Phenomenological Demonstration of

Convolutional Neural Networks in BSM Physics Search w/ LArTPCs

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New Perspectives 2022
FERMILAB-SLIDES-22-056-V

The Higgs Portal – *The Model*

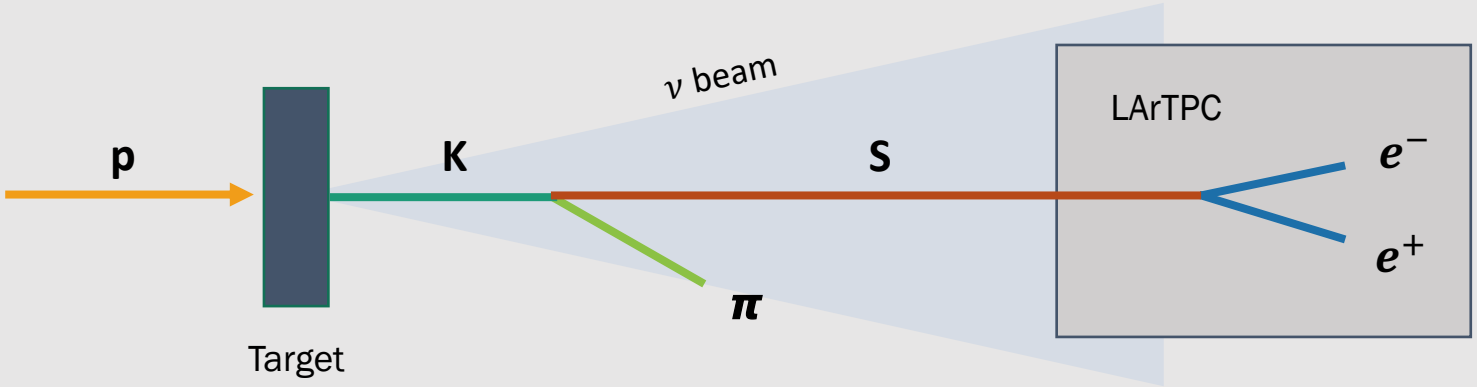
- S mixes with the Higgs boson, and provides an avenue by which Dark Matter can couple to the SM
- Two parameters: m_S, θ_S
- Primary production mode: $K \to \pi S$
- Decay: $S \to e^- e^+, \mu^- \mu^+, \pi^- \pi^+$

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

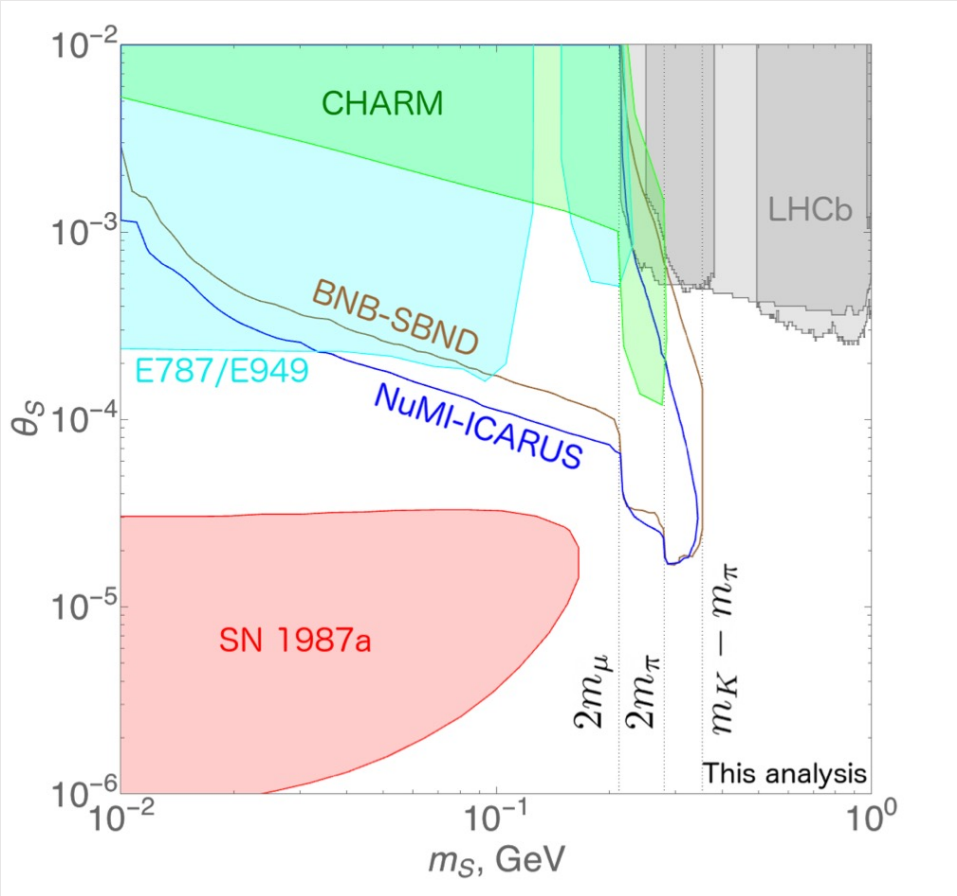
→ The Higgs Portal Model is testable at current and near-term neutrino experiments!



