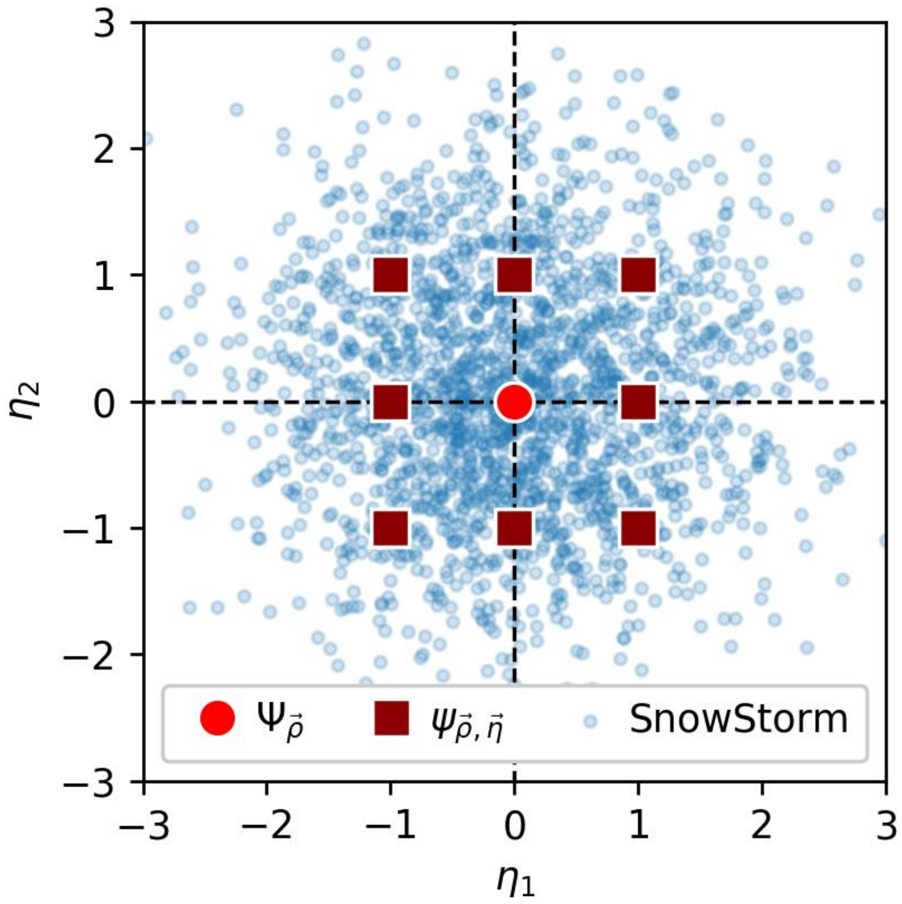
SnowStorm – A Method for Simulating and Treating Detector Systematic Uncertainties

ERIK GANSTER

SnowStorm – Table of Content

- What is the SnowStorm method?
  - How does it differ from „standard“ simulation sets?
- How does it work?
- What can it be used for?
- How can I use it?



What is SnowStorm?

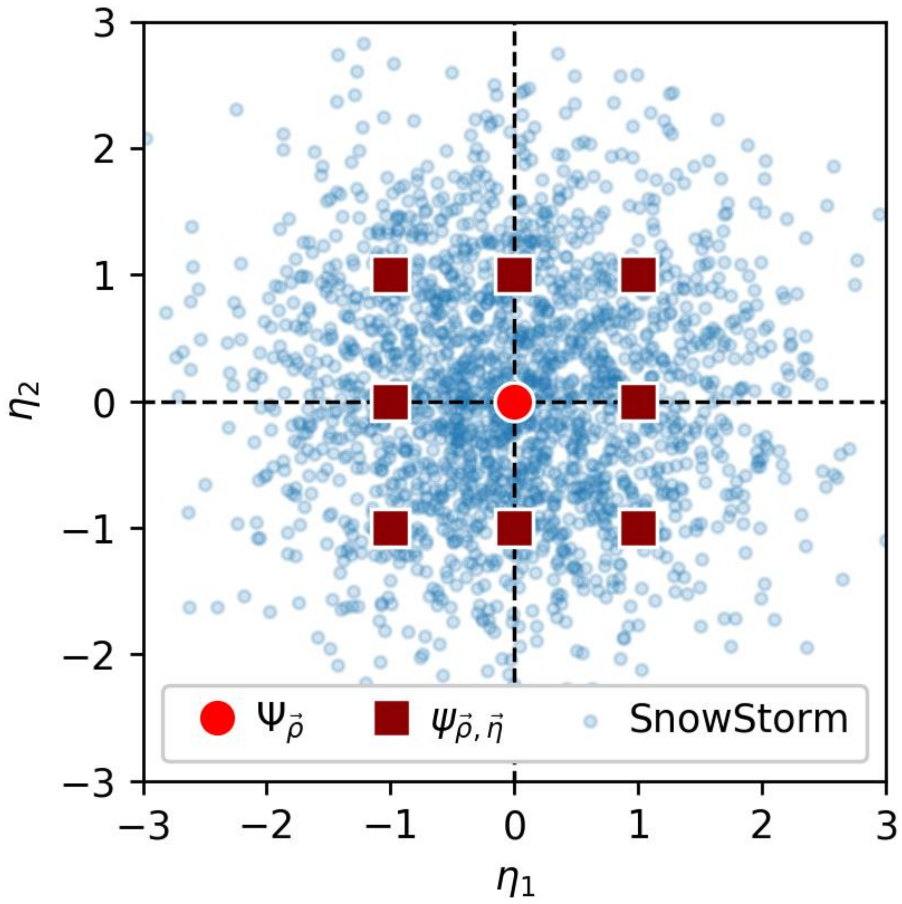
- SnowStorm is a method for producing Simulations and for treating systematic uncertainties in an analysis
  - When comparing a model prediction (based on simulations) to data one must account for statistical and systematic uncertainties:
    - Statistic: how much simulation do we have, how much data have we measured?
    - Systematic: one must assume some detector response functions during simulation; how do these assumptions influence the analysis?

- Described in detail in the SnowStorm technical paper “Efficient propagation of systematic uncertainties from calibration to analysis with the SnowStorm method in IceCube” (arxiv)

“Standard” Simulation and Systematic treatment

One option for treating/evaluating the effect of systematic uncertainties:

- Decide for some baseline model/parameters (η_1, η_2) that model/describe the detector response
- Produce a simulation (MC) set for this choice (red circle)
  - This set can be used as the “default/baseline“ model prediction in the analysis
- Produce additional sets with the detector response (parameters) varied (red squares)
- Find some way to interpolate between these discrete sets to model the effect of a varied detector response compared to the baseline model



Detector Systematic - Example

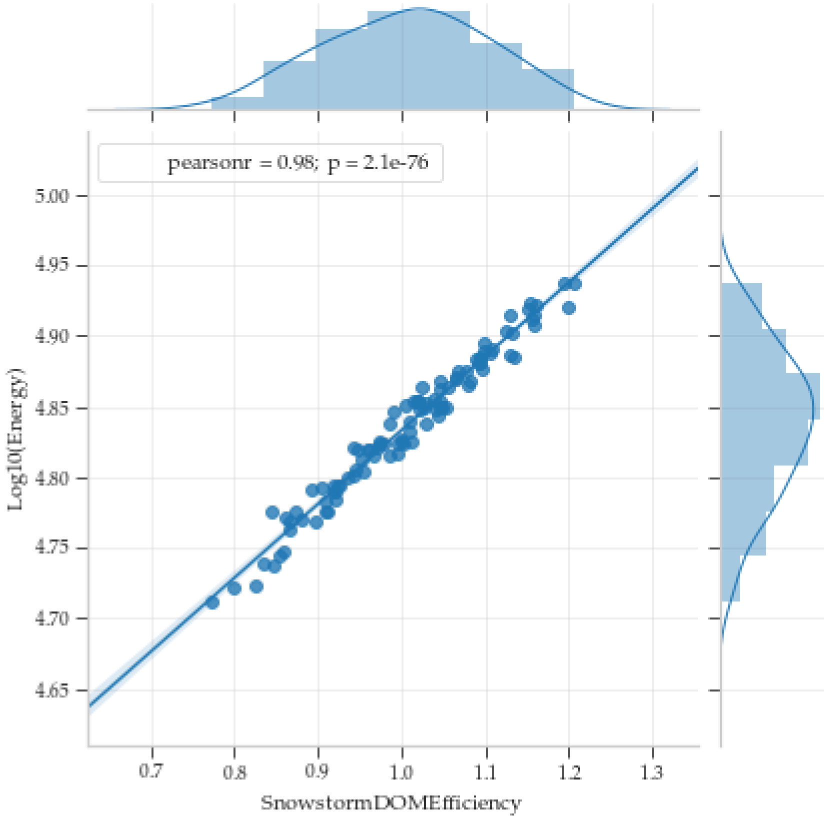
Re-simulating the same event (cascade) several times but using a different detector response model each time:
Reconstructed energy vs. "DOM Efficiency"

