ML Methods for Super-K Solar *ν* Classification

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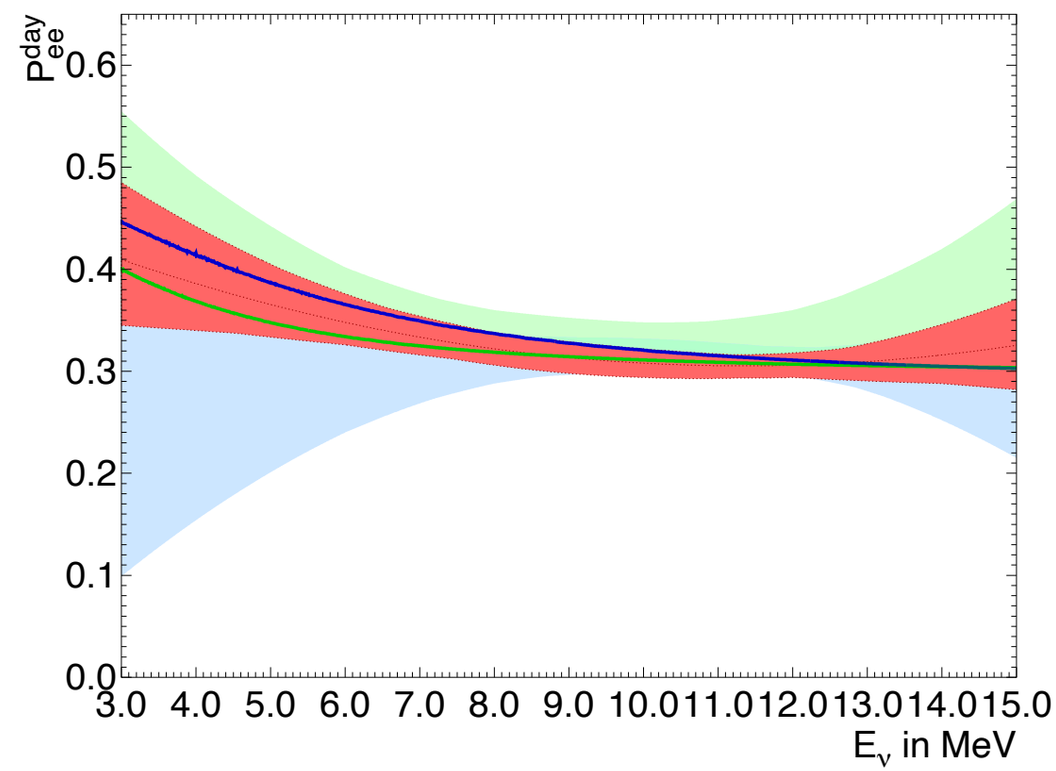
Mikheyev–Smirnov–Wolfenstein Effect

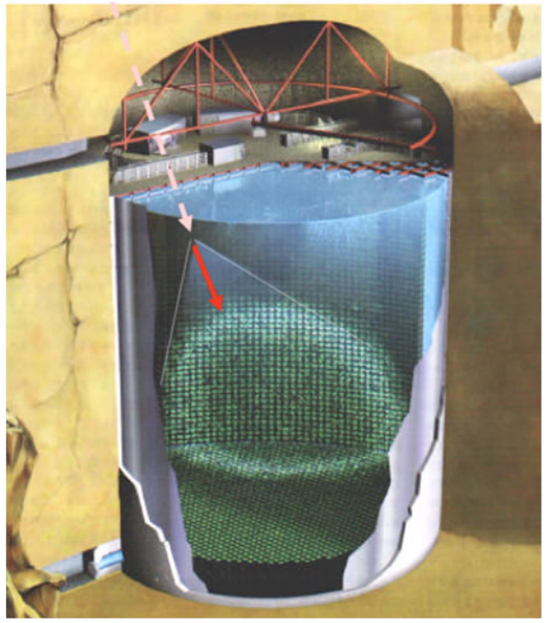
- Neutrino flavor conversion at SK-observable energies is dominated by the MSW effect.
- ν_e produced in the core of the sun through ^{8}B decay adiabatically convert to mass state ν_2 via the MSW effect as they pass through a resonant mass density region.
- Lower energy ν_e do not undergo this conversion.
- The transition from MSW-dominant to vacuum-dominant flavor conversions leads to an upturn in the ν_e survival probability.

