KDIF -> Higgs Portal Dark Matter -> e^-e^+

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ICARUS ML Workshop @ CSU

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BSM Physics at ICARUS

- The intense proton beams at SBN and LArTPC reconstruction capability make the SBN experiments sensitive to a wide class of dark sector models that can compliment neutrino physics program.
  Examples: Higgs Portal, Heavy Neutral Leptons, and Heavy QCD axions

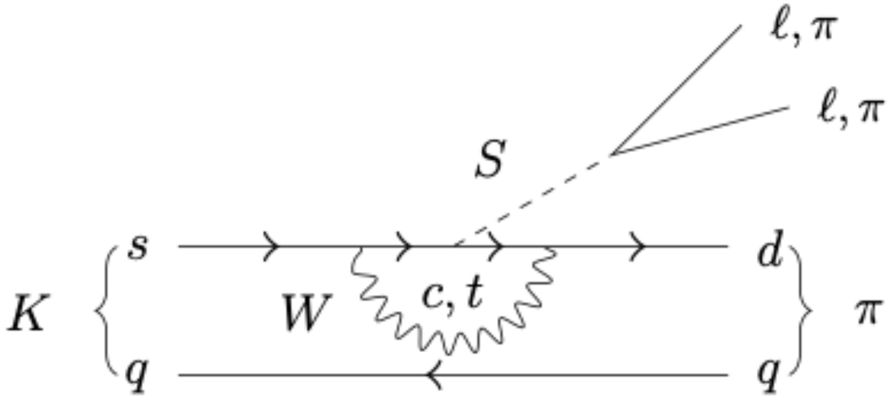
- Each of these models introduces a mediator particle which is produced either from meson decay or mixing, then can travel to the detector where it will decay into visible final state particles.

- For a review of the physics and technical implementation of how these models are simulated at SBN, see **32019-v2**.

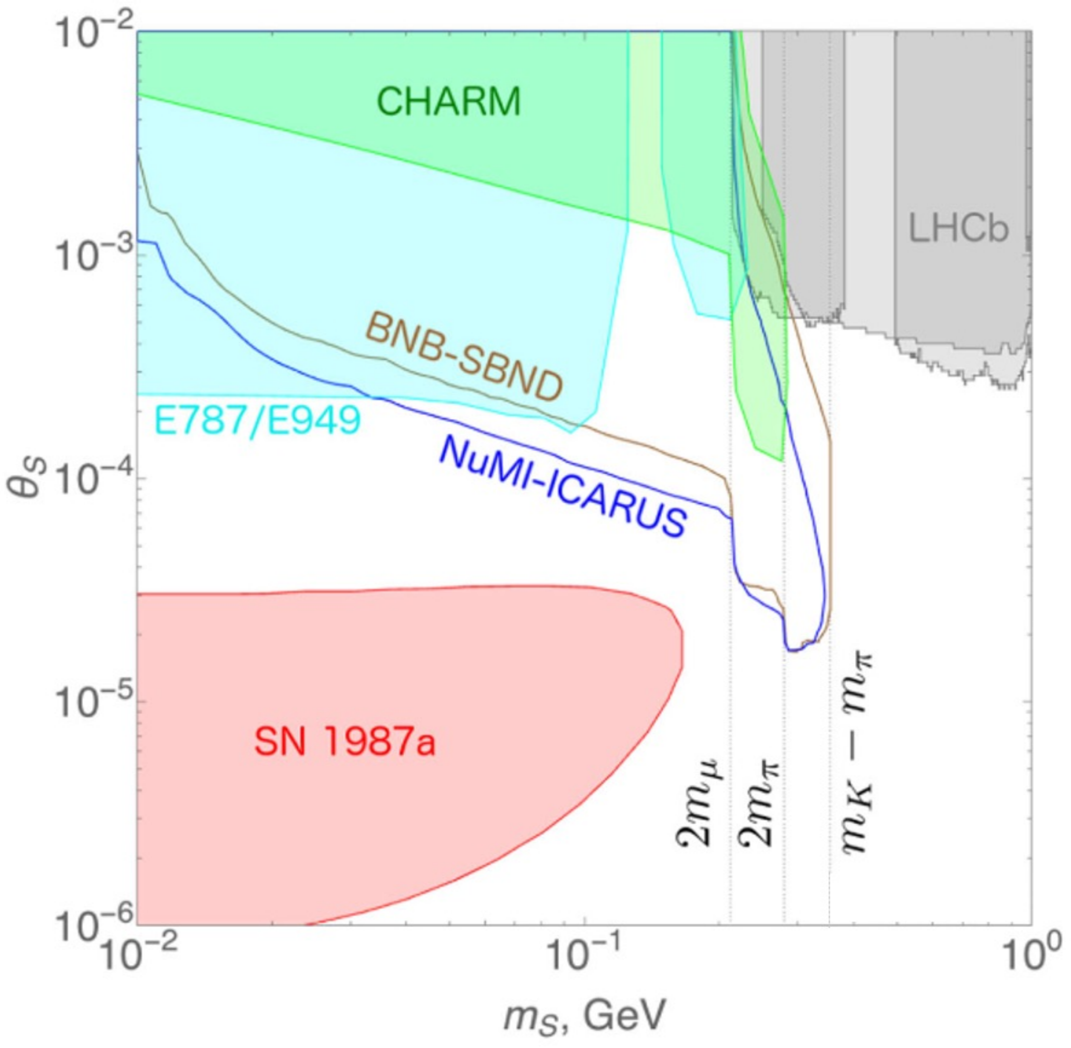
Higgs Portal Scalar

A dark scalar S couples to the SM through mass mixing with the Higgs.

Production: $K \rightarrow \pi S$
Decay: $S \rightarrow e^- e^+, \mu^- \mu^+, \pi^- \pi^+$



ICARUS is projected to have leading sensitivity w/ NuMI beam for scalar masses order 100 MeV.



B. Batell, J. Berger,and A. Ismail, Phys. Rev. D 100, 115039 (2019)

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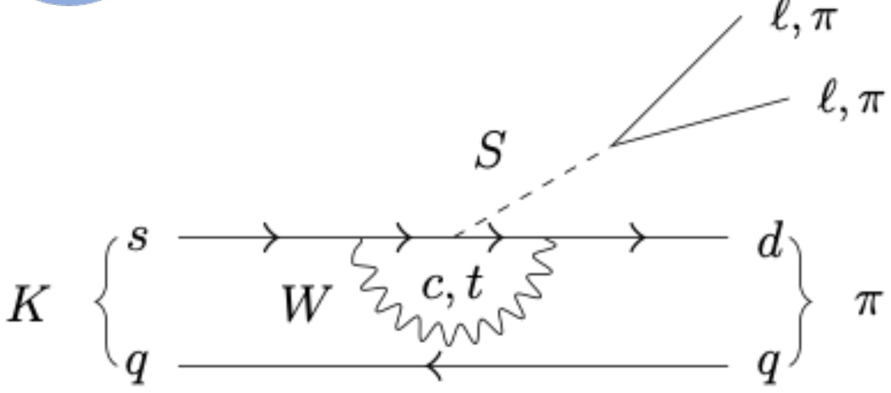

