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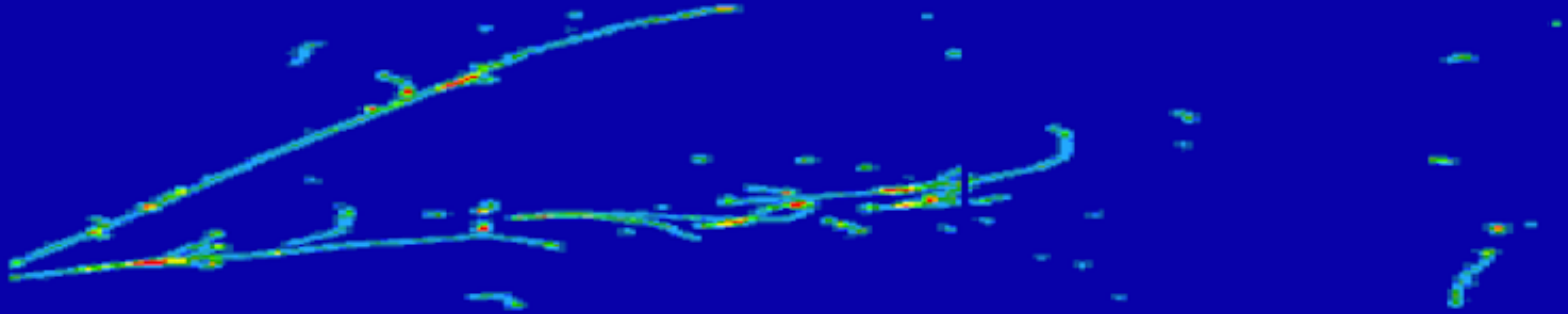


Search for low mass Higgs Portal scalars

Aditya Bhanderi

IOP HEPP & APP Annual Conference 2022

3-6 April 2022

Higgs Portal Scalars

- **Higgs Portal Model:** An extension to the SM with Lagrangian

$$-\mathcal{L} \supset (AS + \lambda S^2)H^\dagger H$$

new scalar singlet

renormalizable portal couplings

- **After electroweak symmetry breaking:**

$$\mathcal{L} \supset -\frac{1}{2} m_S^2 S^2 + \sin\theta\, S \left(\frac{2m_W^2}{v} W_\mu^+ W^{\mu +} + \frac{m_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right)$$

scalar mass

mixing angle

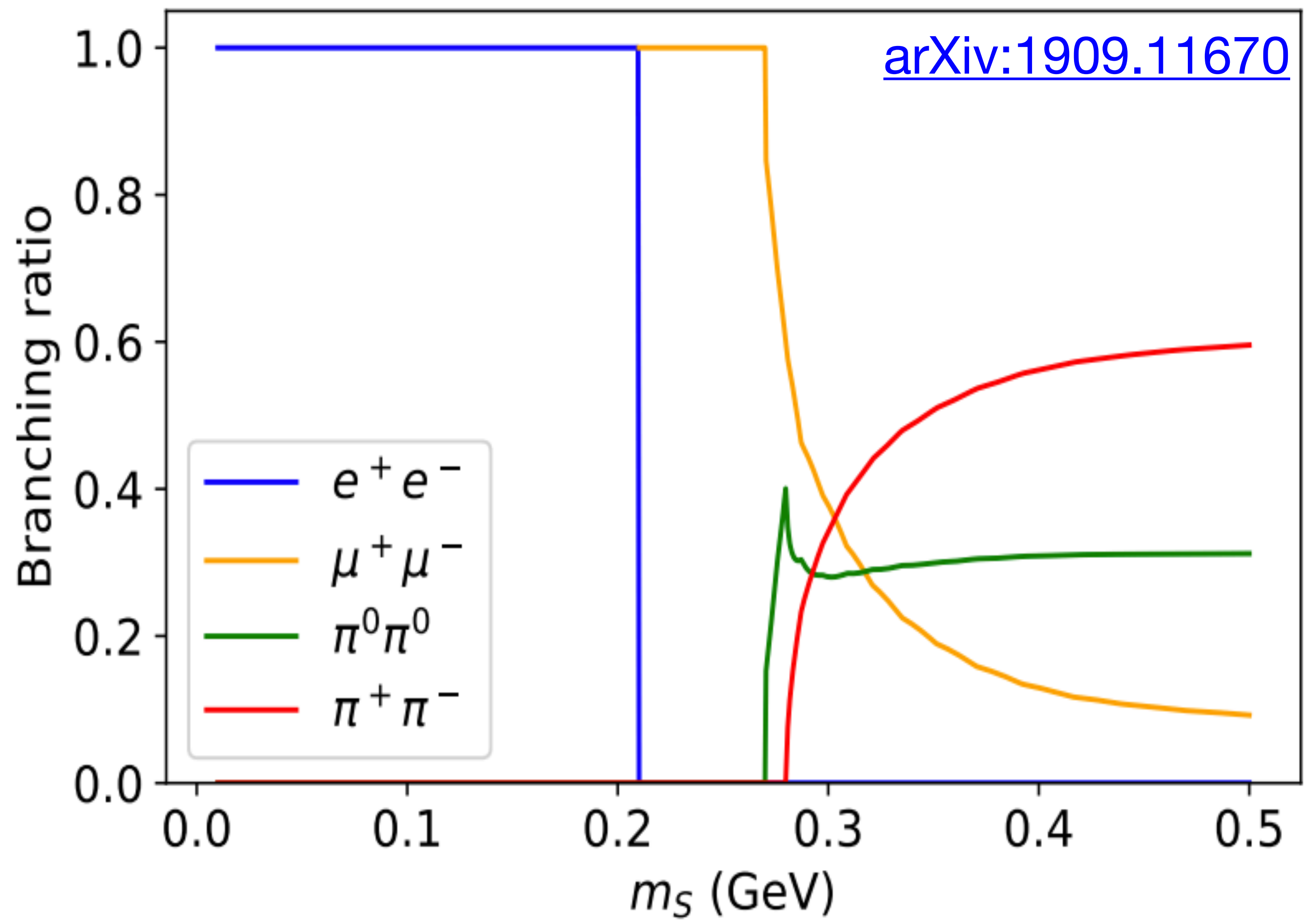
coupling to SM fermions

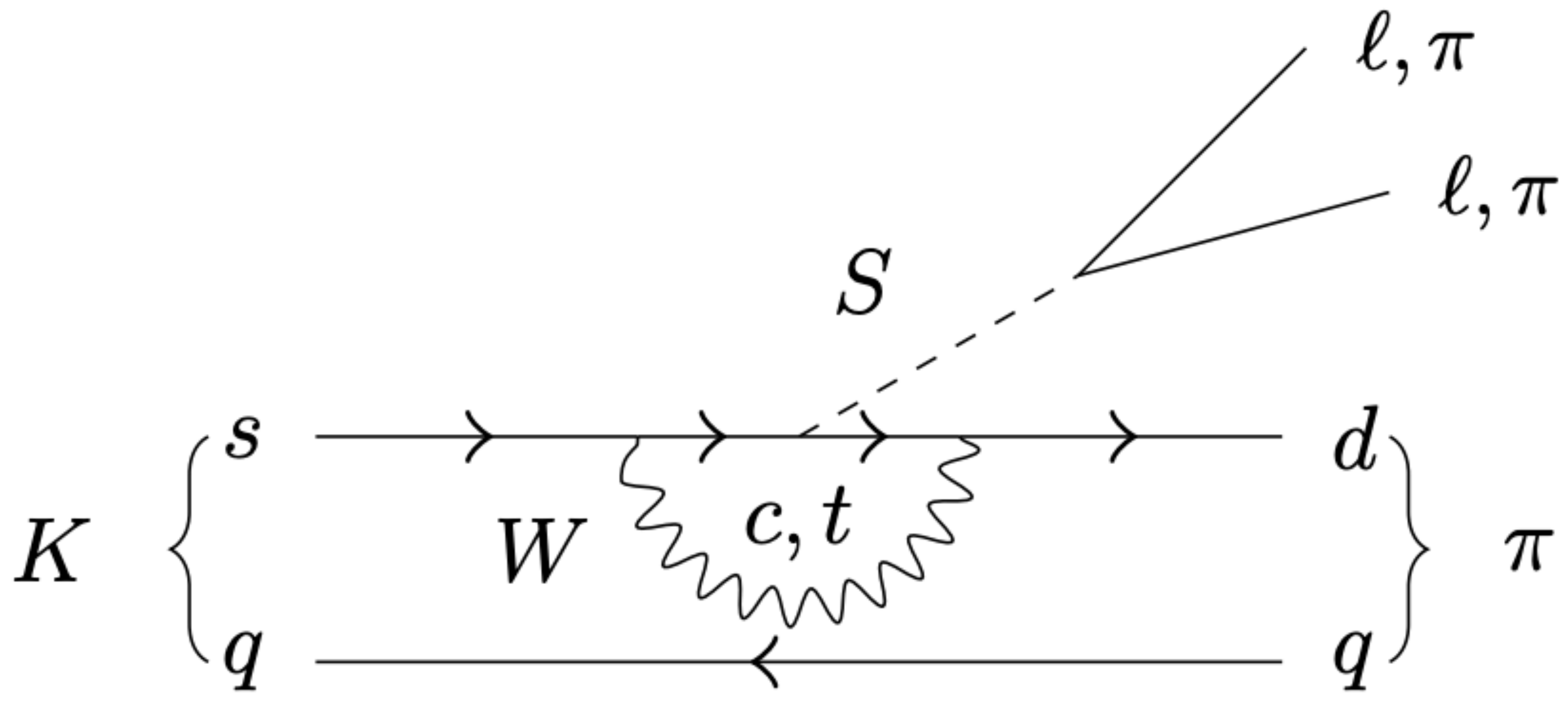
arXiv:1909.11670

- Dark sector scalar, **S mixes with the Higgs Boson with mixing angle, θ**
- S acquires coupling to the fermions via the Higgs Yukawa coupling and sin(θ)

Production of the Scalars in our Experiment

- In our study **we search for the low mass** (<~200 MeV) **Higgs Portal scalar bosons** that decays to **e^+e^-**
- For this energy range, scalars are mostly produced in Kaon decays via a top quark in a penguin decay.





- Production of neutrinos involves kaons so we can search for Higgs Portal Scalars in the neutrino beams.
- We consider three different scalar masses: 100, 150 and 200 MeV/c^2

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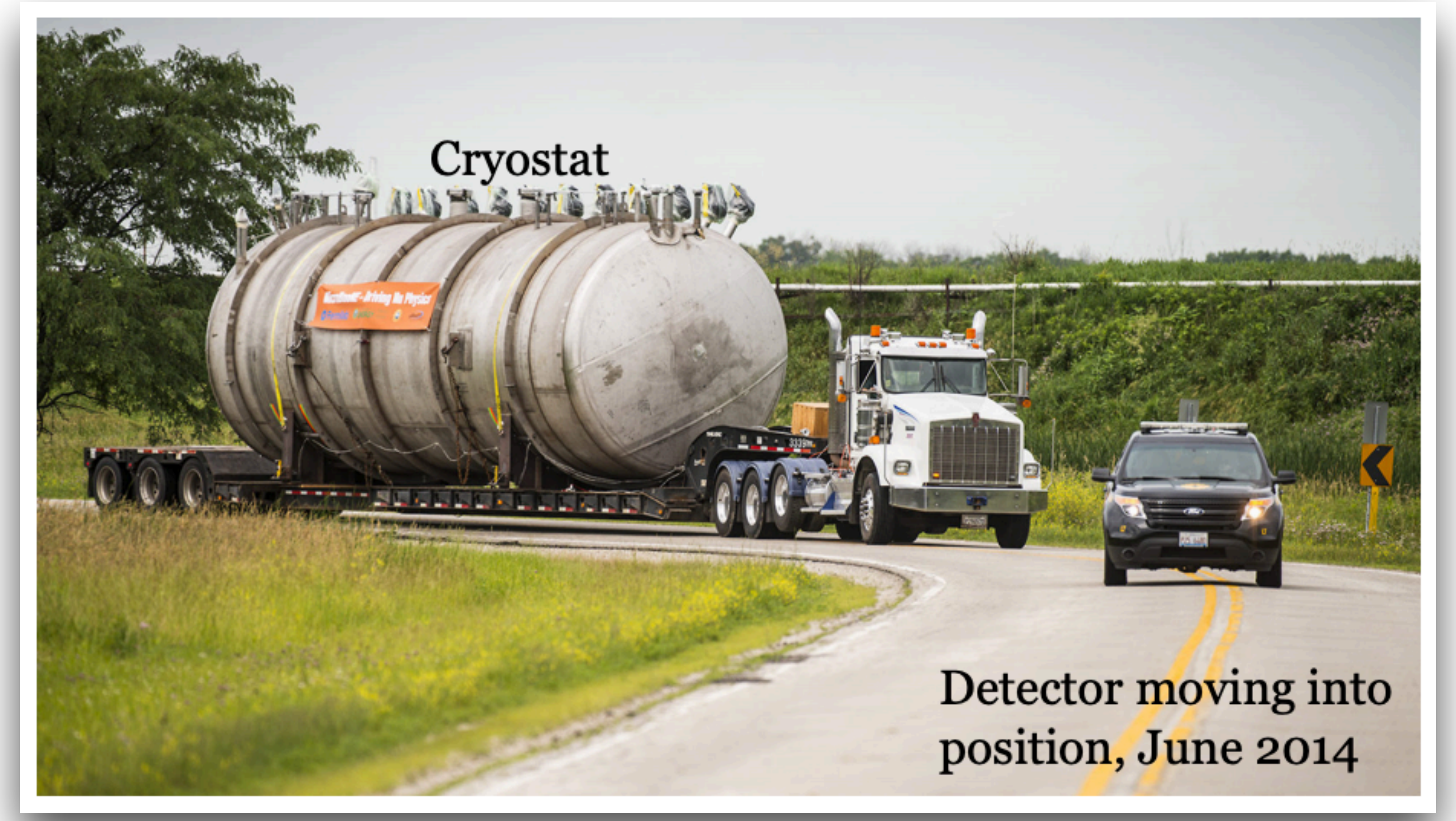
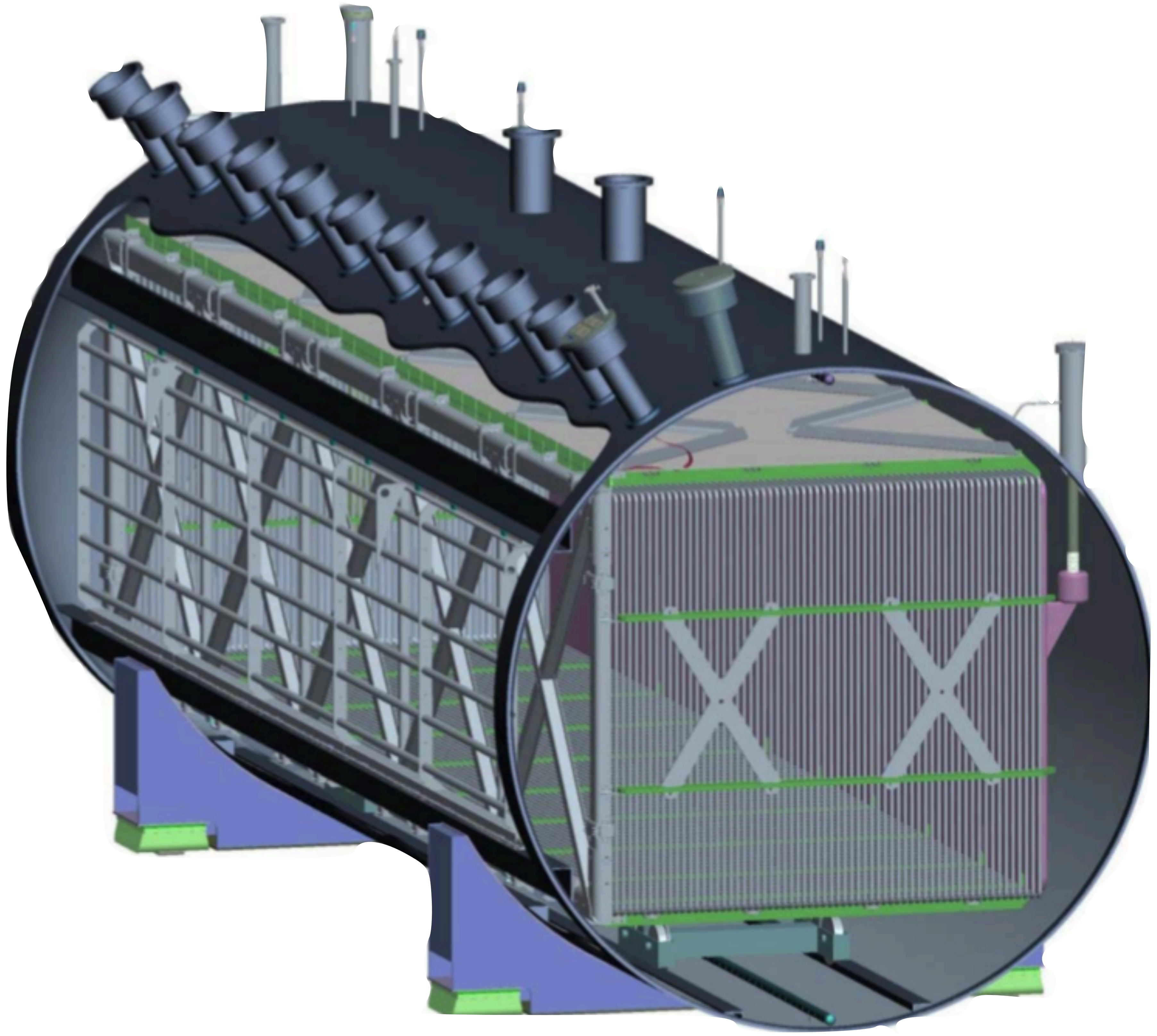
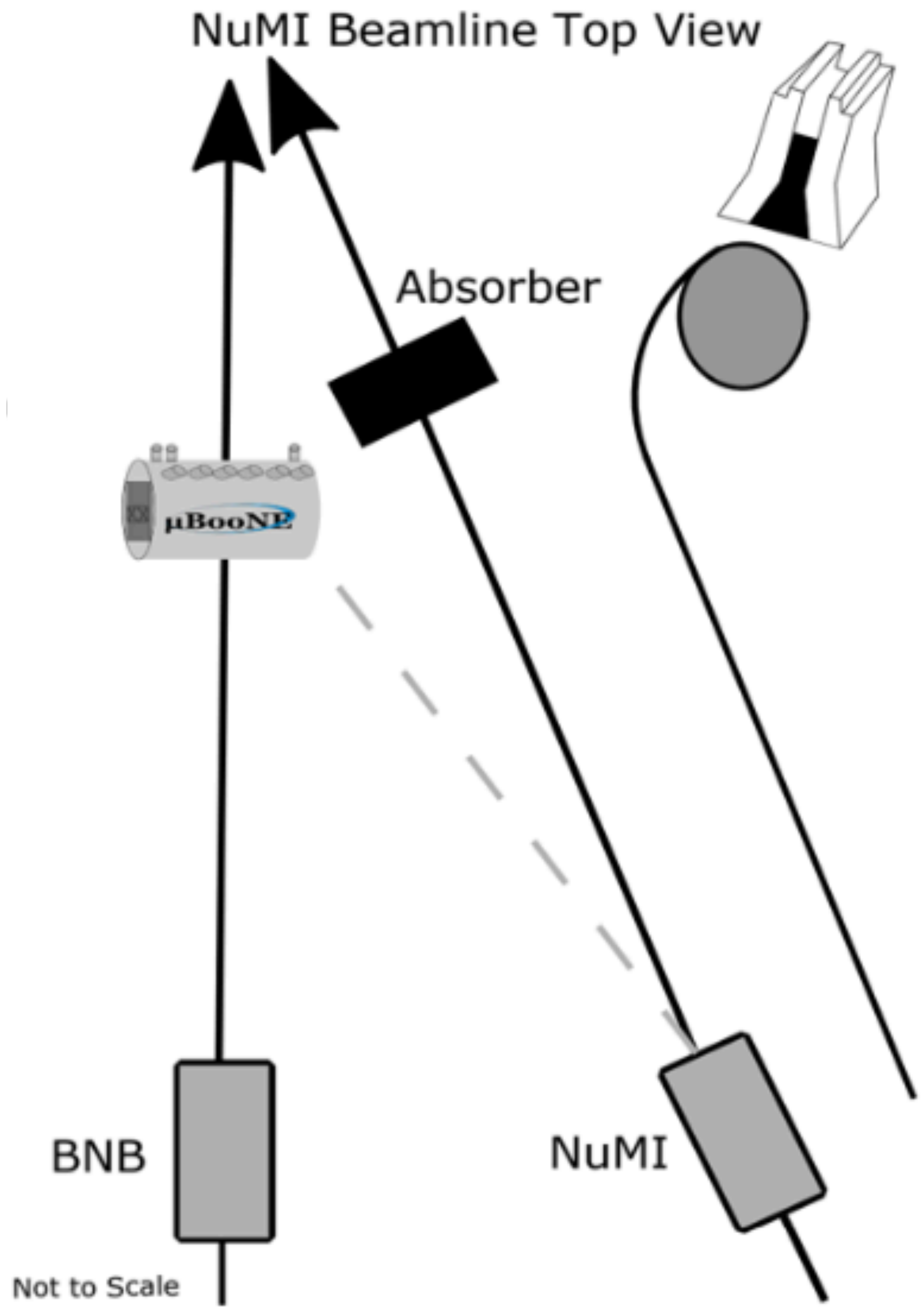
MicroBooNE Experiment