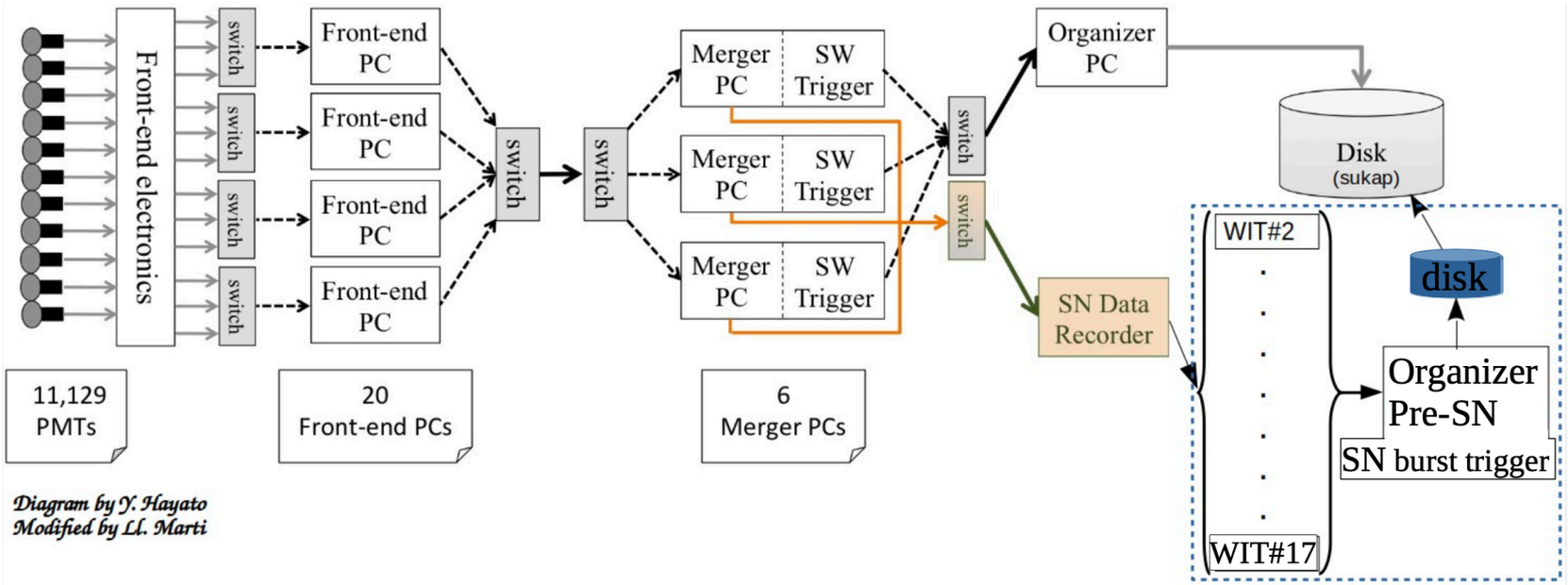


Predicted ν_e survival probability vs. energy. The best quadratic fit for all solar experiments (green line), solar+KAMLAND (blue line), and 1σ region for SK (green band), SNO (blue band), and SK+SNO (red band) are shown.

Super-K

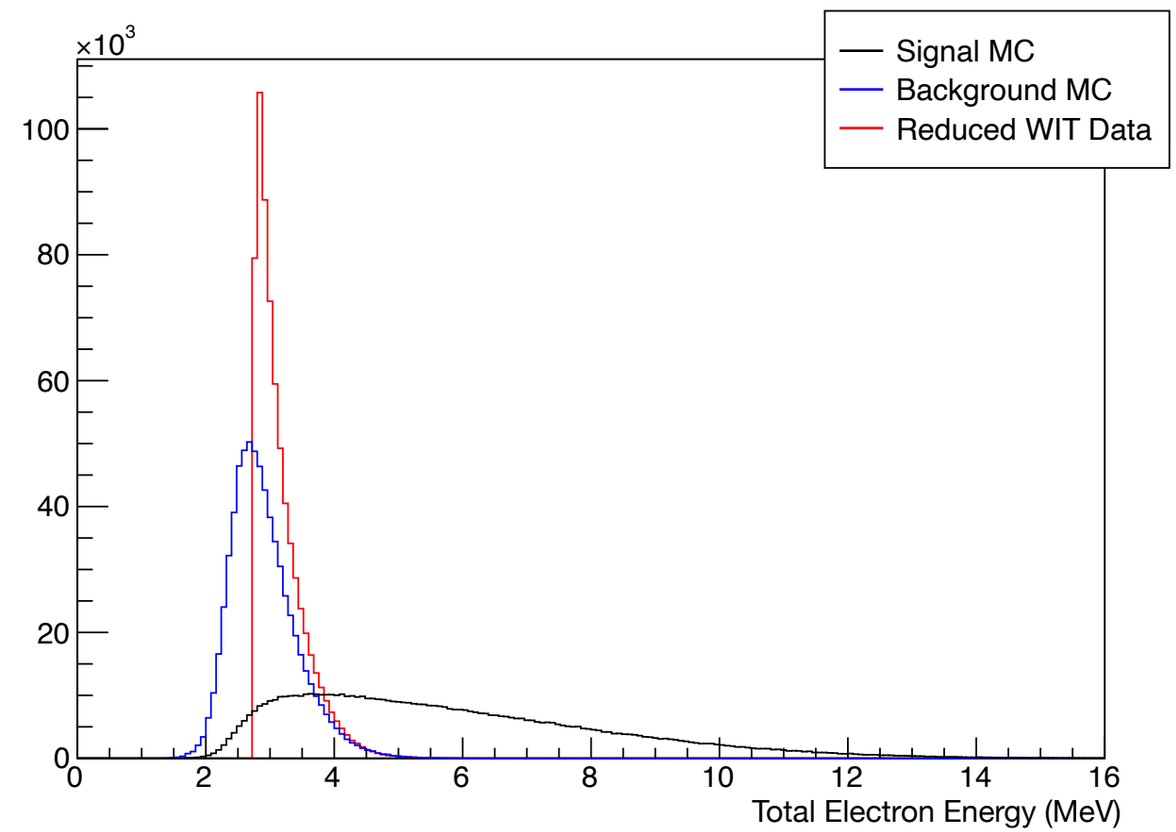
- 50 kton water Cherenkov detector 1 km under Mt. Ikeno, Japan.
- 11,129 20” photomultiplier tubes (PMTs) in inner detector.
- SK-IV (Sep. 2008 - May 2018) is the longest phase of the experiment with the lowest energy threshold.
- Wideband intelligent trigger (WIT) is a system of CPUs that conducts online event reconstruction and triggering in parallel to preserve lower energy events.





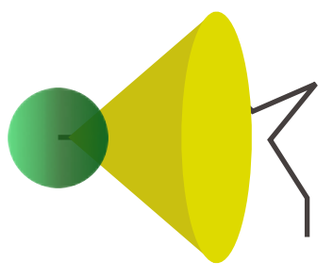
Motivation

- Super-K solar analysis excludes events below 3.49 MeV kinetic (4 MeV total) recoil electron energy.
  - Radioactive background dominates in this region.
- Want to identify solar neutrinos at lower energies with SK-IV reduced WIT data (redwit).

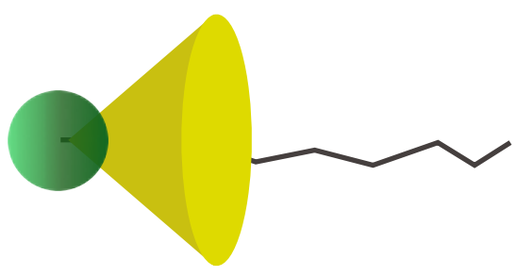


Energy distribution of Solar ^{8}B MC (black) and radioactive ^{214}Bi background MC (blue) both with WIT trigger simulation but before first reduction and data events after first reduction (red).