DOM Efficiency or optical efficiency:

- scale the overall detection efficiency of IceCube DOMs (e.g. due to errors/offsets in calibration)
- Higher values increase the detection efficiency, thus more light is "seen" by IceCube

The reconstruction does not know what the chosen DOM efficiency is (was)

➢ Reconstructed energy is higher for events that were simulated with a higher optical efficiency



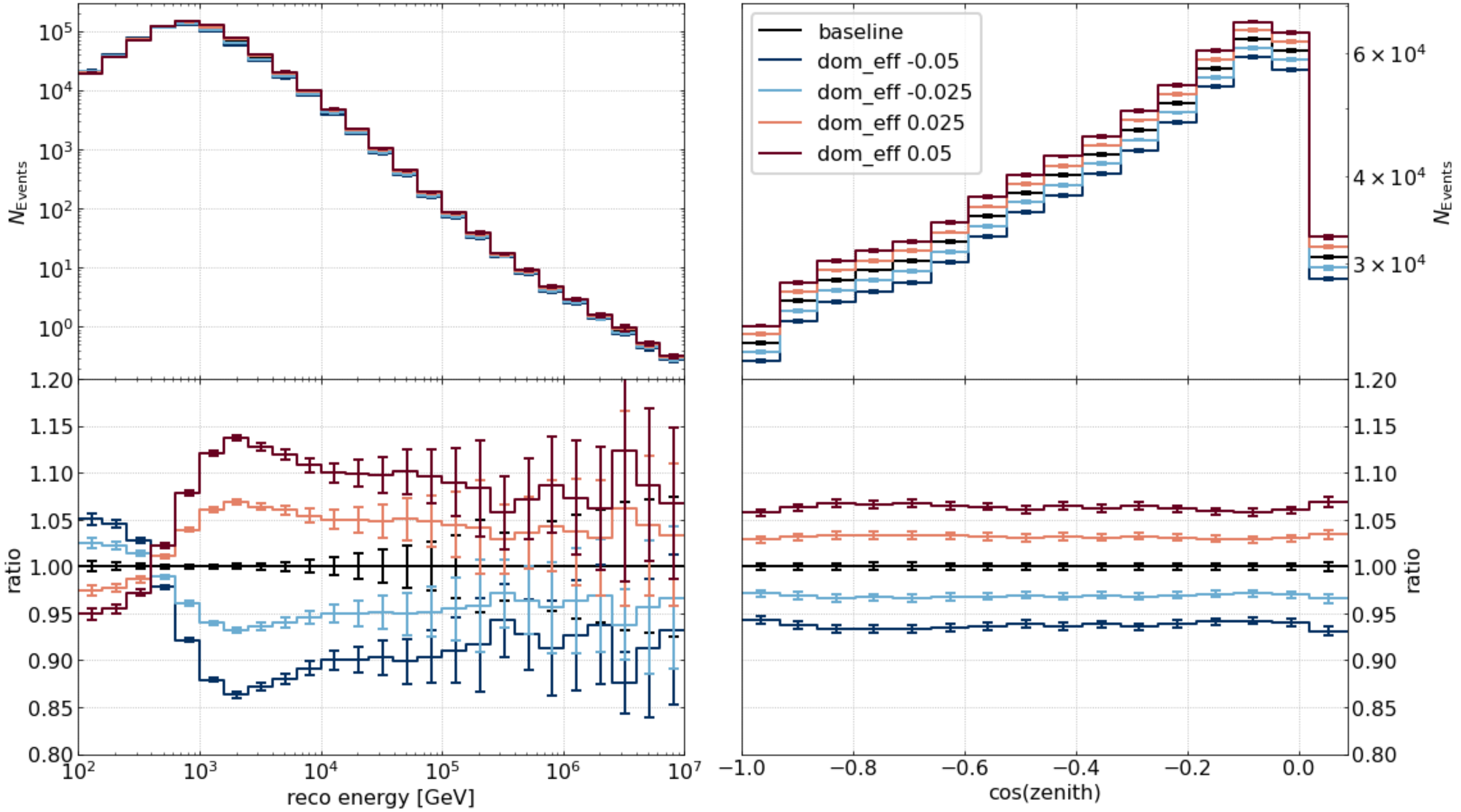
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

Detector Systematic – Example 2

Similar example but now not on single event basis but for a the expected (diffuse) energy and zenith spectrum for an event selection focused on through.going muon tracks

- Similar effect as before, however, more complicated in the low energy region

➢ Detector systmetics might change the MC expectation quite a bit: it is important to allow/account for some variance

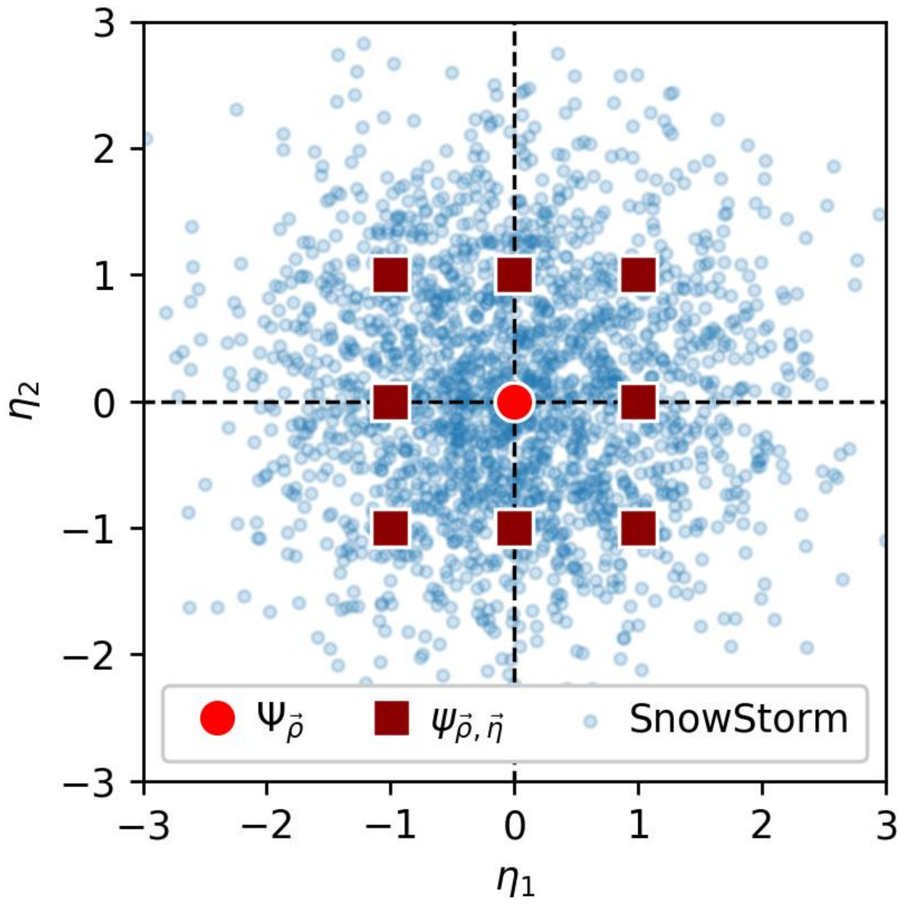


“Standard” Simulation and Systematic treatment

Classical approach of using a baseline + multiple “discrete” systematic sets has some limits:

- There is more than just the optical efficiency: absorption and scattering of photons in the glacial ice, “hole-ice” model of re-frozen string holes after drilling, …
- Need at least 2 additional sets for each systematic
- Vary more than one systematic at once to account for correlations?