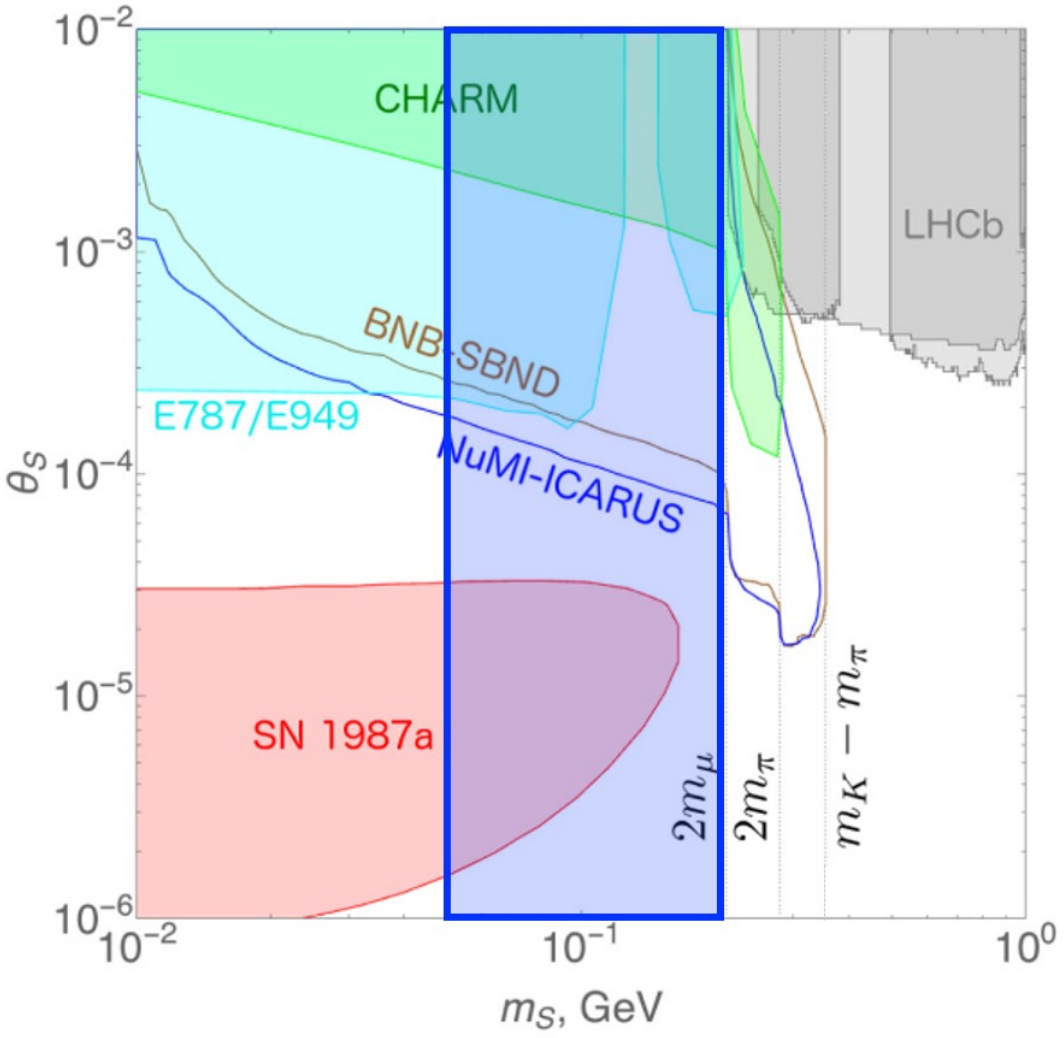

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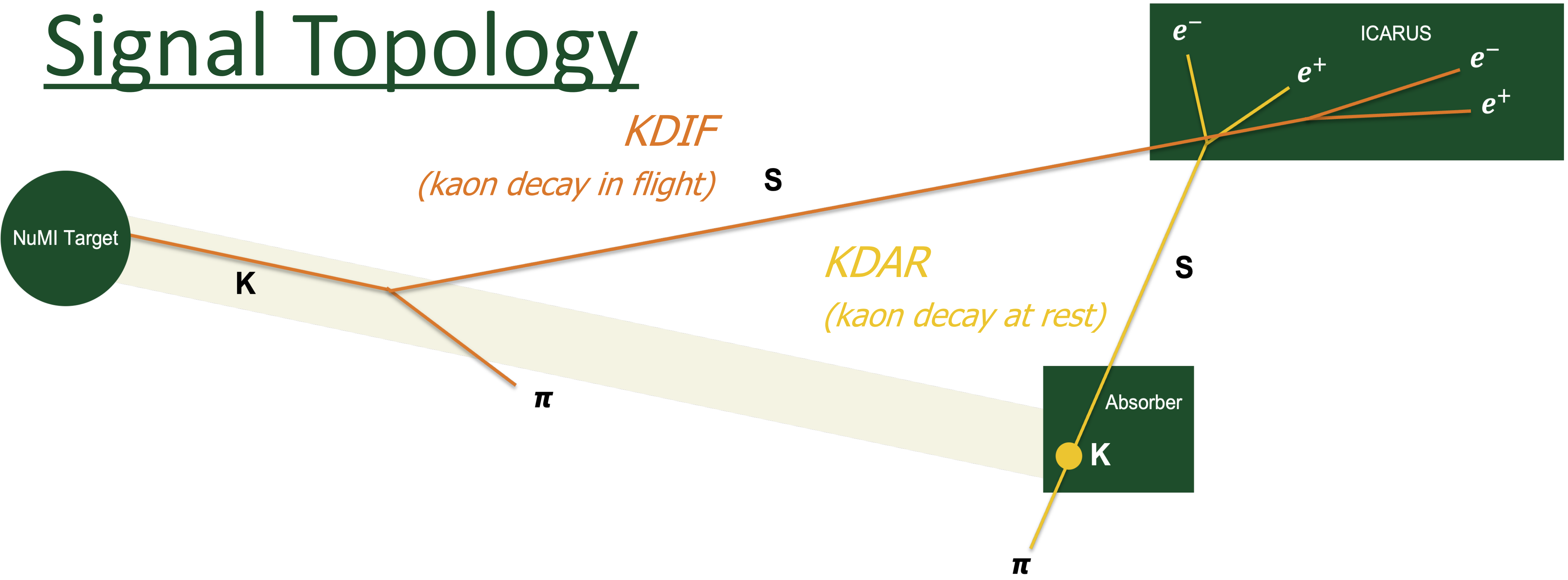
Signal Topology