Motivation

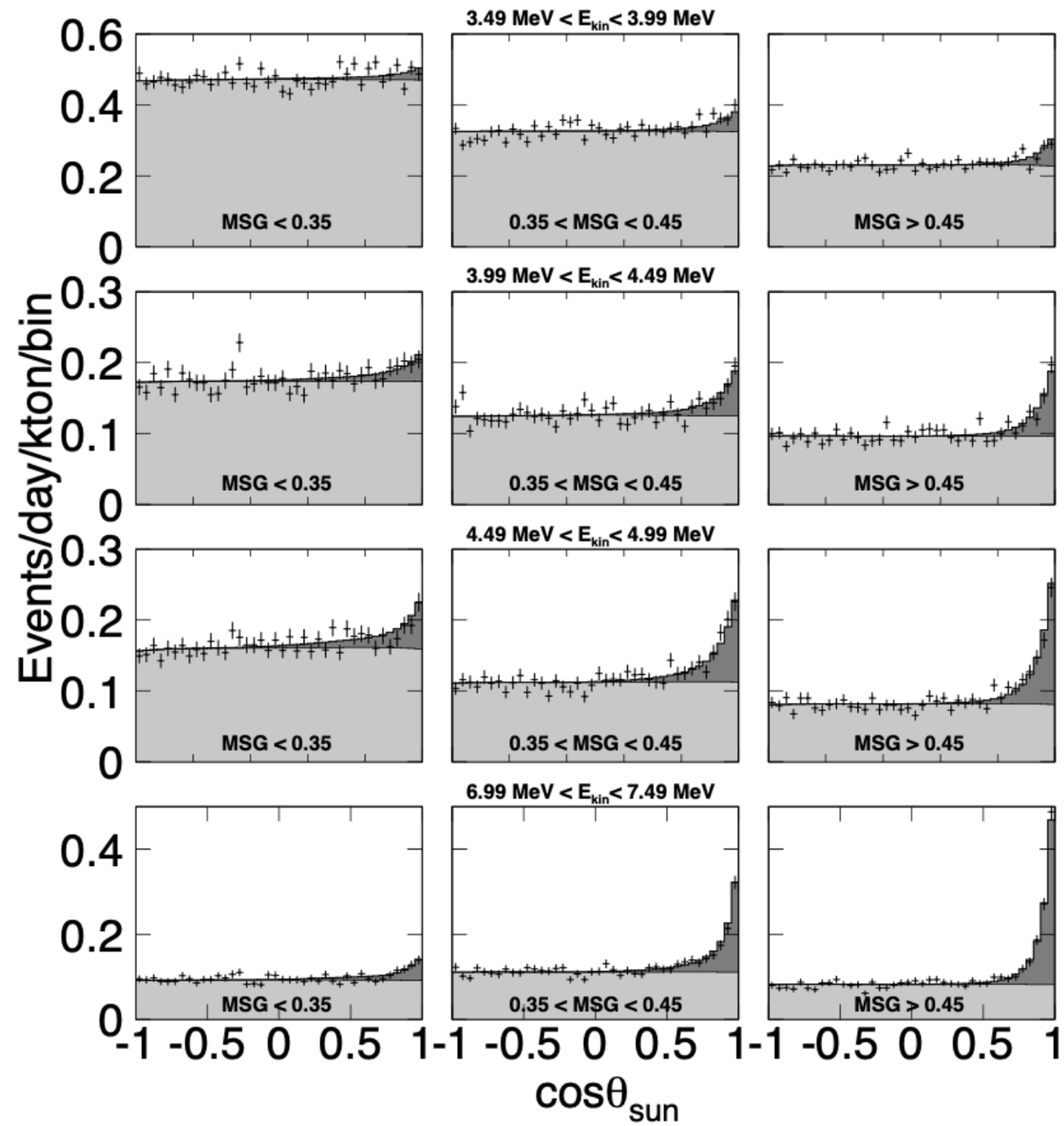


Low energy event
More scattering



High energy event
Less scattering

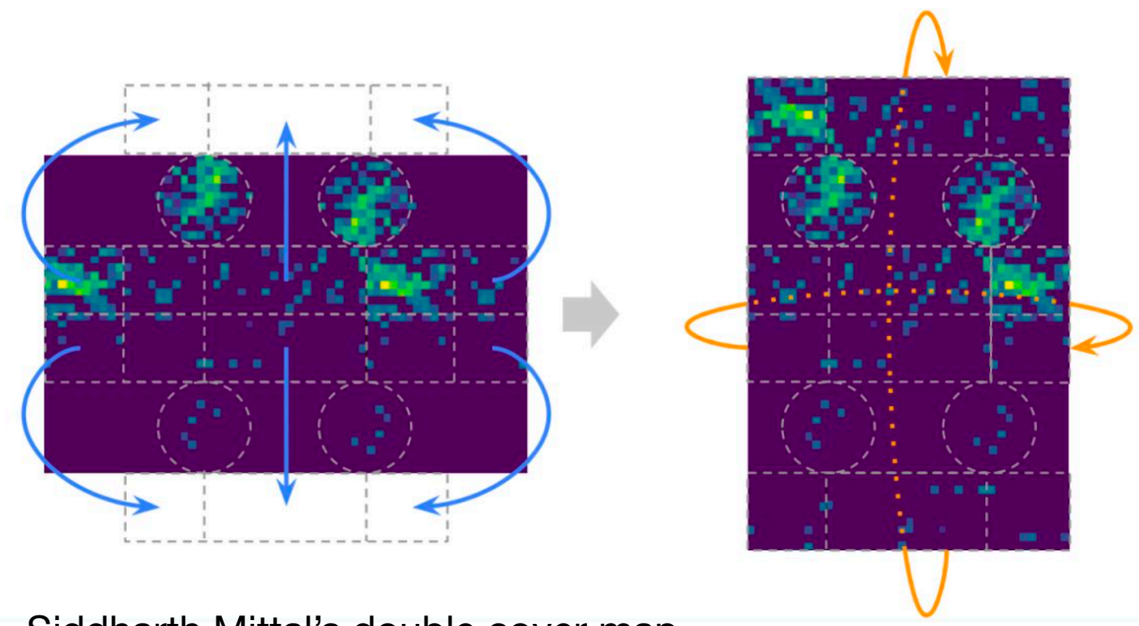
Illustration of Coulomb scattering and multiple Cherenkov cones.