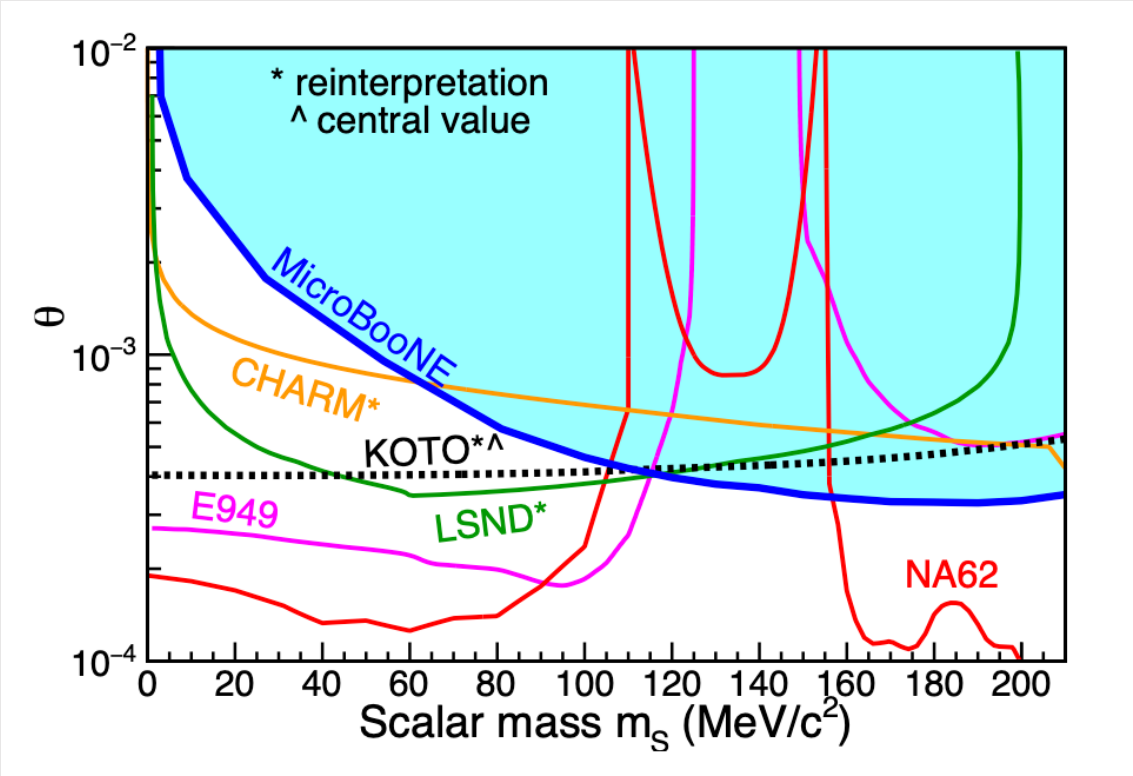
The Higgs Portal – *Sensitivity at Fermilab SBN Program*

Batell, Berger, Ismail (2019)
arXiv:1909.11670

- Projected 2σ sensitivity to 5 signal events $m_S = \mathcal{O}(100\ \mathrm{MeV})$ demonstrated for ICARUS detector with w/ NuMI beam over 5 years of operation (~$3 * 10^{21}$ POT)