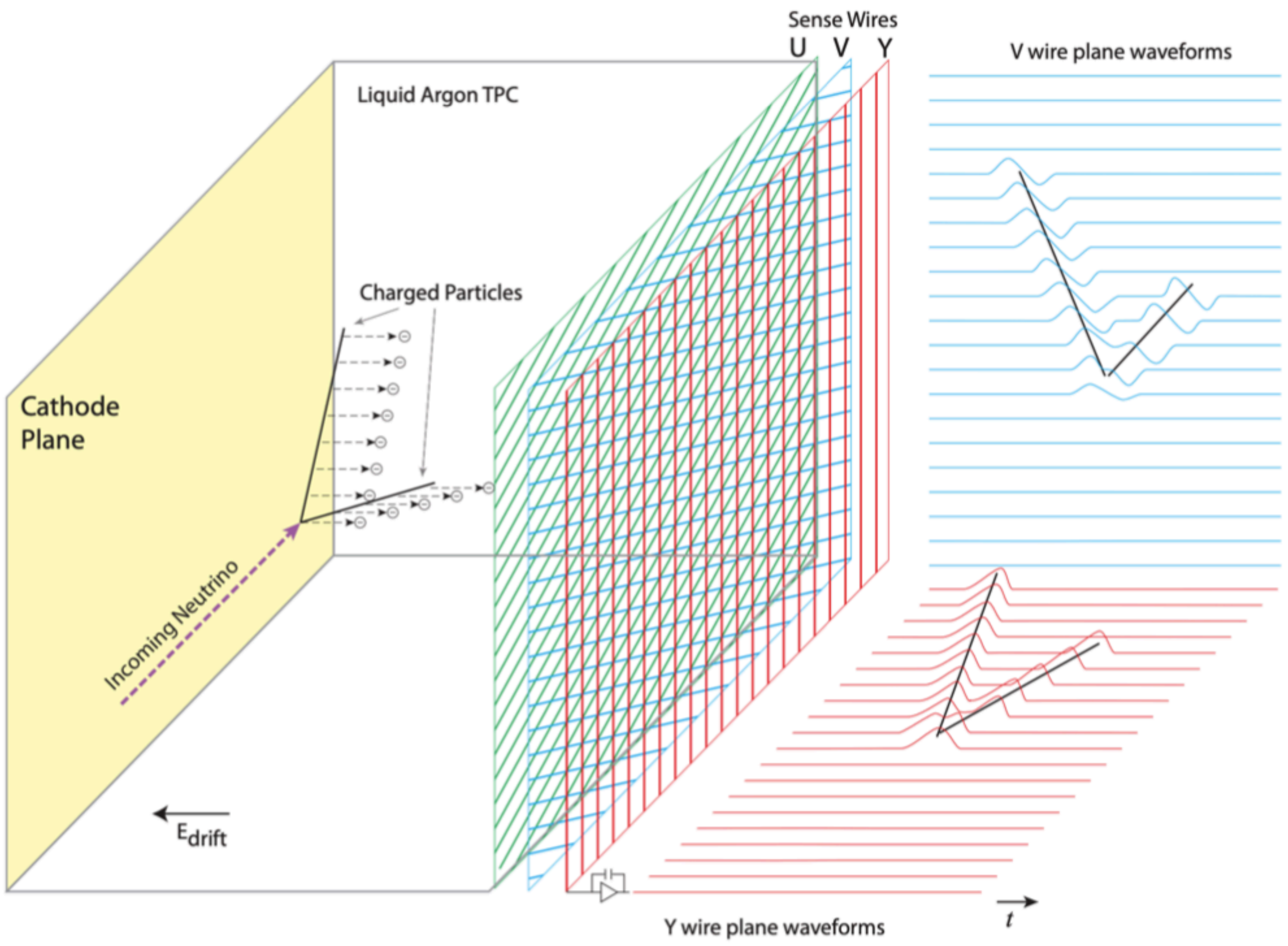


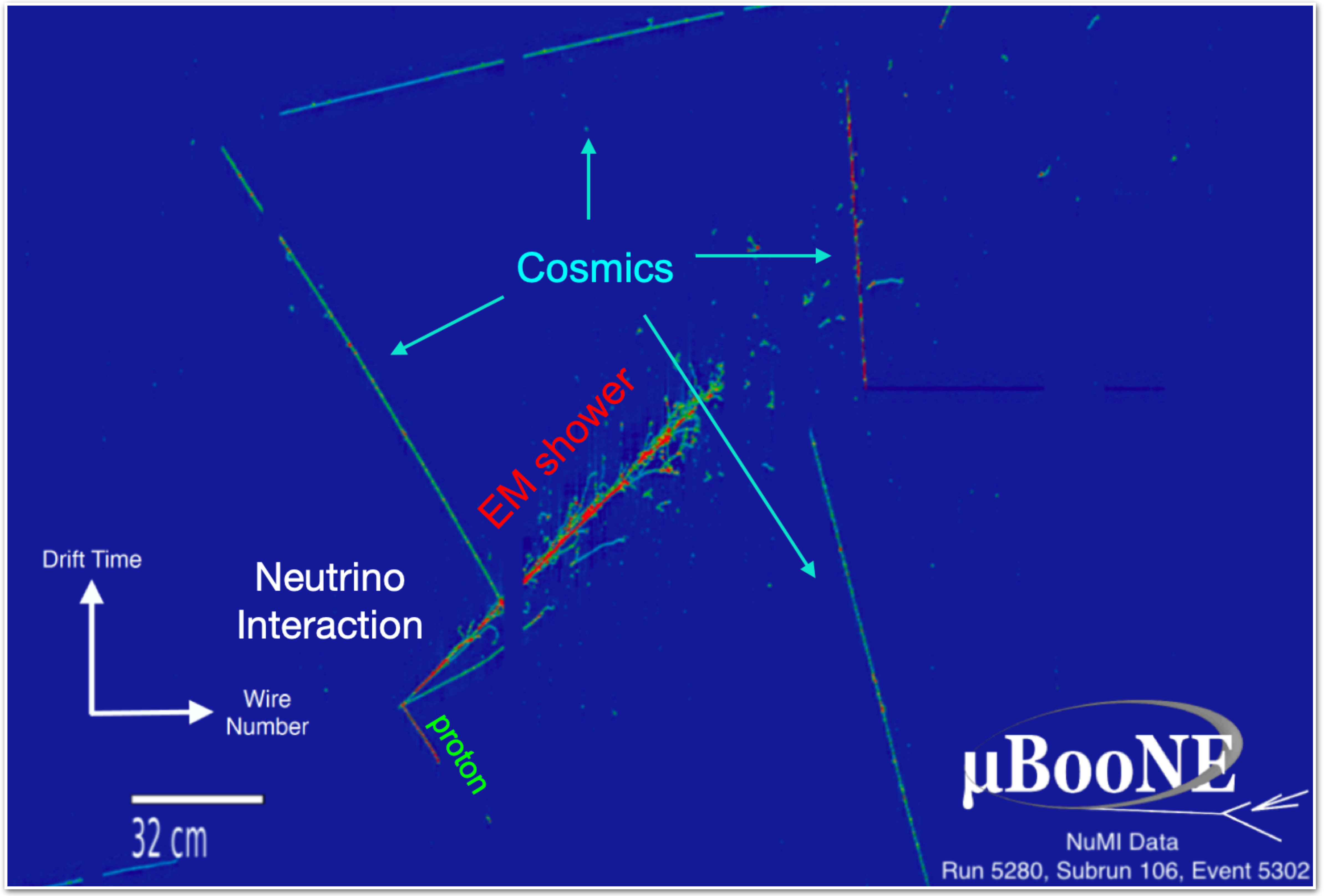




- MicroBooNE is an 85 tonne LArTPC exposed to the BNB and NuMI beams at Fermilab.
- Cryostat houses the **active volume of the TPC**.
- **Cosmic Ray Tagger** to veto cosmic rays (half of the dataset).

LArTPC

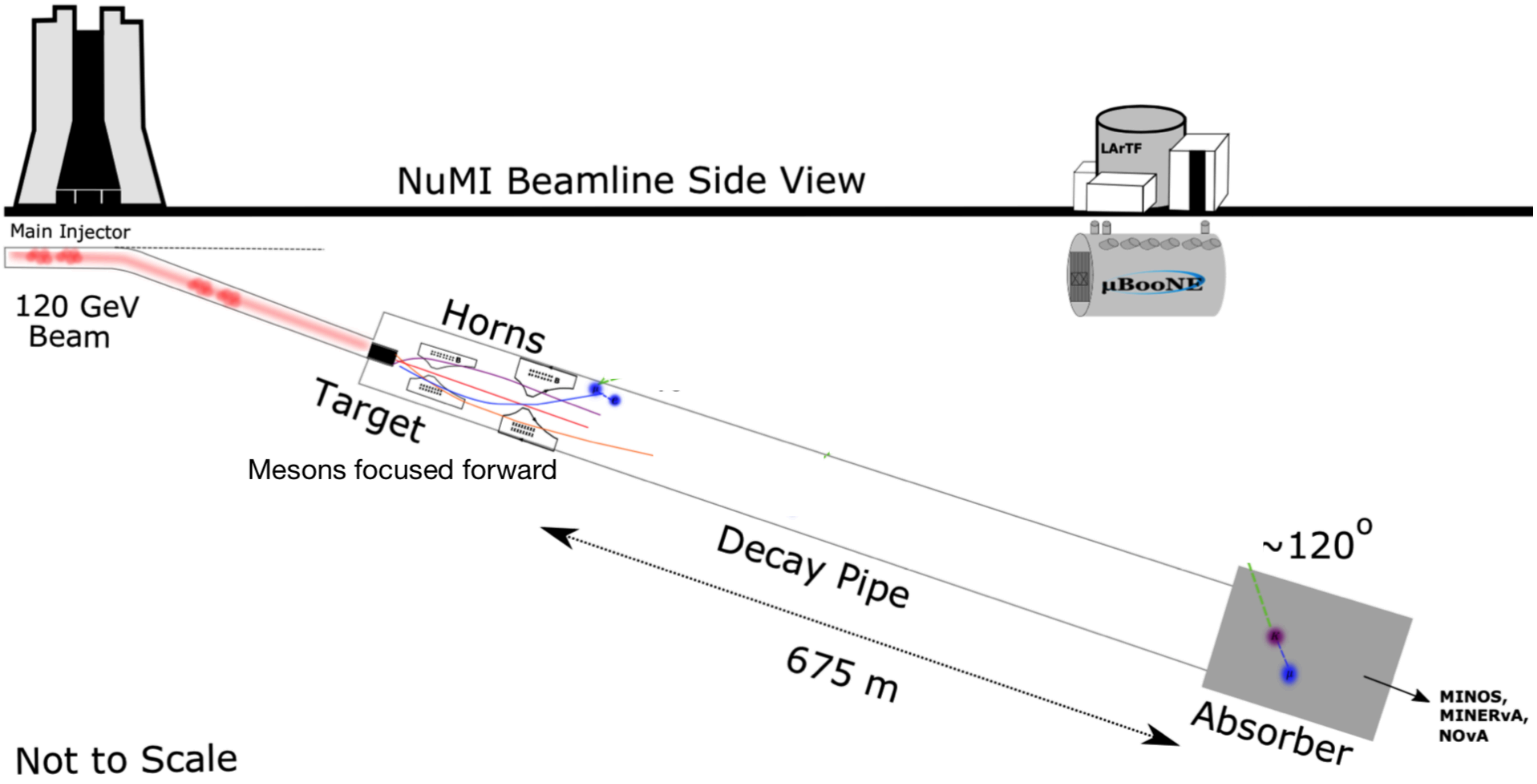




- Bubble chamber like images using scintillation and ionisation signals produced by the charged particle.
- Exploited to search for Higgs Portal Scalars.

- Excellent spatial resolution and calorimetry.
- Excellent particle identification.

MicroBooNE relative to NuMI beamline

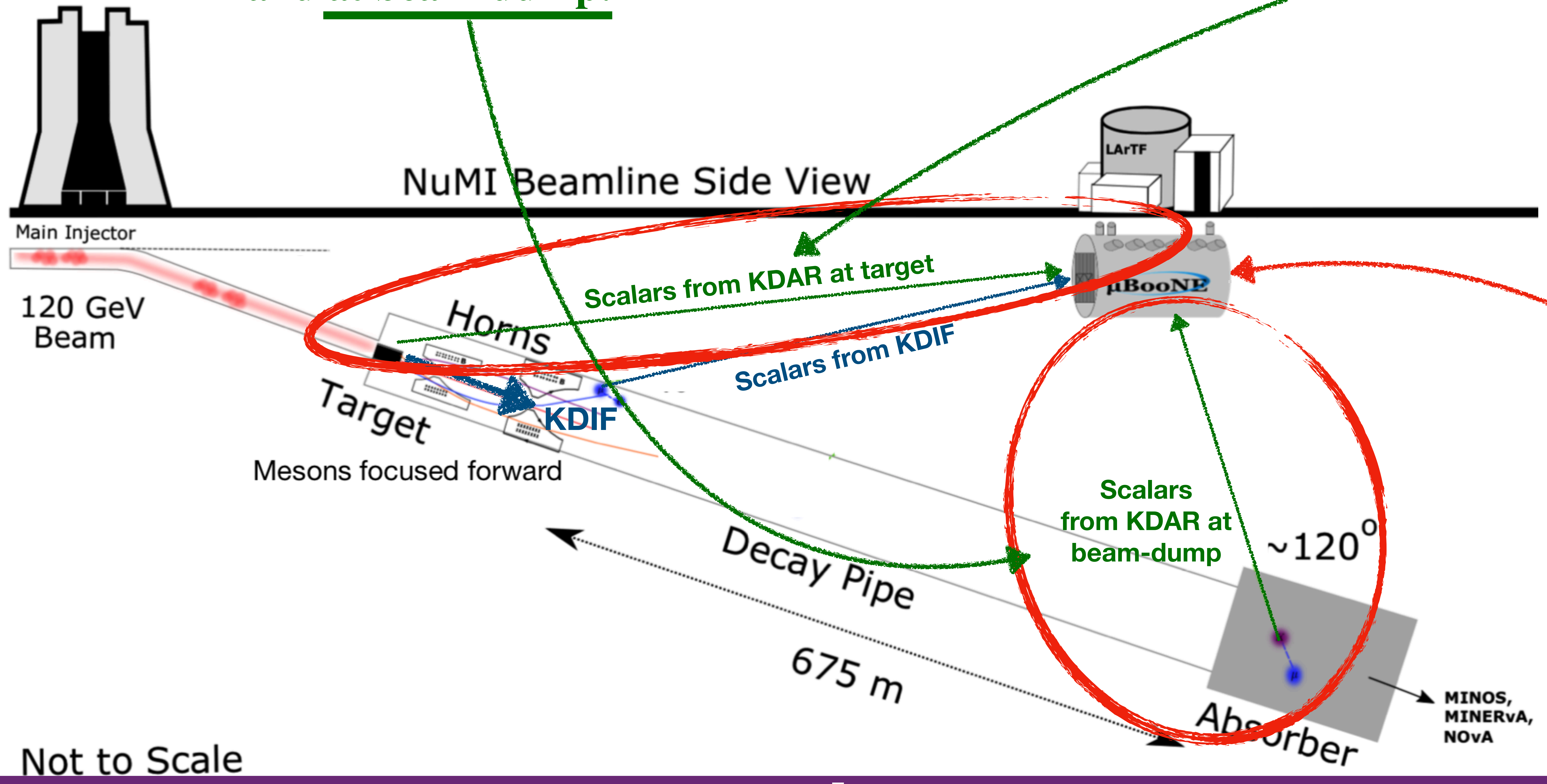


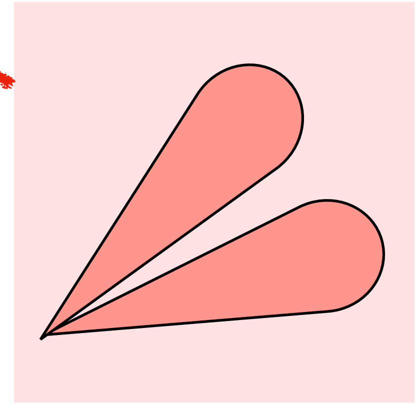
Courtesy: Krishan Mistry

Production of the Scalars from KDAR

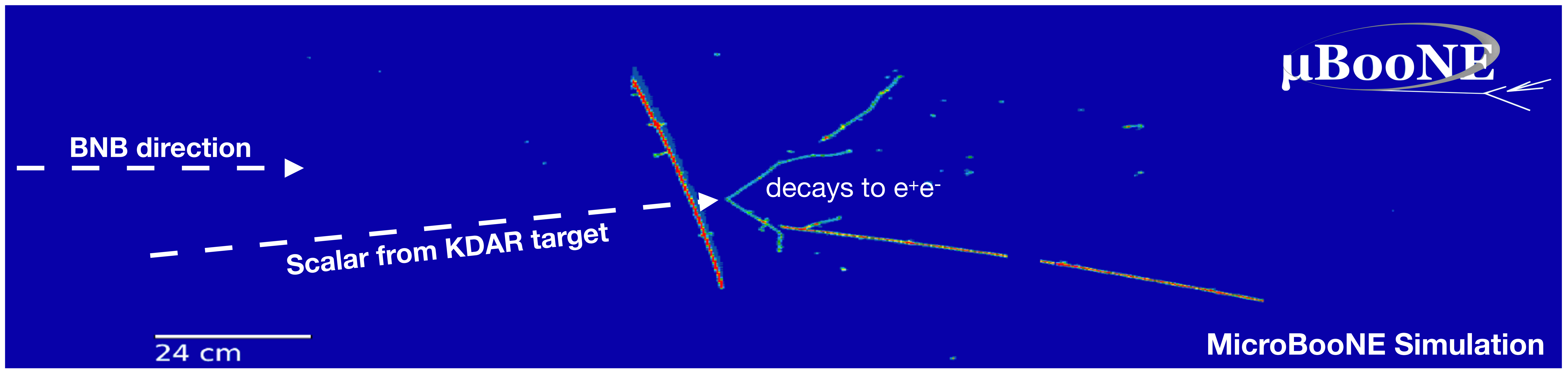
We will study the scalars produced from the following two:

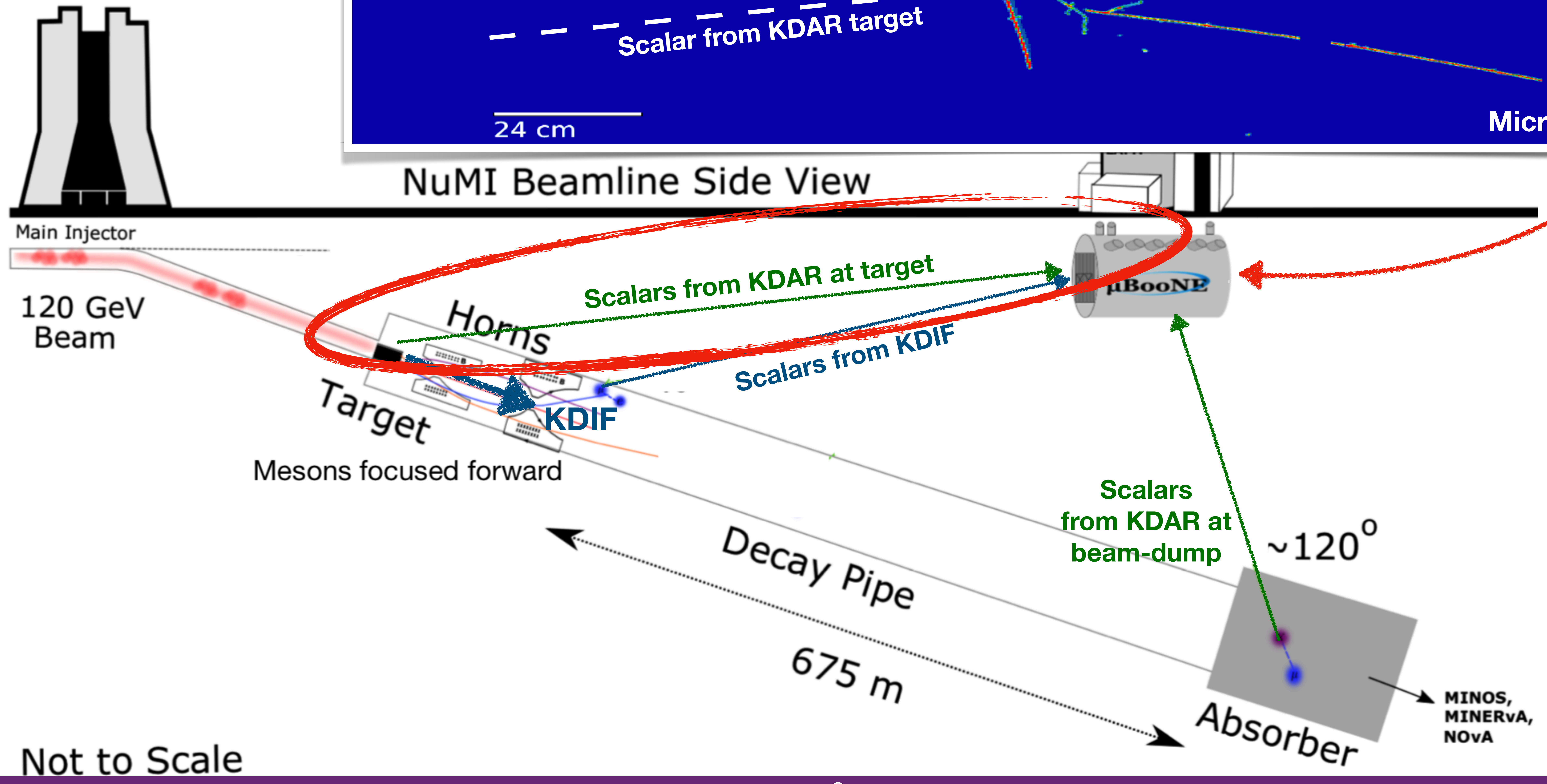
1. **Scalars produced from Kaons Decaying At Rest (KDAR) at Target and at beam-dump.**