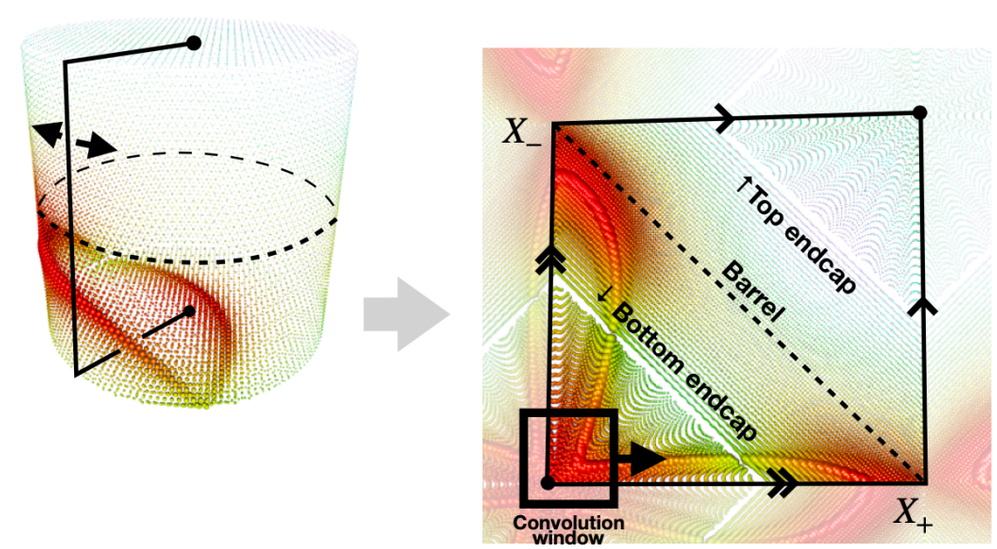
Solar angle distributions for SK-IV solar analysis in energy and multiple scattering goodness (MSG) bins.
Solar Neutrino Measurements in Super-Kamiokande-IV, 1664 days, Phys. Rev. D 94 052010

WatChMaL

- Water Cherenkov Machine Learning Group aims to provide tools and standardize ML methods for water Cherenkov experiments.
- Cylindrical detector geometry creates problem for CNN training.
- Researching alternative PMT-to-image mappings, 3D networks (PointNet, GraphNet).