➢ SnowStorm



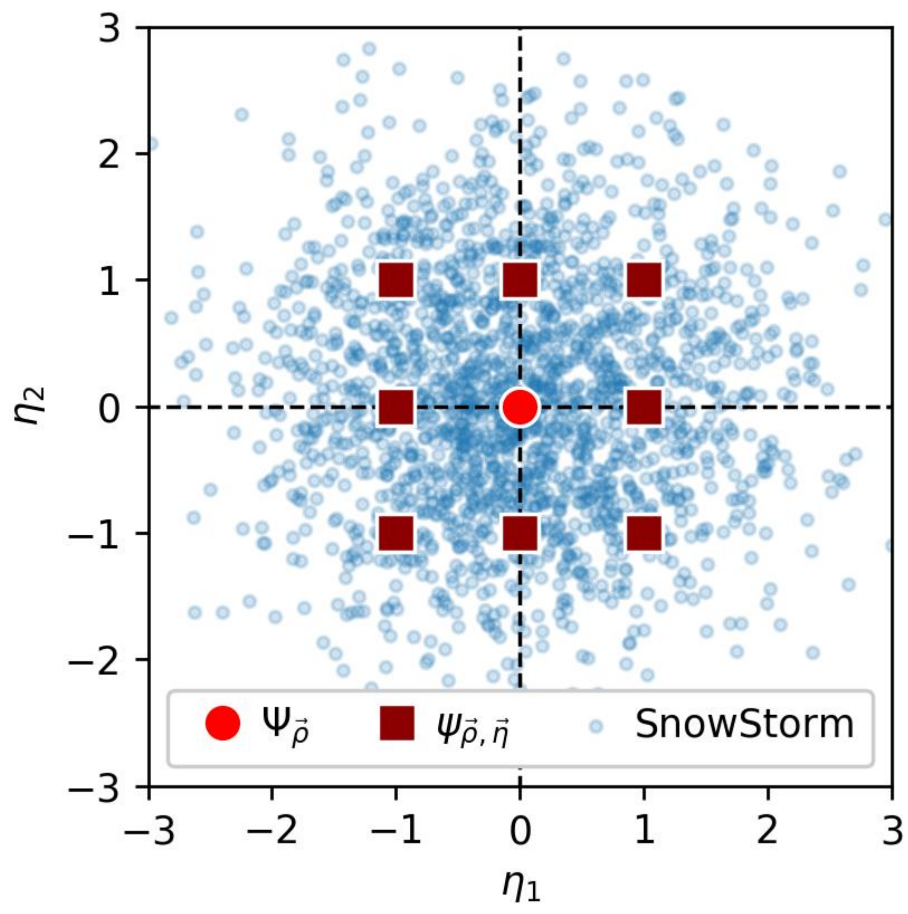
What is SnowStorm?

"Standard method": producing large(r) individual simulation sets with a discrete choice of detector systematics (red circle + squares)

SnowStorm method: Vary the detector response on an event-to-event level and sample a combinaton of (nusicance) parameters modelling the detector response from some given distribution (blue dots)

- So called "SnowStorm event ensemble"
- Each event has its one detector response
- The (allowed) phase-space covered by the ensemble depends on the choice of sampling distributions/ranges (here: Gaussian)

➢ The ensemble can be multi-dimensional and include multiple systematic parameters at once!



How does it work?

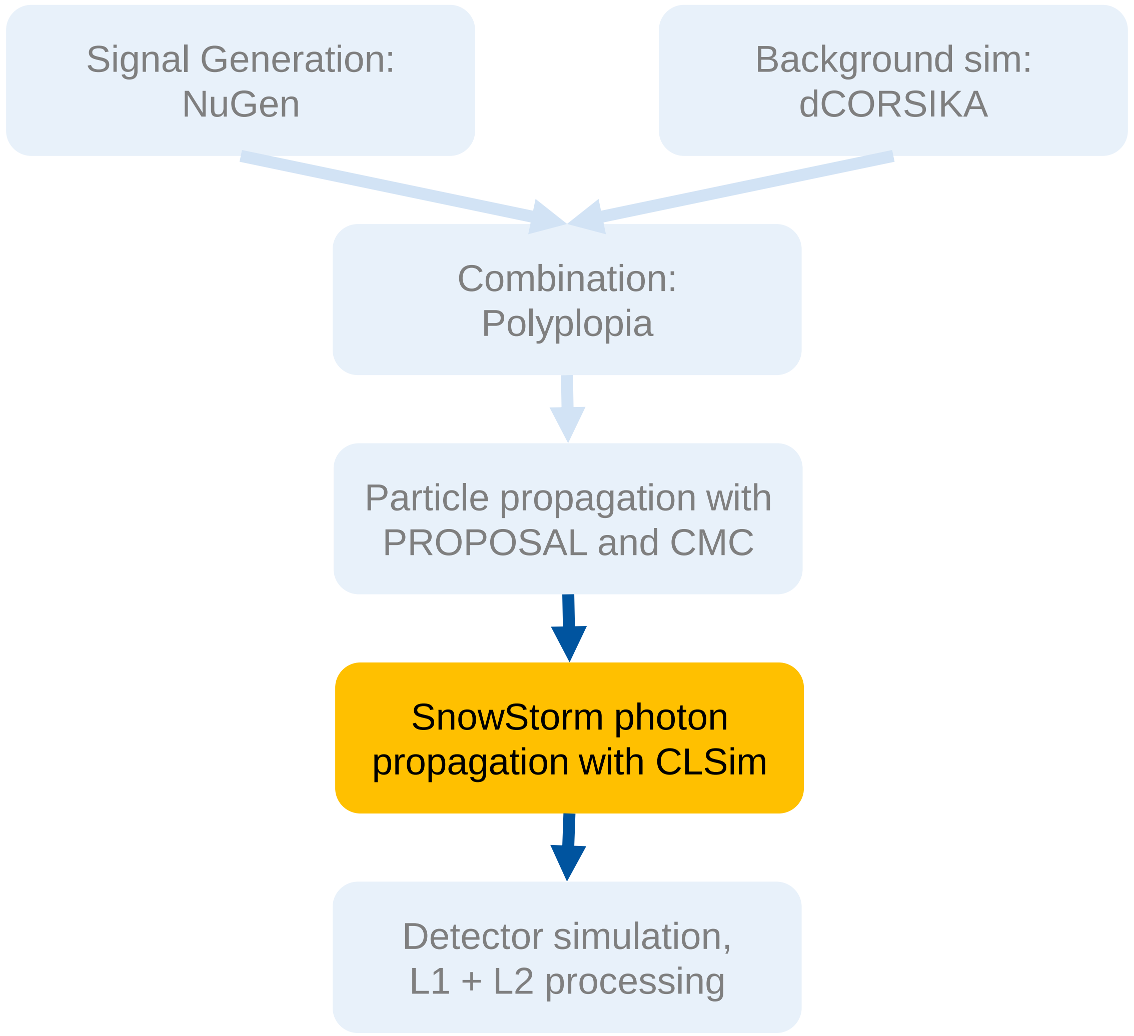
- No need to create multiple discrete systematic sets but a single SnowStorm event ensemble only
- Event ensemble can include multiple systematic parameters at the same time

- Depends on a choice of what parameters to include (vary) and how to vary them (choice of sampling distribution)
  - Table lists the currently supported ones
- No need for interpolating between multiple discrete sets, but one still needs a method to make use of the varied parameters
  - Details/options later

Systematic/Parametrization	Parameter(s)
IceWavePlusModes	12 amplitude + 12 phase shifts
Scattering	Global scaling
Absorption	Global scaling
AnisotropyScale	Strength scaling
DOMEfficiency	Global scaling
HoleIceForward_Unified	p0, p1
HoleIceForward_MSU	p1, p2

How does it work? – Some technical background

- The SnowStorm "magic" happens during photon propagation:
  - Application of a "SnowStorm perturber" that varies the detector response (and ice model) by using pre-defined parametrizations
  - For performance reasons this is not done for each individual event but for a "bunch" of 100-1000 events
- Software locations:
  - `snowstorm` software project within icetray
    - Parametrizations + perturber
  - `SnowSuite` script collection in simprod-scripts
    - Includes the script for running the actual photon propagation step
  - SnowStorm software documentation



SnowStorm – Available Simulation Sets

SnowStorm simulation sets have been produced for the diffuse GlobalFit, but are also meant for general use!