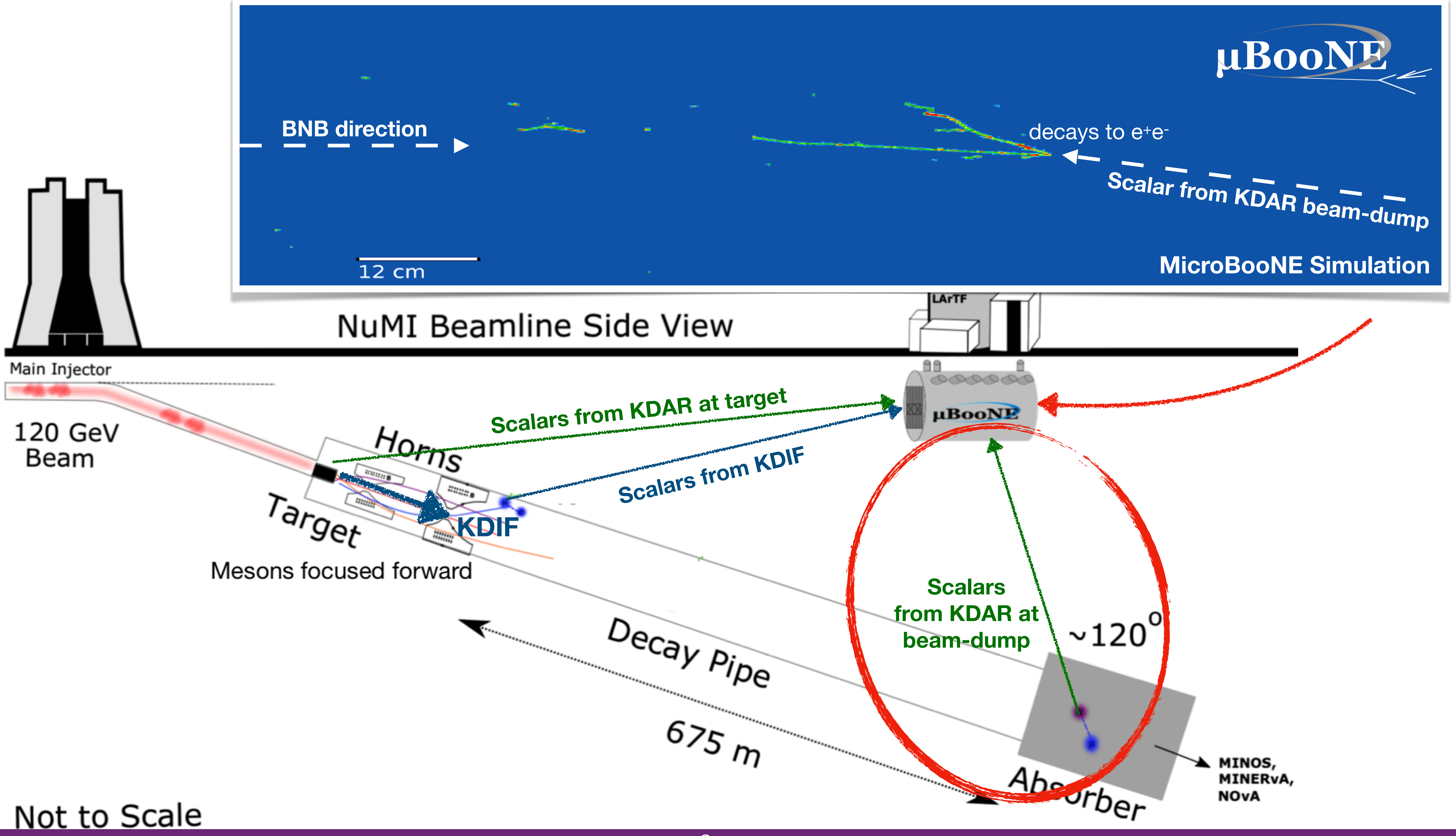


Production of the Scalars from KDAR (Target)





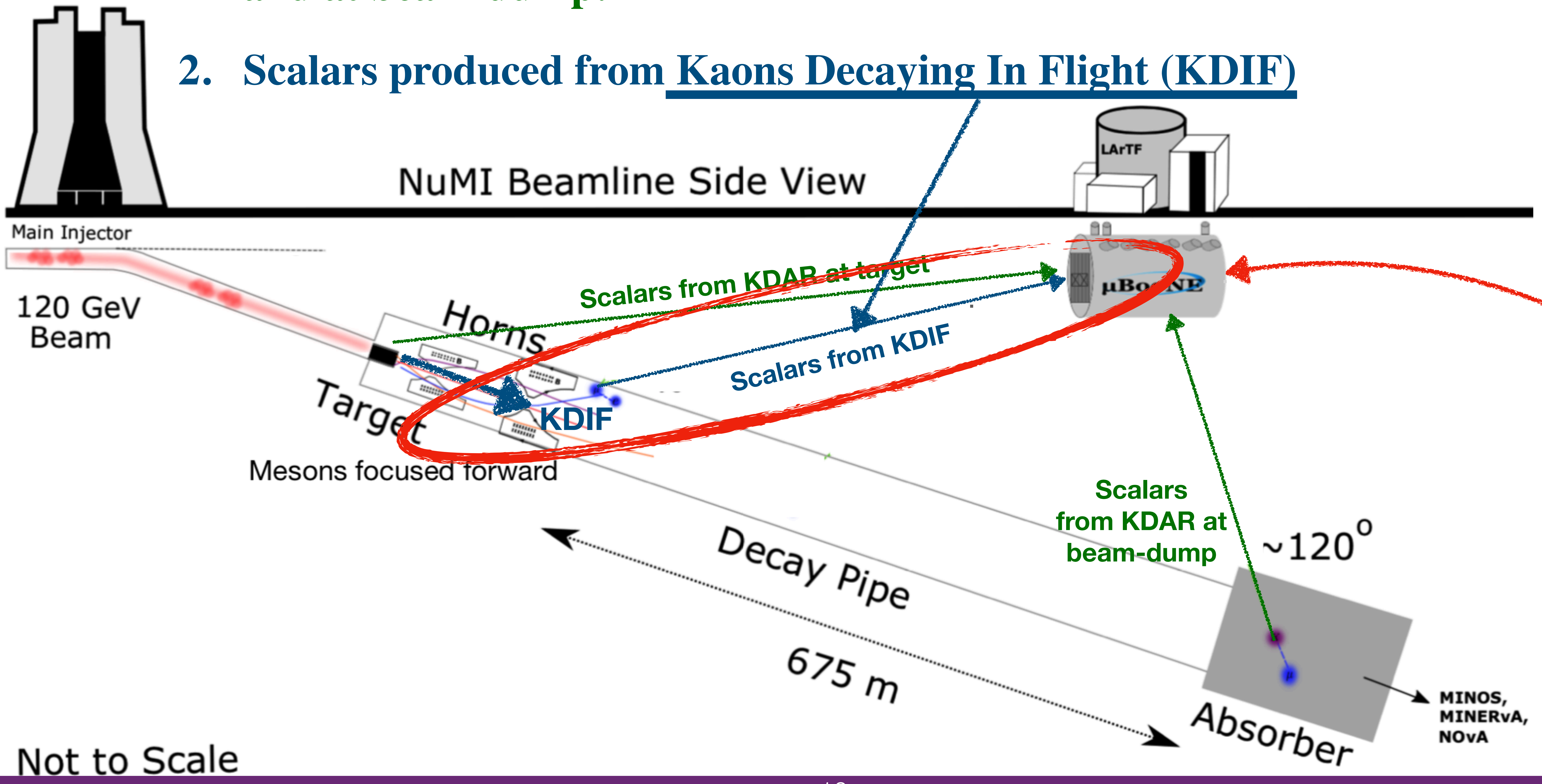
Production of the Scalars from KDAR (Absorber)

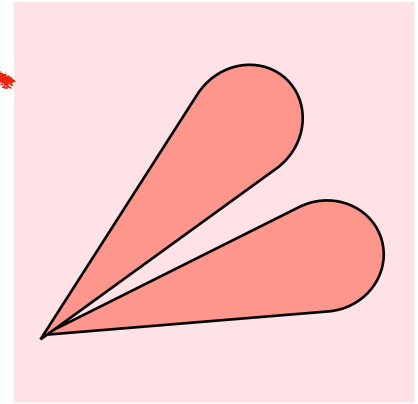


Production of the Scalars from KDIF

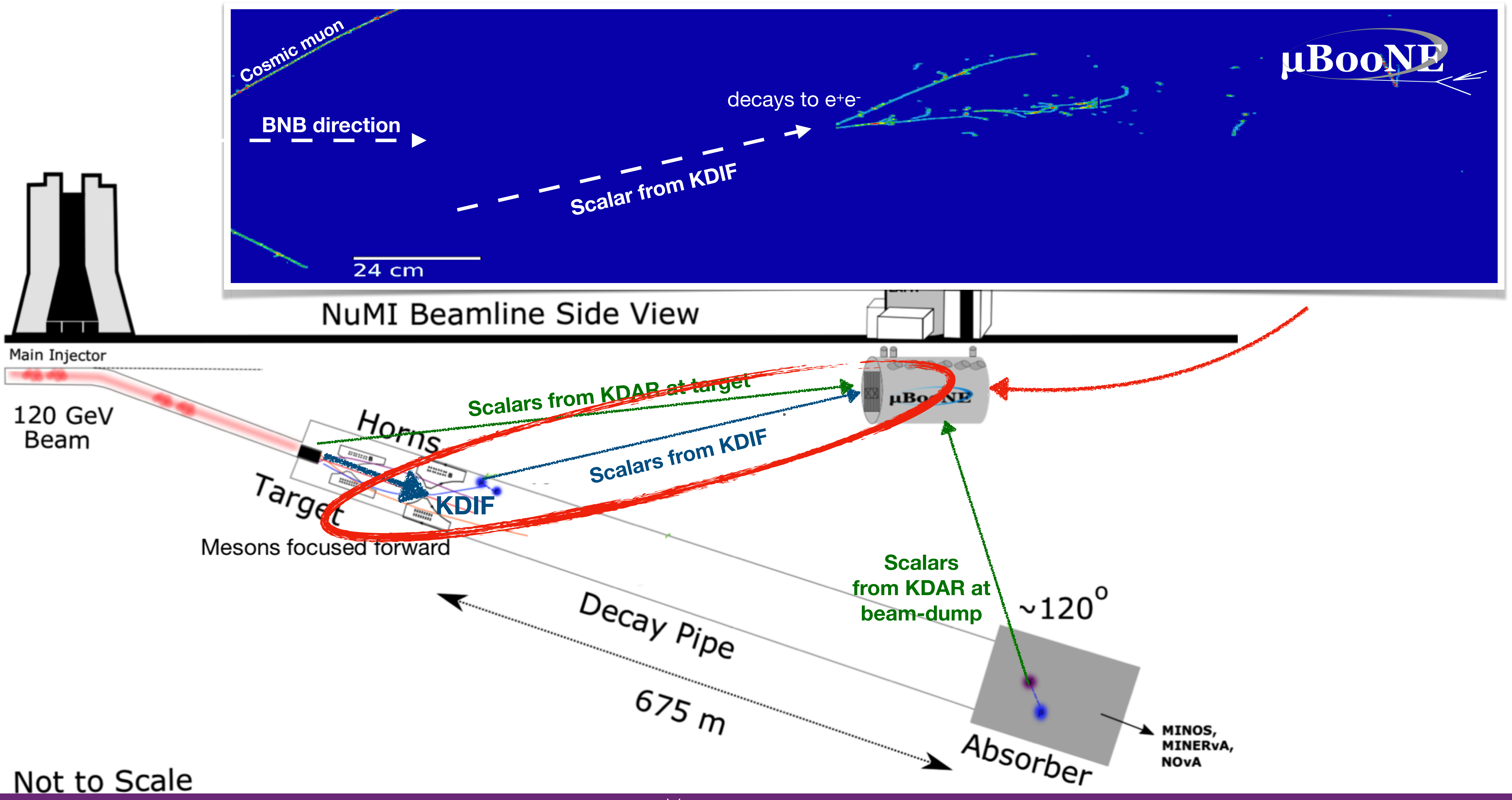
We will study the scalars produced from the following two:

1. **Scalars produced from Kaons Decaying At Rest (KDAR) at Target and at beam-dump.**
2. **Scalars produced from Kaons Decaying In Flight (KDIF)**





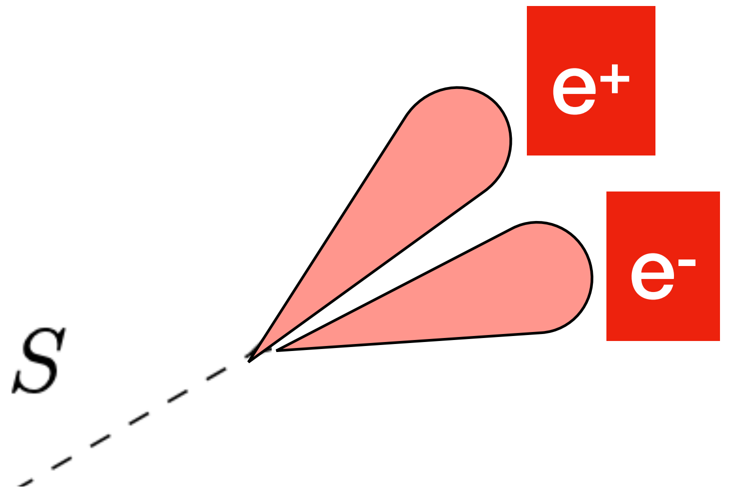
Production of the Scalars from KDIF



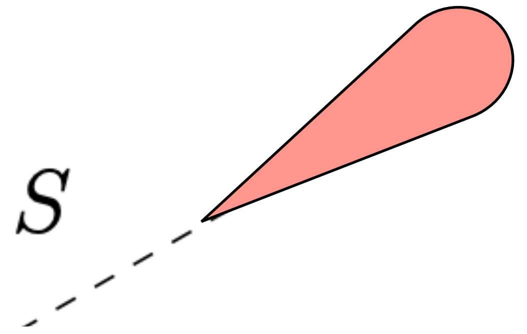
Scalar decays

- We look at the following two types of decay channels for our signal:

1. Scalar decays: reconstructed as **two showers**



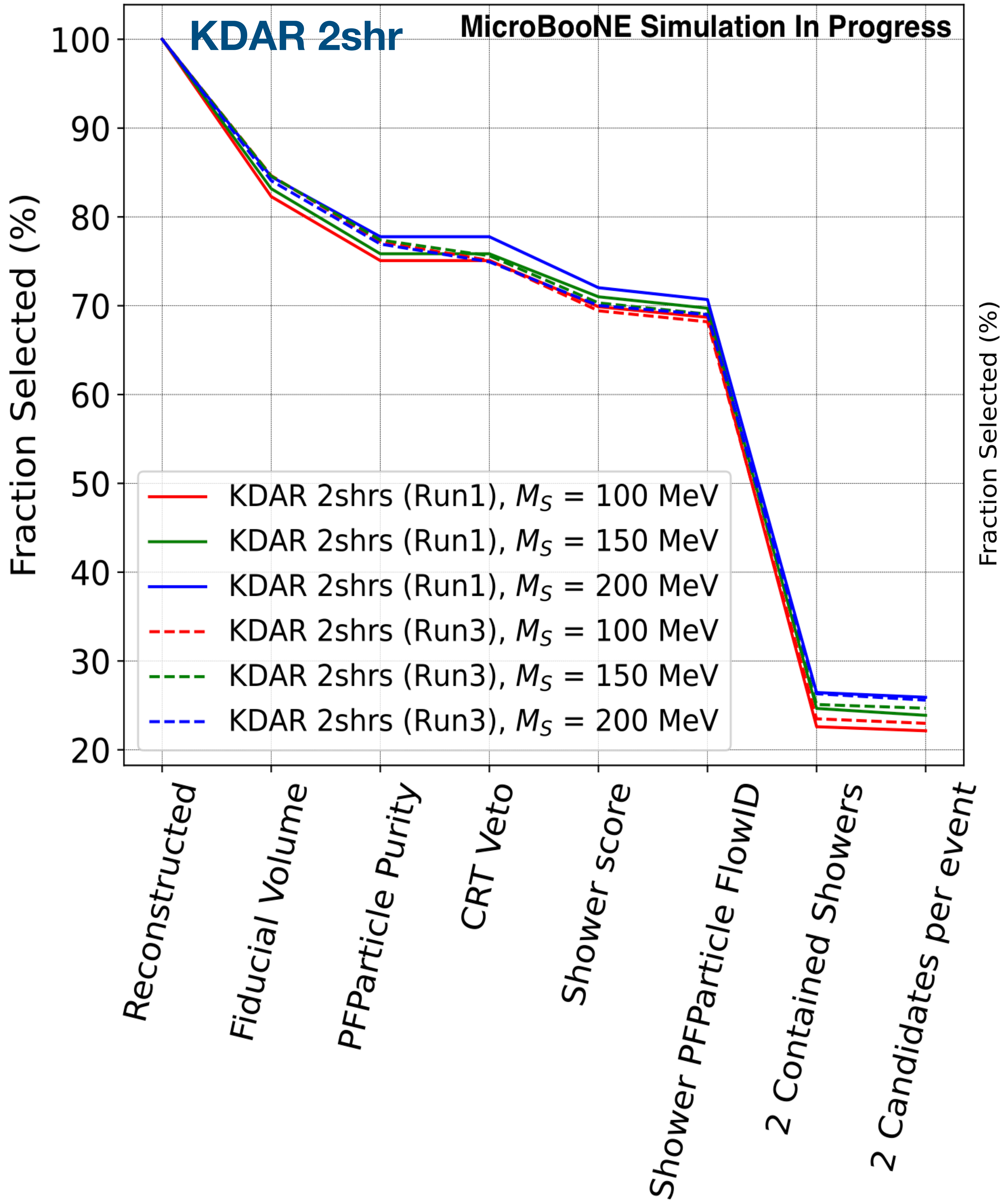
2. Scalar decays: reconstructed as **one shower**

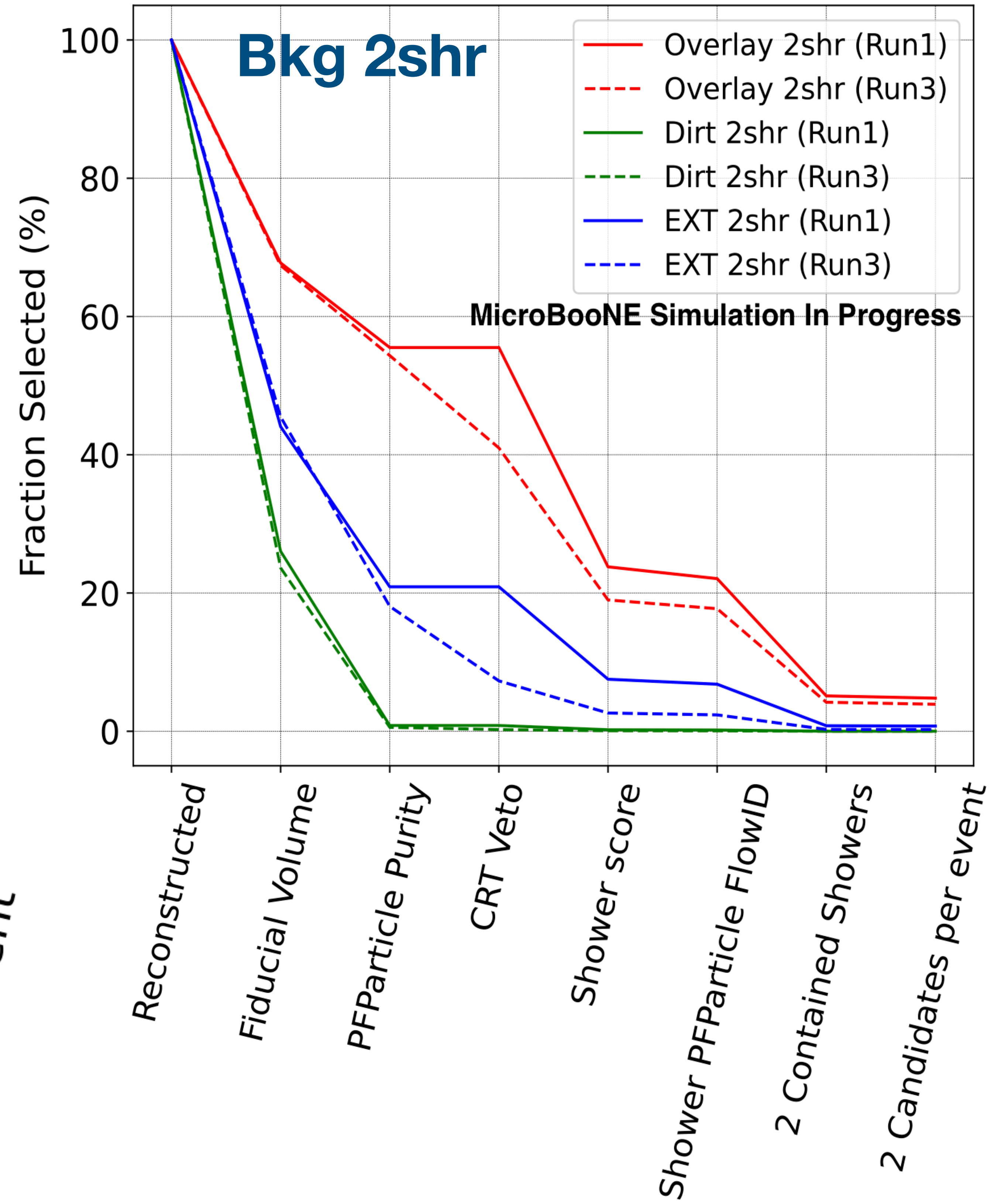


- This is done to increase statistics and improve sensitivity of these low mass scalars to MicroBooNE.