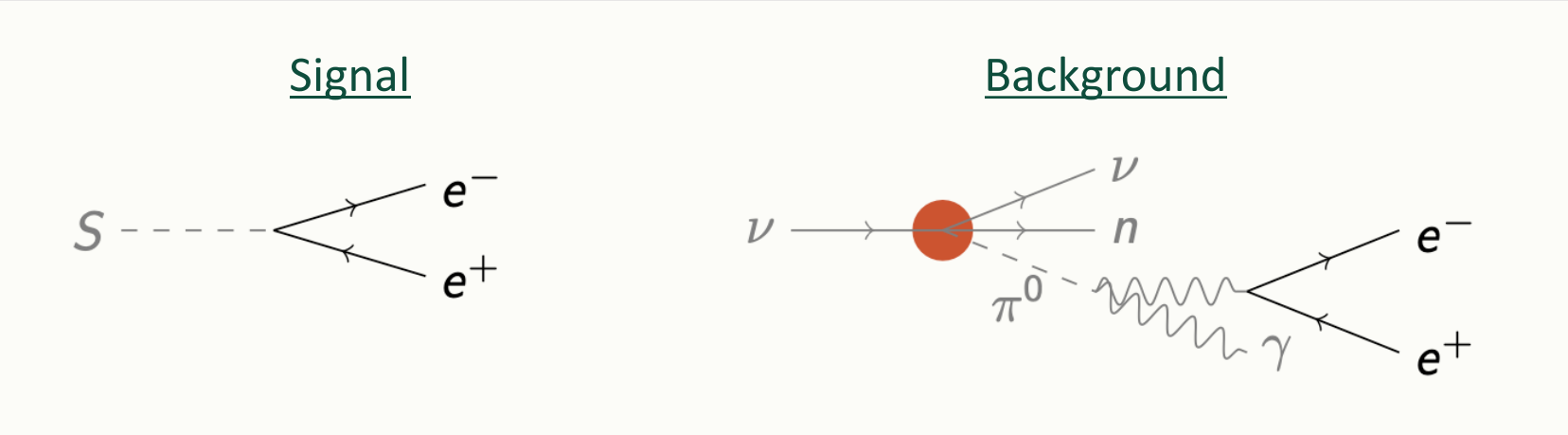


The Higgs Portal –
The Search is Happening Now!



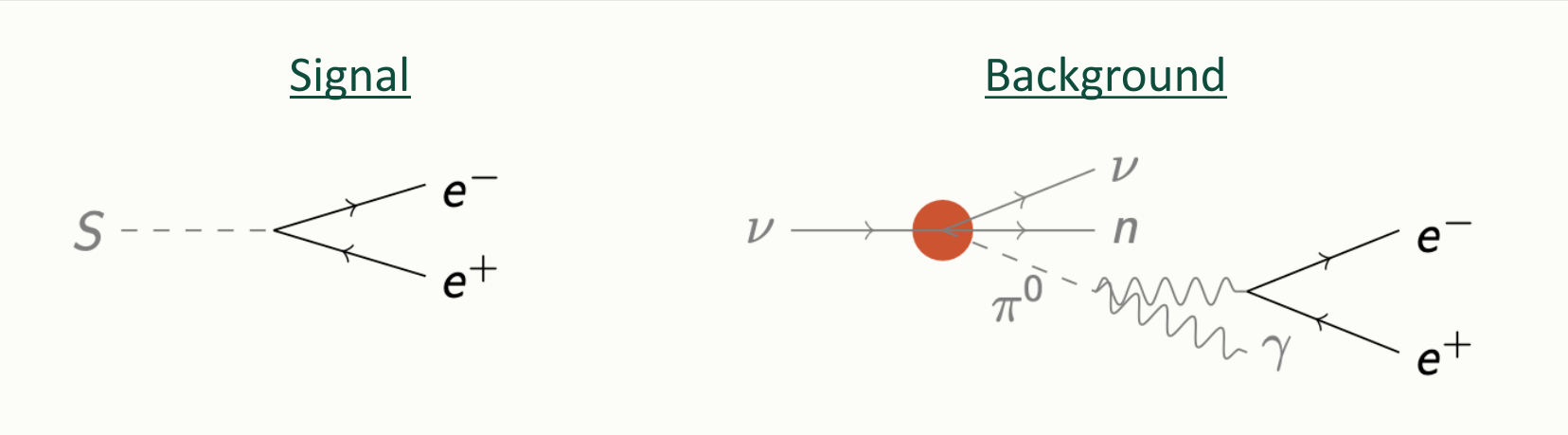
Microboone Collaboration (2021)
arXiv:2106.00568

The Higgs Portal – *Background*



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

The Higgs Portal – *Background*



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Can machine learning be leveraged to discern signal from background?