- Parameters + Sampling ranges chosen based recommendations of the calibration groups and parameters used in previous IceCube analyses (using the approach of multiple discrete sets)

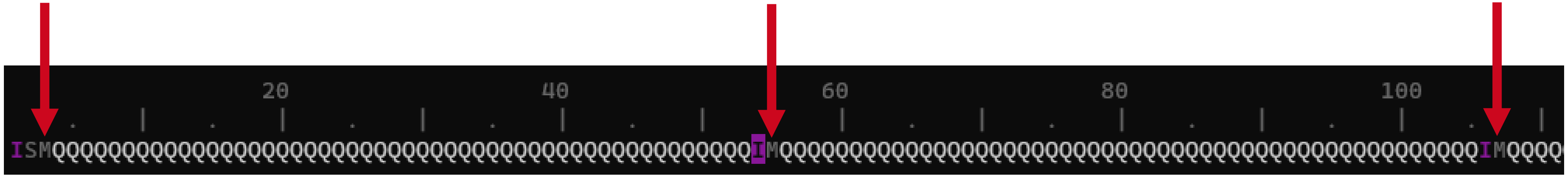
Systematic	Sampling Distribution	Sampling Range
Scattering	uniform	[0.9, 1.1]
Absorption	uniform	[0.9, 1.1]
AnisotropyScale	uniform	[0.0, 2.0] (= 0-15%)
DOMEfficiency	uniform	[0.9, 1.1]
HoleIceForward_Unified	uniform	p0 [-0.84, +0.3] p1 [-0.134, +0.05]

SnowStorm – Parameter Book-keeping

Book-kepping of the sampled/used parameters (and their sampling distributions) is done in additional “M(odel)” frames in the i3files:

- M-frames are inserted during simulation whenever new values get sampled (every 100-1000 events)
- Most important content: SnowstormParameterDict:
  - Dictionary mapping parameter_name: value

Name	Type
AngularAcceptance	I3CLSimFunctionPolynomial
MediumProperties	I3CLSimMediumProperties
SnowstormEventsPerModel	I3PODHolder<unsigned long>
SnowstormParameterDict	I3Map<__cxx11::string, double>
SnowstormParameterRanges	I3Vector<pair<unsigned long, unsigned long> >
SnowstormParameters	I3Vector<double>
SnowstormParametrizations	I3Vector<__cxx11::string >
SnowstormProposalDistribution	snowstorm::Composite
WavelengthAcceptance	I3Map<OMKey, boost::shared_ptr<I3CLSimFunction const> >
WavelengthGenerationBias	I3CLSimFunctionFromTable

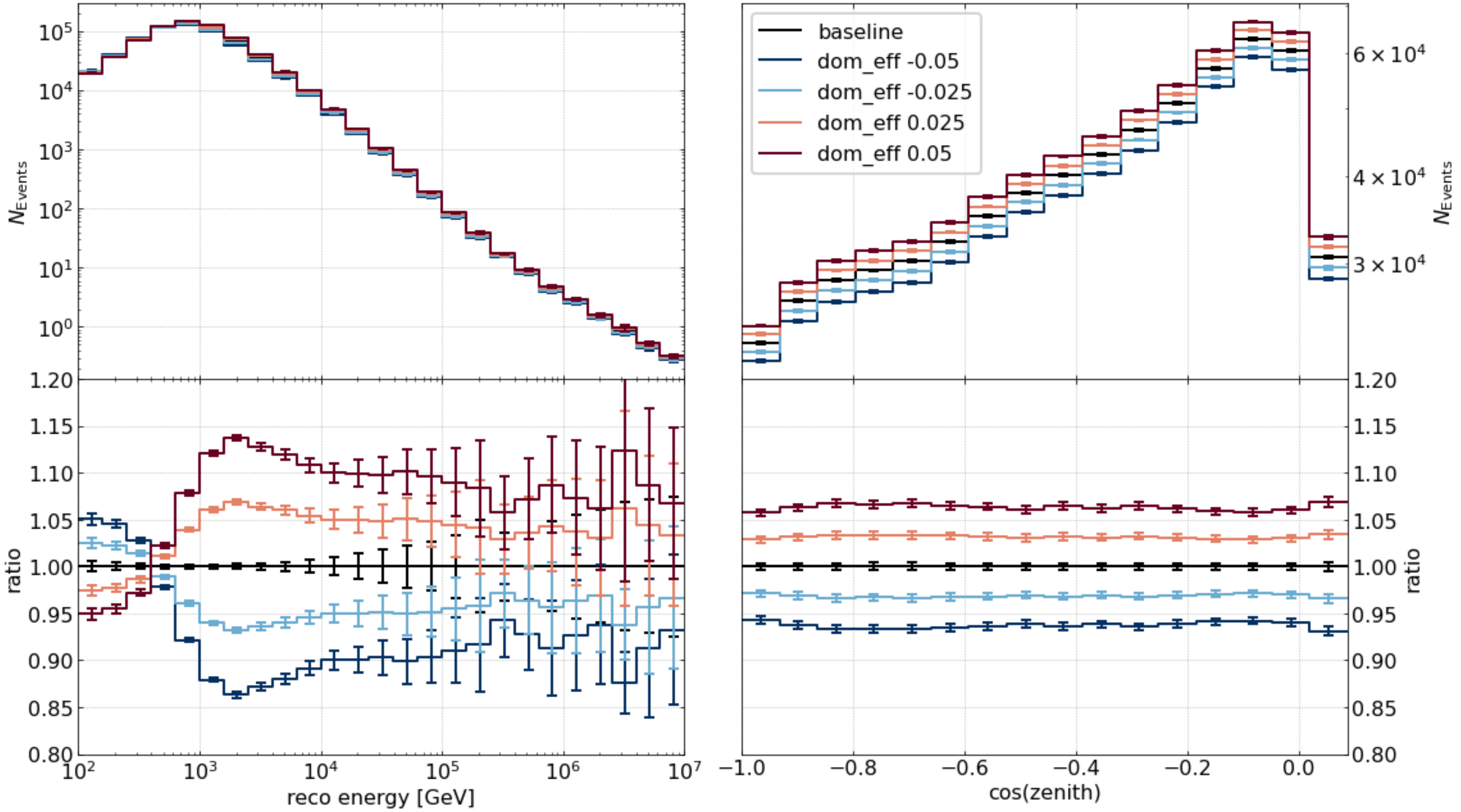


SnowStorm Event Ensemble – How to Use It

How to obtain the MC prediction for a given (discrete) choice ofsysteamtic parameter values from the ensemble?

Example show different values of DOM/optical efficiency, but how does was it done/made?