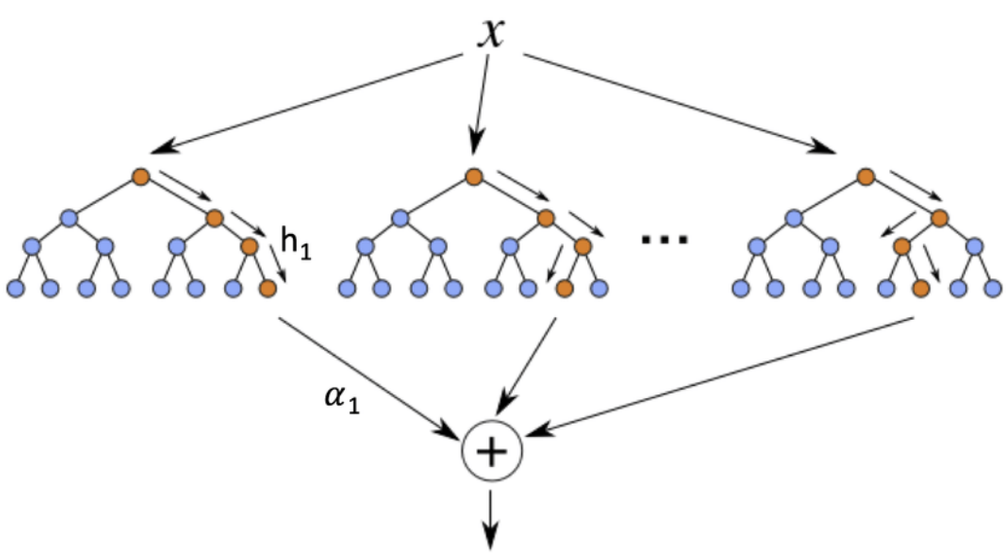
Siddharth Mittal's double cover map

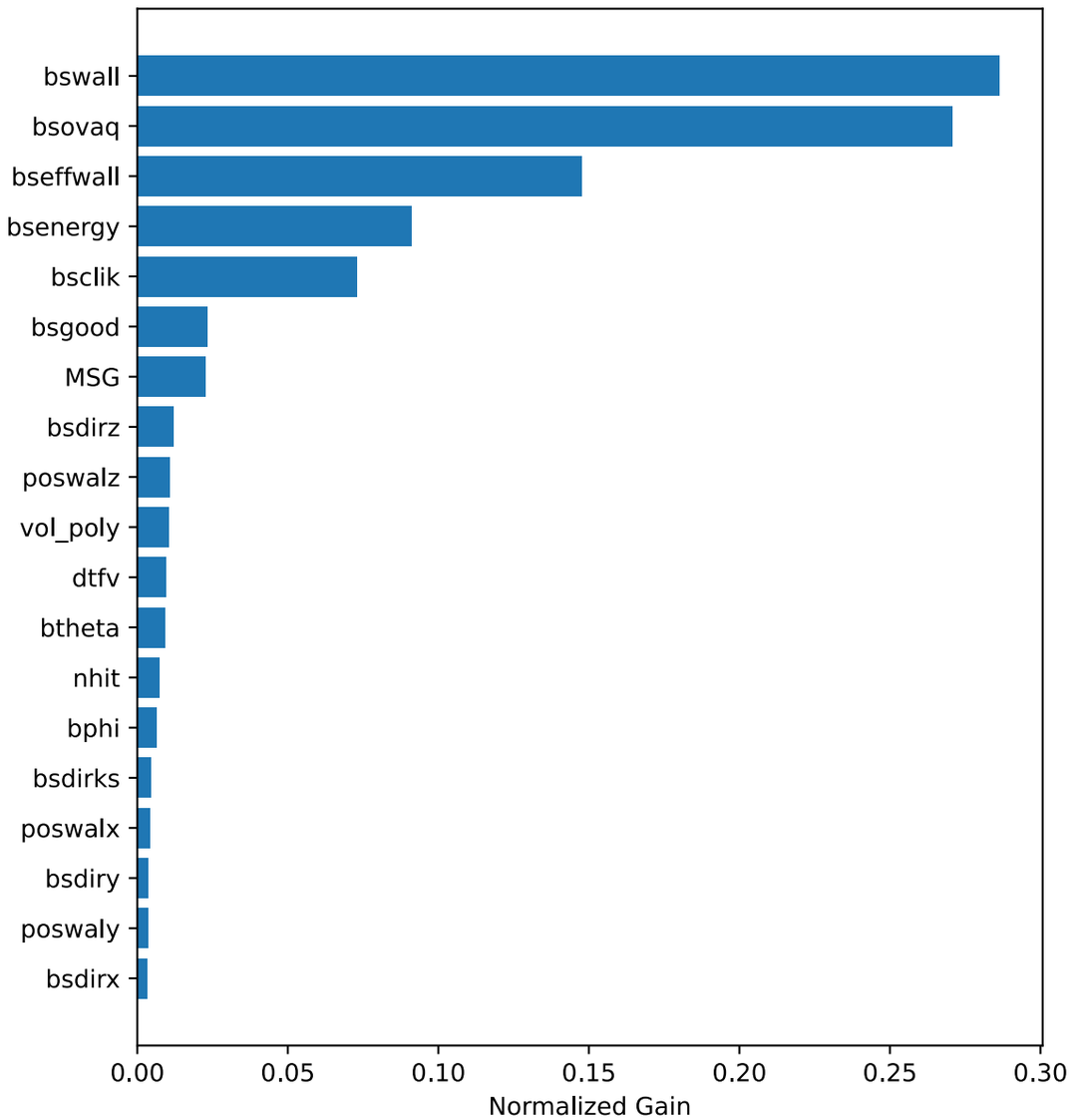


Lukas Bern's topological map to square

Boosted Decision Tree

- Trained on reconstructed variables used in solar analysis.
- 100 trees with max depth of 7 added to give event score.

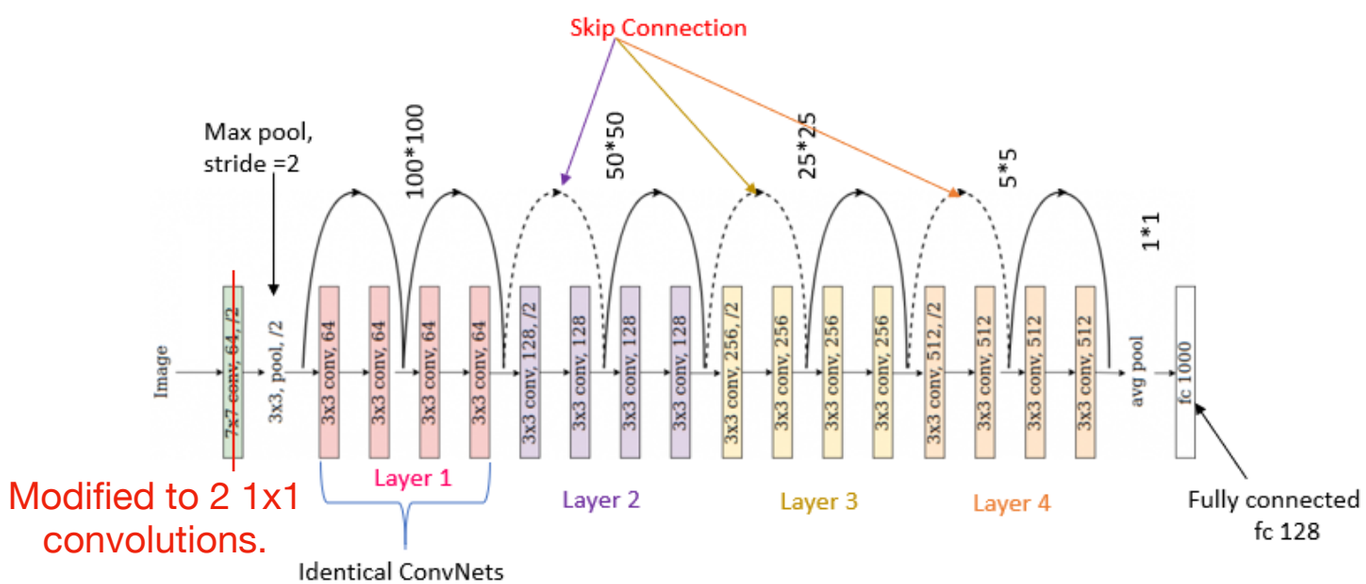




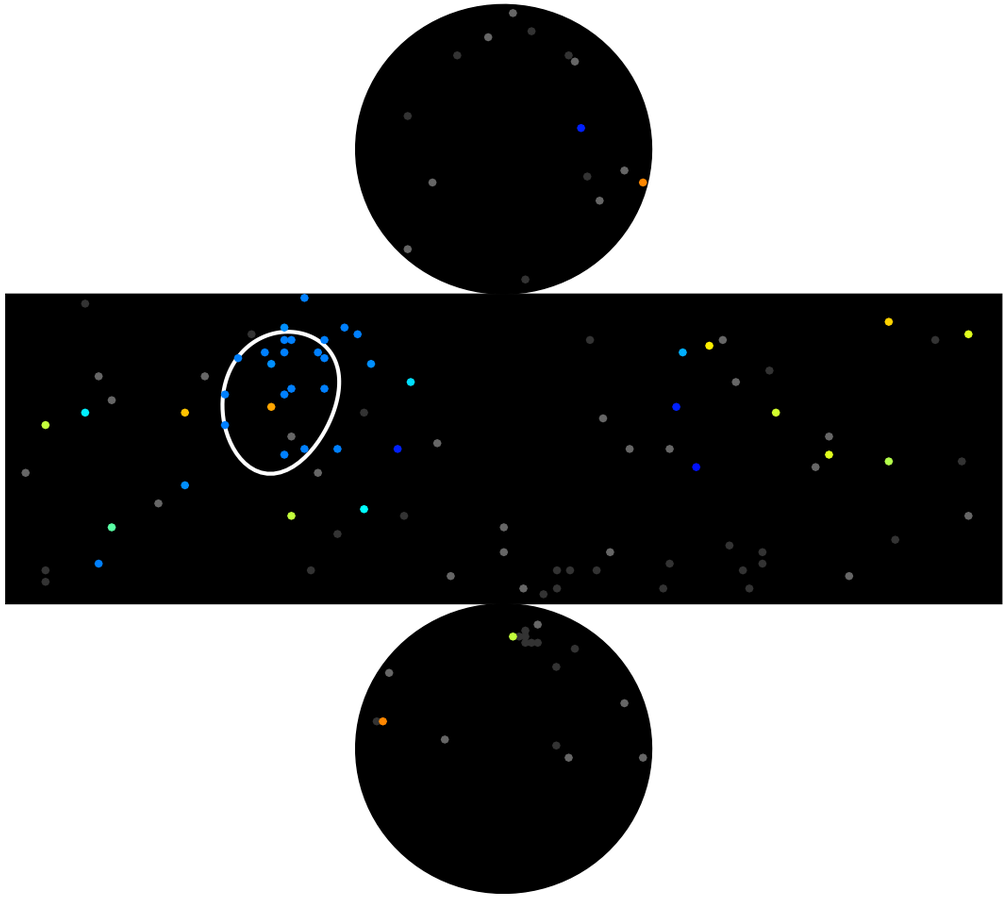
Inputs for the BDT and their relative importances. Definitions in backup slides.