This Work

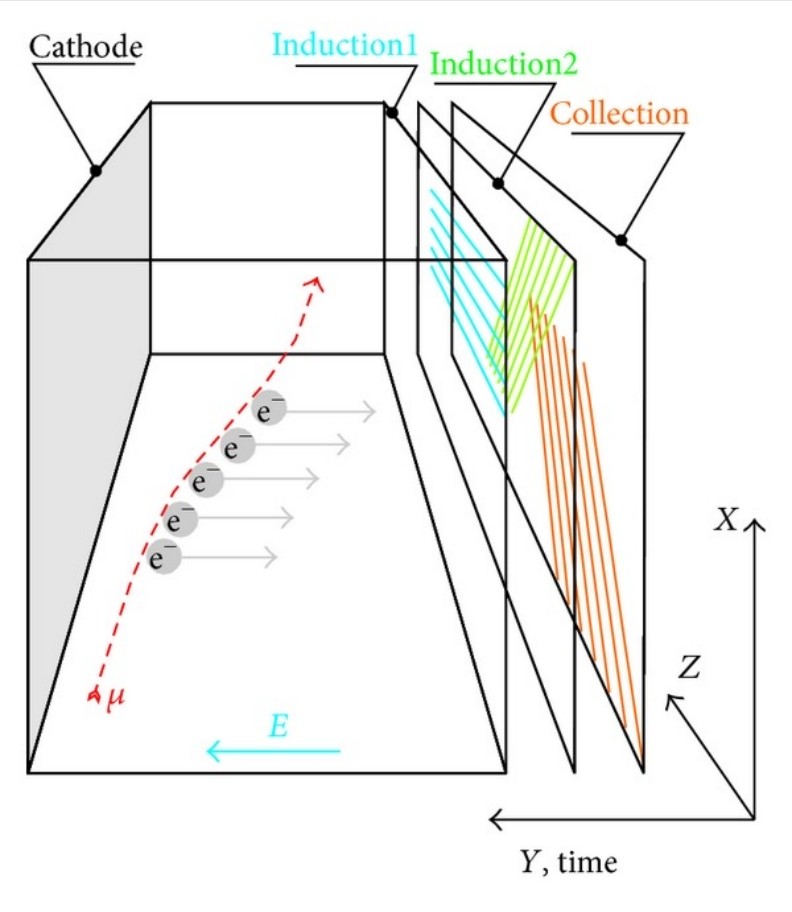
Compare sensitivity to 10 MeV Higgs Portal Scalar using traditional cut-and-count analysis vs. convolutional neural network (CNN).

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:

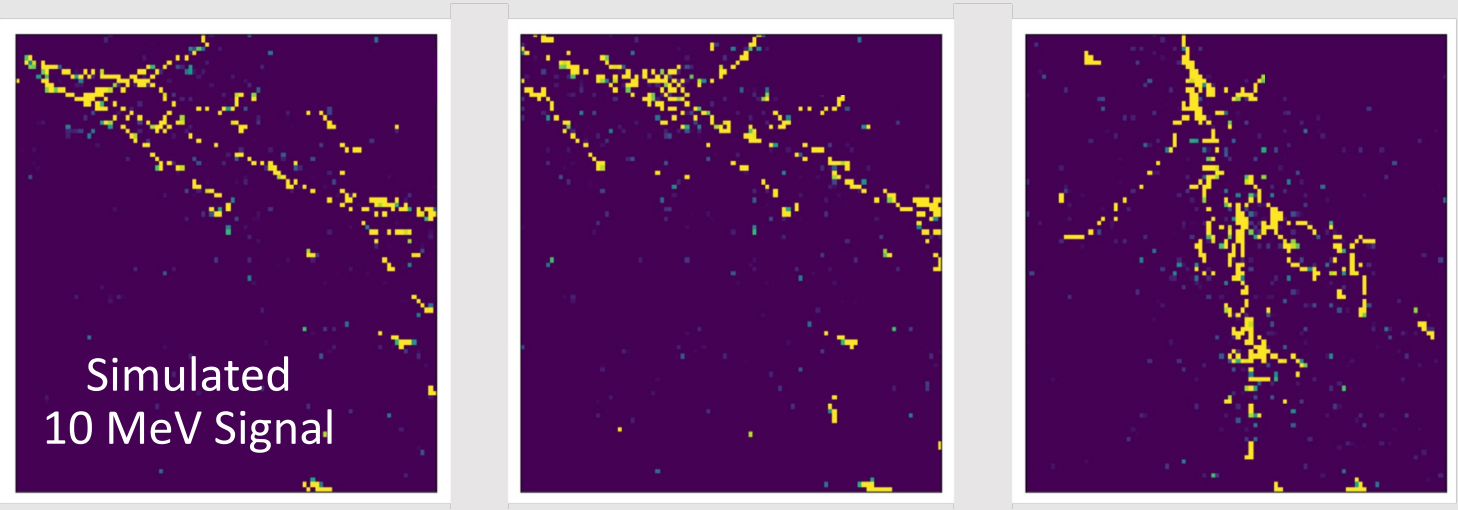
$$Q_{dep} \approx E_{dep}/W_{ion}$$

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



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

Simulation, cont.