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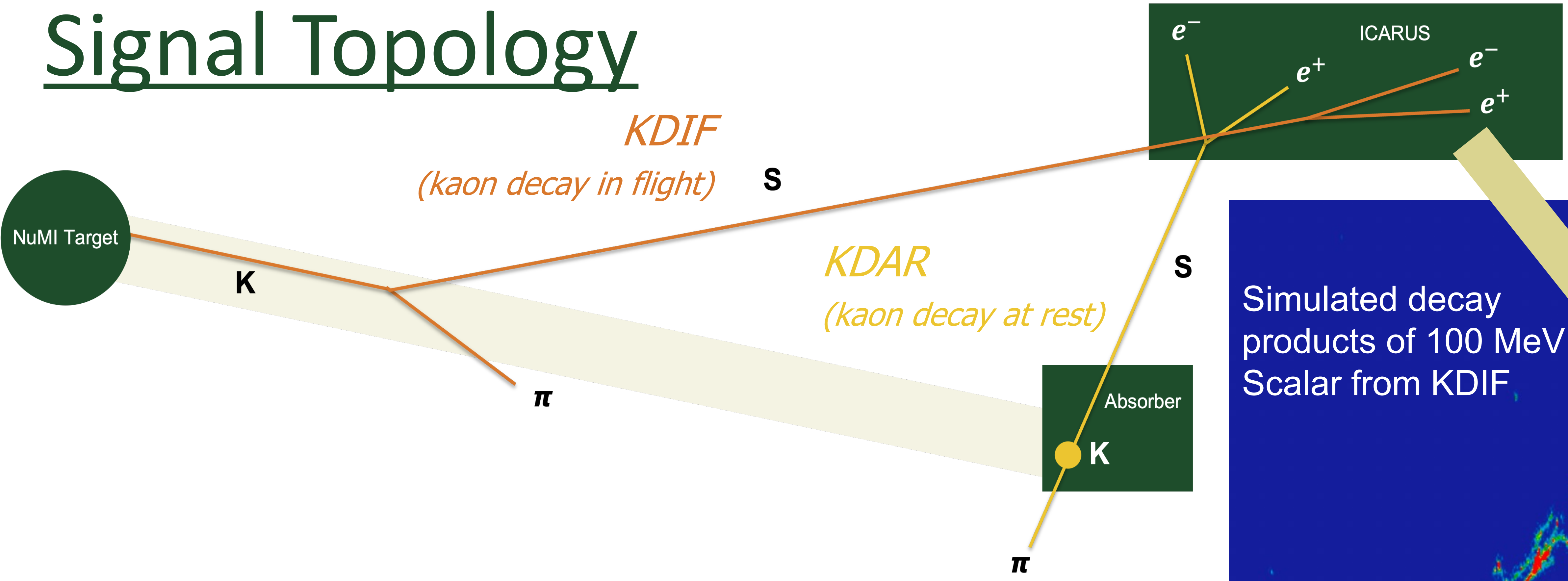
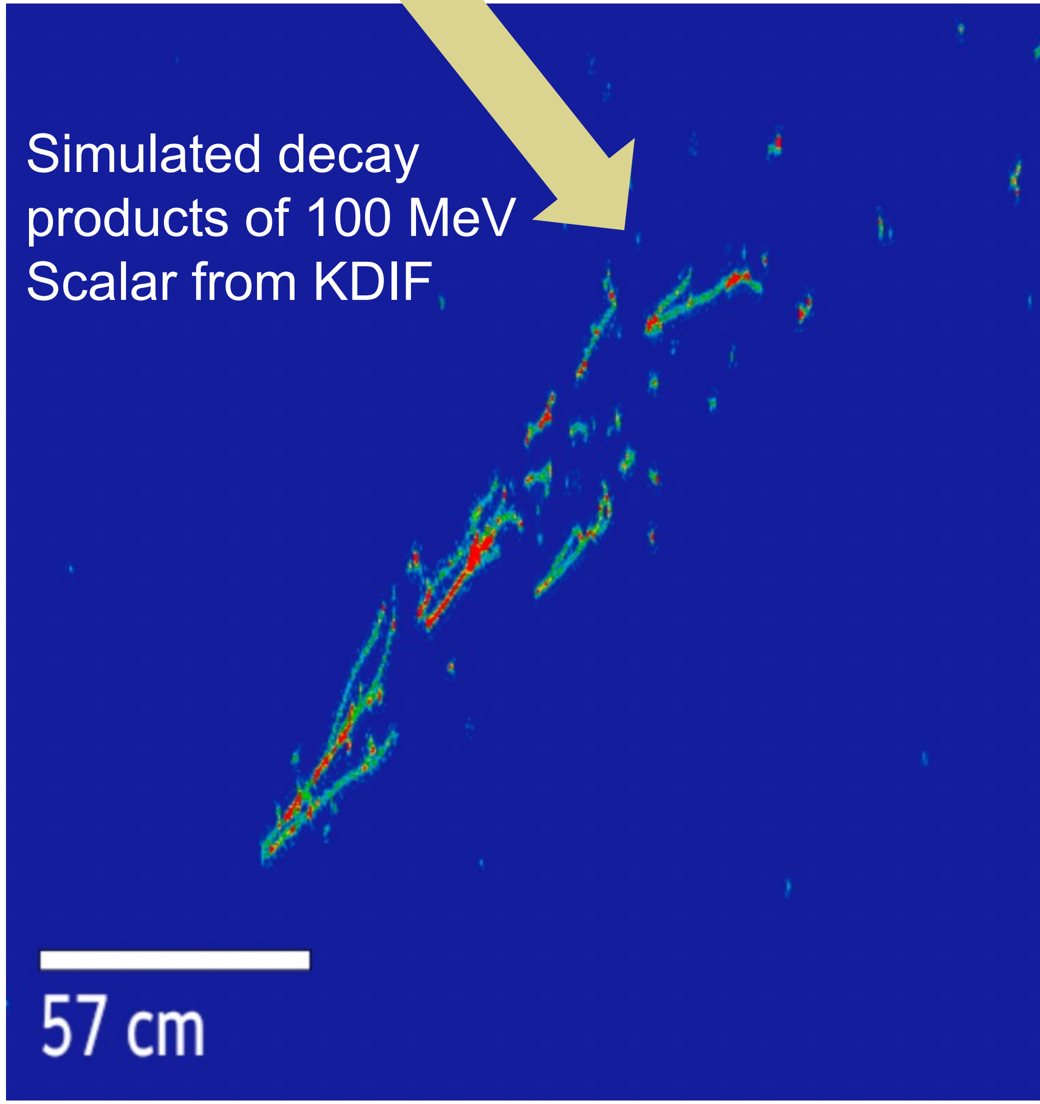