ResNet CNN

- WatChMaL modified ResNet18.
- Trained with standard 2D event display PMT-to-image map.
- Fill pixels with PMT hit charges and times relative to fit vertex.



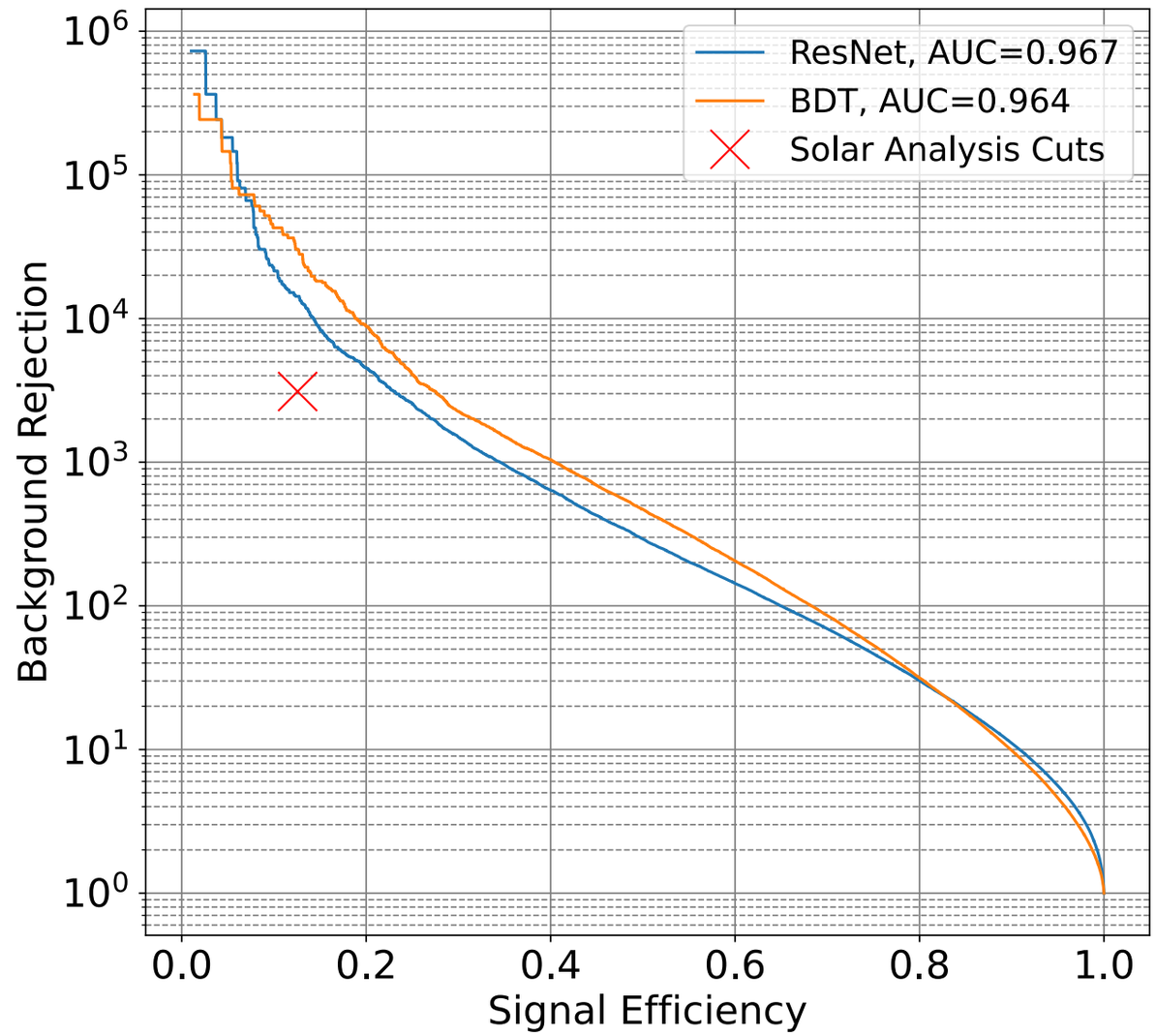
Modified ResNet18 architecture.



Typical low energy data event with PMT relative times. Reconstructed Cherenkov cone in white.

ROC Curves

- Evaluate performance of methods using solar MC as signal and data as background.
- BDT rejects 6x background as solar analysis cuts for same efficiency.