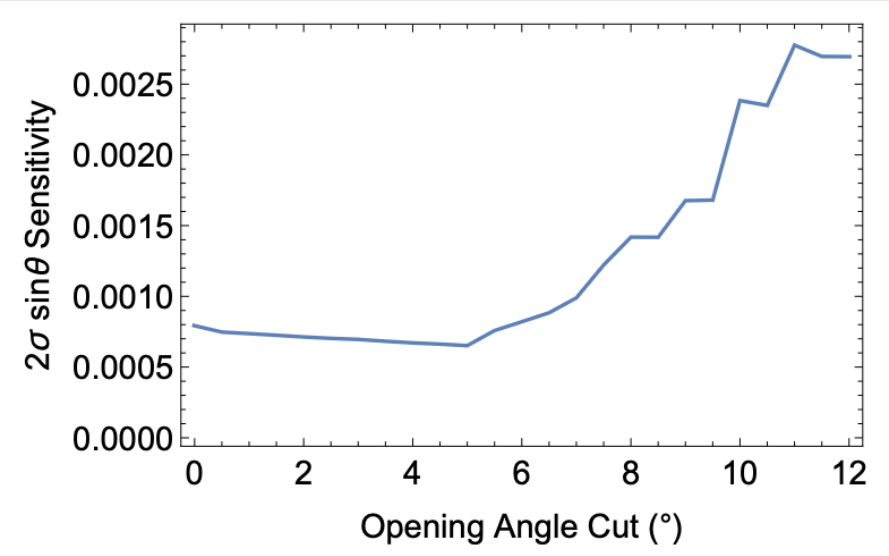
Advantages of this simulation pipeline:

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

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

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

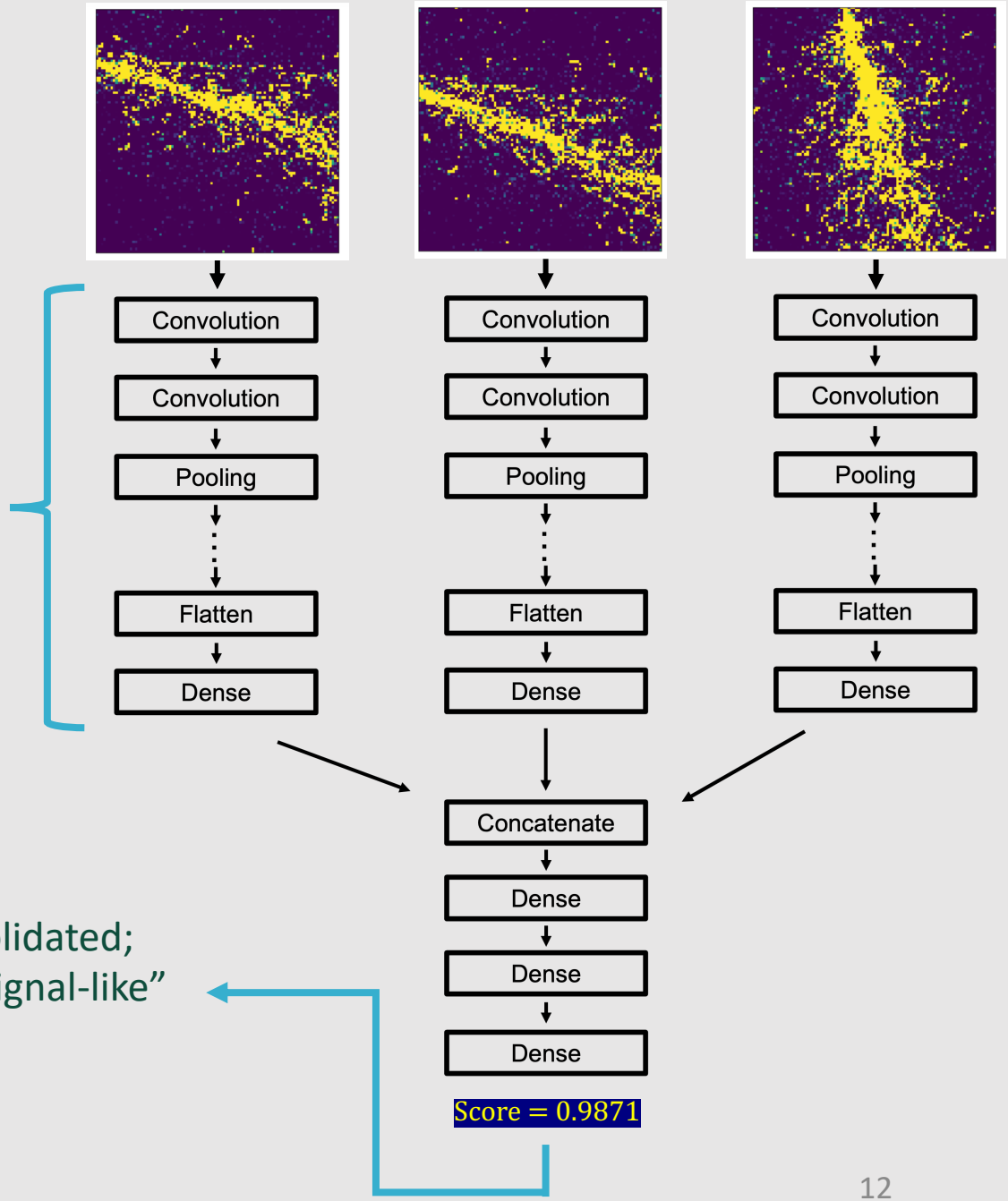


The CNN

Wire plane images first evaluated with separate branches of CNN

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

Info from wire planes is consolidated; score between 0-1 for how “signal-like” the event is is generated.