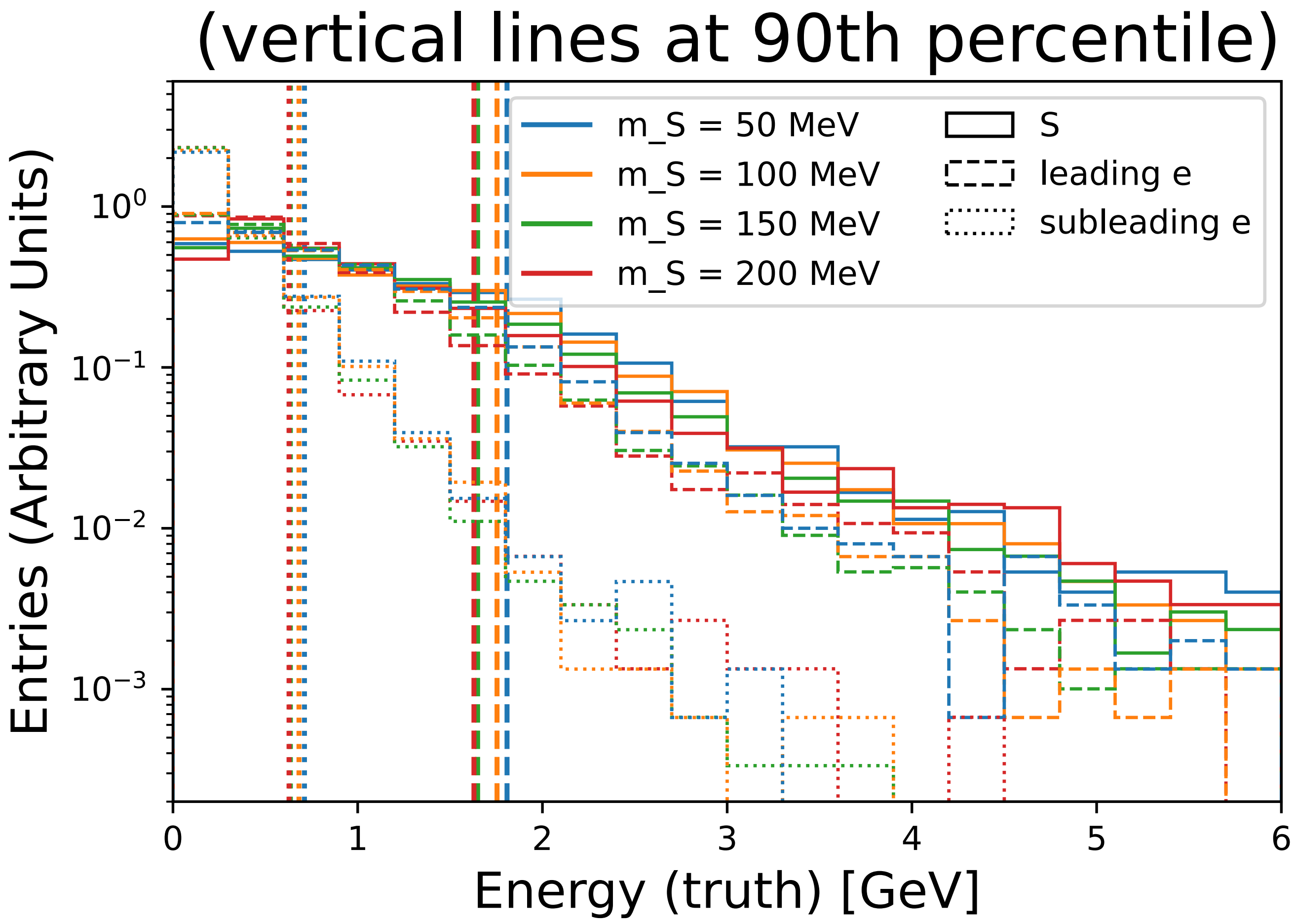


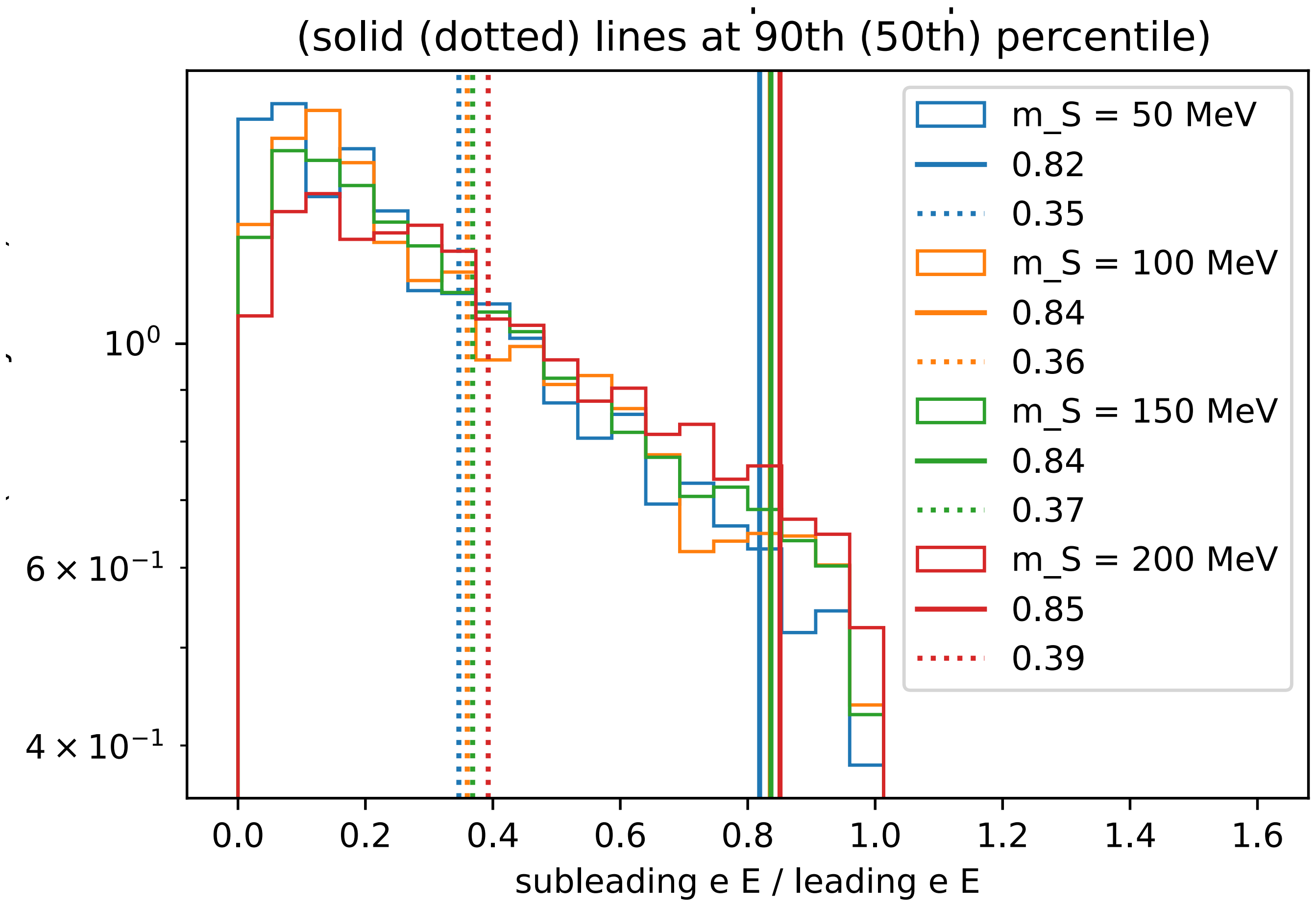
- Two showers connected at the vertex

- Most KDIF happens near target, so scalars' momenta are along LOS from target to ICARUS. This results in final state particles being boosted along direction that makes small angle wrt NuMI beamline.

Truth-level kinematics

- Distributions for scalars from KDIF; 5K-10K KDIF events per benchmark scalar mass