- There is not “one method to rule them all”
- Rather new simulation technique, different methods/options still under development/testing

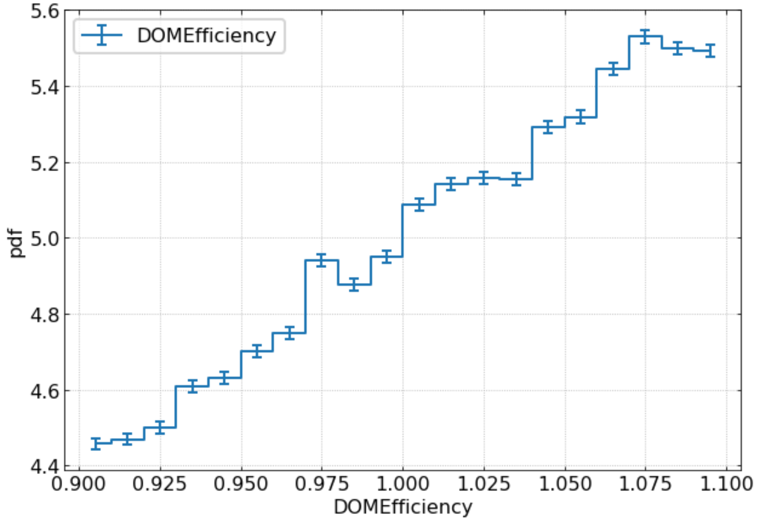


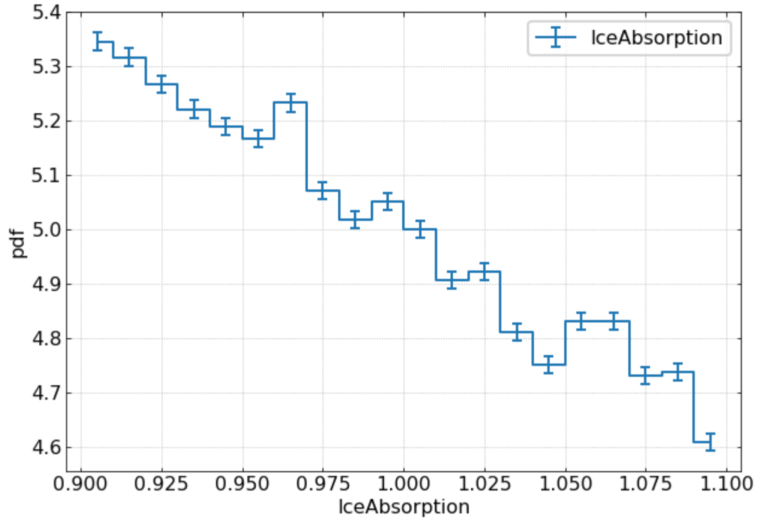
SnowStorm Event Ensemble – How to Use It

The SnowStorm event ensemble yields to a continuous function/distribution of observables/events with respect to the systematic parameters on the final analysis level

Plots show this distribution for the optical efficiency (top) and ice absorption (bottom) for the through-going muon track sample

- Not uniform anymore: This is the effect of the systematic for the event selection
- One could use only events in an (infinite) small range of each parameter
  - This greatly reduces the MC statistic as most events are discarded





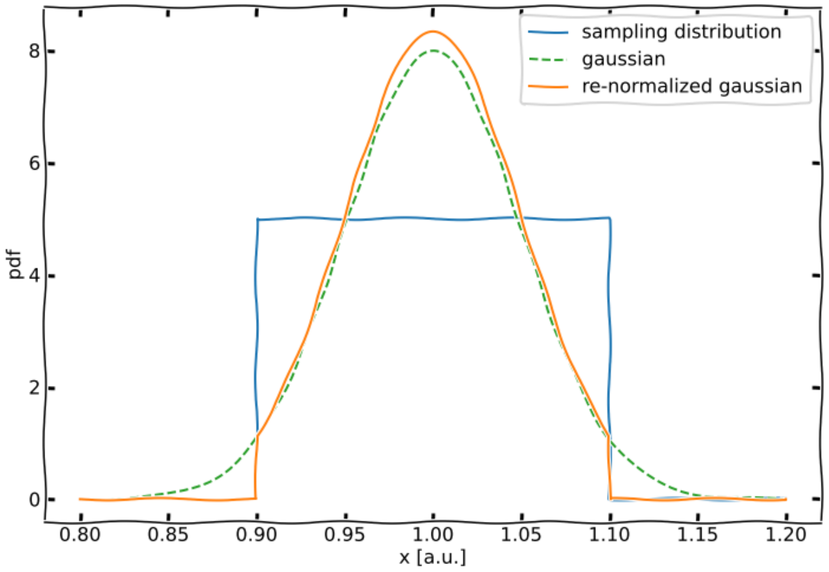
SnowStorm – Detector Systematic Reweighting

One option: re-weight the event ensemble to e.g., a normal/Gauss distribution on the final analysis level.

This can easily be done by adding an (additional) weight to each event which is given by

$$w_i = \frac{p_{sys}\left(sys_i, \xi_i\right)}{p_{sys}^{sim}(sys_i)} \cdot \ldots$$

p_{sys}: reweighting distribution
p_{sys}^{sim}: sampling distribution
sys_i: event's systematic value
ξ_i: nuisance parameter



- Make sure to re-normalize the re-weighting kernel wrt. the initial sampling distribution
- Reweighting-factor is independent of e.g., the analysis binning!

SnowStorm – Detector Systematic Reweighting

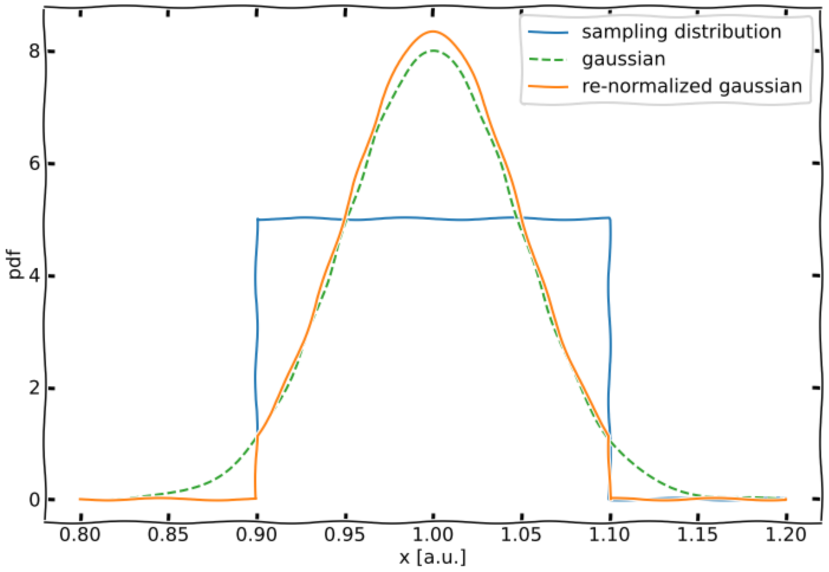
One option: re-weight the event ensemble to e.g., a normal/Gauss distribution on the final analysis level.

This can easily be done by adding an (additional) weight to each event which is given by

$$w_i = \frac{p_{sys}\,(sys_i, \xi_i)}{p_{sys}^{sim}(sys_i)} \cdot \ldots$$

p_{sys}: reweighting distribution
p_{sys}^{sim}: sampling distribution
sys_i: event′s systematic value
ξ_i: nuisance parameter

- Make sure to re-normalize the re-weighting kernel wrt. the initial sampling distribution
- Reweighting-factor is independent of e.g., the analysis binning!



- Multidimensional re-weighting can take correlations between the parameters into account
  - re-weighting kernel in each dimension must be “sufficiently small”
- Choice of the re-weighting distribution? What width to choose for the Gauss kernel?

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

SnowStorm – Gradient Method

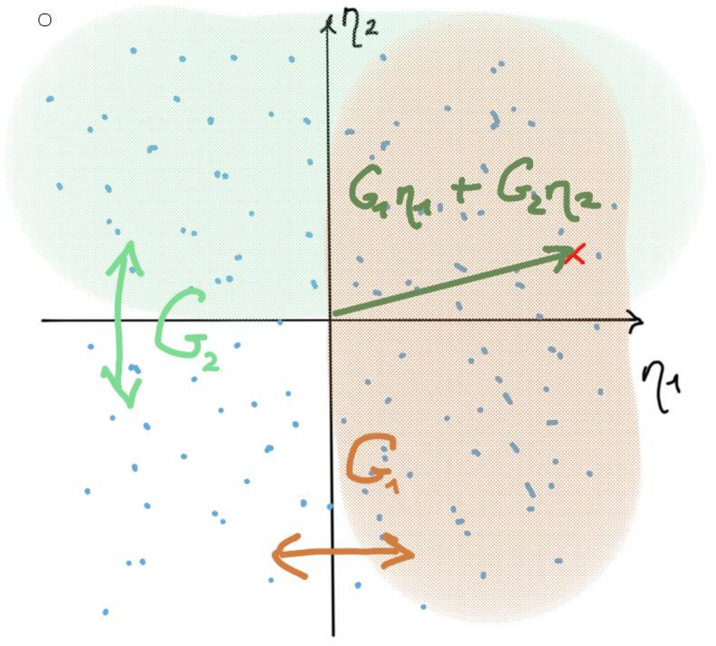
Described in the paper: use of the SnowStorm event ensemble to extract the „nuisance parameter gradient vector“:

- Split the ensemble in half (at central value)
- Calculate "upper" and "lower" prediction to calculate the gradient with respect to the nuisance parameter the split was performed for:

$$G_{\vec{\rho},i} = \frac{1}{\sigma}\sqrt{\frac{\pi}{2}}\left(\psi_{\vec{\rho}}^{i+} - \psi_{\vec{\rho}}^{i-}\right)$$

- Repeat for all (systematic) nuisance parameters
- Prediction for a specific (discrete) choice of the nuisance parameter values is then given by

$$\psi_{\vec{\rho},\vec{\eta}} = \Psi_{\vec{\rho}} + \vec{\eta}.\vec{G}_{\vec{\rho}}$$



SnowStorm – Gradient Method

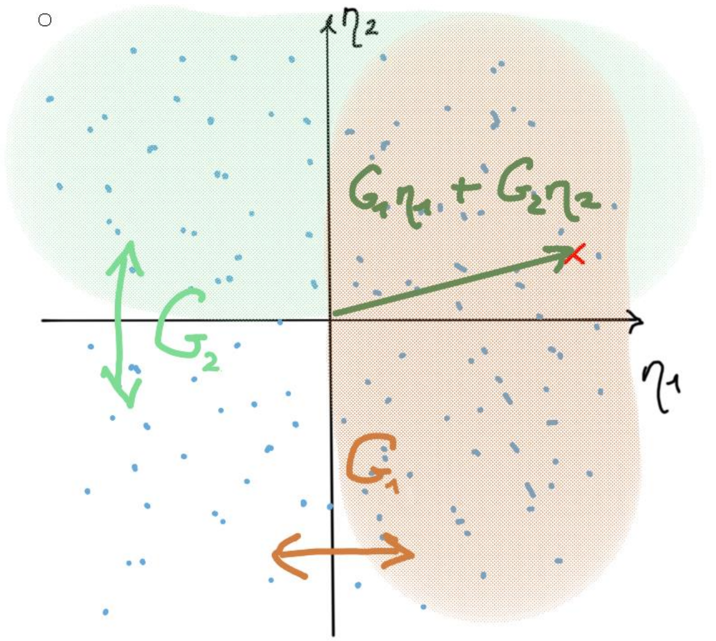
Described in the paper: use of the SnowStorm event ensemble to extract the „nuisance parameter gradient vector“:

- Split the ensemble in half (at central value)
- Calculate “upper” and “lower” prediction to calculate the gradient with respect to the nuisance parameter the split was performed for:

$$G_{\vec{\rho},i} = \frac{1}{\sigma}\sqrt{\frac{\pi}{2}}\left(\psi_{\vec{\rho}}^{i+} - \psi_{\vec{\rho}}^{i-}\right)$$

- Repeat for all (systematic) nuisance parameters
- Prediction for a specific (discrete) choice of the nuisance parameter values is then given by

$$\psi_{\vec{\rho},\vec{\eta}} = \Psi_{\vec{\rho}} + \vec{\eta}.\vec{G}_{\vec{\rho}}$$



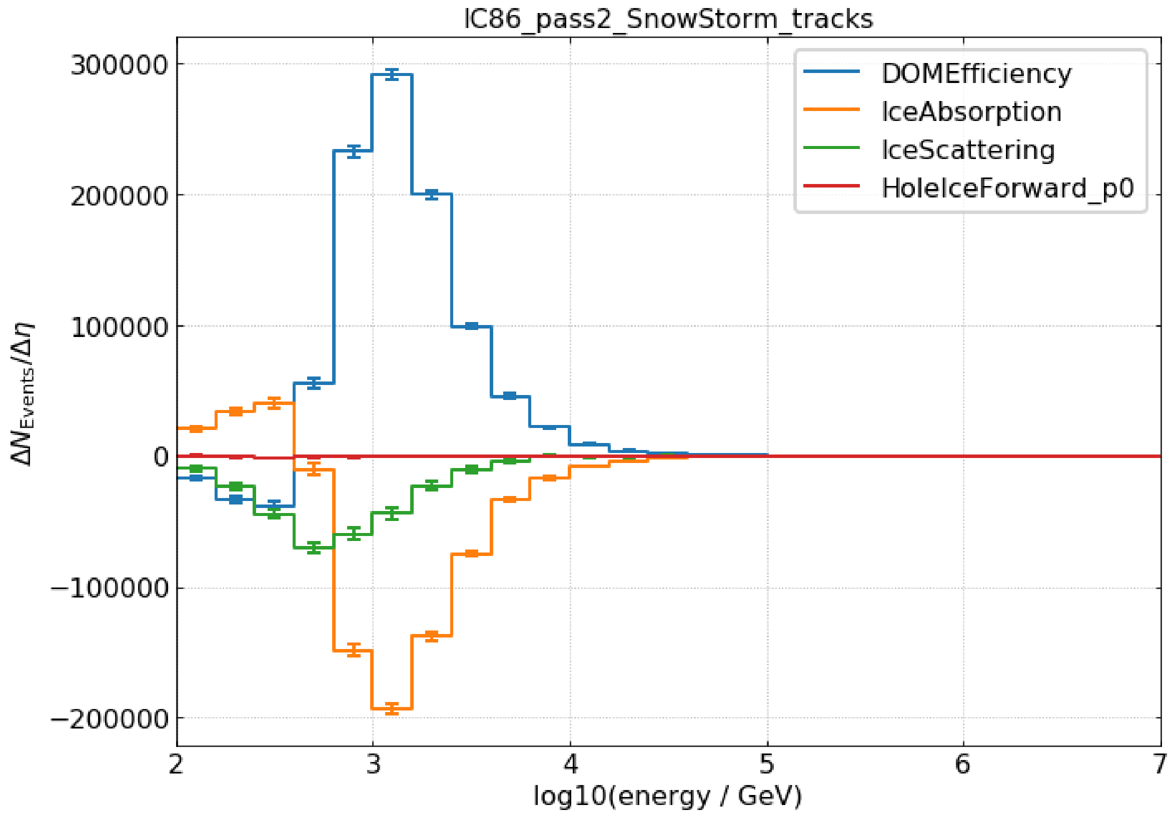
- (Only) a first order, linear approximation
- Unit: events per parameter change
- Calculated for one specific binning + observable
- Can also take correlations into account (not discussed here but in the paper)

SnowStorm – Gradient Example

Visualization of the gradient vector for different detector systematic parameters (again for the through-going muon track sample)

- Gradient calculated for a 2D histogram of energy/zenith but here only the 1D projection is shown
- Unit of the y axis!
- One can directly see/check for what a specific nuisance parameter does/how it compares to another one

➢ One still needs a “baseline” set to apply the Gradient to
  ➢ Assuming linearity one can use the full SnowStorm ensemble (without re-weighting/splitting) but has to show that this assumption is valid (paper)



