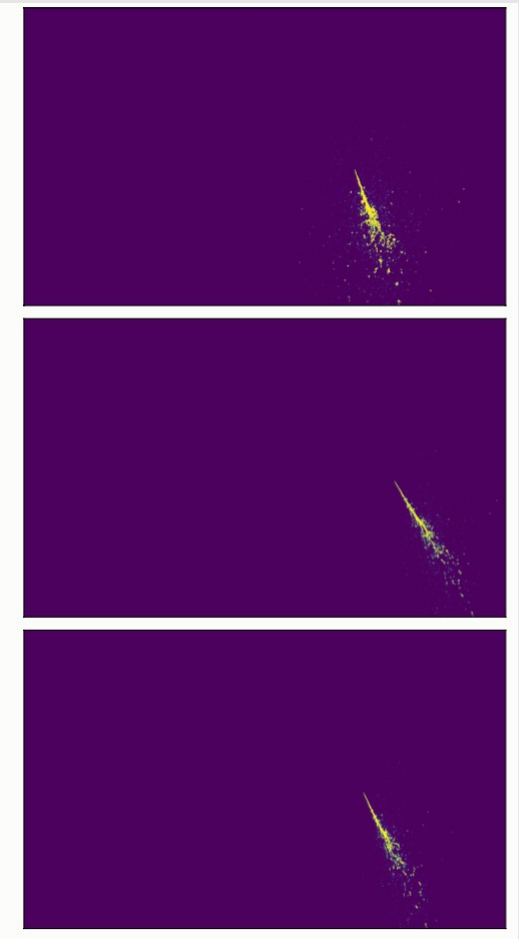


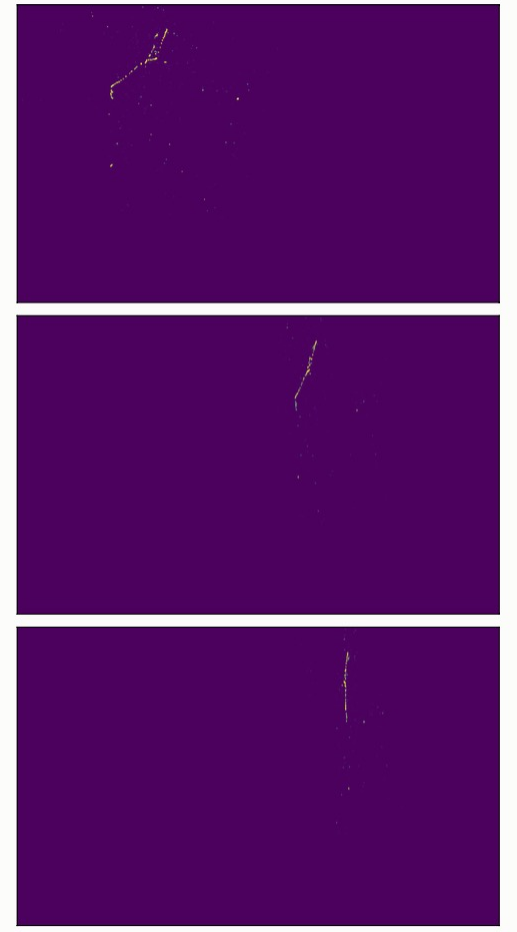
ICARUS LArTPC Schematic.
Antonello et. al. (2013)
https://doi.org/10.1155/2013/260820

Example Events

Signal

Background





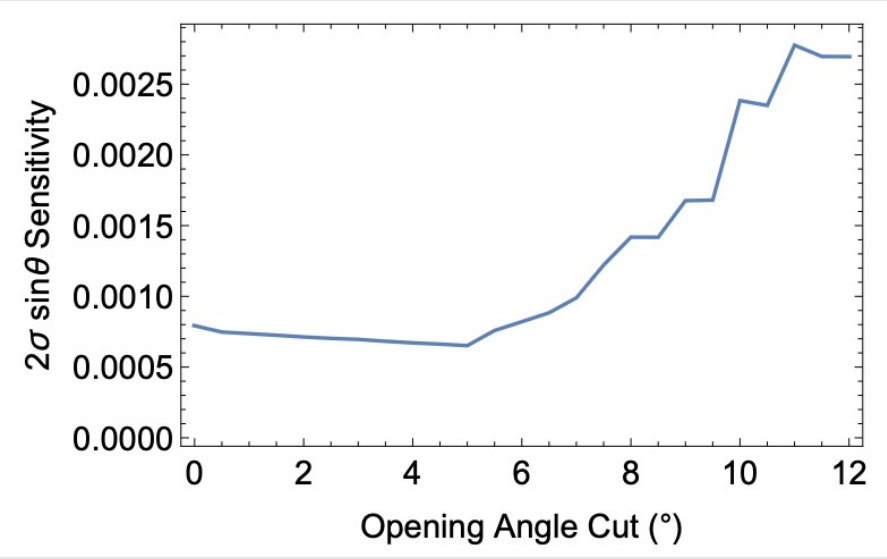
Advantages of this simulation pipeline:

- Much faster than a full detector simulation
- More detailed than GENIE or BSM generator four-vectors

Cut and Count Analysis

- Determine the efficiency and background rejection of opening angle cut as function of choice of angle
- Minimize $sin\theta$ for 2σ using

$$Z \sim \frac{signal}{\sqrt{background}} \sim (efficiency) * (\sin^4 \theta) * \sqrt{rejection}$$

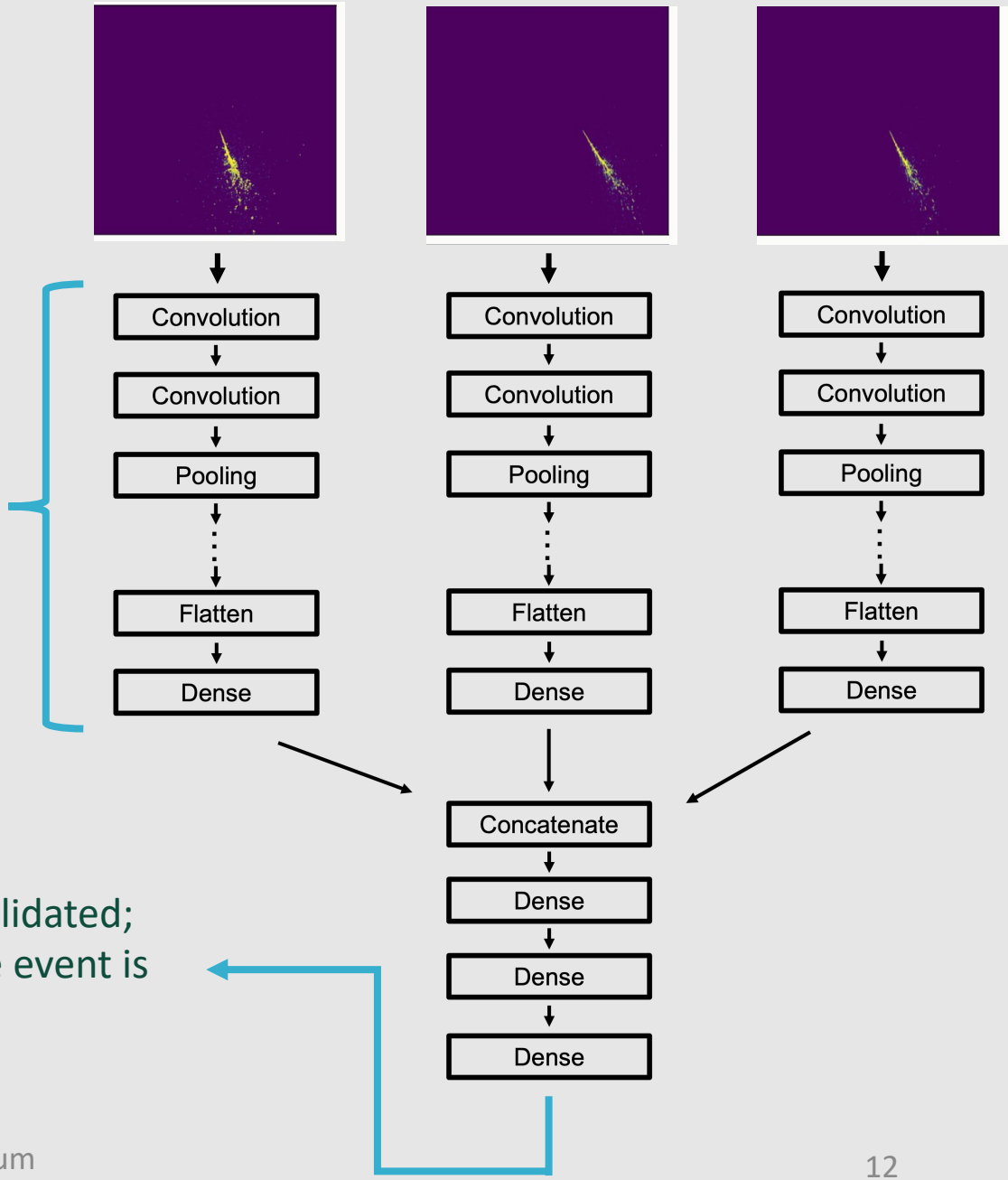


The CNN

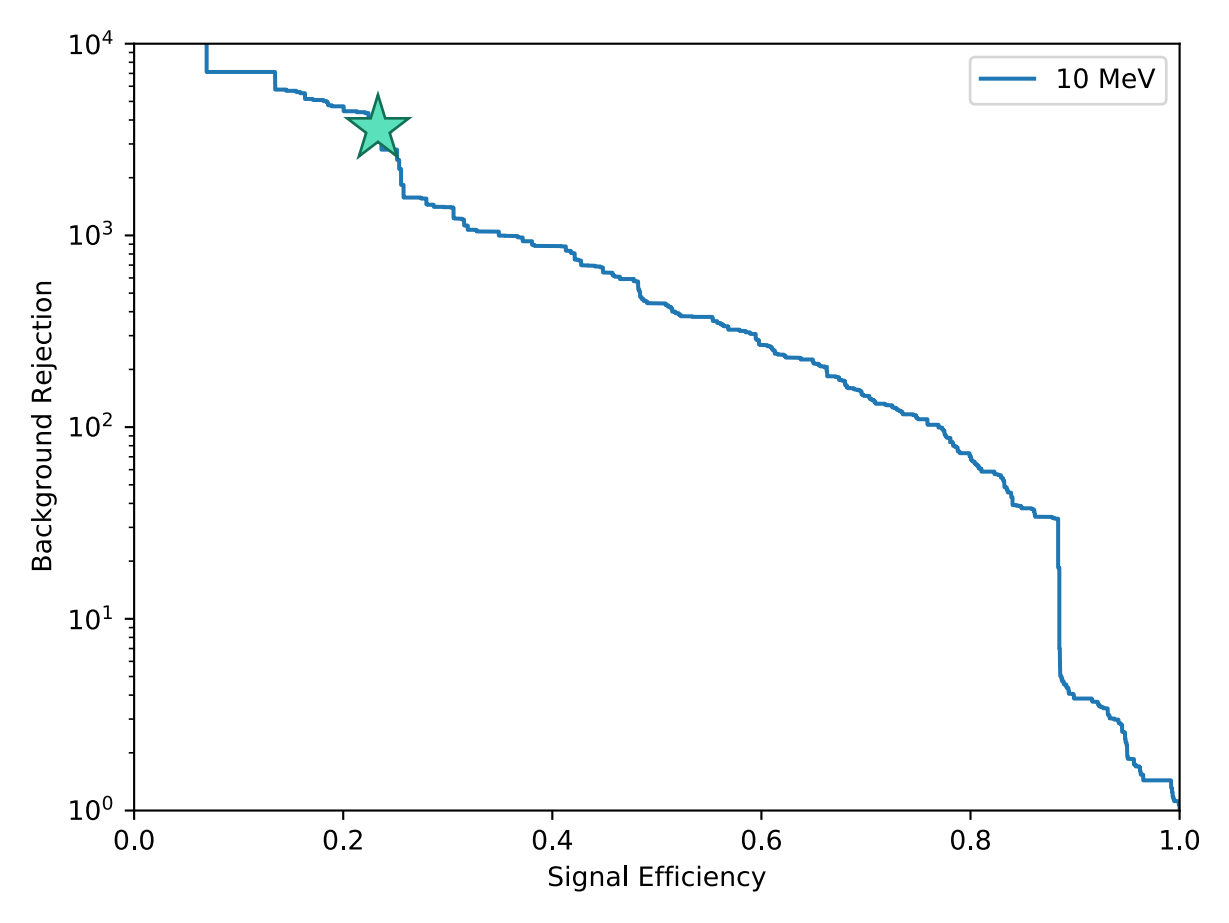
Wire plane images first evaluated with separate branches of CNN

Network finds correlations between spacially-distant pixels vias convolution and pooling steps

Info from wire planes is consolidated; score for how “signal-like” the event is is generated.



CNN Background Rejection vs. Efficiency



Results

Analysis	Limit on sinθ for 10 MeV S
Cut-based	$8.1 * 10^{-4}$
CNN	$5.48 * 10^{-4}$

- Modest improvement for sinθ
- Event rate $\propto \sin^4\theta$
- Significant improvement in the rate

Takeaways & Outlook

- Argon-configured Geant4 simulation provides efficient and detailed simulation pipeline accessible to theorists.

- Described simulation + machine learning techniques can be used to improve sensitity to BSM models within LArTPCs at current and near-term experiments.