Preselection cuts

- A **fiducial volume cut** to ensure the interaction vertex is located within the fiducial volume of the detector.
- Shower selection cut: select only the showers and **reject tracks.**
- **Contained shower cut** to choose events with exactly **two showers** and exactly **one shower.**
- An additional **Cosmic ray tagger cut** will be applied to the data for which CRT is available.





BDT

After applying the preselection to our **signal** and **NuMI background**.

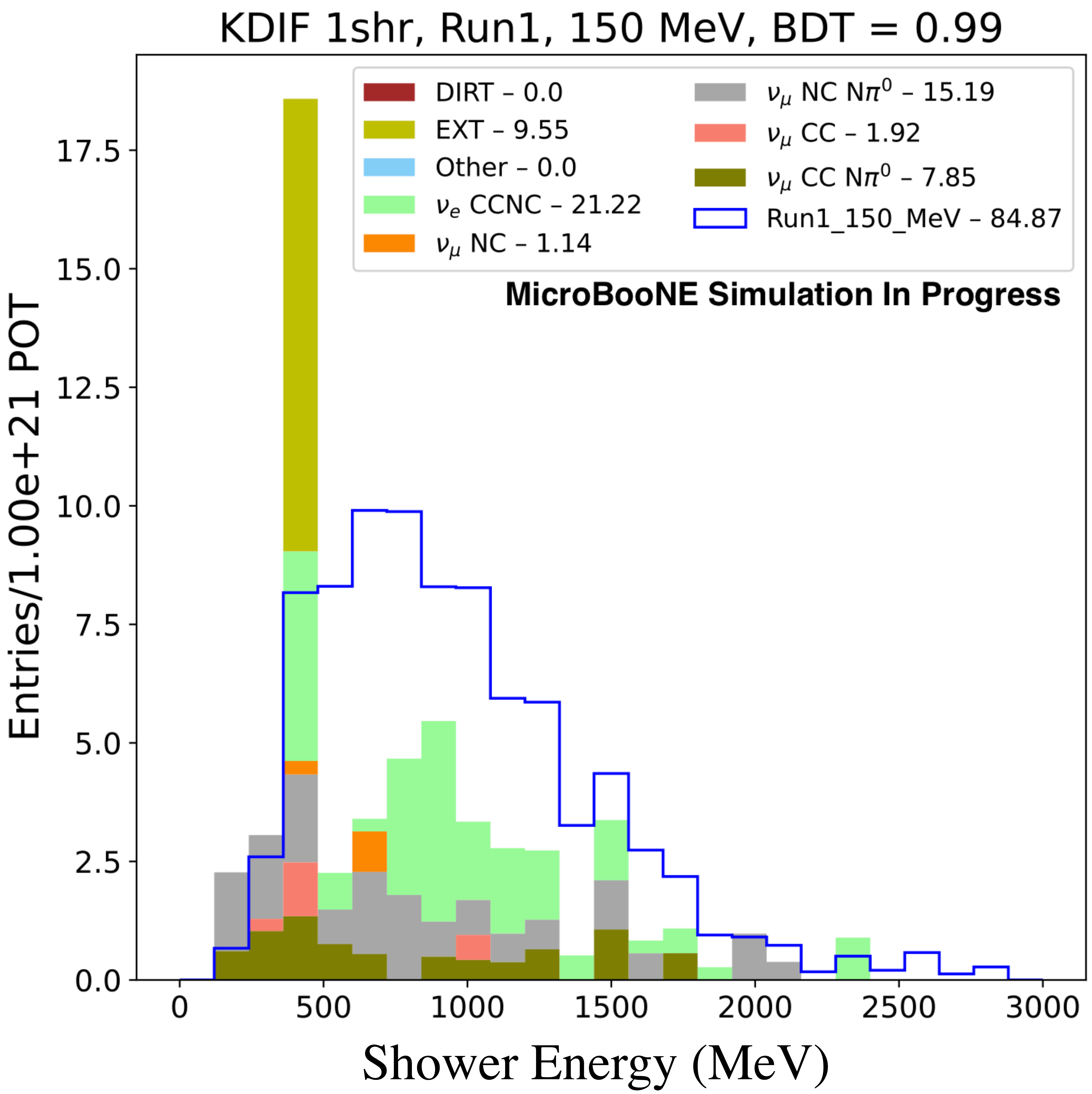
We trained 24 different BDT models in our analysis:

- Run1 and Run3 **(2x)**
- KDIF and KDAR 1-shr and 2-shr **(4x)**
- Three different masses of scalar: 100 MeV/c^2, 150 MeV/c^2 and 200 MeV/c^2 **(3x)**

In this presentation, we will only show the plots for **Ms = 150 MeV/c^2** to save time.

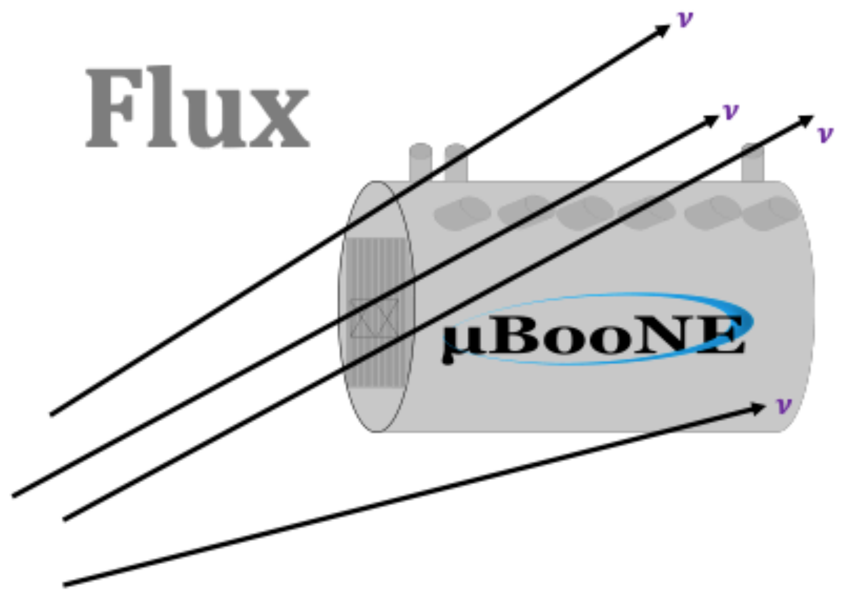
KDIF 1-shr after BDT

- **Signal** and **background** after applying pre-selection cuts and BDT.

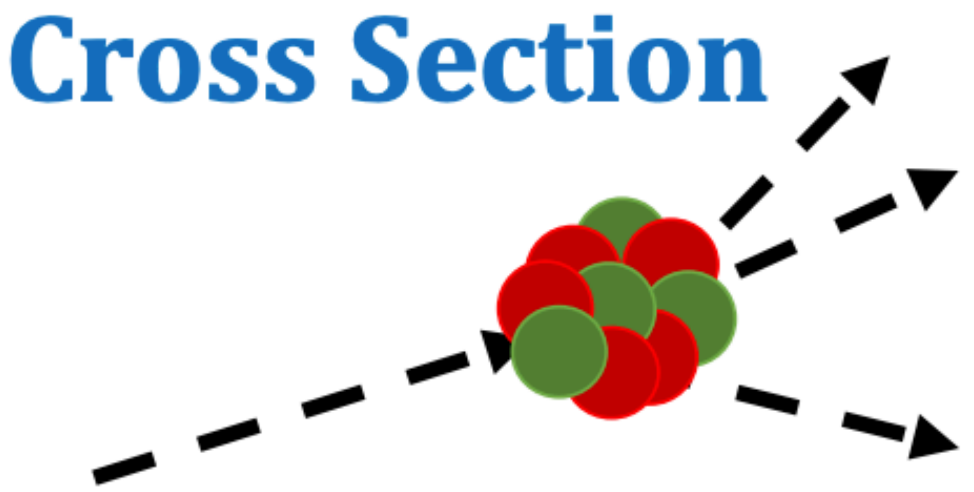


Systematics uncertainties

- **Flux uncertainties:** associated with the hadron production as well as simulation and modelling of the NuMI beamline.

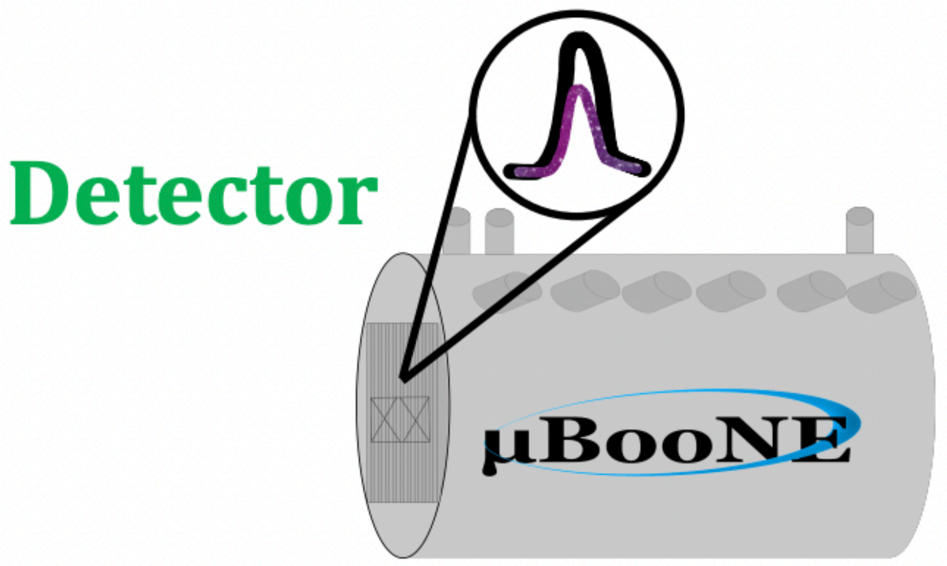


- **Cross-section uncertainties:** associated with the modelling of neutrino interactions from the GENIE neutrino generator and re-interactions of daughter particles in the argon (Background only).

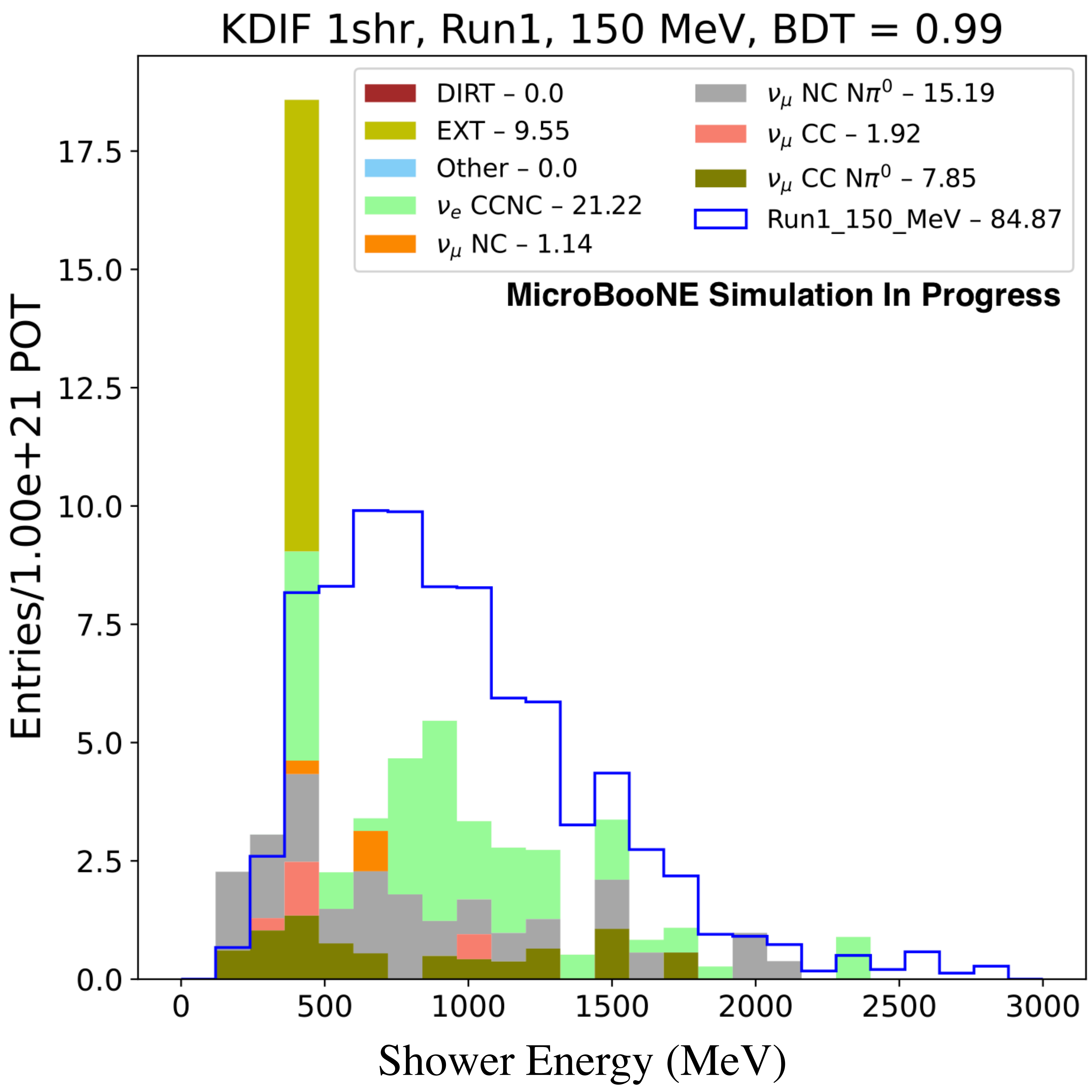


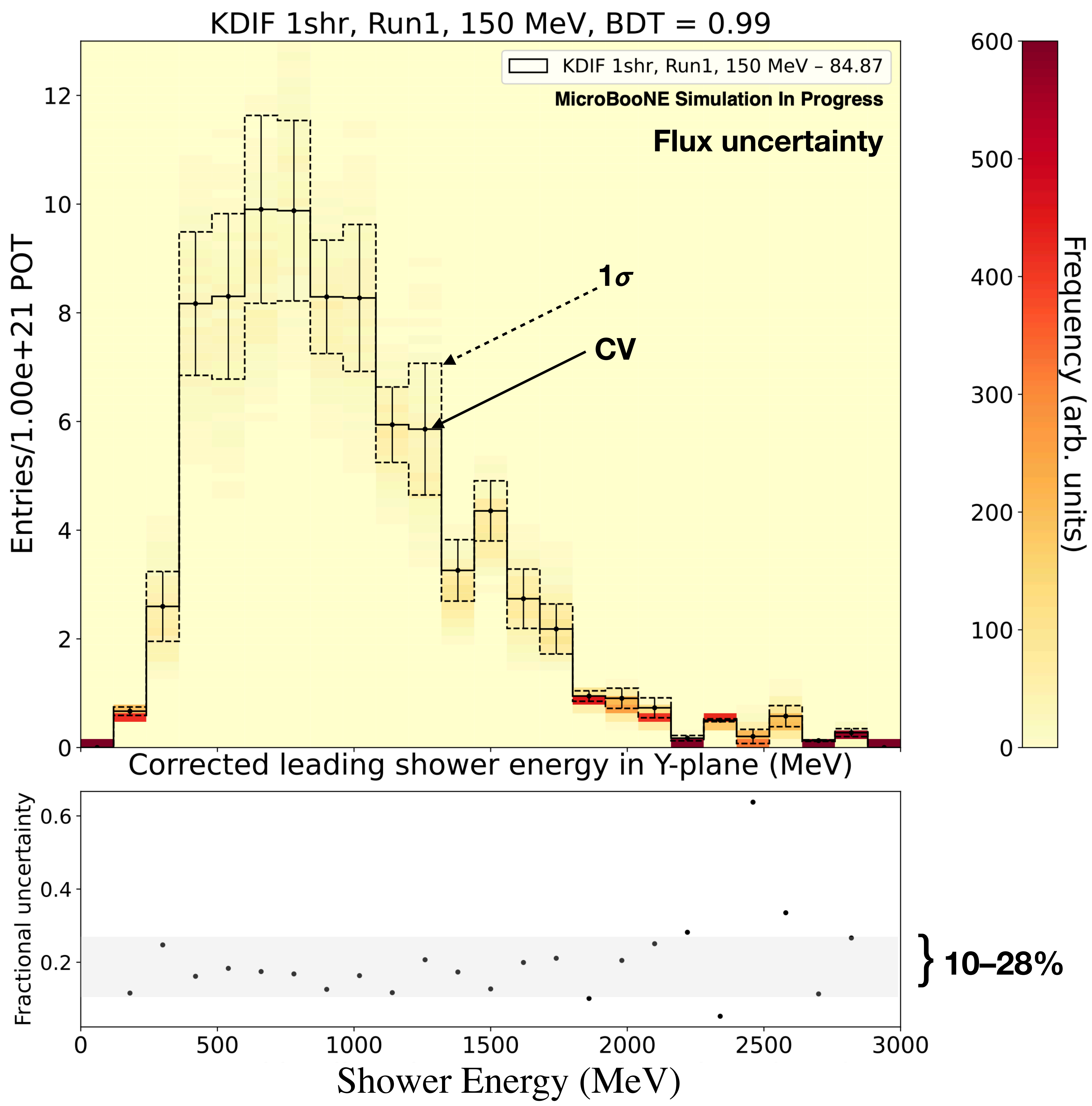
- **Re-interaction uncertainties:** associated with the **re-interactions of the daughter particles** (protons and pions) during propagation in the argon medium.