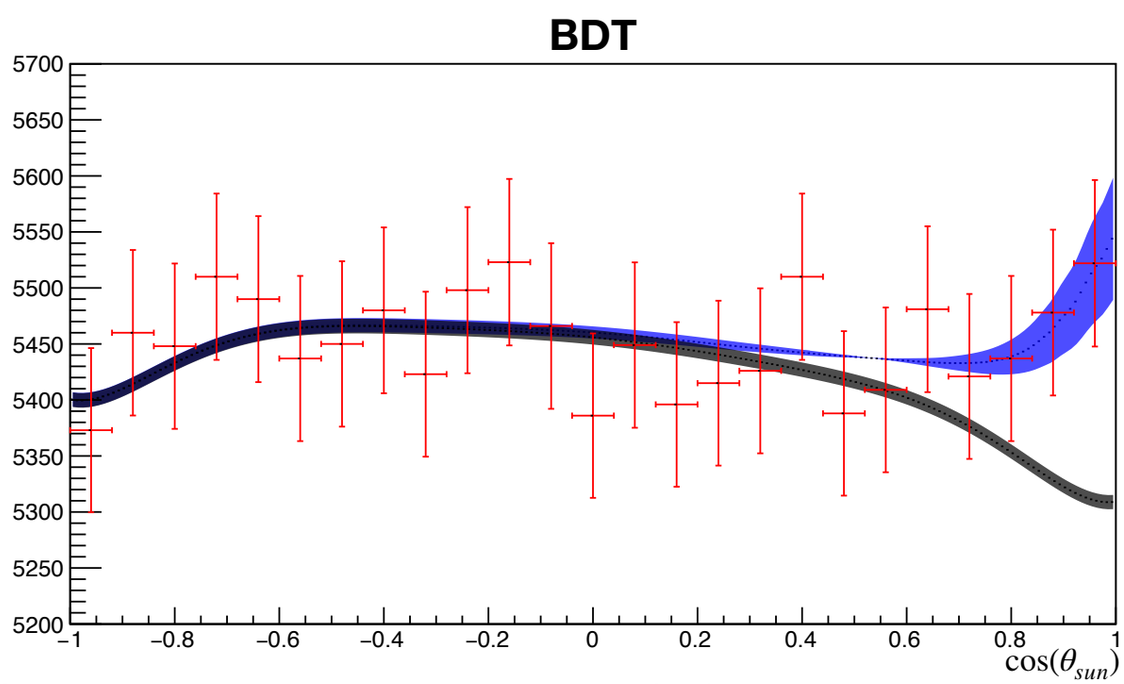
1/FPR vs Signal Efficiency. All events 2.49 MeV < E_{kin} < 3.49 MeV.

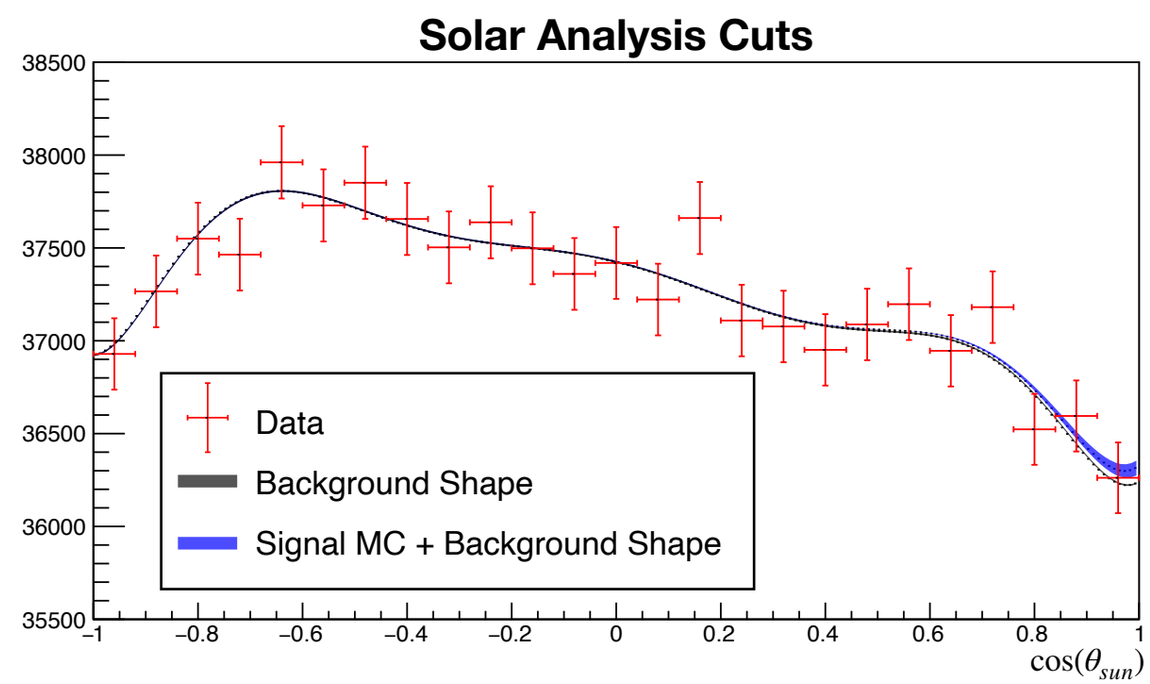
BDT Implementation

- Applied BDT to all usable SK-IV redwit data (Oct 2015 - May 2018) with 2.49 MeV < E_{kin} < 3.49 MeV.
  - SK livetime: 858 days
  - WIT livetime: ≈614 days
- Only included solar analysis cuts that easily remove one particular source of background.
  - Calibration source spot cut
  - PMT flasher cut
  - Convection period cut
  - Spallation cut (spallation log likelihood, neutron cloud cut, multiple spallation cut)
- Picked BDT output cut >0.9991 to match traditional analysis 12.6% signal efficiency according to ROC curve.

Solar Angle Distributions

- After BDT selection, use same methods as SK solar analysis.
  - BDT trained on MC with randomized solar direction.
- Generate background shape by scrambling solar direction and event direction for all events.
- Generate signal shape with polynomial fit to unmodified signal MC.





Solar angle distribution for data selection (red), calculated background shape (black), and polynomial fit of signal MC added to background shape (blue) all with 1σ error bands.

Extracted Signal Events

- "Solfit" maximum likelihood fitter gives number of events in each energy and multiple scattering goodness bin.