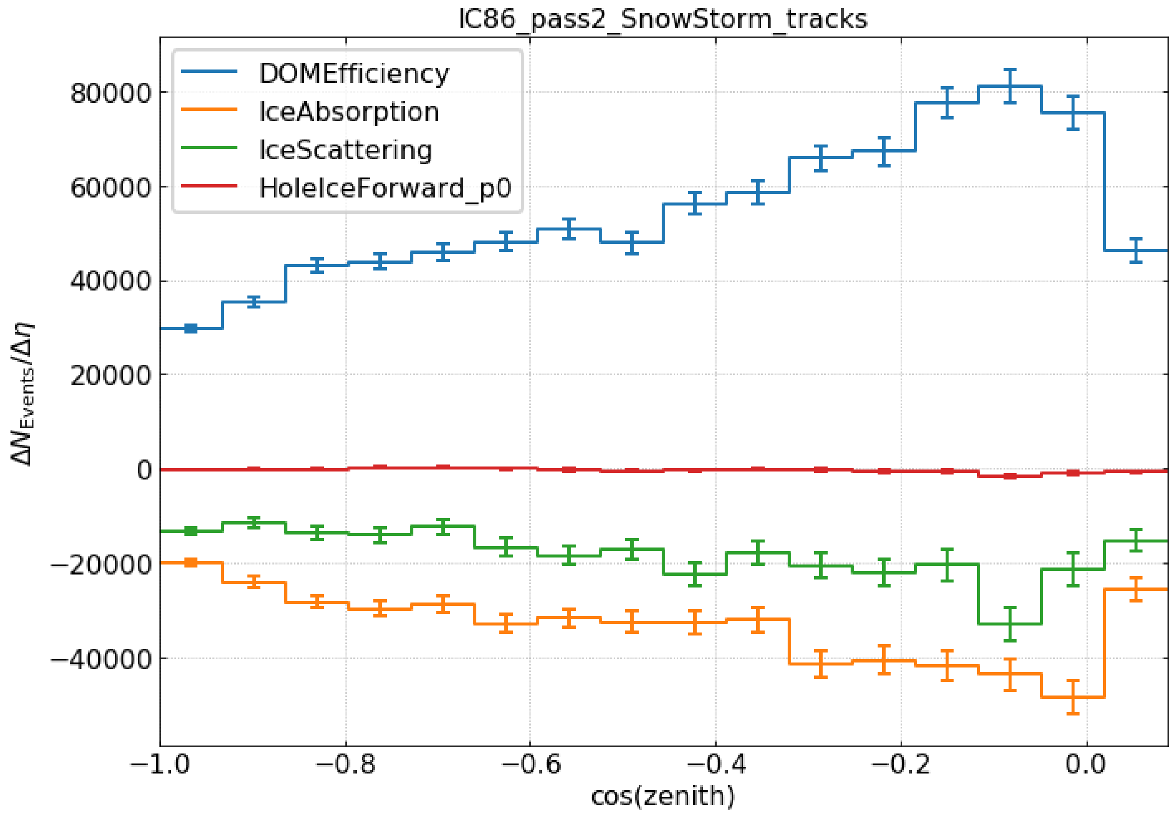
SnowStorm – Gradient Example

Visualization of the gradient vector for different detector systematic parameters (again for the through-going muon track sample)

- Gradient calculated for a 2D histogram of energy/zenith but here only the 1D projection is shown
- Unit of the y axis!
- One can directly see/check for what a specific nuisance parameter does/how it compares to another one

➢ One still needs a “baseline” set to apply the Gradient to

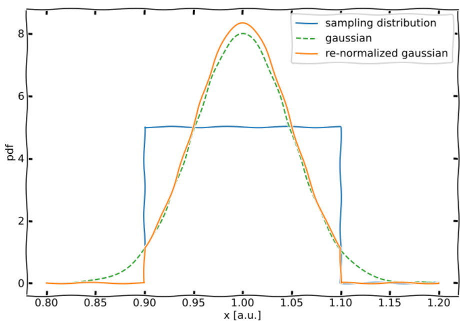
  ➢ Assuming linearity one can use the full SnowStorm ensemble (without re-weighting/splitting) but has to show that this assumption is valid (paper)

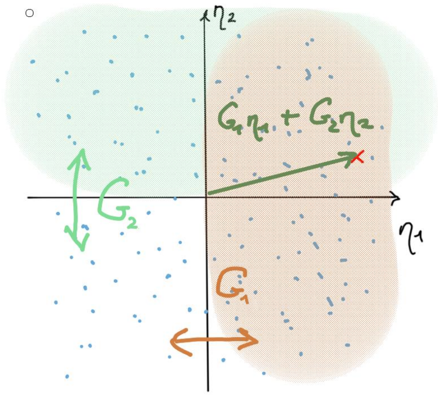


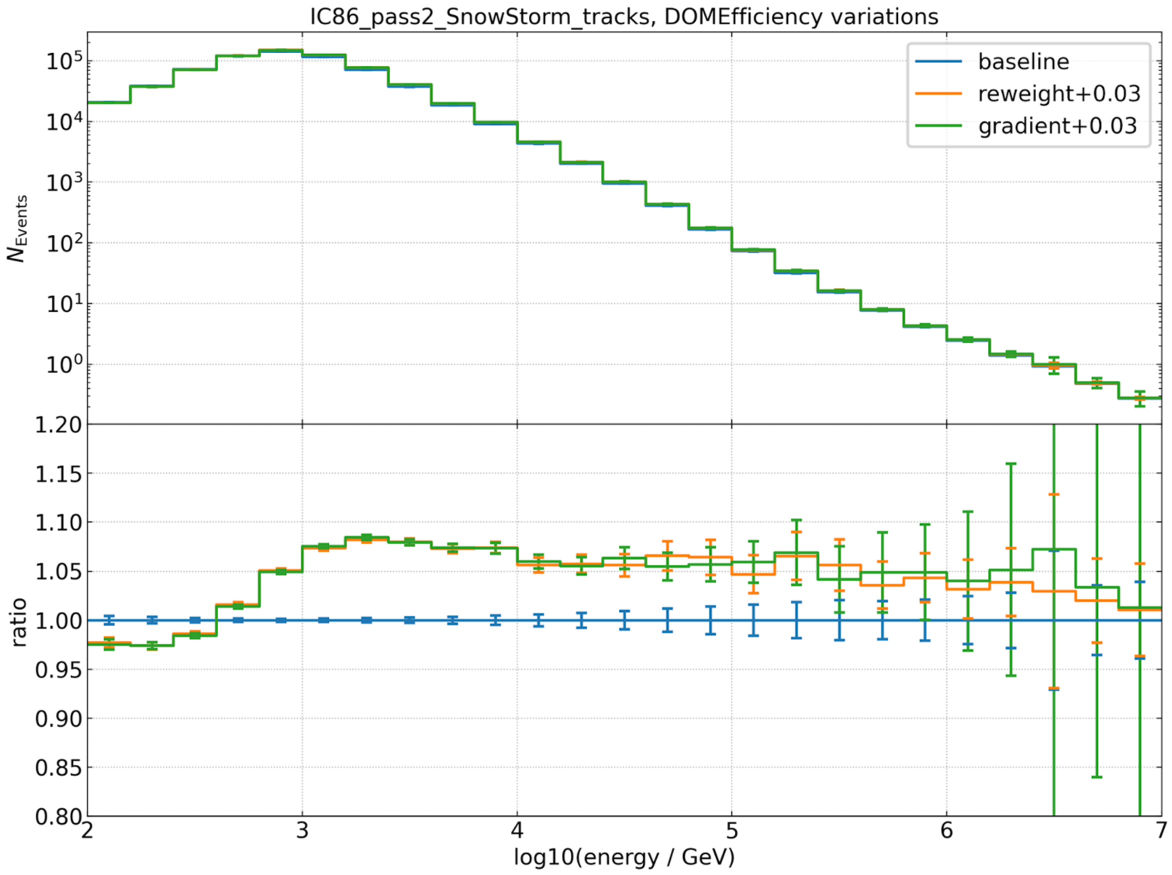
SnowStorm – Quick Method Comparison

Model the effect of a +3% shift in the optical efficiency with the re-weighting method (orange) and the gradient approach (green) compared to the full ensemble baseline prediction (blue)

- Predictions agree very well
  - For this particular event selection and choice of observalbles (reconstructed energy)
- “Go to” method may vary for different analyses using different event selctions/observables