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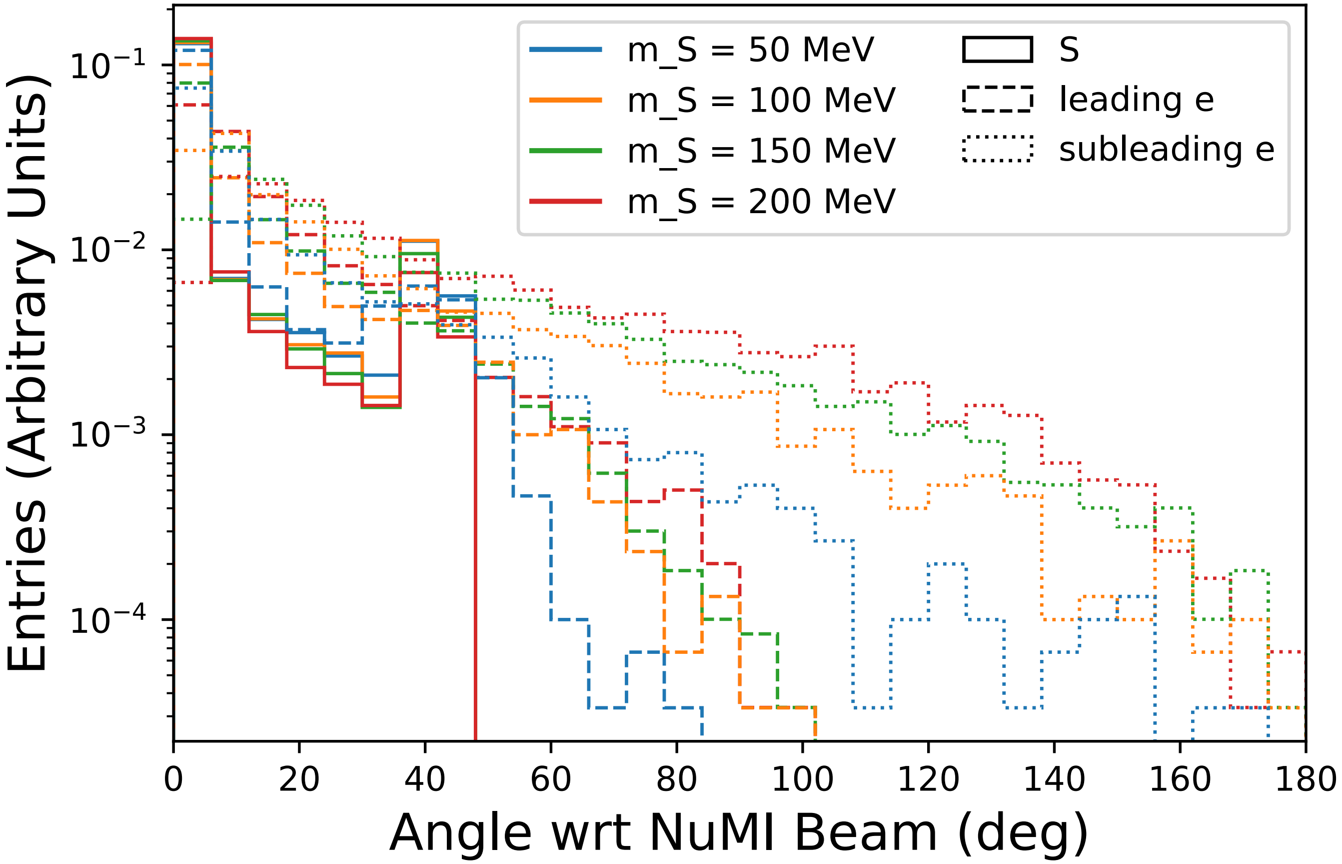
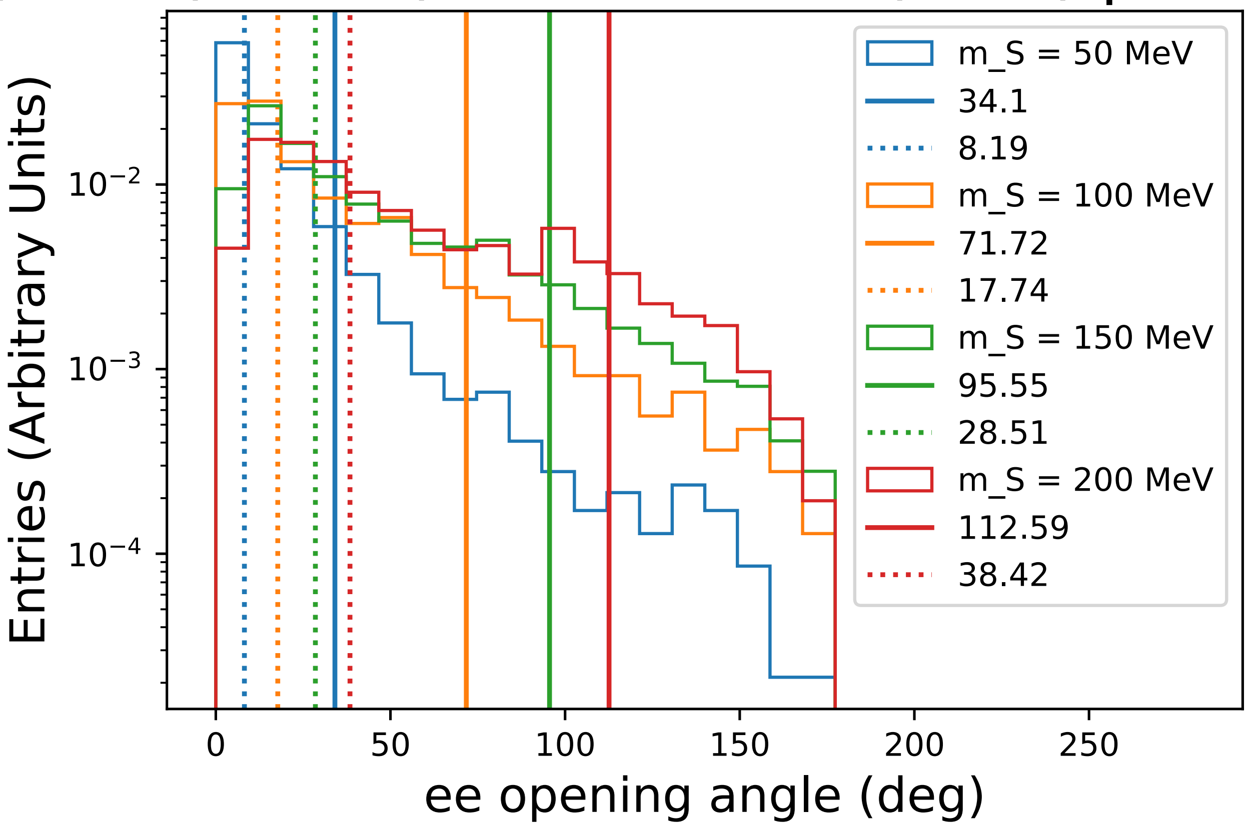
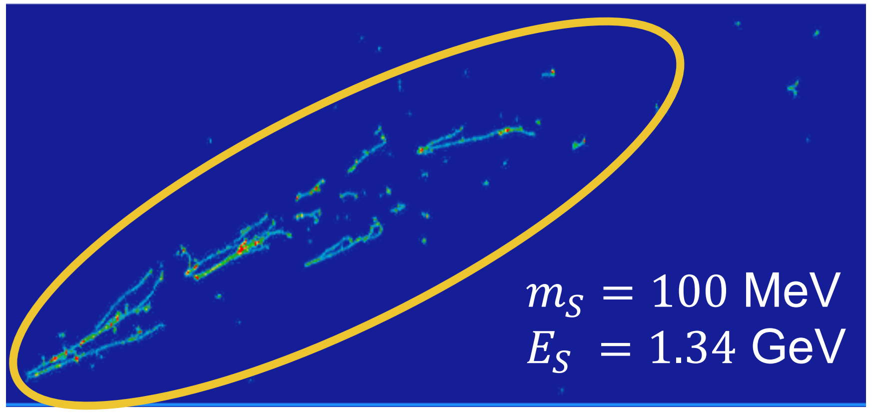
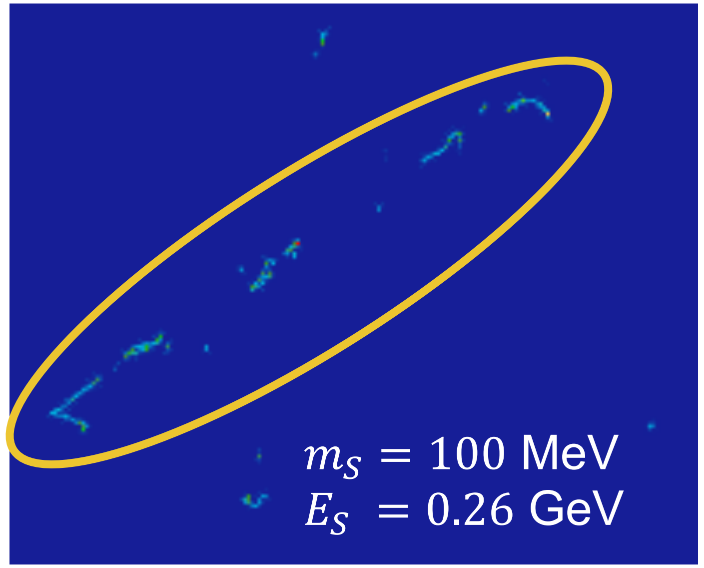