E_{kin} Bin Range		MSG Bin Range		BDT Events		Cuts Events	
Min	**Max**	**Min**	**Max**	**Total**	**Signal**	**Total**	**Signal**
2.49 MeV	2.99 MeV	0	0.35	8,004	-60^{+60}_{-60}	498,341	-220^{+500}_{-500}
2.49 MeV	2.99 MeV	0.35	0.45	12,760	70^{+60}_{-60}	223,243	-50^{+250}_{-250}
2.49 MeV	2.99 MeV	0.45	1	17,110	80^{+60}_{-60}	111,957	70^{+150}_{-150}
2.99 MeV	3.49 MeV	0	0.35	26,814	130^{+120}_{-110}	51,708	80^{+160}_{-160}
2.99 MeV	3.49 MeV	0.35	0.45	31,125	180^{+100}_{-100}	28,701	130^{+90}_{-90}
2.99 MeV	3.49 MeV	0.45	1	40,463	280^{+90}_{-90}	17,686	80^{+60}_{-60}
2.49 MeV	2.99 MeV	0	1	37,874	90^{+110}_{-110}	833,541	70^{+370}_{-370}
2.99 MeV	3.49 MeV	0	1	98,402	580^{+160}_{-150}	98,095	210^{+110}_{-110}
2.49 MeV	3.49 MeV	0	1	136,276	$\mathbf{630^{+170}_{-160}}$	931,636	$\mathbf{220^{+120}_{-120}}$

Statistical errors only

Future Work

- ResNet data processing in progress.
- Implement a “hybrid method” e.g. include output of CNN as BDT input.
- Try other types of networks.
- Calculate event rate and flux.
- Systematic error analysis.

Backup

BDT Inputs

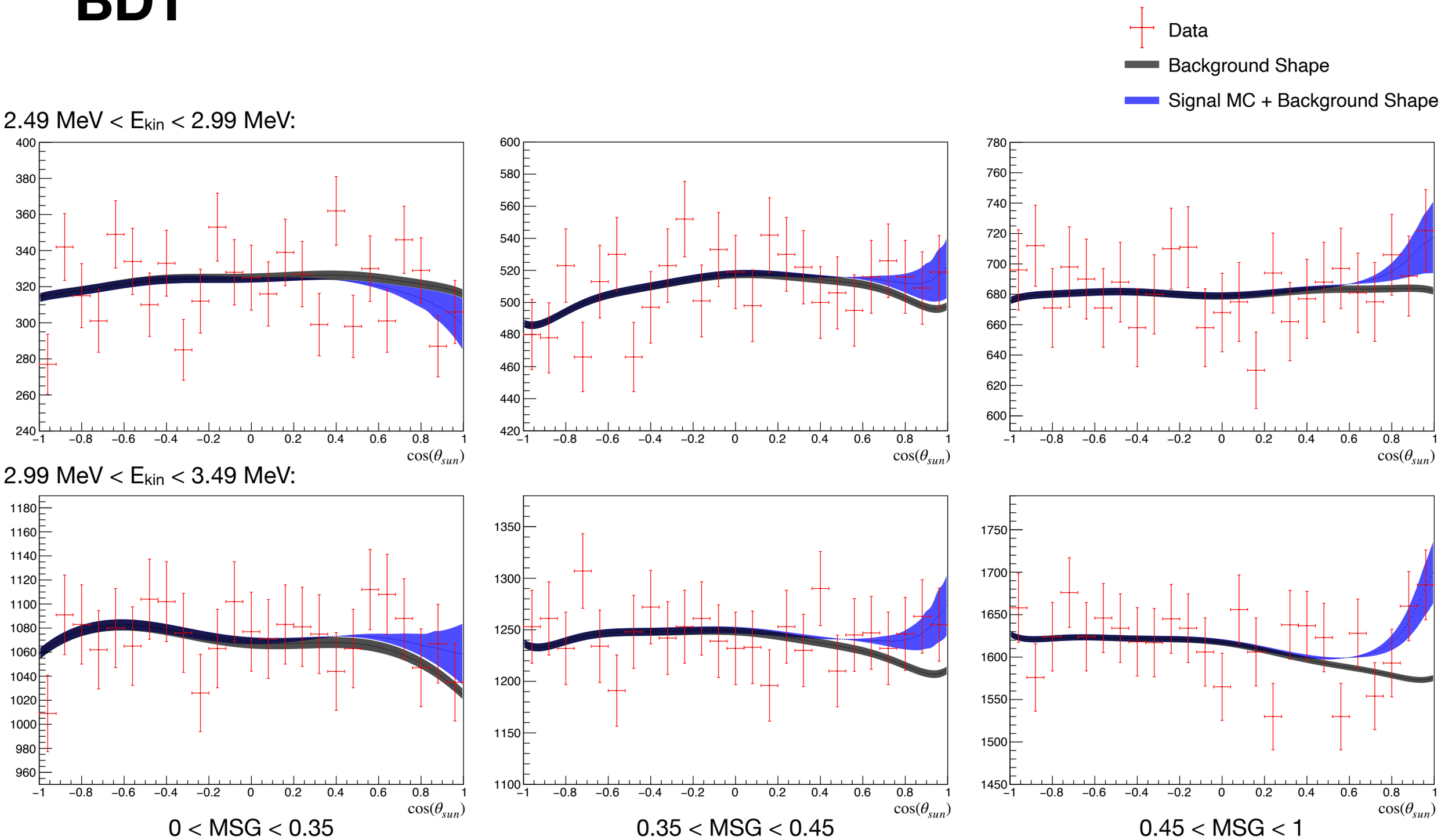
- bsvertex[x,y,z]: position of offline reconstructed BONSAI vertex
- b[x,y,z]: online WIT vertex position

Removed in favor of dtfv and val_poly

- bsdir[x,y,z]: direction vector (cartesian)
- btheta, bphi: online WIT direction vector (spherical)
- bswall: closest distance from vertex to wall
- poswal[x,y,z]: position of intersection of wall along reverse of direction vector
- bseffwal: distance between bsvertex and poswal
- dtfv: closest distance to tight fiducial volume boundary
- val_poly: value of 2D polynomial fit to background vertex positions in r^2 and z
- nhit: number of PMT hits
- bsenergy: reconstructed total event energy
- bsgood: goodness of fit calculated with PMT time residuals
- bsdirks: goodness of direction fit, lower for more symmetric Cherenkov cones
- bsovaq: $bsgood^2$ - $bsdirks^2$
- bsclik: lower for events with small clusters of PMT hits
- MSG: Ariadne multiple scattering goodness quantifies amount of Coulomb scattering using degree of alignment among best direction candidates

Energy and MSG Bins

BDT



Energy and MSG Bins

Solar Analysis Cuts