- **The detector uncertainties:** associated with simulation of the detector calculated by generating new MC samples with slightly different detector parameter

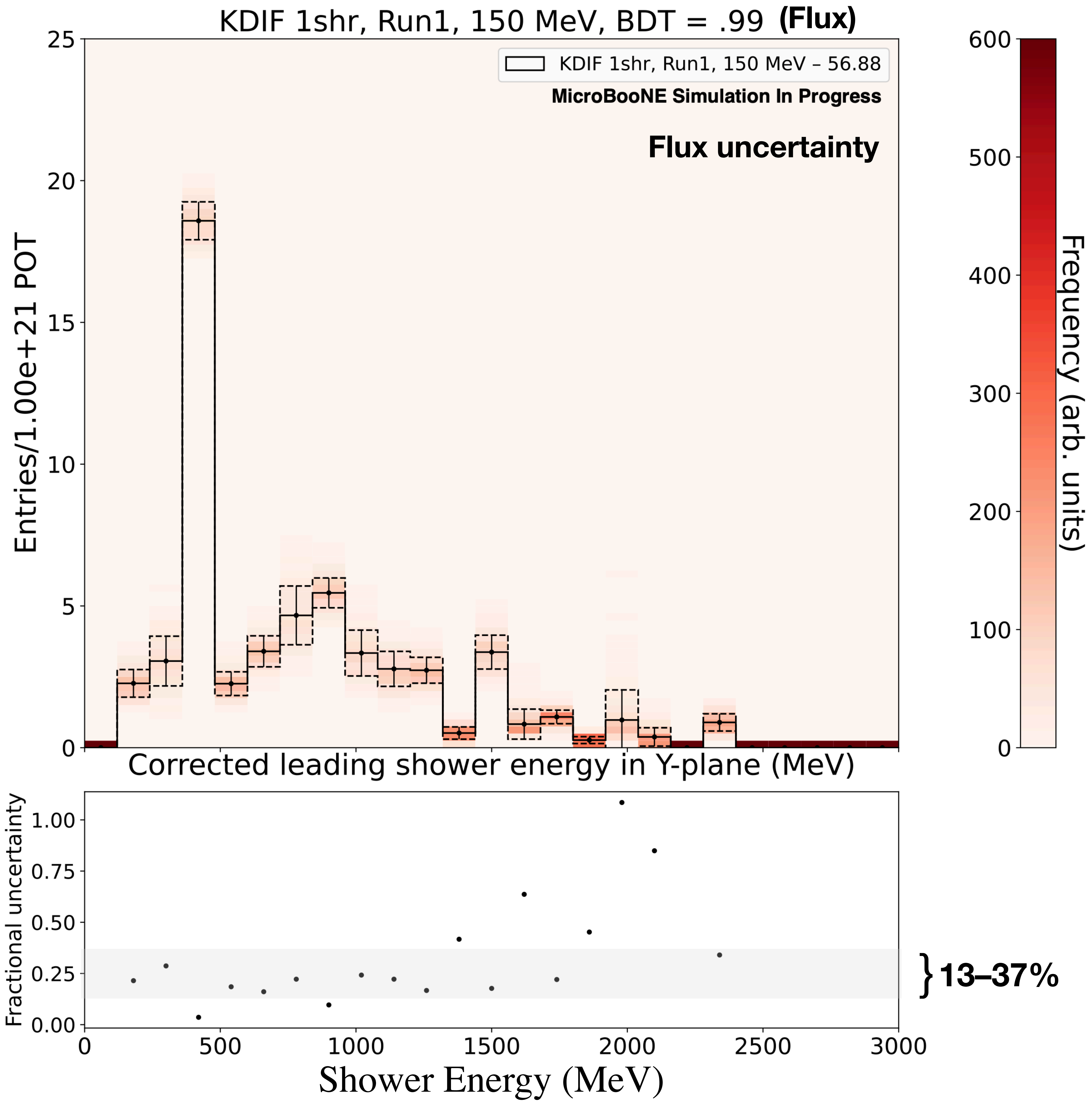


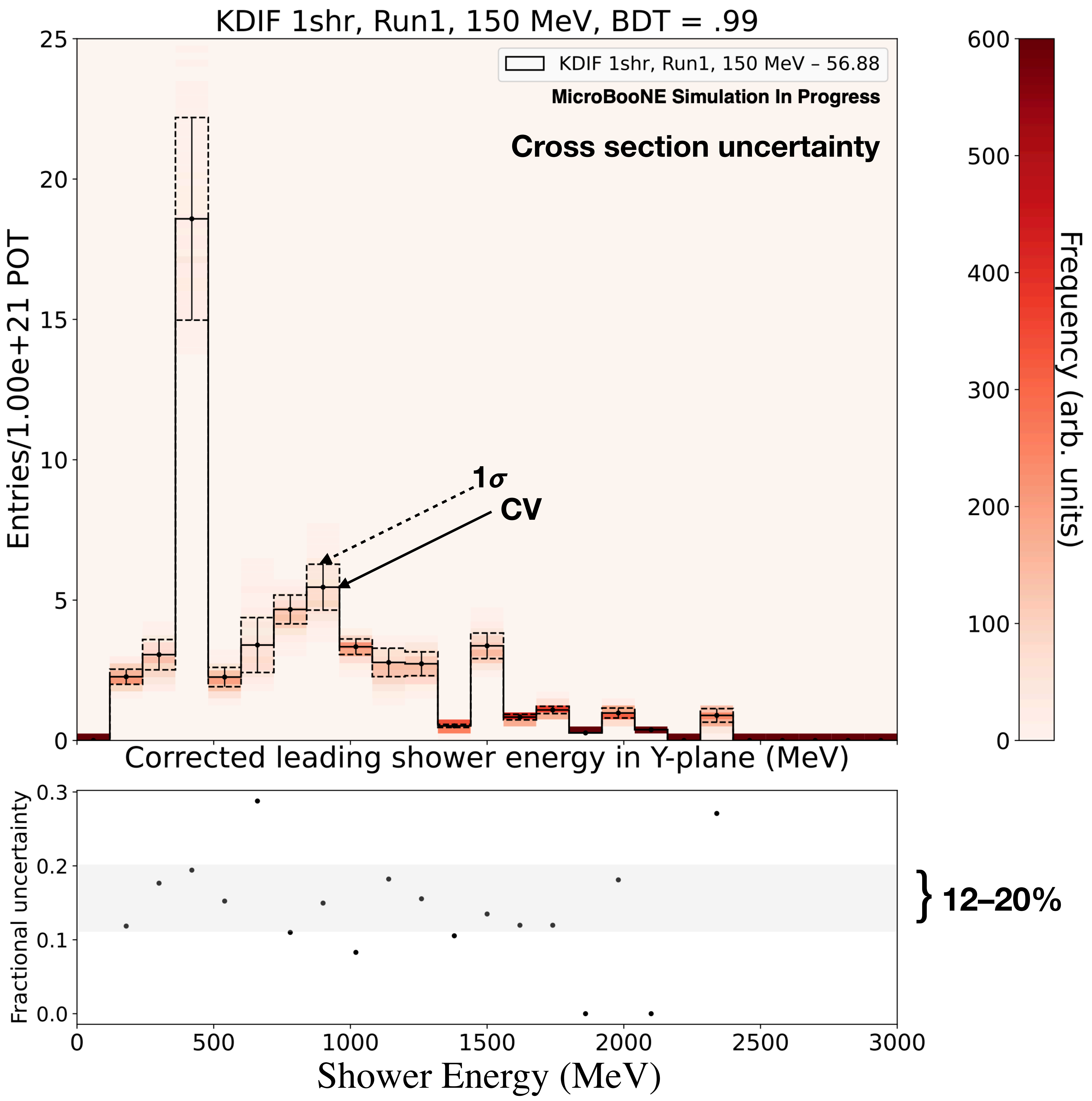
Signal: Flux uncertainty (KDIF 1-shr)



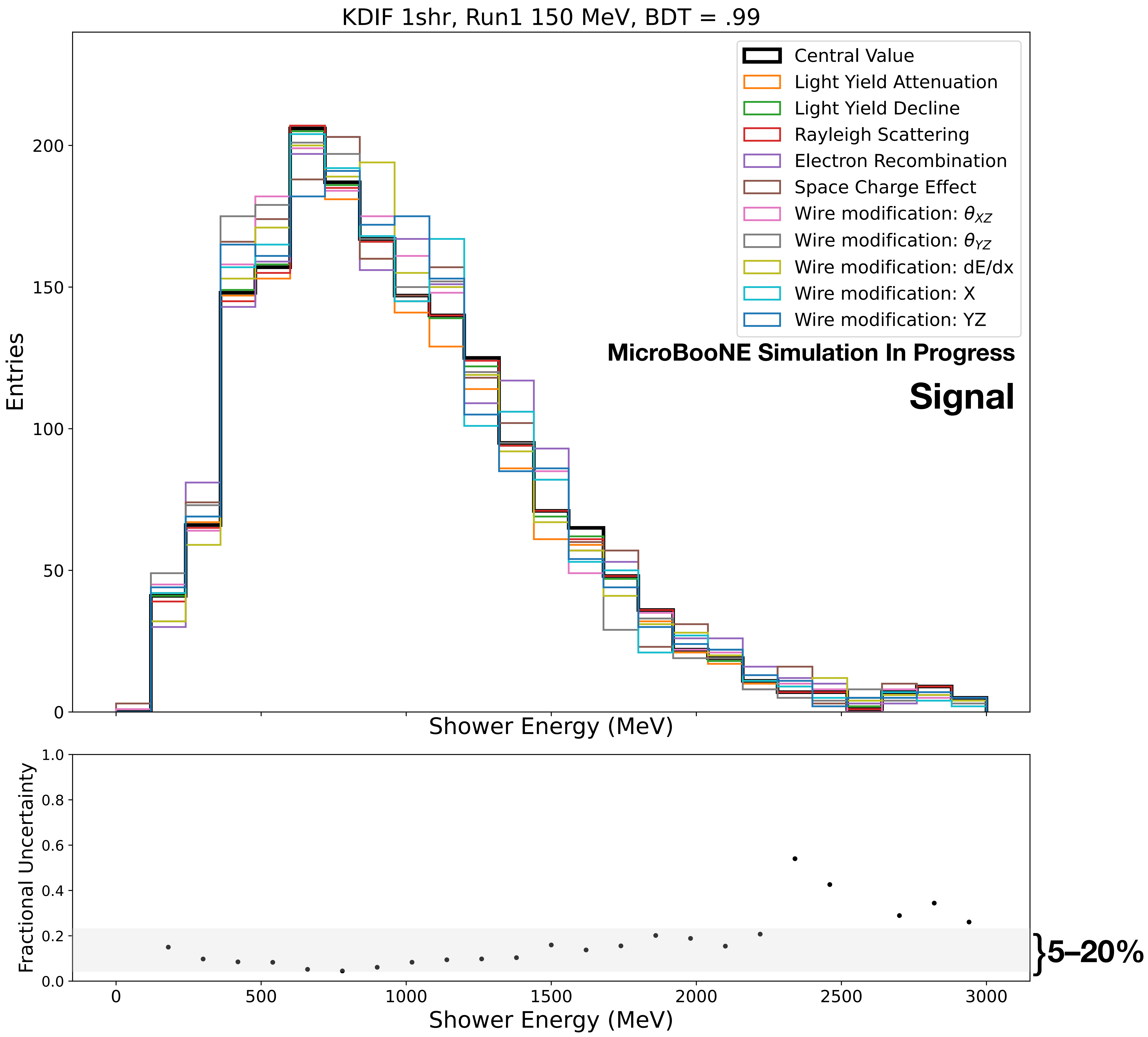


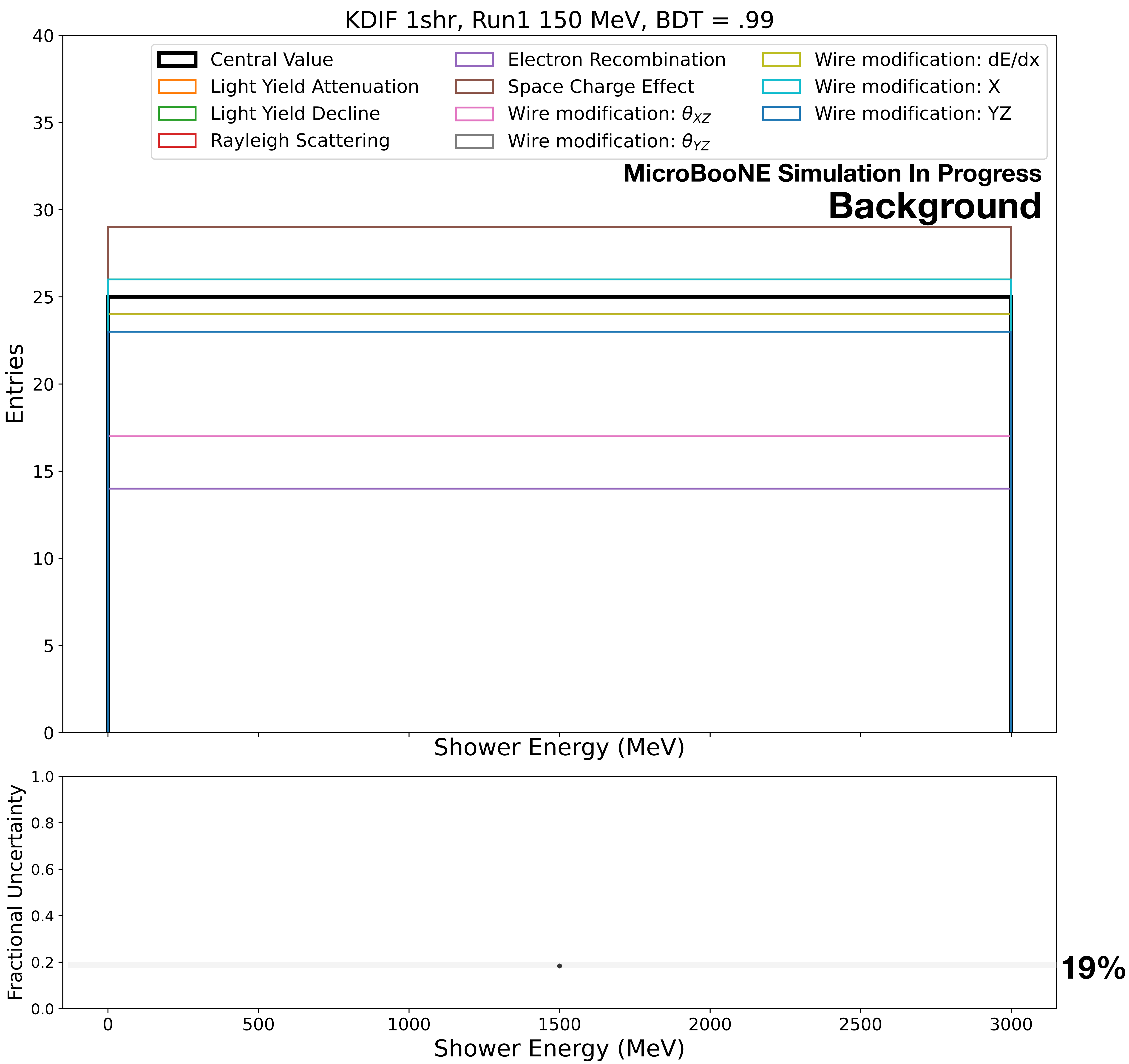
Background: Flux & Cross-section uncertainty (KDIF 1-shr)





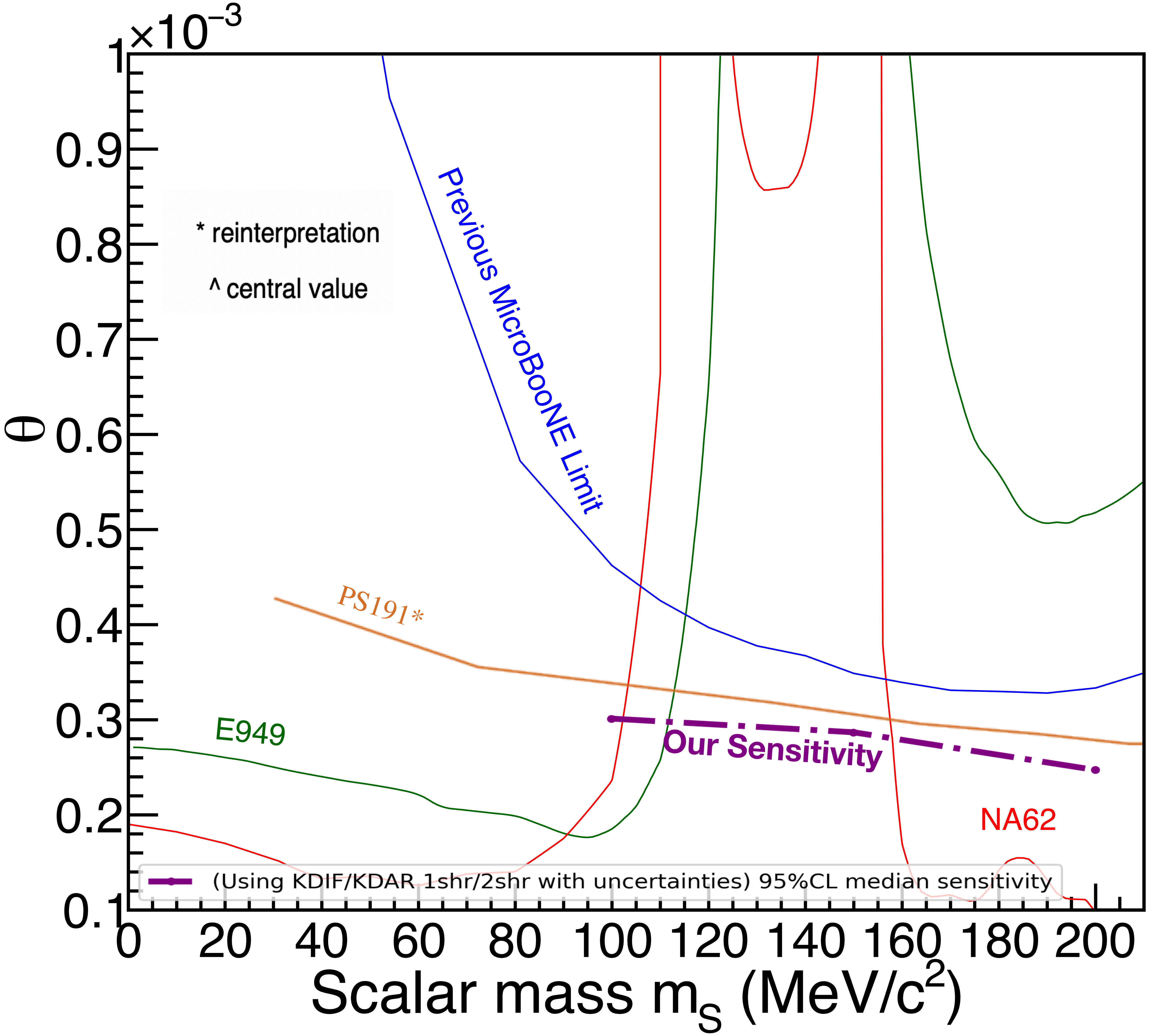
Detector systematics (KDIF 1-shr)





Sensitivity

- Combined all the channels for different masses of the scalar for our detector configuration and different signal topologies.
- 95% CL sensitivity.
- Our sensitivity is better than the results published by recent reinterpretation of PS191 arXiv:2105.11102.
- Phenomenologists estimated MicroBooNE sensitivity using the BNB arXiv:1909.11670 and we are exceeding these limits using NuMI data.



Conclusions and Future tasks

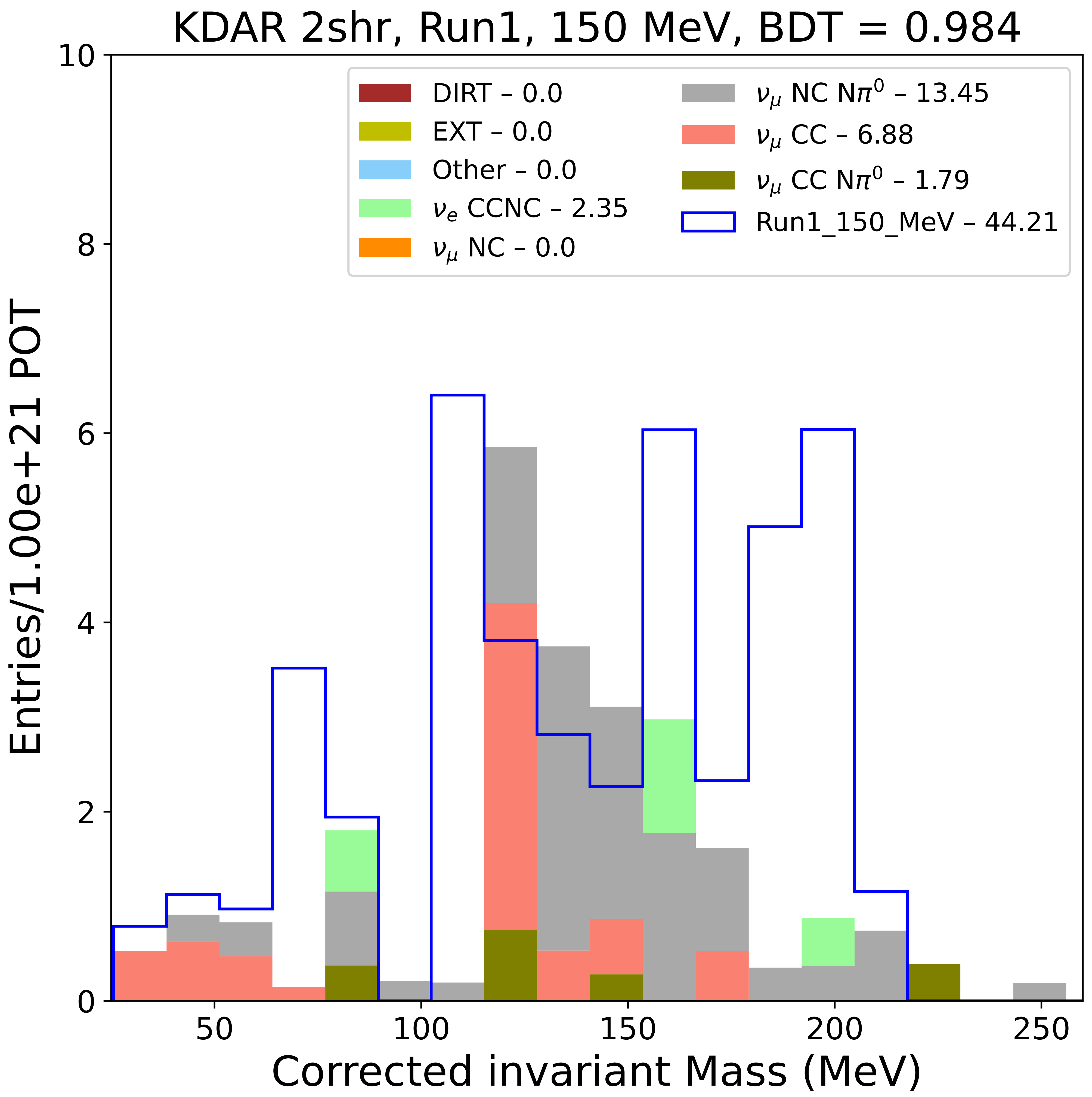
- We studied the sensitivity of the MicroBooNE detector to these low mass Higgs Portal scalar by including the flux uncertainty to signal, and flux and cross-section uncertainty to the background.
- This analysis will improve on the previous MicroBooNE limit.
- Apply my analysis to data and set the world's best limit.