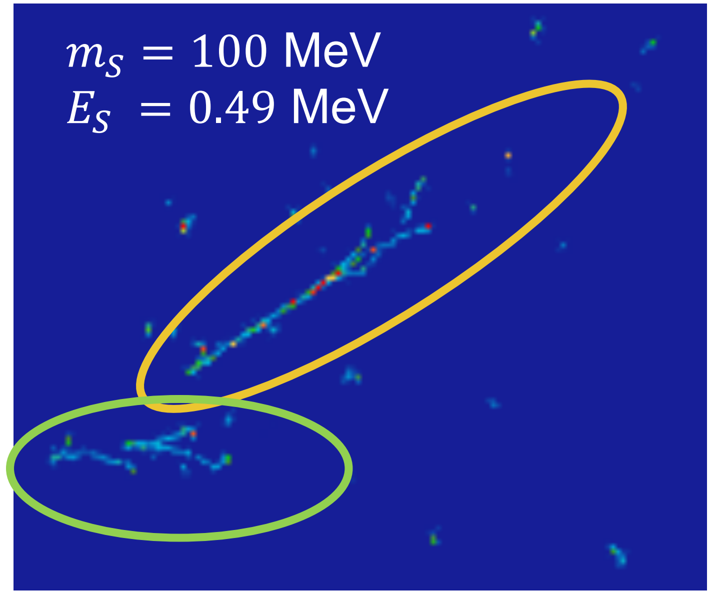


Pandora Based Reconstruction

Only one shower reconstructed

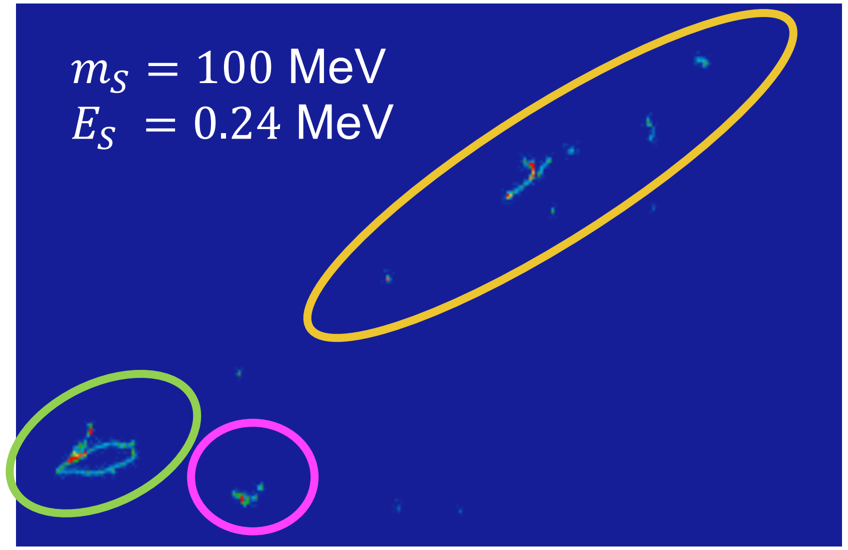






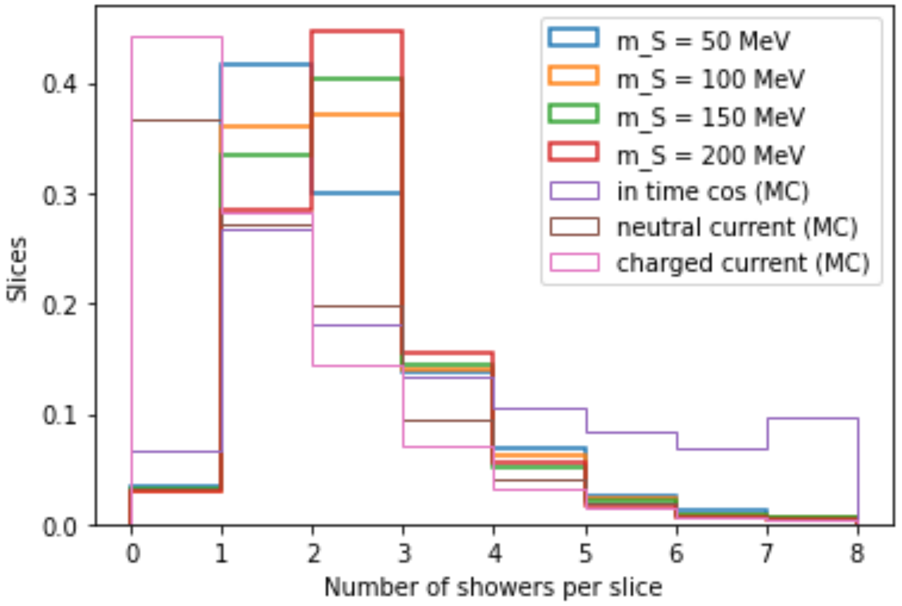
Two showers in single slice, but vertices are separated

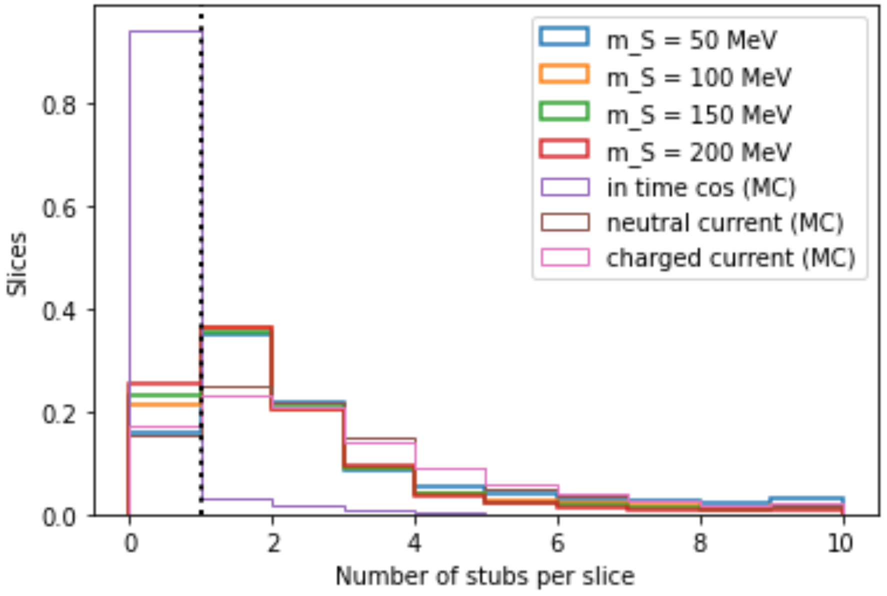
>2 showers reconstructed, not necessarily w/ close vertices, sometimes across >1 slices