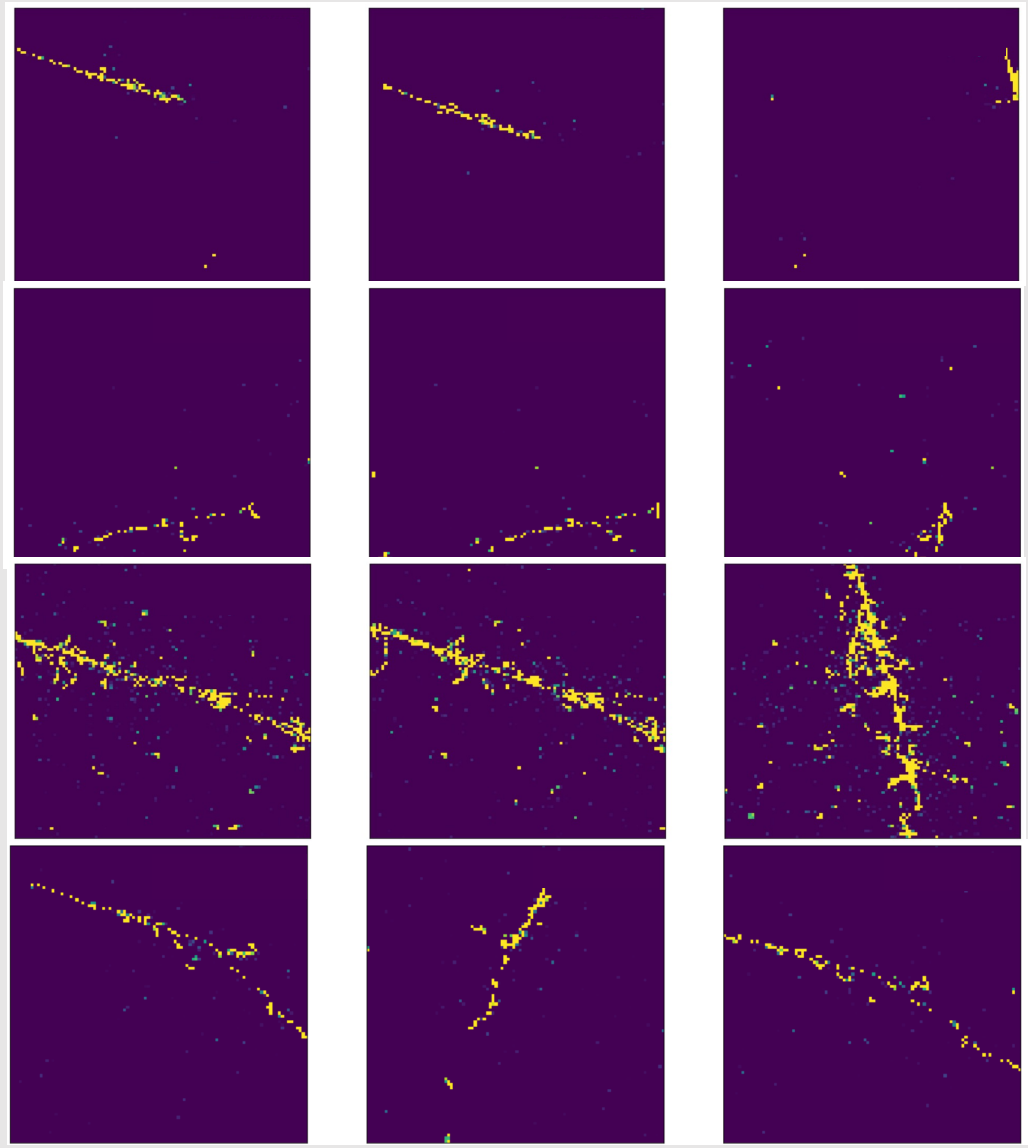
CNN Scores - Examples

S
Score: 0.9949
(success)

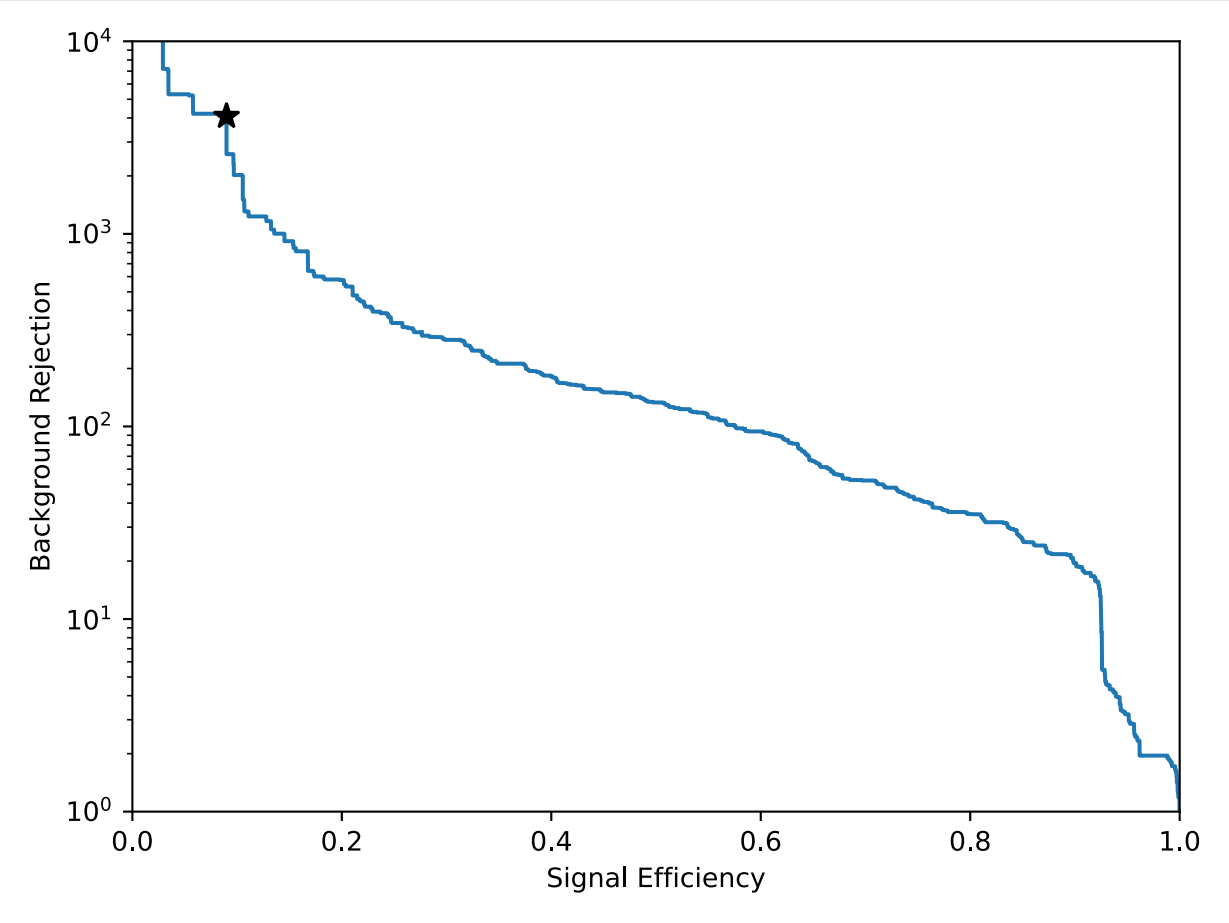
υ_e
Score: 0.0010
(success)