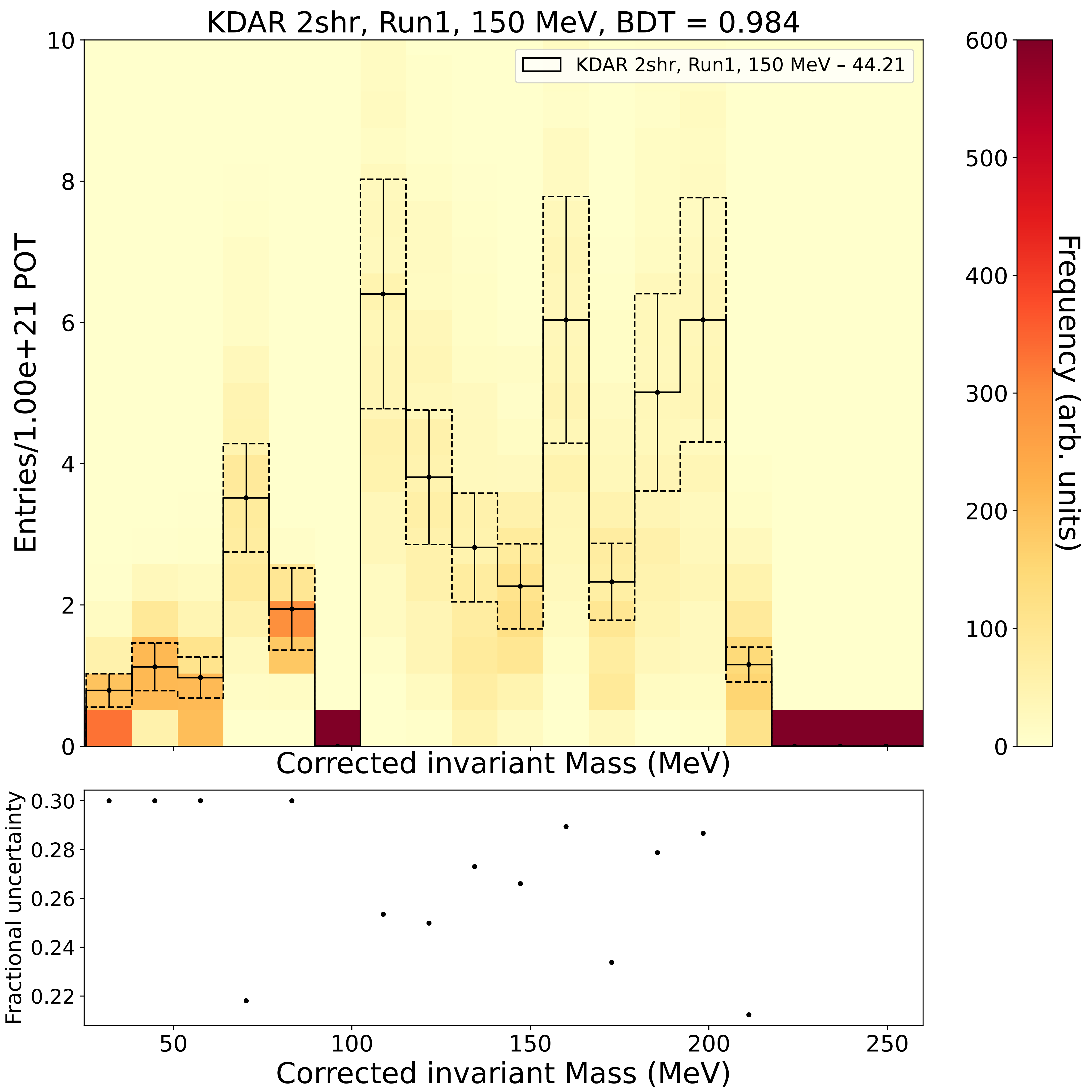
Thank you.

Back up slides

KDAR 2-shr

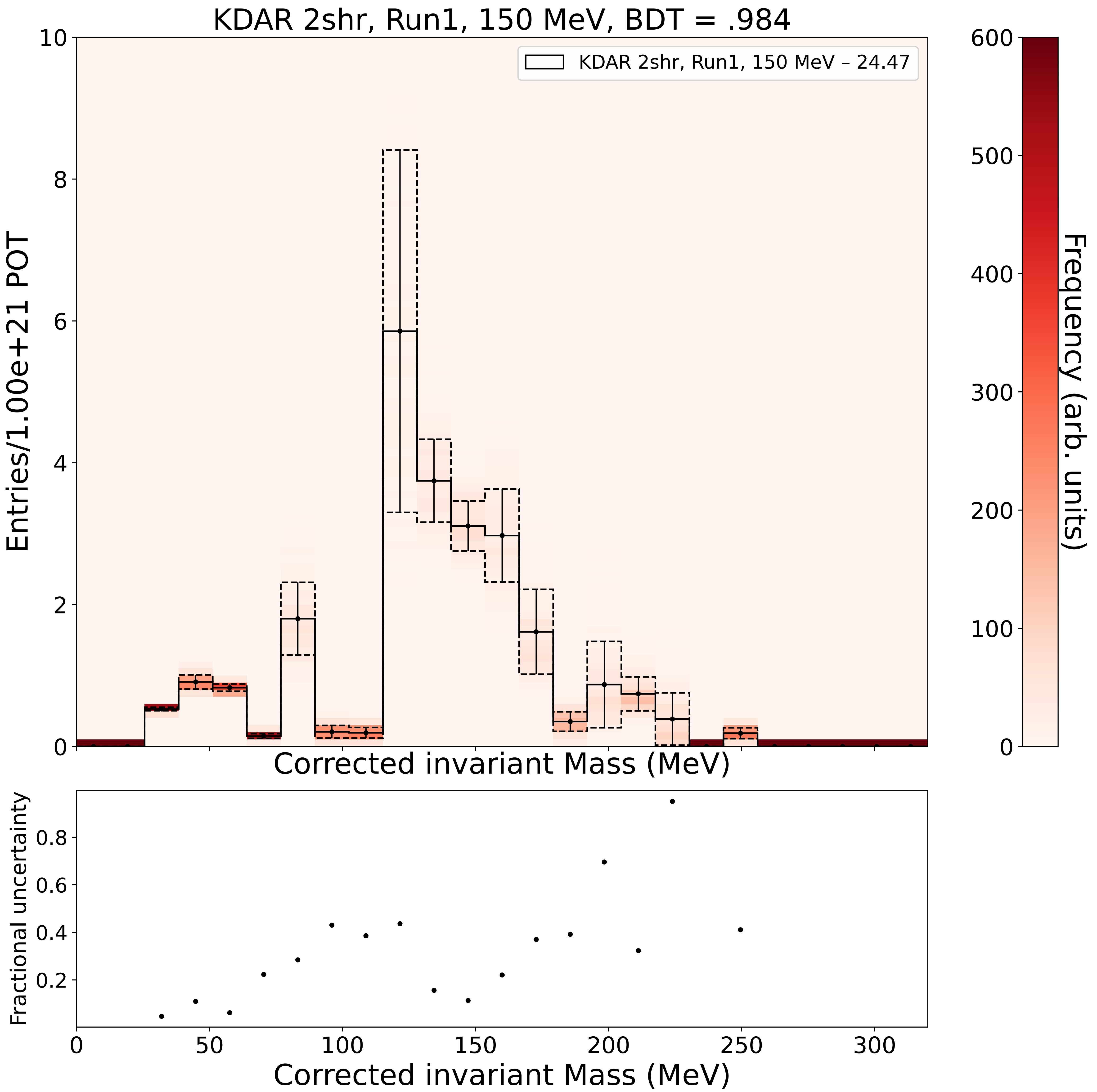
Signal: Flux uncertainty (KDAR 2-shr)

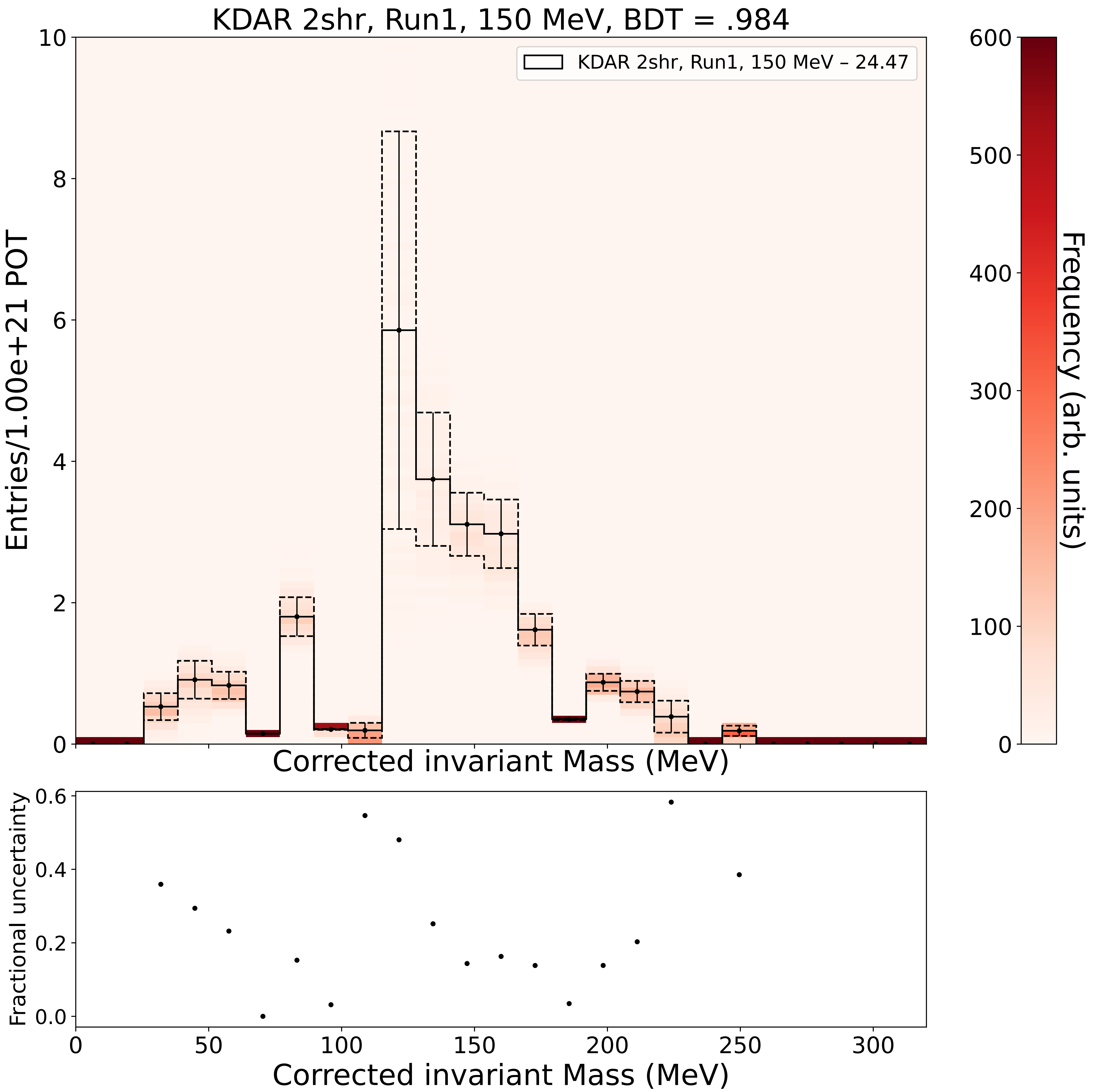




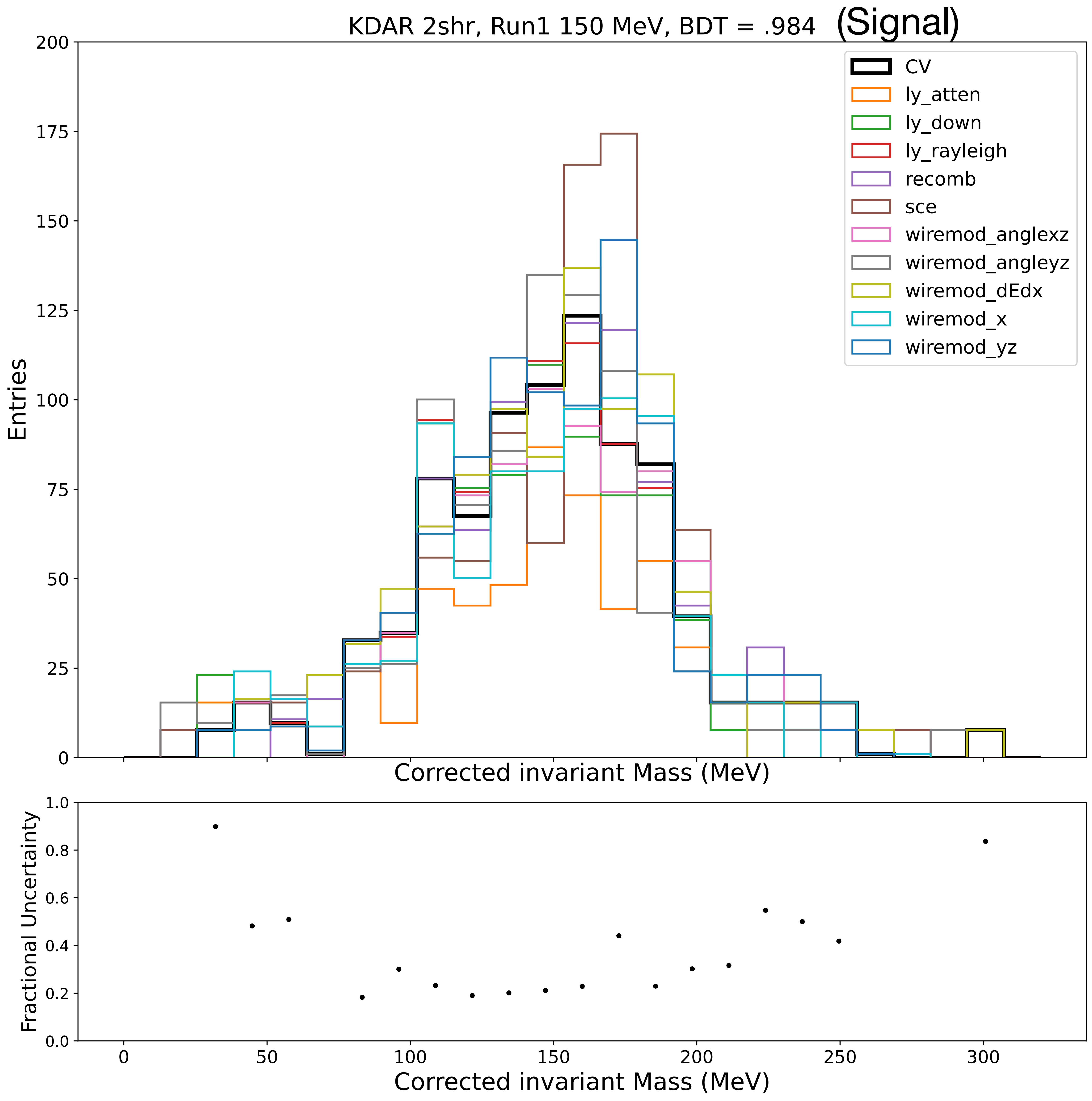
For the signal, there is a rate-only flux uncertainty, with a value of 30% as in the MiniBooNE KDAR measurement. [arXiv: 1801.03848](https://arxiv.org/abs/1801.03848)

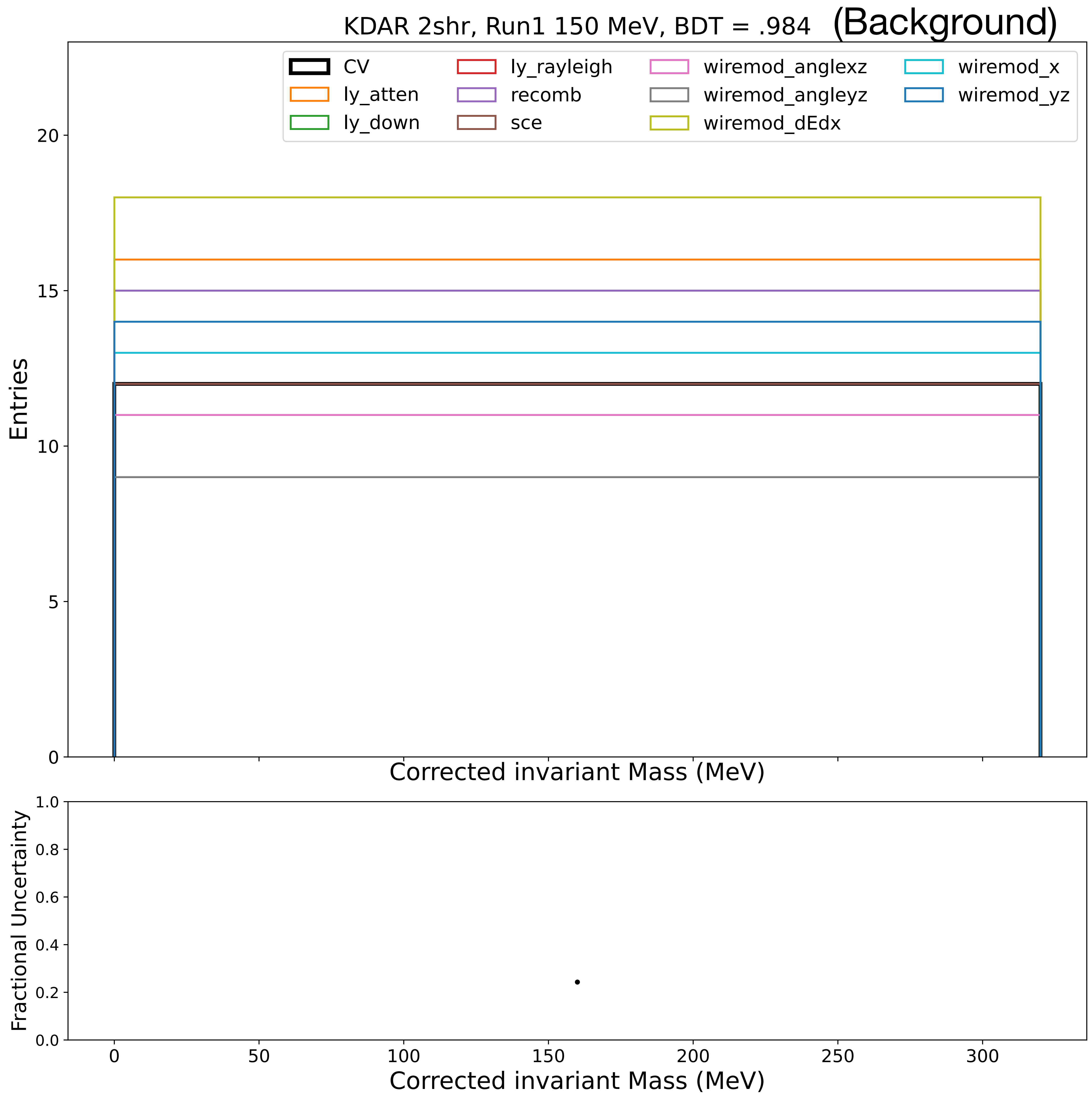
Background: Flux & Xsec uncertainty (KDAR 2-shr)





Detector systematics (KDAR 2-shr)





BDT

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BDT: Feature Importances

- A total of **~470 reconstructed variables** were fed into the BDT to find the variables that were crucial in separating the signal from background.
- An example for different masses of the scalar produced from KDIF 2-shr Run1 is shown on right.
- We notice that some variables such as **n_tracks_ls, contained_fraction_ls etc are common** for different masses of the scalar.
- First 20 most important features were selected in training the BDT models.
- The explanation for these variables is in backup slides

100 MeV

Feature_names	importances
n_tracks_ls	0.098552
shrclusdir1_ls	0.076318
contained_fraction_ls	0.052455
shr_id_MCStool_ls	0.036266
trk_energy_ls	0.032472
shrStartMCS_2_5cm_ls	0.023369
shrclusdir0_ls	0.019939
trk_energy_hits_tot_ls	0.019843
shr_pitch_u_v_ls	0.019102
trk_chipr_best_ls	0.016665
pi0_dir1_z_ls	0.014028
shr_pz_ls	0.014015
NeutrinoEnergy2_ls	0.011461
shr_theta_ls	0.009723
trk_energy_muon_mcs_ls	0.009638
hits_u_ls	0.009005
dtrk_ls	0.008550
trk_dir_z_v_ls	0.008240
hits_v_ls	0.008131
shr_pz_v_sls	0.007949