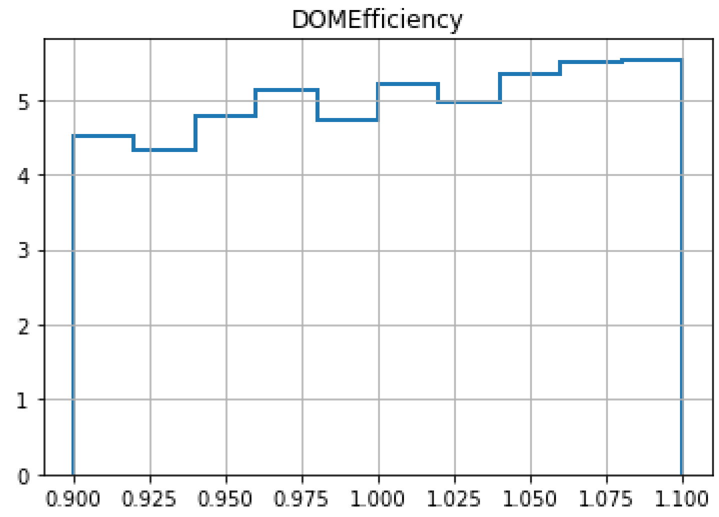




SnowStorm – Optional Hands On

- I put together a small dataset (=SnowStorm event ensemble) of the through-going muon track (diffusenumu/northern track sample):
  - `/data/user/eganster/shared/bootcamp/dataset_tracks_bootcamp_small.hdf`
  - Single pandas dataframe containing MC truth, some reconstruction and the sampled/used systematic parameter values

				energy_muex	energy_muex_exists	reco_dir_fit_status	reco_dir_exists	zenith_MPEFit	azimuth_MPEFit	energy_truncated_exists	energy_truncated
22016	0	3904	0	1240.216316	1	0	1	2.288008	4.495579	1	644.542156
		5548	0	653.793635	1	0	1	1.755745	2.417271	1	375.046623
		5876	0	567.649429	1	0	1	2.523353	0.436347	0	0.000000
		6111	0	3574.341472	1	0	1	1.758717	0.403047	1	5731.928145
		7029	0	832.776642	1	0	1	1.907874	3.268694	1	539.683864
		10128	0	479.433754	1	0	1	1.775588	4.547529	1	242.326742
		10216	0	697.287331	1	0	1	1.834690	3.500862	1	415.035267
		11900	0	1293.554835	1	0	1	1.880129	4.162371	1	4063.305791
		13286	0	1038.693077	1	0	1	2.970344	0.831079	1	845.156450
		13796	2	412.656463	1	0	1	2.349261	5.695556	1	350.391403



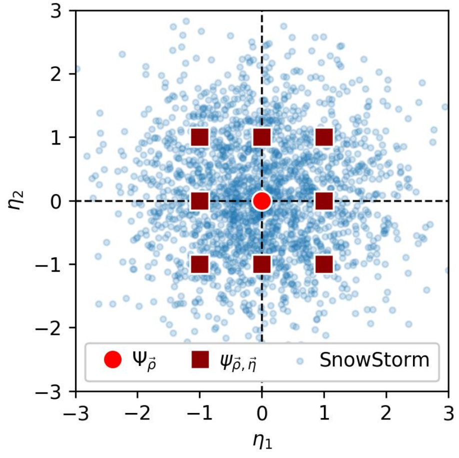
SnowStorm - Summary

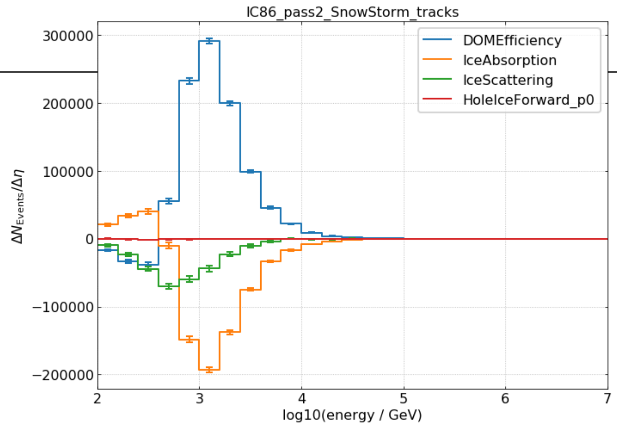
- SnowStorm: Method for efficient simulation + propagation of systematic uncertainties for an analysis

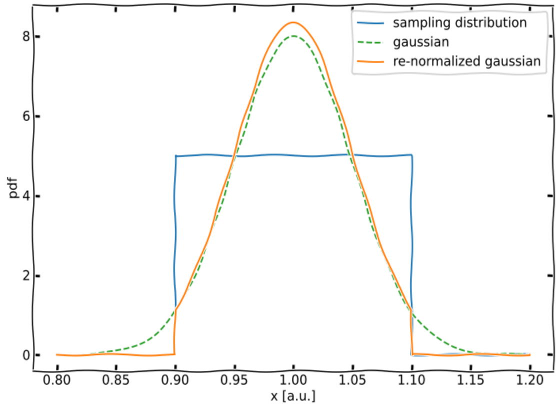
- Single SnowStorm event ensemble opposed to multiple discrete simulation sets

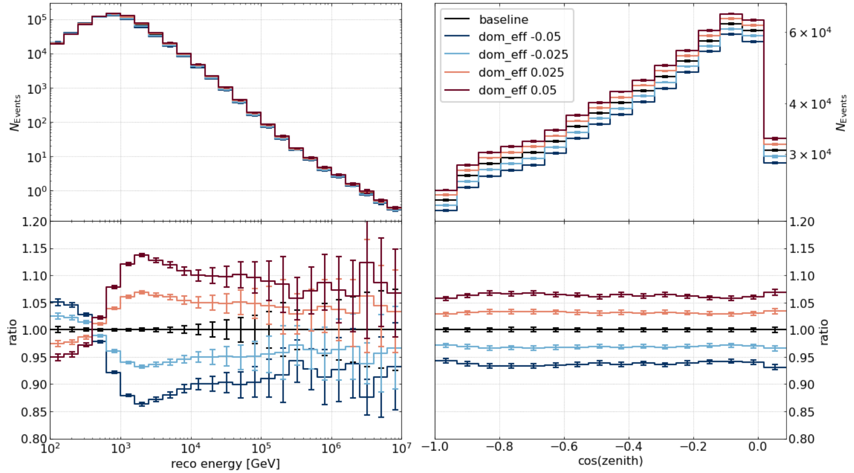
- Different “How to Use” methods for this ensemble: re-weighting and gradient approach
  - Not discussed here, but the ensemble can also be used in machine learning

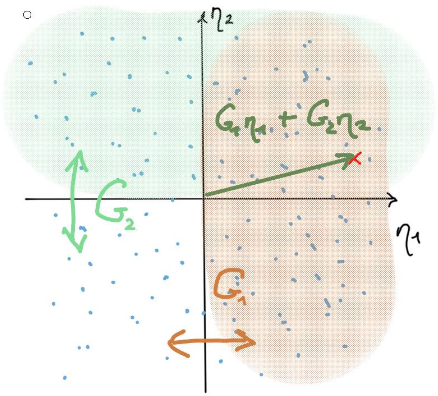
- One option for systematic treatment in your analysis? ☺











ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Appendix

SnowStorm Simulation Sets – How To use them

- All SnowStorm parameters, ice-model settings, etc. are stored in M and S frames
  - All SnowStorm simulations can be processed/used in the same way as previous/other NuGen simulations
  - ➢ Make sure to not drop M+S frames during further processing of the files

- You can use any recent combo/icetray version for processing that can deal with custom frame types
  - combo/V01-00-02 was used for production which is available in /cvmfs/icecube.opensciencegrid.org/…

SnowStorm Simulation Sets – How To use them

- All SnowStorm parameters, ice-model settings, etc. are stored in (new) M and S frames
  - All SnowStorm simulations can be processed/used in the same way as previous/other NuGen simulations
  - ➢ Make sure to not drop M+S frames during further processing of the files

- You can use any recent combo/icetray version for processing that can deal with custom frame types
  - combo/V01-00-02 was used for production which is available in /cvmfs/icecube.opensciencegrid.org/…

- S-Frame:
  - Only one per file
  - Simulation frame for bookkeeping:
    - initialized SnowStorm parametrizations (parameters)
    - SnowStorm sampling distributions

SnowStorm Simulation Sets – How To use them

- All SnowStorm parameters, ice-model settings, etc. are stored in (new) M and S frames
  - All SnowStorm simulations can be processed/used in the same way as previous/other NuGen simulations
  - ➢ Make sure to not drop M+S frames during further processing of the files
- You can use any recent combo/icetray version for processing that can deal with custom frame types
  - combo/V01-00-02 was used for production which is available in /cvmfs/icecube.opensciencegrid.org/…

- S-Frame:
  - Only one per file
  - Simulation frame for bookkeeping:
    - initialized SnowStorm parametrizations (parameters)
    - SnowStorm sampling distributions
- M-Frame:
  - One per every “bunch” of events
  - Sampled SnowStorm parameters
    - It also tells you how many events/frames the ice-model was applied to during simulation (before triggering)