υ_e
Score: 0.9895
(failure)

υ_e
Score: 0.9995
(failure)



CNN Background Rejection vs. Efficiency



Results

Analysis	Limit on sinθ for 10 MeV S
Cut-based	$8.1 * 10^{-4}$
CNN	$7.0 * 10^{-4}$

- Modest improvement for sinθ
- Event rate $\propto \sin^4\theta$
- Significant improvement in the rate (~45%)

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 sensitivity to BSM models within LArTPCs at current and near-term experiments.
- Work is ongoing to extend approach to other scalar mass points, paying careful attention not to over-train the CNN to any particular mass point. Preliminary results are promising.

Acknowledgements

This material is based upon work supported by…

- The **National Science Foundation** under Grant No. 2112789
- The **U.S. Department of Energy** under Grant No. DE-SC0007914.

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Presentation of this work at the FNAL 55th Annual Users Meeting is supported by the **Visiting Scholars Award Program of the Universities Research Association**.

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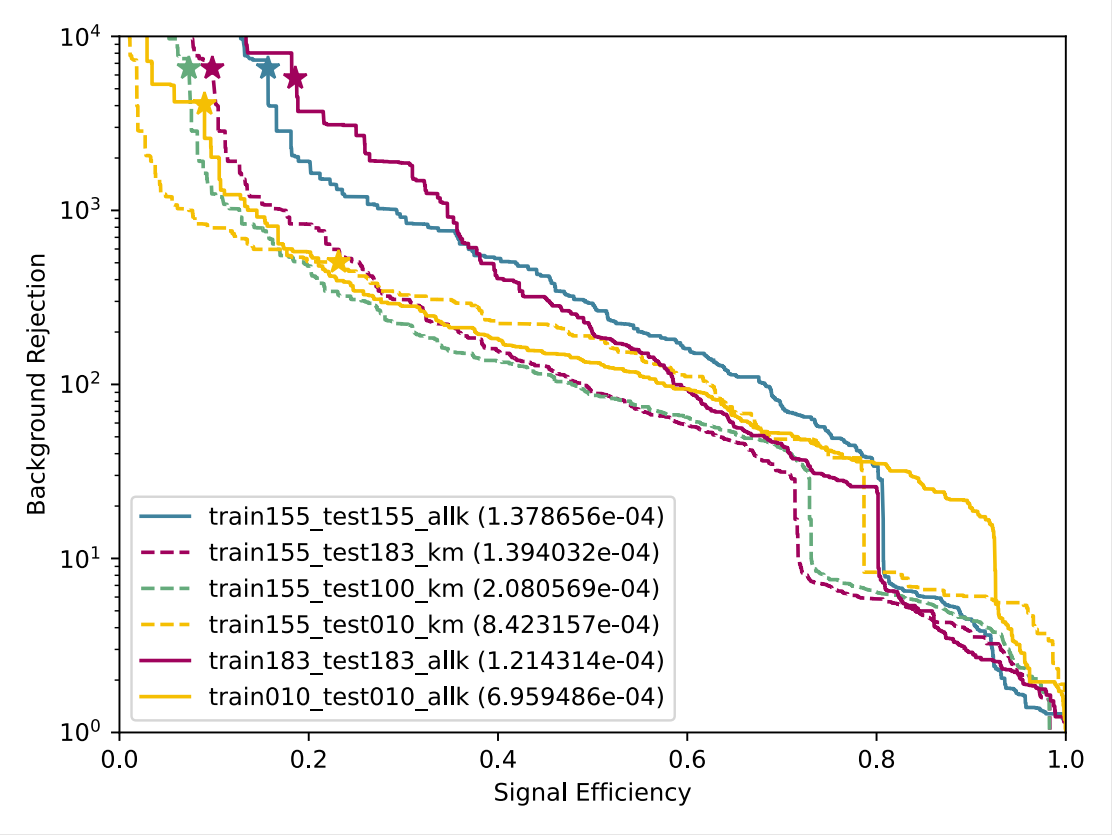
Thank you!

Backup Slide - Mass Dependence of CNN Performance



- As expected, networks tested and trained on same scalar mass point perform better than networks trained and tested on different mass points, but…
- Background Rejection vs. Efficiency curves for the latter have same general shape as the former and may still be used to further probe the Higgs Portal Scalar parameter space, even if not optimal.