150 MeV

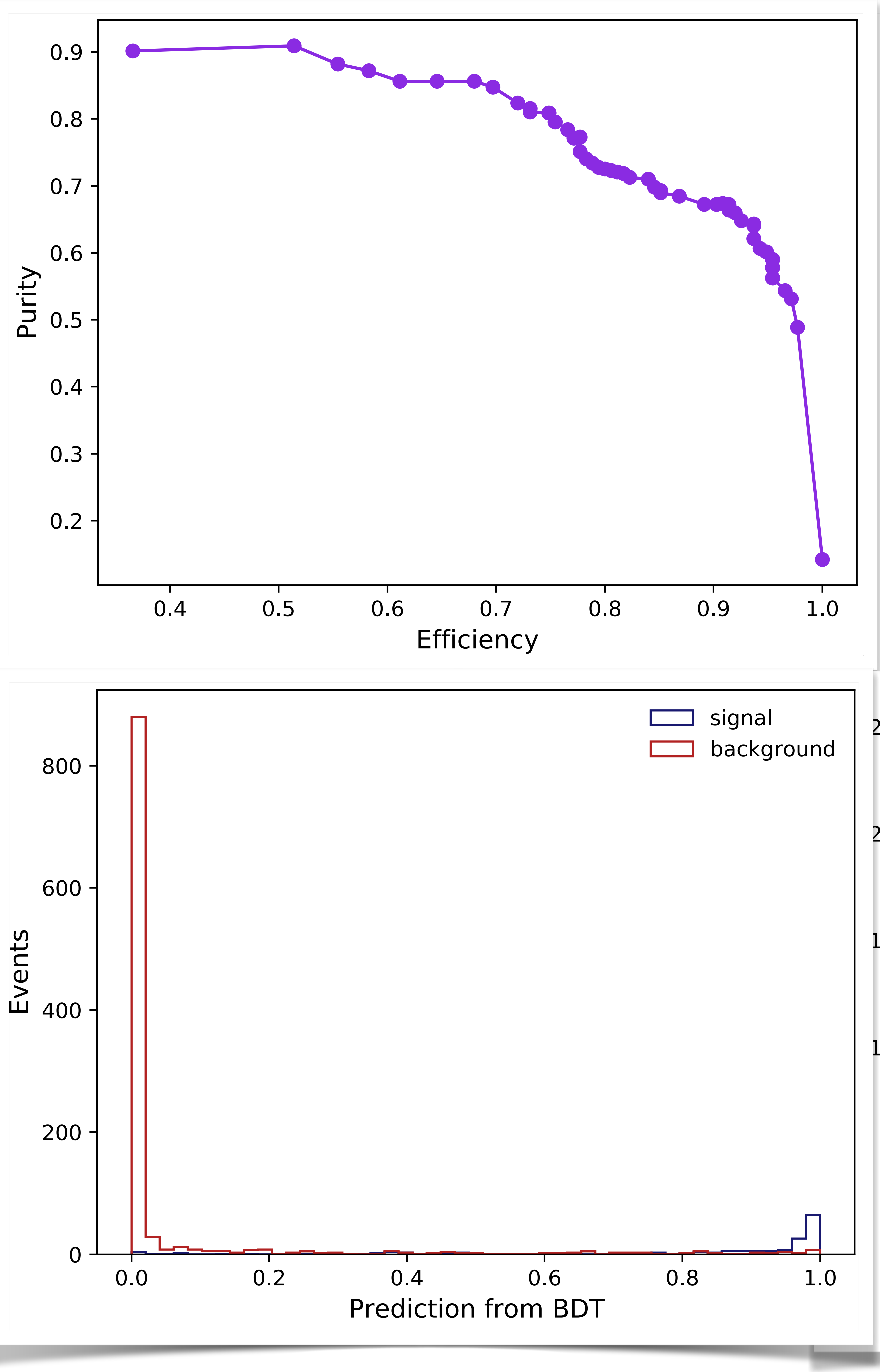
Feature_names	importances
n_tracks_ls	0.117267
contained_fraction_ls	0.087658
shrclusdir1_ls	0.062230
shr_theta_ls	0.057308
slpdg_ls	0.041782
trk_energy_hits_tot_ls	0.020703
trk_energy_ls	0.019234
pi0_dir1_x_ls	0.014535
trk_chipr_best_ls	0.013994
shr_dedx_Y_ls	0.013959
trk_dir_z_v_ls	0.012543
CylFrac_2cm_ls	0.012487
shr_pitch_u_v_ls	0.011665
shr_pz_ls	0.011074
NeutrinoEnergy2_ls	0.010624
pi0_radlen1_ls	0.010142
shr_px_v_sls	0.009956
pfnplanehits_Y_sls	0.008638
dtrk_ls	0.008421
shr_py_ls	0.008224

200 MeV

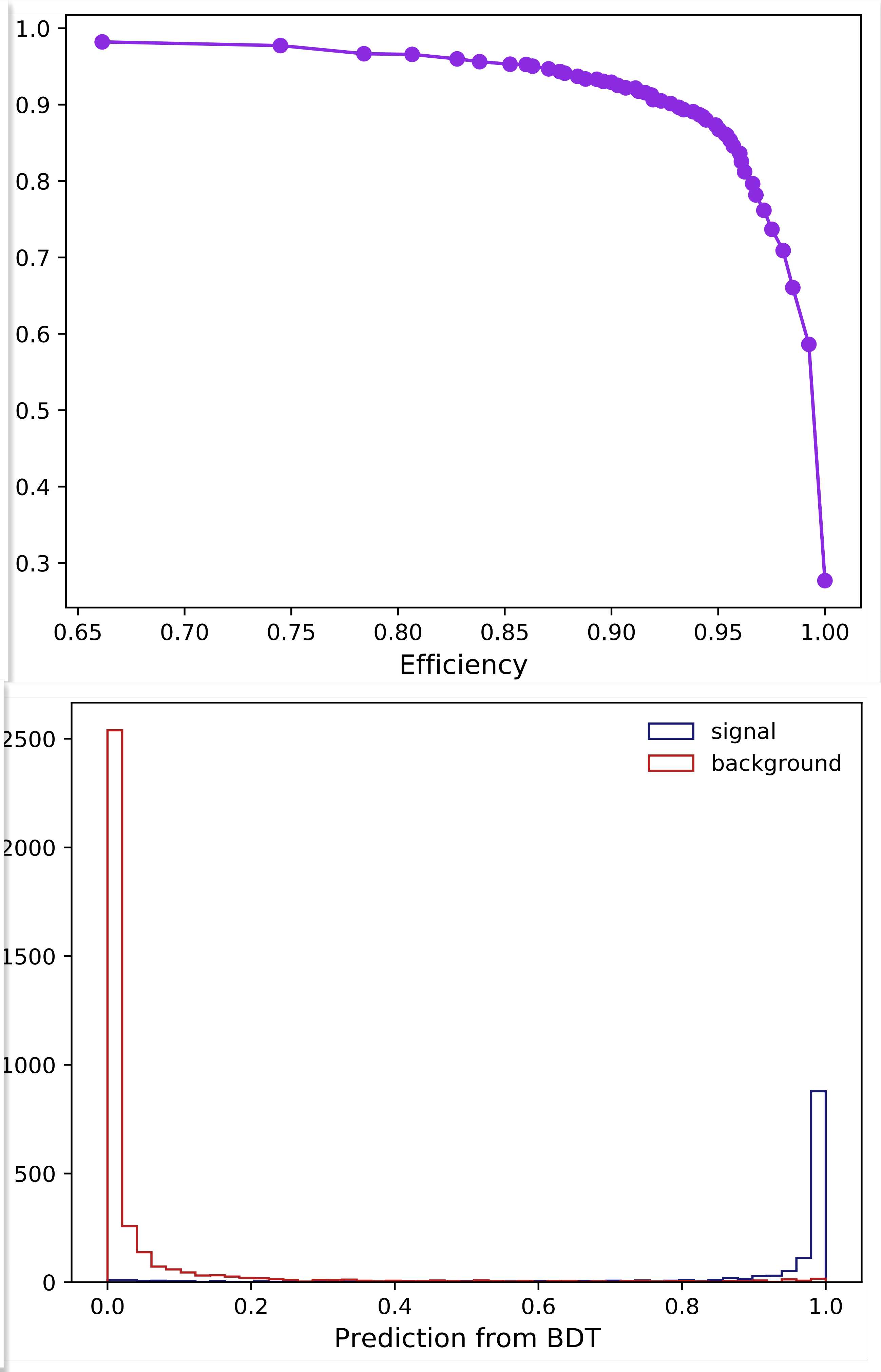
Feature_names	importances
n_tracks_ls	0.212598
shr_theta_ls	0.129819
shr_pz_ls	0.045105
shr_id_MCStool_ls	0.034578
trk_dir_z_v_ls	0.030590
trk_hits_u_tot_ls	0.024603
contained_fraction_ls	0.023849
shrclusdir1_ls	0.022463
dist_bw_showers	0.014173
trk_chipr_best_ls	0.013173
shr_distance_ls	0.010803
shr_energy_tot_ls	0.009934
shr_px_v_sls	0.009472
NeutrinoEnergy2_ls	0.008628
trk_dir_z_v_sls	0.008560
shrclusdir0_ls	0.008370
pi0_energy1_Y_ls	0.007918
pi0_dir1_z_ls	0.007058
shr_dedx_V_ls	0.006931
pi0_dir1_x_ls	0.006768