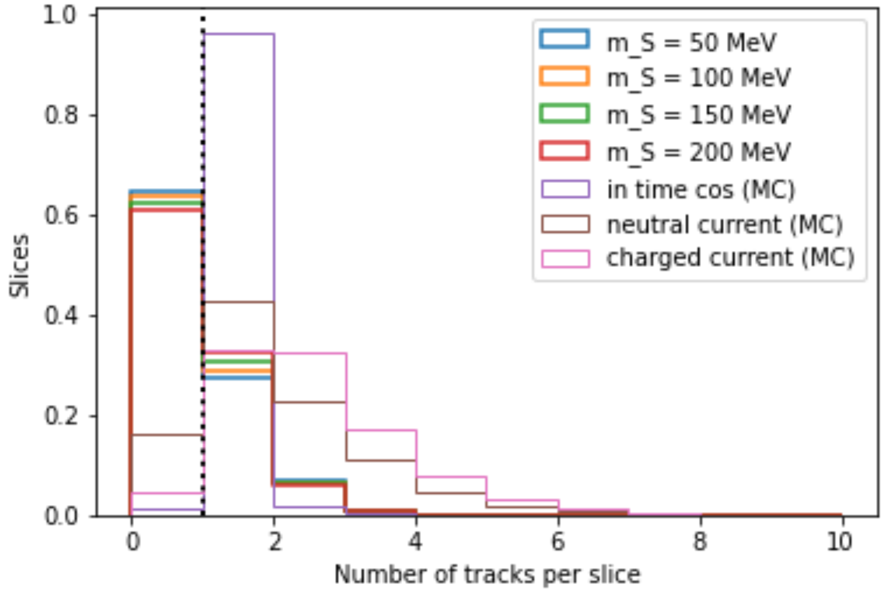


Pandora Based Reconstruction

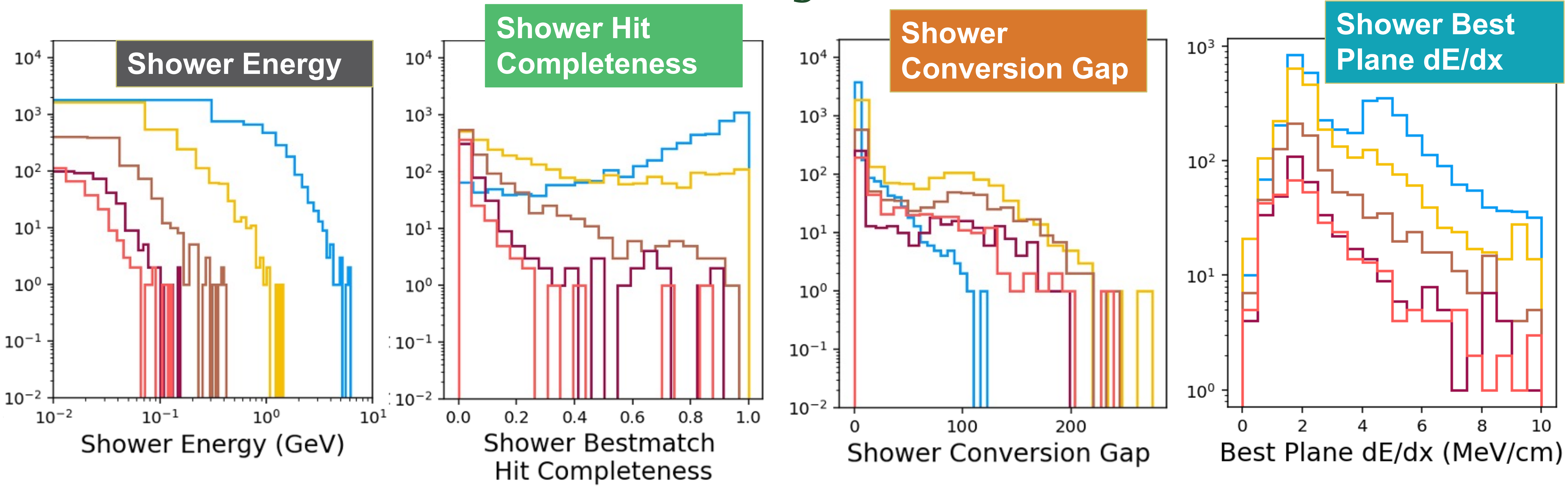
- Number of showers, stubs, and tracks reconstructed per "slice" (reconstructed interaction) for signal-only KDIF events and background sample of NuMI neutrino + in time cosmic overlay







Investigation of Pandora Reco by “Energy Rank” of Reco’d Showers in Interaction: $m_S = 100\ MeV$



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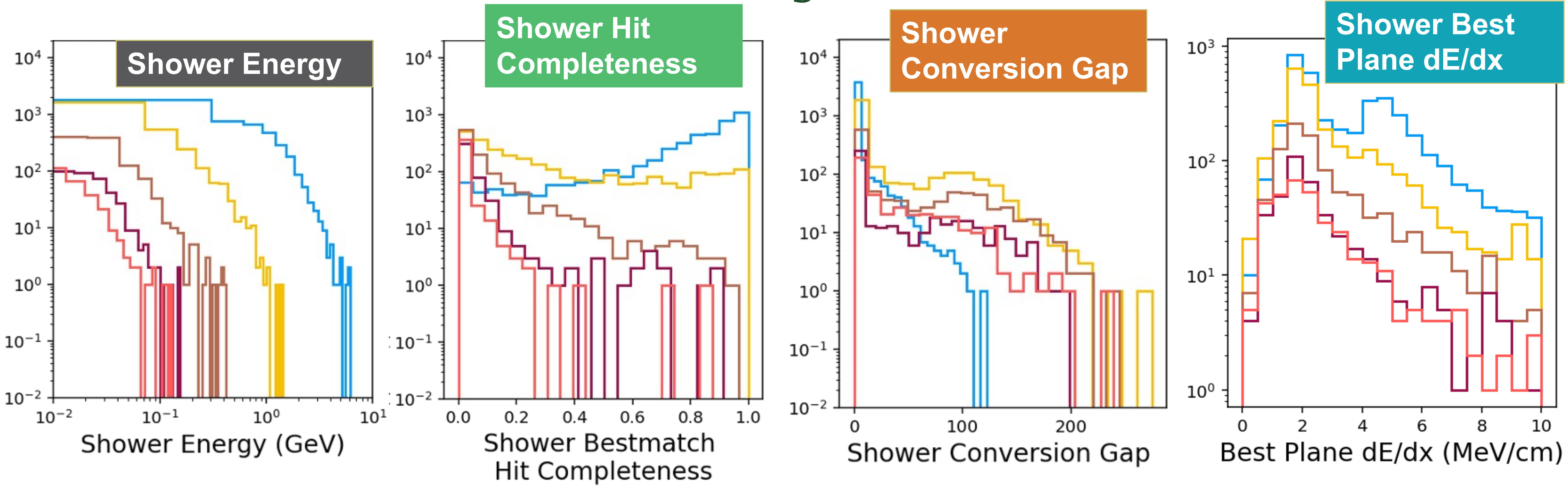

- Presumably, the showers in 3rd+ most energetic showers should have been clustered with the other two showers, so it makes sense that their hit completeness is low.
- Peak at zero for 2nd most energetic probably because hits are being lumped into 1st most energetic.
- 2nd Most Energetic showers are more peaked at 1 for the more massive scalars (not shown here). This is consistent w/ hypothesis that reconstruction performs better for less boosted/columnated scalar decay products.

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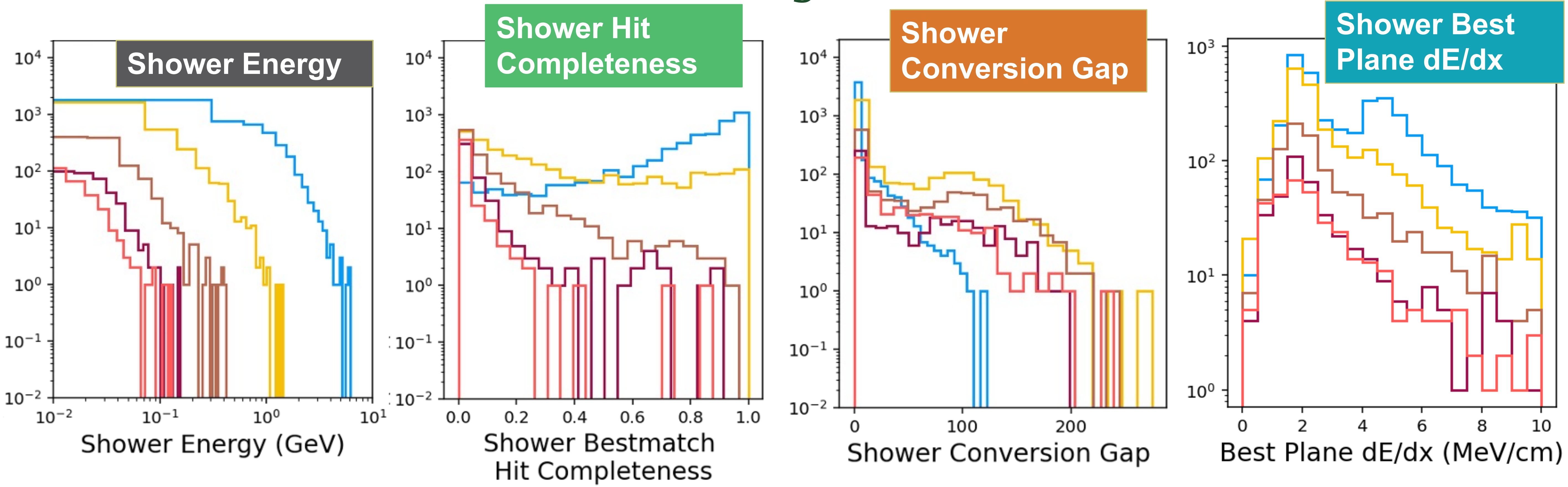

- High conversion gap bump for 2nd+ leading showers: Pandora mistakes gaps in shower as conversion gap for subleading decay product.
- * Not sure what is special about location of bump at 100 cm

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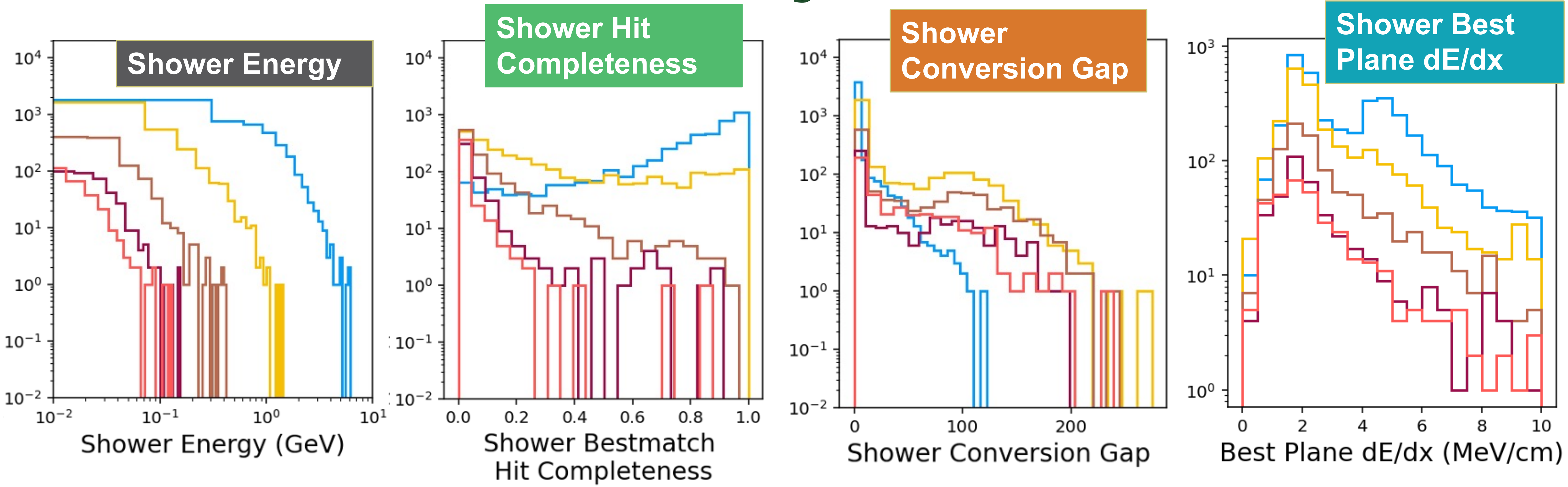


- Bump at 4 for leading shower likely due to both e being lumped into same shower.
- ^Hypothesis consistent with more prominent high dE/dx peak for lower mass scalars, which have more columnated decay products.

Steps Towards Selection (w/ Pandora)

Comparing a sample of signal-only KDIF events to NuMI neutrino + in-time cosmic overlay events (all simulated):

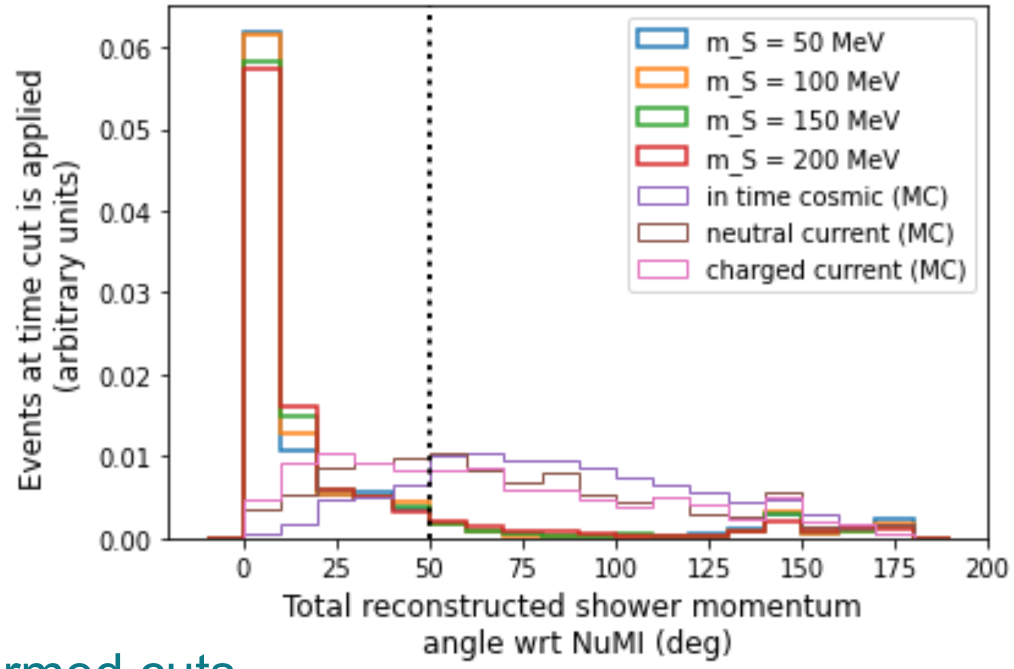
interaction not tagged as Clear Cosmic

- interaction vertex contained in fiducial volume
- number of reconstructed showers in slice > 0

preselection

- combined momentum of all reconstructed showers in interaction makes an of < 50° w/ NuMI beam
- leading trk length < 50 cm
- leading shower length > 20 cm

physics-informed cuts



These cuts keep about half of the signal while removing 99.96% of cosmics, 97% of CC neutrino interactions, and 87% of NC interactions: much better selection efficiency and background rejection are needed considering low rate of these BSM events (order few to tens per year, depending on mass).

Takeaways

- One could imagine designing further topological cuts that branch, informed by reconstruction performance and classification of failure modes.
  - For example, select:
    2 showers connected at vertex with dE/dx ~ 2 MeV/cm **OR** single shower with dE/dx ~ 4 MeV/cm and no conversion gap
- It is likely we will need to design some branching set of selection cuts to retain signal selection efficiency considering the challenge associated with trying to reconstruct overlapping showers, but optimized reco is still very helpful…

Enter: lartpc_mlreco3d!

Backup – Cut Performance

	50MeV	100MeV	150MeV	200MeV	all_bg	cosmics	NC	CC
all_slices	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
not_clear_cosmic	0.986756	0.990265	0.988619	0.988433	0.140440	0.107214	0.976793	0.982893
vertex_in_fid_volume	0.606061	0.615265	0.604088	0.608904	0.067200	0.043918	0.704641	0.644894
nshw > 0	0.597531	0.604867	0.595249	0.601266	0.038786	0.024753	0.476793	0.373769
shw_NuMI_angle < 50°	0.520314	0.536947	0.523646	0.526844	0.010815	0.004668	0.198312	0.158631
leading trk length < 50 cm	0.510887	0.525221	0.512486	0.514186	0.004680	0.002531	0.151899	0.036288
leading shw length > 20 cm	0.470932	0.478097	0.475912	0.483195	0.002040	0.000427	0.113924	0.025402