ROC Curves and separation plots, M_s = 150 MeV

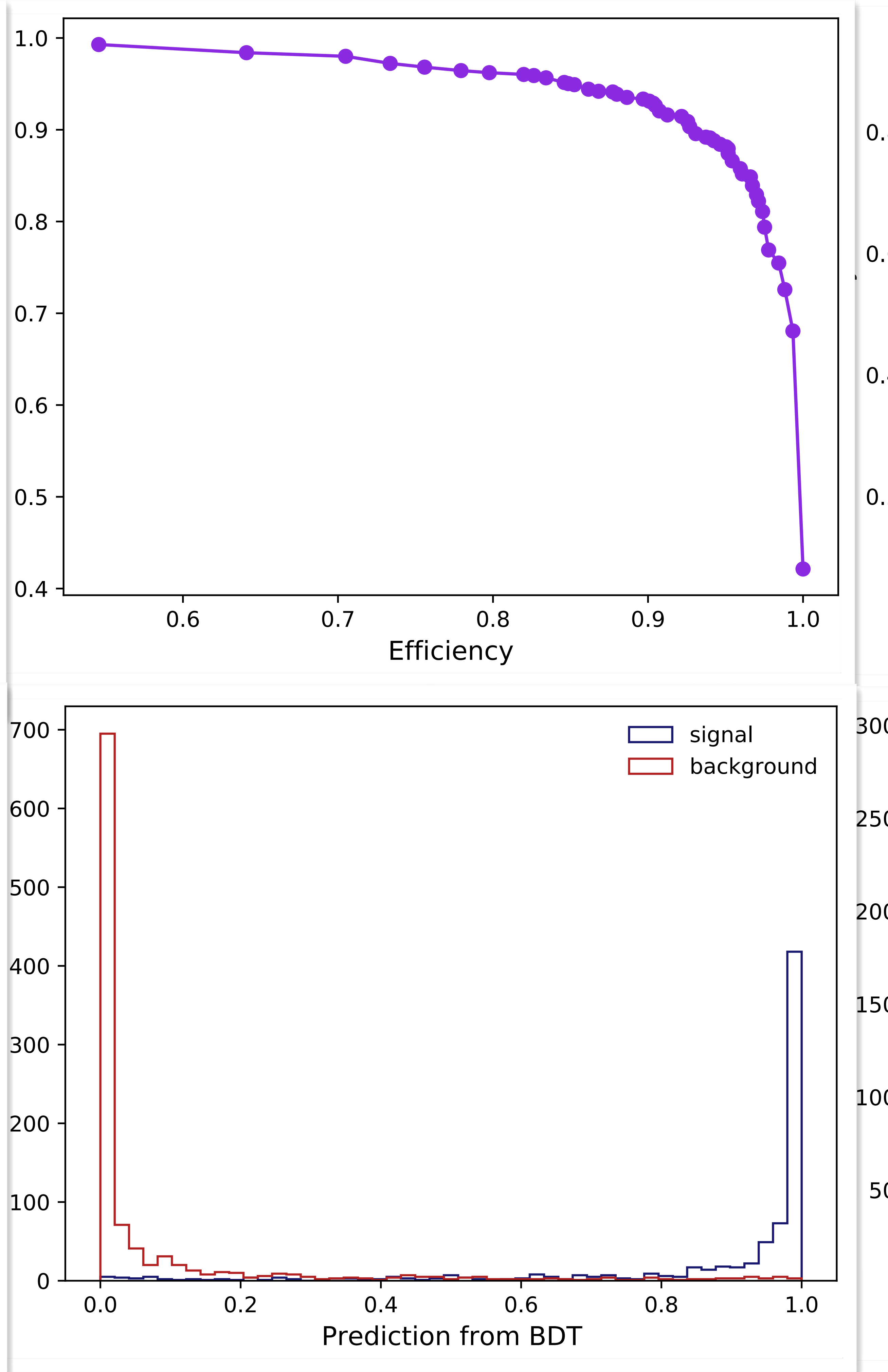
KDAR 2-shr



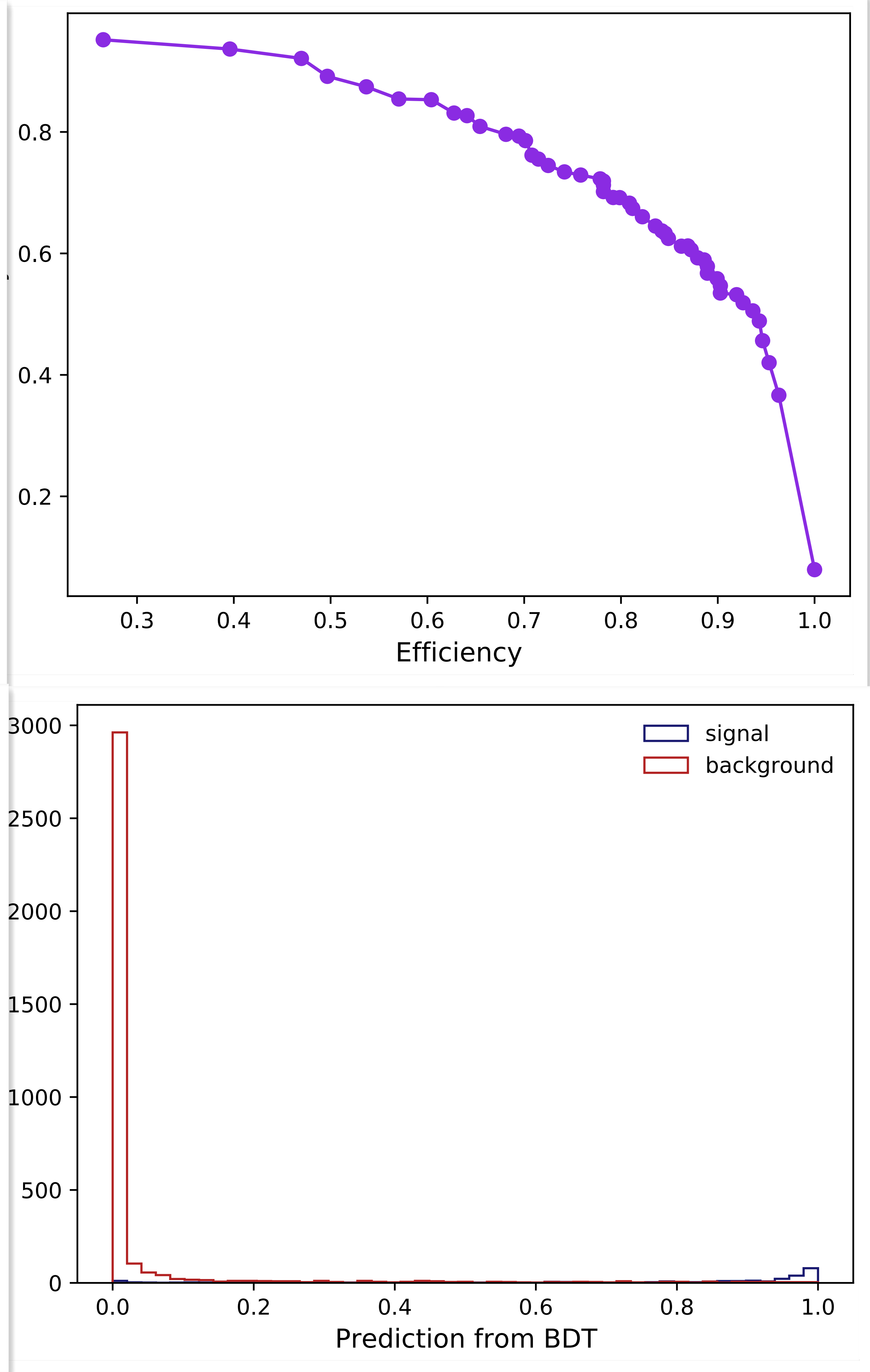
KDIF 1-shr



KDIF 2-shr

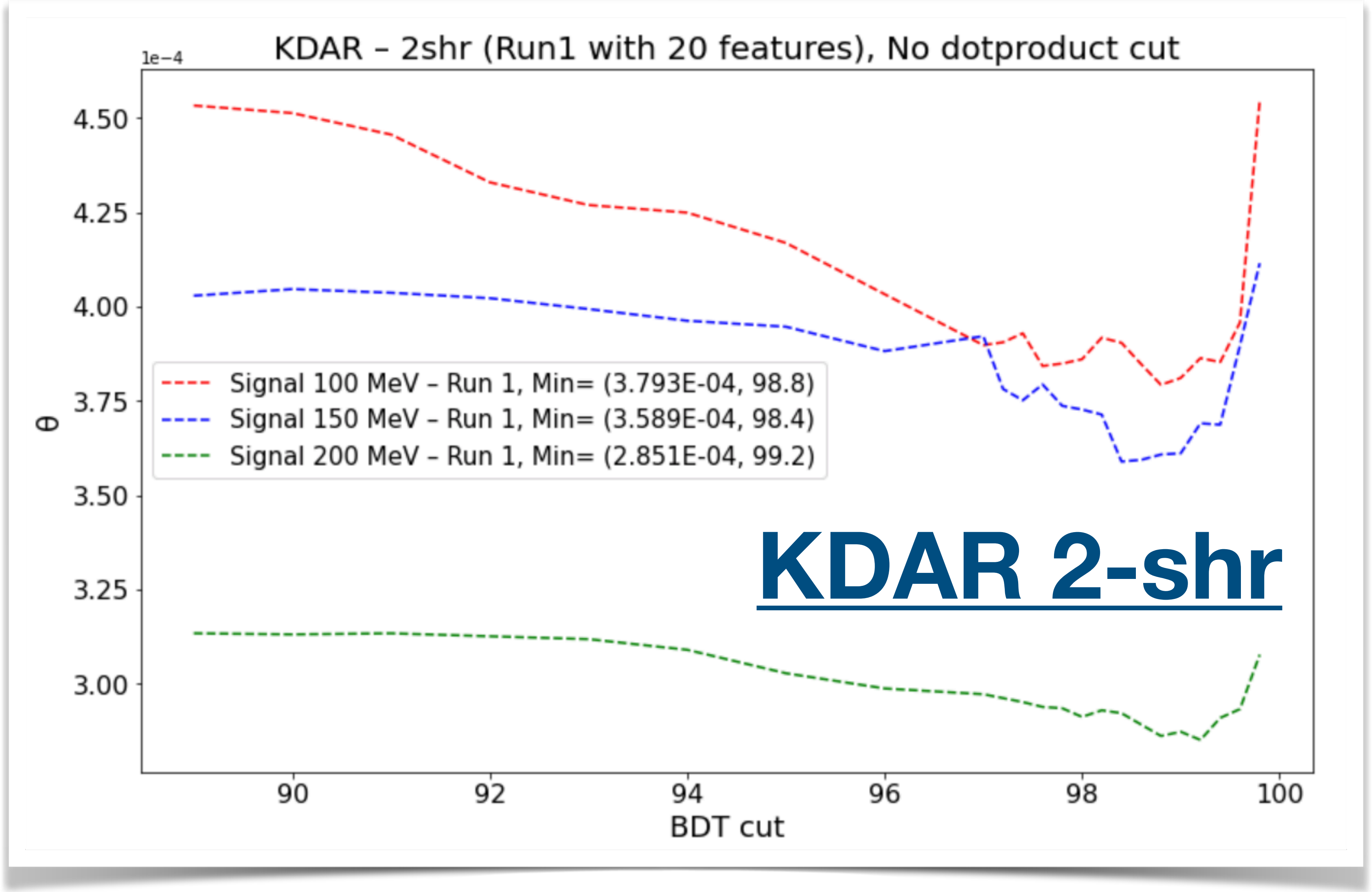


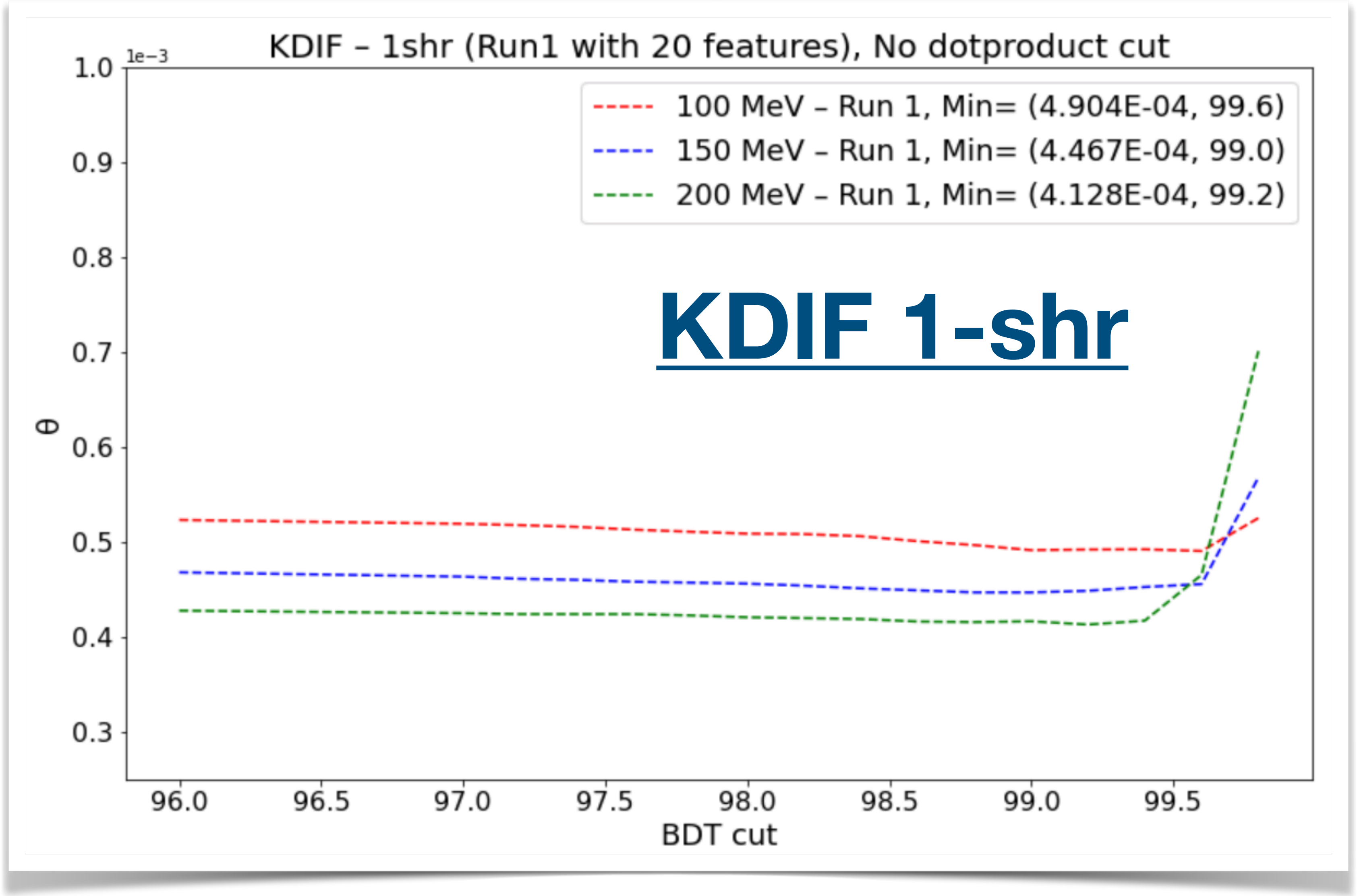
KDAR 1-shr

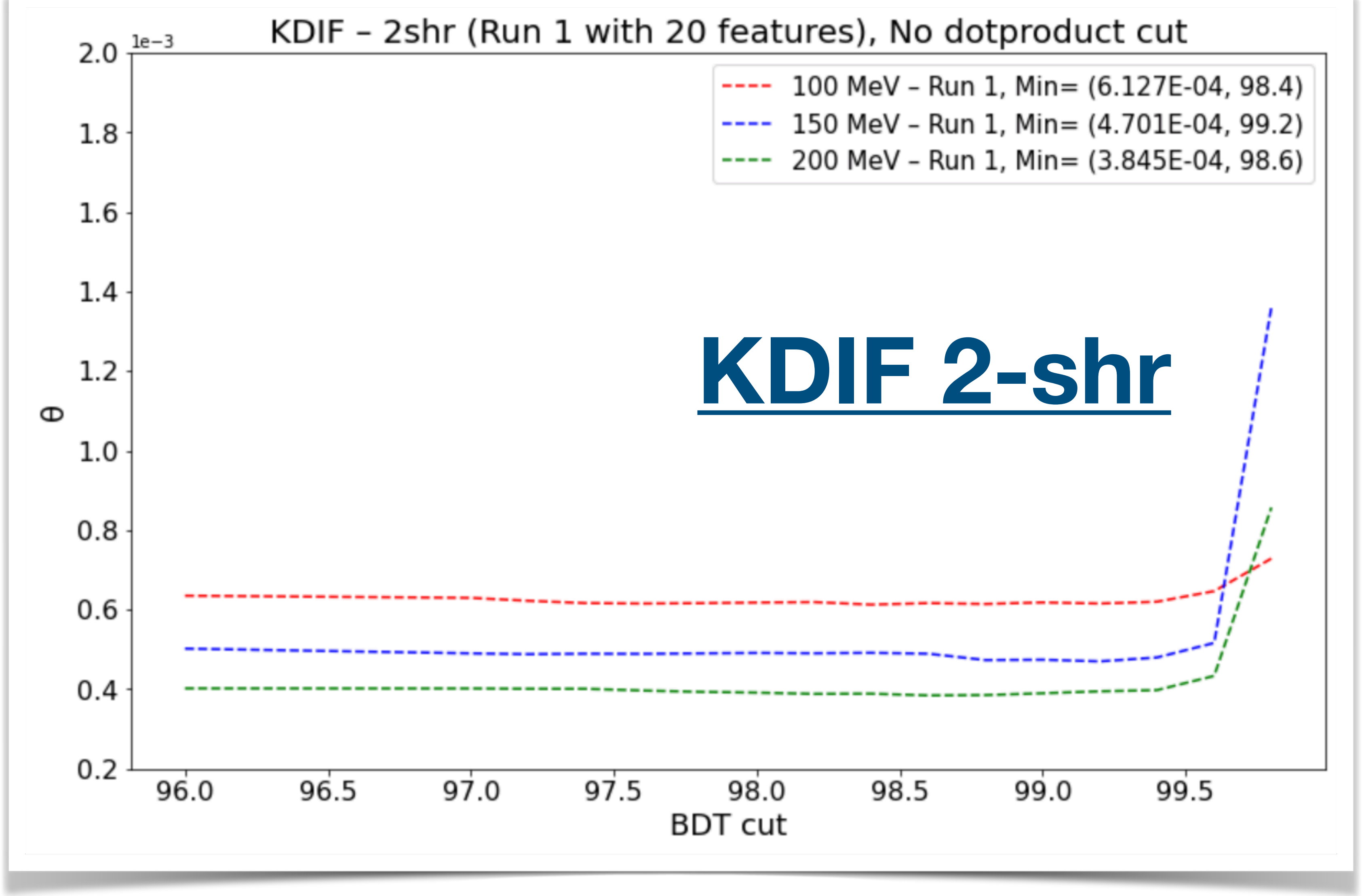


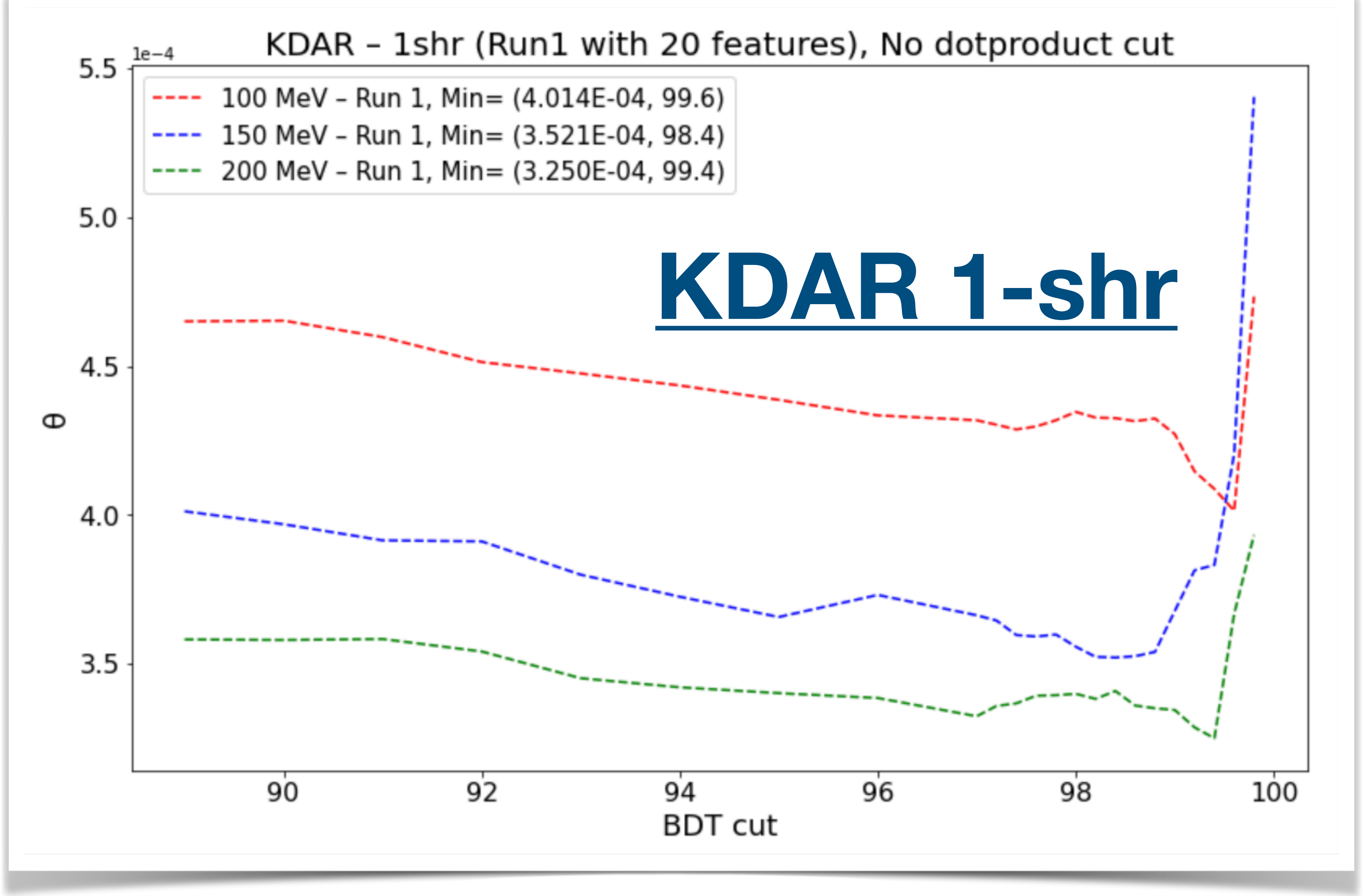
Optimal BDT cut

- ~22% of the total events produced are KDAR and remaining are KDIF and therefore the area under the ROC curves for KDAR 1-shr and 2-shr is small
- To improve the sensitivity of the MicroBooNE to these dark sector scalars, we evaluated the optimal BDT cut for which the value of our mixing angle **θ** is minimum.
- We use these BDT cuts for all the different masses of the scalars for Run1 and Run3.





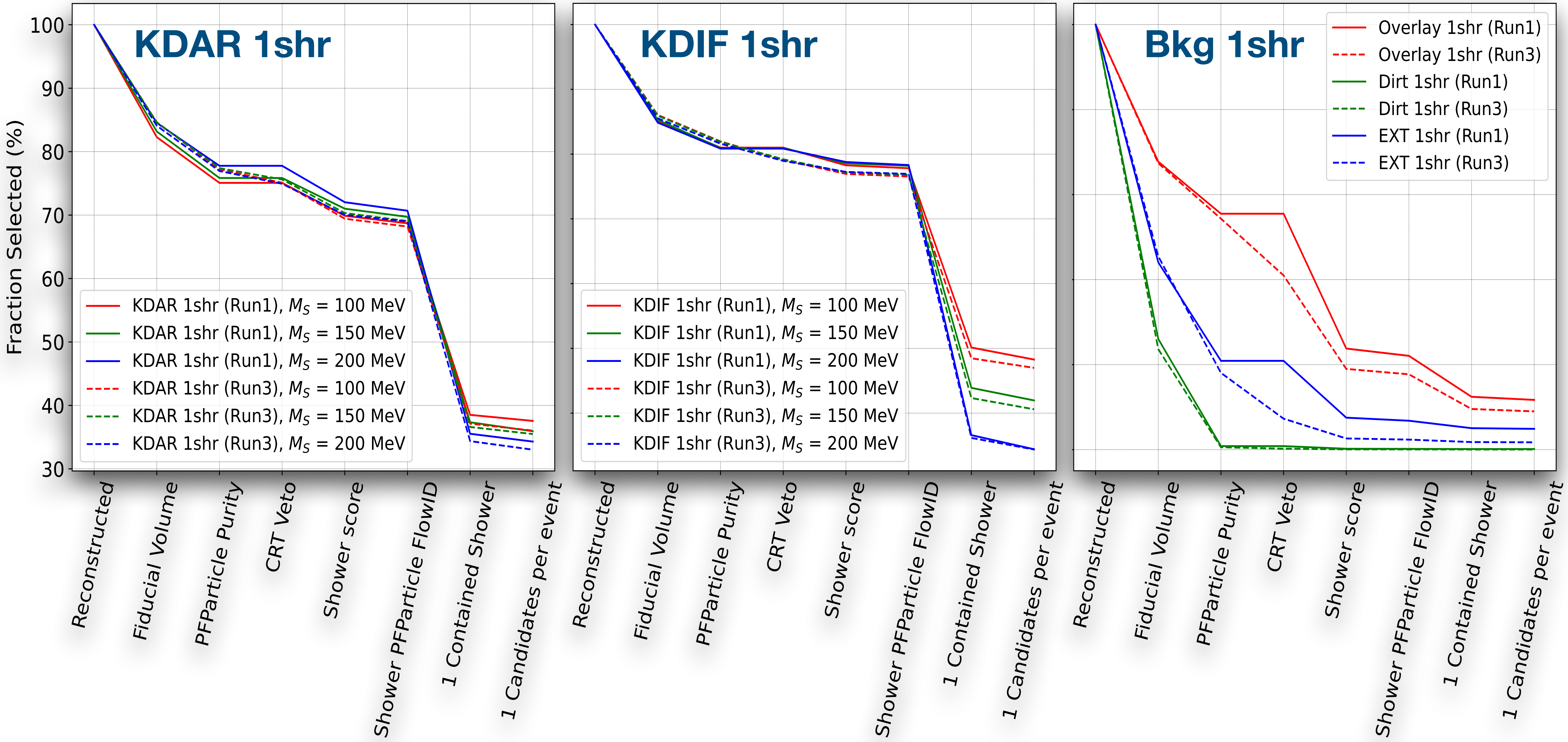




Comparing selection cuts for KDIF, KDAR and Bkg 1-shr

Preselection cuts

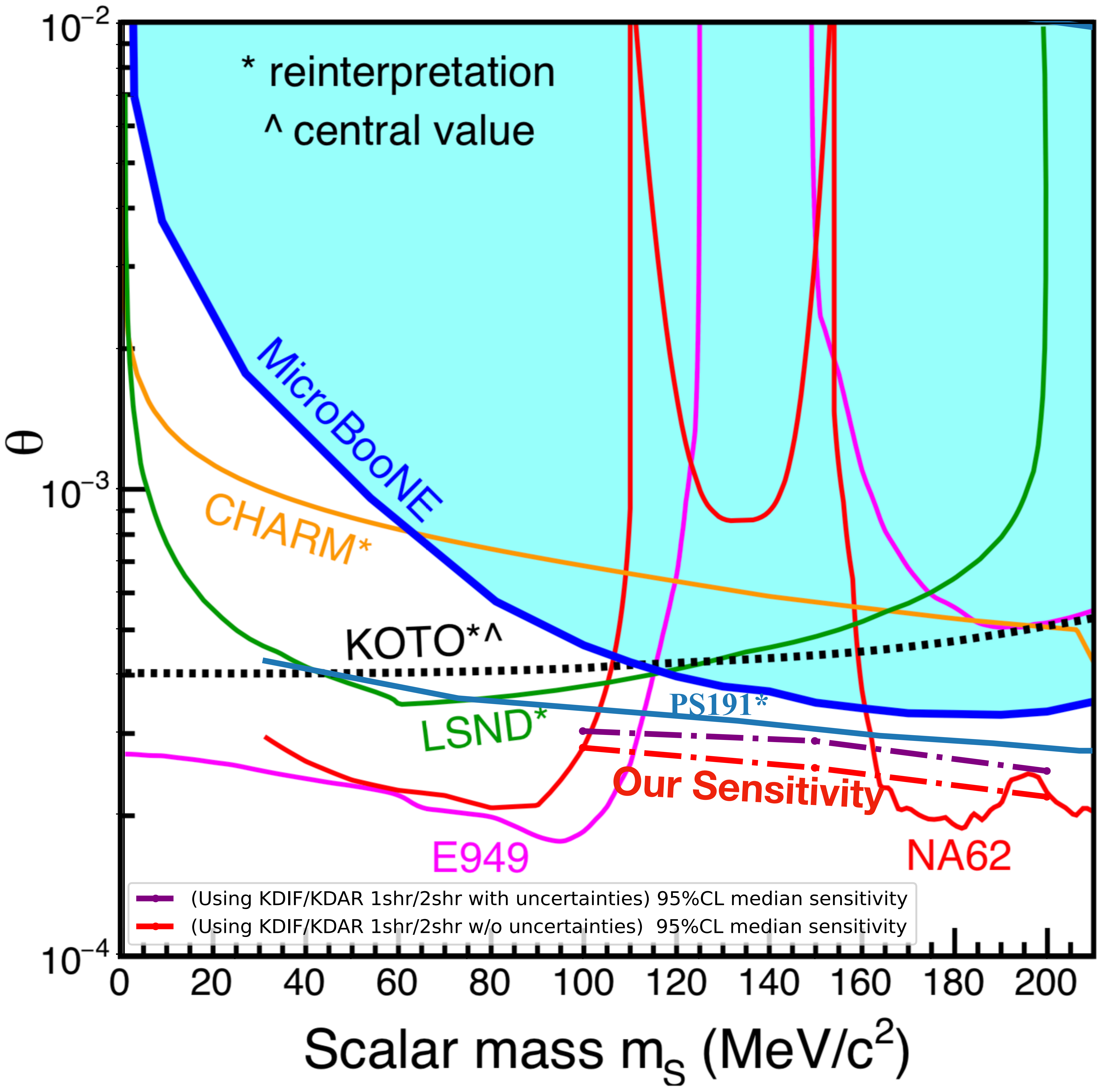
- Analysis: we have used **PeLEE searchingfornues module** to produce the ntuples.
- A **fiducial volume cut** to ensure the interaction vertex is located within the fiducial volume of the detector.
- **Shower score cut** to select only the showers and **reject tracks** with score greater than 0.5.
- **Contained shower cut** to choose events with exactly **two showers** and exactly **one shower.**
- An additional **CRTVeto cut** will be applied for Run 3 data to veto the cosmic rays.



Comparing sensitivity with other experiments

Sensitivity

- To calculate the sensitivity, we use **Collie Limit Setting Software.**
- We feed all the histograms to Collie for different masses of the scalar: 100, 150 and 200 MeV for KDIF/KDAR 1–shr, 2–shr for Run1 and Run3 with flux and cross-section uncertainty.
- The plot on right shows the current experimental limits on these Higgs Portal scalars.
- The sensitivity with flux and cross-section uncertainty (**red**) and without flux and cross-section uncertainty (**purple**) are shown on plot on right.
- Our sensitivity is better than the results recently published by PS191 experiment. arXiv:2105.11102



Detector variations used for systematic uncertainties

Detector variations used for systematic uncertainties

- Central Value
- Light Yield Attenuation
- Light Yield Decline
- Rayleigh Scattering
- Electron Recombination
- Space Charge Effect
- Wire modification: θ_{XZ}
- Wire modification: θ_{YZ}
- Wire modification: dE/dx
- Wire modification: X
- Wire modification: YZ

Parameter	Description
Wire Modification	
Wire Mod X	Modifications to the deconvolved waveforms in x.
Wire Mod Y	Modifications to the deconvolved waveforms in y.
Wire Mod Theta XZ	Modifications to the deconvolved waveforms in θ_{xz} plane.
Wire Mod Theta YZ	Modifications to the deconvolved waveforms in θ_{yz} plane.
Light	
Light Yield Down	Overall 25% decrease in the light yield.
Light Yield Rayleigh	Increase the Rayleigh scattering length from 60 cm to 90 cm.
Other	
Space Charge	Use an alternative map to account for space charge effects.
Recombination	Reduce the value of β' in the Modified Box model by 0.028 (-13%).

Table 9.5: A summary of the detector variations used to estimate the systematic uncertainties.

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